Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

Institute of Aerodynamics
and Flow Technology

# Towards Forced Eddy Simulation for Installed Nozzle-Wing Configurations

Andrej Neifeld, Roland Ewert
German Aerospace Center (DLR), Braunschweig

CEAA 2018 Aeroacoustics Conference
18.-23. September 2018
Svetlogorsk, Russia

# Aim of the Work
## Installed Jet Noise Simulation

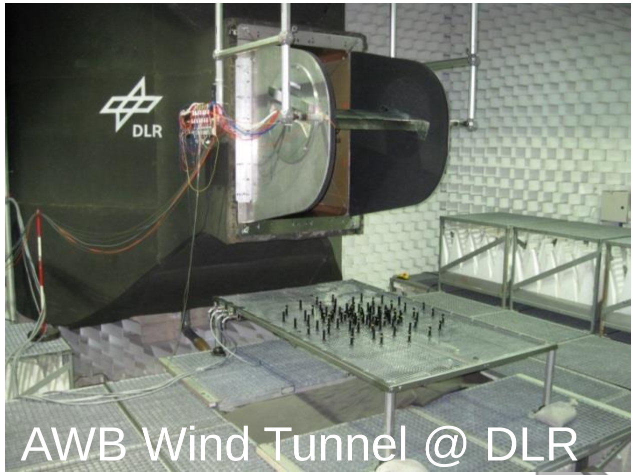
- Direct Noise Computation (DNC[1]) of a jet-flap installation noise wind tunnel setup tested in the Acoustic Wind Tunnel Braunschweig (AWB) at DLR
- DNC[1] using a zonal RANS/VLES[2] approach based on Non-Linear Disturbance Equations (NLDE)[3]
  - Zonal VLES of the entire wind tunnel setup using a standard CFD/CAA framework
  - Evaluation of the potential to lower resolution requirements using an active stochastic backscatter model
  - Transfer of stochastic backscatter from DHIT[4] to use cases

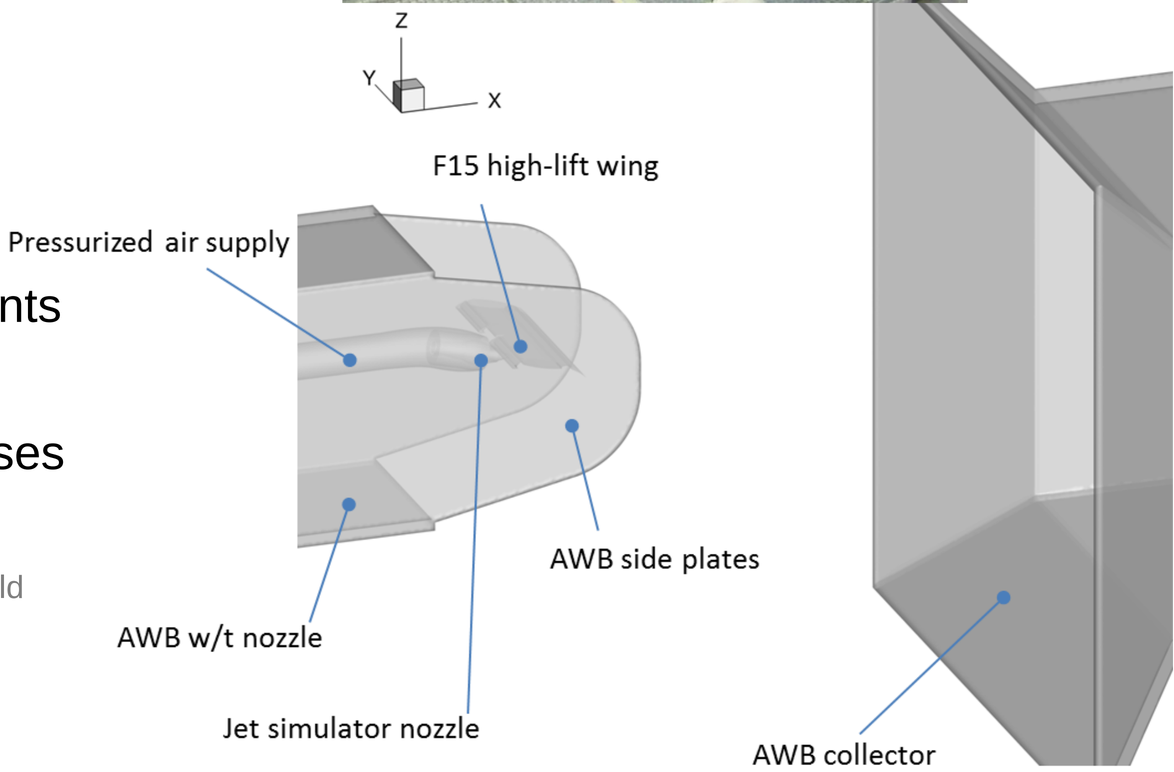
[1]Bailly, Bogey & Marsden '10: solving the compressible Navier-Stokes equations to determine simultaneously the aerodynamic field and the acoustic field

[2]Very-large-eddy simulation: filter and grid are too coarse to resolve 80% of the energy (Pope 2000)

[3]Morris '97, Sagaut & Labourasse '02, Terracol et al. '06, Batten et al. '04

[4]Decaying Homogeneous Isotropic Turbulence



# Outline

- **Simulation Problem**
- Methodology
- Results of cold isolated single stream jet
- Results of installed UHBR configuration
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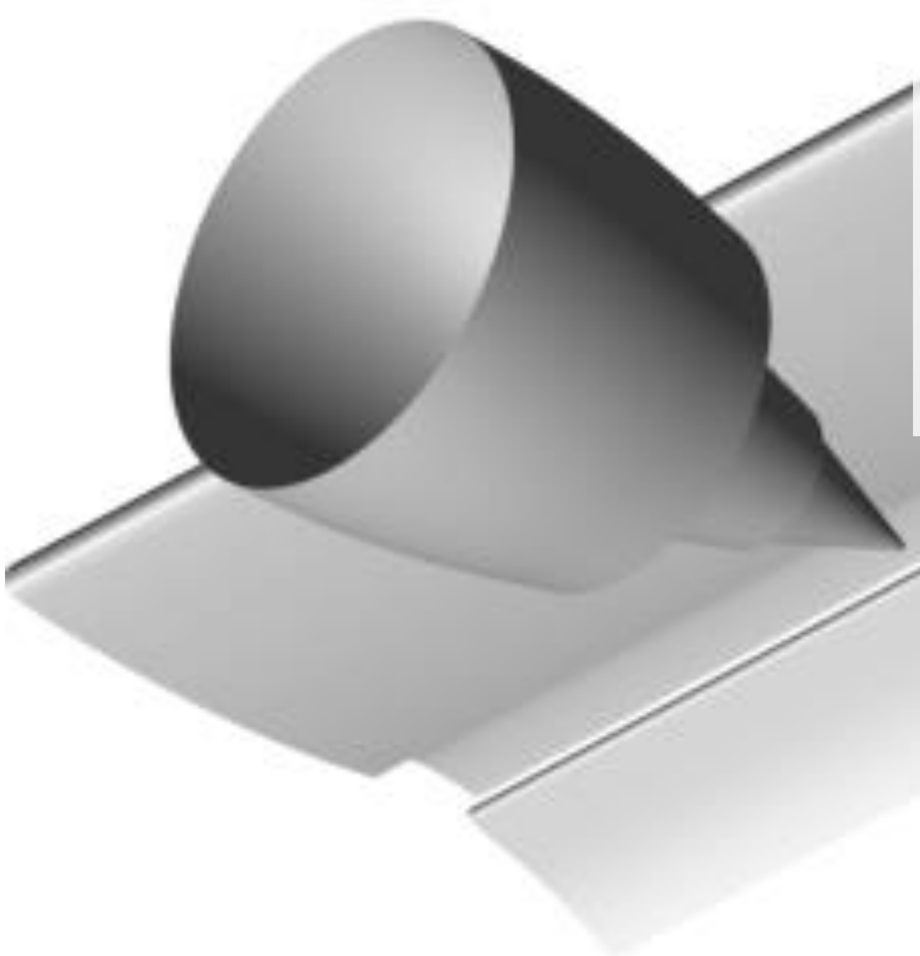
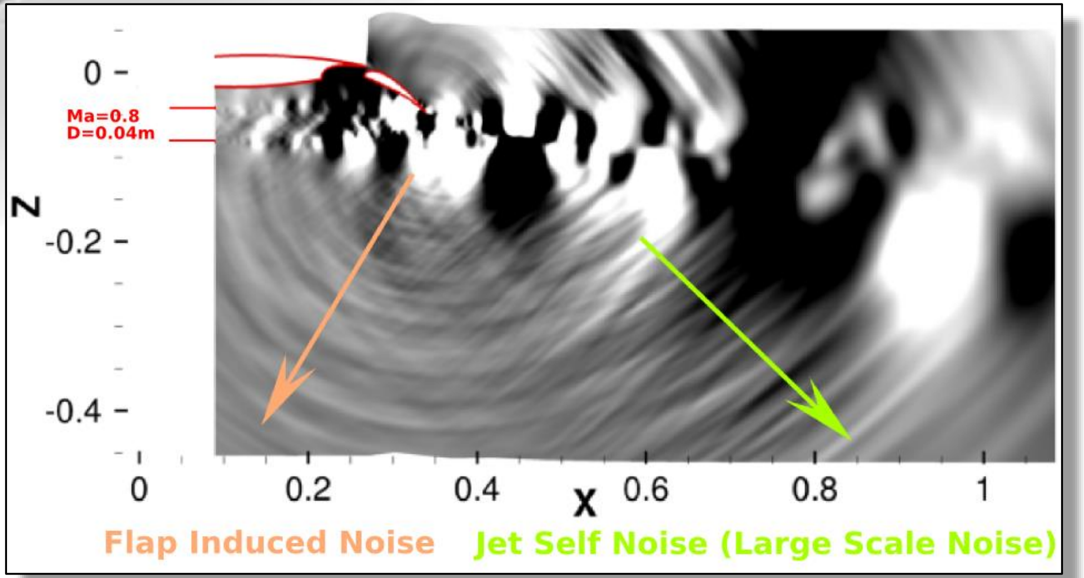
# Simulation Problem
## UHBR Installation Noise



- Noise prediction for configurations with nozzle mounted closely to wing
- The installation noise from jet-airframe interaction potentially is one of the prominent noise source
- This noise generation mechanism is attributed to coherent hydrodynamic fluctuations passing by the airfoil trailing edge
- Qualitatively different noise generation mechanisms as can be observed in directivity pattern:
    - Airframe → maximum to forward arc
    - Jet Noise → maximum to rearward arc



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# Methodology: Zonal RANS/VLES Approach

## NLDE[4] (Non-Linear Disturbance Equations)

[4]Morris '97, Sagaut & Labourasse '02, Terracol et al. '06, Batten et al. '04

- Navier-Stokes equations for primitive variables:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \mathcal{N}(\boldsymbol{U}) = \boldsymbol{0} \qquad \boldsymbol{U} = \begin{pmatrix} \rho \\ v_i \\ p \end{pmatrix}$$

- Triple decomposition of variables:

$$\boldsymbol{U} = \underbrace{\boldsymbol{U}^0 + \overline{\boldsymbol{U}}'}_{\overline{\boldsymbol{U}}} + \boldsymbol{U}''$$

RANS mean-flow

resolved fluctuations

subgrid fluctuations

resolved flow

- NLDE Variant 1: $\boxed{\dfrac{\partial \overline{\boldsymbol{U}}'}{\partial t} + \mathcal{N}\left(\overline{\boldsymbol{U}}\right) = \boldsymbol{f}_{sgs}(\boldsymbol{U}'')}$

- NLDE Variant 2: $\boxed{\dfrac{\partial \overline{\boldsymbol{U}}'}{\partial t} + \mathcal{N}'\left(\boldsymbol{U}^0, \overline{\boldsymbol{U}}'\right) = \boldsymbol{f}^0_{visc} + \boldsymbol{f}_{sgs}}$

$$\mathcal{N}\left(\overline{\boldsymbol{U}}\right) = \mathcal{N}'\left(\boldsymbol{U}^0, \boldsymbol{U}'\right) + \mathcal{N}^0\left(\boldsymbol{U}^0\right)$$

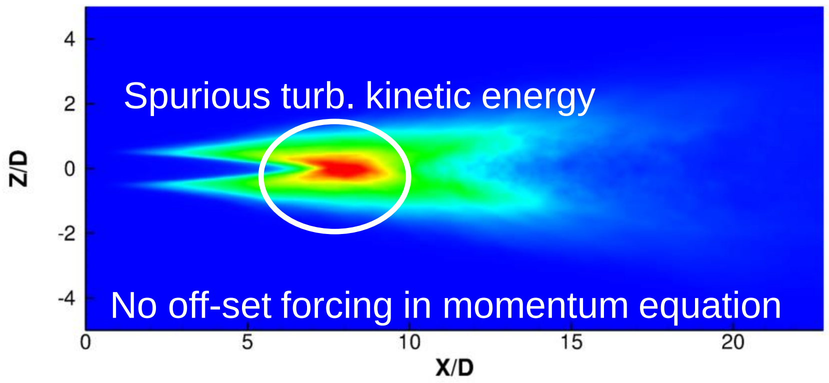
$$\mathcal{N}^0\left(\boldsymbol{U}^0\right) = -\boldsymbol{f}^0_{visc}\left(\boldsymbol{U}^0\right)$$

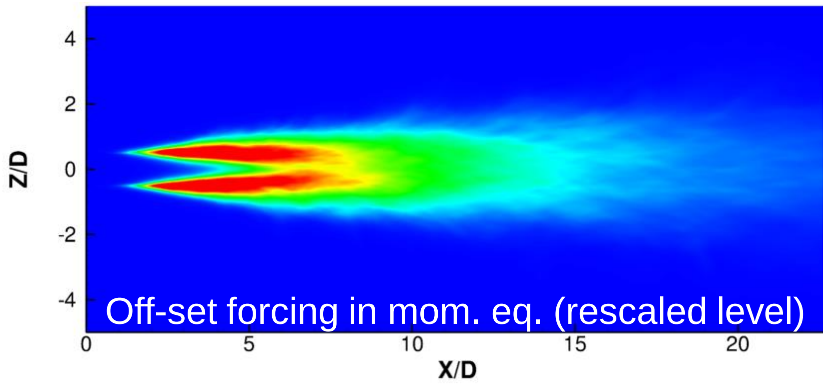
≡RANS

# Methodology
## NLDE (Non-Linear Disturbance Equations)

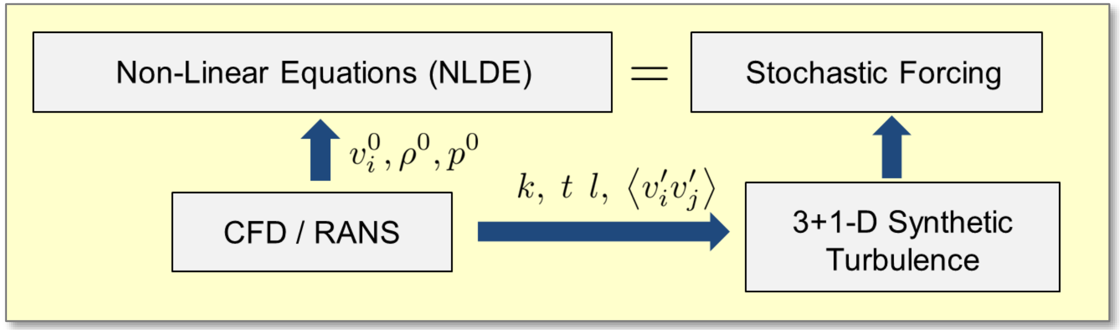
- NLDE Variant 1: $$\frac{\partial \overline{\boldsymbol{U}}'}{\partial t} + \mathcal{N}\left(\overline{\boldsymbol{U}}\right) = \boldsymbol{f}_{sgs}(\boldsymbol{U}'')$$ off-set forcing w/o forcing
- NLDE Variant 2: $$\frac{\partial \overline{\boldsymbol{U}}'}{\partial t} + \mathcal{N}'\left(\boldsymbol{U}^0, \overline{\boldsymbol{U}}'\right) = \boldsymbol{f}^0_{visc} + \boldsymbol{f}_{sgs}$$ explicit off-set forcing

- Constant off-set necessary to avoid spurious turbulence in single stream jet
- “Variant 1” used for momentum equation (“off-set forcing w/o forcing”)
- “Variant 2” used for density + pressure equations (no off-set forcing)
- Background RANS flow from DLR CFD solver TAU
- NLDE realized with DLR code PIANO
  - $4^{th}$ order DRP scheme of Tam & Webb
  - High-order (HO) filter to remove spurious waves
  - Optimized $4^{th}$ order Runge-Kutta time integration



# NLDE + Stochastic Backscatter
## = FES (Forced Eddy Simulation)



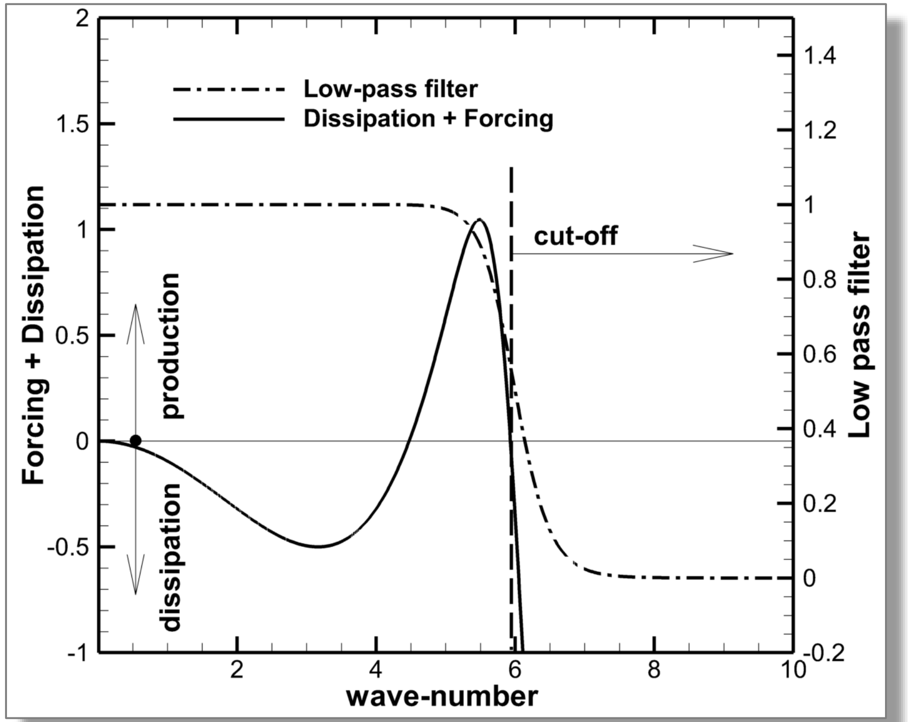

$$\boldsymbol{f}_{sgs} = \underbrace{-\nabla \times (\bar{\rho}\nu_r\, \boldsymbol{\omega}')}_{\boldsymbol{f}_D^{(5)}} + \underbrace{\nabla \times \boldsymbol{q}}_{\boldsymbol{f}_F}$$

*r.h.s. vector force* *dissipation* *stochastic forcing*

- Smagorinsky-like vector-force sgs-model[4] of fluctuations
- High-order filtered equations + sgs-model: mixed model[5]
- 3+1-D stochastic forcing provides turbulent backscatter[1,2,3] from non-resolved scales

[4]Dantinne, Jeanmart, Winckelmans, Legat, Carati, Applied Scientific Research (59), 1998

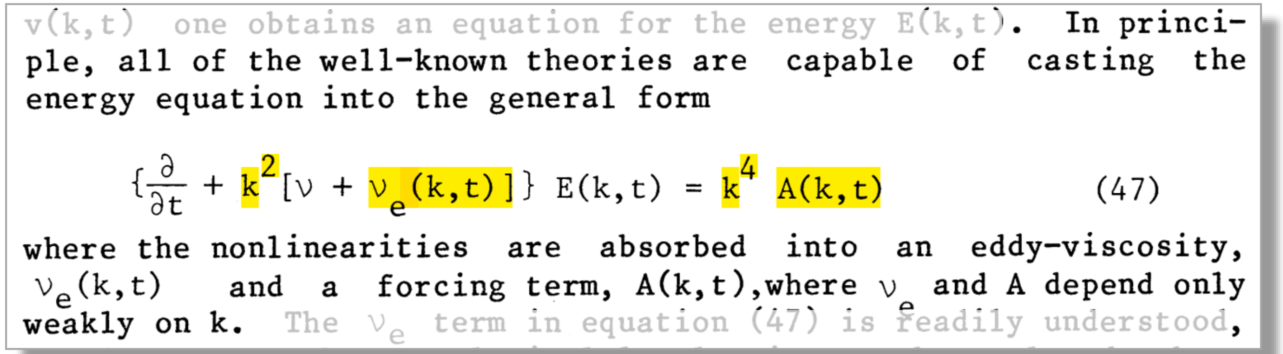
[5]Bardina, Ferziger, and Reynolds, 1980




[1]C.E. Leith, Physics of Fluids A 2, 297, [2]U. Schumann, Proc. R. Soc. London A (1995), [3]Zamansky et al., J. of Turb. 11, (2010).

DLR

# NLDE + Stochastic Backscatter
## = FES (Forced Eddy Simulation)



$\nu(k,t)$ one obtains an equation for the energy $E(k,t)$. In principle, all of the well-known theories are capable of casting the energy equation into the general form

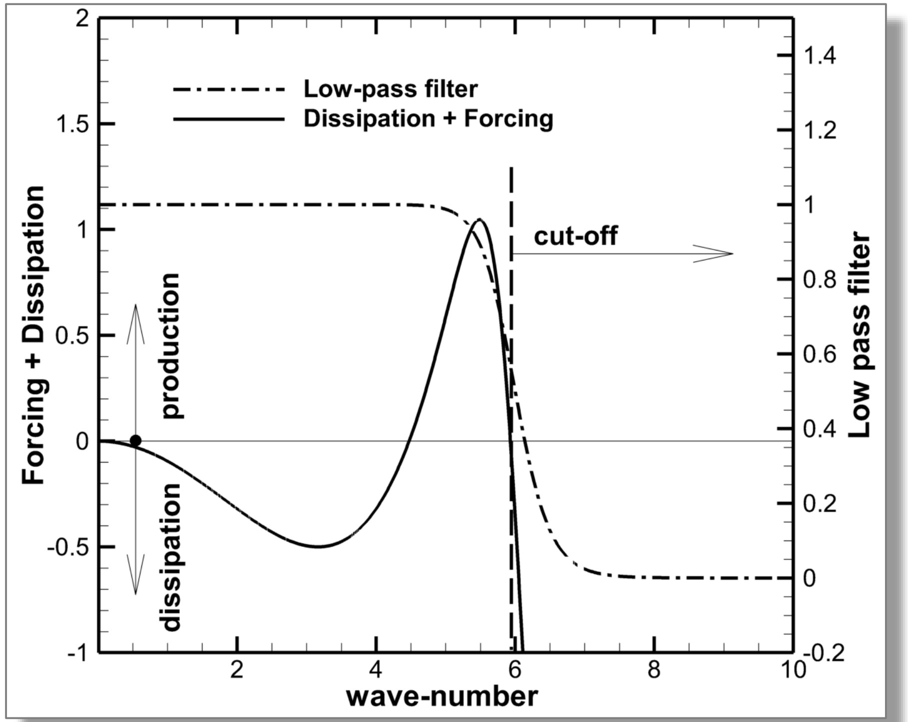
$$\{\frac{\partial}{\partial t} + k^2[\nu + \nu_e(k,t)]\}\ E(k,t) = k^4\ A(k,t) \qquad (47)$$

where the nonlinearities are absorbed into an eddy-viscosity, $\nu_e(k,t)$ and a forcing term, $A(k,t)$, where $\nu_e$ and A depend only weakly on k. The $\nu_e$ term in equation (47) is readily understood,

Marcus, 'NUMERICAL MODELING OF SUBGRID-SCALE FLOW IN TURBULENCE ROTATION AND CONVECTION',1986

$$\boldsymbol{f}_{sgs} = -\underbrace{\nabla \times (\bar{\rho}\nu_r\,\boldsymbol{\omega}')}_{\boldsymbol{f}_D^{(5)}} + \underbrace{\nabla \times \boldsymbol{q}}_{\boldsymbol{f}_F}$$

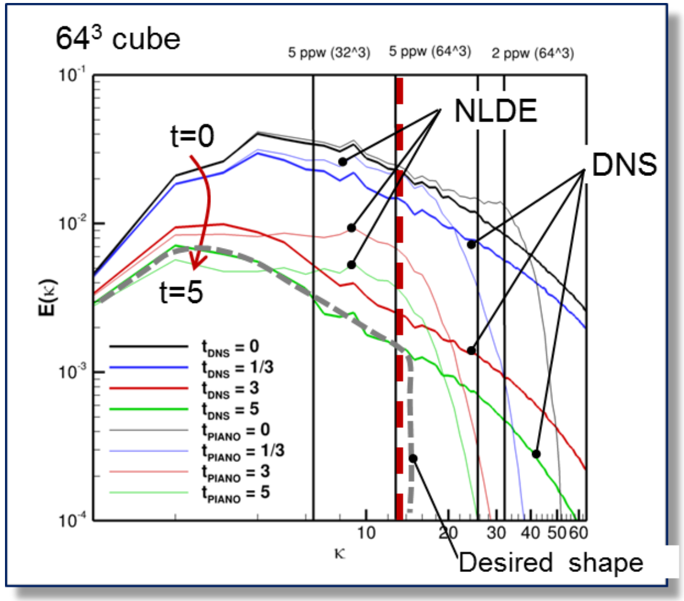
*r.h.s. vector force* *dissipation* *stochastic forcing*



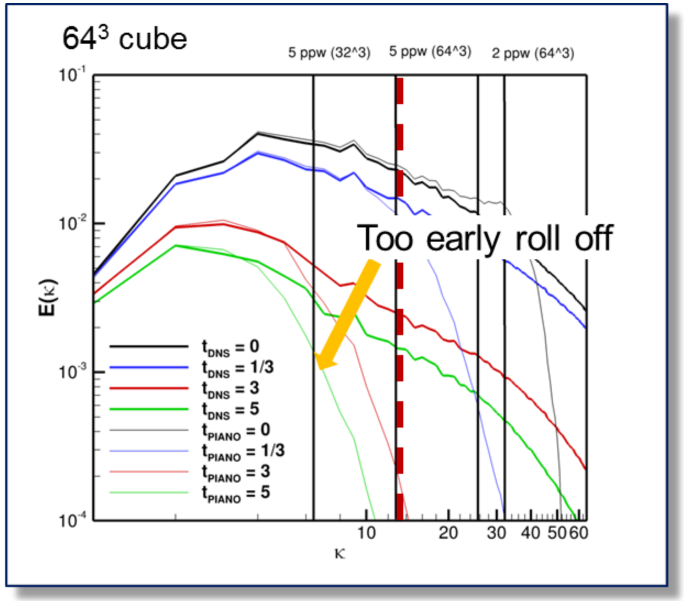

- Backscatter forcing features as discussed in literature
  (Kraichnan 1976, Leith 1990, , Mason & Thomson 1992, Schumann 1995, Lesieur 1980, Marstop 2007)
  - $k^4$-backscatter-spectrum
  - divergence-free (solenoidal) forcing
  - spatial correlation length scale of forcing from local mesh resolution
  - forcing defined in Lagrangian frame
  - realization of finite local turbulent time scale

# Backscatter Calibration for DHIT (AIAA 2017-3017)

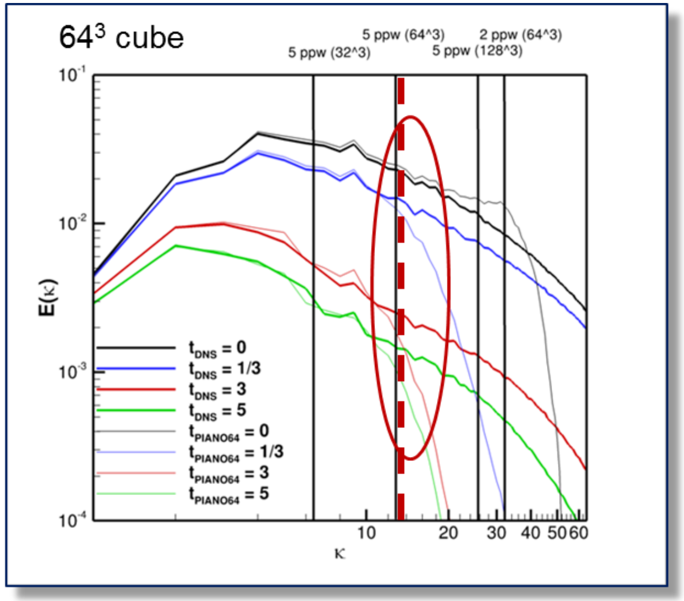
## Status Accomplished




No eddy viscosity, no forcing




Calibrated eddy viscosity, no forcing



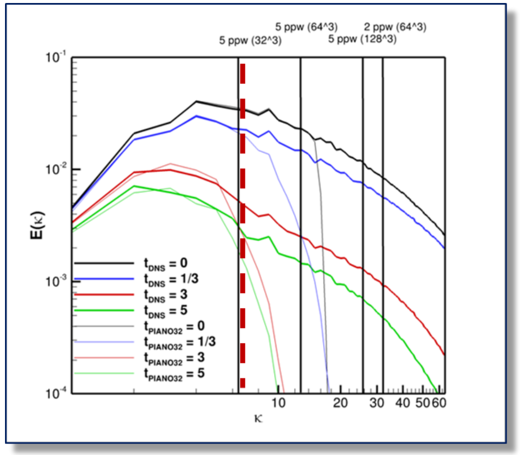

Calibrated eddy viscosity + forcing

- Results derived from Decaying Homogeneous Isotropic Turbulence (DHIT) simulation (Wray data*)
  i. $k^4$-scaling of backscatter forcing from literature confirmed
  ii. Forcing scaling derived (as a function of cut-off wave number / length scale)
  iii. Proper scaling of residual eddy viscosity derived from calibration
  iv. High order filtering of equations not sufficient, eddy-viscosity needed to avoid energy pile-up in spectrum (subgrid forcing comprises dissipative <u>and</u> productive parts)

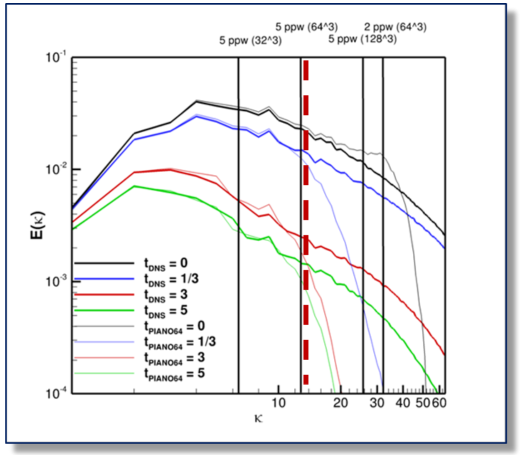
**DNS Data available on AGARD database; A. Wray 1997; http://torroja.dmt.upm.es/turbdata/agard/chapter3/HOM02/*

# Backscatter Calibration for DHIT (AIAA 2017-3017)

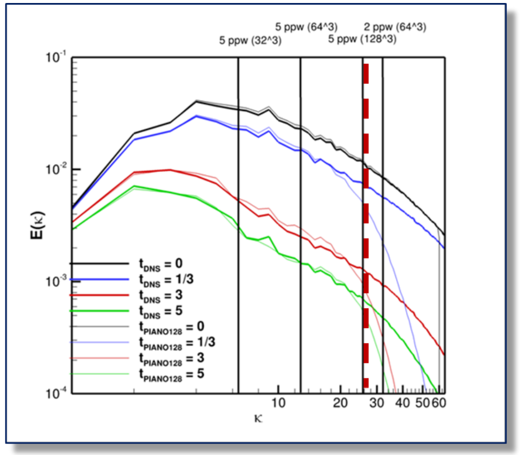
- Methods works for different mesh resolutions




$32^3$ cube




$64^3$ cube

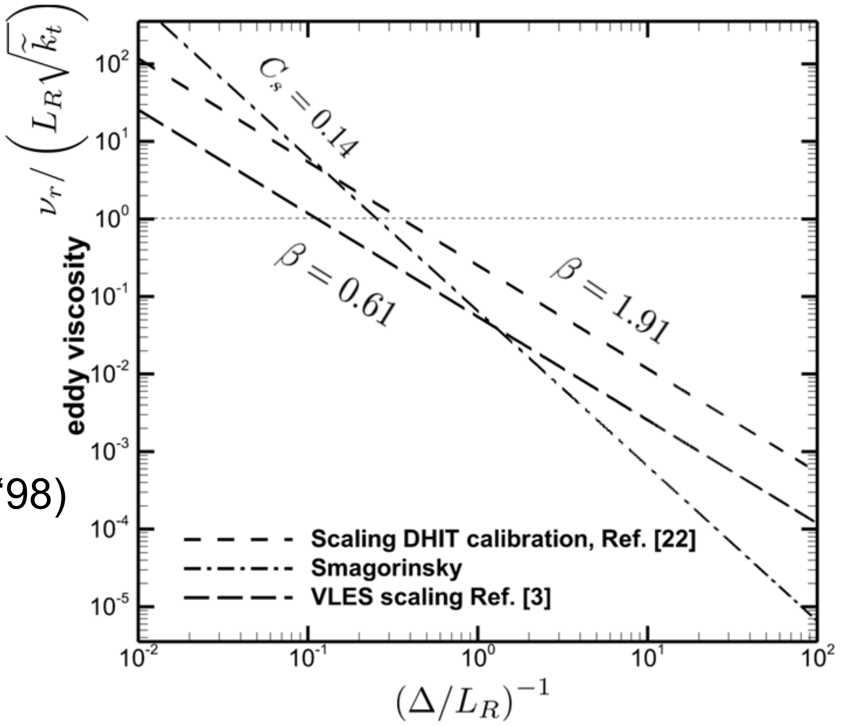



$128^3$ cube

- Eddy viscosity calibration yields a modified damped eddy viscosity model (Speziale ‘98)
- Scaling function based on the RANS length scale $L_R$ instead of Kolmogorov scale

$$\nu_r = F_r\, \nu_t \qquad \boxed{F_r = \left[1 - \exp\left(-\beta\Delta/L_R\right)\right]^n}$$

$$\Delta = \textit{cut-off length scale},\ L_R = k_t^{3/2}/\epsilon,\ n = 4/3,\ \beta \approx 1.91$$




*Cut-off depending eddy-viscosity scaling; Smagorinsky vs. damped eddy viscosity model (from calibration)*

- Corresponds with VLES model of Han et al.[1], albeit with larger beta-value

[4]J. Sci China-Phys Mech Astron, 2012

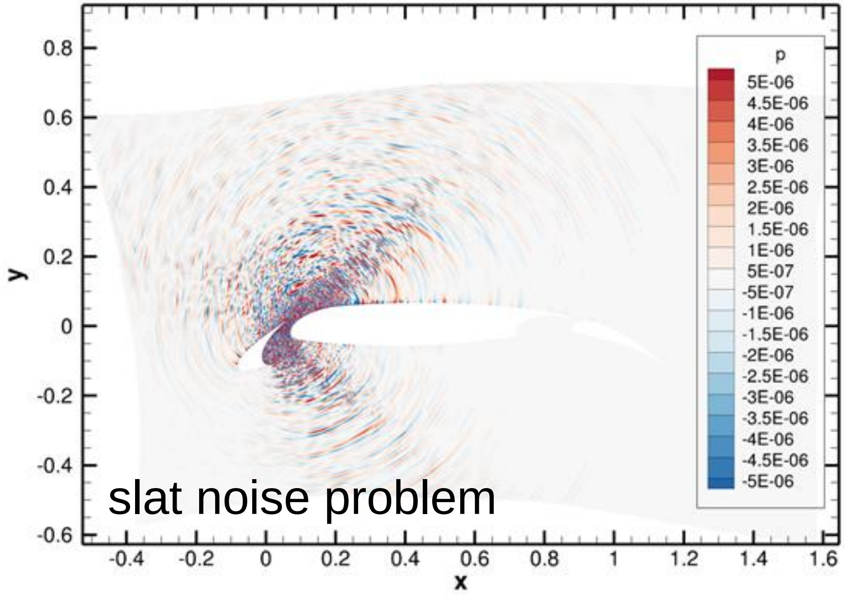
# Extension of DHIT calibration to use cases

## Modification of dissipative part

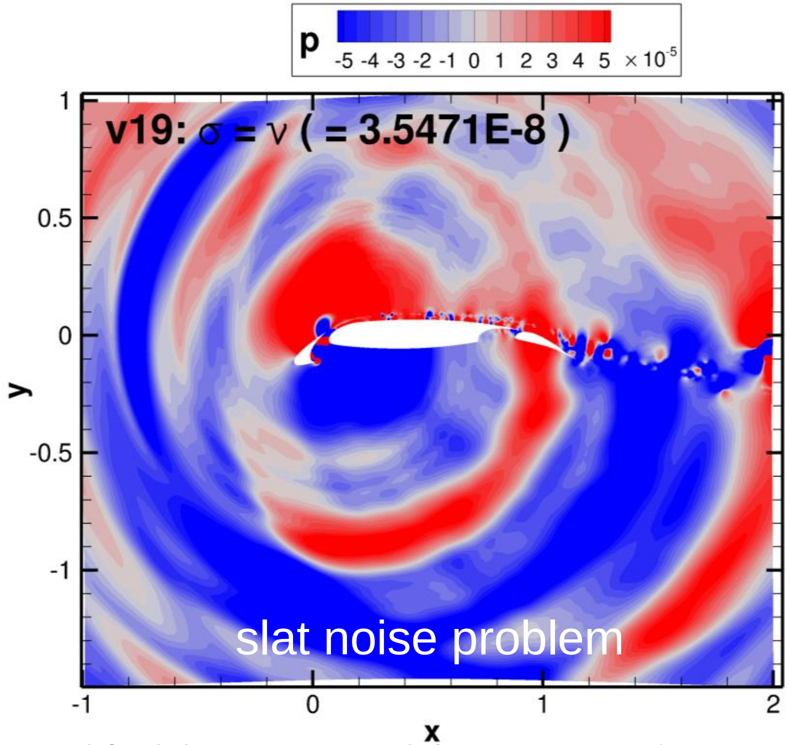
$$\nu_r^\star = \sqrt{\frac{\widetilde{k}_t}{k_t}}\,\nu_r$$

- Slat noise with calibrated backscatter model (Heitmann & Ewert 2018)
  - Observation: calibrated damped residual eddy viscosity at start of comp. too high (no resolved fluctuations)
  - Solution: eddy viscosity scaled with resolved TKE from moving-averaging of solution
  - Moving-average time scale from background RANS

$$\widetilde{k}_t^{n+1}(\boldsymbol{x}) = \theta\,\widetilde{k}_t^{n}(\boldsymbol{x}) + (1-\theta)\frac{\left|(\boldsymbol{v}')^n\right|^2}{2}, \quad \theta := \exp\left(-\frac{\Delta t}{\tau_s}\right)$$

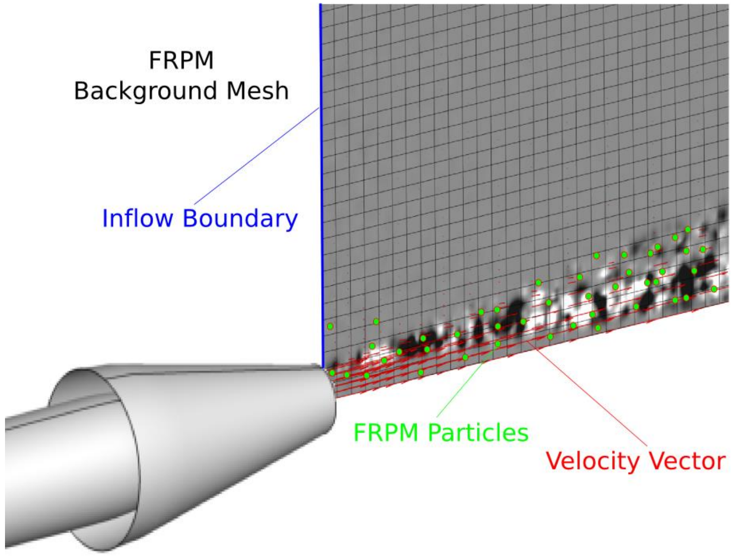



Example high-lift slat-noise: frequency content too high at slat, i.e., low frequency noise missing



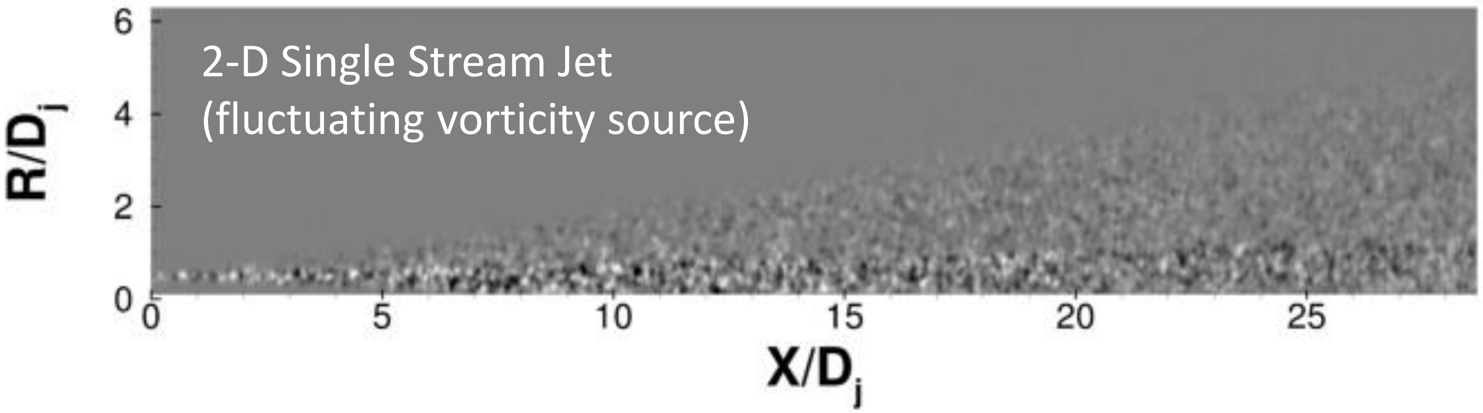

**Modified dissipative model**: proper sound generation @slat

# 3+1-D Stochastic Backscatter Forcing
## FRPM: Fast Random Particle-Mesh Method




- Velocity field divergence-free (solenoidal)
- Convection property of vorticity in non-uniform mean-flow
- Local reconstruction of target turbulent kinetic energy from RANS
- Local reconstruction of turbulent time- & length-scales from RANS
- Broadband spectra realized
- Computationally efficient / parallelized

AIAA Pap. 2005-2862 / AIAA Pap. 2006 / Comp. & Fluids 37 (2008) / AIAA 2007-3506 / AIAA 2009-3369 / AIAA 2009-3175 / JSV 330 (2011) / Comp. & Fluids 132 (2016)



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- Simulation Problem
- Methodology
- **Results for cold isolated single stream jets**
- Results of installed UHBR configuration
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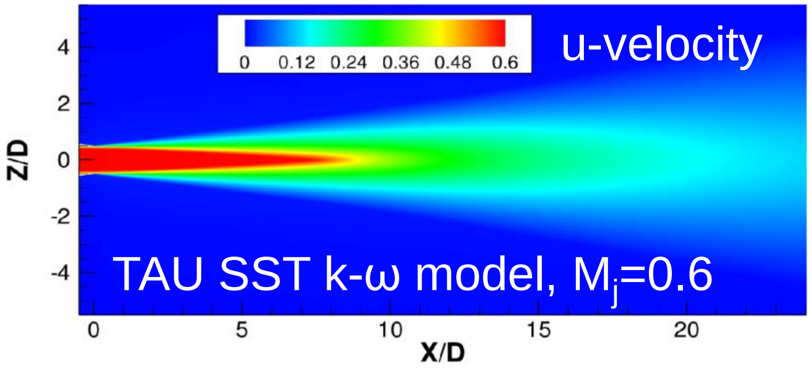
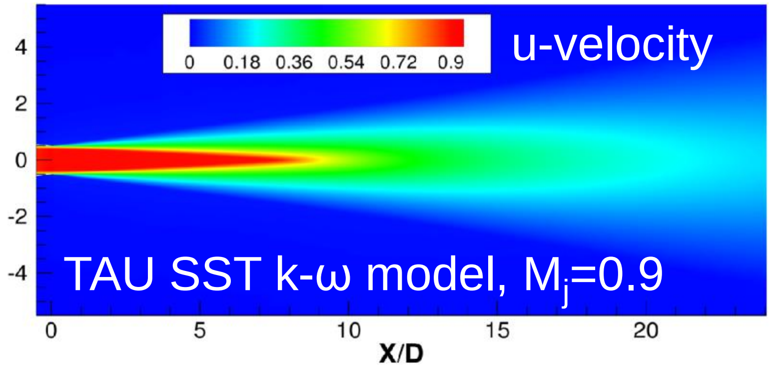
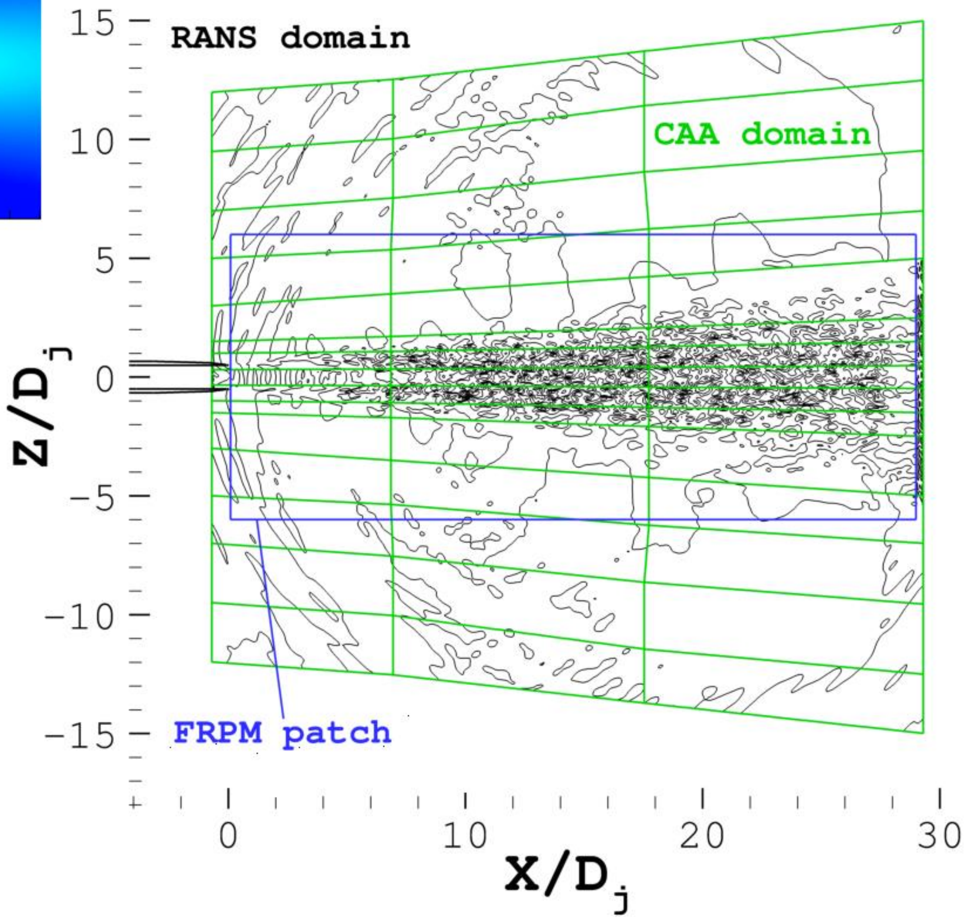
# Results for cold isolated single stream jet

## Computational Setup for Single Stream Jet FES



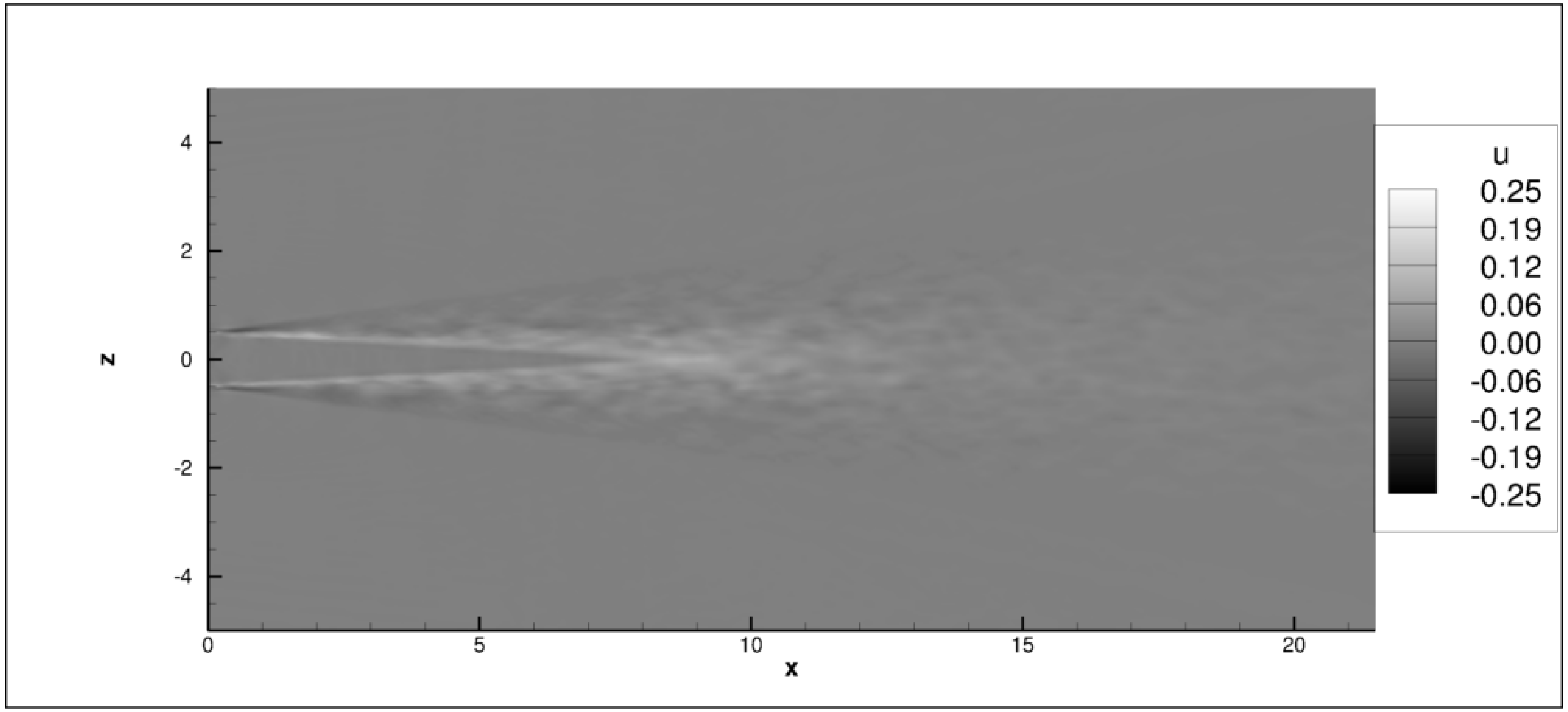




- Two computational cases are used to validate the FES approach
- 3-D cold isolated single stream jet (SSJ) computation for nozzle exit Mach numbers 0.6 (Re=0.68M) and 0.9 (Re=1M)
- Both SSJ in static condition
- CAA mesh with 87 grid blocks and approx. 9.7 Mio. grid points (O-mesh topology, approx. 20kHz Resolution, St~3.6)
- FRPM patch is resolved with approx. 2.6 Mio grid points
- Computations are performed on 88 CPUs with runtime of 4-7 days
- FES domain excludes nozzle interior



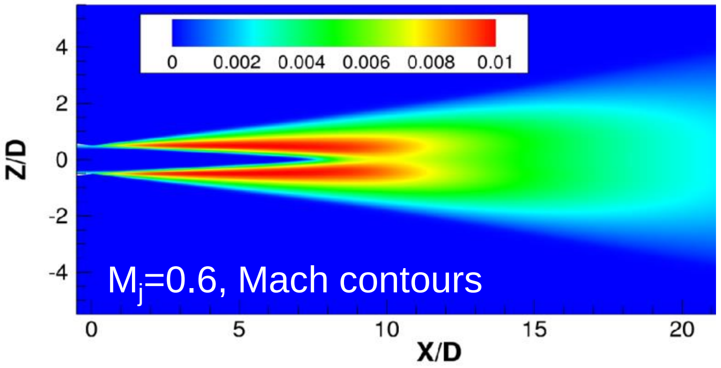
# Results for cold isolated single stream jets II
## Flow Properties

u-velocity $M_j$=0.9 jet

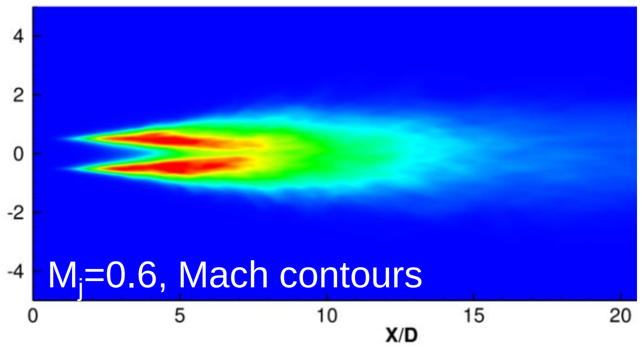


# Results for cold isolated single stream jets III
## Flow Properties

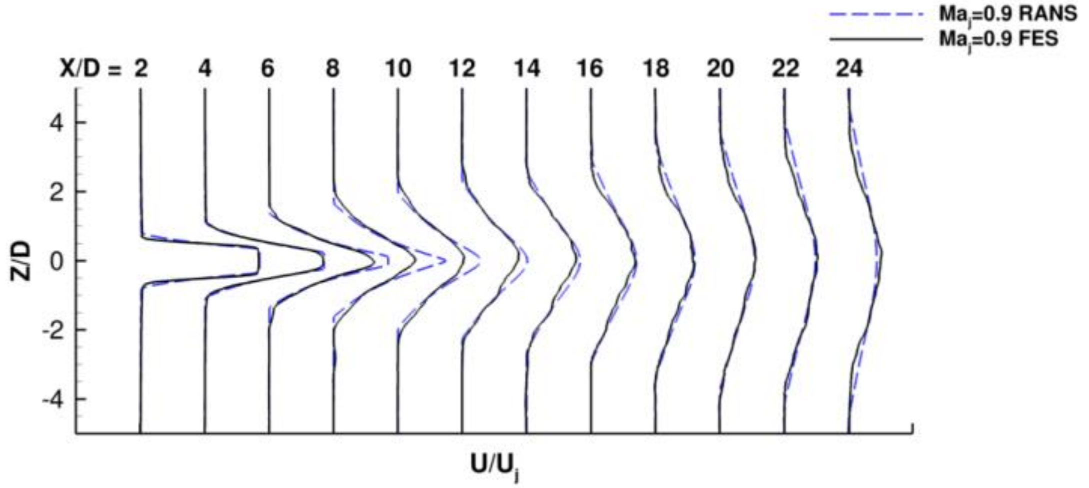
- Dissipation extended by mean-part: too fast decay observed



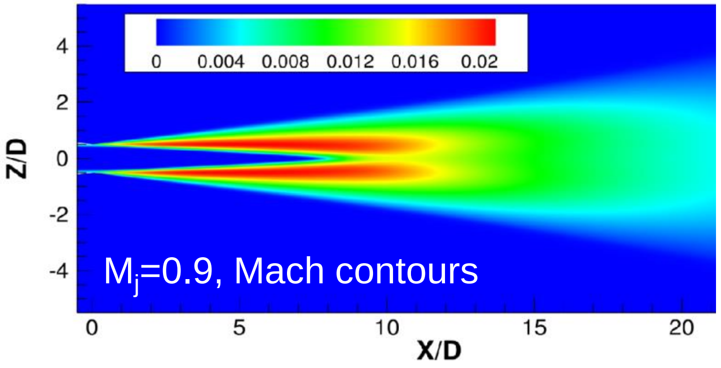

(c) $Ma_j = 0.6$, turbulent kinetic energy.



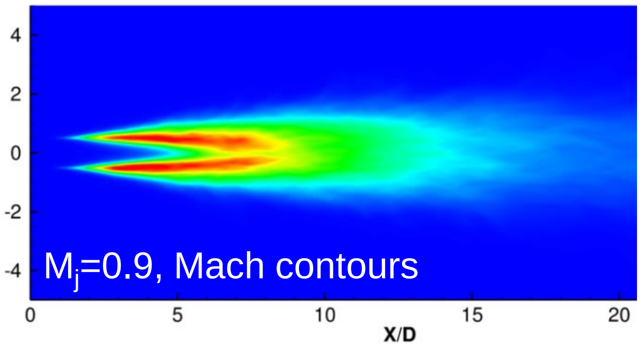

(a) $Ma_j = 0.6$



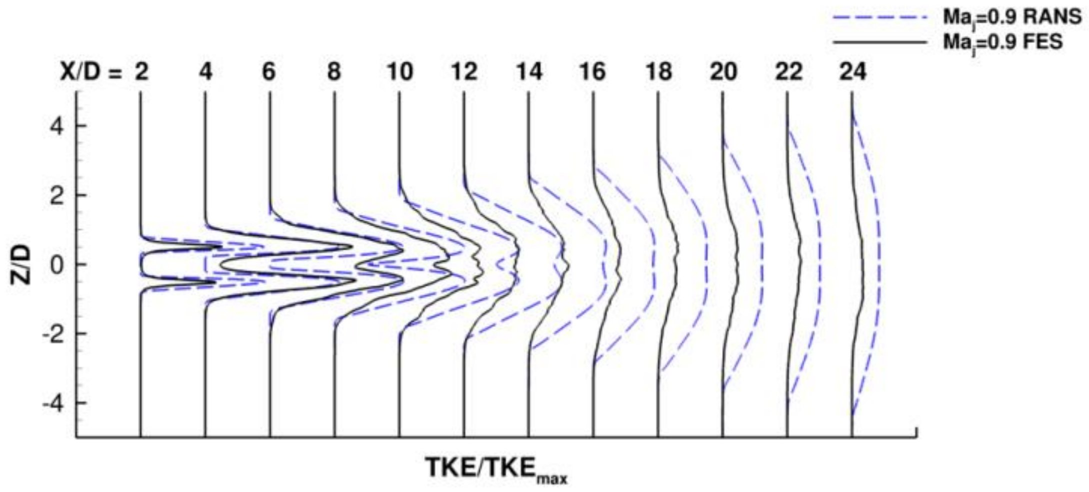

(a) Radial profiles of axial velocity.




(d) $Ma_j = 0.9$, turbulent kinetic energy.




(b) $Ma_j = 0.9$



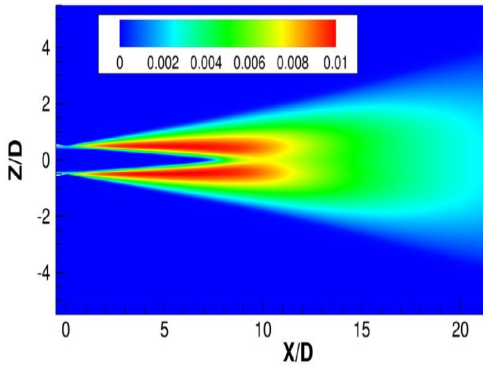

(b) Radial profiles of TKE.

RANS TKE

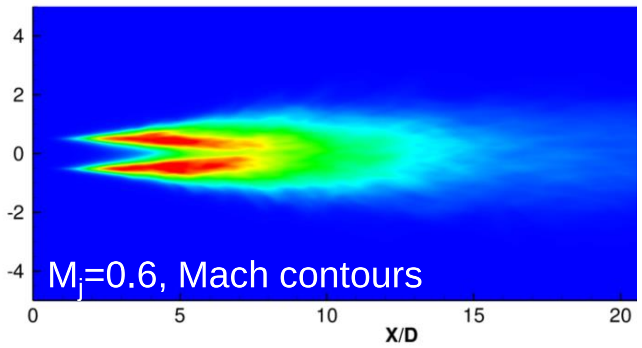
FES Resolved TKE

# Results for cold isolated single stream jets III
## Flow Properties

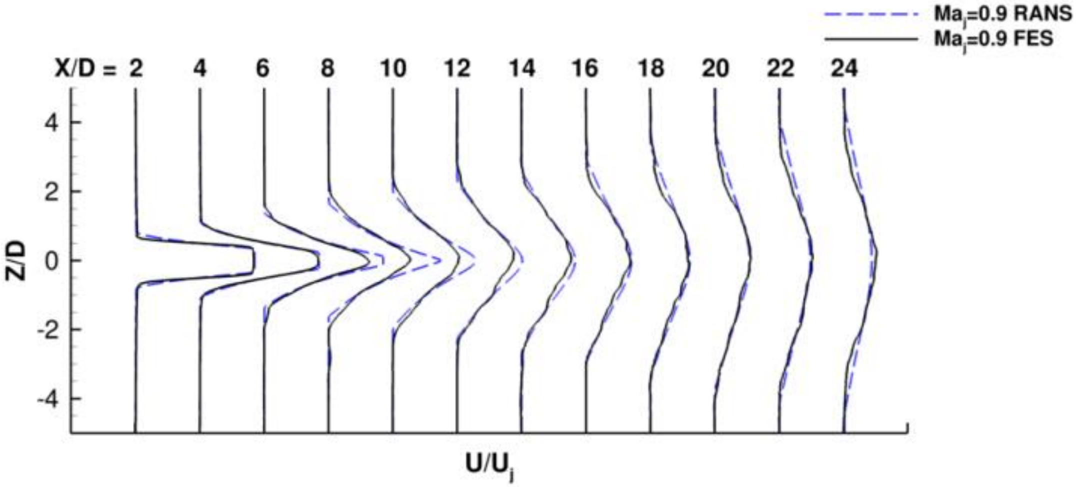
- Dissipation extended by mean-part: too fast decay observed



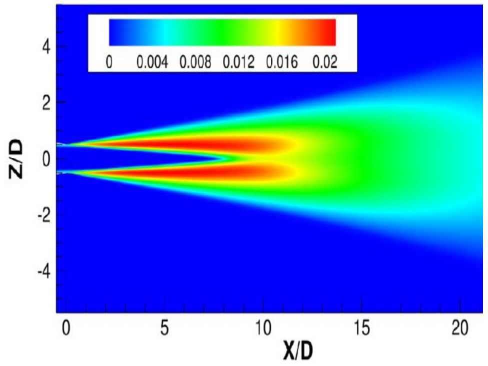
(c) $Ma_j = 0.6$, turbulent kinetic energy.



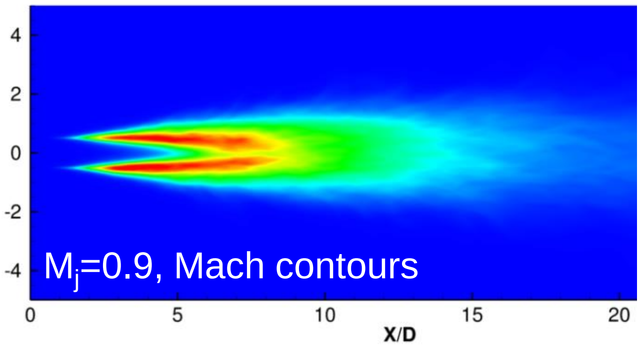
(a) $Ma_j = 0.6$



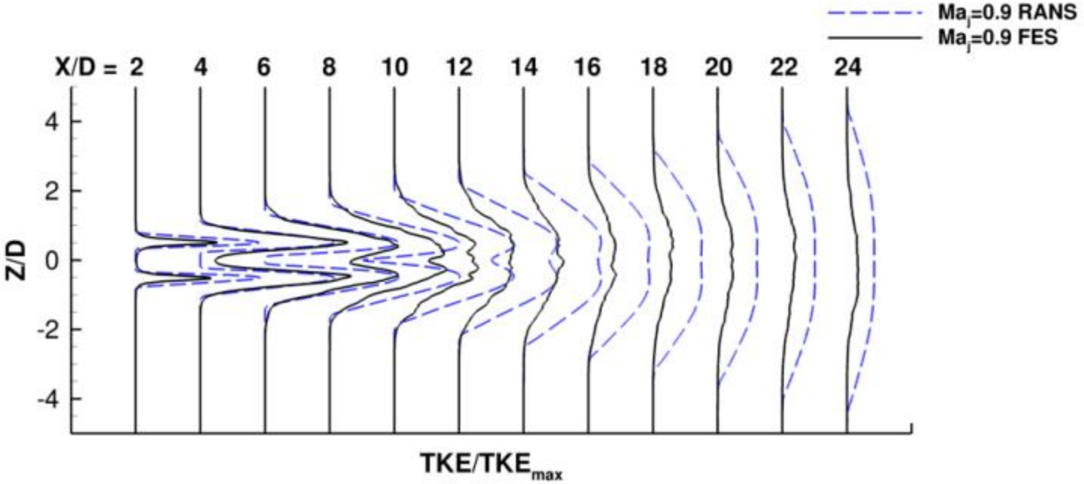
(a) Radial profiles of axial velocity.



(d) $Ma_j = 0.9$, turbulent kinetic energy.



(b) $Ma_j = 0.9$



(b) Radial profiles of TKE.

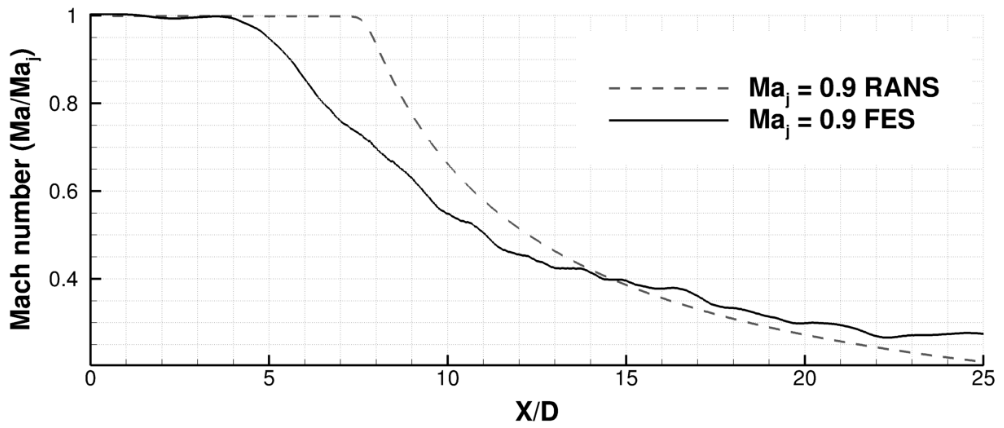
RANS TKE, 33.3% squeezed

FES Resolved TKE

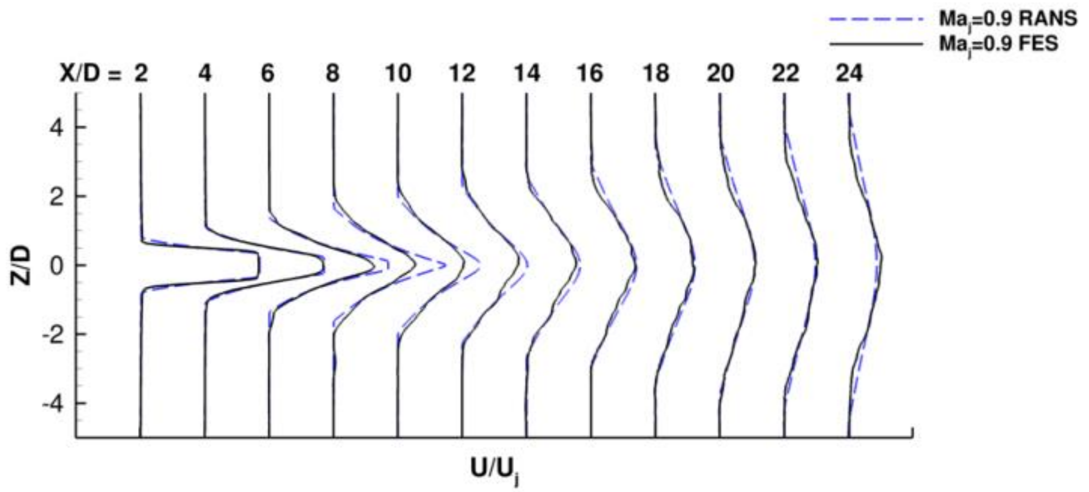
# Results for cold isolated single stream jets IV

## Flow Properties

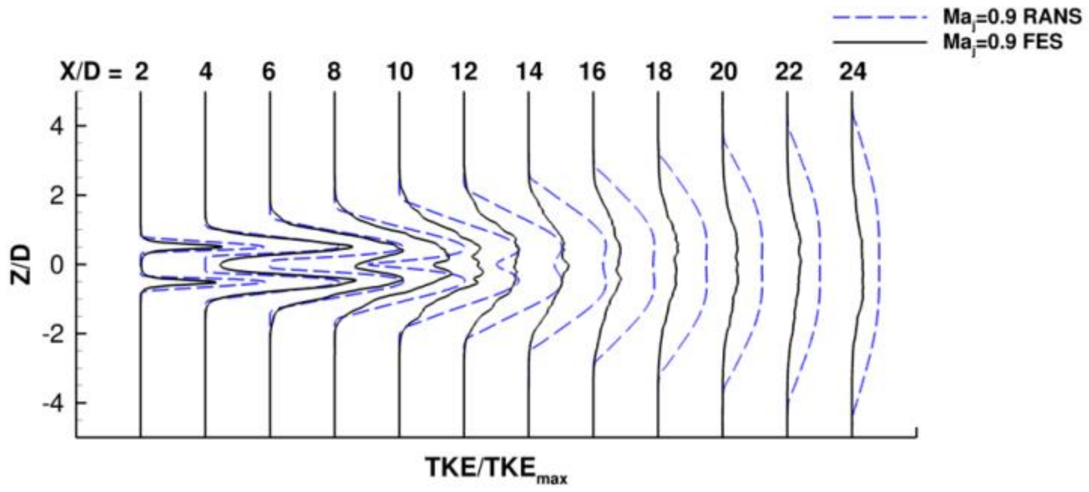
- Potential core of RANS too long (7.5D) and drop-off too steep
- RANS mean-flow corrected by NLDE-FES
- Qualitatively right correction of center line Mach number
- FES Potential core (4.5D) slightly too short (4-6D expected)
  → may indicate slightly too strong shear layer mixing
    - stochastic forcing slightly too strong
    - too much filtering




Center line Mach number




(a) Radial profiles of axial velocity.

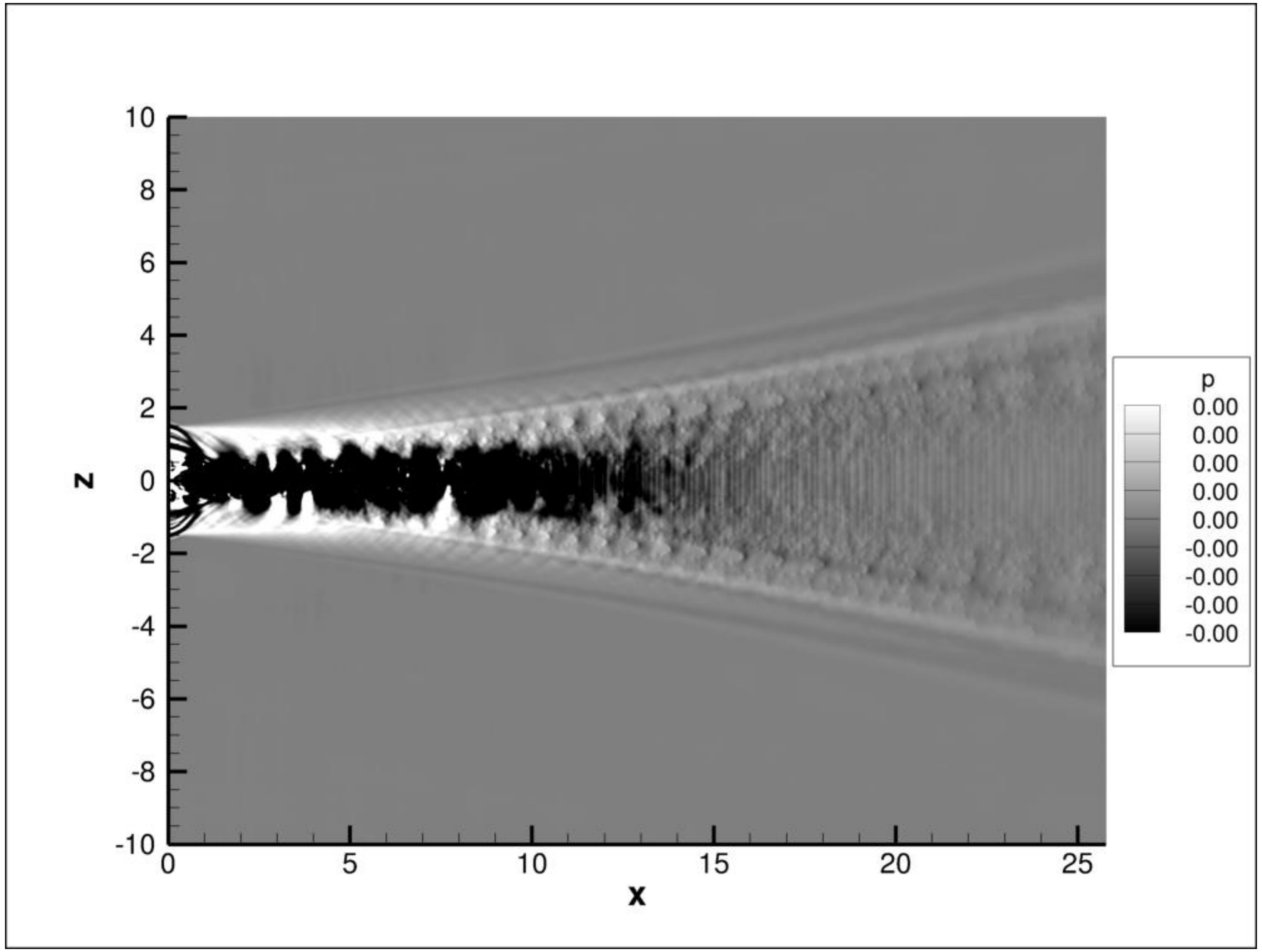


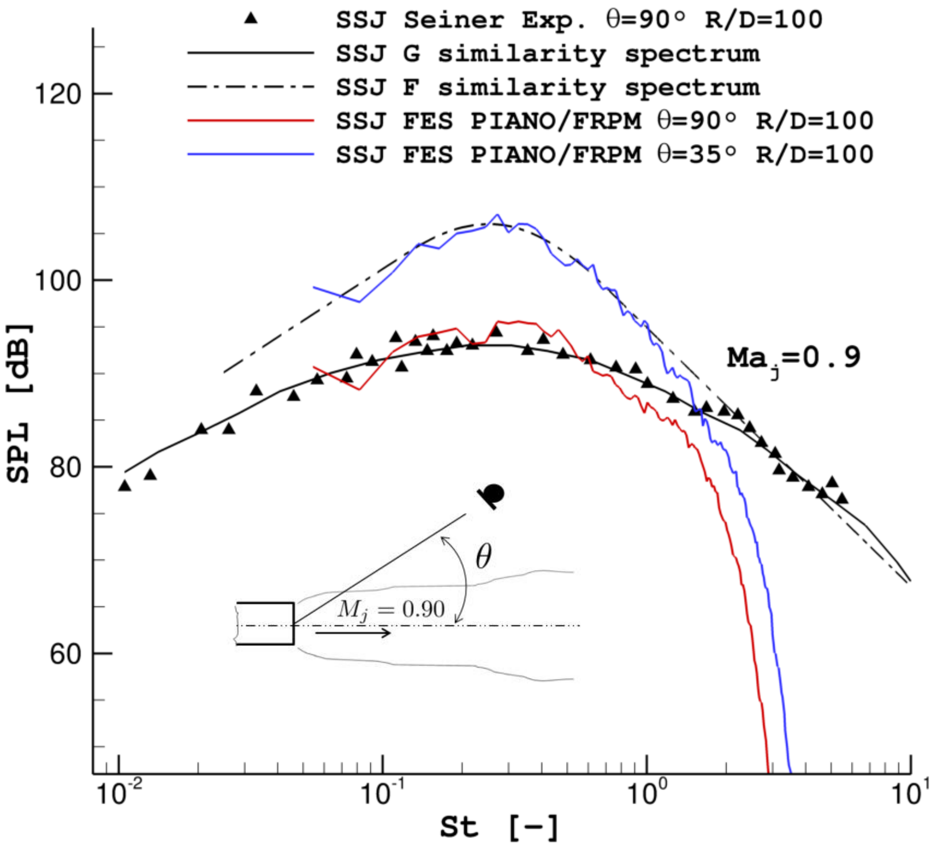

(b) Radial profiles of TKE.

# Results for cold isolated single stream jets V

## Resolved Sound Field $M_j$=0.9

p', fluctuating pressure $M_j$=0.9 jet



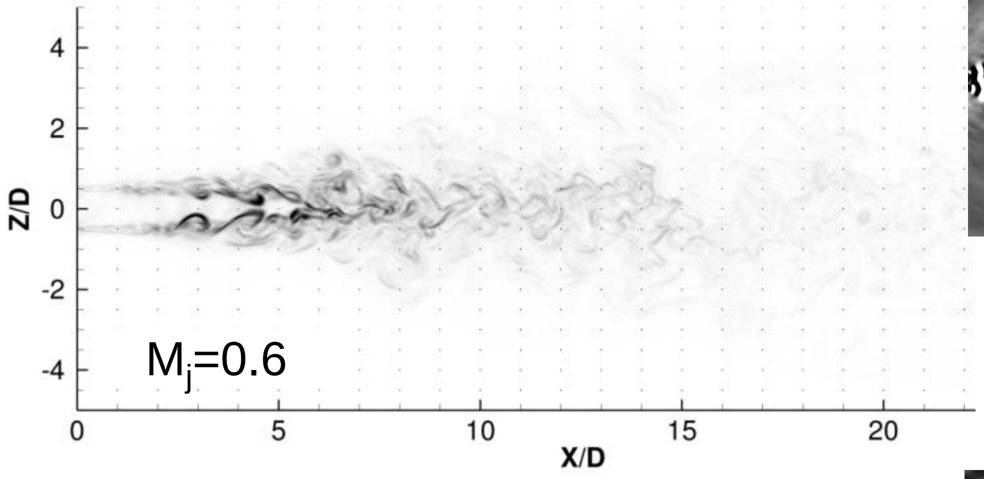



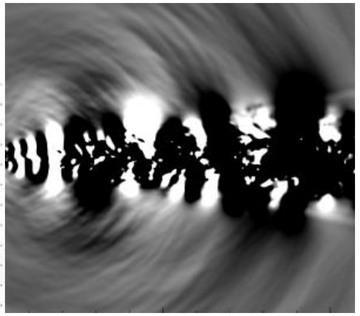

Comparison of spectra with reference

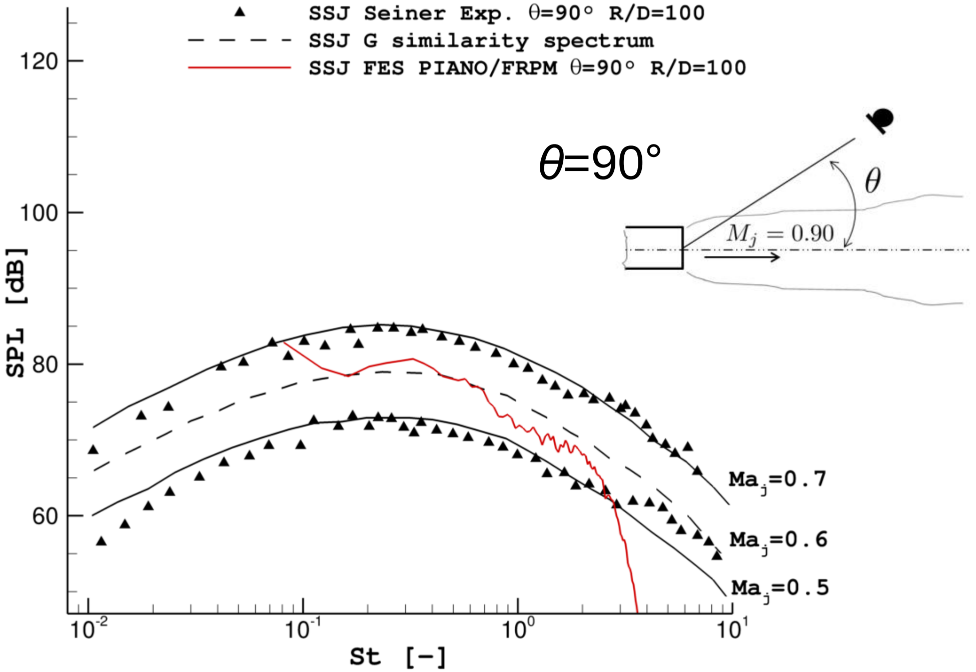
- No enhanced laminar-to-turbulent shear-layer transition and increased noise due to vortex pairing

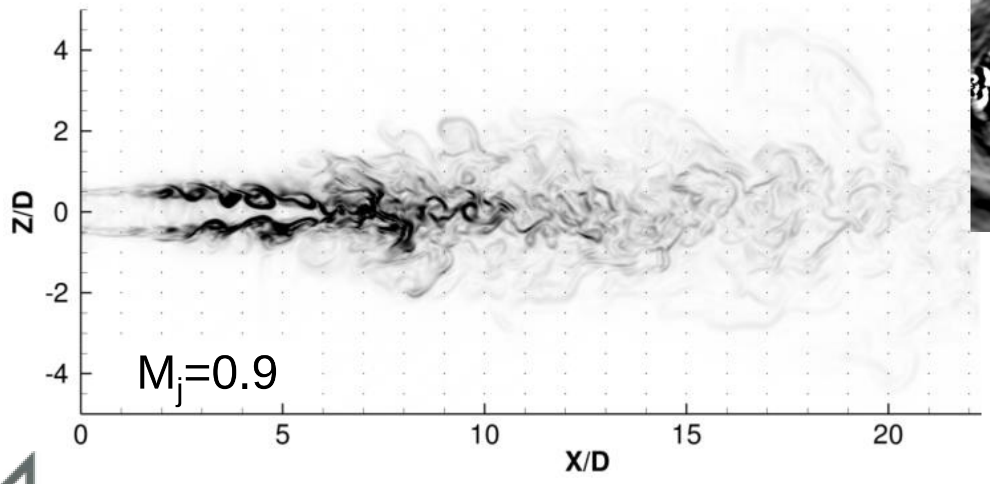
# Results for cold isolated single stream jets VI
## Flow Properties

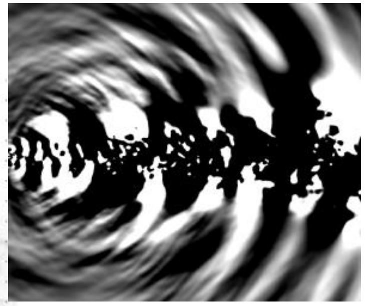
- Right Mach-number scaling

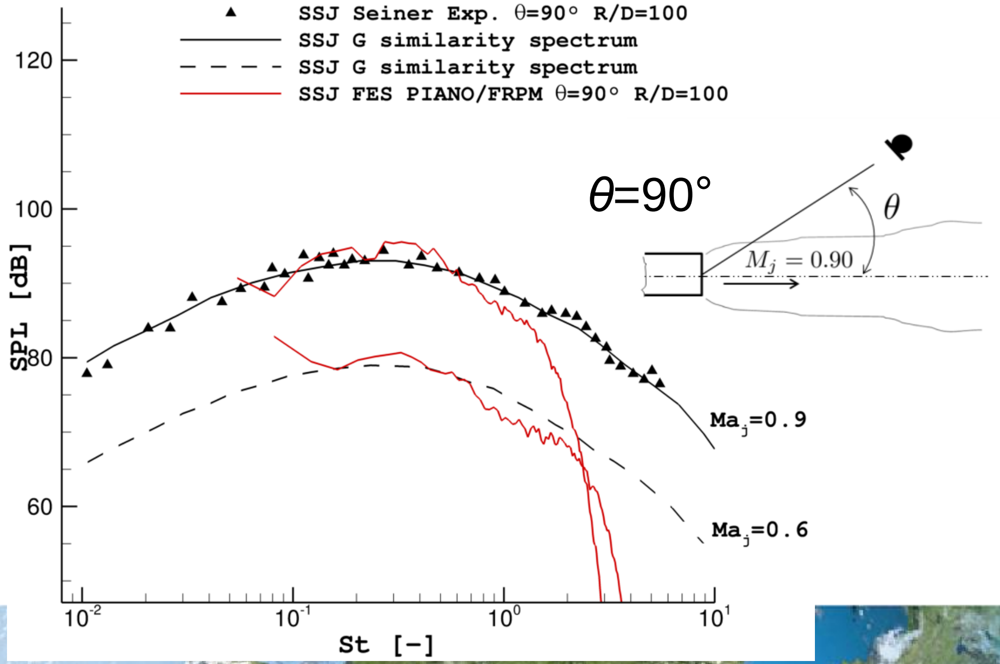




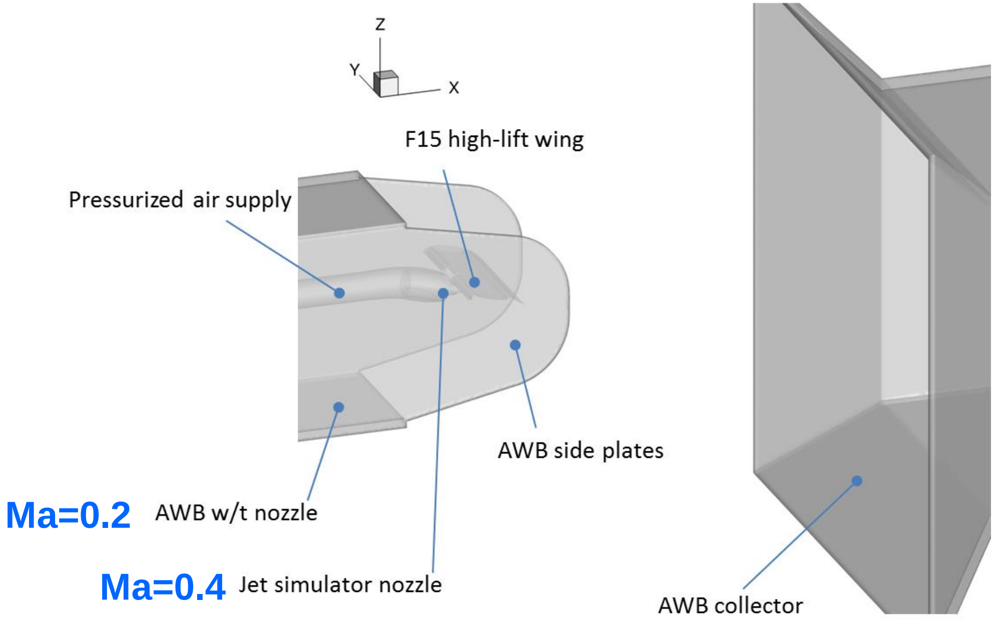



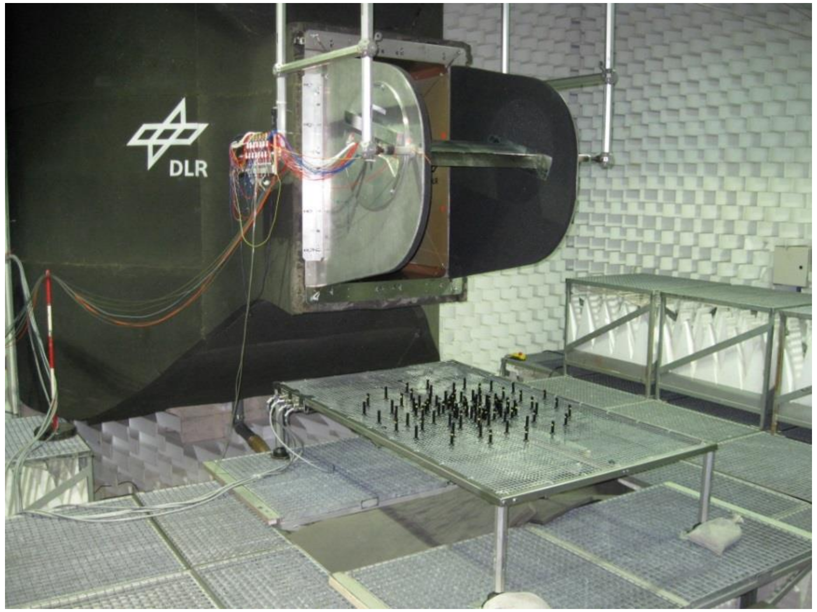


# Outline

- Simulation Problem
- Methodology
- Results for cold isolated single stream jets
- **Results of installed UHBR configuration**
- Summary & Conclusions

# Results of installed UHBR configuration
## Installed UHBR configuration in AWB wind tunnel I



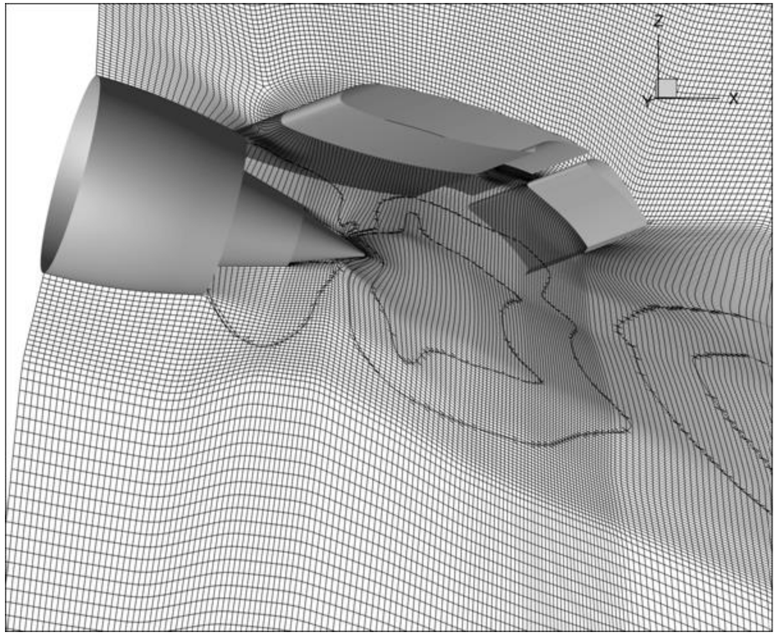




Experimental setup of LIST configuration

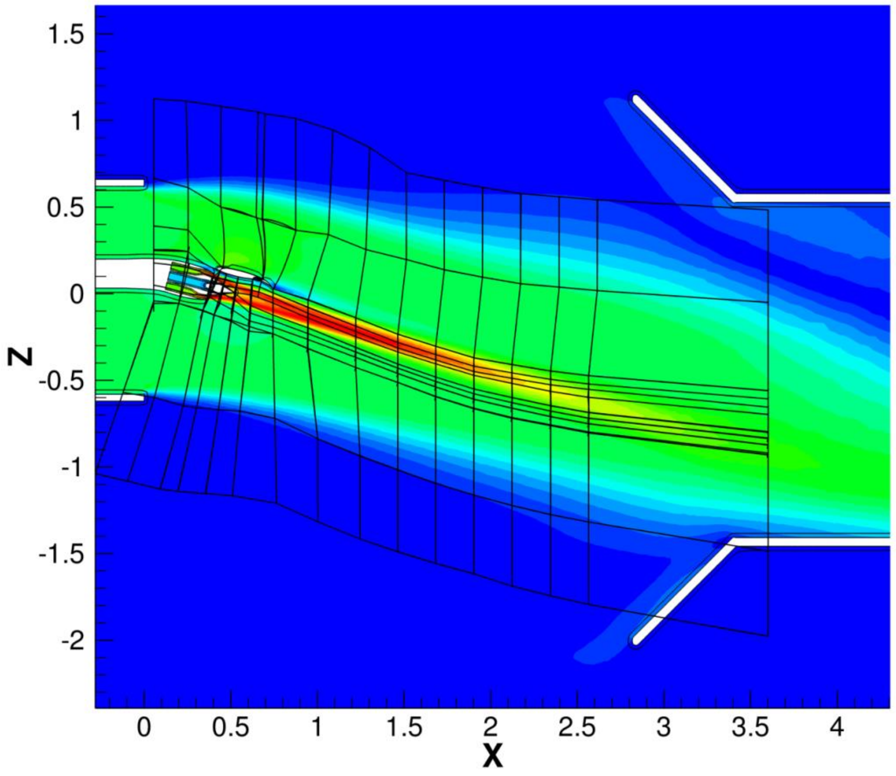
- Numerical setup is reproducing the experimental setup of AWB for installed UHBR configuration
- Computational domain is limited to area of interest, i.e. between the AWB nozzle and collector; in spanwise direction between the side plates
- Flow conditions are emulating the approach conditions with flap angle 25°

# Results of installed UHBR configuration
## Computational Chain

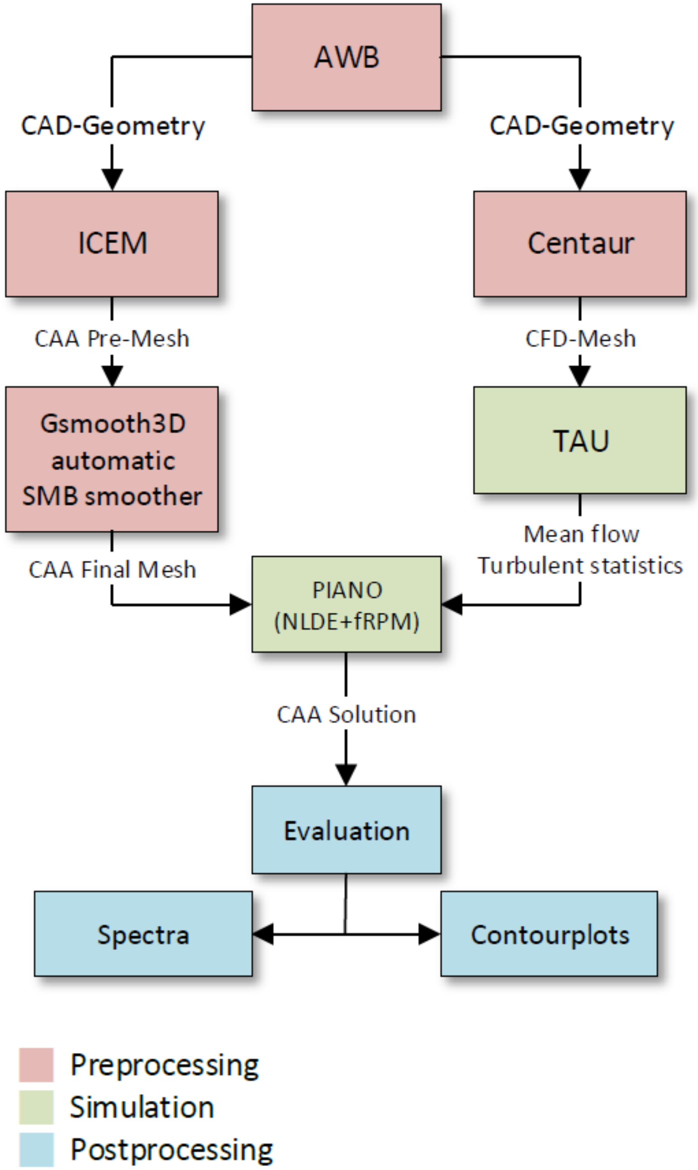
- Smoothed SMB mesh, AWB jet-wing installation, 350 blocks, 30mio points



CAA mesh

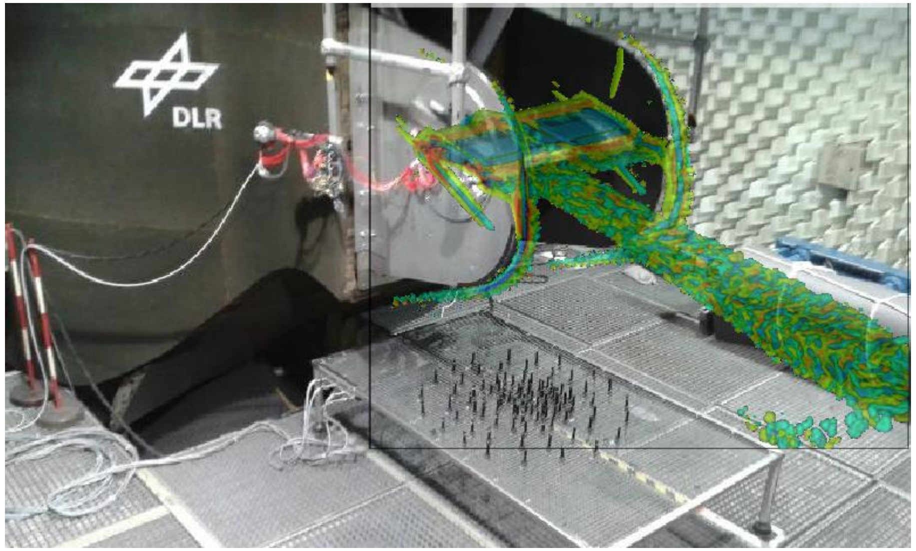



TAU RANS mean-flow and CAA mesh

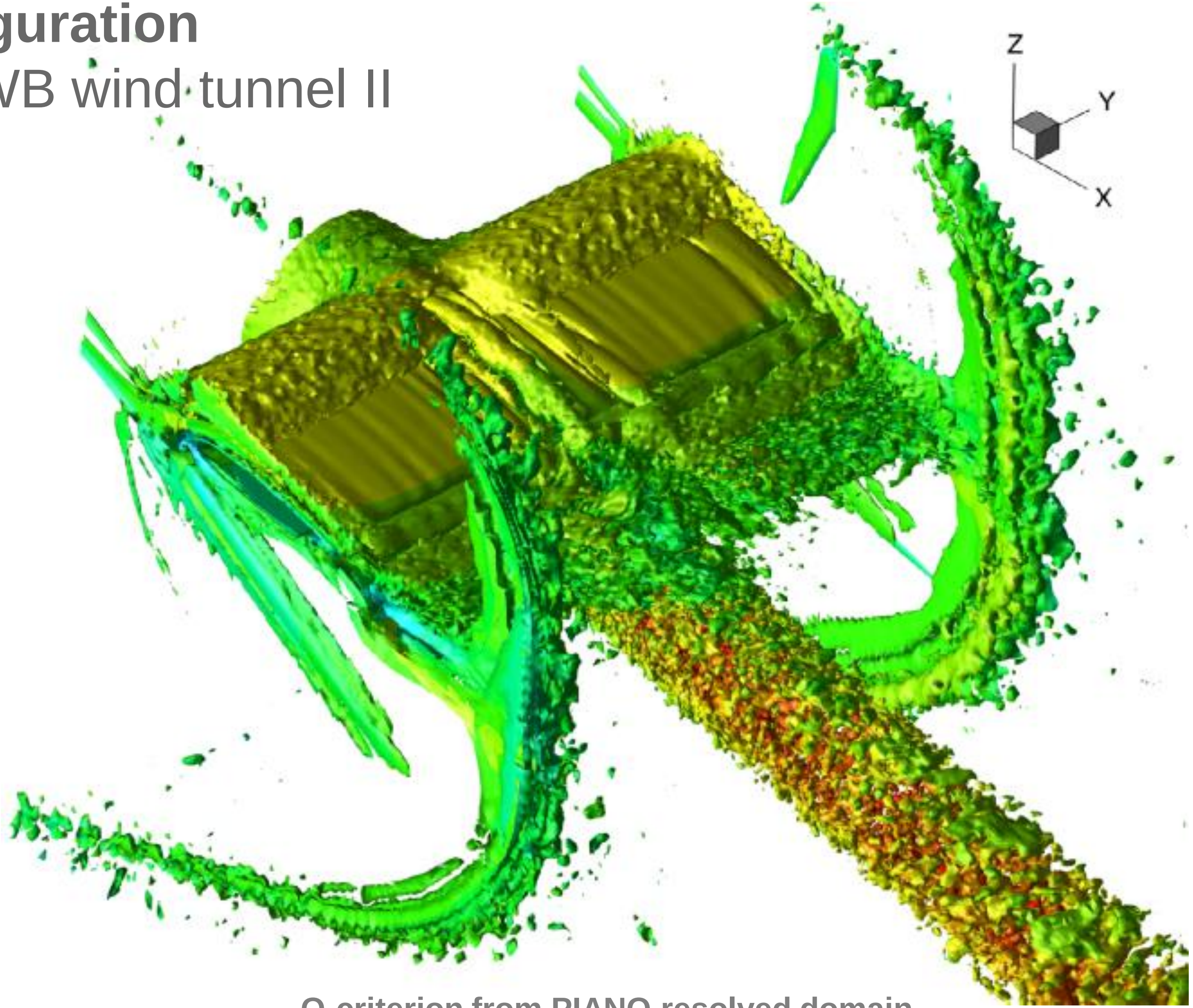


# Results of installed UHBR configuration

## Installed UHBR configuration in AWB wind tunnel II



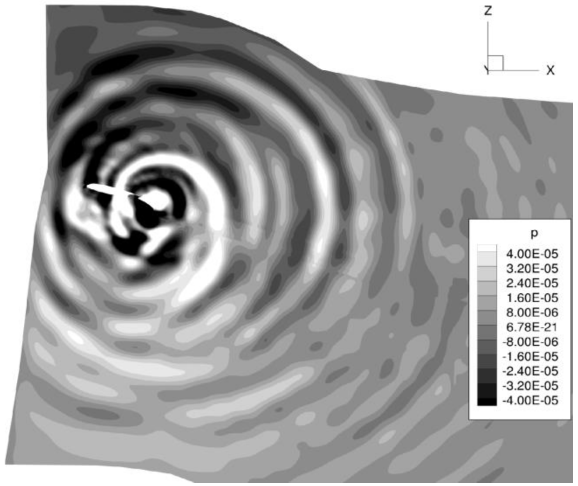

- Q-criterion (iso-surfaces) colored with the flow velocity
- Spanwise extend of computational domain does not include w/t side plates but are closely positioned to it
- Appearance of wake structures from the trailing edges of side plates
- Vortex shedding on the upper side of the wing is triggered by close position of the UBHR nacelle0



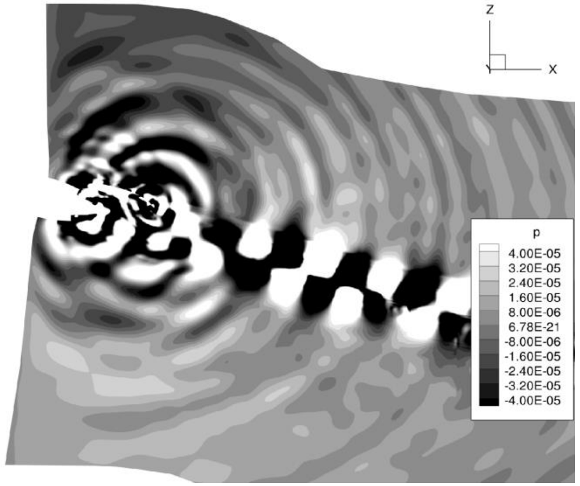

Q-criterion from PIANO resolved domain

# Results of installed UHBR configuration

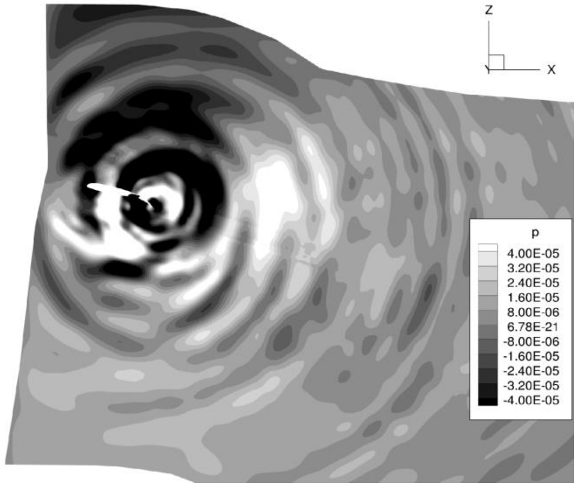
## Installed UHBR configuration in AWB wind tunnel III




**y=-0.3m**




**y=0.0m**




**y=0.3m**

- Contour plots of pressure fluctuations at three different spanwise cuts; in the symmetry plane of UHBR nozzle and to the left/right with 0.3m separation
- Strong circular noise radiation is observed with its origin at the flap trailing edge
- The hydrodynamic pressure fluctuations of the UHBR jet are observed  in the cut at the centerline
- Noise radiation to the bottom side appears to be less intensive compared to region above wing

# Outline

- Simulation Problem
- Methodology
- Results of cold isolated single stream jet
- Results of installed UHBR configuration
- **Summary & Conclusions**

# Summary & Conclusions

- **Method**
  - Application of stochastic backscatter method to technical problem: Forced Eddy Simulation
  - Successful transfer of DHIT calibration to single stream jet test case

- **Single stream jet**
  - NLDE provide correction to RANS mean flow (potential core length)
  - TKE level properly reproduced in magnitude by resolved fluctuations with respect to RANS
  - Slight modification of the TKE topology
  - Proper prediction of absolute level, spectra, directivity and Mach number scaling

- **Installed jet noise**
  - Tool chain established
  - RANS simulation of entire wind tunnel set up
  - FES simulations running
  - Jet-flap interactions identified in results

# Thank You!


DLR