CFD-Guided Prediction of Launch-Vehicle Aeroacoustics

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Aero-Induced Surface Fluctuating Pressures

- **Unsteady pressure loads imposed on structure by flowfield**
  - Not acoustic in origin
  - The distinction between “aeroacoustic“ effects and buffet may be blurry
- **Why is accurate prediction of surface fluctuating pressure (SFP) important in the design of launch vehicles?**
  - SFP drives structural vibration which may damage internal components
    - Electronics
    - Small mechanisms
  - Many launch failures have been attributed to such vibration
  - Currently-used SFP-prediction methodologies are weak in physical veracity
    - Prediction of structural vibration from defined SFP environments are considerably more reliable and accurate

Aero-Induced Surface Fluctuating Pressures

- **SFP in general scales with dynamic pressure**
  - For launch vehicles, the highest q occurs in the transonic / low supersonic Mach range
- **A number of generic flowfield features have been identified which can create significant SFP:**
  - Nearfield plumes
  - “Necklace” vortex upstream & in near-wake of protuberance
  - BL reattachment with accompanying terminal shock
    - Transonic (0.6 < M < 1.2)
  - BL reattachment w/o terminal shock
  - Shock upstream of compression corner
  - Homogeneous separated flow (body of separation bubble)
    - Expansion-induced – larger for M < 1.2
    - Compression-induced – larger for M > 1.2
  - Bluff-body wakes
  - Attached TBL

Why can't you just compute the unsteady flow?

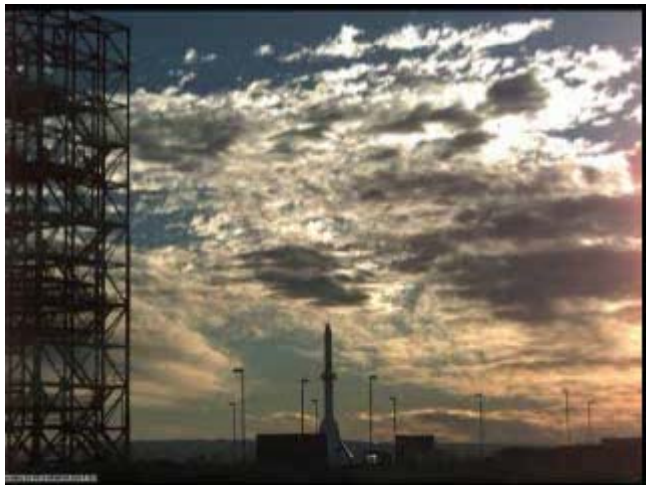
- **For now, the size of the problem is too large**
  - The resolution required in any dimension is proportional to the range of scales to be simulated
    - Turbulent flows, particularly above very modest Reynolds numbers, are very broadband both in space and in time
      - 100's of millions of points, thousands of time steps
  - Large-eddy simulation (LES) methods presently aren't much help for wall-bounded flows
    - LES is based on being able to model small-scale, nearly isotropic, turbulence
    - Near the wall, turbulence is anisotropic down to very small scales
    - But! We need to pursue this venue for the future.

The Problem of SFP Transmission

- **The efficiency with which a region of SFP is converted to structural vibration is related to the product of the SFP space-time correlation (cross-spectrum) and the structure's response modes.**
  - Usually cast as convection velocity and coherence decay parameters
- **The only reasonably-reliable measurements of cross-correlation are for attached turbulent BL's**
  - Of little interest for launch-vehicle problems, since ATBL's have low SFP levels
  - Used as approximation for all flowfields in the absence of other data
  - While the SFP-generating flowfield features discussed here many be streamwise-localized, they have slow coherence decay in the spanwise direction

Plume-Induced SFP

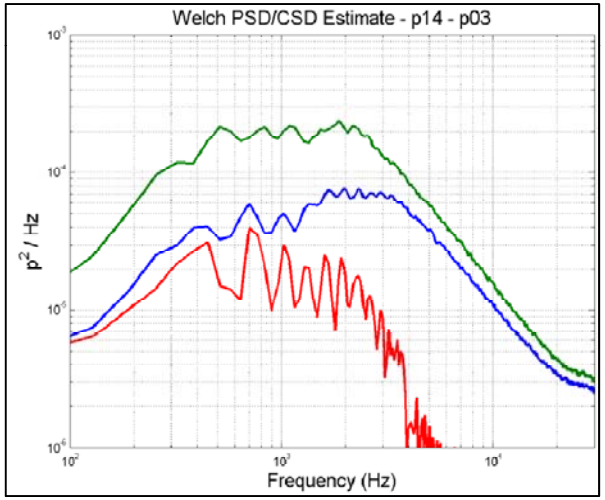
- On the basis of static tests, the plume-induced environment on the Orion LAV is expected to exceed 175 dB – **internal component damage likely.**
- A serious analysis unknown is the efficiency of such loads to drive vibration and vibro-acoustic transmission of a structure.



Pad-Abort-1 test launch – May 2010
- confirmed high SFP levels

Measurement via Sensor Array

Array-instrumented test firing at MSFC May 2010



- **Prediction of response to fluctuating-pressure loading requires estimates of:**
  - Spectrum & level:
  - Space-time correlation / cross-spectrum:
    - Corcos, 1963 and 1964

$$G_{12}(\omega,\xi,\eta) = \Phi(\omega) e^{-\alpha(\omega)\xi} e^{-\beta(\omega)\eta} \left(\cos\left(\frac{\omega\xi}{U_c(\omega)} \right) - i \sin\left(\frac{\omega\xi}{U_c(\omega)} \right) \right)$$

Auto-Spectrum

Decay in Flow Direction

Decay Across Flow Direction

Propagating Term

SFP Estimates Guided by CFD

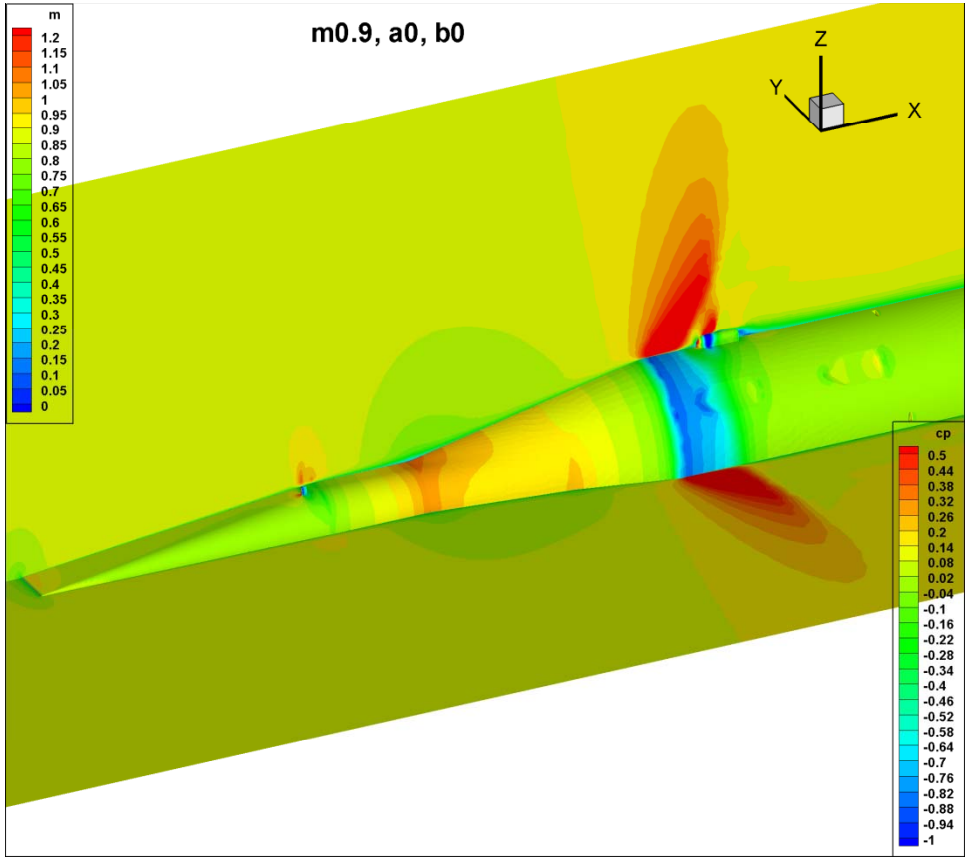
Method under development to enhance application of legacy SFP-correlation databases via use of flowfield details from steady RANS CFD solutions.

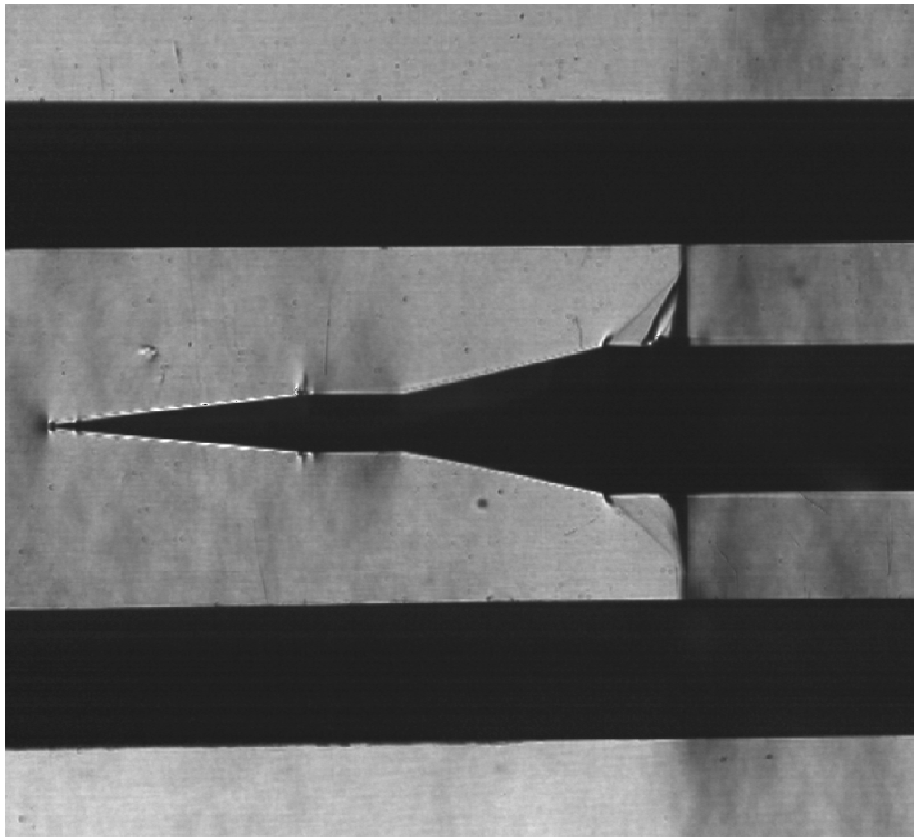
Estimates are made in the following stages:

- From a portfolio of consistent CFD solutions (M, α), identify a region on vehicle where flowfield shows an SFP-generating feature
  - Shock, separated BL, reattachment, etc.
- Measure from CFD solution quantities required by correlations
  - Local BL / separated-region thickness
    - Separation may break into cells – multiple measurements
  - Local BL / separated-region edge velocity
  - Local BL thickness & edge velocity upstream of compression-corner shock
  - Compression-corner separation length

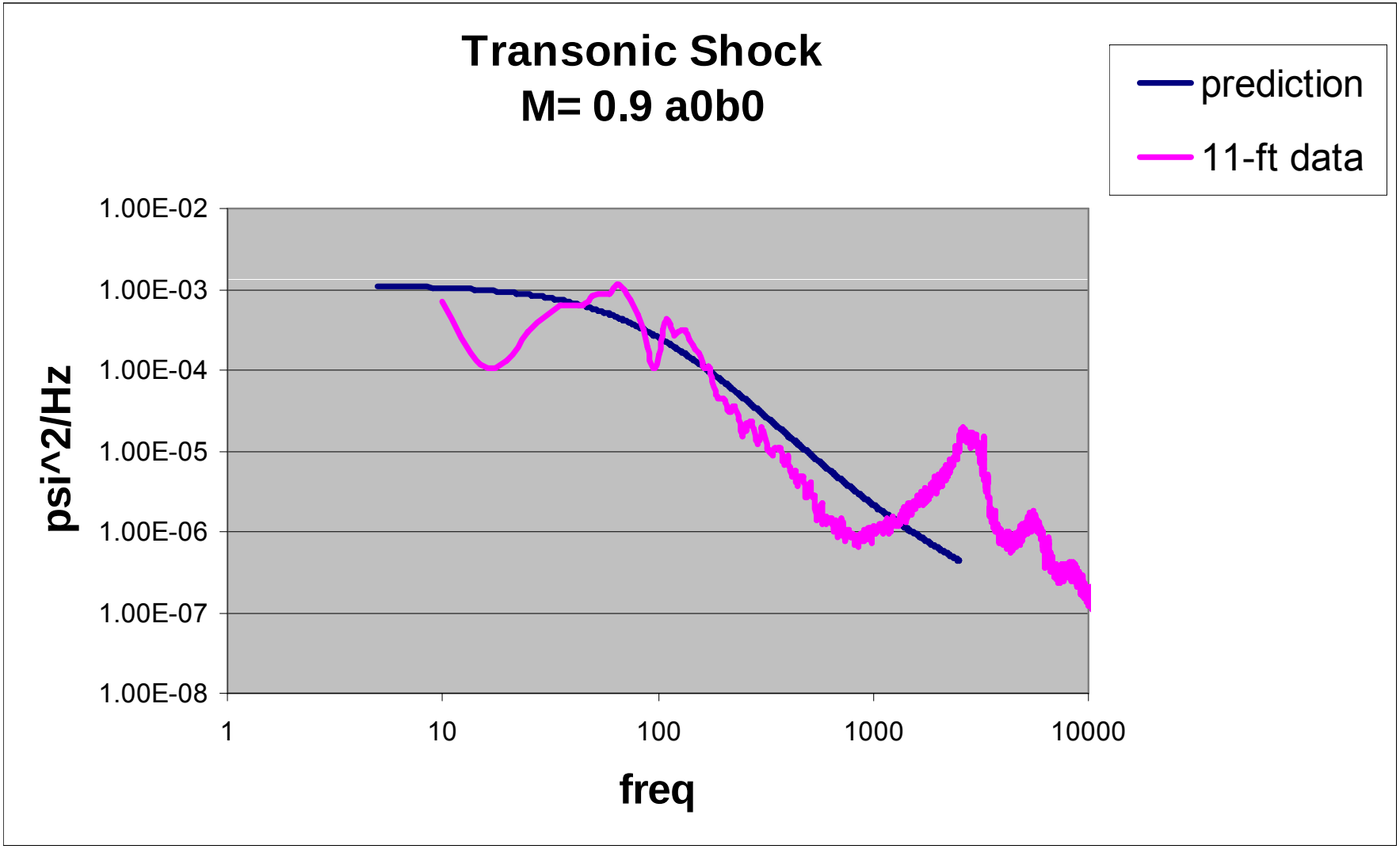
Shock-Induced SFP on ALV

- **Significant energy in low frequencies was observed at the forward transducers for M= 0.9**
  - CFD and shadowgraph show transonic shock sitting squarely at transducer station





Yeah, right…

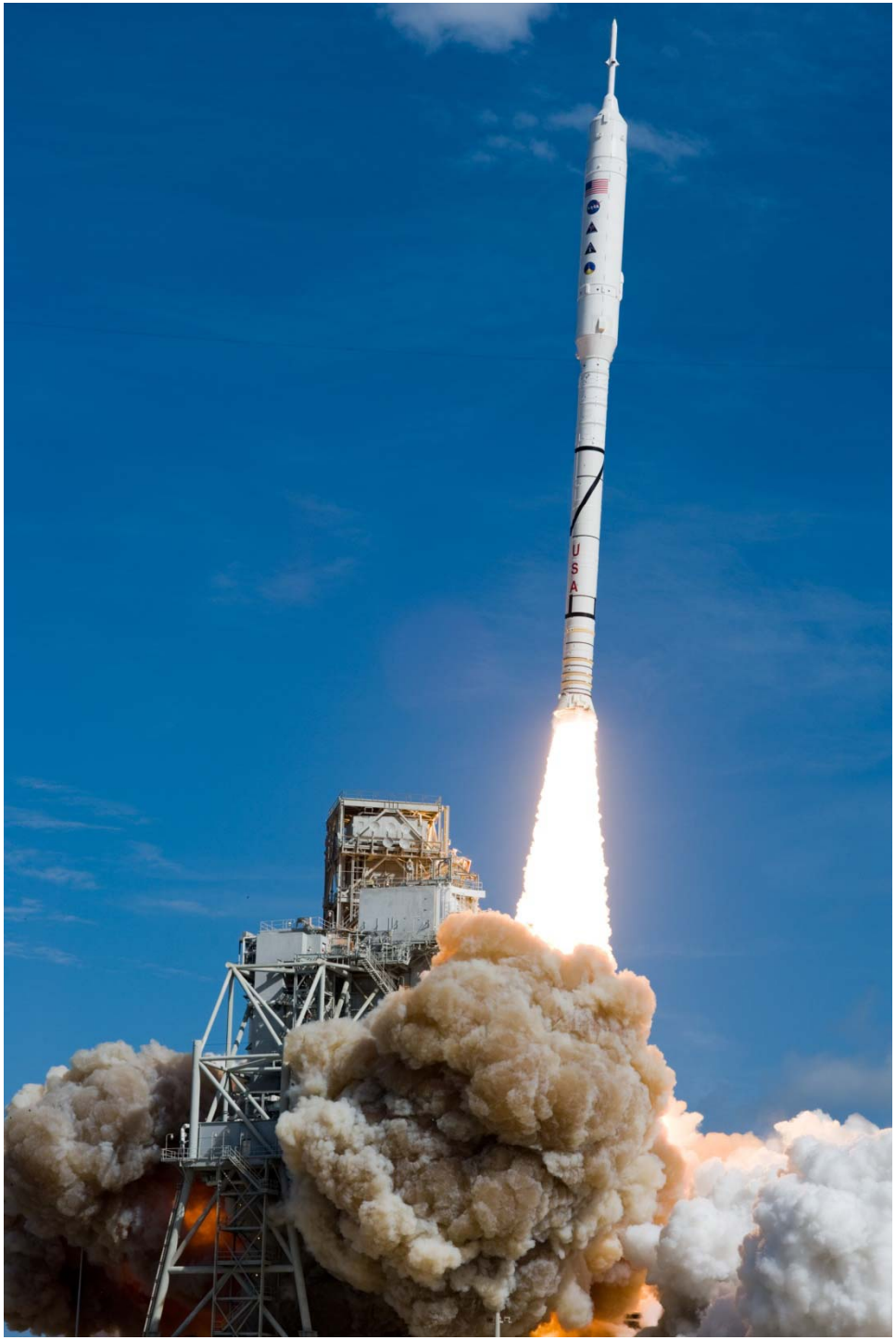

Transonic Shock
M= 0.9 a0b0
prediction
11-ft data
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
psi^2/Hz
1
10
100
1000
10000
freq

SFP Estimates Guided by CFD

Method developed to enhance application of legacy SFP-correlation databases via use of flowfield details from steady CFD solutions.

- From a portfolio of consistent CFD solutions (M, AoA), identify a region on vehicle where flowfield shows an SFP-generating feature.
- Over a structural "zone", method would be used to predict the levels & spectra (auto- & cross-) from each feature in the zone, and the fraction of the zone area loaded by the feature
- Predictions would benefit greatly from augmenting legacy database with results from select "building-block" LES's of generic flowfield features
  - Spatially-varying cross-spectra

AI-X FLIGHT



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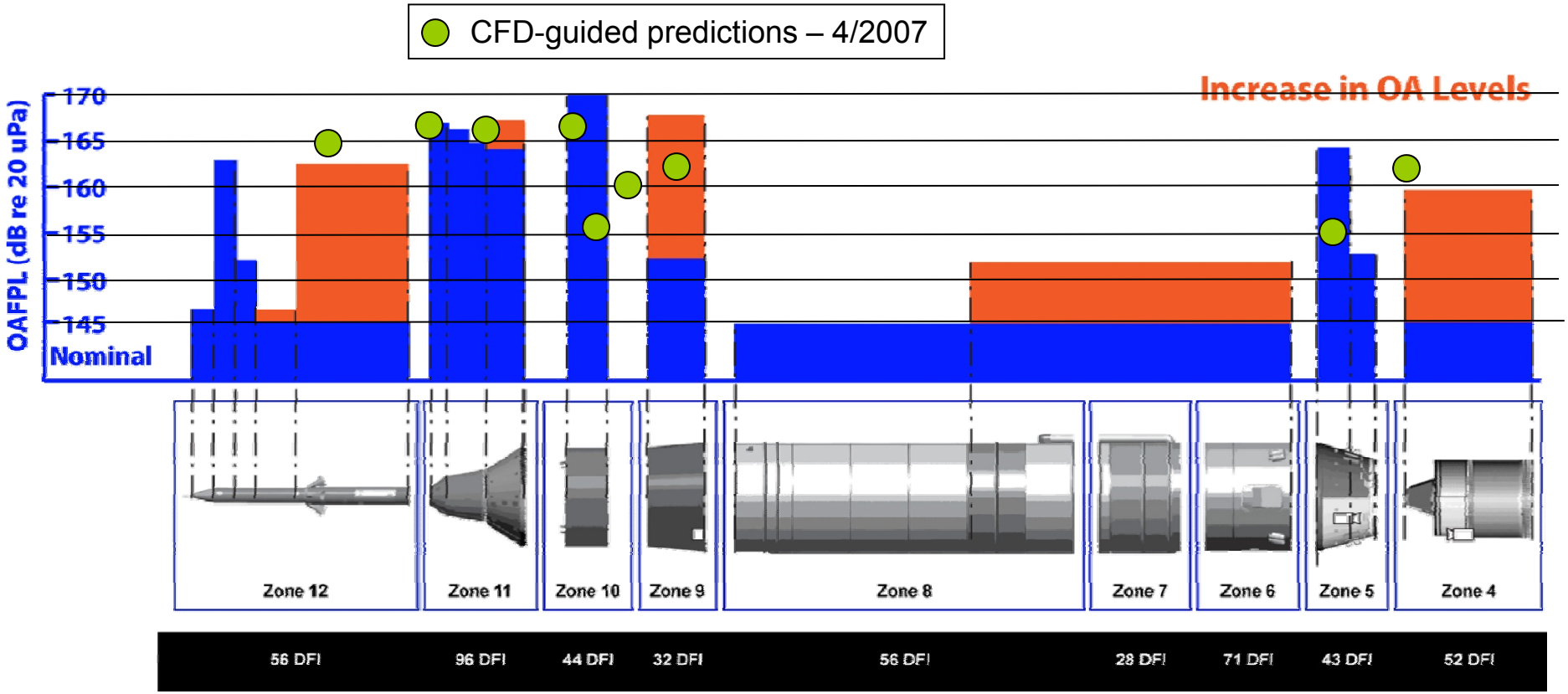
Ascent Acoustic Environments Challenge
(LaRC/K. Rivers chart – 7/2008)

- **WT-derived acoustic environments exceed predictions in some locations**
  - Predictions were based on 40+ yrs of historical data
  - Based on limited number of acoustic measurements taken during Ares 1X rigid buffet test (orange deltas)

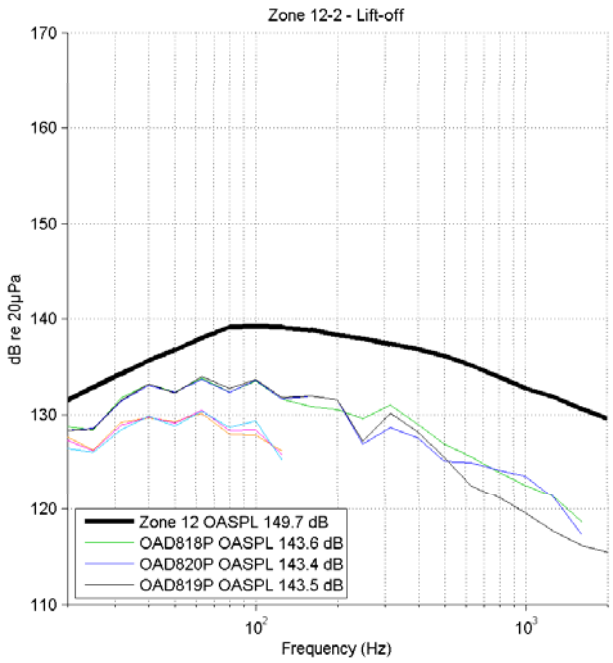


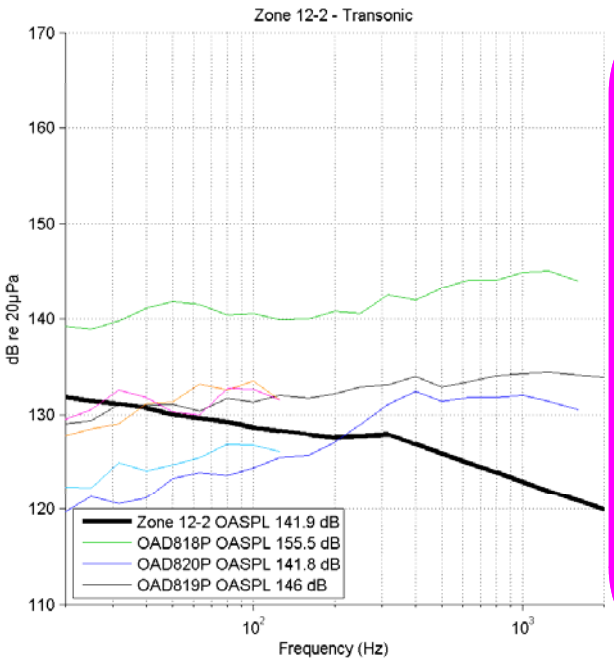
Whence the Exceedances?

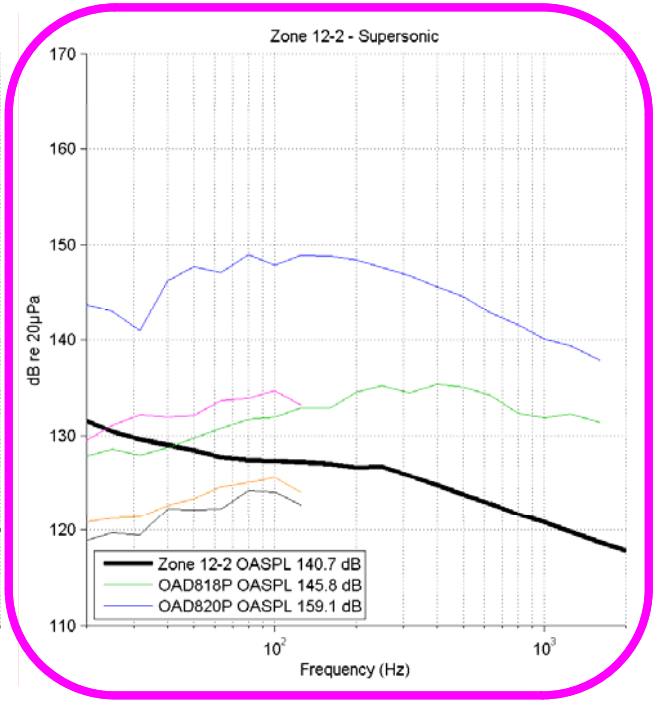
- For the most part, observed exceedances are due to a localized high-FPL feature
  - Feature sits on or passes over transducer
  - How local?
  - Is its duration short-term, or does it move with Mach, AoA, etc?
- Localization (in space & time) influences importance of these high levels on structural response and component damage

⇨ **Details of these features must be understood**

Zone 12-2







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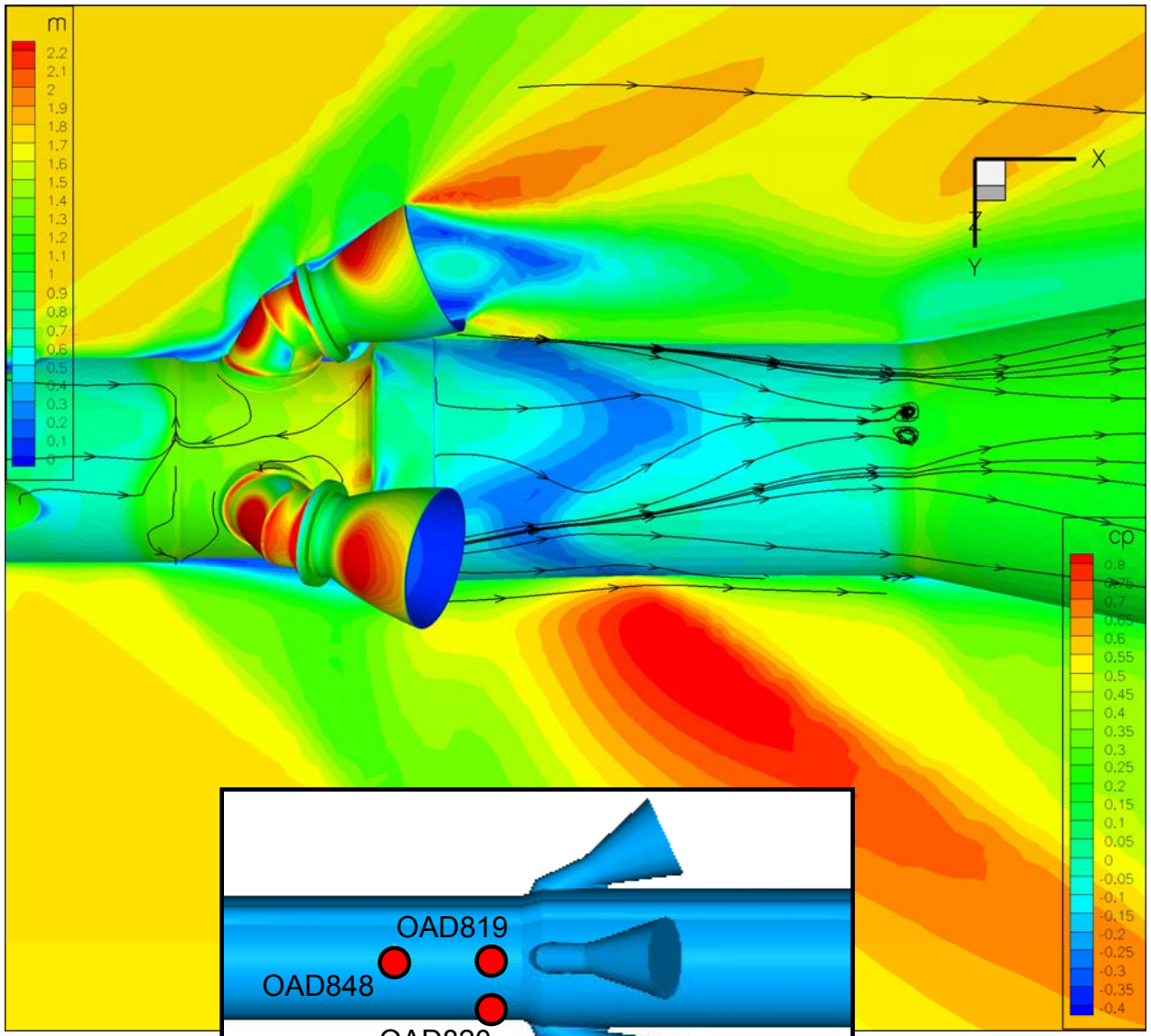
M= 2.1 near LAM Nozzles

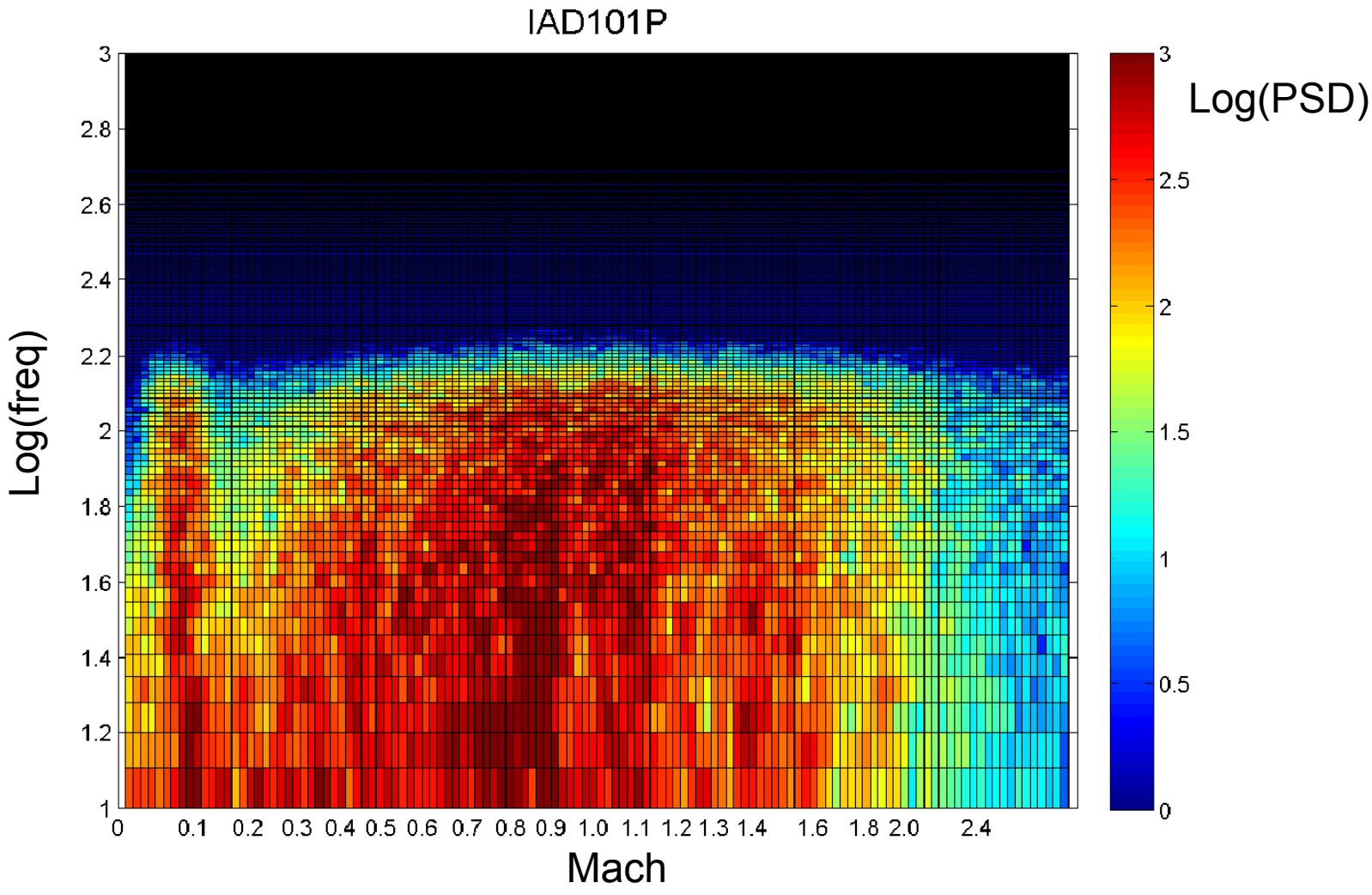
Plane thru nozzle CL

Plane between nozzles



Spectrograph Display

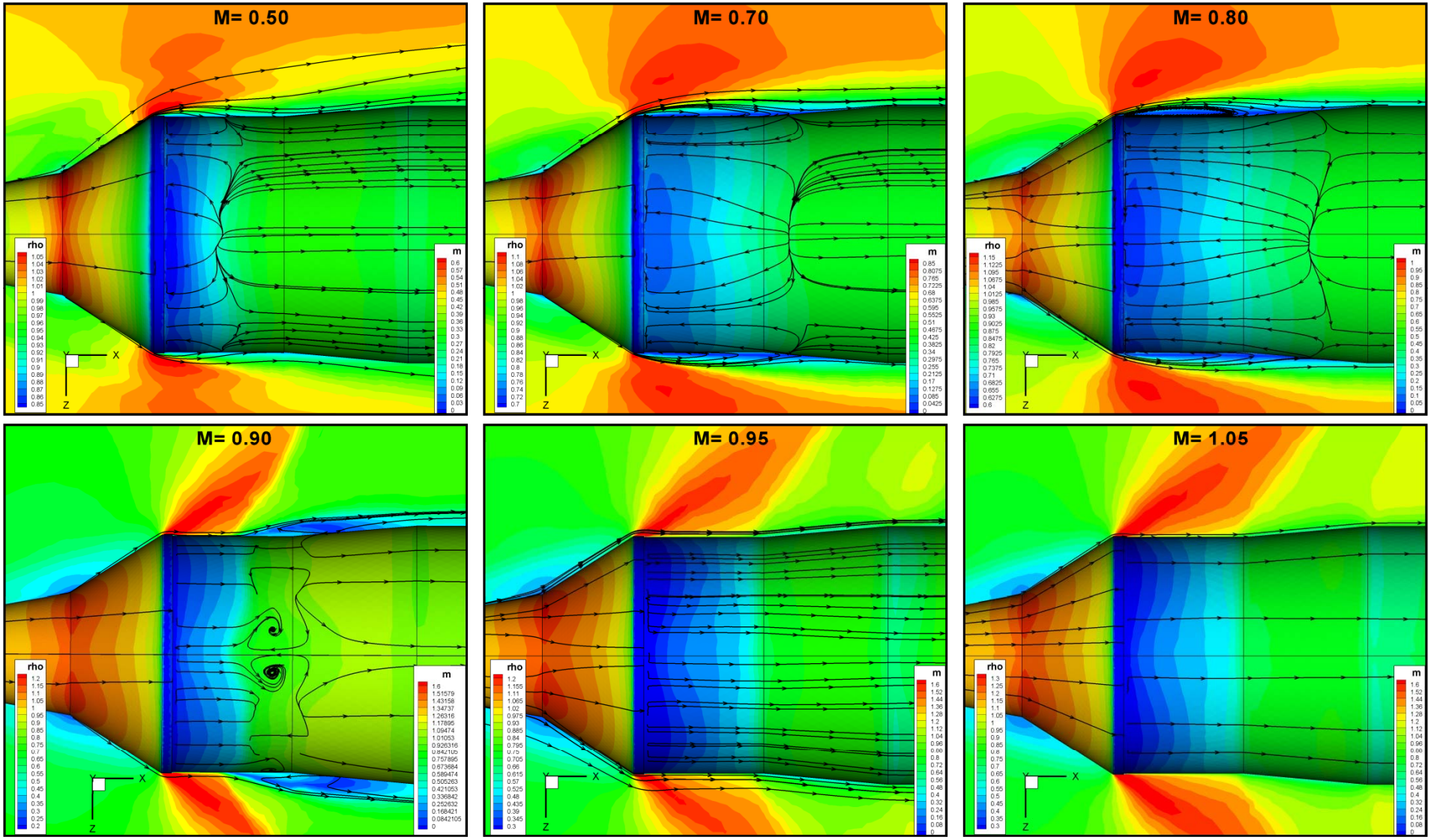
- Results will be shown using contours of log(power-spectral density) v. log(frequency) with Mach number (from BET2 & time).



Expansion-Corner at CM-SM

- **Previous studies indicated that a rapid change in flowfield would occur when local Mach number in expansion sufficiently exceeds M=1.**
  - Subsonic flow yields long separated region
    - High SFP, especially near reattachment point
  - Supersonic flow yields attached flow
    - Terminates in normal shock, which moves aft with Mach number
- **In a WTT, holding Mach constant in this narrow range often leads to the flow jumping back & forth between these conditions**
  - "alternating flow", potentially asymmetric
  - Much feared pre-flight, but only a minor blip

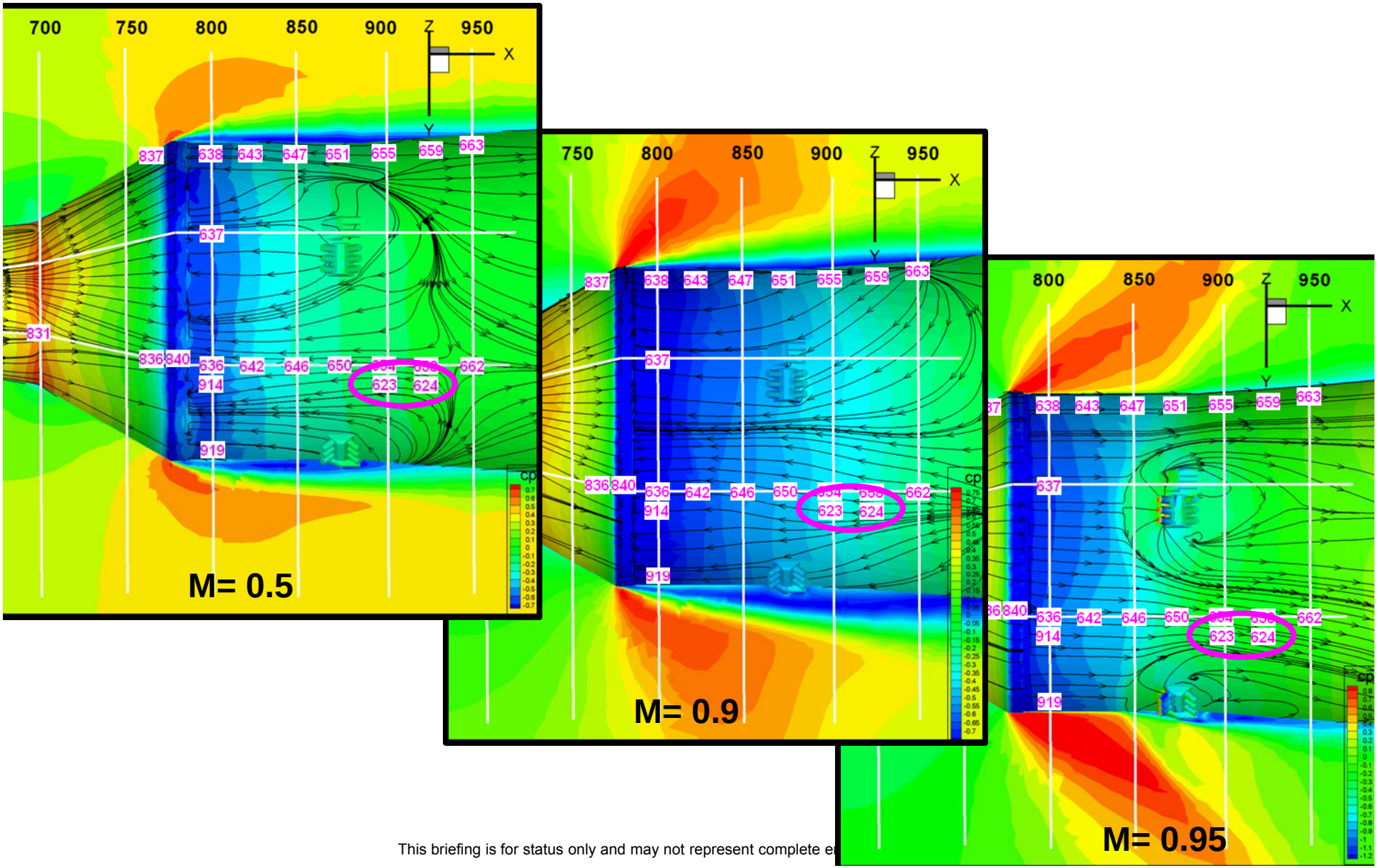
CM-SM Expansion-Corner Flowfield



No-protuberance configuration

may not represent complete engineering information

CFD for AI-X BET2 Conditions



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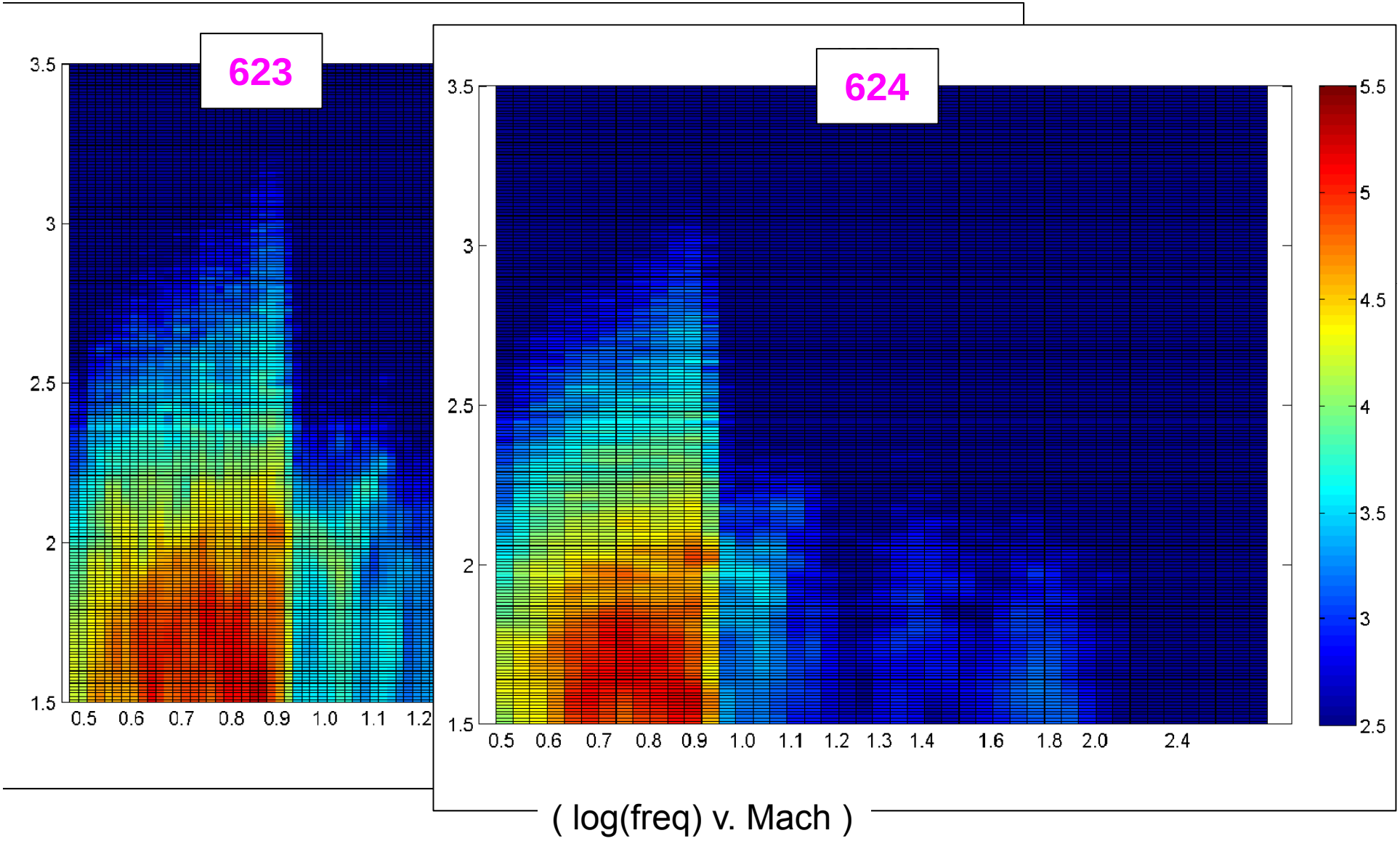
PSD Maps w/ Mach number

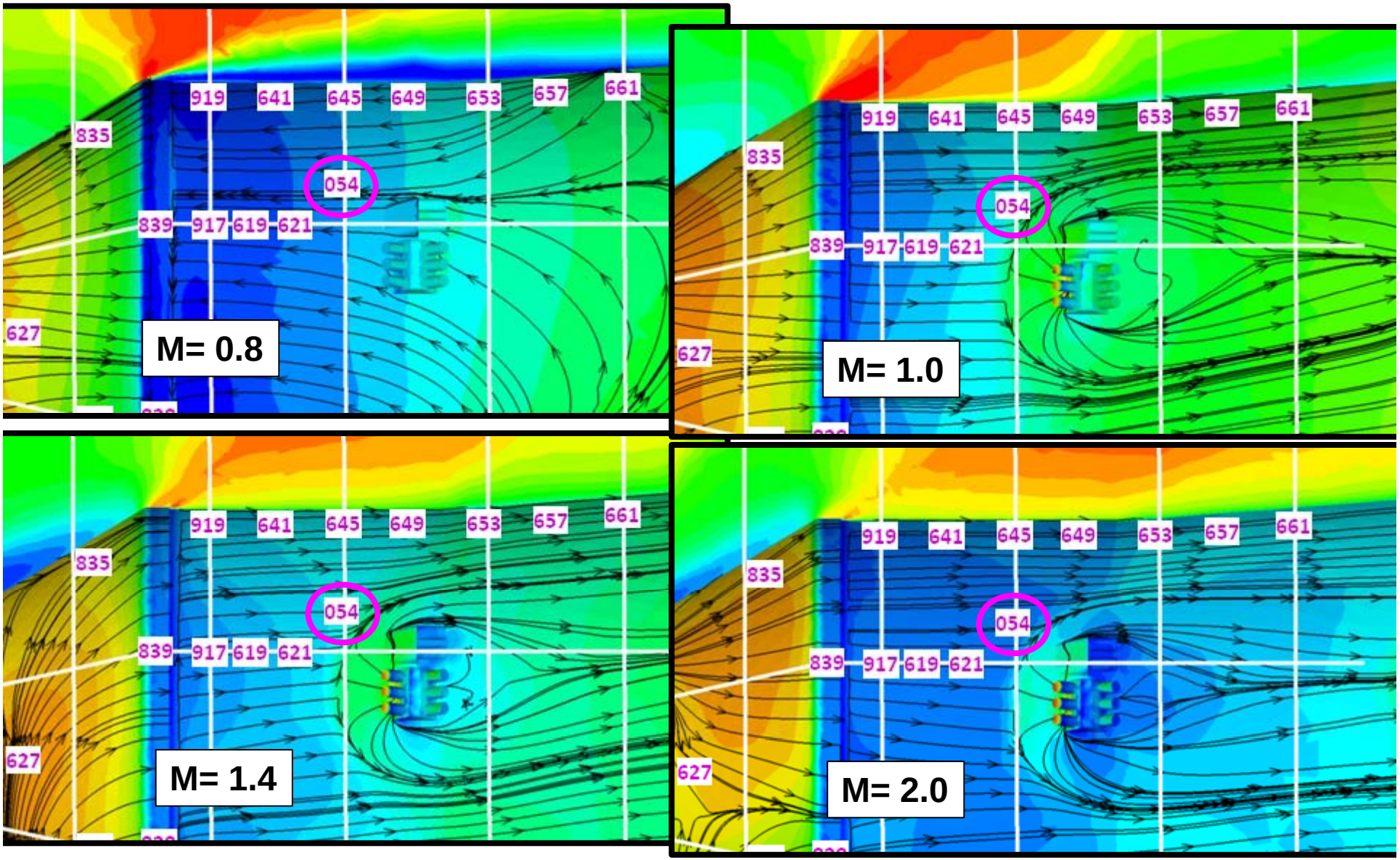


(log(freq) v. Mach)

Flowfield around 3D Protuberances

- **Protuberances with leading-edge normal to surface have been studied the most**
  - Most severe SFP environment
  - Critical to predict footprint of affected area
- **Dominant flowfield feature is "necklace" vortex**
  - Created by BL separation on symmetry plane / stagnation streamline ahead of leading edge
  - Vortex wraps around protuberance laterally, carrying & creating turbulent fluctuations
  - For supersonic oncoming flow, strong oblique shock created ahead of separation, sweeping laterally into 3D shock surface
    - Additional strong SFP-generating mechanism
      - SBLI
    - Shock weakens as vortex sweeps downstream

CFD for AI-X BET2 Conditions



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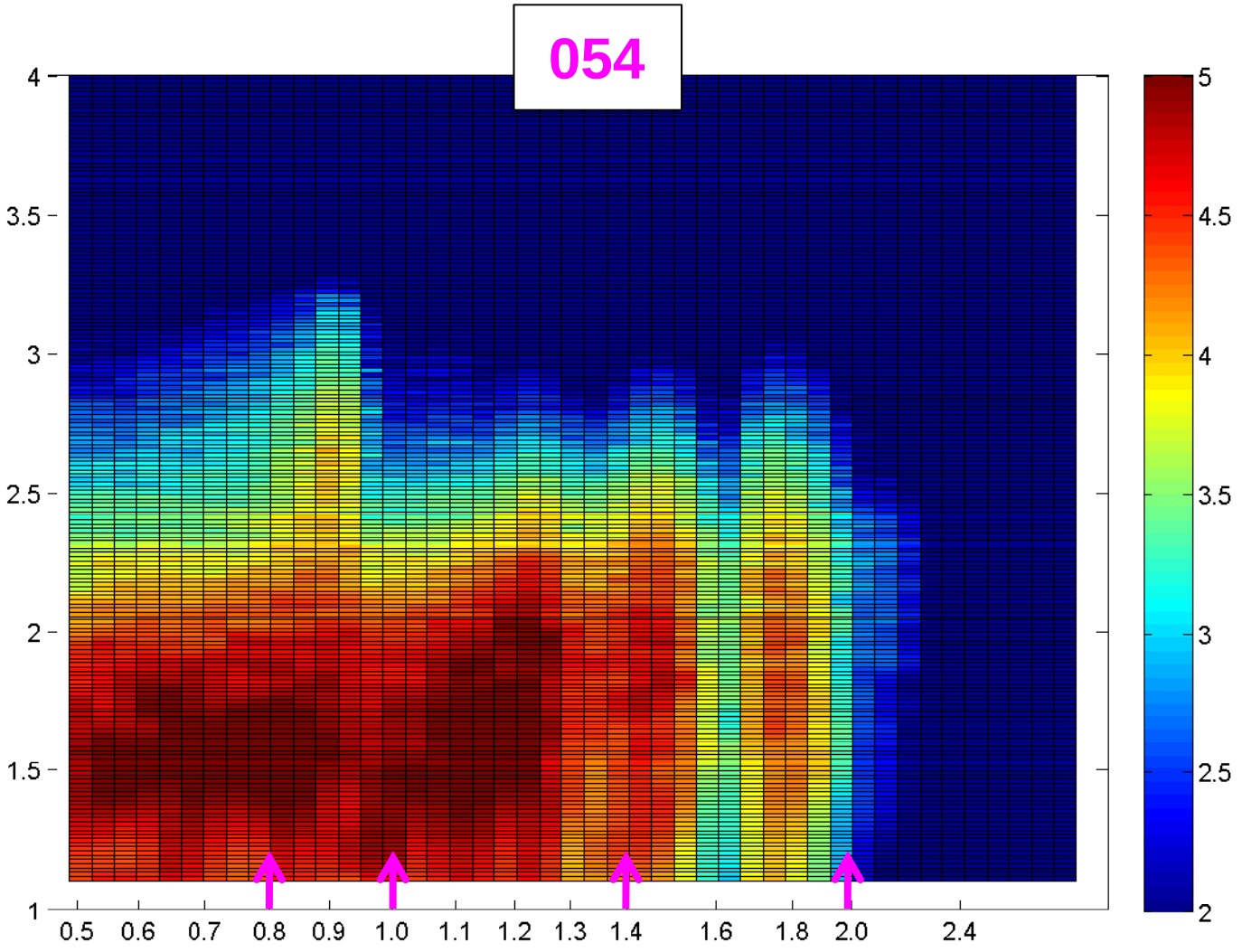
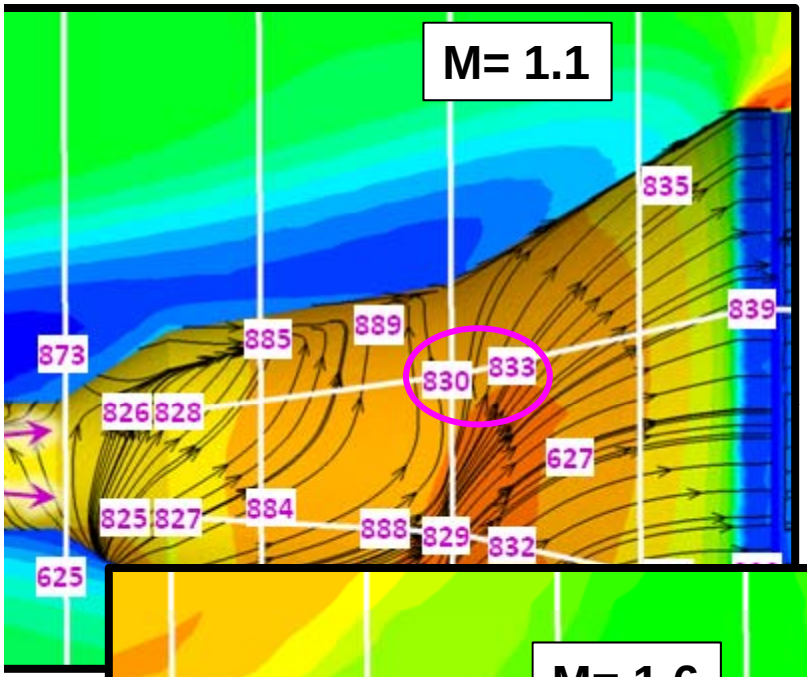


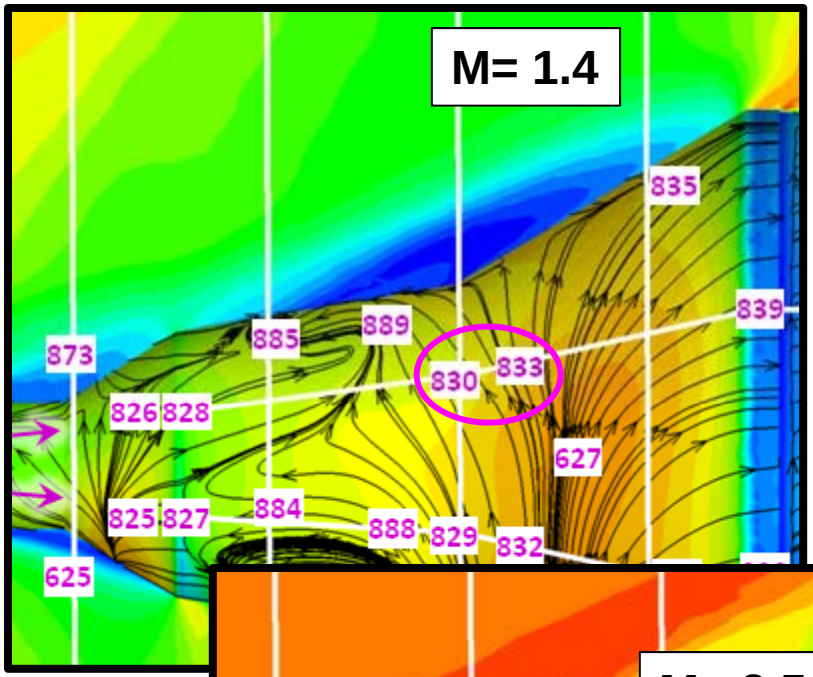
(log(freq) v. Mach)

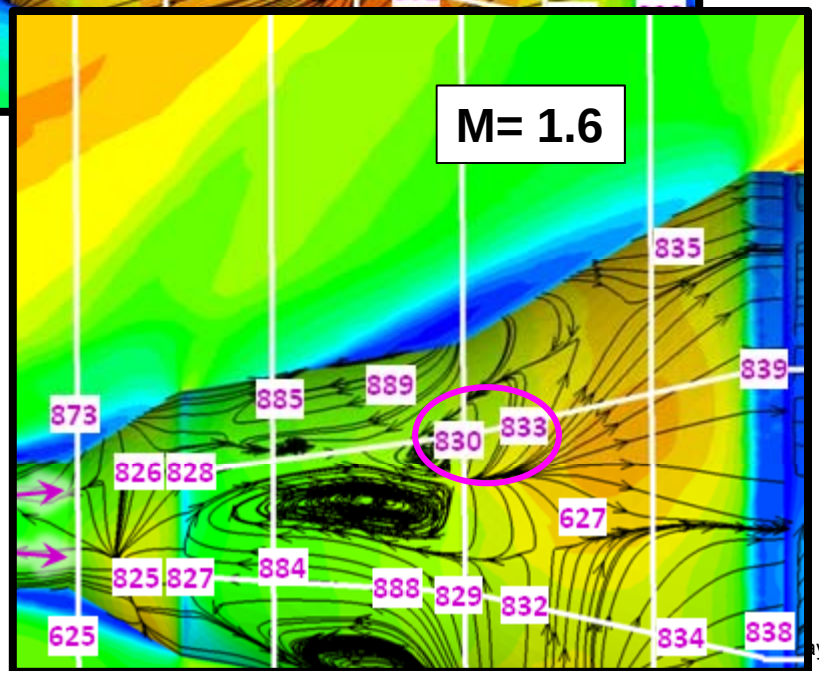
Shock-Induced Separation: SBLI

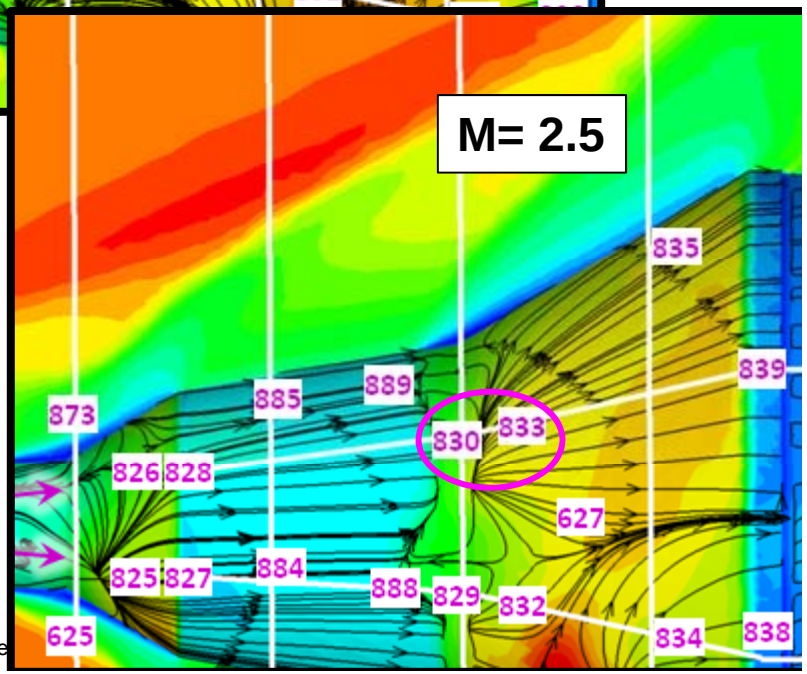
- **The oblique shock from a compression corner in low-Mach number flow produces a local BL separation, which moves the pressure rise somewhat upstream, and causes high SPF levels due to shock oscillation and separated-flow reattachment.**
  - Both levels and spectrum can be predicted well using steady CFD / database method
    - Well-studied problem, large experimental database
    - Numerical simulations in progress
  - On AI-X, SBLI occurs at “Party-Hat” – CM junction
    - Some complication from interaction with AM-nozzle wakes

CFD for AI-X BET2 Conditions









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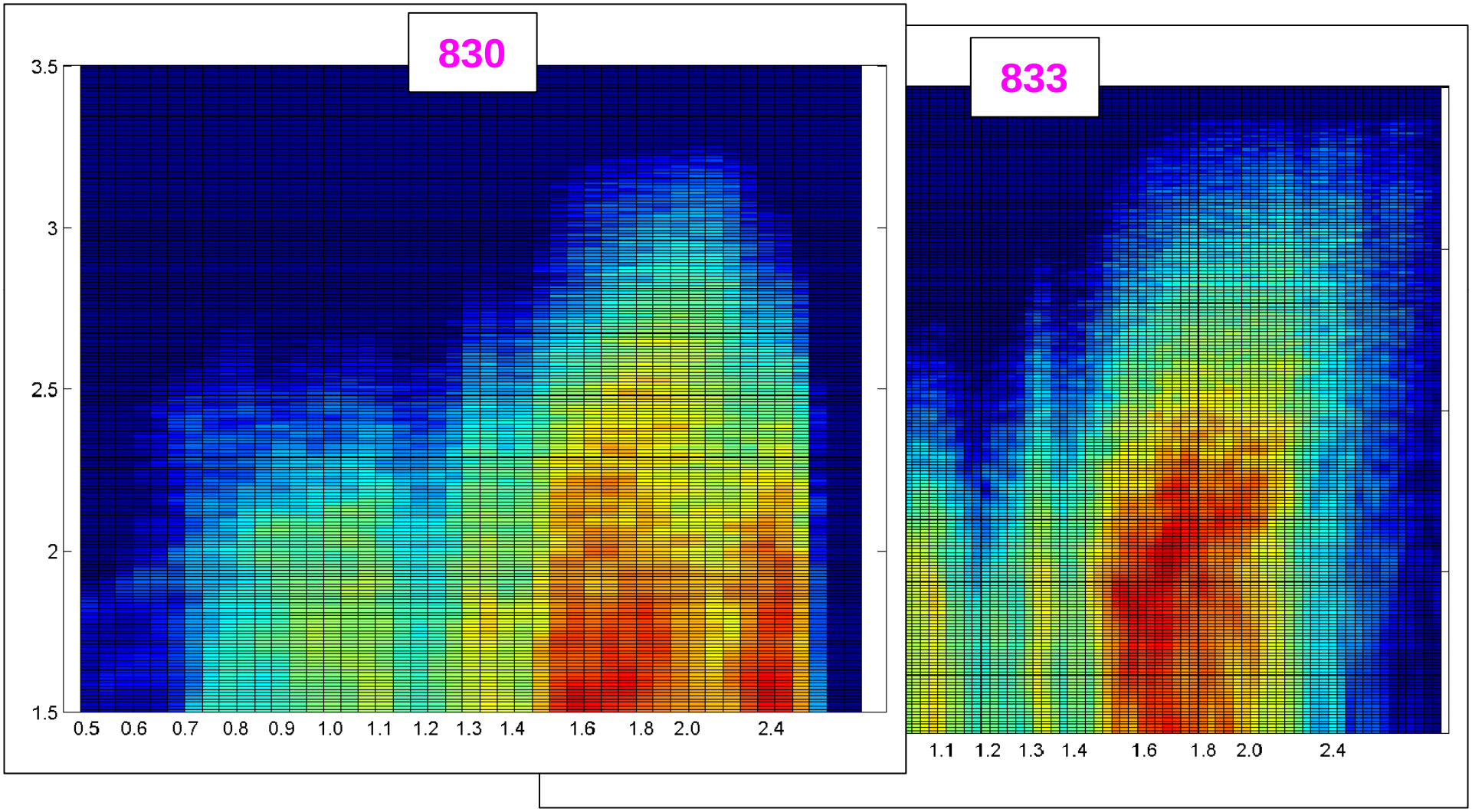
PSD Maps w/ Mach number



(log(freq) v. Mach)

Conclusions

- **Flowfield predictions from steady CFD can (for the most part) be interpreted to explain local levels of SFP in a qualitative sense.**
  - Extrapolate a reliable set of measurements to a new (but similar) vehicle configuration or trajectory
- **SFP from "basic" flowfield features on simple OML's can be predicted with reasonable accuracy**
- **Flowfields on "real" configurations are sometimes too complex for quantitative prediction of SFP to be reliable with current databases.**
- **Serious lack of cross-correlation data for flowfield features which generate high SFP levels.**
  - Excessive conservatism, or ***?***