Development of the Boeing/AFOSR Mach-6 Quiet Tunnel at Purdue University

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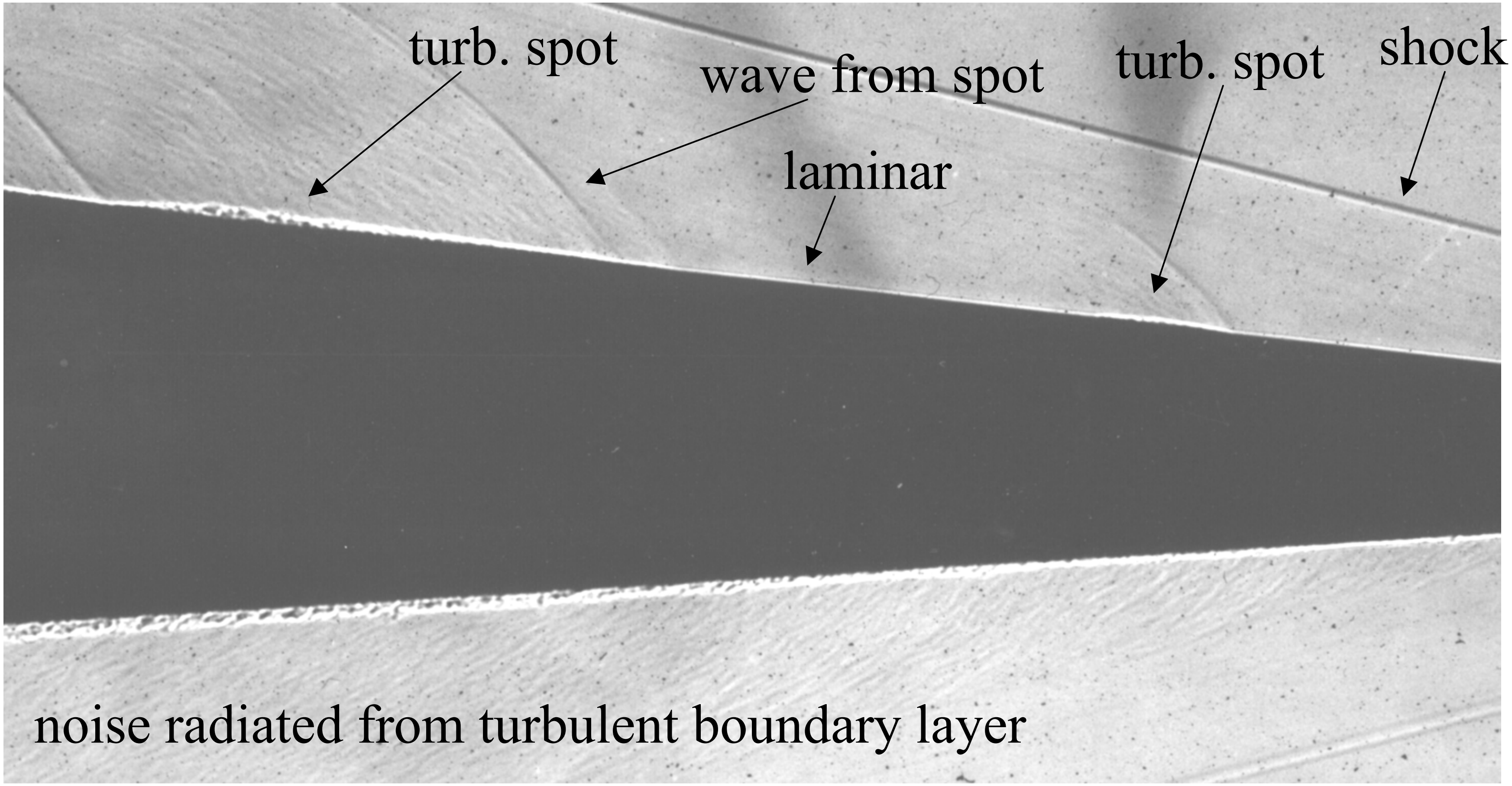
A 50-minute summary of the tunnel development and the progress towards achieving quiet flow. For more details, see http://roger.ecn.purdue.edu/~aae519/BAM6QT-Mach-6-tunnel/

Acknowledgements

- Boeing/AFOSR/BMDO/Purdue/Sandia/Langley, Development of Mach-6 Quiet Ludwieg Tube ($1m, 1995-2001)
- Based on three decades of work by NASA Langley and others
- AFOSR research, transition on generic scramjet forebody
- Generic forebody geometry from the Hyper-X program office
- Sandia/Northrop-Grumman research, transition on RV's
- Langley research, transition on generic RLV

Schlieren of Transition on Sharp Cone at Mach 4



5-deg. half-angle cone in NOL Ballistics Range at Mach 4.31. Shot 6728, Dan Reda, AIAA Journal v. 17, number 8, pp. 803-810, 1979. Re_∞=2.66E6/inch, cone length is 9.144 inches. Cropped

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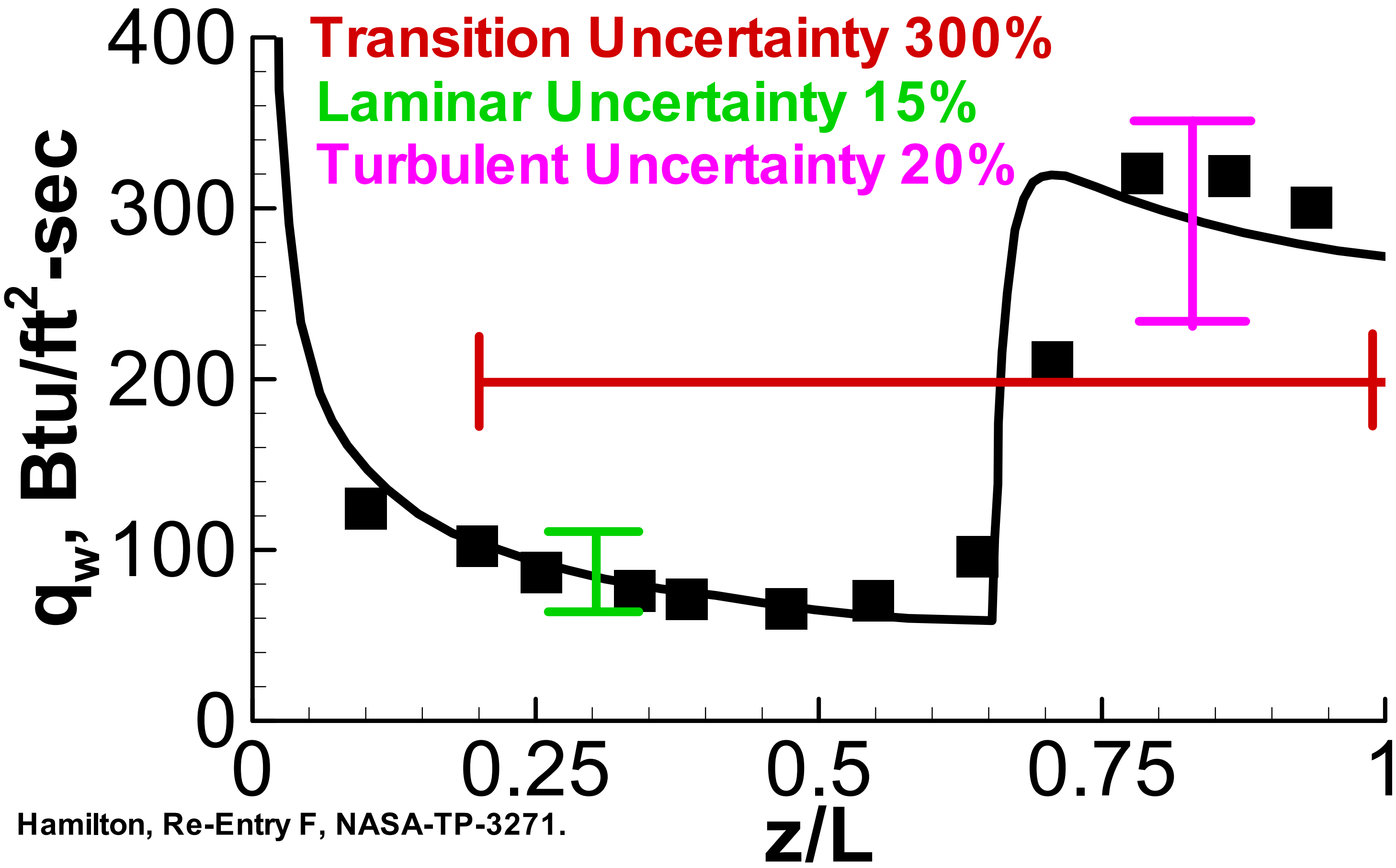
Aeroheating Rises By a Factor of 3-8 at Transition

13-foot Beryllium Cone at Mach 20 in Reentry
CFD predicts heating well --ONLY IF--
transition location picked to match flight



Hamilton, Re-Entry F, NASA-TP-3271.

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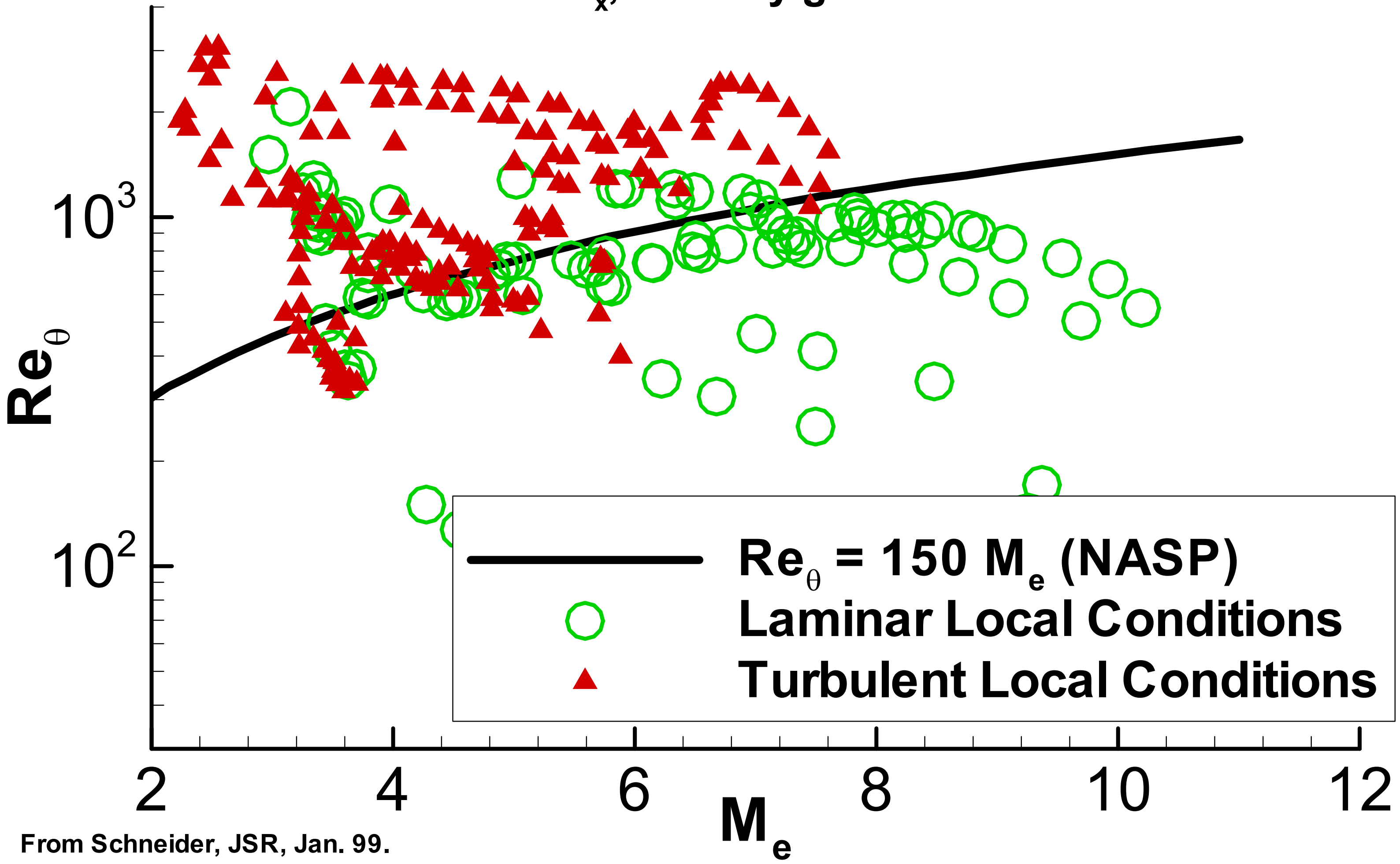
Existing Correlations Have a Large Uncertainty

Kuntz, Sandia SWERVE maneuvering flight vehicle
Empirical Correlations Typically Scatter by a Factor 3 in Re_θ, or a factor 10 in Re_x, for fairly general datasets



From Schneider, JSR, Jan. 99.

Hypersonic Transition is Critical to Large Scramjet Accelerator Vehicles

- Multistage Airbreathing to Orbit will still be similar to NASP -- a large hypersonic scramjet-powered vehicle
- National Aerospace Plane Review by Defense Science Board, 1988: *Estimates [of transition] range from 20% to 80% along the body ... The estimate made for the point of transition can affect the design vehicle gross take off weight by a factor of two or more.*
- National Aerospace Plane Review by Defense Science Board, 1992: *The two most critical [technology areas] are scramjet engine performance and boundary layer transition… Further design development and increased confidence in these two technical areas must be of paramount importance to the NASP program.*
- The propulsion problems are being worked under various programs. However, transition research is reduced to a shell. Will transition technology be ready when the combustor is?

AD-A201124, Report of the DSB Task Force on the NASP Program, Sept. 1988
AD-A274530, Report of the DSB Task Force on the NASP Program, Nov. 1992

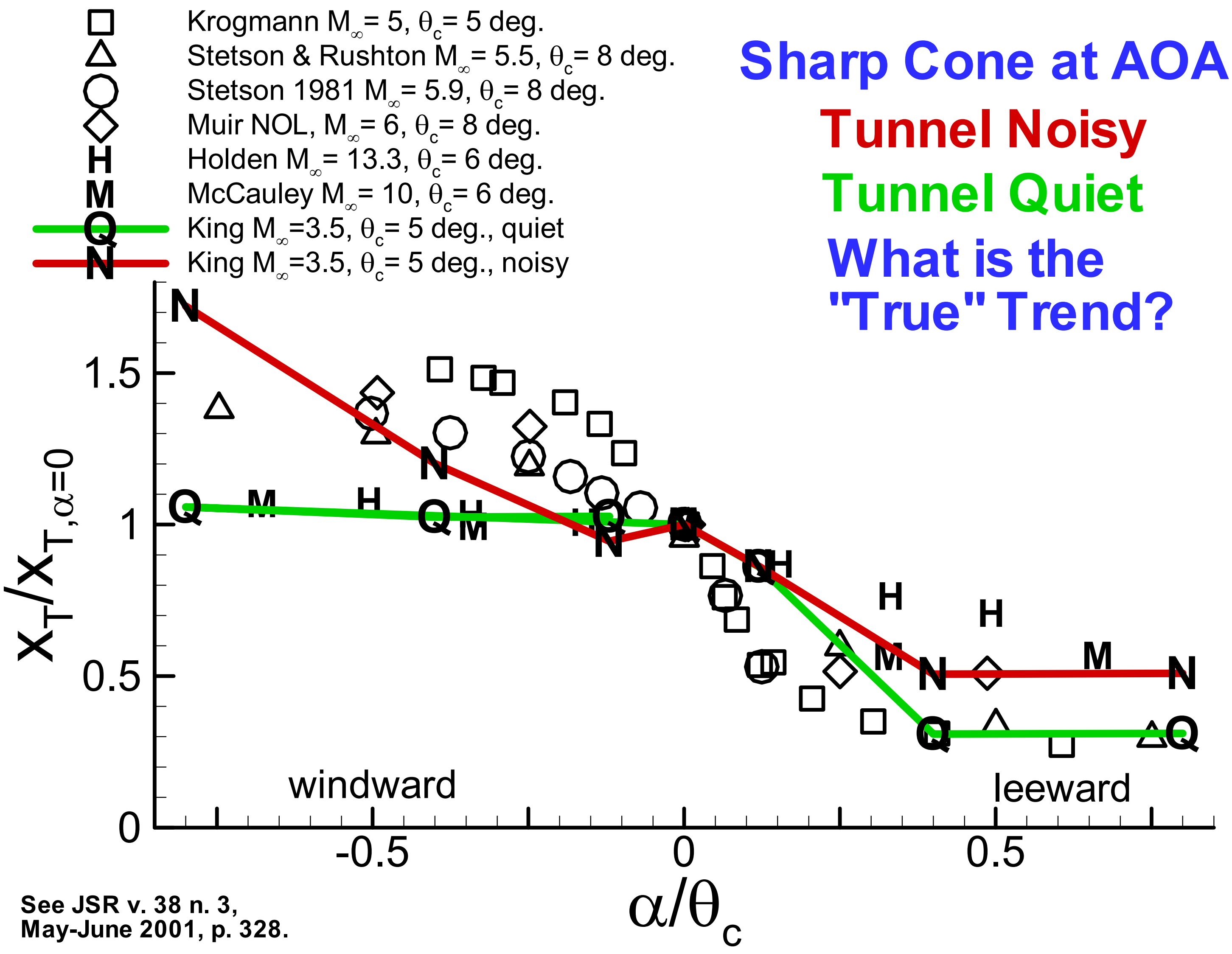
Transition is Critical to RLV Reentry Aeroheating

- Aeroheating affects TPS weight, type, and operability – a low-maintenance metallic TPS may not be possible if transition occurs early
- Reentry trajectory is iterated to achieve acceptable aeroheating, and therefore depends on transition
- Crossrange is critically dependent on aeroheating
- TPS selection affects roughness and surface temperature and therefore boundary-layer transition
- Uncertainty in transition drives TPS temperature margin, 200+F for shuttle (per Stan Bouslog)
- A metallic TPS may have a more repeatable and smaller roughness which might permit delaying transition

Conventional Wind and Shock Tunnels are Noisy!

1. **Fluctuation level typically 1%**: > 10 times higher than flight
2. **Major Source: Acoustic radiation** from turbulent boundary layers on the nozzle walls.
3. **Causes early transition:** perhaps 3-10 times earlier than in flight.
4. **Can change trends in transition:**
   - a) Sharp cone transition data in conventional tunnels scales with noise parameters alone, independent of Mach number.
   - b) $Re_{T, CONE} = 2\ Re_{T, PLATE}$ in conv. tunnel, but $Re_{T, CONE} = 0.7\ Re_{T, PLATE}$ in quiet tunnel and e**N analysis. Flat Plate is later, NOT cone!
   - c) Bluntness, crossflow, and roughness effects all differ in quiet and noisy conditions.
   - d) Transitional extent typ. 2-4 times longer in conv. tunnel than in flight or quiet tunnel.
5. **Transition in Conventional Facilities is NOT a reliable predictor for flight!** Except for certain limiting cases, such as transition that occurs at a roughness element.

Simple Conventional Transition Measurements Often Don't Give "Correct" Trends



Sharp Cone at AOA.

Tunnel Noisy

Tunnel Quiet

What is the "True" Trend?

See JSR v. 38 n. 3, May-June 2001, p. 328.

Quiet Tunnels Have Been Under Development Since the 1960's to Address the Noise Problem

1. Must solve the Acoustic Radiation Problem
2. Must Control Laminar-Turbulent Transition on the nozzle walls!
3. Quiet Tunnels also require low-noise core flows.
4. Laminar Nozzle-Wall Boundary Layers requires mirror-finish nozzle walls, specially designed nozzles, particle-free flow
5. Accurate Fabrication of the Nozzle with tight tolerances and a mirror finish is expensive and risky.
6. NASA Langley built a dozen nozzles between 1970 and 1990, and worked out many of the problems: **Mach 3.5** since 1982, **Mach 6** from 1990-97 (presently boxed)
7. No High Reynolds Number Hypersonic Quiet Tunnel presently in operation anywhere. Purdue effort leads. Langley Mach-6 may be reinstalled ca. 2004.

Need Measurements of the Mechanisms of Transition

- Transition data by itself is ambiguous. What caused the transition? Roughness? Crossflow? 1st mode? All 3? Tunnel noise? stray roughness? AOA errors?
- Need detailed measurements of the transition mechanisms (rare field measurements of small fluctuations, preferably with controlled disturbances).
- Detailed measurements and computations of the mechanisms can provide physical understanding.
- Can improve scaling from wind-tunnel to flight conditions
- Such measurements are difficult; development of the capability requires a sustained effort. Purdue is now the only U.S. lab making hypersonic hot-wire measurements

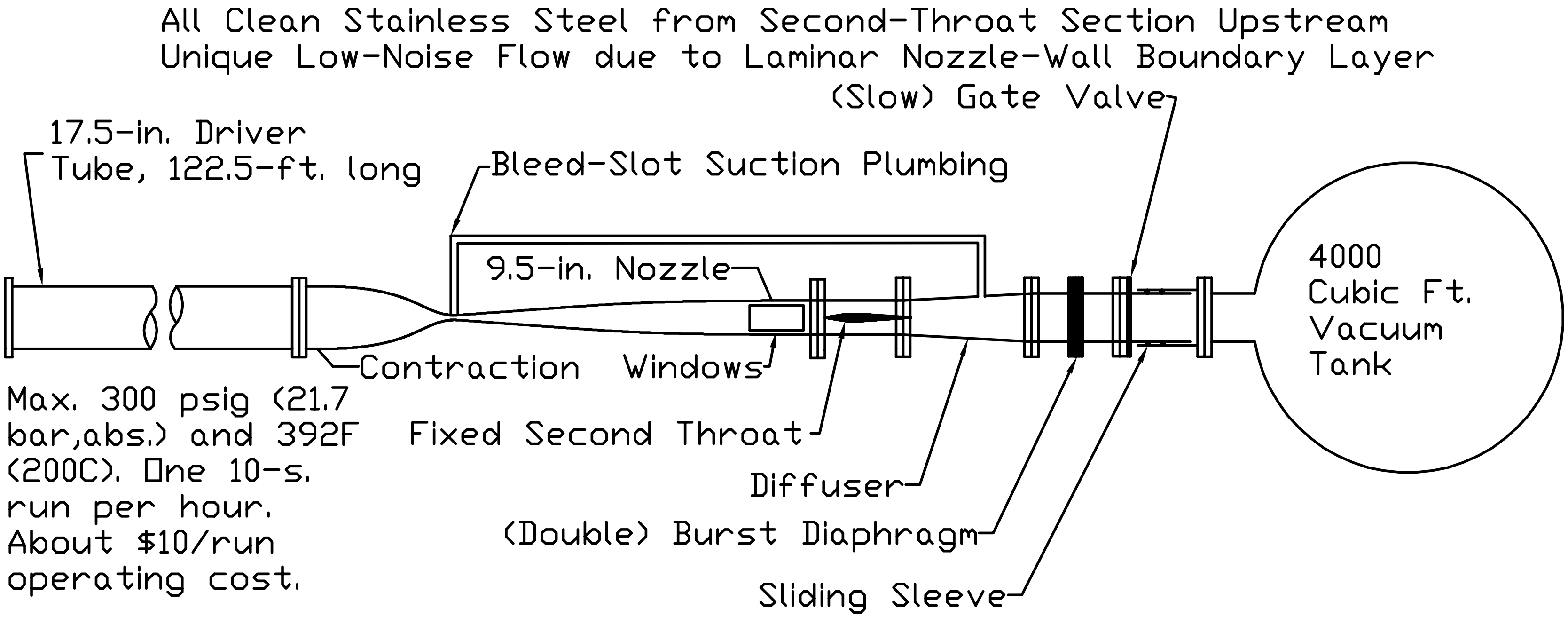
Reliable Predictions Must Be Based on Mechanisms

- Instabilities that lead to transition can be computed (now or soon) (1st & 2nd mode, crossflow, Gortler, algebraic, etc.)
- Seek semi-empirical mechanism-based methods similar to e**N, where N=ln(A/A0) is the integrated growth of the most-amplified instability, incorporates all mean-flow effects on wave growth
- Computations must be developed and validated based on detailed measurements in ground facilities
- Computations must be compared to flight data
- Dominant Mechanisms on Shuttle, X-33, X-38, Hyper-X remain to be determined; little or no data at present
- Bridge gap between users and researchers

Summary of Purdue Effort, 1990-99

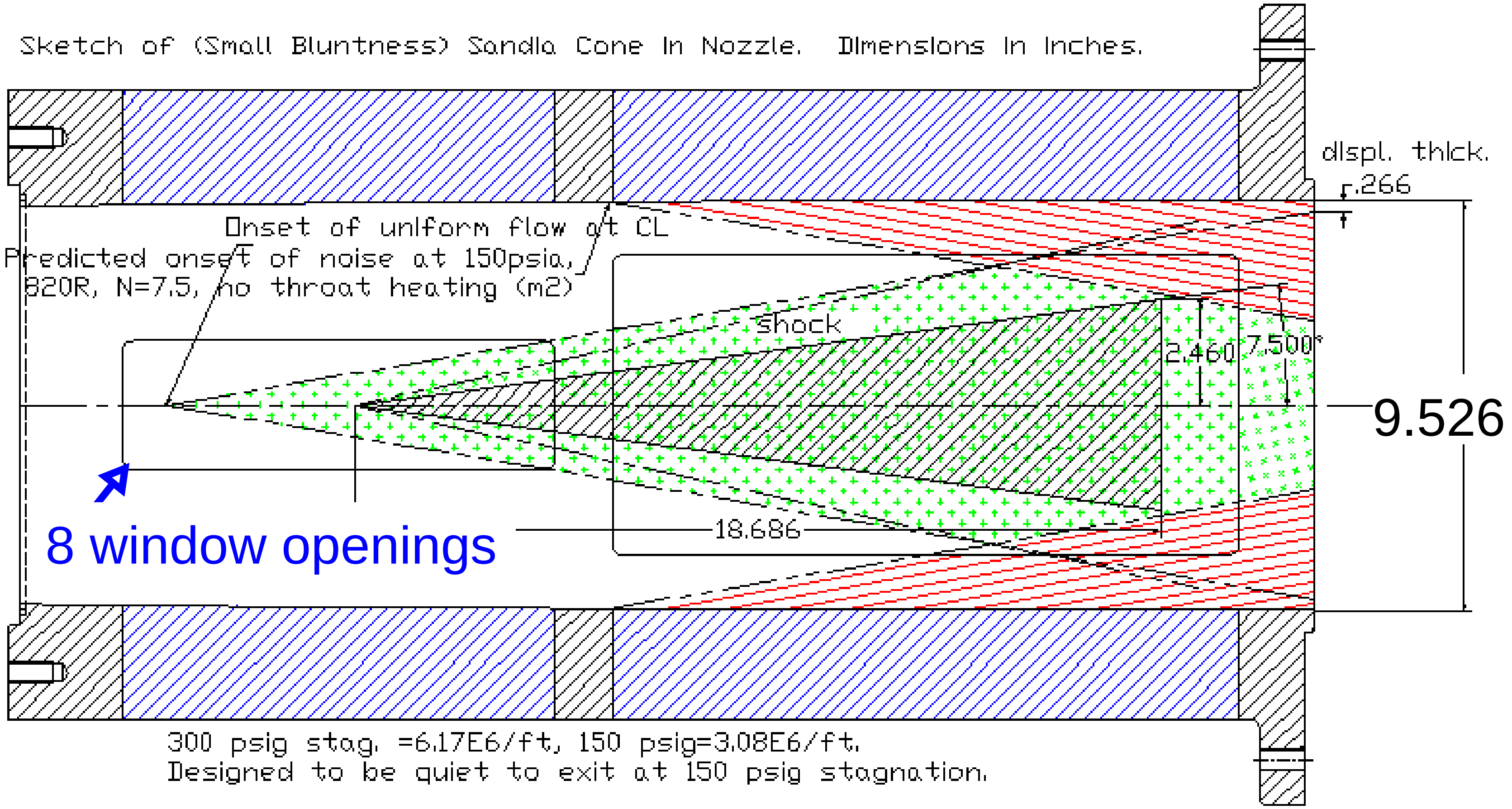
1. Development of Mach-4 Ludwieg Tube, Quiet to Re = 400,000, 1990-94.
2. Tests of Heated Driver Tube (Munro, 1996)
3. Development of Hot-Wire and Glow-Perturber Technique
4. Controlled Wave Growth of factor 2-3 on Cone at AOA under quiet conditions (Ladoon Ph.D., 1998)
5. Development of Pulsed Laser-Perturber for Generating Local Perturbations in Freestream for Receptivity Work (Schmisseur Ph.D., 1997)
6. Controlled Measurements of Damping in Forward-Facing Cavity, Explained Low Heat Transfer in 1961 Flight Data (1997-99)
7. Developed of High-Sensitivity Laser Differential Interferometer ala Smeets. Receptivity on Blunt Nose. (Salyer Ph.D., 2002)
8. Development of High-Reynolds Number Mach-6 Quiet Ludwieg Tube (1995-present)

Boeing/AFOSR Mach-6 Quiet Tunnel



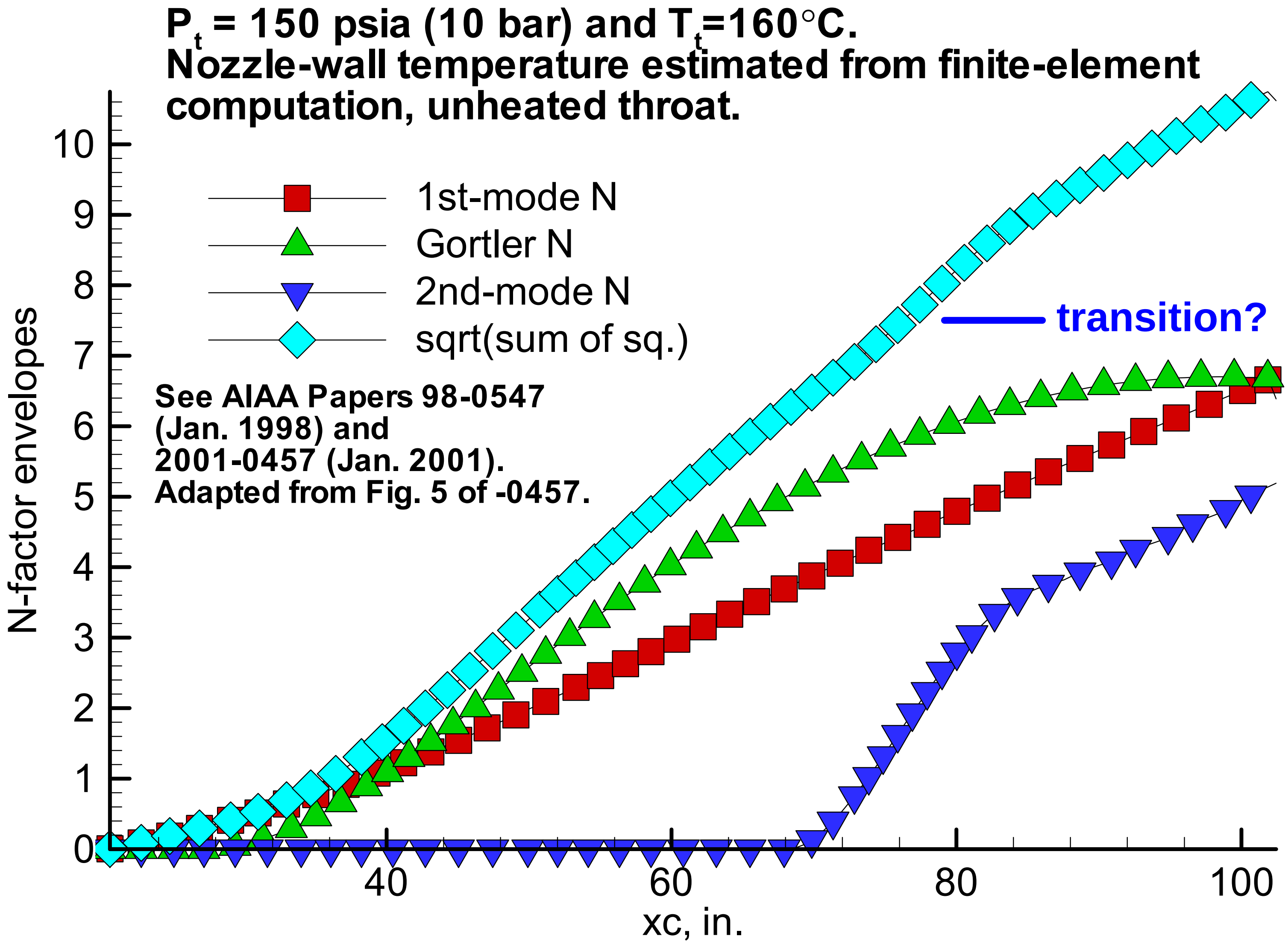
About $1 million in fabrication cost. $0.5m for nozzle

Schematic of Mach-6 Quiet Nozzle



8 window openings

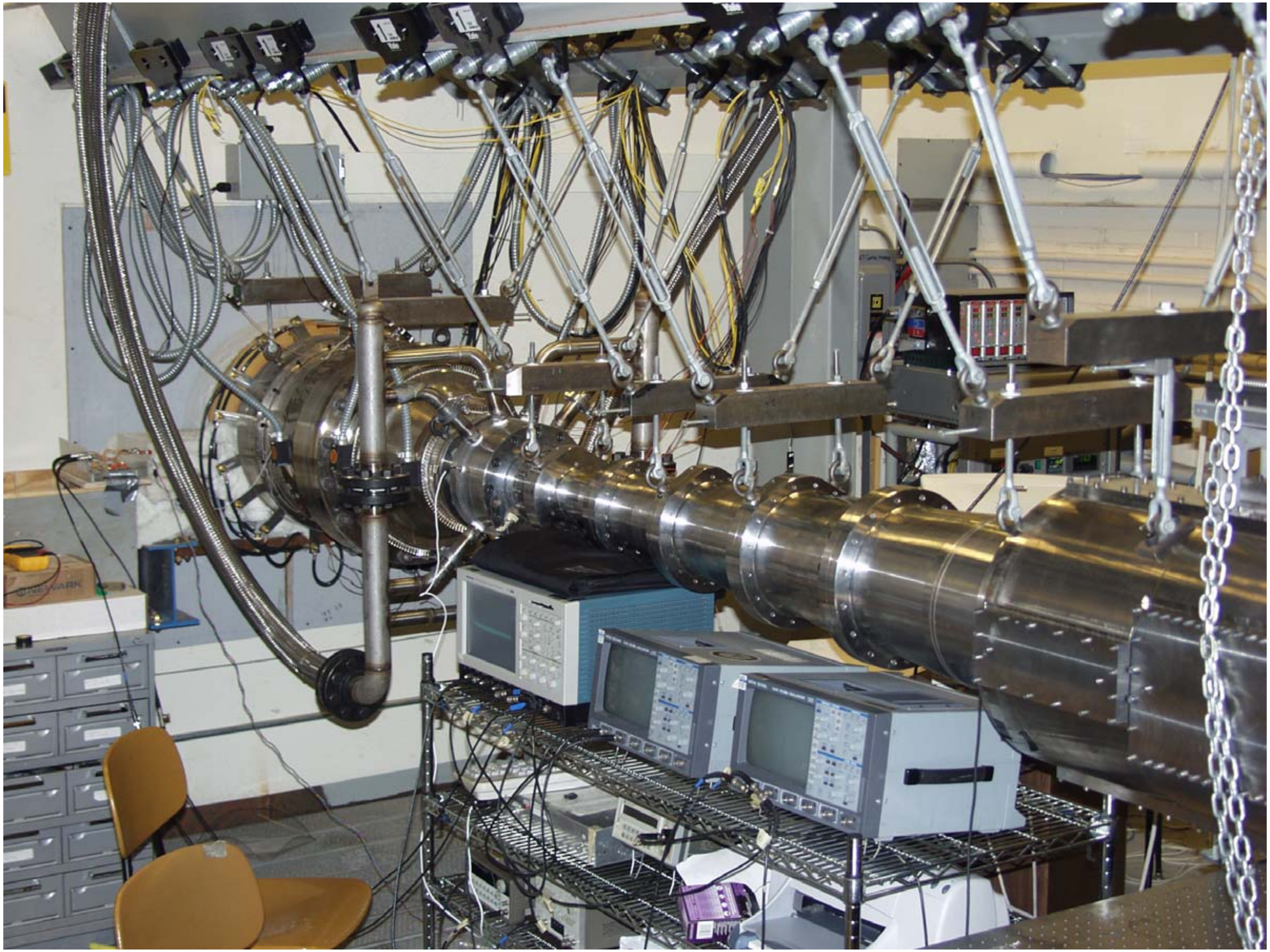
Nozzle Designed Using Linear Stability Theory (e**N)



P_t = 150 psia (10 bar) and T_t=160°C.
Nozzle-wall temperature estimated from finite-element computation, unheated throat.

See AIAA Papers 98-0547 (Jan. 1998) and 2001-0457 (Jan. 2001). Adapted from Fig. 5 of -0457.

Mach-6 Nozzle and Test Area, Feb. 2003



Entrance to Electroformed Nozzle Throat Section

shows bleed lip and mirror finish on inside of throat section. Purdue nozzle

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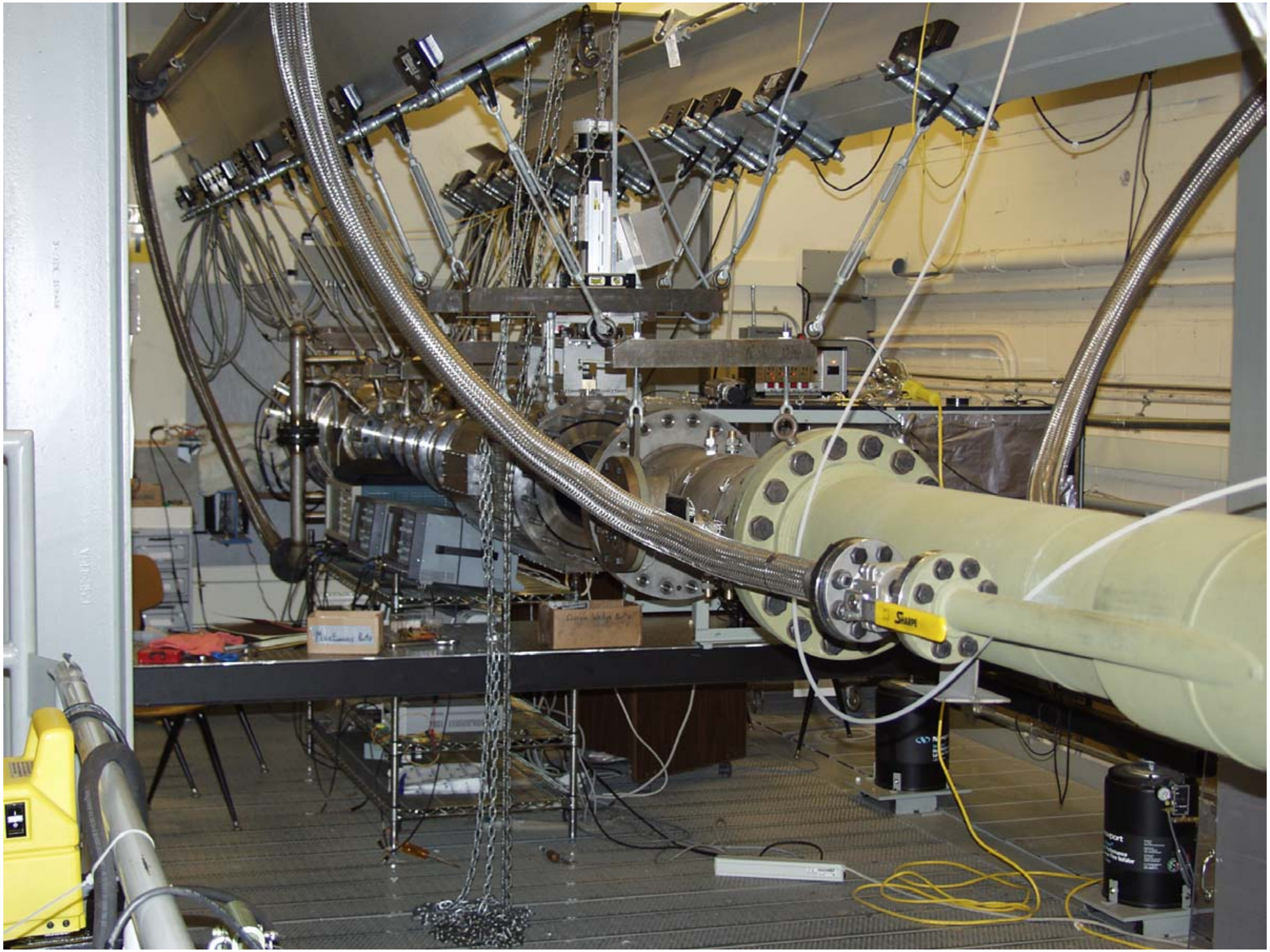
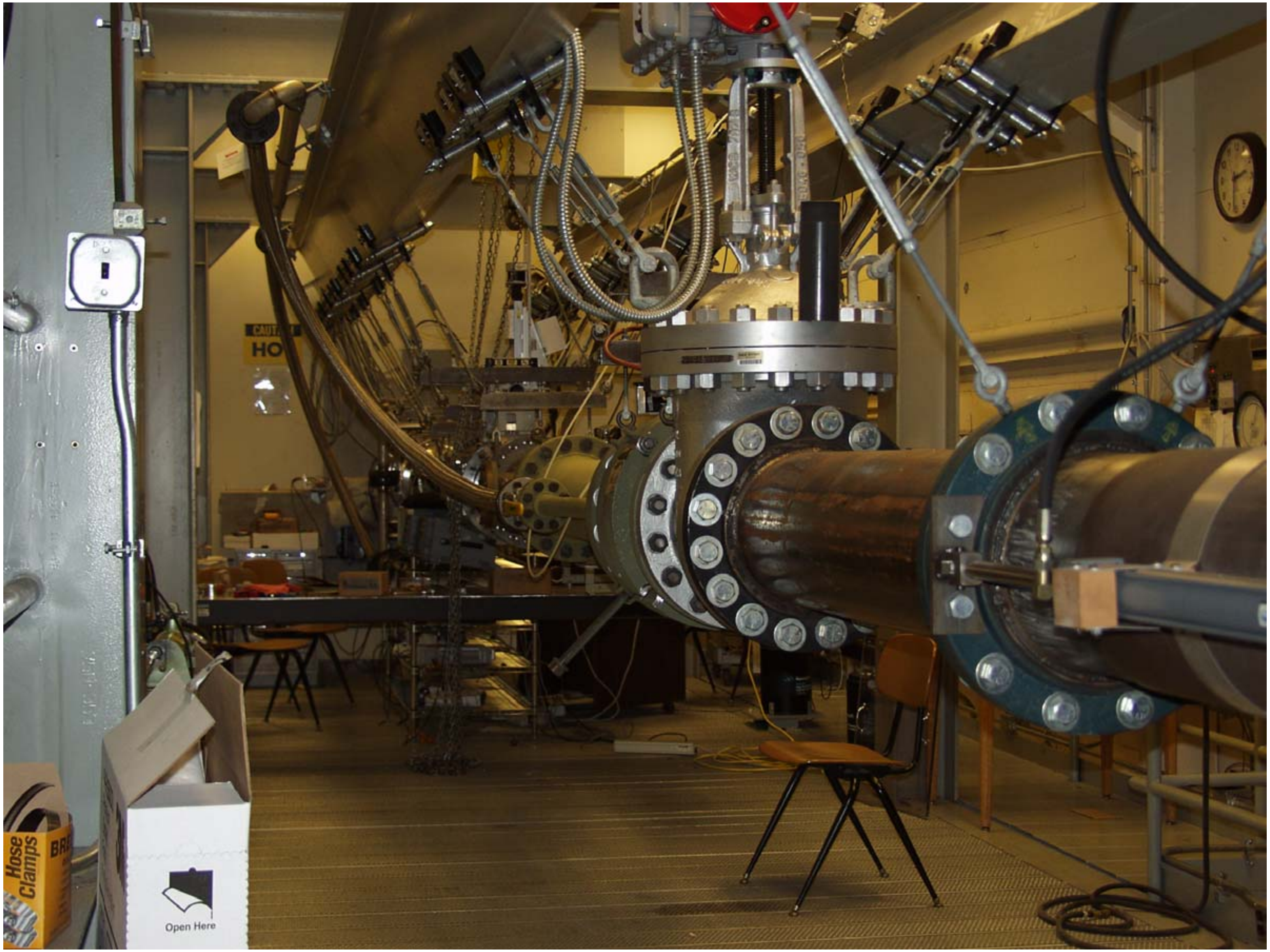
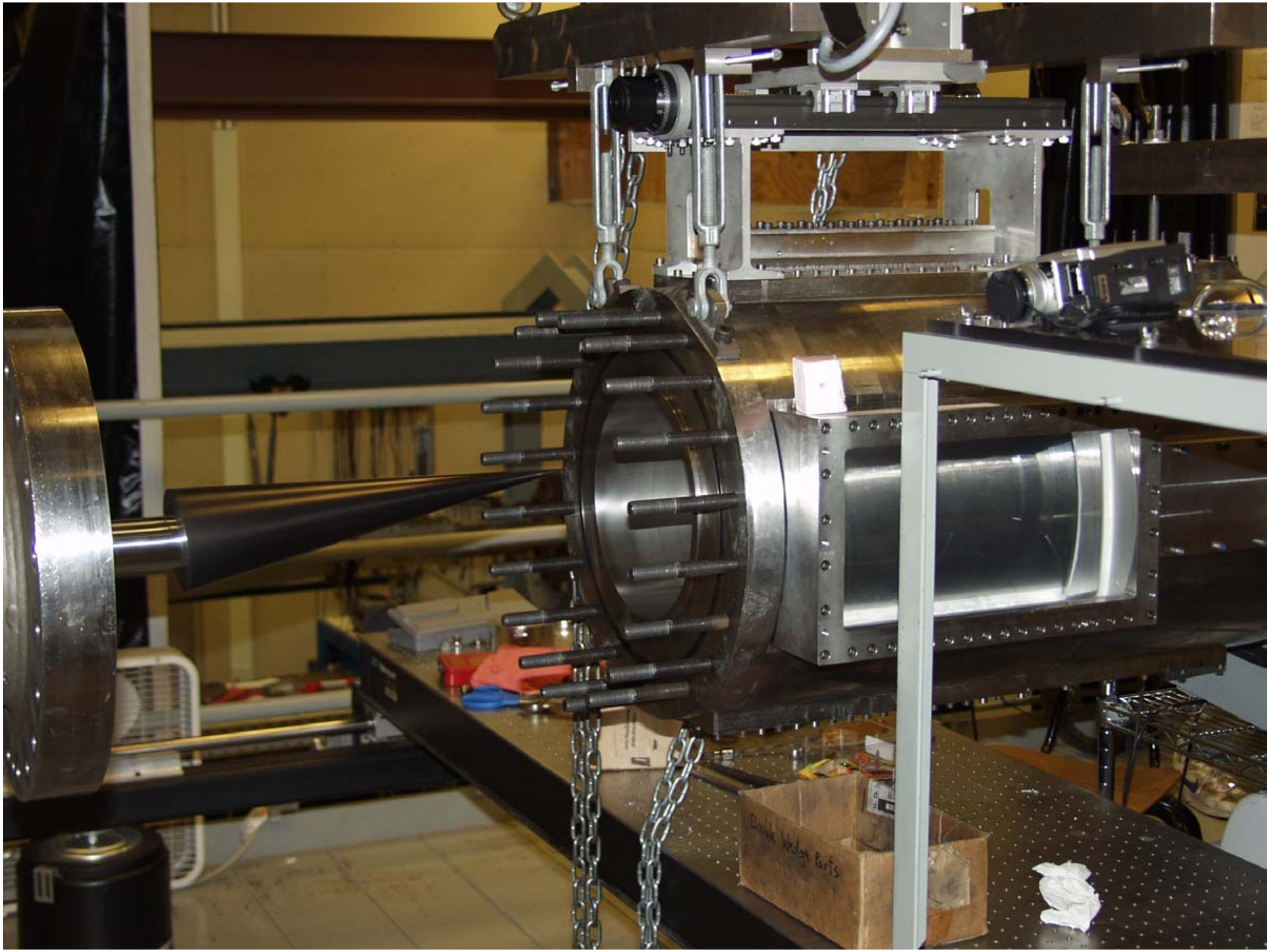
Nozzle and Diffuser, Looking Upstream



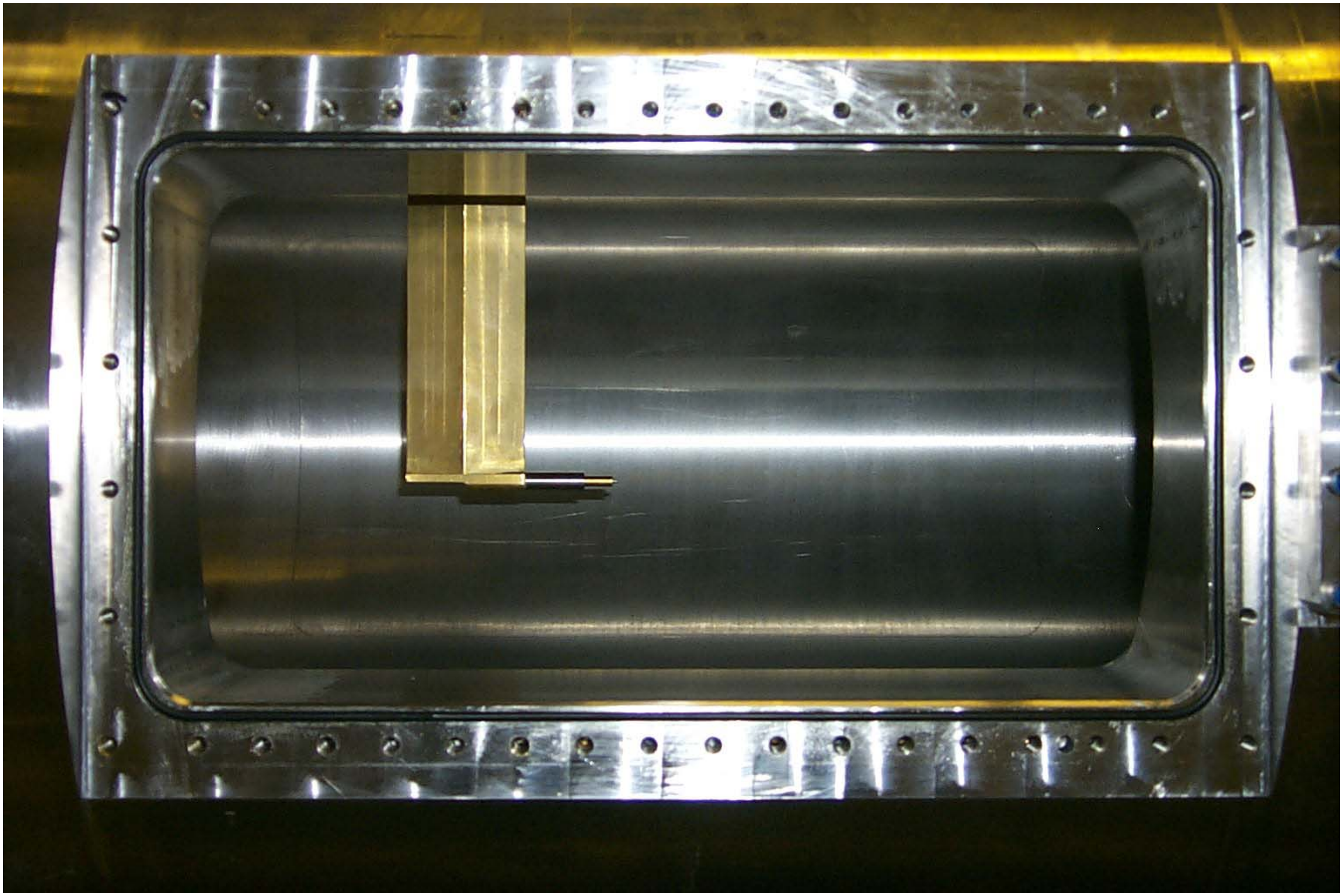
Sliding Sleeve, Slow Valve, Burst Diaphragm, Looking Upstream



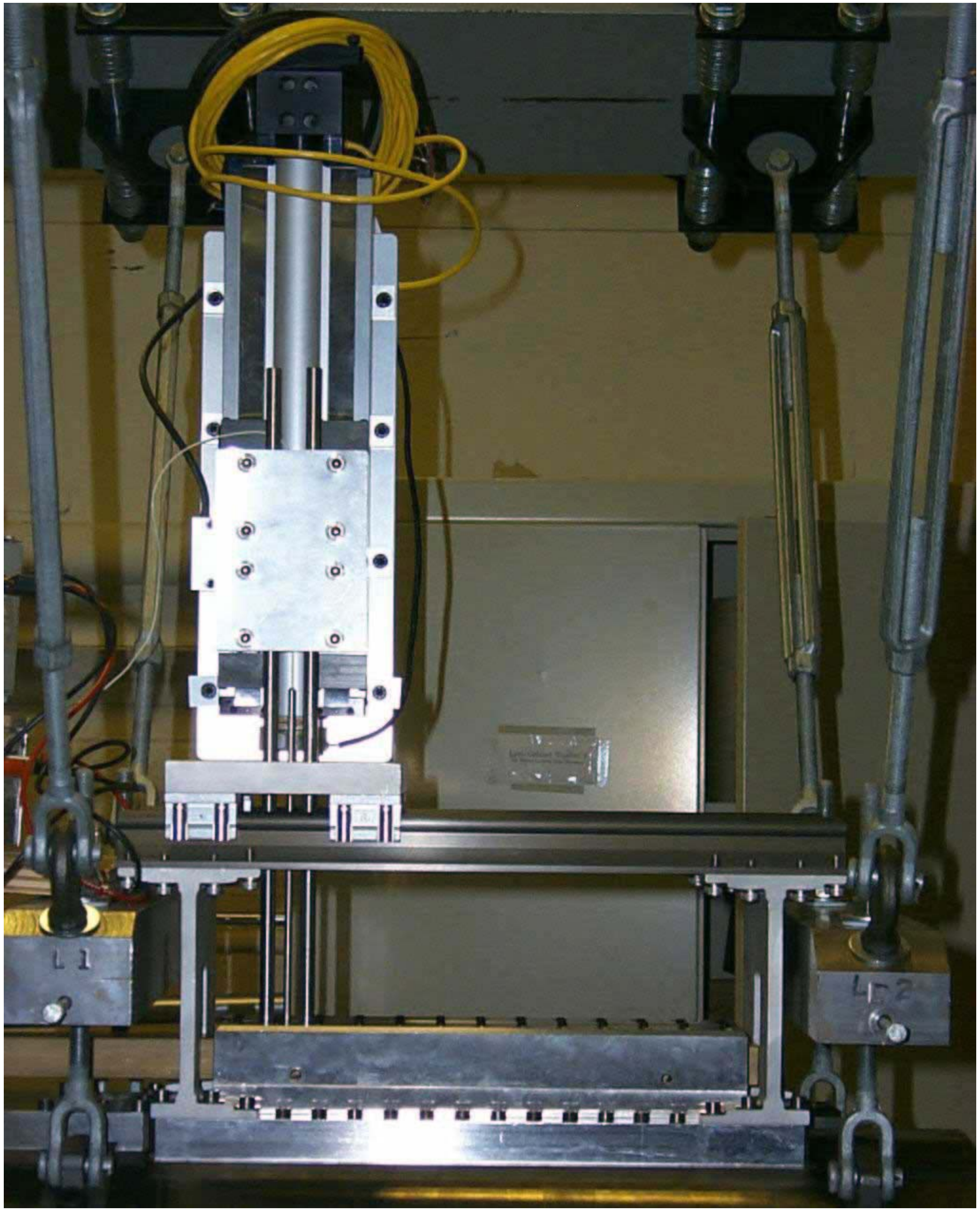
Cone at AOA, Preparing to Insert in Nozzle, Window View



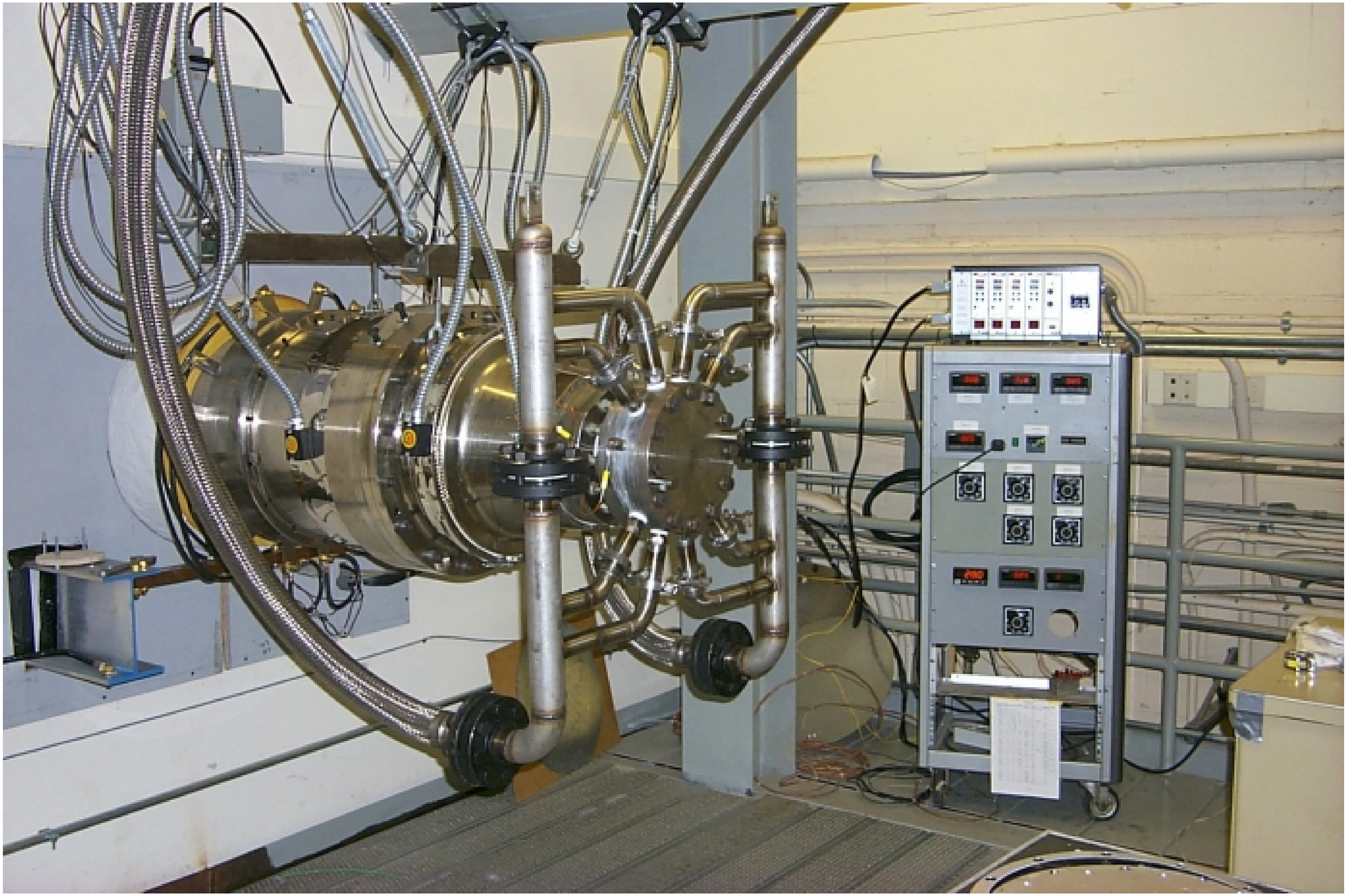
Probe in Nozzle, Viewed With Window Removed



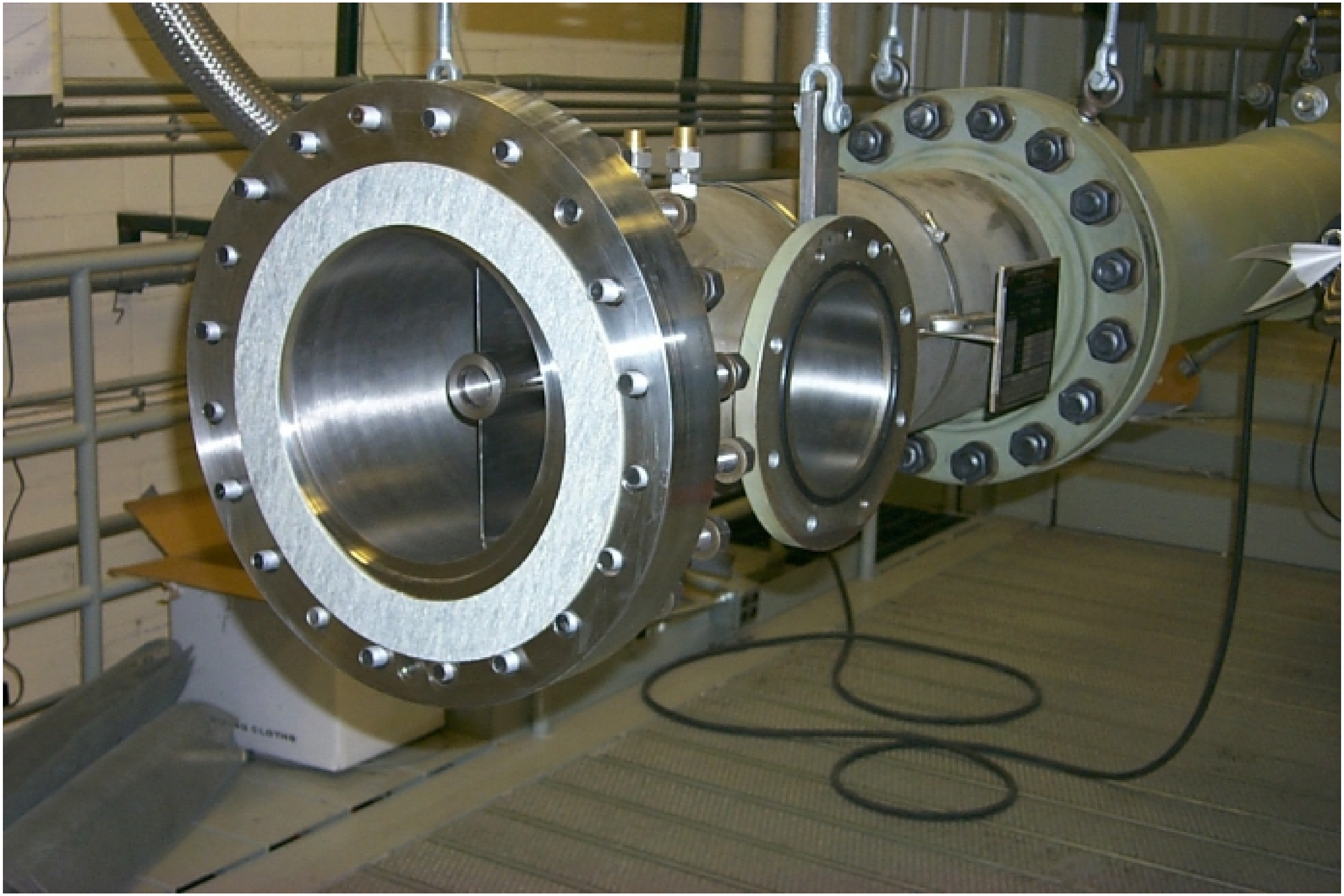
Probe Traverse with Vertical Automation



Contraction and Bleed Vacuum with Heaters

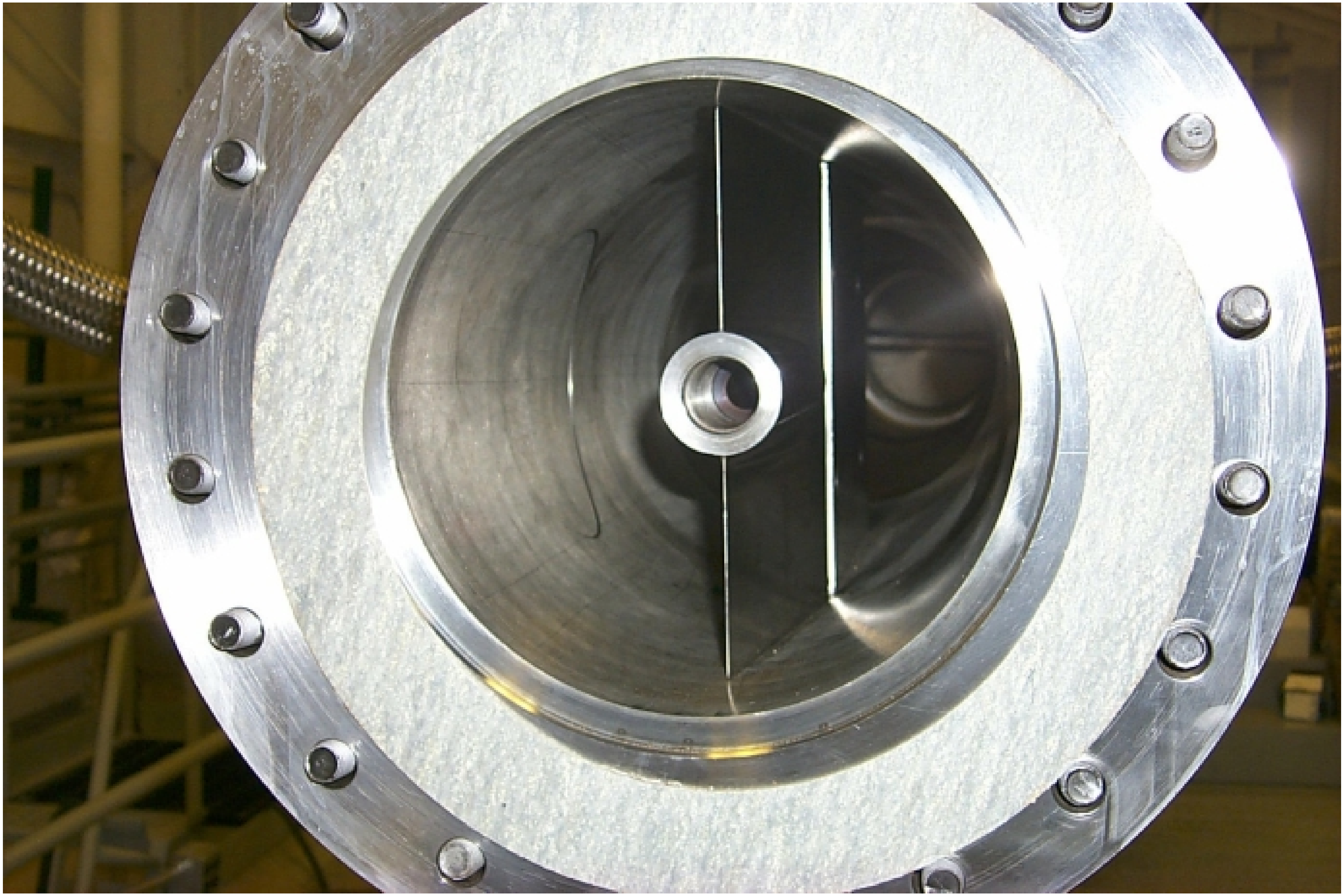


Double-Wedge Second-Throat Section

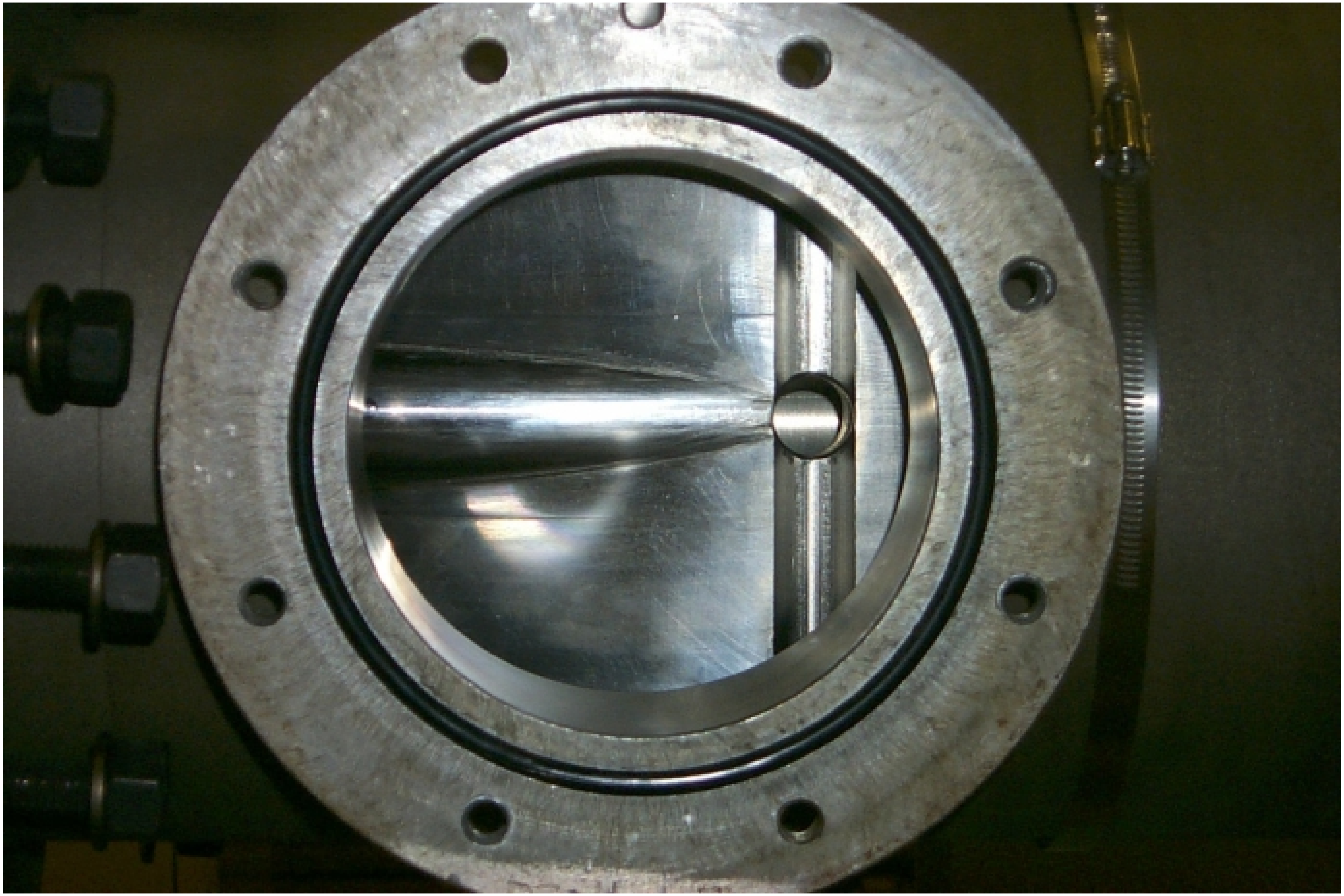


Double Wedge during Fabrication

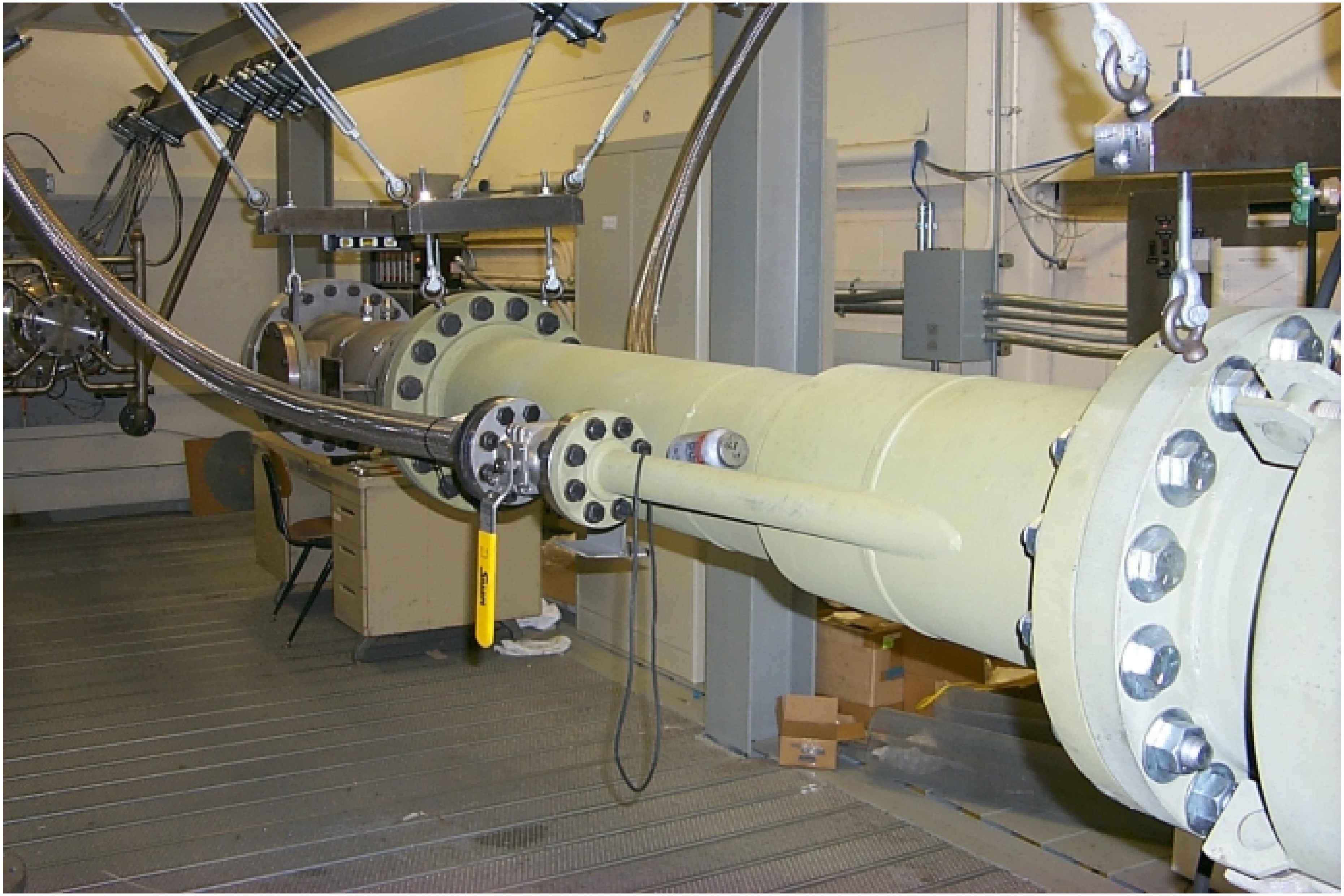
Double Wedge Sting Support



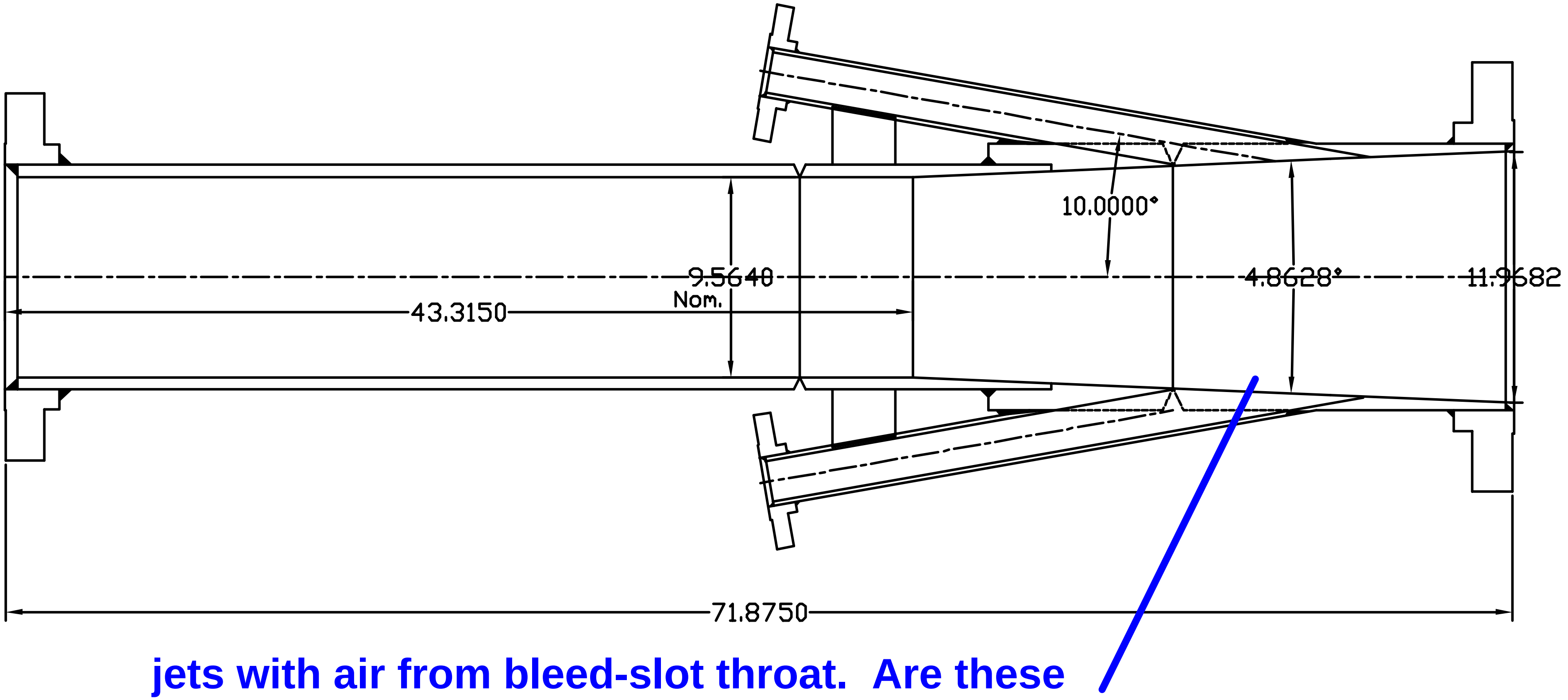
Side Access Port for Model Wiring



Downstream Bleed-Slot Vacuum System



Diffuser for Mach-6 Tunnel

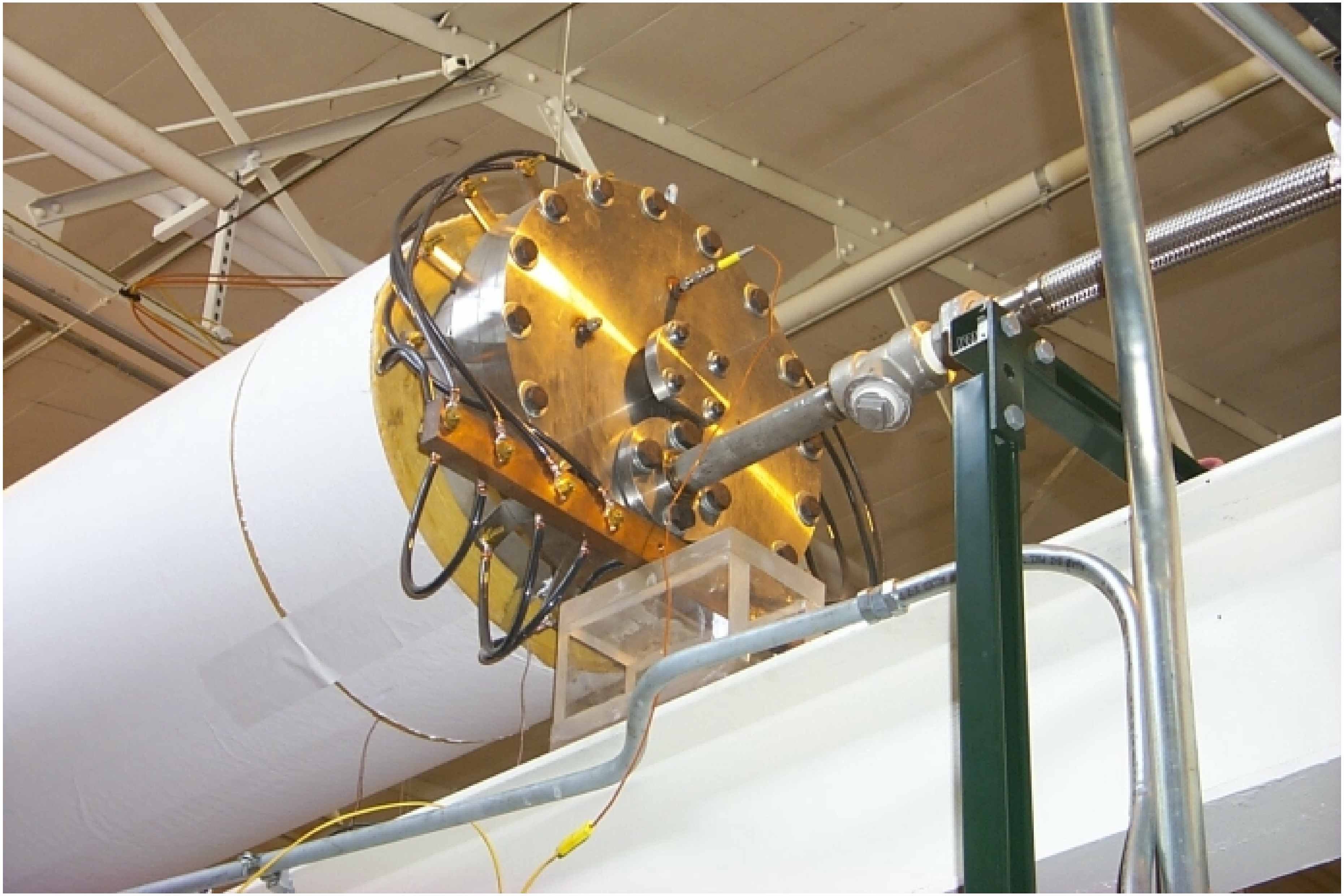


jets with air from bleed-slot throat. Are these downstream disturbances acceptable?

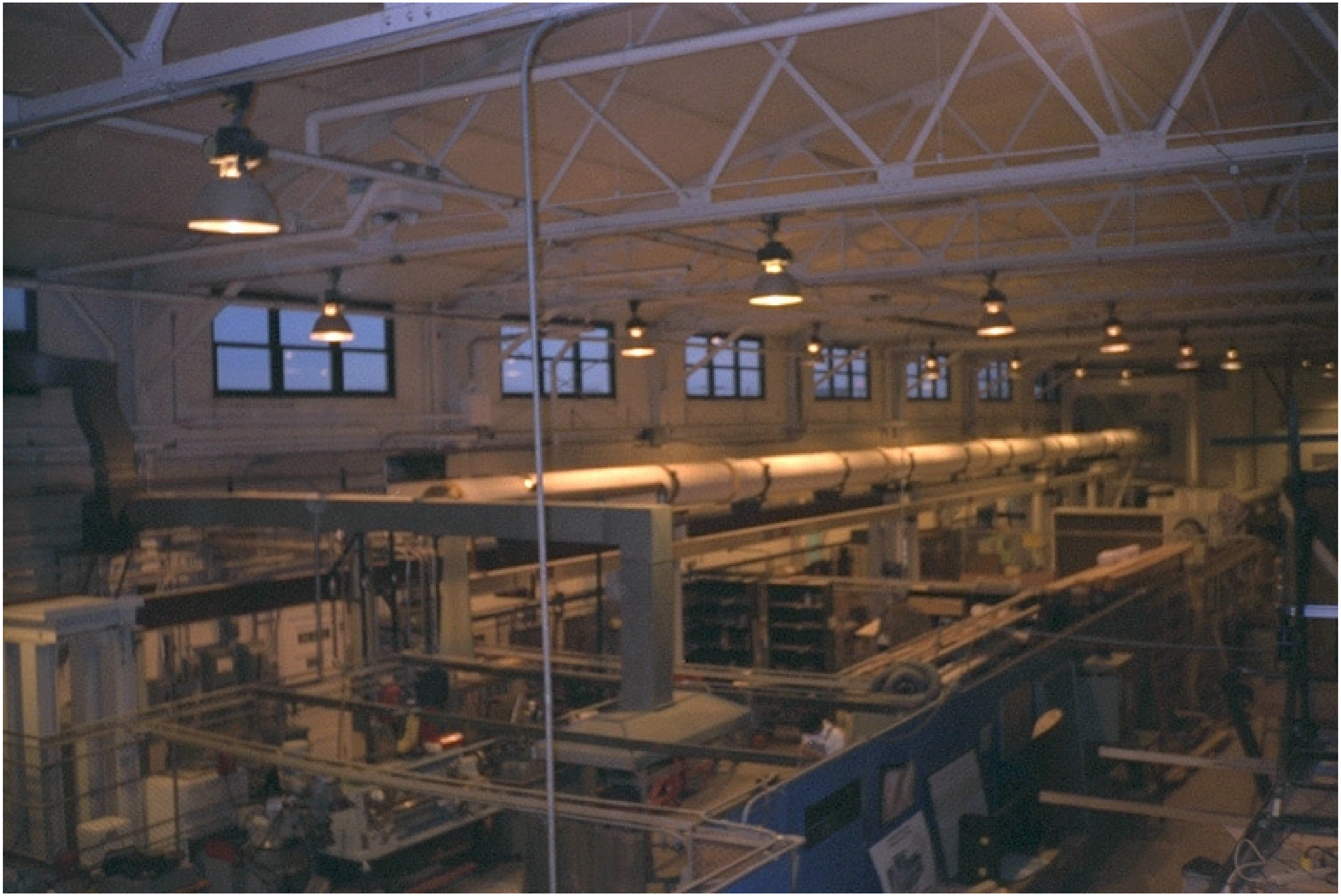
dimensions in inches

Looking Upstream into Diffuser

Upstream End of Driver Tube



Driver Tube



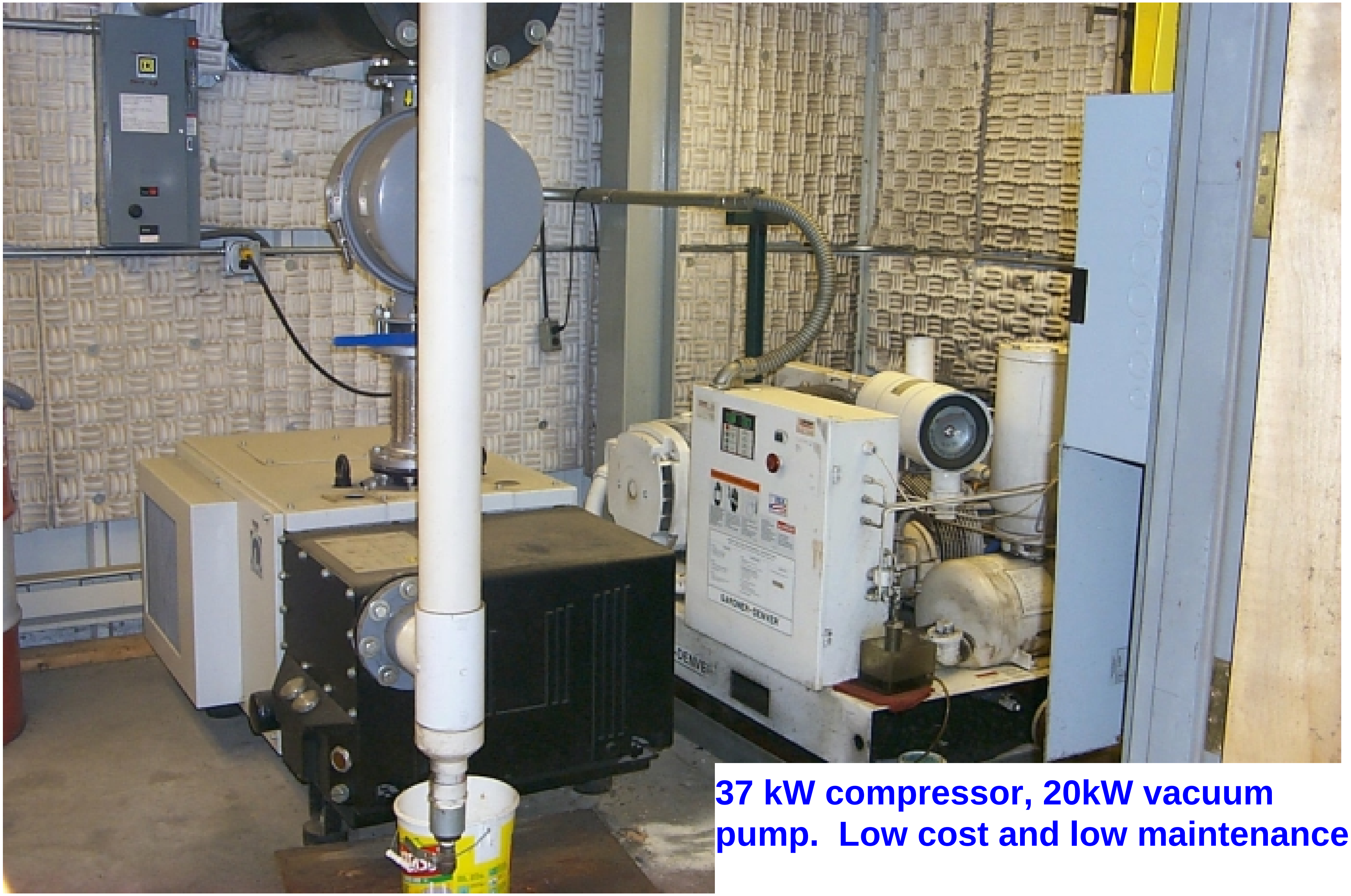
Power Supplies for Driver Heating

Driver-Air Filters, Circulation Heater, and Clean Supply Piping.

Vacuum Tank(s) and Bldg. Extension

Vacuum Tanks and Lines

Compressor and Vacuum Pump Room



37 kW compressor, 20kW vacuum pump. Low cost and low maintenance.

Automated Air Dryer

Summary of Purdue Effort, 1999-2003

1. **Completion of Mach-6 Quiet-Flow Ludwieg Tube**. Rufer, M.S. 2000, burst diaphragm tests. Skoch, M.S. 2001, heaters and initial tests. Initial Operation, April 2001.
2. **Development of Automated Vertical-Plane Traverse** (probe profile in single run). Swanson, M.S. Dec. 2002
3. **Modifications to Bleed-Slot Throat Yield Initial Quiet Flow** (but only at low Reynolds number).
4. **Hot-wires survive in Mach-6 flow, stable CTA operation,** 2001-2003 (up to 50 runs at total pressures to 10 atm.).
5. **Skoch/Rufer operate Ladoon's glow perturber** and hot wire apparatus in Mach-4 tunnel, 2002. (New student education).
6. **Matsumura/Swanson develop temperature-sensitive paints** for measuring stationary vortex growth, 2001-2003.
7. **Matsumura measures streak/vortex growth on Hyper2000** with controlled roughness perturbers.
8. **Schneider surveys flight data for transition,** summer 2002-2003

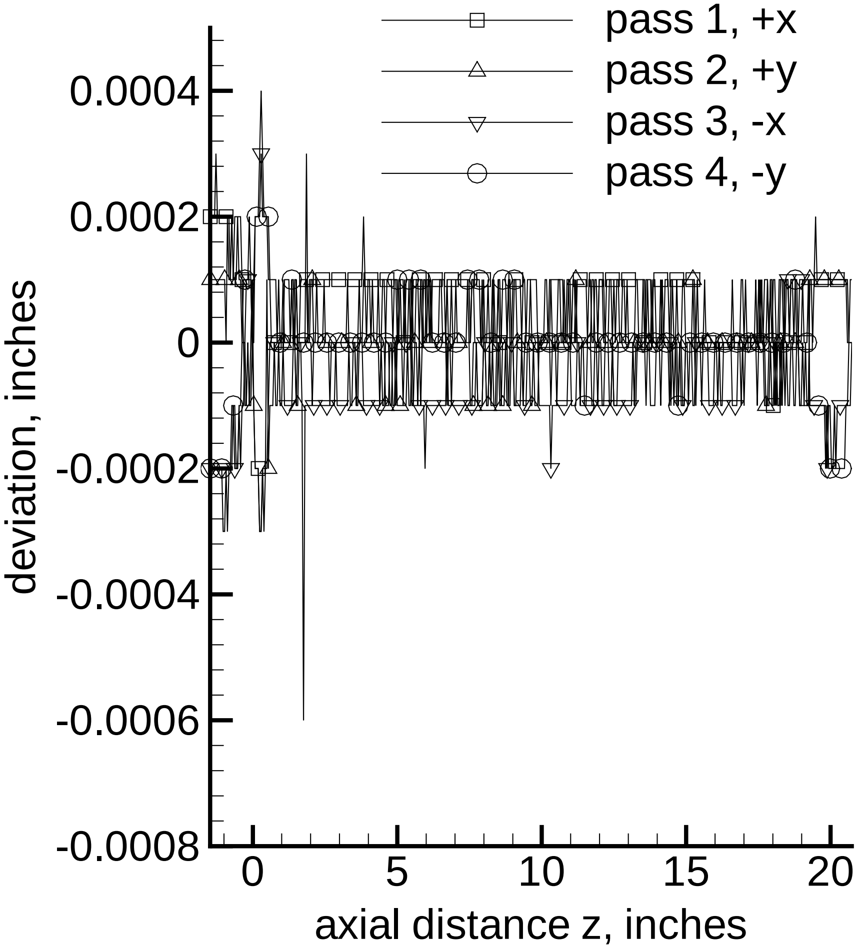
Deviation of Mandrel Coordinates from Design

Mandrel for electroform for nozzle throat.

Four rows of measurements at 90-deg. azimuthal angles.

3rd attempt.

See AIAA Paper 2000-2592, June 2000.



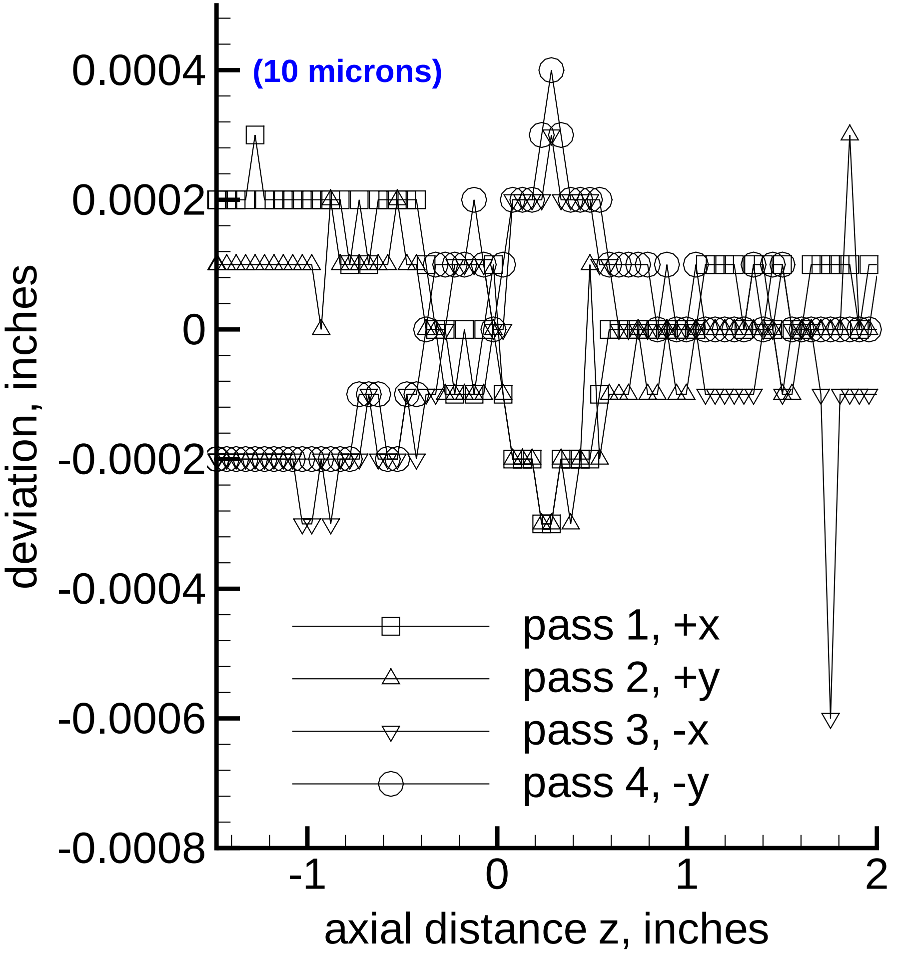
Throat Detail, Deviation of Mandrel Coordinates

Mandrel for electroform for nozzle throat.

3rd attempt.

See AIAA Paper 2000-2592, June 2000.

contour flaws held below 0.001 inches (25 microns)



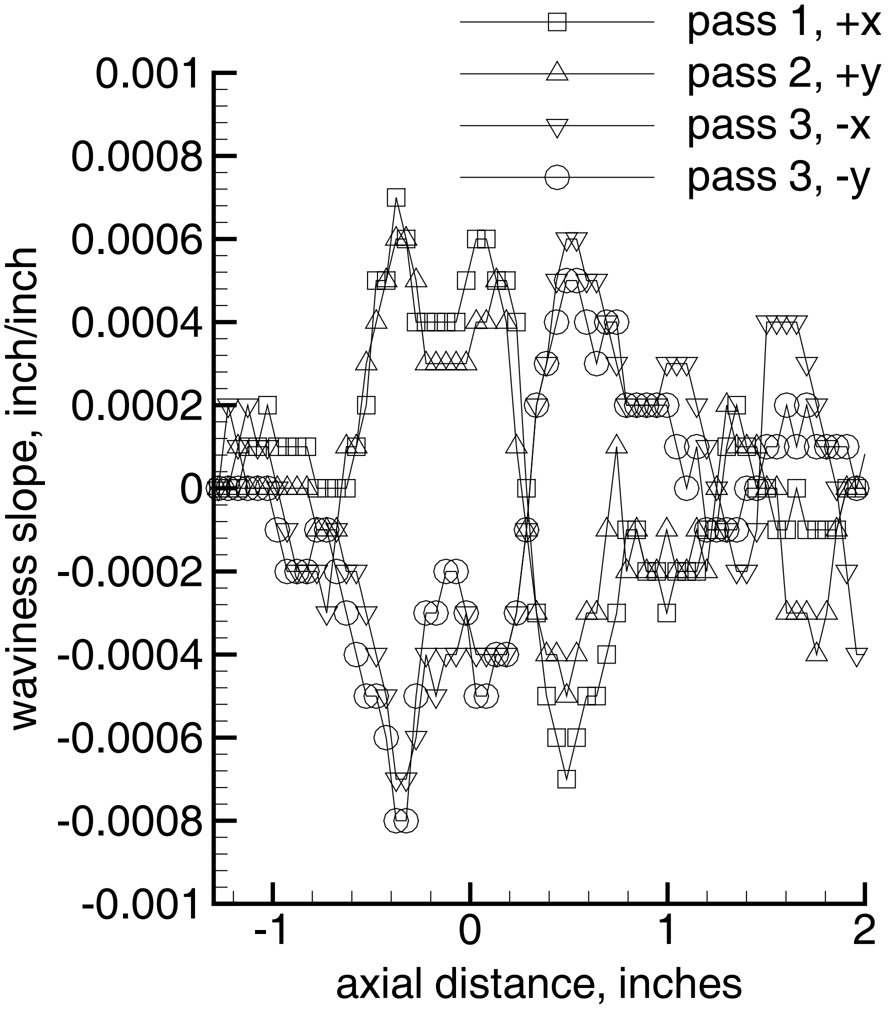
Waviness of Mandrel Coordinates

Mandrel for electroform for nozzle throat.

3rd attempt.

See AIAA Paper 2000-2592, June 2000.

waviness held below 0.001 inch/inch

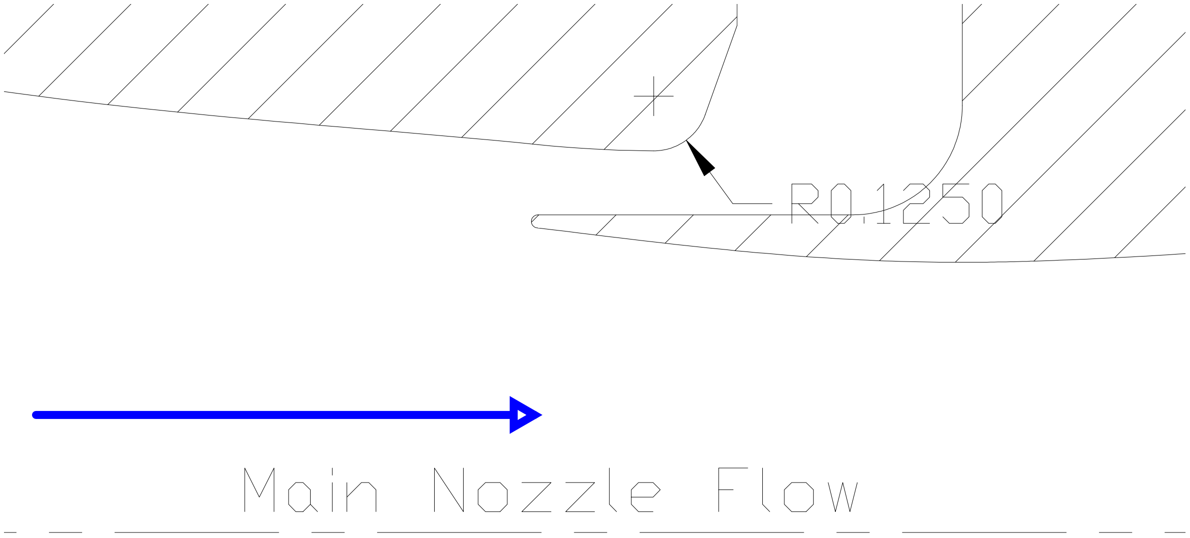


Tunnel Quiet Only at Low Reynolds No. – Why?

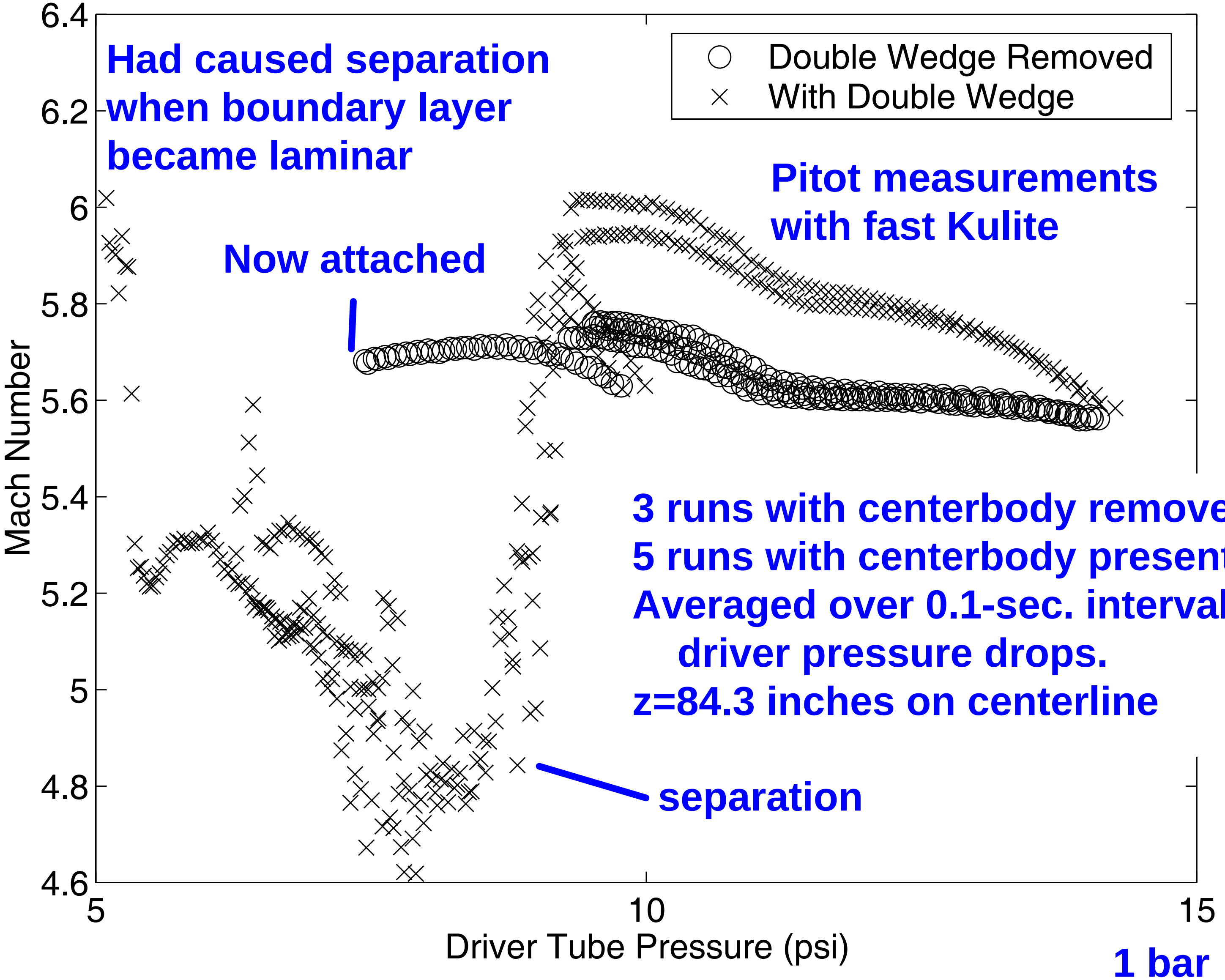
1. Fluctuations generated at bleed-slot lip? (Tried Case 7)
2. 0.001-0.002-in. step at aft end of electroform? Lack of polish on downstream sections? (Polished downstream)
3. Leaks which we have not found yet?
4. Upstream effect of diffuser fluctuations? (current focus) LaRC quiet tunnels all open jet
5. Vibrations of tunnel & bleed lip?? M4 had no lip. But these damp with time, no time dependence observed
6. Residual noise in driver? Plan hot-wire measurements
7. Something else?
8. Nozzle length twice Langley Mach-6 quiet nozzle (was quiet to 145 psia). We drop quiet at 8 psia in downstream half of nozzle. Bypass!?

Design of Seventh Bleed Slot Throat

- 1D streamtube analysis ala Beckwith, full 1D both sides of bleed lip. See AIAA 2003-1130, Jan. 2003
- Increase from 30% to 38% suction
- Move stagnation point from 2/3 below top of hemicircle to 4/5 below top



Effect of Centerbody on Upstream Mach Number



Had caused separation when boundary layer became laminar

Now attached

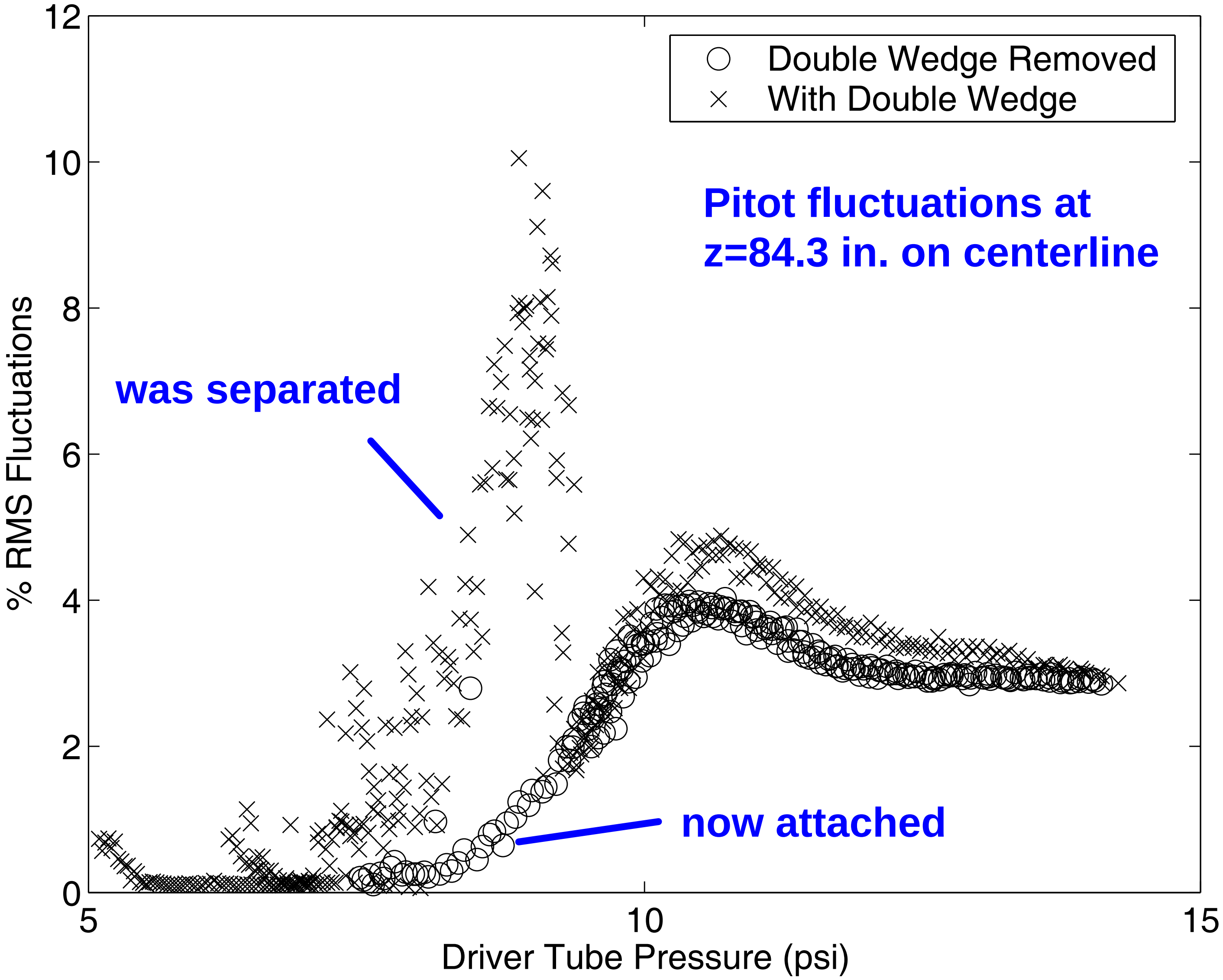
Pitot measurements with fast Kulite

3 runs with centerbody removed.
5 runs with centerbody present.
Averaged over 0.1-sec. intervals as
driver pressure drops.
z=84.3 inches on centerline

separation

1 bar

Effect of Centerbody on Upstream Pitot Fluctuations

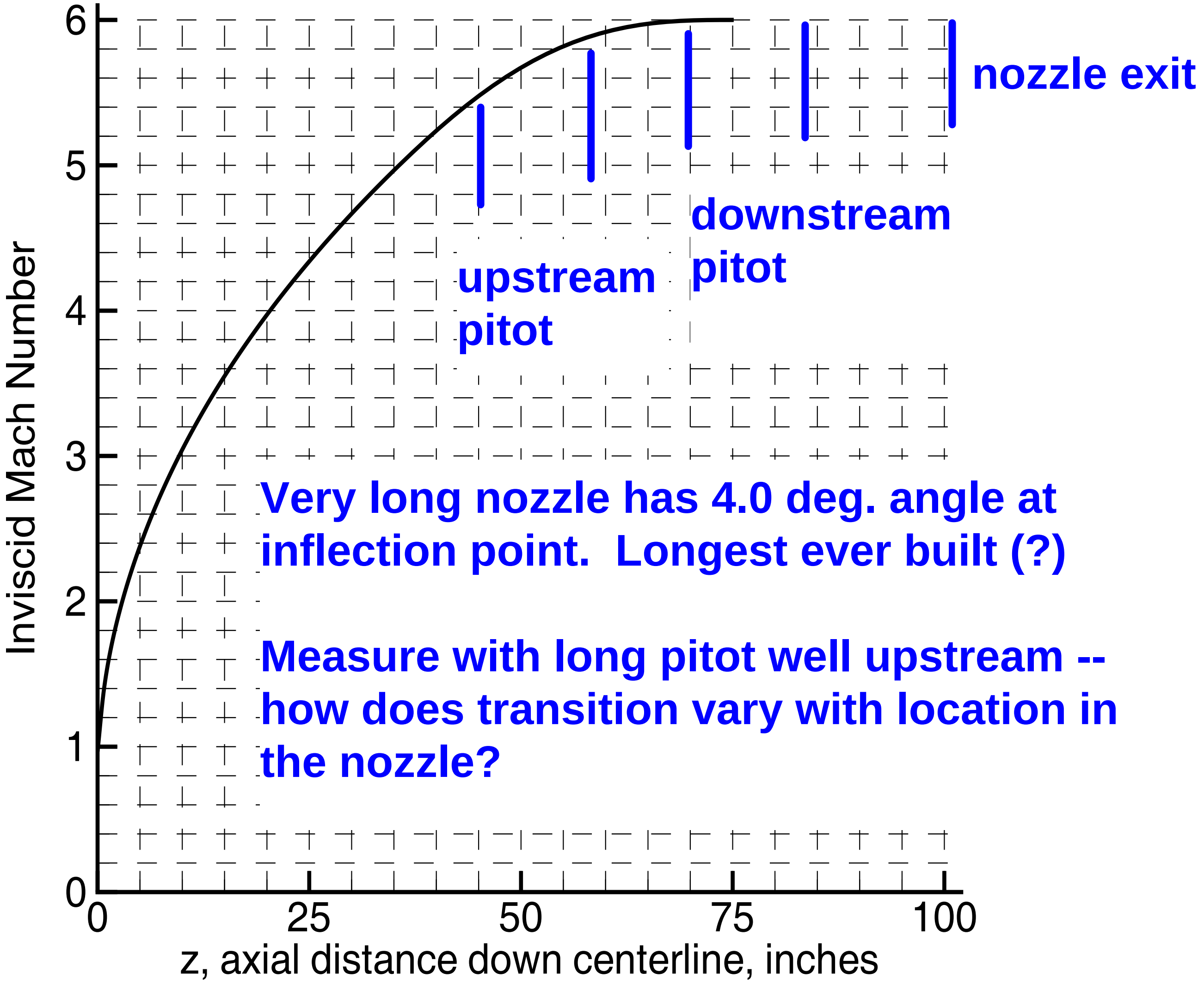


Pitot fluctuations at z=84.3 in. on centerline

was separated

now attached

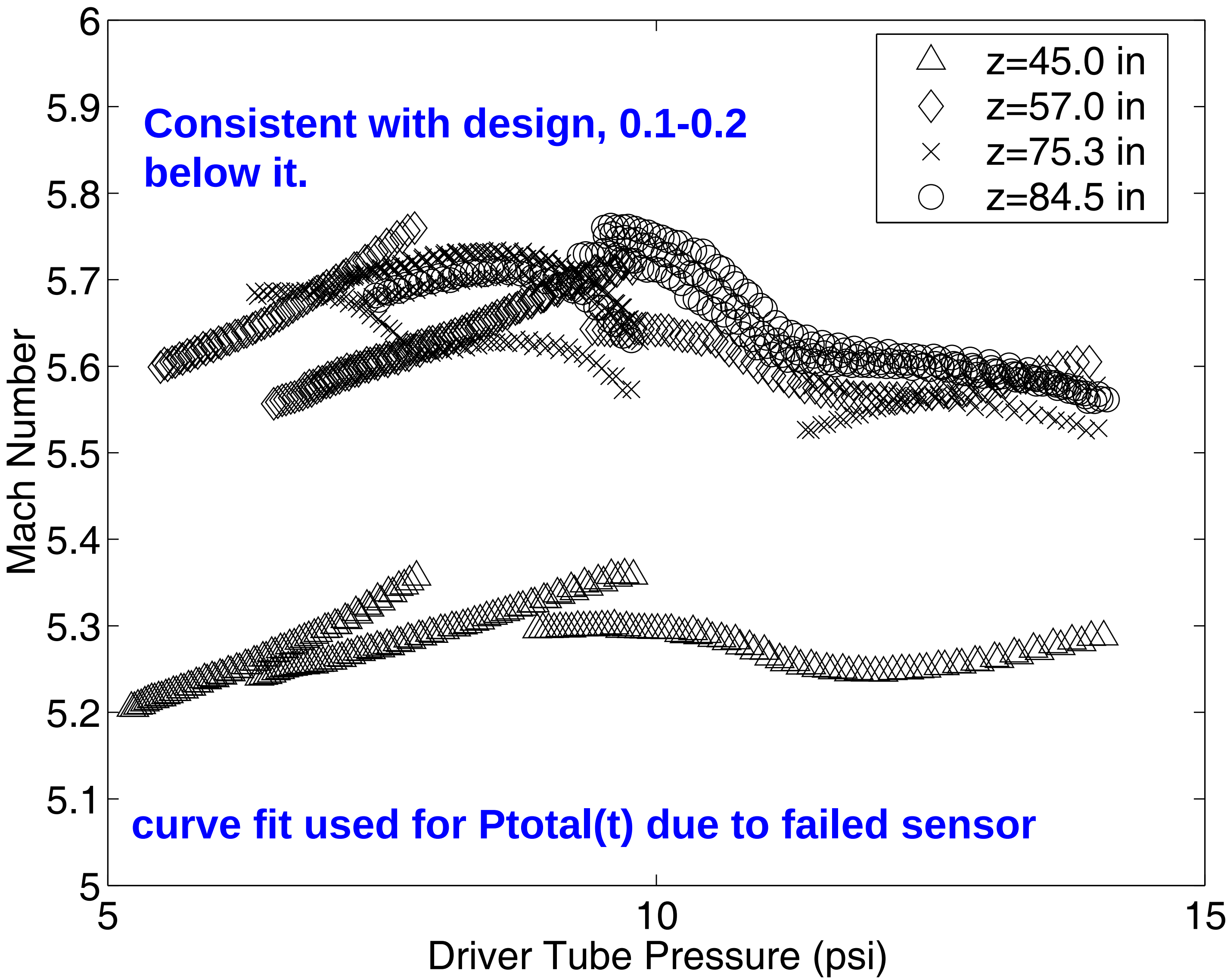
Inviscid Mach Number on the Nozzle Centerline



Very long nozzle has 4.0 deg. angle at inflection point. Longest ever built (?)

Measure with long pitot well upstream -- how does transition vary with location in the nozzle?

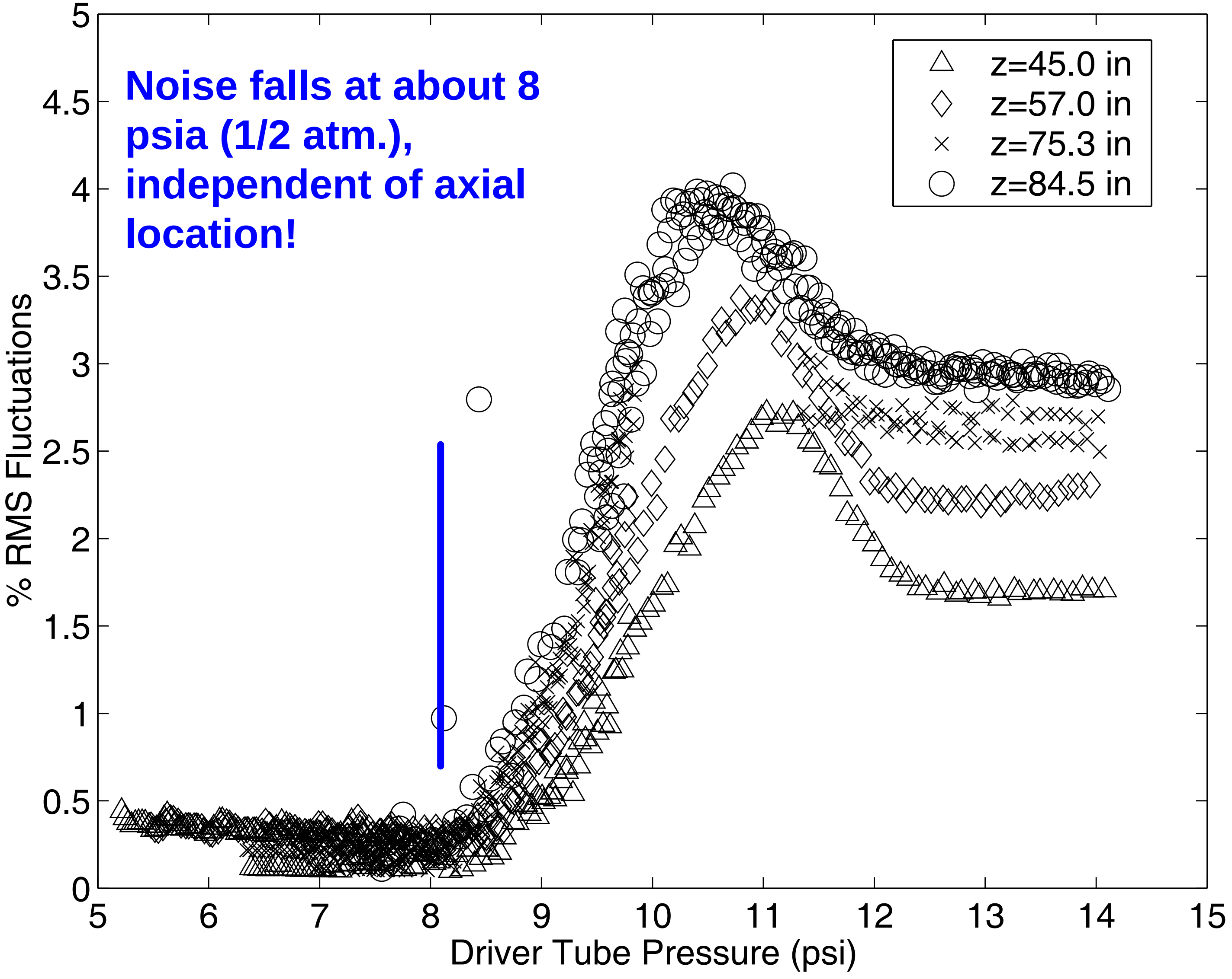
Mach Number in the Quiet Nozzle



Consistent with design, 0.1-0.2 below it.

curve fit used for Ptotal(t) due to failed sensor

Pitot Fluctuations in the Quiet Nozzle



Noise falls at about 8 psia (1/2 atm.), independent of axial location!

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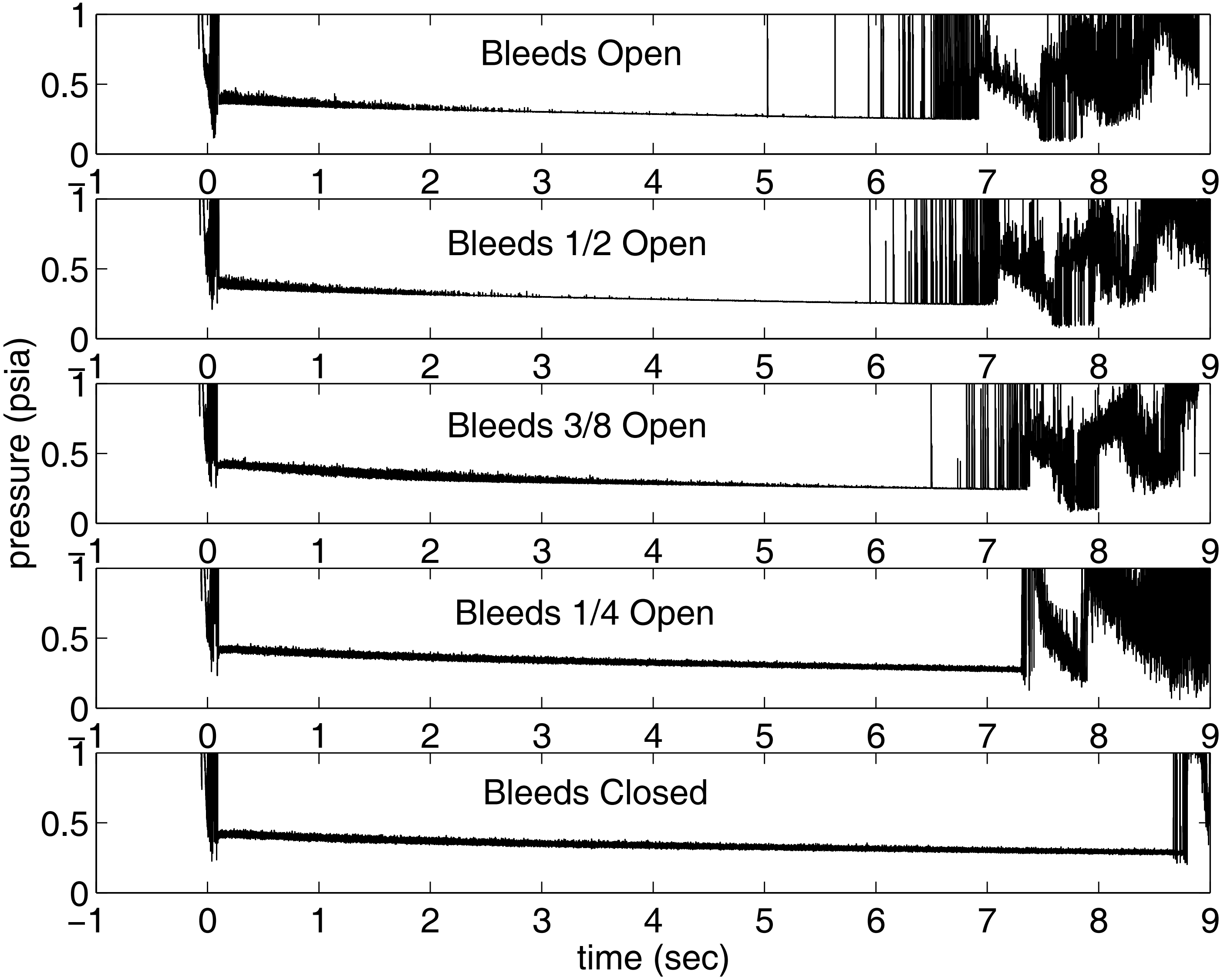
Pitot Traces with Throttled Bleeds

runtime is longer without bleed air bypassing nozzle



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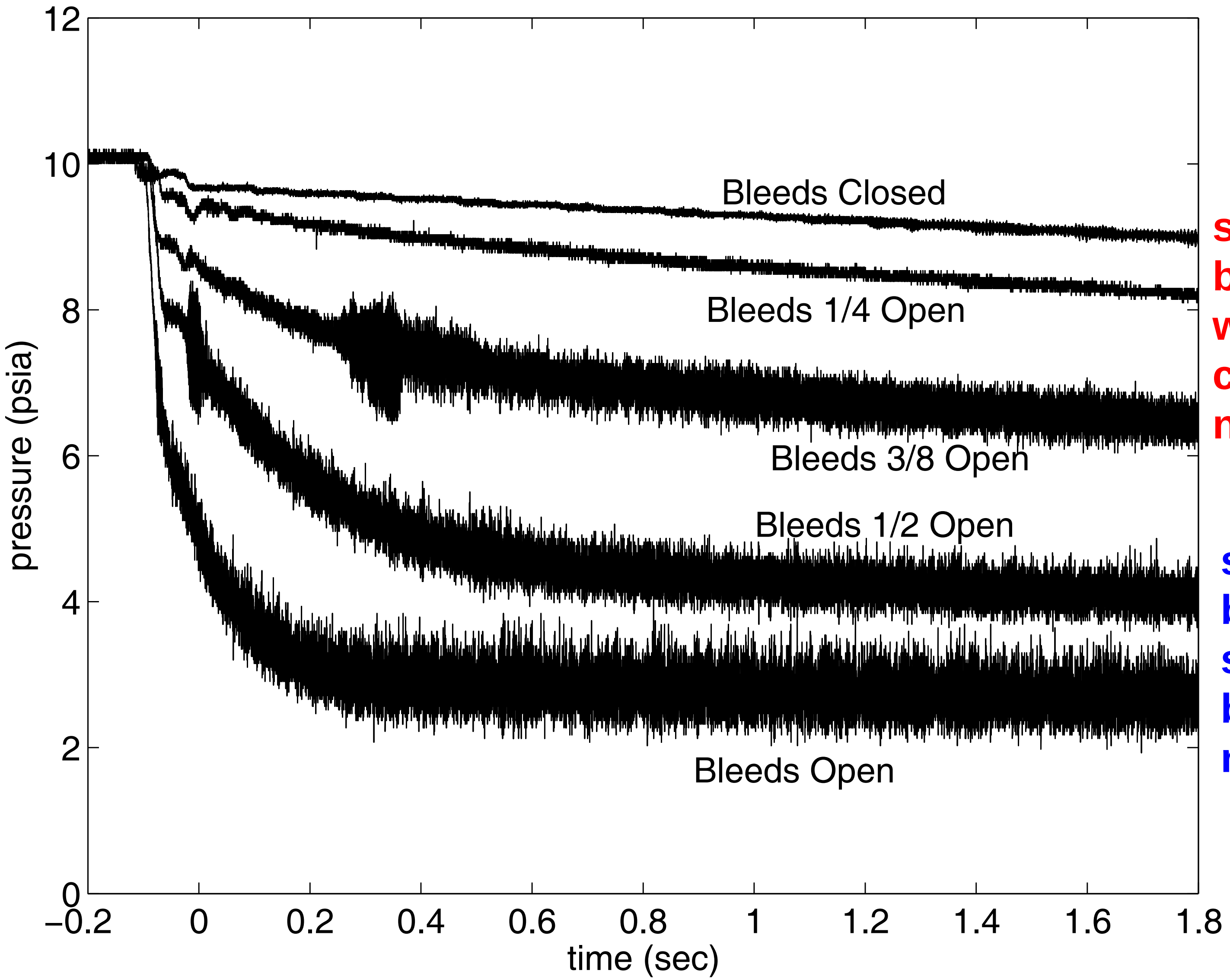
Suction-Plenum Pressures with Throttled Bleeds



subsonic bleed slot will cause noise

sonic bleed slot blocks noise

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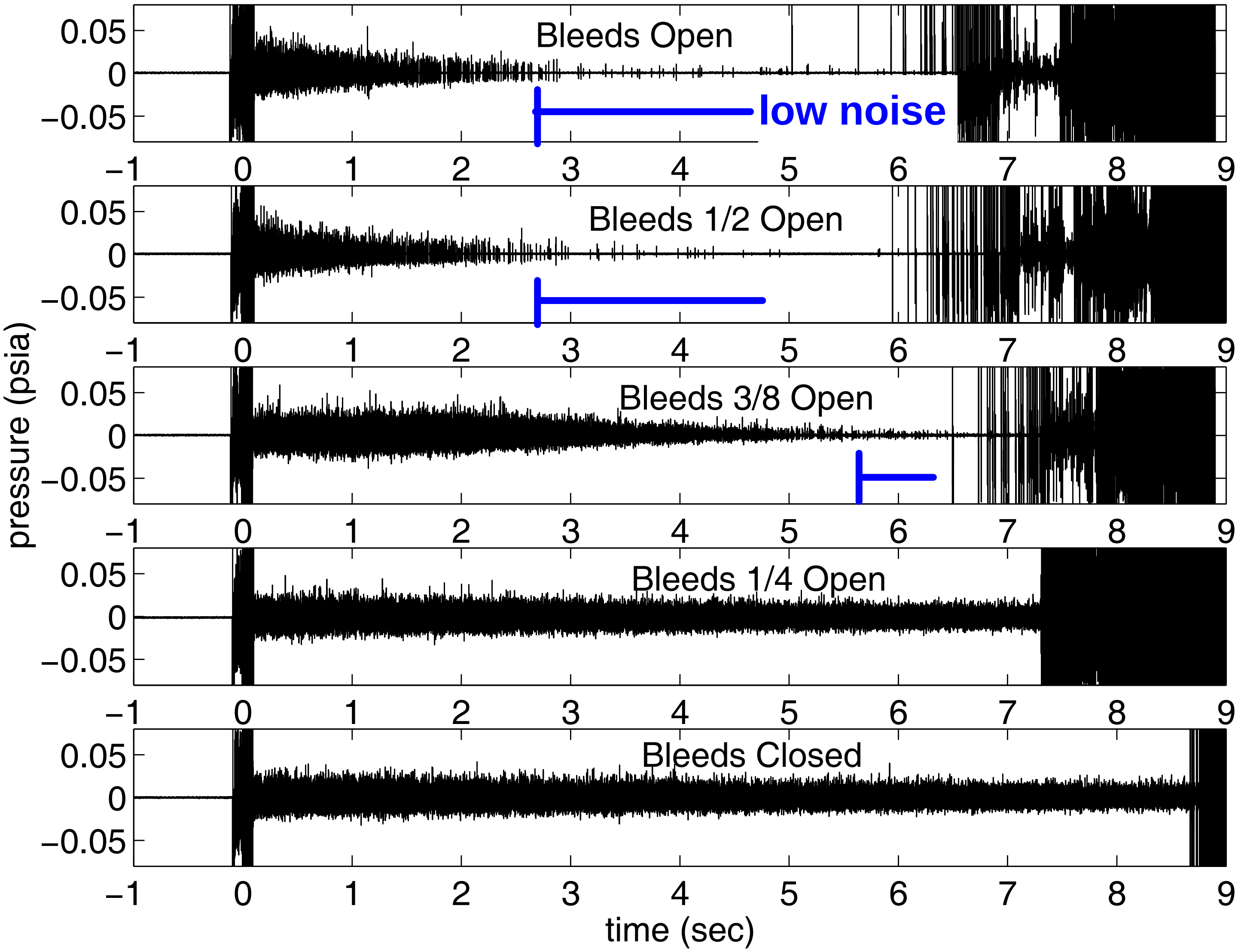
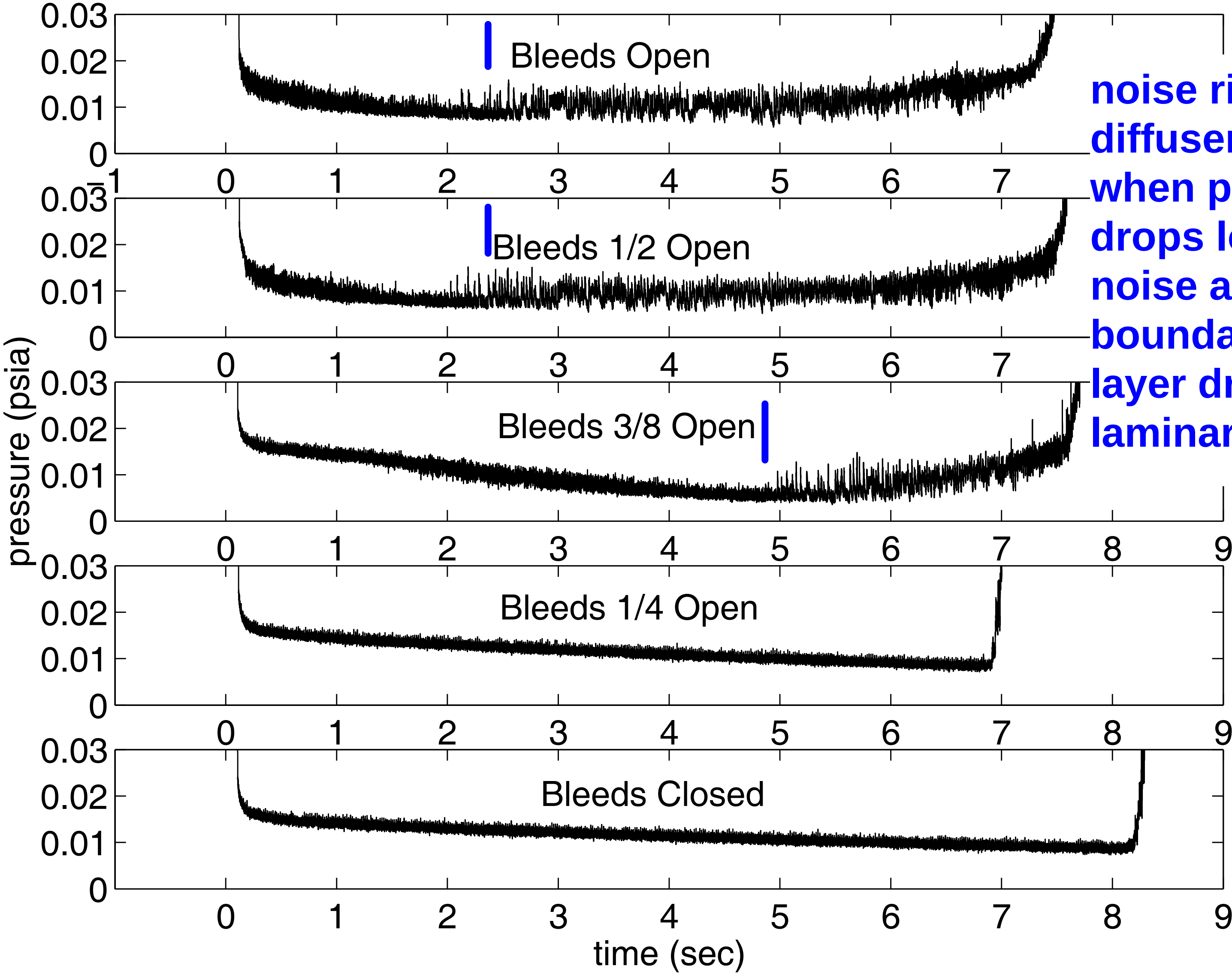
Pitot Fluctuations with Throttled Bleeds

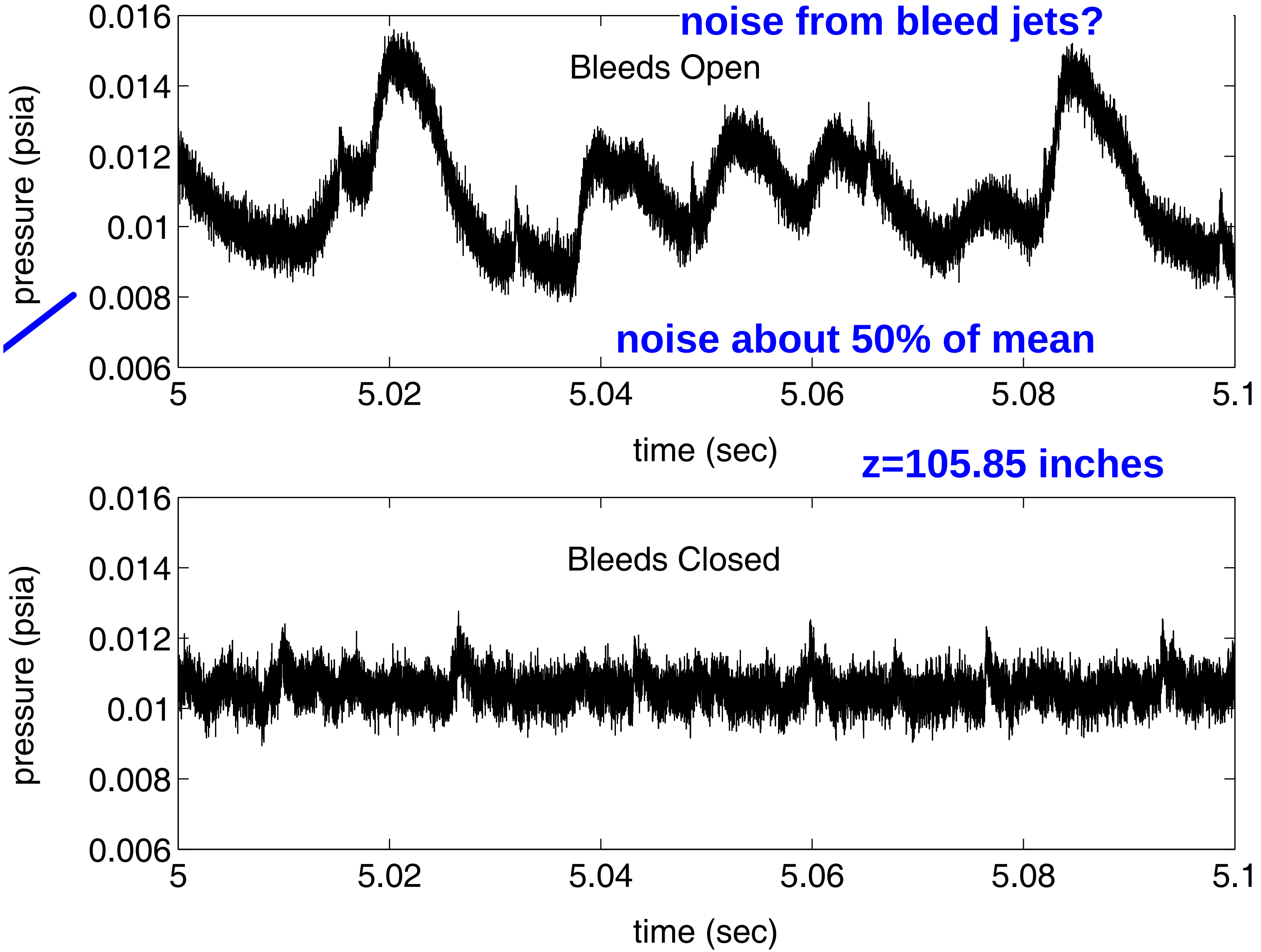


Diffuser Static Pressures with Throttled Bleeds



noise rises in diffuser inlet when pitot drops low noise and boundary layer drops laminar

Detail of Diffuser Pressures with Throttled Bleeds



noise from bleed jets?

noise about 50% of mean

z=105.85 inches

Theory for Mach 5.8 from 10 psia. Limited accuracy in p.

Summary

- Tunnel runs quiet, now without separation, at 8 psia, Mach 5.7. Model support/second throat had excessive blockage. A new streamlined support is under construction.
- Bypass causes nozzle-wall transition at 8 psia
- Prime suspect is still fluctuations from downstream
- Work toward quiet flow continues

What Next?

- Are Disturbances Fed from Downstream Tripping the Upstream Boundary Layer? Centerbody DID cause separation. Now plumbing bleed air direct to vac. tank. Modify diffuser further? How?
- Oil-Flow on Nozzle Walls to Look for Gortler instability
- Need computation of flow in Bleed Slots,
  more measurements
- Measure flow in contraction entrance, confirm low noise
- Check for leaks with helium sniffer
- Measure on diffuser and with hot-wire on nozzle wall
- Make sled-mounted probe to measure wall b.l. upstream?