AEROACOUSTIC RESEARCH AND NOISE REDUCTION FOR AIRCRAFT – MECHANISMS, TECHNOLOGIES, PERSPECTIVES –

FAN 2025 09-11 April 2025, Antibes, France

Jan Delfs

DLR - Institut of Aerodynamics and Flow Technology

Braunschweig, Germany

DLR

Outline

- noise reduction – why?
- aerodynamic sources of sound at transport aircraft (…and fans)
- noise reduction technologies – from basics to fly-over tests and back
- source noise localization & quantification – prerequisite for low noise design
- summary + conclusions

Why? Community noise !

- source noise reduction
- flight paths/routing
- passive measures (sound insulation buildings)
- air traffic restrictions

- By 2050 technologies, operational improvements and noise abatement procedures reduce the perceived noise emission of flying aircraft by 65%[13] per operation relative to the 2000 baseline;

[13] a reduction of 65% equals ~ **-15dB**/operation = **-97%** in sound intensity

Sources of sound at turbofan aircraft

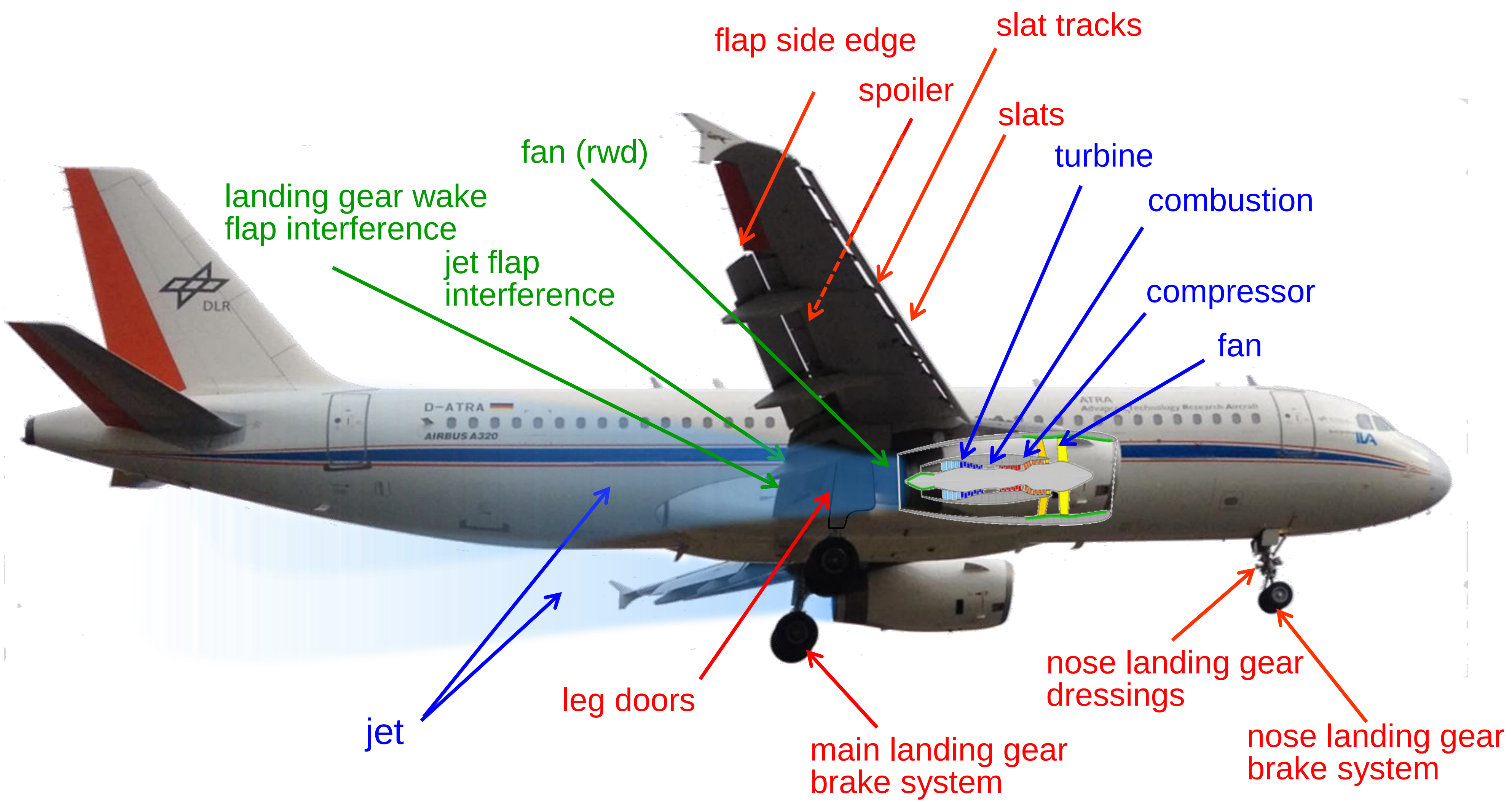


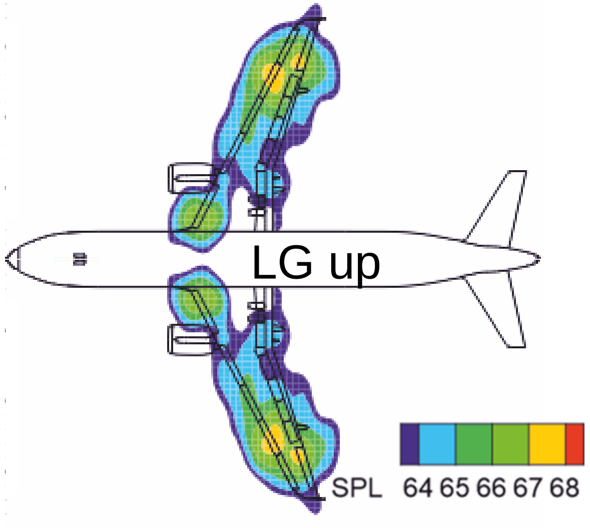
Photo: H. Siller

sources:

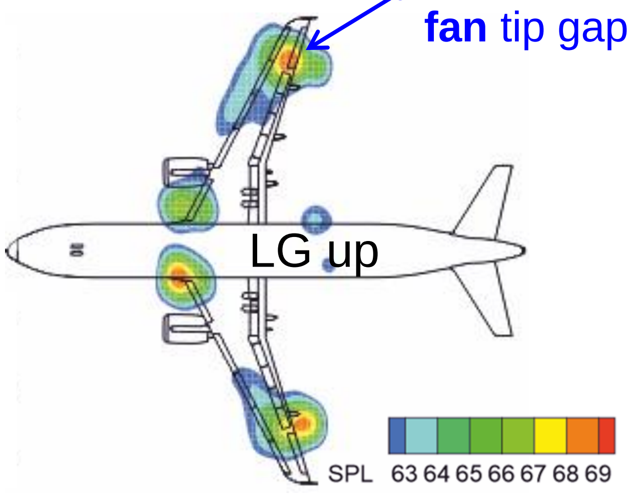
engine
airframe
installation

Sources of airframe noise – flyover array results

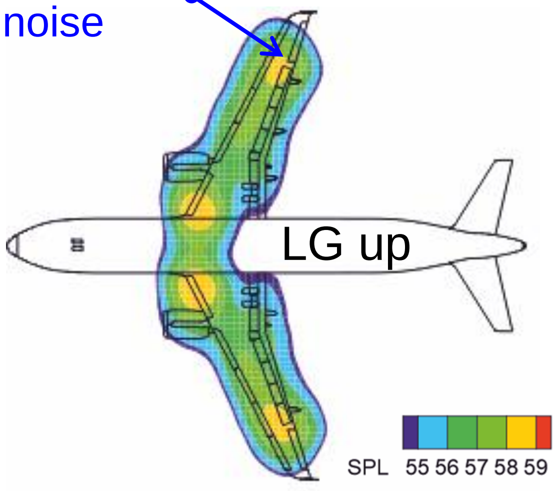
not so different from
fan tip gap noise



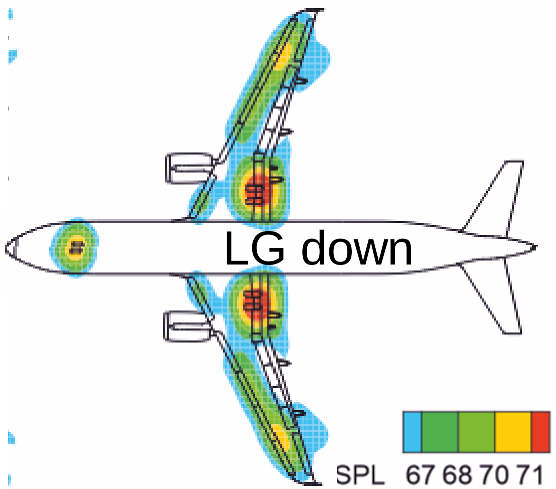
$f_m = 800\text{Hz}$



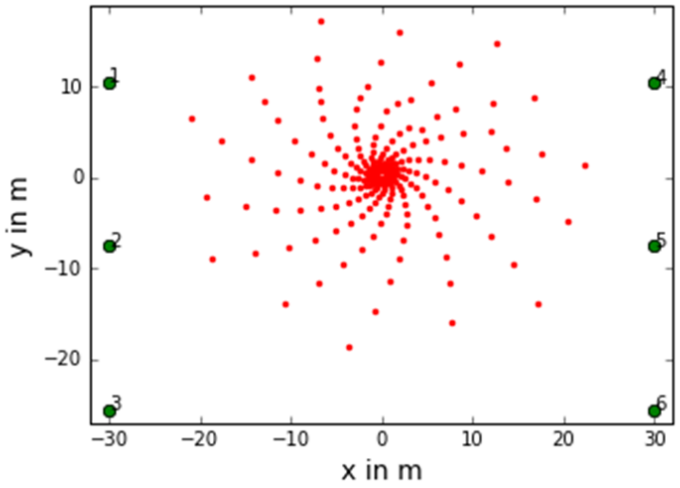
$f_m = 1250\text{Hz}$



$f_m = 3150\text{Hz}$



flaps full – 170kts overhead

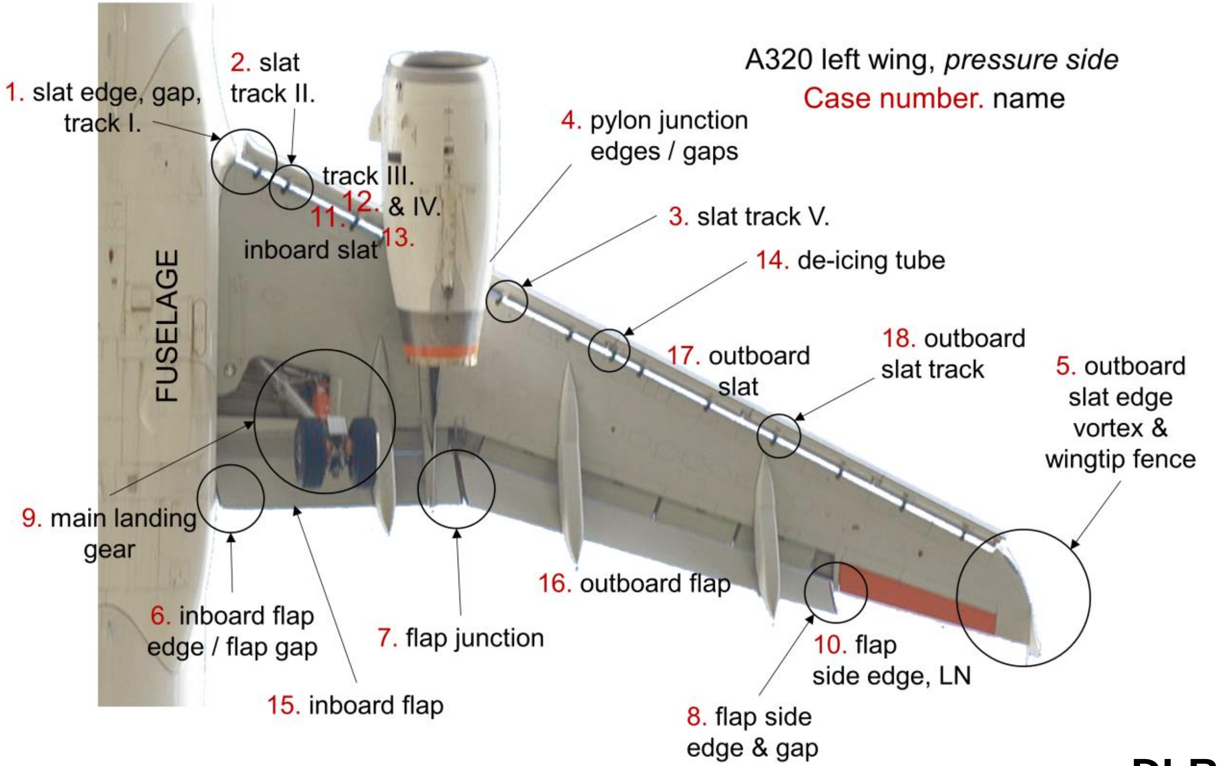


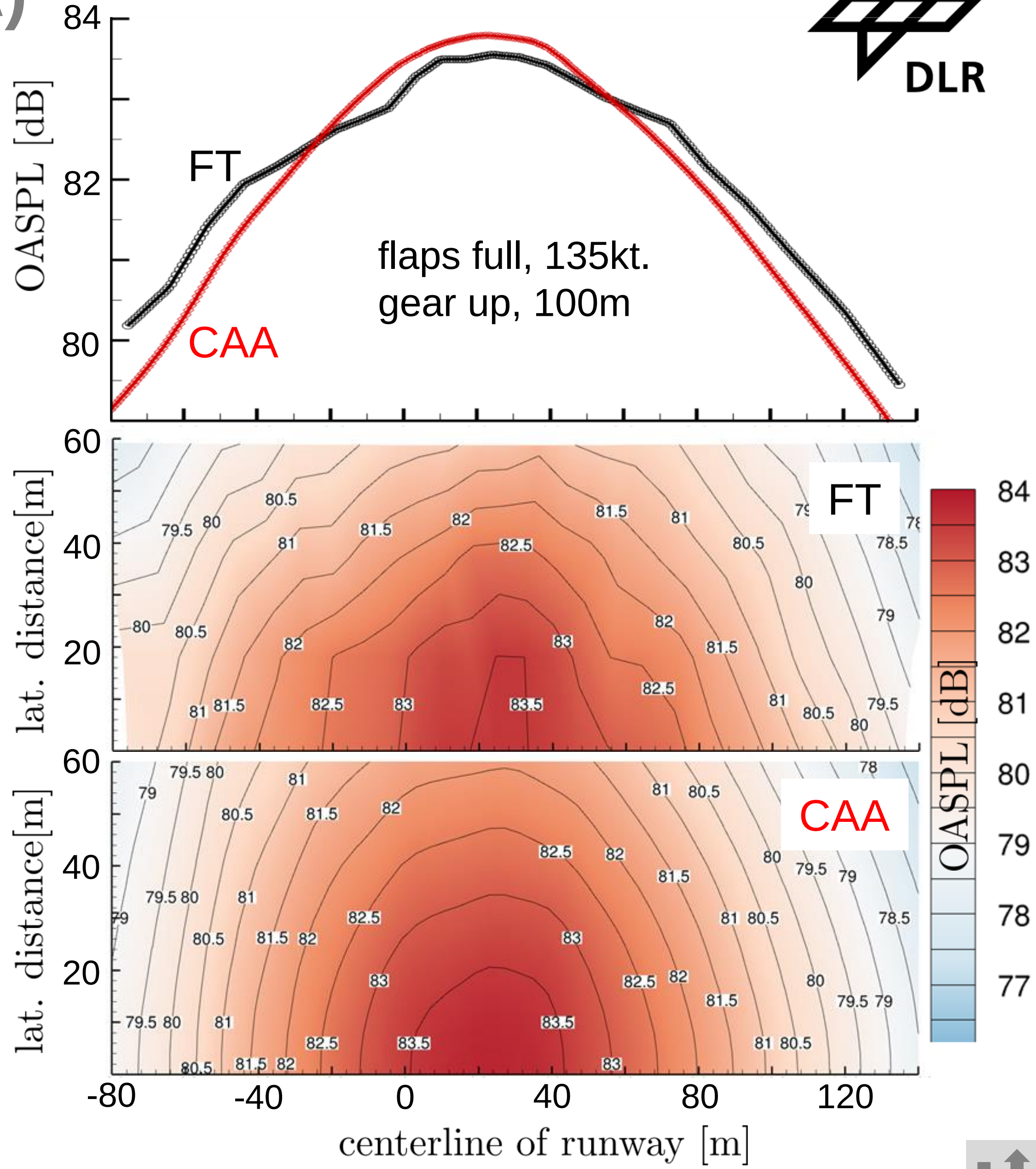
H. Siller, T. Schumacher W. Hage, AIAA 2021-2160

Full scale Flyover simulation (ATRA)

mean flow: **TAU**
sources: **FRPM**
acoustics: **DISCO++/FW-H**

component wise simulation





DLR SIAM

S. Proskurov et al., AIAA 2024-3242

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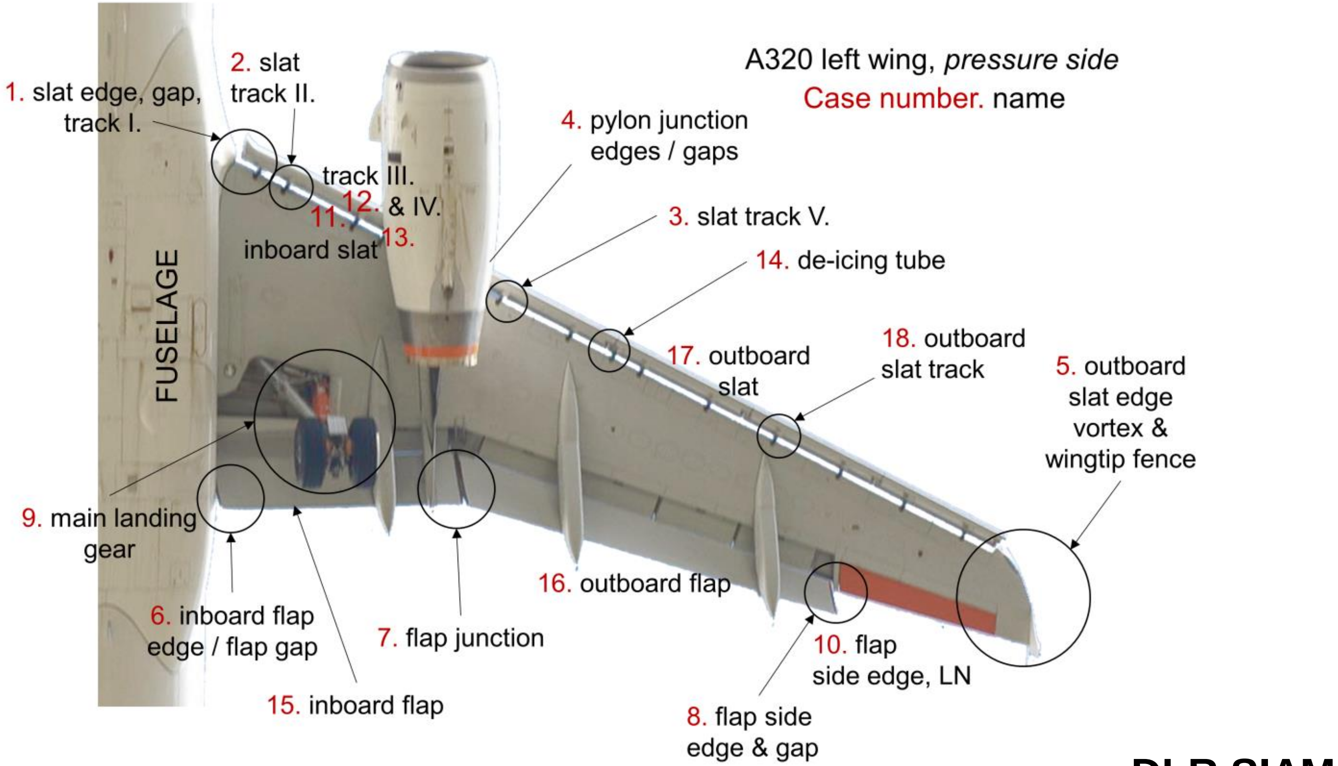
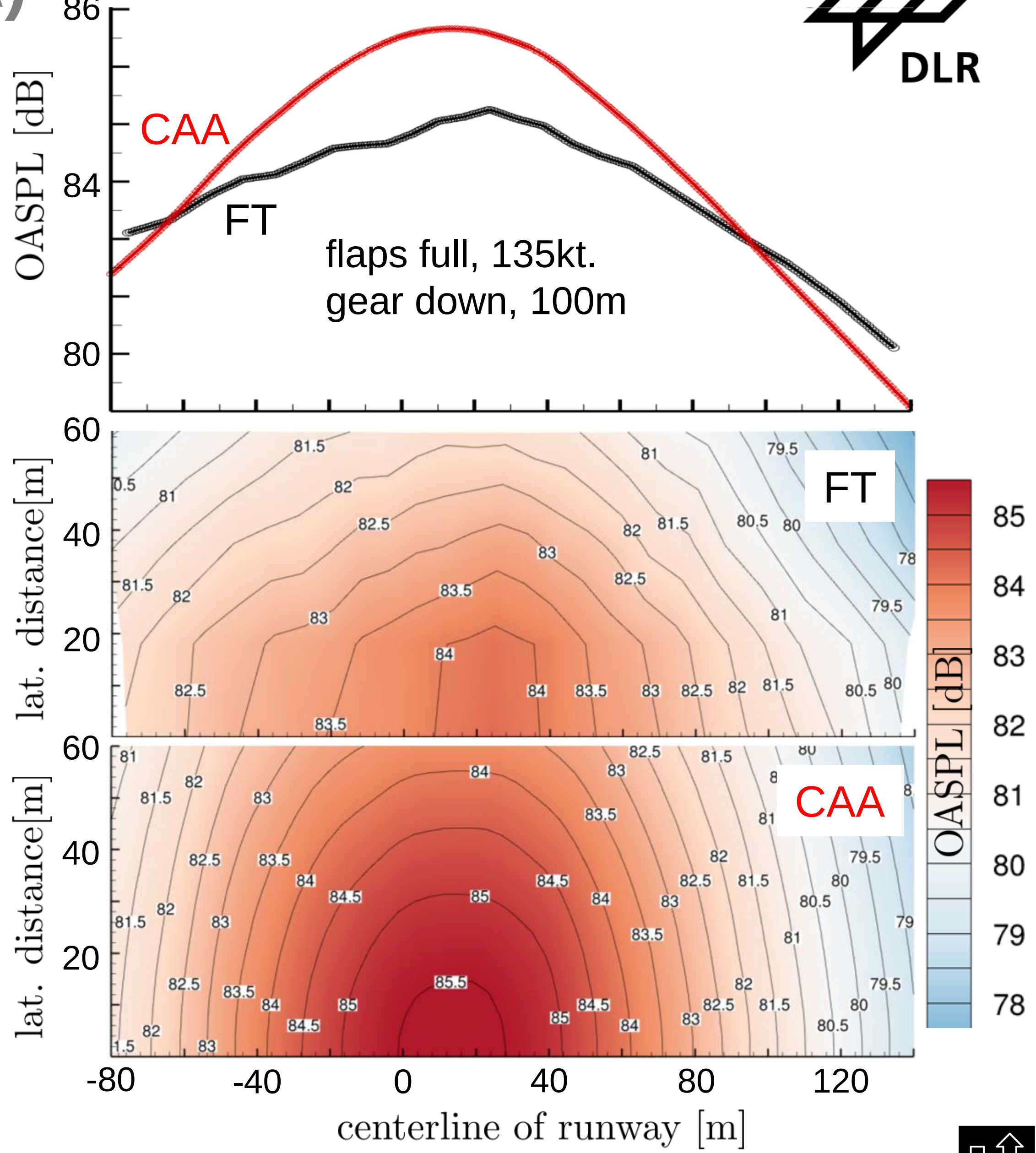


DLR SIAM



S. Proskurov et al., AIAA 2024-3242

LN-ATRA

→ A DLR project to **demonstrate** the potential of **noise reduction technologies** (NRT) for current transport aircraft
→ Implementation/test of known airframe+jet NRTs on real a/c

Flight test for noise reduction technologies

LNATRA

Concept:

Test of all measures simultaneously at DLR **A**dvanced **T**echnology **R**esearch **A**ircraft

Programme:

- Reference test 2016
- 1. part test 2017 (co-operation with EU AFLoNext)
- 2. part test 2018 (5 years preparation)
- main test, 1. part 2019
- ~~main test, 2. part 202x~~ –prepared, not flown–

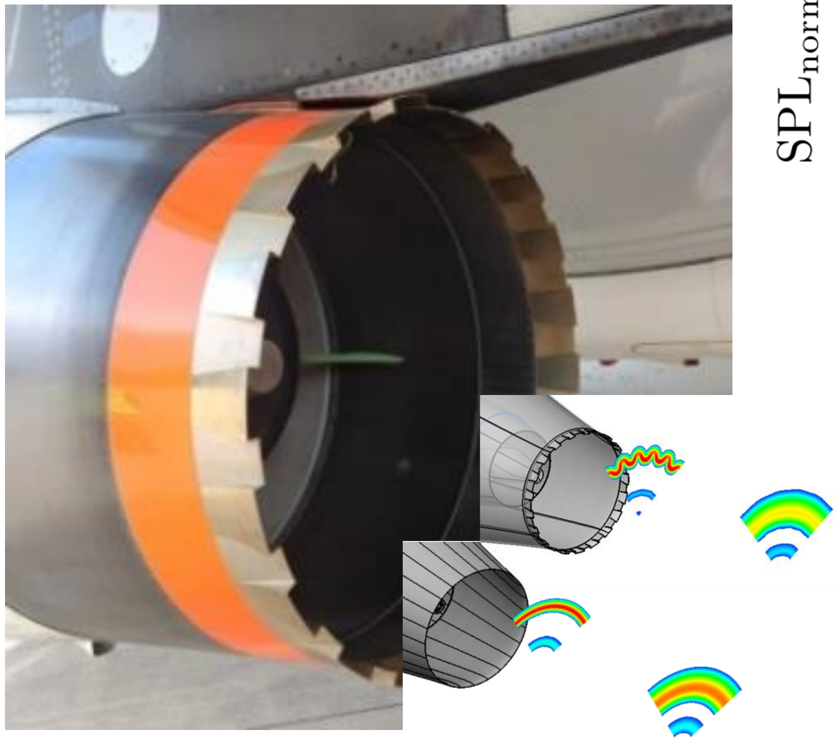
Partners:

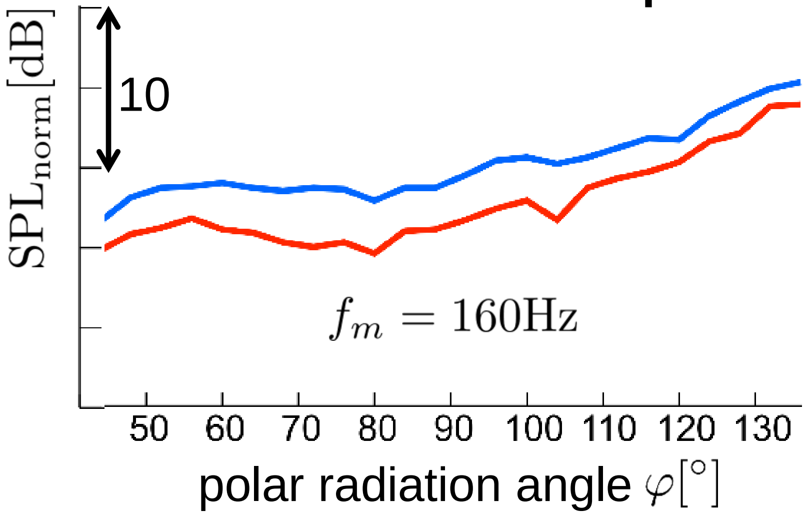
SAFRAN, Deharde, SPÖRL, AMAS technology, AIRBUS, Lufthansa Technik, asco, SONACA, Leichtwerk AG

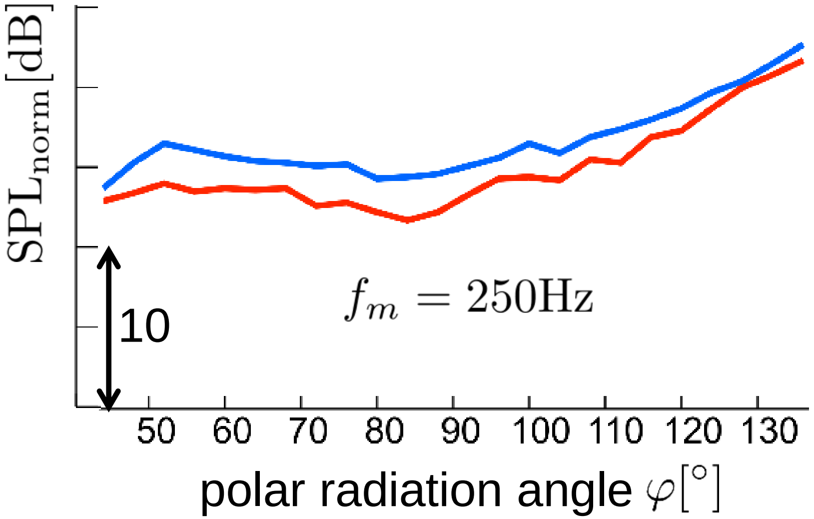
Jet noise

take-off – flaps 2: 22°/20° - gear up

Nozzle modification







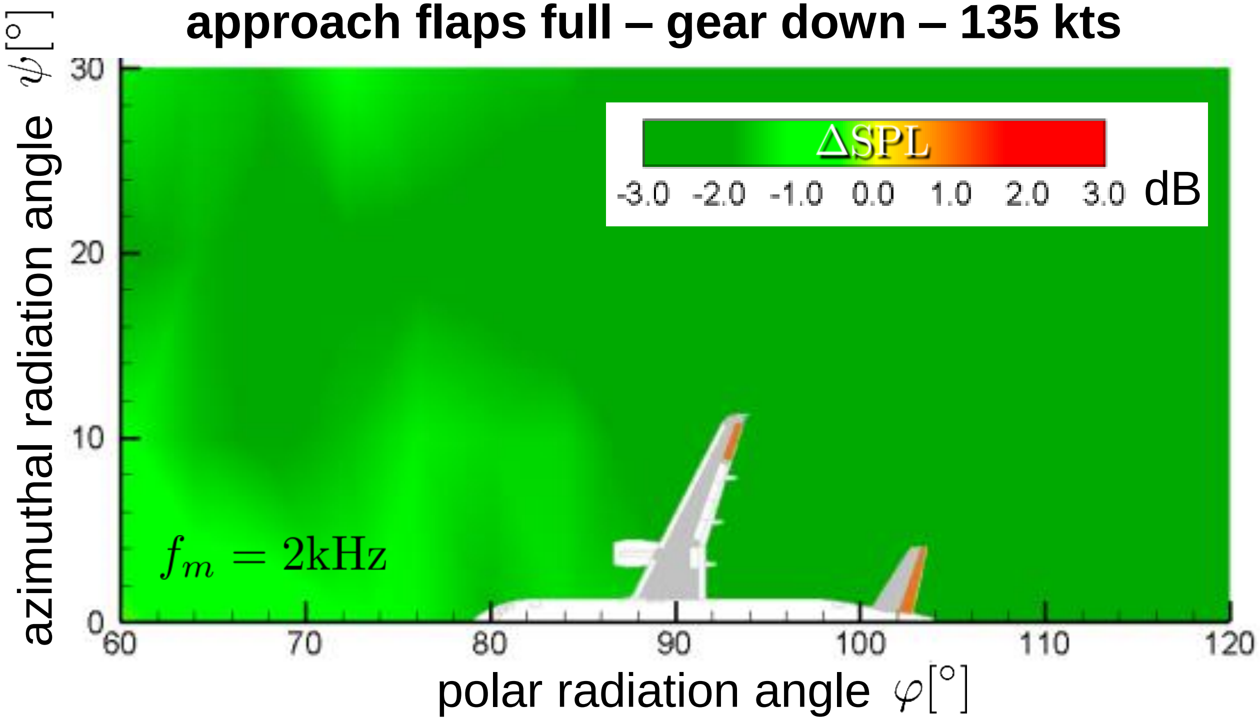
standard nozzle (2016)
modified nozzle (2019)

$$\mathrm{SPL}_{\mathrm{norm}} = \mathrm{SPL}_{\mathrm{meas}} - 80\,\mathrm{lg}\left(\frac{v_{\mathrm{jet}} - v_{\mathrm{tas}}}{c_{\mathrm{ref}}}\right)[\mathrm{dB}]$$

- significant reduction at low frequencies, slight increase (~1dB) at high frequencies

Landing gear noise reduction

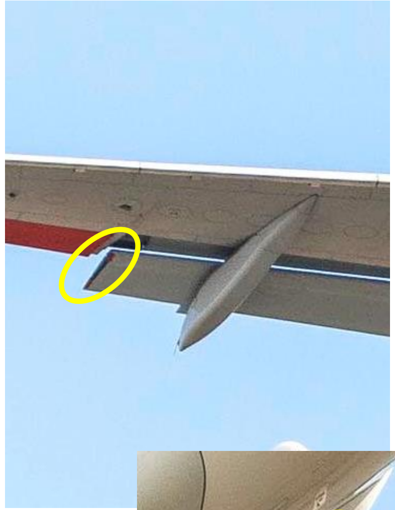
Nose/Main LG modification



- wide area broadband noise reduction ~ 2-3dB (single mics!)

High Lift noise reduction

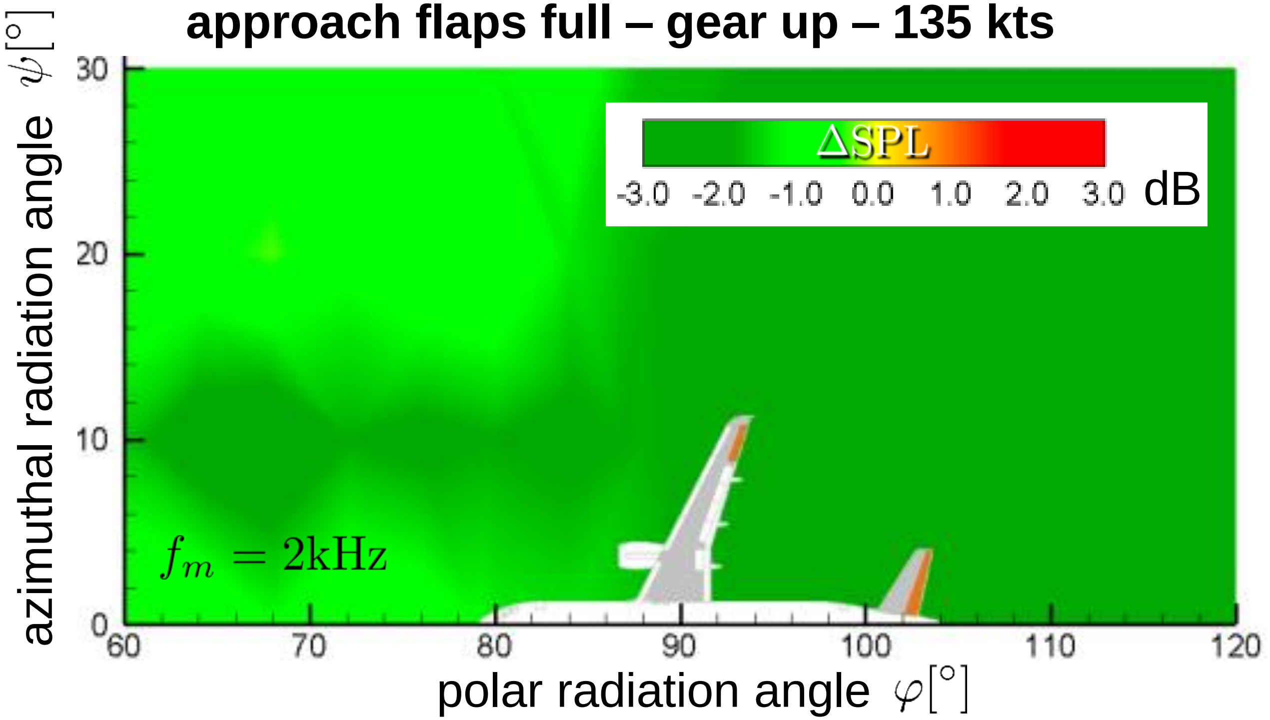
HLD side edge modification



aluminum foam

open cell urethane foam

approach flaps full – gear up – 135 kts



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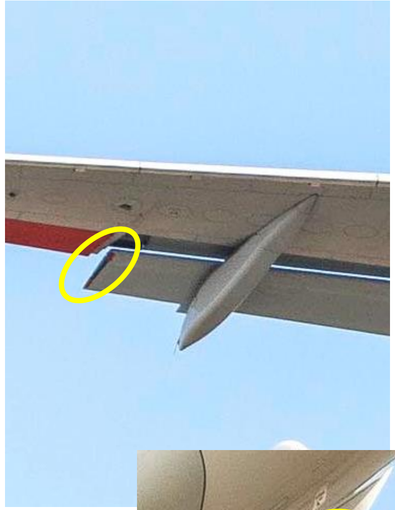
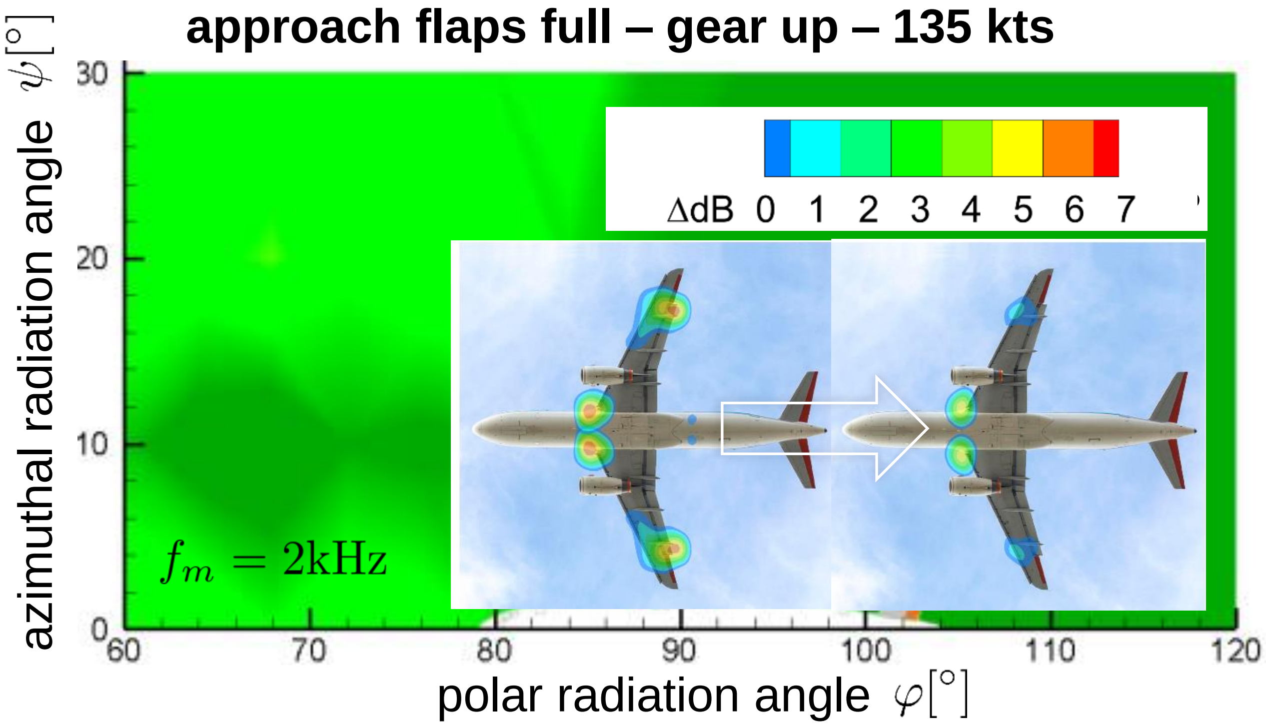


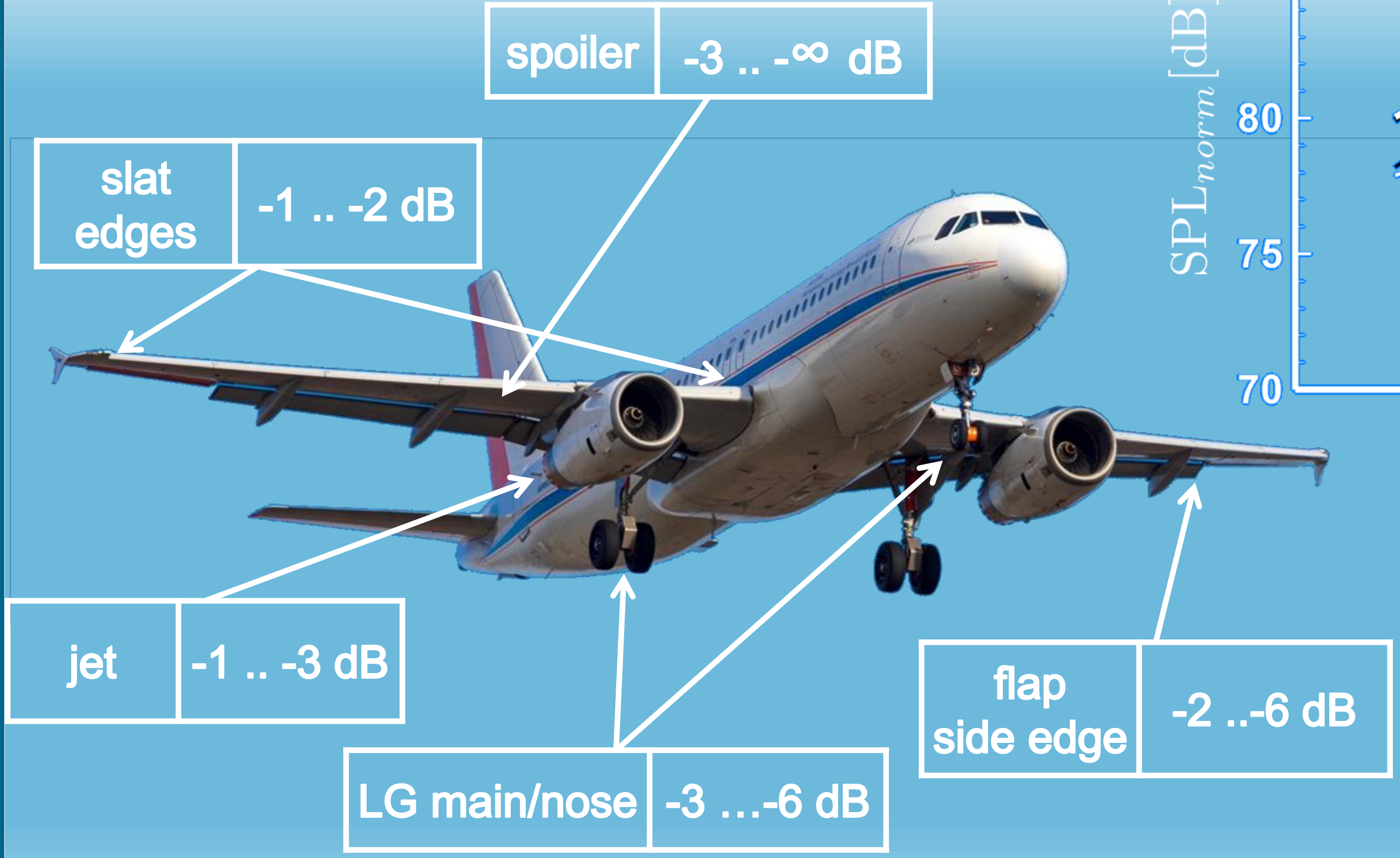
aluminum foam

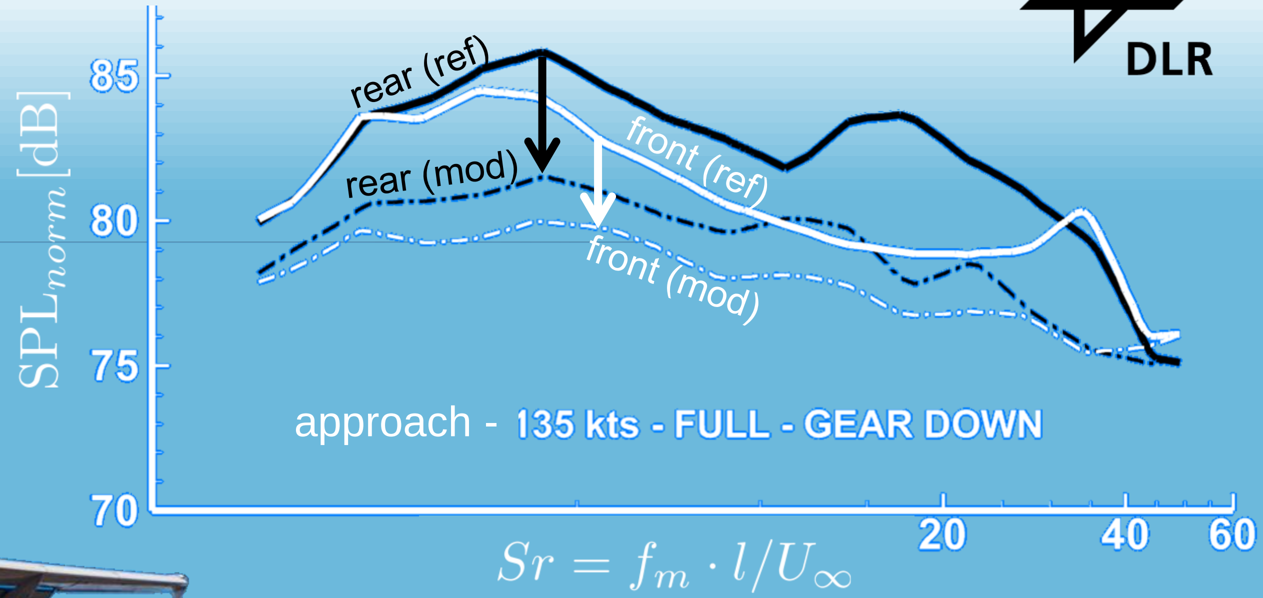
open cell urethane foam



- wide area broadband noise reduction ~ 2-3dB (single mics!)

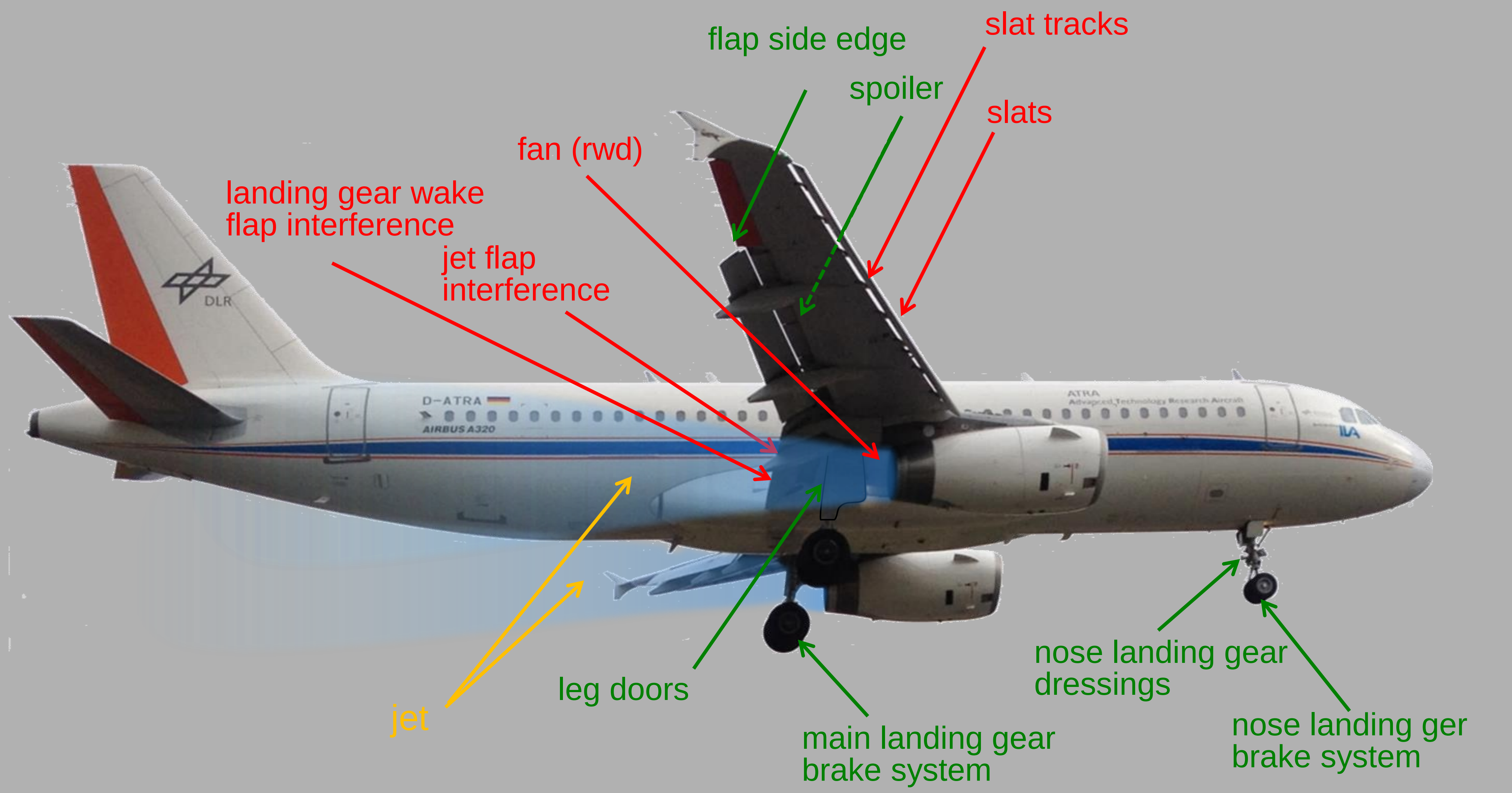
Low noise ATRA - synopsis





- ✓ broadband reduction 3 – 4 dB for standard approaches
- ✓ spoiler noise eliminated
- ✓ 1 – 2 dB reduction at departure

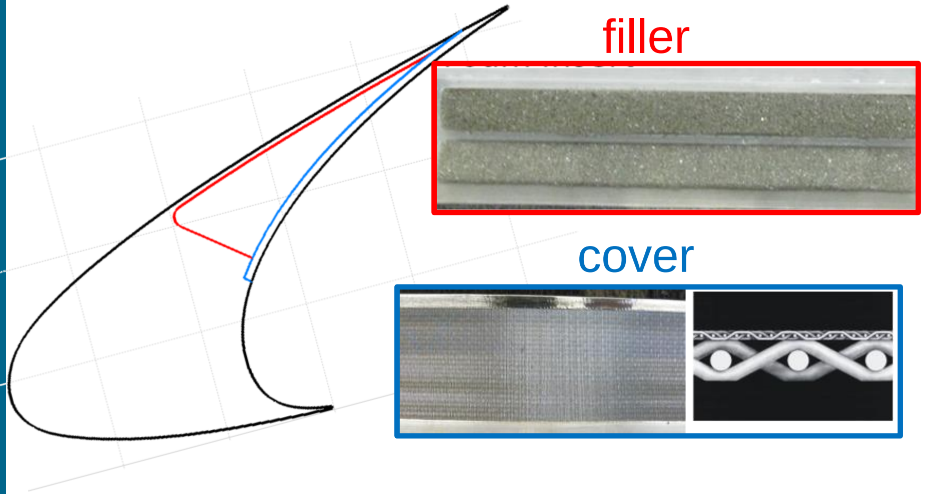
- up to **5dB reduction** at approach (if including slat modification)



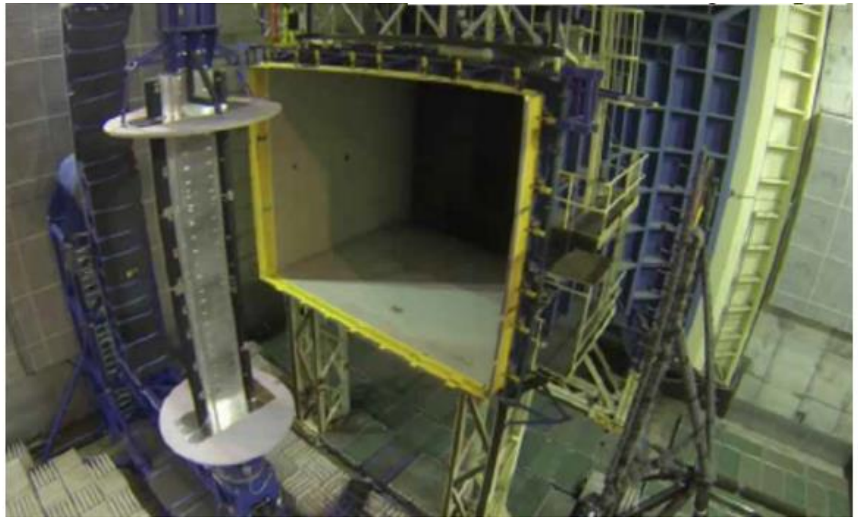
BEYOND LNATRA

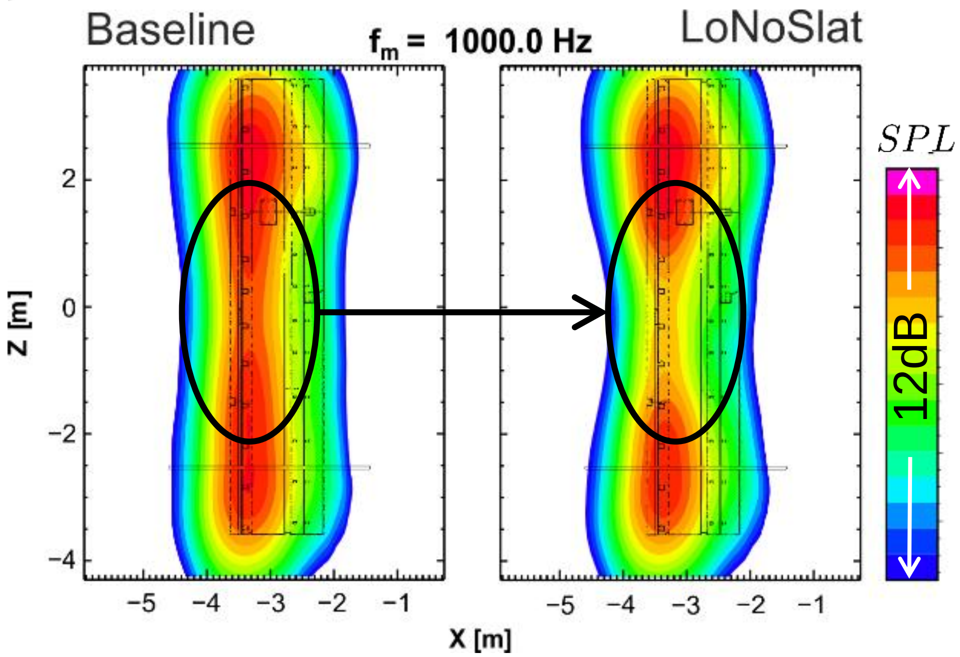
→ Further research on sources of sound and respective noise reduction technology

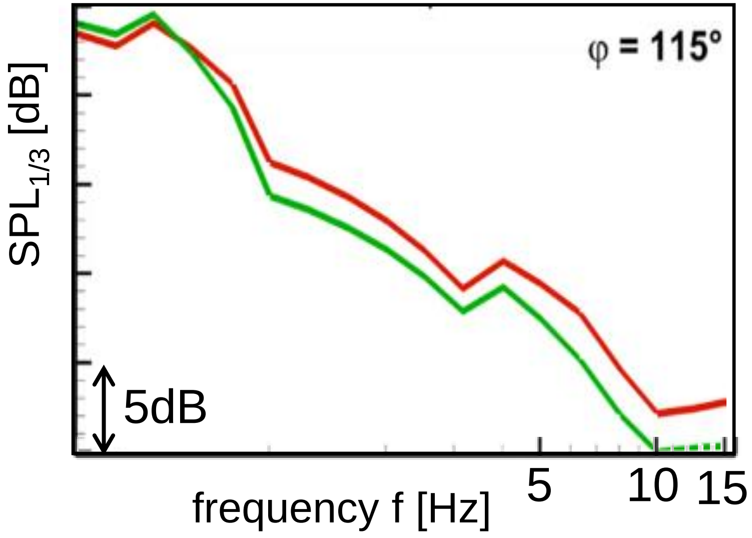
SLAT - noise reduction by slat cove liner



F15LS (4:1 sister of F16)
1200 mm chord,
Re ~ 4 Mio.@ 55 m/s





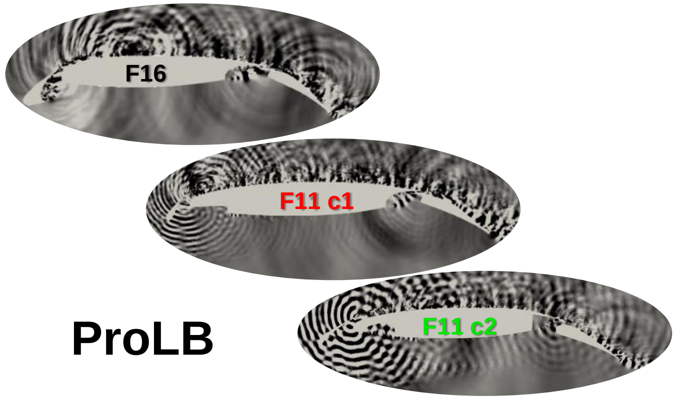


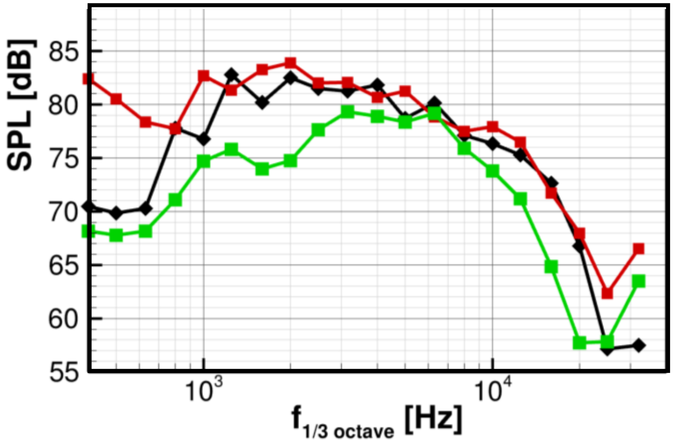
- 2-3 dB reduction broadband
- no lift penalty

Lufo MOVE.ON

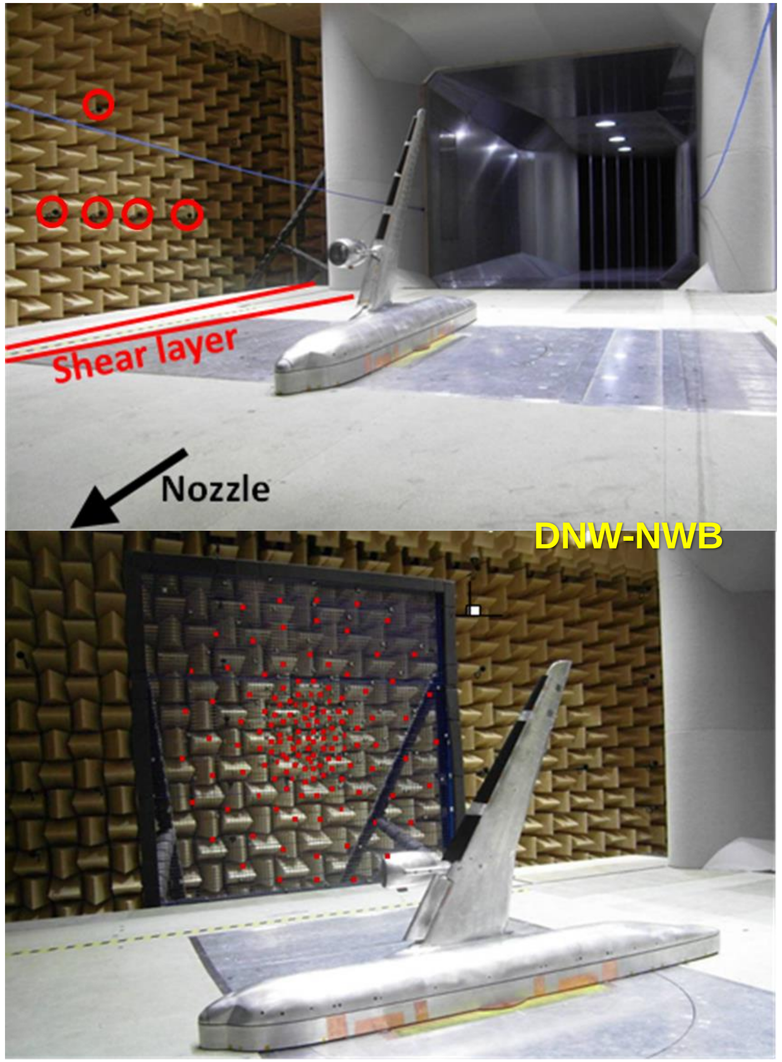
M. Pott-Pollenske, AIAA 2021-2114

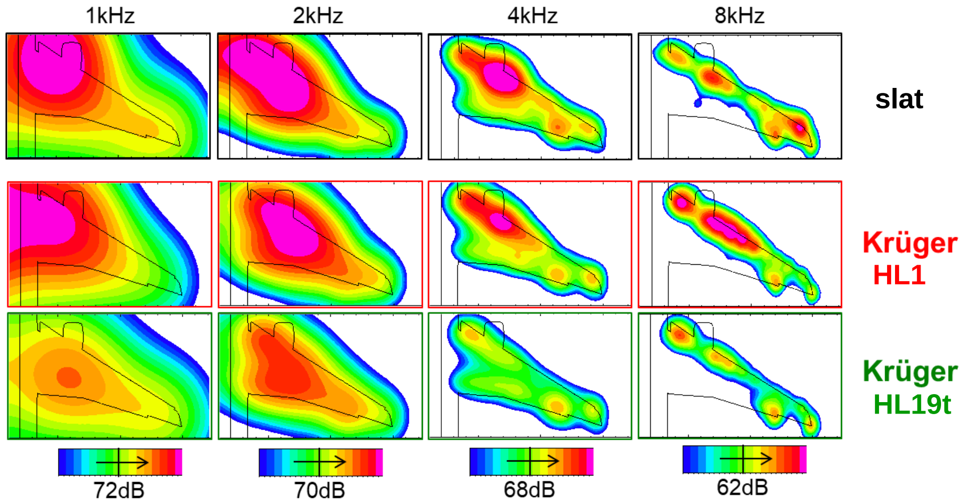
Low noise high lift: leading edge device shapes

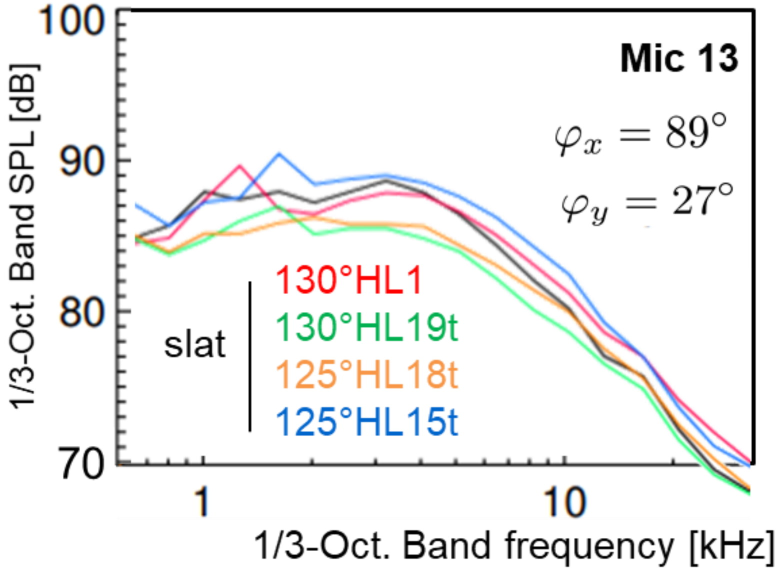




same high lift performance



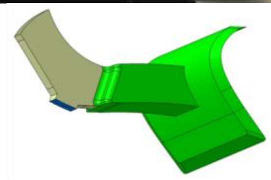


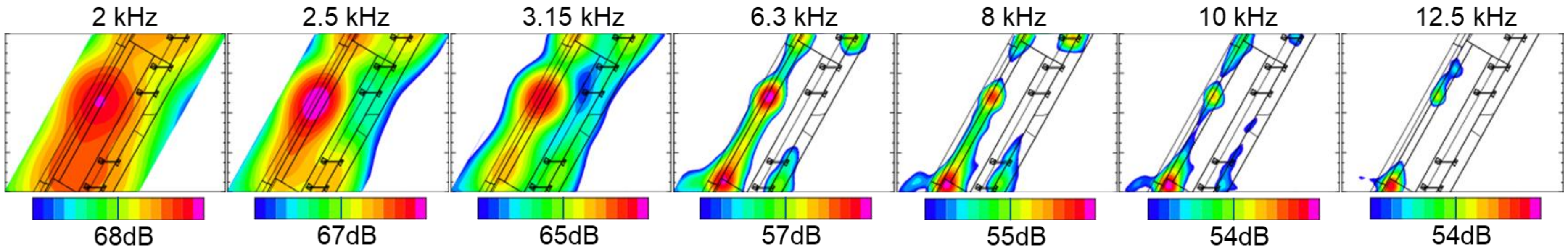


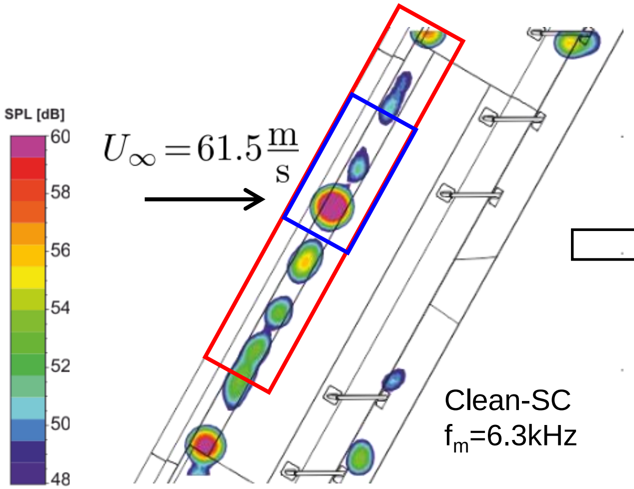
→ **3D proof of low noise potential of Krüger flaps**

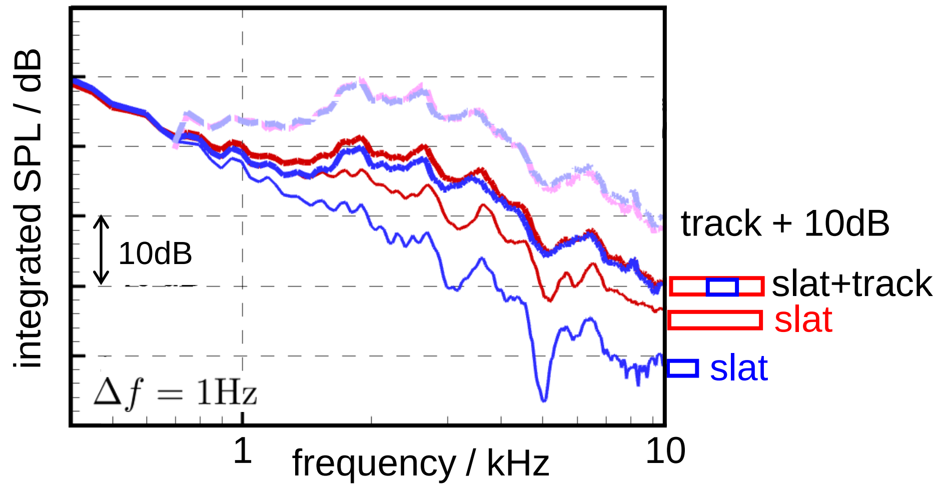
M. Pott-Pollenske, A. Büscher / Lufo-INTONE 2021

Importance of **SLAT TRACK** noise





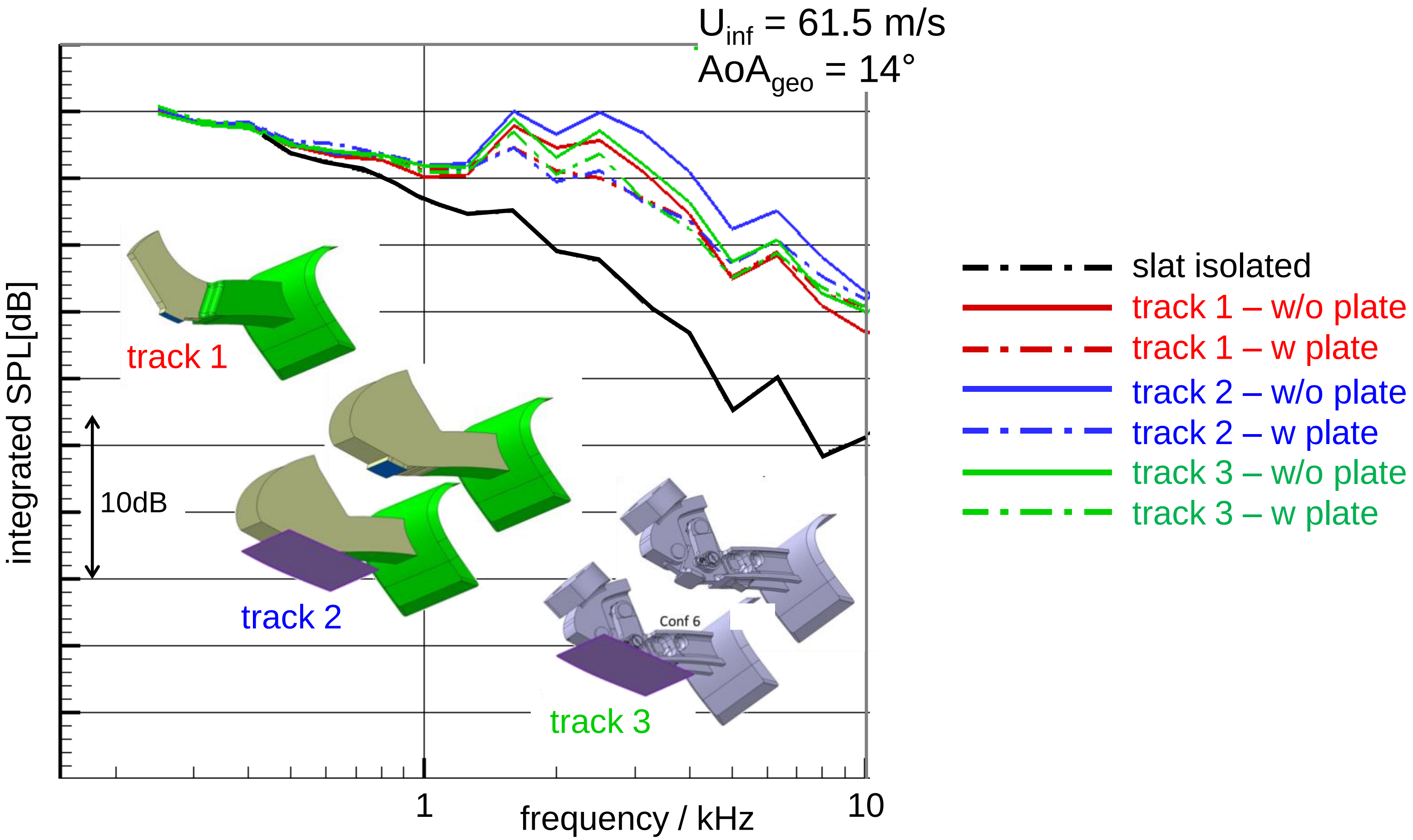




- **track noise may dominate spectrum in wide frequency range**

Lufo 5-3 INTONE
Pott-Pollenske, Jansen, AIAA 2002-2807

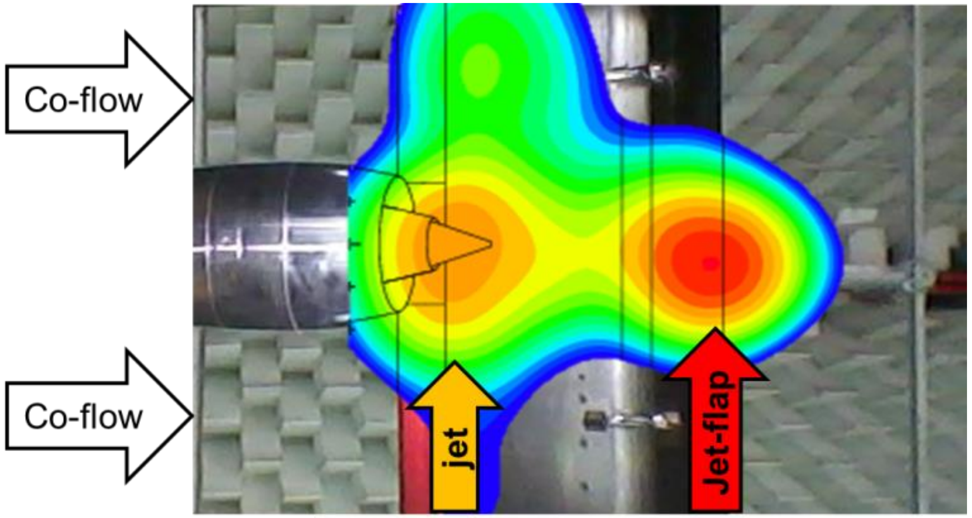
Importance of **SLAT TRACK** noise – influence of shape

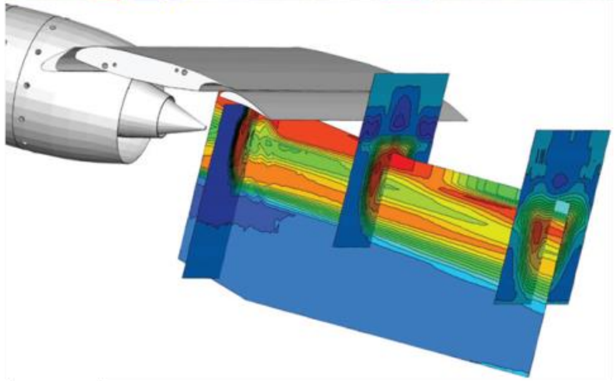


- **noise reduction by design**

JET-FLAP INTERFERENCE noise

Measurement of JFI noise dual stream nozzle in DLR-AWB (F16 High lift)

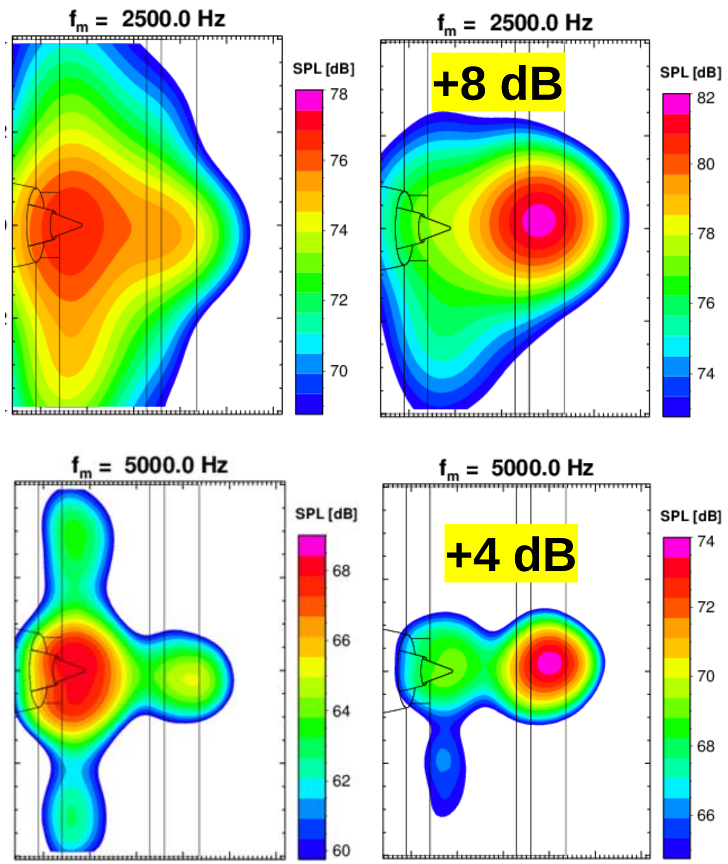




U_{Fan} = 129 m/s U_{Core} = 108 m/s

flap setting

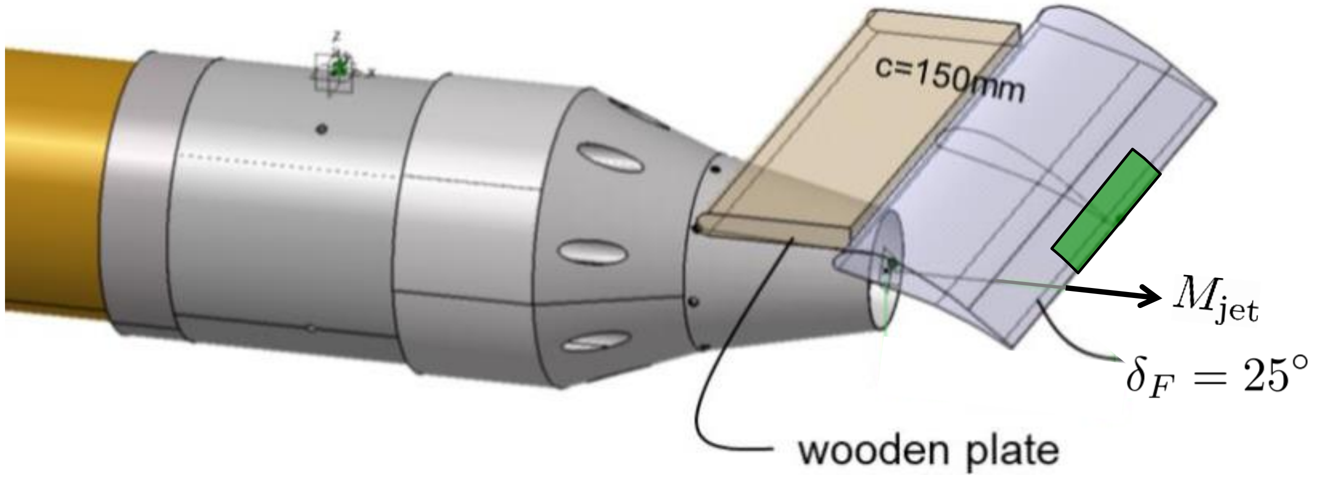
δ_F=25° δ_F=35°

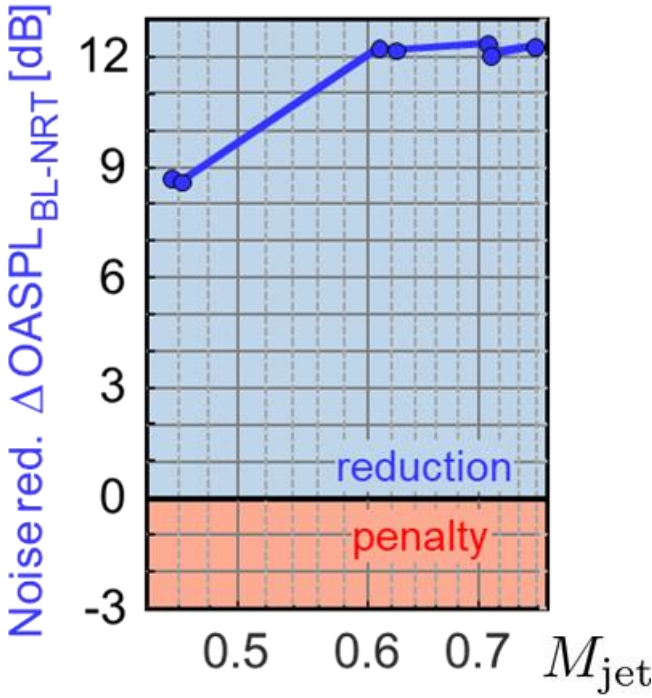


M. Pott-Pollenske, R. Meier, Lufo Power25

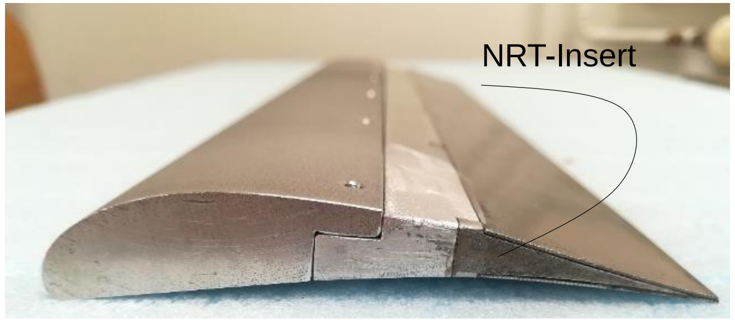
JET-FLAP INTERFERENCE noise reduction

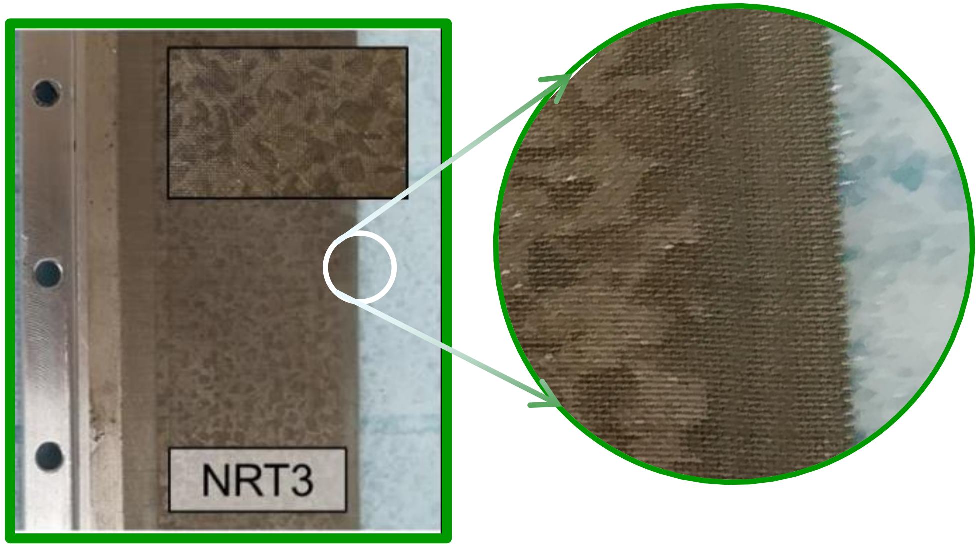
Test of single stream jet combined with F16 flap / effect of porous flap inserts





best variant:
coarse porous metal + mesh cover

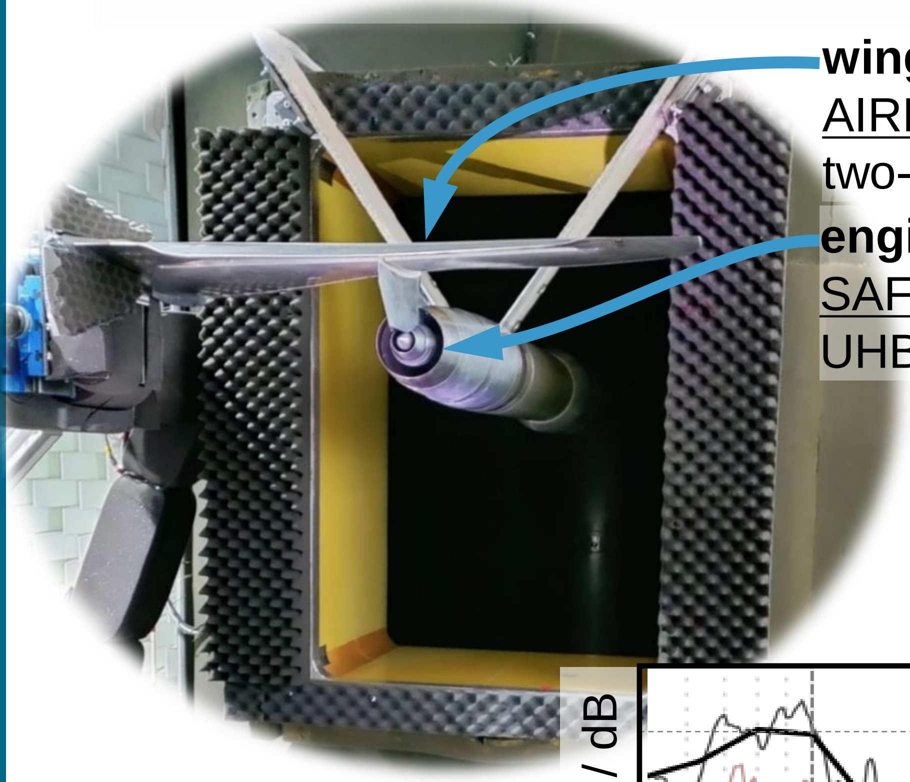




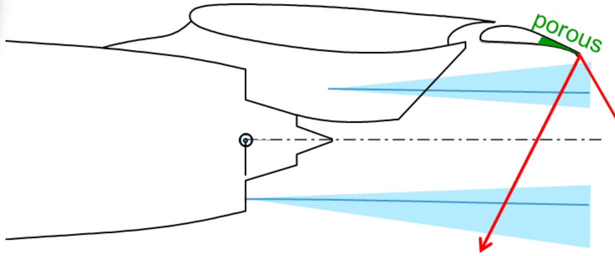
→ **appropriate materials extremely effective**

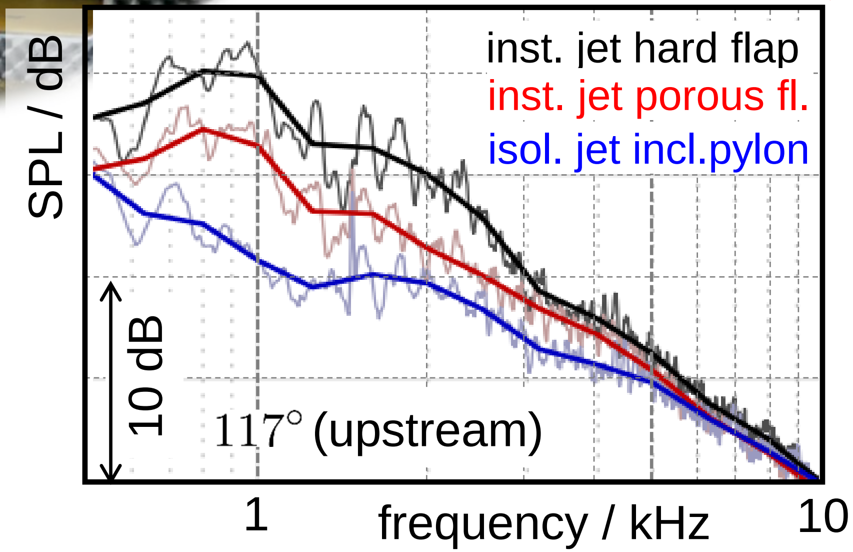
Chr. Jente, J. Schmidt, J. Delfs, M. Pott-Pollenske, H. Siller AIAA 2022-3040

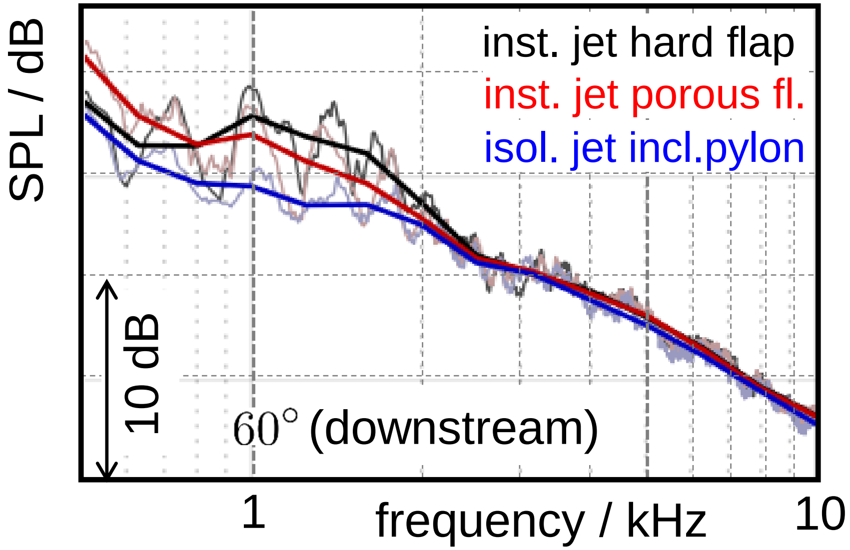
JET-FLAP INTERFERENCE noise reduction



wing model
AIRBUS RDJ80
two-element wing flap δ_F=14°
engine model
SAFRAN dual stream short cowl
UHBR A_{Byp}/A_{Core}~7, D_{mix} ~ Ø100mm



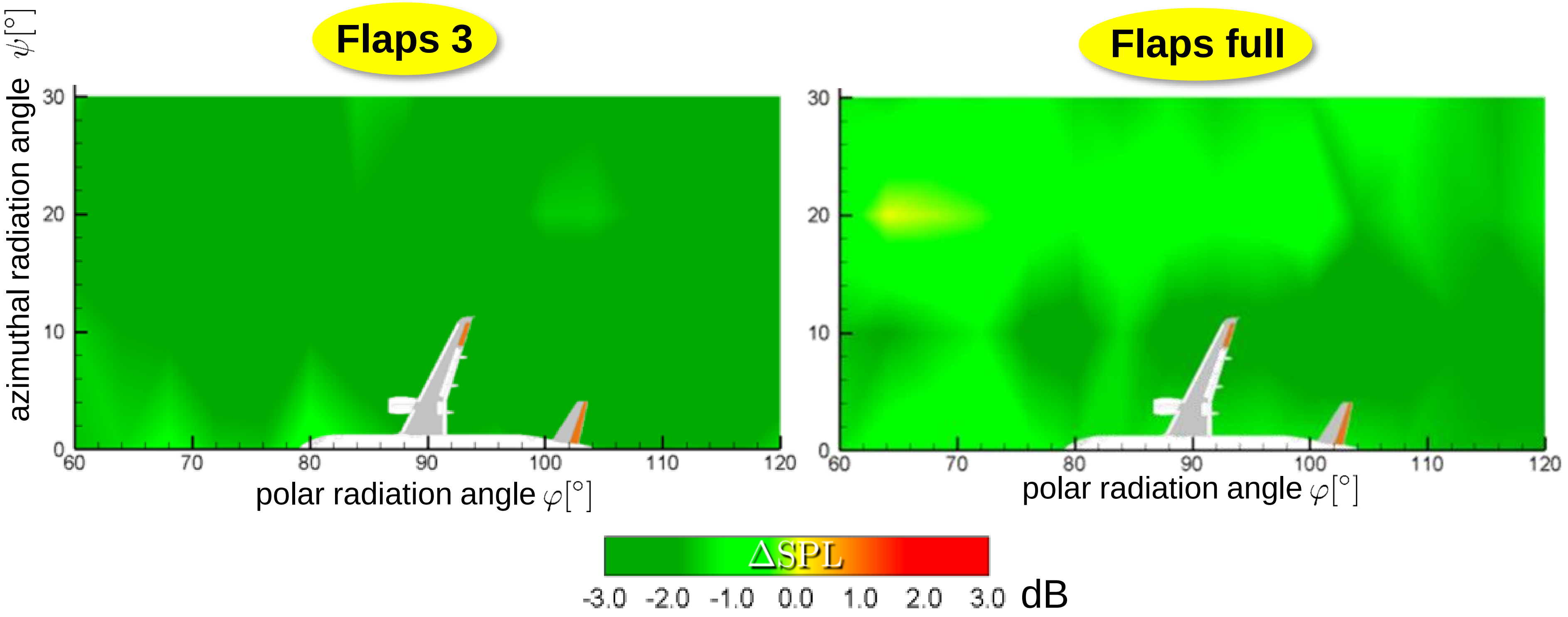




Chr. Jente, J. Schmidt, J. Delfs, M. Pott-Pollenske, H. Siller AIAA 2022-3040

LANDING GEAR – FLAP INTERFERENCE noise

approach– gear down – 135 kts

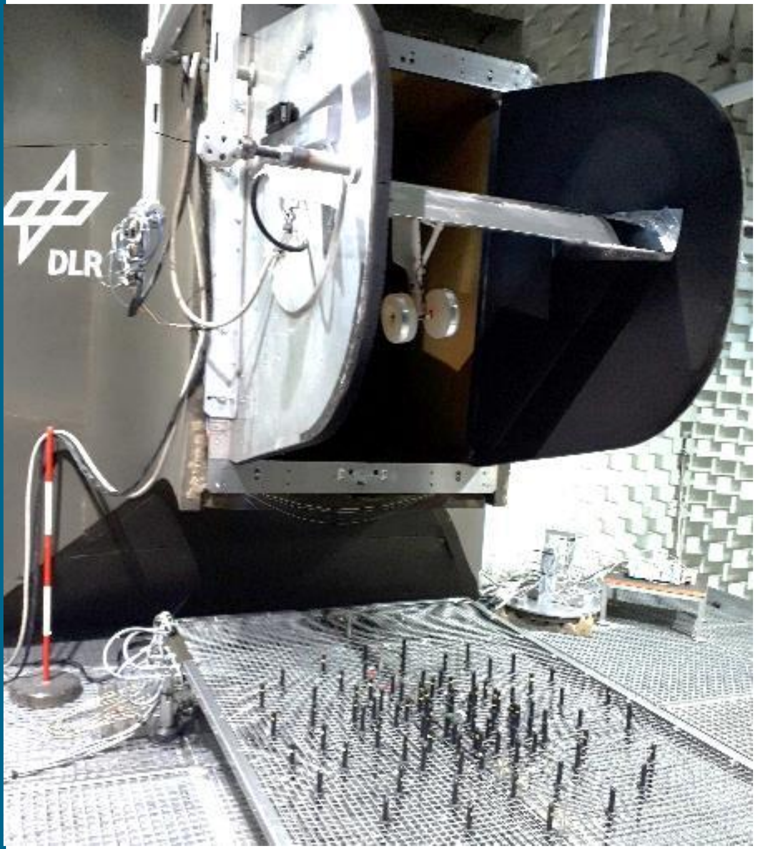


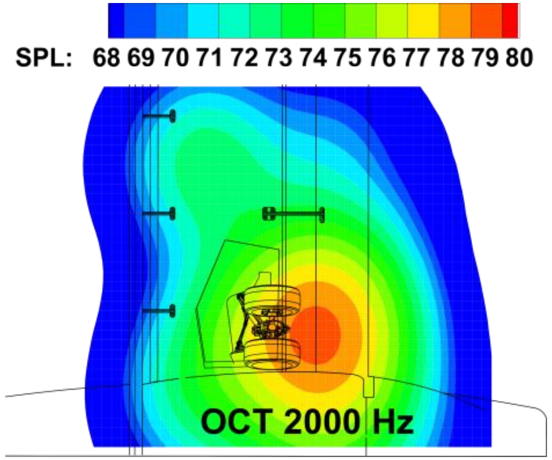
→ at large deployment angle installation excess noise increased

M. Pott-Pollenske et al., DLR-LNATRA 2021

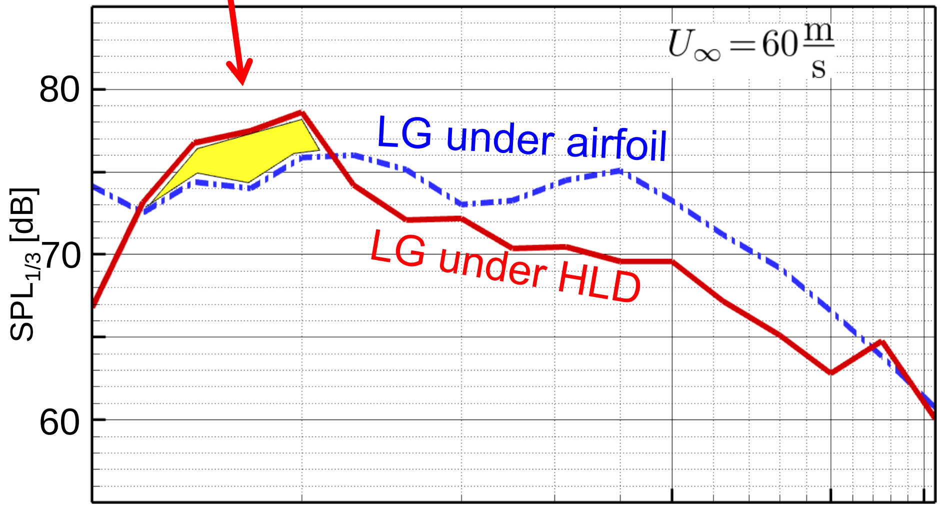
LANDING GEAR – FLAP INTERFERENCE noise

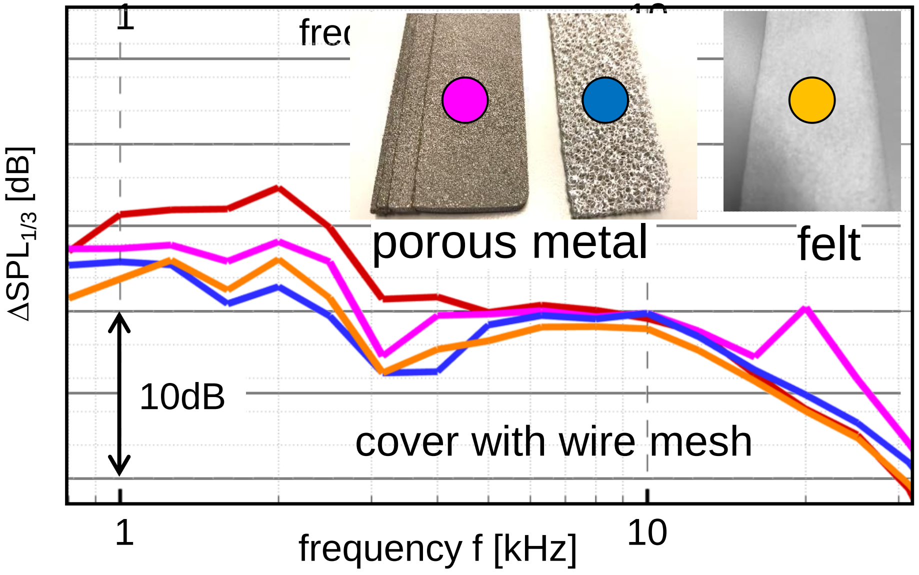
Acoustic Windtunnel studies AWB





Gear wake / flap interaction noise



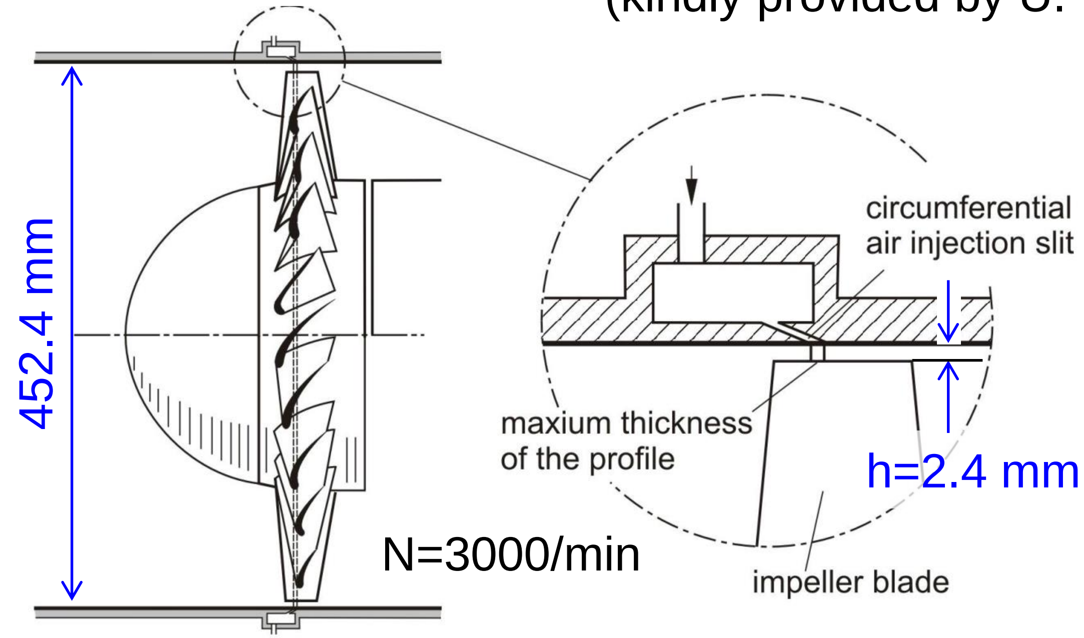


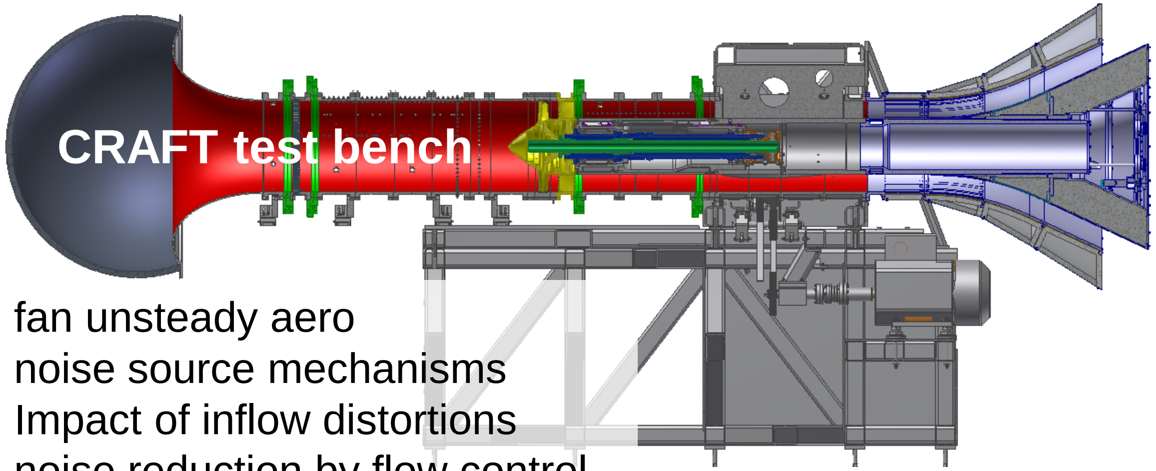
→ **significant low frequency noise source at flap leading edge**

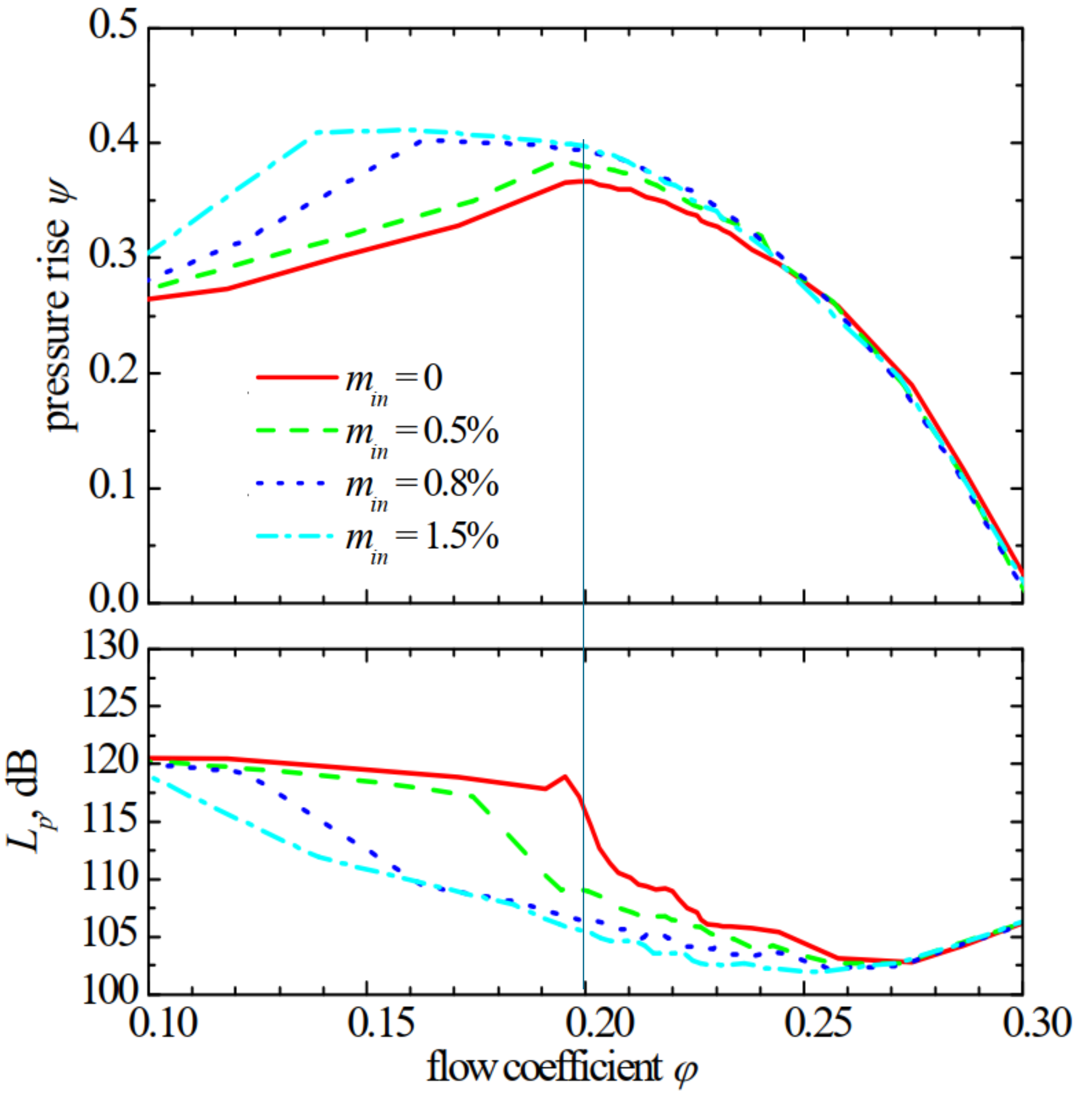
M. Pott-Pollenske 2020 EU ARTEM

FAN TIP CLEARANCE NOISE - reduction by flow control

(kindly provided by U. Tapken, DLR Institute of propulsion technology)





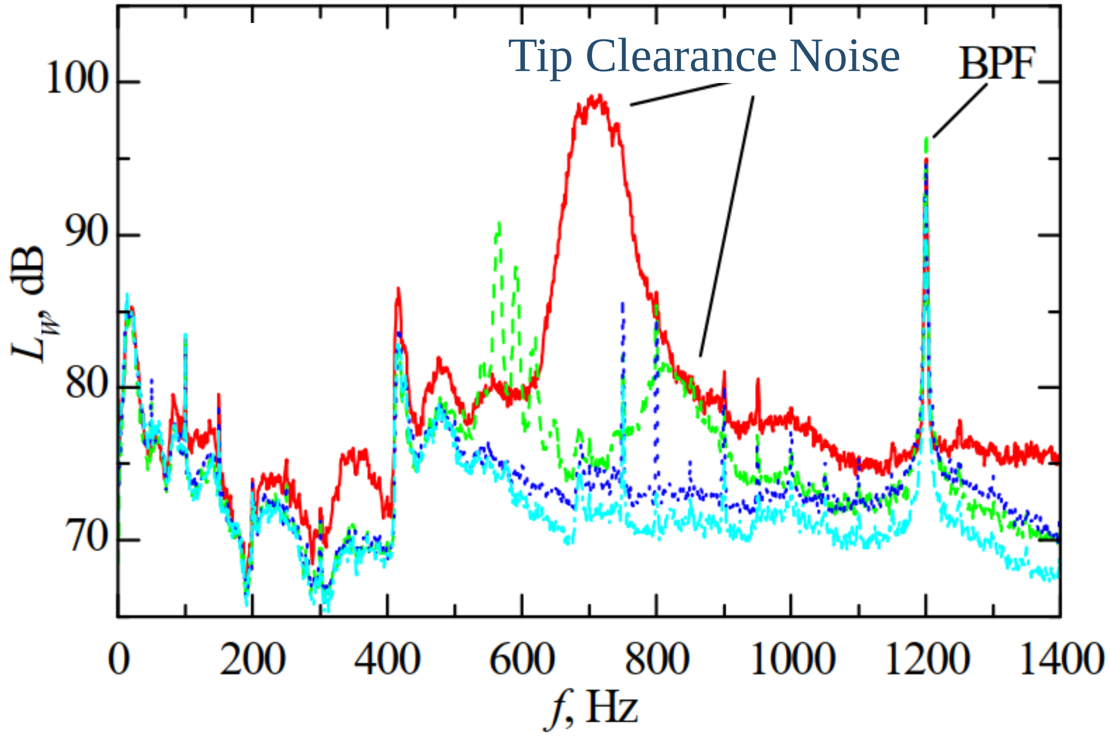


- fan unsteady aero
- noise source mechanisms
- Impact of inflow distortions
- noise reduction by flow control

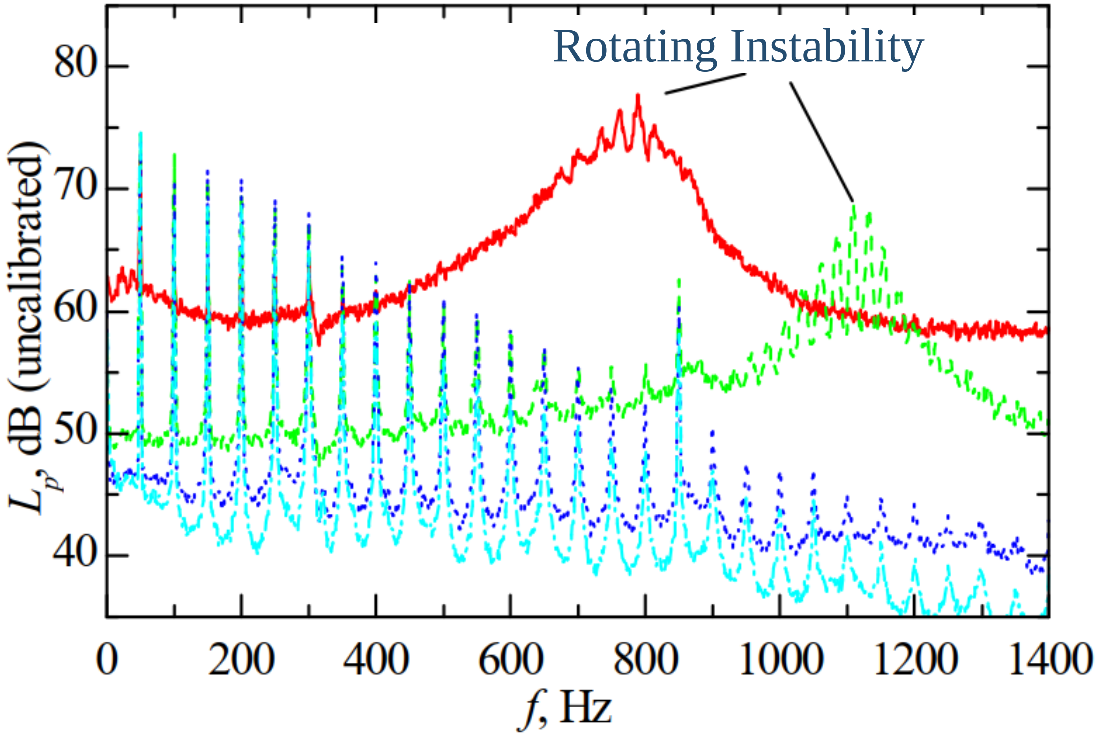
FAN TIP CLEARANCE NOISE - reduction by flow control

steady air injection at rotating instability operating point (φ=0.2)

sound power in fan outlet (far-field)



wall pressure on rotor blade suction side



$m_{in} = 0$, $\psi = 0.367$, $\eta = 0.736$ — $m_{in} = 0.5\%$, $\psi = 0.376$, $\eta = 0.738$

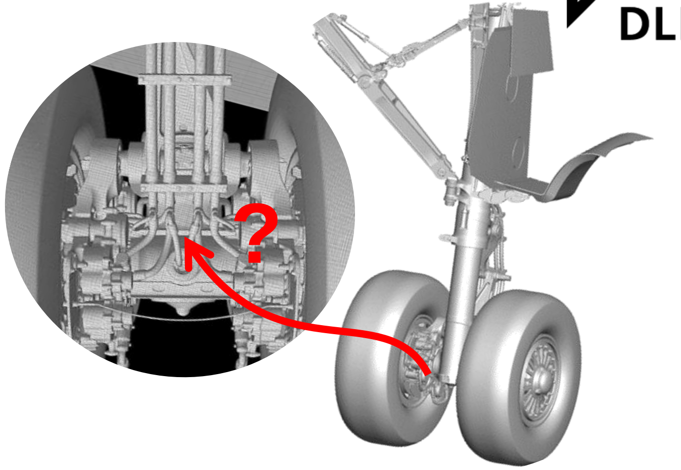
$m_{in} = 0.8\%$, $\psi = 0.383$, $\eta = 0.751$ — $m_{in} = 1.5\%$, $\psi = 0.394$, $\eta = 0.731$

noise reduction technologies - conclusions

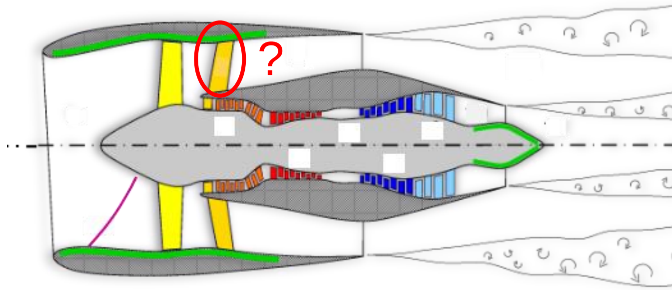
effective aeronoise reduction may be achieved by

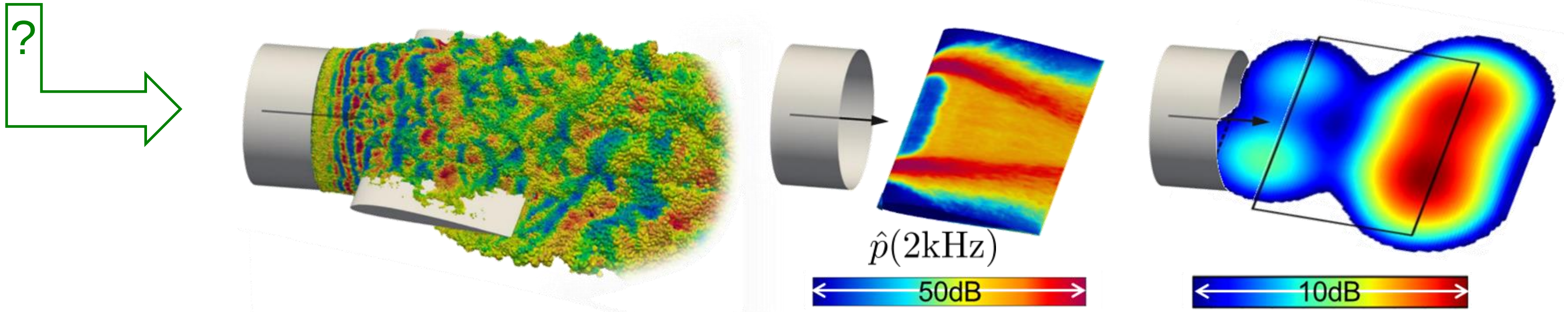
- aero-shaping — But: how to arrive at „best shape“ in MD context?
- materials — But: what are „best properties“?
  - with existing materials
  - modified materials (graded, anisotropic)
  - newly designed materials, i.e. taylored (meta) materials
- flow control — But: what is the most effective/efficient way of air injection?

Source noise localization & quantification – a pre-requisite for low noise design –



- Where exactly happens the sound **generation** inside a complex structure ?
- How unique are beamforming maps ?
- Sound **generated** at installed components ?
- What is a „source of sound“ at all?
  → Can one define a „surface source quantity“?
- Can one extract a „source indicator“ without propagation to the farfield ?
- Can one overcome assumptions in beamforming and do localization based on first principles ?
- Can‘t we just use the surface pressure fluctuation $\hat{p}$ as source indicator ?

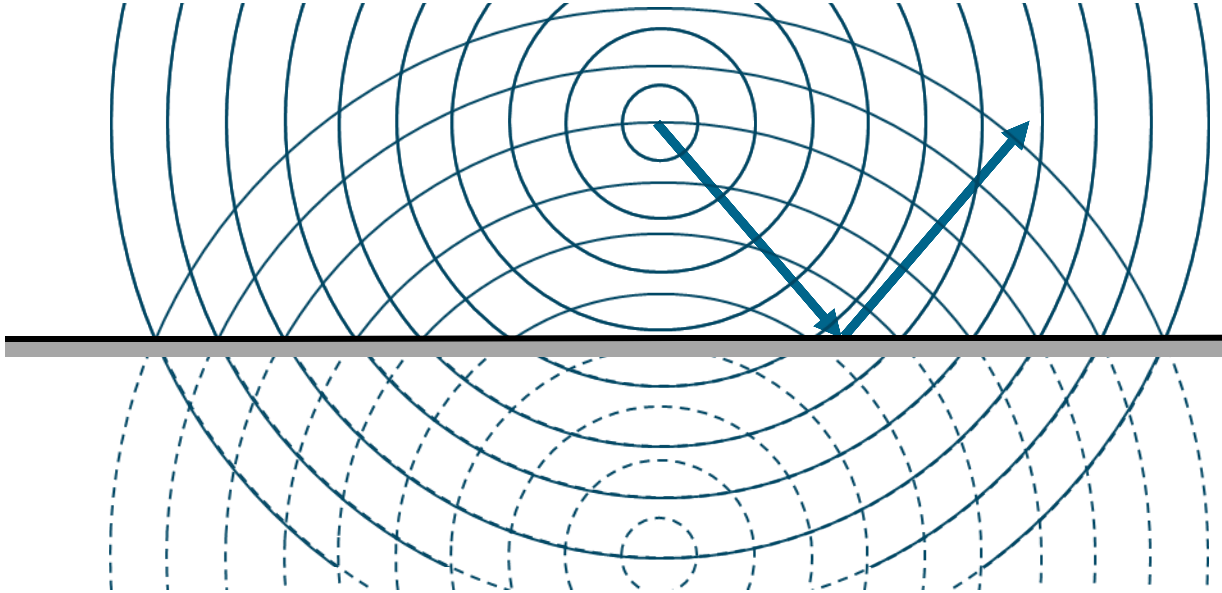


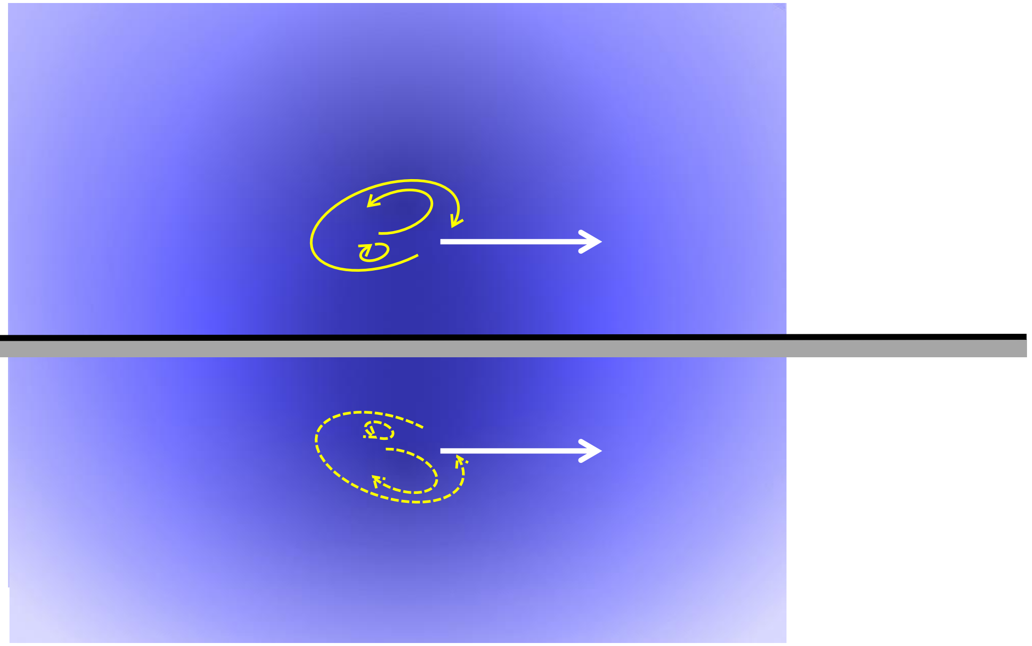


⇨ no!
we can‘t

Concept for alternative source localization – **source hypothesis**

no sound **generation** by pure **reflection** of an incident pressure field





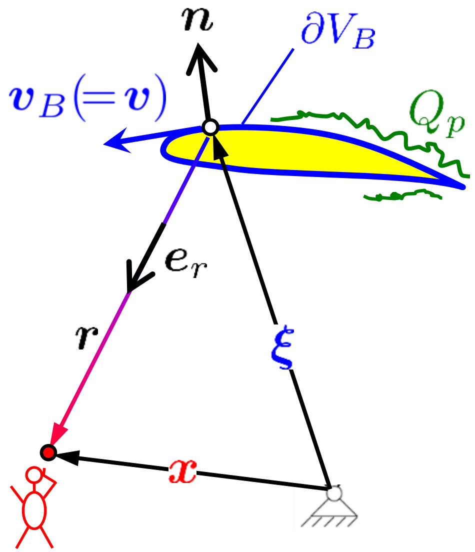
Concept for alternative source localization – **translation to math**

Ffowcs-Williams & Hawkings (Kirchhoff) equation, solid surface (low Mach no., freq. domain):

$$\hat{p}(\boldsymbol{x}) = \hat{p}_f(\boldsymbol{x}) + \frac{1}{4\pi}\int_{\partial V_B} \exp(-ikr)\left[(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}(\boldsymbol{\xi}) - \underbrace{\frac{1}{r}\frac{\partial \hat{p}}{\partial n}}_{\approx 0}\right] dS(\xi)$$

$$\hat{p}_f(\boldsymbol{x}) = \frac{1}{4\pi}\int_{V_\infty^+} \frac{\hat{Q}_p^{\mathrm{LH}}}{r} \exp(-ikr)\; dV(\xi)$$

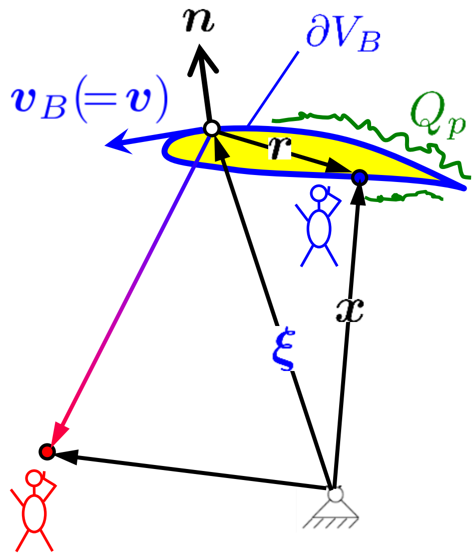
free field signature of volume sources



Choose reception point $\boldsymbol{x}$ on surface:

$$\hat{p}(\boldsymbol{x}) = 2\hat{p}_f(\boldsymbol{x}) + \frac{1}{2\pi}\;-\!\!\!\!\!\!\int_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}(\boldsymbol{\xi})\; dS(\xi)$$

solve for

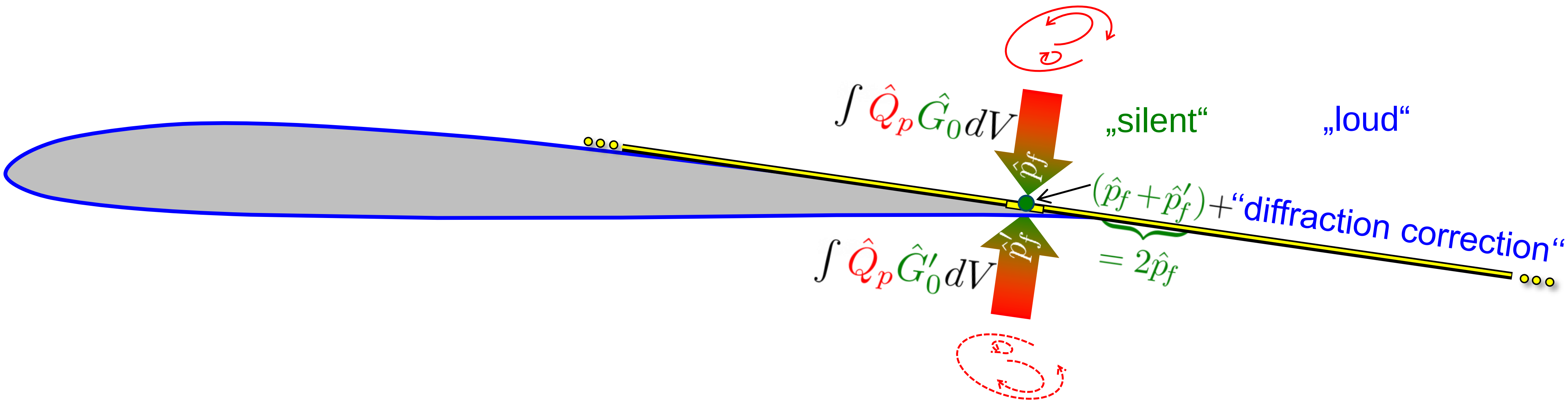


Concept for alternative source localization – **reading the equation**

no sound **generation** by pure **reflection** of incident pressure field $\hat{p}_f$

⇒ source of sound on surfaces is **pure diffraction** of pressure field

$$\hat{p}(\boldsymbol{x}) = 2\hat{p}_f(\boldsymbol{x}) + \frac{1}{2\pi} \oint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}\, dS(\xi)$$



Acoustic surface pressure $\hat{p}_S$ and the surface source $\hat{q}$

$$\hat{p}(\boldsymbol{x}) = 2\hat{p}_f(\boldsymbol{x}) + \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}\; dS(\xi)$$

$$\hat{p} = \hat{p}_S + 2\hat{p}_f$$

$$\hat{p}(\boldsymbol{x}) - 2\hat{p}_f(\boldsymbol{x}) = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}\; dS(\xi)$$

$$\Rightarrow \hat{p}_S(\boldsymbol{x}) = 2\hat{q} + \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}_S(\boldsymbol{\xi})\; dS(\xi)$$

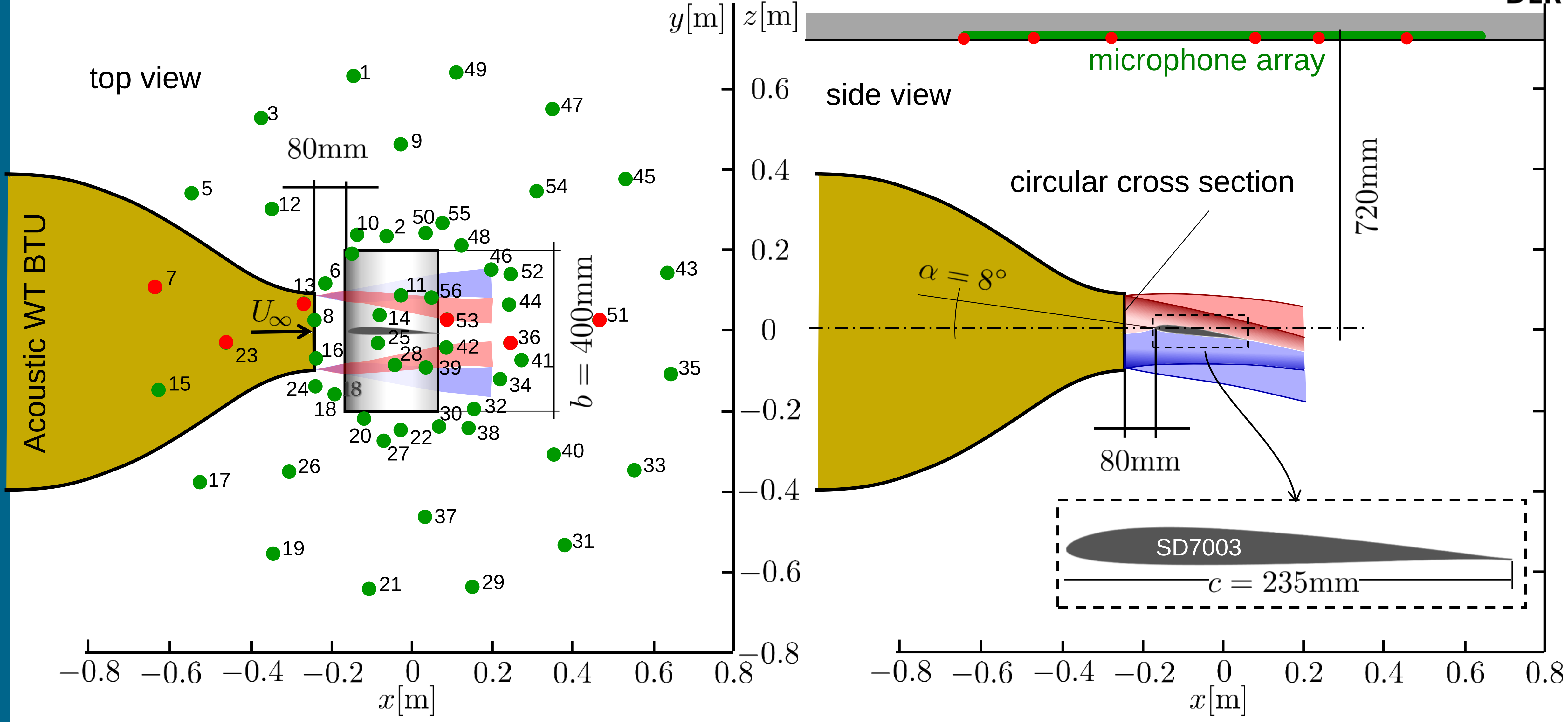
(Kirchhoff equation)

$$\hat{q}(\boldsymbol{x}) = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{p}_f(\boldsymbol{\xi})\; dS(\xi)$$

$\Leftrightarrow \hat{p}_S$ is physically realizable pressure field

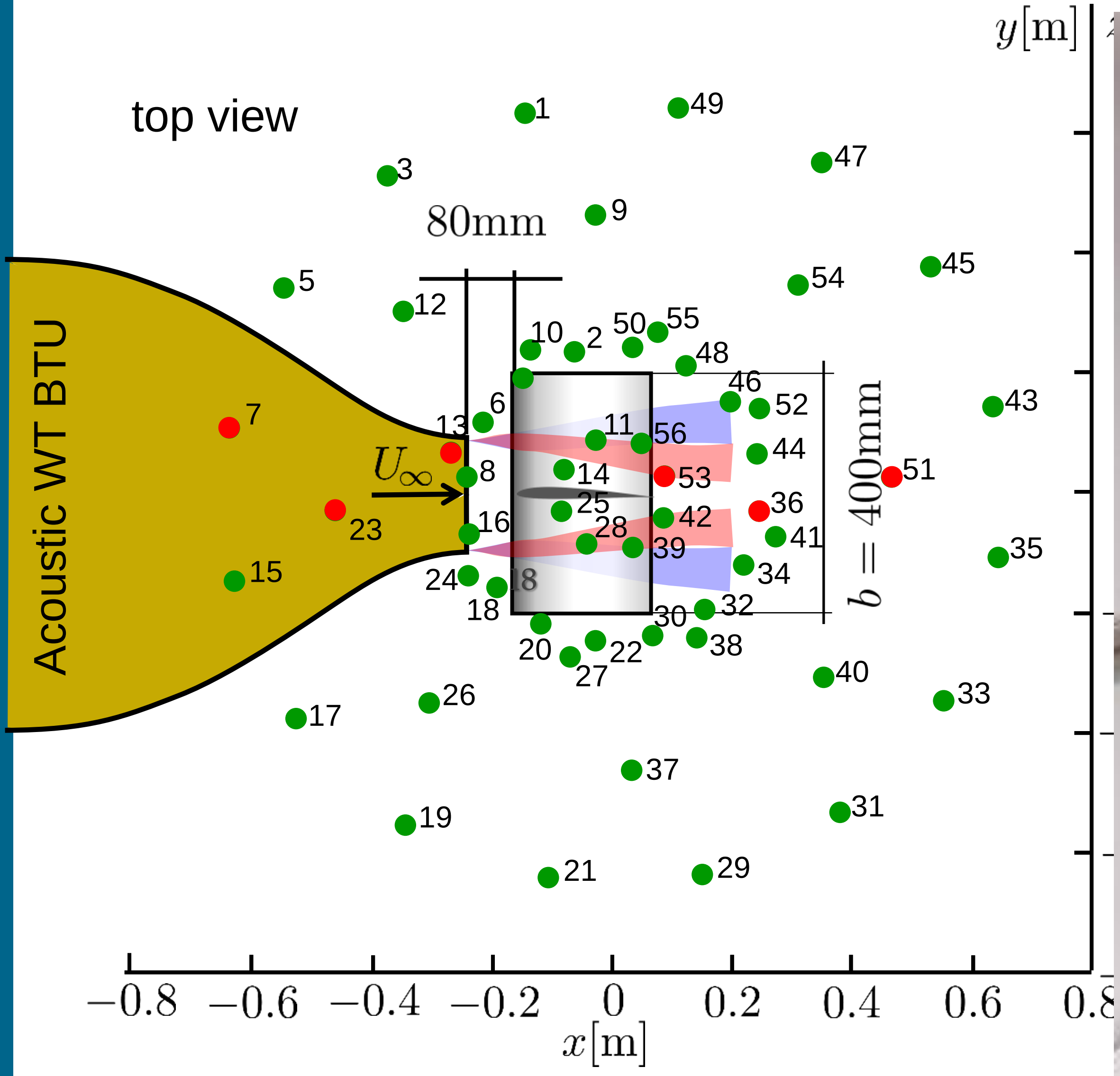
$$F_d[\hat{(.)}] = \frac{1}{2\pi} \fint_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r \cdot \boldsymbol{n}}{r^2}\hat{(.)}\; dS(\xi)$$

Test case airfoil edge noise



Courtesy of ebmpapst

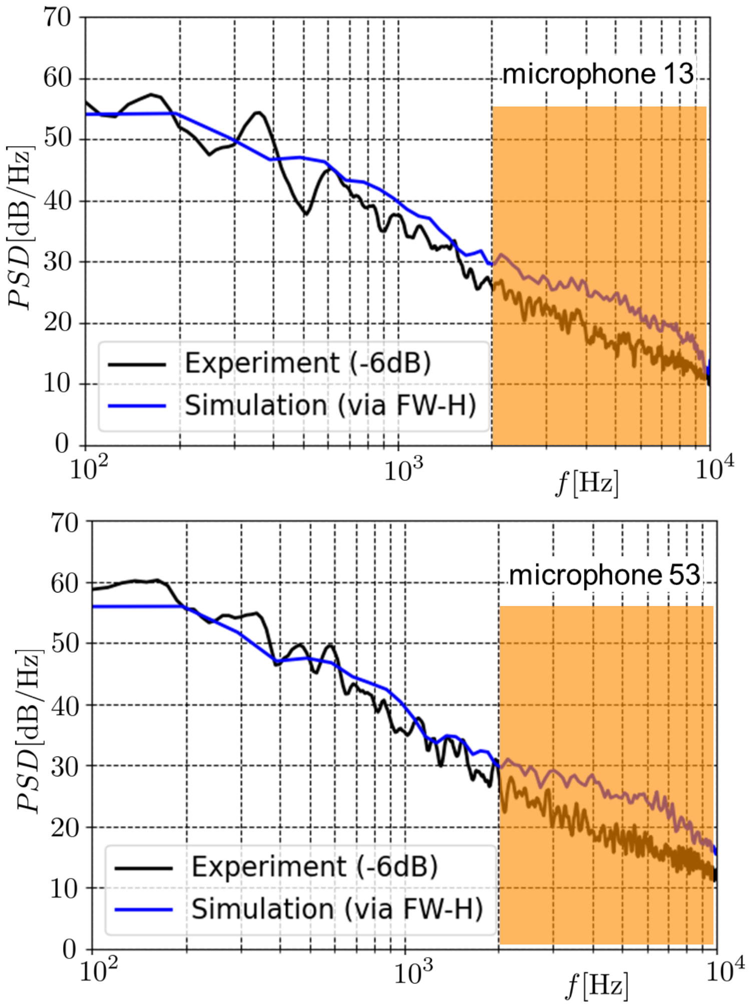
Test case airfoil edge noise

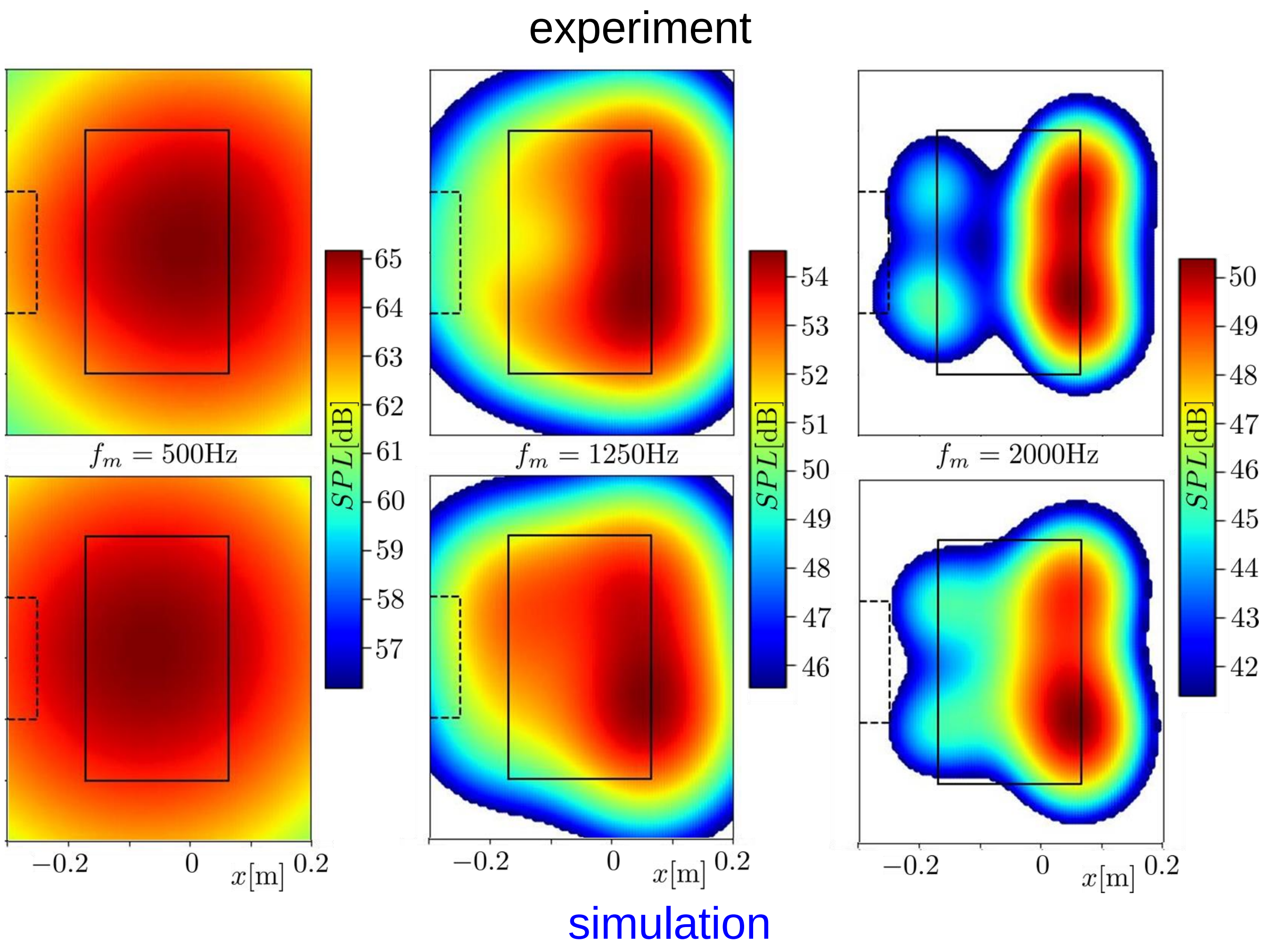


Courtesy of ebmpapst

Test case airfoil edge noise – simulation data base

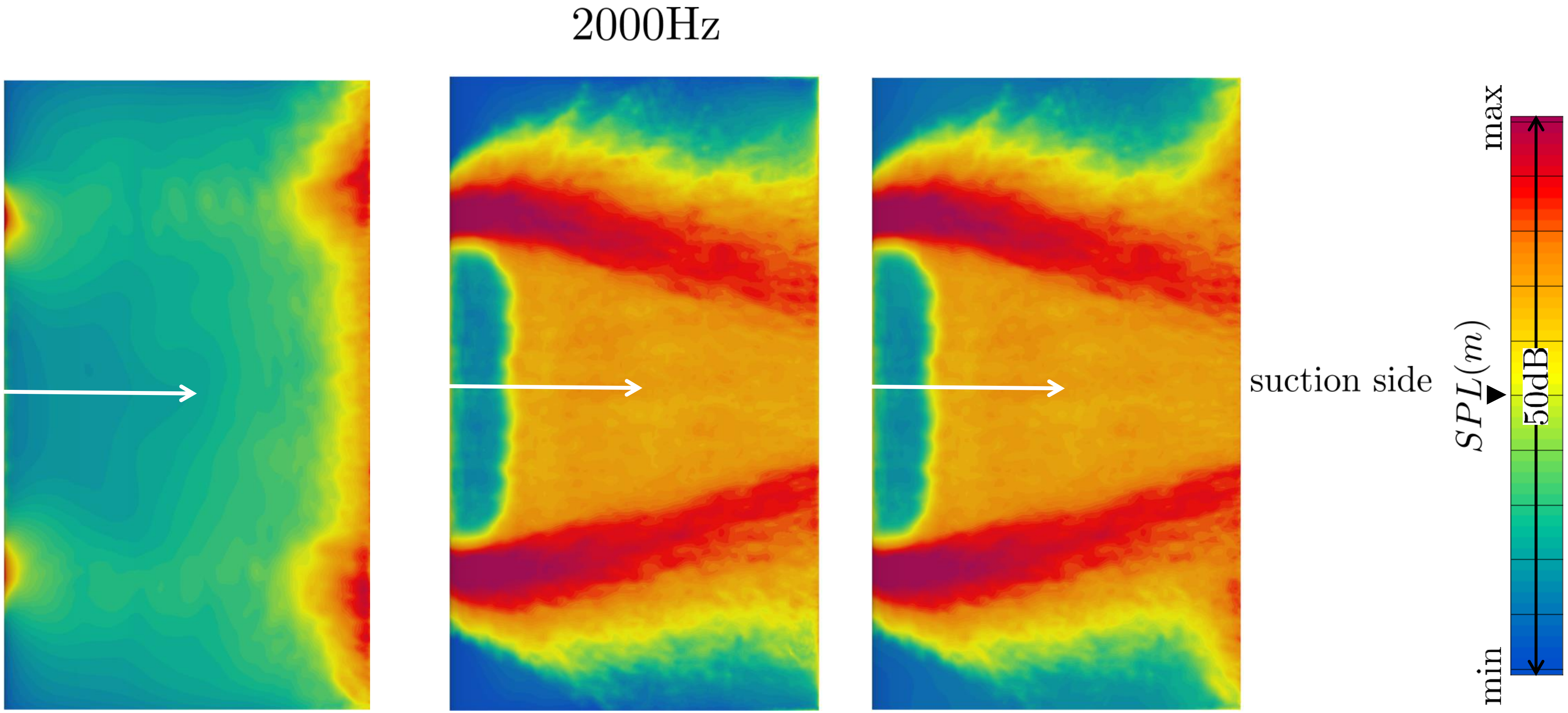
SRS/FW-H results, 23M polyeder cells, Siemens Star-CCM+, courtesy of ebm-papst





Courtesy of ebmpapst

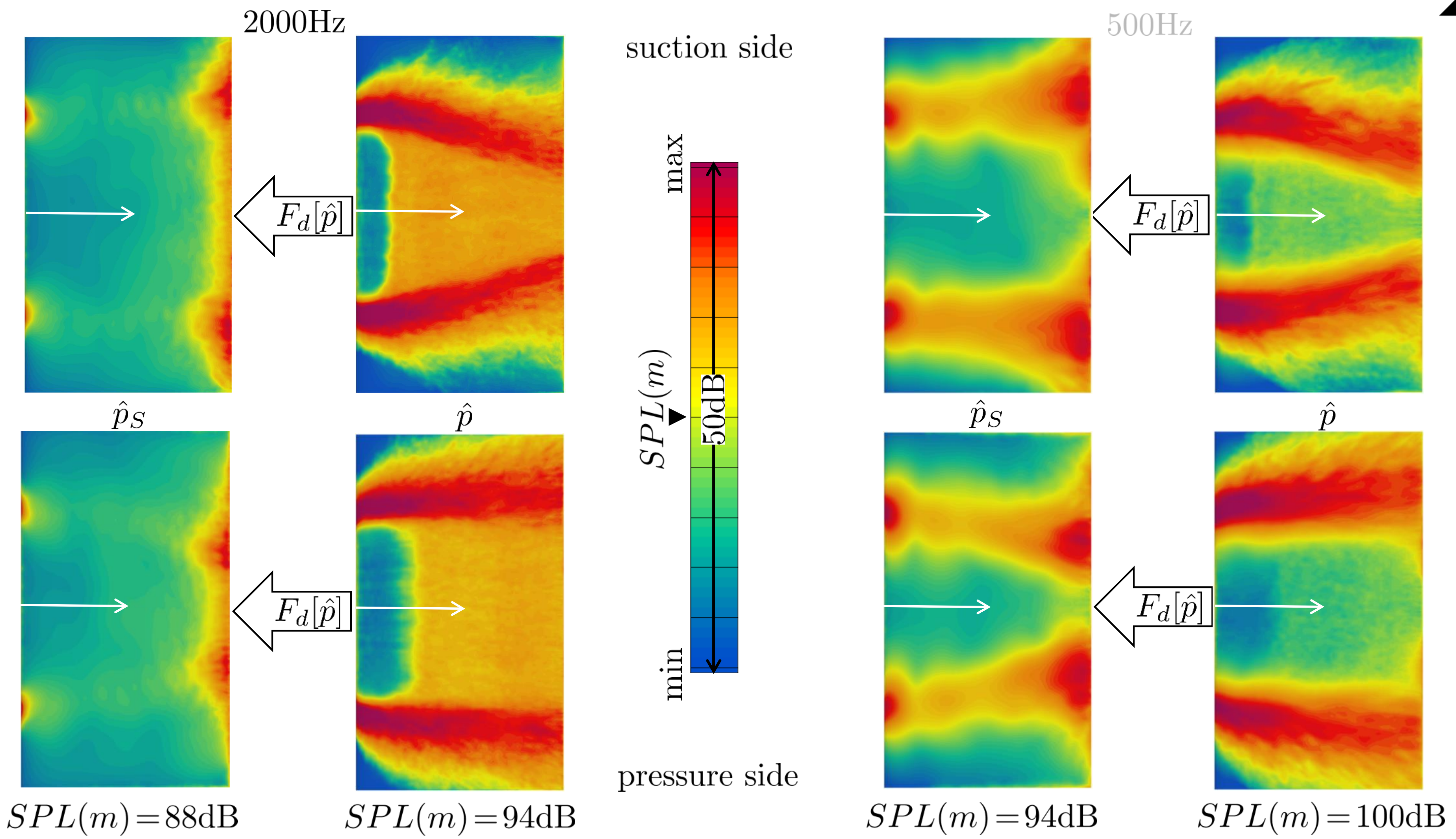
Results: acoustic surface pressure $\hat{p}_S$



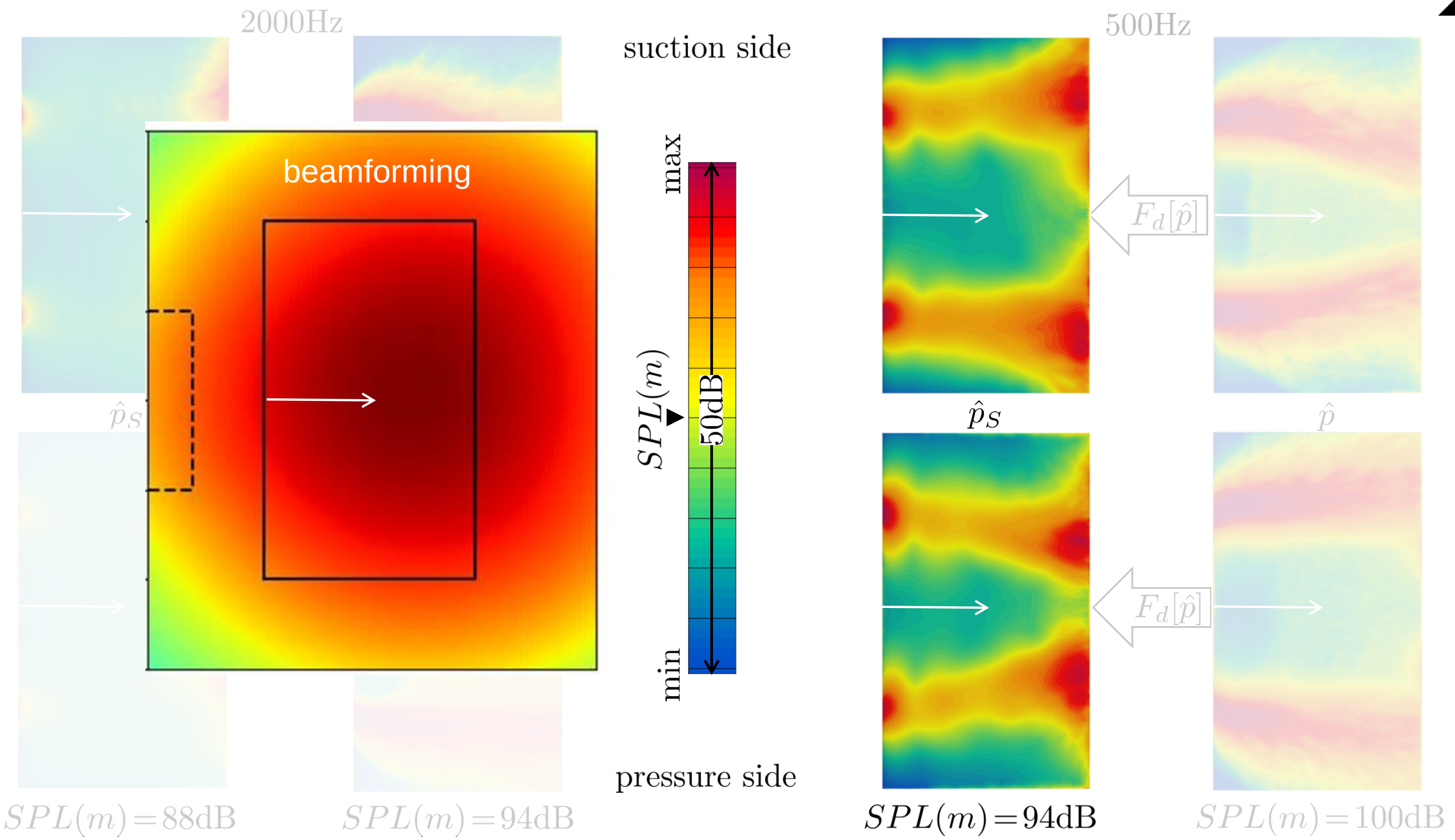
$$\hat{p}_S = \hat{p} - 2 \times \hat{p}_f$$

$SPL(m) = 88\text{dB}$ $SPL(m) = 94\text{dB}$

Results: acoustic surface pressure $\hat{p}_S$

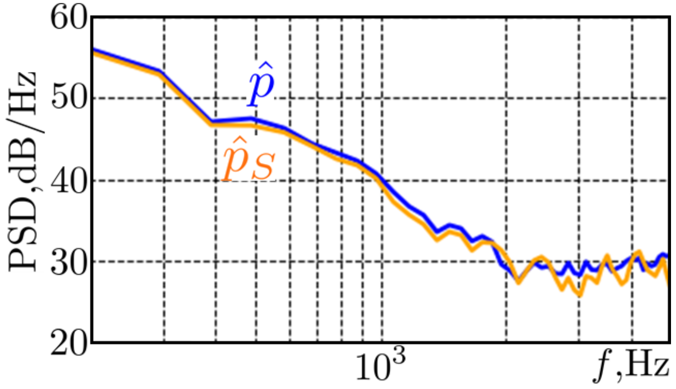


Results: acoustic surface pressure $\hat{p}_S$



Concept validation – acoustic surface pressure

Does $\hat{p}_S$ carry the source information of the original surface pressure $\hat{p}$?



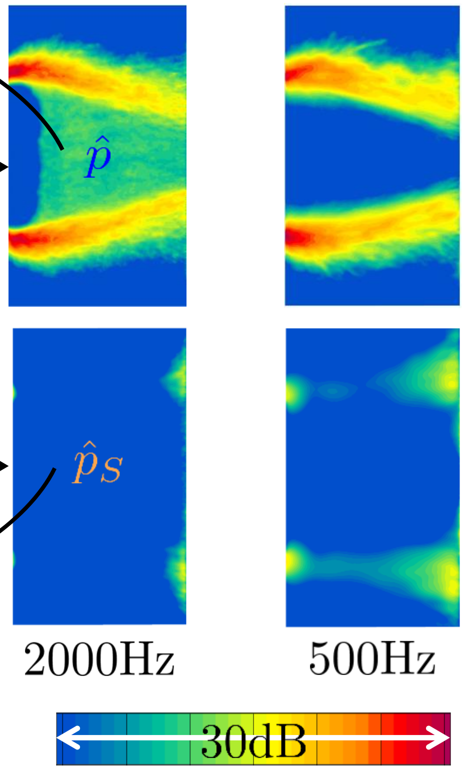
$$\hat{p}(\boldsymbol{x}) = \hat{p}_f + \frac{1}{4\pi}\int_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r\cdot\boldsymbol{n}}{r^2}\hat{p}(\boldsymbol{\xi})\; dS(\xi)$$

negligible in ff for low M

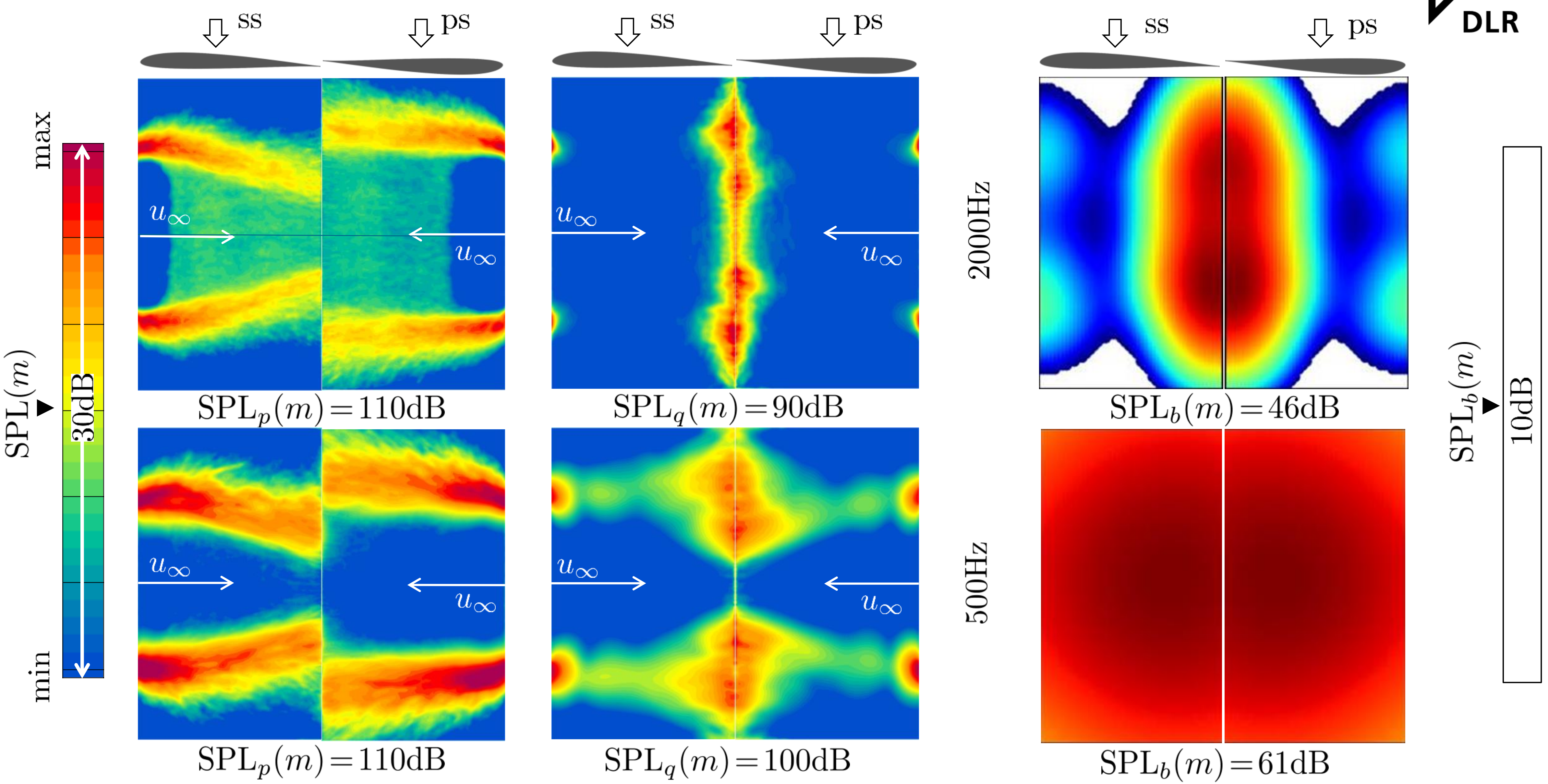
$$\hat{p}_S(\boldsymbol{x}) = \hat{q} + \frac{1}{4\pi}\int_{\partial V_B} \exp(-ikr)(ikr+1)\frac{\boldsymbol{e}_r\cdot\boldsymbol{n}}{r^2}\hat{p}_S(\boldsymbol{\xi})\; dS(\xi)$$

u_∞

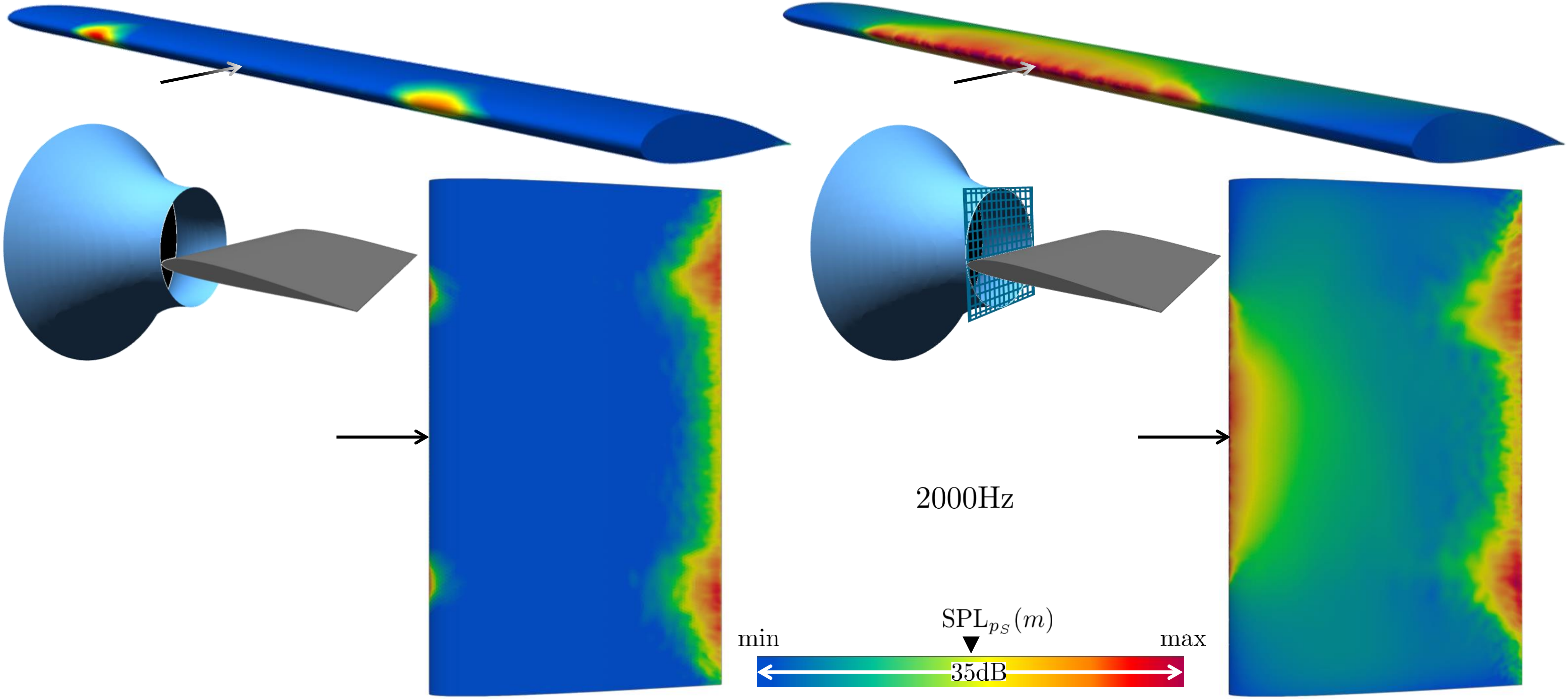
u_∞



Summary: pressure $\hat{p}$ ⇨ surface source $\hat{q}$ vs. beamforming $\hat{b}$

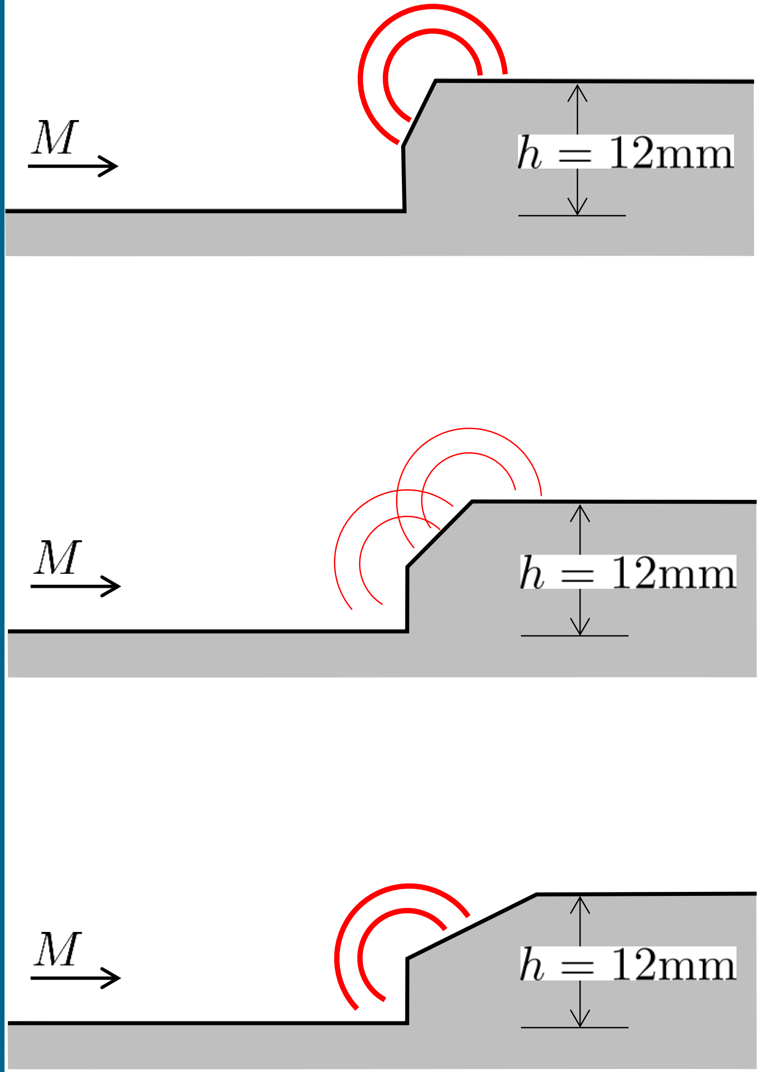


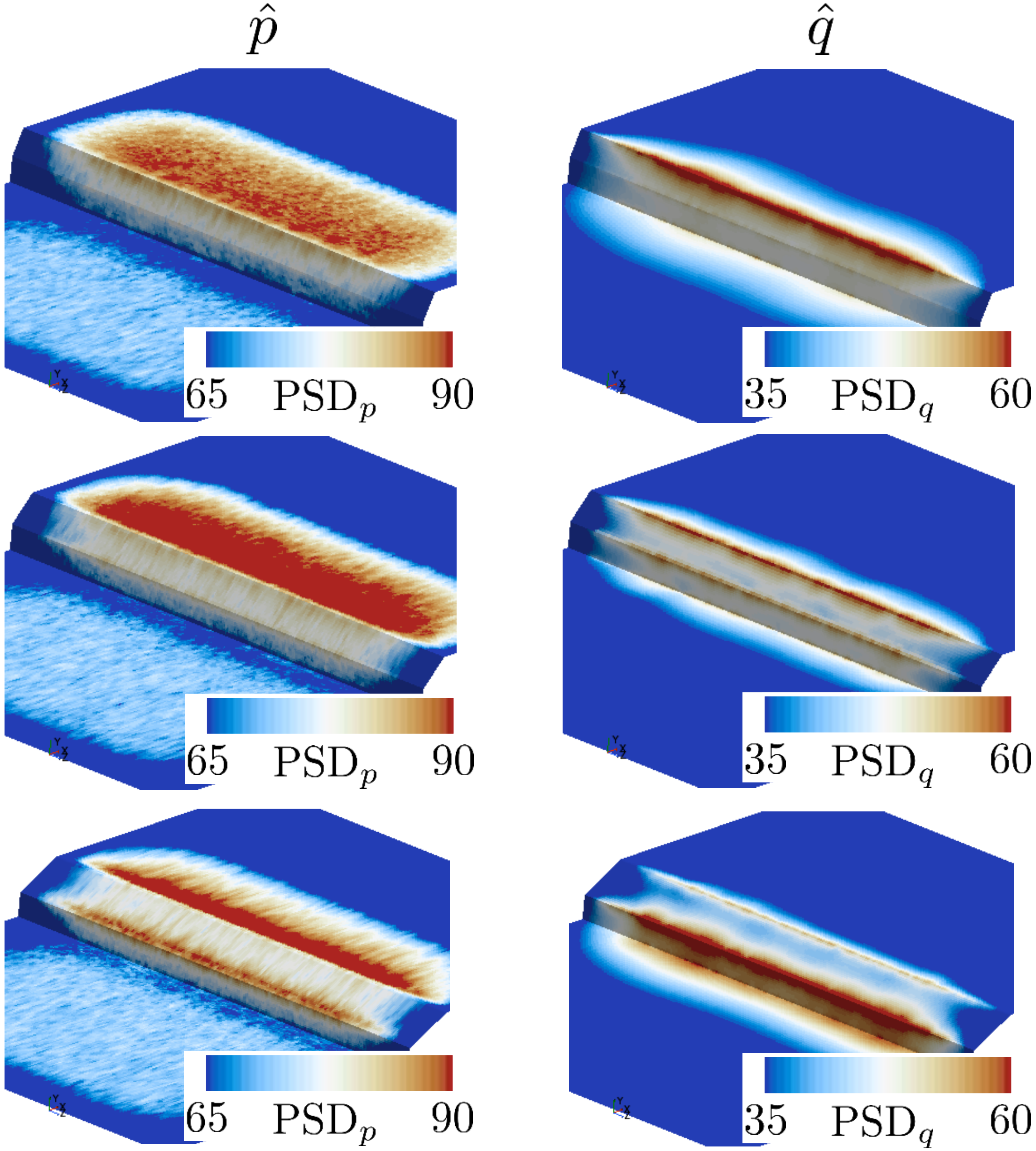
Leading edge noise from inflow turbulence - $\hat{p}_S$



Some more edges…

DLR





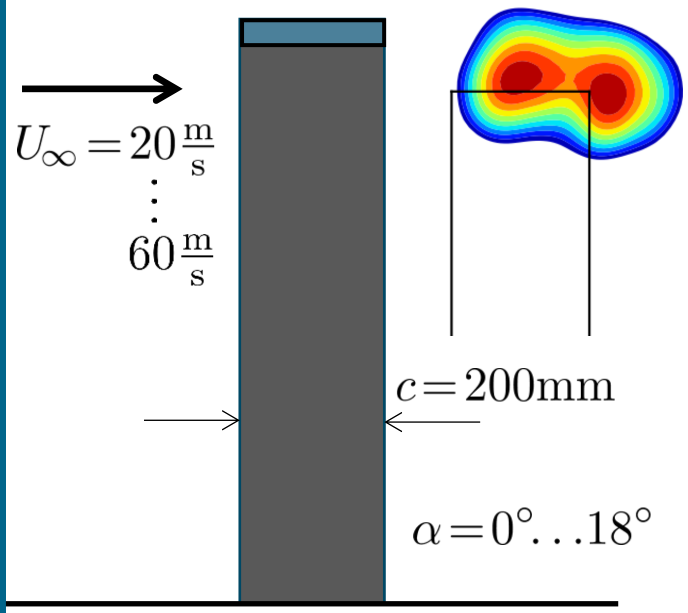
$Re_h = 30000$
$M = 0.11$
4000Hz

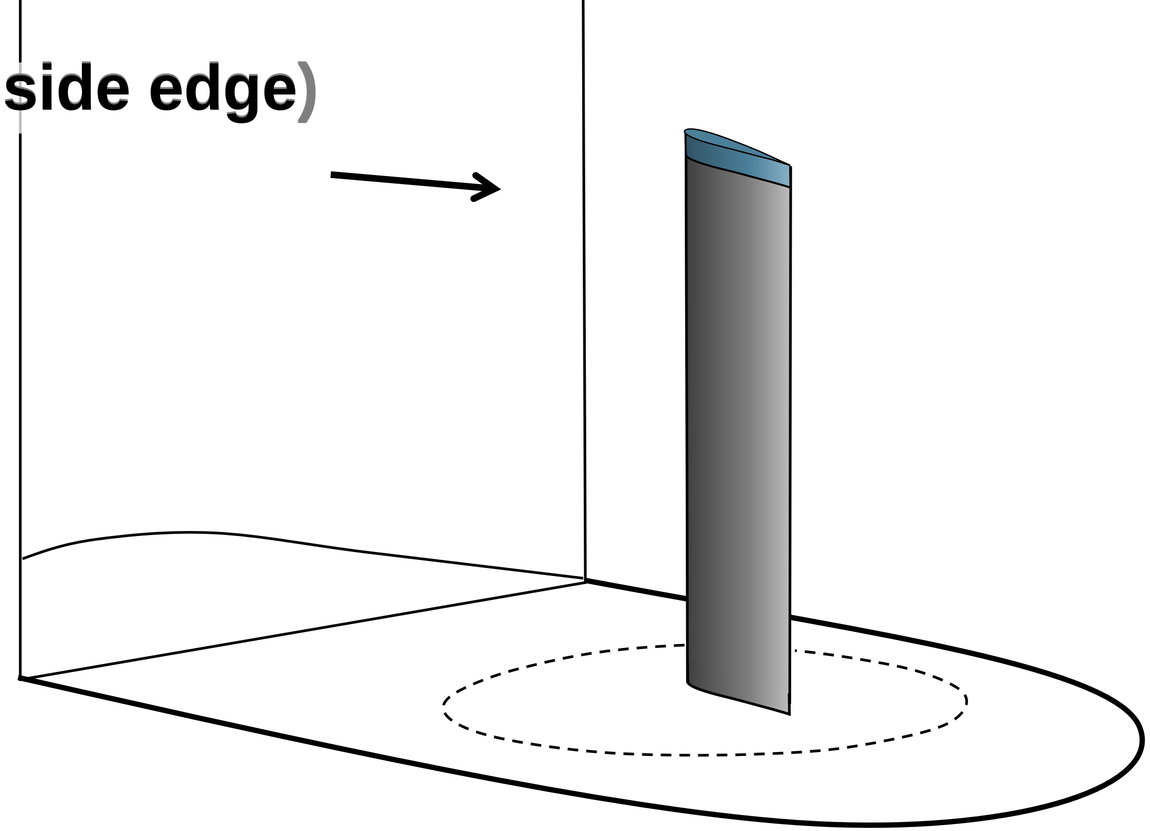
acoustically compact up to $\approx 28\text{kHz}$!

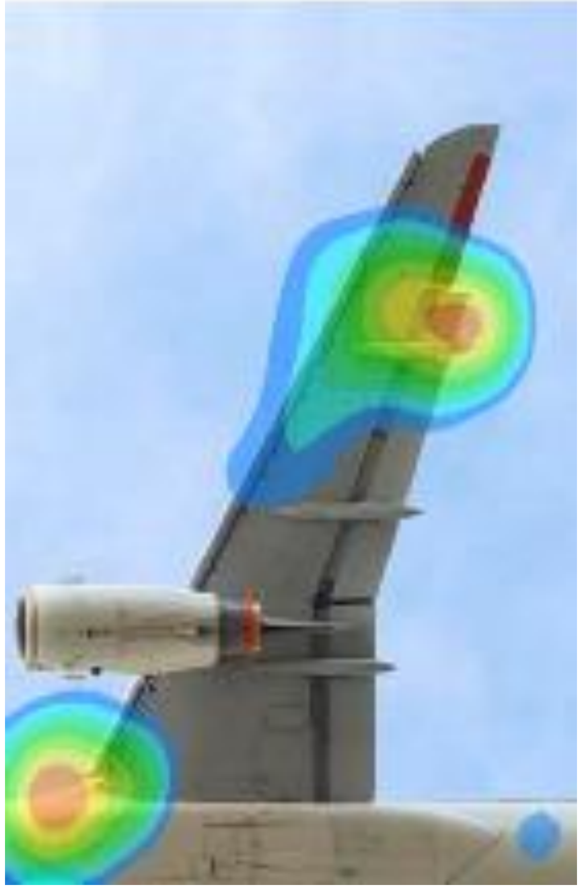
Courtesy of Philipp Uhl

Mercedes-Benz

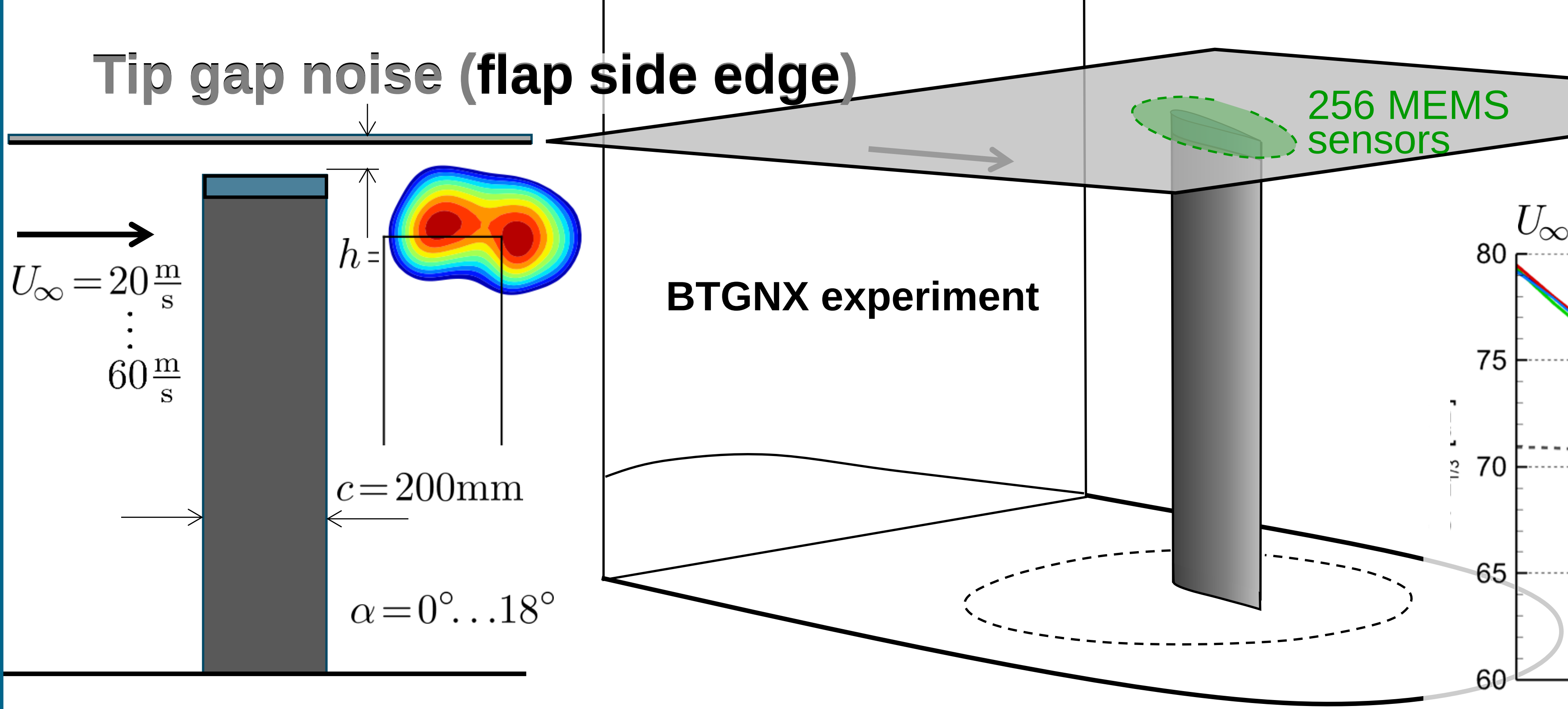
Tip gap noise (flap side edge)

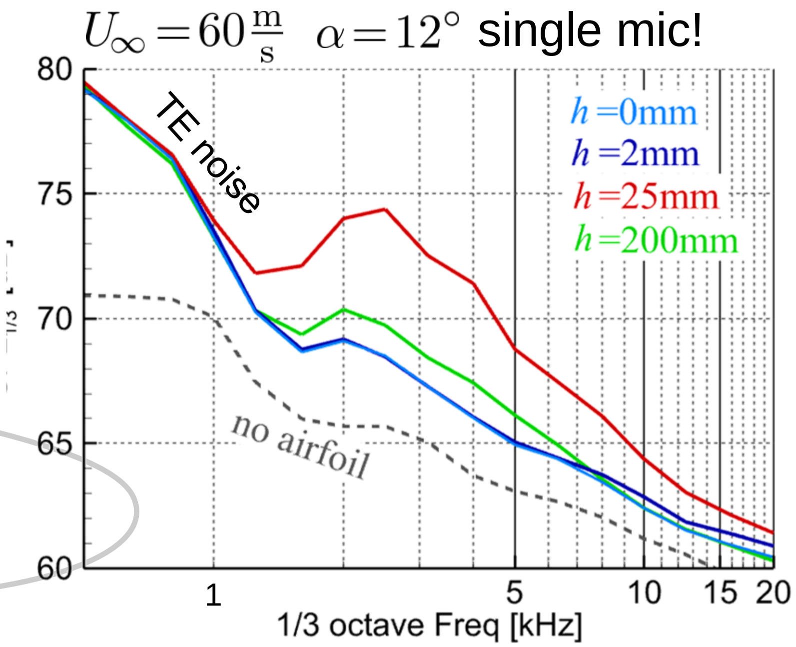




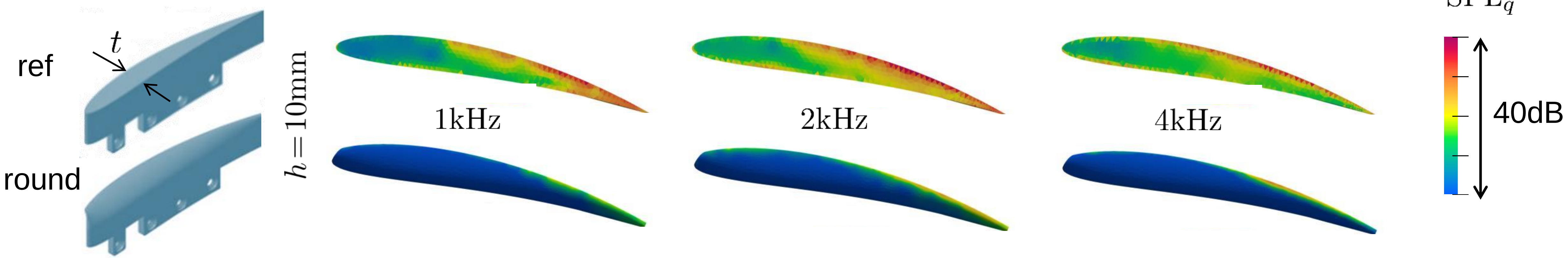


Tip gap noise (flap side edge)



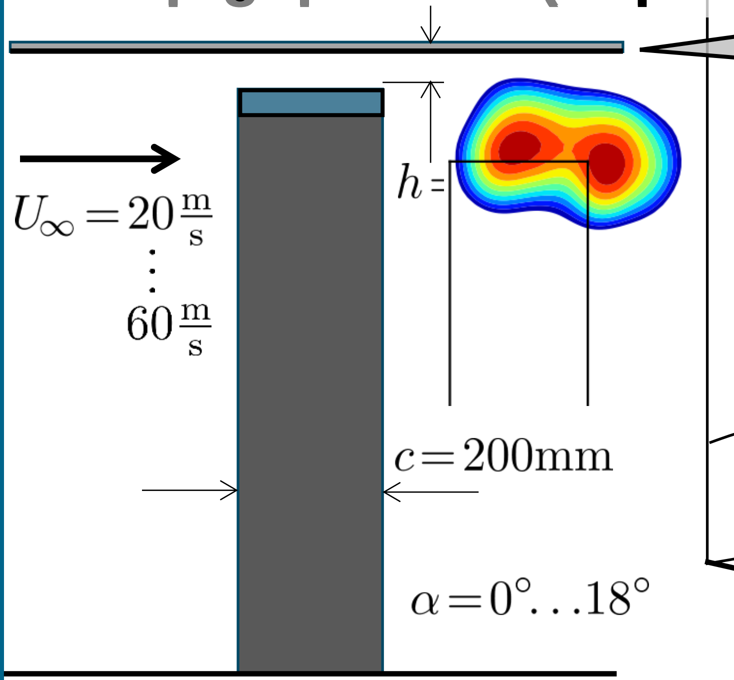


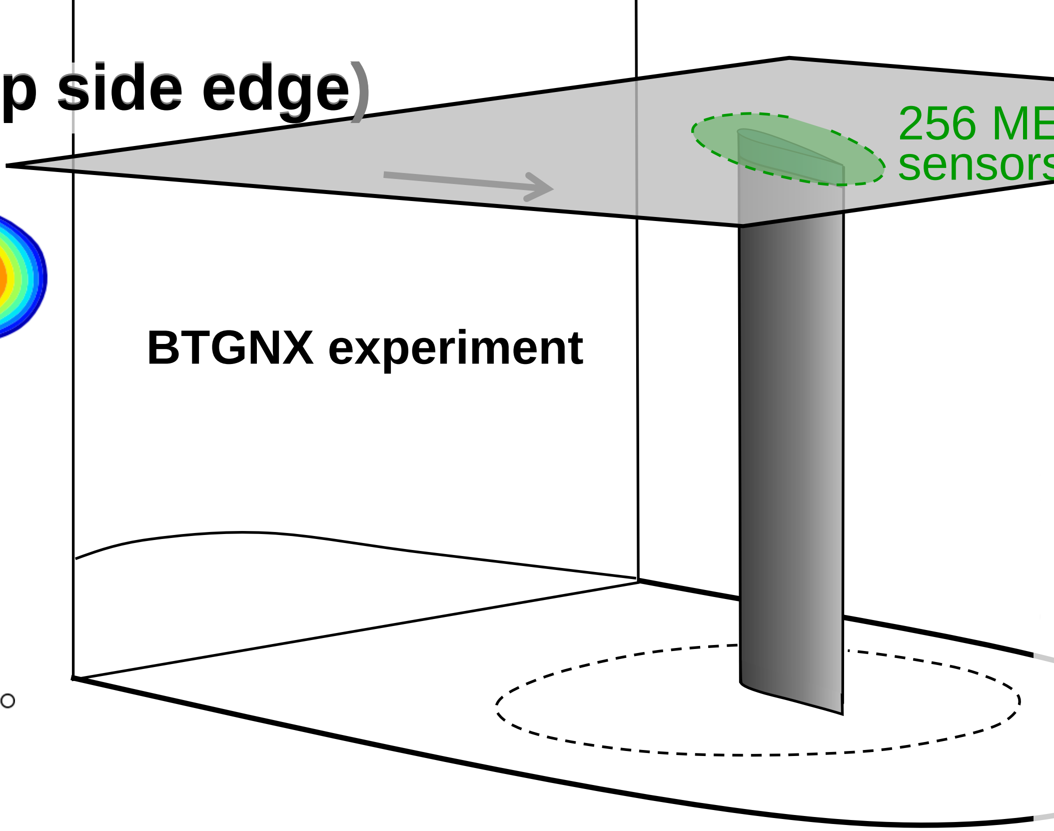
SRS simulation → localization $f(\mathrm{He}_t = 1) \simeq 18\mathrm{kHz}$

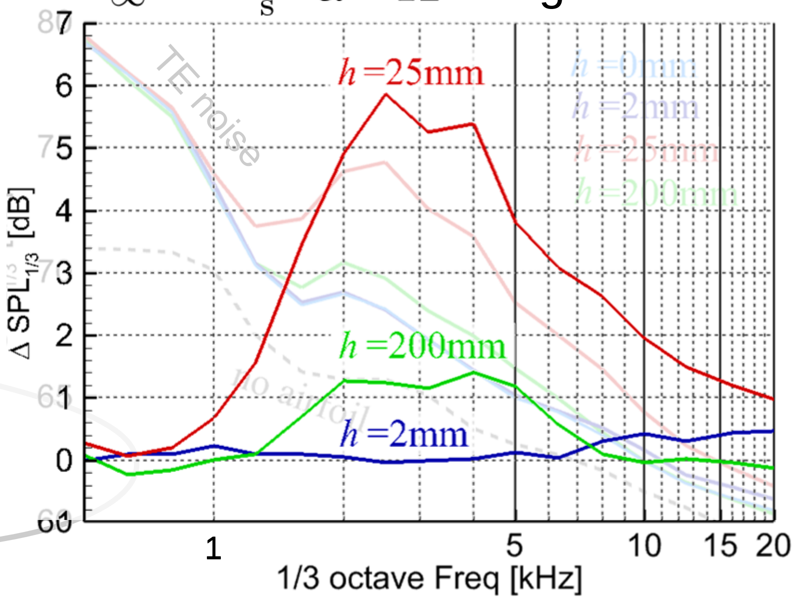


computation: courtesy of V. Lebedev, ebmpapst 2024

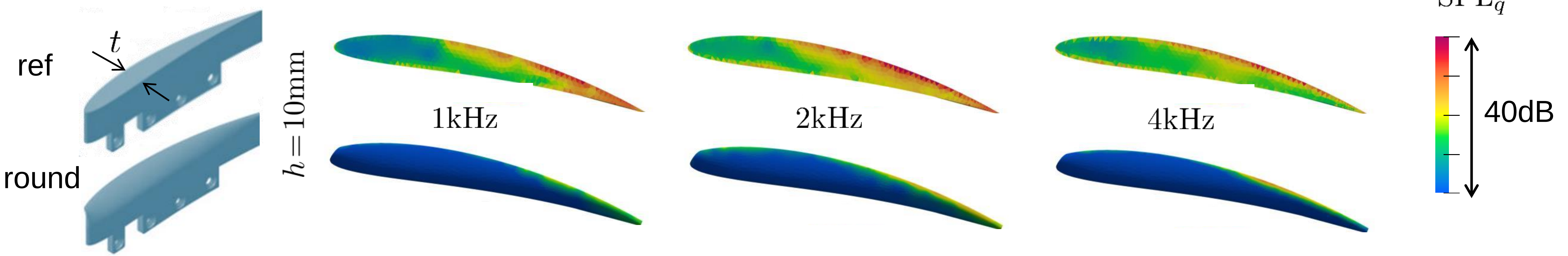
Tip gap noise (flap side edge)





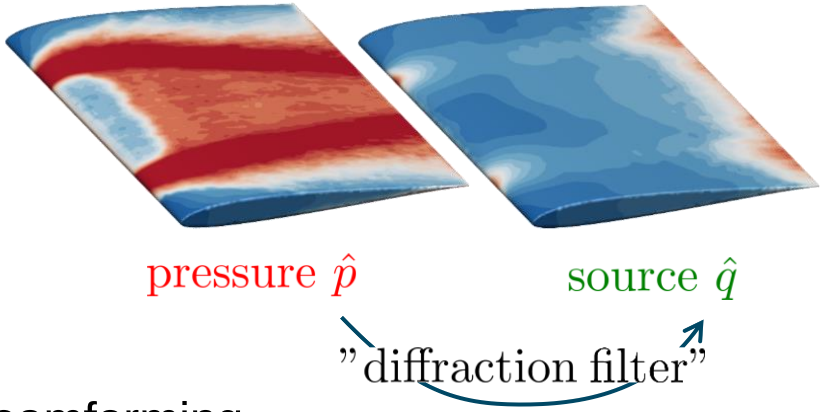


SRS simulation → localization $f(\mathrm{He}_t = 1) \simeq 18\mathrm{kHz}$

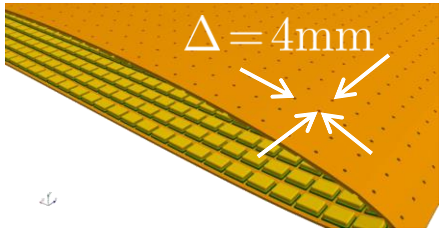


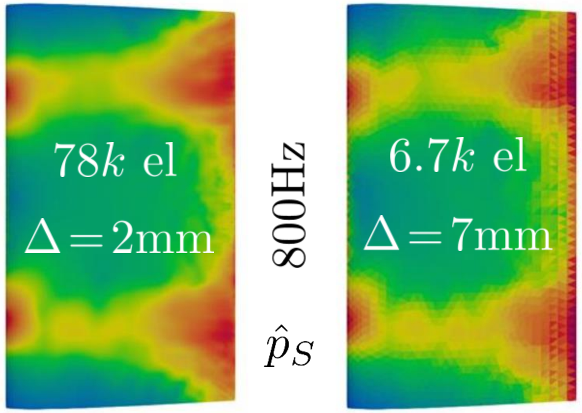
computation: courtesy of V. Lebedev, ebmpapst 2024

Conclusions on source localization



- surface source quantity $\hat{q}$ enables source identification w/o beamforming
- localization first principles based on the hypothesis, that reflection does not generate sound
- source quantity $\hat{q}$
  - super resolution
  - objective (not depending on observer, nor acoustic installation)
  - natural basis for aeroacoustic cost function (optimisation)
- given flush surface mounted MEMS technology $\hat{q}$ could be determined experimentally





Summary & Conclusions

- **demonstrated that aircraft noise may be reduced at the source**
  - know, what to do (1st set of dominant sources successfully treated by „1st gen“ NRTs)
- **any further improvement? → yes!**
  - 2nd set of dominant sources identified, sucessfully treated by „1st gen“ NRTs
  - Next: go from „1st gen“ to optimum (2nd gen) NRTs
    - aero-shaping (in sense of MDO)
    - materials (best placing, inverse design of meta materials, adaptive/switchable)
    - active (steady flow control, ultimately unsteady source control ← MEMS-sensors/actuators+num. simulation+AI)
- **How?**
  - Exploit today‘s (num./exp.) capabilities to generate relevant detailed/high quality data
  - Make sense out of data; use **relevant source quantities**, physical + correlation based models with ordinary brains and AI-brains.
- aeroacoustic problems in a/c and ventilation fans very similar
  - **learn from each other (→ meet on conferences like this)**

Thank you !