Comparative Assessment of Sound Generated Using Laser-Induced Plasma

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Laser-induced plasma benchmark study

3rd Hybrid Anechoic Wind Tunnel Workshop

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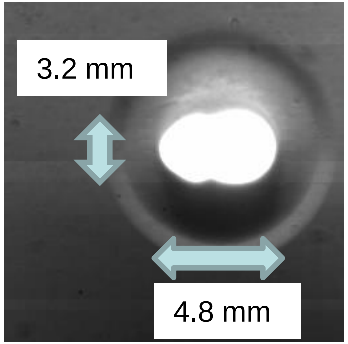
Contents

- **Overview** of laser-induced plasma and its properties
- Design of **laser-optical setup** (best practices)
- List of **facilities**
- List of **experimental setups**
- **Comparative study** of acoustic signatures
- **Health and safety** measures
- **Application examples**

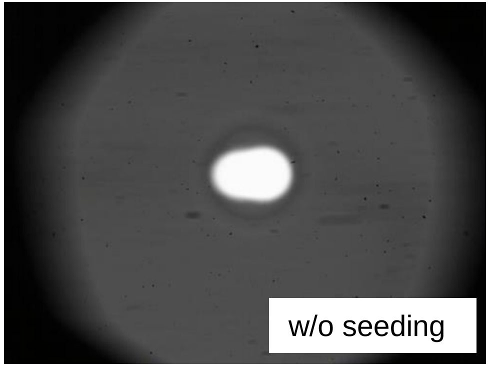
Overview of laser-induced plasma (LIP)

- **Properties of LIP**
  - **Tight-focusing of laser beam** results in **plasma formation** once a sufficiently high energy density is reached
  - Also generates an **acoustic source**
  - Source is **well localized**
  - **Repeatable**
  - **Good temporal characteristics** (initially supersonic propagation)
  - **Good omnidirectionality** (no flow)
  - With flow: convection effect (**Doppler** shift)
    - **Can be accounted for** (AIAA-2015-3146)
  - **Suitable for high-frequency** analysis (2-100 kHz) + good **signal-to-noise** ratio (loud)
- Laser-optical **requirements primarily rely on laser head** (PIV) and **secondarily on optics** (also cost-wise)
- Observed **waveform depends on instrumentation** <u>hence this collaborative effort.</u>

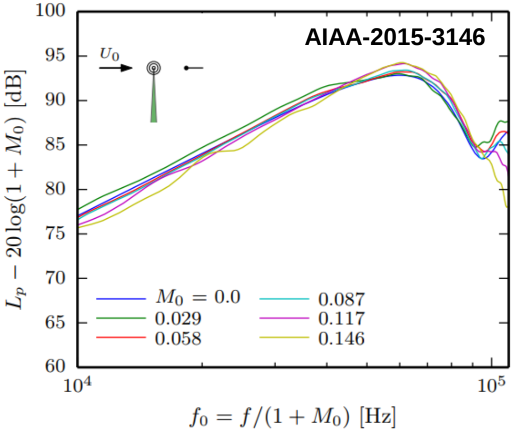
VT



FSU

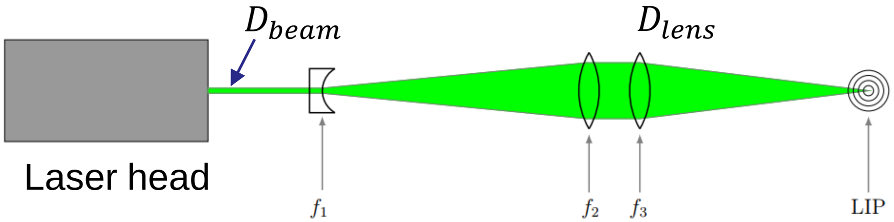


200 kFrames/sec (5 μs)
1.62 μs exposure time
Timespan: 100 μs



Laser-optical design

- Using a **beam expander** plus **focusing optics**
- **Laser properties**: energy per pulse, pulse width (ns), beam: diameter (D_{beam}), area, divergence (mrad), wavelength (λ).
- Determine **focusing optics** from WTL test section size (f_3)
- Calculate **magnifing power** (MP) to select beam expander
  - **Image lens** focal length (f_1)
- Calculate "**spot size**" (ϕ_{spot})
  - Diffraction, and **aberration** limits (aspherical lens)
  - **Minimize** f_3/D_{lens} (i.e., f-number) for tight-focusing
  - **Laser beam quality** (M^2)
- Calculate **energy density** in spot
  - Exceed threshold* of $\mathbf{3.5 \cdot 10^{16}}$ **W/m²**

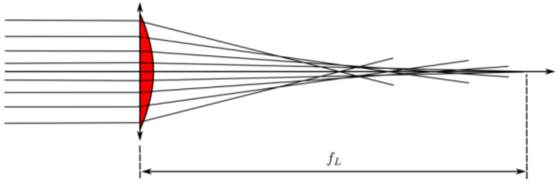


$$MP = \frac{D_{beam}}{D_{lens}} = -\frac{f_2}{f_1} \rightarrow f_1 = -\frac{f_2}{MP}$$

$$\phi_{\text{Spot Size}} = \phi_{\text{Diffraction}} + \phi_{\text{Aberration}} = \frac{4\lambda M^2 f}{\pi D} + \frac{kD^3}{f^2}$$

https://www.edmundoptics.com/knowledge-center/application-notes/lasers/beam-expanders/

Primary limitation: spherical aberration
~O(1) greater than diffraction (VT, DLR)



*Phuoc, T.X.: Laser spark ignition: experimental determination of laser-induced breakdown thresholds of combustion gases. Opt. Commun. 175(4), 419–423 (2000)

Laser-optical arrangments

OPTICAL/PLASMA PROPERTIES	VT SWT	NASA Langley QFF	DLR (AWB)	FSU	JAXA
Focal length	**1200 mm**	**~500 mm (approx.)**	**500 mm**	**500 mm**	**1200 mm**
Laser head	**Quantel Evergreen 200**	**New Wave Gemini**	**New Wave Gemini**	**Quantel Evergreen 200**	**Thales SAGA 230**
Laser energy (E_L)	**200 mJ**	**120 mJ**	**120 mJ**	**200 mJ**	**1250 mJ**
Laser pulse width	**10 ns**	**3-5 ns**	**3-5 ns**	**10 ns**	**8 ns**
Laser stability (% RMS)	2%	3.5%	3.5%	2%	1.2%
Wavelength	532 nm	532 nm	532 nm	532 nm	532 nm
Beam diameter (nominal)	**6.35 mm**	**5 mm**	**5 mm**	**6.5 mm**	**13 mm**
Laser repetition rate used	5/second	5/second	10/second	2/second	10/second
Calculated beam energy density at focal point (W/m^2)	**1.70E12**	**N/A**	**6.9E13**	**3.4E12**	**1.5E12 @ 120 mJ** **4.8E12 @ 400 mJ** **(beam E_L measured)**
Optical setup expenses	**$3000** - 2 pcs of Celestron AVX 6" telescopes (2x$1500) $200 – hardware **$1200** - smaller optics (f=200 mm)	**$3500 –** lenses and lens holders $160 - photodetector $550 - glass panel for use in QFF sidewall	**$1200**	**$920** - beam expander ($600) + converging lens ($120) +hardware ($200)+ + Dantec beam expander (cost unknown)	N/A
M^2 number used	20	N/A	30	6	9.6
front lens f number	8		12.5	4	8

Facilities overview

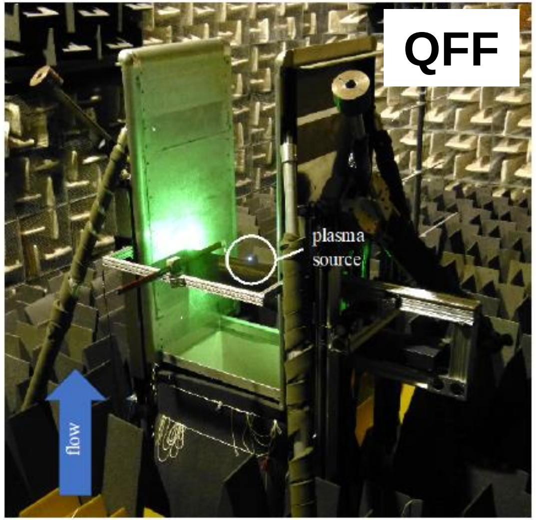
	VT SWT	NASA Langley QFF	DLR (AWB)	FSU	JAXA
Test section size (ft & m)	6’ x 6’ x 24’ 1.83 m x 1.83 m x 7.3 m	2’ x 3’ x 6’ 0.6 m x 0.91 m x 1.83 m	2.6’ x 3.9’ x 9.8’ 0.8 m x 1.2 m x 3.0 m	3’ x 4’ x 10’ 0.91 m x 1.22 m x 3 m	6.6’ x 6.6’ x 13.1’ 2 m x 2 m x 4 m
Flow speed range	20 - 70 m/s	0 - 58 m/s	0 - 60 m/s	0 - 70 m/s	0-67 m
Reynolds number (max)	5 million/m	4 million/m	4 million/m	5 million/m	4.4 million/m
Typical test object size (e.g., chord)	0.6 - 0.9 m	0.2 - 0.5 m	0.2 - 0.5 m	0.2 - 0.5 m	1 m
Observer angles: polar (defined wrt. Mach vector)	40-140 deg	45-135 deg	~ +/- 180 deg		~ 45 – 135 deg
Observer angles: azimuth	~ +/- 30 deg	~ +/- 30 deg	~ +/- 60 deg		+/- 30 deg
Frequency range of interest	250 Hz - 20 kHz	~ 1 kHz - 80 kHz (5 - 50 nom.)	~ 1 kHz - 80 kHz (5 - 50 nom.)	250 Hz - 20 kHz	315 Hz – 80 kHz
Tunnel type(s):	Kevlar walls	Open-jet, Kevlar panel	Open-jet	Open-jet, Kevlar panel, glass panel	Kevlar walled test section Solid wall Gust wind test section Open jet test section

Facilities I.

Kevlar walls

6’ x 6’ x 24’
(1.83 m x 1.83 m x 7.3 m)
f = 1200 mm

Open-jet



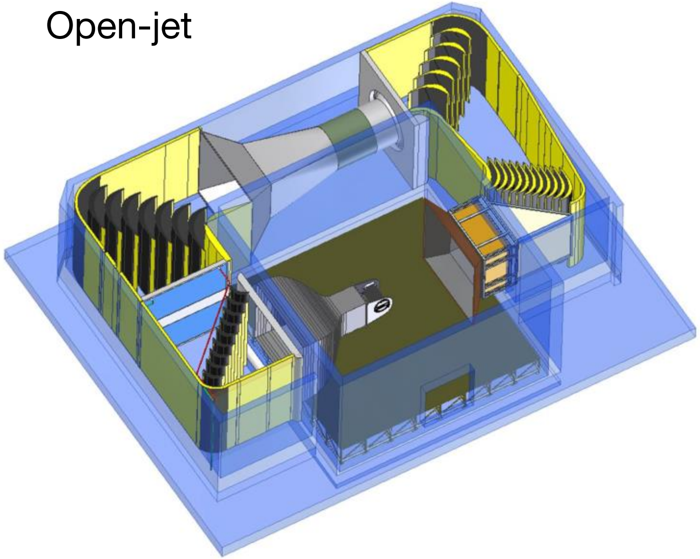
2’ x 3’ x 6’
(0.6 m x 0.91 m x 1.83 m)
f ≈ 500 m

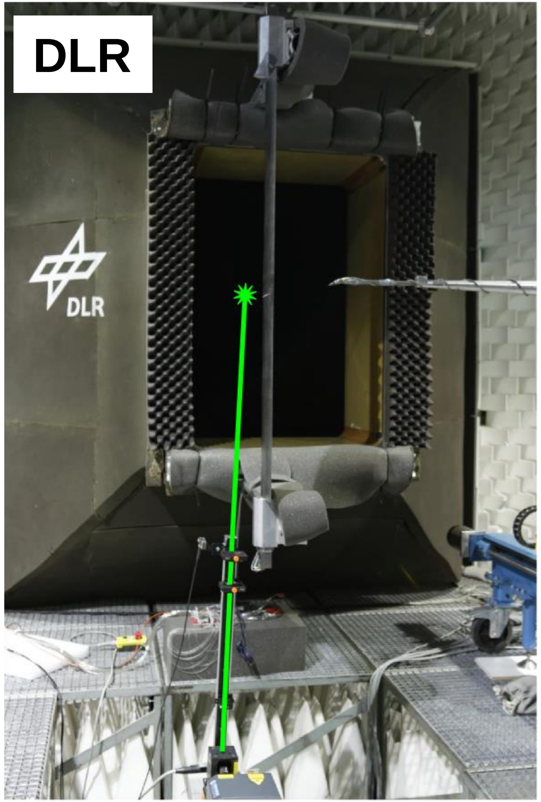
Kevlar panel

AIAA-2020-1253

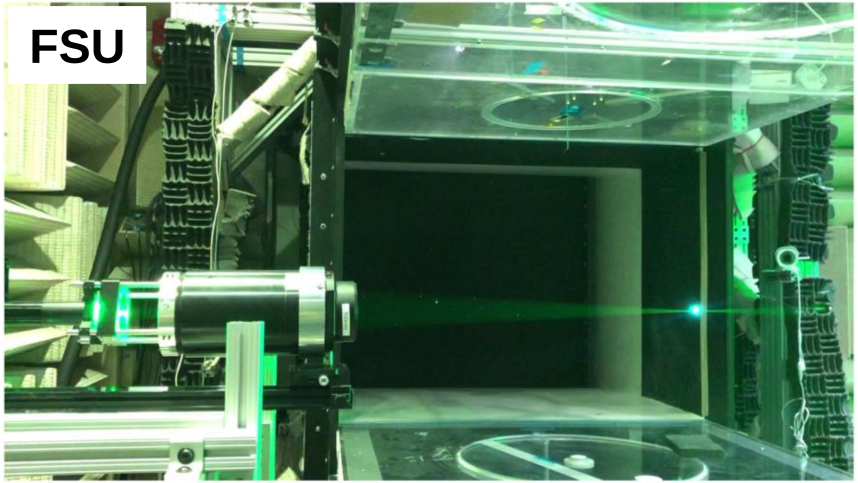
Facilities II.

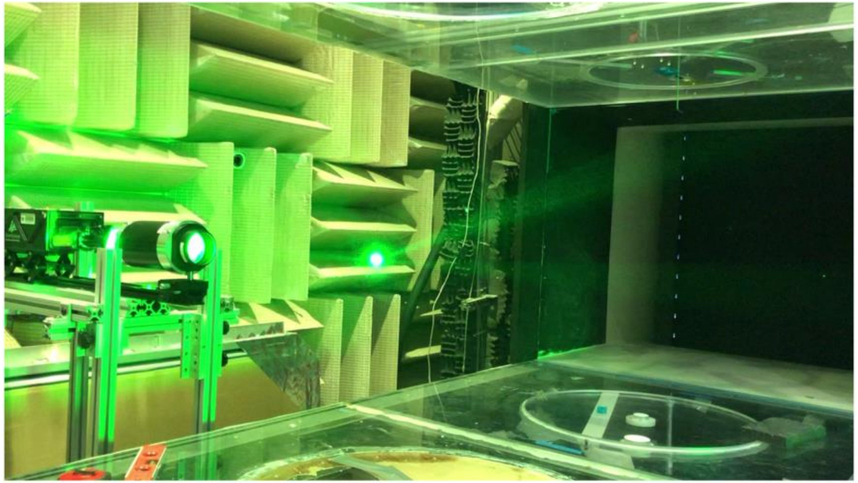
Facility: **AWB**
2.6’ x 3.9’ x 9.8’
(0.8 m x 1.2 m x 3.0 m)
f ≈ 500 mm
Open-jet





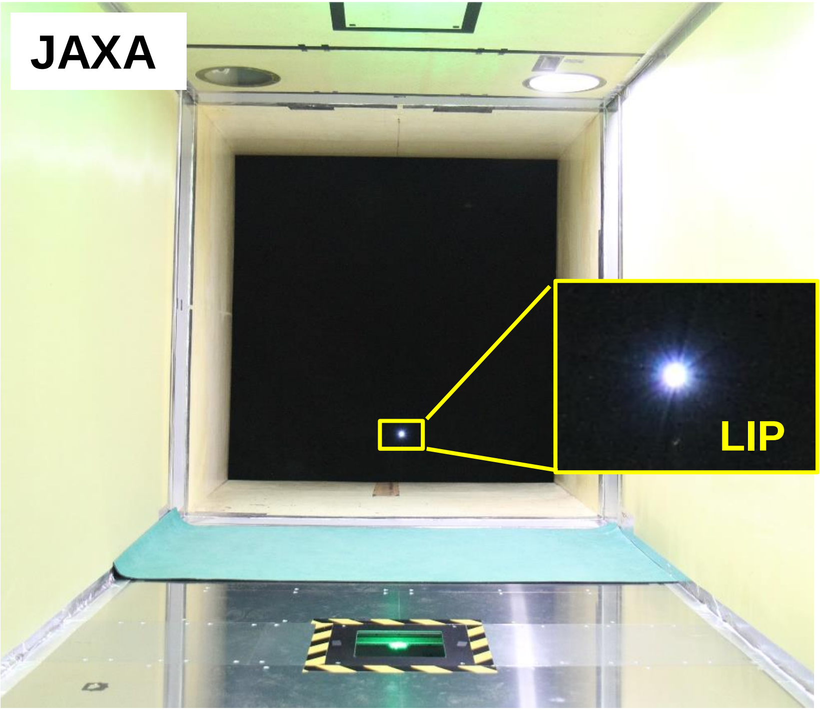
Facilities III.





3’ x 4’ x 10’
(0.91 m x 1.22 m x 3 m)
f = 500 mm
Kevlar walls

Facilities IV.



6.6’ x 6.6’ x 13.1’
(2 m x 2 m x 4 m)
f = 1200 mm
Kevlar walls

Instrumentation

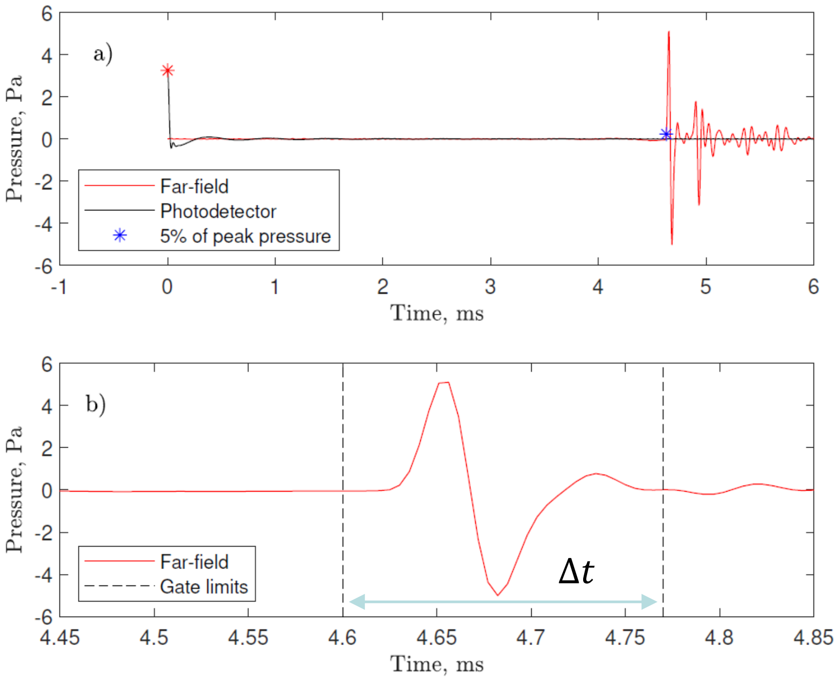
INSTRUMENTATION	VT SWT	NASA Langley QFF	DLR (AWB)	FSU	JAXA
Microphones available	GRAS 40 PH (50 Hz - 20 kHz)	B&K 4138 (6.5 Hz - 140 kHz); B&K 4938 (4 Hz - 70 kHz)	GRAS 40 DP (6.5 Hz - 140 kHz)	GRAS 40BE (4 Hz - 80 kHz); B&K 4958 (10 Hz - 20 kHz)	B&K 4939 (4 Hz - 100 kHz),
DAQ system	General Standards Corp. PCIe-16A64SSC	NI PXI 6120; NI PXIe 4480; NI PXI-5122	GBM Viper 48 Channels (3X)	NI PXI-1045; NI PXI-4462	NI PXI-4462
Sampling rate	192 kS/s	250 kS/s (800 nom.); 1.25 MS/s (20 streaming); 100 MS/s	250 kS/s	204.8 kS/s	204.8 kS/s
Laser emission detection	Photodetector signal	Photodetector signal, Q-switch	Q-switch	Photodetector signal	N/A
Filters	Low-pass 20kHz	Low-pass 100 kHz		Low-pass 80 kHz	
Flow speed range	0-70 m/s	0-58 m/s	0-65 m/s	0-70 m/s	0-65 m/s
LIP to observer distance	ranging between 1.6 m and 2.5 m	variable within several meters	variable within several meters	< 2 m	1.865 m

Comparative study of acoustic signatures

- **Ensemble-averaged time signature** of the pressure wave for a single microphone (without flow)
- **Fourier transform** of the gated ensemble-averaged pressure wave signal of a single microphone (without flow)
- **Uncertainty analysis** of LIP **arrival time** and LIP **sound level**

Processing steps – Current study

- **High-pass filtering** at 1 kHz to remove facility-dependent **background noise**
- **Block** formation (laser emission at $t = 0$ s), **LIP** sound **identification** (reject if needed)
- **Arrival time** (τ_a) calculation: given % threshold of peak pressure
- **Normalizing** with peak pressure
  - $\hat{p} = p/p_{max}$
- **Gating** ($\hat{p}_G$), **windowing** (25% Tukey), **zero padding** (0.1s)
- **Fourier** transform
- **Sound energy** calculation
  - $E = \frac{1}{\Delta t}\int \hat{p}_G^2(t)\mathrm{d}t$
- **Uncertainty** calculation (95% confidence)
  - $\delta_\tau = 1.96 \cdot \mathrm{std}(\tau_a)$
  - $\delta_p = 1.96 \cdot \mathrm{std}(10\log_{10} E)$



Comparative study of acoustic signatures

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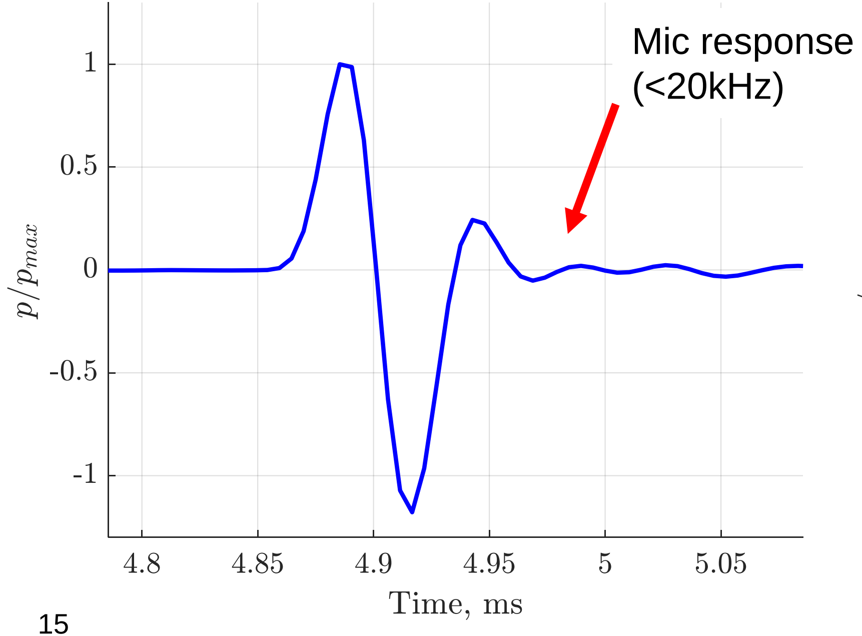
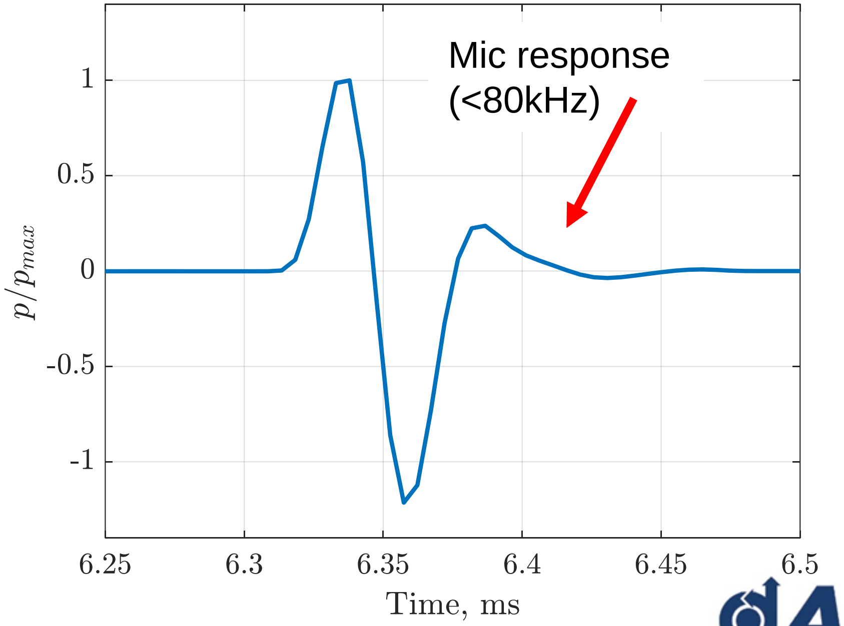
Time signature of pressure wave I.

Virginia Tech data
GRAS 40PH 1/4”, with gridcap
LIP-to-mic distance: 1671 mm
f_s = 192 kS/s

Evergreen laser heads

Florida State Uni data
GRAS 40BE 1/4”, with gridcap
LIP-to-mic distance: 2150 mm
f_s = 204.8 kS/s



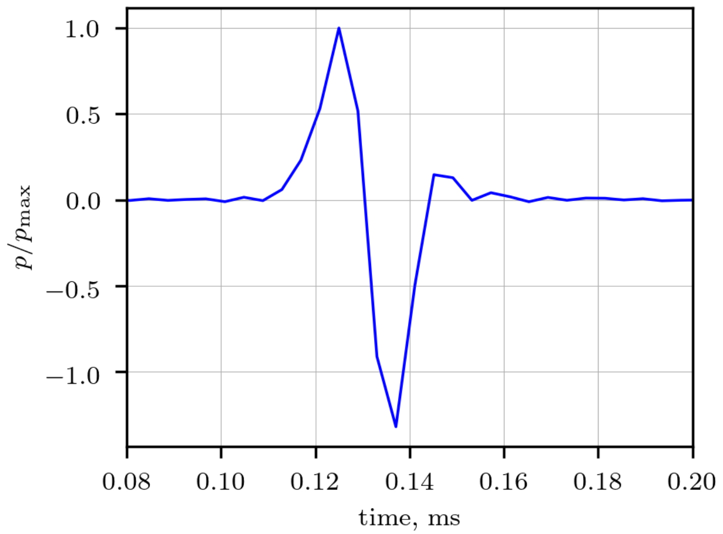


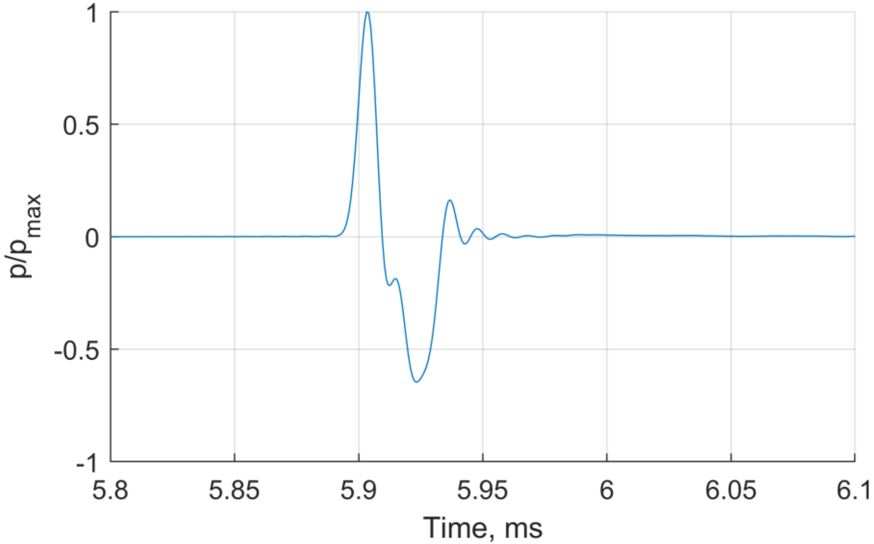
Time signature of pressure wave II.

DLR data
GRAS 40DP 1/8", with gridcap
LIP-to-mic distance: 1000 mm
f_s = 250 kS/s

New Wave laser heads
$f_s \approx$ 200 kS/s is at the lower end
Time domain is more sensitive for f_s

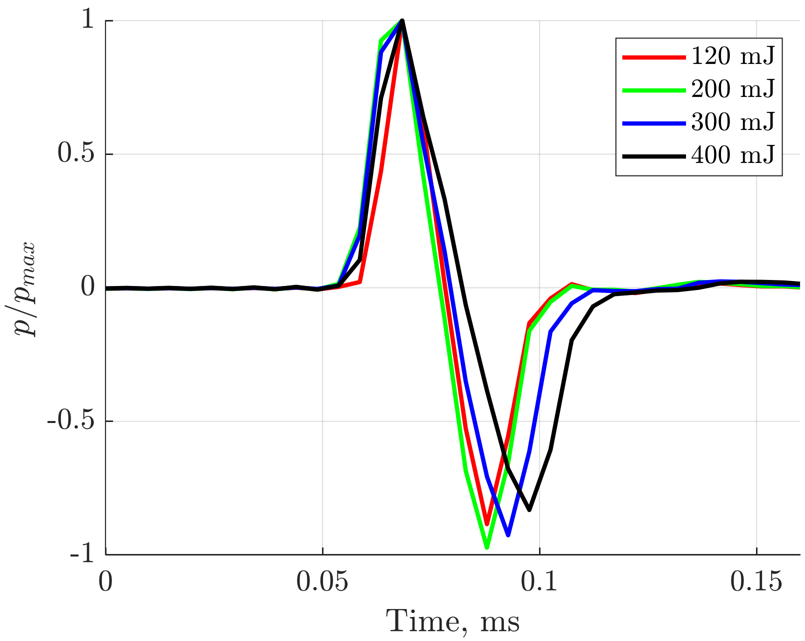
NASA Langley QFF data
B&K 4138 1/8", with gridcap
LIP-to-mic distance: 2019 mm
f_s = 1.25 MS/s





Time signature of pressure wave III.

JAXA data
B&K 4939 1/4”, without gridcap
LIP-to-mic distance: 1865 mm
f_s = 204.8 kS/s



- **Pressure front** collapses relatively well
- **Effect of laser power** is more significant in the second half of the signal
- The **time difference between the positive and negative peaks increases**
- **Further investigations** might shed light on (a) initial non-linear propagation properties and (b) plasma "lifetime"

Comparative study of acoustic signatures

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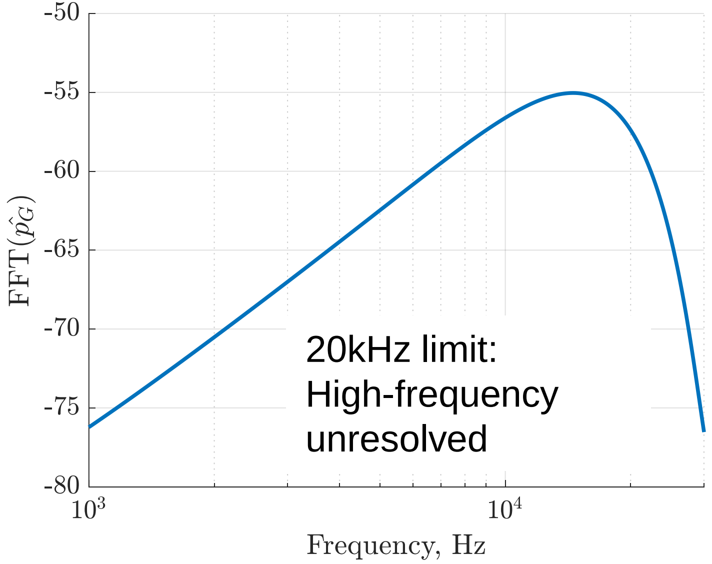
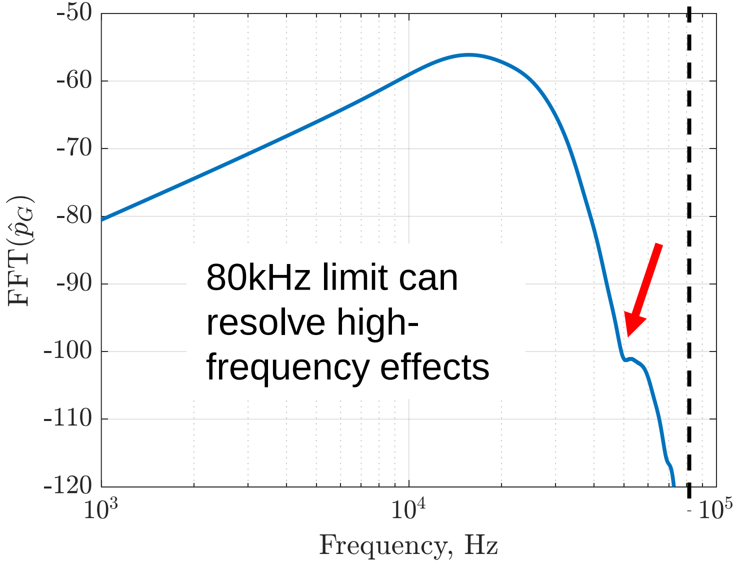
- Uncertainty analysis of LIP arrival time and LIP sound level

Frequency domain I.

Virginia Tech data
GRAS 40PH 1/4" (50 Hz – 20 kHz)
1 kHz high-pass, 20 kHz anti-alias
200 mJ Evergreen laser



Florida State Uni data
GRAS 40BE 1/4" (4 Hz – 80 kHz)
1 kHz high-pass, 80 kHz low-pass
200 mJ Evergreen laser

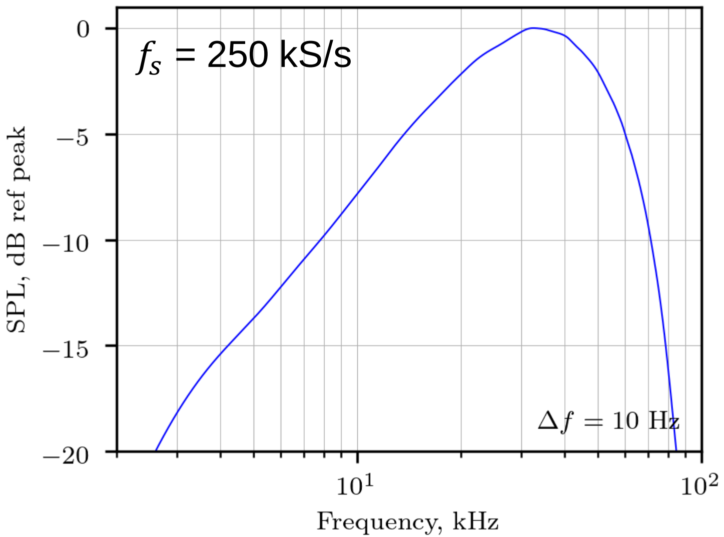


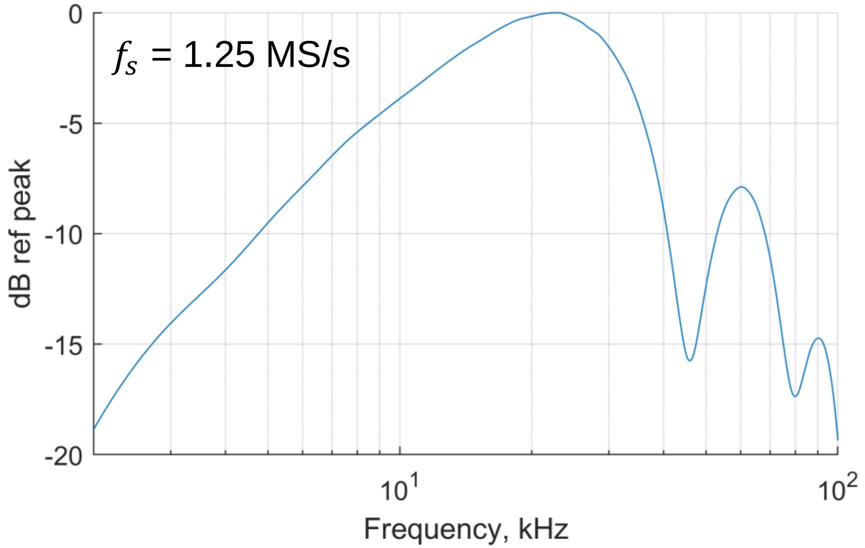
High-frequency effects ≠ nearfield violation

Frequency domain II.

DLR data
GRAS 40DP 1/8” (6.5 Hz – 140 kHz)
2 kHz high-pass, 100 kHz low-pass
120 mJ New Wave Gemini laser

NASA Langley QFF data
B&K 4138 1/8” (6.5 Hz – 140 kHz)
2 kHz high-pass, 100 kHz low-pass
120 mJ New Wave Gemini laser

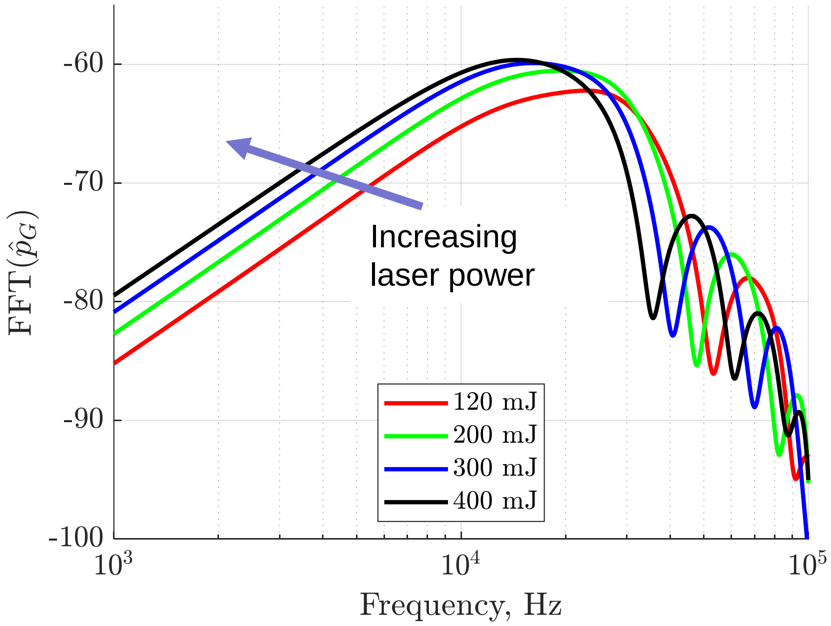




$f_s \approx$ 200 kS/s seems to suffice for frequency domain analysis
The acoustic signatures of the two LIP formations may differ

Frequency domain III.

JAXA data
B&K 4939 1/4” (4 Hz – 100 kHz)
1 kHz high-pass
Thales SAGA 230 laser (1250 mJ)



- **Frequency** response remains **linear below 10 kHz,** while levels increse with laser power (5 dB)
- High-frequency effects shift to **lower frequencies** with **increasing laser power**

Comparative study of acoustic signatures

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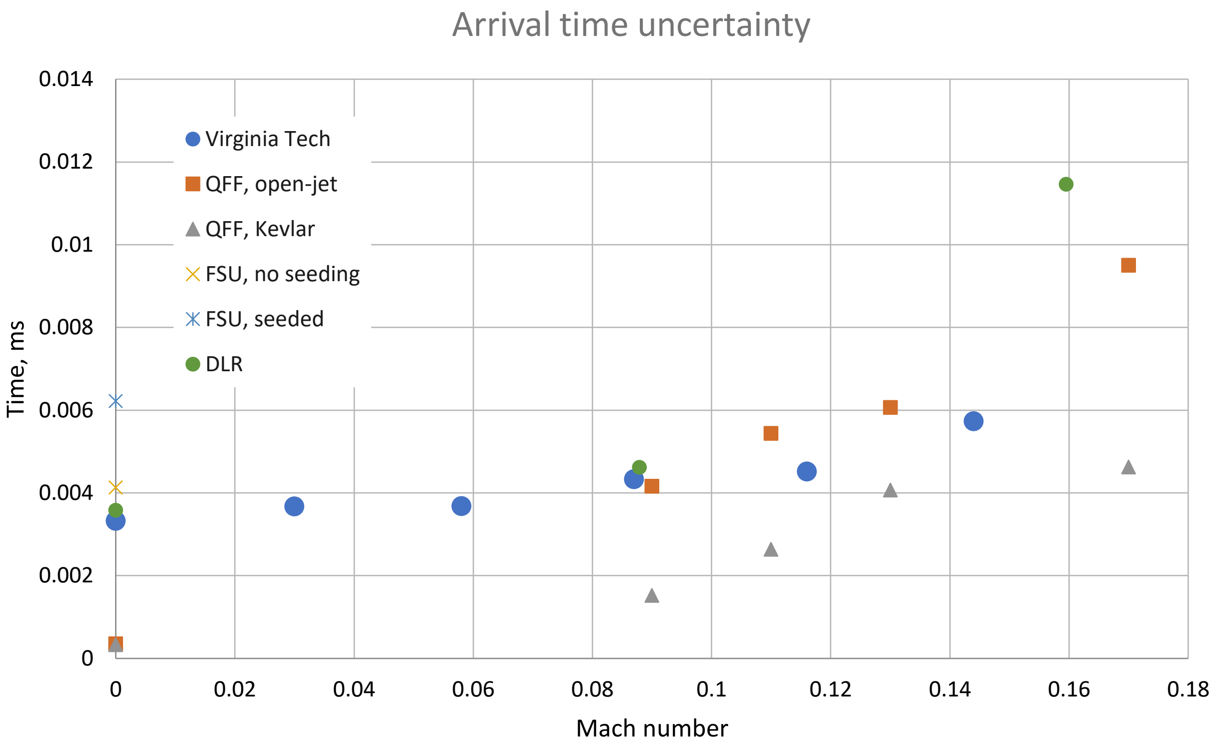
- Fourier transform of the gated ensemble-averaged pressure wave signal of a single microphone (without flow)
- **Uncertainty analysis** of LIP **arrival time** and LIP **sound level**

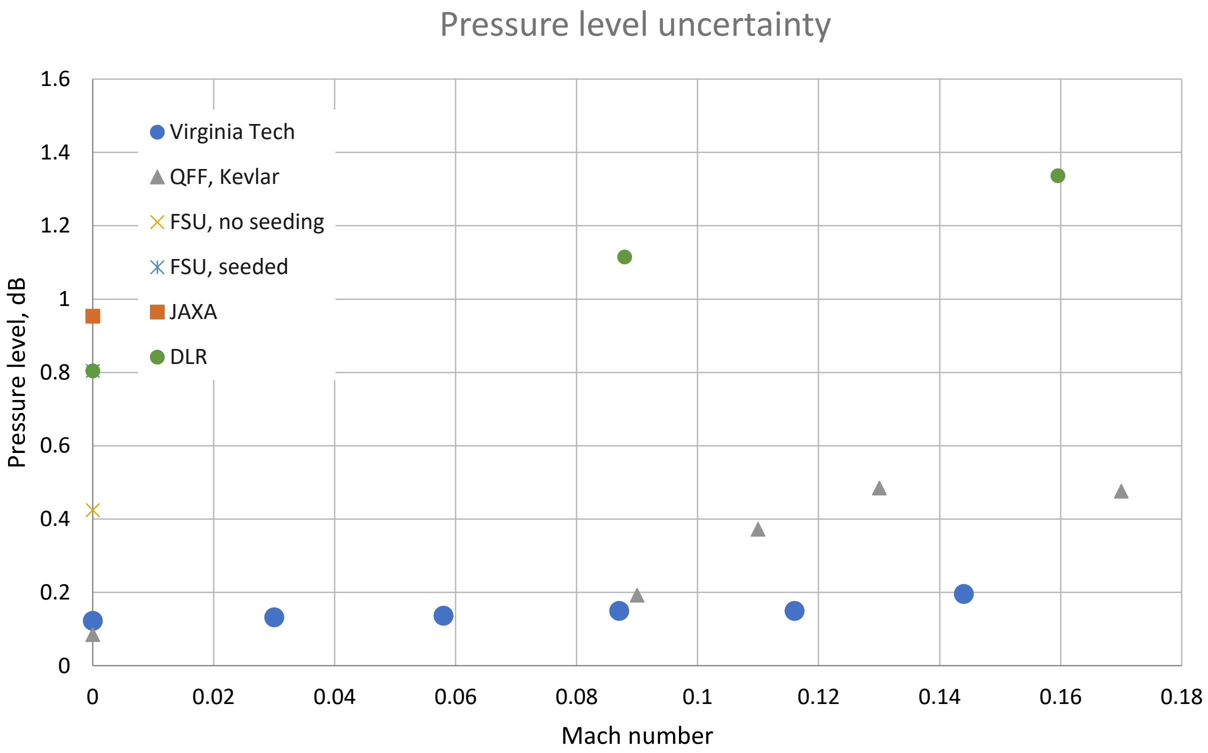
Uncertainty analysis I.

- **Arrival time uncertainty**
  - $\delta_\tau = 1.96 \cdot \mathrm{std}(\tau_a)$
- **Limit**:
  $1/f_s$ = 0.004-0.005 ms
  (except for QFF:
  $1/f_s$ = 0.0008 ms)
- **Somewhat below limit** (thanks to linear interpolation to find τ_a)
- **Uncertainty increases with flow speed:** unsteady, turbulence effects
- **Kevlar shows reduced flow effects compared to open-jet**
- **PIV seeding increases temporal uncertainty (FSU)**
  - LIP location becomes uncertain: $\pm$ 2 mm ($\approx \pm$ 0.006 ms)



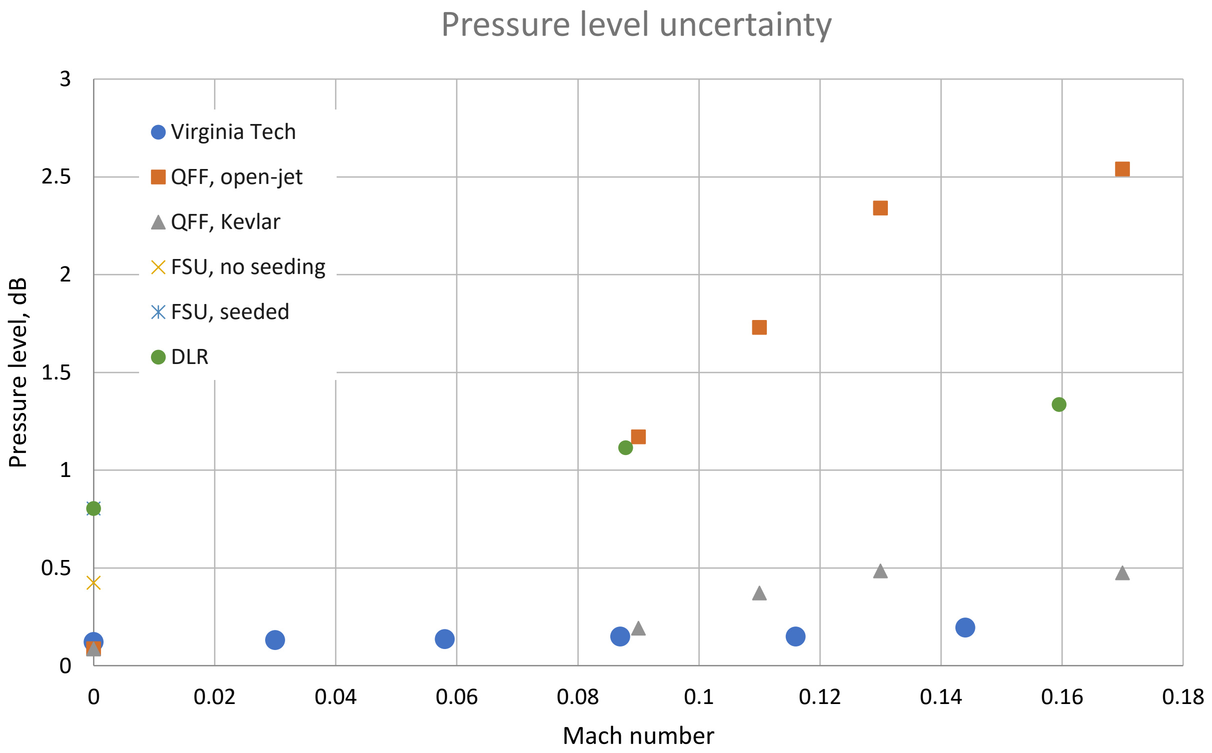
Uncertainty analysis II.

- **Pressure level uncertainty**
  - $\delta_p = 1.96 \cdot \mathrm{std}(10\log10(E))$
- At **M = 0, instrumentation limited**
- **Increases with flow speed**
- QFF vs. VT results with flow suggest **insufficient temporal resolution (**f_s ≈200kS/s**) to resolve unsteady effects below M=0.1**
- **PIV seeding increases pressure uncertainty, too**



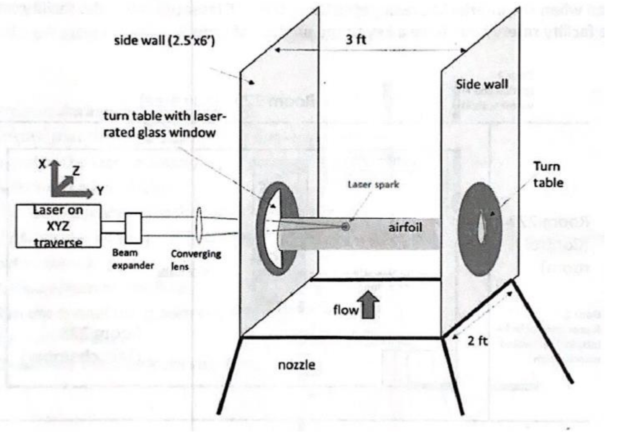
Uncertainty analysis III.

- **Pressure level uncertainty**
  - $\delta_p = 1.96 \cdot \mathrm{std}(10\log10(E))$
- **Pressure level uncertainty is dramatically higher for open-jet configuration** (almost by a factor of 5)
- Kevlar + BL and sound interaction is significantly weaker than shear-layer and sound interaction

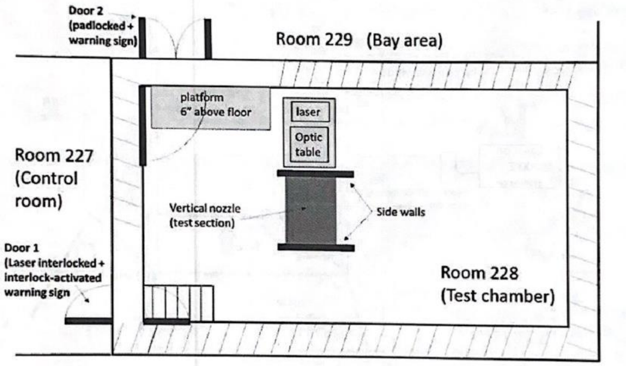


Health and safety (H&S) measures (QFF, DLR, VT)

- Approached H&S **as a PIV experiment** (laser safety)
- **Personnel exposure**
  - Participants must take **laser safety training** prior to testing
  - **Minimize personnel** in chamber
  - Wear laser safety **glasses at all times**
  - ***Hearing protection*** *was not required*



- Experimental **setup**
  - **Warning signs** and **lights** tied to laser interlock
  - Optical **barricades, CCTV** camera, microphone
  - **Cover and clear laser beam path,** verify sufficient beam divergence for "safe" reflections w.r.t. ablation, combustion when beam is not covered
  - Develop **remote operation of laser**
  - **Interlocks** tie access door to laser power (open door = power cut off)
  - **Padlocked auxiliary doors –** only approved operators or facility coordinator/safety head can lock/unlock these
  - *Always* ***keep the area around the focal point (LIP) clear***

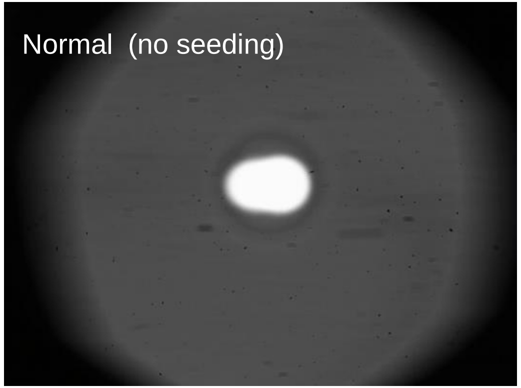


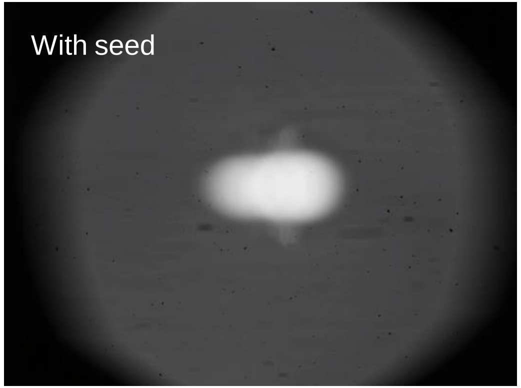
see Appendix for extra details on H&S

Application examples

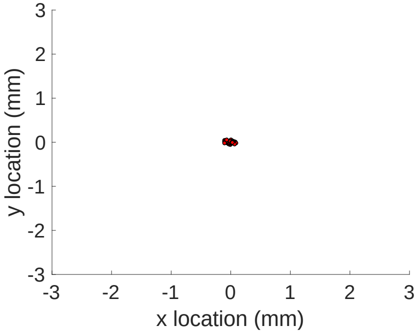
Shadowgraph analysis of seeding effect (FSU)

Sparks without and with PIV seeding

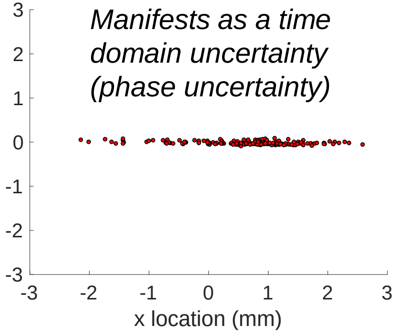


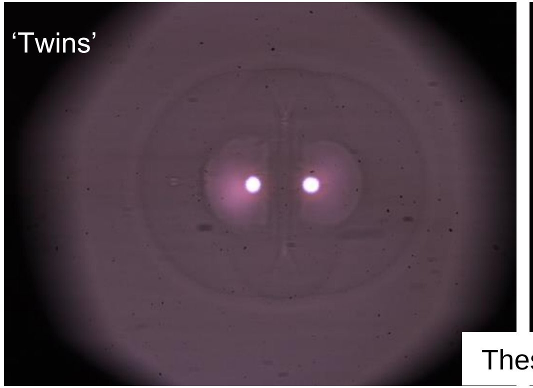


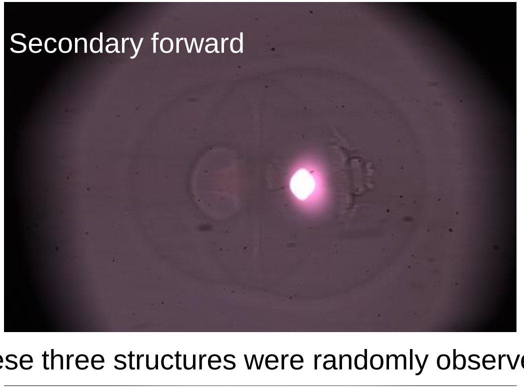
No seeding cases

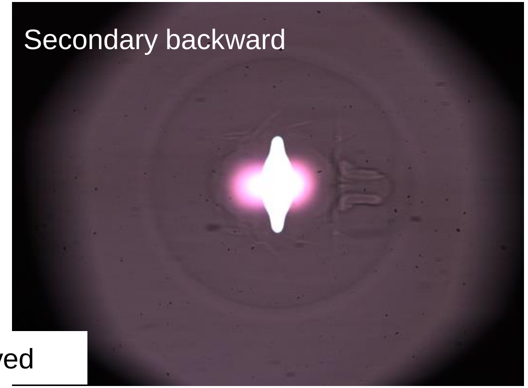


Seeding cases





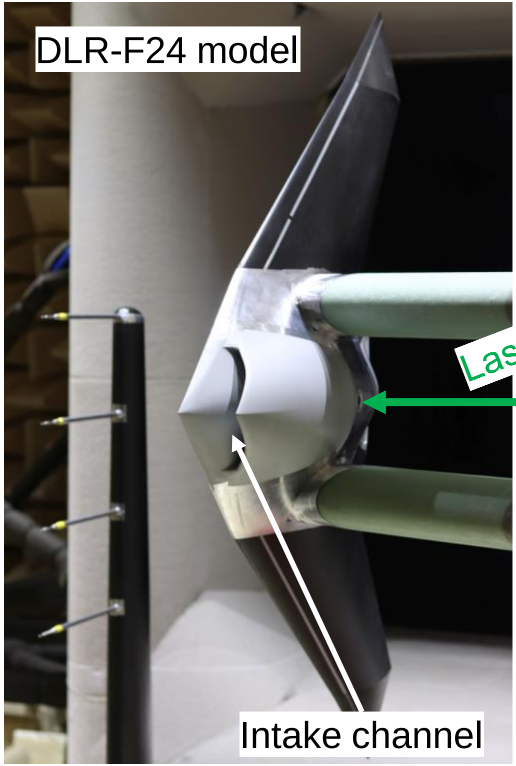


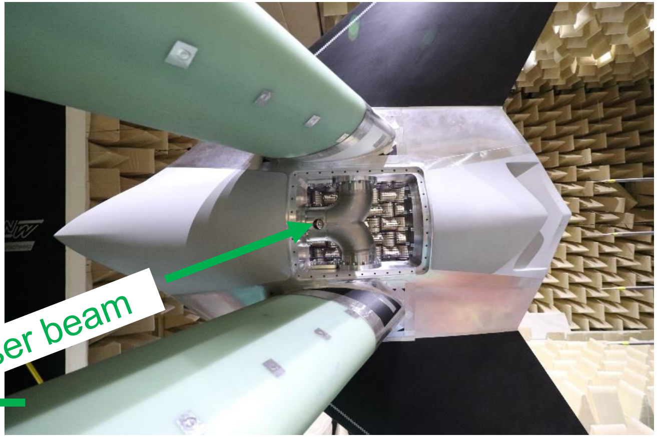


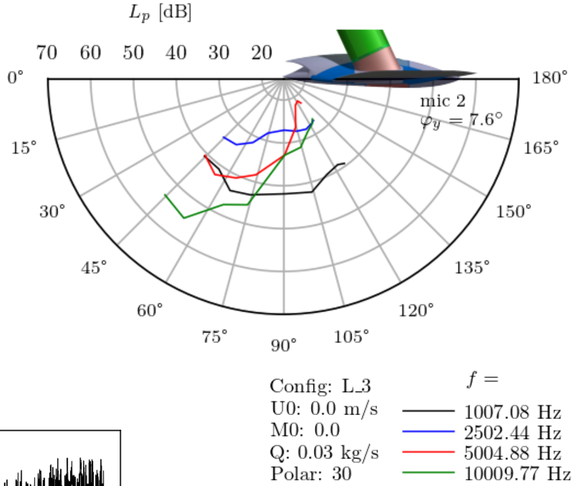
These three structures were randomly observed

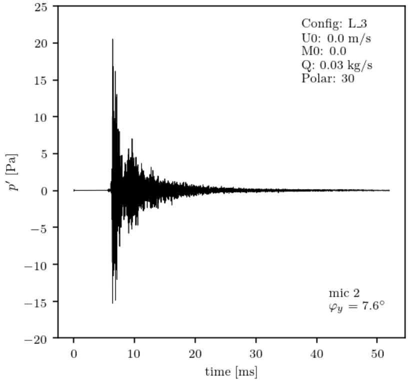
Application examples: DLR

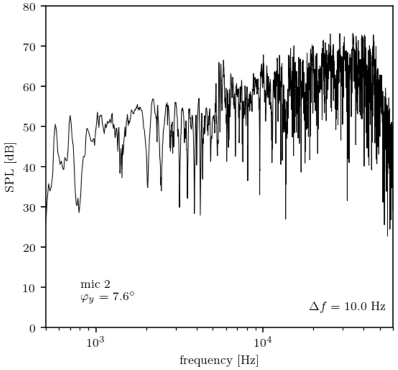
Triggering acoustic channel modes under no flow conditions (DNW-NWB, 2021)







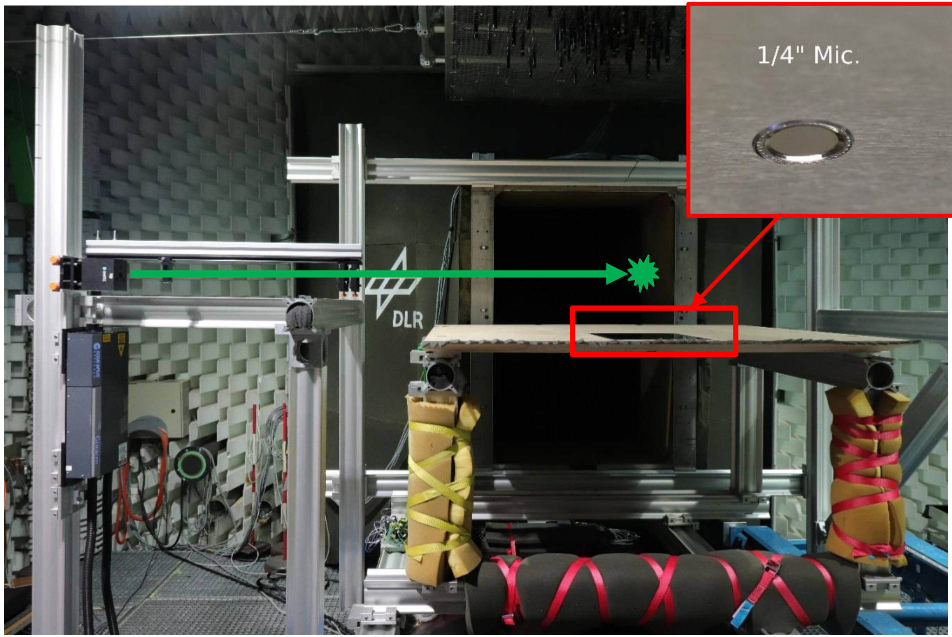


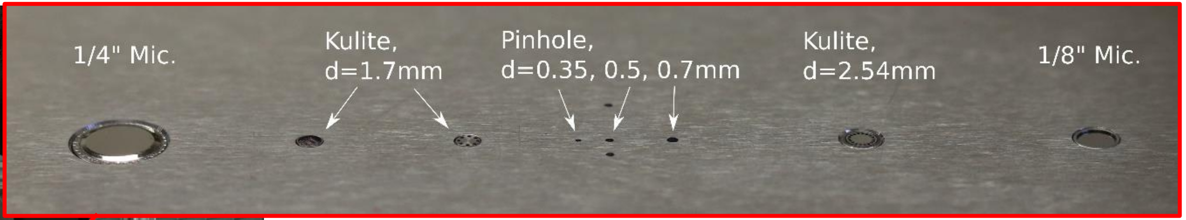


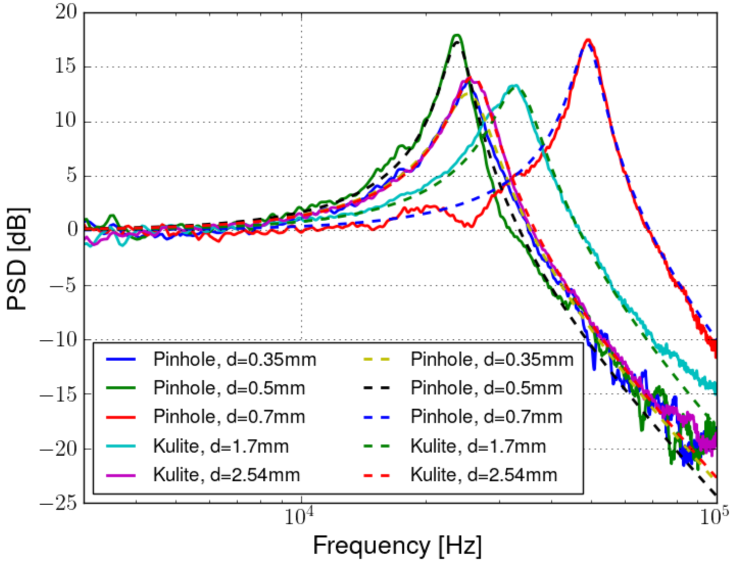
Currently validating against CAA results. Implementation of LIP in CAA is straightforward.

Application examples: DLR

Calibration of flush-mounted microphones using a reference microphone (AWB, 2019)



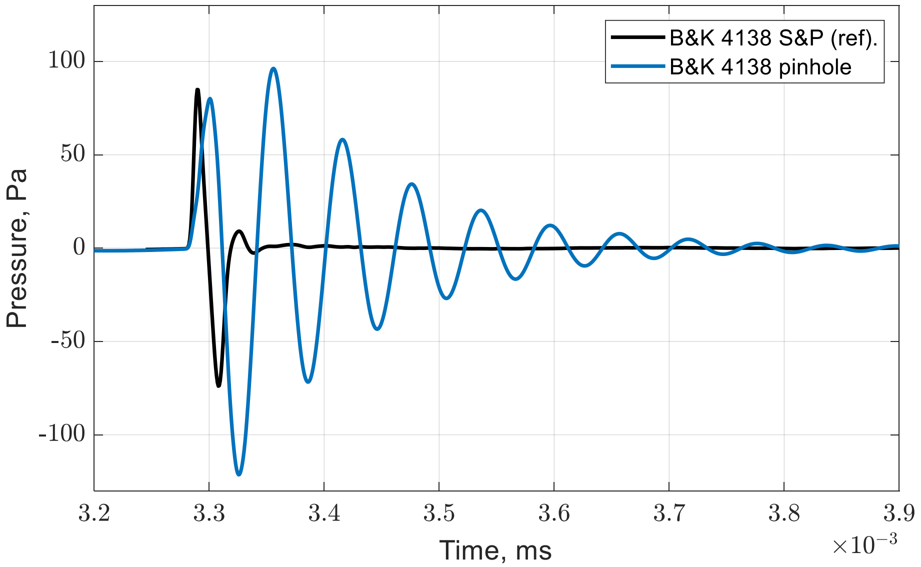


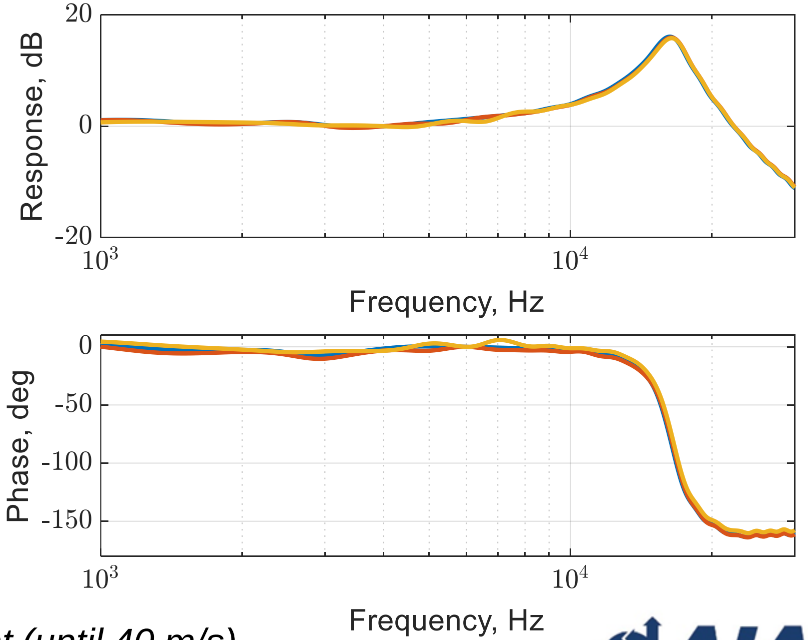


Courtesy of Nan Hu (DLR)

Application examples: VT

Calibrating a B&K 4138 (1/8”) flush-mounted **pinhole microphone** at high-frequencies using another flush-mounted B&K 4138 (1/8”) as a reference (gridcap) microphone.



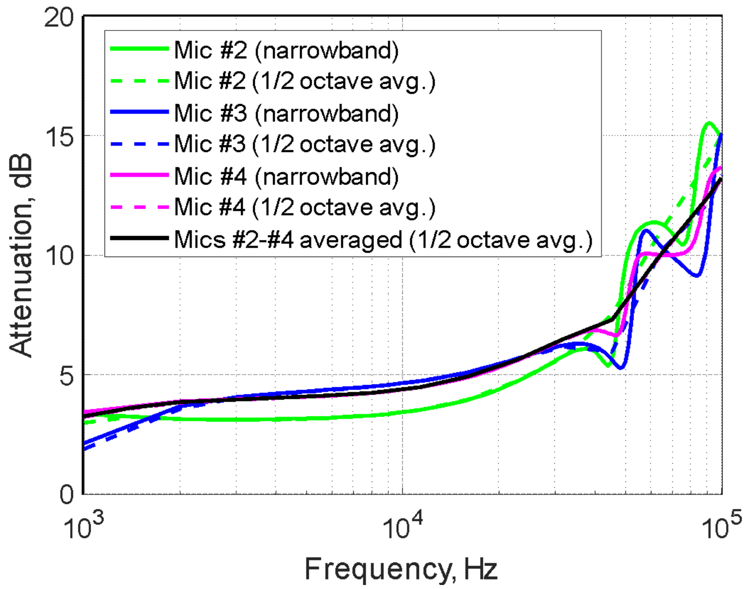


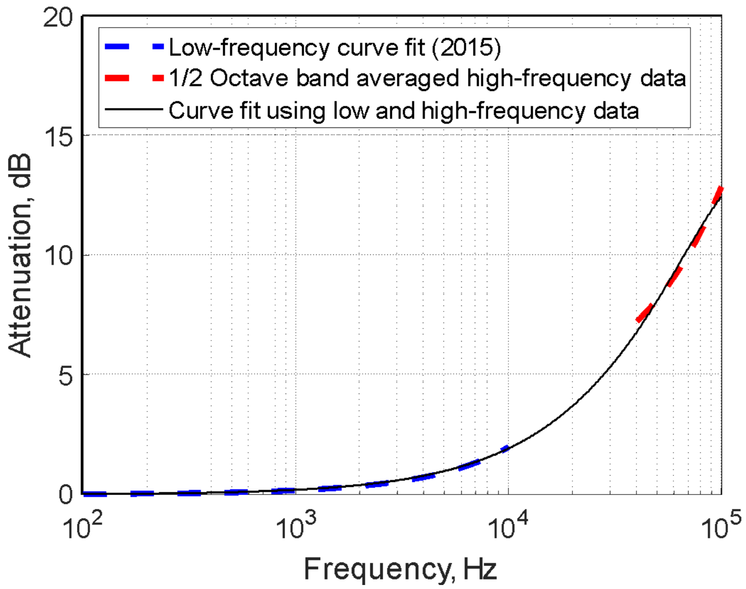
Highly repeatable, flow-independent (until 40 m/s)

Application examples: VT

Measuring **Kevlar transmission loss at high-frequencies** using two B&K 4138 (1/8”) microphones: (a) one inside the test section and (b) one behind the Kevlar.

Comparing a given LIP formation across identical types of microphone pairs.





- **Potential future work**
  - Effects of laser power on acoustics & quantifying laser power level at the focal point
  - Instrumentation effects (microphones used, incidence angle, sampling rate etc).
  - Convection effect on plasma formation (high-speed shadowgraph)

- **Potential discussion items**
  - What % of threshold to use for detecting arrival time?
  - Alternative windowing options for data processing?
  - Is there an interest in performing a benchmark analysis of LIP?

Thank you!

VIRGINIA TECH

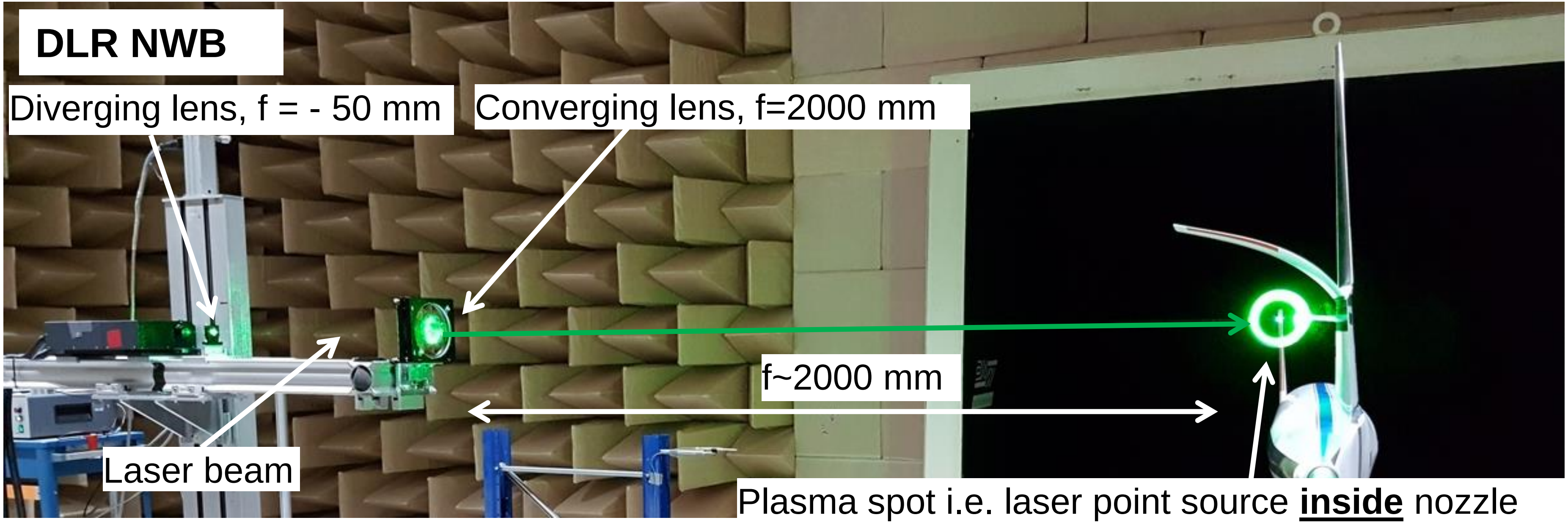
FLORIDA STATE UNIVERSITY

AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS

DLR

Appendix

Facilities - Extra

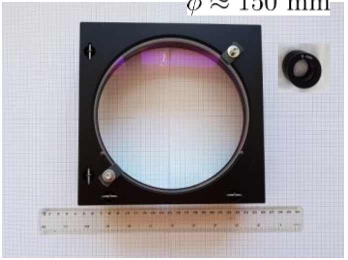


Plasma spot i.e. laser point source **inside** nozzle

AIAA 2017-3195

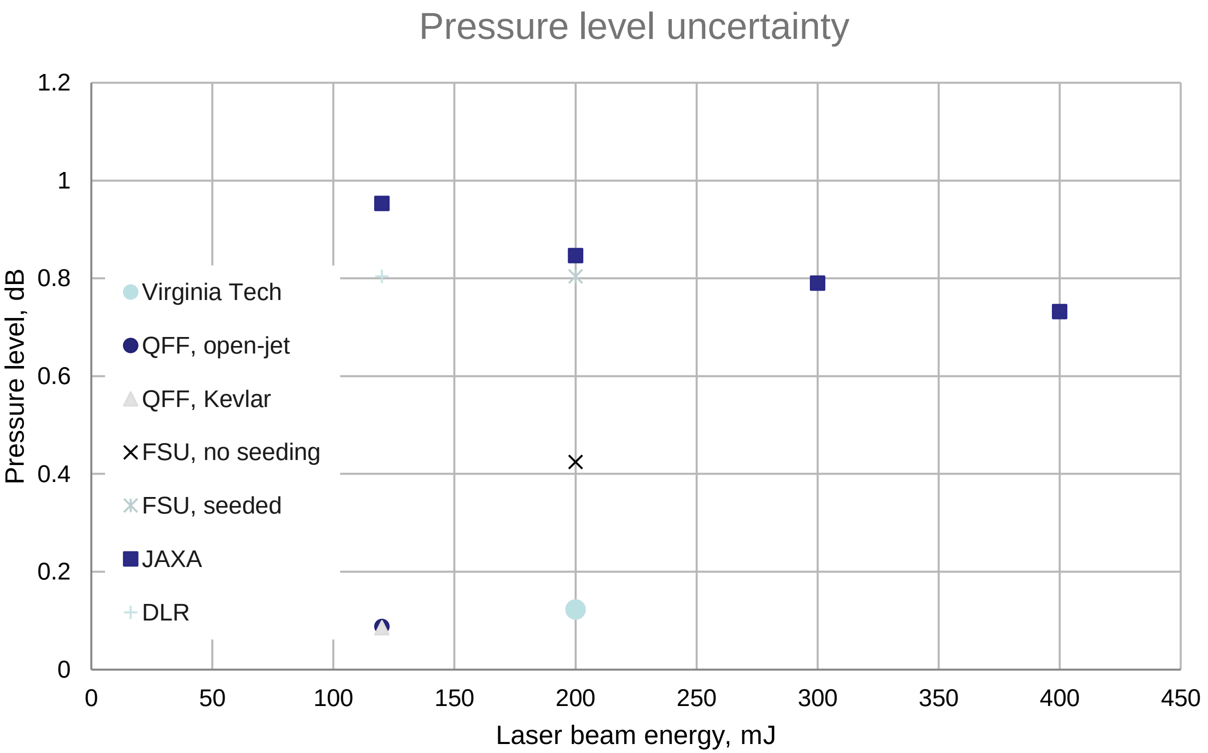
2.6’ x 3.9’ x 9.8’
(0.8 m x 1.2 m x 3.0 m)

$\phi \approx 150$ mm



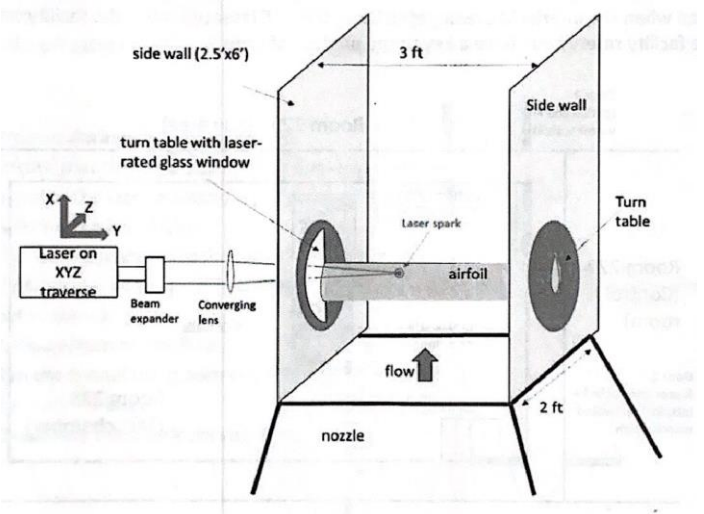
Uncertainty analysis IV.

- **Pressure level uncertainty vs. laser beam energy**
- **More investigations required** to quantify laser beam energy effect on LIP acoustic signature
- Might shed light on optimal energy-density.



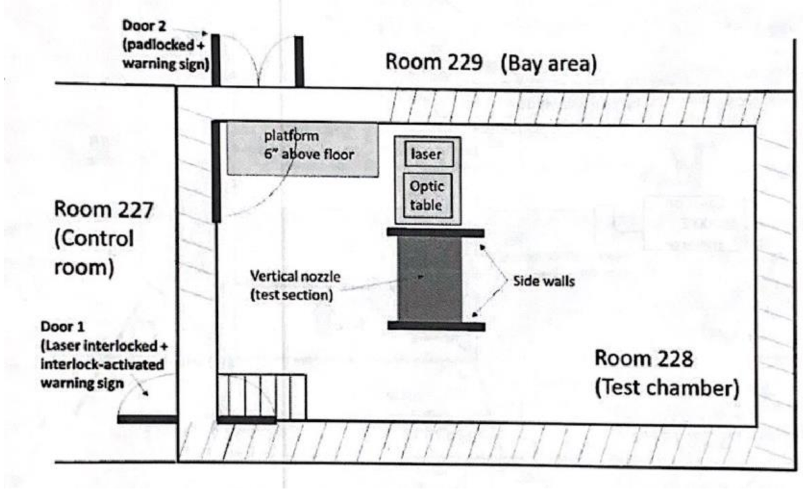
QFF safety operating plan

- Personnel exposure
  - **Minimize personnel** in chamber
  - Laser **safety glasses** at all times
- Facility and **Interlocks**
  - Interlocks tie access door to laser power (open door = power cut off)
  - **Warning signs/lights** tied to door interlock
  - Padlocked auxiliary doors – only approved operators or facility coordinator/safety head can lock/unlock these
  - No windows from facility exterior to test section
- **Beam path** – verify sufficient beam divergence for “safe” reflections w.r.t. ablation, combustion



QFF safety operating plan

- Normal operational procedures
  - Ensure only essential personnel is present
  - Personnel equip **safety eyewear** (if required to be in test chamber)
  - **Activate interlocks**, closing and locking doors & turning on warning lights
  - **Activate laser**
  - Start **experiments**
  - **Turn off laser** when complete
  - **Disengage interlocks**
  - Remove eyewear

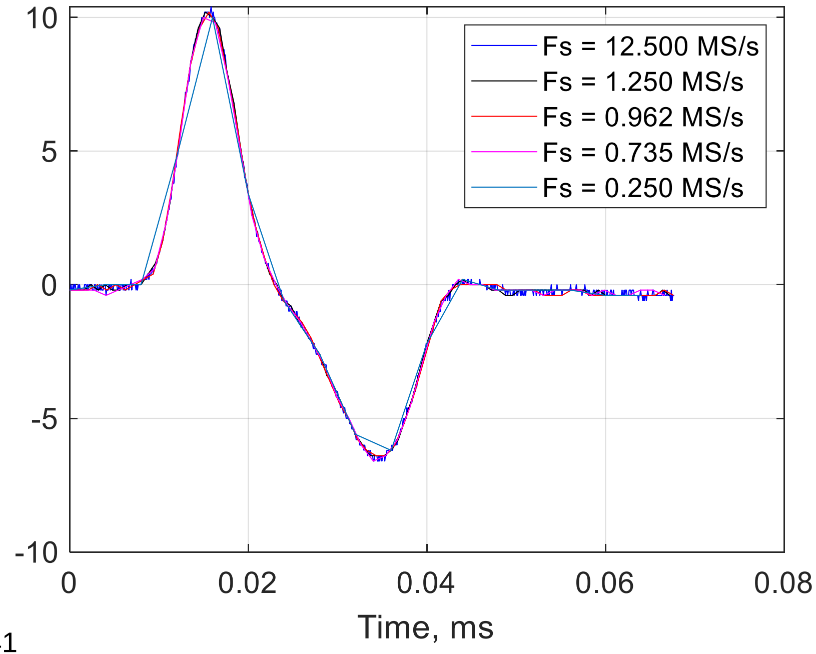


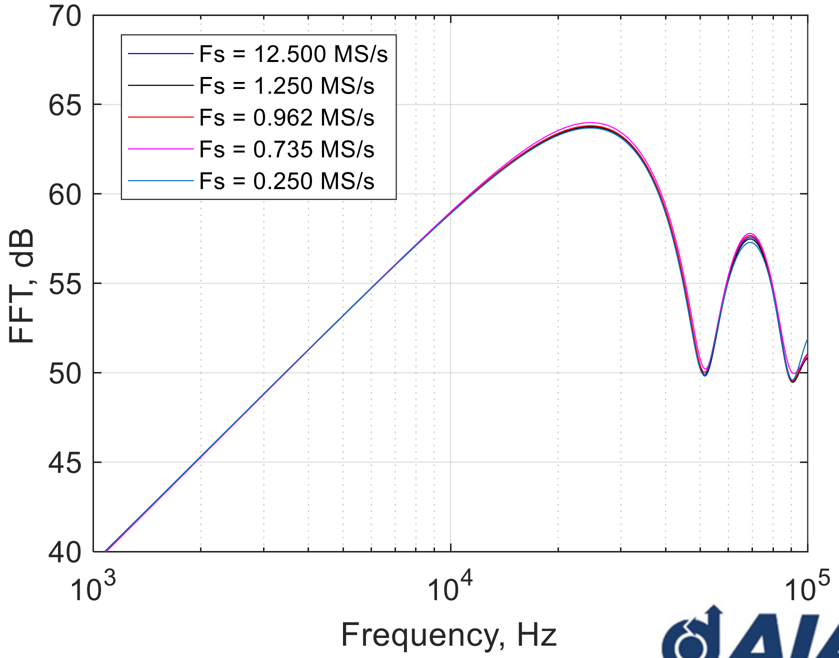
Health and safety measures: DLR

- Ensure only **essential personnel** present
- Operating personnel must receive **training** prior to using the laser
- Non-operating personnel must be **informed about safety measures** prior to tests
- Use **safety eyewear** when inside the perimeter of possible laser light emission at all times
- **Interlock** on main power line to the laser
- **Warning signs** and lights tied to laser interlock
- **No windows**
- Ensure **beam path** is cleared
- **Remote** operation of the laser possible

Sampling rate analysis

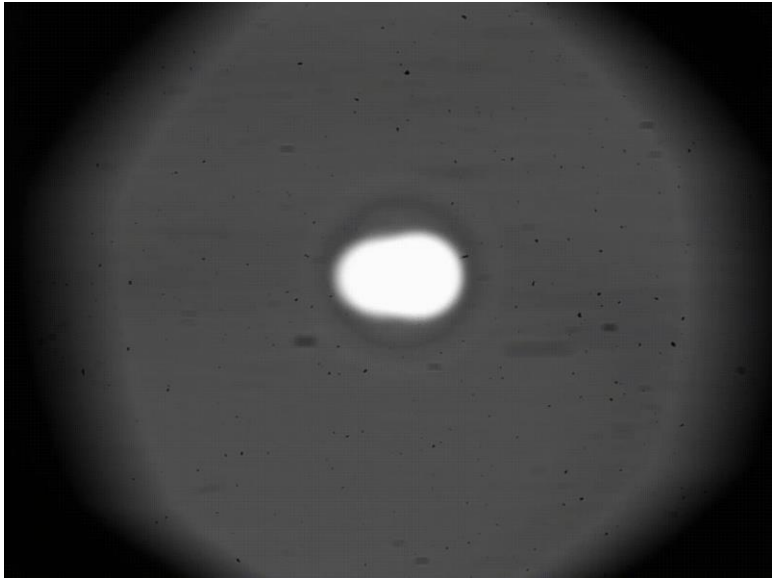
Downsampling VT's results of June 2021
Acquired using o-scope and B&K 4138 1/8" (with gridcap)





Shadowgraph analysis of seeding effect (FSU)

Sparks without seedings

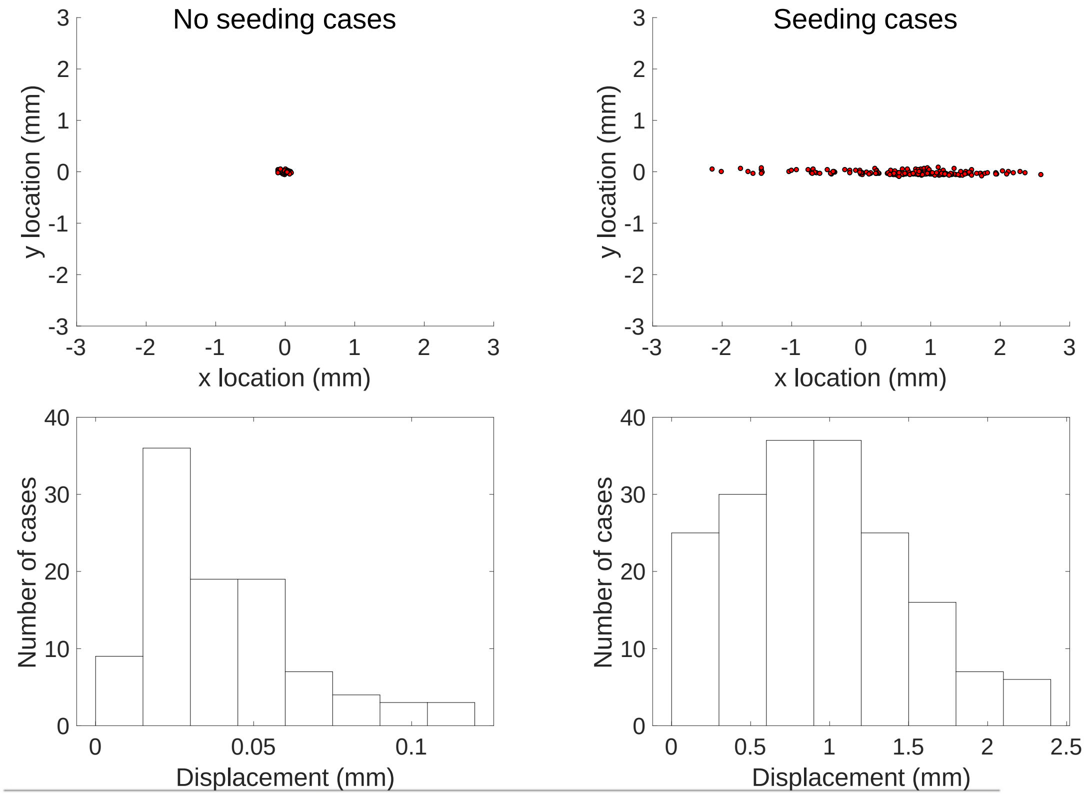


Sparks with seedings

- ‘Phase locked’ frames
- Averaged from 100 images per time delay
- Initial time delay at 0s.

Shadowgraph analysis of seeding effect (FSU)

Statistics of the spark center location



- (x,y) = (0,0) represents the mean center of the no seeding cases
- 100 samples in the no seeding case vs. 180 samples in the seeding case
- Only one of the spark center is identified for the ‘double-spark’ in the seeding cases.
- Spark location with no seeding is significantly more consistent than that of the seeding cases.