Modern numerical and analytical methods in duct acoustic simulations

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Can CAA really be used in a numerical experiment to replace real experiments today?

- What is possible with time-domain CAA, today? – An inventory from the developers:
  - Complex geometries can be handled with some effort
    - E.g. using Chimera approaches in connection with Finite Difference methods
  - Very detailed approximations of the base flow conditions (incl. boundary layers, shear layers and choked flows) can be handled by CAA.
  - Development of ideally non-reflective boundary conditions is not jet finished – often reflections are smaller than with “anechoic terminations” in the experiment.
  - Noise reduction devices (acoustic lining and connected systems of resonators) can be modeled in the time domain
    - There are still many questions in this area
    - An accurate link between model and liner hardware is provided only by experiments
  - Main advantage of the time domain simulation: Arbitrary source signals are possible without extra effort. – This is rarely studied – Why?
- High-fidelity simulations for all ducts of an aeroengine are possible! – Can this be used for numerical experiments?
  - Requires methods for analysis and interpretation of the CAA result.
  - What is then required to make mechanized targeted optimization with CAA methods possible.

Overview

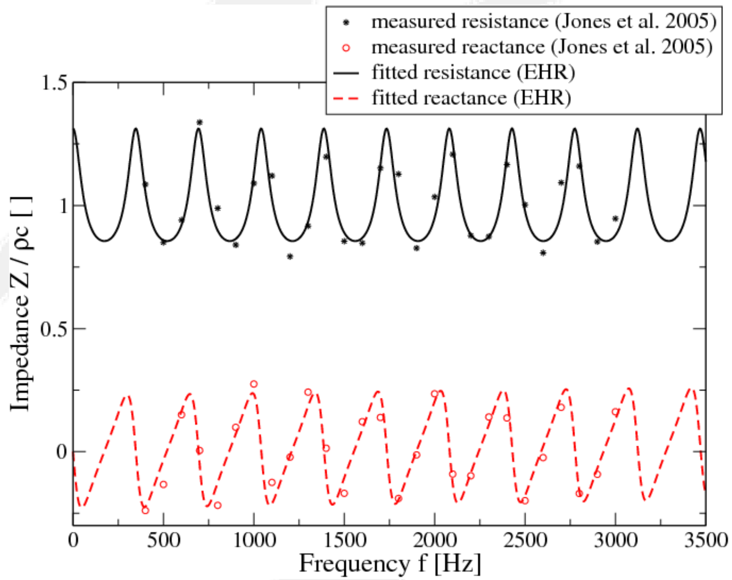
- ➢ Time domain CAA methods and related issues
  - Time domain impedance boundary conditions
  - Handling of complex geometries
  - Results validation and reliability
  - Tools for interpreting the results
  - Optimization and simulation time issues
- ➢ Selected results are presented inline with the related methods

Time domain impedance boundary conditions

Time-domain impedance boundary conditions (TDIBC's)

- TDIBC's are a generalization of the hard wall and fully non-reflective boundary conditions.
- The are applicable with CAA as well as for CFD
- Can model acoustic lining, soft walls, connected resonators or the frequency response of connected ducts instead of anechoic properties!

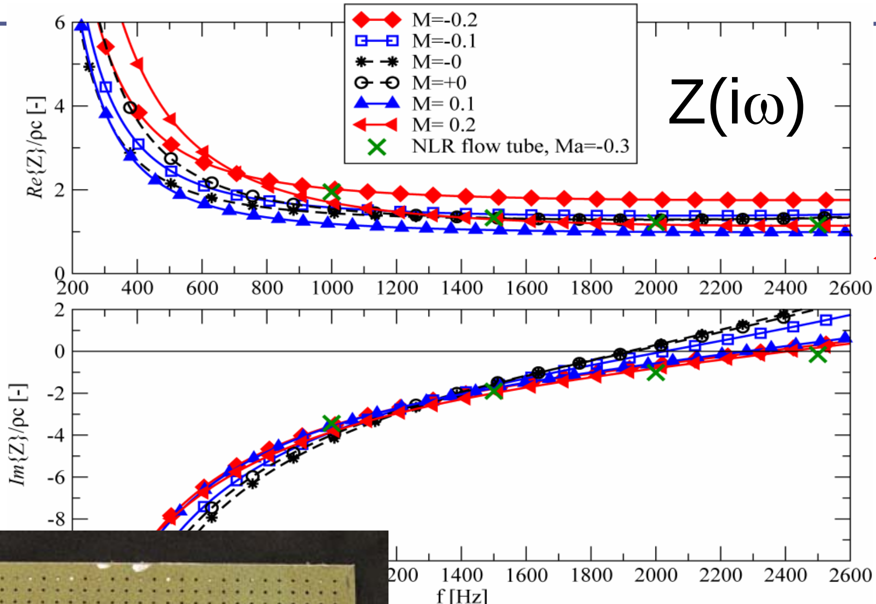
- Preconditions for the application of TDIBC's:
  - How to obtain the model parameters for a specific liner?
  - Model or resolve boundary layer effect on the impedance of the lined wall?
  - Time-domain impedance boundary conditions require a model for the frequency response of a liner – Can all types of liner be covered?



The Extended Helmholtz Resonator [Rienstra, 2006] is applied here to model the frequency response of a liner → Only single Helmholtz Resonator, but can fit termination impedance of NASA flow duct over lagre frequency range!

A way to obtain TDIBC-model parameters – Impedance Eduction from measurements

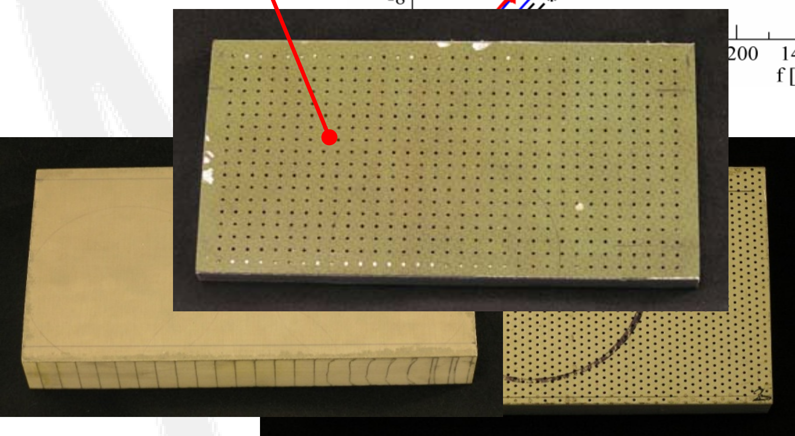
Model parameters and Z(iω) = ?



Model parameters

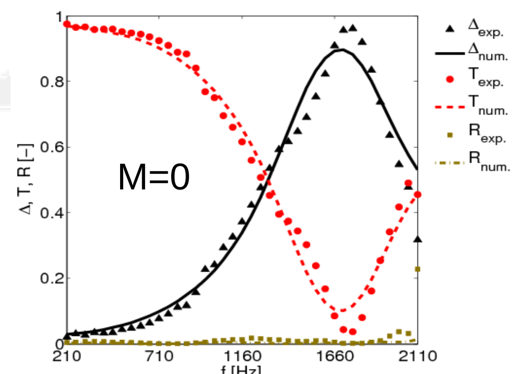
Optimization (MATLAB)

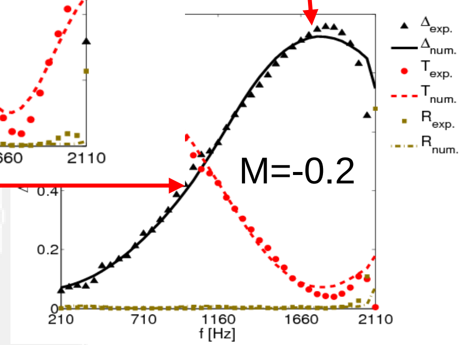
MATLAB Optimization tool calls TUBA, Variation of the model parametes, Objective: Fit measurement result

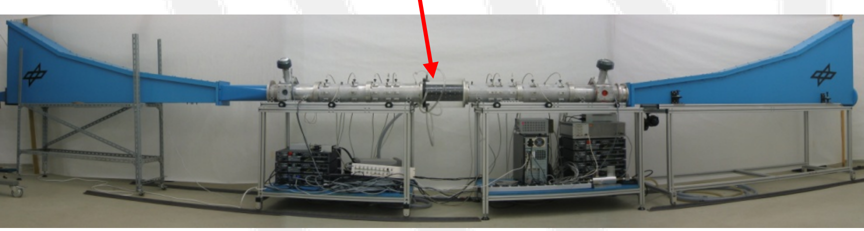


Result: Parameters and Impedance of a liner under relevant flow conditions

Multifrequency excitation, Grid size <20000 cells, Turn around time ~5…90 min



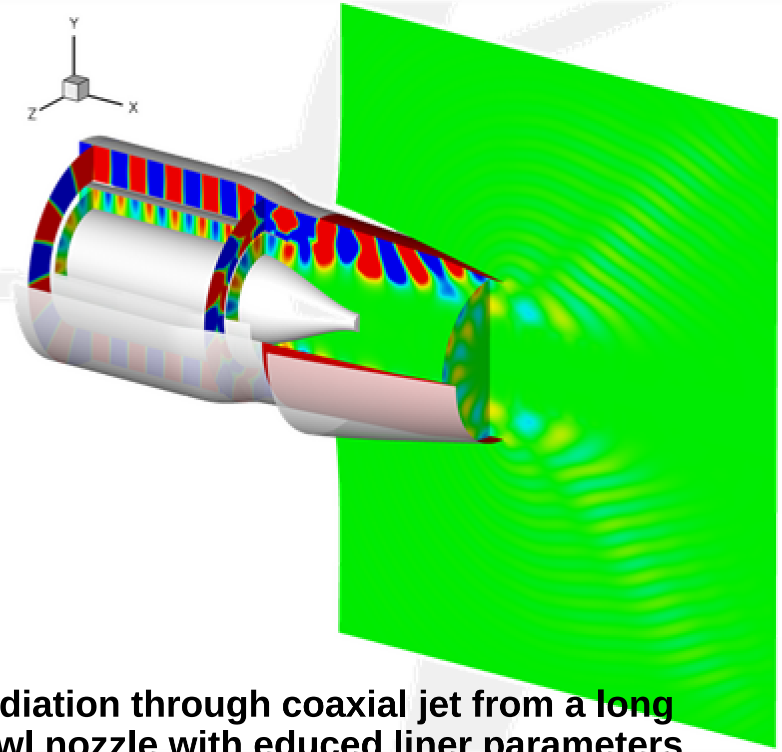




Measurement of reflection and transmission factors under relevant flow conditions

Results of the impedance eduction in the time-domain

- The **impedance eduction** in the time domain provides a set of parameters for the impedance model
  - This parameter-set is best approximating the experimental observation
  - Parameters describe the frequency response of the impedance.
  - Parameters provide a relation between physical hardware (e.g. geometry) and measurement result under flow conditions
    (eventually, only if a physical interpretation of these parameters exists)
- The result allows a predictive simulation of the liner effect under application conditions:
  - Presuming that the measurement can reproduce all necessary basic conditions (flow velocity, temperature, frequency) as the practical application
- The result allows to give directions for an improvement of the liner towards the designated impedance



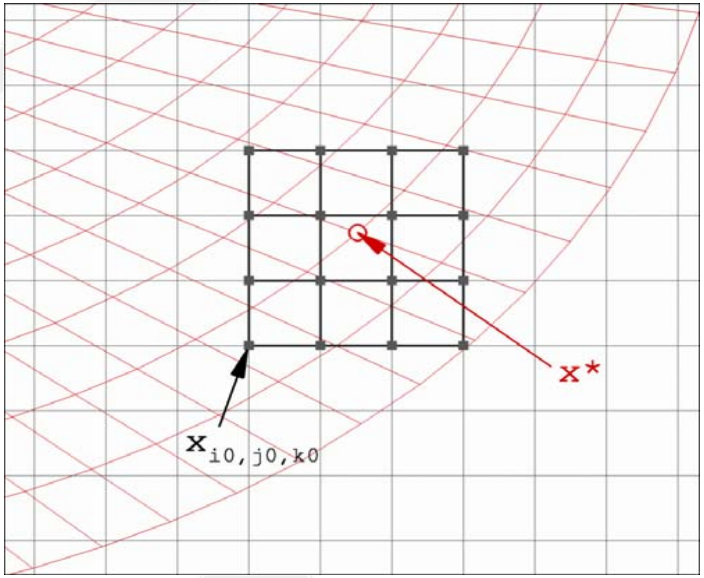
Radiation through coaxial jet from a long cowl nozzle with educed liner parameters

Handling of complex geometries: Chimera technique

Chimera

- Requirements of standard finite difference block structured CAA methods clearly conflict with the aim of handling complex geometries:
  - Extremely **challenging** and time consuming grid generation in 3D.
  - **Distorted** cells in the mesh have to be avoided, to
    - Keep the accuracy of the method high,
    - Avoid instabilities, and
    - Keep the simulation time acceptable.

- An **overset-grid-method** is applied (Chimera) to avoid penalties due to the meshing of complex geometries:
  - Allows Orthogonal and equidistant host mesh
  - Separate body fitted overset meshes
  - Requires Interpolation between the meshes
  - High-order FD-schemes require **high-order interpolation**, here based on Lagrangian-polynomials on 4x4x4 (5x5x5) points

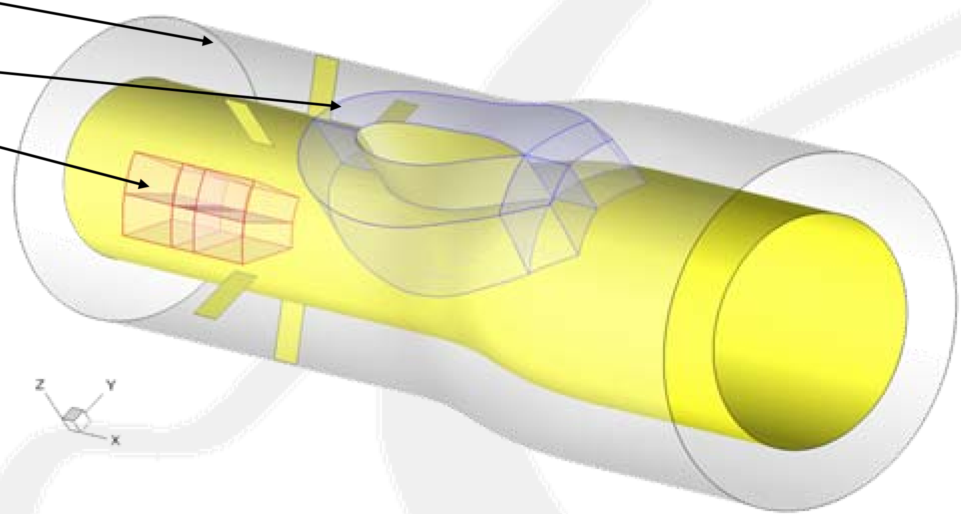


Example of a 2D interpolation stencil

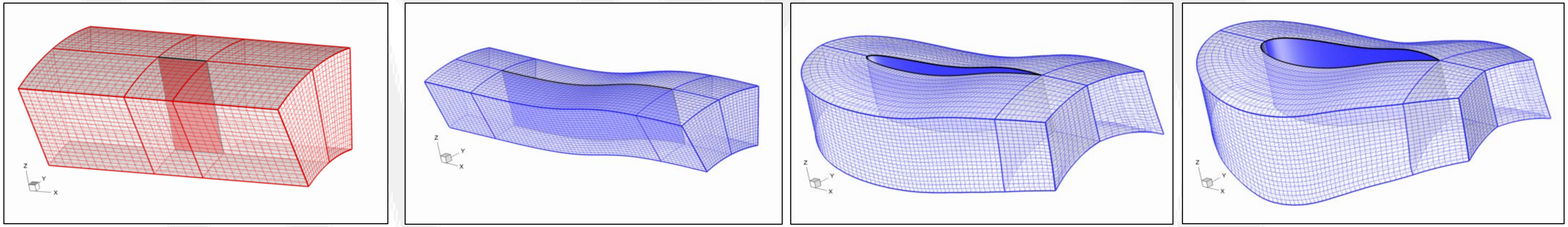
Meshing of an S-duct with installations

➢ Meshing of an S-duct with installations using the Chimera technique

- Host grid:
  - uniform and local orthogonal O-type grid
- Overset grids:
  - Body fitted C-type for profile bifurcations
  - 6-block H-type grid for struts and planar plate bifurcation



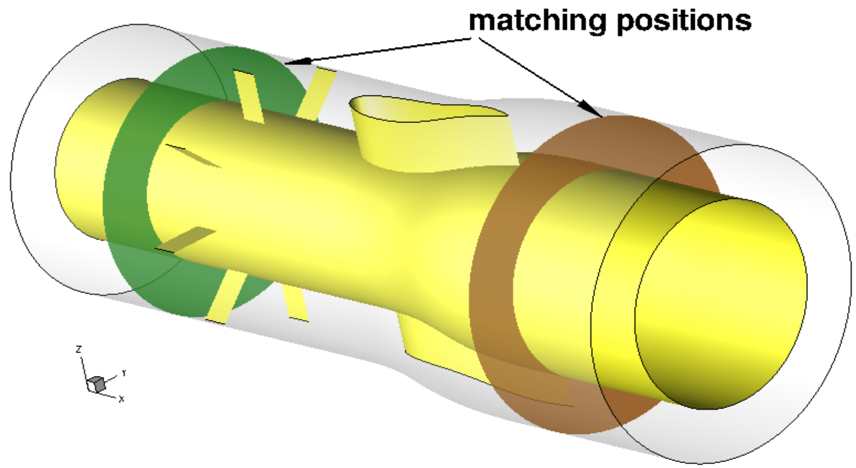
- 2.1 – 2.4 Million nodes
- 4 – 12% interpolated nodes (w and w/o struts)

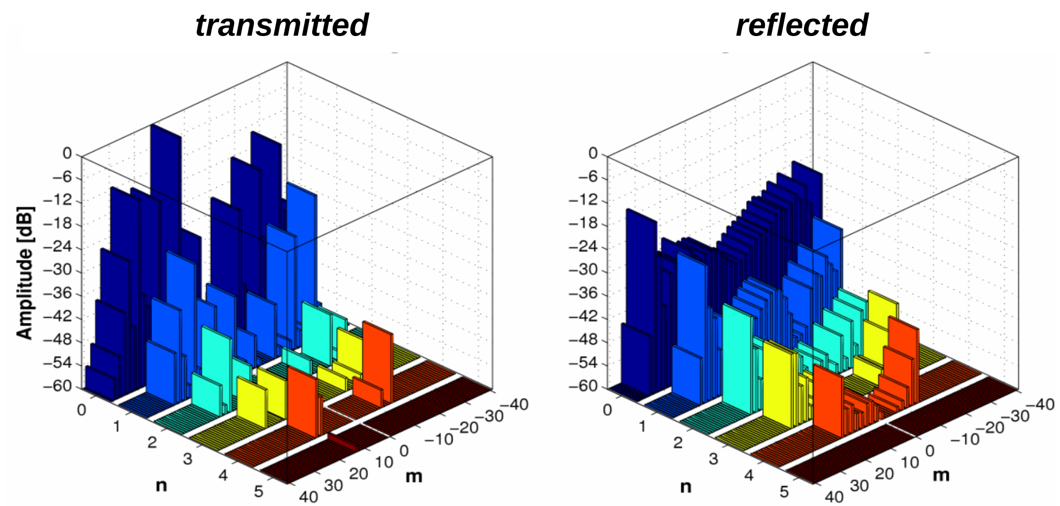


Interpretation of the CAA results

Mode analysis for CAA

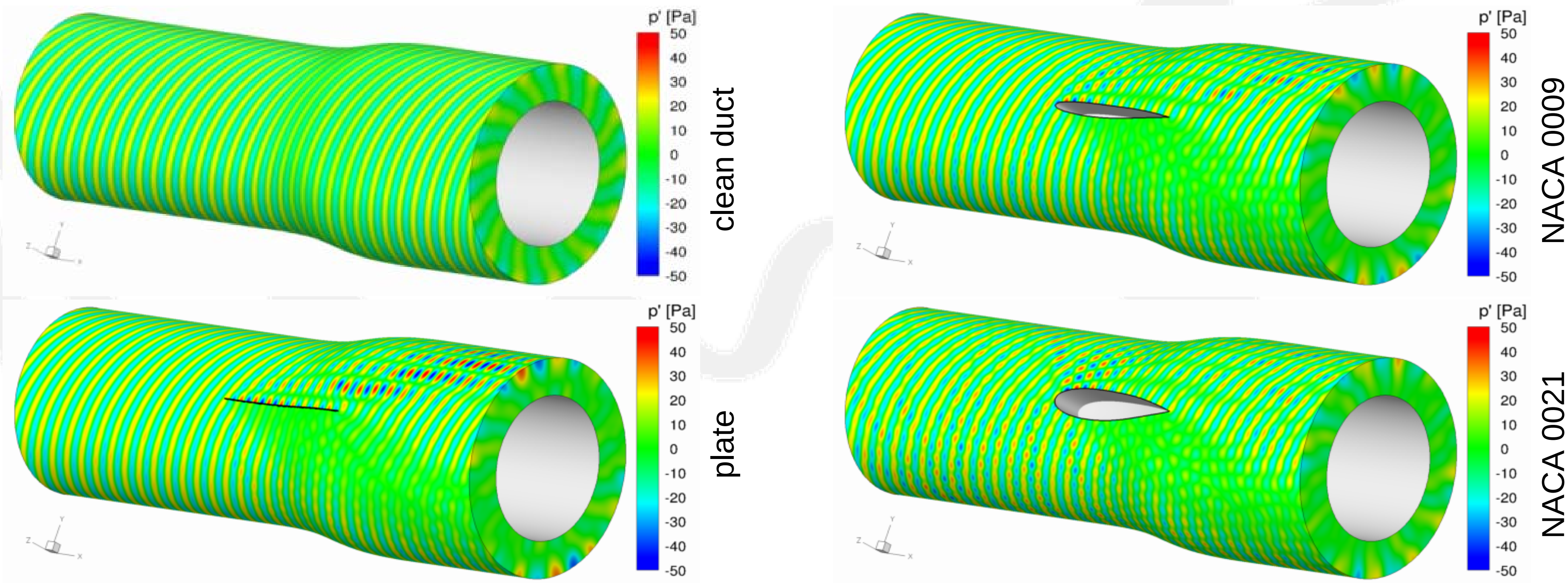
- Analysis with mode-matching method [Ovenden & Rienstra, 2004]
- Originally developed for extraction of acoustic components from unsteady CFD data
- Also suitable for modal analysis of the propagated sound field at arbitrary planar cross-sections in the duct
- Provides amplitudes and phases of all present modes for a given frequency
  - Azimuthal mode *m*
  - Radial mode *n*
  - Propagation direction (transmitted, reflected)





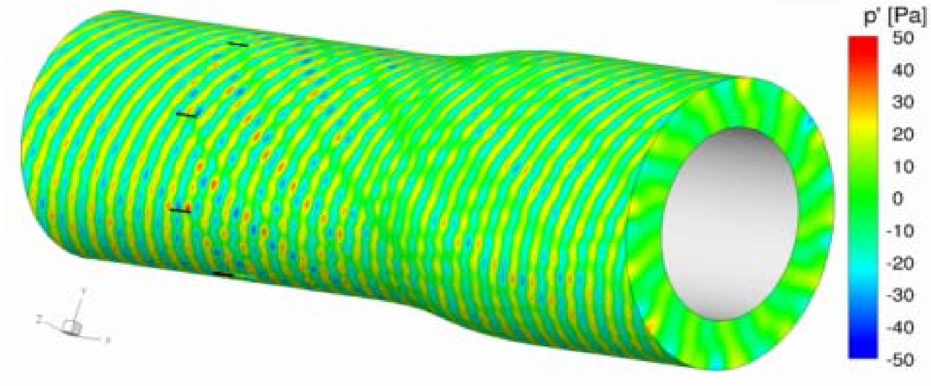
Installation effects in a S-duct – Effect of the profile width

- Splitters disturb the mode propagation
  - Reflections on the exposed side and shadowing on the rear side in propagation direction
- Increasing of the profile width
  - Decreased downstream transmission
  - Increased upstream reflection

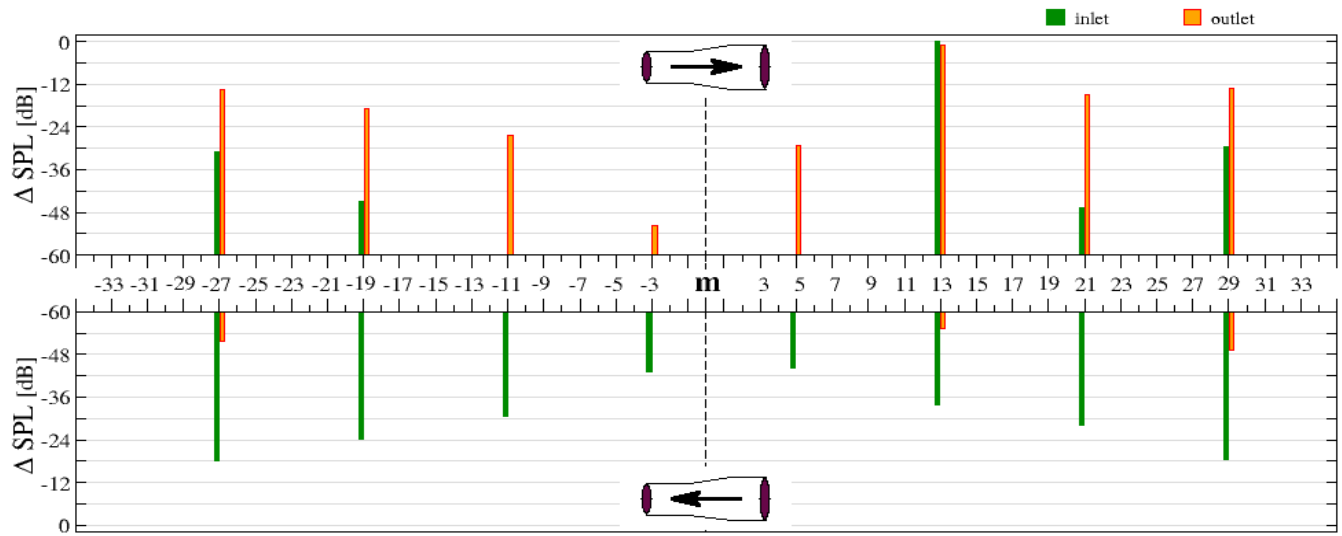


Modal analysis of installation effects – Struts

- Due to the 8 struts every 8th azimuthal mode is excited: theory of TYLER & SOFRIN (1962)



- Source mode m=13 keeps dominant
- Amplitude loss of source mode
  - ~1 dB
  - Cause: smaller number of scattered modes



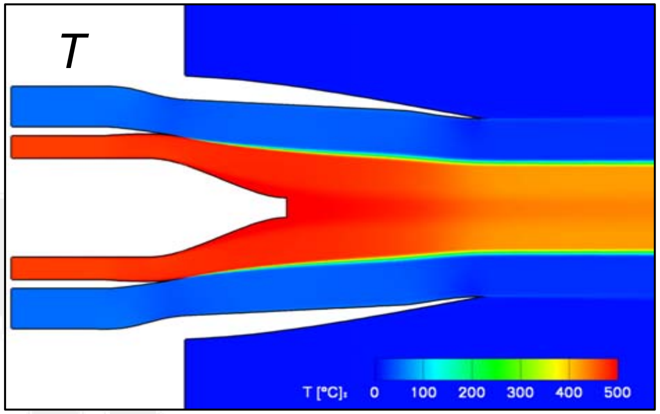
- Scattered modes at least 12 dB quieter
- Smaller influence compared to splitters

Numerical Experiment:
Radiation from a lined coaxial nozzle

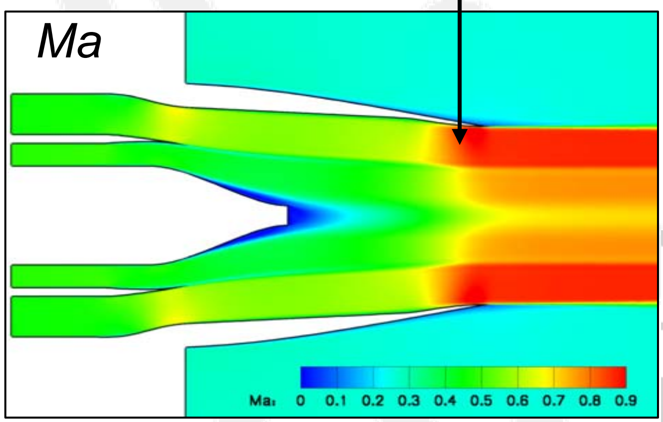
Numerical Experiment: Radiation from lined coaxial nozzle with splitter

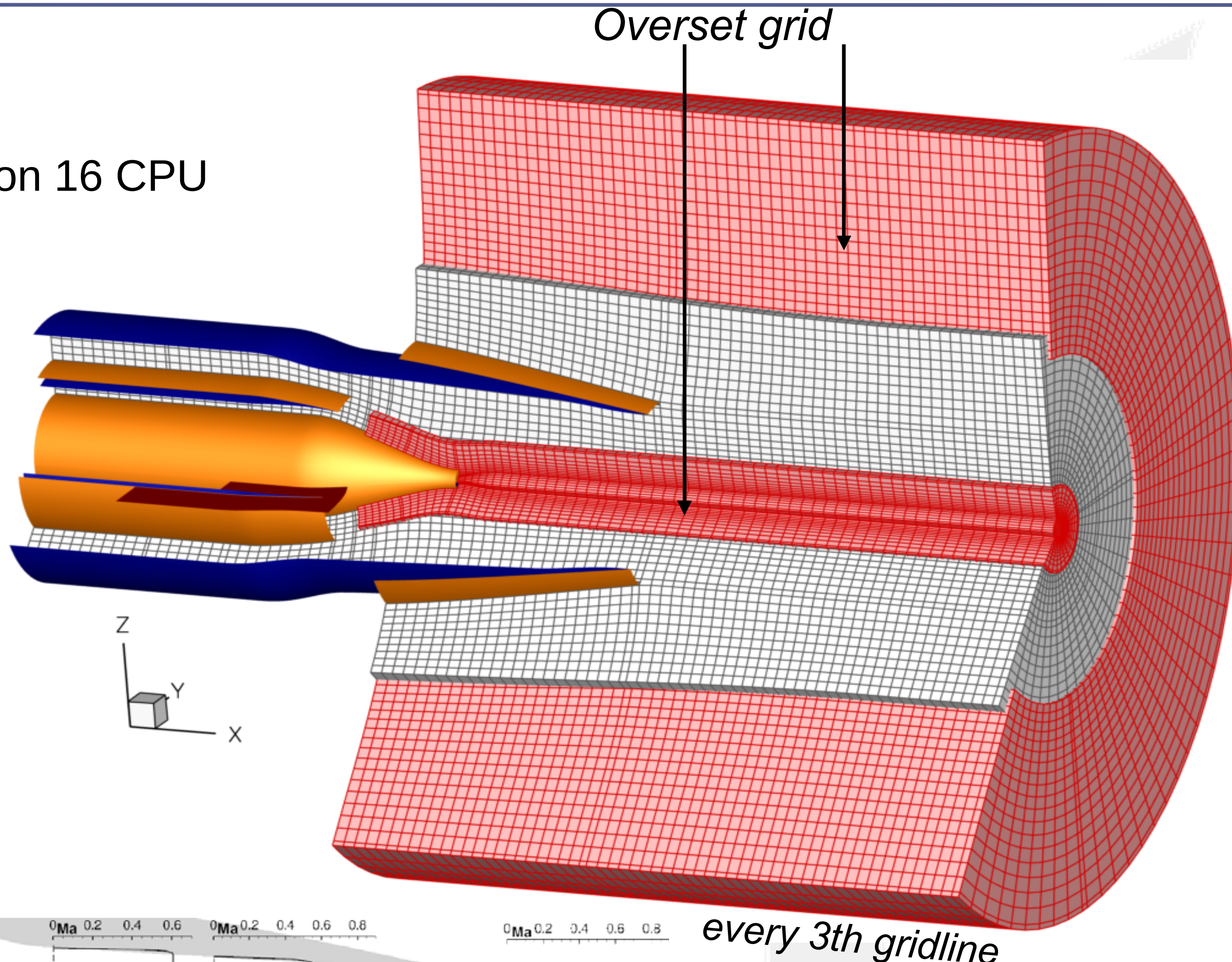
➢ Chimera mesh

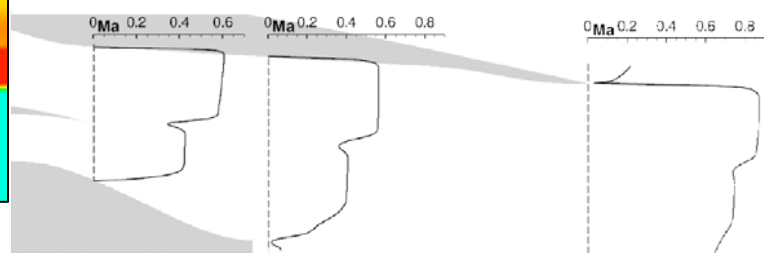
- $6 \cdot 10^6$ grid points
- 12 h computational time on 16 CPU cores



$M_{max} = 0.9$

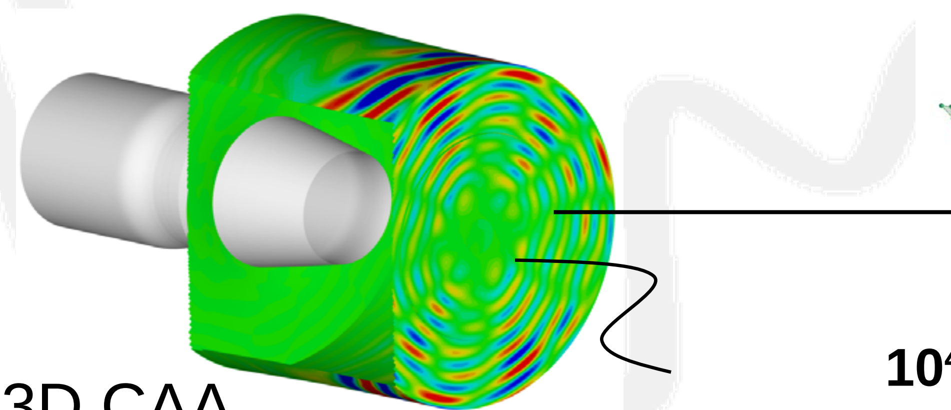


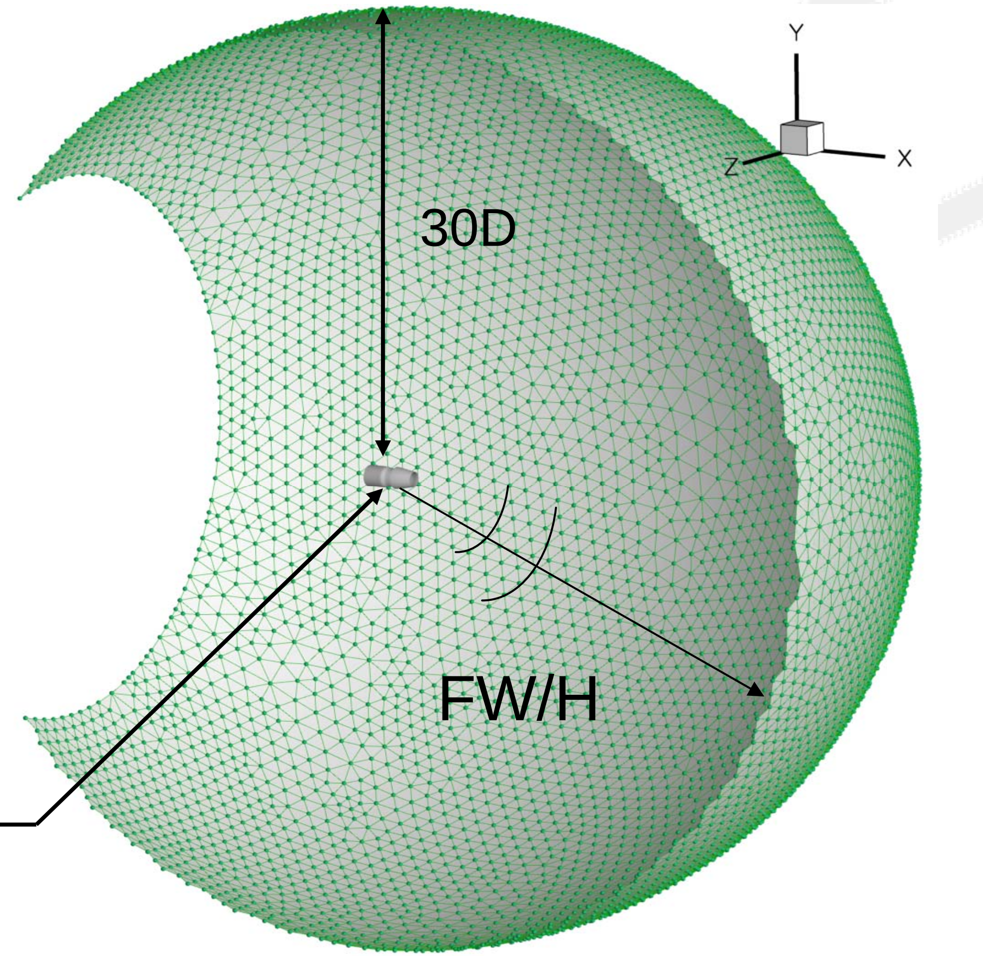




Acoustic analogy of Ffowcs-Williams & Hawkings for far field radiation

- Far-field calculation based on spatial and time resolved CAA simulation still impossible with current computing resources.
- Acoustic analogy of Ffowcs-Williams & Hawkings much faster
  - Parallel implementation (MPI)
  - Computational time: **1h** on 4 CPU

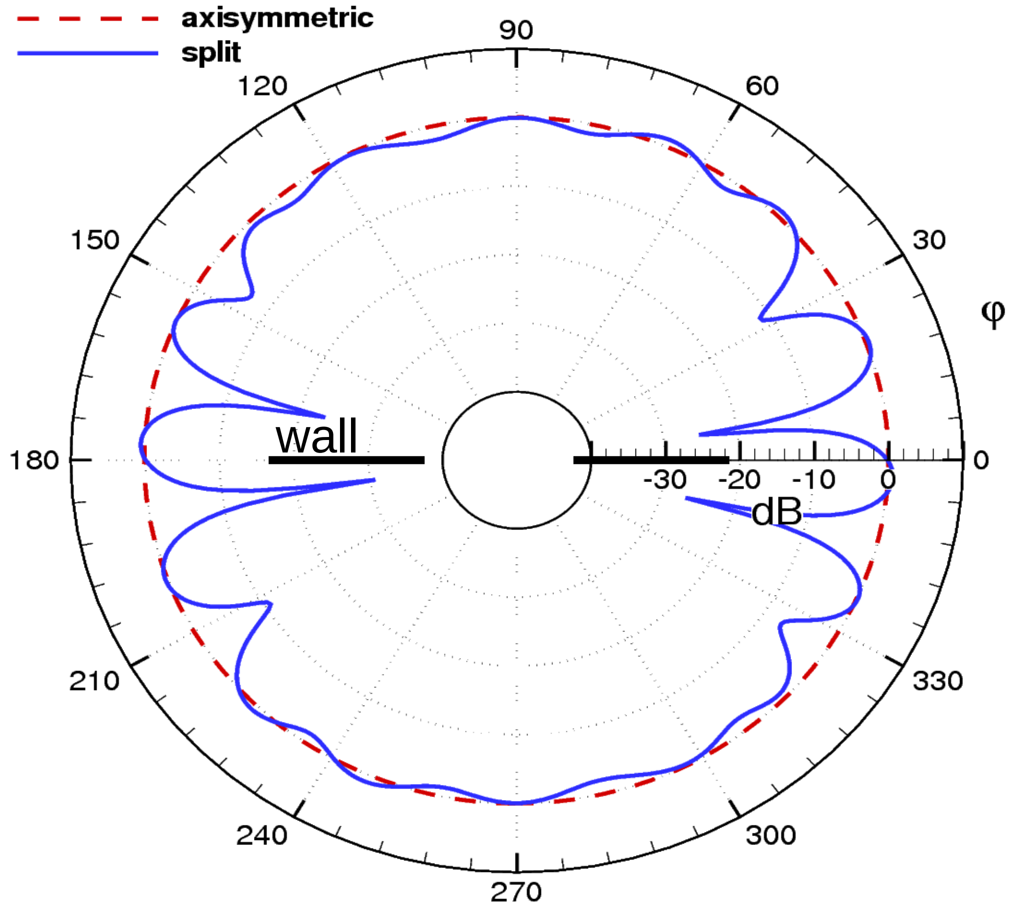




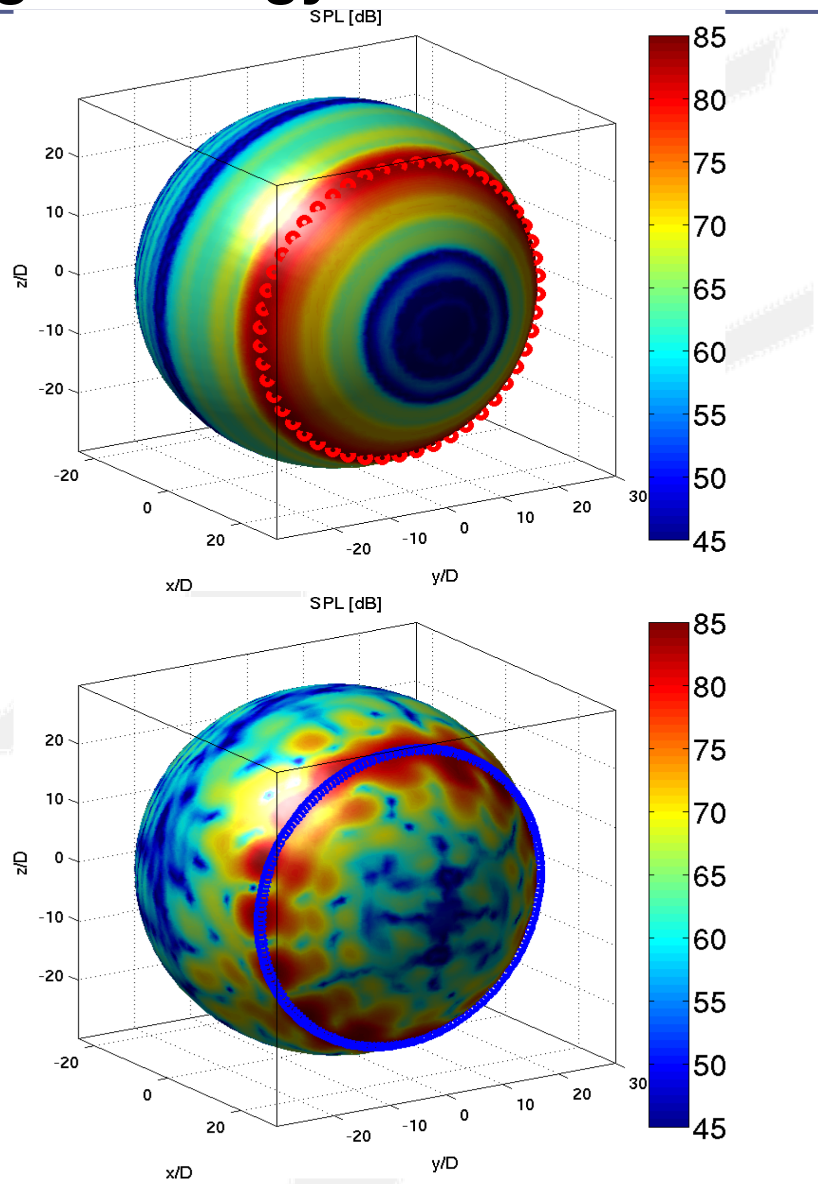
$\mathbf{10^4}$ **Observer** on sperical surface around coaxial exit nozzle (R = 30 D)

Far field radiation characteristics obtained with Ffowcs-Williams & Hawkings Analogy

- Bifurcation produces irregular radiation characteristics



Polar angle ψ=55°



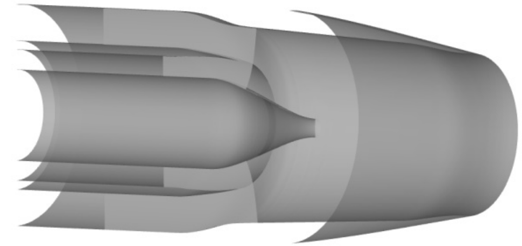
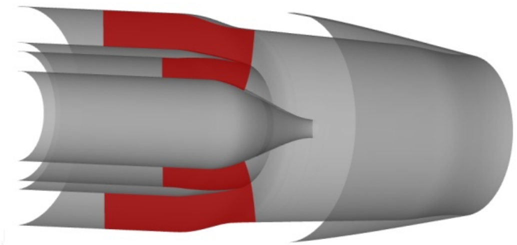
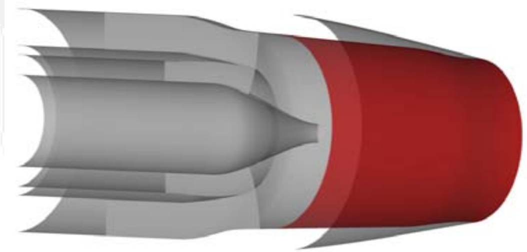
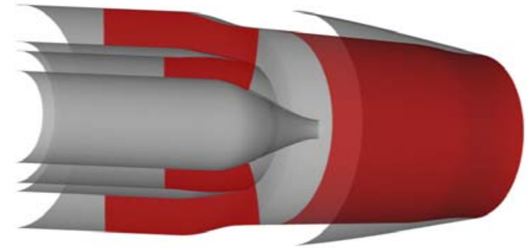
Radiation from a coaxial nozzle – Liner positions

- Extended-Helmholtz-Resonator (**EHR**) Model with 5 Parameters [RIENSTRA, 2006]

- Resolved wall boundary layers and shear layers in the base flow

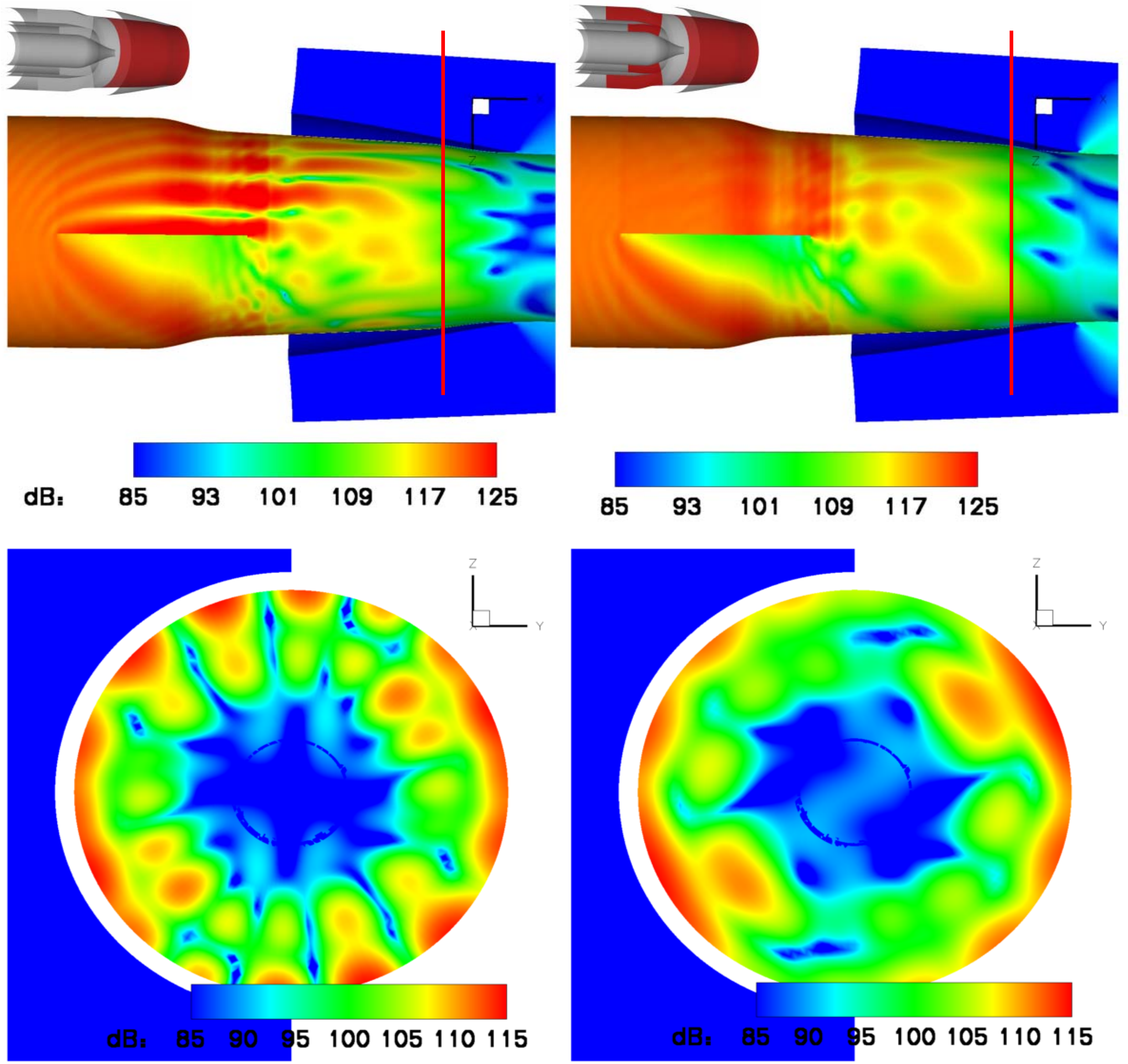
- **Model parameters are obtained from “impedance eduction“** with an inlet liner from AleniaAermacchi [BUSSE ET AL., 2008],

- Inlet liner not optimized and practical applicable in the bypass duct → numerical experiment!

No lining, hard bifurcations (reference)	
Lined bifurcations	
Lined exit nozzle	
Lined exit nozzle and bifurcations	

Application of educed model for inlet liner – Numerical experiment: Radiation from a coaxial nozzle

Only nozzle lined

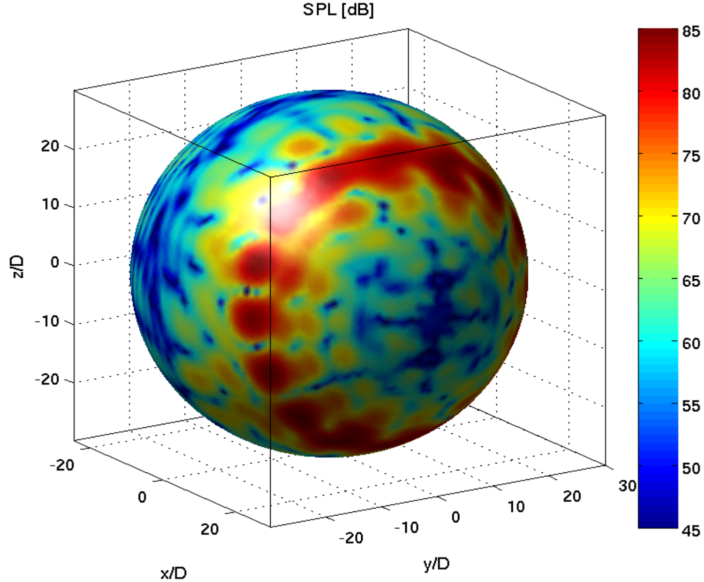


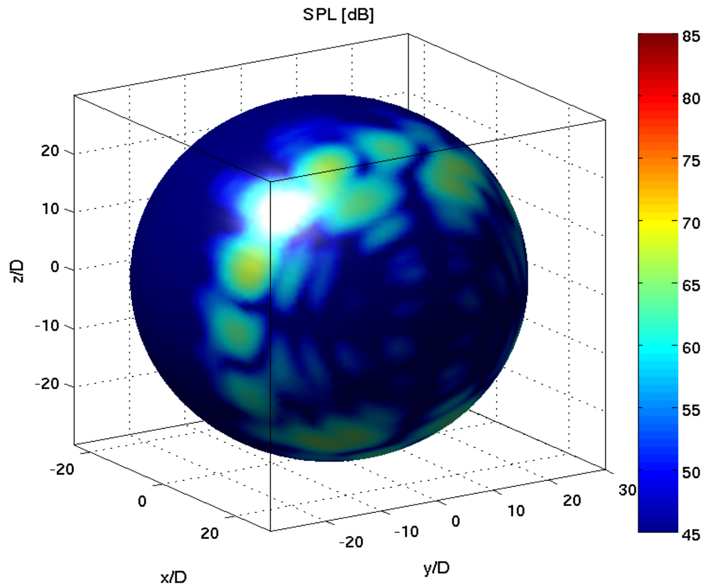
Nozzle and splitter walls lined with typical inlet liner

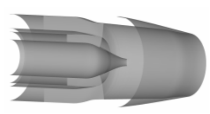
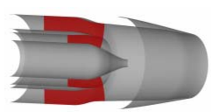
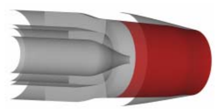
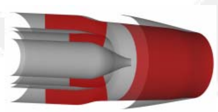
Cut at x = -0.5

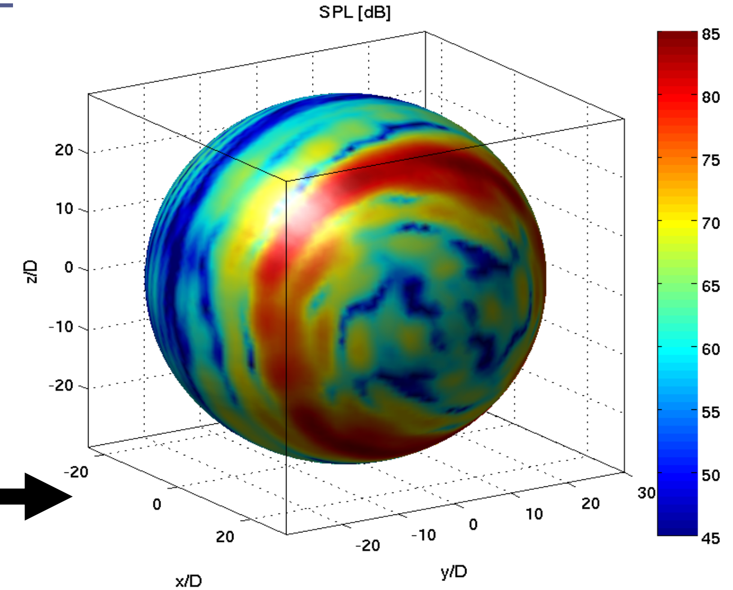
P_{RMS} [dB]

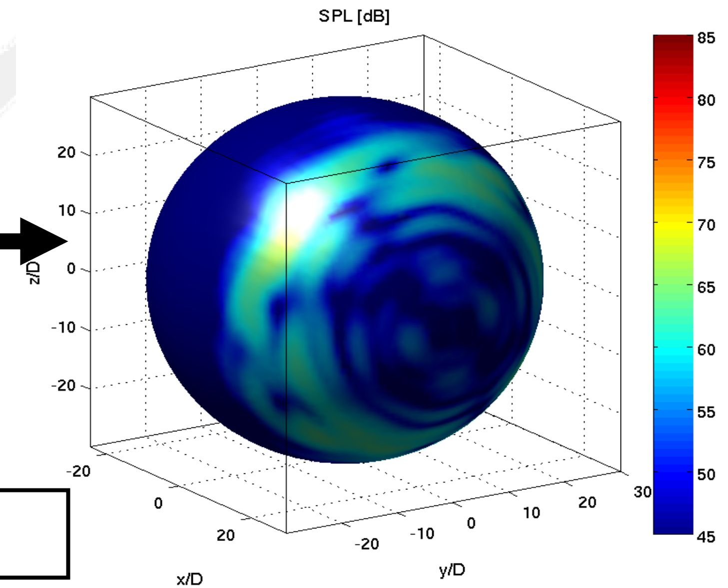
Radiation from a lined coaxial nozzle – Radiated power





Radiated power	
Fall	**P_a [dB]**
	**0**
	**-0.6**
	**-17.5**
	**-17.3!**

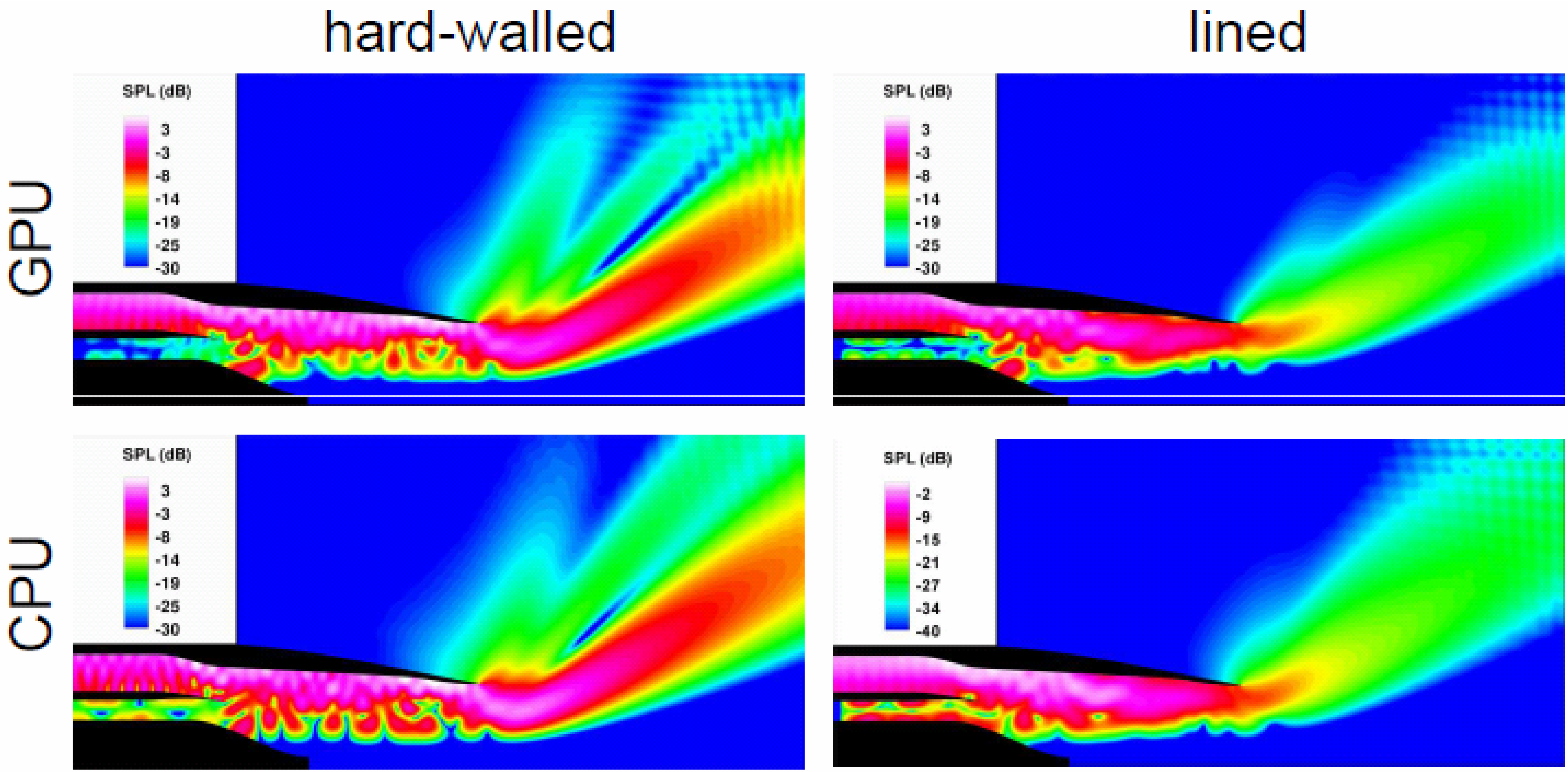




Scaling 45-85 dB

GPU based acceleration of the simulation for optimization purposes

GPU based simulation of the lined coaxial nozzle configuration in 2D



- CPU and GPU in reasonably agreement (non-reflective BC missing for GPU)
  - TUBA3D: 8.560 minutes
  - GPU: 22 minutes

→ Speed up of over 300

Large speed-up by GPU computing possible

CPU		GPU
High fidelity University research	→	Calculable for single configuration in industrial application
Calculable for single configuration in industrial application	→	Optimizable (calculates multiple configurations)
Optimizable (calculates multiple configurations)	→	Real time simulation?

GPU computing makes optimization available for many applicatoins at low hardware costs!

Observed speed up requires writing a new code!

Conclusions

Conclusions

- Numerical experiments predicting sound propagation and radiation are possible today:
  - Can give deep **insight** to real physics of the sound propagation in ducts, 3D data available
  - Simulation of complex geometries and with complex flow conditions
  - **Cost effective** parameter studies
  - **GPUs** will allow optimization in near future
  - Validation and analysis of each specific result remains essential part of the task.
- Experiments cannot be avoided:
  - Accurate experiments are required more than ever to provide **model parameters** and input for CAA.

Thank You!

The DRP based CAA solver TUBA

CAA method

- 3D finite difference based time-domain method
  - Spatial discretization:
    Dispersion-Relation-Preserving Scheme (DRP), [Tam & Webb, 1993]
  - 7-point central difference scheme, 4th order optimized
- Time discretization:
  - 5/6, resp. 5-stage Runge-Kutta scheme, [Hu, 1996 / Carpenter, et al, 1994]
  - Storage optimized (2N-storage), [Stanescu & Habashi, 1998]
- Spatial low-pass Filter
  - Up to 10th order, 11 point filter stencil
  - Secure supression of no-resolved short waves
  - Low dissipation of waves resolved above 7 PPW
- TUBA – One method several mathematical models:
  - 2D, modal axisymmetric (AXI), fully 3D
  - Linearized Euler equations (LEE), nonlinear Euler equations (PENNE), isentropic/non-isentrop variants
  - Parallel Implementation (MPI)

Boundary conditions

- Boundary Conditions:
  - Source Boundary
    - Analytical source model (modes, frequencies, amplitudes)
      - Modal analyses of experimental data
      - Modal matching approach of CFD data [OVENDEN & RIENSTRA, 2004]
    - Direct input of unsteady CFD data
  - Non-reflecting boundary conditions
    - Radiation/outflow condition [BAILLY & BOGEY, 2002]
    - Sponge Layer [ISRAELI & ORZAG, 1981]
    - Perfectly Matched Layer (PML) [HU, ET AL. 1996/2001]
  - Wall boundary conditions
    - Hard wall
    - Lined wall, Extended Helmoltz Resonator (EHR) [RIENSTRA, 2006]

  - Structured multi domain method

  - Overset Grid Method (Chimera)

Anwendung des EHR Modells

Das erweiterte Helmholtz-Reosonator (EHR)-Impedanzmodell im Zeitbereich

- EHR-Modell (Rienstra 2006)
  - Fünf Parameter-Modell für den Frequenzgang der Impedanz
  - SDOF (Totzeit T_l)
  - Massenreaktanz der Deckschicht m_f und Reaktanz des Volumens, sowie offene Fläche in β berücksichtigt
  - Dämpfung der Deckschicht R_f und des Volumens ε berücksichtigt
- Verknüpfung zum klassischen Modell für tiefe Frequenzen über Laurent-Reihe
  - **Verknüpfung zu geometrischen Größen!**

$$Z_{\mathrm{EHR}}(i\omega) = R_f + i\omega\, m_f - i\beta \cot\left(\frac{1}{2}\,\omega\, T_l - i\,\frac{1}{2}\,\varepsilon\right)$$

$$= \frac{\left(R_f + i\omega\, m_f\right)\,\left(1 - e^{-\alpha}\right) + \beta\,\left(1 + e^{-\alpha}\right)}{1 - e^{-\alpha}},$$

with $\quad \alpha = i\omega\, T_l + \varepsilon.$

Randbedingung im Zeitbereich:

$$\frac{\partial u_n'}{\partial t}(t) = \frac{1}{m_f}\left[\mu(t) - (R_f + \beta)\, u_n'(t)\right] \underbrace{- \frac{1}{m_f}\, e^{-\varepsilon}\left[\mu(t - T_l) - (R_f - \beta)\, u_n'(t - T_l)\right] + e^{-\varepsilon}\,\frac{\partial u_n'}{\partial t}(t - T_l)}_{\text{storage term}},$$

Annäherung des Kotangens über eine Laurent-Reihe

$$Z_{\mathrm{EHR}}(i\omega) \approx R_f + \frac{1}{6}\,\varepsilon\,\beta + \frac{2\,\beta\,\varepsilon}{T_l^2 + \left(\frac{\varepsilon}{\omega}\right)^2} + i\omega\,\left(m_f + \frac{\beta\, T_l}{6}\right) + \frac{1}{i\omega}\,\left(\frac{2\,\beta\, T_l}{T_l^2 + \left(\frac{\varepsilon}{\omega}\right)^2}\right)$$

Verknüpfung der Modellparameter des EHR Modells zu geometrischen Größen

- Vorteil der Optimierung im Zeitbereich:
  - Optimierung der Modellparameter für mehrere Frequenzen (z.B. BPF und 2xBPF) liefert direkt die Geometrie des optimalen Liners
  - Aus Erfahrungen mit der *impedance eduction* für Linern im Prüfstand des DLR (AT-TA) kann die Verknüpfung überprüft werden

Verhältnis zwischen korrigierter Hals-Länge und Open Area

$$\frac{L}{\sigma} = m_f + c_0 \frac{1}{6} \beta T_l.$$

Verhältnis aus Fläche und Volumen

$$\frac{S}{V} = \frac{1}{c_0} \frac{2 \beta T_l}{T_l^2 + \frac{\varepsilon^2}{\omega^2}}.$$

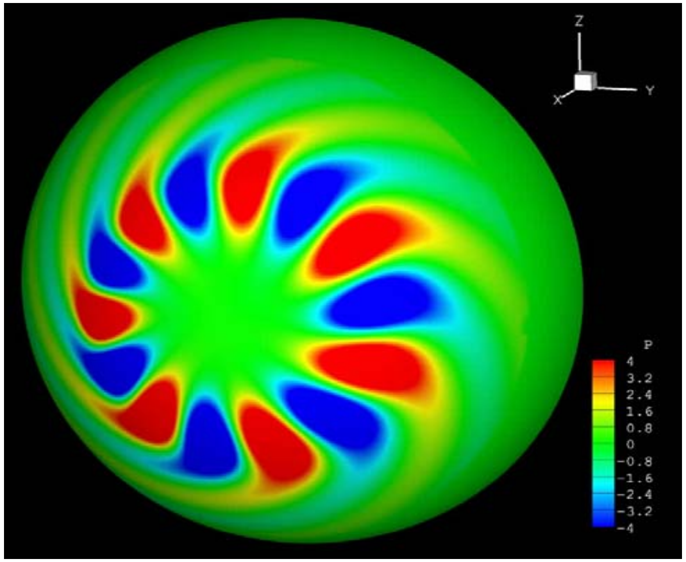
Näherung für die Dämpfung *(Re{Z})*

$$R_f + \frac{2 \beta \varepsilon}{T_l^2 + \left(\frac{\varepsilon}{\omega}\right)^2} + \frac{1}{6} \beta \varepsilon$$

Beispiel für eine 3D-Rechnung mit Liner

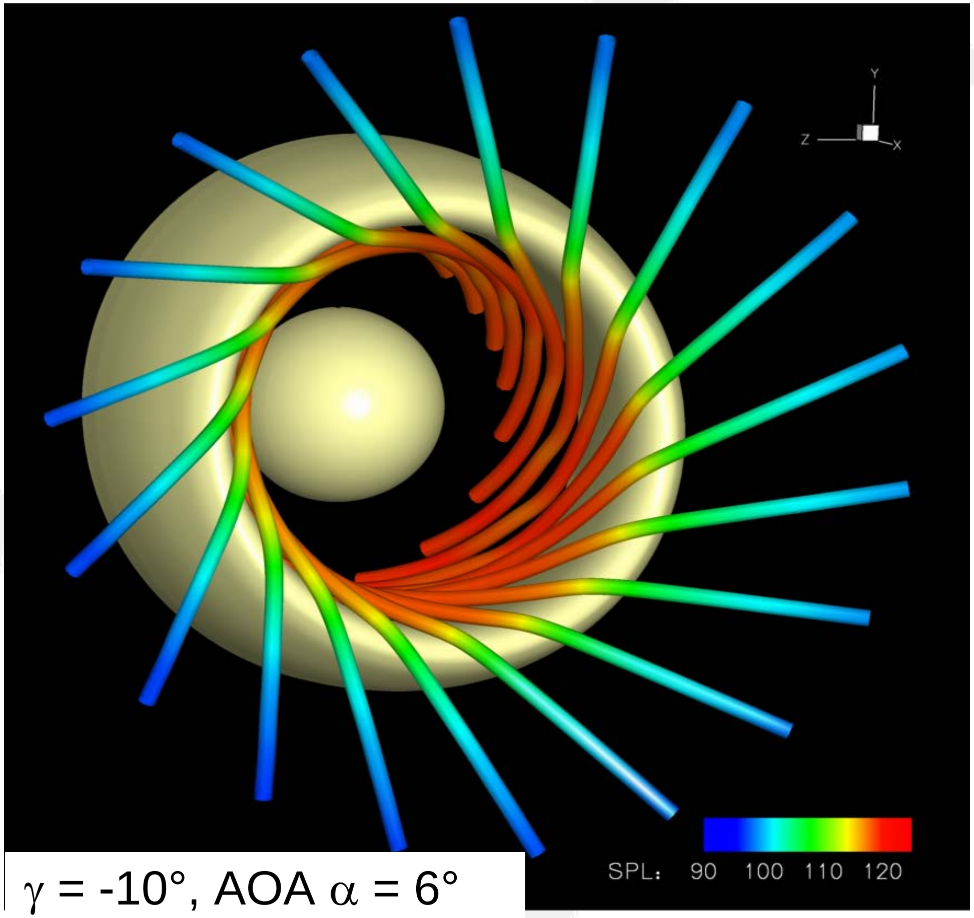
3D scarfed Intake: Auswertung der Schallintensität

- Stromlinien der akustischen Intensität zeigen den Weg des Schalls durch den Einlauf auf.
  - Beeinflussung der Absttrahlung nach unten muss dem Pfad des nach unten abgestrahlten Schalls folgen.
  - (7,0) mode, $f = 1$ kHz
  - $M_{\text{flight}} = 0.2 \qquad M_{\text{fan-plane}} = 0.35$



Momentan-aufnahme des Schalldrucks

FW/H Austauschfläche, Abstand 1m

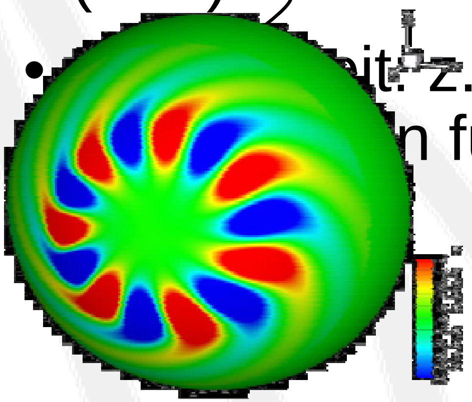


γ = -10°, AOA α = 6°

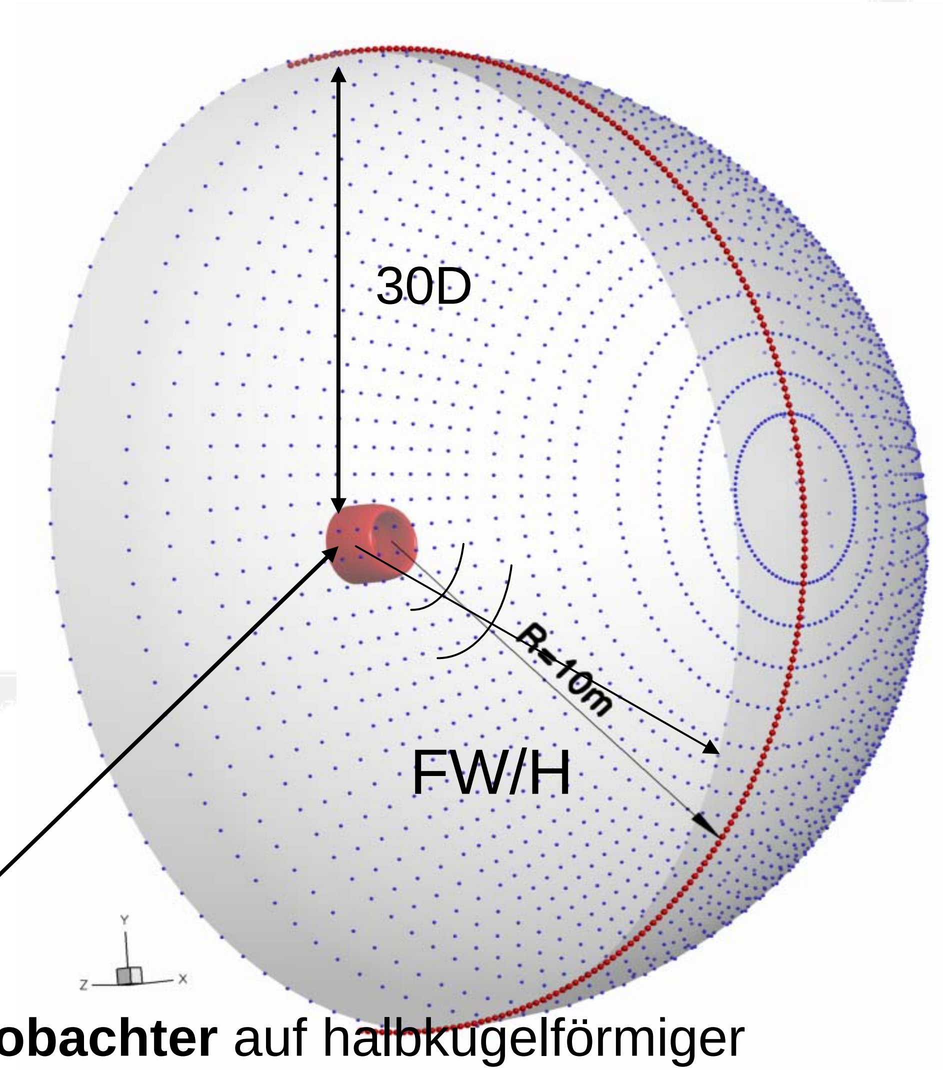
Anwendung der akustischen Analogie von Ffowcs-Williams & Hawkings

- Akustische Analogie nach Ffowcs-Williams & Hawkings (FW-H)
  - Ausnutzung der Zeit-Periodizität möglich (nicht notwendigerweise harmonisch!)
  - Parallele Implementierung (MPI)
  - ...it: z.B. **1h** auf 4 ...n für 10^4

Austauschfläche



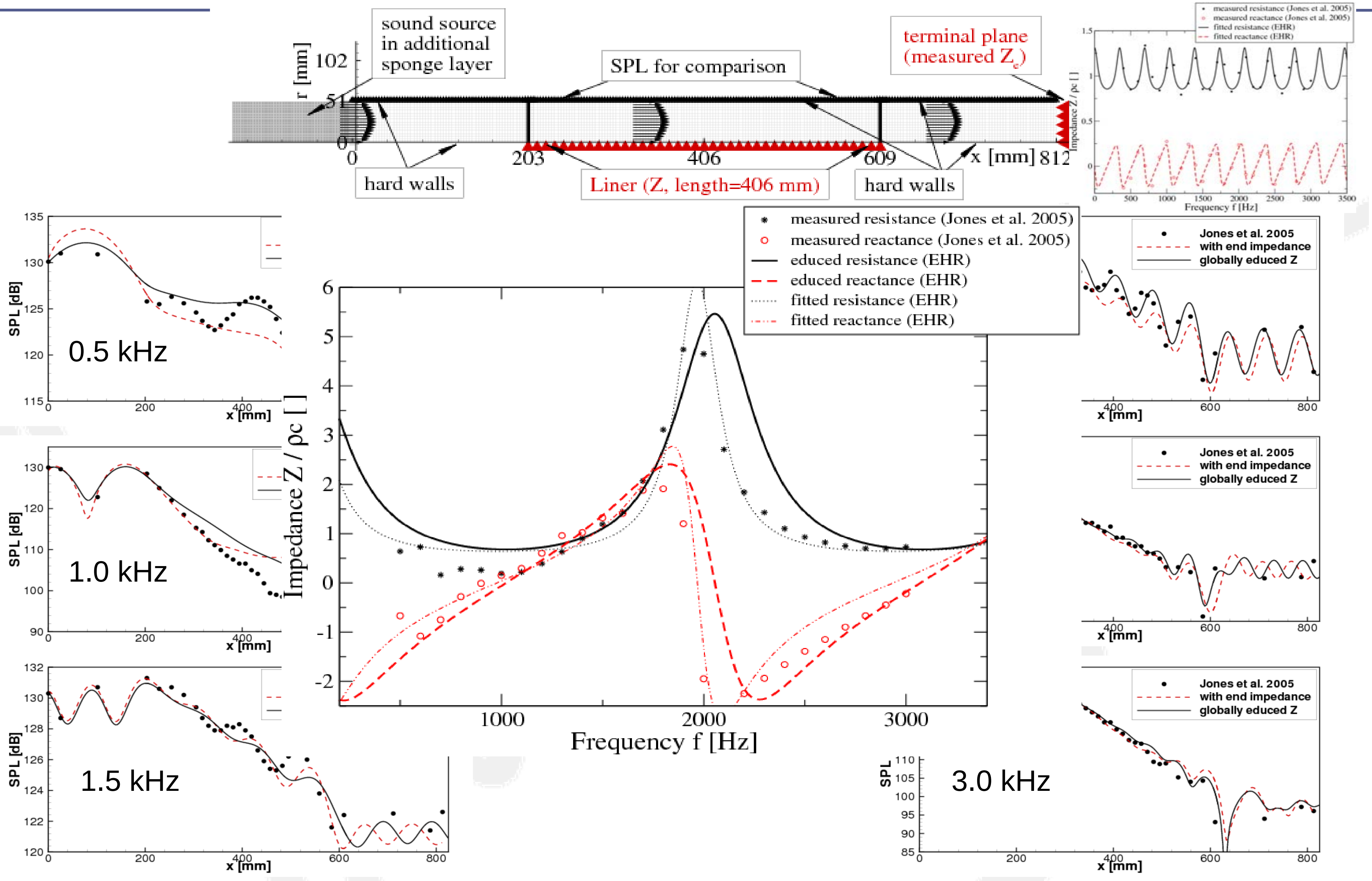
3D CAA



Beobachter auf halbkugelförmiger Fläche vor dem Einlauf

Validierung des Verfahrens mit Liner

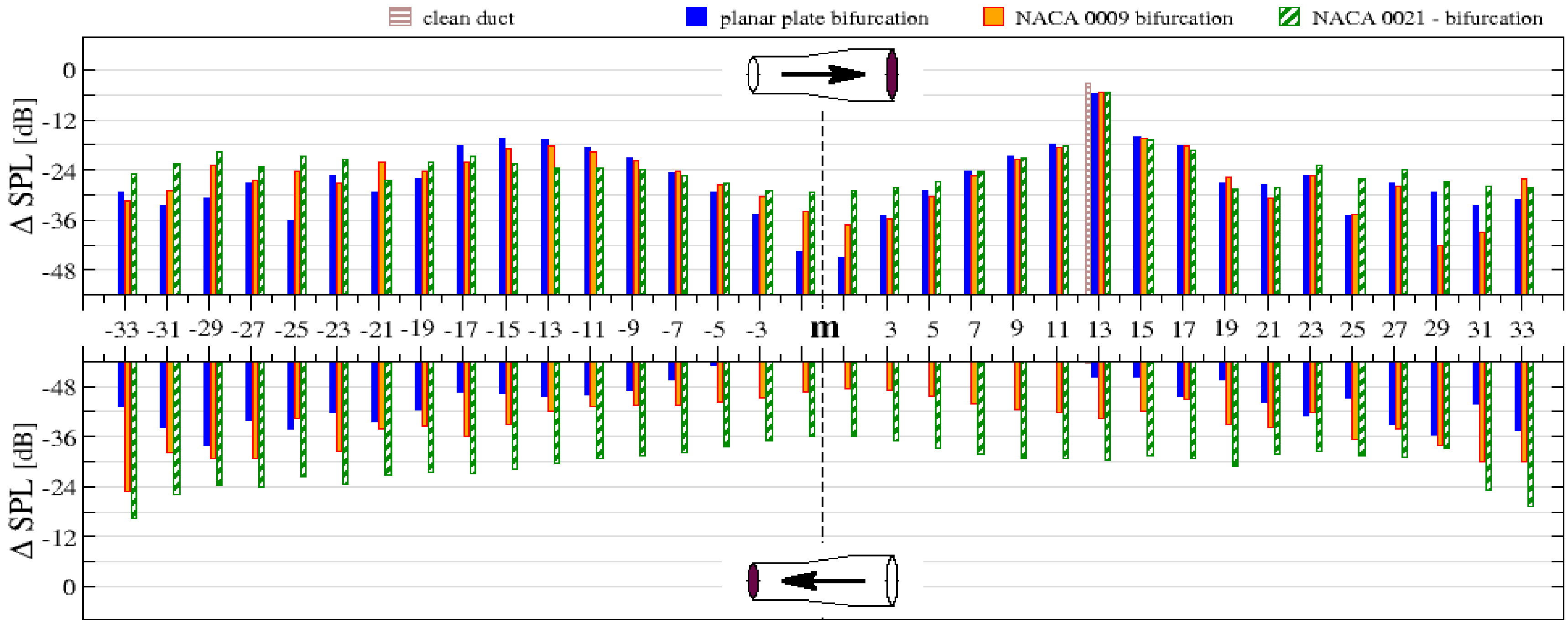
NASA GIT Experiment, AIAA Journal 2007



- Folgende Folien sind aus dem Original entfernt

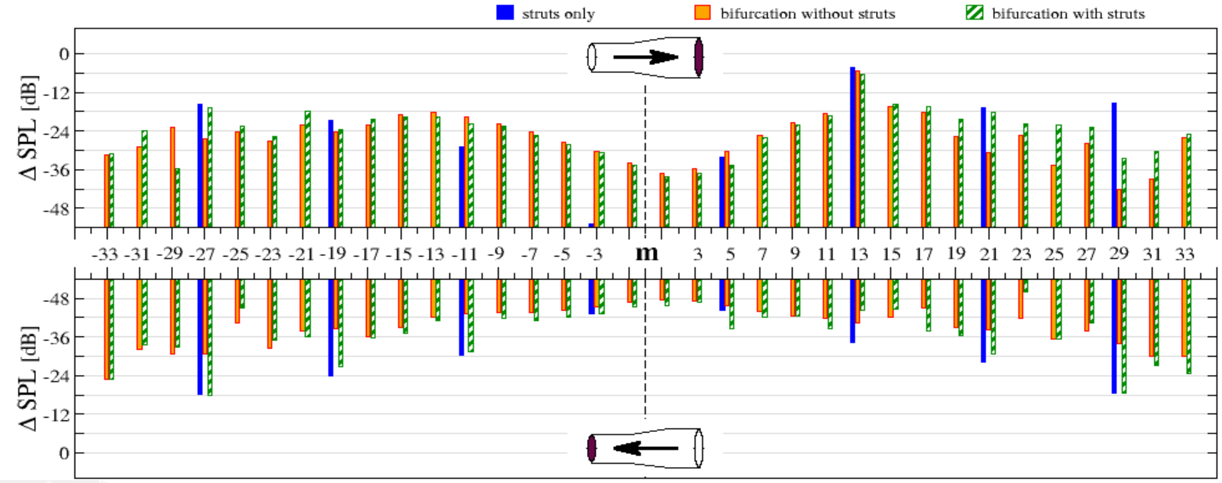
Modal analysis of installation effects – Effect of the bifurcation profile width

- Correspondingly to the theory of TYLER & SOFRIN (1962) the two splitter cause a scattering of the source mode into every second propagation capable mode (m±2S; S is a natural number)
- Source mode (13,0) keeps dominant
- Scattering cause a reduction of the source mode amplitude by ~2.5dB
- Scattered modes are at least 12dB quieter than source mode

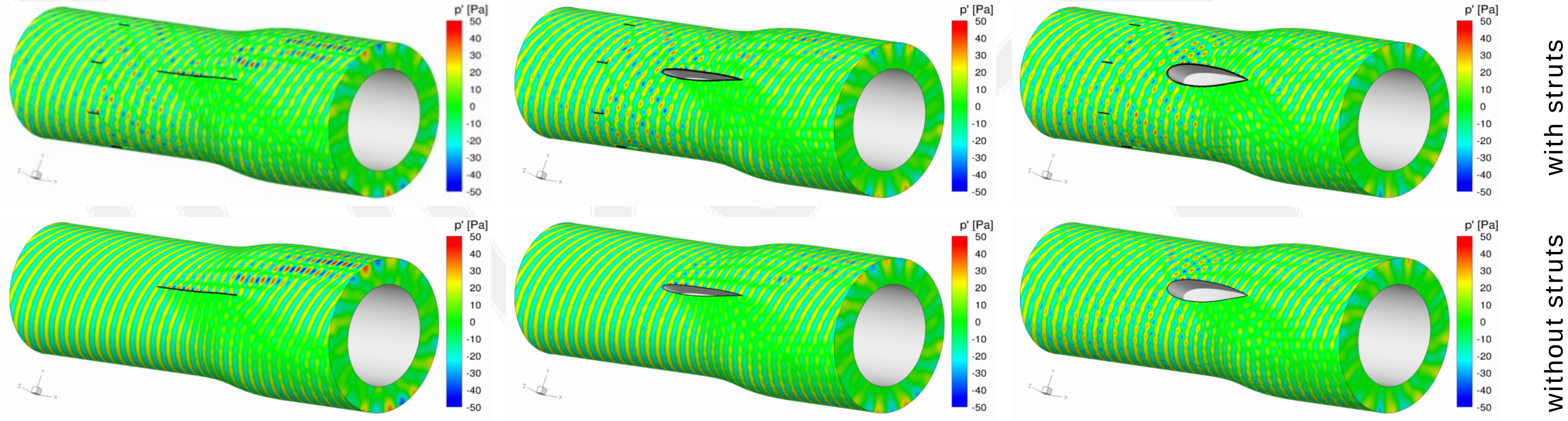


Mode analysis of installation effects – Combination of struts and splitter

- Combination of Splitters and struts



- Similar mode spectrum for cases with and without struts
- Only modes excited in both configurations change noticeable, especially near the inlet



Validation of each specific CAA result

Motivation for a general validation methodology

- Finite difference based CAA methods have no conservation properties.
  - It is easy to get 20dB of numerical dissipation by choosing a wrong setting for the filter or having under resolved meshes in crucial regions.
- How to monitor the correctness of a CAA result and secure the interpretations and conclusions drawn from the numerical experiment?

- Suggested solution: Assessment of the acoustic energy conservation.
- Problem: perturbation equations are applied as CAA-model, for which no conservation properties can be stated in general:
  - Conservation of energy, momentum and mass applies only for the whole flow field.
  - Most general formulation is perturbation energy conservation for the acoustic energy by Morfey [1971] applies in a potential flow field with acoustic perturbation modes only.
  - However, allows limited validation of the results.

Intensity based analysis

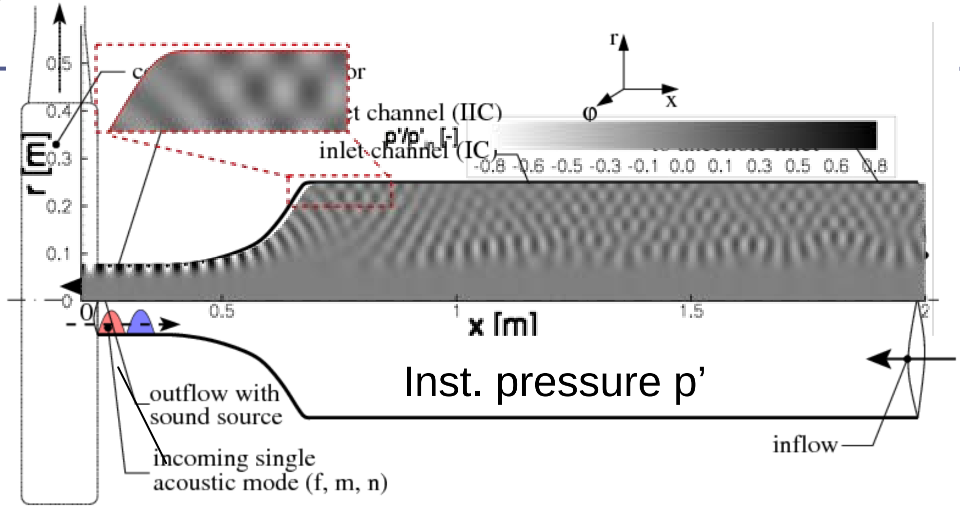
- A *by view* analysis of the solution quality by watching the sound pressure cannot capture scattered modes and transient processes as well.
- Acoustic intensity is calculated accordantly to the definition of [MORFEY, 1971] during the simulation an averaged in time (e.g. over one period of a harmonic oscillation)
- Entire energy flux at arbitrary axial positions is given as integral of the time averaged acoustic intensity over the cross-section:

$$P_a(x) = \int_{A(x)} \underline{I}_a \cdot d\,\underline{A}$$

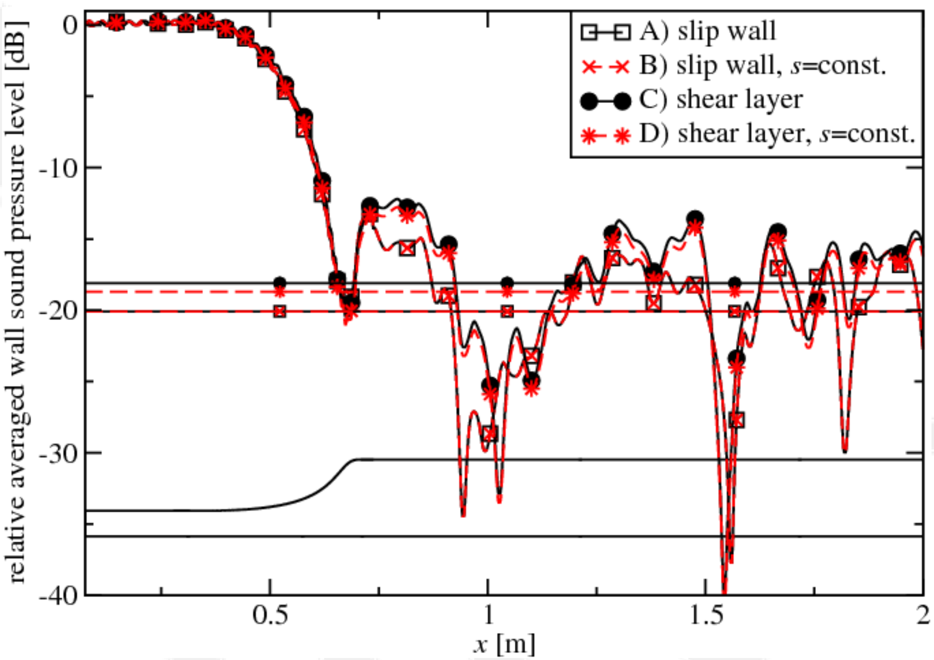
- Acoustic power at all cross sections should be constant in source and sink free hard walled ducts (with potential flow and acoustic modes only).
- With liner, there is a power flux into the lined wall
  - Global conservation of the incoming and outgoing acoustic energy should apply for each control volume.
- Acoustic power is suitable to quantify numerical dissipation.
- Divergence of the time averaged acoustic intensity is a measure for the local source strength → identifies regions with large dissipation.

Intensity analysis for a centrifugal compressor inlet duct

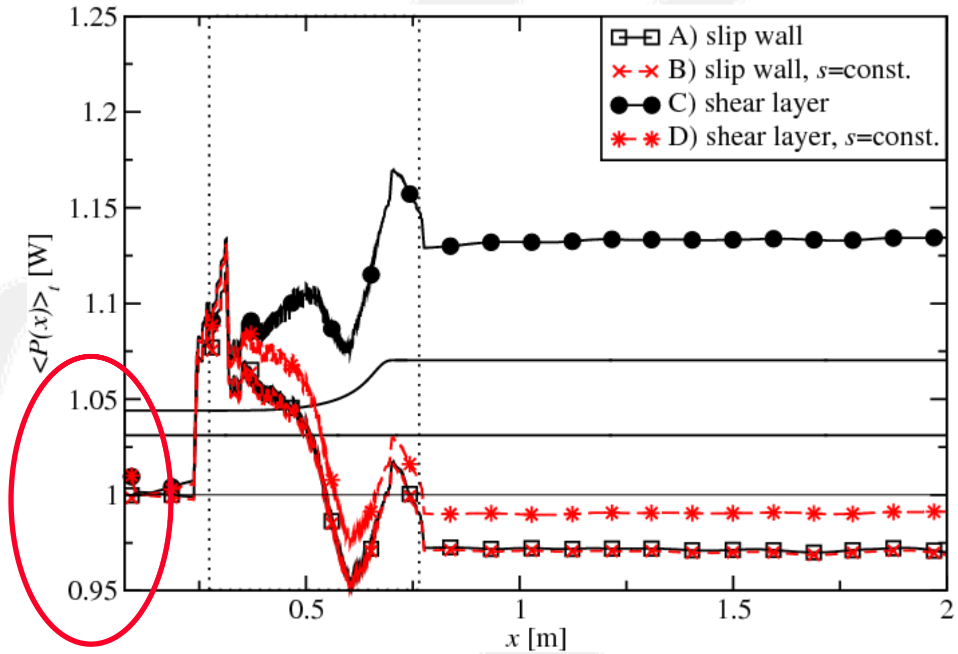
<u>Excitation</u> of a single m=13, n=0 mode and strong mode scattering at inlet nozzle



<u>Background flow:</u> realistic boundary layer (Stokes) and potential flow (Euler) at Ma=0.3 at the inlet



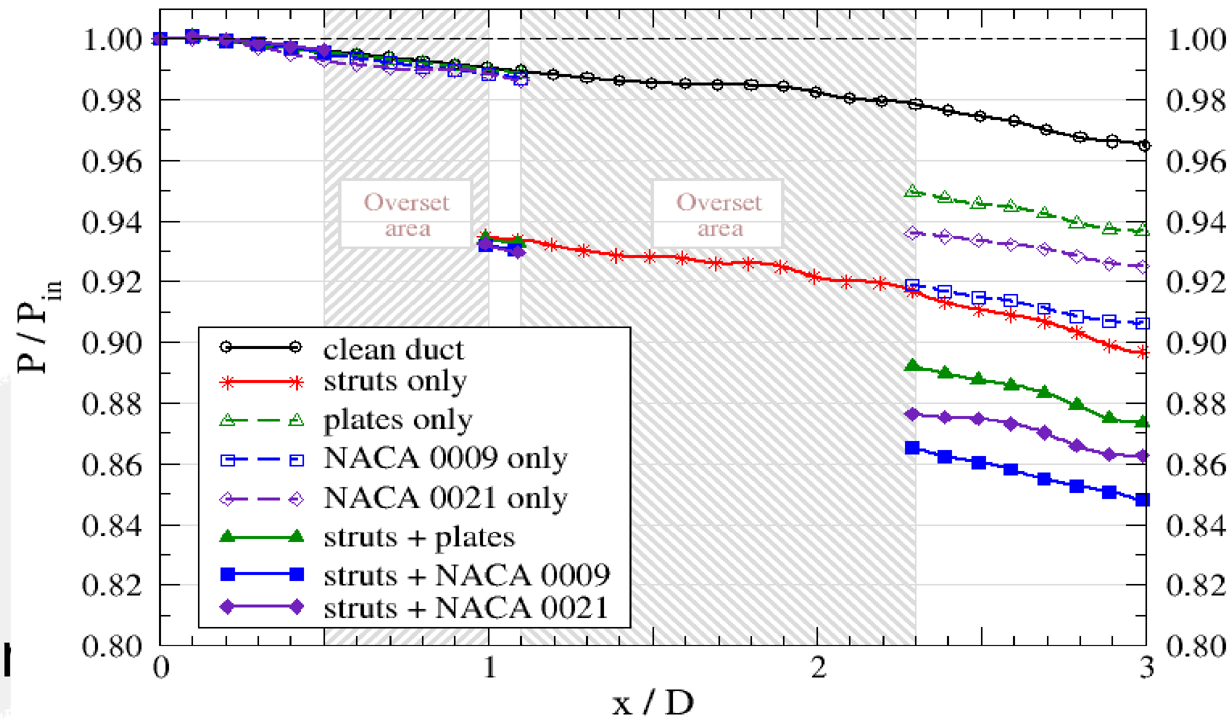
Wall sound pressure level shows a „loss“ of ~20 dB! – Would you expect this result can be correct?



Acoustic power is dissipated or amplified by up to 15% (3% for potential flow) → errors are small.

Intensity analysis of the solution quality in a bifurcated S-duct with Chimera applied

- Back to the S-duct configuration
- Acoustical power distribution in axial direction
  - 3% general dissipation by discretization errors
  - 3-12% extra dissipation by interpolation errors and stronger grid distortion



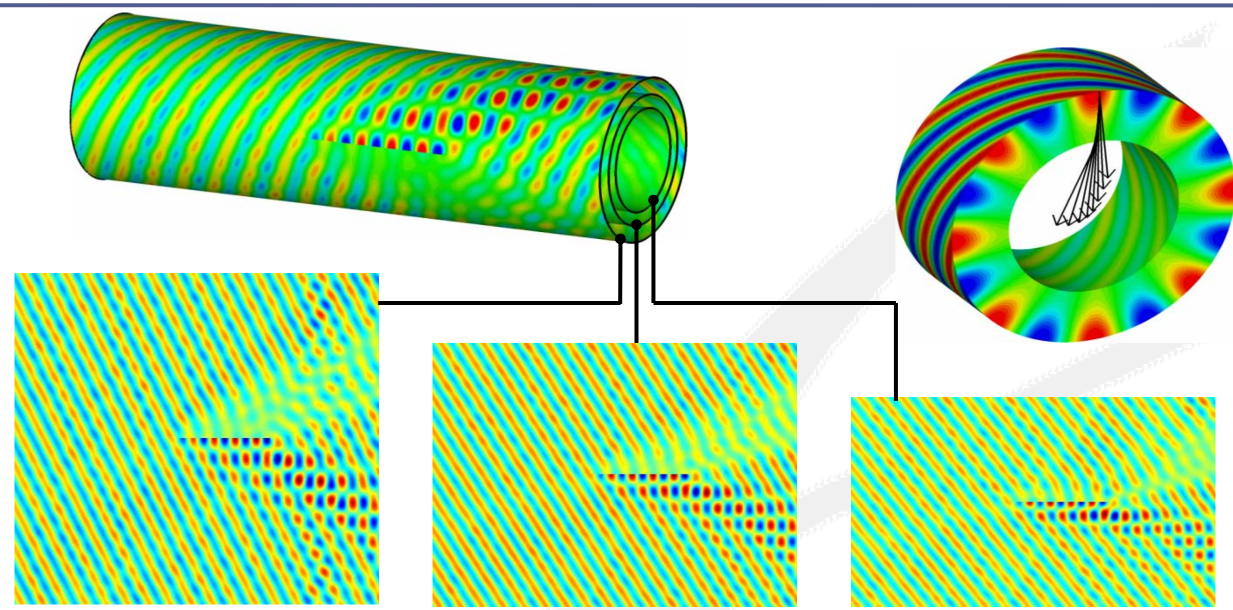
- Overall error:
  - up to 15% loss of acoustical power
  - up to 0.7dB loss of sound pressure
- Acceptable for industrial applicatio

Development of an analytical model from the CAA result – unroll radius

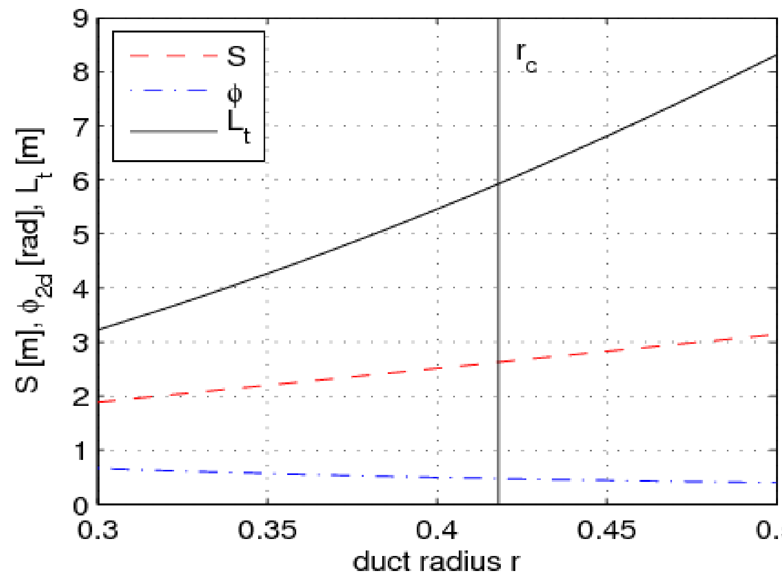
At which radius should the duct be unrolled?

- Reversion length depends on
  - Propagation angle φ
  - Splitter distance S
- Caustic radius [Chapman, 1994] and outer radius are limits of the perfect radius to unroll the duct
- Unroll radius depends on the geometry and the mode (eigenvalue)
- Caustic radius:

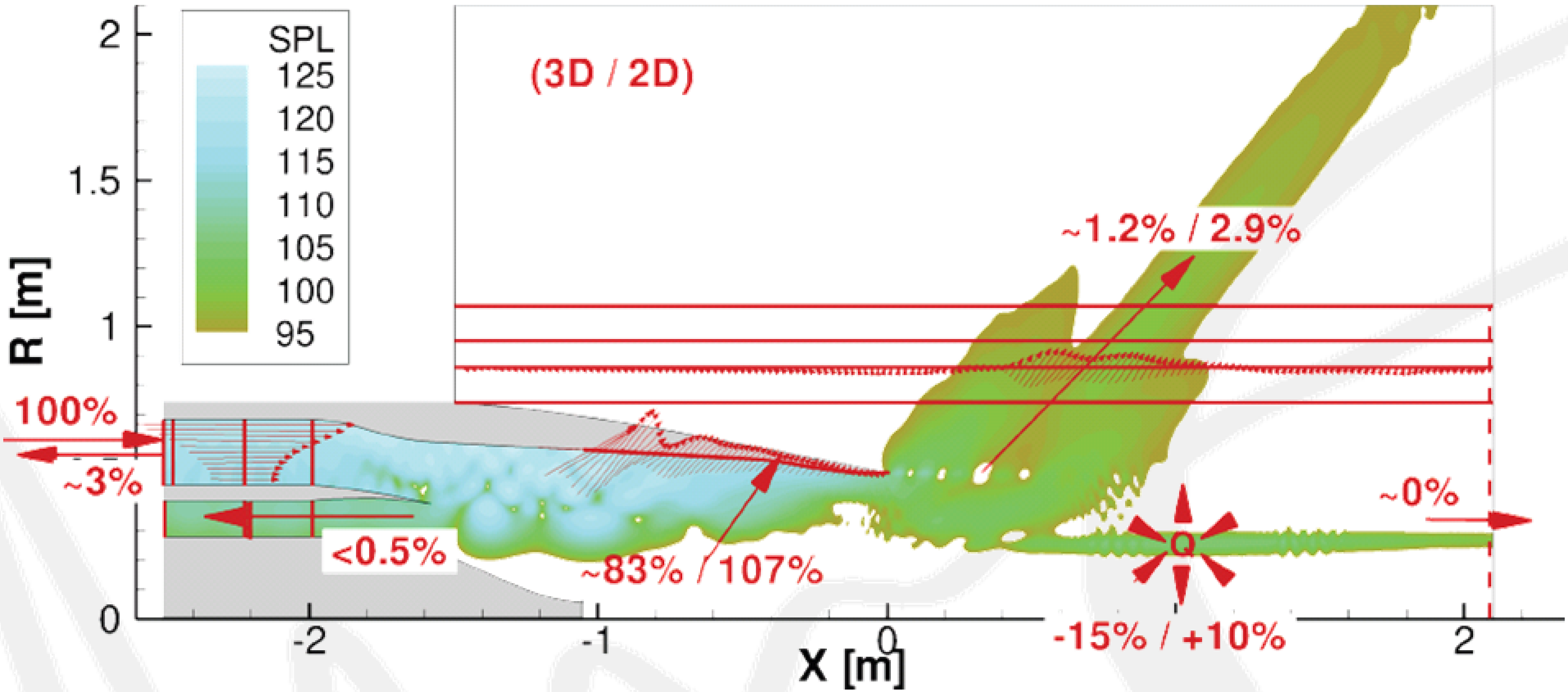
$$r_c = \frac{|m|}{\sigma_{mn}} R$$



largest radius mid radius smallest radius



Radiation from a coaxial nozzle (2D/3D) – Detailed analysis of the acoustic energy flux

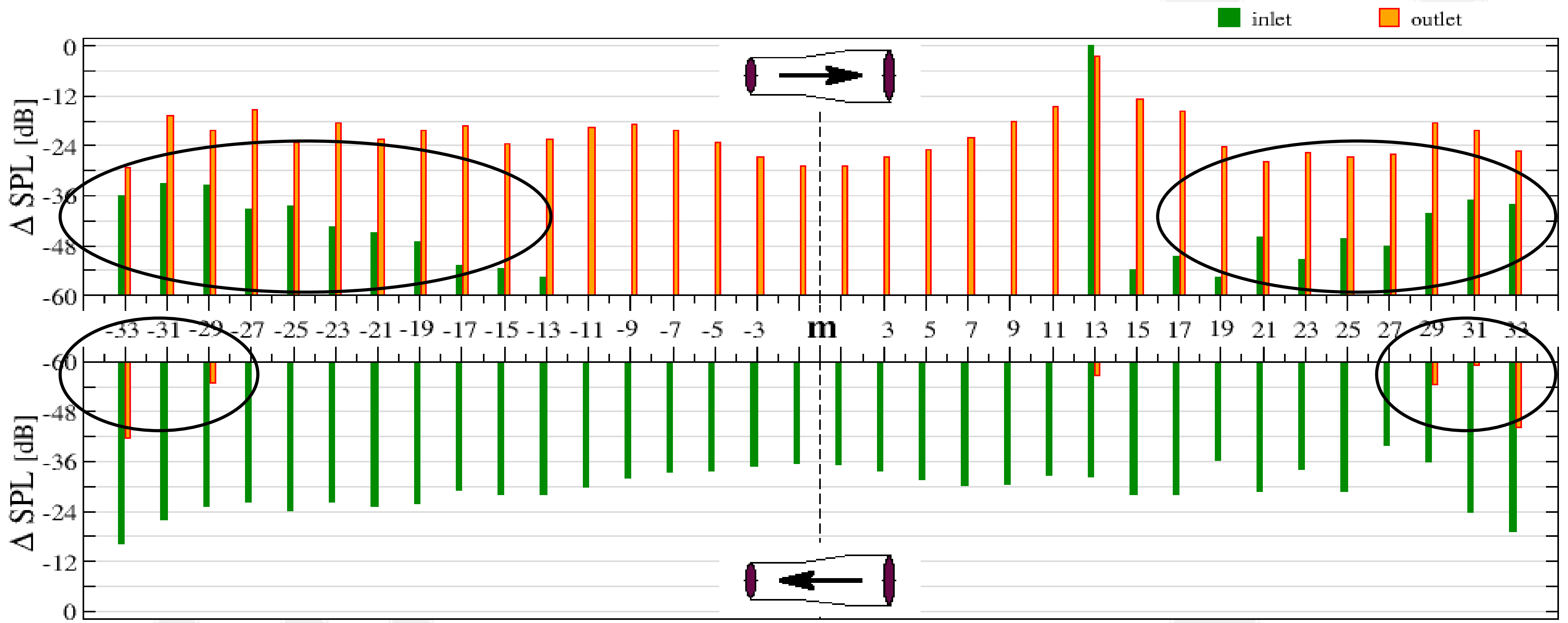


- Global energy balance:
  - Source input is 100 %
  - Outgoing fluxes over bypass duct, core duct, liner and nozzle exit
  - Production and annihilation of ac. energy: non-isentropic, non-potential flow and numerical dissipation
- In the hard walled case all acoustic energy (104 %) is radiated.

The potential of GPU computing

Modal analysis provides validation of the non-reflective properties of the BC's

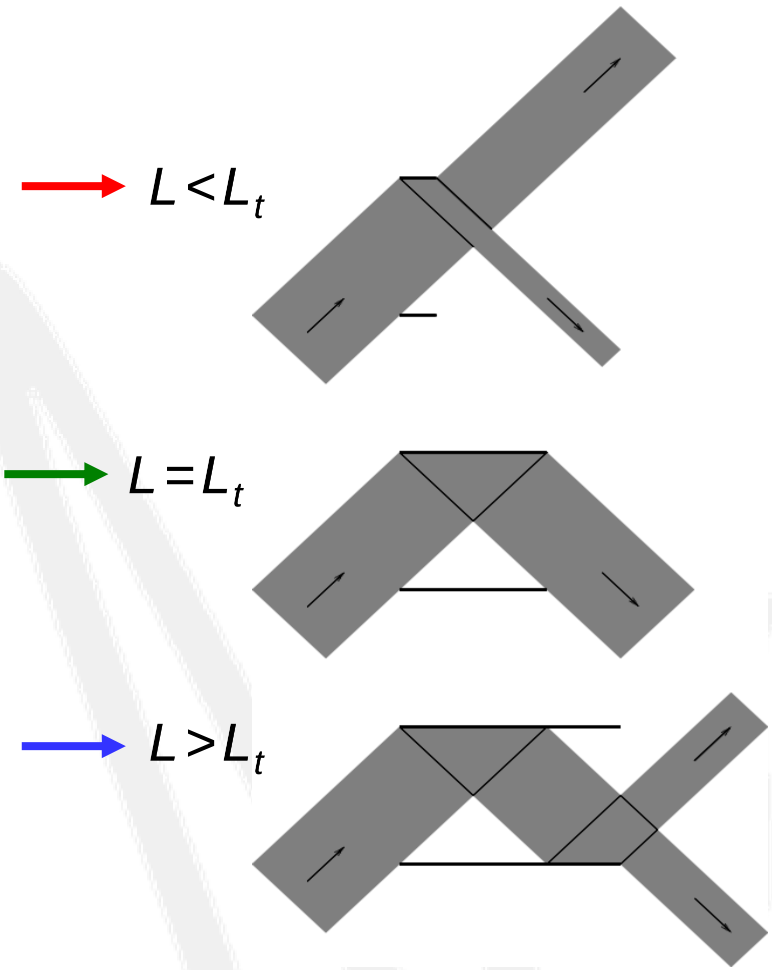
- Visible non-physical reflections in a clean duct:
  - At inlet and outlet boundary, for high azimuthal mode orders
  - Amplitudes more than 12dB lower than physical modes and 30dB lower than source mode ➔ small impact on the entire solution
  - **PML** at outlet performs **better** then sponge layer at inlet



How to describe the sound field in the bifurcation?

Derivation of a theoretical model from the CAA results – Definition of a mode reversion length

Definition of a characteristic length L_t, for which source mode is reversed totally (m → -m)!



$$L_t = \frac{S}{\tan^{-1} \phi_{2d}}$$

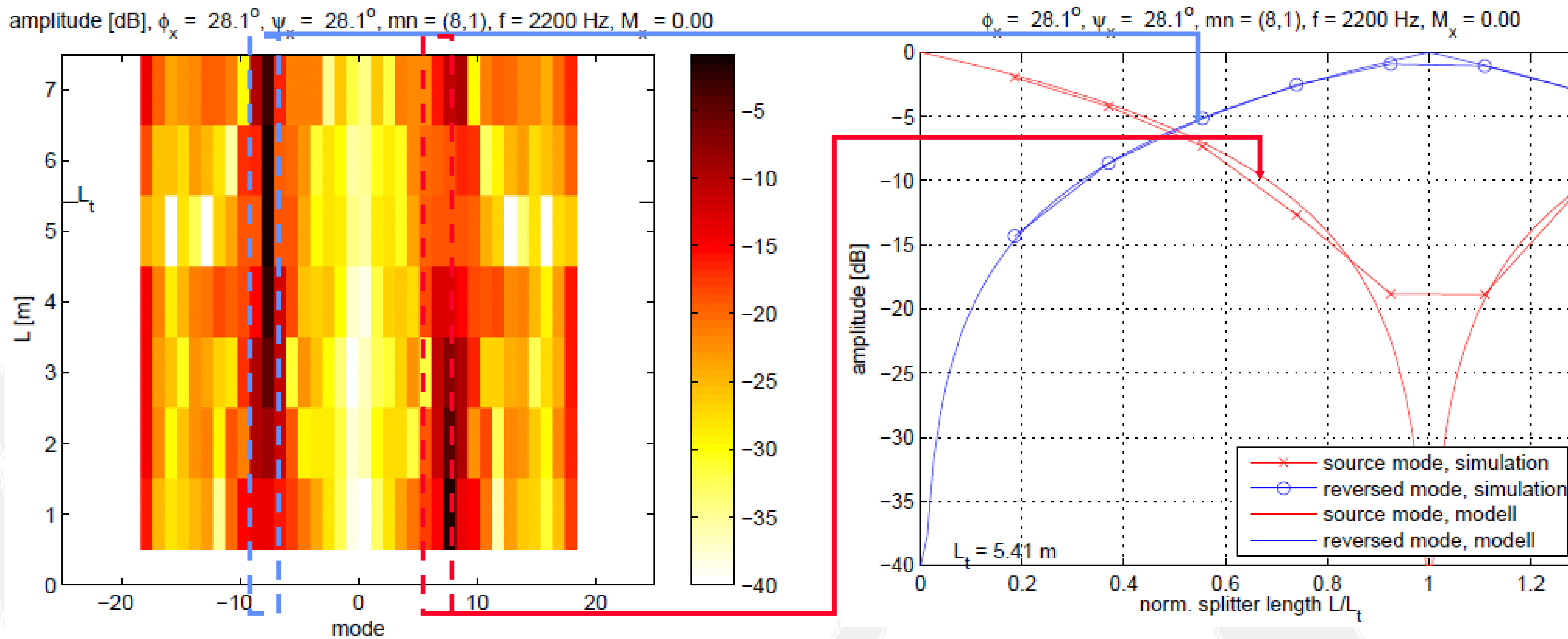
$$f(L) = \begin{cases} 1 - \frac{L}{L_t} & \text{for } 0 \leq L \leq L_t \\ -1 + \frac{L}{L_t} & \text{for } L_t < L \leq 2\,L_t \end{cases}$$

$$g(L) = 1 - f(L)$$

f(l) ist the amplification factor for the initial source mode (m),

g(l) denotes the amplification of the reversed mode (-m)

Attenuation of modes by hard infinite thin splitter – analytical model based on CAA simulations



Mode amplitude after splitter over splitter length and mode

Mode amplitude for |m|=8 behind splitter over splitter length

- Acoustic energy oscillates periodically between positive and negative modes with increasing splitter length.
- Periodicity of spectum over splitter length