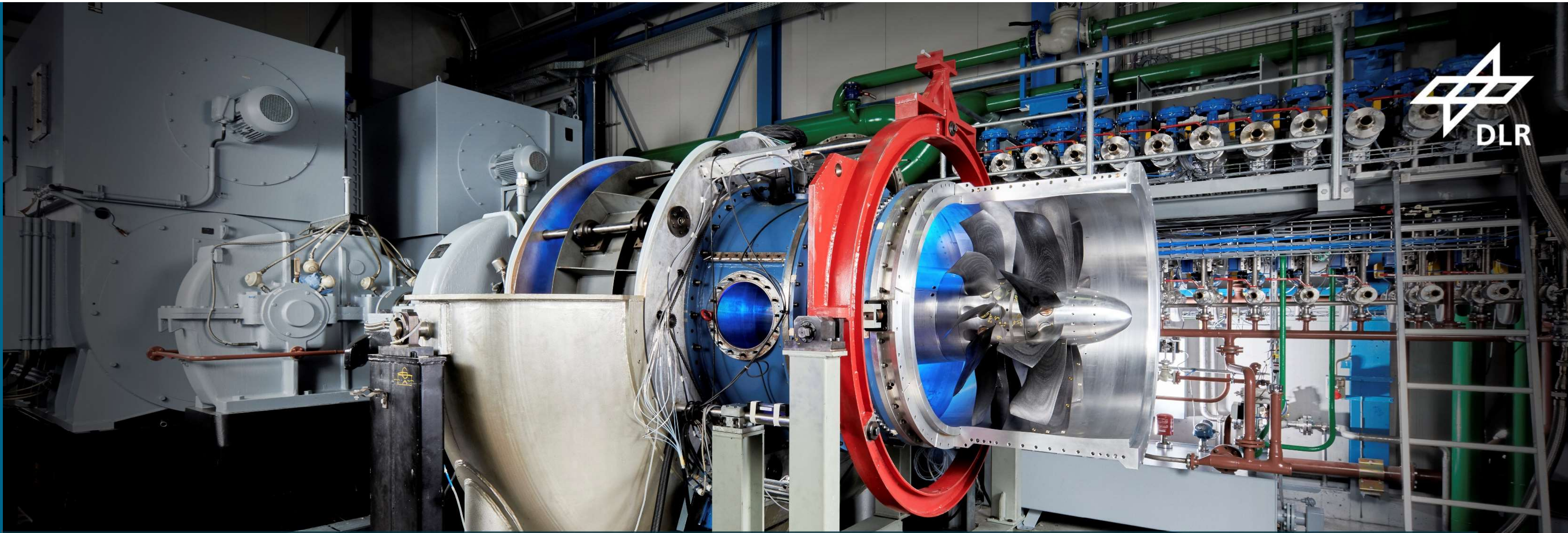
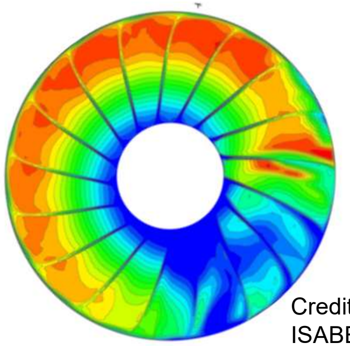


DJINN-ENODISE Conference, Berlin, 22-24 Nov 2023

EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF BOUNDARY LAYER INGESTION ON TURBO-FAN NOISE GENERATION

Ulf Tapken[1], Robert Meyer[1], Lukas Klähn[1], Maximilian Behn[1], Timea Lengyel-Kampmann[2]
DLR Institute of Propulsion Technology, Engine Acoustics[1], Fan and Compressor[2]

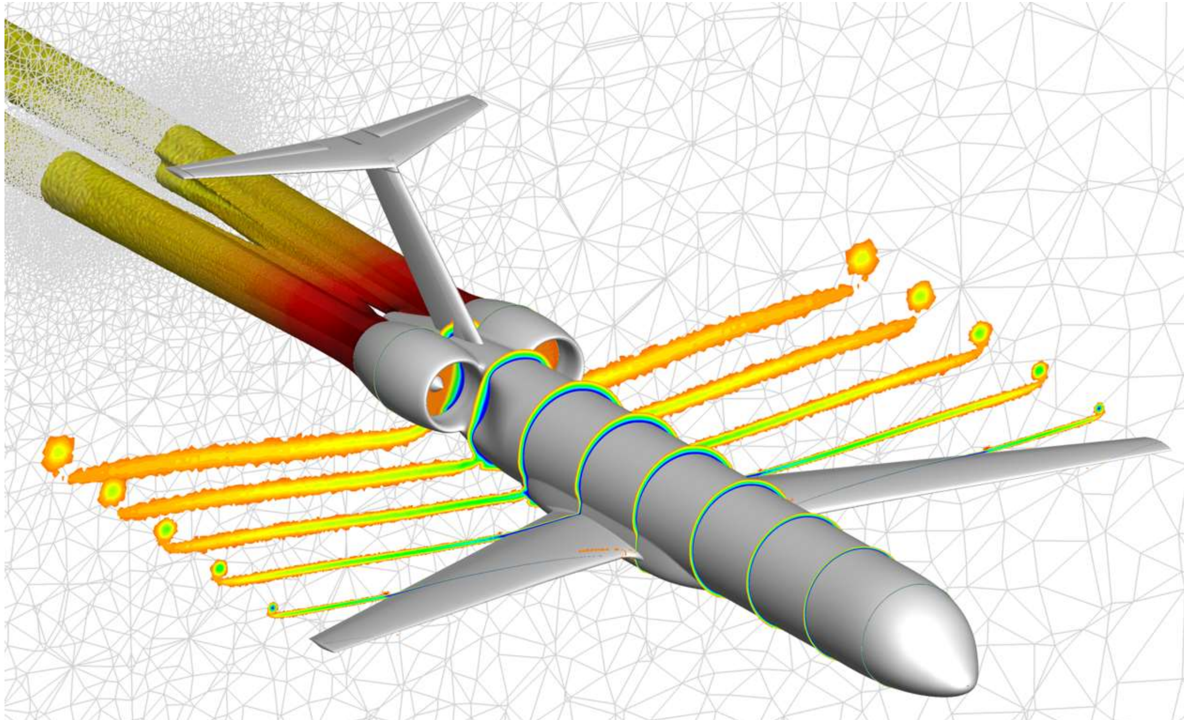
Impact of boundary layer ingestion on aeroengine fans



Credits: Schönweitz et al, ISABE-2015-22008

Fan blade experiences varying incident flow, leading to e.g.

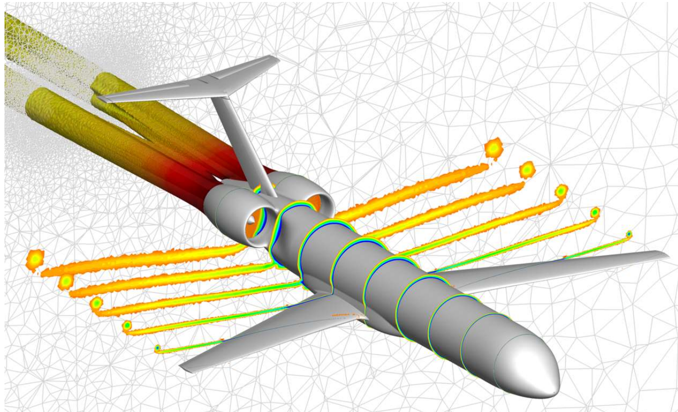
- reduced fan efficiency
- blade vibrations of low orders
- transient structural loads
- additional noise sources



DLR project AGATA^{3S} (2017-2022)

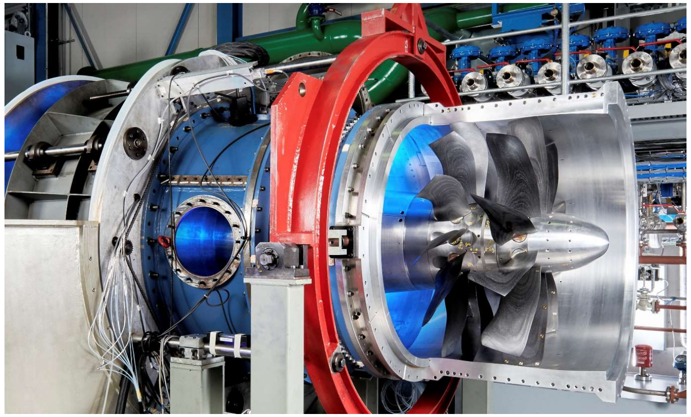
Modelling of aircraft and engine

Experiments under realistic conditions



test cases

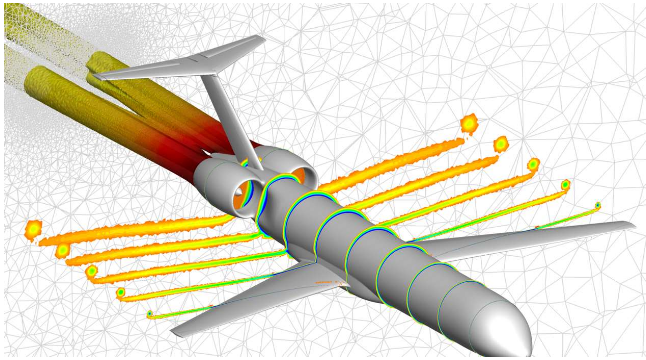
findings



- Institute of Propulsion Technology
  Engine Acoustics (Berlin), Fan and Compressor (Cologne), Engine (Cologne), Engine Measurement Systems (Cologne)
- Institute of Aeroelasticity
  Aeroelasticity of Turbomachinery (Göttingen)
- Institute of Structures and Design
  Design and Manufacture Technologies (Stuttgart)
- Institute of Aerodynamics and Flow Technology
  Transport Aircraft (Braunschweig), Technical Acoustics (Braunschweig)

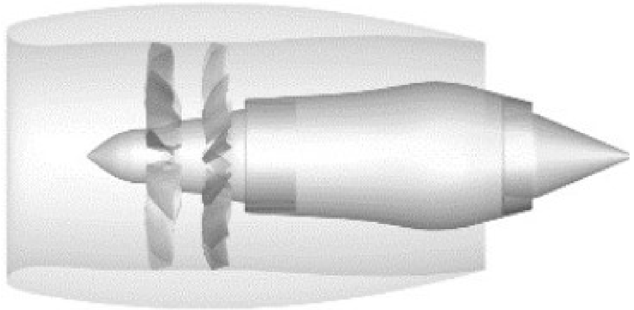
Derivation of representative BLI test cases

CFD airplane,
A320 type



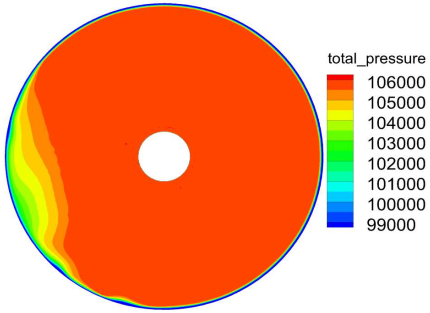
length	37.57 m
wing surface	122 m²
span width	34 m

UHBR engine,
CR turbo-fan

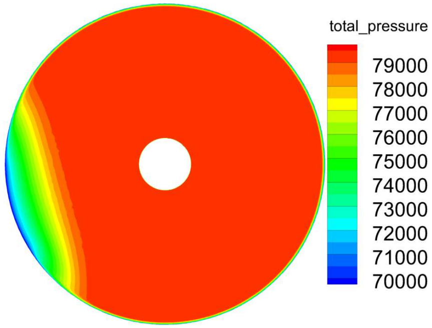


fan diameter	2.343 m
blade numbers	10/12
bypass ratio	17:1

embedding grade 30%, Take-Off

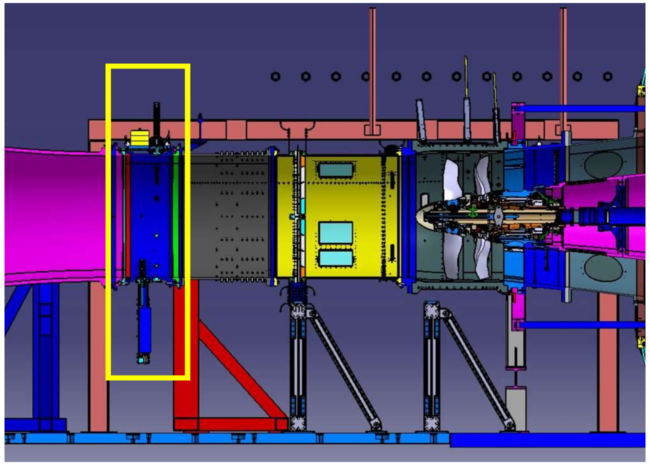


embedding grade 15%, Climb



Test bench and Fan rig

settling chamber	fan inlet and outlet	CRISPmulti (Counter Rotating Integrated Shrouded Propfan)



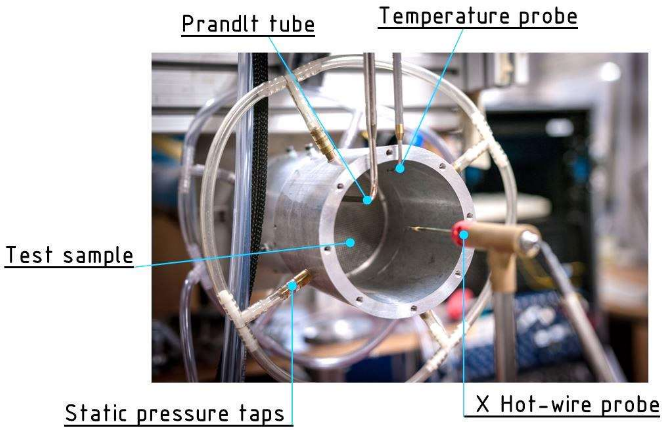
Multi-stage 2-shaft compressor test bench M2VP at DLR Cologne

carbon composite blades

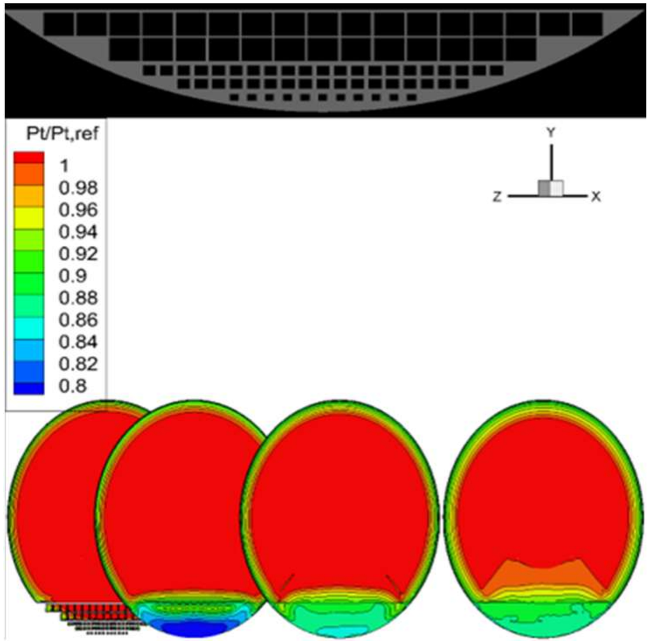
fan diameter	1 m
blade numbers	10/12
PR @ ADP	1.3
mass flow@ADP	159 kg/s

Development of inflow distortion device (IFD)

Testing of IFD effectiveness at high-speed windtunnel

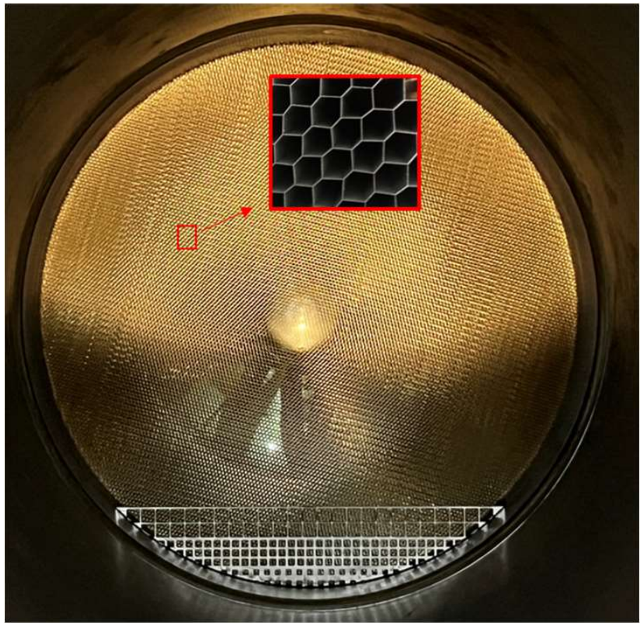


CFD optimization of fence perforation



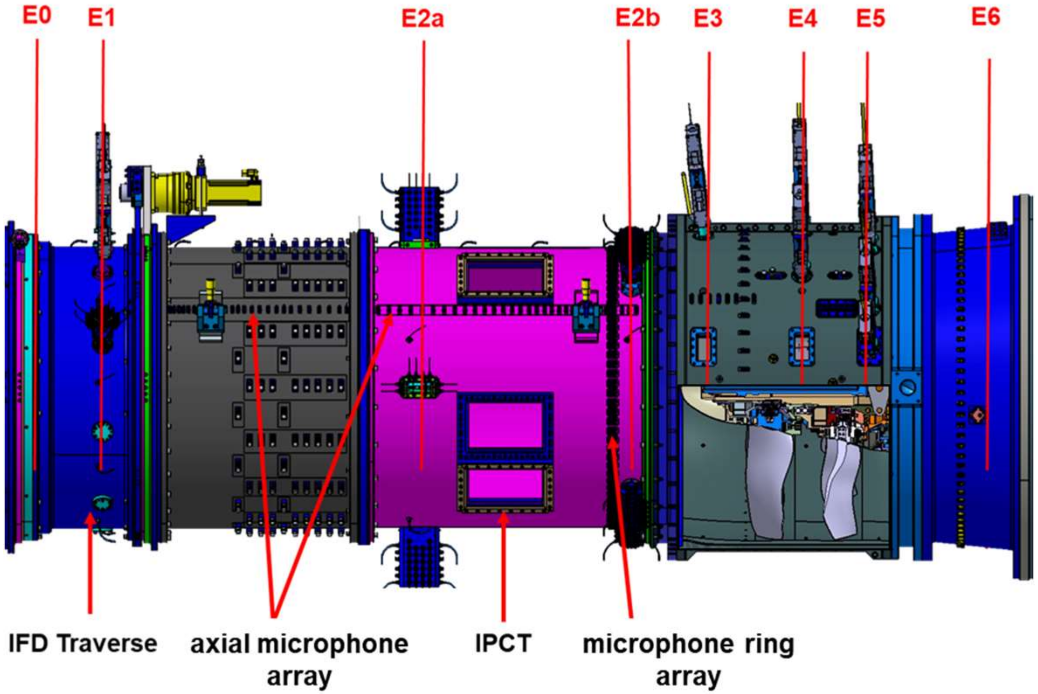
fence	p_{tot} probe	fan entry plane
x=0	x=1.333 m	x=2.5 m

Traversable distortion fence used at M2VP combined with honey comb



TEST CAMPAIGN 2022

Multi-disciplinary test campaign May-June 2022



Aerodynamics

- total pressure rakes,
  total temperature rakes,
  boundaray layer rakes
- 5-hole probes,
- instationary pressure sensors
- hotwire anemometry
- particle image velocimetry (PIV)

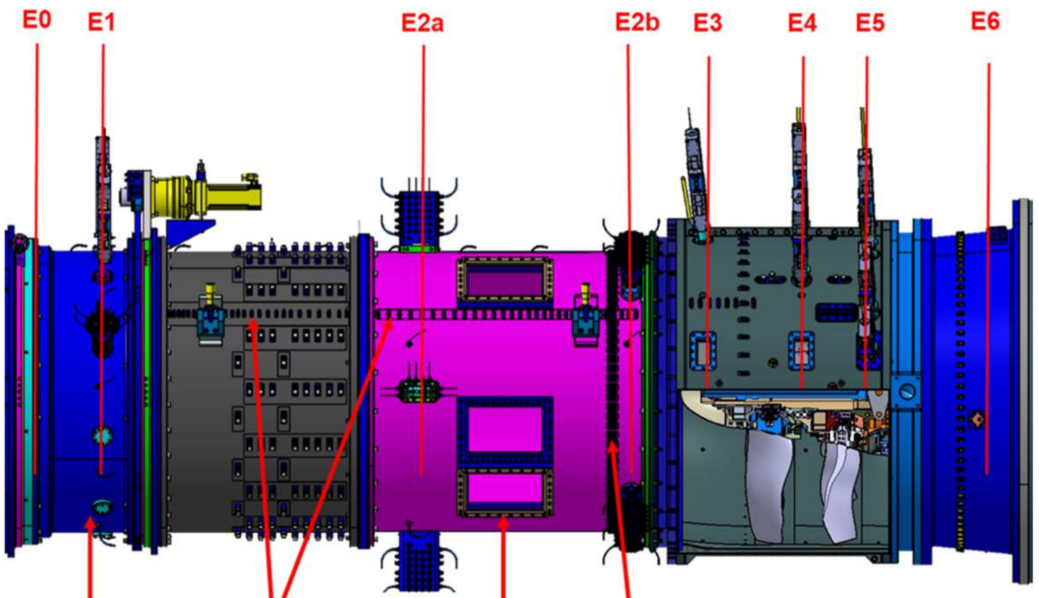
Aeroelastics, Structure

- Image Pattern Correlation Technique
- DMS, BSSM

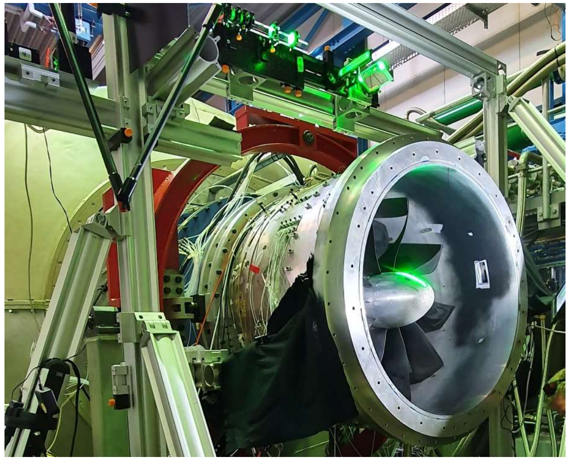
Acoustics

- microphone arrays

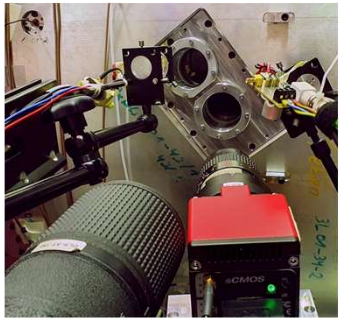
Multi-disciplinary test campaign May-June 2022



Stereo PIV of mean flow

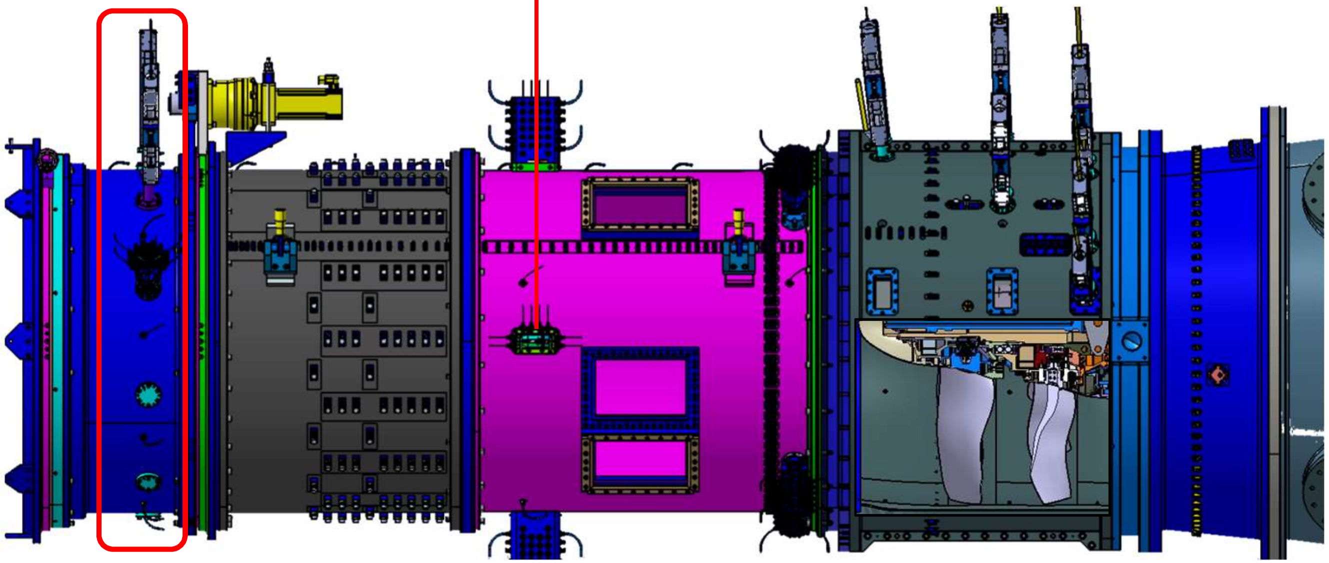


Optical measurement of blade displacements and deformations



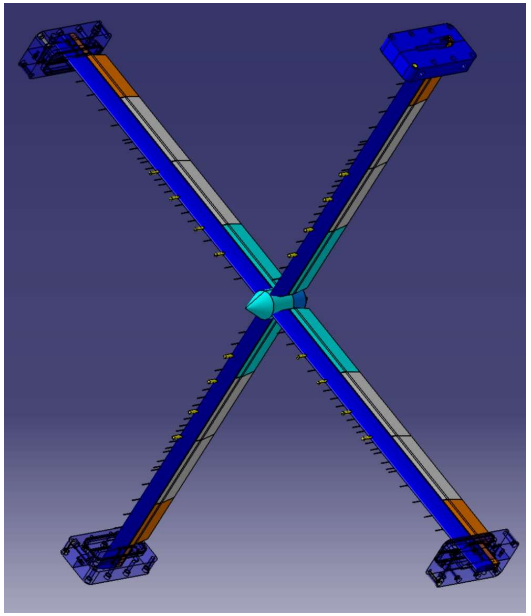
Measurement of total pressure distribution of fan inflow

E2a

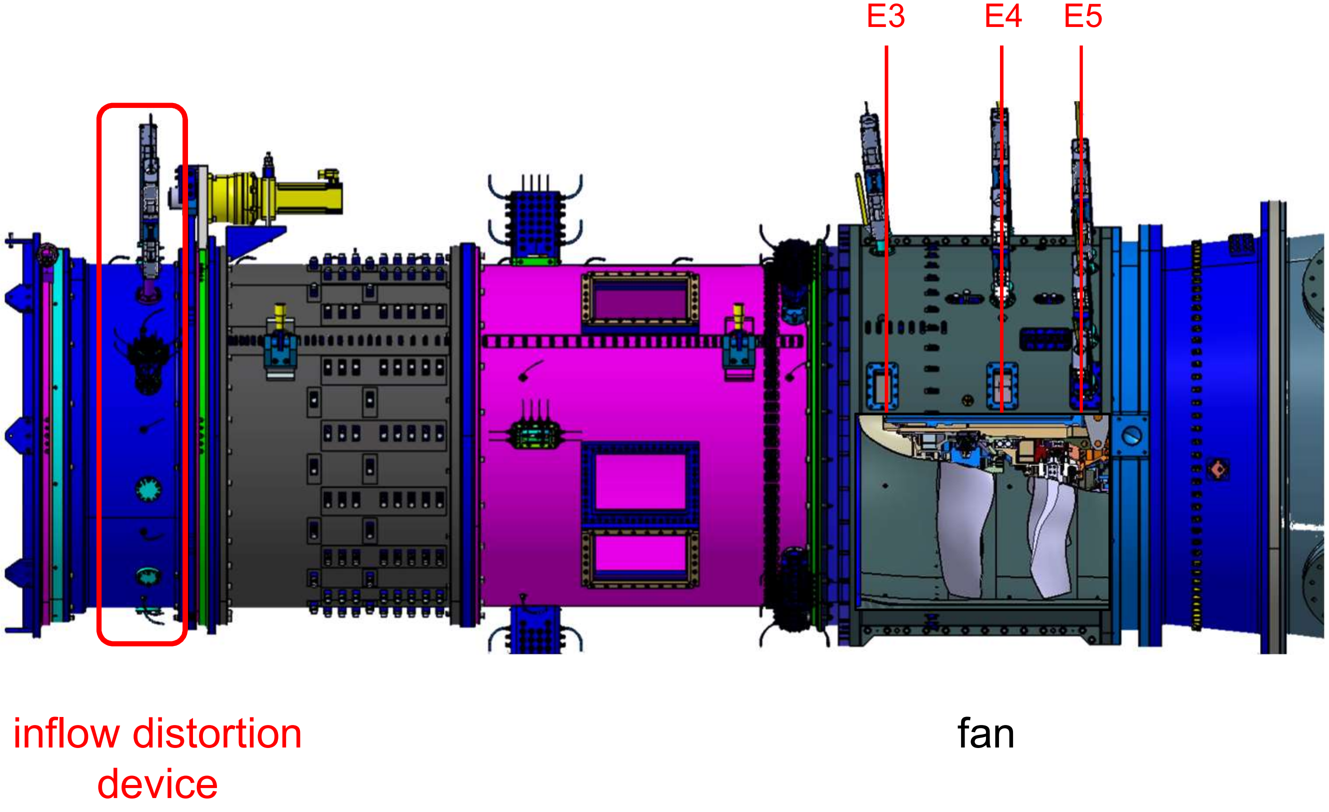


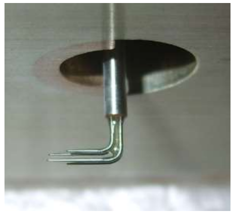
inflow distortion device

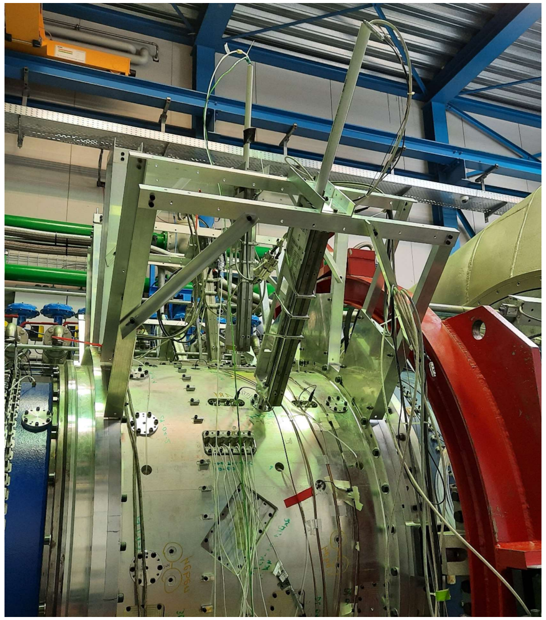
fan



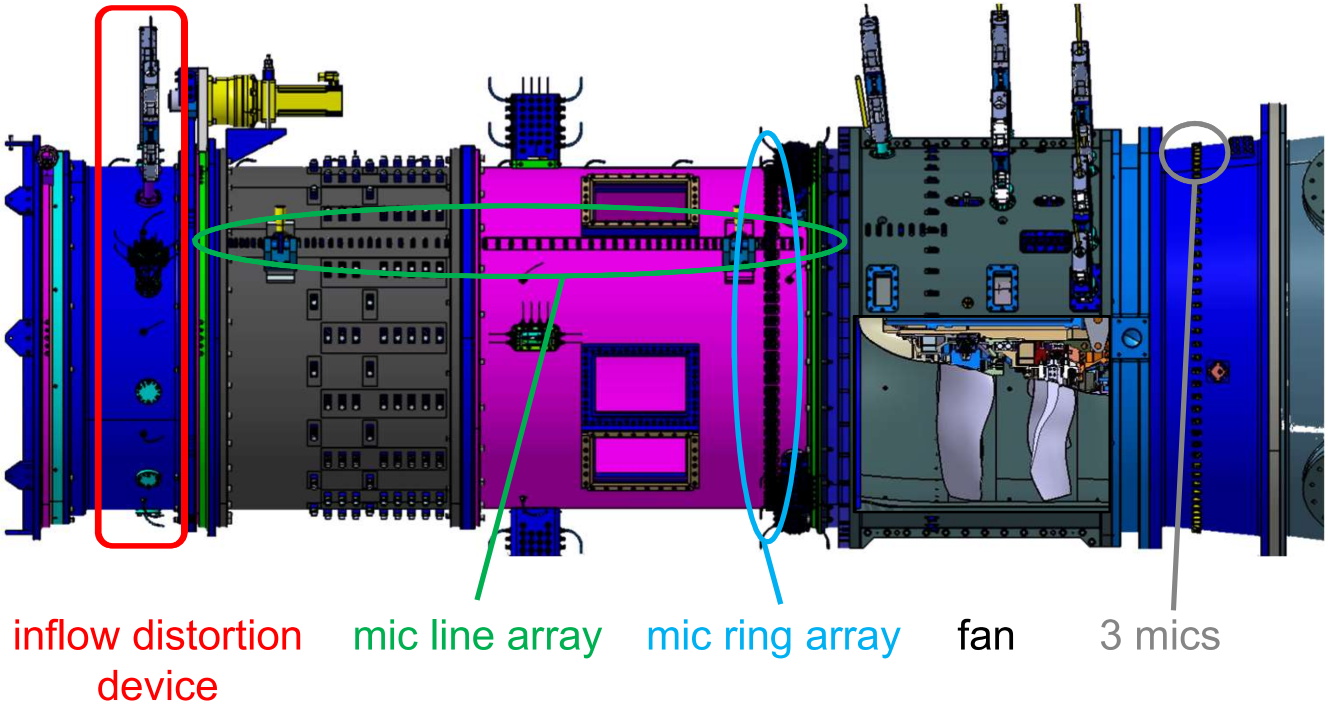
Hotwire measurements upstream / interstage / downstream of fan

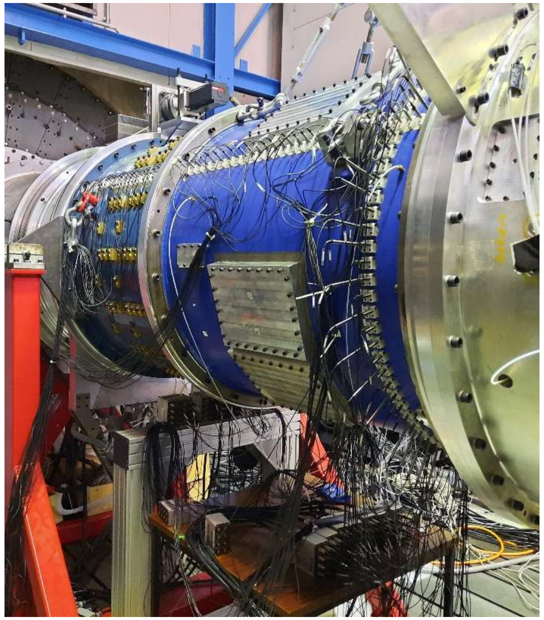






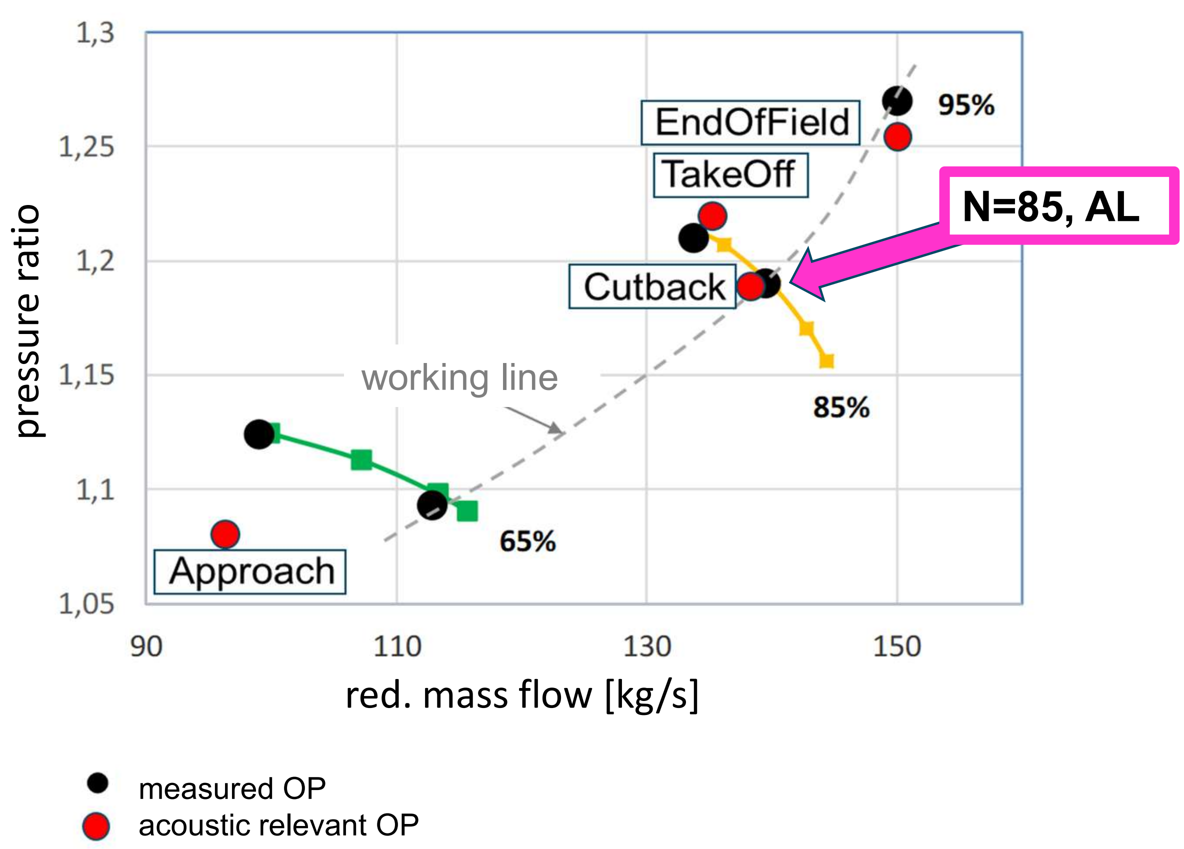
Acoustic measurements upstream / downstream of fan



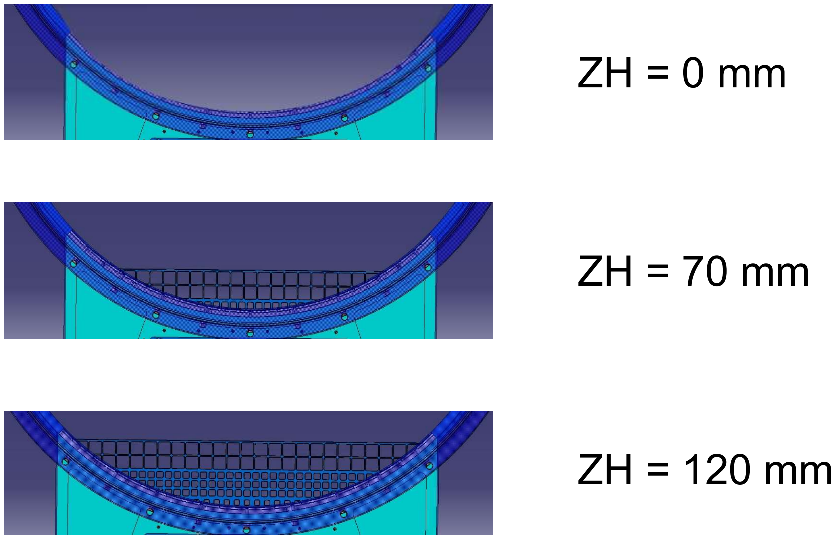


SOME RESULTS

Selected fan operating points with BLI



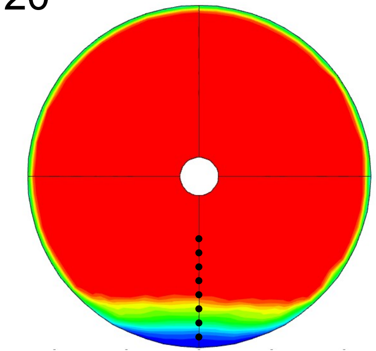
distortion fence variation

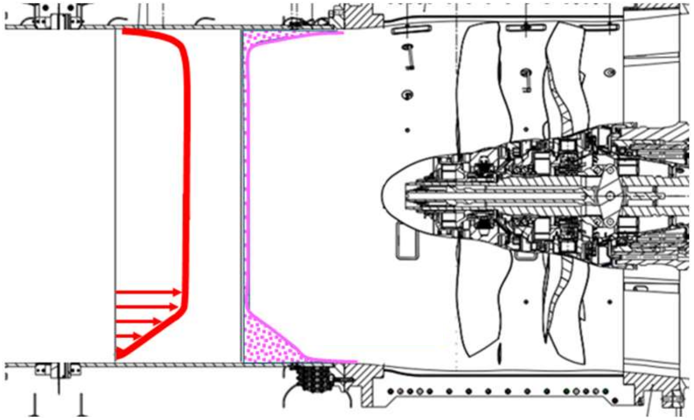


ZH = Zaun-Höhe = fence height

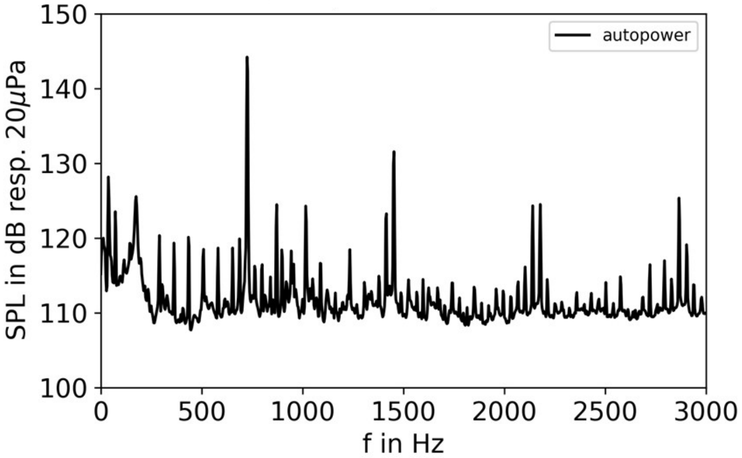
Goal: Assess BLI impact on four fan noise components

N=85,AL
ZH=120



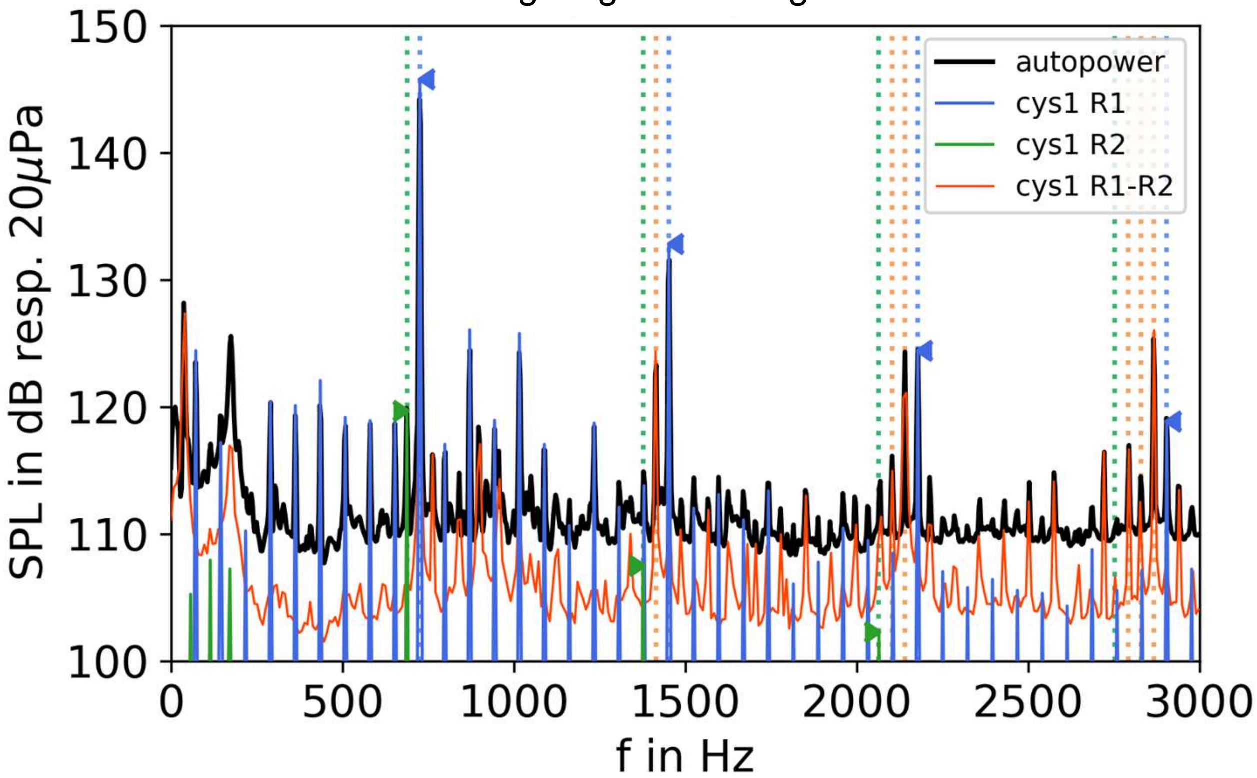


average signal mic ring A1



Noise components separated by cyclostationary analysis
N=85, AL, distortion fence 120 mm

average signal mic ring A1



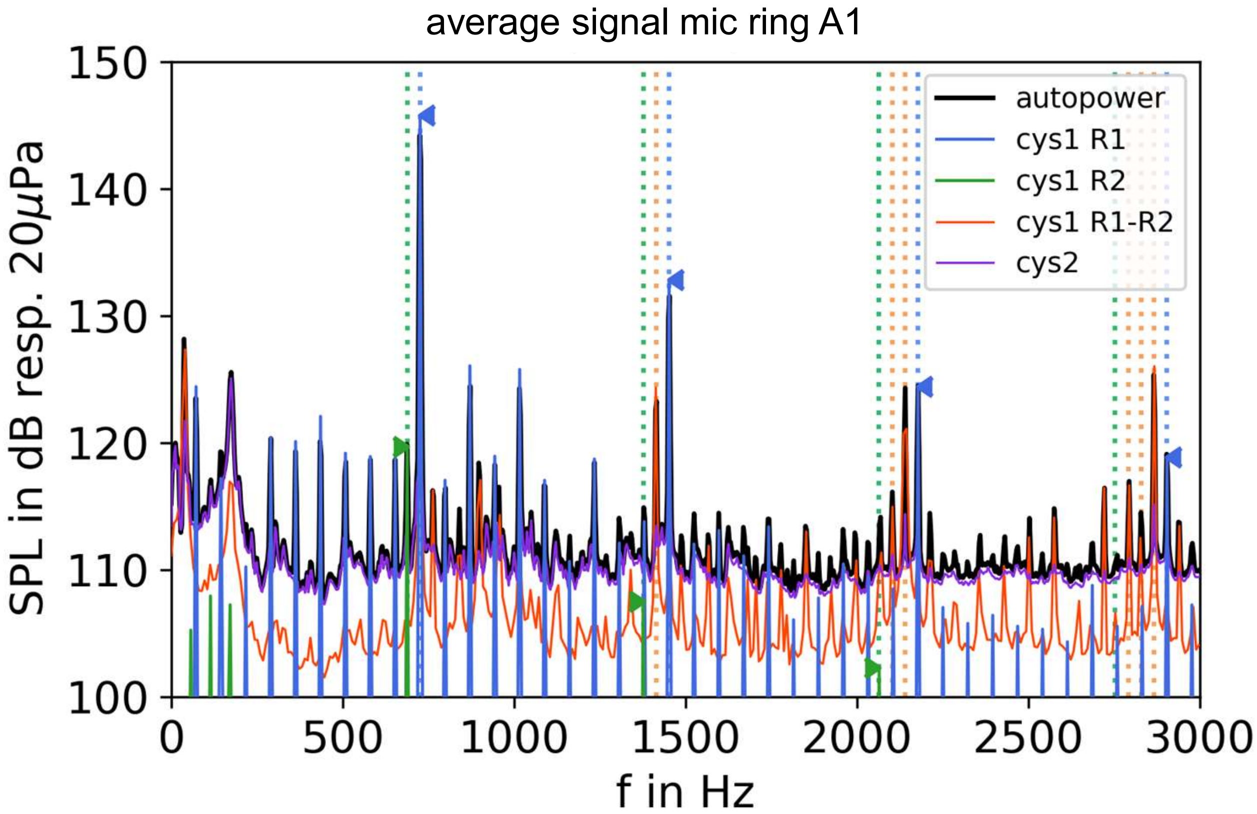
rotor 1 blade tones @ $f = h_1 B_1 f_{rot1}$

rotor 2 blade tones @ $f = h_2 B_2 f_{rot2}$

rotor 1 x rotor 2 interaction tones

@ $f = h_1 B_1 f_{rot1} + h_2 B_2 f_{rot2}$

Noise components separated by cyclostationary analysis
N=85, AL, distortion fence 120 mm



rotor 1 blade tones @ $f = h_1 B_1 f_{rot1}$

rotor 2 blade tones @ $f = h_2 B_2 f_{rot2}$

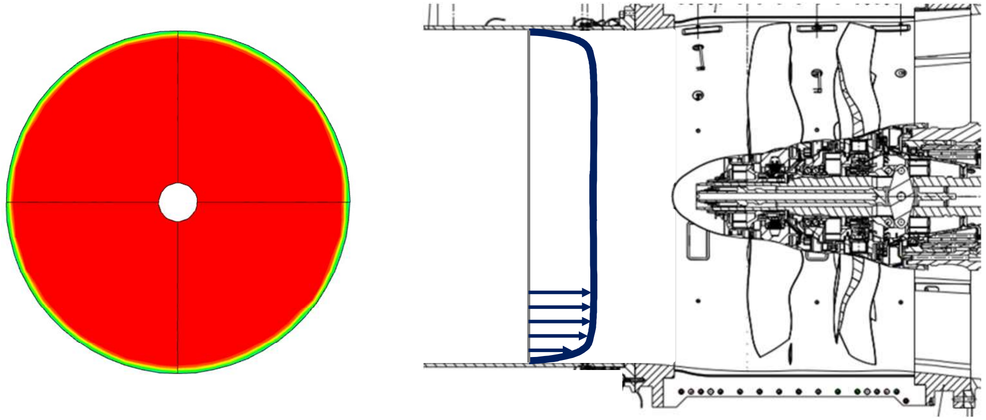
rotor 1 x rotor 2 interaction tones

@ $f = h_1 B_1 f_{rot1} + h_2 B_2 f_{rot2}$

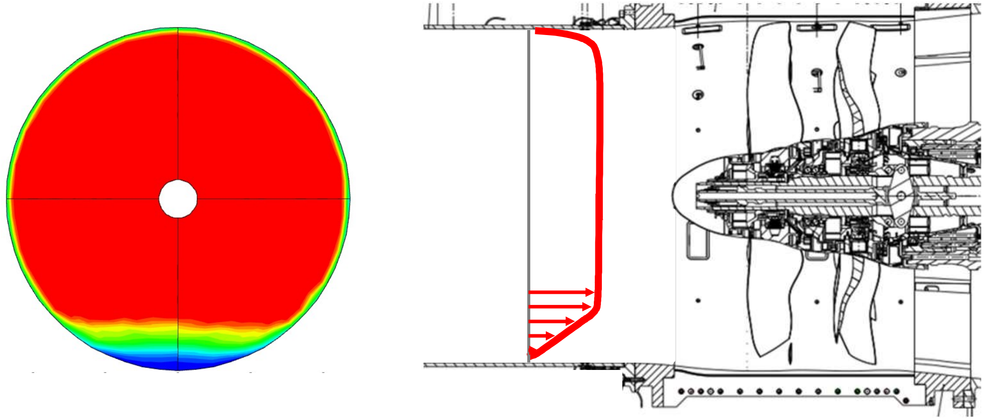
rotor incoherent components

BLI impact on blade tones rotor 1 and rotor 2

main noise generating mechanisms

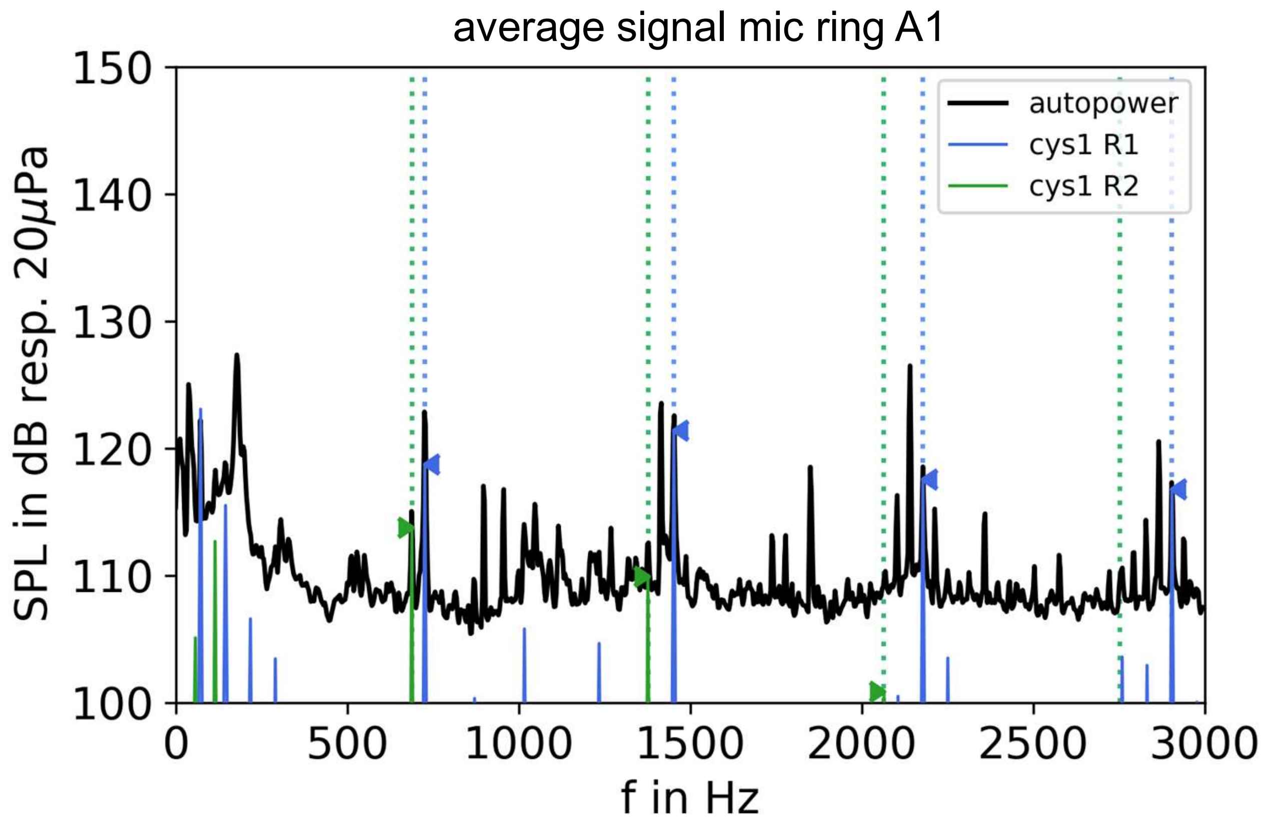


- **Steady blade forces in uniform steady flow → acoustically <u>cut-off</u> at subsonic operation**
- (buzz saw tones at supersonic fan operation)



- **Unsteady blade forces due to interaction with non-uniform steady flow**
- (modification of buzz saw noise sources at super sonic fan operation)

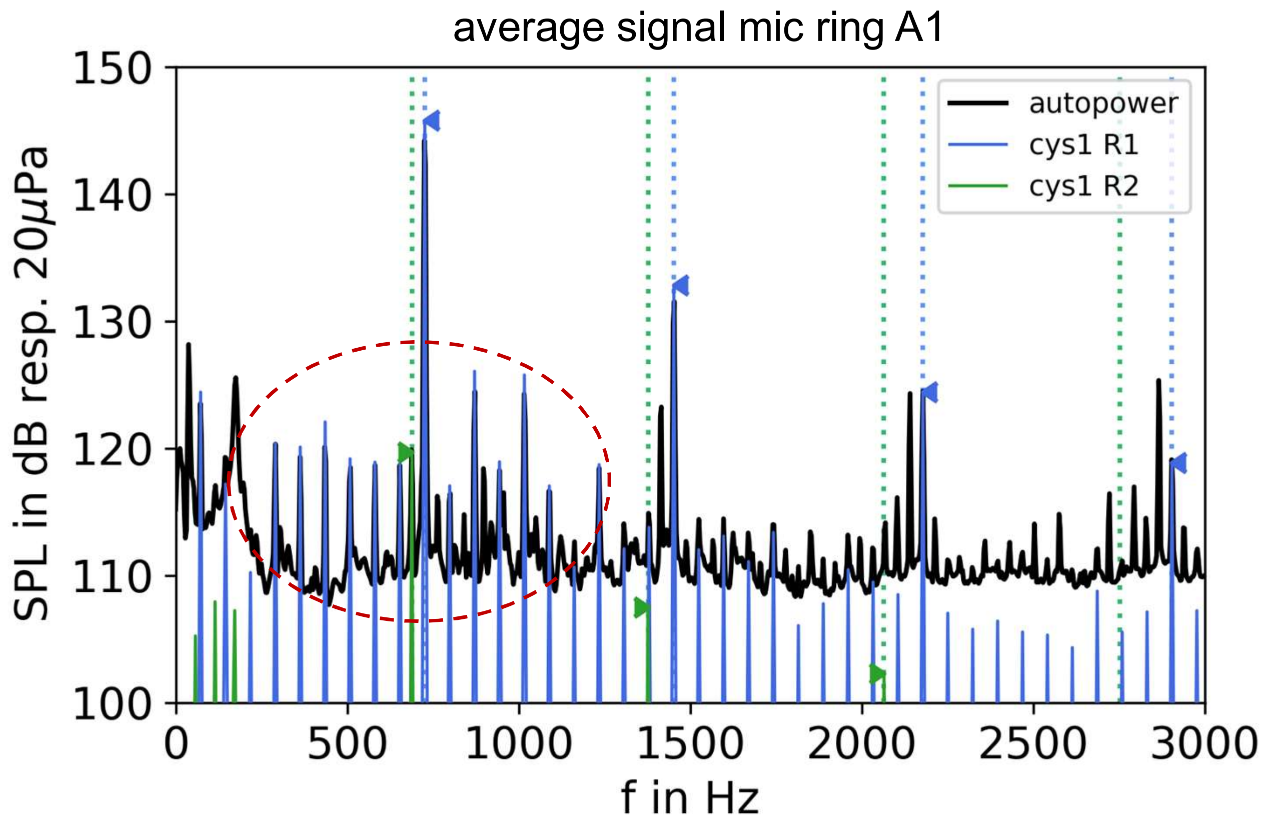
Blade tones of rotor 1 and rotor 2
N=85, AL, without distortion fence



rotor 1 blade tones @ $f = h_1 B_1 f_{rot1}$

rotor 2 blade tones @ $f = h_2 B_2 f_{rot2}$

Blade tones of rotor 1 and rotor 2
N=85, AL, with distortion fence 120 mm

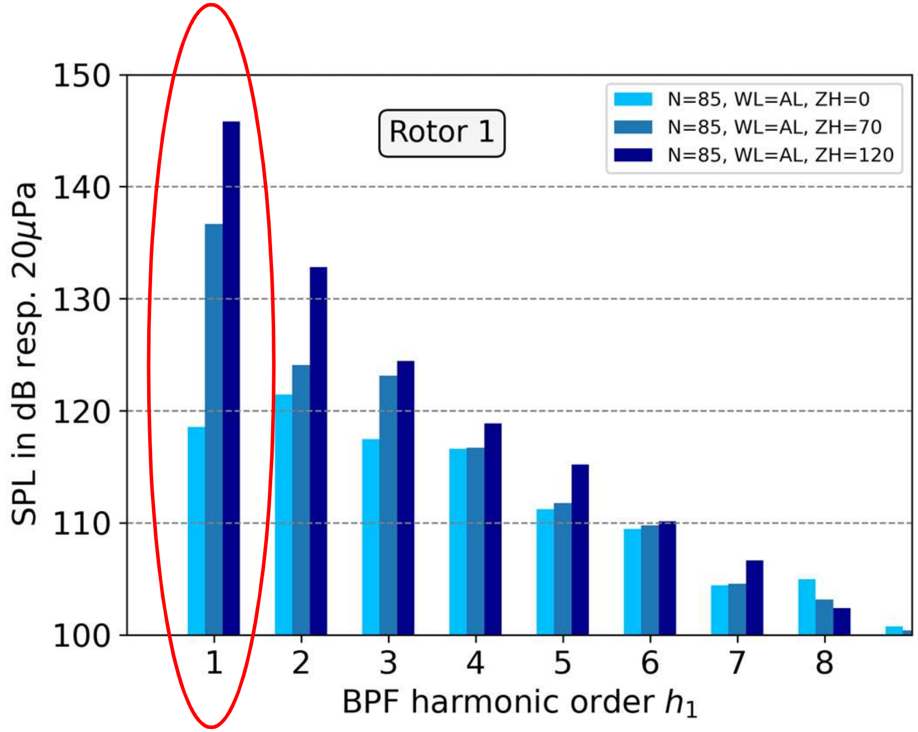


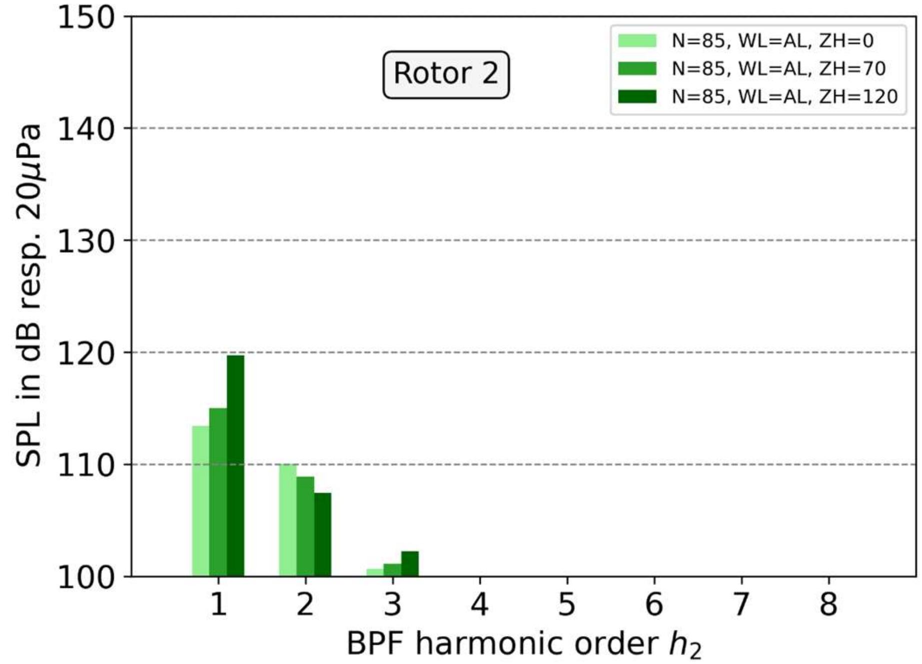
rotor 1 blade tones @ $f = h_1 B_1 f_{rot1}$

rotor 2 blade tones @ $f = h_2 B_2 f_{rot2}$

engine order harmonics due to blade deformations caused by BLI?

BLI impact on blade tones rotor 1 and rotor 2
N=85, AL

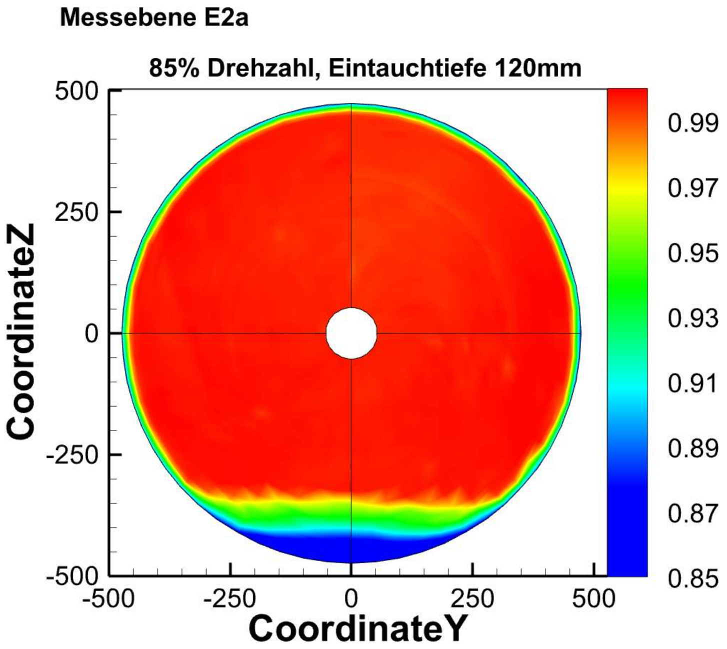


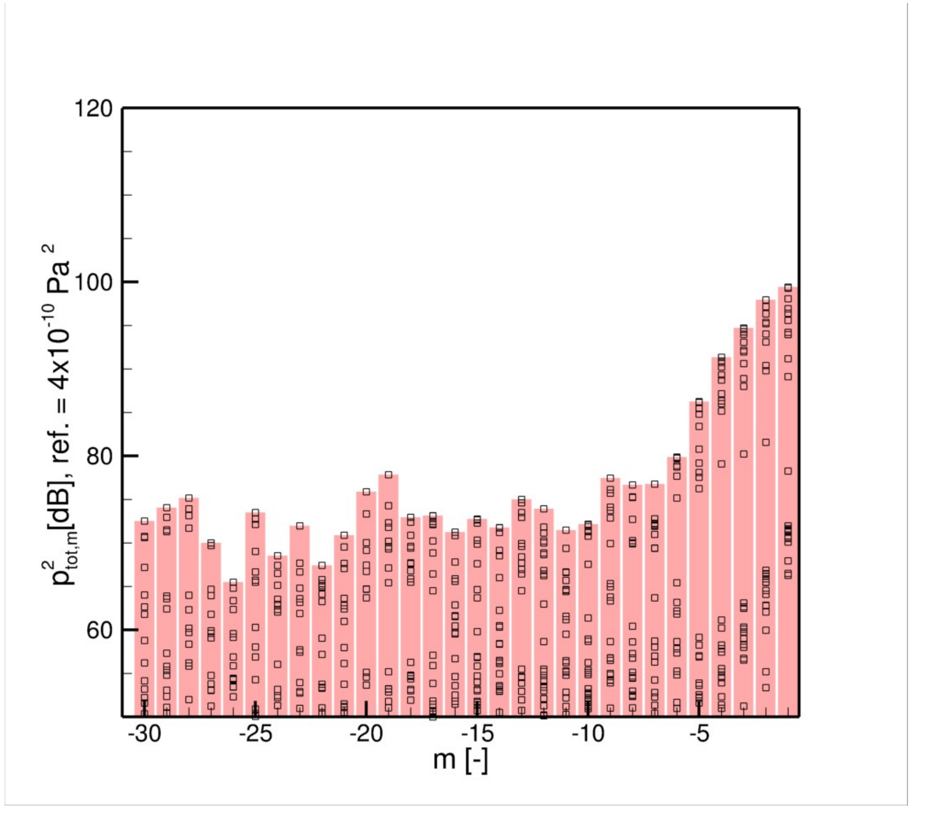


strong aerodynamic excitation at low orders

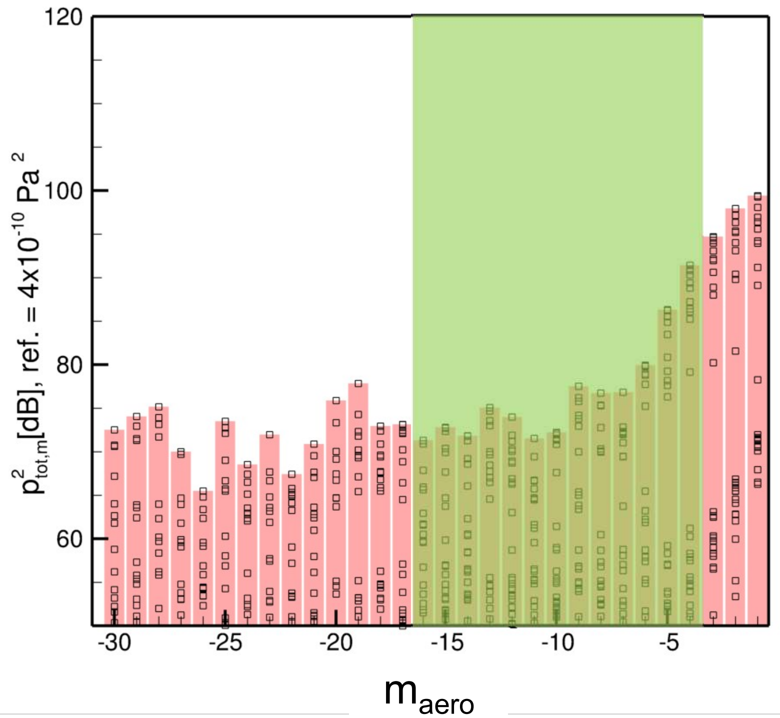
interaction BLI / rotor 2 is subordinate

Inflow distortion decomposed into circumferential modes

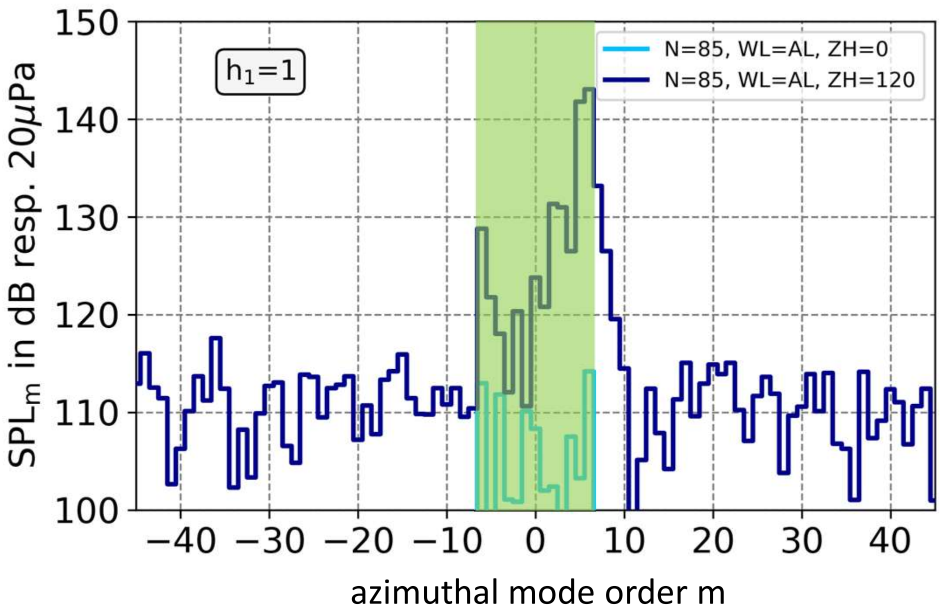




Relation of aerodynamic and acoustic modes N=85, AL, 1BPF1

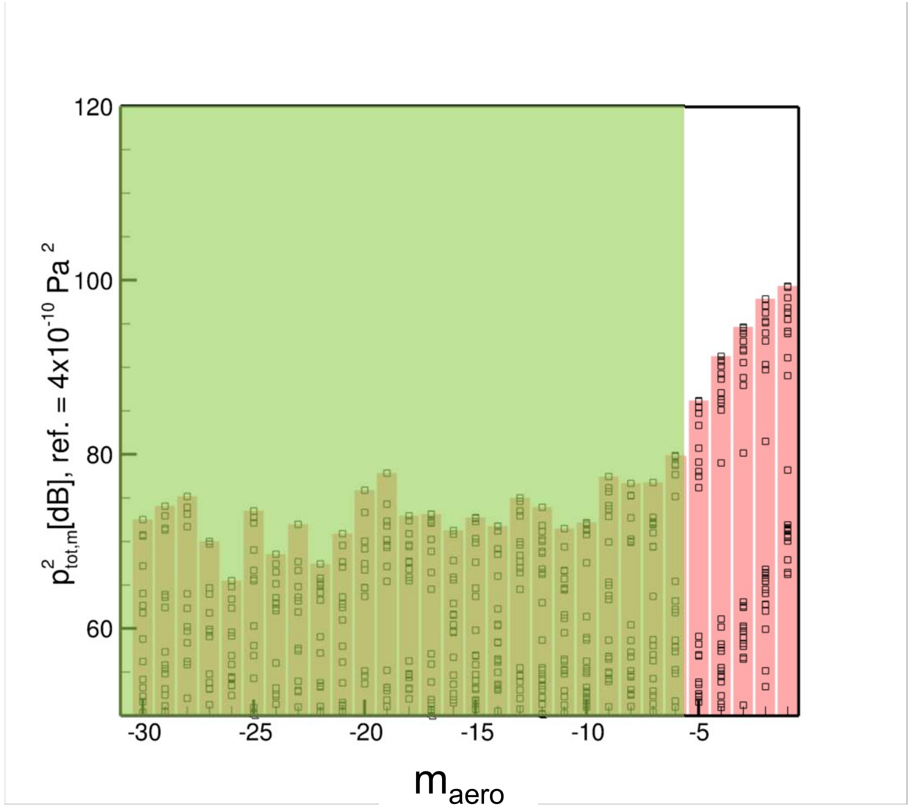


$$m_{acoustic} = h_1 B_1 + m_{aero}$$

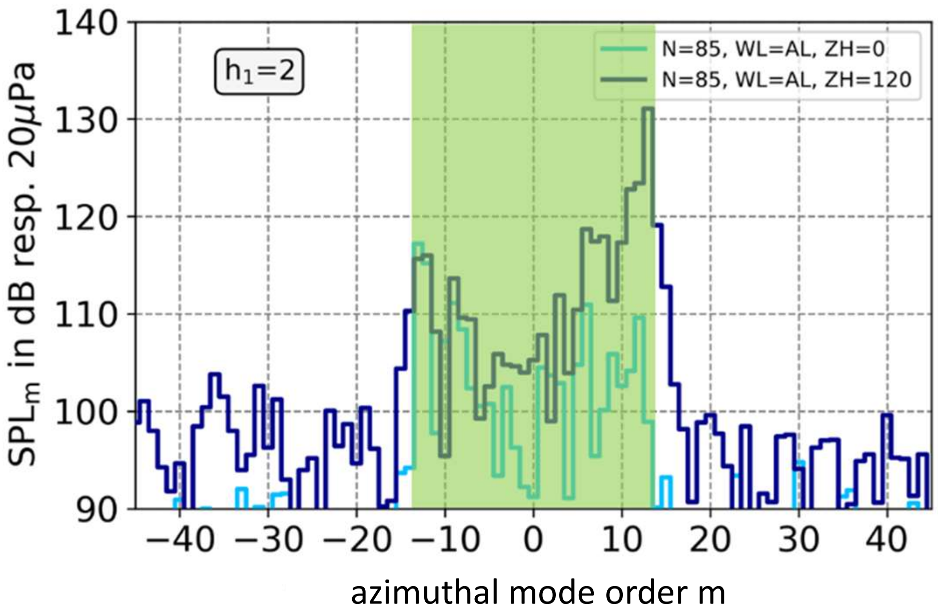


- level increases of aerodynamic and acoustic modes correlate
- asymmetrical mode excitation due to alignment of the dipole sources
- resonance and propagation effects to be considered

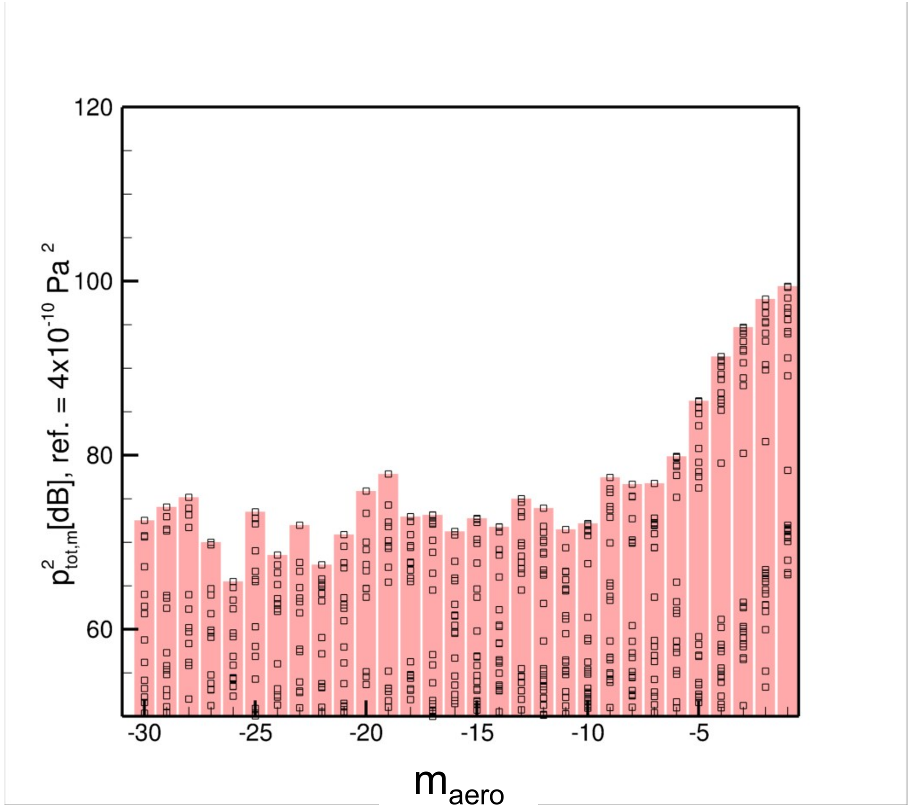
Relation of aerodynamic and acoustic modes
N=85, AL, 2BPF1

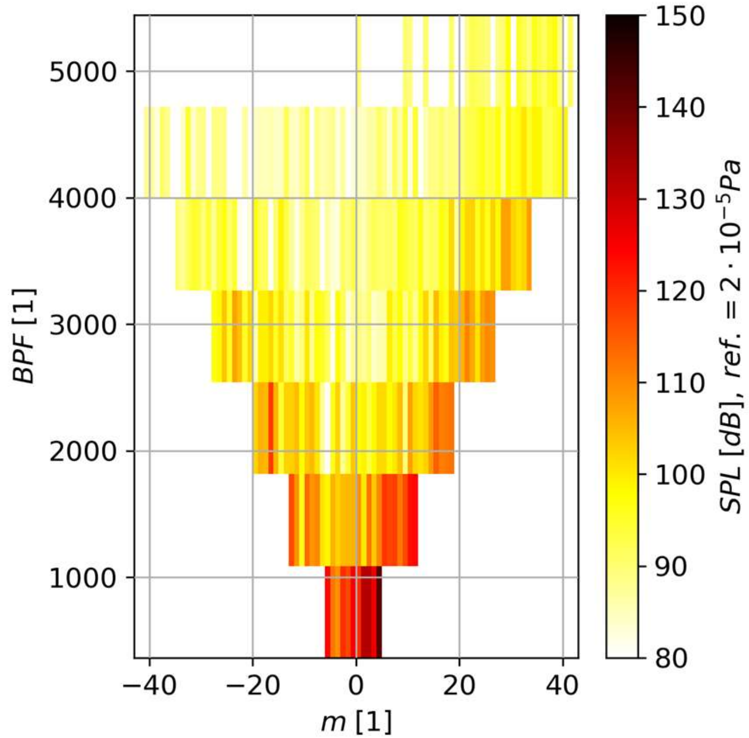


$$m_{acoustic} = h_1 B_1 + m_{aero}$$

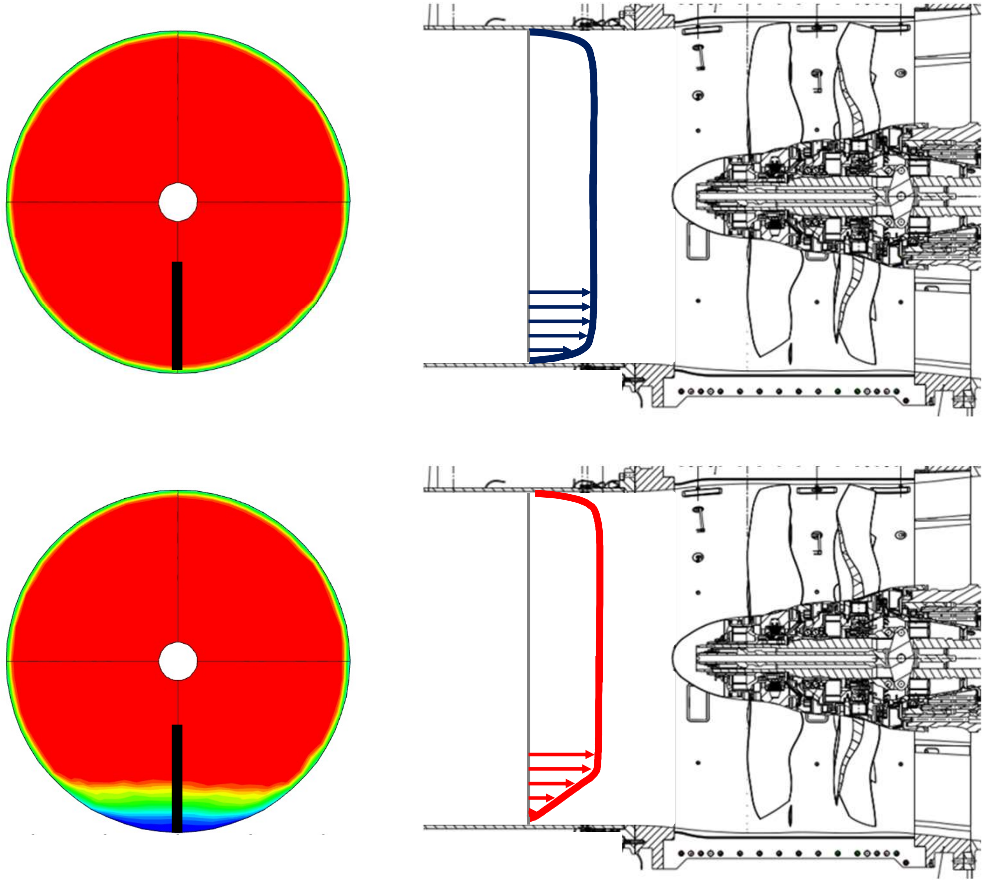


Relation of aerodynamic and acoustic modes
N=85, AL, hBPF1





BLI impact on rotor 1/rotor 2 interaction tones



main noise generating mechanisms

- interaction rotor 1 wakes / rotor 2
- interaction potential fields rotor 1 / rotor 2

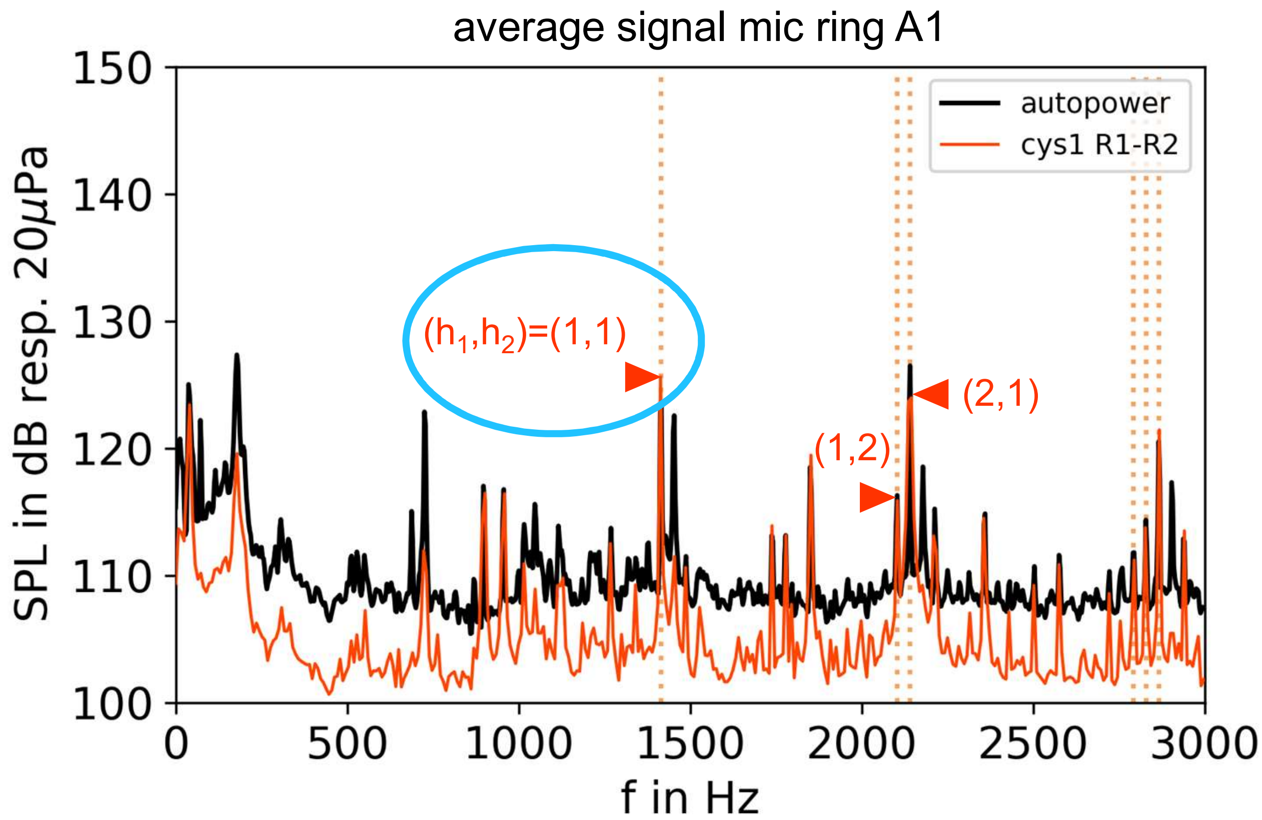
→ interaction modes according to Tyler&Sofrin

$$m = h_1 B_1 - h_2 B_2$$

- rotor 1 wakes vary during rotation
- potential fields of rotor blades vary during rotation

→ generation of modes adjacent to Tyler&Sofrin modes

Separation of rotor 1/rotor 2 interaction tones
N=85, AL, no distortion fence

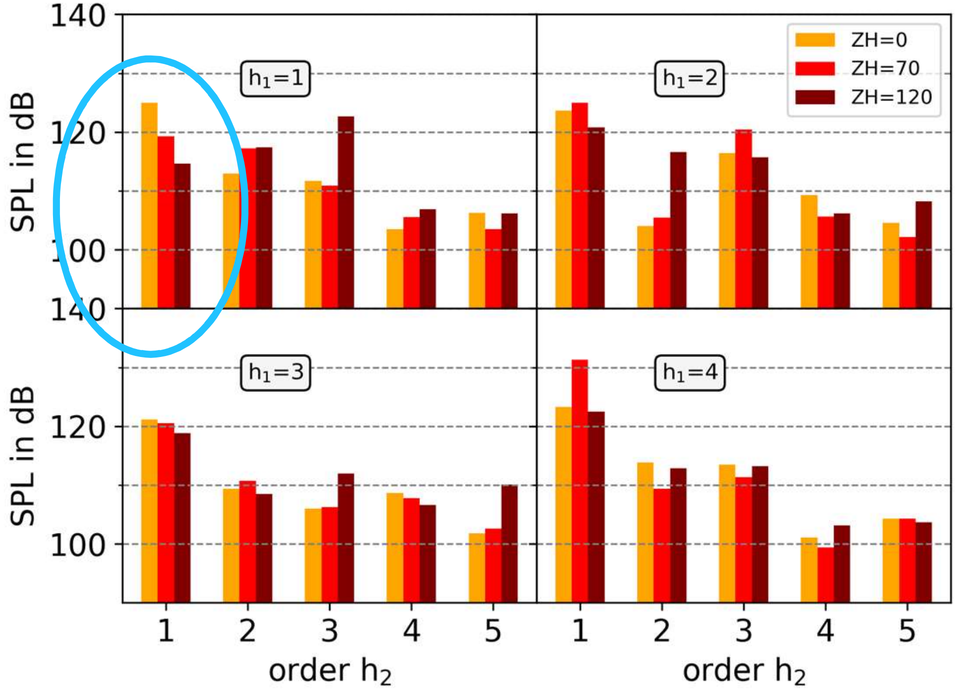


tones rotor 1 x rotor 2

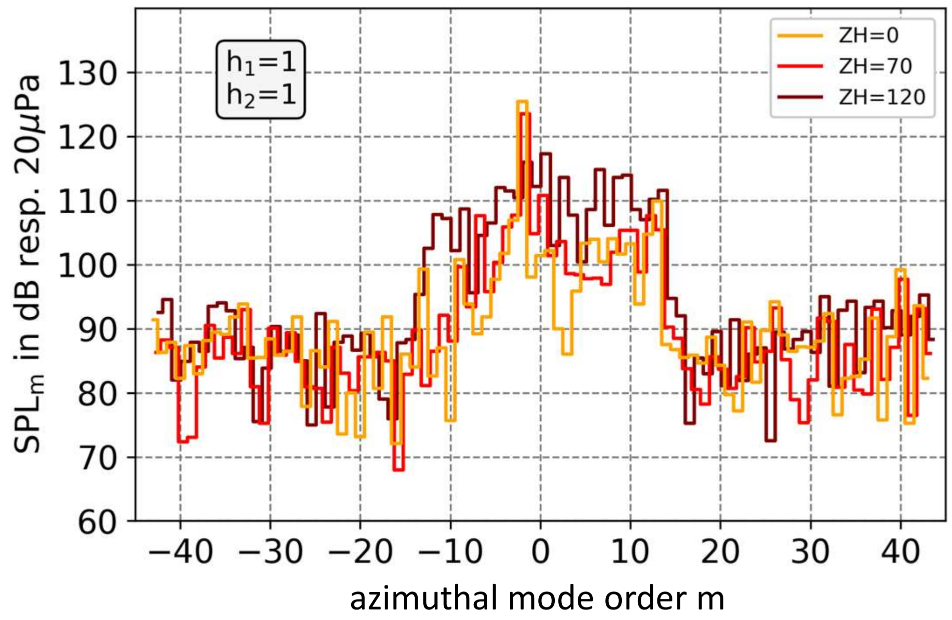
@ $f = h_1 B_1 f_{rot1} + h_2 B_2 f_{rot2}$

BLI impact on rotor 1/rotor 2 interaction tones N=85, AL

average tones in ring A1

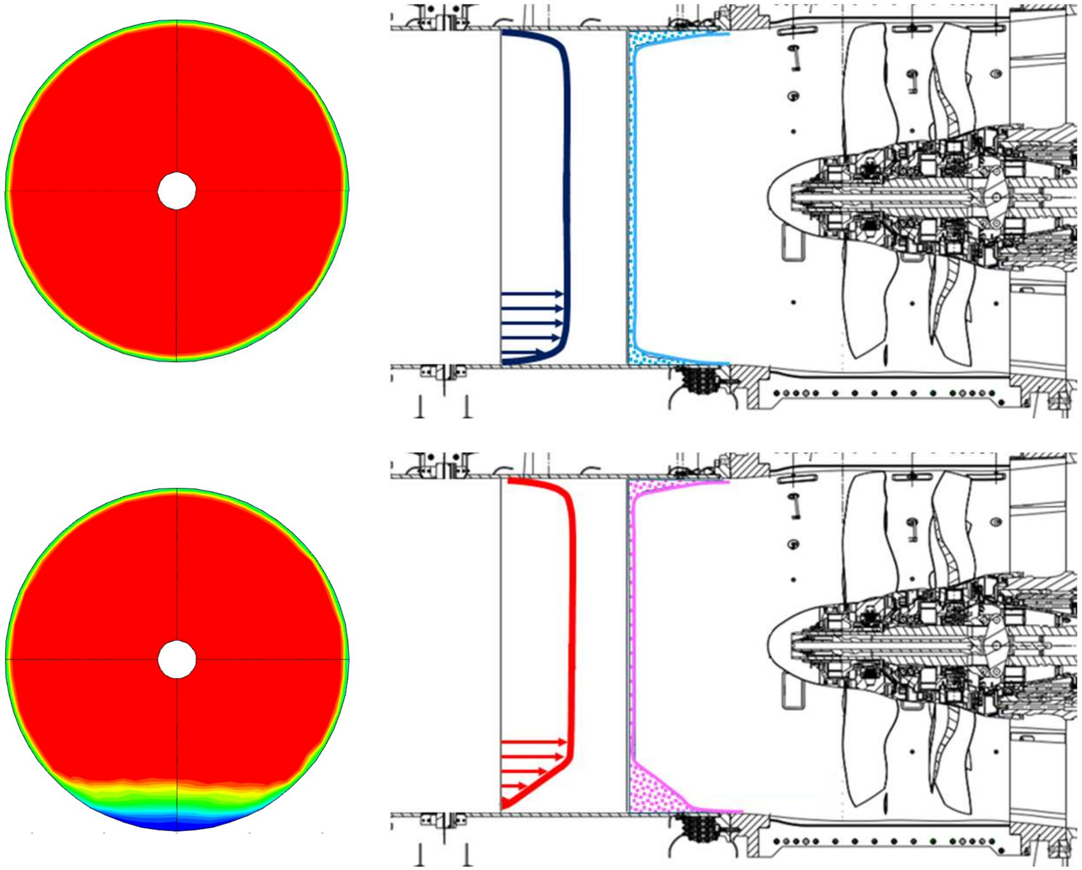


azimuthal modes in ring A1



- BLI modifies blade wake and potential field
- blade deformations may have an impact
- propagation effects to be considered

BLI impact on rotor-incoherent noise sources



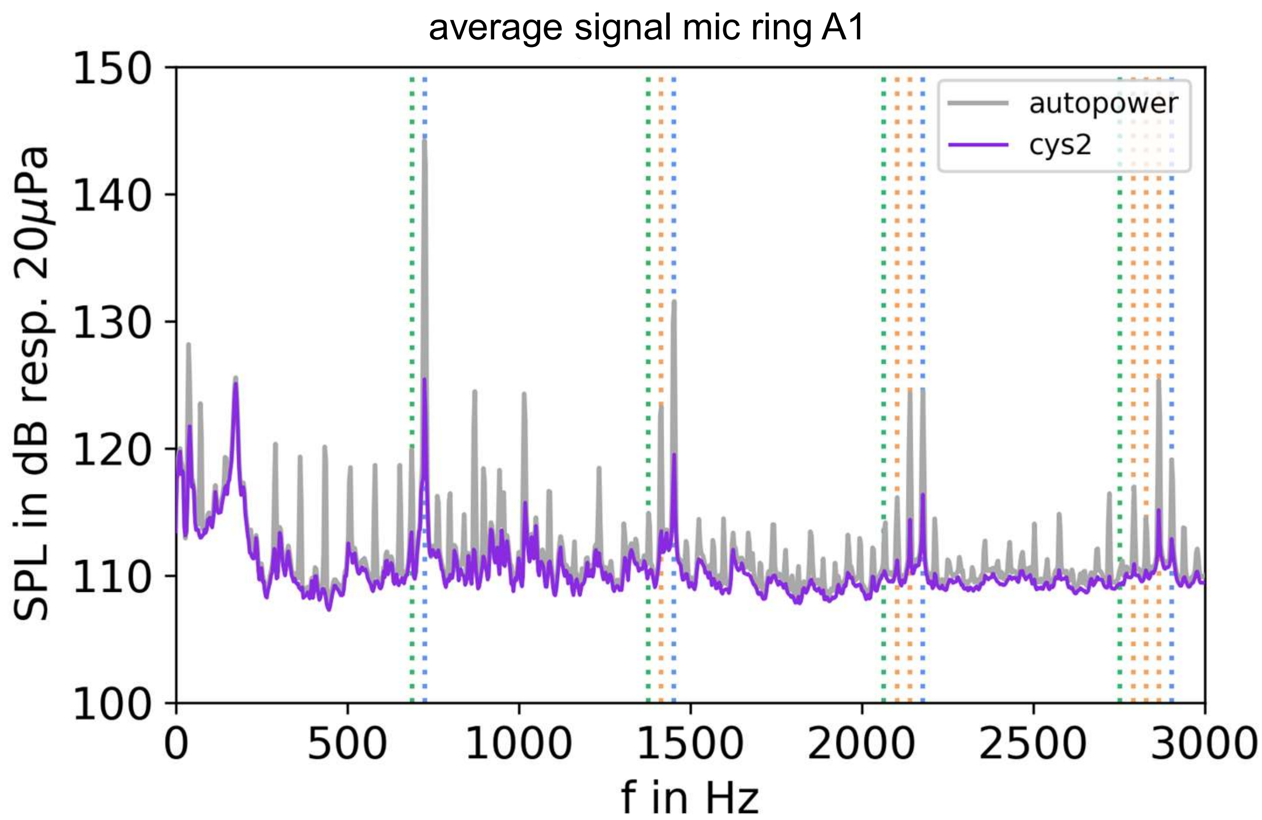
main noise generating mechanisms

turbulence interaction

- inflow → rotors
- rotor 1 wakes → rotor 2
- rotor blade tip vortices → rotor 2

- modification of aforementioned mechanisms
- BLI → rotor 1 and rotor 2

Separation of rotor incoherent signal components
N=85, AL, distortion fence 120 mm



tones rotor 1 @ $f = h_1 B_1 f_{rot1}$

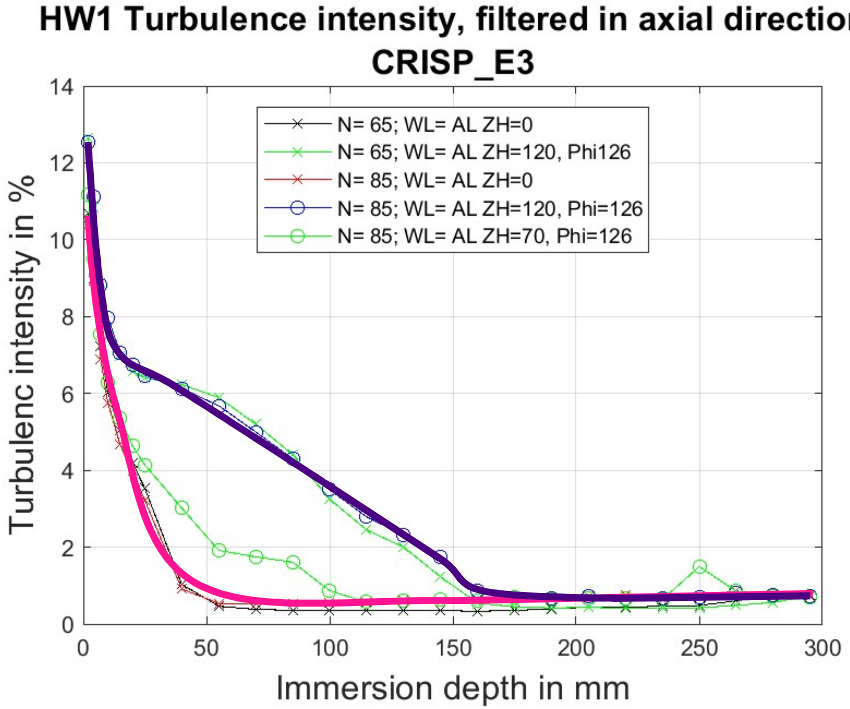
tones rotor 2 @ $f = h_2 B_2 f_{rot2}$

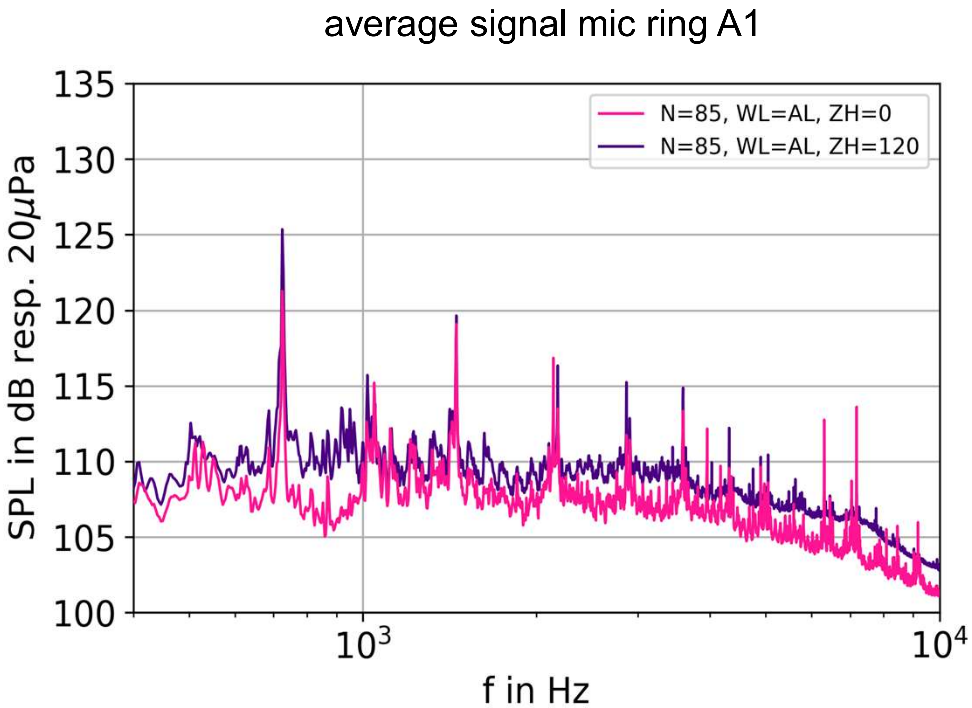
tones rotor 1 x rotor 2

@ $f = h_1 B_1 f_{rot1} + h_2 B_2 f_{rot2}$

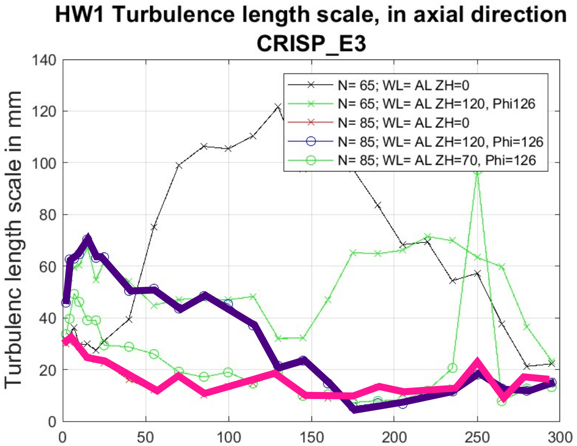
rotor incoherent signal

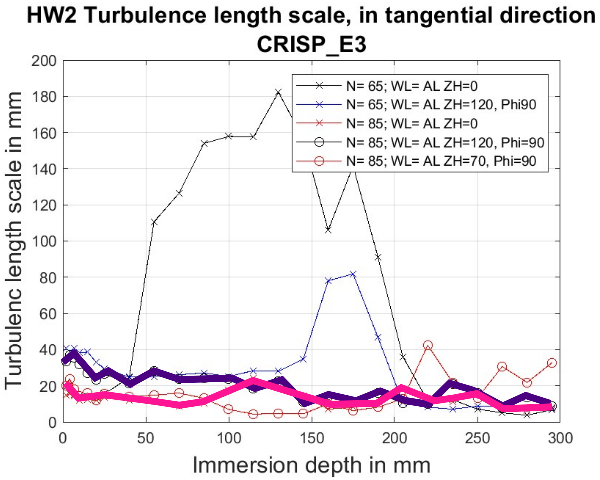
BLI impact on rotor-incoherent noise sources
N=85, AL

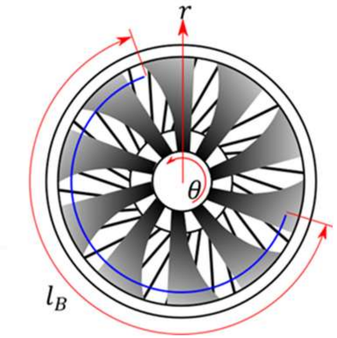




Relation to turbulence length scales
N=85, AL

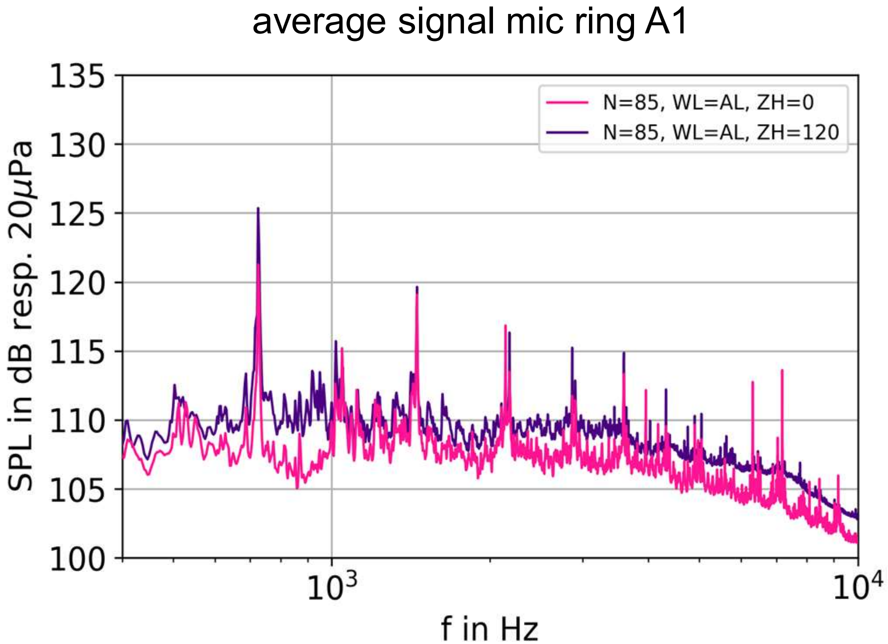






$$l_b = \sqrt{l_t^2 + \left(2\pi \frac{f_{rot} r}{U(r)} l_l\right)^2}$$

$$\frac{coherence\ length\ l_b}{blade\ spacing\ s} = 0.3$$

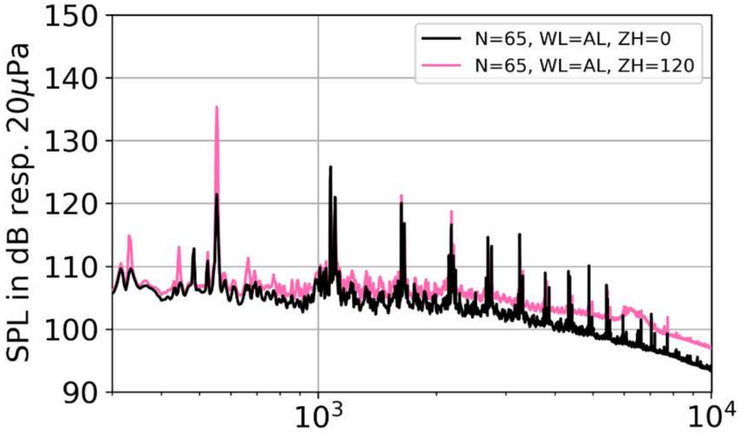


- sources of successive blades are not correlated
- no ‘haystacking’ around BPF harmonics
- how representative are length scales?

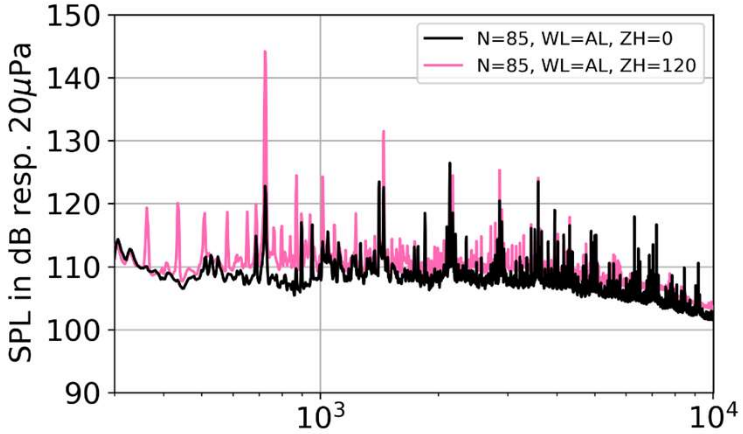
Overview of main measured test points

average autopower spectra

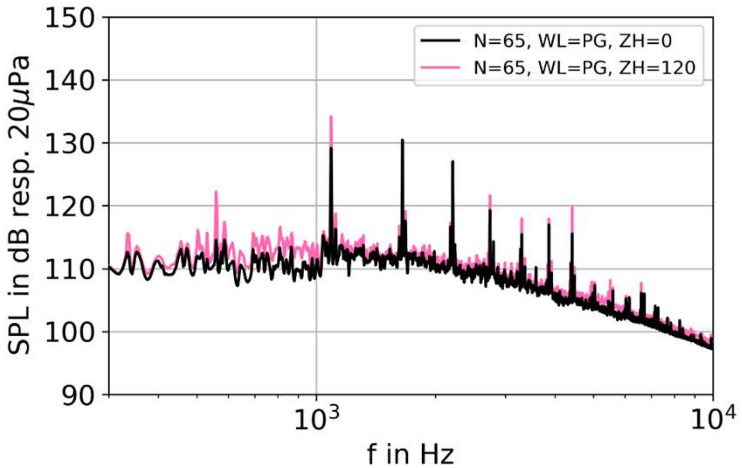
N=65 AL



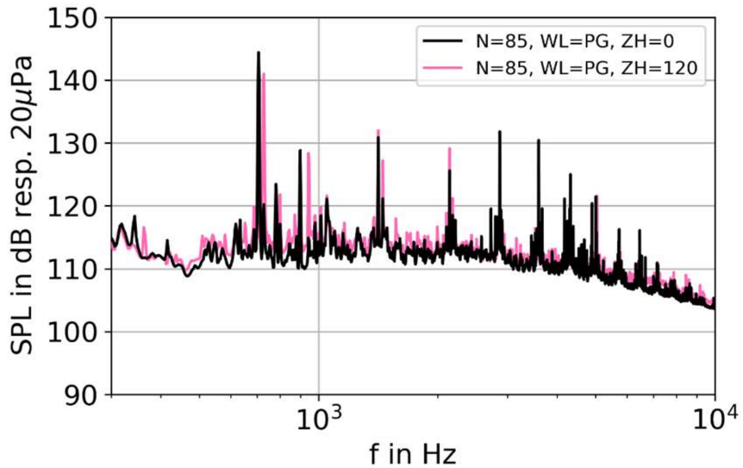
N=85 AL



N=65 throttled



N=85 throttled



Conclusion

- Comprehensive data base of tests under realistic engine conditions available
  - Aerodynamics, acoustics, blade deformations & vibrations
- Significant BLI effects on fan aeroacoustics measured
  - strong excitation of rotor 1 tones (isolated from other stage interactions)
  - modification of blade wake and potential field interaction of rotor 1 and rotor 2
  - rotor-incoherent excitation correlates well with turbulence intensity and length scales

Outlook / Ideas for further studies

- Paper at the AIAA/CEAS Aeroacoustics Conference 2024 in Rome
- Radial mode analysis under consideration of boundary layer profile
- Validation of fan noise prediction methods

THANK YOU FOR YOUR ATTENTION

Bildquelle: DLR, AT-FUV

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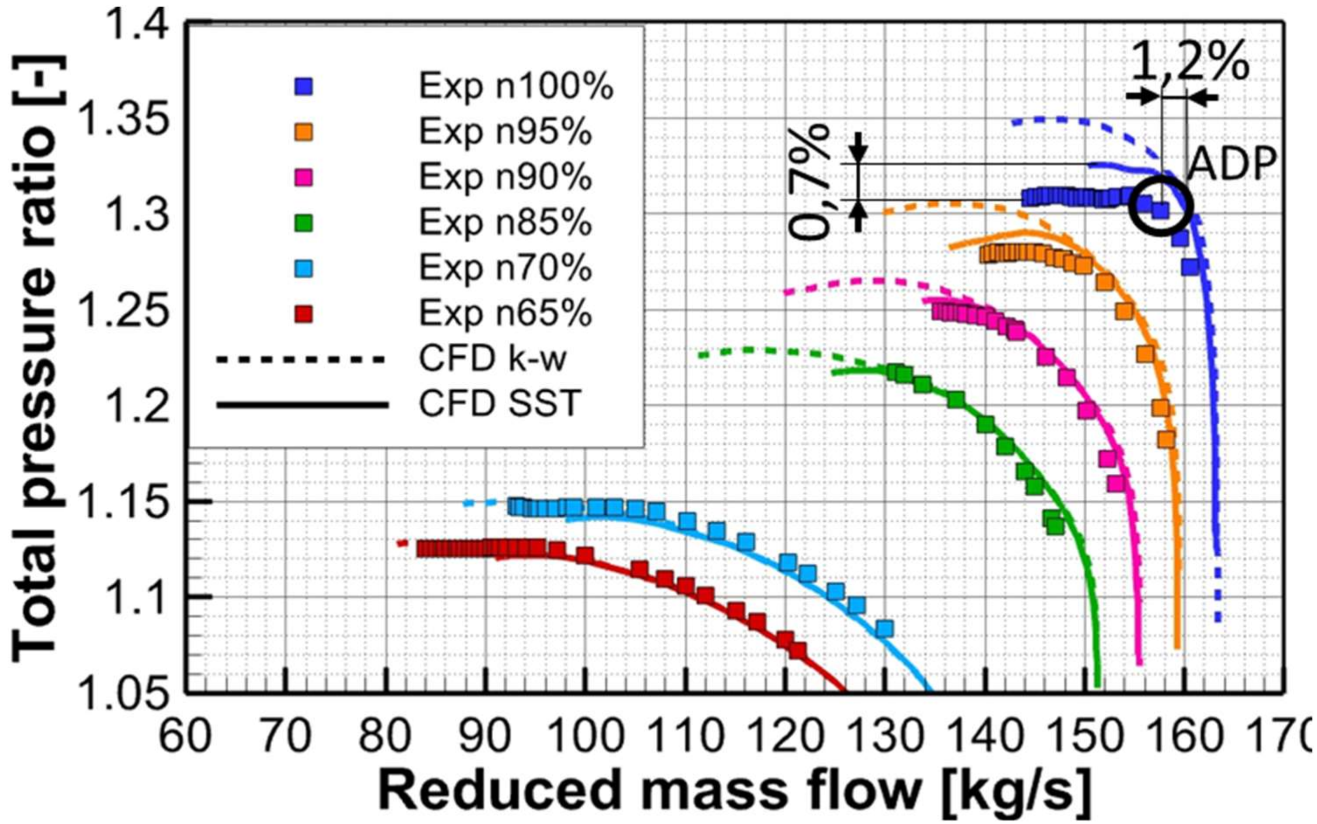
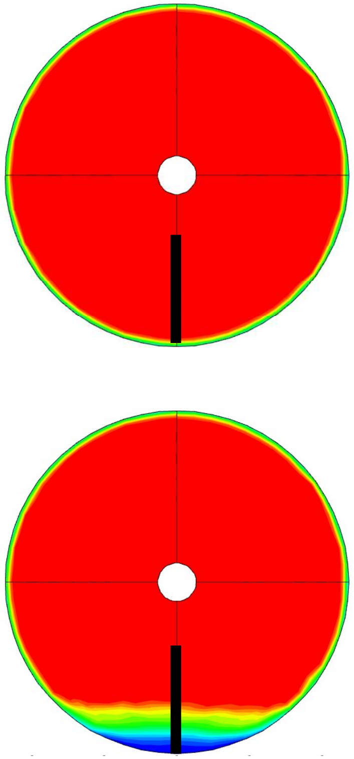
Fan map



Total pressure ratio [-]
Reduced mass flow [kg/s]
1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
60
70
80
90
100
110
120
130
140
150
160
170
Exp n100%
Exp n95%
Exp n90%
Exp n85%
Exp n70%
Exp n65%
CFD k-w
CFD SST
1,2%
0,7%
ADP

BLI impact on mean flow profile in fan inlet
N=85, AL

plane E2a



plane E3