

Experimental Investigation of Hypervelocity Shock Wave–Boundary-Layer Interactions on a Deflected Control Surface

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ABSTRACT

Three-dimensional shock wave–boundary-layer interactions generated by a cone–slice-ramp geometry were experimentally investigated in the T5 Free-Piston Reflected Shock Tunnel. Four air test conditions were examined, spanning $Re_{edge} = 2 \times 10^6$ to $6 \times 10^6 \text{ m}^{-1}$ at nominal $h_0 = 8 \text{ MJ kg}^{-1}$, with one higher enthalpy condition at $h_0 = 14 \text{ MJ kg}^{-1}$ and $Re_{edge} = 3 \times 10^6 \text{ m}^{-1}$. Surface heat flux measurements, high-speed schlieren imaging, focused laser differential interferometry, and surface dynamic pressure measurements were used to characterize the mean interaction, surface heating, and separated shear layer unsteadiness.

The test conditions produced both laminar and transitional incoming boundary layers, with separated shear layers that either remained laminar or transitioned within the separation region. Increasing unit Reynolds number at $h_0 = 8 \text{ MJ kg}^{-1}$ promoted earlier transition within the separated shear layer, reducing the separation extent and altering both the streamwise and spanwise heating distributions on the ramp. For all test cases, the reattached flow transitioned to turbulence on the ramp surface, and peak streamwise heating was measured in this turbulent region downstream of reattachment. Increasing stagnation enthalpy at constant unit Reynolds number delayed transition onset, causing the separated shear layer to remain laminar and increasing the separation extent.

A separated shear layer instability was observed whose dominant frequency decreased and whose amplitude increased downstream. These disturbances appeared above the separated shear layer as Mach radiation and inside the separation bubble as coherent wave-like density gradient structures. The instability frequencies were not collapsed by either Rossiter-type scaling based on the separated shear layer length or Kelvin-Helmholtz scaling based on the separated shear layer thickness. In contrast, wall-normal acoustic scaling based on the shear layer height above the wall collapsed the dominant frequencies upstream of the ramp, suggesting acoustic communication between the separated shear layer and the model surface. Downstream of the ramp leading edge, this scaling breaks down and the phase relationship between structures inside and above the separation bubble changes, indicating that a different, presently unresolved mechanism influences the downstream shear layer instability.

PUBLISHED CONTENT AND CONTRIBUTIONS

The articles below contain material that is adapted for parts of this thesis. The author is the primary contributor for experiments, post-processing of experimental data, and analysis and interpretation of the data.

Stramenga, Michael et al. (Jan. 2025). “Separation Region Instabilities in Hypervelocity Flow on a Cone-Slice-Ramp”. In: *AIAA SCITECH 2025 Forum*. American Institute of Aeronautics and Astronautics. DOI: [10.2514/6.2025-2215](https://doi.org/10.2514/6.2025-2215). URL: <http://dx.doi.org/10.2514/6.2025-2215>.

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Chapter 1

INTRODUCTION

1.1 Motivation

Shock wave-boundary-layer interaction (SBLI) can create complex, potentially unsteady, flow regions that can impose highly localized heating and pressure loads on a super/hypersonic vehicle (Clemens and Narayanaswamy, 2014; Dolling, 2001). SBLI may occur near deflected control surfaces, where the adverse pressure gradient can result in boundary layer separation from the vehicle surface, with the separated shear layer subsequently impinging downstream. Flow separation can reduce control authority, increase unsteady surface loading, and generate highly localized heating near or downstream of reattachment. In hypersonic flight, these shock-dominated flows are also susceptible to real gas (thermochemical) effects, both in the mean flow and unsteady interactions.

SBLIs have been the subject of extensive studies. Comprehensive reviews of both two and three-dimensional interactions, particularly at supersonic conditions, can be found in Babinsky and Harvey, 2011; Dolling, 2001; Gaitonde and Adler, 2023; Sabnis and Babinsky, 2023. The present discussion focuses on summarizing the recent work most relevant to the current experiments.

1.2 Cone-Slice-Ramp Geometry

During flight, vehicle control surfaces are subject to inherently three-dimensional SBLI effects. Recommendations have therefore been made for future SBLI studies to place greater emphasis on flight relevant three-dimensional geometries, helping bridge the gap between insights gained from two-dimensional canonical studies and flight (Dolling, 2001; Settles and Dodson, 1994). One geometry developed to address this need for three-dimensional SBLI data was the Computational/Experimental Aerodynamics Program (JCEAP, or Oberkampf) model (Oberkampf and Roy, 2013; Oberkampf and Aeschliman, 1992b). This model consists of a slender cone with a horizontal slice cut into its aft end, over which a ramp spans the top of the slice to emulate a deflected control surface. This configuration is referred to hereafter as the cone-slice-ramp geometry. A flow feature unique to this geometry, relative to two-dimensional SBLI configurations, is the presence of a counter-rotating vortex pair that impinges on the compression ramp (Figure 1.1).

This vortex pair has been shown to produce heating and pressure “streaking” on the control ramp surface (Thome et al., 2018). Experiments have quantified these streaks as sharp spanwise variations in surface loading; under certain experimental conditions, blowdown facility measurements showed surface heating varying from approximately 7.6 kW m^{-2} to 3.6 kW m^{-2} over distances of 2 mm or less (Francis et al., 2025).

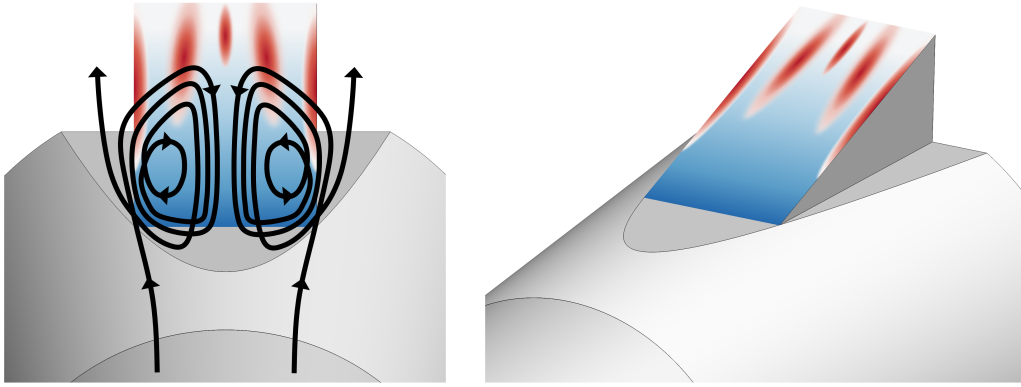


Figure 1.1: Streamlines in black highlighting the counter-rotating vortex pair that impinges on the compression ramp resulting in heating and pressure “streaking” on the ramp. Based on the simulations of Thome et al., 2018.

From the standpoint of model complexity, the cone-slice-ramp provides an intermediate geometry between canonical SBLI geometries and flight representative ones (Figure 1.2). Simple axisymmetric or nominally two-dimensional cases remain valuable because they allow for the isolation of certain SBLI mechanisms and detailed characterization of the incoming boundary layer; however, they cannot fully reproduce the three-dimensional flow effects associated with finite-span deflected control surfaces. The cone-slice-ramp retains this canonical upstream condition on the fore-cone, while introducing a finite span compression surface that generates more flight relevant three-dimensional SBLI behavior. Although an even more flight realistic configuration would include a non-canonical incoming boundary layer, doing so would significantly increase the complexity of the problem. The cone-slice-ramp is therefore a valuable intermediate geometry, as it captures key three-dimensional effects of deflected control surfaces while preserving the relative simplicity of a canonical incoming boundary layer.

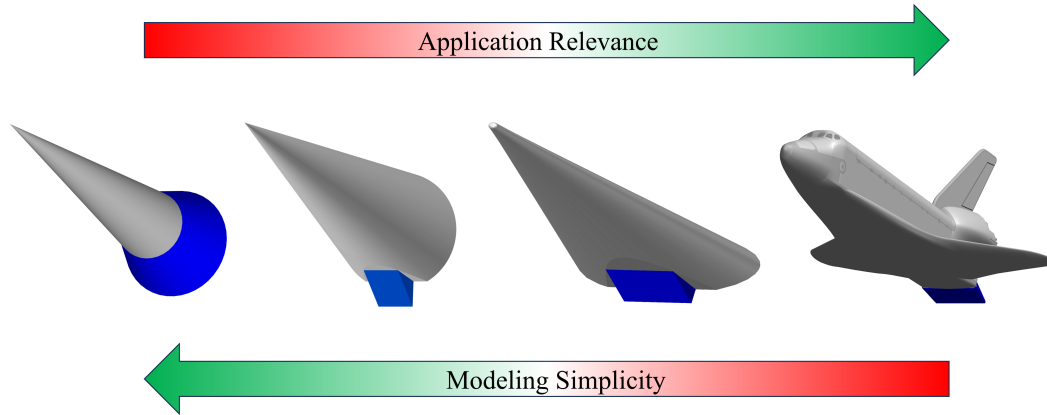


Figure 1.2: Schematic illustrating the range of possible geometries that can be used to study deflected control surface SBLI, from canonical configurations (left) to flight relevant ones (right).

1.2.1 Development of Cone-Slice-Ramp Geometry–JCEAP

The Joint Computational/ Experimental Aerodynamics Program (JCEAP) was initiated by Sandia National Laboratories from 1990 to 1997 as a coordinated computational and experimental program intended to improve both hypersonic CFD capability and wind tunnel testing, while also establishing how the two could be used together in rigorous validation studies (Oberkampf and Roy, 2010). Over the course of the program, it produced an extensive database of force, moment, and surface pressure measurements on the cone-slice-ramp geometry and helped define many of the principles now associated with high quality validation experiments (Aeschliman and Oberkampf, 1998; Aeschliman et al., 1995, 1994; Oberkampf and Aeschliman, 1992a; Oberkampf and Blottner, 1998; Oberkampf et al., 1993, 1995, 1996; Walker and Oberkampf, 1992).

A central design requirement for the JCEAP geometry was that the flow over the model remain fully laminar, since only laminar conditions were considered suitable for the CFD validation. This requirement drove the selection of the test condition in the Sandia Hypersonic Wind Tunnel (HWT), operating at the lower pressures of the performance envelope with a Mach 8 nozzle (Oberkampf and Roy, 2010). The model geometry was chosen to balance flow simplicity, computational tractability, and relevance to maneuvering hypersonic flight vehicles. The final configuration was a 10-degree half angle spherically blunted cone with a longitudinal slice beginning at 70% of the body length and fitted with interchangeable flaps deflected at 0–30 degrees in 10 degree increments. The slice and flap represented a control surface configuration of practical interest, while the geometry remained simple enough for

careful CFD comparison. The nose was deliberately blunted to 10% of the base radius to provide a well-characterized tip that would survive multiple experiments, and also avoid rarefaction effects associated with a sharper nose, for computational comparisons.

1.2.2 Cone-Slice-Ramp Blowdown Facility Experiments

Experiments on the cone-slice-ramp geometry under quiet and conventional noise conditions were conducted in BAM6QT at Purdue University (Chynoweth et al., 2017; McKiernan, 2020). The model consisted of a 7-degree half angle cone with ramp angles ranging from 10 to 30 degrees. Transition on the ramp surface, for unit Reynolds numbers from 2.2 to $9.2 \times 10^6 \text{ m}^{-1}$, was identified through broadband increases in the power spectra measured by surface-mounted pressure transducers. Under quiet flow conditions, no distinct frequency peaks were detected on the ramp surface; however, the introduction of artificial disturbances produced convective instabilities in the 50–90 kHz range. These measurements were complemented by temperature sensitive paint, which confirmed the presence and structure of heating “streaks” on the ramp surface.

Extensive work on instability measurements for the cone-slice-ramp geometry has also been carried out at Sandia National Laboratories in the Sandia HWT facility at Mach 5 and 8 (Pandey and Casper, 2021; Pandey et al., 2024, 2020, 2022b). Surface pressure sensors, high-speed schlieren imaging, and scanning FLDI were used to investigate instability frequencies on a 7-degree half angle cone with a 30-degree ramp angle. These studies showed that second mode instabilities on the cone surface (130–280 kHz) propagated along the separated shear layer and remained present in the reattached boundary layer. A medium frequency instability (10–50 kHz) was also observed in both the separated shear layer and on the surface across the separation region, with the instabilities peak frequency decreasing downstream. This instability was attributed to a shear layer “flapping” motion, which radiated pressure waves toward the surface and Mach radiation above the shear layer. Ultra low frequency bubble breathing motion (<3 kHz) and separation shock/shear layer unsteadiness (3–10 kHz) were also observed. Infrared thermography was later applied to the same cone-slice-ramp model at both Mach 5 and Mach 8 conditions to obtain spatially resolved surface heat flux measurements over the slice-ramp SBLI region (Lee et al., 2026). These heat flux results were quantitatively compared with several Reynolds averaged Navier–Stokes simulations, which struggled to accurately predict both the peak heating and the separation location.

1.2.3 Cone-Slice-Ramp High Enthalpy Facility Experiments

High enthalpy SBLI experiments have recently been performed on the cone-slice-ramp geometry in Sandia's Hypersonic Shock Tunnel using the same 7-degree half angle cone and 30-degree ramp configuration as in Sandia's blowdown HWT facility, with the aim of examining real-gas effects. Jans et al., 2025 used 100 kHz NO-PLIF together with fast response surface pressure sensors to characterize complex SBLI transients during the facility startup. NO-MTV was also used to produce velocity profiles for flow above and below the separated shear layer at $h_0 = 3.8 \text{ MJ kg}^{-1}$, $\text{Re}_\infty = 7.9 \times 10^5 \text{ m}^{-1}$.

Rubio et al., 2026 used double-pass schlieren to measure the separation and reattachment locations of the separated shear layer while independently varying stagnation enthalpy from 4.15 to 12.6 MJ kg^{-1} at a constant unit Reynolds number of $3 \times 10^5 \text{ m}^{-1}$. Increasing stagnation enthalpy shifted both the separation and reattachment positions downstream and reduced the overall size of the separation bubble. These results support earlier findings that incipient separation and the characteristic scales of separated SBLI regions may be strongly influenced by thermochemical effects (Holden, 2018).

1.2.4 Theoretical Overview of the Cone-Slice-Ramp SBLI

Drawing on prior experimental studies of the cone-slice-ramp geometry, this subsection provides a conceptual overview of the key flow features that develop within the SBLI region (Figure 1.3).

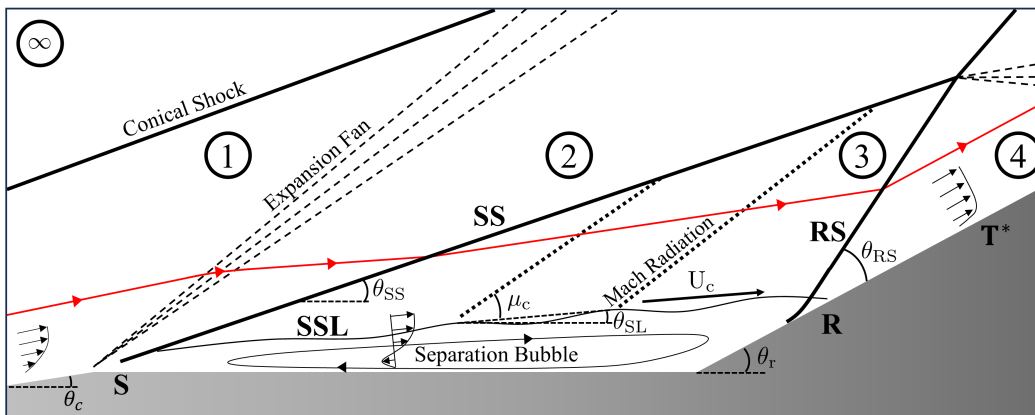


Figure 1.3: Illustration of the principal flow features in the cone-slice-ramp shock-wave/boundary-layer interaction. The red line denotes a representative streamline.

Freestream flow ∞ first passes through the conical shock formed at the vertex of the cone resulting in a conical flow field whose edge conditions are set approximately

by the Taylor–Maccoll solution ① . As this flow reaches the leading edge of the slice, it encounters an expansion corner, which can relaminarize the incoming boundary layer, making it more susceptible to the downstream compression induced separation (Pandey et al., 2024).

Downstream of the slice expansion ②, the ramp compression imposes an adverse pressure gradient on the slice boundary layer. This adverse pressure gradient slows the low momentum fluid nearest the wall more than the outer flow, promoting an inflected velocity profile, flow reversal, and eventual separation at location **S**. This separation is accompanied by a separation shock **SS** and the formation of a separated shear layer **SSL** that spans over a recirculating separation bubble on the slice. The flow above the shear layer ③ remains supersonic, while the region beneath it is a low speed recirculation zone bounded by the separation (**S**) and reattachment (**R**) points.

Within this separated shear layer, instabilities can develop as the shear layer convects downstream. Cone-slice-ramp experiments observed a streamwise waviness of the shear layer which produces Mach radiation above the shear layer (Pandey et al., 2022b). Farther downstream, the separated shear layer impinges on the ramp and reattaches at location **R**. This reattachment is associated with a reattachment shock **RS**. As the reattached boundary layer in the post reattachment shock region ④ convects downstream along the ramp, it may undergo transition **T***, yielding a turbulent boundary layer and elevated heat flux on the ramp surface.

1.3 Separated Shear Layer Instabilities

Separated hypersonic shear layers, such as the one formed in the cone-slice-ramp SBLI, can support several distinct classes of instability. The most familiar is the Kelvin–Helmholtz instability, which is associated with large scale shear layer waviness and vortex roll-up and has been studied extensively in incompressible (Ho and Huerre, 1984) and compressible free shear layers (Papamoschou and Roshko, 1988). Linear stability analysis of compressible mixing layers also predict additional vortical instability modes above a critical Mach number, commonly referred to as the fast and slow branches, which are distinct from acoustic boundary layer instabilities (Jackson and Grosch, 1989). In addition, hypersonic shear layers can support Mack mode disturbances. Although these disturbances are commonly associated with high speed boundary layers, experiments have shown that they can also persist within separated shear layers (Benitez et al., 2023a; Butler and Laurence, 2021a).

1.3.1 Kelvin–Helmholtz Instability

Kelvin–Helmholtz instability is a fluid dynamic instability that develops at the interface between two fluids, when a velocity difference exists across a shearing region. The vortices that form have been observed to amalgamate via three separate mechanisms; vortex pairing, vortex tripling, and vortex tearing. Vortex pairing, observed by Freymuth, 1966 and Winant and Browand, 1974 at low Reynolds number, occurs when coherent structures moving downstream at nearly constant speed merge so that the characteristic scale grows linearly in the downstream direction. Vortex tripling, reported by Dimotakis and Brown, 1976, refers to the merger of three vortices into a single structure. Vortex tearing, proposed by Moore and Saffman, 1975 and later observed by Hernan and Jimenez, 1982 and Dimotakis and Brown, 1976, occurs when a vortex is destroyed by neighboring vortices and absorbed into them. These studies also indicate that vortex pairing is the dominant amalgamation process.

The study of compressibility effects on free jets and mixing layers showed that large velocity gradients exert a stronger influence on instability growth rates than large temperature gradients (Crane, 1957; Crane and Pack, 1957). Maydew and Reed, 1963, studying turbulent mixing in free jets over the range $M_\infty = 0.7$ to 1.96, found that the growth rate remains roughly constant in subsonic flow and decreases as Mach number increases into the supersonic regime. Brown and Roshko, 1974, using flow visualization of plane turbulent mixing between nitrogen and helium streams, concluded that the instability growth rate depends primarily on compressibility effects rather than on the density ratio between the two streams.

Bogdanoff first introduced a shear layer compressibility parameter, M^+ , by estimating the convection velocity of the large coherent structures and forming the Mach numbers of these structures relative to the high and low speed streams (Bogdanoff, 1983). Building on this interpretation, Papamoschou and Roshko, 1988 argued that compressibility effects in turbulent shear layers are most naturally described in a reference frame moving with the dominant large scale coherent structures, rather than in the laboratory frame. They therefore defined the convective Mach number, M_c , in terms of the convective velocity of the large scale vortical structures, U_c , as,

$$M_{c1} = \frac{U_1 - U_c}{a_1}, \quad M_{c2} = \frac{U_c - U_2}{a_2}, \quad (1.1)$$

where a_i and U_i is the sound speed and velocity of the corresponding streams respectively.

For equal pressure across both streams, U_c can be expressed as,

$$U_c = U_1 \frac{1 + \frac{U_2}{U_1} \left(\frac{\rho_2}{\rho_1} \right)^{1/2}}{1 + \left(\frac{\rho_2}{\rho_1} \right)^{1/2}} \quad (1.2)$$

for estimating the convective velocity of the large structures in the shear layer.

1.3.2 Fast and Slow Shear Layer Instability Modes

Linear stability analysis has also been used to study the inviscid spatial stability problem for the compressible mixing layer. Using linear, inviscid theory, Mack studied Mach 3 single jet and wake profiles showing that the most amplified disturbance was the lowest sinuous mode rather than an acoustic mode. In these confined free shear flows, the unstable waves included both subsonic and radiating disturbances (Mack, 1990). For parallel compressible mixing layers, Jackson and Grosch found that once the Mach number exceeds a critical value, the instability separates into two groups of unstable waves: a fast branch with phase speeds greater than 1/2, supersonic relative to the stationary stream, and a slow branch with phase speeds less than 1/2, supersonic relative to the moving stream. They emphasized that these fast and slow supersonic modes are vorticity modes, not acoustic modes (Jackson and Grosch, 1989).

1.3.3 Mack Mode Instabilities

A key instability mechanism relevant to hypersonic boundary layers is the acoustic second (Mack) mode. Mack, 1984 showed that, at sufficiently large edge Mach numbers and especially for cold wall conditions, the dominant linear instability can shift from lower frequency viscous modes to a higher frequency trapped acoustic mode. The boundary layer acts as an acoustic waveguide, amplifying acoustic disturbances at frequencies that scale approximately as $f \approx k \frac{U_{edge}}{2\delta}$ (Fedorov, 2011). This scaling was later supported experimentally by Kendall, 1975, Demetriades, 1977, and Stetson et al., 1983, 1984, 1989.

The second mode instability has been measured in the boundary layer over a slender 5-degree cone in T5 at high stagnation enthalpy conditions by Rasheed et al., 2002, Jewell, 2014, and Parziale et al., 2015. Parziale used Focused Laser Differential Interferometry (FLDI) to measure the second mode frequency directly. In related numerical work, Bitter and Shepherd, 2014 examined the effect of wall tem-

perature on instability growth and found that, for the wall-temperature ratios and Mach numbers typical of high enthalpy impulse facilities, the first mode remained stable while the second mode was highly unstable.

The second mode instability is not limited to attached boundary layers and has also been observed experimentally within the separated shear layers of SBLI. Butler and Laurence, [2021a](#) and Benitez et al., [2023a](#) reported second mode disturbances propagating through the separated shear layer in canonical cone-flare and cone-cylinder-flare geometries in blowdown facilities. Pandey et al., [2022b](#) likewise measured second mode disturbances traversing the SBLI region through the separated shear layer on a cone-slice-ramp geometry, with the disturbance later reappearing in the reattached boundary layer. Surface pressure measurements showed no second mode peak beneath the separated shear layer, suggesting that the instability remained confined to the shear layer itself.

1.3.4 Separated Shear Layer Instability Experiments

The instability mechanisms discussed above have been examined in a wide range of free shear layers and separated SBLI flows. Rather than provide a comprehensive review of this broader literature, the present subsection highlights a limited set of canonical experiments that more closely resemble the separated shear layer formed in the current cone-slice-ramp experiments. Emphasis is placed on studies performed in blowdown and high-enthalpy facilities where instability measurements were obtained in separated shear layers produced by cone-flare, cone-cylinder-flare, double-cone, and double-wedge interactions. These studies provide useful context for interpreting the instability frequencies measured in the present work.

1.3.4.1 Canonical Blowdown Facility Experiments

Experiments on an asymmetric cone-flare geometry at the University of Maryland's HyperTERP facility investigated the effects of a compression corner on laminar boundary layer disturbances (Butler and Laurence, [2020](#); Butler and Laurence, [2021a](#), [2022](#)). The model consisted of a 5-degree cone with a flared compression corner of 5 to 15 degrees, tested at a unit Reynolds number of $3.3 \times 10^6 \text{ m}^{-1}$. Instability frequencies were measured using high-speed schlieren imaging, spectral proper orthogonal decomposition (SPOD), and on-surface pressure sensors. For the 10-degree compression corner, second mode disturbances at 200–300 kHz were observed in both the upstream boundary layer and the separated shear layer. A

separate shear layer disturbance at 60–90 kHz was also identified, independent of the second mode. This instability grew in amplitude as it convected downstream through the separated shear layer and then decayed, but did not disappear, in the reattachment region. As the compression ramp angle increased, the dominant modal content shifted toward lower frequencies. At a 15-degree ramp angle, shear layer disturbances at 40–50 kHz dominated, with no evidence of second mode waves in the separated shear layer.

Shear layer instabilities on a cone-cylinder-flare geometry have also been investigated under quiet-flow conditions in BAM6QT at Purdue University (Benitez et al., 2020, 2023a; Benitez et al., 2023b). These experiments combined off-surface focused laser differential interferometry (FLDI) measurements with on-surface PCB pressure measurements at a high unit Reynolds number ($Re_\infty = 12 \times 10^6 \text{ m}^{-1}$), while maintaining fully laminar separation and reattachment. Initial experiments with a 10-degree flare angle observed second mode instabilities along the detached shear layer and in the reattached boundary layer at frequencies between 170 and 290 kHz. A second shear layer instability at 50–170 kHz was observed off-surface just upstream of reattachment and both on- and off-surface downstream of reattachment. These findings were supported by computations showing that this shear layer instability is oblique and becomes amplified along the shear layer Paredes et al., 2022. Later experiments performed with a 12-degree flare measured similar instability frequencies, but also observed turbulent spots downstream of a laminar separation bubble that were believed to evolve from shear layer instability wave packets.

1.3.4.2 Canonical High Enthalpy Facility Experiments

In the T5 Free-Piston Reflected Shock Tunnel at Caltech, SBLI experiments were performed over a canonical 25–55 degree double-cone geometry (Yu et al., 2026; Yu, 2024). Focused laser differential interferometry (FLDI) was used to measure instability frequencies in the separated shear layer for both air and nitrogen test conditions ($h_0 = 8 \text{ MJ kg}^{-1}$, $Re_\infty = 2 \times 10^6 \text{ m}^{-1}$). Low frequency wave packets ($\approx 50 \text{ kHz}$) were observed and attributed to Kelvin–Helmholtz instabilities in the separated shear layer. Broadband medium frequency peaks ($\approx 370\text{--}450 \text{ kHz}$) were also observed in the same FLDI signal. These peak frequencies decreased monotonically along the length of the shear layer. Yu argues that, upstream of the corner, this trend is consistent with an acoustic scaling based on the local shear layer height above the wall, $H(x)$, but notes that the scaling breaks down downstream of the cor-

ner. Higher frequency peaks (≈ 1 MHz) were also observed in some experiments and were attributed to second mode disturbances propagating through the separated shear layer.

Knisely, 2016 conducted T5 experiments at $h_0 = 8 \text{ MJ kg}^{-1}$ in air and nitrogen on 30–55 degree double-wedge, 25–55 degree double-cone, and 25–48 degree double-cone geometries to study high enthalpy SBLI and the associated heat flux response. For the double-cone cases, Type V interactions on the 25–55 degree model and Type VI interactions on the 25–48 degree model were identified. Highly localized peak aft-body heating was demonstrated to be caused by the post-reattachment impinging shock location.

Experiments focusing on changes in separation length due to real-gas effects were also conducted in T5 (Davis, 1999; Davis and Sturtevant, 2000). These experiments used nitrogen at stagnation enthalpies spanning roughly 3.9 to 28 MJ kg^{-1} over two-dimensional double-wedge geometries with various ramp angles. For laminar interactions, the high-enthalpy cases exhibited scaled separation lengths approximately three times larger than the corresponding low enthalpy cases. This increase became apparent only when the scaling included the parameter Λ_1 , which accounts for wall temperature effects on a nonreacting boundary layer. Davis attributed this increase in scaled separation length to an internal real-gas mechanism, likely recombination effects in the free shear layer downstream of separation.

1.4 Project Outline and Scope

The primary objectives of this thesis are twofold. First, it investigates the streamwise and spanwise heating produced by the three-dimensional cone-slice-ramp shock wave/boundary-layer interaction across a range of freestream Reynolds numbers in hypervelocity flows. Second, it examines the unsteadiness of the interaction, with particular attention to how the observed instabilities vary with Reynolds number, stagnation enthalpy, and streamwise location.

The thesis is organized as follows. Chapter 2 describes the experimental facility, freestream conditions, model geometry, and the instrumentation and diagnostics used throughout the study. Chapter 3 presents the surface heat flux measurements used to characterize the incoming boundary layer, including comparisons with boundary layer theory, and then examines the streamwise and spanwise heating of the three-dimensional SBLI in relation to flow visualization observations. Chapter 4 investigates the unsteadiness of the interaction using FLDI, SPOD, and surface

pressure measurements to identify the dominant instability frequencies. It also explores scalings of these instability frequencies and the coupling between different SBLI flow features. Finally, Chapter 5 summarizes the main findings of the thesis and outlines directions for future work.

Chapter 2

EXPERIMENTAL FACILITY & DIAGNOSTICS

This chapter describes the T5 Free-Piston Reflected Shock Tunnel used in this study, together with the test model and diagnostic instrumentation employed in the experiments. It first summarizes the operation of the facility and the methods used to determine the freestream test conditions. It then presents the cone-slice-ramp model and the diagnostics used to measure the relevant flow and surface quantities.

2.1 T5 Free-Piston Reflected Shock Tunnel

The experiments in this study were conducted in the T5 Free-Piston Reflected Shock Tunnel at the California Institute of Technology, a high-enthalpy impulse facility designed to generate flight-relevant conditions for hypervelocity aerothermodynamics research (Hornung et al., 1992). T5 is the fifth facility in a series of reflected shock tunnels and is capable of producing freestream stagnation enthalpies on the order of $5\text{--}25 \text{ MJ kg}^{-1}$. The facility consists of five principal sections: the secondary reservoir (2R), compression tube (CT), shock tube (ST), test section (TS), and dump tank (DT), as shown in Figure 2.1. A stainless steel primary diaphragm initially separates the CT and ST, while a 0.003 inch Mylar secondary diaphragm at the nozzle throat separates the ST from the TS and DT. To improve shot-to-shot repeatability, the primary diaphragm is mechanically scored so that rupture occurs at the desired burst pressure.

Prior to a shot, the CT, ST, TS, and DT are evacuated to below 0.04 kPa, after which the ST is filled with the test gas and the CT is charged with a prescribed helium/argon driver mixture. The 2R is then filled with compressed air, and a 120 kg piston is positioned at the upstream end of the CT. A small release of air behind the piston initiates its motion, uncovering the ports between the 2R and CT and allowing the compressed air in the 2R to accelerate the piston downstream. As the piston travels through the CT, it adiabatically compresses the helium/argon mixture until the primary diaphragm bursts. This generates a strong incident shock that propagates through the ST, reflects from the end wall, and establishes a stagnant, high temperature, high pressure nozzle reservoir. The reflected shock also vaporizes the Mylar secondary diaphragm, allowing the reservoir gas to expand through the contoured converging-diverging nozzle of area ratio 100:1 and into the test section,

where the final freestream condition is produced.

Facility operation is monitored using vacuum gauges, static pressure transducers, and dynamic pressure transducers (PCB 119M44). During filling and evacuation, the static pressure transducers on the DT, ST, CT, and 2R are used to verify the prescribed initial fill conditions, after which these gauges are isolated to prevent damage during the shot. Dynamic pressure transducers record the primary diaphragm burst pressure, the incident shock speed in the ST, and the nozzle reservoir pressure near the end wall. The reservoir pressure signal is also used to trigger diagnostic data acquisition. These pressure signals are recorded on National Instruments PXIe-6368 16-bit depth DAQ cards at 2 MS/s for post shot analysis. The measured burst pressure, shock speed, and reservoir pressure are then used as inputs for the calculation of the freestream test condition.

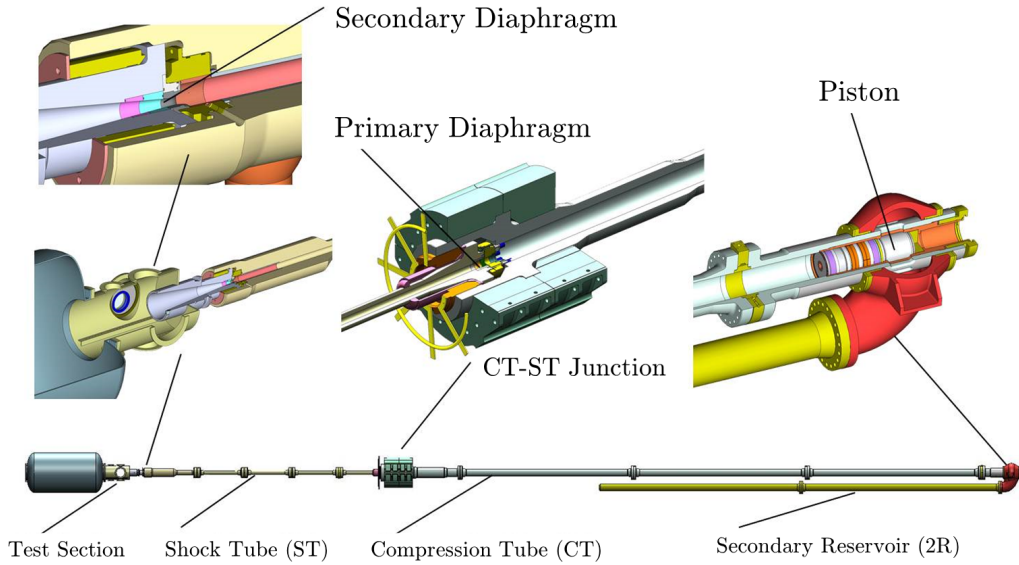


Figure 2.1: Schematic of the T5 Free-Piston Reflected Shock Tunnel.

2.2 Freestream Conditions

A set of test conditions was chosen to allow for the boundary layer on the cone surface upstream of the slice-ramp region of the model to remain fully laminar for most test conditions, through to transitional for the highest Reynolds number considered. Prior boundary layer transition work on slender 5-degree cones in T5 has experimentally measured the transition length $x_{Tr} \approx 0.68$ m for the nominal $h_0 = 8 \text{ MJ kg}^{-1}$, $Re_\infty = 2 \times 10^6 \text{ m}^{-1}$ test condition and $x_{Tr} \approx 0.51$ m for the nominal $h_0 = 8 \text{ MJ kg}^{-1}$, $Re_\infty = 6 \times 10^6 \text{ m}^{-1}$ test condition (Jewell, 2014). Since the cone length upstream of the slice is 0.638 m, these conditions allow both laminar

and transitional incoming boundary layers to be investigated over the available Reynolds number range. The $h_0 = 8 \text{ MJ kg}^{-1}$, $\text{Re}_\infty = 2 \times 10^6 \text{ m}^{-1}$ condition has been thoroughly characterized through laser-absorption spectroscopy together with static-pressure and pitot-probe measurements (Finch et al., 2023; Yu et al., 2025).

An intermediate freestream unit Reynolds number of $\text{Re}_\infty = 3 \times 10^6 \text{ m}^{-1}$ was explored between the bounding freestream unit Reynolds numbers at $h_0 = 8 \text{ MJ kg}^{-1}$ to isolate the effects of changing freestream unit Reynolds numbers on the SBLI region. A higher stagnation enthalpy of $h_0 = 14 \text{ MJ kg}^{-1}$ was also explored at the same freestream unit Reynolds number to isolate stagnation enthalpy effects on the SBLI region. The nominal freestream properties for these cases are summarized in Table 2.1, with shot specific values provided in Appendix A.2.

Table 2.1: Nominal T5 freestream conditions.

Condition	M_∞ [-]	U_∞ [m/s]	ρ_∞ [kg/m ³]	T_∞ [K]	P_∞ [Pa]	Re_∞ [1/m]
H8-Re2-Air	5.54	3516	0.0201	984	5751	1.71×10^6
H8-Re3-Air	5.47	3633	0.0304	1081	9551	2.54×10^6
H8-Re6-Air	5.46	3747	0.0765	1163	25740	6.31×10^6
H14-Re3-Air	4.98	4708	0.0379	2080	23876	2.83×10^6

For each T5 shot, the freestream state is determined through a two stage procedure. In the first stage, the nozzle reservoir condition is reconstructed from the initial shock tube fill pressure, P_1 , the measured primary shock speed, U_s , and the measured reservoir pressure during test time, P_{res} . The post reflected shock state is then computed in Cantera using the Shock and Detonation Toolbox (EDL, 2023) with an equilibrium normal shock calculation, after which the gas is isentropically expanded up to the nozzle throat to record the reservoir pressure P_r . This yields the thermodynamic state supplied to the nozzle calculation.

In the second stage, the University of Minnesota Nozzle Code (Candler, 2005) is used to simulate the steady expansion through the contoured nozzle using the reconstructed nozzle reservoir state as input. The solver treats the flow as an axisymmetric reacting Navier–Stokes expansion with a turbulent nozzle-wall boundary layer. Turbulence is modeled with Spalart–Allmaras (Spalart and Allmaras, 1992) together with the Catris–Aupoix (Catris and Aupoix, 2000) compressibility correction, and implicit time integration is performed using the data-parallel line relaxation method (DPLR) (Wright et al., 1998). Inviscid fluxes are evaluated with Steger–Warming

flux splitting (Steger and Warming, 1981) and the van Leer limiter to obtain second-order spatial accuracy (Liou and Van Leer, 1988). The chemistry model employs the Park two-temperature formulation with the updated Bose–Candler nitric-oxide reaction rates (Bose and Candler, 1996, 1997). The nozzle geometry was discretized using a structured mesh with 492 axial cells and 219 radial cells. For each condition, the reported freestream properties were extracted at the nozzle centerline at the exit plane. Across the exit plane, the freestream conditions varied by less than approximately 0.5% between the centerline and the nozzle wall boundary layer edge.

Boundary layer edge conditions reported along the cone surface were computed by taking the freestream conditions obtained at the nozzle exit, as described above, and solving the Taylor–Maccoll equations for inviscid, axisymmetric conical flow. Under the conical-flow similarity assumption, the governing Euler equations reduce to an ordinary differential equation in the polar angle, with local flow properties remaining constant along rays emanating from the cone vertex. Following the solution approach outlined in Anderson, 1990, the inviscid outer flow solution evaluated at the cone surface polar angle was taken as the local boundary layer edge condition. To assess the effect of the perfect gas assumption, the edge conditions were computed in Cantera using both frozen composition and chemical equilibrium models. The resulting edge unit Reynolds numbers differed by less than 1%. The nominal equilibrium boundary layer edge properties for each shot condition are summarized in Table 2.2, with shot specific values provided in Appendix A.3.

Table 2.2: Nominal boundary layer edge conditions.

Condition	M_{edge} [-]	U_{edge} [m/s]	ρ_{edge} [kg/m ³]	T_{edge} [K]	P_{edge} [Pa]	Re_{edge} [1/m]
H8-Re2-Air	5.23	3382	0.0265	1083	8376	1.99×10^6
H8-Re3-Air	5.18	3489	0.0400	1185	13794	2.92×10^6
H8-Re6-Air	5.17	3601	0.1007	1272	37063	7.22×10^6
H14-Re3-Air	4.75	4379	0.0483	2244	32845	2.92×10^6

2.3 Cone-Slice-Ramp Model

The cone-slice-ramp model used in this study consisted of a slender 5-degree half-angle cone with an axial length of 0.75 m. A 10 mm deep tangential cut was introduced from the outer aft diameter of the cone to form the slice section of the model. The fore-cone length was selected to permit investigation of both laminar and transitional incoming boundary layers over the range of freestream conditions

available in T5, as described in Section 2.2. A 20-degree ramp was mounted to the slice, with a spanwise width of 38.5 mm and a streamwise length of 77 mm. The leading corners of the ramp were coincident with the hyperbola formed by the slice, similar to the JCEAP cone-slice-ramp model. The model was mounted to a sting in the T5 test section and aligned to a zero-degree angle of attack.

The model was machined from 4340 steel, except for the cone nose tip, which was made of molybdenum. The nose tip was initially machined sharp to a radius of 0.1 mm, but eroded during the test campaign to a radius of 0.25 mm. A sharp nose tip was selected to isolate the influence of the entropy gradient associated with nose bluntness on the SBLI region of the model. Throughout the experimental campaign, the nose remained sufficiently sharp for the entropy layer to be swallowed well within the conical portion of the model, with a maximum estimated entropy-swallowing distance of approximately $x_{sw} \approx 50$ mm based on measurements for a 5-degree half-angle cone reported by Lachowicz, 1996. Figure 2.2 shows the CAD design of the cone-slice-ramp model, and Figure 2.3 shows the model mounted to its sting in the T5 test section.

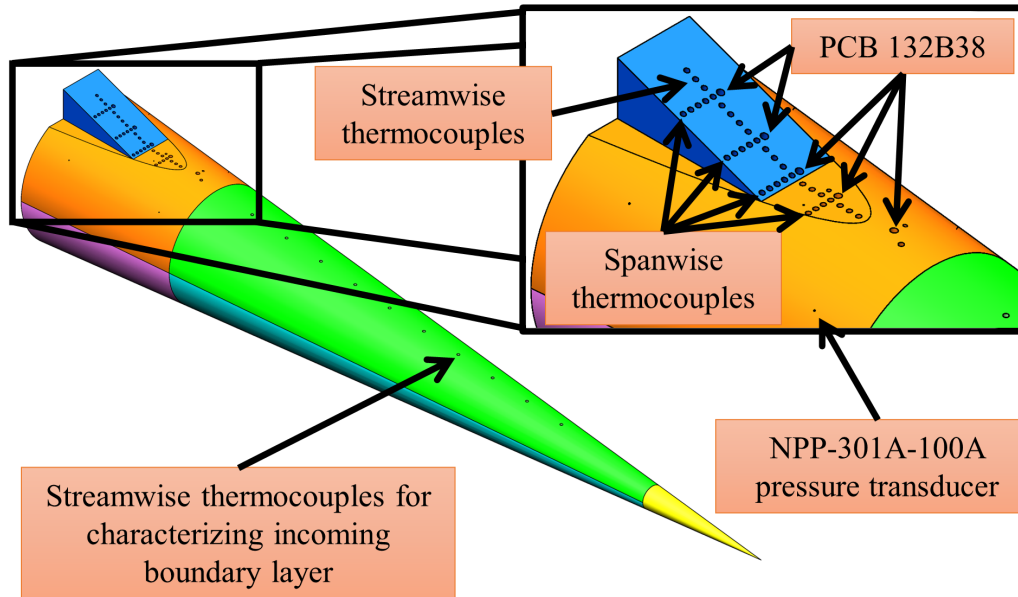


Figure 2.2: CAD model of cone-slice-ramp model with sensor locations annotated.

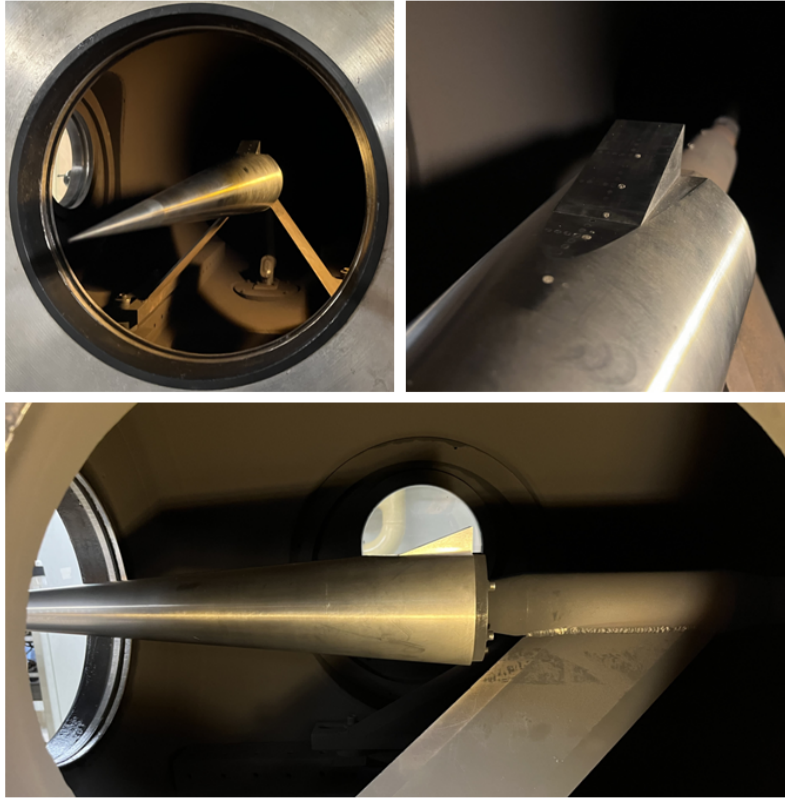


Figure 2.3: Cone-slice-ramp model installed in T5 test section.

2.4 Surface Diagnostics

The cone-slice-ramp model was instrumented extensively to characterize both aerodynamic pressures and thermal loading over both the cone surface and the slice-ramp SBLI region. The instrumentation suite consisted of 46 thermocouples for heat flux measurements, 9 static pressure sensors, and 5 dynamic pressure sensors. For clarity, Figure 2.4 summarizes the sensor types, locations, and naming convention used in this study.

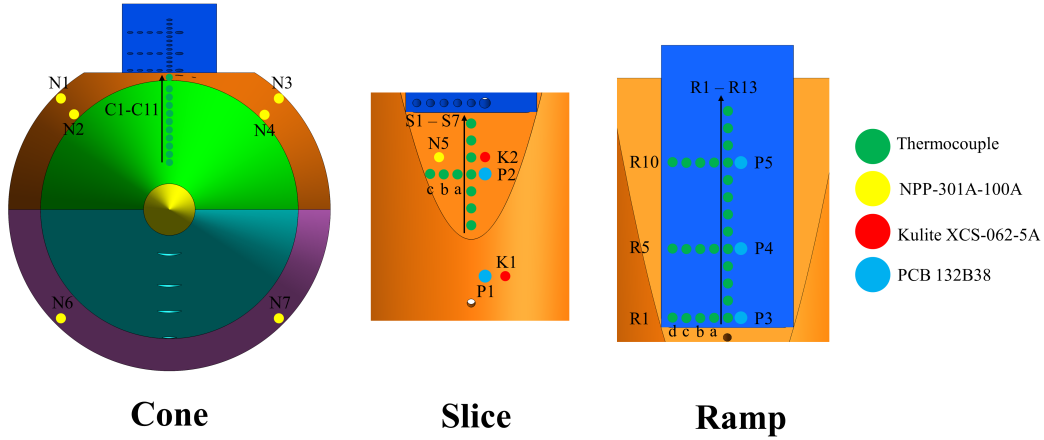


Figure 2.4: Sensor type and naming convention for all surface mounted sensors on the cone-slice-ramp model.

2.4.1 Surface Heat Flux Measurements

Surface heat flux measurements were obtained using 2.4 mm diameter, Type E (constantan–chromel) thermocouples manufactured in-house. They are based on the design and operating principles of Sanderson, 1995 for use in T5. Established test time for this work (Section 3.1.2) are on the order of 1 ms making the reported effective response times of the gauges $1 \mu\text{s}$ (Sanderson and Sturtevant, 2002) to $7 \mu\text{s}$ (Damazo, 2013) adequate for the experiments.

The thermocouple voltage output is passed through a signal conditioner with a nominal gain of 100 and recorded using the National Instruments DAQ system at a sampling rate of 2 MS/s. The measured voltage is converted to temperature using standard NIST thermocouple tables. Surface heat flux is then recovered through spectral decomposition. The thermocouple is modeled as a one-dimensional semi-infinite solid undergoing unsteady heat conduction under the assumption of small temperature gradients. The governing heat equation is,

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \quad (2.1)$$

with boundary conditions,

$$T(x, 0) = T_i, \quad \left. \frac{\partial T(x, t)}{\partial x} \right|_{x \rightarrow \infty} = 0, \quad (2.2)$$

$$T(0, t) = T_i + \Delta T(t), \quad \left. \frac{\partial T(x, t)}{\partial x} \right|_{x \rightarrow 0} = \dot{q}(t). \quad (2.3)$$

Here, x is the coordinate normal to the surface, α is the thermal diffusivity, $\dot{q}$ is the surface heat flux, T is the temperature, and t is time. The thermal diffusivity is defined as

$$\alpha = \frac{k}{\rho c}, \quad (2.4)$$

where k is the thermal conductivity, ρ is the density, and c_p is the specific heat. Material properties used are averaged between the constantan–chromel as reported by Sundqvist, 1992.

Because the conduction equation is linear, the temperature response of the thermocouple can be represented through a convolution integral,

$$\Delta T(x, t) = \int_0^t g(x, t - \tau) \dot{q} d\tau \quad (2.5)$$

where ΔT is the temperature rise and $g(x, t)$ is the impulse response function,

$$g(x, t) = \sqrt{\frac{\alpha}{\pi k^2 t}} \exp\left(-\frac{x^2}{4\alpha t}\right), \quad t > 0. \quad (2.6)$$

In this expression, x is the thermocouple junction depth. Based on the measurements of Davis, 1999, a junction depth of $1 \mu\text{m}$ is used in the present calculations.

The heat flux signal is recovered by transforming the measured temperature history into the frequency domain using a discrete Fourier transform and then applying the inverse transform after deconvolution,

$$\dot{q} = FFT^{-1} \left[\frac{\Phi Z}{G} \right]. \quad (2.7)$$

Here, Z is the Fourier transform of the measured temperature time series, Φ is the filter function, and G is the Fourier transform of the impulse response $g(x, t)$. A low-pass Butterworth filter with a cutoff frequency of 20 kHz is then applied to the

recovered heat flux signal. Further details of this procedure are given by Sanderson and Sturtevant, 2002 and Davis, 1999.

Uncertainty in the mean heat flux arises from several sources, including uncertainty in the NIST temperature conversion tables, uncertainty in the thermocouple material properties, and shot-to-shot fluctuations in the freestream conditions. According to Davis, 1999, the NIST temperature conversion introduces an uncertainty of 1.7%, while the material properties contribute an uncertainty of 8%. The effect of freestream fluctuations is represented using a 95% confidence interval following Flaherty, 2010. These sources are combined and reported as error bars on the mean heat flux measurements.

Each thermocouple was installed in the cone-slice-ramp model using a jig to maintain a consistent junction depth across all gauges. After curing, the gauges were sanded flush with the model surface to ensure that no step remained. Eleven thermocouples were placed at regular 38 mm intervals along the slender cone upstream of the SBLI region to characterize the incoming boundary layer as laminar or transitional. Twenty additional thermocouples were positioned along the centerline of the slice-ramp at 5 mm intervals to measure the streamwise development of the SBLI through the separation region. A further fifteen thermocouples, arranged in four spanwise rows with 4 mm spacing, were installed on the slice-ramp to examine finite-span effects associated with the three-dimensional flow. The streamwise thermocouple locations are overlaid on the high-speed schlieren image in Figure 2.5 for visual reference.

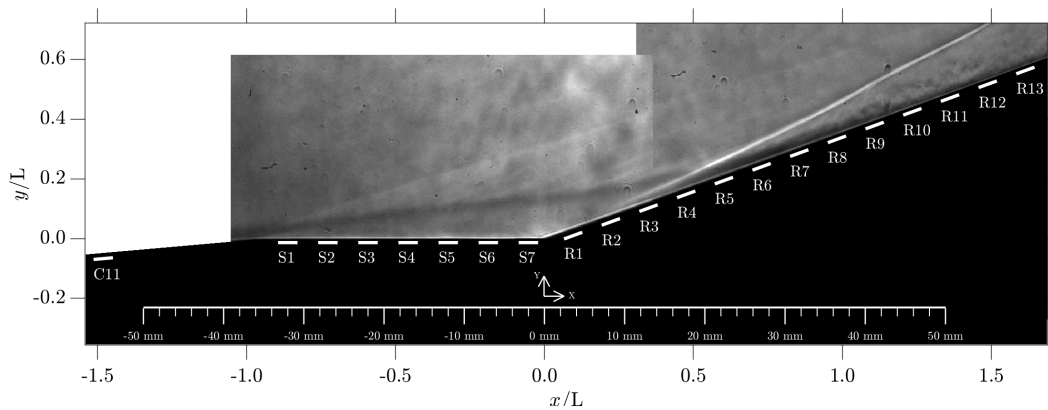


Figure 2.5: Annotated locations of surface thermocouple sensors.

2.4.2 Surface Static Pressure Measurements

Surface static pressure was measured using two surface-mounted Kulite XCS-062-5A gauges, one located on the fore-cone and one in the separation bubble. Six NPP-301A-100A pressure sensors (Figure 2.6) were also mounted farther aft on the cone at 90 degree azimuthal increments. These sensors provided a cost-effective means of measuring cone surface static pressure and were used to help identify any cone misalignment relative to the freestream flow. Section 3.1.1 describes the procedure used in conjunction with these sensors to determine cone misalignment. An additional NPP-301A-100A sensor was also installed in the separation bubble to provide a redundant measurement of pressure on the slice.

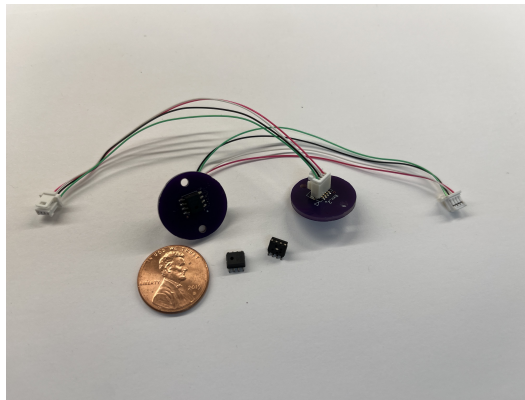


Figure 2.6: NPP-301A-100A pressure transducers mounted on a printed circuit board.

The NPP-301A-100A sensors have previously been used in the High Enthalpy Shock Tunnel Göttingen (HEG) to monitor the angle of attack and yaw angle of a cone model (Camillo et al., 2020). In Figure 2.7, the performance of the NPP-301A-100A sensors in T5 on the fore-cone surface is compared with that of a Kulite XCS-062-5A gauge mounted at the same streamwise location. Although the NPP-301A-100A response time is slower than that of the Kulite, the sensors respond quickly enough to reach the surface static pressure during the facility test time. This makes them suitable for use as surface static pressure gauges in the current work.

The NPP-301A-100A sensors were soldered to custom printed circuit boards designed in-house and sealed with a gasket over a 0.6-mm-diameter static pressure port drilled into the model surface. Both the Kulite and NPP-301A-100A sensors were connected to a Vishay Micro-Measurements 2310 signal-conditioning amplifier, and the signals were recorded using a National Instruments DAQ system at a sampling rate of 2 MS/s.

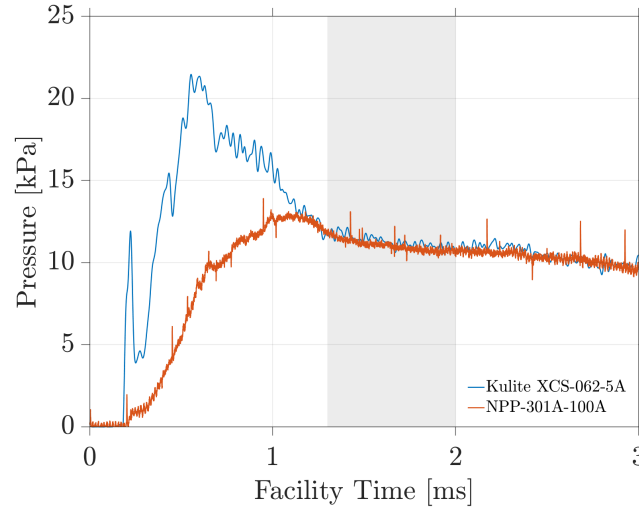


Figure 2.7: Comparison of the response times of the NPP-301A-100A and Kulite XCS-062-5A sensors on the fore-cone surface. The shaded gray region denotes the facility test time.

2.4.3 Surface Dynamic Pressure Fluctuation Measurements

On-surface pressure fluctuations were measured using PCB Model 132B38 sensors manufactured by PCB Piezotronics (hereafter referred to as PCB sensors). These sensors have a reported frequency response from 11 kHz to 1 MHz; however, only frequencies up to 200 kHz were considered in the present study because resonant peaks begin near ≈ 300 kHz (Ort and Dosch, 2019). The PCB sensors were connected via shielded cables to a PCB Model 481 signal conditioner. Pressure data were acquired at 100 MHz using a Yokogawa DL850E oscilloscope equipped with a 720211 12-bit isolation module. The PCB sensors were mounted flush with the model surface using RTV silicone adhesive.

A total of five PCB sensors (P1–P5) were installed on the cone-slice-ramp model. Sensor P1 was located on the fore-cone upstream of the SBLI region, P2 and P3 were located within the separation bubble, and P4 and P5 were located downstream of the reattachment shock on the ramp surface. The locations of the PCB sensors are summarized in Table 2.3, together with the FLDI measurement locations described in Section 2.5.2. For visualization of the sensor locations relative to the flow field, Figure 2.8 shows the locations of P1–P5 overlaid on high-speed schlieren images.

For the power spectral density (PSD) plots presented later in this work for PCB data of a given shot condition, the mean PSD and its confidence interval were computed as follows. For each test case, the PSD is first computed for each individual shot using Welch’s method, and the ensemble mean spectrum is then formed as the

arithmetic mean of the shot PSDs at each frequency. The confidence interval on this mean PSD is computed using the standard chi-square model for Welch spectral estimates, with the effective degrees of freedom taken as twice the total number of contributing Welch segments across all shots in the ensemble.

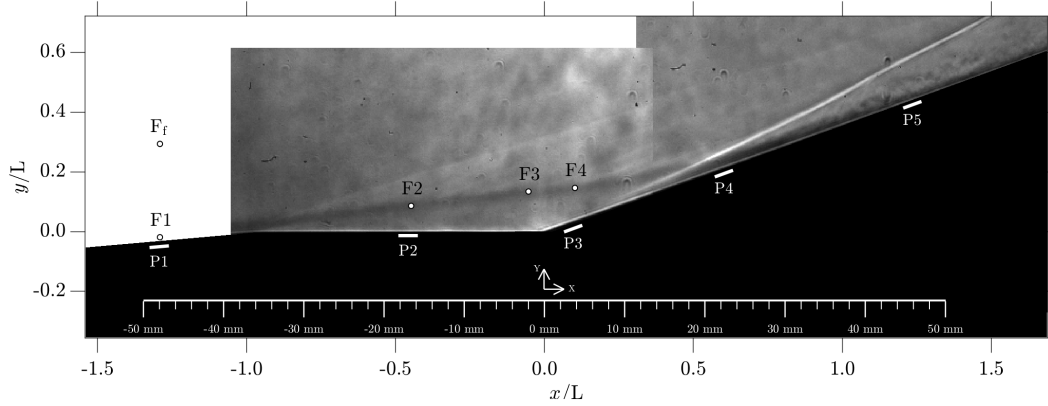


Figure 2.8: Annotated locations of surface PCB sensors P1–P5 and FLDI beam positions F_f & F1–F4.

Table 2.3: Summary of dynamic pressure sensors and FLDI beam locations. Locations are reported in global x -, y -, and z -coordinates, where the origin is defined at the slice-ramp corner at the model centerline.

Sensor Label	Description	x [mm]	y [mm]	z [mm]
P1	PCB on fore-cone surface	-47.9	-1.1	-4.0
P2	PCB in the separation bubble, centered on the slice	-17.9	0.0	-4.0
P3	PCB in the separation bubble at the base of the ramp	2.9	1.0	-4.0
P4	PCB at one-quarter of the ramp length	21.7	7.9	-4.0
P5	PCB at one-half of the ramp length	45.2	16.4	-4.0
F_f	FLDI beam in the post-conical-shock flow	-47.6	10.9	0.0
F1	FLDI beam above P1 in the incoming boundary layer	-47.8	-0.8	0.0
F2	FLDI beam above P2 in the separated shear layer	-17.6	3.2	0.0
F3	FLDI beam between F2 and F4 in the separated shear layer	-2.9	5.0	0.0
F4	FLDI beam above P3 in the separated shear layer	2.9	5.4	0.0

2.5 Flowfield Diagnostics

This section describes the non-intrusive diagnostics used to measure the flow field above the cone-slice-ramp model including the use of high-speed schlieren imaging and Focused Laser Differential Interferometry (FLDI).

2.5.1 High Speed Schlieren Imaging

High-speed Z-type schlieren imaging was used to characterize the flow features over the slice-ramp portion of the model. These images were used to identify the mean locations of SBLI features and resolve unsteadiness of the SBLI. The schlieren system employed a conventional Z-type optical arrangement, as shown in Figure 2.9.

Illumination was provided by a CAVILUX® HF pulsed diode laser operating at a wavelength of 635 nm, with pulse durations of 20 ns. The laser output was first condensed with an aspheric lens through an iris and then collimated through the test section using f/15 collimation mirrors of 203.2 mm diameter. A second iris positioned near the focal point was used to reject facility luminescence traveling with, but not parallel to, the collimated beam. At the focal point a knife edge was positioned horizontally to resolve vertical gradients in refractive index. The image was then focused onto the camera sensor using a $f=1200$ mm plano-convex lens. A 635 nm bandpass filter was mounted in front of the camera to reduce the contribution of broadband luminescence. Image acquisition was performed with a Phantom TMX 7510 high-speed camera at 875 kHz, using an exposure time of 150 ns. At these settings, the Phantom TMX 7510 was capable of recording 640 by 128 pixel frames.

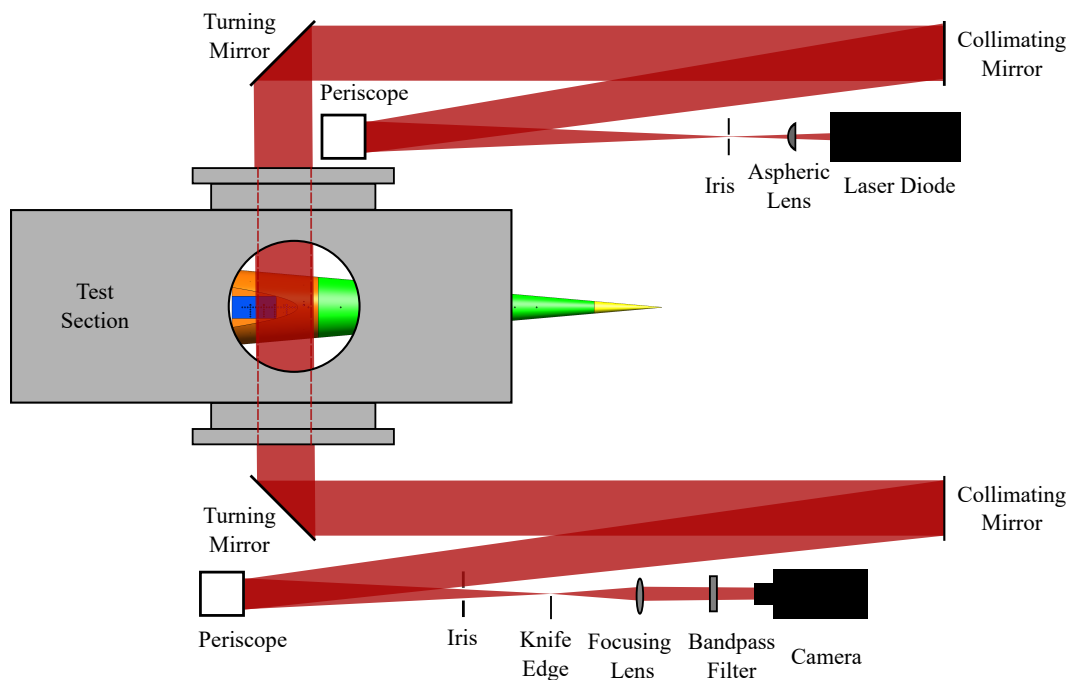


Figure 2.9: T5 Z-type schlieren imaging optics.

2.5.2 Focused Laser Differential Interferometry

This subsection introduces Focused Laser Differential Interferometry (FLDI), a non-imaging optical diagnostic used to measure localized flow disturbances. It first reviews the operating principles and development of FLDI, then describes the interpretation of the measured signal and the specific optical configuration used in the present experiments.

2.5.2.1 Background

In its most fundamental form, the FLDI is a shearing interferometer consisting of two coherent, orthogonally polarized light beams whose principal rays are parallel and separated by a small distance, Δx . The beams are focused to small waists at the region of interest, after which they expand, are recombined, and interfere on a photodetector. The resulting output is a single voltage time signal proportional to the interference caused by changes in the index of refraction between the two beams. Because the beams are focused, the diagnostic is less sensitive to refractive index disturbances away from the focal plane compared to conventional non-focusing laser differential interferometry, thereby reducing line-of-sight integration effects. This combination of high temporal bandwidth and sub-millimeter spatial resolution has made FLDI particularly attractive for measurements in hypersonic facilities, where intrusive diagnostics are often impractical and other optical techniques can suffer from strong path integration effects.

FLDI was first proposed by Smeets and George, [1973](#), but early limitations in laser and detector technology prevented its widespread adoption. The modern use of FLDI in hypersonics began with Parziale et al., [2012](#), who demonstrated a practical implementation in T5 for measuring freestream tunnel noise and acoustic instability waves in cone boundary layers (Parziale, [2013](#)). Schmidt and Shepherd, [2015](#) subsequently developed a transfer function based theoretical framework for FLDI, providing a more rigorous analytical basis for predicting and interpreting the instrument response to a given density field. Settles and Fulghum, [2016](#) obtained a similar result to Schmidt and Shepherd through an independent treatment by modeling the propagation of polarized electric fields using Jones vectors. Lawson (Lawson et al., [2019](#); Lawson and Austin, [2021](#), [2023a,b](#); Lawson et al., [2020](#)) further advanced FLDI through detailed characterization studies, investigations of its response to shock waves, and the development of more general inversion methods for recovering density disturbance spectra from measured phase signals.

FLDI has been applied to an expanding range of high-speed flow problems, including the study of instability waves in separated hypersonic shear layers. Benitez (Benitez et al., 2021, 2020, 2023a) applied FLDI in the Purdue Mach 6 Quiet Tunnel to a cone-cylinder-flare model, using the diagnostic to characterize disturbances within the separated shear layer and to assess FLDI response in axisymmetric separated flows. Pandey et al., 2022b used a scanning FLDI system to measure second-mode disturbances propagating through the separated shear layer over a cone-slice-ramp model in the Sandia Hypersonic Wind Tunnel. At hypervelocity conditions in T5, FLDI has also been used over a double-cone geometry, where low frequency Kelvin–Helmholtz instabilities, mid-frequency shear layer instabilities, and high frequency Mack mode disturbances were identified (Yu, 2024). FLDI was also combined with schlieren in T5 by Luo, 2026 to identify convecting shear layer disturbances in the near wake of a cylinder in hypervelocity flows.

2.5.2.2 Theory and Signal Interpretation

As with classical interferometry, the operating principle of FLDI is the conversion of optical path differences into measurable intensity fluctuations. The instrument is arranged in an infinite fringe configuration, so that at rest only a single fringe is observed and small phase perturbations appear as brightening or darkening of the recombined beam on the photodetector. The measured signal may therefore be interpreted as a time-varying phase response, $\Delta\Phi(t)$, associated with the refractive-index field traversed by the two beams.

The refractive index n may be related to the gas density ρ using either the Gladstone-Dale relation,

$$n = K\rho + 1, \quad (2.8)$$

where K is the Gladstone-Dale constant that is wavelength dependent (Gladstone and Dale, 1863; Merzkirch, 1987) or the Lorenz-Lorentz relation,

$$R_L = \left(\frac{n^2 - 1}{n^2 + 2} \right) \left(\frac{1}{\rho} \right), \quad (2.9)$$

derived from first principles where R_L is likewise wavelength dependent (Gardiner et al., 1981; Kragh, 1991). For gases at sufficiently low density, where $n \approx 1$, the two relations approach each other, with $K \approx 3R_L/2$. Together, these relations show

that FLDI measures density fluctuations indirectly through the refractive index perturbations they produce. Since the beam spacing is typically on the order of $O(100\mu\text{m})$ and photodetector bandwidths are typically $O(10\text{ MHz})$ or greater, FLDI offers both a high spatial and temporal resolution measurement of density fluctuations in a flow field.

For many applications, the raw voltage trace is sufficient to extract the dominant frequency content of the disturbances. However, expressing the measurement in terms of density fluctuations provides a more physically intuitive interpretation of the signal. An early analytical relation introduced by Parziale, 2013 related the measured voltage to an average density difference between the two beams:

$$\frac{\Delta\rho}{\bar{\rho}} = \frac{\lambda_L}{2\pi K \zeta \bar{\rho}} \sin^{-1} \left(\frac{V}{V_0} - 1 \right), \quad (2.10)$$

where λ_L is the laser wavelength, $\bar{\rho}$ is the local mean density, V is the photodetector output voltage, V_0 is a reference voltage associated with the center of the infinite fringe, K is the Gladstone-Dale constant, and ζ is an empirically determined sensitive length. For sinusoidal disturbances, Parziale further introduced the correction factor

$$c(\lambda) = \sin \left(\frac{\pi \Delta x}{\lambda} \right), \quad (2.11)$$

to account for finite beam separation relative to the disturbance wavelength. Owing to its simplicity, this approach has been widely used in the FLDI literature (Benitez et al., 2021; Ceruzzi et al., 2020; Hameed and Parziale, 2021).

Since Parziale's approach does not, in general, account accurately for the wavelength dependence of the FLDI sensitive length, Schmidt and Shepherd developed a more complete theoretical treatment in which the two FLDI beams are represented as parallel focusing ray bundles separated by a constant Δx (Schmidt and Shepherd, 2015). Let the source and detector planes be denoted by S and D , and let the normalized beam intensity distribution over the detector coordinates (ξ, η) be $I_0(\xi, \eta)$. The refractive index field sampled by the two beams is $n(\mathbf{x}_1, t)$ and $n(\mathbf{x}_2, t)$, and the corresponding ray-path parameterizations are s_1 and s_2 . The phase response is then

$$\Delta\Phi(t) = \frac{2\pi}{\lambda_L} \iint_D I_0 \sin \left[\frac{2\pi}{\lambda_L} \left(\int_S^D n(\mathbf{x}_1, t) ds_1 - \int_S^D n(\mathbf{x}_2, t) ds_2 \right) \right] d\xi d\eta. \quad (2.12)$$

Under the small-angle approximation, this expression may be linearized to

$$\Delta\Phi(t) = \frac{2\pi}{\lambda_L} \iint_D I_0 \left(\int_S^D n(\mathbf{x}_1, t) ds_1 - \int_S^D n(\mathbf{x}_2, t) ds_2 \right) d\xi d\eta. \quad (2.13)$$

This formulation makes clear that FLDI measures the weighted optical path difference between the two focused beams. It also shows why the instrument may be interpreted as a finite difference measure of the refractive index gradient in the beam separation direction: the response depends on the difference between the two closely spaced beam paths, rather than on a single integrated path quantity.

For a one-dimensional sinusoidal disturbance of wavenumber k , Schmidt and Shepherd derived a transfer function of the form

$$H(k) = H_s(k)H_w(k) = \frac{2}{k\Delta x} \sin\left(\frac{k\Delta x}{2}\right) \exp\left(-\frac{w^2 k^2}{8}\right), \quad (2.14)$$

where w is the Gaussian beam radius at the disturbance location. The first term,

$$H_s(k) = \frac{2}{k\Delta x} \sin\left(\frac{k\Delta x}{2}\right), \quad (2.15)$$

arises from finite beam separation, while the second term,

$$H_w(k) = \exp\left(-\frac{w^2 k^2}{8}\right), \quad (2.16)$$

represents spatial filtering due to the finite beam width. This decomposition is physically useful because $H_s(k)$ represents the effect of finite beam separation, while $H_w(k)$ represents the effect of finite beam width. The latter term is responsible for the spatial filtering of FLDI, since w increases away from the focal plane and the response to wavelengths much smaller than the local beam width is strongly attenuated. Accordingly, the sensitive length of the instrument is wavenumber dependent rather than fixed.

Lawson and Austin, [2023a](#) extended this framework by considering generalized plane waves and solving the inverse problem for a broader class of refractive index fields. For a generalized time-varying plane wave,

$$n(\mathbf{x}, t) = A \cos(\mathbf{k} \cdot \mathbf{x} - \omega t + \varphi), \quad (2.17)$$

where A is the wave amplitude, $\mathbf{k}$ is the wavevector, ω is the angular frequency, and φ is the phase, they derived an analytical expression for the FLDI phase response of the form

$$\begin{aligned}
\Delta\Phi(t) &= \frac{2\pi A}{\lambda_L} \cdot \frac{4\sqrt{2}\pi^{3/4}w_0}{\sqrt{\mathbf{k}_x^2 + \mathbf{k}_y^2}\lambda_L} \cdot \sin\left(\frac{\mathbf{k}_x\Delta x}{2}\right) \cdot \sin(\omega t - \varphi) \\
&\quad \cdot \exp\left(-\frac{w_0^2}{8}\left[\mathbf{k}_x^2 + \mathbf{k}_y^2 + \frac{16\pi^2\mathbf{k}_z^2}{(\mathbf{k}_x^2 + \mathbf{k}_y^2)\lambda_L^2}\right]\right) \\
&\quad \cdot \Re\left[\operatorname{erf}\left(\frac{(\mathbf{k}_x^2 + \mathbf{k}_y^2)L\lambda_L^2 + i4\pi^2\mathbf{k}_z w_0^2}{2\sqrt{2}\pi\sqrt{\mathbf{k}_x^2 + \mathbf{k}_y^2}\lambda_L w_0}\right)\right] \\
&= A \cdot h(\mathbf{k}) \cdot \sin(\omega t - \varphi)
\end{aligned} \tag{2.18}$$

where i is the imaginary unit, $\Re$ denotes the real part, erf is the error function, and $h(\mathbf{k})$ collects the grouped wavenumber dependent terms of the FLDI response. In this form, the result provides an exact forward model for the response of FLDI to a single sinusoidal plane wave. More importantly, by extension to superpositions of such waves, Lawson showed that the inverse problem is solvable in a spectral sense for refractive index fields composed of arbitrary superpositions of sinusoidal plane waves and uniform convecting flows.

This result also clarifies the limitations of earlier approximate interpretations of FLDI data. In particular, Lawson showed that the expression proposed by Parziale is restricted to the special case of plane sinusoidal waves propagating only in the FLDI separation direction. Outside that special geometry, the measured phase signal depends on the full disturbance wavenumber content and propagation direction through the response function $h(\mathbf{k})$, so inconsistent assumptions can introduce quantitative error in reconstructed density spectra.

Accordingly, in the present work, results are reported in terms of the denoised power spectral density of the phase shift, $\text{PSD}\{\overline{\Delta\Phi(t)}\}$, with units of $\text{rad}^2 \text{Hz}^{-1}$, for FLDI measurements in the incoming boundary layer and along the separated shear layer (F1–F4). This choice is made because the disturbance field remains too complex to justify reconstruction of the instrument response under the assumption of sinusoidal plane waves. For freestream measurements in the post-conical-shock flow (F_f), reconstructed density spectra are reported with all required assumptions stated explicitly, and with the corresponding FLDI response function, $h(\mathbf{k})$, defined in Appendix B.

2.5.2.3 Specifics of the Present FLDI System

The optical configuration used in the present work follows the general FLDI arrangement adopted by Parziale et al. (2012) and Lawson et al. (2019). Figure 2.10 shows a schematic of the FLDI system, including the spacing between optical components while Figure 2.11 shows the aligned FLDI beams in the T5 test section above the model. A Cobolt Samba 1500 mW 532 nm laser produces light that is nominally linearly polarized in a single direction, which is first expanded using a diverging lens (D). The expanded beam is then converted to circularly polarized light using a quarter-wave plate (QWP). This circularly polarized beam is subsequently split into two orthogonally polarized beams by a Wollaston prism (WP). The beam pair is then focused by a plano-convex lens (F), producing two closely spaced foci in the test section focal plane.

Downstream of the focal plane, a second plano-convex lens and Wollaston prism recombine the beams. This reduces the beam diameter and brings the two orthogonally polarized beams back together with a phase difference between polarizations corresponding to the differential optical path length. Transmission of the recombined beams through a linear polarizer (LP) causes the two beams to interfere, such that the optical intensity is modulated by the differential phase signal. The light then passes through a bandpass filter (BP) to reject facility luminescence before being recorded by the photodetector (PD). A complete list of optical components used in the present work is given in Table 2.4.

The spacing between the two beam foci was measured to be $145 \pm 2 \mu\text{m}$, while the beam diameter at the focal plane was $10.6 \pm 2 \mu\text{m}$. These measurements were obtained by focusing the beam pair at the model centerline and using a Thorlabs BP209-VIS scanning-slit beam profiler. The FLDI beam pair was oriented at $5.0 \pm 0.2^\circ$ relative to the cone centerline for F_f measurements and at $6.50 \pm 0.1^\circ$ for $F1$ – $F4$ measurements. These orientations ensured that the FLDI beam pair remained approximately parallel to the boundary layer and the separated shear layer, respectively.

Precise alignment of the beams relative to the model was performed by first using a 3D-printed target to establish the desired laser location before installing any optics. After the pitch side optics were aligned, the entire pitch side was raised by 2 inches to accommodate the height of the beam profiler at the model centerline, where the beam measurements described above were obtained. Once the correct focus, beam spacing, beam orientation, and beam separation had been verified, the optics were

carefully lowered back to the original height used during the initial alignment. Burn paper was then used to verify and report the final beam position relative to the model. The FLDI photodetector signals were recorded on a Yokogawa DL850E oscilloscope at a sampling rate of 100 MHz.

As in Lawson et al., 2019, calibration is required to relate the raw photodetector voltage to phase shift. The voltage-phase relationship is modeled as

$$V = A \sin(\Delta\Phi - \Delta\Phi_0) + D, \quad (2.19)$$

where A , D , and $\Delta\Phi_0$ are calibration constants. To determine these constants, the receiving Wollaston prism is translated slowly across the full infinite fringe using a Thorlabs LNR25ZFS mechanical stage controlled by a KDC101 stage controller. This produces a sinusoidal photodetector response corresponding to a nearly constant phase sweep, allowing the calibration parameters to be obtained by fitting the measured voltage trace to a sine wave. Prior to facility run, the Wollaston prism is positioned such that the resting detector voltage lies near the center of the dynamic range, thereby maximizing linear sensitivity to small phase perturbations.

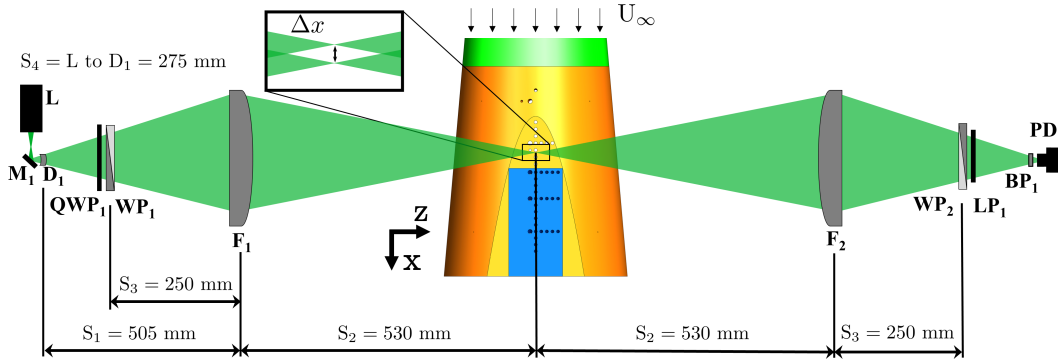


Figure 2.10: Schematic of FLDI setup used in present work.

Table 2.4: FLDI optical components list.

Optic	Abbreviation	Part Details
Laser	L	Cobalt 05-01 Samba 1500 mW 532 nm CW laser
Turning Mirror	M1	Thorlabs BB2-E02 Broadband Dielectric Mirror $\varnothing 76.2$ mm
Diverging Lens	D	Thorlabs LC2067-A - Plano-Concave Lens, $\varnothing 9$ mm, $f = -9.0$ mm
Focusing Lens	F1, F2	Newport PAC095AR.14 - Achromatic Doublet Lens, $\varnothing 76.2$ mm, $f = 250$ mm
Quarter-Wave Plate	QWP	Thorlabs WPQ20ME - 532 nm Mounted Polymer Zero-Order Quarter-Wave Plate, $\varnothing 50.8$ mm
Wollaston Prism	WP1, WP2	United Crystals Inc. Quartz Wollaston Prism, 50×50 mm, 2 arc-min splitting angle
Linear Polariser	LP	Thorlabs LPV1SB100-MP - Mounted Linear Polarizer, $\varnothing 25$ mm
Bandpass Filter - 532 nm	BP	Thorlabs FLH532-10 - Bandpass Filter, $\varnothing 25$ mm, CWL = 532 nm, FWHM = 10 nm
Photodetector	PD	Thorlabs PDA36A2 - Si Switchable Gain Detector

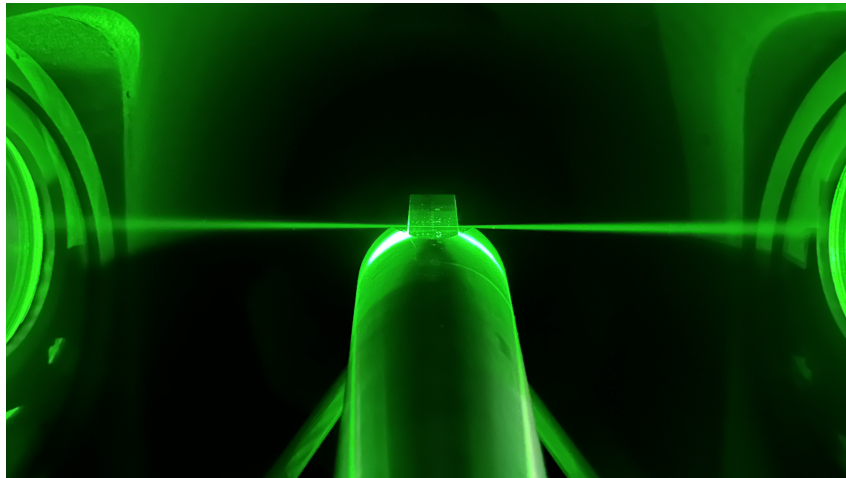


Figure 2.11: FLDI beams aligned above cone-slice-ramp in T5 test section.

Chapter 3

SBLI-INDUCED SURFACE HEAT FLUX: CHARACTERIZATION AND RESULTS

This chapter presents and interprets the surface heat flux measurements obtained across the cone-slice-ramp SBLI region. The first part of the chapter characterizes factors that influence the measured heat flux response, including cone alignment, the definition of usable test time, and the state of the incoming boundary layer.

The second part examines the measured surface heat flux across the SBLI region for the H8-Re2, H8-Re3, H8-Re6, and H14-Re3 test conditions. Streamwise and spanwise heating distributions are analyzed for laminar, mixed, and transitional interactions, with emphasis on the roles of the incoming boundary layer, separated shear layer state, reattachment location, and ramp surface transition. Comparisons with theoretical predictions and prior studies are used throughout to interpret the observed heating trends.

The final section presents measurements of the key mean flow features in the SBLI region. These measurements are used to compare trends in separation region size and to investigate how changes in stagnation enthalpy and unit Reynolds number affect separation length.

3.1 Characterization of Factors Influencing Heat Flux Measurements

This section discusses factors that influence the reported heat flux measurements across the SBLI region. First, cone alignment is quantified for all shots conducted in this work. The viscous and inviscid flow establishment timescales are then compared to ensure that the heat flux data were collected during established flow test time. Finally, the methods used to determine the state of the incoming boundary layer entering the SBLI are reviewed.

3.1.1 Cone Alignment

Experiments conducted at Purdue University, in combination with simulations of the cone-slice-ramp geometry, have shown that spanwise variations in surface heat flux and pressure loading are sensitive to model misalignment relative to the freestream flow (McKiernan, [2020](#); Thome et al., [2018](#)). In these studies, a yaw misalignment of

0.4° produced asymmetric pressure and heat flux loading on the ramp. Experiments in which the angle-of-attack was varied by 2° also showed increased streak density and altered streak patterns on the ramp surface (Francis et al., 2025). Care was therefore taken to minimize alignment errors and to quantify any residual pitch and yaw misalignment during the test campaigns. To quantify this misalignment, surface pressure measurements were acquired during test time using the NPP-301A-100A sensors discussed in Section 2.4.2. The sensors were located aft on the cone surface at 90° intervals.

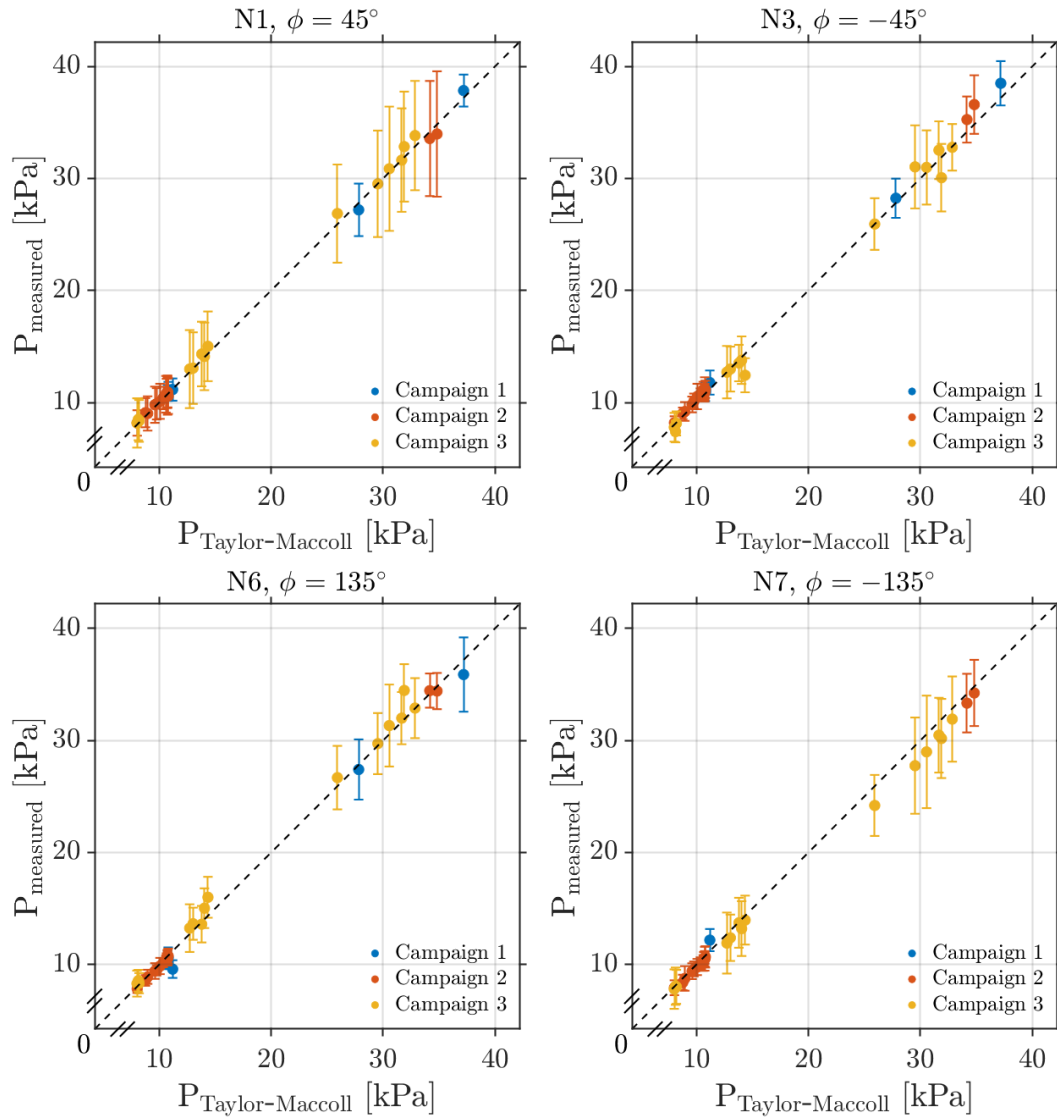


Figure 3.1: Experimental cone surface pressure (P_{exp}) vs theoretical Taylor-Maccoll surface pressure (P_{TM}), assuming zero angle-of-attack. Error bars indicate $\pm 1\sigma$ fluctuations during test time.

An example of measurements from four NPP-301A-100 sensors (N1, N3, N6, and

N7), evenly spaced around the cone circumference, is shown in Figure 3.1. This figure shows the pressure readings from each static pressure sensor across all shot conditions. The data are separated by color into three test campaigns, representing three separate alignments of the cone in the test section. Shot numbers 3032 to 3040, 3064 to 3079, and 3167 to 3187 correspond to each of the three campaigns, respectively.

The experimentally determined cone pressure P_{exp} is plotted against the theoretical inviscid Taylor-Maccoll surface pressure P_{TM} , assuming zero angle-of-attack. The experimental error bars correspond to $\pm 1\sigma$ fluctuations evaluated over test time. Small discrepancies in P_{exp}/P_{TM} were observed between the stations, suggesting misalignment in pitch and yaw.

For sufficiently small angles of attack (α), the deviation in surface pressure from the Taylor-Maccoll solution at the surface ($\bar{p}$) is given by $p = \bar{P} + \eta \cos(\phi)\alpha$ (Kopal, 1947). Here, ϕ is the azimuthal angle measured relative to the pitching or yawing plane. Kopal defines η as an angle-of-attack correction coefficient applied to the zero angle-of-attack pressure P_{TM} .

It is assumed that the cone is subjected to a pitch angle of α_1 in the plane $\phi = 0^\circ$ and a yaw angle of α_2 in the plane $\phi = 90^\circ$, where azimuthal angles are measured relative to the zenith. Under the assumption that the misalignment angles are small, the effects of yaw and pitch can be treated as uncoupled, allowing the pitch and yaw contributions to be linearly superposed. A system of equations can therefore be derived to reconstruct the measured pressure at each sensor location as a function of pitch and yaw misalignment, as given in Eq. 3.1.

$$\begin{aligned}
 \frac{P_{exp,N_1}}{b \cdot P_{TM}} - 1 &= \eta \cos(\theta_1)\alpha_1 + \eta \cos(\theta_1 - \pi/2)\alpha_2 \\
 \frac{P_{exp,N_3}}{b \cdot P_{TM}} - 1 &= \eta \cos(\theta_3)\alpha_1 + \eta \cos(\theta_3 - \pi/2)\alpha_2 \\
 \frac{P_{exp,N_6}}{b \cdot P_{TM}} - 1 &= \eta \cos(\theta_6)\alpha_1 + \eta \cos(\theta_6 - \pi/2)\alpha_2 \\
 \frac{P_{exp,N_7}}{b \cdot P_{TM}} - 1 &= \eta \cos(\theta_7)\alpha_1 + \eta \cos(\theta_7 - \pi/2)\alpha_2
 \end{aligned} \tag{3.1}$$

In these equations, the measured pressure P_{exp} is scaled by an experimental bias factor (b) to account for shots in which all four transducers reported pressures slightly above or below P_{TM} . The correction factor was small, with the majority of

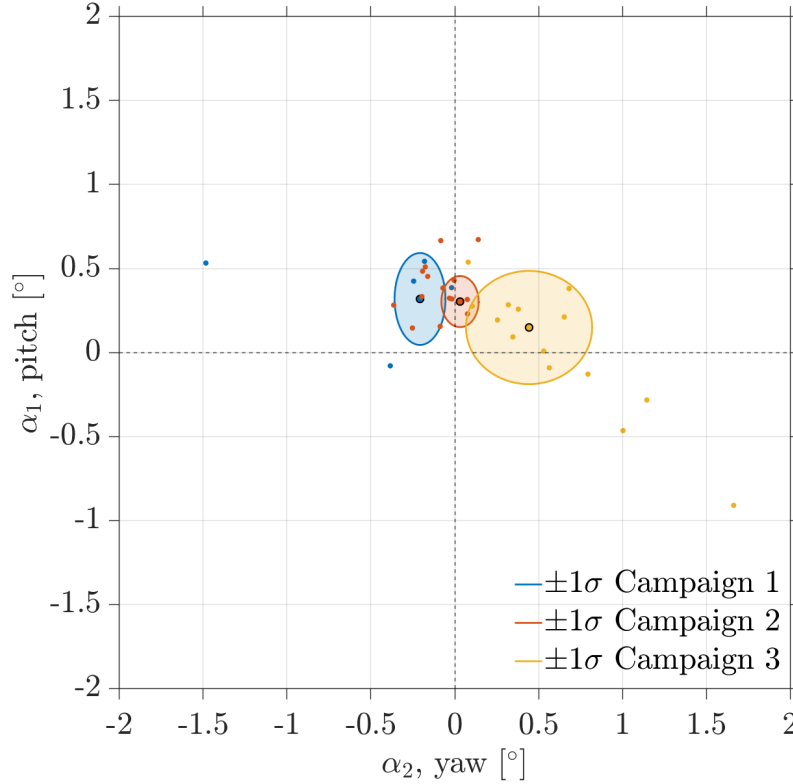


Figure 3.2: Measured pitch and yaw misalignment of cone across all three campaigns. Shaded regions represent the $\pm 1\sigma$ confidence in the reported mean misalignment angles. Positive values of α_1 correspond to pitch up and positive values of α_2 correspond to starboard yaw.

shots falling within $b \sim 0.95\text{--}1.05$. With three free variables (b , α_1 , α_2) and four equations, a linear least-squares solution was used to determine the pitch and yaw misalignment of the cone.

The alignment was found to be satisfactory, remaining within the targeted misalignment tolerance of $\pm 0.5^\circ$. The three campaigns exhibited small upward pitch angles of $\alpha_1 = 0.35^\circ$, $\alpha_1 = 0.31^\circ$, and $\alpha_1 = 0.2^\circ$, respectively. The yaw misalignment varied between campaigns, ranging from port yaw of $\alpha_2 = -0.32^\circ$ for campaign 1, to approximately neutral yaw for campaign 2, and starboard yaw of $\alpha_2 = 0.44^\circ$ for campaign 3.

3.1.2 Defining Test Times and Flow Establishment Timescales

Test times in T5 are on the order of milliseconds, and flow startup transients can be inadvertently included in the dataset if appropriate care is not taken. Including these transients biases the measured heat flux away from the value associated with established flow over the model and should therefore be avoided. When defining the

useful test time, the startup process, the establishment of key flow features, and the end of the usable test interval must all be considered.

The beginning of test time, following nozzle startup, is governed by the establishment of flow over the cone-slice-ramp model, including both viscous and inviscid flow features. Flow establishment times for separated flows in high-speed ground-test experiments have also been considered by Holden, 1971; Ihrig and Korst, 1963; Vanstone et al., 2017. Here, the approach of Swantek and Austin, 2015 is followed because it is most relevant to the present test conditions. The viscous flow establishment time is identified from the wall heating response, with viscous flow considered established when the local heat flux reaches its mean steady state value. For inviscid flow establishment, Swantek tracks the locations of the shock structures in the flowfield and defines establishment as the time at which their locations reach their mean steady state positions.

For viscous flow establishment, five surface thermocouple traces were examined at various locations across the SBLI region. Figure 3.3a) and 3.3b) shows the reported heat flux for the H8-Re2 and H8-Re3 conditions with $h_0 = 8 \text{ MJ kg}^{-1}$. These thermocouple signals are plotted against facility time, where $t = 0 \text{ ms}$ corresponds to the arrival of the transmitted shock at the nozzle throat. At $t = 0.64 \text{ ms}$, the nozzle flow is fully established (Sudani and Hornung, 1998); however, the measured surface heat flux indicates that viscous flow establishment has not yet occurred. At approximately $t = 1.30 \text{ ms}$, a plateau in the reported heat flux is observed for all thermocouples, indicating that viscous flow has been established throughout the slice-ramp region of the model. At $t = 2.00 \text{ ms}$, driver gas contamination defines the end of facility test time, resulting in a usable test-time window from 1.30 to 2.00 ms. Figure 3.3c) shows the same general heat-flux trends for the H14-Re3 condition at $h_0 = 14 \text{ MJ kg}^{-1}$, with a usable test time window from $t = 1.00$ to $t = 1.40 \text{ ms}$.

Inviscid flow establishment in the SBLI region was evaluated qualitatively from schlieren imaging, as shown in Figures 3.4a) to 3.4c). Although inviscid flow is expected to establish on shorter timescales than viscous flow, this comparison provides a useful check. High-speed schlieren imaging was recorded from facility startup to the end of facility test time to track the development of flow features in the SBLI region. At the end of nozzle startup, qualitative comparisons of the separation shock and shear layer locations indicate that the inviscid flow features have not fully established, consistent with the thermocouple data. From the measured start of viscous flow establishment to the end of facility test time, the flow features remain

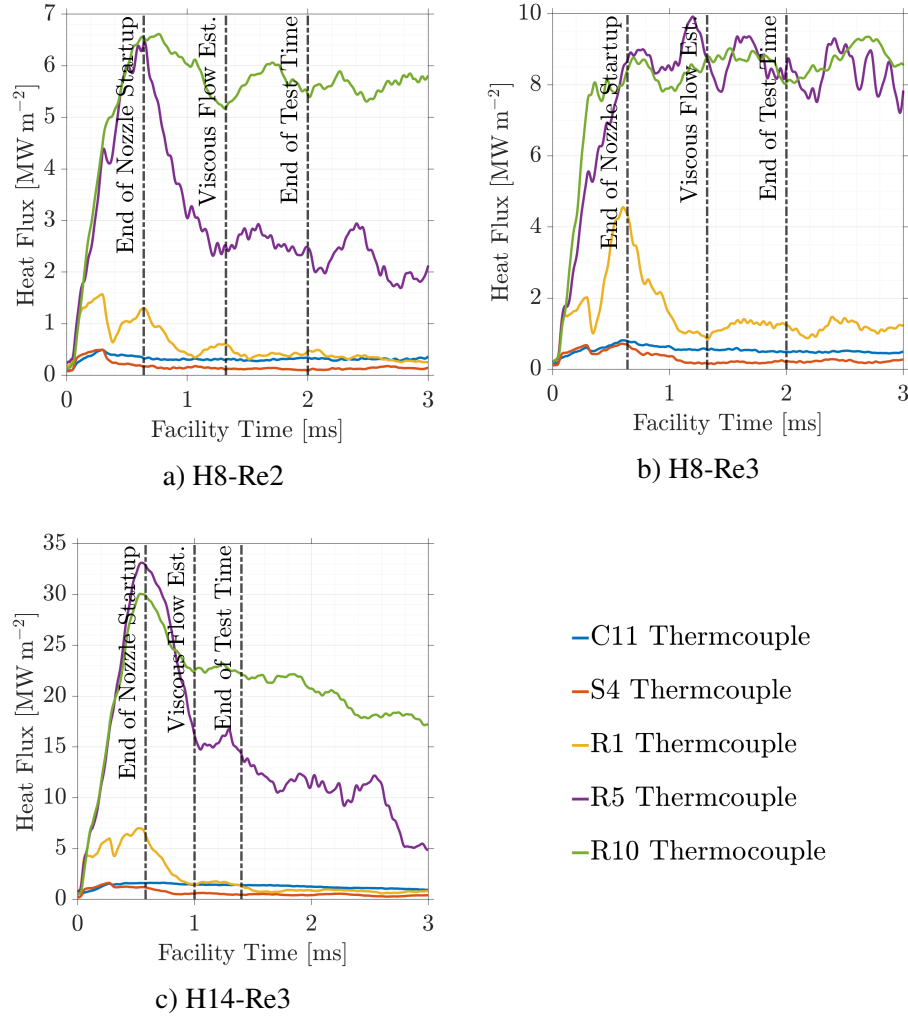
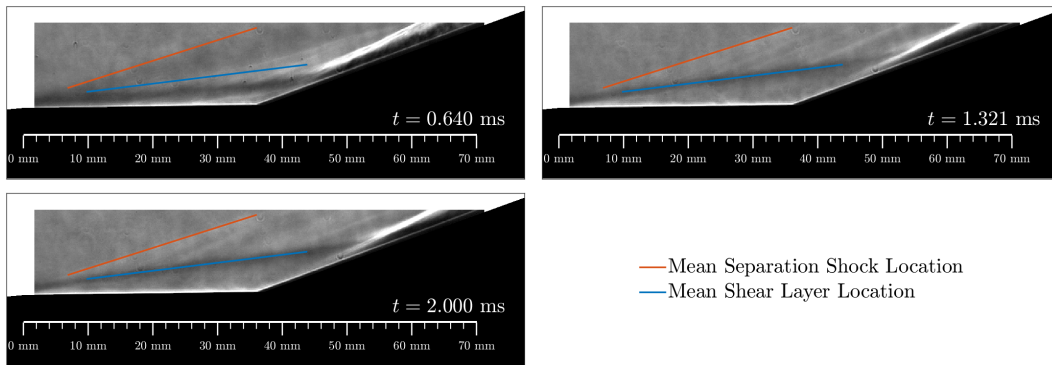


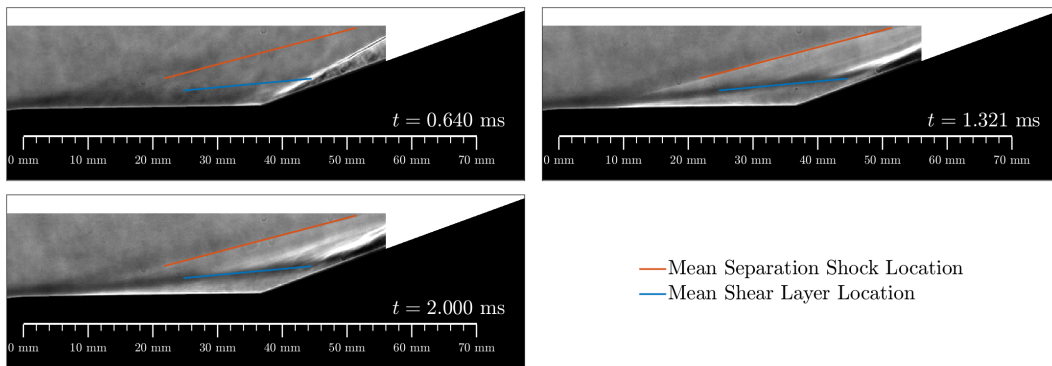
Figure 3.3: Surface heat flux plotted over facility time demonstrating viscous flow establishment for the three shot conditions that produced a separated shear layer.

established about their mean locations, while exhibiting unsteadiness that will be explored in Chapter 4.

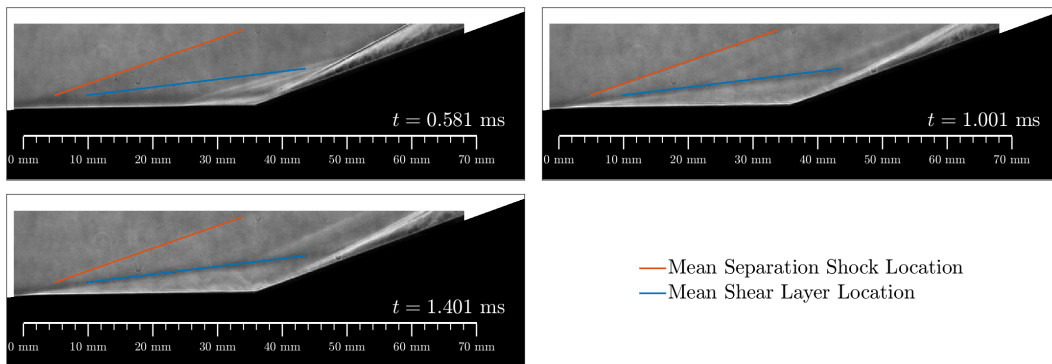
The result of properly defining test time is shown in Figure 3.5, where spectrograms of on-surface pressure measurements inside the separation bubble are plotted. The vertical white lines indicate the test time bounds discussed above. The peak frequencies in the spectrograms remain constant only within the defined test time window, suggesting that the viscous and inviscid flow features remain established but unsteady, as expected. Any references to “test time” throughout this work refer to the $t = 1.30$ to $t = 2.00$ ms window for the $h_0 = 8 \text{ MJ kg}^{-1}$ conditions (H8-Re2, H8-Re3, H8-Re6) and the $t = 1.00$ to $t = 1.40$ ms window for the $h_0 = 14 \text{ MJ kg}^{-1}$ condition (H14-Re3).



a) H8-Re2



b) H8-Re3



c) H14-Re3

Figure 3.4: Schlieren frames taken at the end of nozzle startup, start of viscous flow establishment, and the end of facility test time for the three test conditions that produced a separated shear layer. Flow features remain established about their mean locations throughout test time while exhibiting unsteadiness.

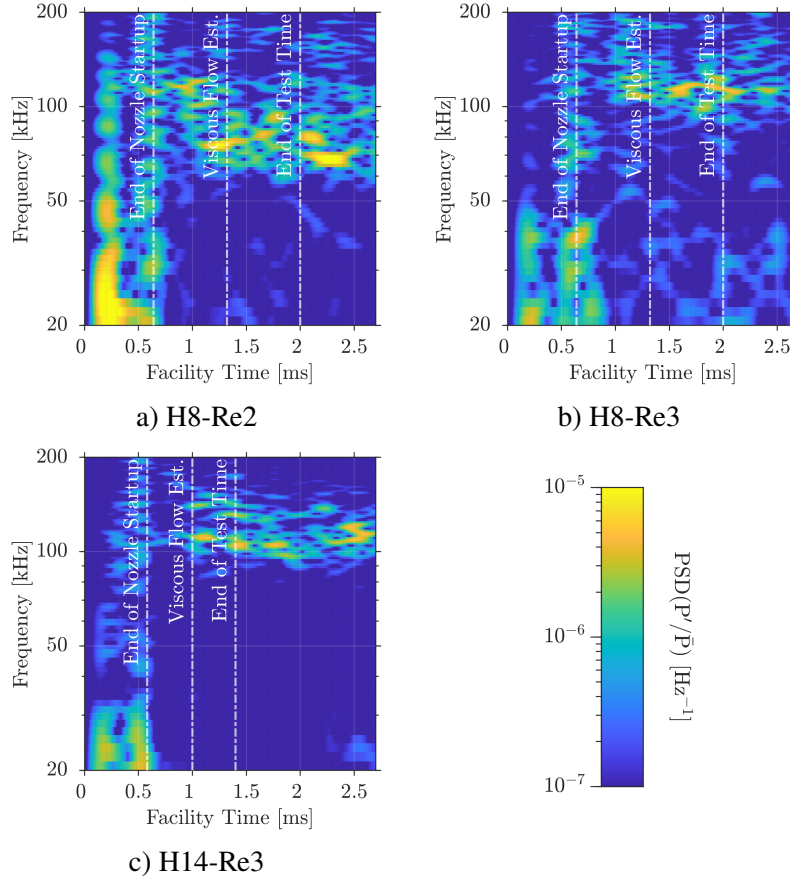


Figure 3.5: Spectrograms of surface pressure sensor P3 inside the separation bubble. Peak frequencies remain constant throughout test time suggesting an established, yet unsteady SBLI region.

3.1.3 State of Incoming Boundary Layer

The size and location of flow features in an SBLI are sensitive to the state of the boundary layer entering the interaction region (Gray, 1967; Pandey et al., 2020). To determine whether the incoming boundary layer on the cone-slice-ramp geometry was laminar, transitional, or turbulent, surface heat flux data were normalized by the freestream mass flux and the effective recovery enthalpy difference as defined by the Stanton number (St)

$$\text{St} = \frac{\dot{q}(x)}{\rho_e U_e \left[h_{res} - \frac{1}{2} U_e^2 (1 - r) \right]} \quad (3.2)$$

where the recovery factor r is taken to be $r_{\text{lam}} = \sqrt{\text{Pr}}$ for laminar flow and $r_{\text{turb}} = \text{Pr}^{1/3}$ for turbulent flow (Anderson, 2003).

These non-dimensional heat flux values were then compared to laminar and turbulent boundary layer theory to determine the state of the incoming boundary layer. As with previous studies of the 5-degree cone in T5 (Germain and Hornung, 1997; Jewell, 2014), the computation of the theoretical laminar boundary layer Stanton number, a Reynolds analogy based relation for a laminar high-speed boundary layer is used,

$$\text{St} \approx \frac{1}{2} C_f \text{Pr}^{-2/3} \quad (3.3)$$

Here, the skin friction coefficient C_f is approximated using the incompressible Blasius flat-plate result (White, 1991),

$$C_{f,\text{inc}}(x) \approx \frac{0.664}{\sqrt{\text{Re}_x}} \quad (3.4)$$

An approximate compressible correlation is obtained by introducing the Chapman–Rubesin correction factor. Due to strong property variation throughout the hypervelocity boundary layer from edge conditions, density and viscosity are evaluated at the Dorrance reference temperature (Dorrance, 1962),

$$C_{f,\text{comp}}(x) \approx \frac{0.664}{\sqrt{\text{Re}_x}} \sqrt{C^*}, \quad C^* = \frac{\rho^* \mu^*}{\rho_e \mu_e} \quad (3.5)$$

where

$$\frac{T^*}{T_e} = \frac{1}{2} + \frac{\gamma - 1}{2} \frac{\sqrt{\text{Pr}}}{6} M_e^2 + \frac{1}{2} \frac{T_w}{T_e} \quad (3.6)$$

For conical, axisymmetric flow, the Lees–Illingworth relation (Lees, 1956) relates the cone result to the flat-plate result,

$$C_{f,\text{cone}} = \sqrt{3} C_{f,\text{plate}} \quad (3.7)$$

Here the Prandtl number is evaluated using Eucken’s approximation (Thompson, 1972),

$$\text{Pr} = \frac{4\gamma}{9\gamma - 5} \quad (3.8)$$

For the determination of the theoretical turbulent boundary layer Stanton numbers, the Reynolds analogy is again used to relate heat transfer to skin friction,

$$\text{St} \approx \frac{1}{2} C_f \text{Pr}^{-2/3} \quad (3.9)$$

The incompressible turbulent flat-plate skin friction coefficient is approximated by White, 1991,

$$C_{f,\text{inc}} \approx \frac{0.455}{\ln^2(0.06 \text{Re}_x)} \quad (3.10)$$

Using the Morkovin hypothesis (Morkovin, 1962), compressibility effects are accounted for by transforming the incompressible boundary layer skin friction relation,

$$C_{f,\text{comp}} = \frac{1}{F_c} C_{f,\text{inc}}(\text{Re}_x F_{\text{Re}}) \quad (3.11)$$

Here F_c is a skin-friction correction factor, and F_{Re} is evaluated using the formulation provided by White and Christoph, 1972. These factors are a function of adiabatic wall temperature and wall-to-edge property ratios. For conical flows, similar to the laminar case, an additional axisymmetric correction is applied (Driest, 1952),

$$C_{f,\text{cone}} \approx 1.10 C_{f,\text{plate}} \quad (3.12)$$

The Stanton numbers obtained from measurements along the cone surface were plotted along with the Stanton numbers for laminar and turbulent boundary layer heat transfer theory outlined above. The Stanton numbers were plotted against Reynolds number calculated using boundary layer edge conditions from the Taylor-Maccoll solution,

$$\text{Re}_x = \frac{\rho_e u_{ex}}{\mu_e} \quad (3.13)$$

where x is the distance along the surface from the nose tip.

3.2 Surface Heat Flux

This section presents surface heat flux measurements over the slice-ramp portion of the cone-slice-ramp model for the four primary freestream conditions examined

in this work. Two nominal stagnation enthalpy conditions were investigated: $h_0 = 8 \text{ MJ kg}^{-1}$ and $h_0 = 14 \text{ MJ kg}^{-1}$. For the $h_0 = 8 \text{ MJ kg}^{-1}$ cases, the freestream unit Reynolds number was varied among $\text{Re}_{edge} = 2 \times 10^6 \text{ m}^{-1}$, $\text{Re}_{edge} = 3 \times 10^6 \text{ m}^{-1}$, and $\text{Re}_{edge} = 6 \times 10^6 \text{ m}^{-1}$, corresponding to the H8-Re2, H8-Re3, and H8-Re6 conditions, respectively. At $\text{Re}_{edge} = 3 \times 10^6 \text{ m}^{-1}$, the stagnation enthalpy was increased to $h_0 = 14 \text{ MJ kg}^{-1}$, corresponding to the H14-Re3 condition, to examine the effect of increased stagnation enthalpy on the SBLI region.

Each case is examined separately, beginning with a characterization of the incoming boundary layer to determine whether the flow entering the SBLI region is laminar, transitional, or turbulent. Schlieren imaging of the SBLI flow features is then presented to identify the separation and reattachment locations and to assess whether transition occurs within the separated shear layer. Based on the state of both the incoming boundary layer and the separated shear layer, the interactions are classified as “laminar” if both remain laminar, “mixed” if the incoming boundary layer is laminar but transition occurs within the separated shear layer, and “transitional” if the incoming boundary layer is transitional before reaching the leading edge of the slice.

This terminology differs slightly from conventional SBLI literature, where “laminar” interactions describe cases in which the reattached boundary layer also remains laminar. In the present experiments, however, transition was observed on the ramp surface downstream of reattachment for all shot conditions. The classification used here is therefore intended to distinguish between cases with laminar and transitional separated shear layers, rather than to describe the state of the downstream reattached boundary layer.

Finally, the streamwise heat flux along the slice-ramp portion of the model is presented to examine how heating evolves along the ramp surface. Spanwise variations in surface heating are also examined to confirm the presence of heating “streaks,” which reflect the inherently three-dimensional nature of the cone-slice-ramp interaction.

3.2.1 H8-Re2 Condition – Laminar Interaction

In Figure 3.6, the non-dimensionalized heat flux is plotted against the Reynolds number along the surface of the cone. If the boundary layer along the cone surface remains laminar, the non-dimensionalized heat flux is expected to collapse onto the laminar theory line. For the H8-Re2 condition, this behavior is observed for all

thermocouples on the fore-cone surface, confirming that the incoming boundary layer remains laminar at this condition.

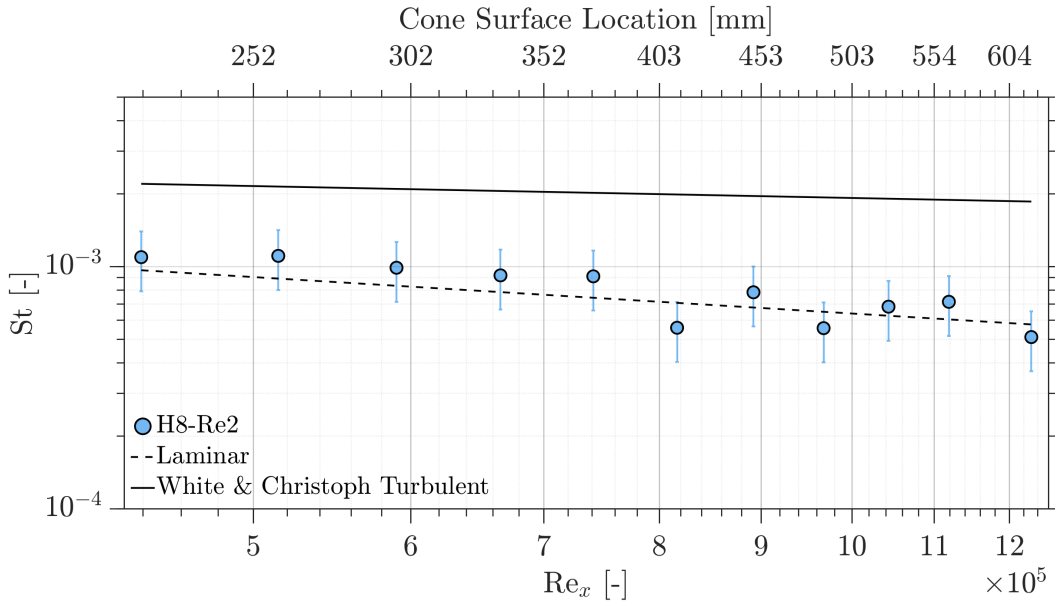


Figure 3.6: Time-averaged non-dimensional plot of fore-cone surface heat flux for the H8-Re2 condition in terms of Stanton number vs. Reynolds number. If transition onset were present, Stanton number would deviate from the laminar theory line and approach the turbulent theory line. The incoming boundary layer is shown to be laminar.

As the boundary layer enters the slice-ramp region of the model, it is observed to separate at $x/L = -0.95$, with the formation of a separation shock, and to reattach at $x/L = 0.46$ (Figure 3.7). This is consistent with cone-slice-ramp blow down experiments conducted at Purdue University (McKiernan, 2020), which observed separation at the leading edge of the slice for all tested freestream conditions. The separated shear layer is not observed to undergo transition above the separation bubble based on inspection of the schlieren imaging, as the separated shear layer does not become irregular or thicken excessively. As will be shown later in this work, the shear layer instability frequency can be recovered downstream of the reattachment point on the ramp surface (Section 4.4), which strongly suggests that the separated shear layer remains laminar for the H8-Re2 condition, since transitional effects are expected to destroy coherent frequency content. Therefore, using the definition provided above, the SBLI at this condition is classified as a laminar interaction.

The streamwise heat flux recorded over the SBLI region is now considered using the centerline mounted thermocouple gauges at this condition. Figure 3.8 presents the data obtained from the centerline thermocouples. From top to bottom, the figure

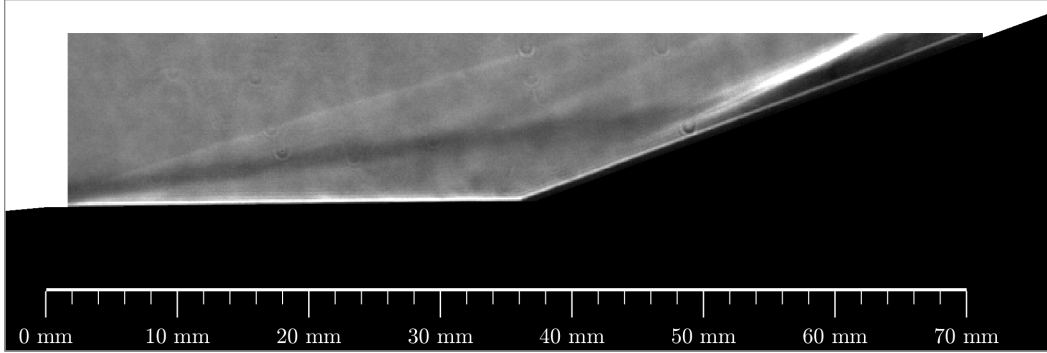


Figure 3.7: Schlieren frame displaying SBLI flow features for the H8-Re2 condition.

shows an annotated schlieren frame indicating the relative locations of the centerline thermocouples instrumented throughout the SBLI region, a swarm chart overlaid with a box plot illustrating the statistical spread of heat flux values recorded by each thermocouple during test time, and a plot of the mean heat flux obtained by averaging the readings over test time.

The swarm chart was generated by introducing an offset in the x -direction to the heat flux readings at each discrete thermocouple location. This offset was determined from uniformly distributed random values weighted by a Gaussian kernel density estimate constructed from the heat flux data at each location. The swarm chart is shown for a single shot and is useful for identifying trends associated with transition on the ramp surface. In the bottom plot, data from three shots are overlaid to demonstrate measurement repeatability.

Moving downstream through the separation region, from thermocouples S1 to R4, a monotonic increase in heat flux is observed, rising from 75 kW m^{-2} to 1.5 MW m^{-2} , as is characteristic of compression corner separation bubbles (Babinsky and Harvey, 2011). As the separated shear layer reattaches on the ramp and the reattachment shock forms near R4, the heat flux increases rapidly from 1.5 MW m^{-2} to 5.5 MW m^{-2} between R4 and R10. Examination of the statistical spread in the swarm chart shows large variations in the heat flux recorded by each thermocouple in this region, indicating that the reattached laminar shear layer undergoes transition to turbulence on the ramp surface. In transitional boundary layers, fluctuations in heating rates and surface pressure have been shown to exceed those of fully turbulent boundary layers (Casper et al., 2009; Casper et al., 2014b). This behavior, together with qualitative observations of the breakdown of the reattached boundary layer over this region, supports that interpretation.

The transition to fully turbulent flow is identified by the decrease in the coefficient of variation of the measured heat flux as the mean heat flux begins to plateau and the spread of reported heat flux values narrows. By the R11 thermocouple, turbulent flow is believed to be established, with a mean turbulent heat flux of approximately 5 MW m^{-2} over the downstream portion of the ramp.

The formation of spanwise nonuniform heating “streaks” has been widely reported in the literature for both compression-ramp flows (Broadley and Hewitt, 2025; Dwivedi et al., 2019) and cone-slice-ramp flows (Francis and Jewell, 2024; Francis et al., 2025; McKiernan, 2020; Thome et al., 2018). For the cone-slice-ramp geometry in particular, these heating streaks are generally attributed to a pair of counter-rotating vortices that develop around the slice and subsequently impinge on the ramp surface. From a heat flux measurement point of view, these streaks appear as spanwise nonuniform variations in heating at fixed streamwise locations.

Figure 3.9 shows the spanwise rows of thermocouples at the streamwise stations S4, R1, R5, and R10. The spanwise coordinate is non-dimensionalized by the ramp half-width, such that $z/W = 0$ corresponds to the thermocouples located on the model centerline. Weak spanwise variation in heat flux is observed within the separated region at row S4, with values remaining approximately constant at 0.13 MW m^{-2} . This behavior is consistent with previous observations that the separation bubble formed on the cone-slice-ramp geometry exhibits relatively weak spanwise pressure variations (Pandey et al., 2020). Farther downstream, however, increasingly large spanwise variations in heat flux develop, with distributions that are non-monotonic and irregular. This behavior is consistent with the formation of a heating streak pattern on the ramp surface. The maximum same row heat flux variation reaches approximately 3 MW m^{-2} for the aftmost thermocouple row, R10, representing a significant spanwise surface heating load.

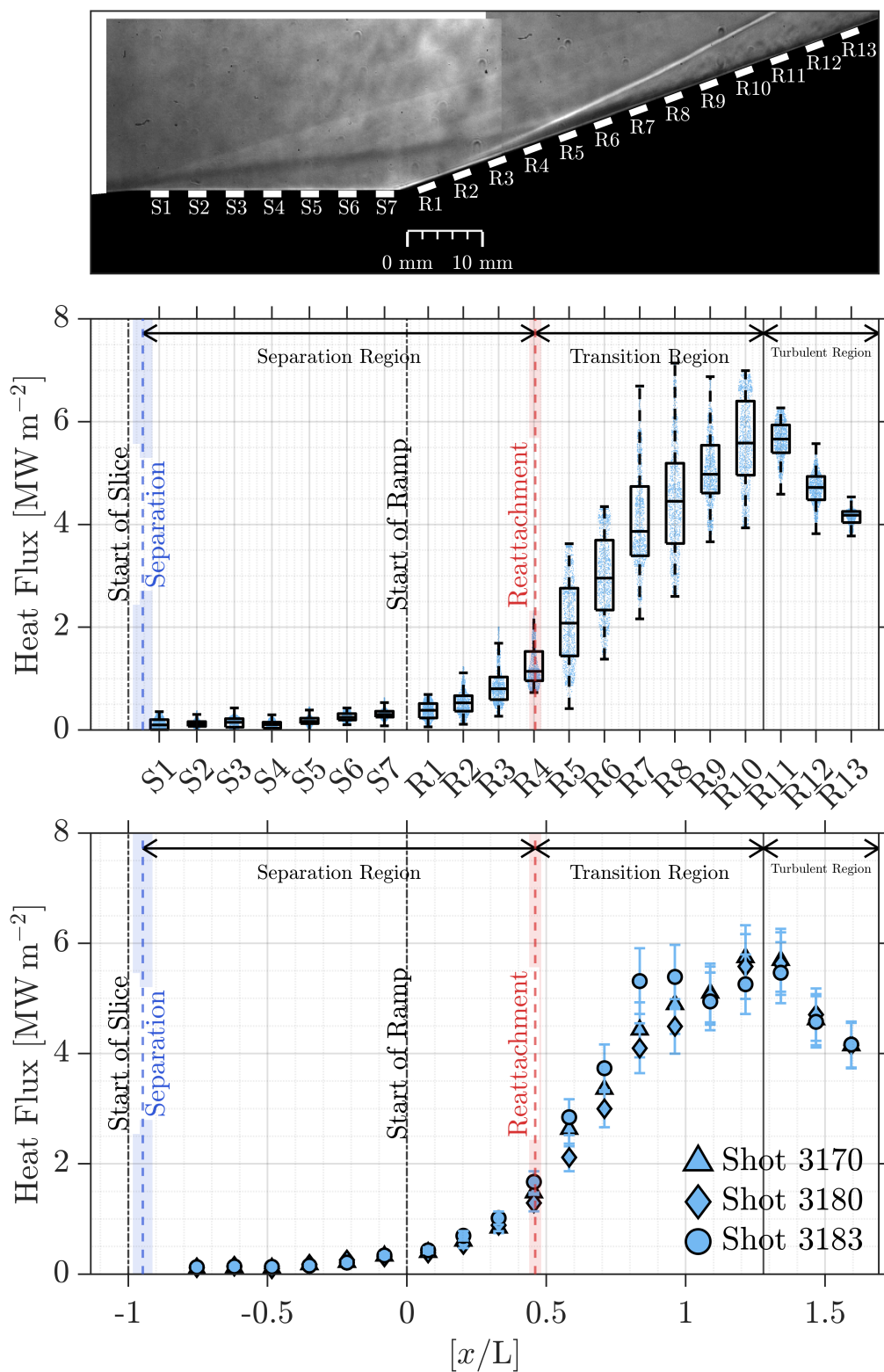


Figure 3.8: Centerline streamwise heat flux measurements for the H8-Re2 condition. Top: Schlieren frame with thermocouple locations annotated. Middle: Swarm chart showing statistical spread in reported heat flux throughout the duration of test time. Bottom: Mean reported heat flux across multiple shots.

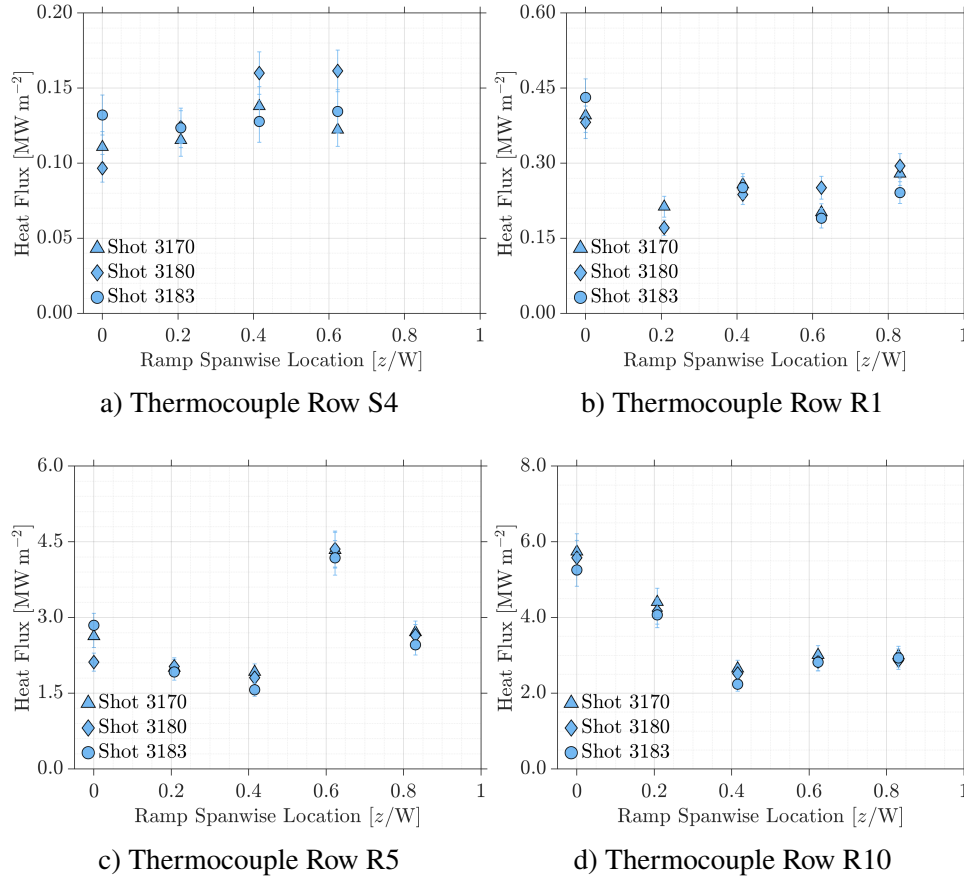


Figure 3.9: Spanwise variations in surface heating for the H8-Re2 condition.

3.2.2 H8-Re3 Condition – Mixed Interaction

For the H8-Re3 condition, Figure 3.10 plots the non-dimensionalized heat flux against the Reynolds number along the fore-cone, with all values aligning with the laminar boundary layer theory line. As in the H8-Re2 condition, the incoming boundary layer is therefore determined to be laminar.

Interestingly, for the modest increase in unit Reynolds number between the H8-Re2 and H8-Re3 cases ($Re_{edge} = 2 \times 10^6 \text{ m}^{-1}$ vs $Re_{edge} = 3 \times 10^6 \text{ m}^{-1}$), separation is observed to occur on the slice portion of the model (Figure 3.11). This is a departure from the H8-Re2 case, where separation occurred near the leading edge of the slice. Boundary layer separation on the slice was not observed in previous cone-slice-ramp work conducted at Purdue University, despite variations in freestream unit Reynolds number from $Re_{\infty} = 0.9 \times 10^6 \text{ m}^{-1}$ to $Re_{\infty} = 7.0 \times 10^6 \text{ m}^{-1}$ (McKiernan and Schneider, 2021). This motivated later work in which the slice angle was inclined to induce separation on the slice (Francis et al., 2025). Separation at the beginning of the slice was also observed in blow down cone-

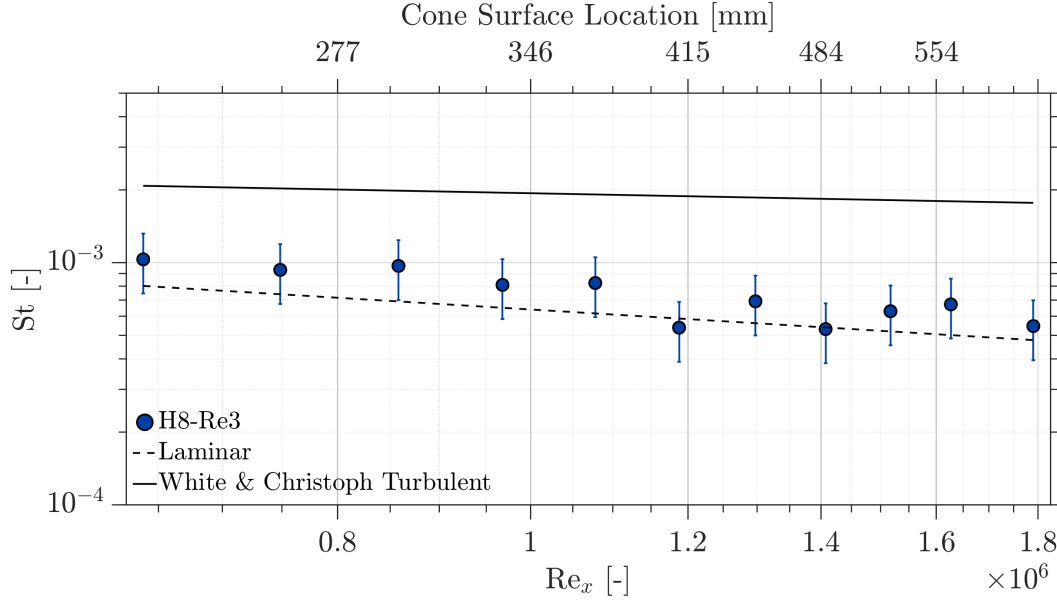


Figure 3.10: Time-averaged non-dimensional plot of fore-cone surface heat flux for the H8-Re3 condition in terms of Stanton number vs. Reynolds number. The incoming boundary layer is shown to be laminar.

slice-ramp experiments conducted at Sandia National Laboratories, although in those experiments the separation remained at the expansion corner for $Re_\infty = 4.3 \times 10^6 \text{ m}^{-1}$ to $Re_\infty = 5.8 \times 10^6 \text{ m}^{-1}$. It was not until Sandia repeated these experiments using the same geometry at higher stagnation enthalpies that they observed separation on the slice, similar to that observed in the present work (Pandey et al., 2020; Rubio et al., 2026), albeit at much lower unit Reynolds numbers ranging from $Re_\infty = 3 \times 10^5 \text{ m}^{-1}$ to $Re_\infty = 7.2 \times 10^5 \text{ m}^{-1}$.

The separation location is observed to shift downstream to $x/L = -0.75$, while reattachment shifts upstream to $x/L = 0.24$, representing an overall reduction in separation bubble size. The leading expansion fan is also visible, with a measured leading edge angle of $\mu_1 = 17.2 \pm 0.2^\circ$, followed immediately by the downstream separation shock. This expansion may attenuate disturbances in the incoming boundary layer through a relaminarization process, thereby increasing its susceptibility to downstream compression induced separation (Pandey et al., 2024). In cone-slice-ramp experiments with turbulent incoming boundary layers, Pandey et al. found evidence of separation for both 10 and 30 degree ramp angles. Of particular interest, separation occurred for the 10 degree ramp despite the ramp angle being smaller than would typically be expected to induce separation in a fully turbulent incoming boundary layer.

The separated shear layer is believed to undergo transition prior to reattachment on the ramp. Evidence of this can be found in the schlieren imaging, which shows that the separated shear layer rapidly thickens and becomes irregular prior to reattachment. A higher concentration of Mach radiation, characteristic of turbulent boundary layers, is also observed above the separated shear layer compared to the H8-Re2 case. For laminar reattaching compression ramp SBLIs, Gray, 1967 notes that increasing Reynolds number results in larger separation regions. However, once increasing Reynolds number causes transition to move into the separated shear layer or upstream of reattachment, Gray notes that this trend can reverse and the separation region can shrink. This description is consistent with the present findings, as the separation bubble size decreases with increasing Reynolds number between the H8-Re2 and H8-Re3 cases. Therefore, the separated shear layer is believed to be transitional for the H8-Re3 case, making this a mixed interaction.

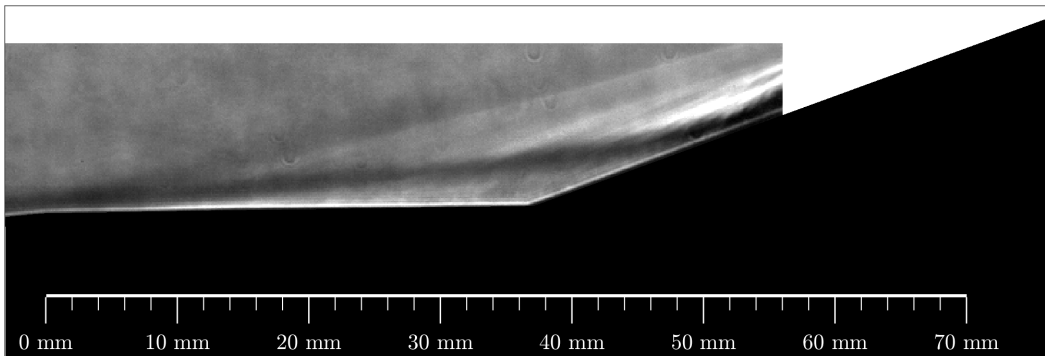


Figure 3.11: Schlieren frame displaying SBLI flow features for the H8-Re3 condition.

Figure 3.13 shows the centerline heat flux distribution for the H8-Re3 condition. Similar to the laminar H8-Re2 case, a steady increase in heat flux occurs through the separation bubble, rising from 0.2 MW m^{-2} to 2.0 MW m^{-2} between S1 and R2. After reattachment, a rapid increase is observed through the transition region on the ramp surface, with heat flux rising from 3 MW m^{-2} to 9 MW m^{-2} between R3 and R6. This is followed by an approximately constant turbulent heat flux of 8.5 MW m^{-2} over the remaining thermocouples.

Relative to the H8-Re2 case, the principal differences are the shortening of the transition region on the ramp surface and the upstream shift of the reattachment point to $x/L = 0.24$, compared to $x/L = 0.46$ for H8-Re2. The turbulent heat flux plateau is reached over a post reattachment distance that is approximately 35% shorter than in the H8-Re2 case. The thermocouple immediately upstream of

the reattachment location, within the separation bubble, also records a heat flux of approximately 2 MW m^{-2} , compared with approximately 1 MW m^{-2} for the H8-Re2 case. This elevated heat flux is believed to be caused by the transitional separated shear layer. Together, the shortened transition length on the ramp and the elevated heat flux within the separation bubble support the conclusion that transition is occurring within the separated shear layer for the H8-Re3 case.

Spanwise heating variations (Figure 3.12) are overall more subdued for the H8-Re3 condition. This is consistent with observations reported in other cone-slice-ramp experiments, where a transitional separated shear layer produced weaker or absent heating streaks (Francis et al., 2025; Pandey et al., 2020). For the H8-Re3 case, the maximum same row heat flux variation occurs at R10, with a maximum variation of 2 MW m^{-2} along the row. In contrast, the H8-Re2 case exhibits a 3 MW m^{-2} maximum variation along the same R10 row.

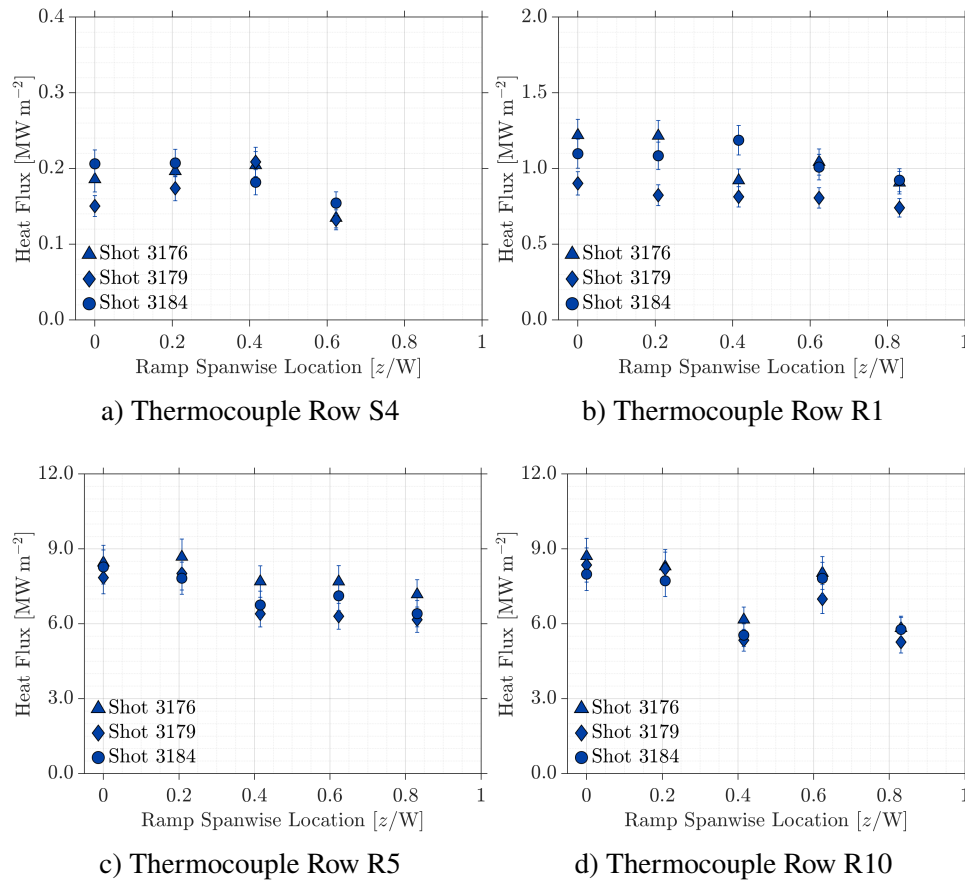


Figure 3.12: Spanwise variations in surface heating for the H8-Re3 condition.

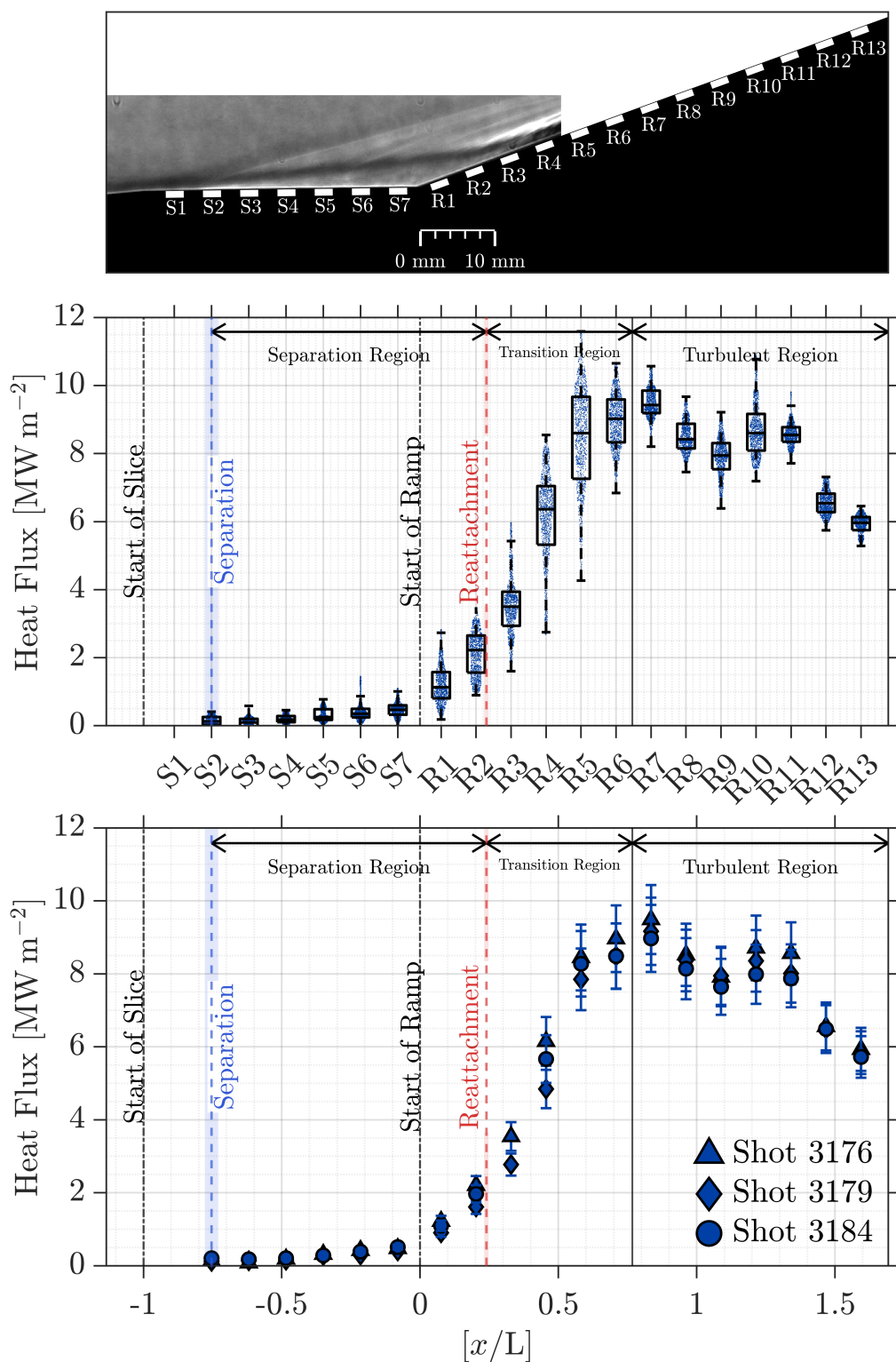


Figure 3.13: Centerline streamwise heat flux measurements for the H8-Re3 condition. Top: Schlieren frame with thermocouple locations annotated. Middle: Swarm chart showing statistical spread in reported heat flux throughout the duration of test time. Bottom: Mean reported heat flux across multiple shots.

3.2.3 H8-Re6 Condition – Transitional Interaction

The onset of transition on the cone surface is observed for the H8-Re6 condition in Figure 3.14. For transitional boundary layers, a deviation from the laminar theory line toward the turbulent theory line is expected. This behavior is observed at $x_{Tr} \approx 0.5$ m, consistent with the transition onset location reported by Jewell for the nominal $h_0 = 8 \text{ MJ kg}^{-1}$, $Re_\infty = 6 \times 10^6 \text{ m}^{-1}$ test condition (Jewell, 2014). This condition is therefore reported as having a transitional incoming boundary layer.

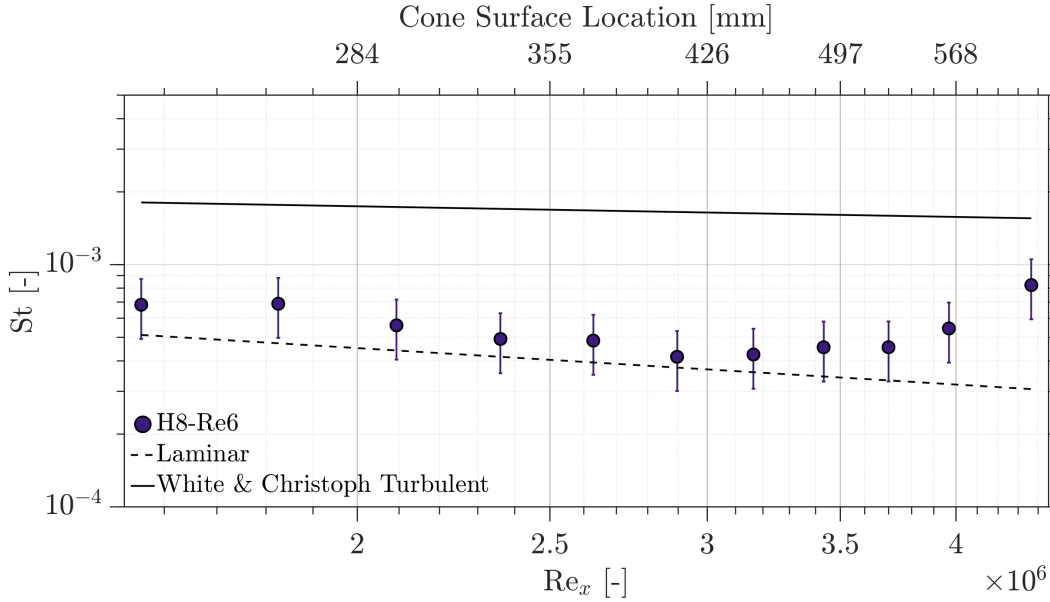
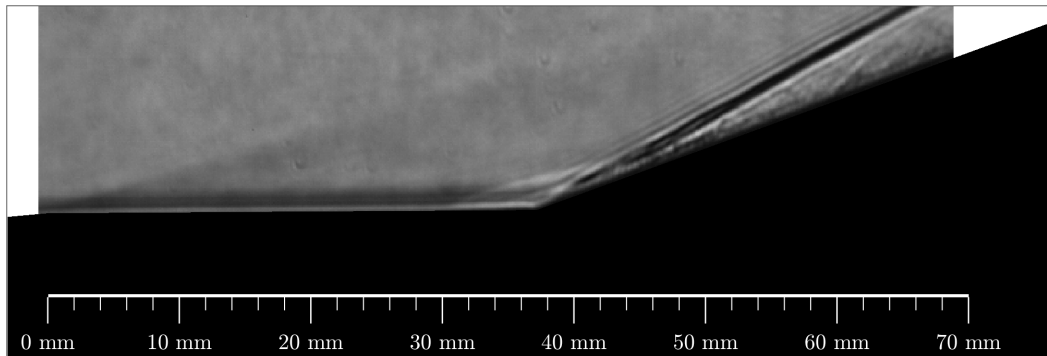


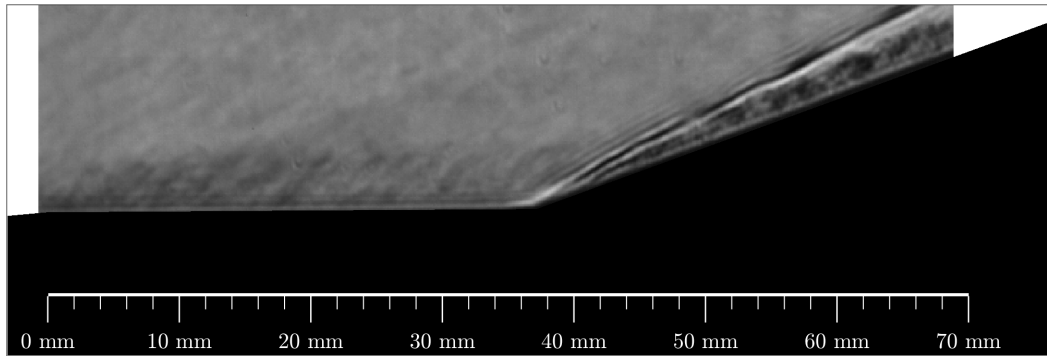
Figure 3.14: Time-averaged non-dimensional plot of fore-cone surface heat flux for the H8-Re6 condition in terms of Stanton number vs. Reynolds number. The incoming boundary layer is shown to be transitional as it deviates from the laminar theory line.

Because the incoming boundary layer remained transitional, intermittency was observed during test time, with the incoming boundary layer exhibiting both laminar-like and turbulent-like behavior. In Figure 3.15, two schlieren images taken at different points during test time capture these two states. During intervals when the boundary layer appears to be laminar, the incoming boundary layer rounds the expansion corner and remains attached along the slice before detaching near the base of the ramp, forming a small separation bubble. The separation region is roughly 8 mm long, considerably smaller than the 52 mm and 37 mm separation region lengths measured for the H8-Re2 and H8-Re3 conditions, respectively. When the incoming boundary layer appears turbulent, no separation or reattachment shocks are present; only the ramp shock emanating from the base of the ramp remains visible. The absence of a separation bubble is consistent with the reported difficulty of inducing

separation in turbulent boundary layers at small compression ramp angles (Coleman and Stollery, 1972).



a) Laminar-like interval showing transient separation bubble formation near the base of the ramp.



b) Turbulent-like interval showing attached flow through the slice-ramp region, with no visible separation or reattachment shocks.

Figure 3.15: Schlieren frames showing intermittent SBLI behavior for the H8-Re6 condition. The transitional incoming boundary layer alternates between laminar-like intervals, during which a small separation bubble forms near the base of the ramp, and turbulent-like intervals, during which the separation region collapses and only the ramp shock remains visible.

Inspection of the high-speed schlieren imaging reveals that, for the majority of the test time, the incoming boundary layer was turbulent, with only brief intervals of laminar-like behavior. To quantify this behavior, an intermittency factor $0 < \Gamma < 1$ was computed, where $\Gamma=0$ corresponds to a fully laminar boundary layer and $\Gamma = 1$ corresponds to a fully turbulent boundary layer. To evaluate the intermittency of the incoming boundary layer, a swarm chart was constructed using data from the thermocouples located near the end of the cone surface immediately upstream of the slice (C9 and C10), together with thermocouples along the slice region (S2 to S7), as shown in Figure 3.16. Overlaid on this plot are the laminar and turbulent heat flux

levels predicted from compressible boundary layer theory, as discussed in Section 3.1.3. For the thermocouples located on the cone surface and the slice, two distinct groupings of heat flux data are observed, colored by grouping. These groupings were identified by first fitting a bimodal distribution using a two-component Gaussian mixture model. The function `cluster()` in MATLAB was then used to assign the data into distinct groups, with the separation threshold defined by the intersection of the weighted Gaussian probability density functions.

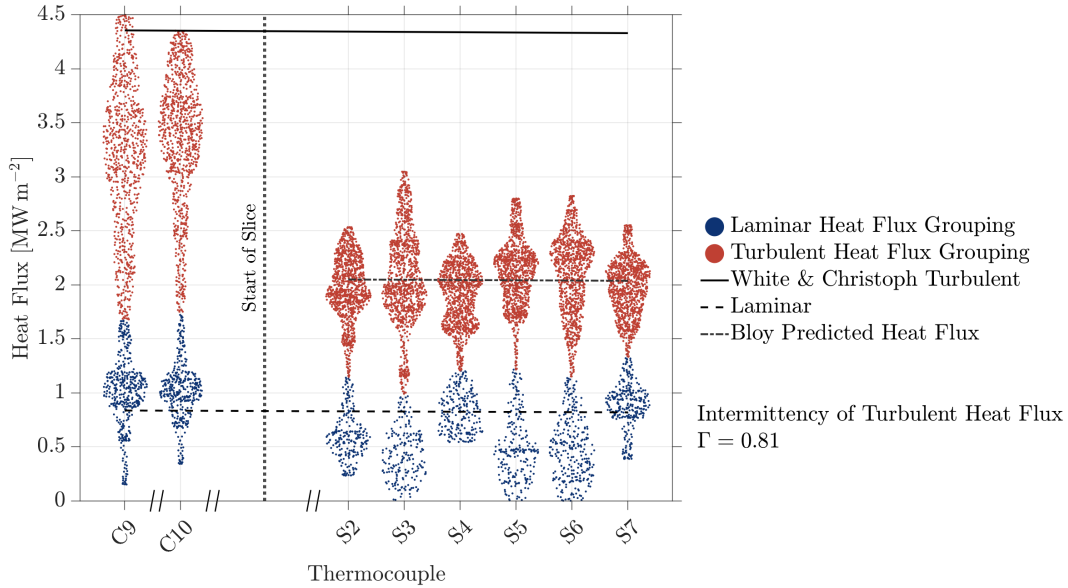


Figure 3.16: Swarm chart of thermocouples immediately before (C9 and C10) and after (S2 to S7) the start of the slice for the H8-Re6 condition. Two groupings of heat flux data have been made representing the turbulent and laminar heat flux experienced by the sensors for the transitional boundary layer observed over the cone surface. Lines annotating the predicted laminar and turbulent heat flux from boundary layer theory in addition to Bloy’s predicted heat flux across a turbulent expansion corner have been overlaid.

When the boundary layer on the cone surface remains laminar, the reported heat flux falls within the lower blue grouping, which aligns with theoretical laminar heat flux predictions. As turbulent flow passes over the sensor, however, the measured heat flux rises into the upper red grouping, which is consistent with turbulent boundary layer theory. By taking the relative proportion of heat flux measurements in each grouping, an intermittency factor, Γ , can be defined. This approach is similar in construction to the intermittency detector function used by Mee and Goynes, 1996, which identifies regions of elevated heat flux associated with turbulence. Using this method, an average intermittency of $\Gamma = 0.81$ was measured for the cone and slice sensors.

As the turbulent boundary layer passes through the expansion corner formed at the leading edge of the slice, a drop in the reported heat flux is measured by the S2 to S7 thermocouples. This is consistent with turbulent boundary layer studies of expansion corners by Bloy, 1975, who found that heat transfer distributions followed trends similar to the pressure distribution around expansion corners. Arguing that the two were correlated through skin friction, Bloy proposed the correlation,

$$\frac{\dot{q}_{\text{exp}}}{\dot{q}_1} = \left(\frac{p_{\text{exp}}}{p_1} \right)^{1.23} \quad (3.14)$$

which provides an approximate estimate of the post-expansion surface heat flux, $\dot{q}_{\text{exp}}$, if the pressures upstream and downstream of the expansion, p_1 and p_{exp} , are known. Using the measured slice static pressures from sensors N5 and K2, the turbulent heat flux prediction along the cone surface, and the Taylor-Maccoll surface solution for cone surface static pressure, Bloy's correlation was used to predict the heat flux downstream of the expansion. Good agreement is obtained between this prediction and the turbulent heat flux levels measured by the S2 to S7 thermocouples.

Figure 3.17 plots the centerline heat flux values for the H8-Re6 condition. The heat flux along the slice remains approximately constant at 1.75 MW m^{-2} , consistent with an attached turbulent boundary layer over the slice surface. As the flow is turned onto the ramp with the formation of the ramp shock, the heat flux rises sharply before reaching an approximately constant ramp surface value of 12 MW m^{-2} , indicating that the flow remains turbulent across the entire ramp. Although this case is primarily characterized by the absence of a separation region under turbulent inflow, intermittent intervals of laminar flow entering the SBLI region occasionally permit the transient formation of a separation bubble. This transient formation of a separation bubble is captured by the R1 thermocouple, where the measured heat flux varies between approximately 2.5 MW m^{-2} during bubble formation and more than 10 MW m^{-2} when the separation region collapses under turbulent inflow.

In Figure 3.18, the spanwise variations in heat flux are plotted for the H8-Re6 condition. The fully turbulent boundary layer on the ramp suppresses spanwise variations in heat flux. Inspecting the R10 row of thermocouples, the maximum percentage change in heat flux from the centerline thermocouple was found to be 55% for the H8-Re2 condition, but decreased to only 34% and 28% for the H8-Re3 and H8-Re6 cases, respectively.

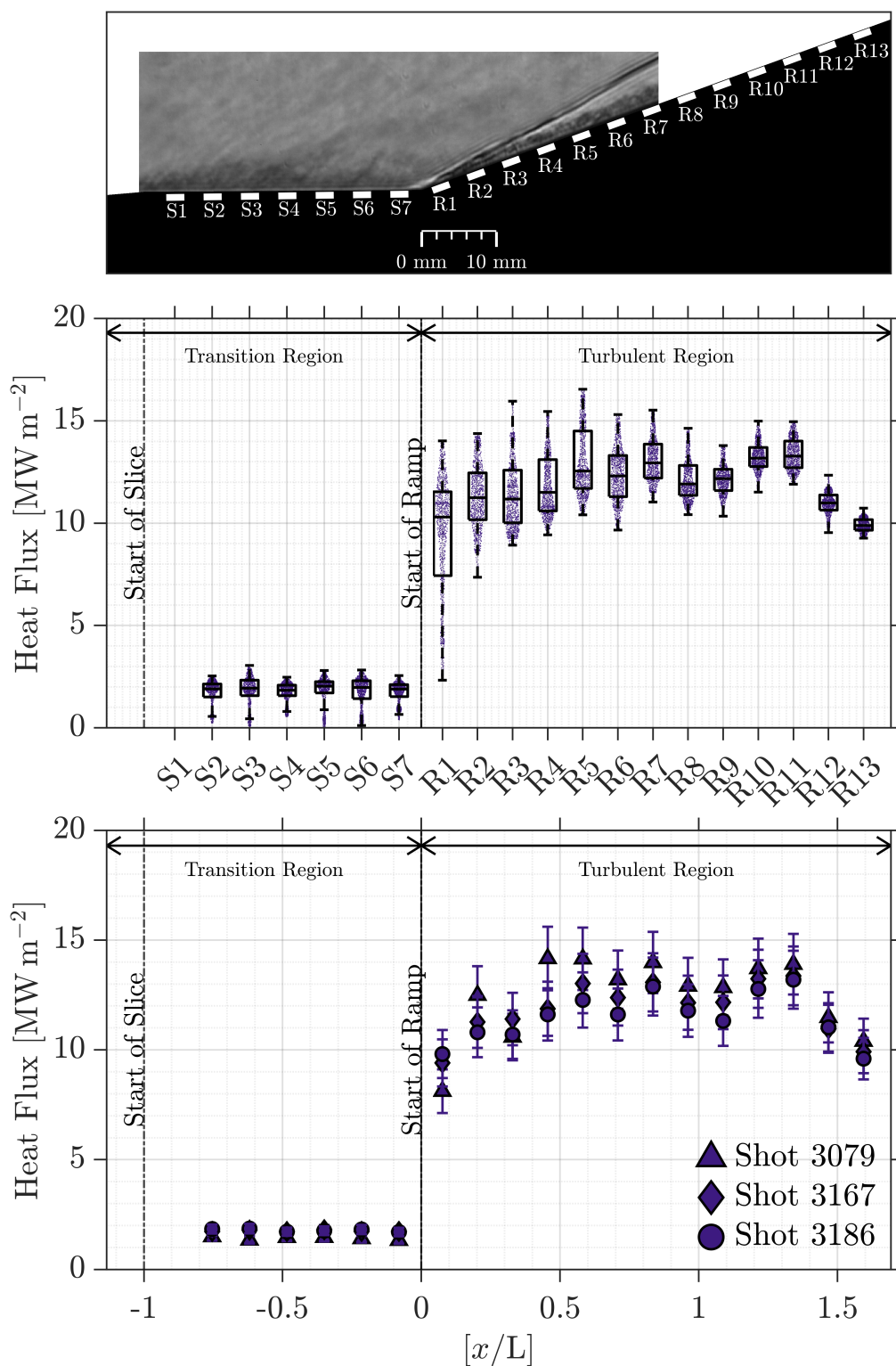


Figure 3.17: Centerline streamwise heat flux measurements for the H8-Re6 condition. Top: Schlieren frame with thermocouple locations annotated. Middle: Swarm chart showing statistical spread in reported heat flux throughout the duration of test time. Bottom: Mean reported heat flux across multiple shots.

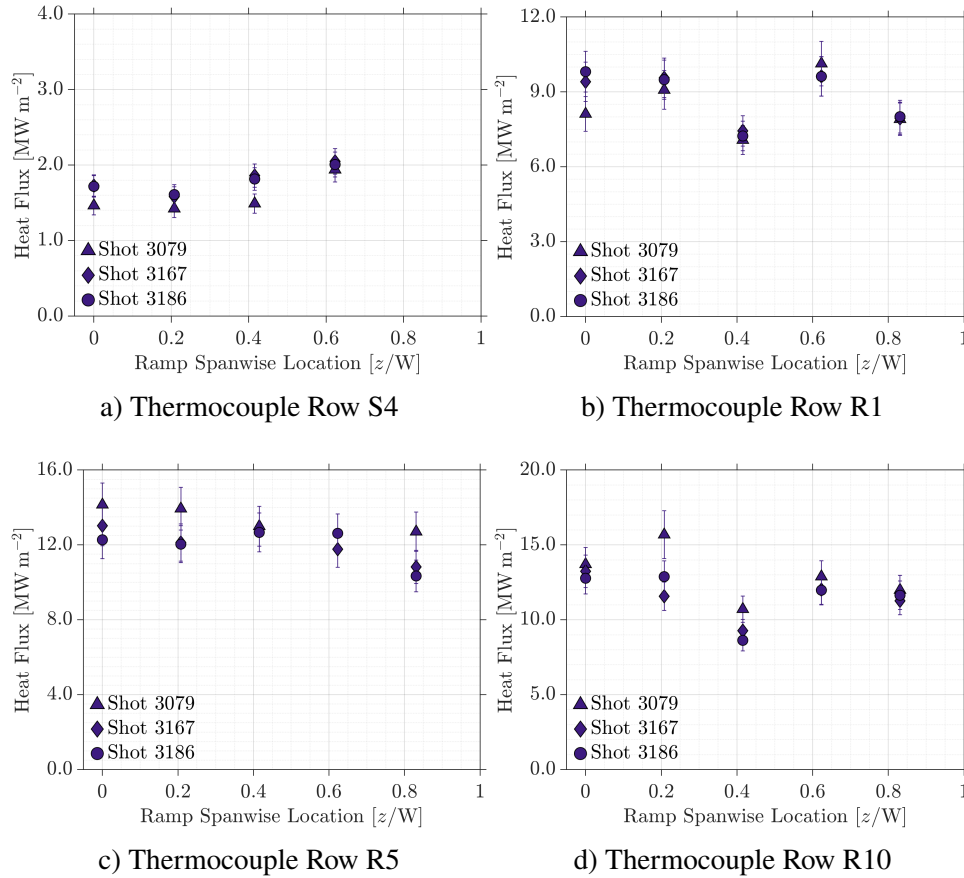


Figure 3.18: Spanwise variations in surface heating for the H8-Re6 condition.

3.2.4 H14-Re3 Condition – Laminar Interaction

For the H14-Re3 test case (Figure 3.19), the incoming boundary layer remained laminar, with the non-dimensionalized heat flux tending toward the laminar theory line. Inspection of the schlieren imaging (Figure 3.20) shows that, compared to the H8-Re3 case, the separation region is clearly larger, with an approximately 27% increase in separation region length. For the H14-Re3 condition, separation occurs near the leading edge of the slice ($x/L = -0.85$) and reattachment occurs at $x/L = 0.40$, making the overall separation region size more consistent with the H8-Re2 condition than with the H8-Re3 condition.

The separated shear layer is not observed to undergo transition above the separation bubble and exhibits visual properties similar to those of the H8-Re2 case. Inspection of the schlieren imaging shows that the separated shear layer does not thicken excessively, and the concentration of shocklet formation is similar to that observed for H8-Re2. This condition is therefore classified as a laminar interaction, as was the H8-Re2 case. Consequently, the H8-Re2 case provides the more appropriate

comparison when evaluating surface heat flux trends.

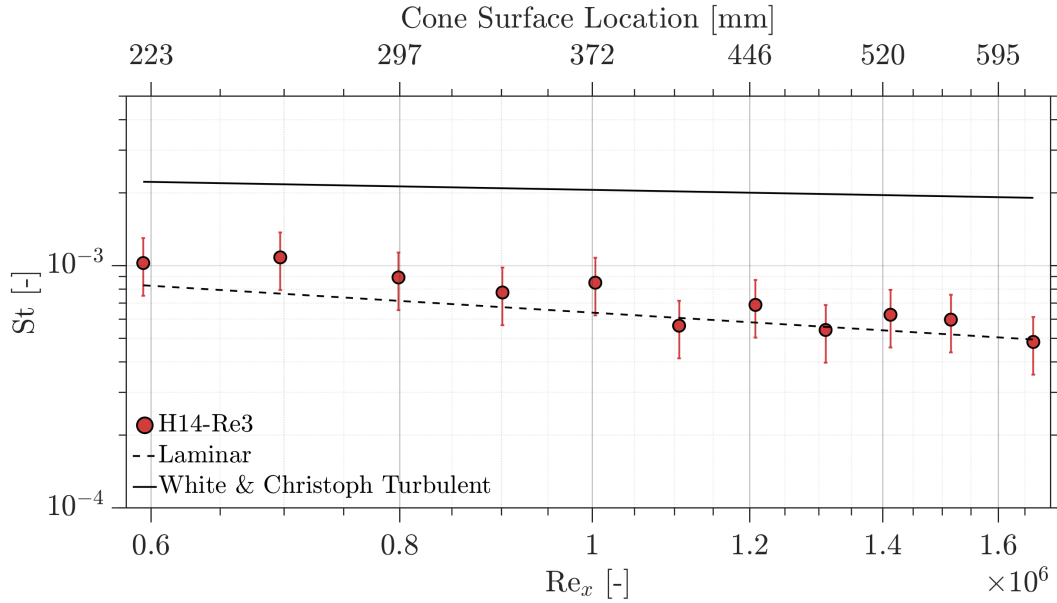


Figure 3.19: Time-averaged non-dimensional plot of fore-cone surface heat flux for the H14-Re3 condition in terms of Stanton number vs. Reynolds number. The incoming boundary layer is shown to be laminar.

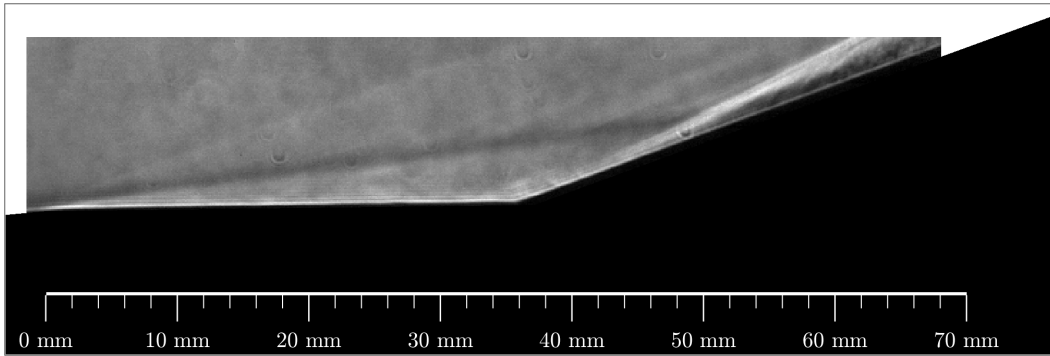


Figure 3.20: Schlieren frame displaying SBLI flow features for the H14-Re3 condition.

In Figure 3.21, the general trends in the streamwise surface heat flux remain consistent with those of the $h_0 = 8 \text{ MJ kg}^{-1}$ laminar interaction, albeit at substantially elevated heat flux levels due to the higher stagnation enthalpy of the flow. A monotonic increase in heat flux is again observed between S1 and R4 in the separation bubble, ranging from 400 kW m^{-2} to 6 MW m^{-2} . Reattachment of the laminar separated shear layer, followed by transition to turbulent flow, is again observed between R4 and R7, as indicated by the rapid increase in both the variation and mean value

of the reported heat flux. A turbulent heat flux value of approximately 20 MW m^{-2} is reported downstream on the ramp after the transition region.

Although the H14-Re3 and H8-Re2 cases have similar reattachment locations, at $x/L = 0.40$ and $x/L = 0.46$, respectively, they differ noticeably in the length of the transition region on the ramp surface. The transition region length is approximately $x/L = 0.37$ for H14-Re3, compared to $x/L = 0.82$ for H8-Re2. While higher stagnation enthalpy is generally expected to delay the onset of transition, the H14-Re3 case was also run at a higher edge unit Reynolds number, which may be the dominant reason for the shorter breakdown distance observed here.

The spanwise variations in heat flux are more consistent with the large variations observed for the H8-Re2 case, again supporting the classification of H14-Re3 as a laminar interaction. Qualitatively comparing the spanwise variations of the R5 and R10 thermocouple rows shows variations more in line with the H8-Re2 case than with the more subdued variations observed for the H8-Re3 condition. Indeed, the maximum percentage change in heat flux from the centerline thermocouple in row R10 was found to be 60%, the largest of all four conditions tested and similar to the 55% reported for H8-Re2. This corresponds to a substantial 15 MW m^{-2} variation in heat flux along the aftmost thermocouple row.

3.2.5 Nondimensionalized Heat Flux

Qualitative visualizations of the mean surface heat flux on the ramp surface were generated using a non-dimensional analysis of the reported ramp heat flux (Figure 3.23). The heat flux was nondimensionalized using the Stanton number, defined in Equation 3.2 using the boundary layer edge conditions at the leading edge of the slice. To approximately account for laminar Reynolds number scaling, the Stanton number was scaled as $St\sqrt{Re_x}$. This scaling has been shown to correlate laminar flat plate heating and is used here as an approximate means of correlating laminar heating in the present experiments (Anderson, 2006).

Cubic interpolation was used to interpolate between discrete thermocouple locations. Non-physical diamond-shaped artifacts are a byproduct of interpolating over ramp regions with sparse thermocouple coverage. The resulting heat flux patterns on the ramp surface qualitatively agree with cone-slice-ramp experiments conducted in blowdown facilities at Purdue (McKiernan, 2020).

For the H8-Re2 condition, the nondimensional ramp heating pattern is qualitatively consistent with the Purdue measurements at approximately $Re_\infty \approx 3 \times 10^6 \text{ m}^{-1}$ under

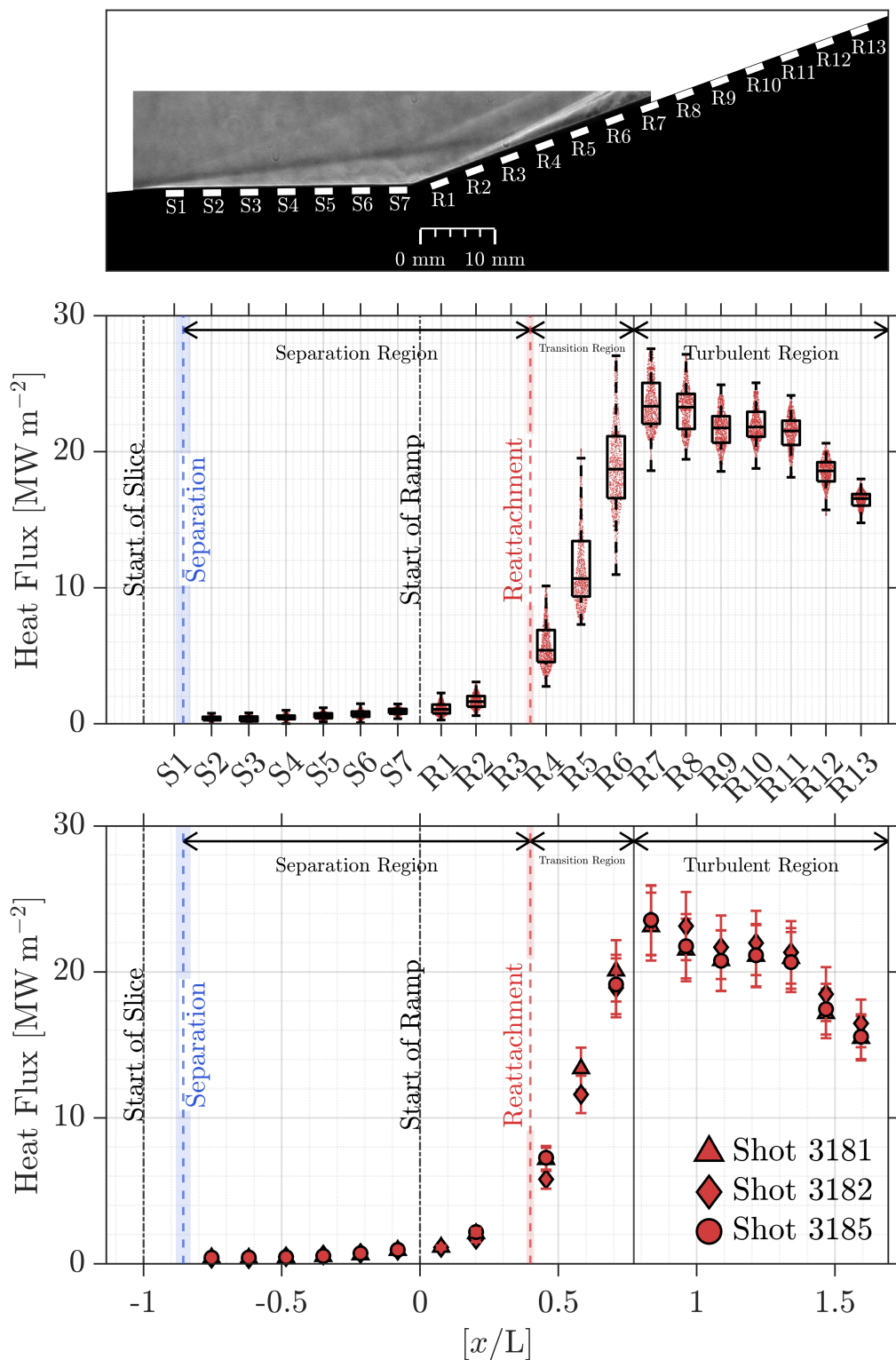


Figure 3.21: Centerline streamwise heat flux measurements for the H14-Re3 condition. Top: Schlieren frame with thermocouple locations annotated. Middle: Swarm chart showing statistical spread in reported heat flux throughout the duration of test time. Bottom: Mean reported heat flux across multiple shots.

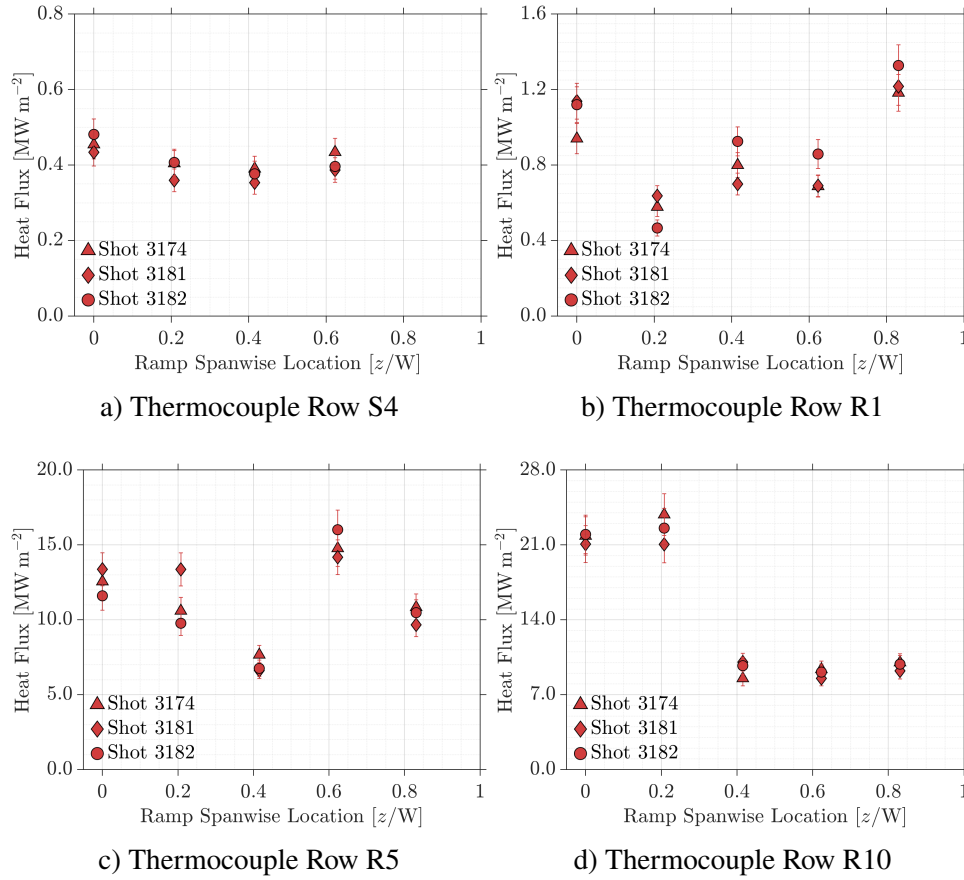
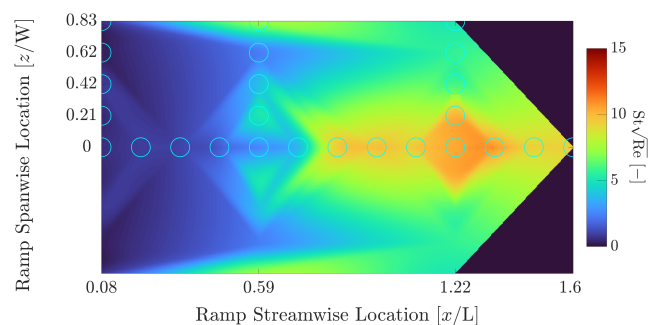


Figure 3.22: Spanwise variations in surface heating for the H14-Re3 condition.

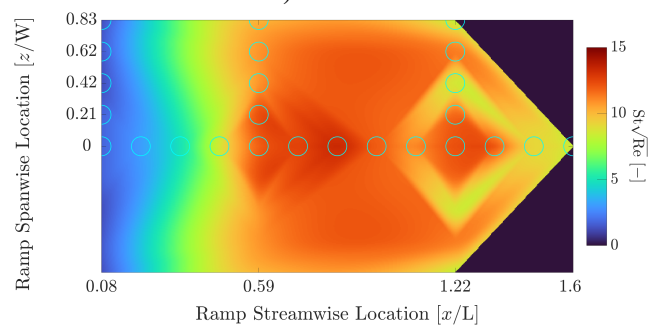
conventional noise conditions and $Re_{\infty} \approx 7 \times 10^6 m^{-1}$ under quiet flow conditions.

During the H8-Re3 case, the heating pattern is consistent with transitional flow on the ramp surface, similar to blowdown experiments at $Re_{\infty} \approx 9 \times 10^6 m^{-1}$ under conventional noise conditions. A comparable transitional heating pattern was not observed in the Purdue quiet flow experiments up to the maximum freestream unit Reynolds number tested, approximately $Re_{\infty} \approx 7 \times 10^6 m^{-1}$.

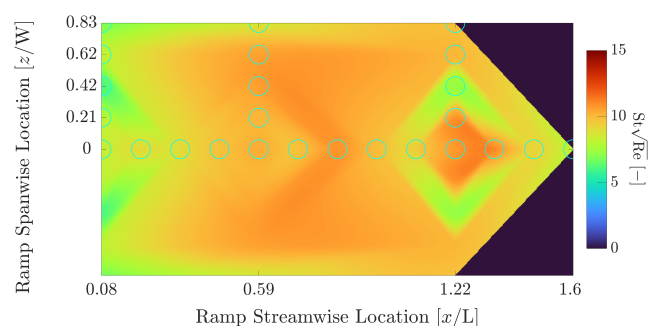
At the H8-Re6 condition, the reduced heat flux region indicative of a separation bubble is no longer evident at $Re_{edge} \approx 6 \times 10^6 m^{-1}$ in the present experiments. This differs from the Purdue blowdown experiments, where separation regions were still observed at approximately $Re_{\infty} \approx 9 \times 10^6 m^{-1}$ and $Re_{\infty} \approx 7 \times 10^6 m^{-1}$ under conventional and quiet flow conditions, respectively.



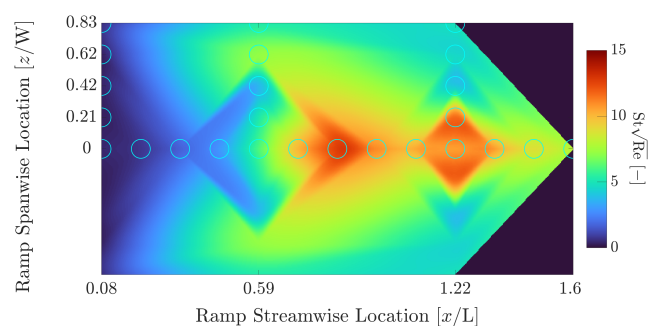
a) H8-Re2



b) H8-Re3



c) H8-Re6



d) H14-Re3

Figure 3.23: Non-dimensional ramp surface heat flux shown for qualitative visualization. Non-physical diamond-shaped features are artifacts caused by insufficient thermocouple density in regions with strong spanwise heat flux variations.

3.3 Effects of Freestream Conditions on Mean SBLI Features

In this section, the mean locations of important SBLI flow features are reported for the three test cases H8-Re2, H8-Re3, and H14-Re3. The H8-Re6 case is excluded due to the intermittency of SBLI feature formation. Comparisons between these three test conditions are made to determine the effect of changing unit Reynolds number and stagnation enthalpy on the size of the separation region.

3.3.1 Mean Flow Feature Measurements

The SBLI flow features were measured by first computing the mean pixel intensity of schlieren frames acquired during test time, thereby averaging out flow feature unsteadiness. Canny edge detection was then performed to evaluate the separation shock angle (θ_{SS}) and reattachment shock angle (θ_{RS}). The separated shear layer angle was determined by fitting edges to the upper and lower bounds of the separated shear layer and averaging the two, thereby accounting for the finite growth rate of the shear layer instability. The Mach-wave radiation, or shocklet, propagation angle, μ_c , was measured during the process of determining the convective propagation speeds of the shear layer disturbances, as discussed in Section 4.5.

Figure 3.24 shows the annotated locations of all relevant angles, and Table 3.1 summarizes the measured angles for convenience. Little variation in the reattachment shock angle or shear layer angle is found among the three test cases explored. The most noticeable difference is observed for the higher stagnation enthalpy case, where the shear layer angle decreases and the reattachment shock angle increases by $\approx 1^\circ$. The separation shock angle is shown to decrease with increasing edge unit Reynolds number, but to increase as the stagnation enthalpy is raised by $\approx 3^\circ$ and $\approx 5^\circ$ respectively.

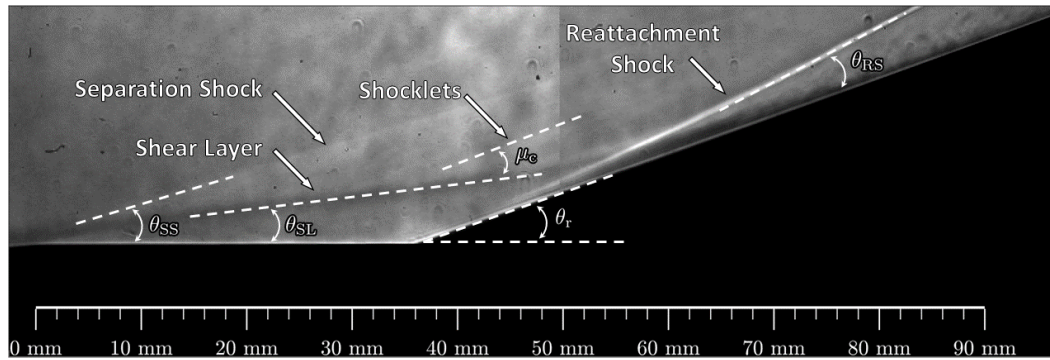


Figure 3.24: Annotated schlieren frame with SBLI flow features and relevant angles labeled.

Table 3.1: Table summarizing measured angles of flow features relevant to the SBLI.

Case	θ_{SS} [°]	θ_{SL} [°]	θ_{RS} [°]	θ_r [°]	μ_c [°]
H8-Re2	18.8 ± 1.4	7.8 ± 0.3	6.8 ± 0.9	20	15.5 ± 1.0
H8-Re3	15.7 ± 0.3	6.1 ± 0.1	7.6 ± 0.6	20	18.2 ± 1.2
H14-Re3	20.2 ± 2.5	7.5 ± 1.0	6.6 ± 1.5	20	16.6 ± 1.3

Important length scales for the SBLI region are annotated in Figure 3.25 and reported in Table 3.2. The separation location (x_{SS}) was computed from the intersection of the fitted separation shock with the fitted shear layer line, projected onto the x -axis. The reattachment location (x_{RS}) was computed similarly, using the intersection between the measured reattachment shock and the fitted shear layer. The length of the separated shear layer (L_{SL}) was then computed as the distance between these two intersections, while the separation region length (L_{Sep}) was defined as the x -axis projection of the separated shear layer. The slice length (L), in addition to the incoming boundary layer thickness (δ_{BL}) determined visually, is also listed for convenience.

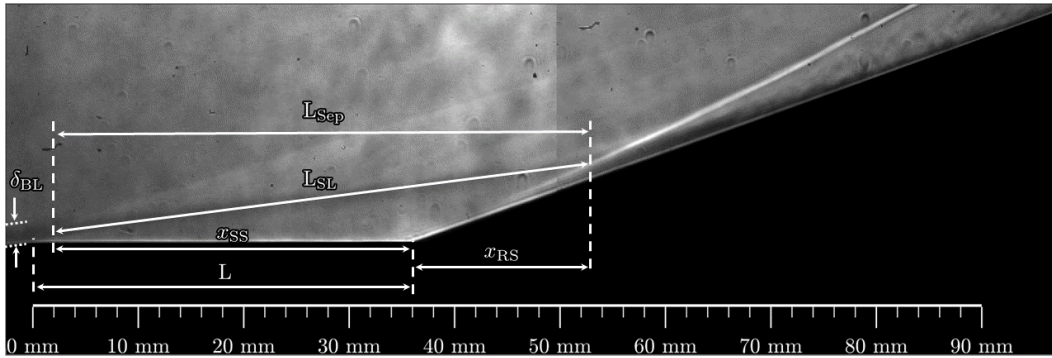


Figure 3.25: Annotated schlieren frame with relevant lengths in the SBLI region identified.

Table 3.2: Table summarizing measured lengths of flow features relevant to the SBLI.

Case	δ_{BL} [mm]	x_{SS} [mm]	x_{RS} [mm]	L_{SL} [mm]	L_{Sep} [mm]	L [mm]
H8-Re2	1.9 ± 0.3	35.2 ± 1.3	17.1 ± 0.8	52.7 ± 0.5	52.3 ± 1.5	37.14
H8-Re3	1.7 ± 0.2	28.0 ± 0.9	8.9 ± 0.3	37.1 ± 1.2	36.9 ± 0.9	37.14
H14-Re3	1.5 ± 0.4	31.8 ± 1.0	14.8 ± 0.5	47.8 ± 2.8	46.6 ± 1.1	37.14

3.3.2 Mean Flow Feature Trends with Freestream Conditions

As the unit Reynolds number is increased from $2 \times 10^6 \text{ m}^{-1}$ to $3 \times 10^6 \text{ m}^{-1}$ at the $h_0 = 8 \text{ MJ kg}^{-1}$ condition, the separation and reattachment locations move closer to the base of the ramp, reducing L_{SL} from 52.7 to 37.1 mm. A clearer view of the corresponding non-dimensional changes in separation location, reattachment location, and separated shear layer length is provided in Figure 3.26. For laminar separation regions, previous studies have shown that increasing unit Reynolds number increases the size of the separation region for cone-cylinder-flare (Benitez et al., 2023a), compression-ramp (Miller et al., 1964; Needham and Stollery, 1966), and cone-slice-ramp (Rubio et al., 2026) geometries. However, when transition occurs within the separated shear layer, this trend can reverse, such that increasing unit Reynolds number instead reduces the size of the separation region (Gray, 1967; Needham and Stollery, 1966). This behavior persists until the transition point moves sufficiently far upstream to lie ahead of the separation point, at which stage the relationship between unit Reynolds number and separation region size changes again.

This suggests that the trend observed in this work, namely the decrease in separation length as Re_{edge} is increased from $2 \times 10^6 \text{ m}^{-1}$ to $3 \times 10^6 \text{ m}^{-1}$, can be attributed to transition occurring within the separated shear layer before the reattachment point. Although the boundary layer on the cone surface remains fully laminar (Figure 3.10), Section 3.2.2 provides evidence supporting transition within the separated shear layer. This evidence includes the higher concentration of Mach radiation emanating from the shear layer just upstream of reattachment, the higher heat flux reported in the separation bubble before reattachment, and the 35% reduction in the transition region length on the ramp surface. Moreover, at an edge unit Reynolds number of $3 \times 10^6 \text{ m}^{-1}$ on a 5-degree slender cone in T5, Jewell, 2014 measured $x_{Tr} = 0.653 \text{ m}$, which places transition over the slice at $x/L = -0.6$ on the current model. This lends further support to the interpretation that the observed decrease in separation length is associated with a transitional separated shear layer.

As the stagnation enthalpy was increased from $h_0 = 8 \text{ MJ kg}^{-1}$ to $h_0 = 14 \text{ MJ kg}^{-1}$ at constant $Re_{edge} = 3 \times 10^6 \text{ m}^{-1}$, the separation region length increased by roughly 27% compared to the H8-Re3 case (Figure 3.27). This trend is contrary to literature suggesting that separation region size decreases with increasing stagnation enthalpy, as observed computationally (Furumoto et al., 1997; Grasso et al., 2001), in double-wedge experiments (Davis and Sturtevant, 2000), and on the cone-slice-

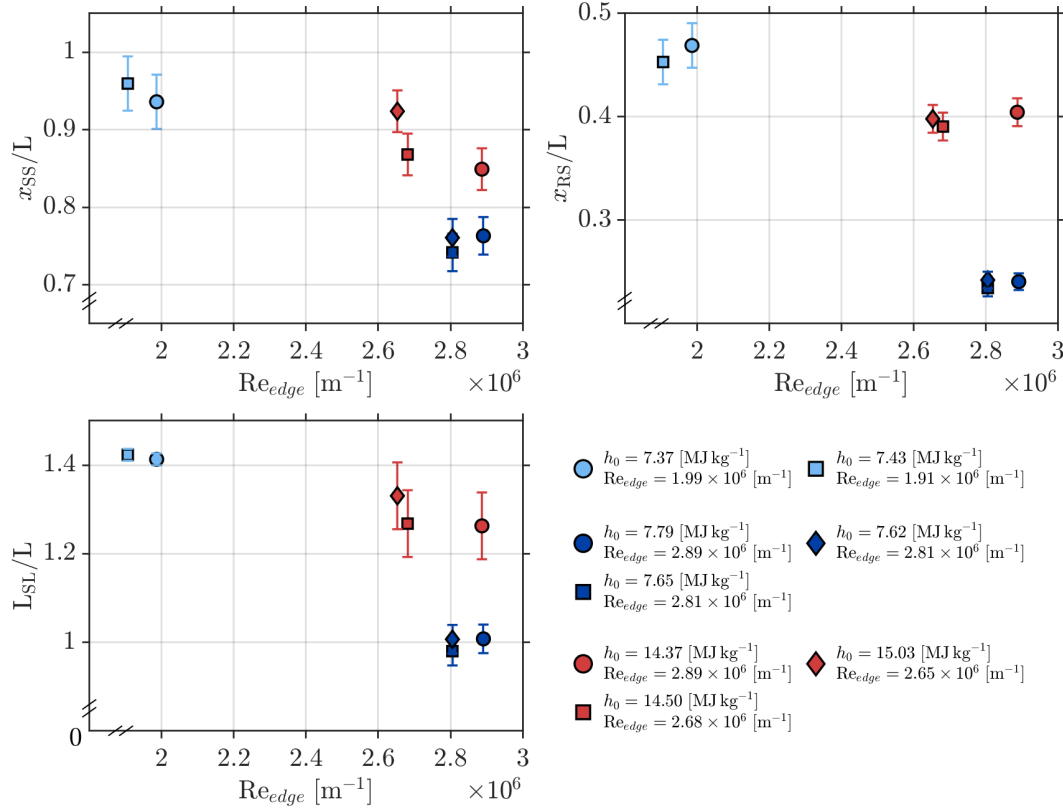


Figure 3.26: Non-dimensional separation location (x_{SS}/L), reattachment location (x_{RS}/L), and length of the separated shear layer (L_{SL}/L) plotted against edge unit Reynolds number (Re_{edge}) of all test cases.

ramp geometry (Rubio et al., 2026; Wagner et al., 2025). A reason for decreasing separation region size with increasing stagnation enthalpy is provided by Davis and Sturtevant, 2000, who attributed the delay in separation to recombination effects in the pre-separation boundary layer.

To explain the observed increase in separation length with stagnation enthalpy, it is important to consider the effect that increasing stagnation enthalpy has on transition Reynolds number. Previous studies conducted in T5 have shown that increasing stagnation enthalpy delays the onset of transition on sharp, 5-degree half-angle cones (Adam and Hornung, 1997; Germain and Hornung, 1997). Above $h_0 = 12 MJ kg^{-1}$, the transition Reynolds number was found to increase rapidly, with experiments unable to induce natural transition at $Re_{edge} = 4 \times 10^6 m^{-1}$ for $h_0 = 14 MJ kg^{-1}$. This delay in transition at higher enthalpies is believed to explain the observed increase in separation length at $Re_{edge} = 3 \times 10^6 m^{-1}$ as the enthalpy is raised from $h_0 = 8 MJ kg^{-1}$ to $h_0 = 14 MJ kg^{-1}$. In effect, increasing stagnation enthalpy pushes transition farther downstream, resulting in a laminar separated shear

layer at a Re_{edge} that would otherwise have been transitional in the lower stagnation enthalpy case. The change in separation size is therefore attributed to a shift from a transitional separated shear layer to a laminar one, caused by the delay in transition associated with increased stagnation enthalpy.

The more appropriate comparison is therefore between the H14-Re3 and H8-Re2 conditions, which were shown earlier to produce laminar interactions. A small decrease in separation region size of ≈ 6 mm is observed at the higher stagnation enthalpy condition, representing a 10% reduction compared to the H8-Re2 condition. In this comparison, two competing effects are present: the increased Re_{edge} and the increased h_0 , which tend to promote growth and contraction of the separation region, respectively. For this specific comparison, the enthalpy effects appear to dominate; however, it is difficult to generalize the relative importance of Re_{edge} and h_0 for this SBLI without additional data.

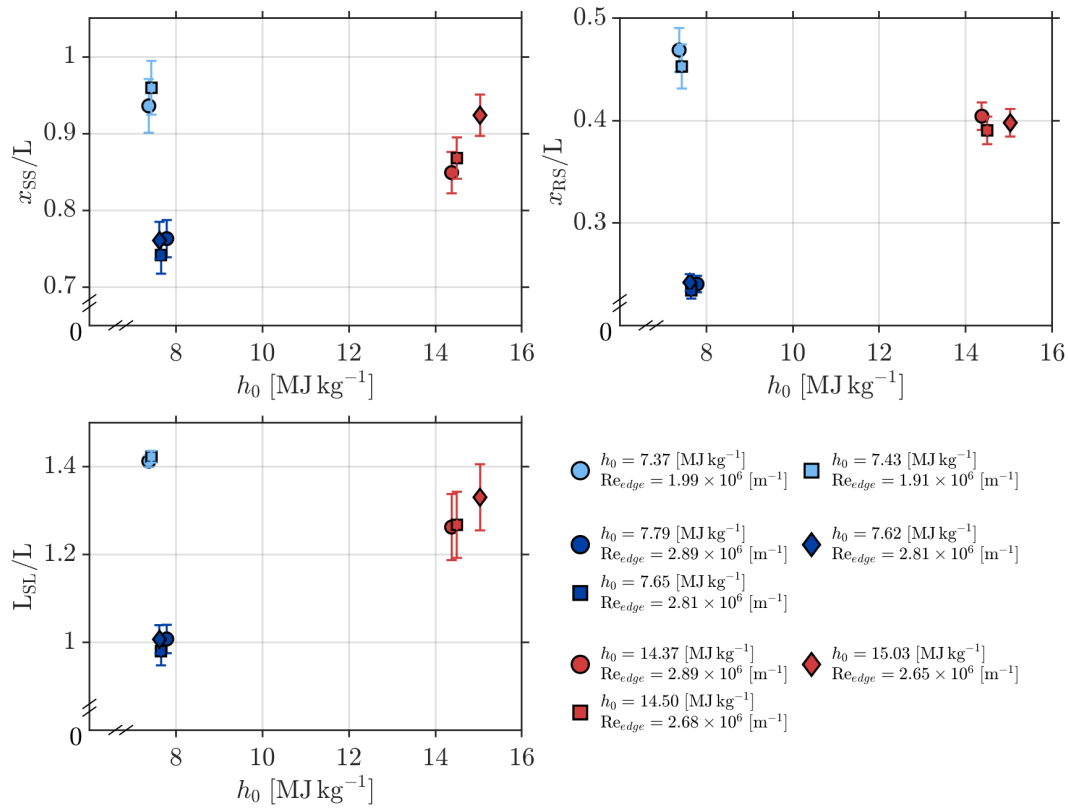


Figure 3.27: Non-dimensional separation location (x_{SS}/L), reattachment location (x_{RS}/L), and length of the separated shear layer (L_{SL}/L) plotted against stagnation enthalpy (h_0) of all test cases.

Chapter 4

SBLI UNSTEADINESS AND SHEAR LAYER INSTABILITIES

This chapter explores the SBLI unsteadiness observed in experiments at the H8-Re2, H8-Re3, and H14-Re3 conditions, for which the separated shear layer exhibited periodic unsteadiness. First, the upstream post-conical-shock flow and boundary layer ahead of the SBLI are examined to characterize the incoming disturbances in the flowfield. The unsteadiness observed above and below the separated shear layer, using FLDI measurements and surface pressure measurements, respectively, is then compared with the SPOD modes calculated from high-speed schlieren, demonstrating agreement in both the spatial locations of the dominant mode shapes and the peak instability frequencies identified. These peak instability frequencies are then scaled using characteristic length scales commonly used in the SBLI literature. Convective disturbances in the shear layer are also computed and compared with the local sound speeds to determine whether the convective velocities are locally supersonic or subsonic. Finally, the coupling between the flow features of the SBLI is examined, and an interpretation of the shear layer instability mechanism is proposed based on the evidence presented.

4.1 Upstream Disturbances

The inflow perturbation environment is important to quantify when assessing flow instabilities. Flow instabilities can be globally stable and behave as noise amplifiers where constant external disturbances are needed to continuously drive the unsteadiness. By contrast, globally unstable flows support at least one self excited global mode that can grow without sustained external forcing (Huerre and Monkewitz, 1990). DNS studies of compression ramp SBLI have reported both globally stable (Cao et al., 2024) and globally unstable (Cao et al., 2021, 2022) behavior. For a smaller ramp angle of 10 degrees, Cao found that the weakly separated flow formed on the compression ramp supported no global instability whereas a modest increase to 15 degrees produced globally unstable behavior. In the absence of a computational investigation into the stability of the present experiments, these findings motivated the current work to examine and quantify the upstream perturbations in the incoming boundary layer and in the post-conical-shock region upstream of the SBLI.

4.1.1 Post-Conical-Shock Noise

Noise characterization in the post-conical-shock region was performed using FLDI. It is worth mentioning that the term post-conical-shock region refers to the flow immediately upstream of the slice-ramp portion of the model. Disturbances in this region originate from freestream tunnel noise that propagates through a weak oblique shock formed at the vertex of the cone. This cone shock remains outside the field of view of the optics used in this work. To avoid confusion with the freestream conditions, which refer to flow properties at the nozzle exit plane, the term post-conical-shock region is used to describe the flow just upstream of the slice-ramp, which effectively acts as the freestream for the SBLI (Region ① in Figure 1.3). The FLDI beams were located at position F_f (Table 2.3), with the beam pair oriented parallel to the flow direction. Figure 4.1 shows the normalized density fluctuation power spectral density, $\text{PSD}\{\rho'/\bar{\rho}\}$, plotted against frequency. The conversion from the differential phase signal $\Delta\Phi(t)$ to normalized density, and the underlying assumptions associated with this conversion, are discussed in Appendix B. Density fluctuations in the post-conical-shock region appear broadband in nature, with no distinct frequency peaks detected. Within the 50–200 kHz band relevant to the SBLI unsteadiness discussed later in this work, the measured spectrum remains above the noise floor but shows no significant spectral peaks. Thus, over the instability frequency range of interest and for the shot conditions explored, the disturbance environment upstream of the SBLI region is broadband.

Investigation of the structure of disturbances in the post-conical-shock region was also performed using Spectral Orthogonal Decomposition (SPOD) as outlined in Appendix D.1. Figure 4.2 shows the eigenspectra for all three shot conditions explored. Prior to computing the SPOD energies, a region of interest in the post-conical-shock region was defined and only pixels within this region were used in the computation. General trends remain consistent between the three shots as the mode energies are distributed across the frequency range of 20 kHz to 200 kHz similar to the broadband disturbance frequency band shown in the FLDI result above. The lack of distinct spectral peaks in the modal energies suggests a broadband disturbance environment consistent with FLDI measurements.

Figures 4.3 and 4.4 show the reconstructed first mode at frequencies spanning the 20 kHz to 200 kHz range of elevated modal energy. Coherent wave structures of disturbances in the post-conical-shock region are observed and attributed to disturbances in the turbulent nozzle wall boundary layer propagating at disturbance

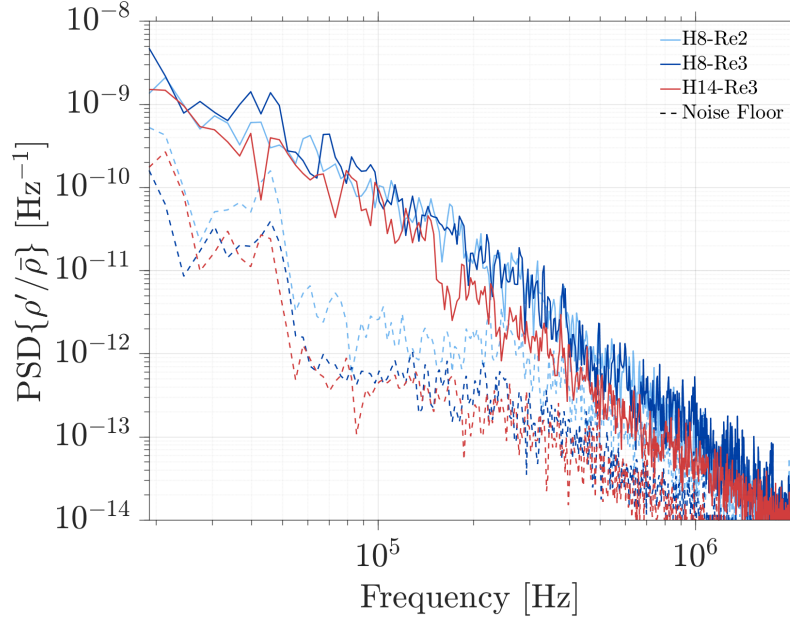


Figure 4.1: Post-conical-shock region density fluctuations at FLDI beam position F_f for the H8-Re2, H8-Re3, and H14-Re3 test conditions.

propagation speed U_c . The wave vector angle produced by disturbance at the nozzle wall will depend on the convective Mach number $M_c = \frac{U_\infty - U_c}{a_\infty}$ as defined by Laufer, 1961. The wave vector angle of the disturbances identified by SPOD is expected to match this wave vector angle, with additional modifications to the angle introduced by the nozzle wall geometry and by acoustic refraction as the waves pass through the oblique cone shock.

A measurement of the convective velocities of disturbance originating from the turbulent nozzle wall is made by measuring the phase speed of the SPOD mode structures assuming $U_c = U_\phi = f \times \lambda$ where f is the frequency of the reconstructed mode and λ is the wavelength of the coherent structure measured along the freestream propagation axis x . As the frequency of the SPOD reconstruction is increased, a decrease in Mach angle and corresponding reduction in disturbance wavelength are observed. Figure 4.6 plots the measured values of U_c , computed using this relation, against the mode frequency. As frequency is increased, convective velocity also increases. This result is shared by the plotted SPOD modes that show the Mach angle becoming more oblique at lower frequencies, consistent with a lower U_c .

Also plotted are lines representing the two-thirds U_∞ convective speeds for disturbances in the nozzle boundary layer previously reported in T5, inferred from the Mach angle of disturbances measured using an interferogram (Germain and

Hornung, 1997). Artificially introduced disturbances in the nozzle boundary layer at Purdue’s Mach 6 quiet tunnel also reported disturbance propagation speeds of $0.64\text{--}0.71 U_\infty$ at Re ranging from $5.8 \times 10^6 \text{ m}^{-1}$ to $10 \times 10^6 \text{ m}^{-1}$ (Casper et al., 2014a). The mean values for the H8-Re2 and H8-Re3 shots are 0.61 and 0.68, respectively, which appear to fall within the range of values expected from these two works. Figure 4.7 plots a comparison of the convective Mach numbers M_c computed using both the measured Mach angle μ and the reported U_c inference from the SPOD mode wavelength. Agreement between these two independent estimates of convective Mach number is expected which is indeed the case with the values of M_c inferred from the SPOD wavelength collapsing onto the $x = y$ line when plotted against those obtained from the measured Mach angle μ .

At the H14-Re3 condition, coherent wave structures are harder to resolve (Figure 4.5). This is due in part to the higher freestream velocities of $\approx 4700 \text{ m s}^{-1}$. Using the same scaling $U_c = (2/3) \cdot U_\infty$ as the $h_0 = 8 \text{ MJ kg}^{-1}$ cases, the expected wavelength range for a 20–200 kHz SPOD reconstruction is $\lambda = 15.7$ to 157 mm. This makes resolving coherent wave structures impractical within the approximately $\approx 20 \text{ mm}$ field of view available in the post-conical-shock region with the optics used in the present work.

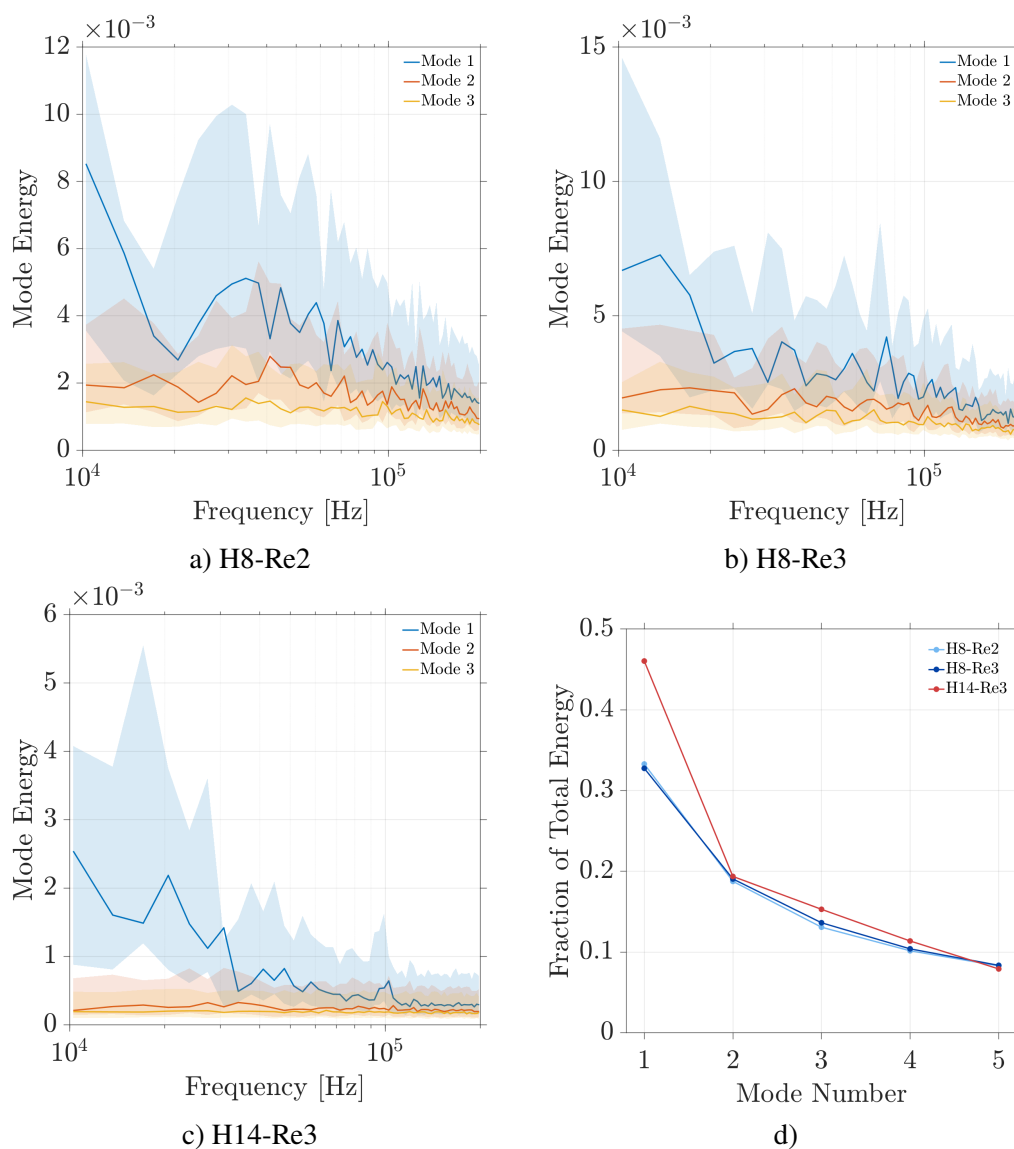


Figure 4.2: SPOD eigenspectrum of post-conical-shock region.

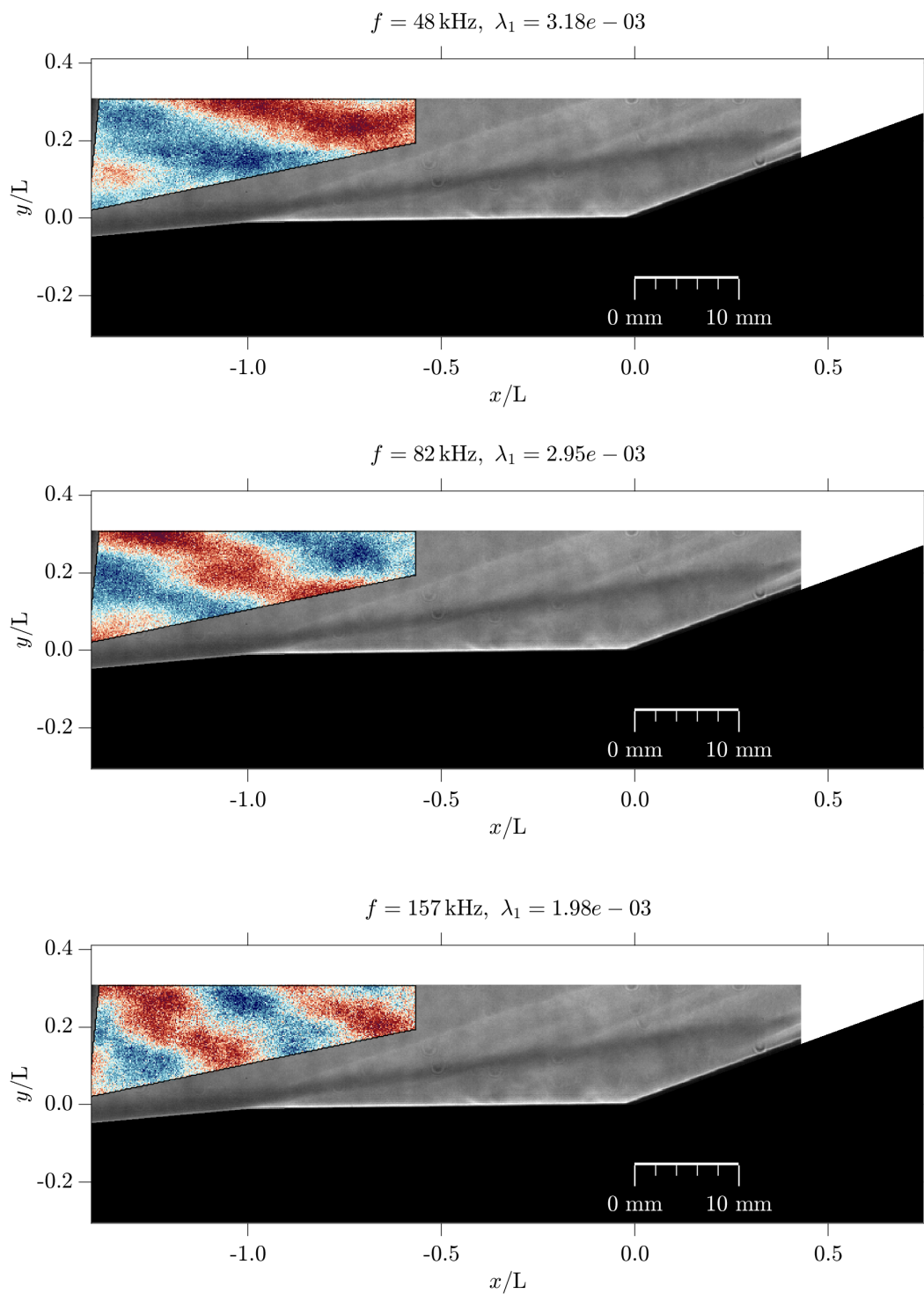


Figure 4.3: Post-conical-shock region SPOD modes for the H8-Re2 condition.

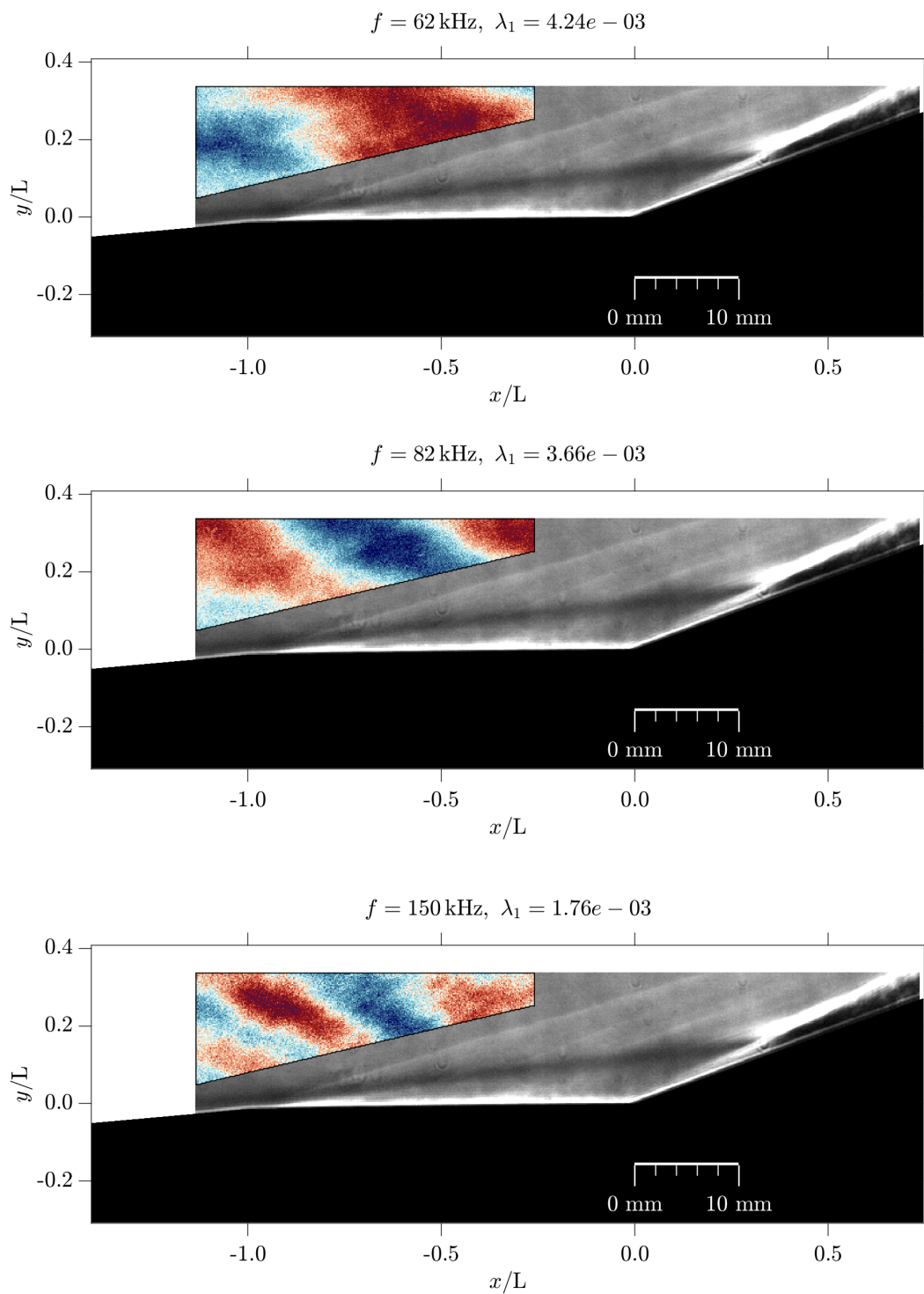


Figure 4.4: Post-conical-shock region SPOD modes for the H8-Re3 condition.

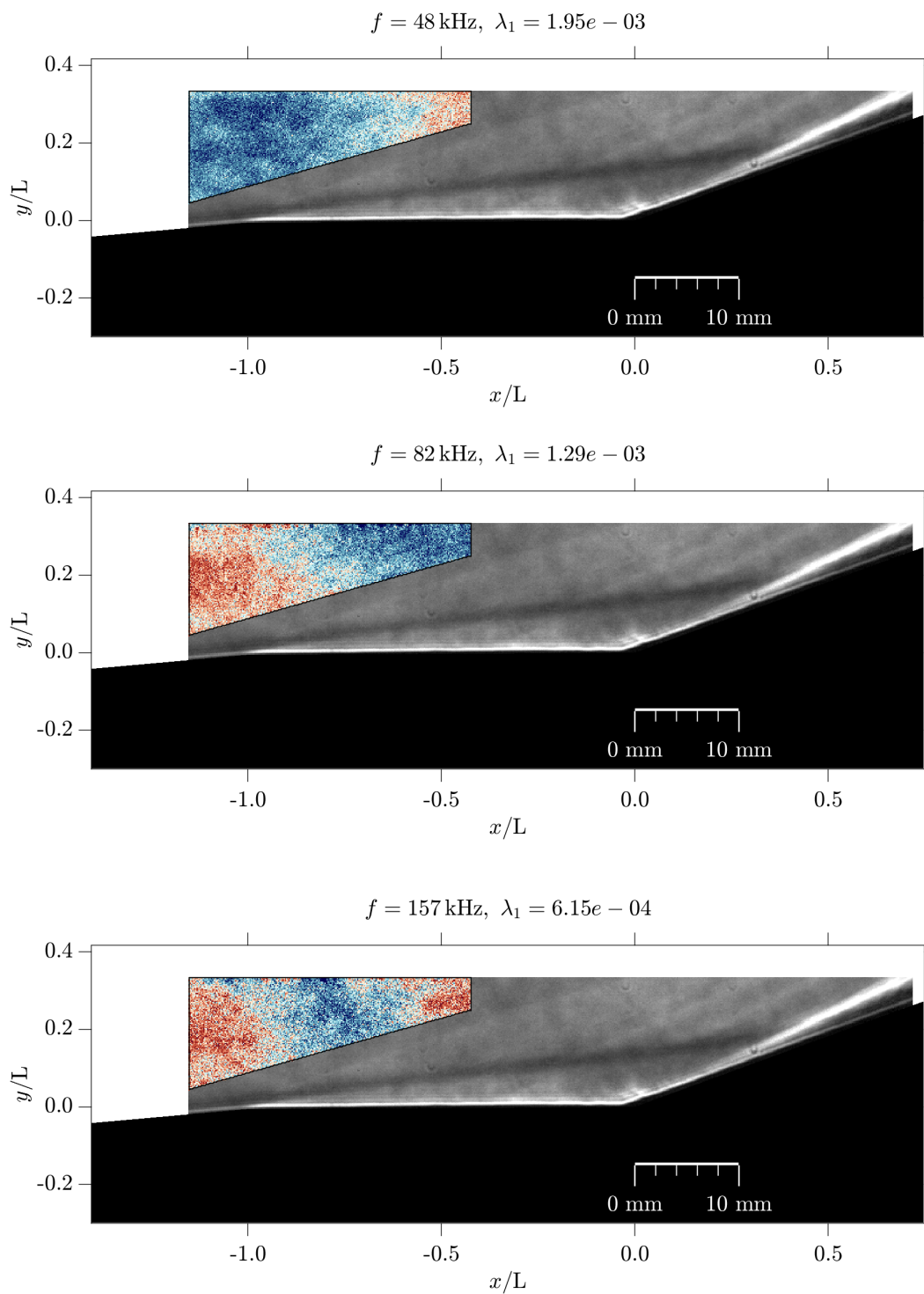


Figure 4.5: Post-conical-shock region SPOD modes for the H14-Re3 condition.

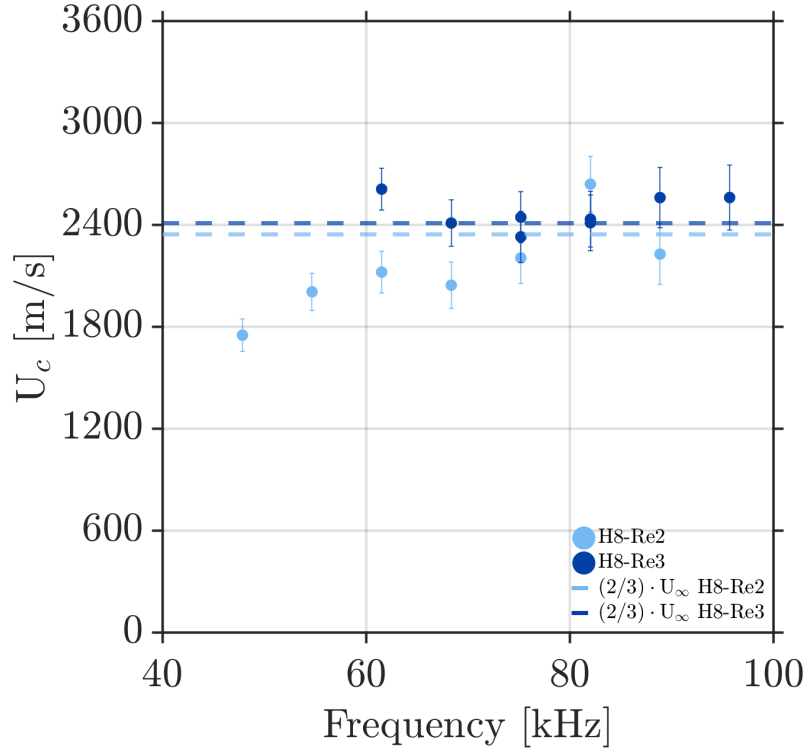


Figure 4.6: Convective velocity measured using $f \times \lambda$ of SPOD mode vs the frequency of the mode.

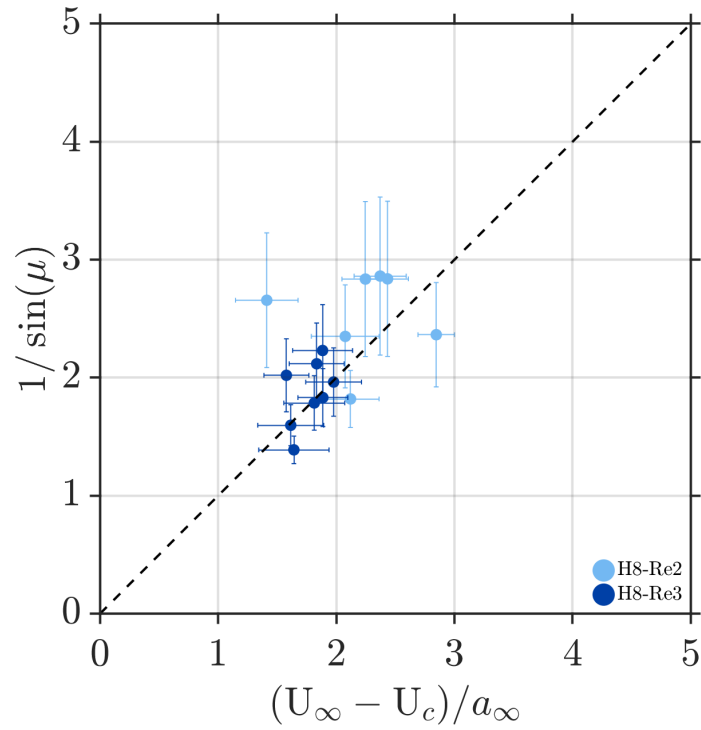


Figure 4.7: Comparison of convective Mach number computed using convective velocity measured from SPOD mode vs Mach angle of SPOD mode structure.

4.1.2 Incoming Boundary Layer Disturbances

The dominant boundary layer disturbance on a slender hypersonic cone is the second (Mack) mode instability. The second mode arises from the amplification of acoustic waves trapped within the boundary layer, as described by Mack, 1984. Another possible instability is the first mode, the high-speed analogue of the viscous Tollmien–Schlichting instability (Malik, 2003). However, for cold walls at high Mach numbers above about 4, first mode disturbances are strongly damped while higher modes are amplified, so for a slender cone at zero angle of attack the second mode is generally expected to be the dominant linear instability leading to transition. For second mode disturbances, the boundary layer acts as an acoustic waveguide for disturbances (Fedorov, 2011), and the frequency of the most strongly amplified second mode disturbance in the boundary layer may be approximated as $f \approx 0.7 \frac{U_{edge}}{2\delta}$ (Stetson and Kimmel, 1992).

To measure incoming boundary layer disturbances, a FLDI beam was positioned within the incoming boundary layer at beam location F1 ($x/L = -1.29$). Figure 4.8 compares the measured F1 frequency spectrum with that measured in the post-conical-shock region at F_f for the H8-Re2 condition. The two spectra are similar aside from a noticeable frequency peak centered around 619 kHz. This peak aligns with the predicted second-Mack mode instability frequency computed using $f \approx 0.7 \frac{U_{edge}}{2\delta}$, where the edge velocity conditions were taken from Table 2.2 and boundary layer thickness was taken from the measured height reported in Table 3.2. Peaks at approximately two and three times this predicted frequency are also present, corresponding to the 2nd and 3rd harmonics respectively. This finding agrees with previous FLDI measurements on a 5-degree slender cone boundary layer reported by Parziale, 2013, which, at a similar H8-Re2 condition, showed peak instability frequencies at 620 kHz. The key takeaway from this measurement is that the upstream boundary layer disturbance environment has a broadband spectrum with similar intensity and frequency content to that of the post-conical-shock region, with the addition of dominant second Mack mode disturbances.

Disturbance measurements of the incoming boundary layer were also obtained by a surface mounted PCB sensor (P1) at the same streamwise location as FLDI beam location F1 ($x/L = -1.29$). Figure 4.9 shows the PSDs measured by the P1 PCB sensor for the three shot conditions, plotted over the useful range of the gauge. The peak at ≈ 180 kHz is associated with a gauge resonance, and it appears in all three shot conditions and persists after test time when the signal spectrograms are

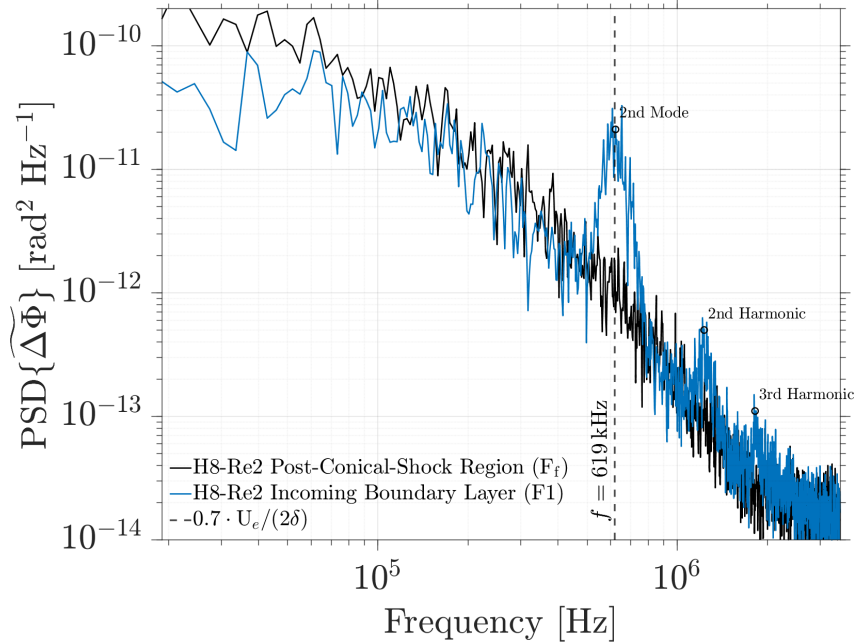


Figure 4.8: Incoming boundary layer disturbances measured at F1 compared to the post-conical-shock region measurements for H8-Re2.

evaluated.

For the lower stagnation enthalpy cases, a broad hump in spectral content is observed from 50 kHz to 100 kHz. Blowdown facility experiments on slender cone boundary layers at Mach numbers greater than 5 have measured disturbances below the predicted second mode frequencies and have attributed them to first mode disturbances (Butler and Laurence, 2022; Casper et al., 2016). Casper et al., 2016 suggests a scaling for these first mode disturbances of $f \approx \frac{U_{edge}}{10\delta}$. The presence of both instabilities first and second mode disturbances in low stagnation enthalpy flows at Mach 5 is further supported by Stability and Transition Analysis for Hypersonic Boundary Layers (STABL) computations (Alba et al., 2010; Casper et al., 2013). However, for the higher stagnation enthalpies explored in this work, the first mode is predicted to be stable for wall temperature ratios of $(T_w/T_e) = 0.3$, as is the case in the current experiments (Bitter and Shepherd, 2014). These disturbances are therefore not believed to be first mode.

Because the FLDI data acquired just above the P1 sensor do not pick up any peaks in this frequency range, the most likely cause of the heightened spectral content is surface effects associated with the surface pressure gauges. Low frequency disturbances due to cross flow caused by slight misalignments in pitch and yaw have been shown computationally to exist, independent of the second mode disturbances (Bal-

akumar and Owens, 2010; Chen et al., 2025; Perez et al., 2013), and may offer an explanation for the low frequency disturbances observed. Moreover, the PCB gauges are sensitive to mounting conditions (Ort and Dosch, 2019), and the low frequency response may be a byproduct of this.

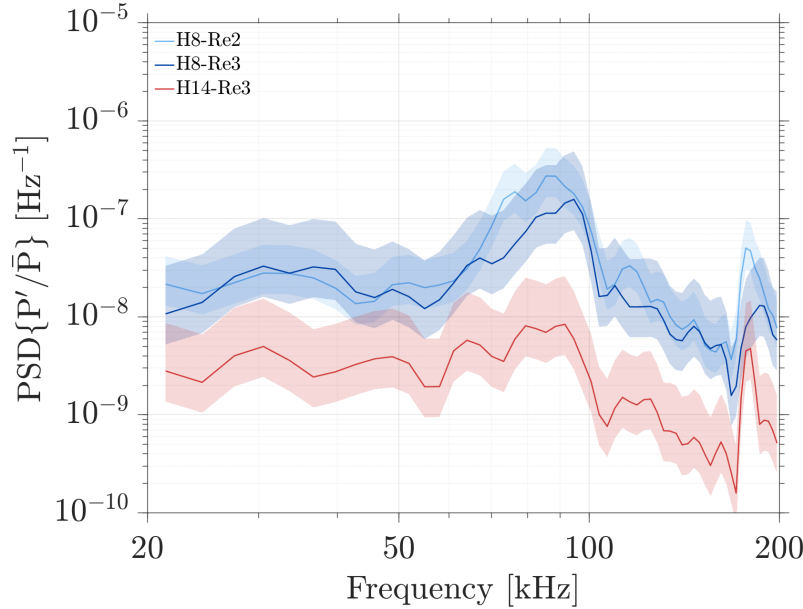


Figure 4.9: PSD of surface pressure fluctuations in the incoming boundary layer at PCB sensor P1 for the H8-Re2, H8-Re3, H14-Re3 conditions.

4.2 Separated Shear Layer

As the incoming boundary layer traverses the expansion corner of the slice, it lifts from the surface, forming a separation shock. Within this separated shear layer, instability frequencies have been observed in prior cone-slice-ramp and cone-cylinder-flare geometries in blowdown facility experiments. Pandey et al., 2022b found that second mode instability frequencies in the incoming boundary layer propagate along the separated shear layer, where they are again observed in the reattached boundary layer under laminar separation. Disturbances in the separated shear layer at frequencies lower than the second mode frequency were also measured and were attributed to a shear layer instability. Cone-cylinder-flare experiments conducted at Purdue similarly observed that second mode instabilities travel above the separation bubble in the separated shear layer for a fully laminar separation and reattachment in quiet flow conditions (Benitez et al., 2023a). A second instability frequency, lower than the second mode, was also measured in these experiments, but at much lower amplitude in quiet flow than in conventional noise conditions.

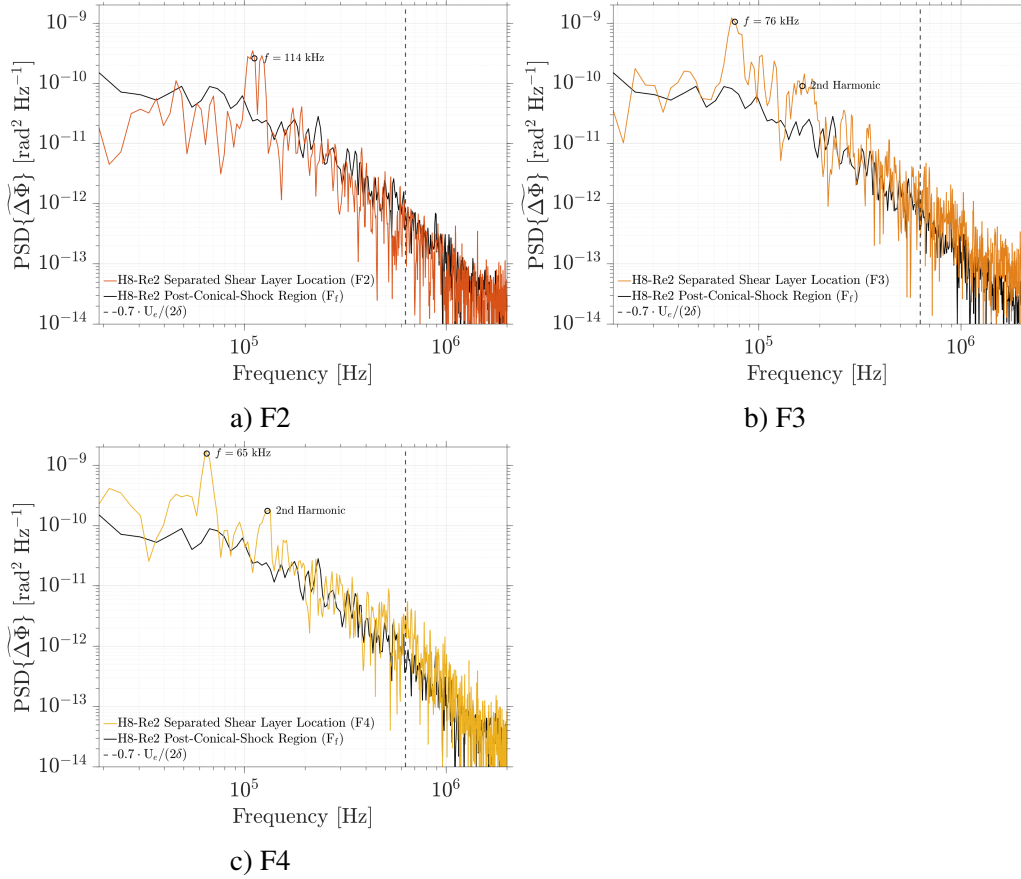


Figure 4.10: Disturbance measurements in separated shear layer at streamwise locations F2, F3, and F4 using FLDI for the H8-Re2 condition.

To measure instabilities in the separated shear layer in the current work, three FLDI measurements were taken inside the separated shear layer for the H8-Re2 condition, corresponding to locations F2 ($x/L = -0.48$), F3 ($x/L = -0.08$), and F4 ($x/L = 0.08$). In Figure 4.10, the PSD spectra are plotted alongside the baseline post-conical-shock region disturbance intensity for each FLDI location. At location F2, a peak in frequency content is observed at 114 kHz. As the measurement location is shifted downstream to F3 and F4, frequency peaks at 76 kHz and 65 kHz are observed, respectively. These measured instability frequencies are believed to be associated with the shear layer instability frequency measured by Pandey and Benitez, as discussed above. The 65–114 kHz range of the measured instability is too low to be the second mode instability, which was measured in the incoming boundary layer at 619 kHz under the same flow conditions. It is also not believed to be associated with the low frequency (3–10 kHz) breathing motion of the separation bubble and bulk undulation of the shear layer, as reported by Pandey et al., 2022b.

As will be explored further in this work, the unsteadiness observed in the shear layer best aligns with the description of the medium-frequency shear layer instability described by Pandey. The absence of second mode disturbances at locations F2, F3, and F4 must also be noted, as this differs from the experiments of Pandey and Benitez, which observed the second mode frequencies in the separated shear layer. This difference may result from transition within the separated shear layer and three-dimensional flow effects, which could disrupt coherent second-mode wave packets.

4.3 Disturbances Above Separated Shear Layer

Flow above the separated shear layer, in the region bounded by the separation and reattachment shocks, remains supersonic. As this flow encounters the more slowly convecting disturbances within the separated shear layer, Mach radiation or “shocklets” form when the relative convective Mach number $M_c = \frac{U_{edge} - U_c}{a_{edge}}$ exceeds one, where U_{edge} is the velocity of the flow above the separated shear layer, U_c is the convective velocity of the disturbance within the shear layer, and a_{edge} is the sound speed above the separated shear layer.

In the present work, Mach radiation is clearly visible in the region above the separated shear layer, originating from the separated shear layer and propagating upward toward the separation shock. In Figure 4.11 a time sequence of schlieren frames is shown that emphasizes the structure and spatial distribution of these shocklets. These images were produced by computing the mean schlieren frame intensity within the region of interest above the separated shear layer, subtracting each instantaneous frame from this mean within the region of interest, and overlaying the result onto the raw schlieren frame. The Mach radiation is observed to convect downstream with the disturbances in the shear layer, with the convective velocities of the Mach radiation reported in detail in Section 4.5 and Mach angles of the shocklets reported in Table 3.1. The angle of the shocklets remains approximately constant but is shown to decrease near $x/L \approx 0$. The three-dimensional nature of the flow is evident in the spanwise intermittency of the shocklets, which appear and disappear abruptly, while multiple closely spaced shock fronts are observed at similar streamwise locations thickening the appearance of the shocks.

The SPOD eigenspectra computed over the same region of interest identify clear tonal features for each of the three test conditions. Figure 4.12 presents the eigenspectra for all three cases and reveals a frequency band over which the SPOD

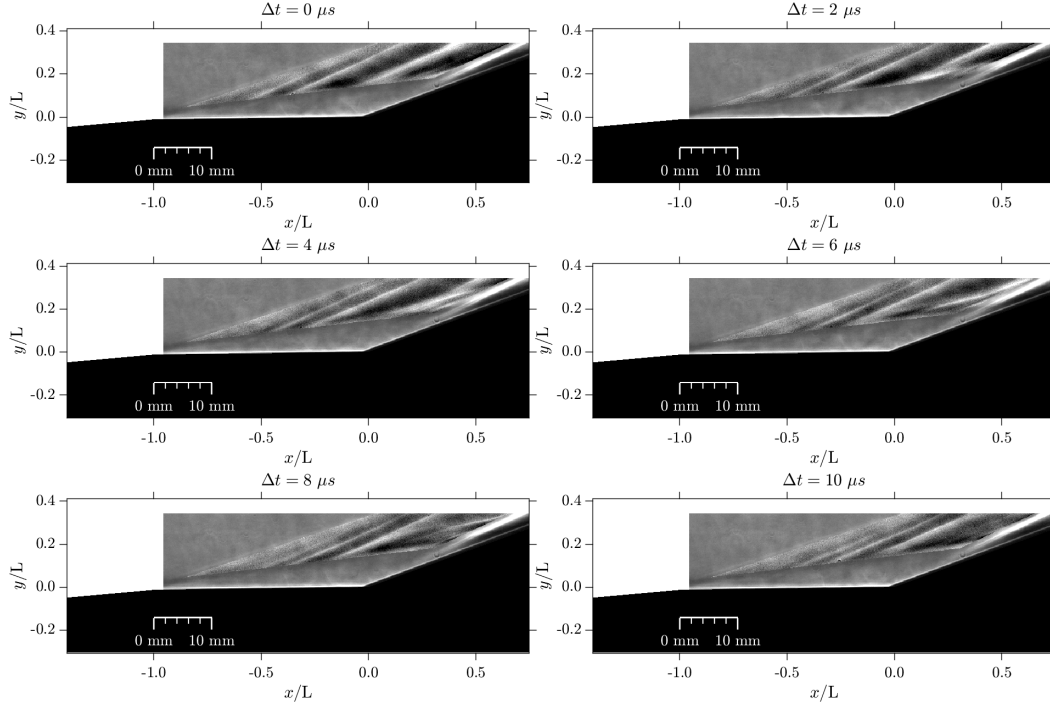


Figure 4.11: Structure and downstream convection of Mach radiation above separated shear layer for the H8-Re2 condition.

spectra exhibit low rank behavior. This frequency band corresponds to 60–140 kHz, 100–168 kHz, and 90–167 kHz for the H8-Re2, H8-Re3, and H14-Re3 test cases, respectively. The frequency of peak modal energy was identified as 68 kHz for the H8-Re2 case, 123 kHz for the H8-Re3 case, and 109 kHz for the H14-Re3 case. Figure 4.12 also shows that the majority of the energy in the SPOD reconstruction is contained within the first mode. This indicates that the dominant coherent dynamics are captured primarily by the first SPOD mode; therefore, only the Mode 1 reconstruction is considered in the subsequent analysis.

Plotting the dominant SPOD mode at selected frequencies within the low rank band reveals coherent wave structures emanating from the separated shear layer, consistent with the Mach radiation observed in the schlieren images. For the H8-Re2 condition, Figure 4.13 presents the leading SPOD mode at frequencies corresponding to the peak instability frequencies measured by the FLDI beams located within the separated shear layer (Figure 4.10). The FLDI beam locations F2–F4 are also annotated to indicate the measurement positions. Excellent agreement is observed between the streamwise locations of the FLDI peak frequencies and the locations where the reconstructed SPOD mode amplitudes are strongest, indicating that the SPOD mode structures align closely with the disturbances measured by FLDI at

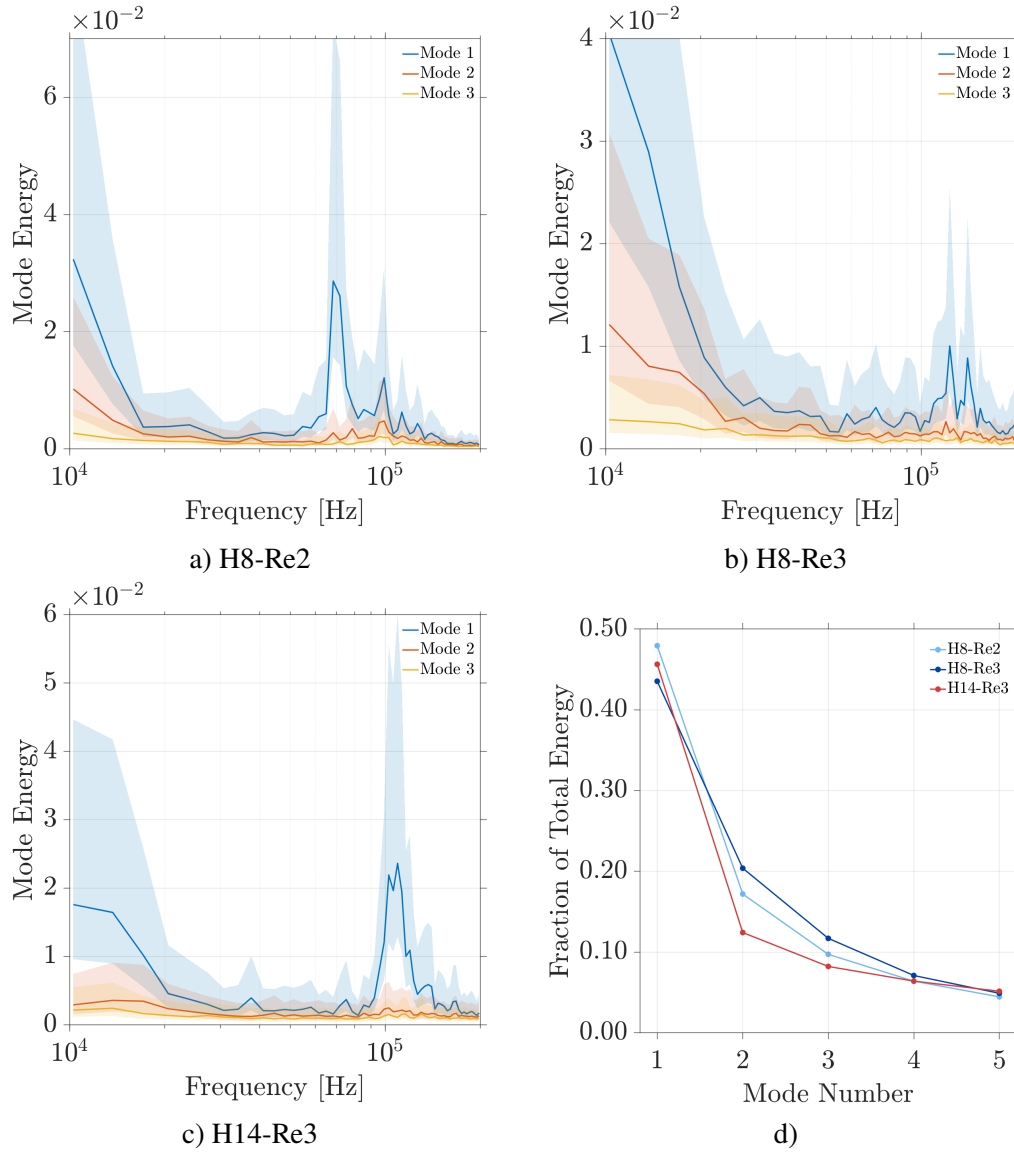


Figure 4.12: SPOD eigenspectrum above the separated shear layer for all shot conditions.

each location. As the frequency of the reconstructed modes increases, the onset of the highest amplitude coherent structures also shifts upstream, a trend also noted by Pandey et al., 2022b and Butler and Laurence, 2022. Downstream of the corner, the angle of the coherent structure decreases and becomes more parallel to the separated shear layer angle. This is consistent with the findings of Butler and Laurence, 2021a, 2022, who observed similar behavior in their SPOD analysis. This behavior is believed to be associated with a downstream "flapping" motion of the separated shear layer (Butler and Laurence, 2022; Pandey et al., 2022a), in which the separated shear layer undergoes larger amplitude wall-normal oscillations while maintaining an approximately constant mean inclination downstream of the corner.

Figures 4.14 and 4.15 plot the dominant SPOD mode for the H8-Re3 and H14-Re3 conditions, respectively. In lieu of FLDI data within the separated shear layer for these shots, the plotted frequencies were selected to align with the peak frequencies measured by the P2 and P3 PCB sensors (Section 4.4), with an intermediate frequency chosen halfway between the two. For the H8-Re3 case, SPOD modes show the same trends as in the H8-Re2 case, with the highest amplitude coherent structures shifting upstream with increasing frequency and the general shapes and angles of the modes aligning the observed Mach radiation above the separated shear layer. The mode energies of the H8-Re3 reconstructions are less prominent than those of the H8-Re2 condition, with peak mode energies approximately three times lower than in the H8-Re2 case. This is due in part to the separated shear layer being transitional and radiating a higher concentration of Mach radiation than in the H8-Re2 case. It is believed this higher density of shocklets reduces the coherence of the radiating structures above the separated shear layer, making the SPOD modes more difficult to resolve and resulting in lower mode energies. Figure 4.15 plots the dominant SPOD mode for H14-Re3. As in the two lower enthalpy cases, the highest amplitude coherent structures shift upstream with increasing frequency. The eigenspectra peaks are stronger for this condition than the H8-Re3 case, with peak mode energies comparable to those of the H8-Re2 case.

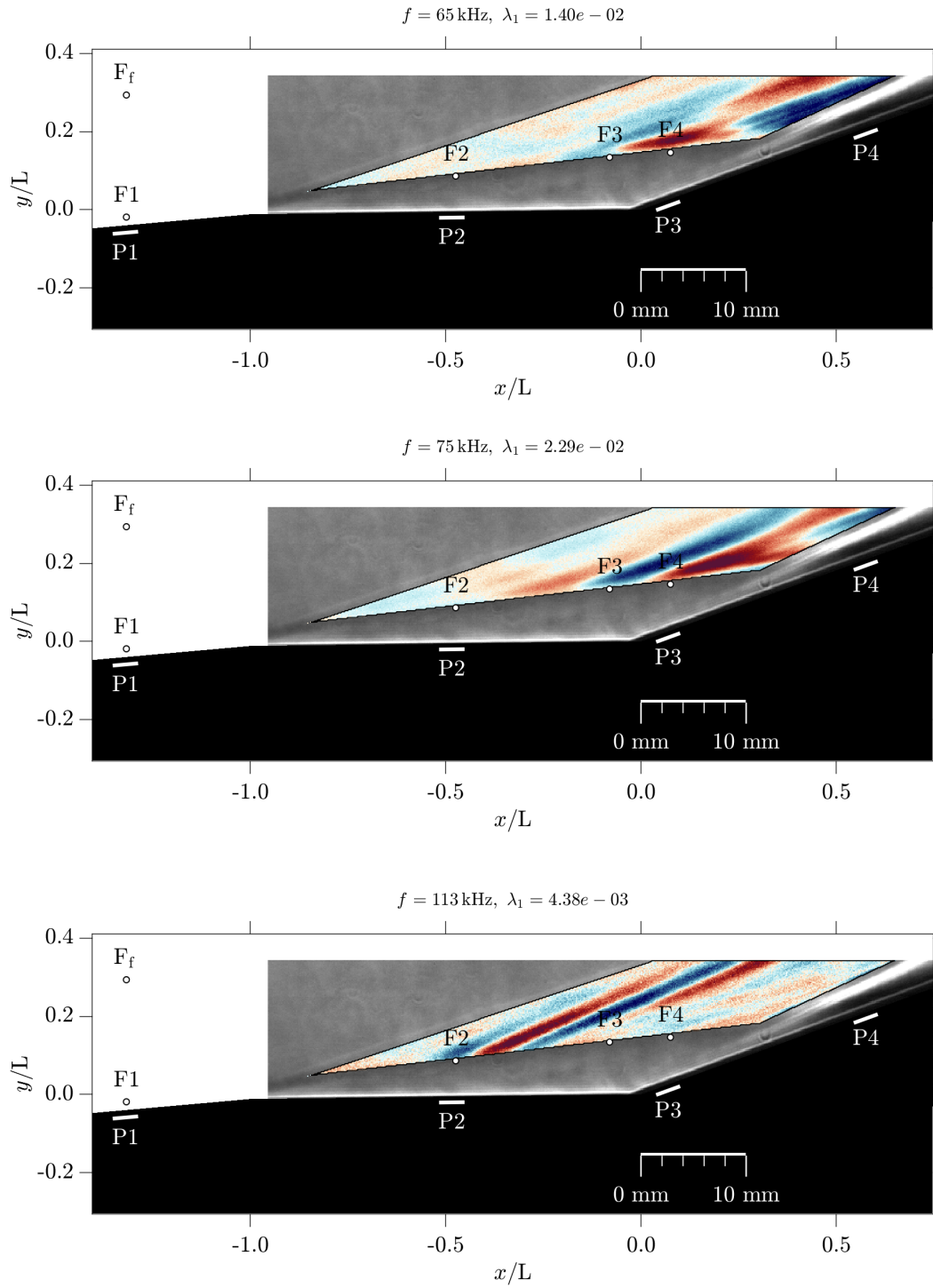


Figure 4.13: SPOD mode shapes of schlieren pixels above separated shear layer for the H8-Re2 condition.

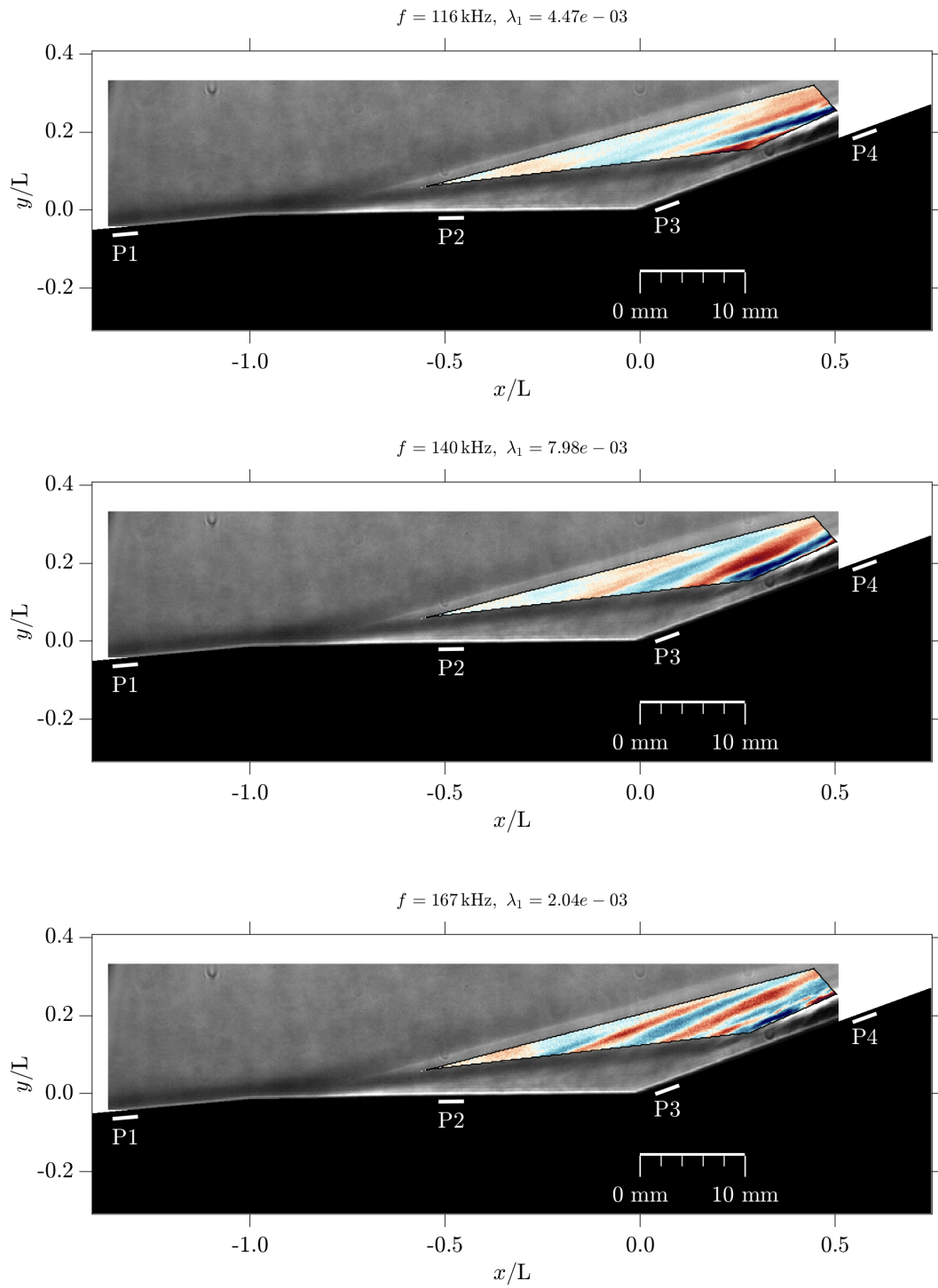


Figure 4.14: SPOD mode shapes of schlieren pixels above separated shear layer for the H8-Re3 condition.

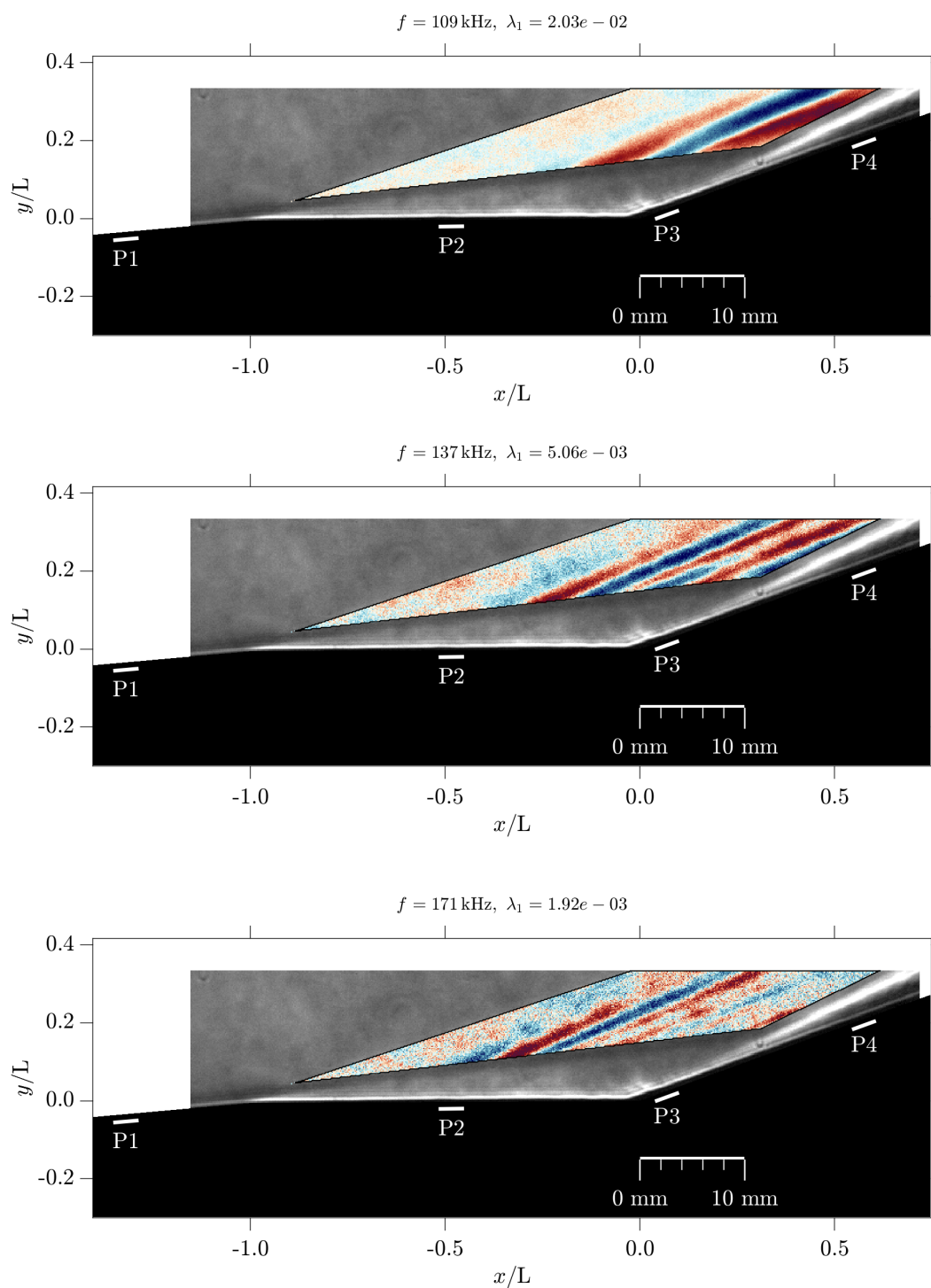


Figure 4.15: SPOD mode shapes of schlieren pixels above separated shear layer for the H14-Re3 condition.

4.4 Disturbances in Separation Bubble

Below the separated shear layer, the separation bubble forms a subsonic recirculating flow region bounded upstream by separation and downstream by reattachment. Pandey et al., 2022b measured surface pressure within the separation region of a cone-slice-ramp geometry and reported peak frequencies that decreased downstream along the separation bubble, matching those observed in the off-surface separated shear layer instability identified using FLDI and schlieren imaging. From this agreement, Pandey inferred that pressure waves radiate from the separated shear layer and are subsequently recorded by the surface pressure transducers within the separation bubble. This inference was made without a direct measurement of the pressure waves themselves, relying instead on the pressure transducer signals and SPOD mode reconstructions, which exhibited the same peak frequencies.

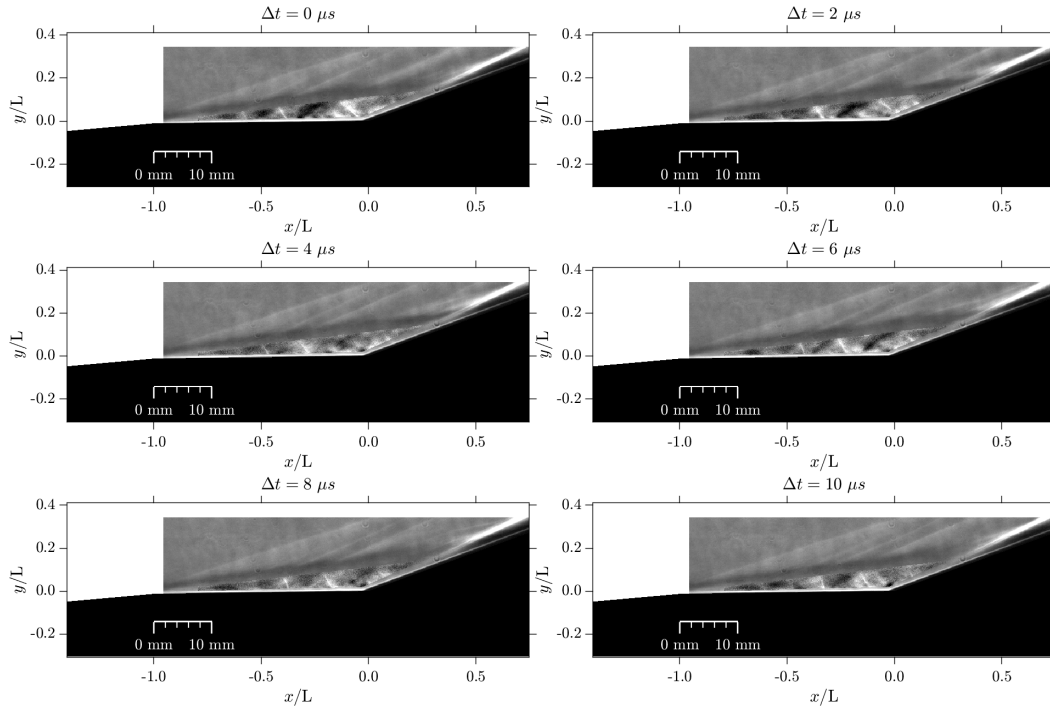


Figure 4.16: Wave-like density gradient structures propagating downstream within the separation bubble for the H8-Re2 condition.

In the present work, coherent wave-like density gradient structures propagating downstream within the separation bubble are directly observed using schlieren imaging, as shown in Figure 4.16. In the schlieren image sequence shown, the mean pixel intensity within the separation bubble is subtracted from each instantaneous frame in that same region, which helps highlight the presence of these wave-like structures. These structures resemble trapped acoustic waves in a waveguide, with

the separated shear layer and the model surface acting as confining boundaries. The waves convect downstream within the separation bubble with velocities that are explored in greater detail in Section 4.5.

Surface mounted PCB pressure transducers placed within the separation bubble (P2 and P3) are used to measure the peak instability frequencies inside the separation bubble. Two additional PCB sensors are placed on the ramp surface (P4 and P5) downstream of the reattachment shock to measure the unsteadiness of the reattached boundary layer. Figure 4.17 plots the normalized pressure PSDs for these four sensors for the H8-Re2 condition. The PSDs were calculated using Welch's method (Hann window, 50% overlap, $\Delta f = 3$ kHz). At location P2 ($x/L = -0.48$), within the separation bubble, a peak frequency of 116 kHz is observed. Farther downstream, still within the separation bubble, at P3 ($x/L = 0.08$), the peak instability frequency shifts downward to 71 kHz. On the ramp surface downstream of the reattachment shock, the P4 transducer ($x/L = 0.58$) records a peak at 67 kHz, while farther downstream on the ramp at P5 ($x/L = 1.22$), a broadband spectrum is observed, characteristic of a transitioned boundary layer.

It is worth noting that the H8-Re2 condition was the only test condition to exhibit a distinct frequency peak at the P4 sensor location. Experiments on cone-cylinder-flare geometries (Benitez et al., 2023b) and cone-slice-ramp geometries (Pandey et al., 2022b) both observed post-reattachment frequency peaks that aligned with the shear layer instability frequency measured upstream of reattachment, consistent with the present result. The absence of a distinct frequency peak at P4 for the H8-Re3 and H14-Re3 cases is likely due to transitional effects. For the H8-Re3 condition, the higher shocklet density in the separated shear layer and the shorter separation region at higher unit Reynolds number suggest transition within the separated shear layer (Section 3.2.2). Inspection of the thermocouple data at R5, adjacent to the P4 transducer, also reveals heat flux values consistent with the turbulent heat flux levels reported farther aft on the ramp (Table 3.13). For the H14-Re3 case, the reattachment location is comparable to that of H8-Re2; however, the transition region on the ramp surface is only half as long (Figure 3.21), indicating that the boundary layer over P4 is more turbulent and therefore less likely to exhibit a distinct instability frequency peak.

Figure 4.18 shows the PSDs of the PCB sensors for the H8-Re3 case. Inside the separation bubble, the P2 sensor ($x/L = -0.48$) records a peak frequency of 164 kHz, considerably higher than the 116 kHz reported at the same location for H8-Re2.

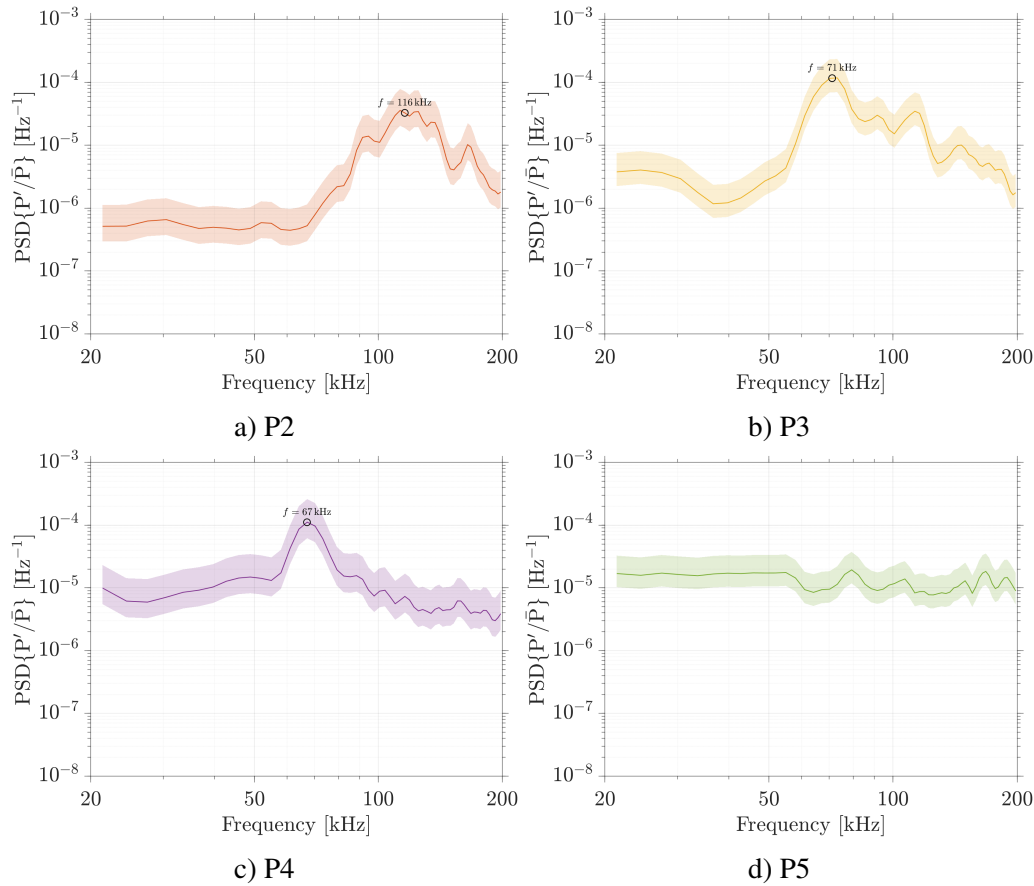


Figure 4.17: Surface pressure transducer PSDs for the H8-Re2 condition.

The peak at 95 kHz observed in Figure 4.18a) is a gauge-resonance peak. This has been verified through inspection of the spectrogram of this sensor across all shots, which shows this peak frequency before, during, and after test time. Moreover, the peak at 95 kHz does not shift between different shot conditions (Figure 4.17a) and Figure 4.19a)), whereas a flow-induced peak would be expected to vary with condition. Farther downstream in the separation bubble, at P3 ($x/L = 0.08$), the peak frequency shifts down to 116 kHz, consistent with the trend observed for H8-Re2, although at a higher overall frequency level. Figure 4.19 shows that, for the H14-Re3 case, the same trend remains with the peak frequency decreasing downstream from 170 kHz at P2 ($x/L = -0.48$) to 106 kHz at P3 ($x/L = 0.08$).

Computing the SPOD eigenspectrum of pixels within the separation bubble (Figure 4.20) reveals tonal features similar to those observed in the eigenspectrum above the separated shear layer (Figure 4.12). For H8-Re2, the low rank frequency band corresponds to 60–140 kHz, with a peak tone at 71 kHz. For the H8-Re3 condition,

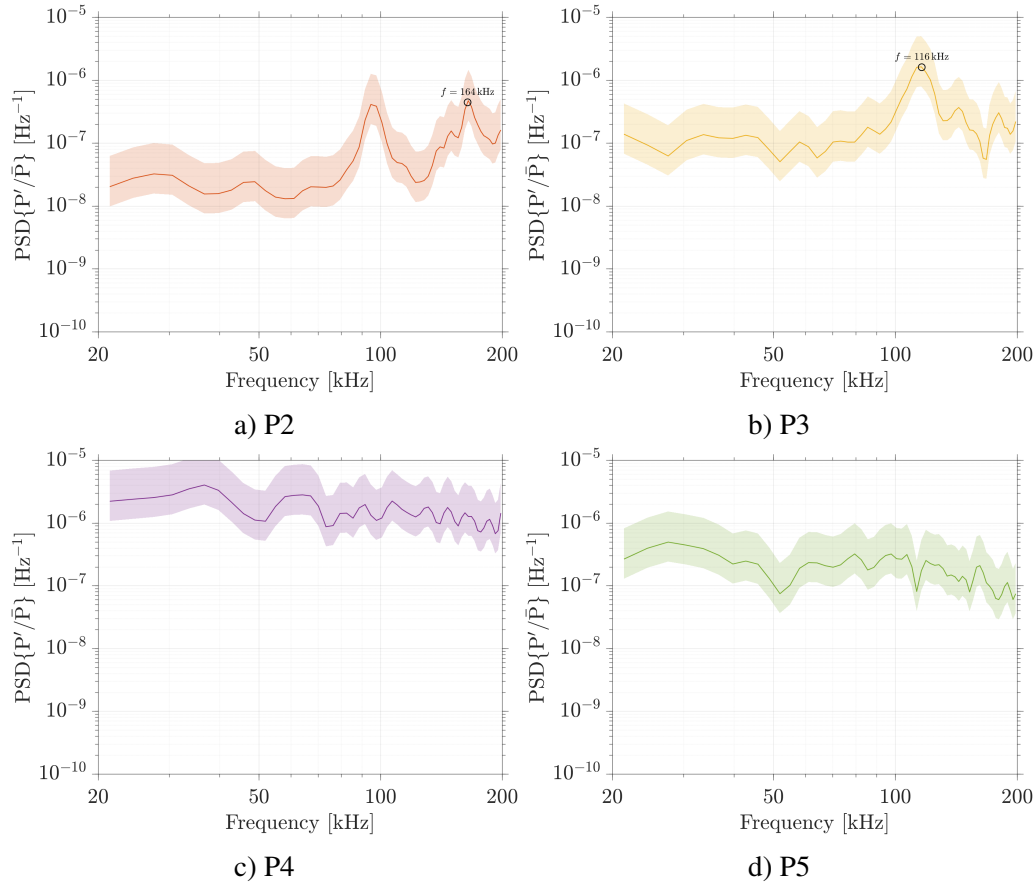


Figure 4.18: Surface pressure transducer PSDs for the H8-Re3 condition.

the frequency band is 109–174 kHz, with a peak modal energy at 123 kHz that is roughly half that of the H8-Re2 case. The H14-Re3 case shows an upward shift in the dominant frequency band to 92–167 kHz, with a peak at 109 kHz that is also roughly half the energy of the H8-Re2 case. Figure 4.20d) shows that the energy is concentrated in the leading mode, as is also found above the separated shear layer; therefore, only Mode 1 is examined further to evaluate coherent structures within the separation bubble.

Figure 4.21 plots the reconstructed SPOD modes at three frequencies corresponding to the peak instability frequencies measured by the surface mounted PCB sensors at P2 (116 kHz) and P3 (71 kHz), along with an intermediate frequency. The reconstructed mode reveals alternating lobes within the separation bubble. These coherent oscillatory structures convect downstream within the separation bubble when propagated in time and align with the wave-like density gradient structures observed in the schlieren imaging (Figure 4.16). Excellent agreement is observed

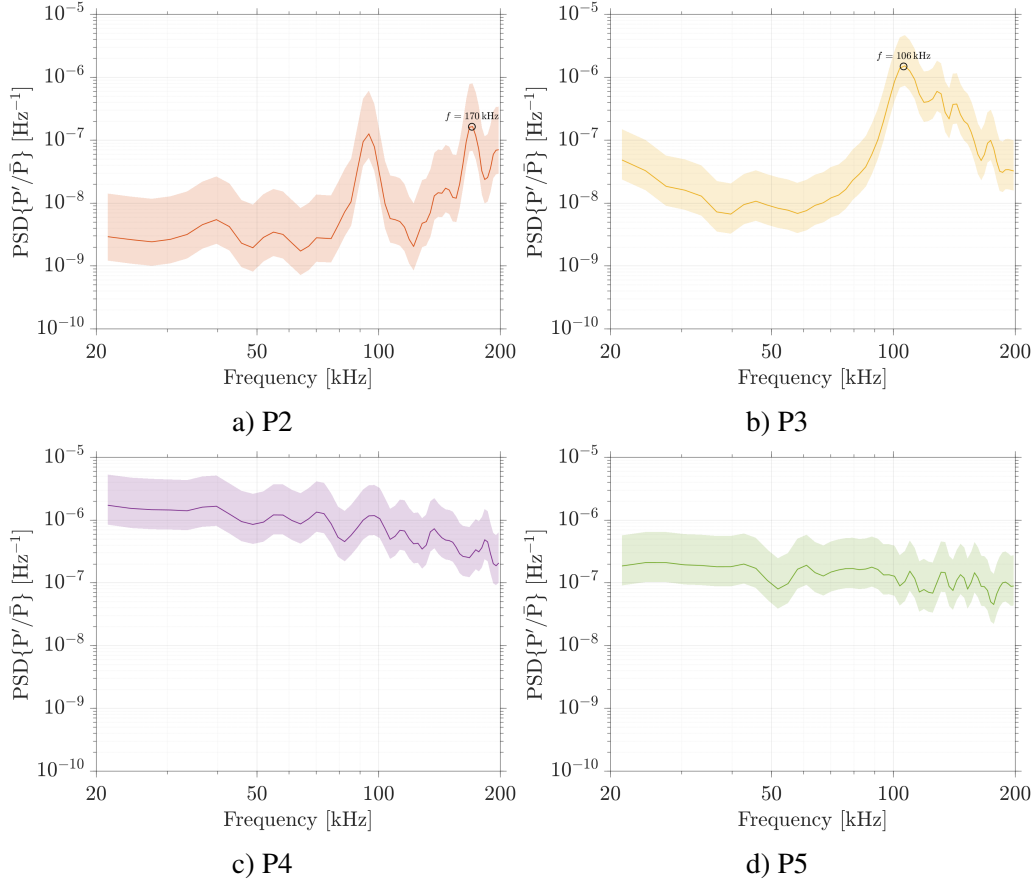


Figure 4.19: Surface pressure transducer PSDs for the H14-Re3 condition.

between the streamwise location high amplitude SPOD structures at a given reconstruction frequency and the location of the surface mounted PCB sensors that measure peak frequencies matching this reconstruction frequency. As the reconstruction frequency decreases, the location of the peak amplitude SPOD structure shifts downstream, consistent with the measurements taken above the separated shear layer.

The reconstructed modes for H8-Re3 (Figure 4.22) and H14-Re3 (Figure 4.23) exhibit the same two primary trends observed for H8-Re2. First, at a given frequency, the streamwise location of the highest amplitude coherent SPOD structure agrees closely with the location of the surface mounted PCB sensor that records a spectral peak at that same frequency. Second, as the reconstruction frequency decreases, the location of this peak amplitude structure shifts downstream. The overall lobe structure also remains similar to that of the H8-Re2 case. The main difference between these cases and H8-Re2 is the higher frequencies observed within the

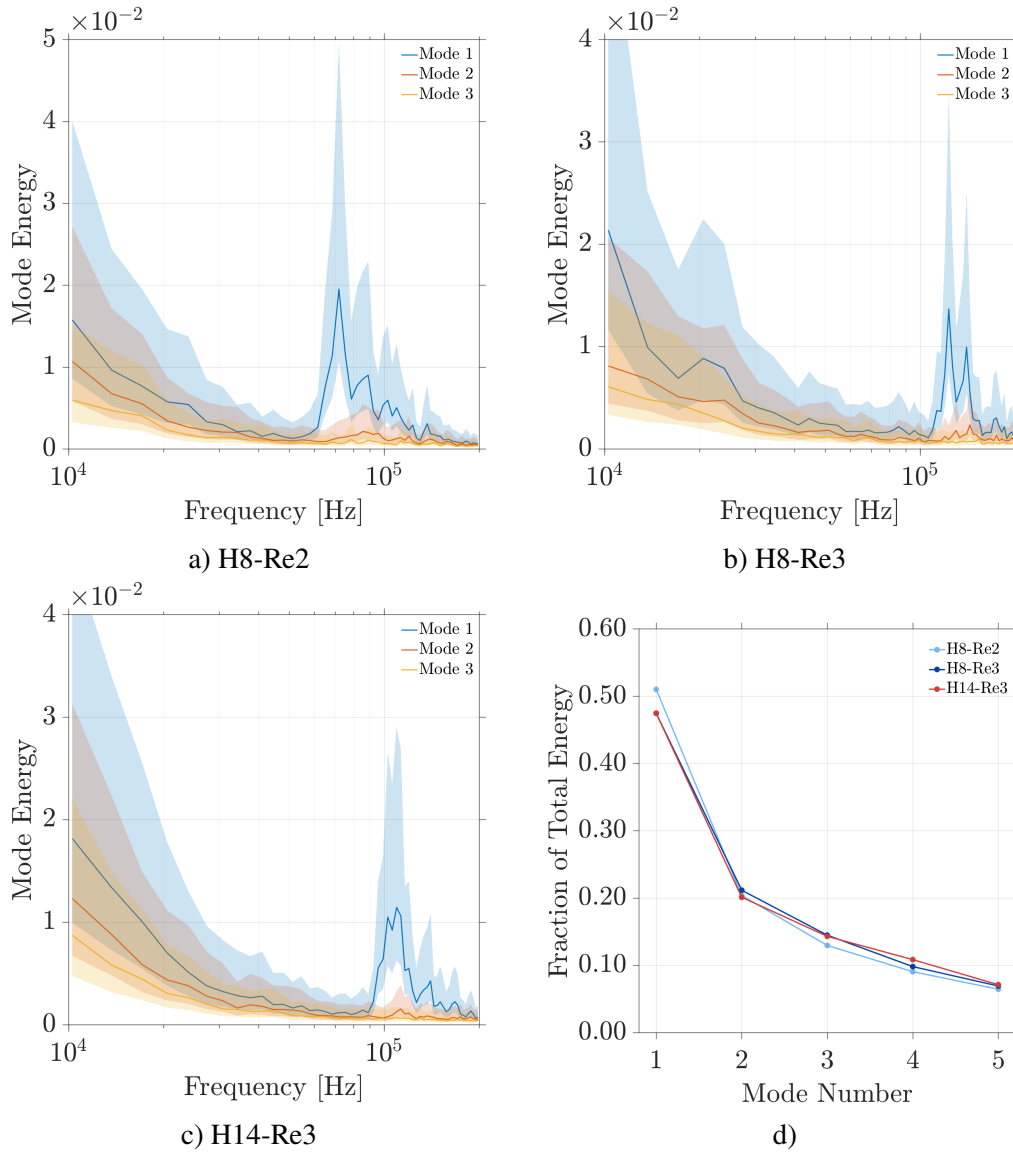


Figure 4.20: SPOD eigenspectrum in separation bubble for all shot conditions.

separation bubble, consistent with the behavior previously identified in the PCB sensor data.

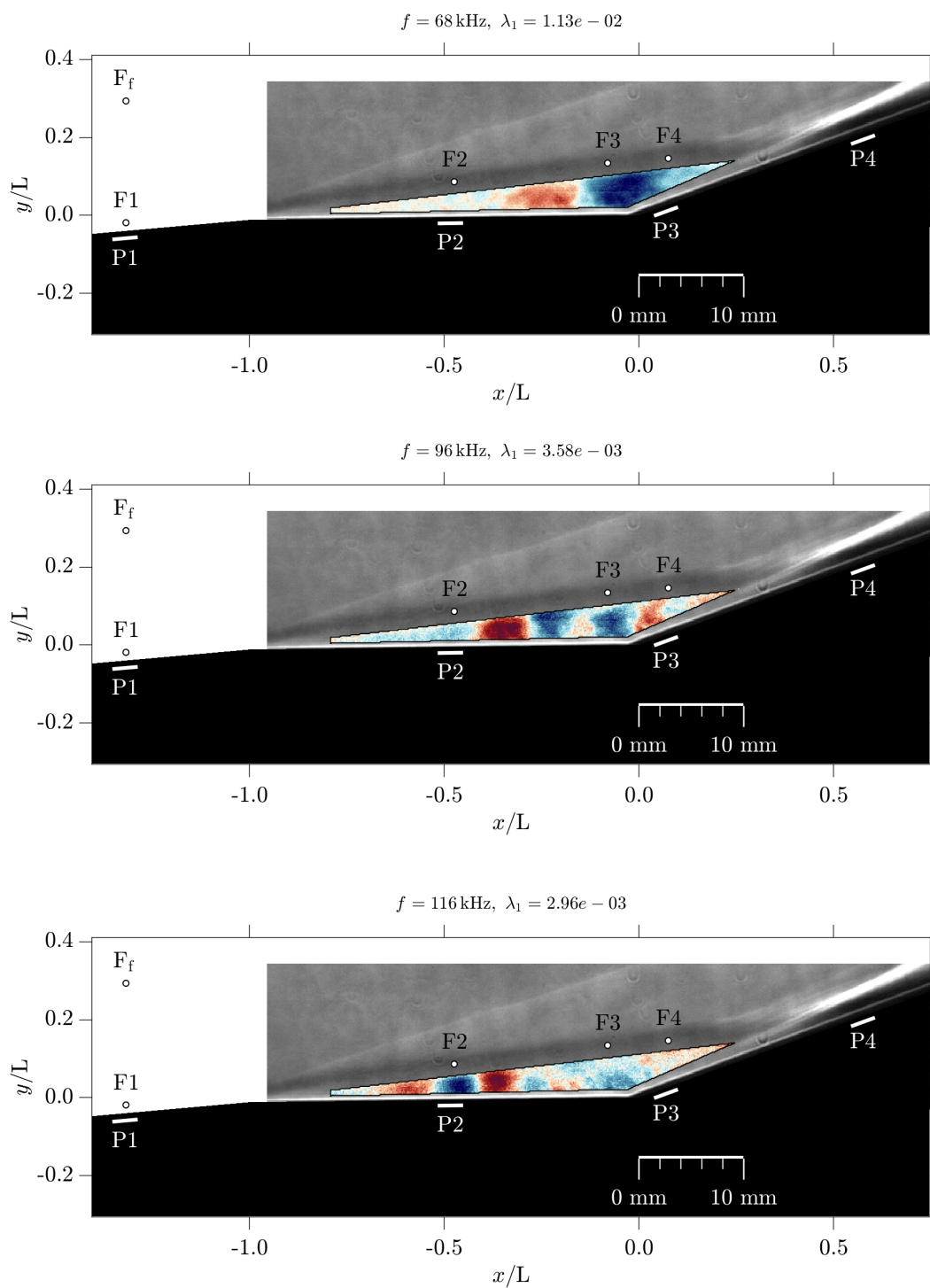


Figure 4.21: SPOD mode shapes of schlieren pixels in separation bubble for the H8-Re2 condition.

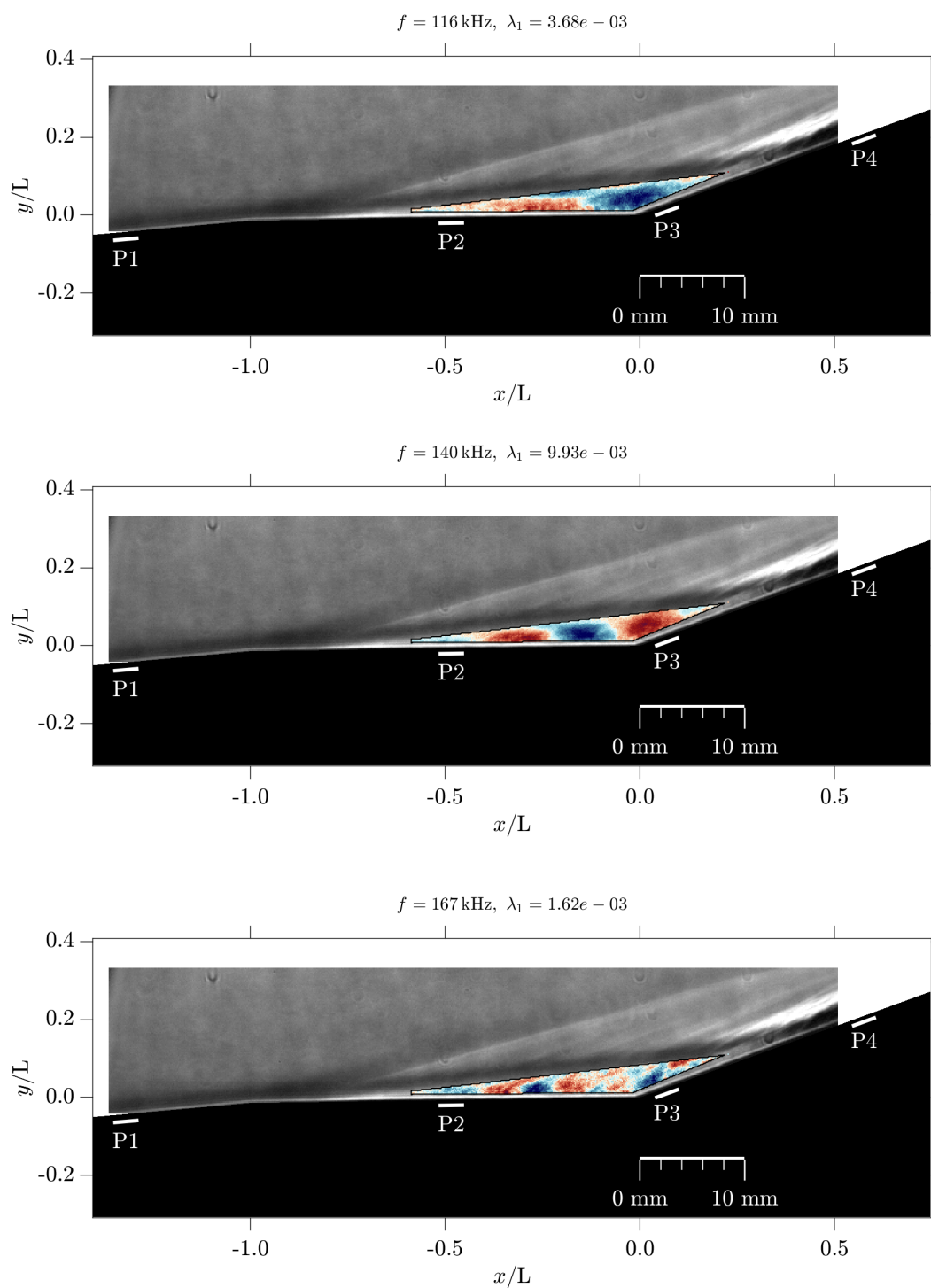


Figure 4.22: SPOD mode shapes of schlieren pixels in separation bubble for the H8-Re3 condition.

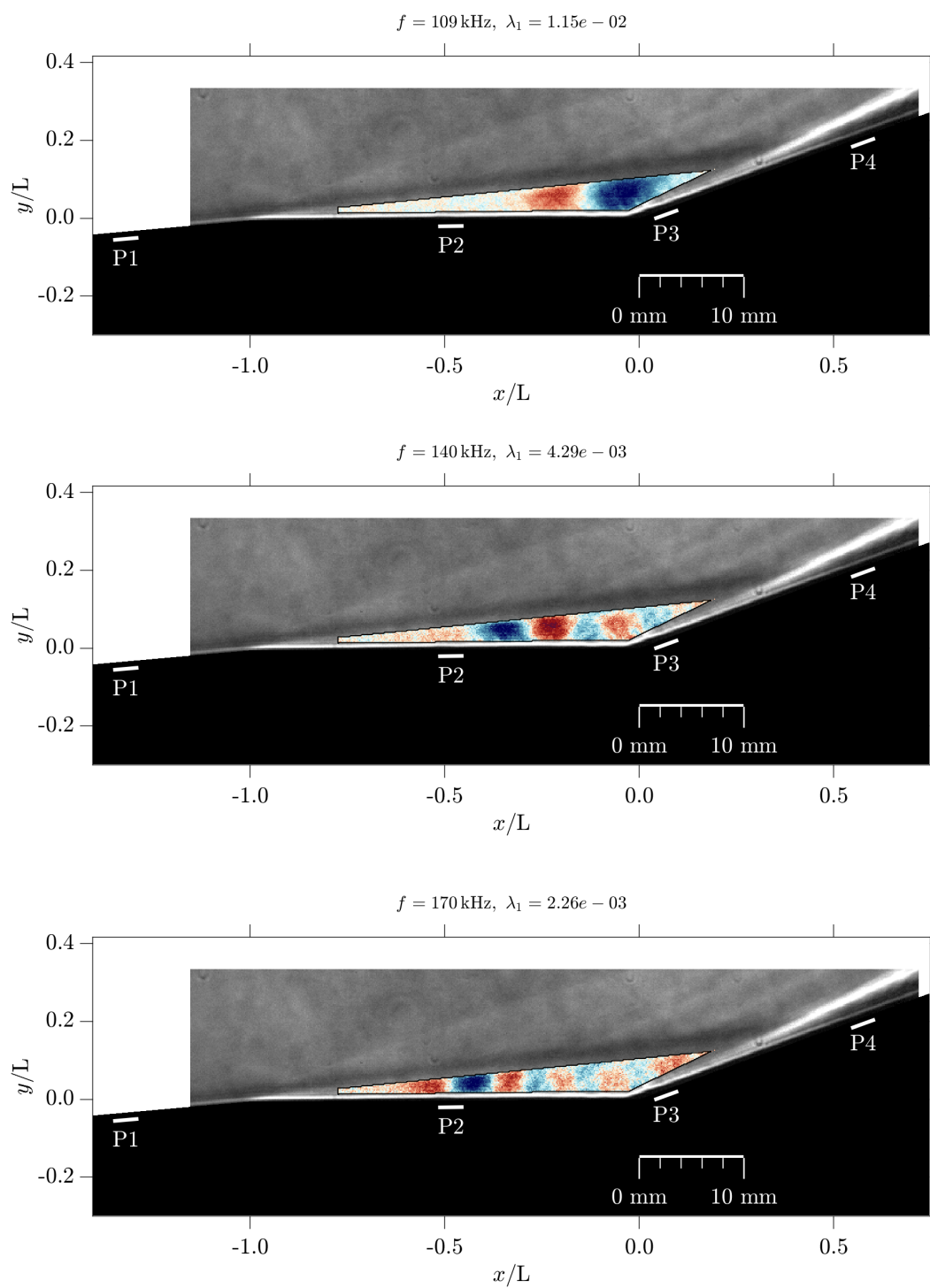


Figure 4.23: SPOD mode shapes of schlieren pixels in separation bubble for the H14-Re3 condition.

4.5 Convective Velocity Measurements

In Sections 4.3 and 4.4, the disturbances above and below the separated shear layer were discussed. Above the shear layer, Mach radiation in the form of shocklets was observed to convect downstream, along with wave-like density gradient structures within the separation bubble. This section examines the convective velocities of these disturbances and determines whether they are locally subsonic or supersonic.

4.5.1 Convective Velocity Measurement Methods

Multiple methods were used to extract the convective velocities of disturbances above and below the separated shear layer. In this work, these are referred to as the temporal, spatial, $f \times \lambda$, feature-tracking, and shock-angle methods. The temporal and spatial methods are described in detail in Appendix C, but in essence they treat the schlieren pixel intensity as a scalar signal that can be correlated in time and space.

The temporal method treats individual pixels as independent signals and correlates neighboring pixels in time resulting in a computed lag time between pixels (Butler and Laurence, 2022). This method could be applied both above and below the separated shear layer. Because each pixel is assessed individually in space, the convective speed can be computed as a function of streamwise location, x/L .

The spatial cross-correlation method (Laurence et al., 2014) determines the convective velocity by taking a row of pixels 1 mm above or below the outer edge of the separated shear layer and spatially shifting that row to compute the maximum spatial correlation between successive frames. This method was only found to be suitable above the separated shear layer, where the shocklets form discrete features that are easier to correlate. In contrast, the flow inside the separation bubble proved difficult to analyze because of recirculation features. Even above the separated shear layer, this method for the current data carries large uncertainty, as the distribution of binned velocities was broad (Figure C.1b)) with $\pm 1\sigma \approx 400 \text{ m s}^{-1}$.

The phase speed of the disturbances can also be estimated using the SPOD modes obtained from schlieren images above and below the shear layer. Above the shear layer, the wavelength of the coherent structures, such as those shown in Figure 4.13, is measured along the shear layer propagation axis for each low rank eigenspectrum frequency f . The convective velocity is then computed as

$$U_\phi = f \times \lambda \quad (4.1)$$

assuming that the convective propagation speed of the disturbance is equal to the measured phase speed, $U_c = U_\phi$. The process is repeated for coherent structures within the separation bubble (Figure 4.21), where the wavelength is estimated using the centroids of the SPOD mode lobes.

The feature tracking method relies on directly tracking Mach radiation features (shocklets) above the separated shear layer. This was performed using image processing and feature grouping algorithms. First, the image was masked above the separated shear layer to isolate the portion of the field in which shocklets were observed. A pixel-intensity threshold was then applied to identify the shocklet structures, followed by Gaussian blurring to reduce image noise. Canny edge detection was applied to the processed images, and a Hough transform was used to fit straight lines to the detected shocklets. For each detected shocklet in each frame, the intercept along the separated shear layer and the angle relative to the shear layer were recorded.

Because the three-dimensionality of the flow can cause the tracking algorithm to jump between nearby shocklets, an iterative random sample consensus RANSAC() algorithm was used to group detections belonging to the same physical shocklet across successive frames as it convected downstream. Within each consistent shocklet track, the convective velocity was then determined from the temporal evolution of the shocklet intercept. For the H8-Re3 case, the transitional separated shear layer produced a higher density of shocklets above the separated shear layer, which made tracking challenging. This case has therefore been excluded from the dataset. Direct feature tracking of the wave-like density gradient structures also proved difficult because of the recirculation features present in the separation bubble and has likewise been excluded.

Finally, the shock-angle method uses the Mach angles, μ_c , computed during the feature tracking analysis to determine the convective Mach number, M_c . Using

$$M_c = \frac{U_{edge} - U_c}{a_{edge}},$$

with U_{edge} and a_{edge} taken from the boundary layer edge conditions processed by the separation shock, the convective velocity of the disturbances, U_c , can then be solved.

4.5.2 Disturbance Convective Velocity Measurements

For the H8-Re2 condition, the measured convective velocities above the separated shear layer and within the separation bubble are compared in Figure 4.24. The average convective velocity measurements above the separated shear layer range from 687–984 m s^{-1} across the different methods, compared with 906–936 m s^{-1} for disturbances within the separation bubble. The scatter between the measurement techniques, especially for the feature tracking and $f \times \lambda$ methods relative to the other techniques, is attributed to three-dimensional flow effects. The three-dimensional unsteadiness of the shear layer may produce a spanwise varying shock front that artificially broaden the measured shocklets, leading to errors in the wavelength extracted from the SPOD reconstruction and incorrect identification of shocklets by the feature tracking algorithm. Despite these limitations, the measured convective velocities below the separated shear layer show reasonable agreement with the velocity range reported above the separated shear layer.

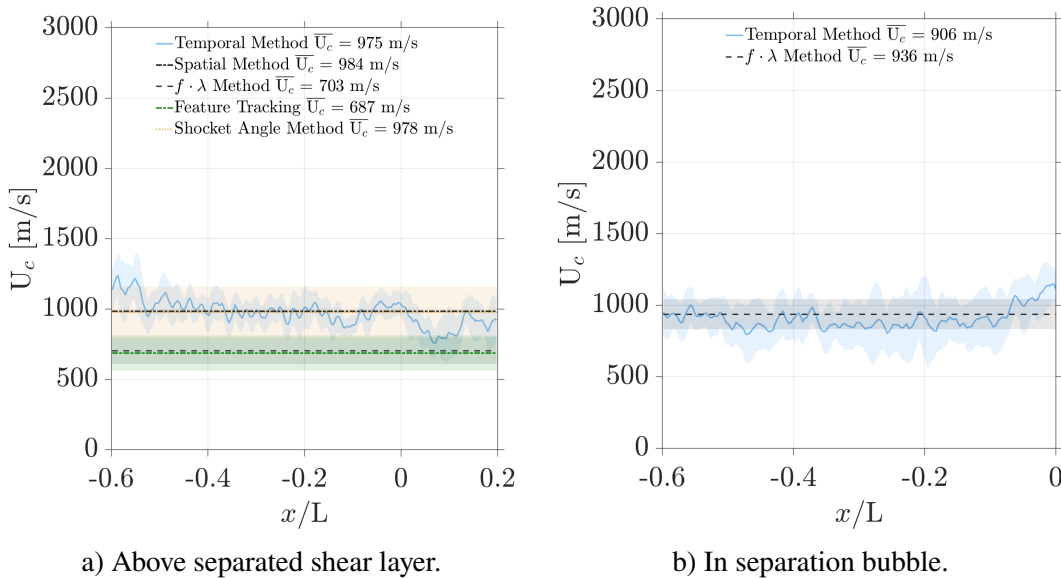


Figure 4.24: Convective velocity measurements for the H8-Re2 condition.

Figure 4.25 shows the convective velocities for the H8-Re3 case. Convective velocities measured above the separated shear layer range from 910–1334 m s^{-1} , while velocities within the separation bubble range from 836–1433 m s^{-1} . The transitional boundary layer of the H8-Re3 condition produced the largest reported variation in convective velocity of the three conditions tested. The high density of shocklets above the separated shear layer made feature tracking untenable, which also carried over into inaccuracies in the reported shocklet angles, causing the shock-angle method to stand out as an outlier. Inside the separation bubble, the coherent SPOD

structures were weaker, with peak mode energies roughly half of those found in the H8-Re2 case (Figure 4.20), which is believed to contribute to the overprediction of the $f \times \lambda$ method within the separation bubble. Although precise velocity measurements at this condition remain challenging, the disturbances appear to fall roughly within the velocity range reported for the H8-Re2 case and remain broadly consistent above and below the separated shear layer.

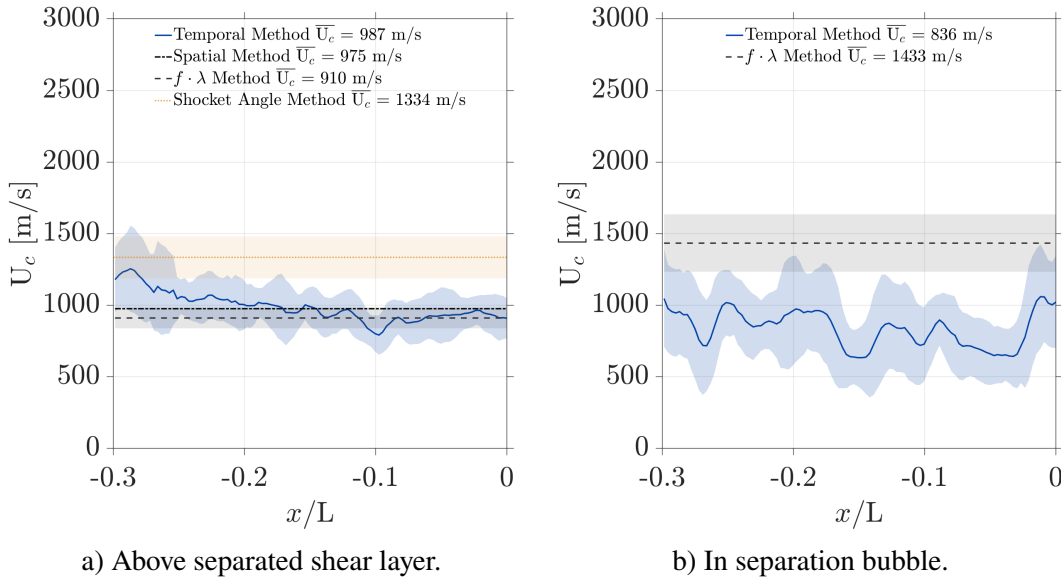


Figure 4.25: Convective velocity measurements for the H8-Re3 condition.

The convective velocities for the higher-stagnation-enthalpy H14-Re3 case are shown in Figure 4.26. The reported convective velocities above the separated shear layer range from $842\text{--}1235\text{ m s}^{-1}$, while the measurements within the separation bubble range from $1301\text{--}1413\text{ m s}^{-1}$. As in the H8-Re2 case, the outlier measurements above the separated shear layer were again associated with the feature tracking and $f \times \lambda$ methods, for the reasons discussed previously. Although significant scatter remains in the reported velocities, a general trend in the measurement techniques consistently report convective velocities that are at least 200 m s^{-1} higher in the H14-Re3 condition than in the H8-Re2 condition is noted.

For convenience, the convective velocities reported above are summarized in Tables 4.2 and 4.1. The $\pm 1\sigma$ uncertainty for each measurement is also included. Although the uncertainty and spread in the mean convective velocities may appear large, it is worth noting that, for the camera settings used in this work, the frame interval of $\Delta T = 1.15\text{ }\mu\text{s}$ and pixel spacing of $\Delta x \approx 0.12\text{ mm}$ imply that a one-pixel tracking error changes the reported convective velocity by approximately 100 m s^{-1} .

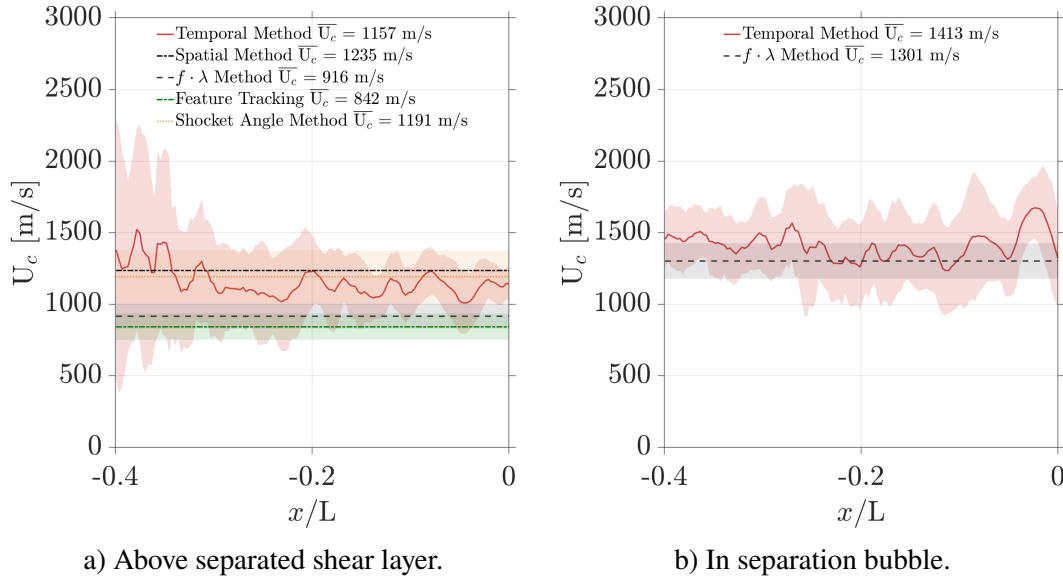


Figure 4.26: Convective velocity measurements for the H14-Re3 condition.

Differences between the feature tracking and $f \times \lambda$ methods, relative to the other measurement techniques, are attributed in part to the three-dimensional flow effects discussed above. Precise measurement of convective velocities of this magnitude is therefore challenging in the current experiment. However, as discussed in the following section, the present measurements are sufficient to determine whether these disturbances are locally supersonic or subsonic.

Table 4.1: Summary of convective velocity measurements above separated shear layer using different measurement techniques.

Case	Temporal Method [m/s]	Spatial Method [m/s]	$f \times \lambda$ Method [m/s]	Feature Track. Method [m/s]	Shock Angle Method [m/s]
H8Re2	975 ± 91	984 ± 348	703 ± 95	687 ± 123	978 ± 183
H8Re3	987 ± 99	976 ± 481	910 ± 73	-	1334 ± 142
H14Re3	1157 ± 105	1235 ± 474	916 ± 88	842 ± 92	1191 ± 183

4.5.3 Local Disturbance Propagation

Applying stability analysis to compressible mixing layers, Jackson and Grosch, 1989 showed that above a critical Mach number the instability field can split into fast and slow branches. Within that framework, the measured convective velocities can be used to assess whether the observed disturbances are locally subsonic or supersonic relative to the fast and slow streams of the shear layer. From Eq. 1.1,

Table 4.2: Summary of convective velocity estimates in separation bubble using different measurement techniques.

Case	Temporal Method [m/s]	$f \times \lambda$ Method [m/s]
H8Re2	906 ± 73	936 ± 105
H8Re3	836 ± 123	1433 ± 199
H14Re3	1413 ± 93	1302 ± 124

$$M_{c1} = \frac{U_1 - U_c}{a_1}, \quad M_{c2} = \frac{U_c - U_2}{a_2}.$$

Consider first the disturbances convecting relative to the fast stream of the shear layer where U_1 as the edge velocity of the shear layer (U_{edge}) and a_1 is the local sound speed above the separated shear layer (a_{edge}). For the H8-Re2 and H8-Re3 test conditions, $U_1 = U_{edge} \approx 3400 \text{ m s}^{-1}$ and $a_1 \approx 660 \text{ m s}^{-1}$. For the disturbances to be locally supersonic above the shear layer, $U_1 - U_c > a_1$. Using the convective velocities measured in the previous section, $U_c \approx 687$ to 1334 m s^{-1} , all reported values lie well within the locally supersonic regime, giving $M_{c1} \approx 3.13$ to 4.11 . The same conclusion holds for the H14-Re3 case, where $U_{edge} \approx 4300 \text{ m s}^{-1}$, $a_1 \approx 920 \text{ m s}^{-1}$, and $U_c \approx 842$ to 1235 m s^{-1} , yielding $M_{c1} \approx 3.33$ to 3.76 .

Determination of the local disturbance Mach number below the shear layer, M_{c2} , is more uncertain because of uncertainties in both the local sound speed a_2 and the measured convective velocities. Using the recovery sound speed relation for cavity flows given by Heller et al., 1971 (Eq. 4.3) as an estimate, with $r = 0$ to 1 , gives $a_2 \approx 660$ to 1500 m s^{-1} for the H8-Re2 and H8-Re3 conditions, and $a_2 \approx 920$ to 1900 m s^{-1} for H14-Re3. Assuming the slow stream within the separation bubble is nearly stationary, $U_2 \approx 0 \text{ m s}^{-1}$, whether the disturbance is locally subsonic or supersonic below the shear layer depends on the ratio of U_c to a_2 . For the H8-Re2 and H8-Re3 cases, $U_c \approx 836$ to 1433 m s^{-1} overlaps substantially with $a_2 \approx 660$ to 1500 m s^{-1} , making a definitive classification of M_{c2} impractical given the uncertainty in both the measured convective velocity and the assumed recovery factor. The H14-Re3 condition shows the same ambiguity, with $U_c \approx 1302$ to 1413 m s^{-1} overlapping strongly with $a_2 \approx 920$ to 1900 m s^{-1} . Therefore, the only robust conclusion is that the disturbances are locally supersonic with respect to the fast stream above the shear layer.

4.6 Scaling of Separated Shear layer Instability Frequencies

In Sections 4.3 and 4.4, a shear layer instability is reported whose frequency decreases with downstream distance. At the same streamwise locations, the measured instability frequencies vary significantly among the H8-Re2, H8-Re3, and H14-Re3 test conditions. This section investigates three possible scalings for the separated shear layer instability frequencies: one based on the shear layer thickness, one based on the separated shear layer length, and one based on the wall-normal height of the shear layer.

4.6.1 Cavity Flow Theory

The appearance of similar dominant frequencies in both the separated shear layer and the surface pressure measurements at comparable streamwise locations suggests that these regions may be dynamically coupled (Section 4.7.2). First, consider the separation bubble as an open cavity flow analogue, in which the separated shear layer bounds a recirculating region and may support an aeroacoustic feedback loop. This interpretation follows the cavity flow description of Rossiter, 1964, who identified discrete tonal oscillations in rectangular cavities as the result of a self-sustained aeroacoustic feedback loop. In Rossiter's model, disturbances generated in the shear layer convect downstream and interact with the cavity trailing edge, producing acoustic waves that propagate upstream to the leading edge. These acoustic waves then excite new shear layer disturbances, thereby closing the feedback loop. The corresponding semi-empirical relation may be written as

$$\text{St}_L = \frac{f L}{U_\infty} = \frac{m - \phi}{\frac{1}{\kappa} + M_\infty} \quad (4.2)$$

where L is the cavity length, m is the mode number, κ is the ratio of the disturbance convection speed to the freestream velocity, and ϕ is an empirical phase delay. In this formulation, the instability frequency is nondimensionalized by the streamwise cavity length because the feedback period is governed by the time required for hydrodynamic disturbances to convect from the leading edge to the trailing edge and for acoustic disturbances to propagate upstream Rossiter, 1964.

Heller et al., 1971 extended this scaling to higher Mach numbers by recognizing that the relevant acoustic speed within the recirculating region is better represented by a recovery based sound speed compared to the freestream static sound speed used

by Rossiter. Using the cavity sound speed

$$a_c = a_\infty \sqrt{1 + r \frac{\gamma - 1}{2} M_\infty^2}, \quad (4.3)$$

where r is a recovery factor typically taken as $\sqrt{\text{Pr}}$ (Nicoll, 1963), the modified Rossiter scaling becomes

$$\text{St}_L = \frac{f L}{U_\infty} = \frac{m - \phi}{\frac{1}{\kappa} + \frac{M_\infty}{\sqrt{1 + r \frac{\gamma - 1}{2} M_\infty^2}}} \quad (4.4)$$

Suppression of the Rossiter feedback mechanism was also explored by Heller and Bliss, 1975. They argued that angling the aft wall backward can stabilize the flow by allowing the shear layer to impinge at a more favorable angle while remaining comparatively uncurved over the cavity length. This reduces the unsteadiness associated with shear layer curvature and trailing edge impingement. Experimental evidence for this idea was later reported by Vikramaditya and Kurian, 2009a,b, who studied rectangular cavities with aft wall ramp angles from 15 degrees to 90 degrees in 15 degree increments at $M \approx 1.6$. Their results showed that ramp angles less than 45 degrees reduced oscillation amplitudes, while cross-correlation analysis indicated that the upstream traveling acoustic waves evident for steeper aft wall angles were no longer discernible for wall angles below 45 degrees.

4.6.2 Summary of Current Instability Frequency Measurements

In Section 4.3, peak instability frequencies in the shear layer were reported using FLDI. In Section 4.4, peak instability frequencies inside the separation bubble were reported using surface mounted PCB sensors. Both measurements reveal a downward shift in peak frequency and an increase in maximum amplitude as the measurement location is moved more downstream. This trend is consistent with previous findings for the cone-slice-ramp geometry by Pandey et al., 2022b, who reported that the shear layer instability frequency decreased from 50 to 10 kHz moving downstream. An approximately order-of-magnitude increase in the maximum amplitude of the surface pressure PSD over the same measurement locations was also observed in the experiments by Pandey.

To consistently characterize the peak frequency and maximum amplitude of the measured instabilities in the present work, a log-normal distribution was fitted to the PSD peaks within the identified interval of elevated frequency content for each

sensor. A Shapiro-Wilk test (Royston, 1992; Shapiro and Wilk, 1965) confirmed that the PSD peaks were consistent with a log-normal distribution, as none of the tests rejected the null hypothesis (all p -values > 0.05). This indicates that the log-transformed data were consistent with a normally distributed population. The peak frequency and maximum amplitude of the log-normal fits are reported in Figures 4.27 and 4.28, respectively. The error bars on the reported peak frequency correspond to $\pm 1\sigma$ from the fitted log-normal distribution, while the uncertainty in maximum amplitude is estimated from chi-square statistics across all shots run at each condition.

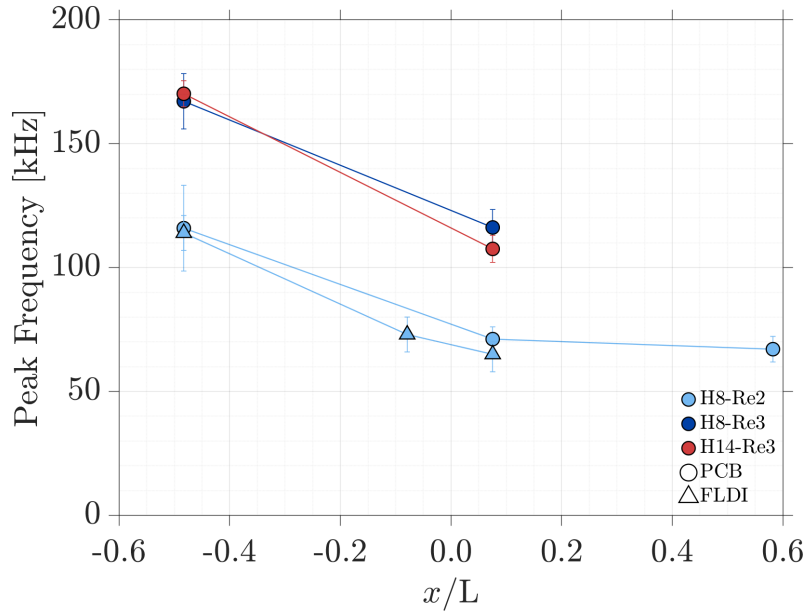


Figure 4.27: Peak observed instability frequency as a function of streamwise position x/L for both FLDI and PCB measurements for all shot conditions.

In Figure 4.27, the downstream shift in peak instability frequency is clearly visible for all three test conditions. For the H8-Re2 case, where both FLDI and PCB data are available, excellent agreement is observed between the peak frequencies reported by the two measurement techniques. At $x/L = -0.48$ and $x/L = 0.08$, the measured peak frequencies are 114 kHz versus 116 kHz and 65 kHz versus 71 kHz, respectively. As discussed in Section 4.4, the H8-Re2 case was also the only condition for which a peak frequency was detected on the ramp surface downstream of reattachment at P4 ($x/L = 0.58$). At this location, the peak instability frequency remains approximately constant at 67 kHz, compared with the upstream value of 71 kHz at $x/L = 0.08$.

For the H8-Re3 case, the peak frequencies are higher at all streamwise positions

compared with the H8-Re2 condition, while the trend of decreasing frequency with downstream measurement location remains consistent. Although the stagnation enthalpies of the H8-Re2 and H8-Re3 conditions are comparable, the length of the separation region, L_{sep} , is reduced by 30%, resulting in a reduced shear layer height above the model surface (Table 3.2).

Comparing the H14-Re3 case with the H8-Re2 case, higher peak frequencies are again observed, while the same downstream decrease in frequency is maintained. The length of the separation region and the locations of separation and reattachment are comparable between the H14-Re3 and H8-Re2 cases, with only a 10% reduction in L_{sep} for the H14-Re3 condition. The main difference between these two test conditions is the higher stagnation enthalpy of the H14-Re3 case, $h_0 = 14 \text{ MJ kg}^{-1}$, compared with $h_0 = 8 \text{ MJ kg}^{-1}$ for the H8-Re2 case.

The maximum instability amplitude at each streamwise location is plotted in Figure 4.28 for all shot conditions using both FLDI and PCB measurements. The PCB and FLDI data report fluctuations in different units, so two separate vertical axes are used. Therefore, the relative vertical positions of the FLDI and PCB data are arbitrary, but trends within each measurement type can still be interpreted. The maximum amplitudes of the instability frequency peaks increase by approximately one order of magnitude from the most upstream measurement location, $x/L = -0.48$, to the most downstream location inside the separation bubble, $x/L = 0.08$. This downstream increase in maximum amplitude is consistent with cone-slice-ramp experiments (Pandey et al., 2022b) and cone-cylinder-flare experiments (Butler and Laurence, 2022), both of which observed an approximately order-of-magnitude increase in shear layer instability amplitude across the separation bubble.

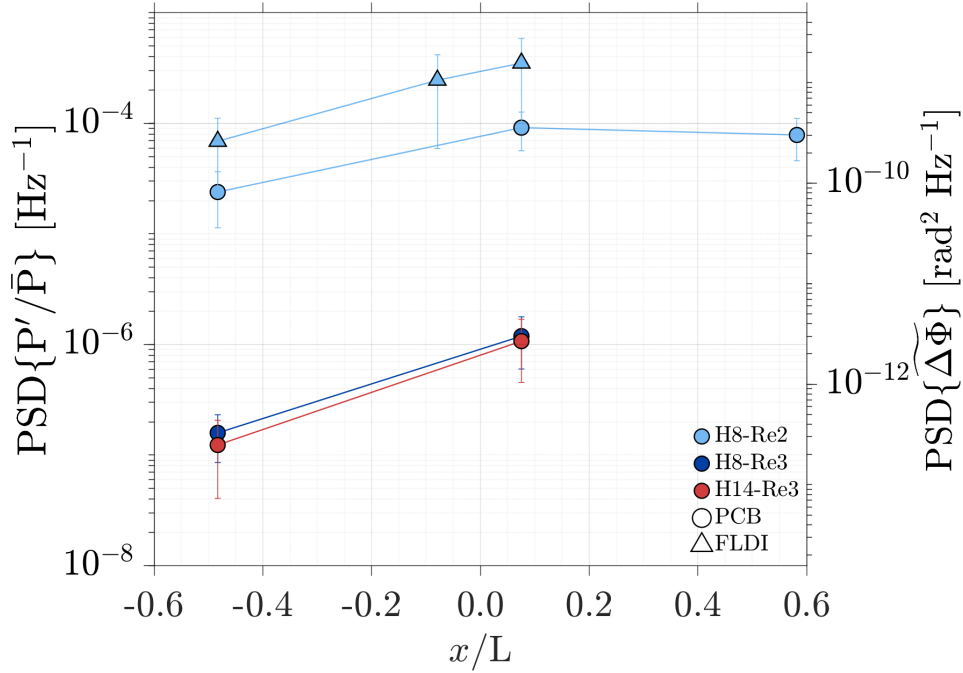


Figure 4.28: Maximum instability amplitude as a function of streamwise position x/L for both FLDI and PCB measurements for all shot conditions.

4.6.3 Strouhal Number Scaling

Scalings based on different characteristic length scales are compared to help identify the mechanisms that may drive the shear layer instability observed in the present experiments. The first scaling assumes that the instability is driven by the fundamental Kelvin-Helmholtz frequency described by a shear layer Strouhal scaling,

$$St_\delta = \frac{f \delta}{U_c} \quad (4.5)$$

where δ is a representative separated shear layer thickness measured from the mean schlieren frame, and U_c is the convection velocity of the disturbance structures measured in Section 4.5. In Figure 4.29, St_δ is plotted as a function of the streamwise measurement location, x/L . Across the three test conditions and all streamwise locations, the resulting Strouhal numbers range from $St_\delta = 0.09$ to 0.18. The H8-Re3 condition exhibits particularly poor collapse, which may be due to uncertainty in estimating the separated shear layer thickness for a transitional shear layer. In either case, the computed Strouhal numbers are low, suggesting that the separated shear layer thickness is not the appropriate length scale for describing the dominant instability frequency.

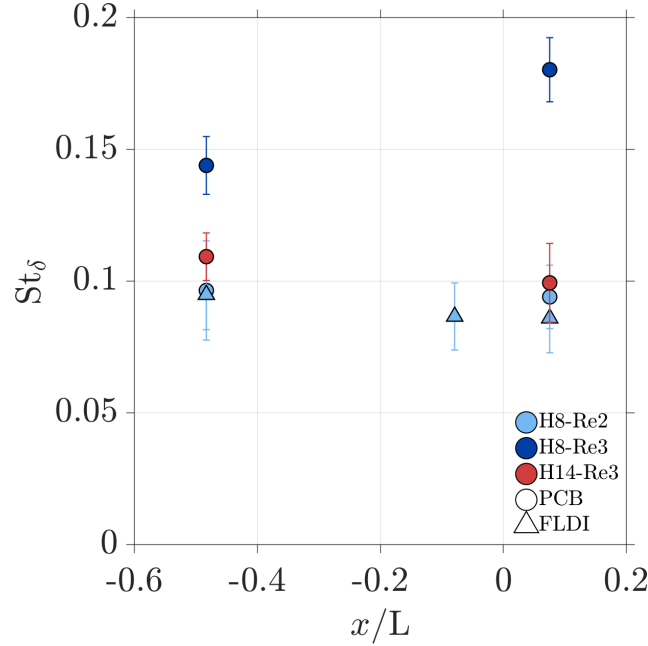


Figure 4.29: Strouhal number with thickness of separated shear layer (δ) as characteristic length vs streamwise position x/L

The next scaling investigated assumes that the instability is driven by a Rossiter-type aeroacoustic feedback mechanism, in which downstream convecting disturbances interact with the aft wall and generate acoustic waves that propagate upstream to close the feedback loop. The Strouhal number for a Rossiter-type feedback mechanism can be expressed as

$$St_L = \frac{fL}{U_\infty} \quad (4.6)$$

where L is taken as the separated shear layer length L_{SL} and U_∞ is equal to the edge velocity above the separated shear layer U_{edge} . In Figure 4.30, the St_L is plotted against the streamwise x/L location of the measurements. Upstream in the separation bubble, a collapse of all measurements at $x/L = -0.48$ to Strouhal numbers $St_L = 1.75$ to 1.85 is observed. However, the Strouhal number is not constant farther downstream in the separation bubble, where values of $St_L = 1.0$ to 1.24 are reported. These streamwise variations in St_L suggest that L_{SL} is not the relevant characteristic length scale for the shear layer instability process observed here.

The other logical feedback mechanism to consider is one in which disturbances from the separated shear layer acoustically communicate with the model surface normal to the shear layer propagation direction, rather than along the streamwise

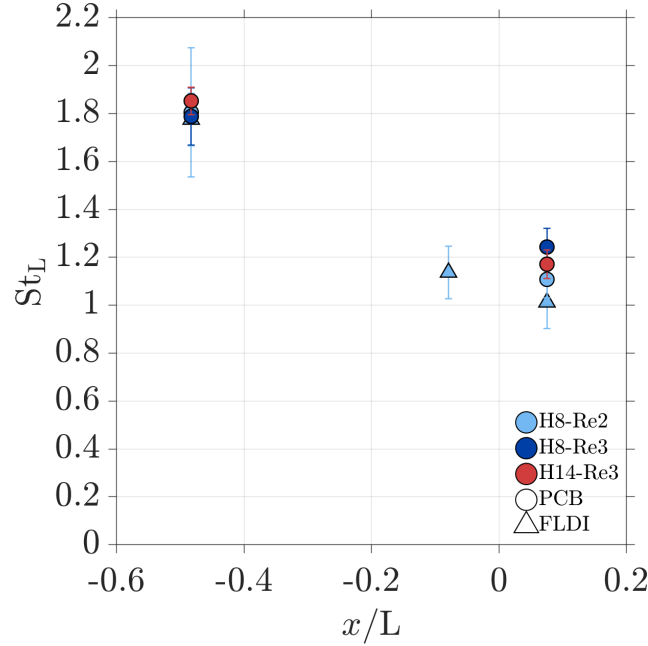


Figure 4.30: Strouhal number with length of separated shear layer (L_{SL}) as characteristic length vs streamwise position x/L

propagation direction. If this is the dominant mechanism, Yu, 2024 suggests that the shear layer instability frequency is expected to scale with the height of the separated shear layer above the wall ($H(x)$), such that

$$f = \frac{a}{2H(x)} \quad (4.7)$$

where a is the sound speed in the separation bubble. The Strouhal number for a wall normal acoustic feedback mechanism can then be expressed as

$$St_H = \frac{f 2H(x)}{a_c} \quad (4.8)$$

where $H(x)$ is taken as the height of the separated shear layer centerline above the model surface in the y -axis at a given streamwise location. The sound speed in the cavity is approximated using Eq. 4.3 with $r = \sqrt{Pr}$, resulting in $a_c \approx 1450 \text{ m s}^{-1}$ for the H8-Re2 and H8-Re3 cases and $a_c \approx 1810 \text{ m s}^{-1}$ for the H14-Re3 case. While the assumed recovery factor may not be correct for the current geometry, it should not affect the collapse of the scaling. Collapse to an approximately constant Strouhal number is observed at all streamwise locations for all three shot conditions, with $St_H = 0.45$ to 0.58 . Yu similarly reported $St_H = 0.42$ to 0.54 for the 370–450 kHz shear layer instabilities measured at various streamwise locations (Yu, 2024),

although direct comparisons between the two experiments remain uncertain due to the assumed recovery factor in the current work. This Strouhal number scaling is expected to break down downstream of the base of the ramp, where the wall height $H(x)$ decreases rapidly without a corresponding increase in measured frequency, as observed for the P4 sensor in the H8-Re2 case (Figure 4.17c)). These findings suggest that, upstream of the compression ramp, the relevant length scale for scaling the shear layer instability frequency is the height of the separated shear layer above the model surface. Downstream of this region, another unknown mechanism appears to dominate.

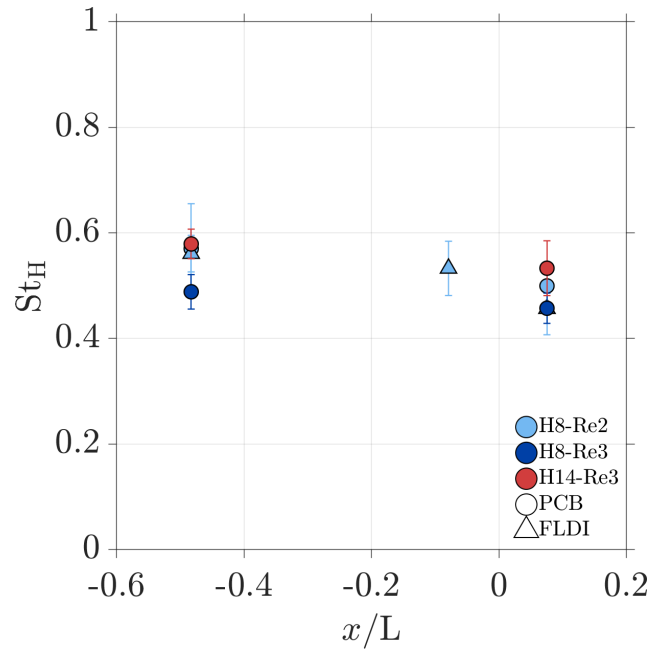


Figure 4.31: Strouhal number with height of the separated shear layer above the wall as characteristic length ($H(x)$) vs streamwise position x/L

4.7 SBLI Feature Coupling

In this section, two forms of coupling within the SBLI are examined. First, the relationship between the wave-like density gradient structures inside the separation bubble and the Mach radiation above the separated shear layer is investigated to determine whether the motions below and above the shear layer are dynamically linked. Second, the correspondence between on-surface pressure fluctuations and off-surface density fluctuations measured with FLDI is examined to assess whether unsteadiness in the separated shear layer communicates with the wall.

4.7.1 Coupling of Disturbances Above and Below Separated Shear Layer

To determine whether the structures inside the separation bubble lag or lead the formation of shocklets above the separated shear layer, schlieren-based PSD visualizations of the entire SBLI region are used. Here, the normalized pixel intensity of each schlieren pixel is treated as a discrete time signal, and its PSD is computed. At a given frequency, PSD amplitudes above a specified threshold are plotted, highlighting the spatial distribution of energy content at that frequency across the entire schlieren frame.

In Figure 4.32, schlieren pixel-intensity PSD contour maps are presented at the peak frequencies recorded by the P2 and P3 pressure sensors, 71 kHz and 116 kHz, respectively, as well as at an intermediate frequency of 96 kHz. Energy content at these frequencies appears both inside the separation bubble and above the separated shear layer at similar streamwise locations. For all three frequencies plotted, however, the energy content inside the separation bubble appears farther upstream than the corresponding energy content above the shear layer. This suggests that the wave-like density gradient structures inside the separation bubble lead the formation of shocklets above the separated shear layer.

This trend, in which the pixel intensity energy is located farther upstream inside the separation bubble than above the separated shear layer, is also observed for the H8-Re3 and H14-Re3 conditions, shown in Figures 4.33 and 4.34, respectively. The upstream shift of the high energy region with increasing frequency, observed for all three conditions, is consistent with the trends presented in Section 4.6.2.

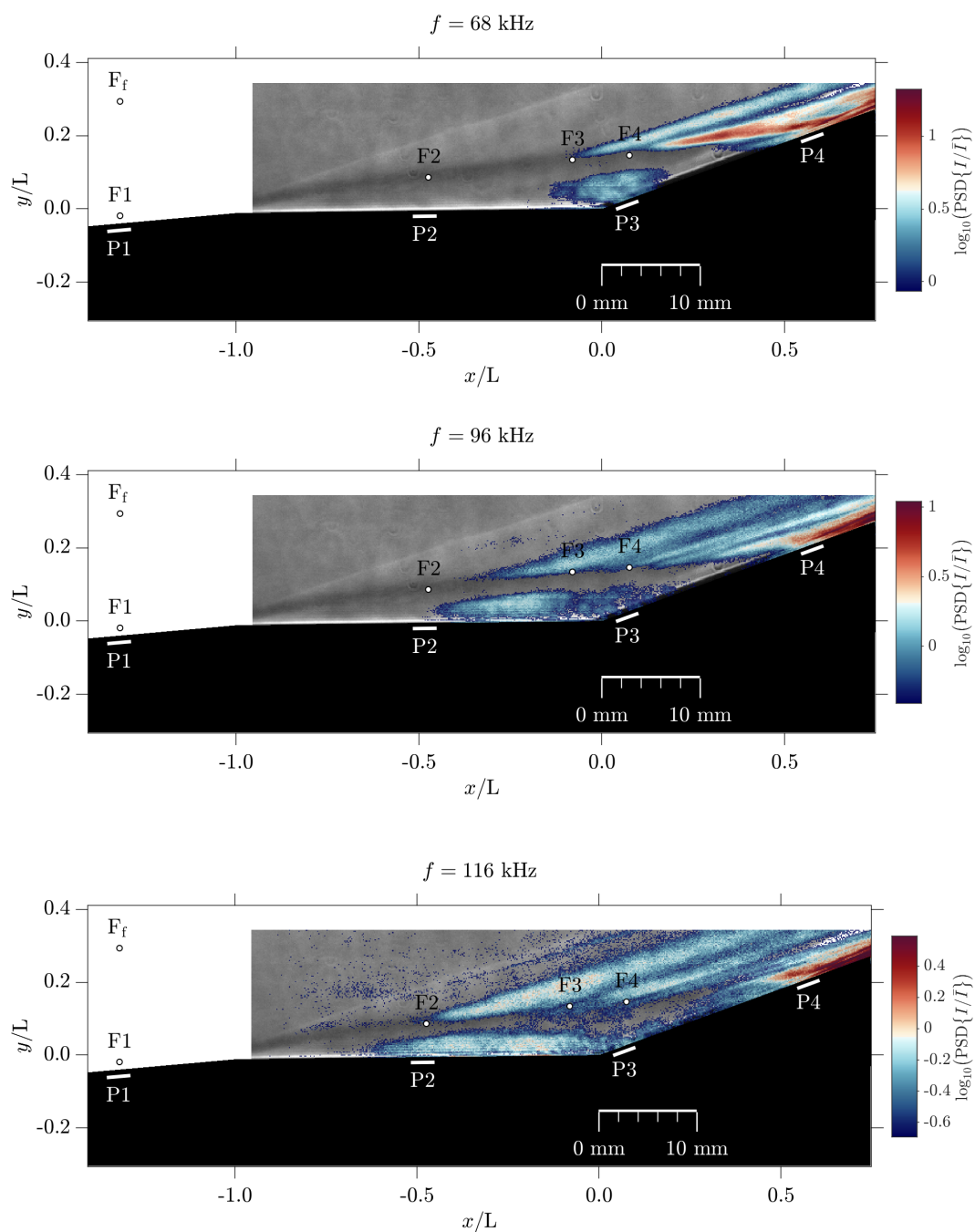


Figure 4.32: Power Spectral Density contour maps of schlieren pixel intensity at peak frequencies for H8-Re2 condition.

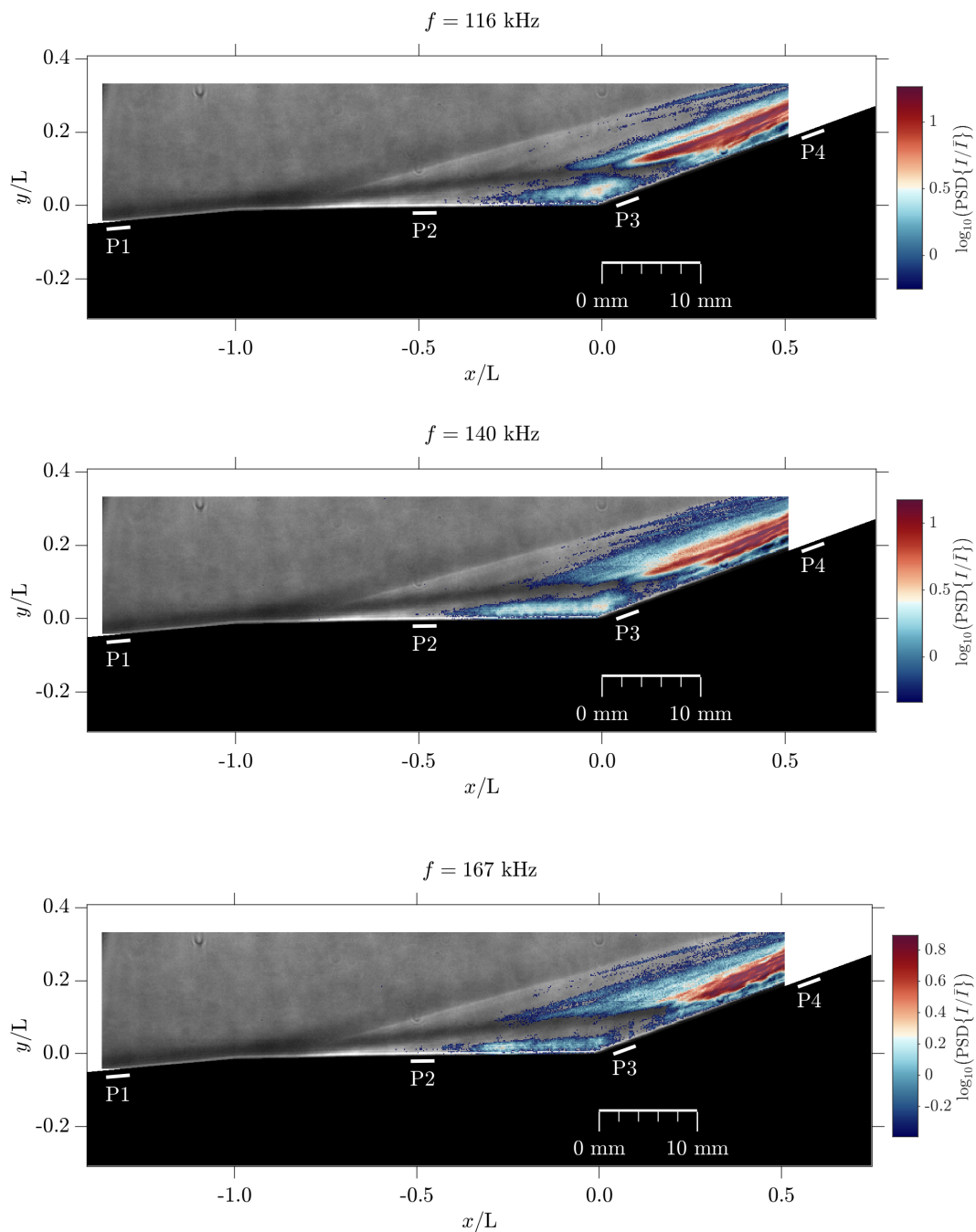


Figure 4.33: Power Spectral Density contour maps of schlieren pixel intensity at peak frequencies for H8-Re3 condition.

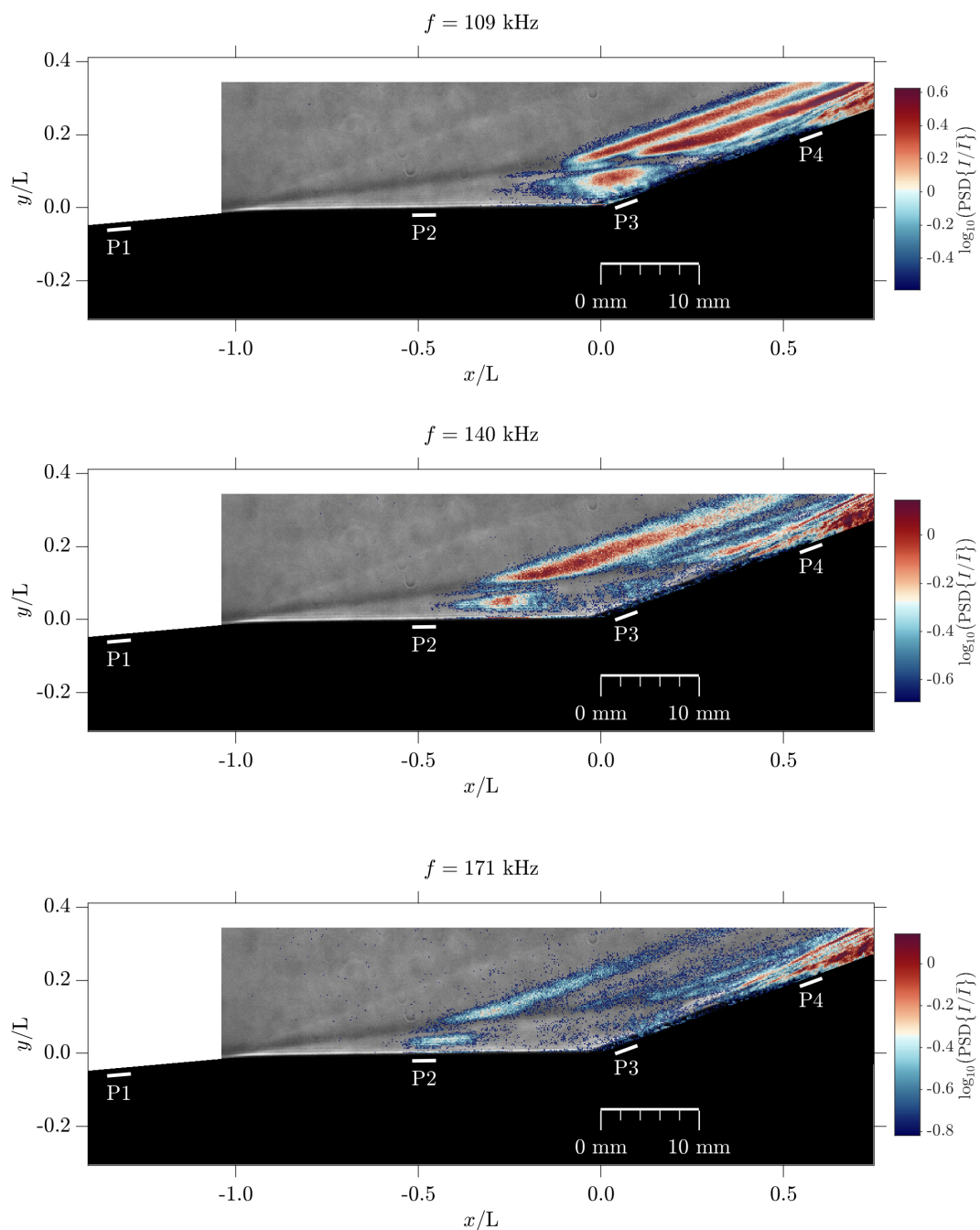


Figure 4.34: Power Spectral Density contour maps of schlieren pixel intensity at peak frequencies for H14-Re3 condition.

Determination of the phase difference between features above and below the separated shear layer utilized the same SPOD mode reconstruction used in Figure 4.13 and Figure 4.21. The SPOD modes for the entire schlieren frame were used instead of those computed separately for the individual regions of interest above and below the separated shear layer. Recall from Appendix D.1 that the complex SPOD mode written in polar form,

$$\psi_j(x, f) = A_j(x, f)e^{i\phi_j(x, f)} \quad (4.9)$$

conveys amplitude information ($A_j(x, f)$), which identifies where the coherent structure is most pronounced, and phase information ($\phi_j(x, f)$), which describes the relative timing of the oscillation across space. By plotting the phase component of the complex SPOD mode ($\phi_j(x, f)$) in Figures 4.35, 4.36, and 4.37, the relative phase of coherent structures at a given frequency is revealed. In these figures, the solid yellow lines denote the upper and lower edges of the separated shear layer computed in Section 3.3.

The relative phase difference between two spatial locations in the flowfield is therefore given as

$$\Delta\phi_{1,2}(f) = \phi(x_1, f) - \phi(x_2, f) \quad (4.10)$$

where computed relative phase differences are only valid between spatial locations at the same reconstructed frequency. The computation of phase difference between features above and below the separated shear layer was carried out by considering a row of pixels 1 mm above and 1 mm below the separated shear layer outer edges respectively. At a given frequency reconstruction, a binary amplitude mask

$$M_j(x, f) = \begin{cases} 1, & A_j(x, f) \geq A_{\text{thresh}}, \\ 0, & A_j(x, f) < A_{\text{thresh}}. \end{cases} \quad (4.11)$$

was applied to the two rows of pixels where A_{thresh} was a prescribed fraction of the maximum modal amplitude. This masking was done to ensure $\Delta\phi_{1,2}(f)$ was only computed in spatial locations associated with coherent modal structures. The phase difference was then computed at each masked y pixel location between the two lines, at each frequency within the SPOD eigenspectra that exhibited low rank behavior.

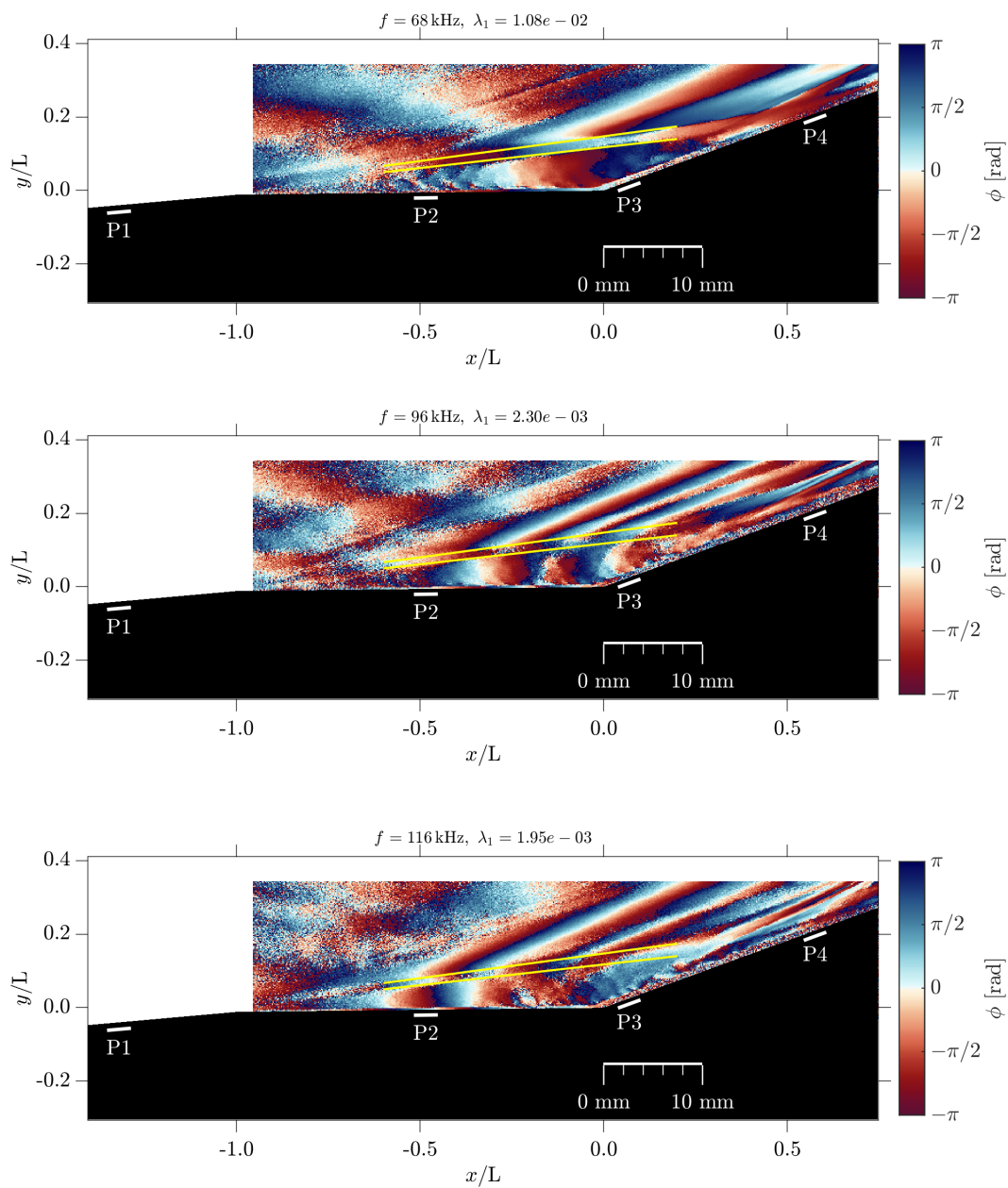


Figure 4.35: SPOD phase of schlieren pixels for the H8-Re2 condition.

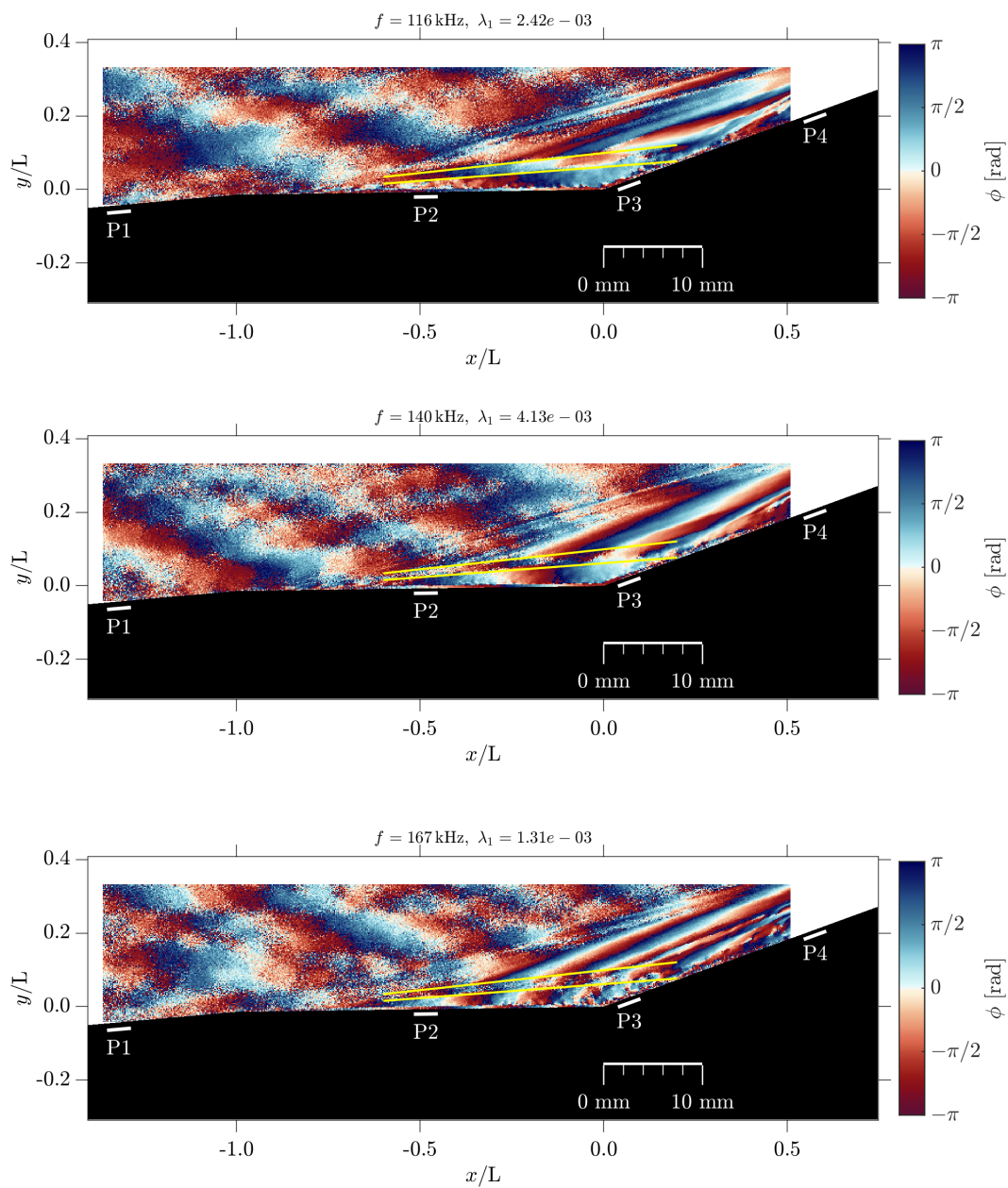


Figure 4.36: SPOD phase of schlieren pixels for the H8-Re3 condition.

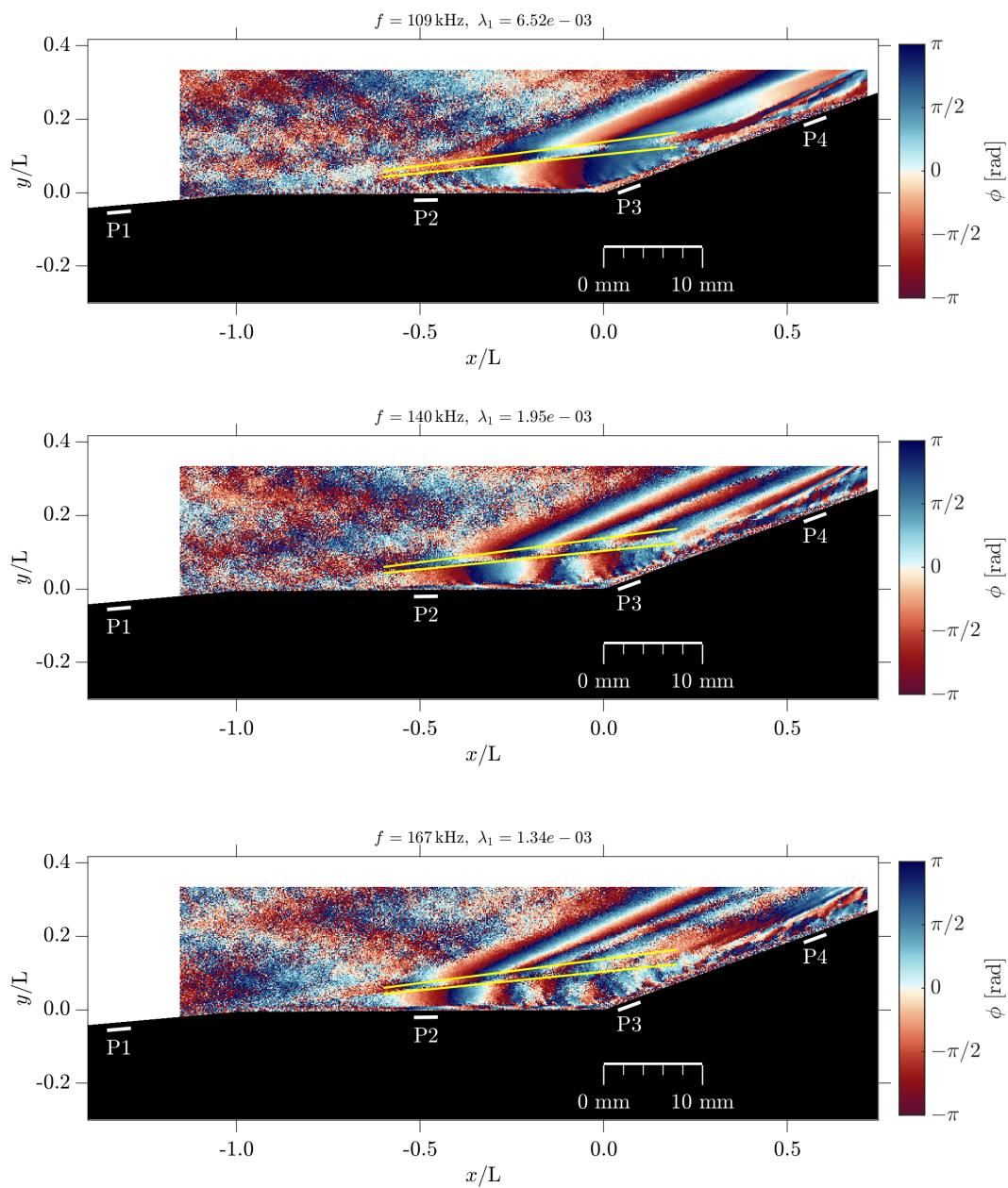


Figure 4.37: SPOD phase of schlieren pixels for the H14-Re3 condition.

In Figure 4.38, the computed phase difference between the structures above and below the separated shear layer, obtained using the method outlined above, is plotted for all three shot conditions. A relatively constant phase difference between features of $\Delta\phi \approx \pi/2$ to $3\pi/4$ radians is observed for all shot conditions upstream of the ramp. Since the schlieren based PSD visualizations suggest that features in the separation bubble lead shocklet formation, this result is interpreted as the shocklets lagging the wave-like density gradient features by between $\pi/2$ to $3\pi/4$ radians. Physical evidence of this behavior can be found upon closer inspection of Figure 4.16, where the wave-like structures in the separation bubble appear farther upstream and out of phase with the shocklets formed above the separated shear layer.

Near the ramp leading edge, however, the phase difference appears to decrease rapidly, such that the structures in the reconstruction above and below the separated shear layer shift into phase with one another. Evidence suggests that the presence of the ramp causes this phase shift, although the exact mechanism involved remains unclear. Consistent with this observation, Section 4.6.3 also notes a breakdown of the frequency scaling near the base of the ramp. These results may therefore be associated with an unknown mechanism responsible for the “flapping” motion of the shear layer, which has also been inferred from the decrease in the angle of the coherent structures above the ramp shown in Figure 4.13.

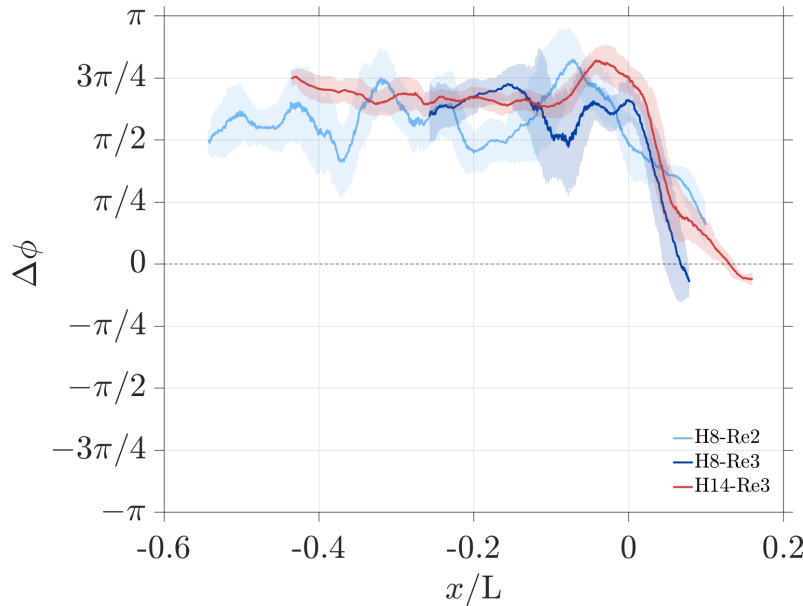


Figure 4.38: Phase difference between wave-like density gradient waves below the separated shear layer and shocklet formation above separated shear layer for all three shot conditions.

4.7.2 Coupling of Disturbances in Separated Shear Layer and On Surface

In Figure 4.27, agreement is shown between the peak instability frequencies measured using FLDI and surface PCB data at similar streamwise locations. The dynamic coupling of these two signals was investigated for the H8-Re2 condition, as this dataset contained simultaneous signals from the FLDI trace and the PCB sensor located directly below it on the model surface. These two signals were compared at two discrete locations: F2 & P2 at $x/L = -0.48$ and F4 & P3 at $x/L = 0.08$.

The magnitude-squared coherence was computed to quantify the degree of linear correlation between each signal pair as a function of frequency. Magnitude-squared coherence is defined as the squared magnitude of the cross-spectral density normalized by the product of the two auto-spectral densities, yielding values between 0 and 1. Values approaching unity indicate that the two signals share a consistent linear relationship at that frequency, suggesting frequency specific coupling.

In Figure 4.39, the magnitude-squared coherence of the two signal pairs is plotted. High magnitude-squared coherence values of ≈ 0.8 are observed for each signal pair, indicating a strong linear relationship between the two signals. The peak coherence frequencies, 116 kHz and 67 kHz respectively, are in agreement with the peak instability frequencies identified from the individual measurements at each streamwise location. Evaluating the cross-spectral density at these peak frequencies allows the absolute phase difference $|\Delta\phi|$ between disturbances in the separated shear layer and pressure fluctuations on the surface to be computed. The resulting values are ≈ 1.31 radians at $x/L = -0.48$ and ≈ 3.12 radians at $x/L = 0.08$. The phase difference is expressed as an absolute value because of the ambiguity in whether the measured FLDI phase shift ($\widetilde{\Delta\Phi}$) corresponds to a positive or negative pressure change.

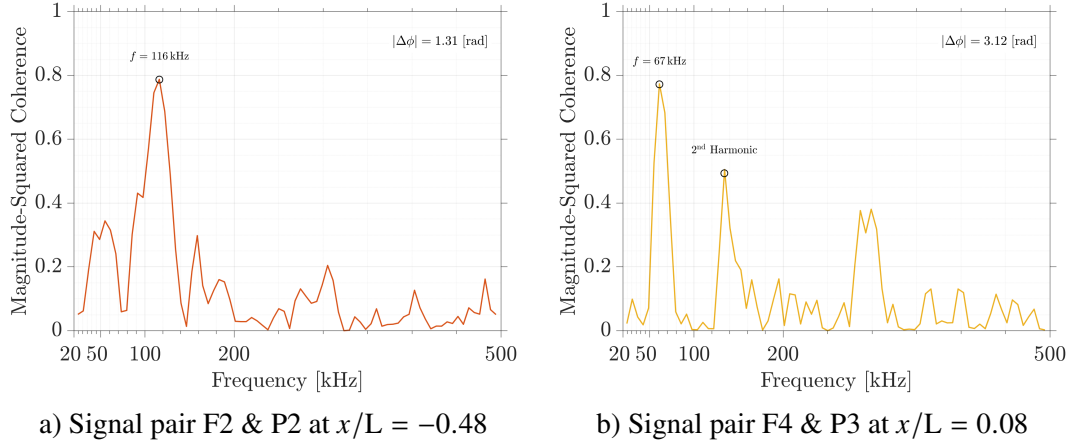


Figure 4.39: Magnitude-square coherence of FLDI and PCB signals for the H8-Re2 condition.

4.8 Interpretation of Shear Layer Instability Mechanism

This section provides a brief summary of the experimental evidence presented in this chapter regarding SBLI unsteadiness and offers an interpretation of the mechanism responsible for the separated shear layer instability observed experimentally.

Post-conical-shock region disturbances were shown to be broadband in nature over the 50–200 kHz frequency range relevant to the separated shear layer instability, with no discernible peak frequencies observed (Figure 4.1). The incoming boundary layer exhibited a similar broadband frequency spectrum in both magnitude and frequency content, with the additional presence of second (Mack) mode instability frequencies (Figure 4.8). Together, these upstream disturbance fields may provide the input forcing to the SBLI region.

As the boundary layer encounters the expansion corner under the Re2 conditions, it separates, forming a separation shock and a separated free shear layer. This shear layer produces coherent disturbances that convect downstream both above and below the separated shear layer. The streamwise convective velocities of these disturbances, measured from the motion of the above shear layer shocklets and the corresponding below shear layer wave-like density gradient structures, were found to be broadly consistent with one another (Section 4.5.2). Disturbances above the separated shear layer were found to be locally supersonic (Section 4.5.3). FLDI measurements taken inside the separated shear layer showed that these disturbances were strongly linearly correlated with fluctuations measured on the model surface (Section 4.7.2). This correlation suggests that disturbances communicate through the separation bubble between the separated shear layer and the wall. Through

an interaction that is not yet fully understood, the shear layer disturbances appear to interact with the wall inside the separation bubble and coalesce into observable wave-like density gradient structures that convect downstream within the bubble (Figure 4.16).

A periodic unsteadiness of the separated shear layer was identified in this chapter and is referred to here as the separated shear layer instability. The dominant frequency bands were 71–116 kHz, 116–164 kHz, and 106–170 kHz for the H8-Re2, H8-Re3, and H14-Re3 cases, respectively. Upstream of the ramp, within the separation bubble, the separated shear layer and the model surface are interpreted as the upper and lower boundaries of an acoustic waveguide. As the flow moves downstream through this region, the wall-normal distance between these boundaries increases. This increase in waveguide height reduces the characteristic acoustic frequency, producing the observed downstream shift of the peak instability frequency to lower values. This interpretation is supported by Strouhal number scaling using the wall-normal height of the separated shear layer as the characteristic length scale, which collapses the separated shear layer instability frequencies at all streamwise positions upstream of the ramp (Section 4.6.3).

As the wave-like density-gradient structures reach the ramp edge, a different, presently unidentified mechanism appears to dominate the separated shear layer instability. Evidence for this includes the breakdown of the frequency scaling downstream of the ramp edge (Section 4.6.3), the phase shift in the SPOD reconstruction features beginning near the base of the ramp (Figure 4.38), and the decrease in the angle of the coherent SPOD structures above the separated shear layer downstream of the ramp edge (Figure 4.13).

One possible interpretation is that, as the wave-like density gradient structures convect downstream through the separation bubble, they encounter the ramp and are partially reflected by the change in geometry. Because the ramp is oblique to the incoming structures, this interaction may introduce upward propagating density gradient fluctuations driving larger amplitude wall-normal oscillations of the shear layer above the ramp. This interpretation is consistent with the absence of a Rossiter-type feedback mechanism in the present separated shear layer instability, since the oblique ramp geometry may inhibit upstream acoustic propagation. However, this explanation remains conjectural. The flow over the ramp inside the separation bubble is complex and is not sufficiently resolved by the present measurements to identify the mechanism definitively.

CONCLUSIONS & FUTURE WORK

The present study examines the three-dimensional SBLI produced by a cone-slice-ramp configuration under hypervelocity flow conditions in the T5 Free-Piston Reflected Shock Tunnel. Four air test conditions were considered: $Re_{edge} = 2 \times 10^6$, 3×10^6 , and $6 \times 10^6 \text{ m}^{-1}$ at a nominal stagnation enthalpy of $h_0 = 8 \text{ MJ kg}^{-1}$, along with $Re_{edge} = 3 \times 10^6 \text{ m}^{-1}$ at $h_0 = 14 \text{ MJ kg}^{-1}$. Experiments were performed using a slender 5-degree half-angle cone with a tangential slice and a 20-degree finite span ramp. The flow was characterized using both surface and off-surface measurements using heat flux gauges, static and dynamic pressure sensors, high-speed schlieren imaging, and focused laser differential interferometry (FLDI).

Streamwise and spanwise surface heat flux measurements were assessed, with emphasis on how heat flux may be influenced by the freestream conditions and mean SBLI flow features. Further, SBLI unsteadiness was interrogated, particularly with respect to experimental observations of separated shear layer instability for the cone-slice-ramp geometry.

5.1 Contributions to Mean Flow Measurements for the Cone-Slice-Ramp Geometry

Thermocouple measurements on the fore-cone surface were used to evaluate the state of the incoming boundary layer for the four shot conditions studied in this work. The H8-Re2, H8-Re3, and H14-Re3 conditions were all found to have laminar incoming boundary layers prior to the leading edge of the slice, while the H8-Re6 condition was found to be transitional, with an intermittency of $\Gamma = 0.81$. For the laminar incoming boundary layer cases, the H8-Re2 and H14-Re3 conditions produced laminar separated shear layers, while the H8-Re3 condition was found to be transitional within the separated shear layer based on the heat flux and schlieren imaging results. For all four test conditions, the reattached boundary layer transitioned to turbulence on the ramp surface downstream of reattachment. Based on the state of the incoming boundary layer and separated shear layer, three distinct interaction types were classified: laminar, mixed, and transitional. These interaction types produced different streamwise effects, including changes in separation region size, transition region length on the ramp surface, and peak centerline heating.

Spanwise heat flux measurements also confirmed that the three-dimensional nature of the cone-slice-ramp SBLI produced nonuniform heating across the ramp surface.

At $h_0 = 8 \text{ MJ kg}^{-1}$, increasing the edge unit Reynolds number from $\text{Re}_{edge} = 2 \times 10^6 \text{ m}^{-1}$ to $3 \times 10^6 \text{ m}^{-1}$ caused the separation region to shrink by approximately 30%, as the separation point moved downstream and the reattachment point moved upstream. This reduction in separation region size is attributed to transition occurring within the separated shear layer, which reverses the expected trend of increasing separation size with increasing Reynolds number for laminar reattaching shear layers. Comparison between the H8-Re2 and H8-Re3 cases also showed a 35% reduction in transition region length on the ramp surface, with the H8-Re3 condition reaching turbulent heat flux levels closer to reattachment than the H8-Re2 condition. Peak centerline heating increased from approximately 5.5 MW m^{-2} for H8-Re2 to 9 MW m^{-2} for H8-Re3, demonstrating the effects of a transitional separated shear layers on ramp surface heating.

When the edge unit Reynolds number was increased further to $\text{Re}_{edge} = 6 \times 10^6 \text{ m}^{-1}$ for the H8-Re6 condition, the transitional incoming boundary layer prevented the formation of a steady separation bubble. Instead, the boundary layer was turned at the base of the ramp, with the formation of a ramp shock. Heating on the ramp surface immediately approached turbulent levels, with a peak centerline heat flux of approximately 13.5 MW m^{-2} . Together, the three $h_0 = 8 \text{ MJ kg}^{-1}$ conditions demonstrate that the present cone-slice-ramp SBLI studied are highly sensitive to relatively modest changes in Reynolds number, producing substantially different centerline heating profiles. At a nominally fixed stagnation enthalpy, increasing Re_{edge} from 2×10^6 to $6 \times 10^6 \text{ m}^{-1}$ shifted the interaction from laminar to mixed to transitional and increased the peak centerline heat flux from approximately 5.5 to 13.5 MW m^{-2} .

Raising the stagnation enthalpy from $h_0 = 8 \text{ MJ kg}^{-1}$ to $h_0 = 14 \text{ MJ kg}^{-1}$ at $\text{Re}_{edge} = 3 \times 10^6 \text{ m}^{-1}$ produced a 27% increase in separation region length. This trend is opposite to the expected reduction in separation region size at higher stagnation enthalpy (Davis and Sturtevant, 2000). The larger separation region is attributed to the delayed onset of transition at higher stagnation enthalpies, as previously observed for slender cones in T5 (Adam and Hornung, 1997; Germain and Hornung, 1997). At the same Reynolds number that produced transition within the separated shear layer for the H8-Re3 condition, increasing the stagnation enthalpy delayed transition until downstream of reattachment, producing a larger laminar separation

region. Compared to the other laminar interaction case, H8-Re2, the H14-Re3 condition exhibited a 55% shorter transition region on the ramp surface downstream of reattachment, achieving a peak heat flux of approximately 23 MW m^{-2} . Together, these results show that stagnation enthalpy can strongly influence both the mean SBLI structure and the downstream surface heating response.

Evaluation of the spanwise thermocouple rows provides evidence of heating “streaks” that produced large spanwise variations in surface heat flux. The magnitude of these spanwise variations depended on the interaction type. For the laminar interactions, the maximum spanwise heat flux variation relative to the centerline thermocouple was 55% for H8-Re2 and 60% for H14-Re3, highlighting the three-dimensional nature of the cone-slice-ramp SBLI. For the cases in which transition occurred either within the separated shear layer or in the incoming boundary layer, the spanwise variations were more subdued. Maximum spanwise heat-flux variations of 34% and 28% were reported for the H8-Re3 and H8-Re6 cases, respectively. This reduction in spanwise variation is consistent with the transitional nature of these interactions, where stronger turbulent mixing weakens the localized heating streaks observed in the laminar cases. Overall, this work provides the first surface heat flux measurements on the cone-slice-ramp geometry at high stagnation enthalpy conditions for both laminar, mixed, and transitional interactions.

5.2 Contributions to Separated Shear Layer Instability Measurements for the Cone-Slice-Ramp Geometry

A combination of FLDI and PCB surface pressure measurements was used to investigate the unsteadiness observed in the separated shear layer for the H8-Re2, H8-Re3, and H14-Re3 conditions. Characterization of these instabilities was first motivated by quantifying the upstream disturbance environment entering the SBLI region. FLDI measurements and SPOD reconstructions of the post-conical-shock region showed that the freestream tunnel noise environment, produced by the turbulent boundary layer on the T5 nozzle wall, was broadband over the observed separated shear layer instability range of 50–200 kHz. Coherent wave-like structures were observed in the SPOD reconstructions between 20–200 kHz and were used to estimate the convective velocities of disturbances associated with the nozzle wall boundary layer. These disturbances were found to propagate at approximately $0.61\text{--}0.68 U_\infty$, consistent with nozzle wall boundary layer measurements reported at Purdue (Casper et al., [2014a](#)).

The incoming boundary layer disturbance environment was then examined for the H8-Re2 condition. A second mode instability was identified at 619 kHz, consistent with previous second mode measurements in T5 at the same freestream conditions (Parziale et al., 2012). Aside from this second mode peak, the incoming boundary layer disturbance environment was broadband and comparable to that measured in the post-conical-shock region. These results indicate that the upstream disturbance environment, both in the post-conical-shock region and within the incoming boundary layer, is primarily broadband. Therefore, the discrete instability frequencies measured downstream in the SBLI region are attributed to flow instabilities generated by the interaction, rather than being directly imposed by the incoming disturbance environment.

As the boundary layer separated and formed a separated shear layer, FLDI was used to measure instability frequencies within the shear layer for the H8-Re2 condition at several streamwise locations. The peak instability frequency decreased from 114 kHz to 65 kHz moving downstream. This frequency content is attributed to a separated shear layer instability. In particular, the absence of second mode frequency content in the separated shear layer indicates that the observed instability is distinct from the second mode disturbances that have been shown to propagate along the separated shear layer in other cone-slice-ramp experiments (Pandey et al., 2022b).

SPOD was applied to the region of schlieren pixels above the separated shear layer. The reconstructions revealed coherent structures resembling the Mach radiation observed directly in the schlieren images. The apparent origin of these structures shifted upstream as the reconstruction frequency increased, matching trends observed in the FLDI measurements. Within the separation bubble, schlieren imaging directly recorded wave-like density gradient structures convecting downstream. Previous cone-slice-ramp (Pandey et al., 2022b) and cone-flare (Butler and Laurence, 2022) experiments inferred the existence of pressure waves radiating from the separated shear layer using SPOD reconstructions of the flowfield and surface pressure measurements. To the author's knowledge, the present work represents the first direct schlieren visualization of these wave-like structures inside the separation bubble.

Surface pressure measurements were used to resolve the peak instability frequencies of these structures. At streamwise measurement locations in the separation bubble, the peak frequencies decreased from 116 to 71 kHz for H8-Re2, 164 to 116 kHz for H8-Re3, and 170 to 106 kHz for H14-Re3. SPOD reconstructions at these peak

frequencies revealed coherent structures inside the separation bubble that resemble the wave-like density gradient structures observed in the schlieren images. The regions of highest SPOD amplitude also overlapped, in the streamwise direction, with the locations of the surface pressure measurements.

Multiple methods, including correlation based approaches, direct feature tracking, and SPOD based measurements, were used to extract the convective velocity of disturbances in the separated shear layer. For all shot conditions, the disturbance velocities measured approximately 1 mm above and below the separated shear layer were broadly consistent, indicating that disturbances propagate at similar speeds on both sides of the separated shear layer. Computing the convective Mach number above the separated shear layer showed that these disturbances were locally supersonic.

The peak frequencies of the separated shear layer instability were nondimensionalized using three characteristic length scales: the shear layer thickness, the separated shear layer length, and the wall normal height of the shear layer above the model surface. These length scales correspond to Strouhal number scalings for a fundamental Kelvin-Helmholtz instability, a Rossiter-type feedback mechanism, and acoustic communication between the separated shear layer and the model surface, respectively. For measurements upstream of the ramp leading edge, the wall-normal height scaling collapsed the instability frequencies for all shot conditions to a nearly constant Strouhal number, $St_H = 0.45\text{--}0.58$. This work is the first to demonstrate a successful collapse using wall-normal height scaling across a broad range of measured shear-layer instability frequencies, 71–170 kHz, spanning different Reynolds numbers and stagnation enthalpies.

Finally, the coupling between the wave-like density gradient structures inside the separation bubble and the Mach radiation above the separated shear layer was analyzed using SPOD phase reconstructions. Across all shot conditions, a nearly constant phase offset of $\Delta\phi \approx \pi/2$ to $3\pi/4$ radians was observed between these features upstream of the ramp leading edge. Near the ramp leading edge, this offset decreased, and the structures became increasingly in phase with one another at downstream locations over the ramp prior to reattachment. This phase shift, combined with the breakdown of the wall-normal height scaling at the ramp leading edge, suggests that an additional, presently unresolved mechanism becomes dominant near the ramp onset and influences the downstream shear layer instability.

5.3 Future Work

Recommendations for future work to expand the knowledge gained from the present study can take many directions, given the flexible nature of the cone-slice-ramp geometry. One possible direction is to investigate the effect of ramp angle. Varying the ramp angle would provide a direct means of further testing the wall-normal scaling of the separated shear layer instability. As the ramp angle is increased, the separated shear layer instability frequency is expected to shift downward. Determining whether the dominant instability mechanism remains consistent with wall-normal acoustic communication, or whether a Rossiter-type interaction becomes more prevalent at higher ramp angles, would provide useful insight into the mechanism driving the observed unsteadiness. Shallower ramp angles could also be explored to determine whether the second Mack mode instability frequency is recoverable in the separated shear layer. Changing the ramp angle would also alter the separation and reattachment locations, allowing for separation length scalings to be examined across different freestream Reynolds numbers and stagnation enthalpies. If such studies are undertaken, static pressure sensors should be added with sufficient spatial density throughout the SBLI region to properly resolve the pressure recovery.

More detailed measurements of fluctuations within the separated shear layer could also be carried out using FLDI. The present work only probed the separated shear layer for the H8-Re2 condition. These measurements were unable to recover the Kelvin–Helmholtz wavepacket structure previously measured in separated shear layers in T5 (Yu, 2024), likely due to the low density of the separated shear layer. Performing FLDI measurements in the separated shear layer at higher Reynolds number conditions may allow these Kelvin–Helmholtz instabilities to be measured. FLDI measurements within the separated shear layer would also be valuable for cases believed to undergo transition in the separated shear layer, as surface measurements and inferences from schlieren imaging provide only limited information about the transitional state of the separated flow.

To enable more thorough interrogation of the separated shear layer using FLDI, multi-beam FLDI is recommended. One possible configuration would use a diffractive optic to split the FLDI laser into an $1 \times N$ array of horizontally spaced beam pairs, allowing simultaneous measurements at multiple streamwise locations during a single shot. This capability would be especially useful for probing along the separated shear layer, where the downstream decrease in the separated shear layer instability frequency and, at higher Reynolds numbers, the transition of the separated

shear layer could be measured directly. It would also enable detailed measurements of the convective velocities of disturbances in the separated shear layer, independent of the line-integrated schlieren based methods explored in the present work.

Future work could also include computational studies, as no numerical simulations currently exist for the present experiments. The present analysis was limited by the lack of detailed density and temperature fields above and below the separated shear layer, making estimates of local disturbance convective Mach numbers within the separation bubble challenging. Simulations and stability analyses would provide valuable comparisons with the experimental measurements.

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Appendix A

T5 TEST CONDITIONS

A.1

Table A.1: Shot & Reservoir Conditions

Shot	Condition	h_0 [MJ/kg]	U_s [m/s]	P_1 [kPa]	P_{res} [MPa]	T_{res} [K]	P_4 [MPa]
3032	H8-Re2-Air	8.28	2999	45	19.2	5255	39.8
3033	H8-Re2-Air	8.01	2945	45	18.8	5148	39.0
3034	H8-Re2-Air	8.06	2958	45	18.7	5165	39.0
3035	H8-Re2-Air	8.24	3005	45	18.5	5234	40.6
3036	H16-Re2-Air	15.62	3974	45	53.6	8098	108.6
3037	H16-Re2-N2	16.01	4040	45	49.2	8758	98.0
3038	H8-Re2-Air	6.95	2800	45	13.8	4684	39.0
3039	H8-Re2-Air	8.59	3146	45	15.9	5338	40.0
3040	H8-Re2-Air	8.04	2981	45	17.4	5144	39.5
3064	H8-Re2-Air	8.24	3007	45	18.5	5257	39.9
3065	H8-Re2-Air	8.04	2954	45	18.8	5183	39.6
3066	H8-Re2-Air	8.37	3044	45	18.1	5301	41.4
3067	H8-Re6-Air	8.33	2943	130	65.7	5550	104.0
3068	H8-Re2-Air	8.36	3038	45	18.3	5301	42.9
3069	H8-Re2-Air	8.08	2965	45	18.7	5194	42.5
3070	H8-Re2-Air	8.06	2992	45	17.2	5173	41.3
3071	H8-Re2-Air	8.06	2988	45	17.3	5171	40.2
3072	H8-Re2-Air	8.08	2988	45	17.6	5183	40.3
3073	H8-Re2-Air	8.20	3040	45	16.5	5216	41.7
3074	H8-Re2-Air	7.70	2910	45	17.0	5032	38.7
3075	H8-Re6-Air	8.46	2990	130	63.1	5599	120.3
3076	H8-Re2-Air	7.18	2845	45	14.3	4799	35.7
3077	H8-Re2-Air	7.56	2903	45	15.9	4964	38.9

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Shot	Condition	h_0 [MJ/kg]	U_s [m/s]	P_1 [kPa]	P_{res} [MPa]	T_{res} [K]	P_4 [MPa]
3078	H8-Re2-Air	7.42	2857	45	16.3	4914	35.4
3079	H8-Re6-Air	8.50	3007	130	61.6	5609	115.8
3167	H8-Re6-Air	8.25	2941	130	62.8	5506	110
3168	H8-Re4-Air	8.93	3083	85	42.7	5712	81.0
3169	H8-Re3-Air	9.45	3167	70	38.0	5898	84.9
3170	H8-Re2-Air	7.37	2881	45	14.8	4878	47.8
3171	H8-Re3-Air	7.85	2927	60	23.8	5155	50
3172	H8-Re3-Air	7.09	2793	75	25.8	4861	50
3173	H16-Re2-Air	15.67	4044	45	47.2	8095	106.1
3174	H14-Re3-Air	14.37	3867	50	47.9	7748	110
3175	H14-Re3-Air	13.68	3798	55	47.0	7531	95.5
3176	H8-Re3-Air	7.79	2918	60	23.4	5124	55.0
3177	H8-Re3-Air	6.86	2738	75	25.5	4766	55.6
3178	H8-Re3-Air	7.65	2906	60	22.2	5062	53.0
3179	H8-Re3-Air	7.62	2886	60	22.9	5055	57.3
3180	H8-Re2-Air	7.43	2908	45	14.4	4896	35.4
3181	H14-Re3-Air	14.50	3920	50	44.7	7760	100.3
3182	H14-Re3-Air	15.03	3997	50	46.0	7917	114.6
3183	H8-Re2-Air	7.52	2927	45	14.4	4929	35.1
3184	H8-Re3-Air	7.76	2924	60	22.6	5106	82.1
3185	H14-Re3-Air	14.26	3892	50	43.4	7680	93.0
3186	H8-Re6-Air	8.19	2965	130	57.5	5467	107.6
3187	H8-Re2-Air	7.24	2862	45	14.3	4821	40

A.2

Table A.2: Freestream conditions.

Shot	Condition	M_∞ [-]	U_∞ [m/s]	ρ_∞ [kg/m ³]	T_∞ [K]	P_∞ [Pa]	Re_∞ [1/m]
3032	H8-Re2-Air	5.43	3691	0.0237	1125	7782	1.96×10^6
3033	H8-Re2-Air	5.46	3639	0.0238	1083	7505	1.99×10^6
3034	H8-Re2-Air	5.46	3648	0.0235	1090	7483	1.96×10^6
3035	H8-Re2-Air	5.44	3682	0.0229	1117	7471	1.90×10^6
3036	H16-Re2-Air	4.94	4859	0.0398	2237	27138	2.94×10^6
3037	H16-Re2-N2	5.58	5035	0.0331	1921	19178	2.76×10^6
3038	H8-Re2-Air	5.62	3413	0.0196	904	5160	1.71×10^6
3039	H8-Re2-Air	5.41	3739	0.0191	1157	6501	1.58×10^6
3040	H8-Re2-Air	5.46	3641	0.0220	1083	6949	1.84×10^6
3064	H8-Re2-Air	5.43	3689	0.0225	1124	7406	1.87×10^6
3065	H8-Re2-Air	5.45	3649	0.0234	1092	7448	1.95×10^6
3066	H8-Re2-Air	5.41	3721	0.0222	1149	7482	1.83×10^6
3067	H8-Re6-Air	5.46	3737	0.0745	1155	24883	6.15×10^6
3068	H8-Re2-Air	5.41	3719	0.0224	1147	7520	1.85×10^6
3069	H8-Re2-Air	5.45	3657	0.0229	1098	7357	1.91×10^6
3070	H8-Re2-Air	5.44	3670	0.0222	1108	7189	1.85×10^6
3071	H8-Re2-Air	5.45	3658	0.0218	1098	6986	1.81×10^6
3072	H8-Re2-Air	5.44	3678	0.0229	1115	7465	1.90×10^6
3073	H8-Re2-Air	5.44	3680	0.0205	1114	6676	1.70×10^6
3074	H8-Re2-Air	5.49	3589	0.0222	1043	6748	1.87×10^6
3075	H8-Re6-Air	5.44	3759	0.0697	1178	23767	5.73×10^6
3076	H8-Re2-Air	5.57	3476	0.0198	953	5496	1.71×10^6
3077	H8-Re2-Air	5.52	3548	0.0205	1009	6038	1.74×10^6
3078	H8-Re2-Air	5.54	3522	0.0214	989	6160	1.83×10^6
3079	H8-Re6-Air	5.42	3780	0.0700	1197	24259	5.73×10^6
3167	H8-Re6-Air	5.46	3747	0.0765	1163	25740	6.31×10^6
3168	H8-Re4-Air	5.34	3861	0.0489	1280	18206	3.93×10^6
3169	H8-Re3-Air	5.28	3948	0.0417	1360	16549	3.31×10^6

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Shot	Condition	M_∞ [-]	U_∞ [m/s]	ρ_∞ [kg/m ³]	T_∞ [K]	P_∞ [Pa]	Re_∞ [1/m]
3170	H8-Re2-Air	5.54	3516	0.0201	984	5751	1.71×10^6
3171	H8-Re3-Air	5.47	3633	0.0304	1081	9551	2.54×10^6
3172	H8-Re3-Air	5.59	3479	0.0355	954	9809	3.06×10^6
3173	H16-Re2-Air	4.95	4878	0.0349	2227	23844	2.60×10^6
3174	H14-Re3-Air	4.98	4708	0.0379	2080	23876	2.83×10^6
3175	H13-Re3-Air	5.01	4612	0.0386	1989	23128	2.89×10^6
3176	H8-Re3-Air	5.48	3619	0.0300	1069	9324	2.51×10^6
3177	H8-Re3-Air	5.63	3429	0.0361	915	9552	3.14×10^6
3178	H8-Re3-Air	5.50	3590	0.0289	1046	8778	2.43×10^6
3179	H8-Re3-Air	5.50	3590	0.0289	1046	8778	2.43×10^6
3180	H8-Re2-Air	5.53	3527	0.0193	992	5588	1.65×10^6
3181	H14-Re3-Air	4.99	4721	0.0352	2076	22185	2.63×10^6
3182	H14-Re3-Air	4.97	4793	0.0352	2146	23032	2.62×10^6
3183	H8-Re2-Air	5.52	3544	0.0192	1005	5646	1.64×10^6
3184	H8-Re3-Air	5.48	3611	0.0291	1063	9005	2.44×10^6
3185	H14-Re3-Air	5.00	4686	0.0346	2040	21420	2.59×10^6
3186	H8-Re6-Air	5.46	3733	0.0703	1154	23484	5.81×10^6
3187	H8-Re2-Air	5.56	3488	0.0196	962	5491	1.69×10^6

A.3

Table A.3: Edge conditions.

Shot	Condition	M_{edge} [-]	U_{edge} [m/s]	ρ_{edge} [kg/m ³]	T_{edge} [K]	P_{edge} [Pa]	Re_{edge} [1/m]
3032	H8-Re2-Air	5.14	3533	0.0311	1232	11195	2.24×10^6
3033	H8-Re2-Air	5.17	3490	0.0313	1187	10835	2.28×10^6
3034	H8-Re2-Air	5.16	3497	0.0310	1194	10796	2.25×10^6
3035	H8-Re2-Air	5.14	3525	0.0301	1223	10754	2.17×10^6
3036	H16-Re2-Air	4.71	4505	0.0506	2411	37182	3.00×10^6
3037	H16-Re2-N2	5.29	4773	0.0440	2097	27813	3.13×10^6
3038	H8-Re2-Air	5.30	3295	0.0261	998	7579	2.01×10^6
3039	H8-Re2-Air	5.12	3567	0.0251	1266	9330	1.79×10^6
3040	H8-Re2-Air	5.17	3490	0.0289	1187	10031	2.10×10^6
3064	H8-Re2-Air	5.14	3530	0.0296	1230	10653	2.13×10^6
3065	H8-Re2-Air	5.16	3498	0.0308	1197	10742	2.23×10^6
3066	H8-Re2-Air	5.12	3556	0.0292	1257	10741	2.08×10^6
3067	H8-Re6-Air	5.17	3592	0.0981	1264	35848	7.05×10^6
3068	H8-Re2-Air	5.12	3554	0.0294	1255	10798	2.10×10^6
3069	H8-Re2-Air	5.16	3504	0.0302	1203	10604	2.18×10^6
3070	H8-Re2-Air	5.15	3514	0.0292	1213	10355	2.11×10^6
3071	H8-Re2-Air	5.15	3503	0.0286	1203	10070	2.07×10^6
3072	H8-Re2-Air	5.14	3521	0.0301	1221	10746	2.17×10^6
3073	H8-Re2-Air	5.14	3520	0.0269	1220	9611	1.94×10^6
3074	H8-Re2-Air	5.19	3446	0.0293	1145	9774	2.15×10^6
3075	H8-Re6-Air	5.15	3611	0.0917	1288	34160	6.54×10^6
3076	H8-Re2-Air	5.26	3348	0.0263	1049	8030	1.99×10^6
3077	H8-Re2-Air	5.21	3410	0.0271	1109	8772	2.01×10^6
3078	H8-Re2-Air	5.23	3389	0.0283	1088	8968	2.12×10^6
3079	H8-Re6-Air	5.14	3629	0.0919	1308	34812	6.53×10^6
3167	H8-Re6-Air	5.17	3601	0.1007	1272	37063	7.22×10^6
3168	H8-Re4-Air	5.07	3692	0.0639	1394	25918	4.43×10^6
3169	H8-Re3-Air	5.02	3762	0.0542	1480	23423	3.68×10^6

Continued on next page

Shot	Condition	M_{edge} [-]	U_{edge} [m/s]	ρ_{edge} [kg/m ³]	T_{edge} [K]	P_{edge} [Pa]	Re_{edge} [1/m]
3170	H8-Re2-Air	5.23	3382	0.0265	1083	8376	1.99×10^6
3171	H8-Re3-Air	5.18	3489	0.0400	1185	13794	2.92×10^6
3172	H8-Re3-Air	5.28	3360	0.0472	1051	14352	3.58×10^6
3173	H16-Re2-Air	4.72	4509	0.0444	2403	32719	2.64×10^6
3174	H14-Re3-Air	4.75	4379	0.0483	2244	32845	2.92×10^6
3175	H14-Re3-Air	4.77	4303	0.0493	2148	31888	3.01×10^6
3176	H8-Re3-Air	5.18	3477	0.0396	1172	13481	2.89×10^6
3177	H8-Re3-Air	5.31	3317	0.0481	1009	14038	3.69×10^6
3178	H8-Re3-Air	5.20	3452	0.0381	1147	12716	2.80×10^6
3179	H8-Re3-Air	5.20	3452	0.0381	1147	12716	2.80×10^6
3180	H8-Re2-Air	5.23	3391	0.0256	1091	8132	1.91×10^6
3181	H14-Re3-Air	4.75	4384	0.0448	2242	30547	2.72×10^6
3182	H14-Re3-Air	4.74	4442	0.0448	2316	31660	2.69×10^6
3183	H8-Re2-Air	5.22	3405	0.0254	1105	8206	1.89×10^6
3184	H8-Re3-Air	5.19	3470	0.0384	1166	13024	2.81×10^6
3185	H14-Re3-Air	4.77	4355	0.0442	2203	29525	2.69×10^6
3186	H8-Re6-Air	5.17	3588	0.0926	1262	33823	6.65×10^6
3187	H8-Re2-Air	5.25	3358	0.0260	1059	8015	1.96×10^6

Appendix B

FLDI DENSITY CONVERSION

The conversion of the denoised power spectral density of the phase shift ($\text{PSD}\{\widetilde{\Delta\Phi(t)}\}$) to the power spectral density of normalized density fluctuations ($\text{PSD}\{\rho'/\bar{\rho}\}$) was performed only for FLDI measurements in the post-conical-shock region (F_f). This choice was informed by the observation of coherent wave structures in the SPOD mode reconstructions within the post-conical-shock region where F_f was measured, which were associated with tunnel noise (Section 4.1.1). These structures could therefore be approximated as sinusoidal plane waves, enabling construction of the FLDI response function and subsequent solution to the inverse problem.

B.1 Density Conversion Theory

To perform the conversion to normalized density, Eq. 2.12 is reconstructed in normalized polar grid coordinates $(\tilde{r}, \theta)$,

$$\begin{aligned} \Delta\Phi(t) = & \frac{2}{\pi} \frac{2\pi}{\lambda_L} \int_{z_a}^{z_b} \left(\int_0^\infty \tilde{r} \exp(-2\tilde{r}^2) \left[\int_0^{2\pi} n_1 d\theta \right] d\tilde{r} \right. \\ & \left. - \int_0^\infty \tilde{r} \exp(-2\tilde{r}^2) \left[\int_0^{2\pi} n_2 d\theta \right] d\tilde{r} \right) dz. \end{aligned} \quad (\text{B.1})$$

where $\tilde{r} \equiv r/w(z)$ is the radius normalized by the local Gaussian beam radius. Here, λ_L is the laser wavelength, z is the optical axis integration coordinate through the measurement volume, and n_1 and n_2 denote the refractive index sampled by the two FLDI beams. This expression defines the forward problem, relating a refractive index disturbance field to the measured phase signal ($\Delta\Phi(t) = f(n(\mathbf{x}, t))$).

The refractive index field may be expressed as a superposition of plane wave disturbances,

$$n(\mathbf{x}, t) = \frac{1}{\sqrt{N}} \sum_{i=1}^M \sum_{j=1}^N A_j \cos(\mathbf{k}_{i,j} \cdot \mathbf{x} - 2\pi f_j t + \varphi_{i,j}). \quad (\text{B.2})$$

In this representation, f_j is the temporal frequency, A_j is the disturbance amplitude at frequency f_j , and $\varphi_{i,j}$ is the phase of the component associated with propagation direction i and frequency j . This formulation represents a superposition of waves propagating in M different directions, each composed of N frequency components.

The factor $1/\sqrt{N}$ is introduced so that the total signal energy scales properly as the number of discrete frequency components changes. Physically, this expression models the freestream disturbance field as a sum of harmonic plane waves spanning a prescribed set of frequencies and propagation directions.

Because the FLDI forward problem is linear in refractive index, the measured phase signal may also be written as a linear superposition of the response to each individual plane wave component

$$\Delta\Phi(t) = \frac{1}{\sqrt{N}} \sum_{i=1}^M \sum_{j=1}^N A_j h(\mathbf{k}_{i,j}) \sin(2\pi f_j t - \varphi_{i,j}), \quad (\text{B.3})$$

where the function $h(\mathbf{k}_{i,j})$ is the FLDI response function evaluated for the plane wave defined by Eq. 2.18, and $\mathbf{k}_{i,j}$ is the wave vector associated with the i th propagation direction and j th frequency. The wave vector is defined as,

$$\mathbf{k}_{i,j} = \frac{2\pi f_j}{|\mathbf{u} \cdot \hat{\mathbf{k}}_i + a|} \quad (\text{B.4})$$

where $\mathbf{u}$ is the convective velocity vector and a is the sound speed.

Each spectral component of the measured phase is related to the corresponding refractive index component through the FLDI response function. In power spectral density form, the refractive index power spectral density ($\text{PSD}\{n'\}$) may be estimated by dividing the measured phase power spectral density ($\text{PSD}\{\Delta\Phi\}$) by the squared magnitude of the effective FLDI response,

$$\text{PSD}\{n'\} = \frac{\text{PSD}\{\Delta\Phi\}}{|\sum_{i=1}^M h_i(\mathbf{k})|^2}. \quad (\text{B.5})$$

Once the refractive index disturbance spectrum has been obtained, conversion to density follows from the Gladstone–Dale relation,

$$n' = K\rho', \quad (\text{B.6})$$

where K is the Gladstone–Dale constant. Since power spectral densities scale with the square of any multiplicative constant,

$$\text{PSD}\{\rho'\} = \frac{\text{PSD}\{n'\}}{K^2}. \quad (\text{B.7})$$

Dividing by the square of the mean density then yields the spectrum of normalized density fluctuations,

$$\text{PSD}\left\{\frac{\rho'}{\bar{\rho}}\right\} = \frac{\text{PSD}\{\rho'\}}{\bar{\rho}^2}. \quad (\text{B.8})$$

B.2 Implementation in Current Work

With the observation of coherent wave structures in the post-conical-shock region, the disturbance field was approximated as a superposition of sinusoidal plane waves. To simplify the inverse problem, the present analysis assumes a single propagation direction, corresponding to $M = 1$. This assumption is not intended to imply that tunnel disturbances originating from the nozzle wall consist of only one planar wave direction. The axisymmetric nozzle likely generates a more complicated disturbance field composed of many superimposed acoustic waves with different propagation directions (Duan et al., 2019); however, modeling these directional sources is outside the scope of the present work. The coherent structures observed in the SPOD modes provide sufficient evidence to proceed with the single plane wave approximation as a reasonable first-order model. The assumed propagation direction is taken to be consistent with disturbances radiating from the upper nozzle wall. Waves with an out of plane component, parameterized by β , would produce a reduced maximum FLDI phase response, $\max |\Delta\Phi|$ (Lawson, 2021), and are not assumed to be the dominant contributors to the coherent structures observed here. Accordingly, the density reconstruction is performed assuming a plane wave originating from the upper nozzle wall, with propagation angle α measured from the streamwise flow direction, $\hat{\mathbf{x}}$, and no out-of-plane component, such that $\beta = 0$.

The wave vector, $\mathbf{k}$, was computed by first measuring the wave angle of the coherent SPOD structures at each frequency reconstruction as shown in Figure B.1. Here, the wave angle is defined as the smaller angle between the coherent SPOD structure and $\hat{\mathbf{x}}$. The wave vector direction, α , is then taken to be normal to this structure, such that α is equal to the measured wave angle ± 90 degrees, depending on whether the disturbance is interpreted as a fast or slow acoustic mode. An average wave angle of 29.6 degrees was obtained for the present experiments; however, the wave angle was also observed to increase with frequency and was therefore also represented using a linear fit.

Four interpretations of $\mathbf{k}$ were considered. First, the freestream noise was modeled as either a fast acoustic mode, for which acoustic disturbances propagate downstream with the flow, or a slow acoustic mode, for which acoustic disturbances propagate upstream relative to the flow but are convected downstream. For each mode, $\mathbf{k}$ was computed using either a constant wave vector direction, $\alpha = \text{constant}$, or a frequency dependent direction, $\alpha = \alpha(f)$, based on the linear fit to the measured wave angles.

Figure B.2 shows the response function, $|h(\mathbf{k})|$, for the four wave vector interpreta-

tions described above. Applying these response functions to Eq. B.5, with $M = 1$ and $\Delta\Phi$ taken as the measured FLDI phase shift signal, enables conversion to the power spectral density of normalized density fluctuations, $\text{PSD}\{\rho'/\bar{\rho}\}$, following the procedure described above. Figure B.3 shows a representative FLDI measurement converted using each of the four response functions. Conventional tunnel freestream noise is commonly interpreted as being predominantly a slow acoustic mode, for which the disturbance wave vector has an upstream pointing component (Wagner et al., 2018), such that $(\mathbf{u} \cdot \hat{\mathbf{k}} < 0)$. Therefore, the converted FLDI spectra reported in Figure 4.1 uses the slow mode response function with the frequency dependent propagation direction, $\alpha = \alpha(f)$.

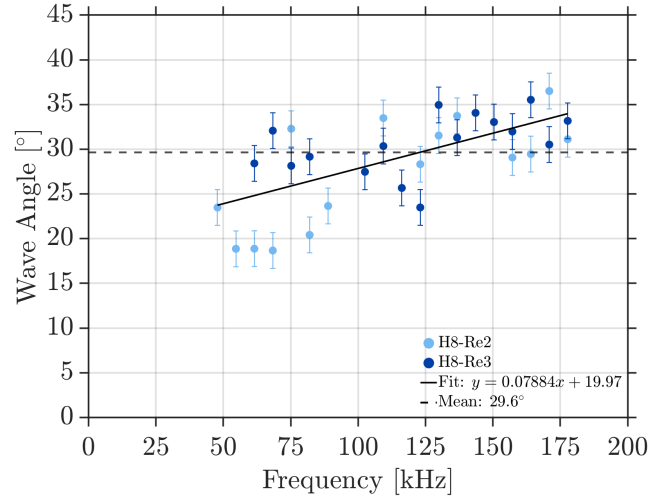


Figure B.1: Coherent structure wave angle measured from SPOD in post-conical-shock region as a function of reconstruction frequency.

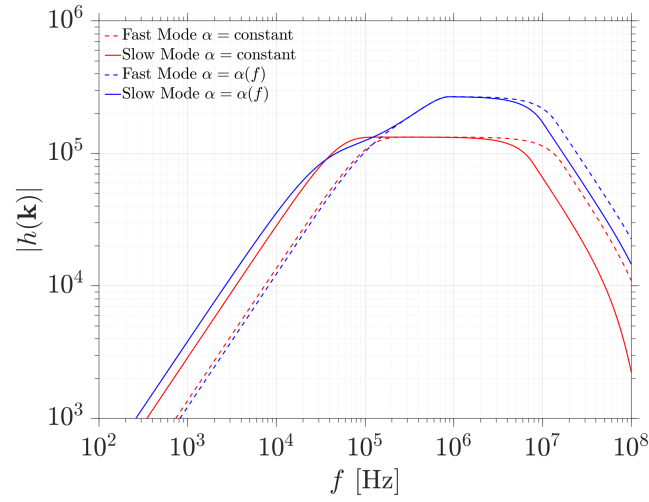


Figure B.2: FLDI response function for fast and slow acoustic modes comparing $\alpha = \alpha(f)$ and $\alpha = \text{constant}$

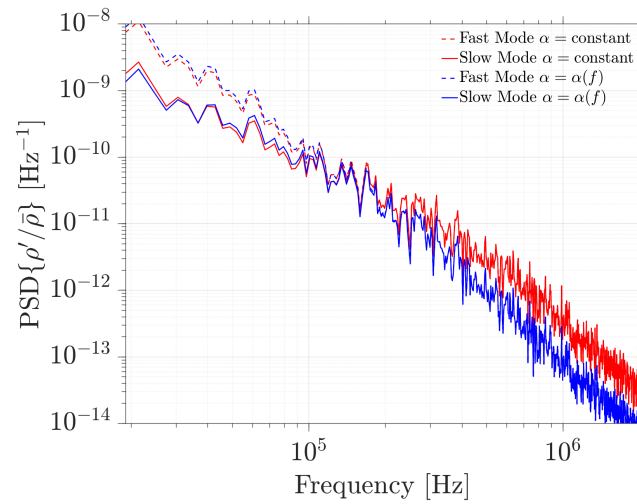


Figure B.3: Comparison of $\text{PSD}\{\rho'/\bar{\rho}\}$ using different response function definitions.

Appendix C

CROSS-CORRELATION METHODS FOR CONVECTIVE VELOCITY MEASUREMENT

The convective velocity of disturbances observed above and below the separated shear layer was estimated using both spatial and temporal cross-correlation methods. The spatial method follows the approach of Laurence et al., 2014, whereas the temporal method follows the procedure described by Butler and Laurence, 2022. In both cases, the schlieren intensity is treated as a scalar signal, and the downstream displacement of correlated intensity features over a known time interval is used to estimate the disturbance convection speed.

C.1 Spatial Cross-Correlation Method

For the spatial method, the intensity profile extracted along a prescribed line of interest is correlated between successive image times to determine the streamwise shift of the observed structure. The schlieren intensity extracted along a line of interest at time t_i is defined as,

$$y_i(x) = I(x, t_i) \tag{C.1}$$

and at a later time t_j as

$$y_j(x) = I(x, t_j) \tag{C.2}$$

Assuming that the dominant flow structure convects downstream at constant velocity without significant distortion over the interval $\Delta T = t_j - t_i$, the later intensity distribution may be approximated as a shifted version of the earlier one,

$$y_j(x) \approx y_i(x - \Delta x), \tag{C.3}$$

where Δx is the streamwise displacement of the feature during the elapsed time ΔT .

To remove cross-correlation bias associated with the mean intensity level, zero-mean spatial intensity profiles are introduced as

$$\tilde{y}_i(x) = y_i(x) - \bar{y}_i, \quad \tilde{y}_j(x) = y_j(x) - \bar{y}_j, \quad (\text{C.4})$$

where $\bar{y}_i$ and $\bar{y}_j$ denote the spatial averages of the intensity along the line of interest at times t_i and t_j , respectively.

The discrete spatial cross-correlation is then evaluated over candidate streamwise shifts Δx according to

$$R_{ij}(\Delta x) = \sum_m \tilde{y}_i(x_m) \tilde{y}_j(x_m + \Delta x), \quad (\text{C.5})$$

where x_m denotes the discrete pixel locations along the line of interest. The streamwise shift corresponding to the maximum correlation is taken as the displacement of the convecting structure,

$$\Delta x^* = \arg \max_{\Delta x} R_{ij}(\Delta x) \quad (\text{C.6})$$

To improve the estimate beyond integer-pixel resolution, the correlation values at the peak and its neighboring locations,

$$R_{ij}(\Delta x^* - \delta x), \quad R_{ij}(\Delta x^*), \quad R_{ij}(\Delta x^* + \delta x), \quad (\text{C.7})$$

are fit with a second-order polynomial, where δx is one pixel spacing. The location of the maximum of this quadratic fit provides the subpixel displacement estimate Δx_{sub}^* . The spatially inferred convective velocity is then computed as

$$U_c(t_i, t_j) = \frac{\Delta x_{\text{sub}}^*}{|t_j - t_i|} \quad (\text{C.8})$$

This procedure is repeated for frame separations of $\Delta T = 1, 2, 3$ frames. Because the correlation is performed between entire spatial intensity profiles, the spatial cross-correlation method provides a bulk estimate of the convective velocity along the prescribed line of interest. Each evaluated image pair produces one displacement estimate, and therefore one convective velocity estimate, based on the streamwise shift that maximizes the correlation between the two profiles.

Figure C.1a) shows representative normalized correlation profiles obtained from the spatial correlation of the intensity profiles for each frame separation. The location

of the peak correlation gives the streamwise displacement used to compute the corresponding convective velocity. Figure C.1b) shows the resulting distribution of measured convective velocities across all evaluated t_i and ΔT , binned using 100 m s^{-1} intervals. The mean and standard deviation of this distribution are used to report the spatial cross-correlation estimate of convective velocity and its associated uncertainty.

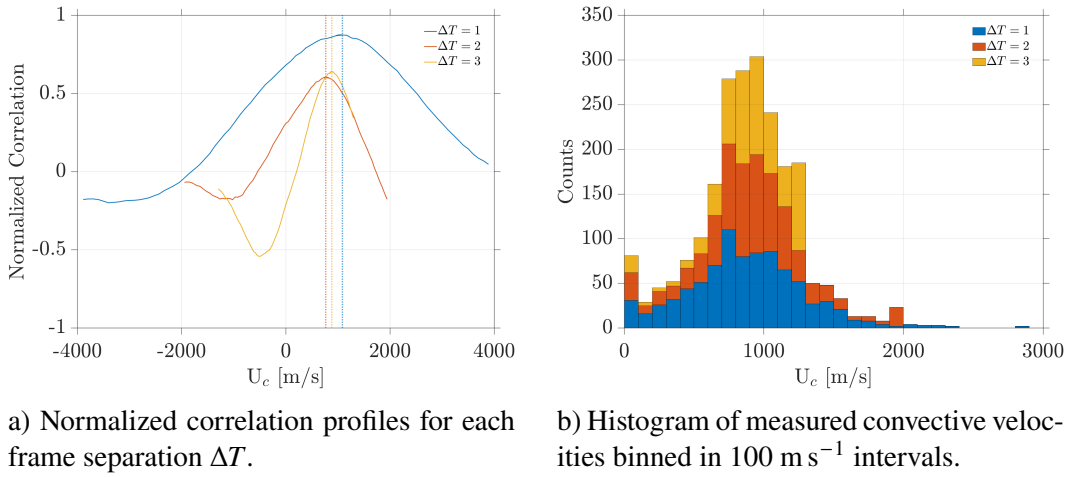


Figure C.1: Spatial cross-correlation method applied to region above separated shear layer for the H8-Re2 condition.

C.2 Temporal Cross-Correlation Method

For the temporal method, the schlieren intensity at each pixel location is treated as a time history. The time series at neighboring spatial locations are correlated to determine the propagation speed of the disturbance between those locations. At a fixed streamwise position x_i , the zero-mean pixel intensity is defined as

$$y_i[k] = I(x_i, t_k) - \overline{I(x_i)}, \quad t_k = k\Delta T, \quad k = 0, \dots, N-1, \quad (\text{C.9})$$

where $\overline{I(x_i)}$ denotes the temporal mean intensity at position x_i . To isolate the dominant oscillatory motion associated with the shear layer instabilities, the time series is bandpass filtered about the relevant frequency range prior to the correlation analysis. A frequency range of 50kHz to 200kHz was selected as the separated shear layer instability frequencies for all shot conditions studied were shown to lie within this range.

The temporal cross-correlation between a reference location x_i and a candidate downstream location x_j is then computed over a set of discrete time lags n as

$$R_{ij}[n] = \sum_{k=0}^{N-1-n} y_i[k] y_j[k+n]. \quad (\text{C.10})$$

The optimal spatial offset and temporal lag are identified by maximizing the correlation coefficient over the candidate search window,

$$\{j^*, n^*\} = \arg \max_{j \in J, n \in \mathcal{N}} R_{ij}[n], \quad (\text{C.11})$$

where J denotes the set of candidate spatial locations and $\mathcal{N}$ is the set of candidate lag values.

Once the maximizing pair $\{j^*, n^*\}$ is identified, subpixel refinement is again introduced by fitting a quadratic to the correlation values at the peak spatial location and its immediate neighbors,

$$R_{i,j^*-1}[n^*], \quad R_{i,j^*}[n^*], \quad R_{i,j^*+1}[n^*], \quad (\text{C.12})$$

which yields a refined spatial position $x_{j^*,\text{sub}}$. The subpixel estimate of the local convective velocity is then,

$$U_c(x_i) = \frac{x_{j^*,\text{sub}} - x_i}{n^* \Delta T}. \quad (\text{C.13})$$

This process is performed for both upstream and downstream candidate locations (Butler and Laurence, 2021b), with the final convective velocity at each pixel location obtained by averaging the two estimates,

$$U_c^{\text{avg}}(x_i) = \frac{1}{2} (U_c^+(x_i) + U_c^-(x_i)) \quad (\text{C.14})$$

The temporal cross-correlation method therefore provides a local estimate of convective velocity as the time delay between neighboring spatial locations is evaluated independently. This allows variations in the convective velocity to be resolved along the line of interest and provides a local measure of the disturbance propagation speed.

Appendix D

SPECTRAL PROPER ORTHOGONAL DECOMPOSITION (SPOD)

D.1 Overview

Spectral proper orthogonal decomposition (SPOD) is a frequency-domain modal decomposition used to identify the dominant coherent structures in statistically stationary flows (Schmidt and Colonius, 2020). It has been used extensively in fluid mechanics to study cavity flows (Aguirre et al., 2025; Desikan et al., 2022), shear layer instabilities (Butler and Laurence, 2021a), shock-wave/boundary-layer Interactions (Cottier et al., 2019), supersonic jets (Nogueira et al., 2022), and extended to cyclostationary flows (Heidt and Colonius, 2024). Unlike POD, which identifies spatial modes from a space only covariance and leaves temporal behavior to the modal coefficients, SPOD decomposes statistically stationary data independently at each frequency through the cross-spectral density, yielding modes that are both spatially coherent and harmonic in time. For a fluctuation field $q(x, t)$, the method is based on the cross-spectral density tensor $S(x, x', f)$, and the SPOD modes are obtained from the eigenvalue problem

$$\int_{\Omega} S(x, x', f) W(x') \psi_j(x', f) dx' = \lambda_j(f) \psi_j(x, f), \quad (\text{D.1})$$

where W is the chosen inner-product weighting, $\psi_j(x, f)$ is the j -th SPOD mode at frequency f , and $\lambda_j(f)$ is the corresponding modal energy. The eigenvalues are ordered such that,

$$\lambda_1(f) \geq \lambda_2(f) \geq \dots \geq 0, \quad (\text{D.2})$$

so that, at a given frequency, the leading mode represents the most energetic coherent structure and higher modes represent progressively less energetic orthogonal structures.

In practice, the cross-spectral density is estimated from finite data by segmenting the time record into overlapping blocks, applying a temporal window, computing the Fourier transform of each block, and averaging across the resulting realizations. This produces a decomposition that is optimal, at each frequency, in the sense of capturing the largest possible variance of the measured field with an orthogonal basis. For statistically stationary data, the fluctuation field may then be represented

as a superposition of harmonically evolving SPOD modes,

$$q(x, t) \approx \sum_j \int a_j(f) \psi_j(x, f) e^{i2\pi f t} df, \quad (\text{D.3})$$

or at a single frequency,

$$q_f(x, t) \approx \sum_j a_j(f) \psi_j(x, f) e^{i2\pi f t}. \quad (\text{D.4})$$

This form shows that each SPOD mode is intrinsically complex, carrying both spatial amplitude and spatial phase information.

For interpretation and plotting, the complex SPOD mode is commonly written in polar form as,

$$\psi_j(x, f) = A_j(x, f) e^{i\phi_j(x, f)} \quad (\text{D.5})$$

where

$$A_j(x, f) = |\psi_j(x, f)| \quad (\text{D.6})$$

is the local modal amplitude and

$$\phi_j(x, f) = \arg(\psi_j(x, f)) \quad (\text{D.7})$$

is the local modal phase. The amplitude field identifies where the coherent structure is most pronounced, while the phase field describes the relative timing of the oscillation across space, so that regions with similar phase values (ϕ_j) oscillate together. Because the measured quantity in the present work, pixel intensity, is real valued, SPOD modes are plotted through their real reconstruction at a chosen phase offset θ ,

$$\Re \{ \psi_j(x, f) e^{i\theta} \} = A_j(x, f) \cos(\phi_j(x, f) + \theta). \quad (\text{D.8})$$

This expression provides the direct connection between the mathematical SPOD mode and the plotted mode shape. Specifically, the displayed field is the amplitude envelope $A_j(x, f)$ modulated by a cosine whose argument contains both the local spatial phase $\phi_j(x, f)$ and the user selected global phase shift θ . Plotting A_j alone highlights the spatial support of the coherent structure, plotting ϕ_j reveals its phase organization, and plotting $\Re \{ \psi_j e^{i\theta} \}$ gives the instantaneous real valued structure associated with that mode at a chosen point in its oscillation cycle. In this sense, SPOD provides not only an energy ranked decomposition of the flow, but also a physically interpretable amplitude-phase description of coherent unsteady structures.

D.2 Present Implementation and Binning

The SPOD code used in the present work is the 2025 revision of the code written by Towne et al., 2018. The choice of temporal block length is an important consideration when plotting SPOD modal energies. Using many short blocks provides a larger number of ensemble realizations, which improves convergence of the cross-spectral density estimate and generally produces less noisy eigenvalue spectra. However, shorter blocks also produce wider frequency bins, causing nearby frequencies to be less well resolved and allowing sharp spectral peaks to leak into neighboring bins. By contrast, using fewer long blocks produces narrower frequency bins and therefore improves frequency resolution, but reduces the number of ensemble realizations. This increases the variance of the spectral estimate and can make the eigenspectrum and modal energies noisier and less statistically converged (Schmidt and Colonius, 2020).

With the finite number of camera frames available during the test time (≈ 700 frames), temporal window lengths ranging from 0.1 to 0.4 ms were tested to determine the best balance between frequency resolution and statistical convergence. Figures D.1 and D.2 show the eigenspectrum and corresponding modal energy breakdown for different temporal block lengths applied to the region above the separated shear layer. Figures D.3 and D.4 show the same comparison for the region inside the separation bubble. Based on these comparisons, a 0.3 ms temporal window was selected because it provided sufficient frequency resolution to resolve finer spectral features while maintaining reasonably converged mode energies.

When plotting the SPOD eigenspectrum and mode shapes throughout this work, several related measures of SPOD modal energy are used. Specifically, quantities labeled as “Mode Energy,” “Fraction of Total Energy,” and “ λ_1 ” represent different normalizations of the SPOD eigenvalues. For clarity and consistency, formal definitions of these quantities are provided below:

Mode Energy

$$\lambda_j(f_i) = \frac{\lambda_j(f_i)}{\sum_{k=1}^{N_f} \sum_{m=1}^M \lambda_m(f_k)} \quad (\text{D.9})$$

Fraction of Total Energy

$$E_j = \frac{\sum_{k=1}^{N_f} \lambda_j(f_k)}{\sum_{k=1}^{N_f} \sum_{m=1}^M \lambda_m(f_k)} \quad (\text{D.10})$$

λ_1

$$\lambda_1(f_i) = \frac{\lambda_1(f_i)}{\sum_{k=1}^{N_f} \sum_{m=1}^M \lambda_m(f_k)} \quad (\text{D.11})$$

Here, N_f is the number of discrete frequency bins and M is the number of retained SPOD modes. The denominator represents the total SPOD energy summed over all frequencies and modes considered in the analysis. Thus, the plotted quantities represent normalized modal energy measures, allowing the relative contribution of individual modes and frequencies to be compared throughout the work.

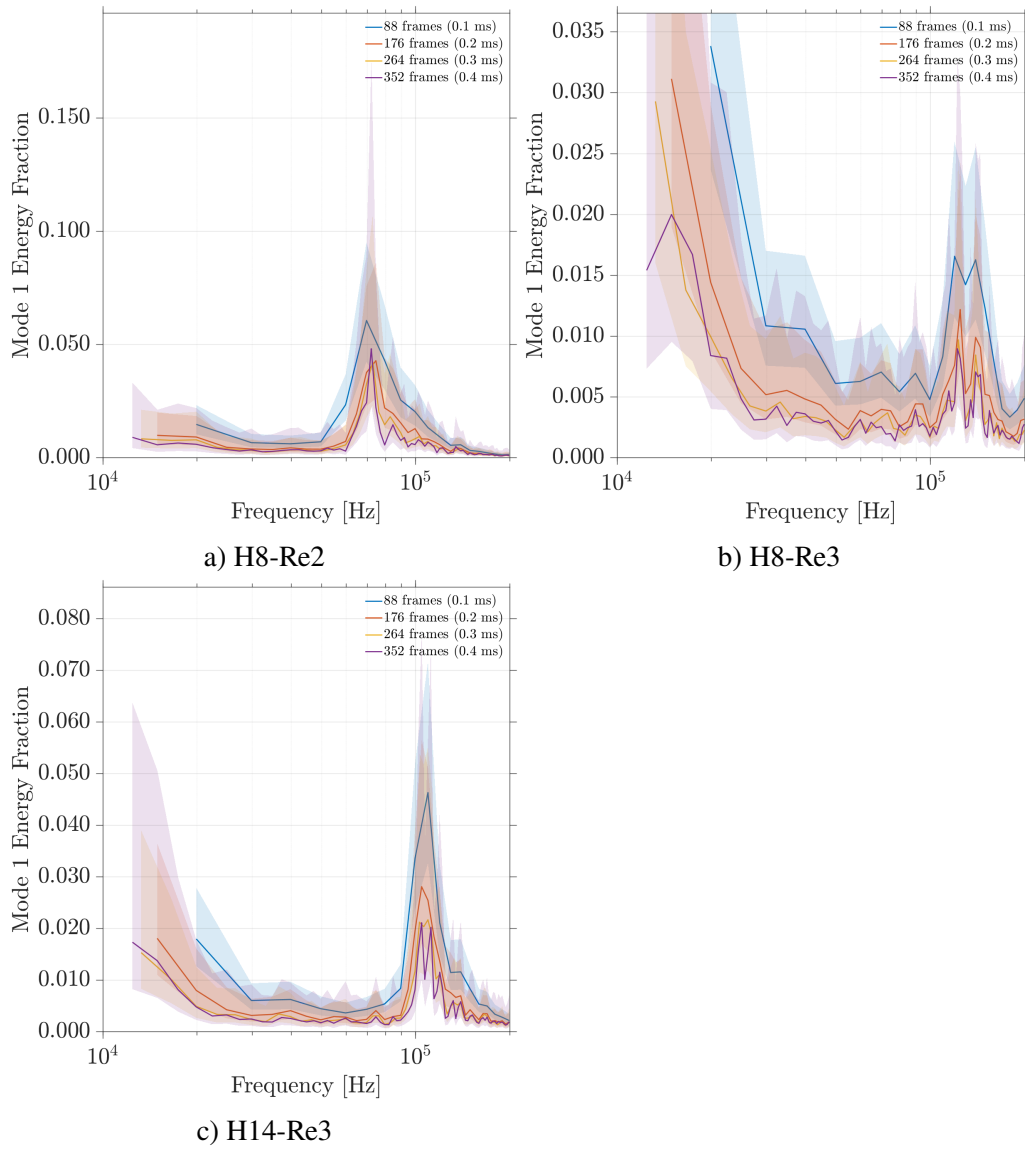


Figure D.1: SPOD bin size eigenspectrum comparison above the separated shear layer for all shot conditions.

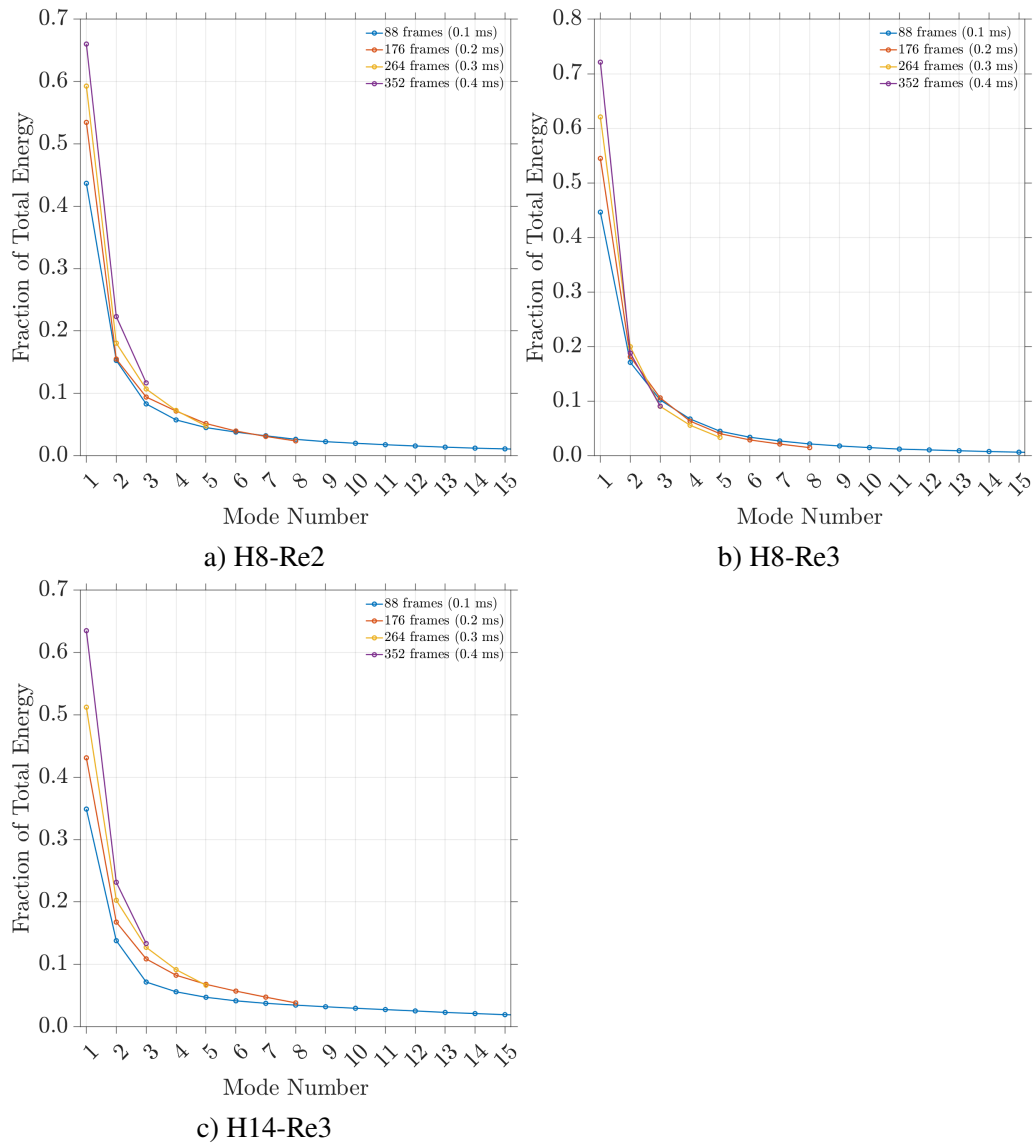


Figure D.2: SPOD bin size mode energy comparison above the separated shear layer for all shot conditions.

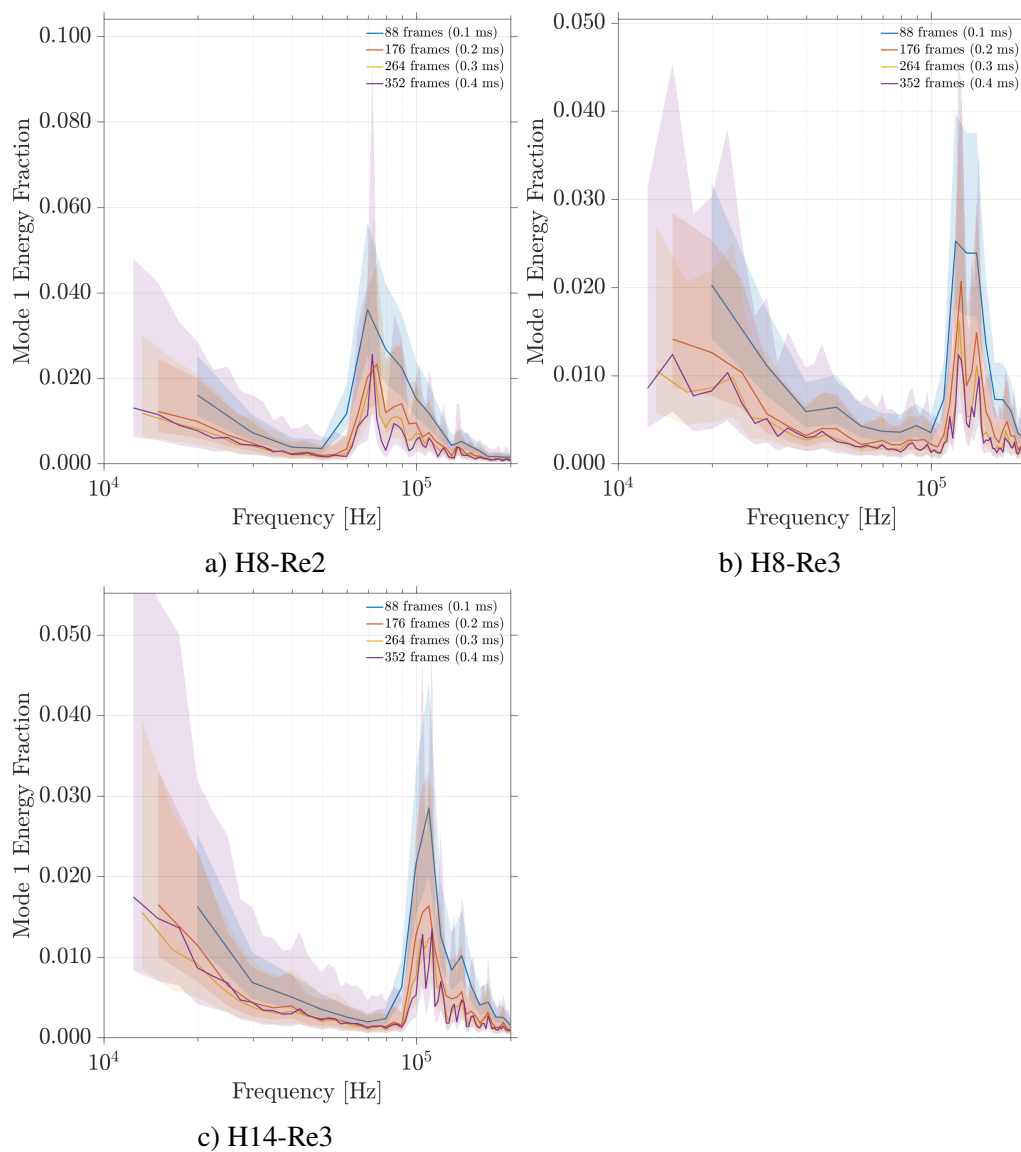


Figure D.3: SPOD bin size eigenspectrum comparison in separation bubble for all shot conditions.

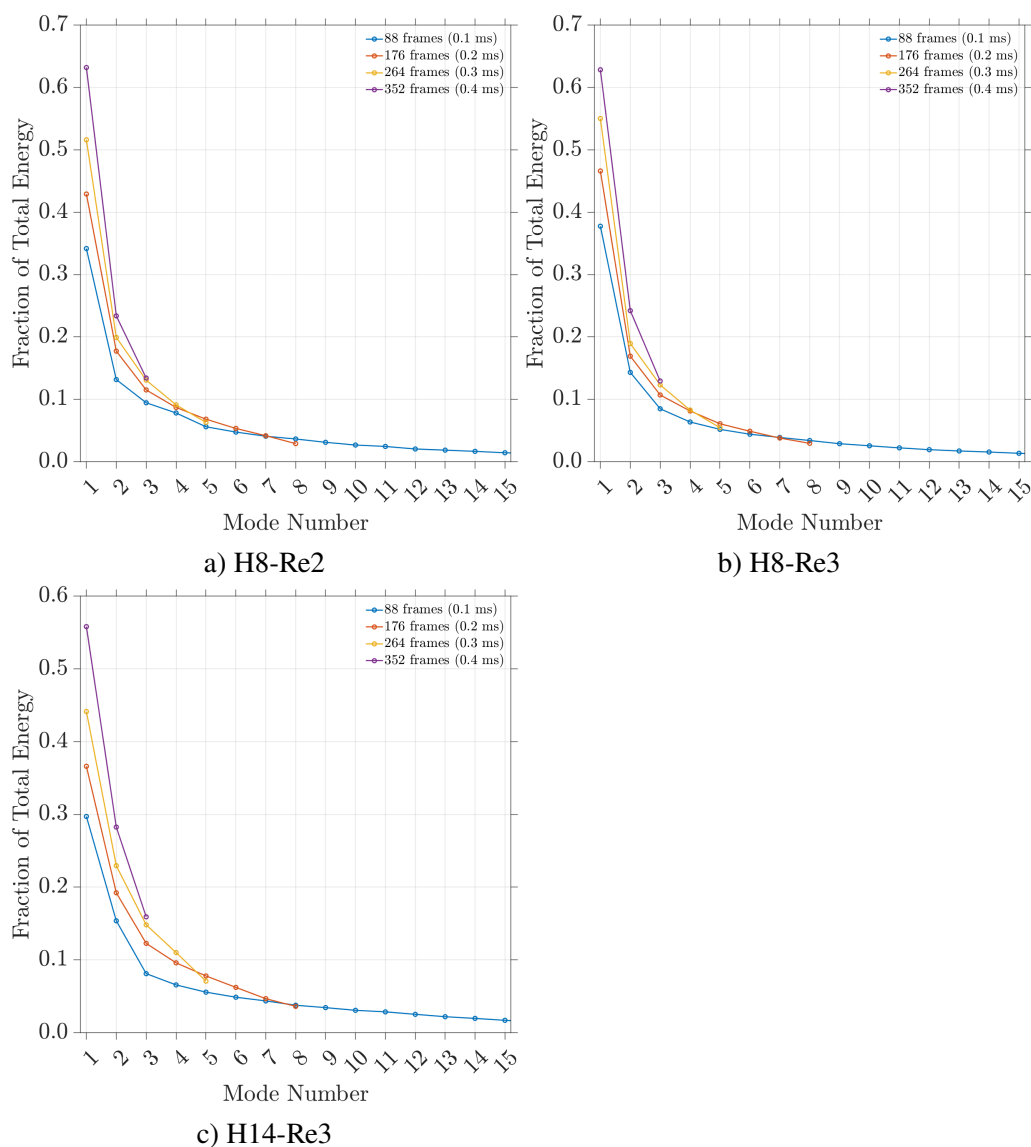


Figure D.4: SPOD bin size mode energy comparison in separation bubble for all shot conditions.