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Why We Withdrew Our Paper on Compressibility Effects in the Shear Layer Over a Finite-Width Rectangular Cavity

Steven Beresh, Justin Wagner, Brian Pruett, John Henfling, and Rusty Spillers

Sandia National Laboratories

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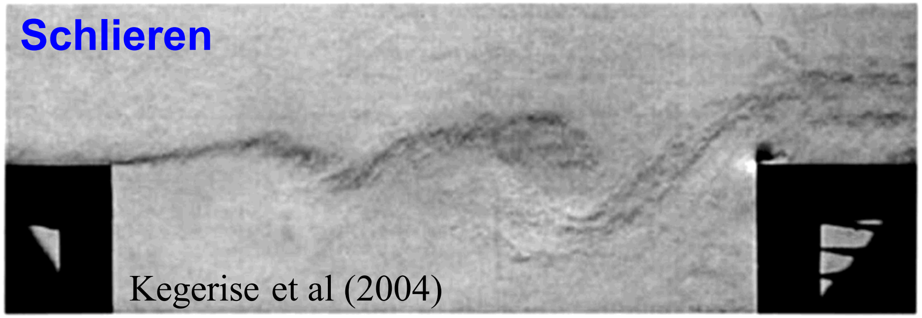
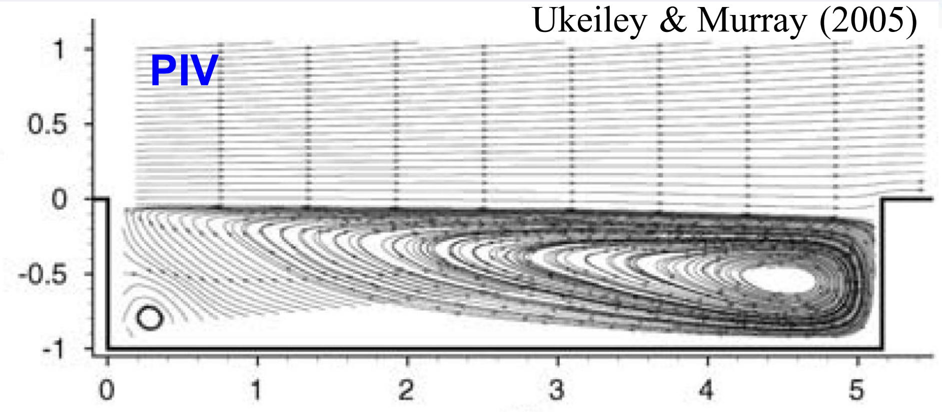
Cavity Flow Dynamics



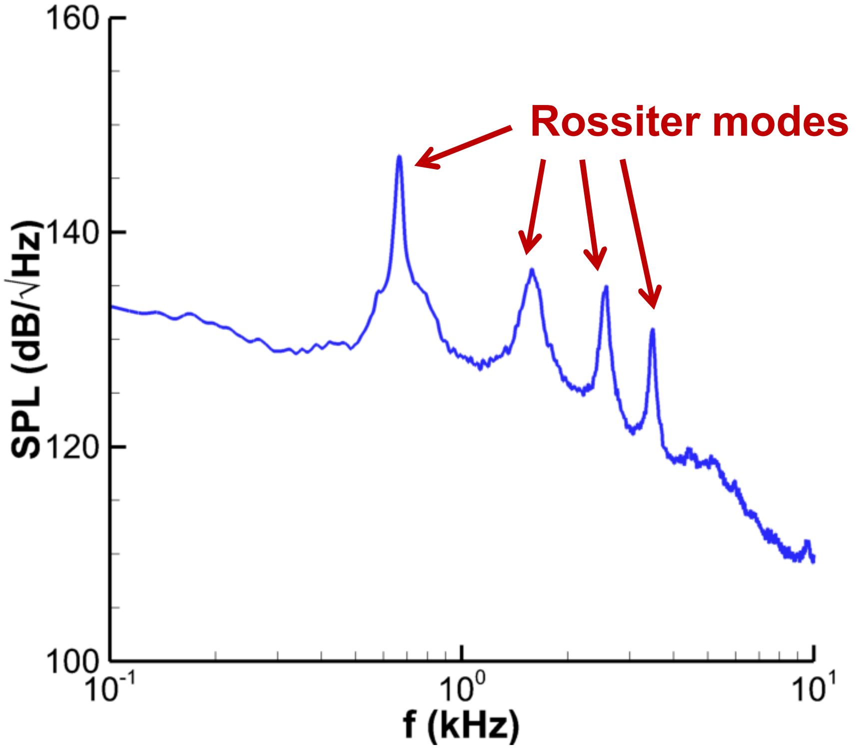


Interaction of free shear layer and cavity walls produces longitudinal resonance tones.

These acoustic tones are associated with specific dynamics of the shear layer vortices.

Prediction of resonance frequencies by the Rossiter equation is fairly robust.

But mode amplitudes are a function of the cavity width.

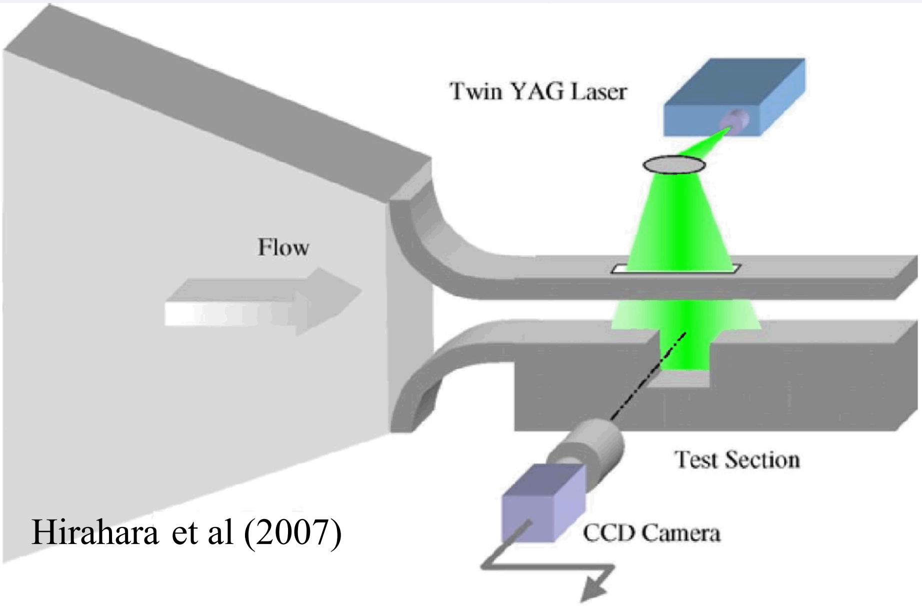


Cavity Flow is Dependent on Geometry

Most experiments study a *two-dimensional* cavity.

Cavity extends to full width of test section, windows on each end.

Aids imaging of the normal streamwise plane.



Hirahara et al (2007)

This doesn't resemble a real weapons bay.

A *three-dimensional* cavity.

Some studies have shown width is an important parameter for narrow cavities.

Alters the flow structure of the shear layer and recirculation region, which alters acoustics.

We recently have been studying width effects from Mach 0.5 to 2.5.

F-35 Weapons Bay

(photo: Lockheed Martin)

Compressibility in Cavity Flows

Many compressibility studies in shear layers; hardly any specifically in cavities.

Compressibility is known to affect shear layer structure, which can be expected to alter acoustic tones.

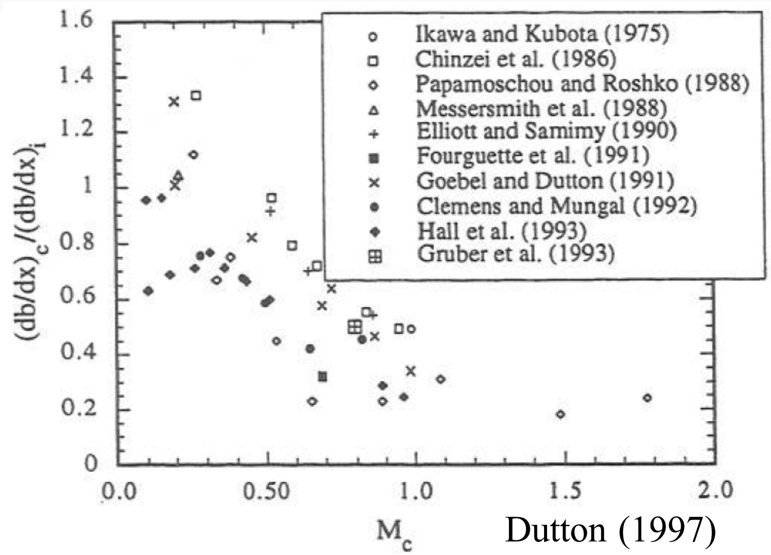
Note that Mach Number is a parameter in the Rossiter equation.

CFD needs to predict compressibility correctly to get acoustics right.

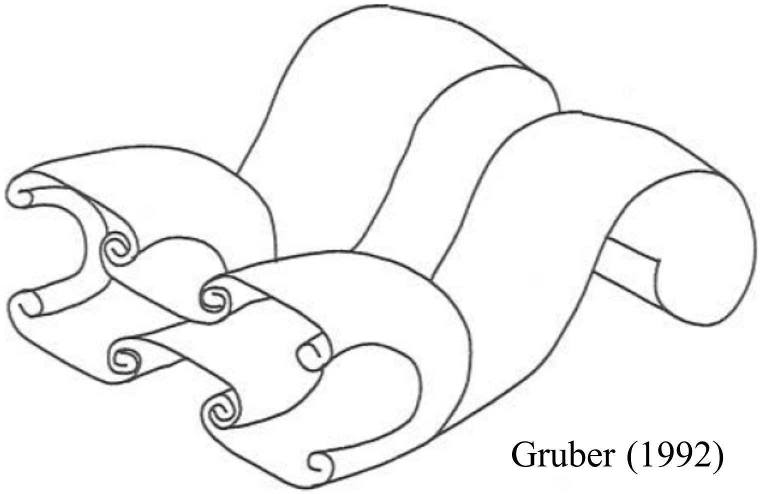
Our data set gives us an opportunity to study compressibility in a cavity.

Compressibility increases spanwise three-dimensionality in shear layers.

- Does this interact with cavity width?
- Does it change flow structure or acoustic tone amplitudes?



Dutton (1997)



Gruber (1992)

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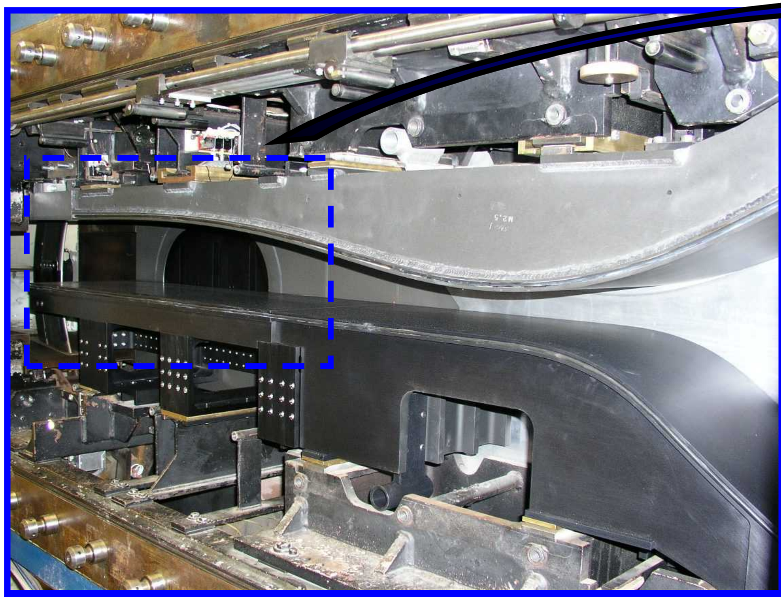
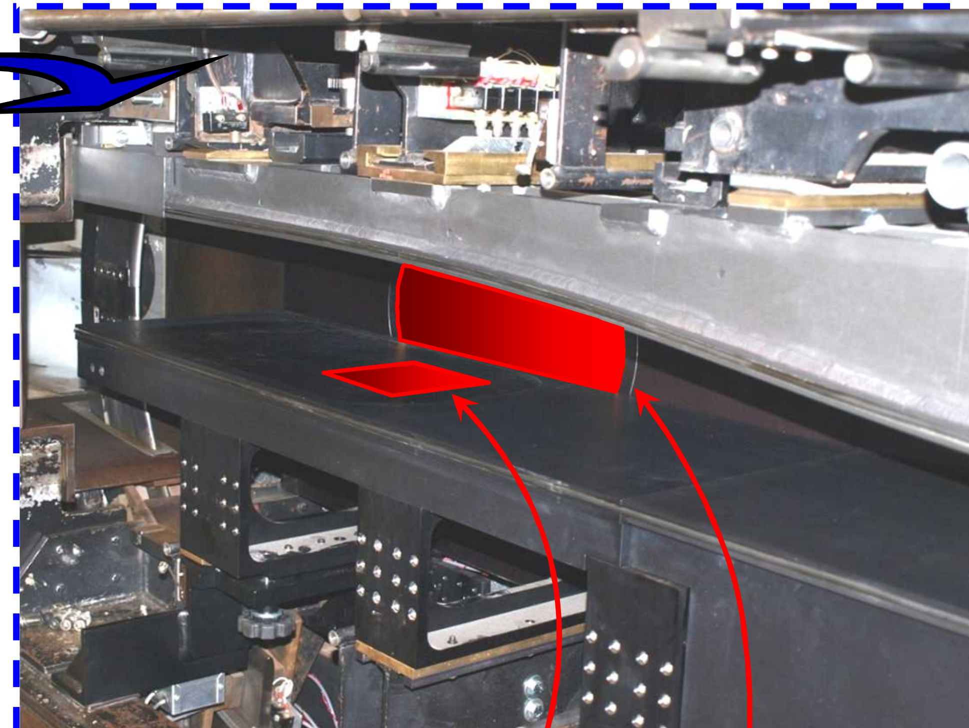
We Began with Supersonic Data

Sandia's Trisonic Wind Tunnel Half-Nozzle Test Section





Build a cavity into the test section wall.

The schlieren side-wall window is adequate for the PIV cameras.

Our 3-D cavity is a rectangular cutout.

Three configurations:

- 5″ long × 5″ wide (127 × 127 mm^2)
- 5″ long × 3″ wide (127 × 76 mm^2)
- 5″ long × 1″ wide (127 × 25 mm^2)

All depths: 1.02 inch (25.9 mm)

The cavity bottom is glass for laser access.

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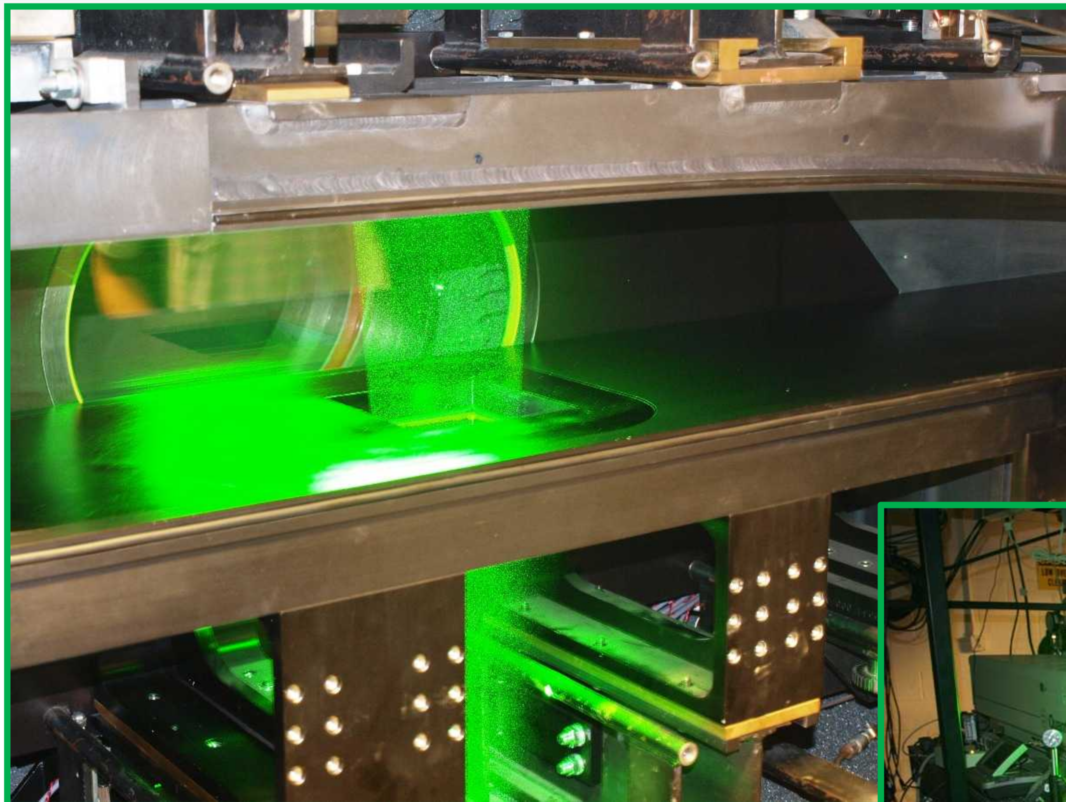
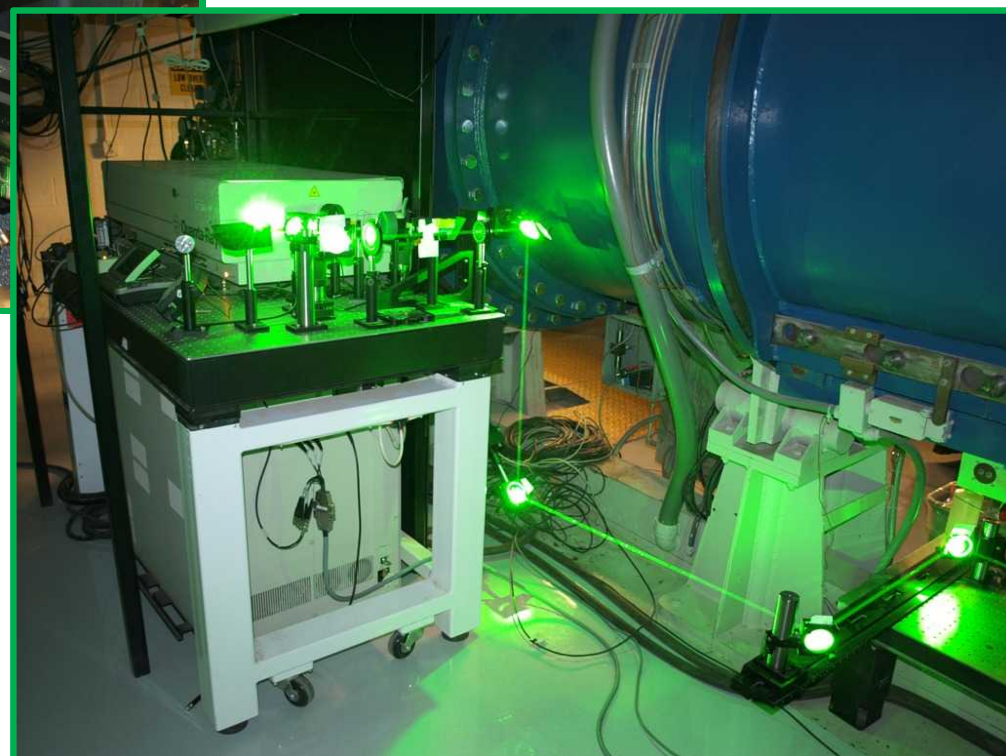
PIV Parameters



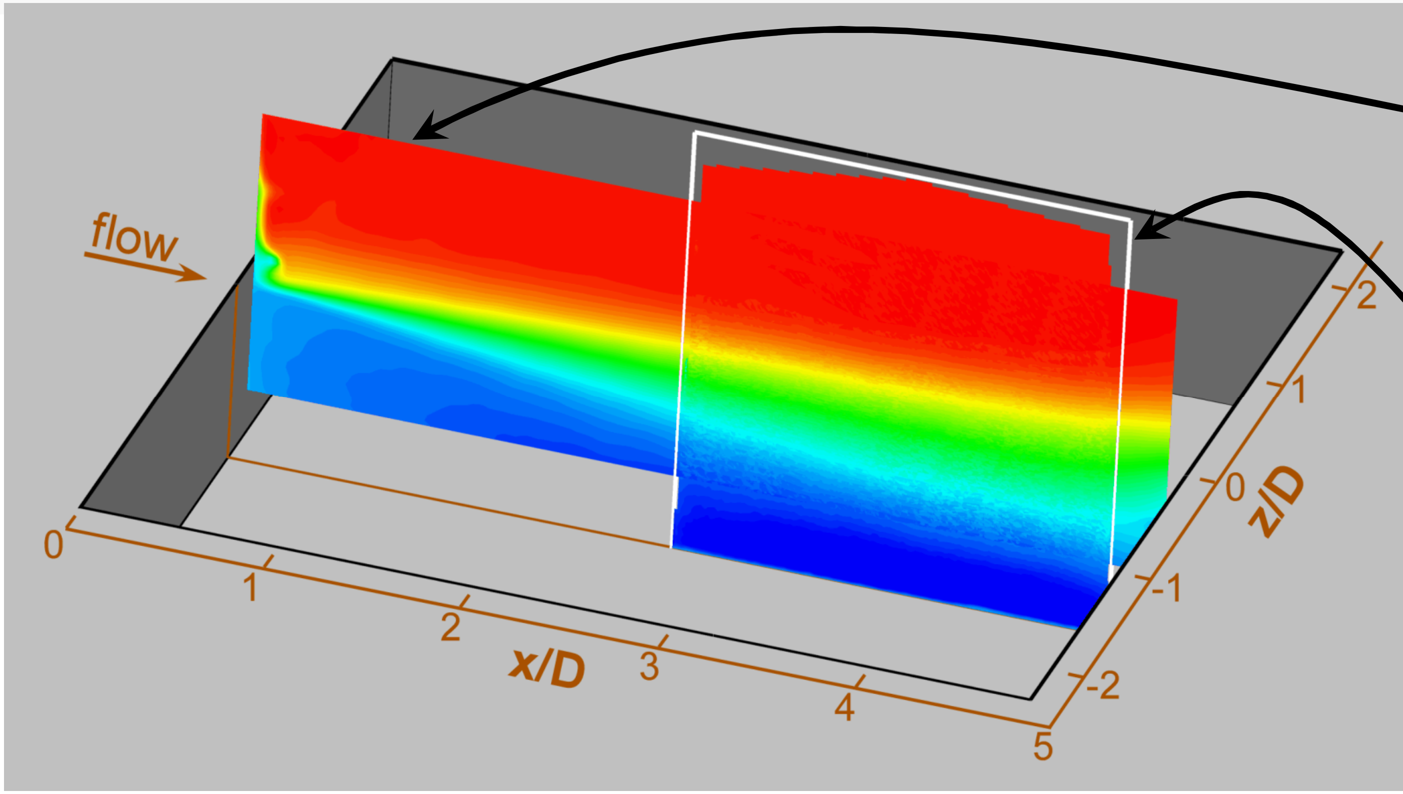
- **Particles 0.7 – 0.8 μm (St < 0.04)**
- **1 mm thick laser sheet aligned to cavity centerline**
- **Δt = 1 - 1.5 μs**
- **4 MP cameras**



Data processed with one interrogation pass at 64 × 64 pix^2, two passes at 32 × 32 pix^2.

All cases have ≥ 750 realizations over 5+ wind tunnel runs.

PIV Measurement Locations



2-C PIV surveyed the entire extent of the cavity, but:

- Had a bias error in the vertical component.
- Could not reach the bottom of the cavity.

Stereo measurements solved both problems.

- Survey the aft end of the cavity.

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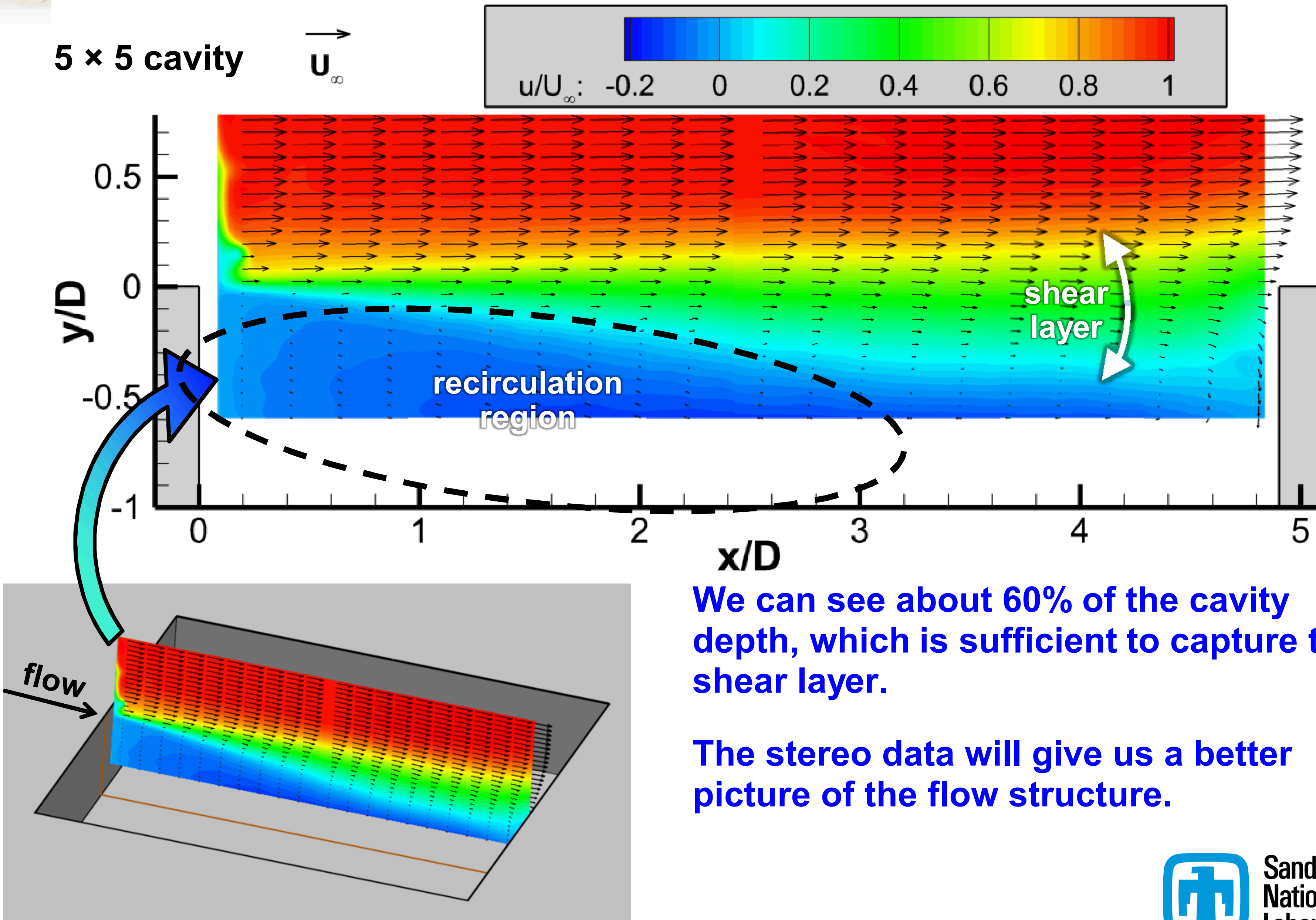
Two-Component Mean Velocity Field



We can see about 60% of the cavity depth, which is sufficient to capture the shear layer.

The stereo data will give us a better picture of the flow structure.

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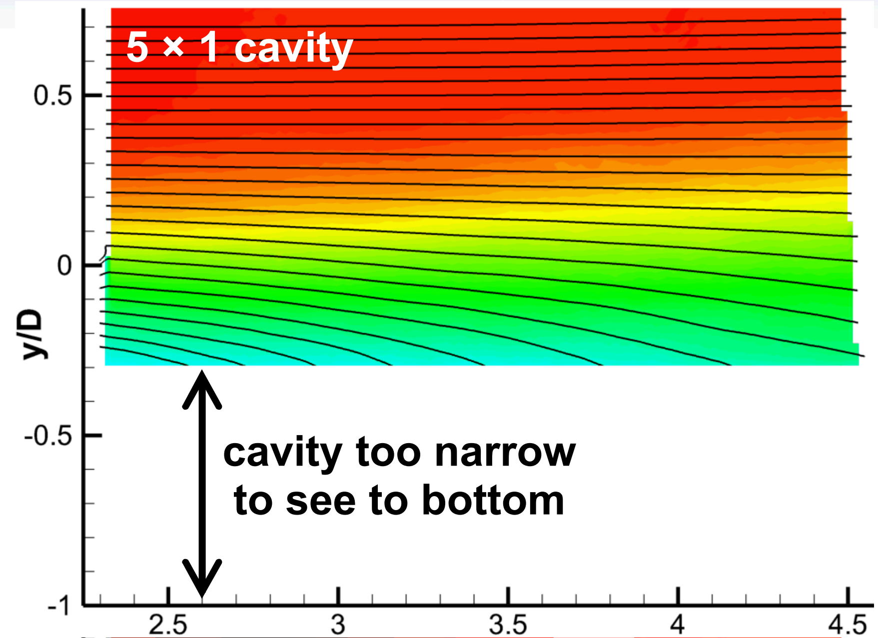
Mean Velocity Fields (Mach 1.5)

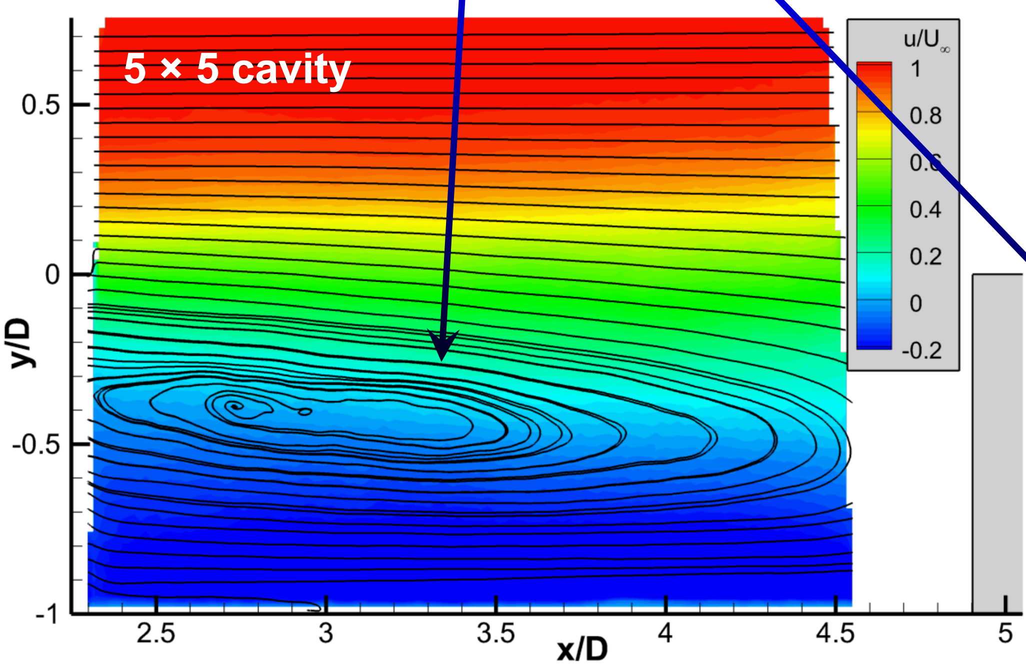
The recirculation region differs for the 5 × 5 and 5 × 3 cavities.

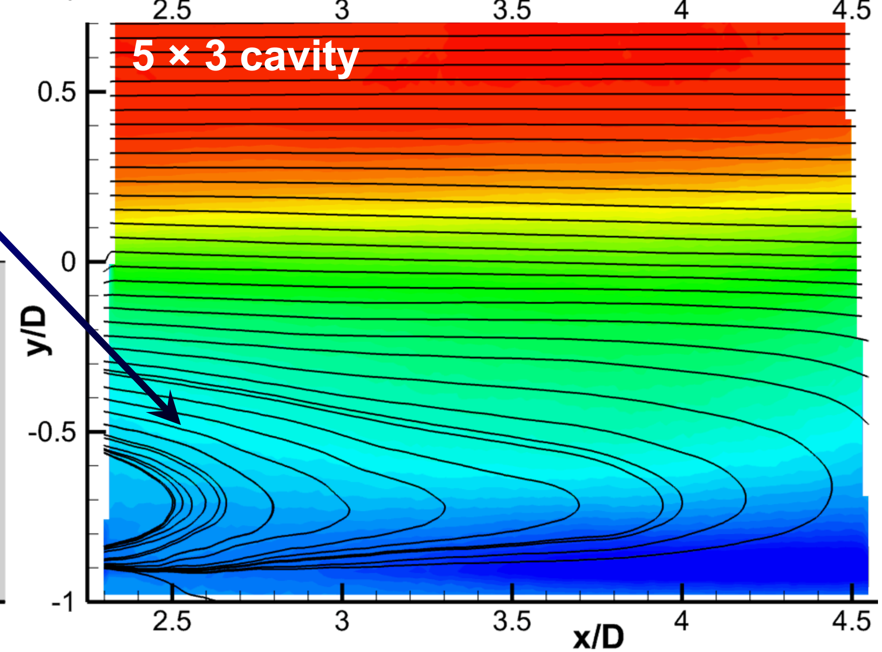
- Different vortex position.
- Smaller reverse velocities for 5 × 3.

The 5 × 1 cavity appears similar to the 5 × 5 cavity.

- Suggested by streamline shape.







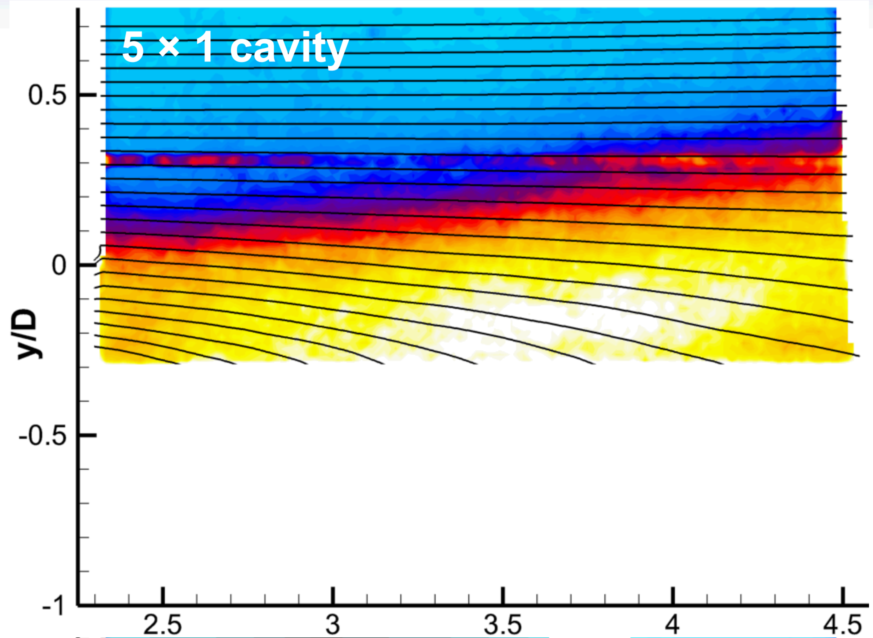
Turbulent Kinetic Energy (Mach 1.5)

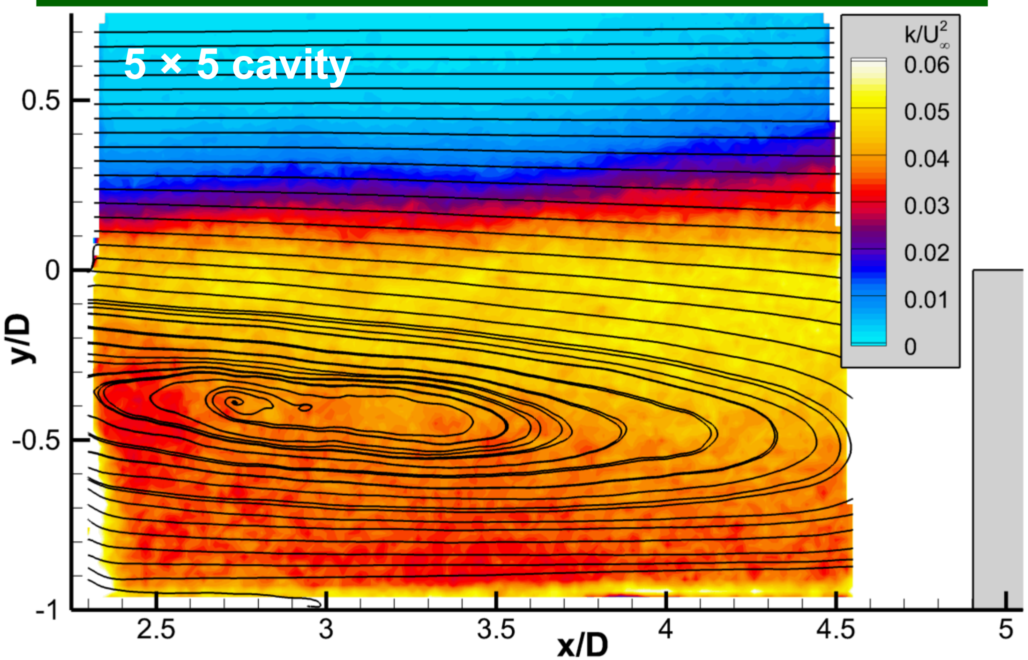
Turbulence is suppressed for the 5 × 3 cavity compared to the 5 × 5 cavity.

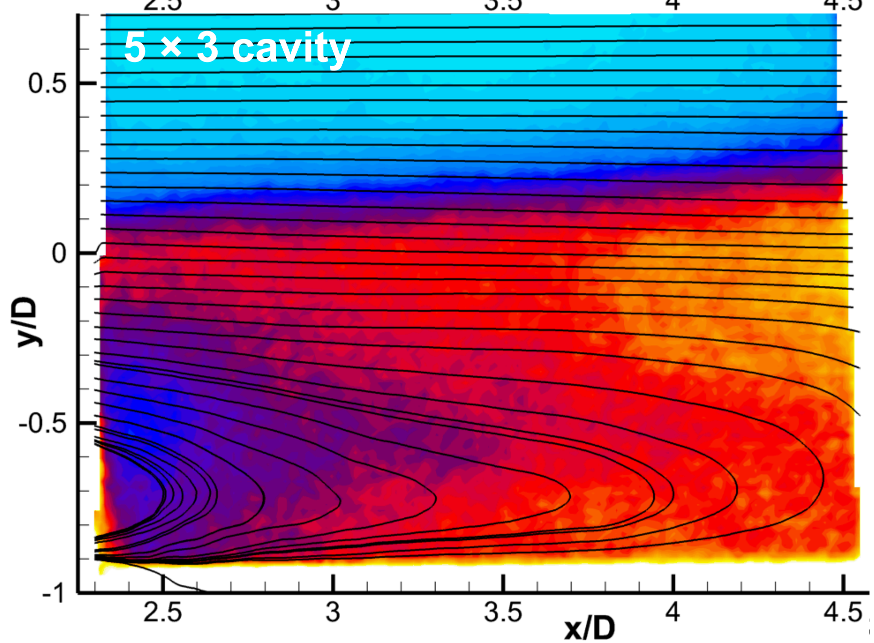
The 5 × 1 cavity has the highest levels of turbulence, but is closer to the 5 × 5 than to the 5 × 3.

The 5 × 3 cavity appears to be different from the 5 × 5 and 5 × 1 cavities.

- **Evidence of an influence of the cavity width?**



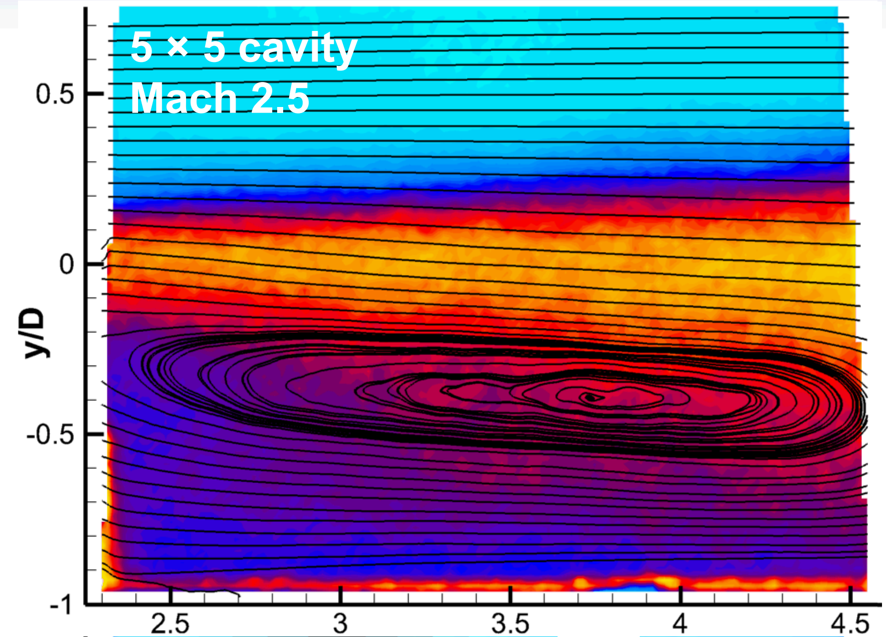


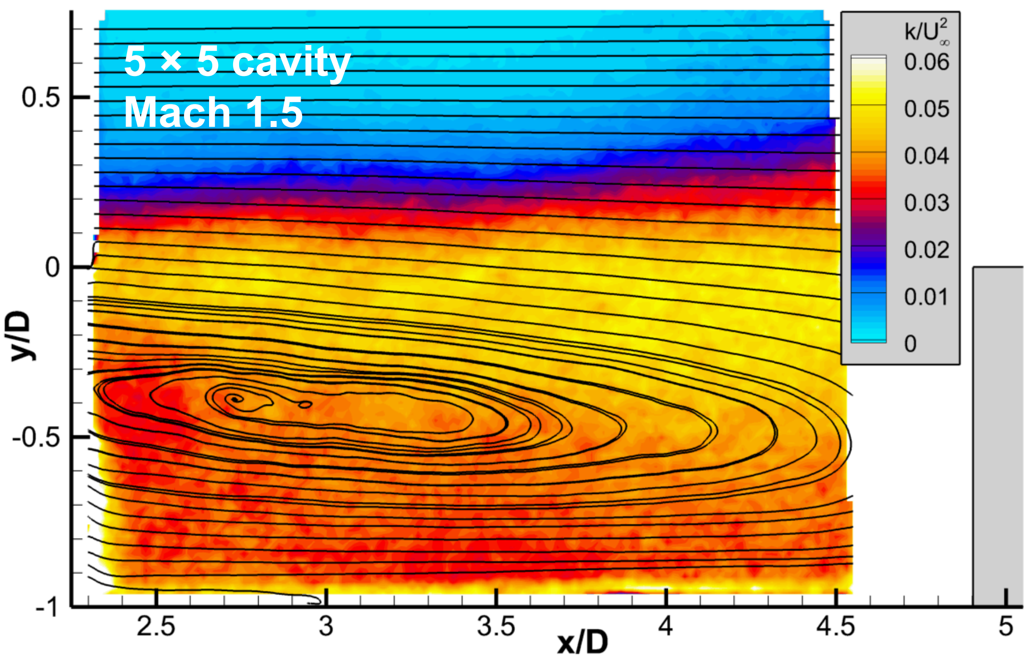


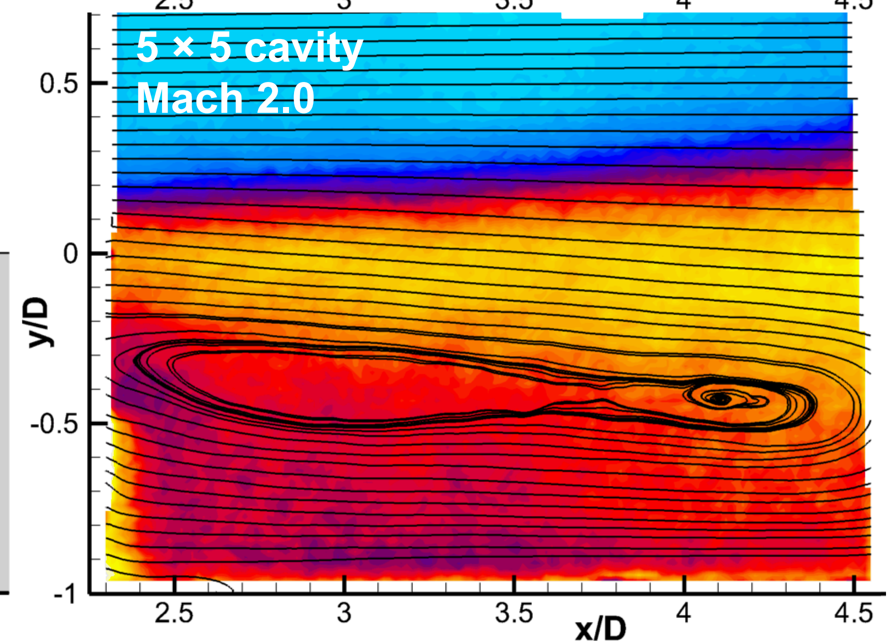
Turbulent Kinetic Energy (Variable Mach)

Despite streamline differences, the recirculation region is positioned similarly for all Mach numbers.

The t.k.e. decreases as Mach number rises, and the shear layer thins.







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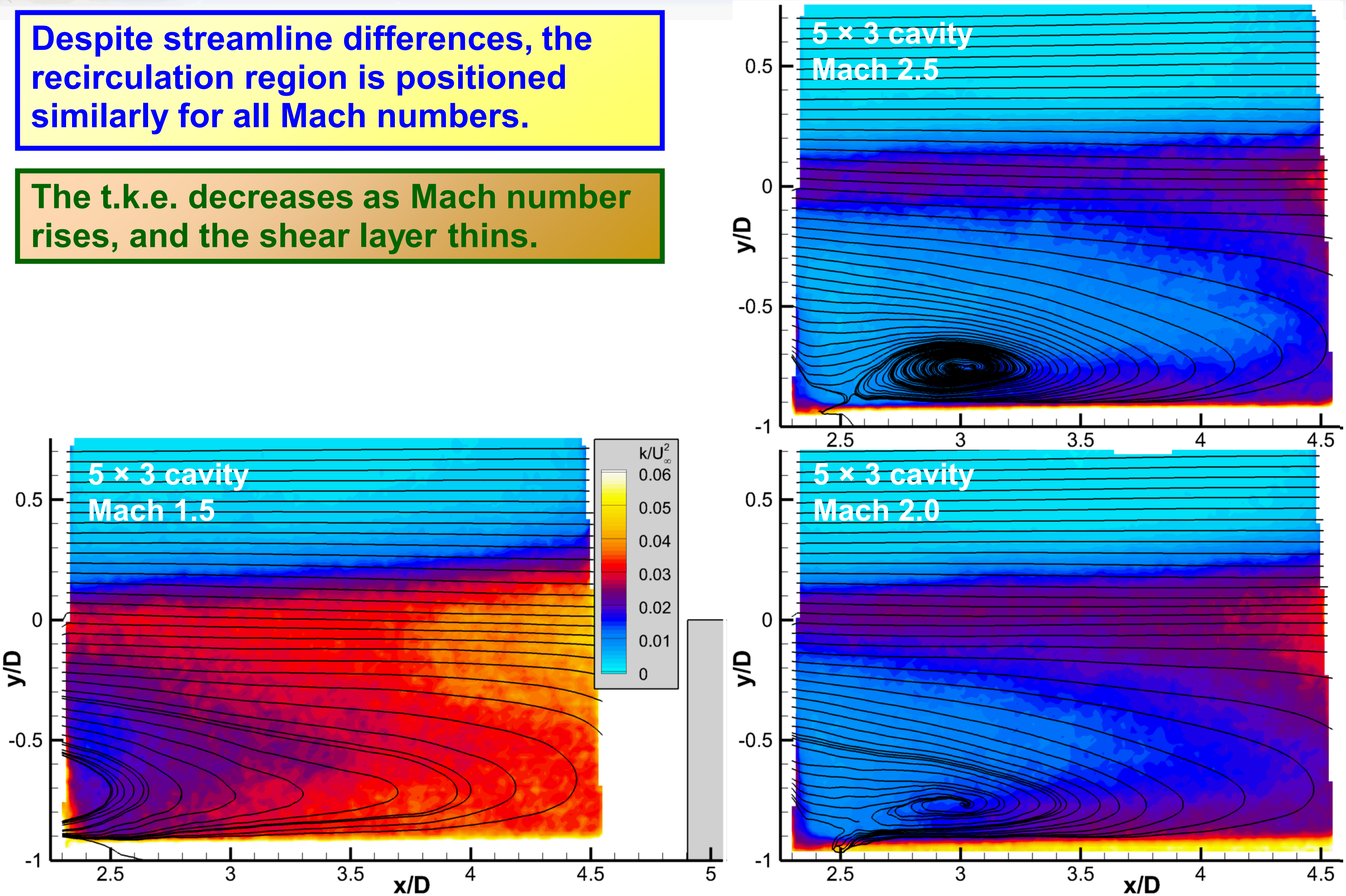
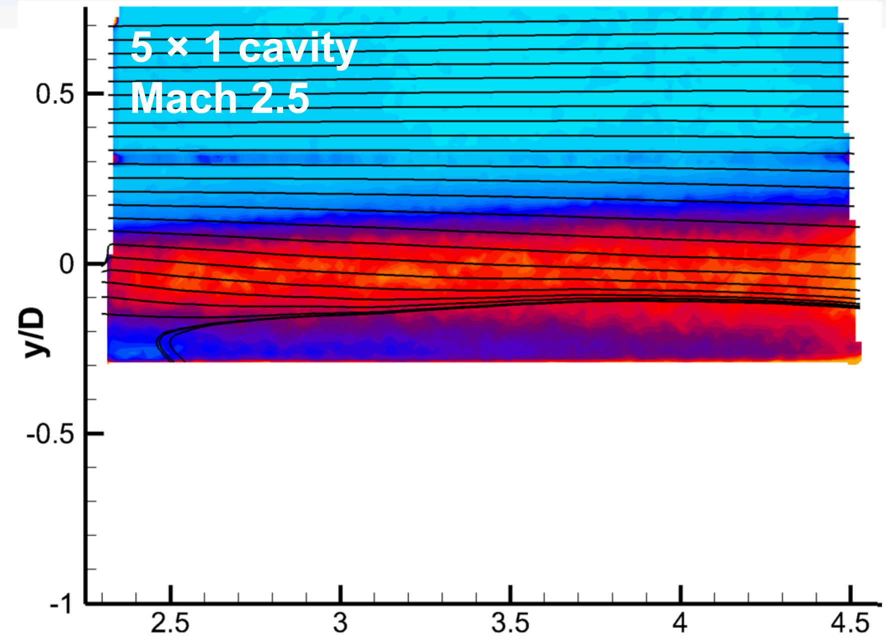


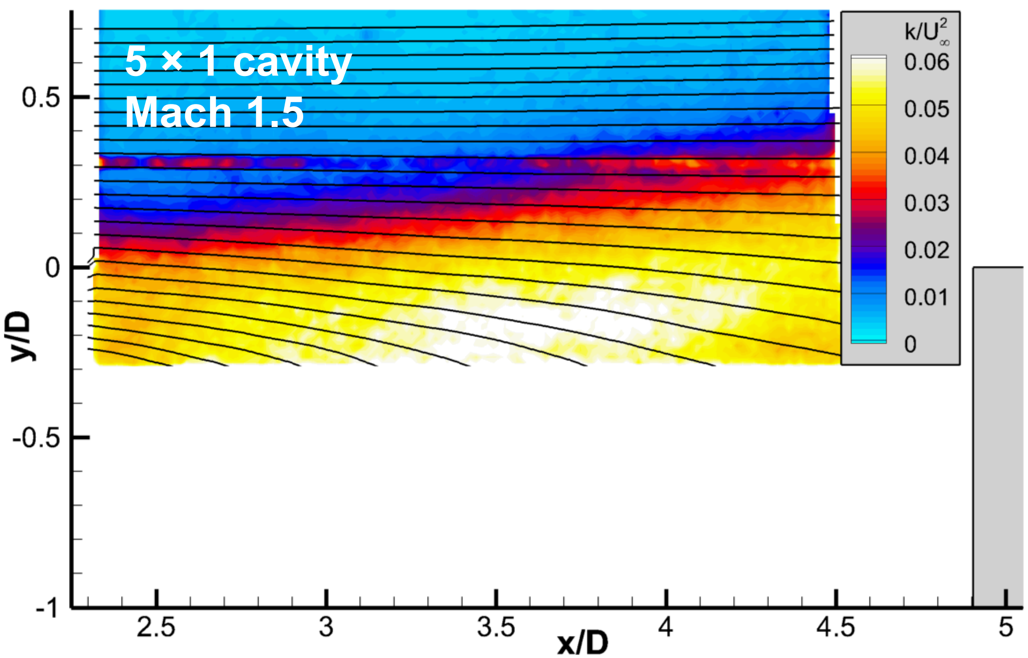
Turbulent Kinetic Energy (Variable Mach)

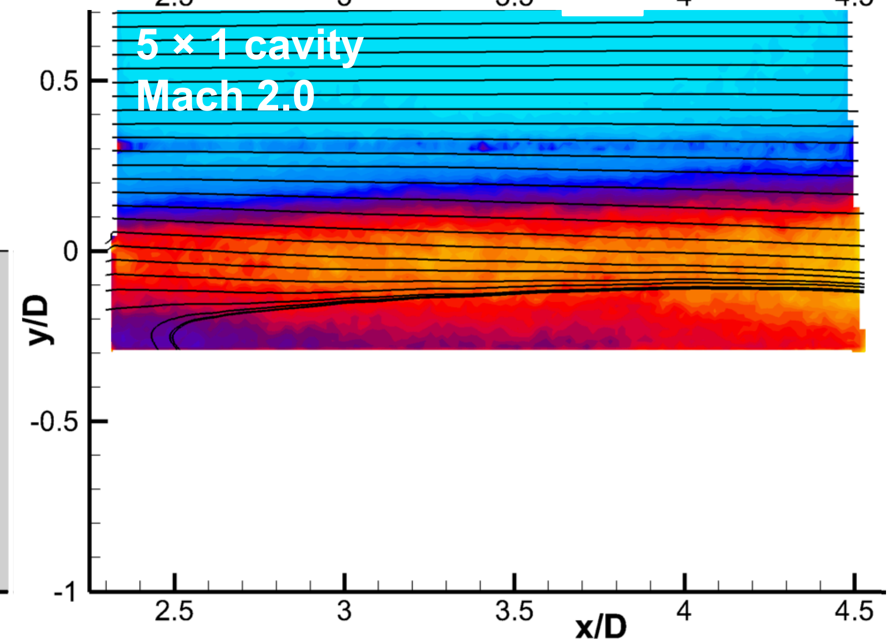
Despite streamline differences, the recirculation region is positioned similarly for all Mach numbers.

The t.k.e. decreases as Mach number rises, and the shear layer thins.

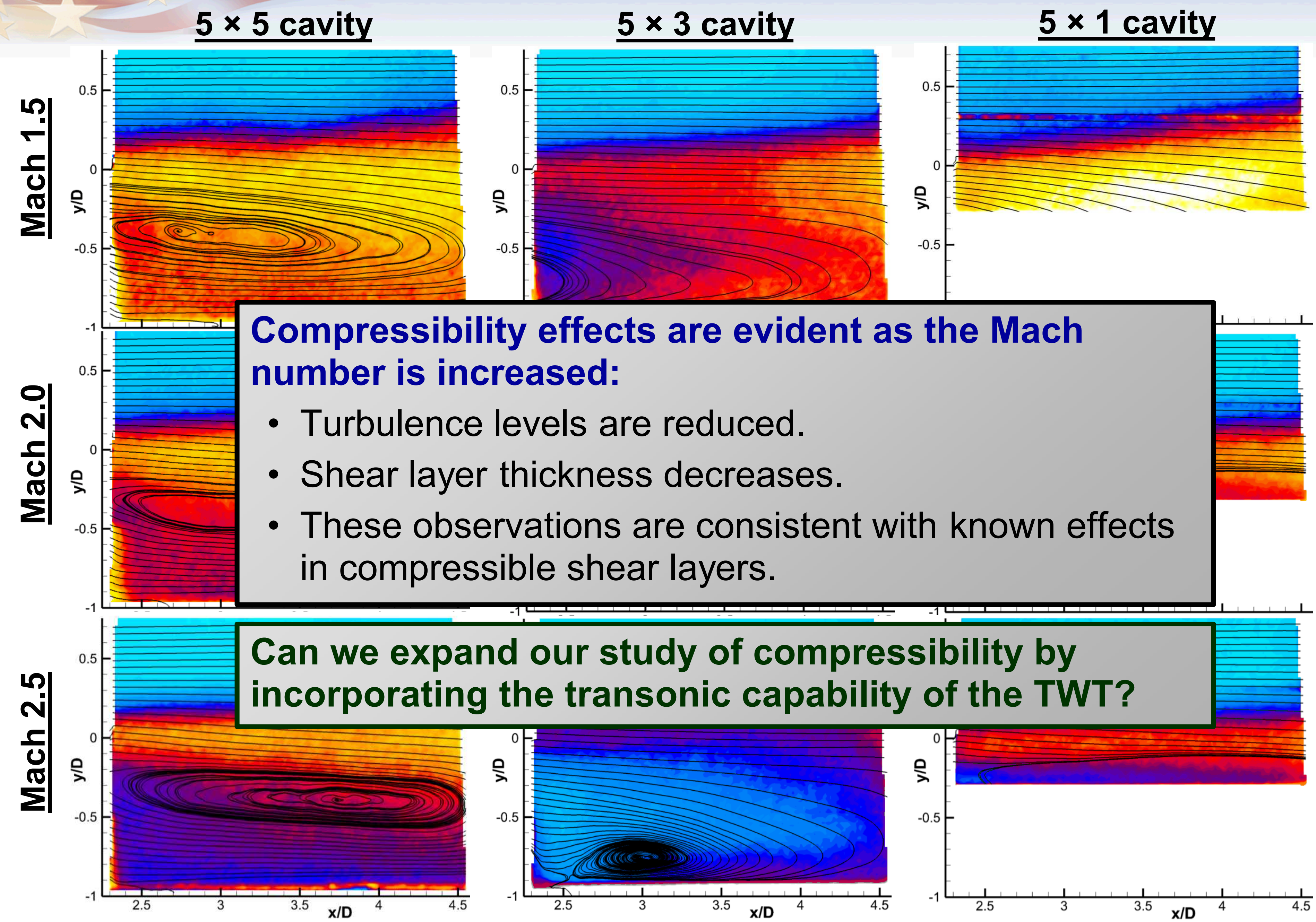
These trends hold for each of the three cavity widths.







All at once, now….

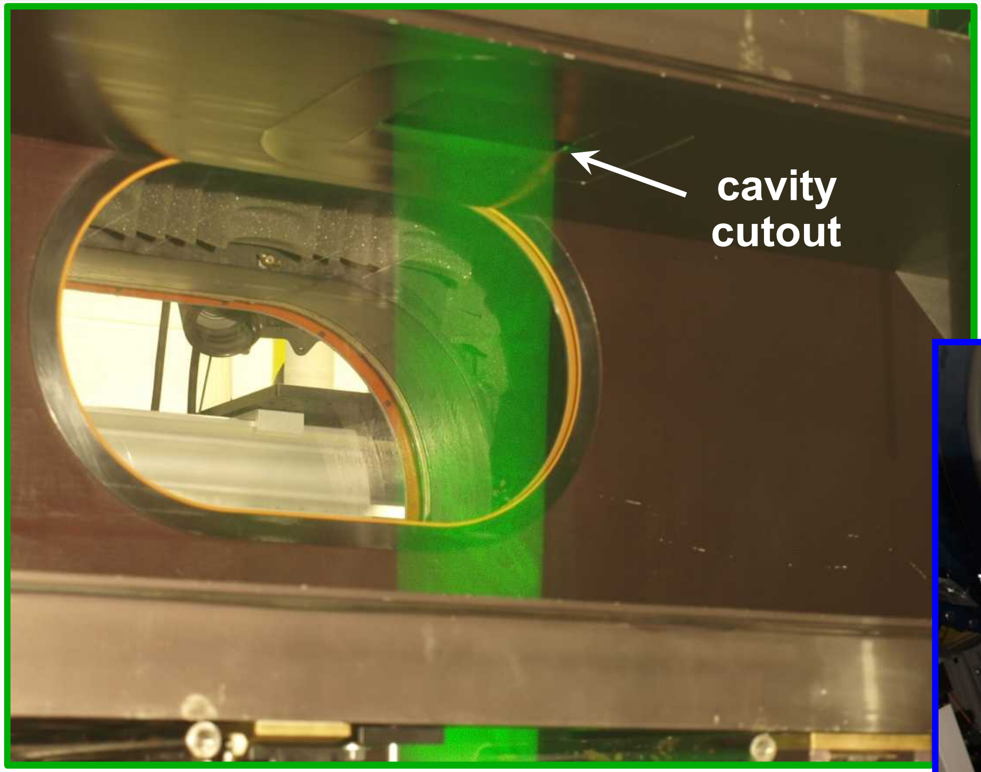


Compressibility effects are evident as the Mach number is increased:

- Turbulence levels are reduced.
- Shear layer thickness decreases.
- These observations are consistent with known effects in compressible shear layers.

Can we expand our study of compressibility by incorporating the transonic capability of the TWT?

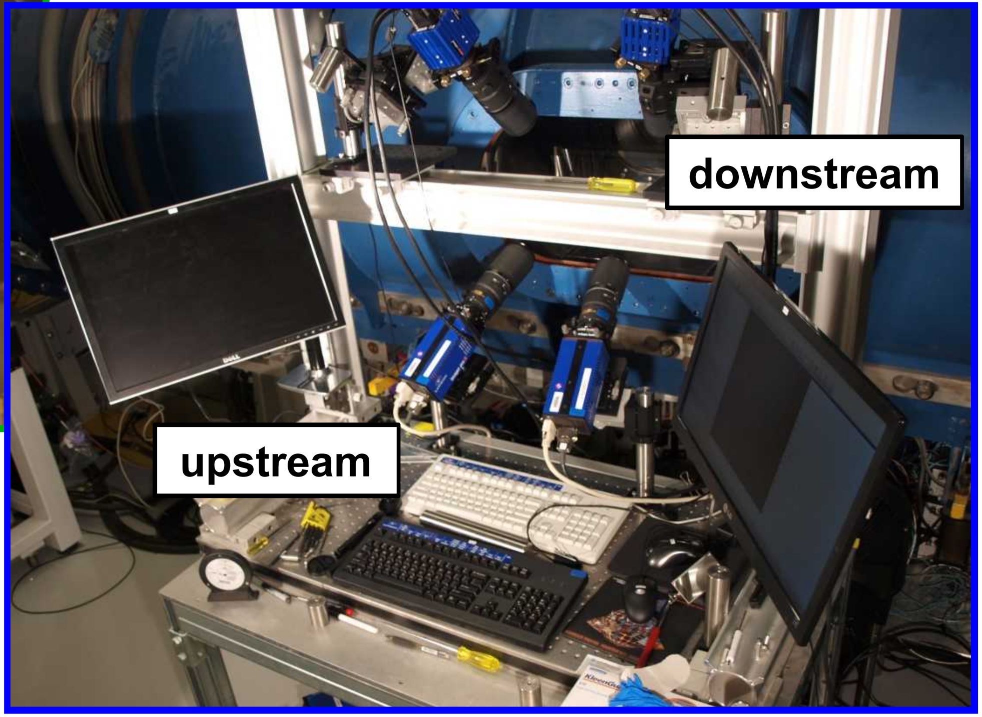
Transonic PIV Data



Cavity is now mounted in ceiling of TWT solid-wall transonic test section.

Use the same cavity geometries.

Test Mach 0.55, 0.8, and 0.89.



Two stereo views to view the entire cavity length at good spatial resolution.

Upstream cameras angled to peer into cavity.

Downstream cameras view cavity through a mirror to reach greater depth.

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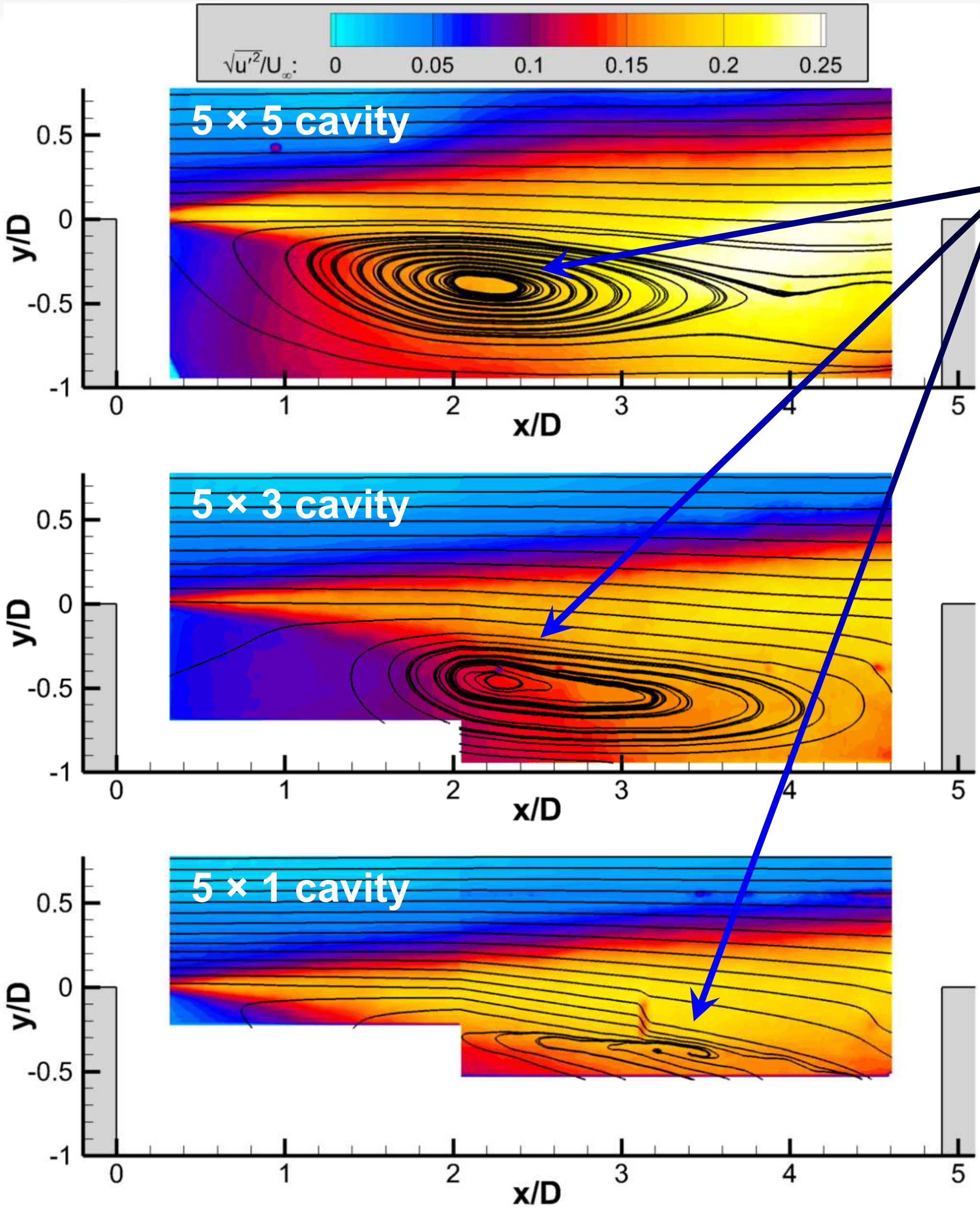
Transonic Flow Structure (Mach 0.8)



Center of recirculation near the middle of the cavity for two wider cavities and slightly downstream for narrowest case.

Different than supersonic experiments.

The two narrowest cavities are a little less turbulent than the widest.

Supersonic, the middle width was greatly lower.

We find the same observations at Mach 0.55 and 0.89.

Why does the transonic flow structure differ from supersonic?

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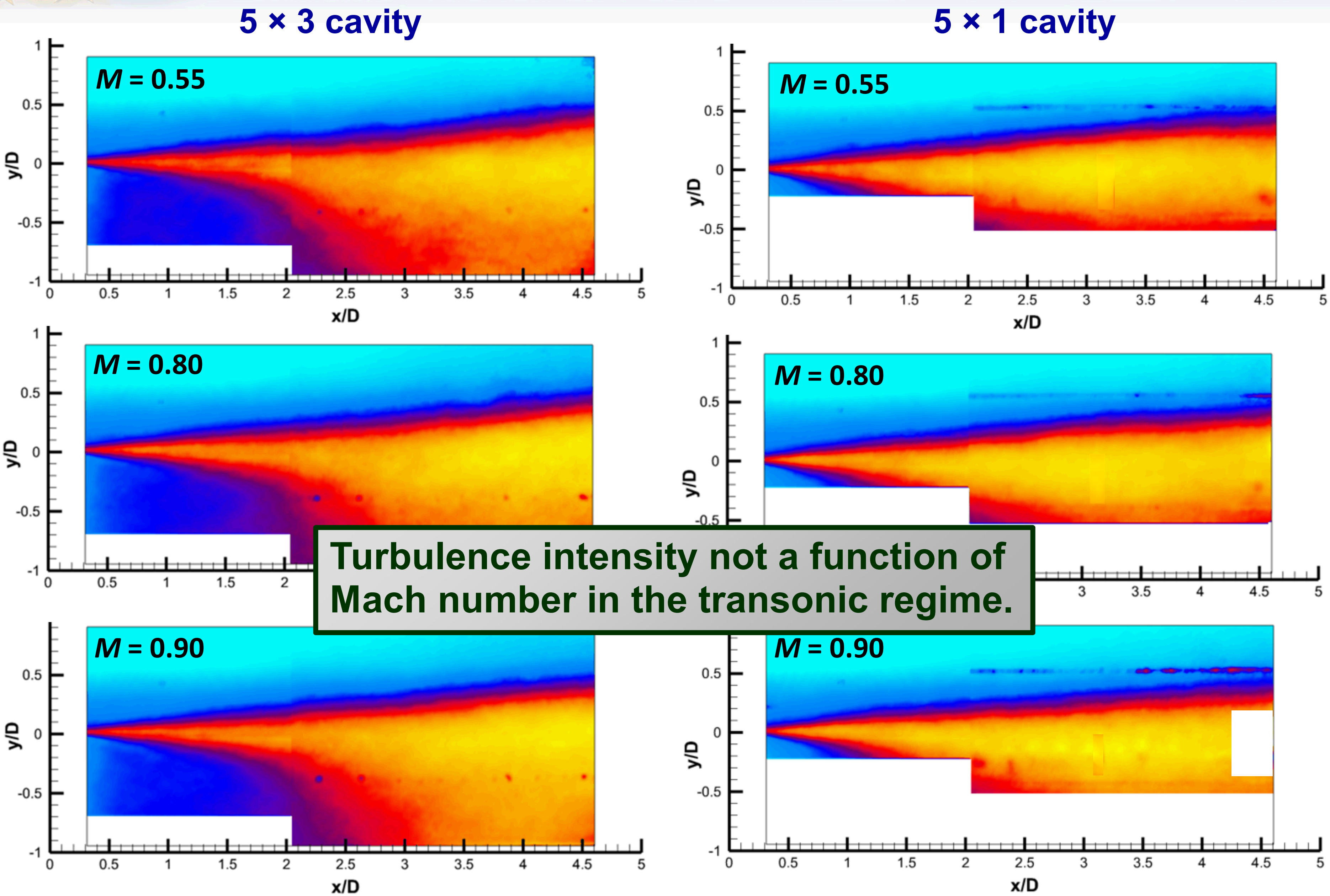
Transonic Turbulence Trends

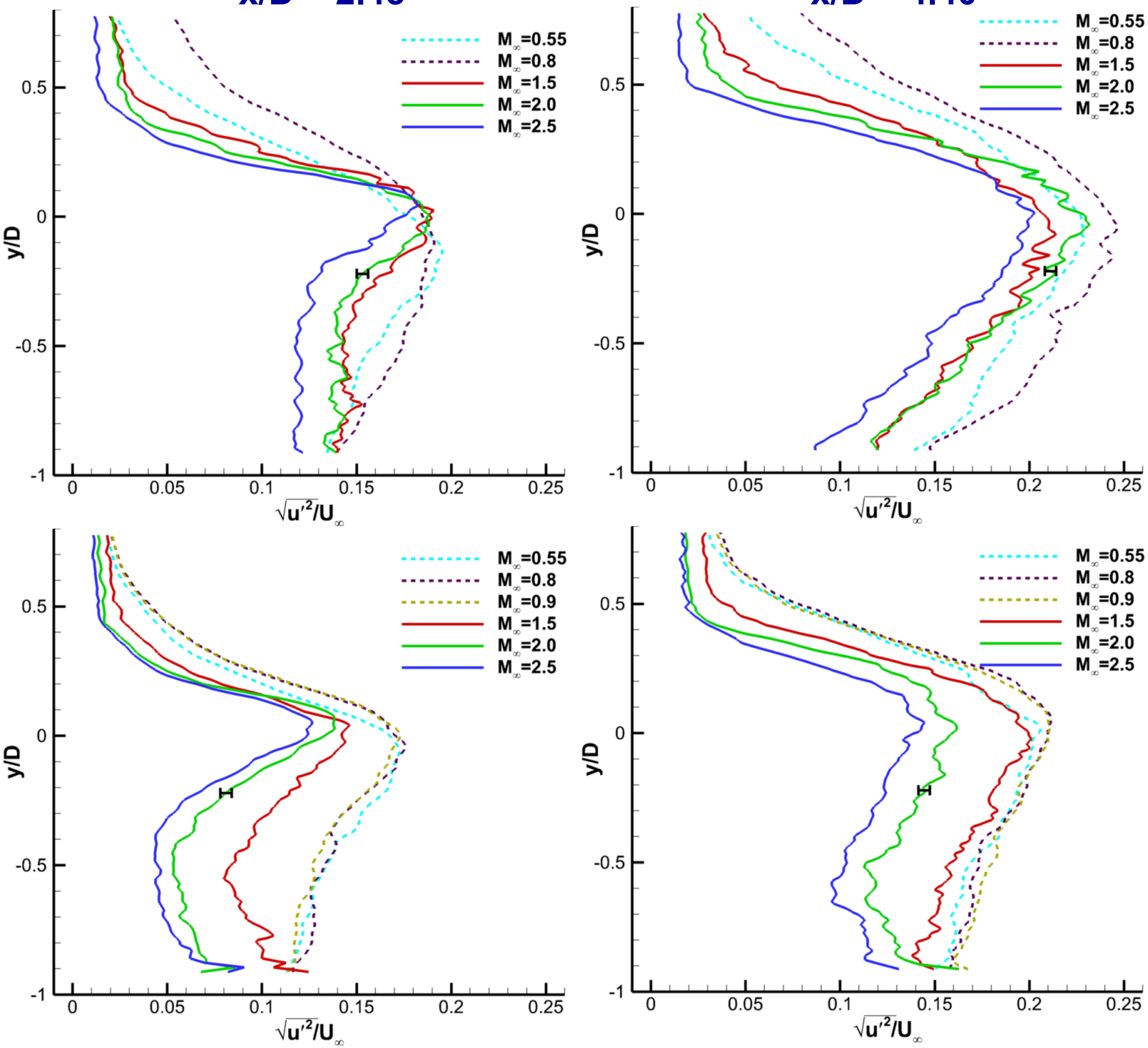


Streamwise Turbulence Intensity Profiles

x/D = 2.45 x/D = 4.40

5 × 5 cavity

5 × 3 cavity



Supersonic cases show a trend of decreased turbulence as Mach increases.

Transonic cases are generally larger in value, but no trend amongst themselves.

Something appears different for transonic cases.

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Wind Tunnel Wall Effects

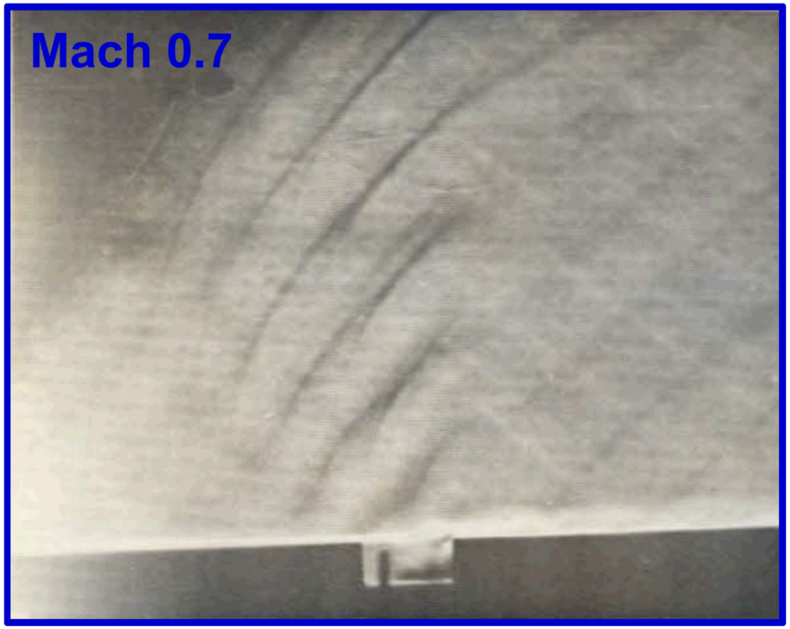
Cavity acoustic waves reflect off the wind tunnel walls.

- **Supersonic, the reflections pass downstream of the cavity.**
  - **No waves travel upstream.**
- **Transonic, the reflections intersect the cavity.**
  - **Acoustic waves travel upstream.**

A resonance can occur due to a wind tunnel duct mode.

- **Created by cavity resonance.**

Wind tunnel walls can interfere with transonic cavity acoustics!



Images from Krishnamurty (1956)

Acoustic Interference from Wind Tunnel Walls

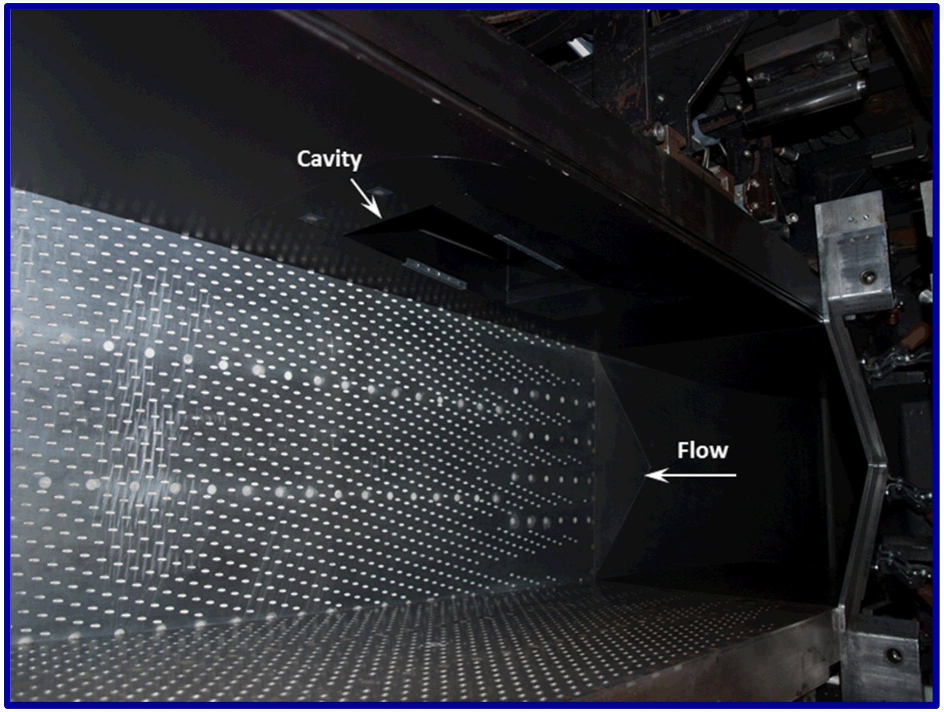
A few researchers have recognized this and mitigated acoustic wave reflections using an acoustic liner on the opposite wall.

Once we understood the problem, we realized we had the right hardware for a solution.

Transonic porous walls!

We have acquired acoustic data from a Mach 0.8 cavity with solid test section walls and with different porous wall configurations.

- Acoustic liner in the wall opposite the cavity.
- Three porous walls.
- Other permutations as well….



A brief summary is presented here.

All the gory details found in:

Wagner et al., AIAA 2014-3026

This afternoon at 4:30, Fairlee room

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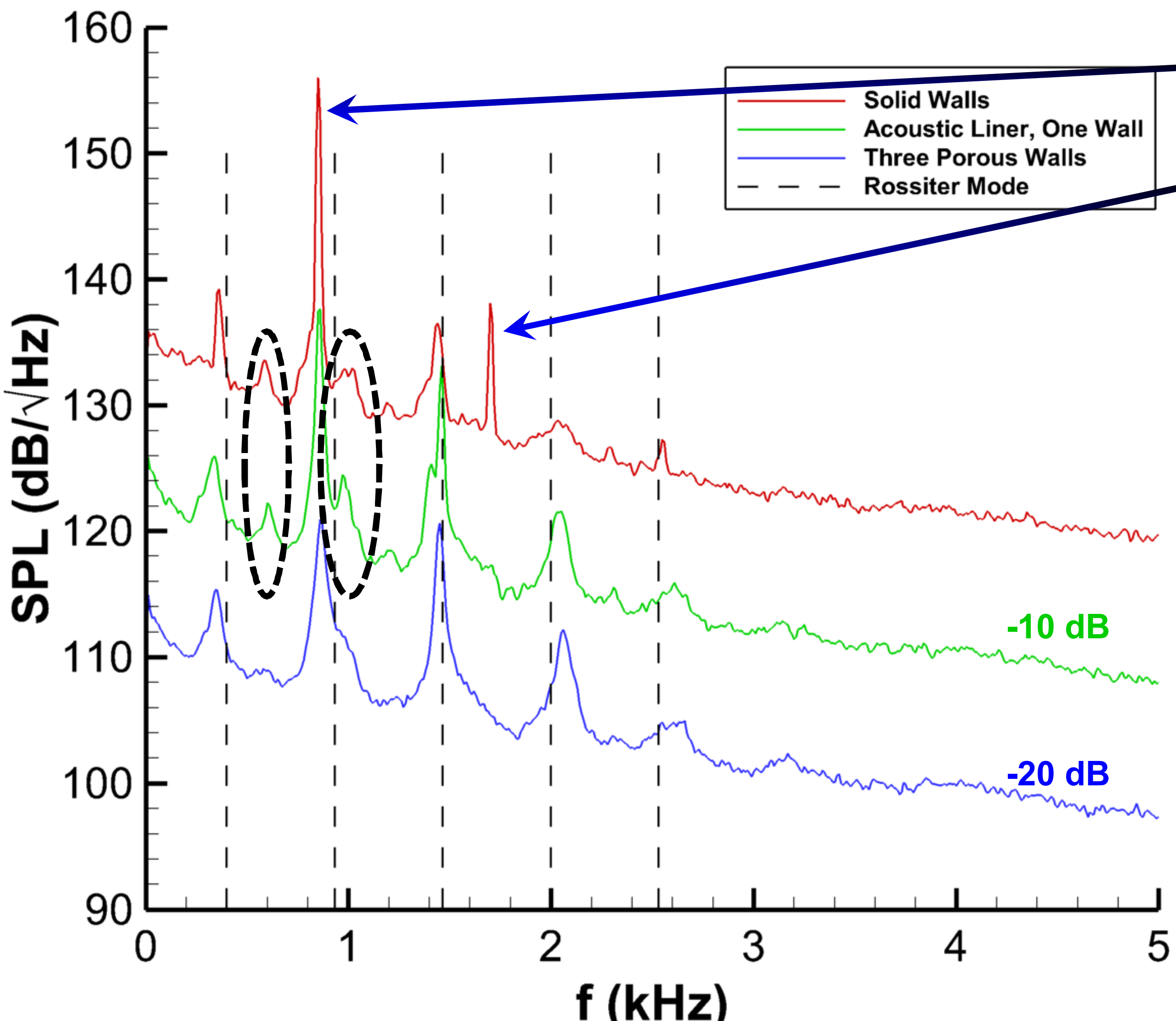
Wind Tunnel Wall Effect on Acoustic Spectra



Solid walls:

Create a dominant frequency.

Also harmonics of this frequency.

One acoustic liner:

Removes dominant frequency and harmonic.

But still observe non-Rossiter peaks.

All porous walls:

Only see Rossiter modes, no dominant amplitudes.

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Our Transonic PIV Data are Contaminated

We can conclude that transonic cavity data in solid-wall test sections have distorted flow fields.

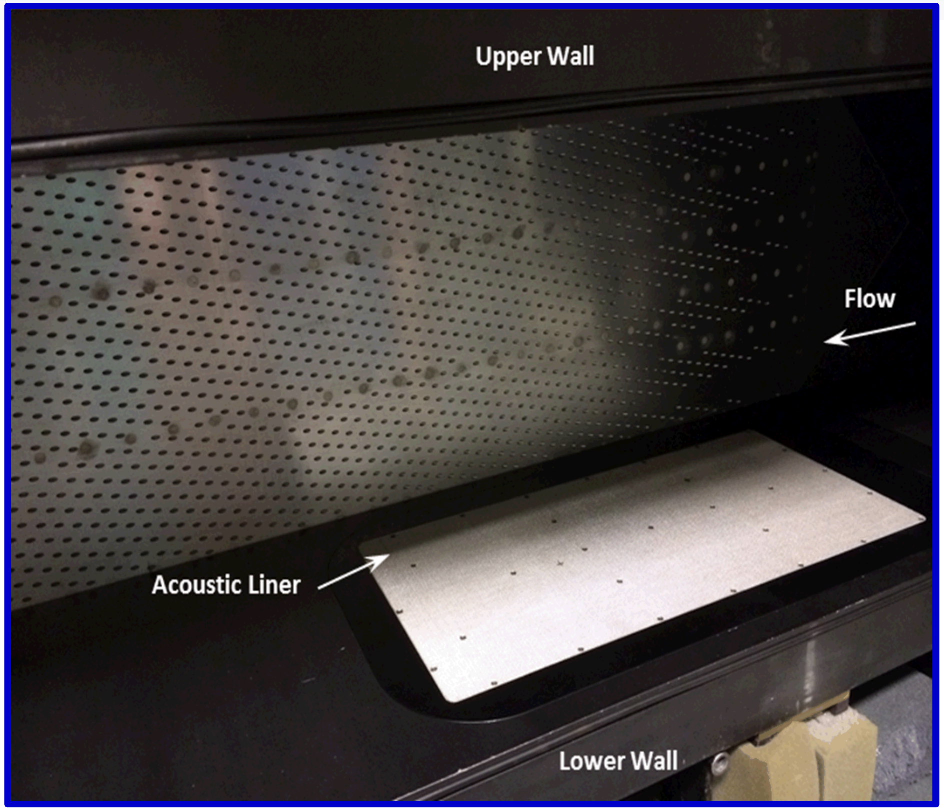
An acoustic liner on the wall opposite the cavity does not fully solve the problem.

Acoustic mitigation is required on the side walls as well.

Porous side walls will interfere with acquisition of PIV images.

Fortunately, we have a solution!

But we could not implement it in time to complete this paper.



See Wagner et al for the details!

Wagner et al., AIAA 2014-3026

This afternoon at 4:30, Fairlee room

Assessing Shear Layer Compressibility

Compressibility effects in shear layers are usually assessed by:

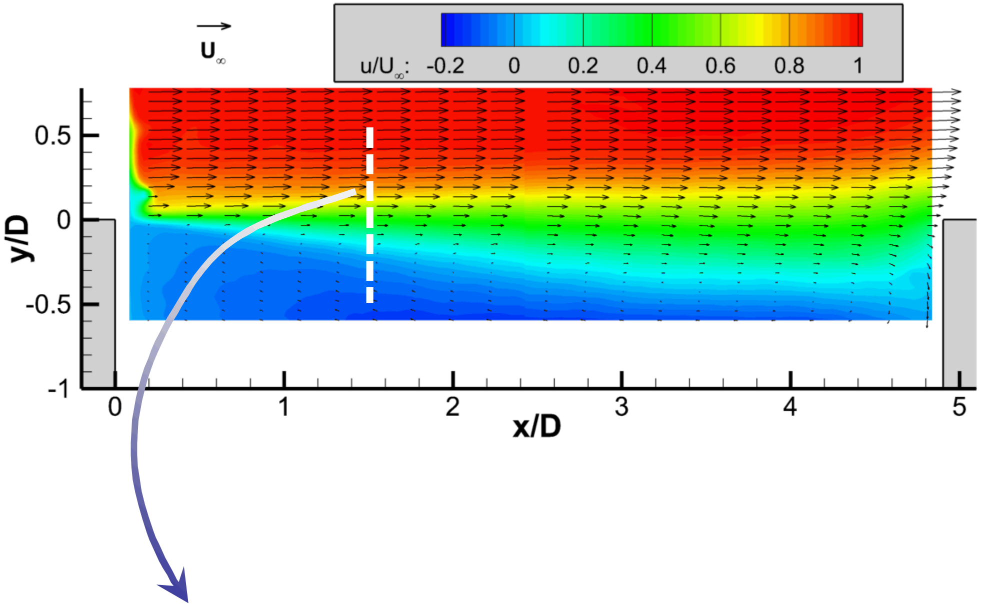
- Shear layer thickness
- Shear layer growth rate

In free shear layers, the momentum thickness works well:

$$\delta_\theta = \frac{1}{\rho_\infty (\Delta U)^2} \int_{-\infty}^{\infty} \rho (U_1 - U)(U - U_2) dy$$

In cavity flows, the recirculation region prefers the vorticity thickness:

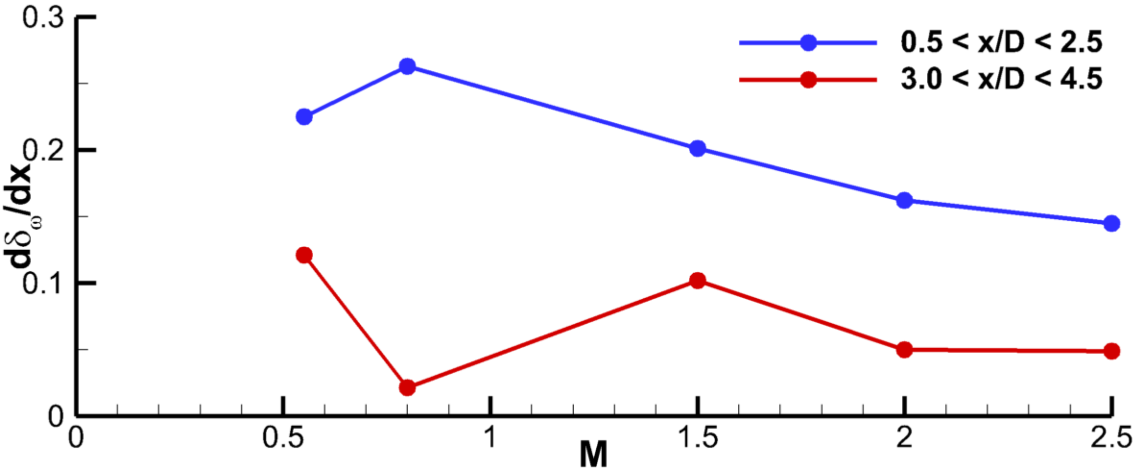
$$\delta_\omega = \frac{U_\infty}{\left(\frac{\partial U}{\partial y}\right)_{max}}$$



Calculate δ_ω at each x.

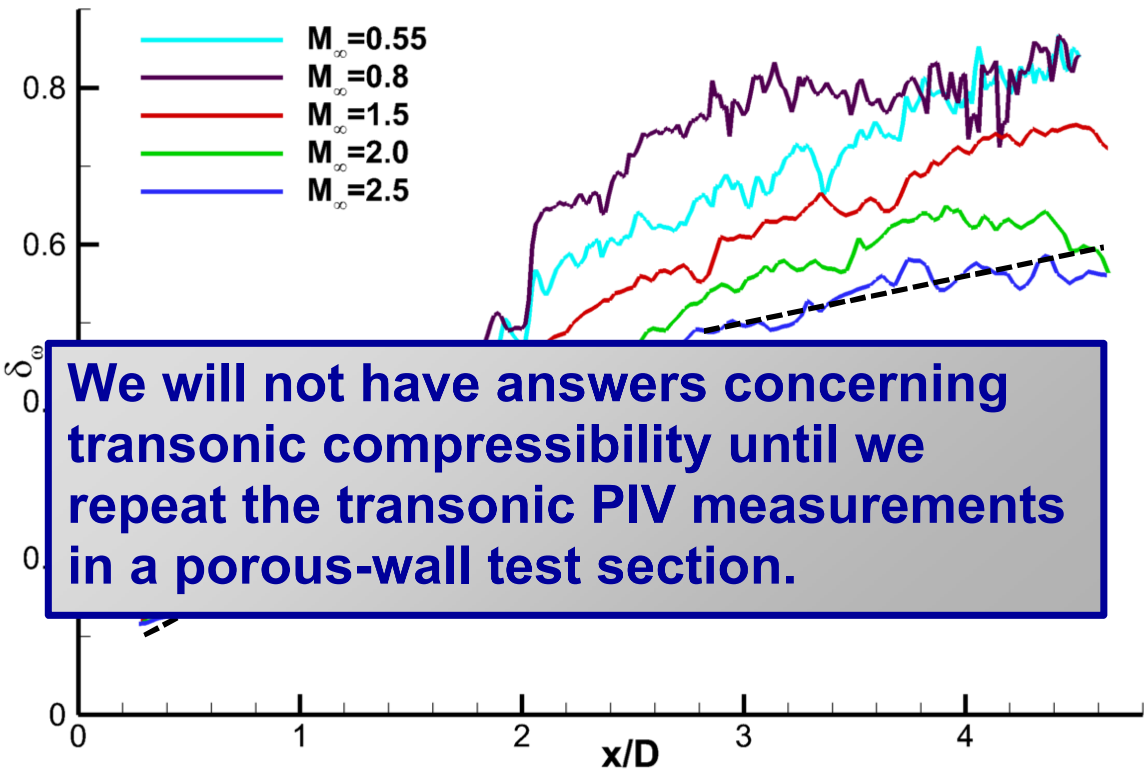
Find the growth rate as $d\delta_\omega / dx$.

Cavity Shear Layer Compressibility



Supersonic data show decreasing shear layer thickness and growth rate as Mach increases.

Two-stage growth has been observed previously and has been attributed to the recirculation region.



Transonic data show a thicker shear layer than supersonic.

But the trend is not monotonic with Mach number.

We will not have answers concerning transonic compressibility until we repeat the transonic PIV measurements in a porous-wall test section.

Is there an additional transonic effect near Mach 1?

Or is this due to wall interference?

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Conclusions

Compressibility effects in the cavity shear layer are observed for supersonic data:

- Turbulence levels are reduced as Mach increases.
- Shear layer thickness and growth are reduced as Mach increases.

Transonic data do not follow this trend.

- These data were found to be contaminated by wind tunnel wall interference.
- We are certain the acoustics are greatly affected but can only infer that the flow structure also is influenced.

We have found a solution to this problem that still allows PIV measurements.

- We will acquire new data shortly and return to questions of compressibility across transonic and supersonic regimes.