Turbulence and Aeroacoustics
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Direct computation of jet noise using Large Eddy Simulation

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Outline

- **Introduction :** experimental results and open questions on jet noise
- **Computations of jets using Large-Eddy Simulation**
  - numerical methods
  - jet inflow specification
- **Effects of jet initial conditions**
  - effects of nozzle-exit turbulence level
  - effects of Reynolds number
- **Influence of jet temperature**
- **Concluding remarks**

Background

- **Motivations**

  investigation of real jets (full scale, complex nozzle geometry, heated, two streams, chevrons, installation effects ...)

  – **providing reliable predictions and better understanding**

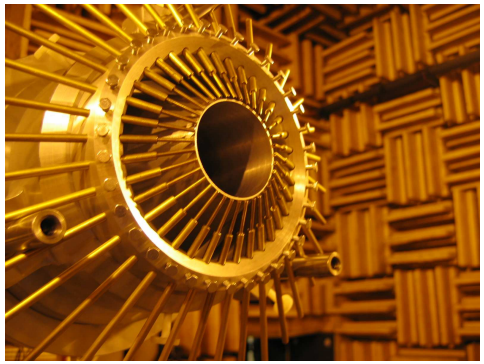
  – **giving insight for flow control and noise reduction**

  Reynolds numbers $\mathrm{Re}_D = u_j D/\nu \sim 10^7$ difficult to reach in experiments and simulations → studies at lower Re_D (DNS $\sim 10^3$, LES/exp. $\sim 10^5$)

  and most are for unheated jets

High-bypass-ratio nozzle (CFM56 type)
(Loheac *et al.*, SNECMA, 2004)

QTD2 - Boeing - NASA
AIAA Paper 2006-2720



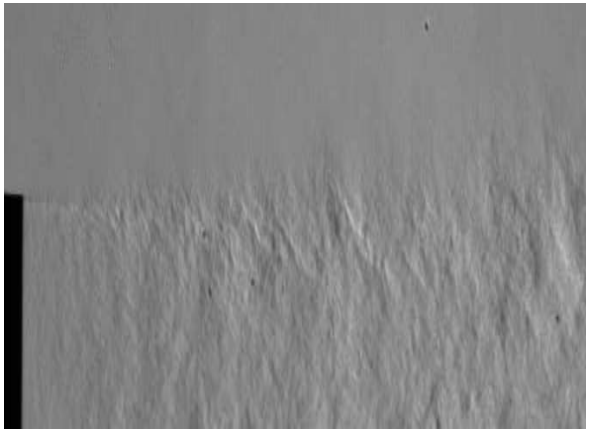
Castelain *et al.*
***AIAA J.*, 2008, 45(5)**

Effects of initial conditions

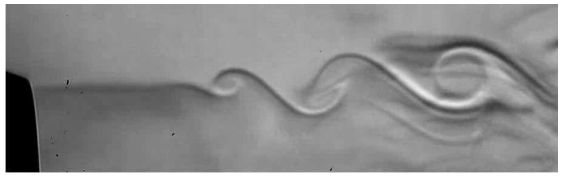
- **Shear-layer visualizations at $\neq \mathrm{Re}_D$**

from Castelain *et al.*, ECL

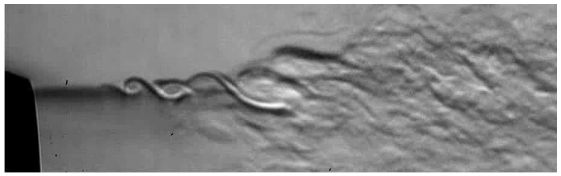
$\mathrm{Re}_D = 870,000$



$\mathrm{Re}_D = 33,000$



$\mathrm{Re}_D = 120,000$



as the Reynolds number increases

– coherent structures are weaker / fine-scale turbulence is stronger

– the laminar-turbulent transition moves upstream,

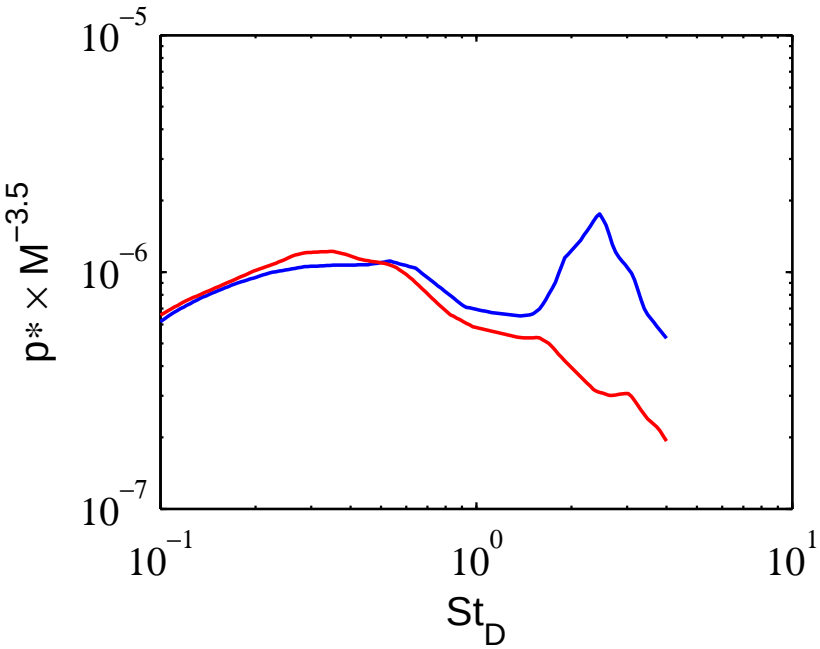
from the mixing layer to the nozzle boundary layer

– the nozzle-exit flow parameters (boundary-layer momentum thickness δ_θ/r_0 and shape factor H, Reynolds number $\mathrm{Re}_\theta = u_j\delta_\theta/\nu$, peak turbulence level u'_e/u_j) vary

Effects of initial conditions

- **Effects of initial conditions on flow and sound fields**

cf experiments by Hussain & Zedan (1978), Gutmark & Ho (1983), Zaman (1985), Raman *et al.* (1989), Bridges & Hussain (1987), ...



e.g. sound spectra at 90 deg.

for untripped/tripped jets with

— laminar exit conditions

— turbulent exit conditions

from Zaman, *AIAA J.* (1985)

several exit parameters vary and may be unknown in experiments

→ what should be prescribed in simulations?

→ what is the influence of each parameter?

there is an ongoing discussion on that issue (cf Viswanathan and Clark (2004), Zaman (2012), Karon & Ahuja (2012) and Bogey *et al.* (2010 ...))

Effects of temperature

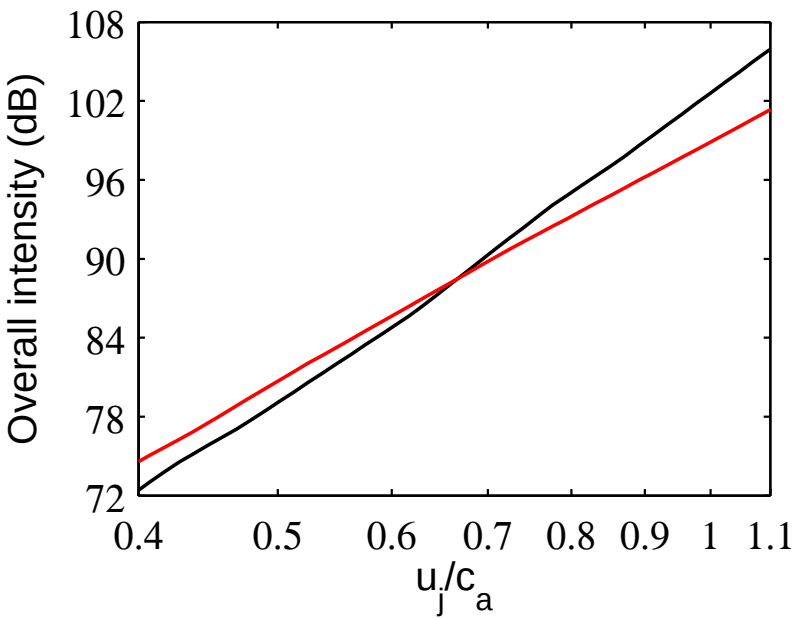
- **Effects of temperature on flow and sound fields**

  cf experiments by Witze (1974), Lau (1981), Lepicovsky (1999), Fisher *et al.* (1974), Tanna (1977), Bridges(05), ...

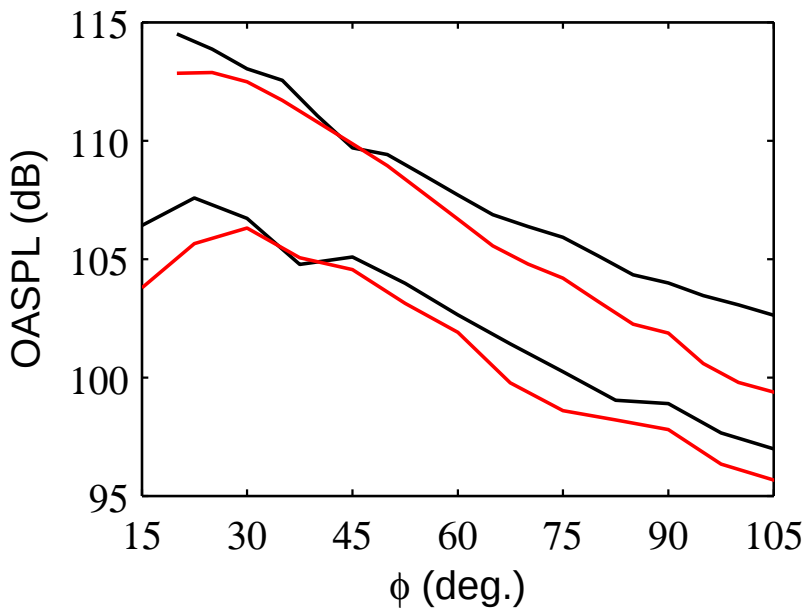
  – **overall noise increase for M $= u_j/c_a < 0.7$, and reduction for M > 0.7**

  – **noise reduction depending on the emission angle ϕ**

noise intensity *vs* **M**



sound levels *vs* ϕ **for M=0.9**



far-field data

cold/isoT

hot

from Tanna(77) and Bridges(05)

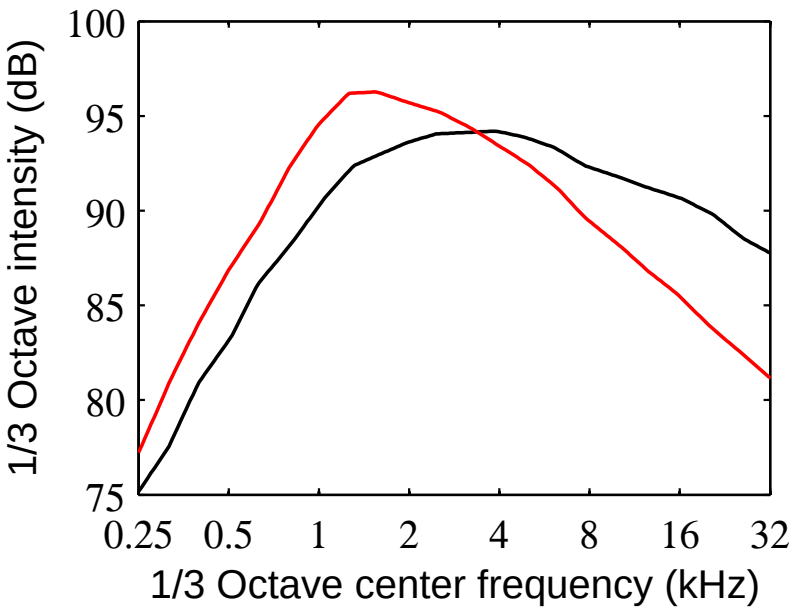
Effects of temperature

- **Effects of temperature on noise components**
  - decrease of sound levels for all freq. in the sideline direction
  - growth of low-freq. components in the downstream direction, attributed to entropy sources (cf Morfey *et al.* (1973 ...))

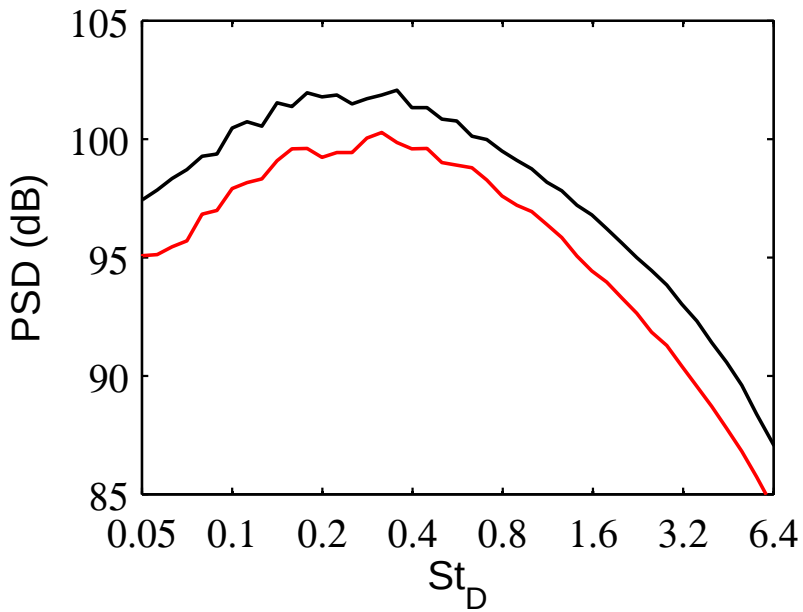
    ... questioned by Viswanathan (2004) (contamination? Re_D effects?)

    $\rightarrow$ is this low-freq. amplification obtained in simulations?

at $\phi = 45°$



at $\phi = 90°$



far-field pressure spectra for M = 0.9

cold/isoT

hot

from Tanna (77) and Bridges (05)

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Present jet simulations

- **Numerical methods**
  - space derivatives : low-dispersion 11-point finite differences
  - time integration : low-dispersion low-dissipation 6-stage Runge-Kutta
  - 11-point selective filtering to relax subgrid energy
  - radiation boundary conditions & outflow sponge zone

  Ref. : *J. Comput. Phys.*, 2004, 194(1) - *Acta Acustica*, 2002, 88(4) - *J. Comput. Phys.*, 2007, 224
  Phys. Fluids, 2006, (18)6 - *J. Fluid Mech.*, 2009, 627

- **LES based on relaxation filtering**

  the flow variables are filtered explicitly after each time step to avoid pile-up of energy at smallest scales

  - grid cut-off wave number (at 2 PPW) and filtering cut-off wave number (at $\sim$ 5 PPW) well separated
  - energy drained by the filtering at smallest scales
  - largest scales unaffected and damped by molecular viscosity

LES based on relaxation filtering

- **In LES, largest scales must be**

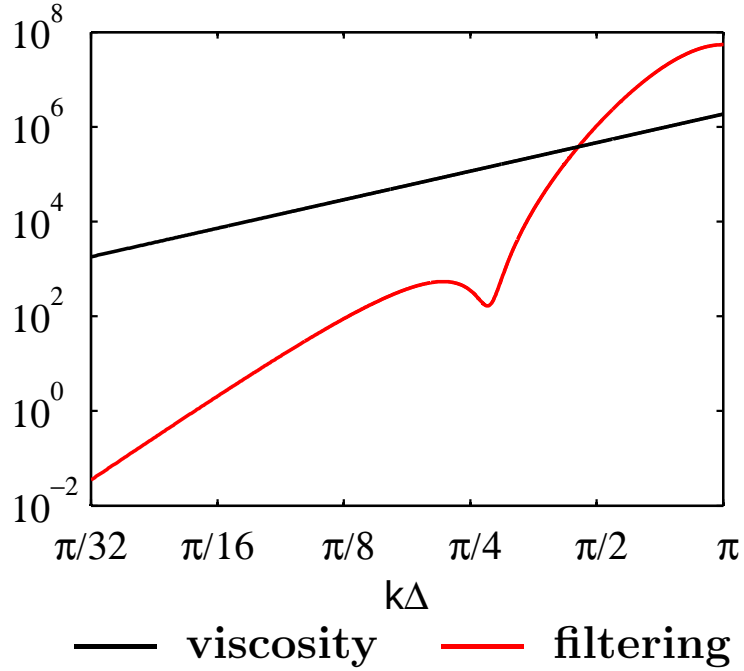
  well calculated, and mainly dissipated by viscosity (not by numeric/SGS models) to capture Reynolds number effects

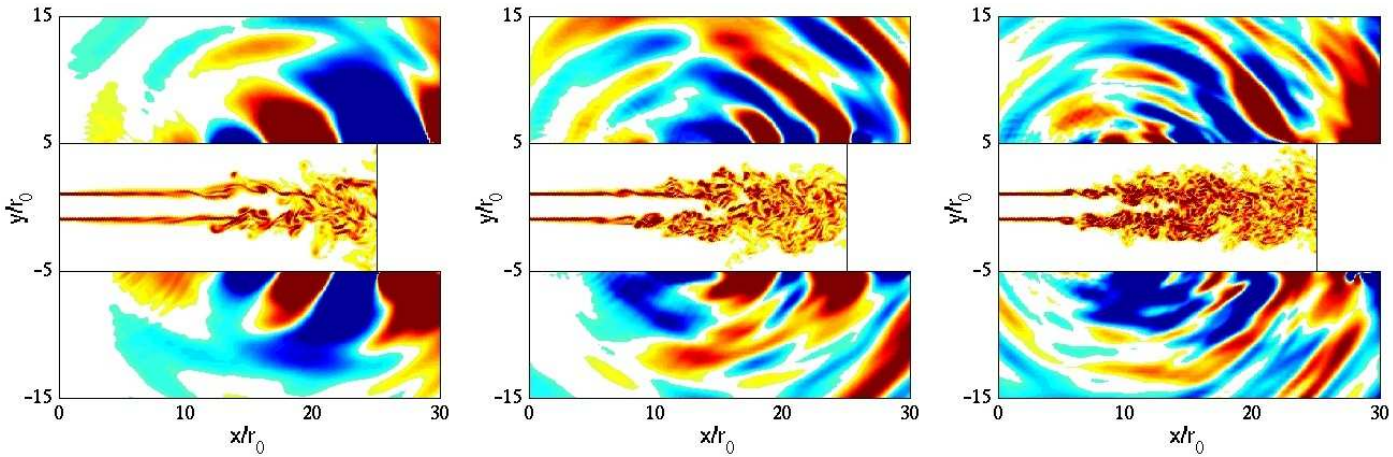
  a priori **dissipation functions**

  – **for viscosity :** $\nu k^2 = \dfrac{\nu}{\Delta^2}\,(k\Delta)^2$

  – **for filtering :** $\dfrac{\sigma_d}{\Delta t}\,D_f^*(k\Delta)$ **with** D_f^* **filter transfer fct**

vs **non-dimensional wave number**





M = 0.9 and Re_D = 1700, 2500 and 5000

vorticity and pressure

Ref.: Bogey & Bailly, *Phys. Fluids*, 2006, 18 - *TCFD*, 2006, 20(1)

Present jet simulations

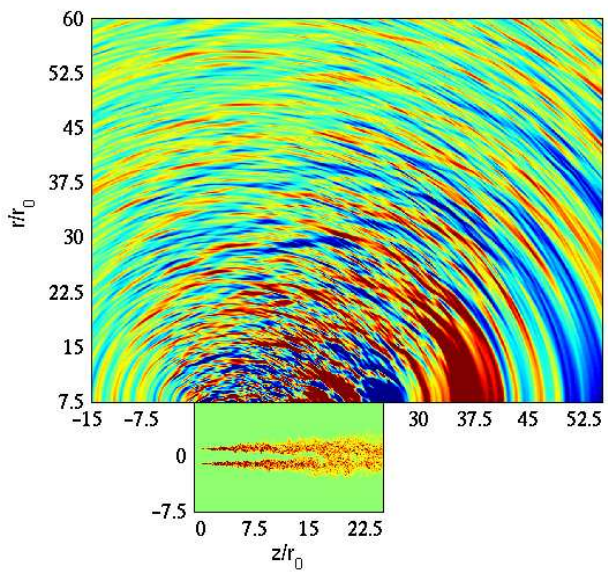
- **LES parameters**
  - grid containing $n_r \times n_\theta \times n_z = 256 \times 1024 \times 962 =$ 252 million points with $\Delta r/r_0 = 0.35\%$, $r\Delta\theta/r_0 = 0.6\%$, $\Delta z/r_0 = 0.7\%$ at the nozzle lip
  - 164,000 time steps

  the baseline LES of an isoT jet at $\mathrm{Re}_D = 10^5$ shown to be accurate

  see Bogey *et al.*, *PoF*, 2011, 23(3)

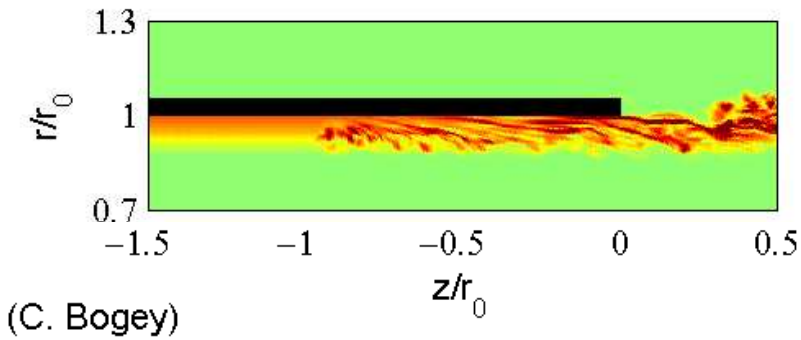
  $\rightarrow$ the LES of the other jets with $\mathrm{Re}_D \leq 10^5$ very likely reliable

- **Far-field wave propagation**
  - to $60r_0$ from the nozzle exit
  - by solving the isentropic linearized Euler eq.
  - from LES fields on a surface at $r = 6.5r_0$
  - $n_r \times n_\theta \times n_z = 835 \times 256 \times 1155 = 247 \times 10^6$

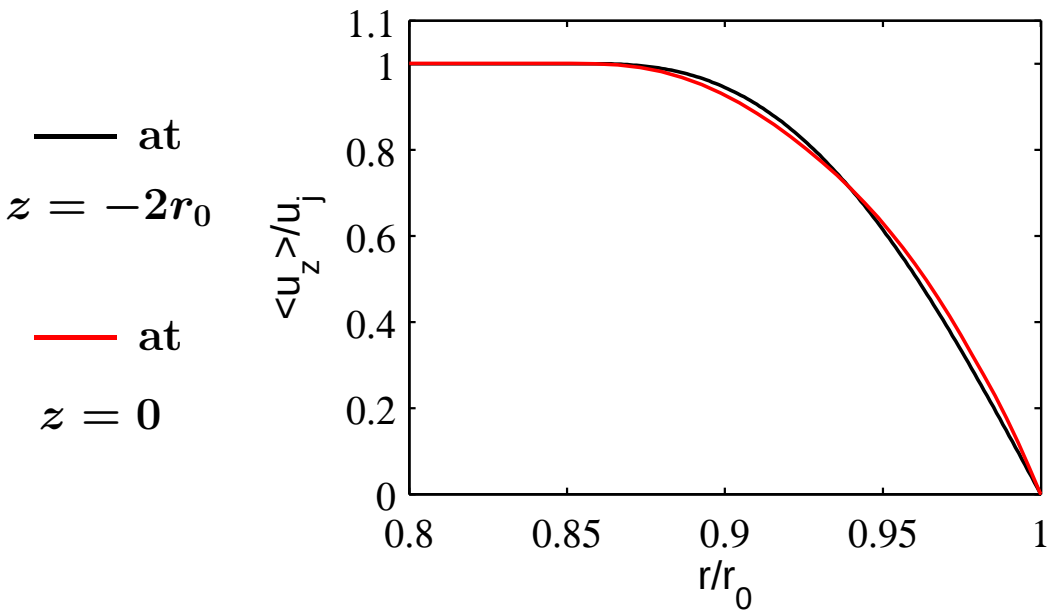


Jet inflow specification

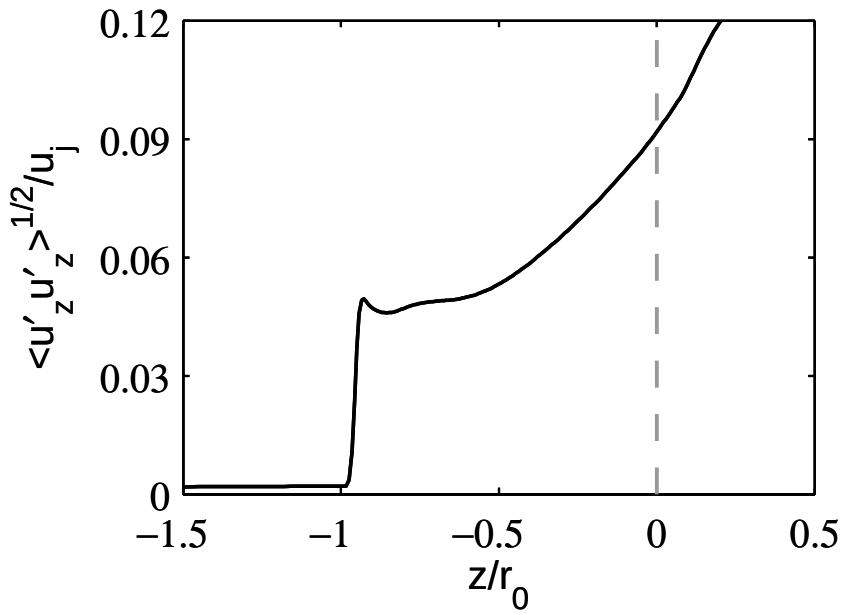
- **Boundary-layer tripping in a $2r_0$-long pipe**
  - Blasius laminar profile at the pipe inlet
  - addition at $z = -r_0$ of random vortical disturbances of magnitude chosen to provide the intended value of u'_e/u_j
  - laminar mean profile at exit (H $\simeq$ 2.3)



mean velocity *vs* r/r_0



peak rms velocity *vs* z/r_0

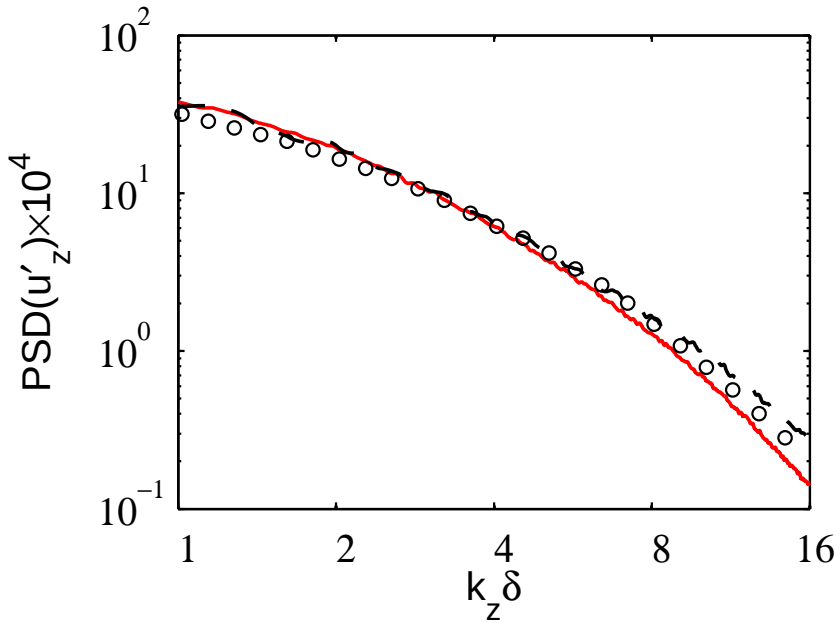


Jet inflow specification

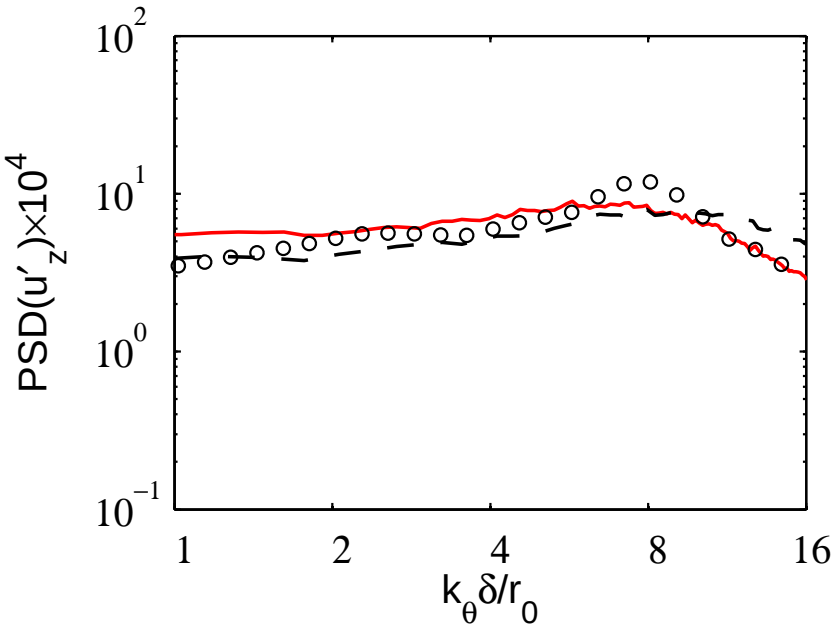
- **Spectra of velocity u'_z at $r = r_0$ and $z = 0.4r_0$**

  vs axial and azimuthal wave numbers normalized by exit BL thickness δ

vs $k_z\delta$ (using Taylor hyp.)



vs $k_\theta\delta/r_0$



—— **baseline LES of an isoT jet at $\mathrm{Re}_D = 10^5$ with $u'_e/u_j = 9\%$**

– – – **LES with twice the resolution** ∘ **DNS (turb. pipe flow, Eggels *et al.* (1994))**

→ **qualitative agreement with spectra in turbulent pipe flow and TBL**

(Tomkins & Adrian (PIV, 2005)) **see Bogey *et al.*, *PoF*, 2011, 23(9)**

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Effects of jet initial conditions

- **Objective**

  identify and distinguish between the effects of initial turbulence level and Reynolds number on laboratory-scale subsonic jets ($\mathrm{Re}_D \simeq 10^5$)

- **LES of isothermal round jets at Mach M = 0.9**

  exiting from a pipe with similar Blasius BL velocity profiles of thickness $\delta_0 = 0.15 r_0$ (momentum thickness $\delta_\theta = 0.018 r_0$) and various peak turbulence intensities u'_e/u_j

  $\rightarrow$ 4 jets with $\mathrm{Re}_D = 10^5$ and $u'_e/u_j = 3\%$, 6%, 9% or 12% ($\delta_\theta = 0.018 r_0$ yielding $\mathrm{Re}_\theta \simeq 900$)

  see in *J. Fluid Mech.*, 2012, 701

  $\rightarrow$ 4 jets with $u'_e/u_j = 9\%$ and $\mathrm{Re}_D = 2.5 \times 10^4$, 5×10^4, 10^5 or 2×10^5 (and $\mathrm{Re}_\theta = 251$, 486, 943 or 1856)

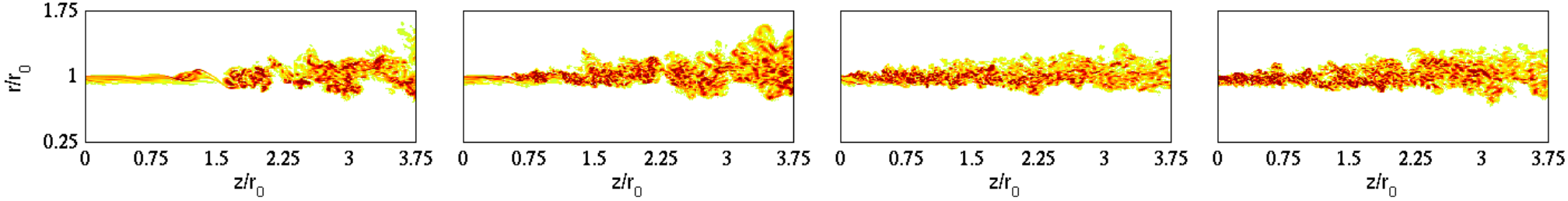
  see in *PoF*, 2012, 24(10)

Effects of jet initial conditions

- **Vorticity norm in the shear layers up to $z = 3.75 r_0$**

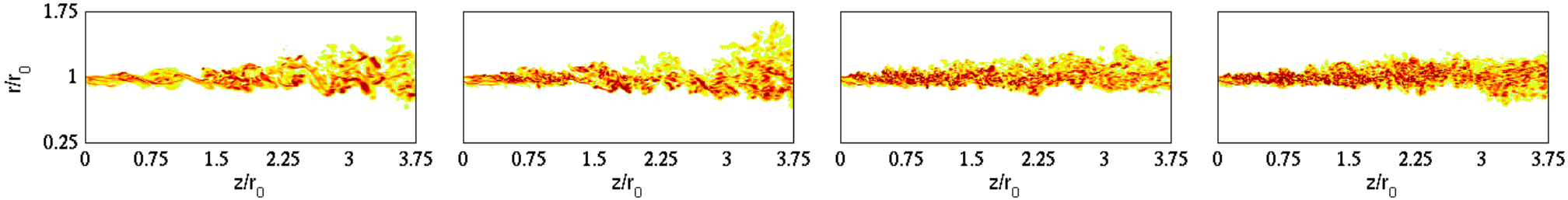
$\rightarrow$ jets with $\mathrm{Re}_D = 10^5$ and

$u'_e/u_j = 3\%$ $u'_e/u_j = 6\%$ $u'_e/u_j = 9\%$ $u'_e/u_j = 12\%$



$\rightarrow$ jets with $u'_e/u_j = 9\%$ and

$\mathrm{Re}_D = 2.5 \times 10^4$ $\mathrm{Re}_D = 5 \times 10^4$ $\mathrm{Re}_D = 10^5$ $\mathrm{Re}_D = 2 \times 10^5$

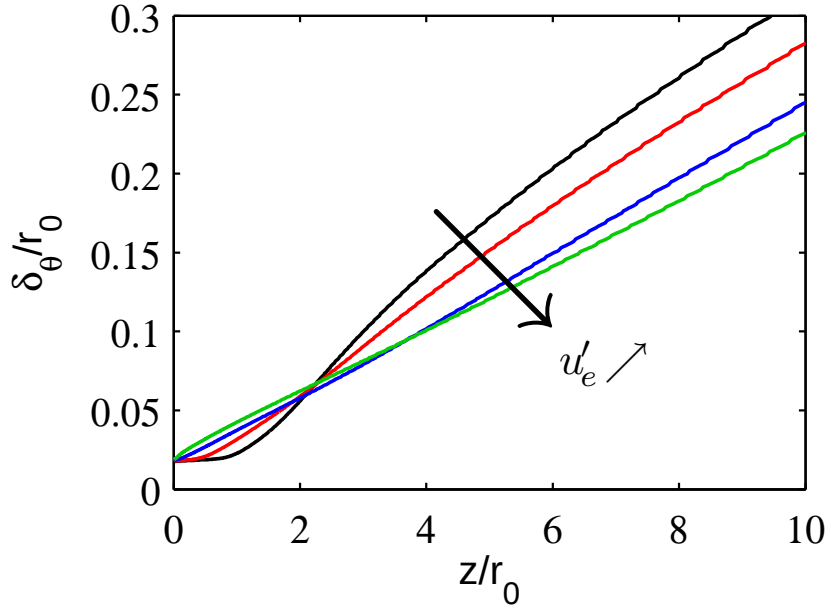


$\rightarrow$ large-scale structures observed at $u'_e/u_j = 3\%$ and $\mathrm{Re}_D = 2.5 \times 10^4$ but stronger fine-scale turbulence with increasing u'_e/u_j or Re_D

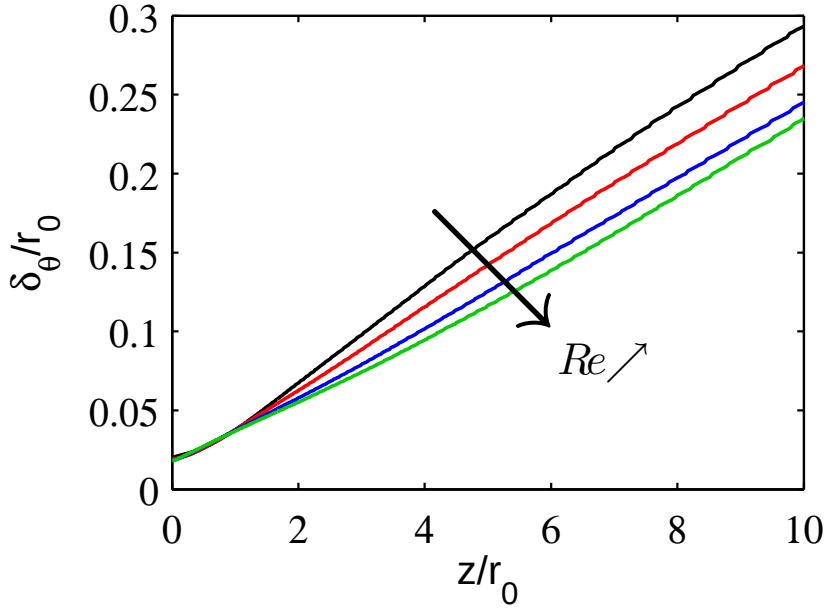
Effects of jet initial conditions

- **Momentum thickness**

$u'_e/u_j = 3\% \nearrow 12\%$



$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$

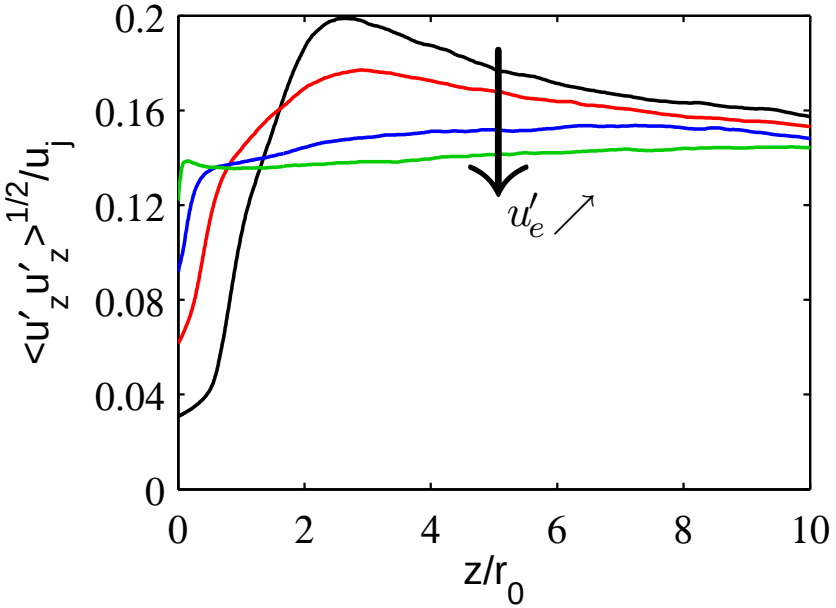


$\rightarrow$ **for higher u'_e/u_j or Re_D, the shear layers develop more slowly with lower spreading rates**

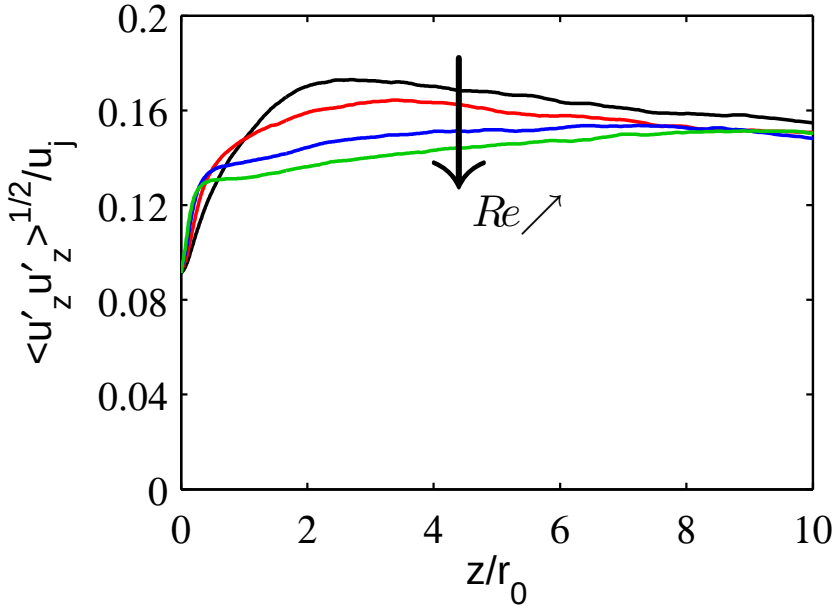
Effects of jet initial conditions

- **Peak axial turbulence intensities**

$u'_e/u_j = 3\% \nearrow 12\%$



$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$

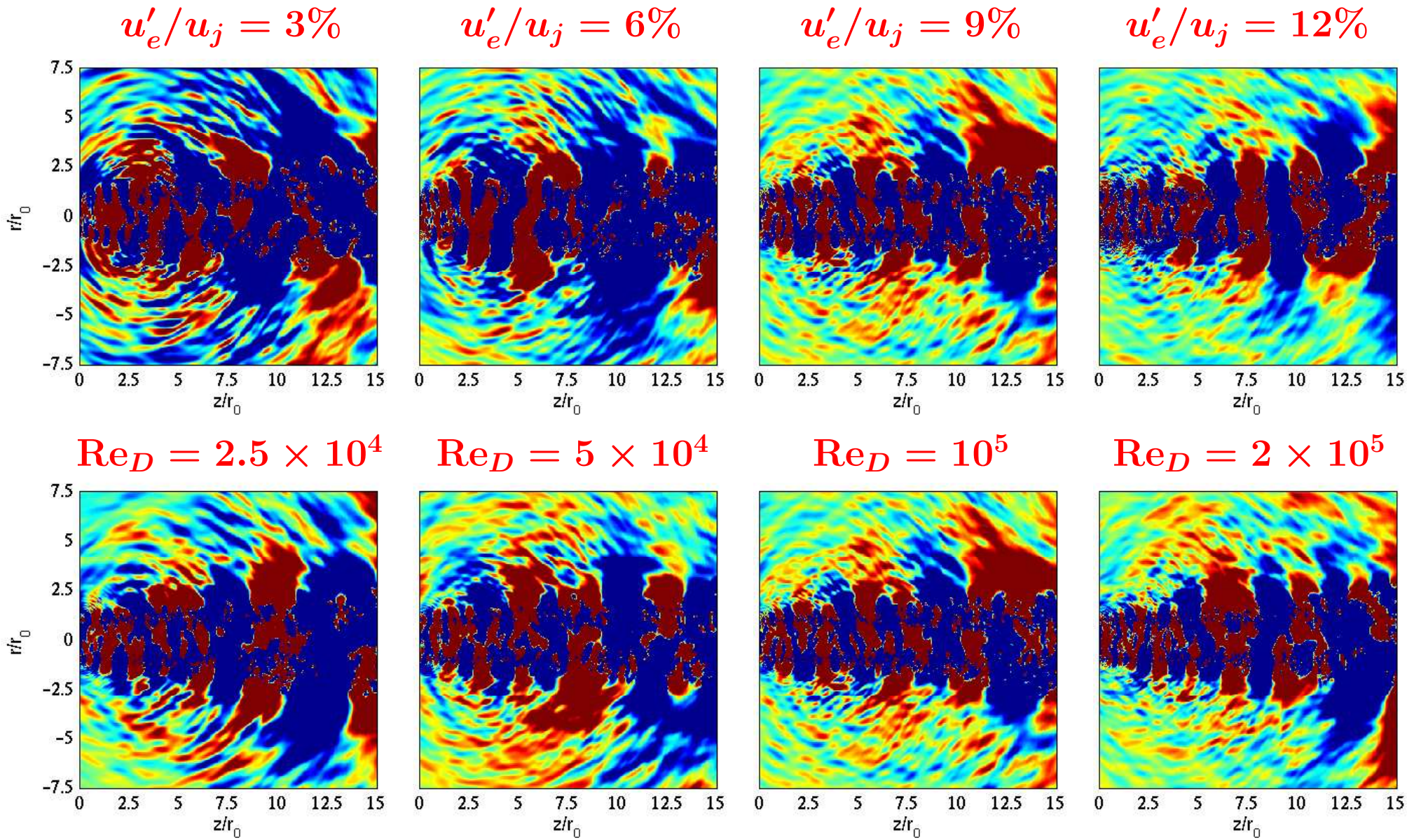


$\rightarrow$ lower rms velocities for higher u'_e/u_j or Re_D

$\rightarrow$ overshoot at $u'_e/u_j = 3\%$ and $\mathrm{Re}_D = 2.5 \times 10^4$
but nearly monotonical trend at $u'_e/u_j = 12\%$ and $\mathrm{Re}_D = 2 \times 10^5$

Effects of jet initial conditions

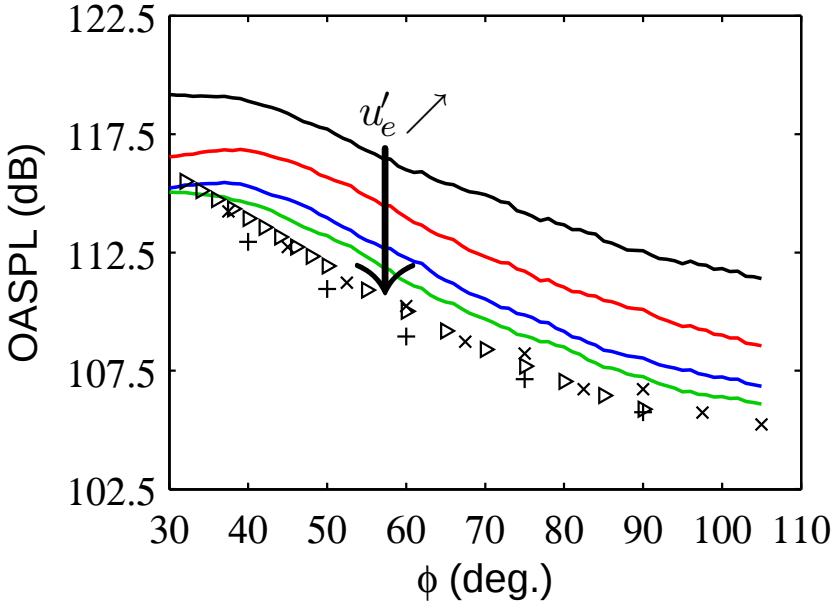
- **Fluctuating pressure**



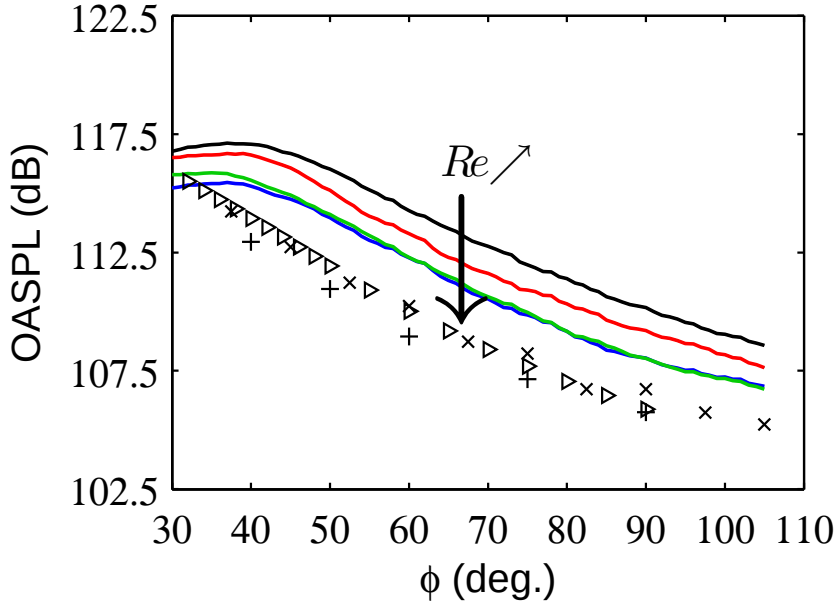
Influence of the jet initial conditions

- **Sound levels at 60 radii from the nozzle exit**

$u'_e/u_j = 3\% \nearrow 12\%$



$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$



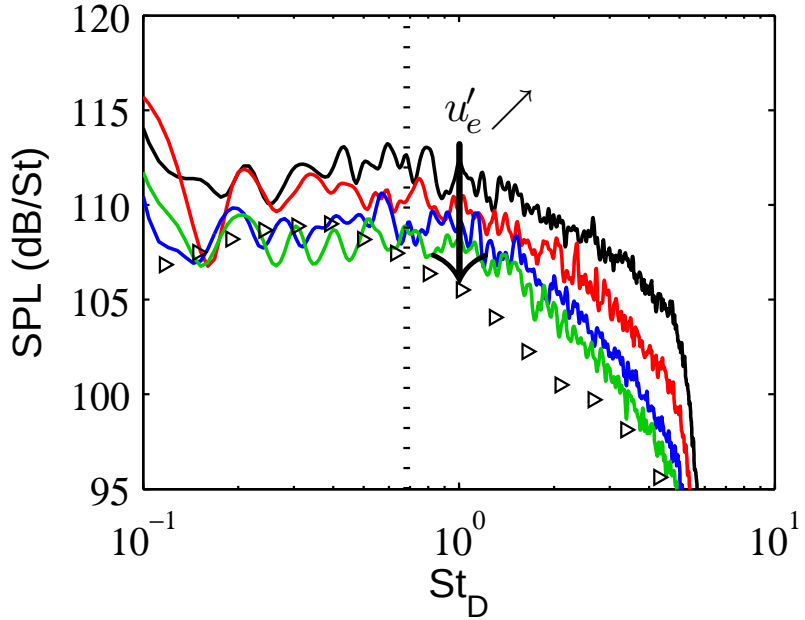
$\triangleright$, $+$, $\times$ **measurements at** $\mathrm{Re}_D \geq 5 \times 10^5$

$\rightarrow$ **as** u'_e/u_j **or** Re_D **increase, OASPL decrease and become closer to those for high-**Re_D **not very likely to generate vortex-pairing noise**

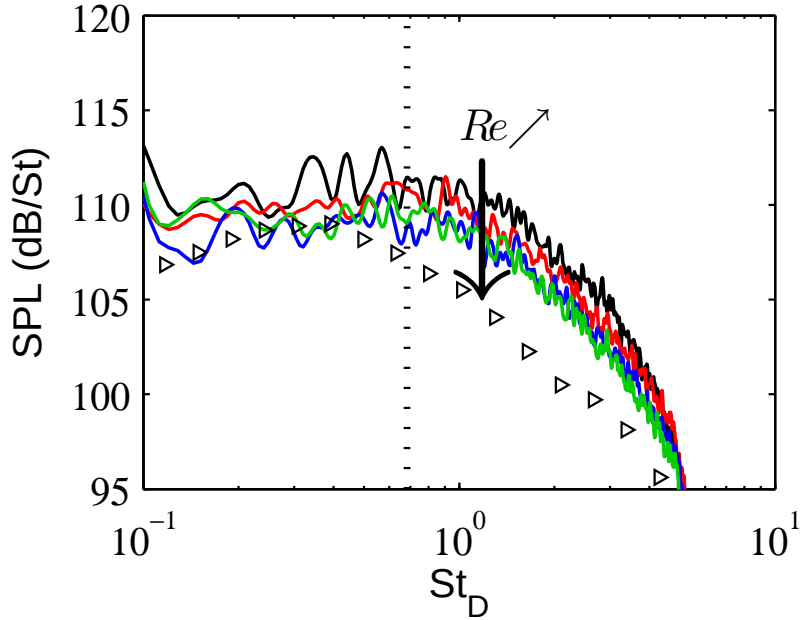
Effects of jet initial conditions

- **Sound spectra at 60 deg.**

$u'_e/u_j = 3\% \nearrow 12\%$



$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$



▷ measurements at $\mathrm{Re}_D \geq 5 \times 10^5$ ····· $\mathrm{St}_\theta = 0.007$ (half of ML dominant freq.)

→ as u'_e/u_j or Re_D increase, the extra hump wrt high-Re_D measurements is weaker, as large-scale structures no longer dominate the shear layers

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Effects of jet temperature

- **Objective**

  to identify and distinguish btw temperature and Reynolds number effects on heated laboratory-scale subsonic jets see AIAA-2013-2140

  Q : is the downstream low-freq. noise amplification due to Re_D?

- **LES of round jets** at Mach $\mathrm{M} = 0.9$

  exiting from a pipe with similar Blasius BL velocity profiles of thickness $\delta_0 = 0.15 r_0$ (momentum thickness $\delta_\theta = 0.018 r_0$) and peak turbulence intensities u'_e/u_j

  $\rightarrow$ one isoT jet at $\mathrm{Re}_D = 10^5$

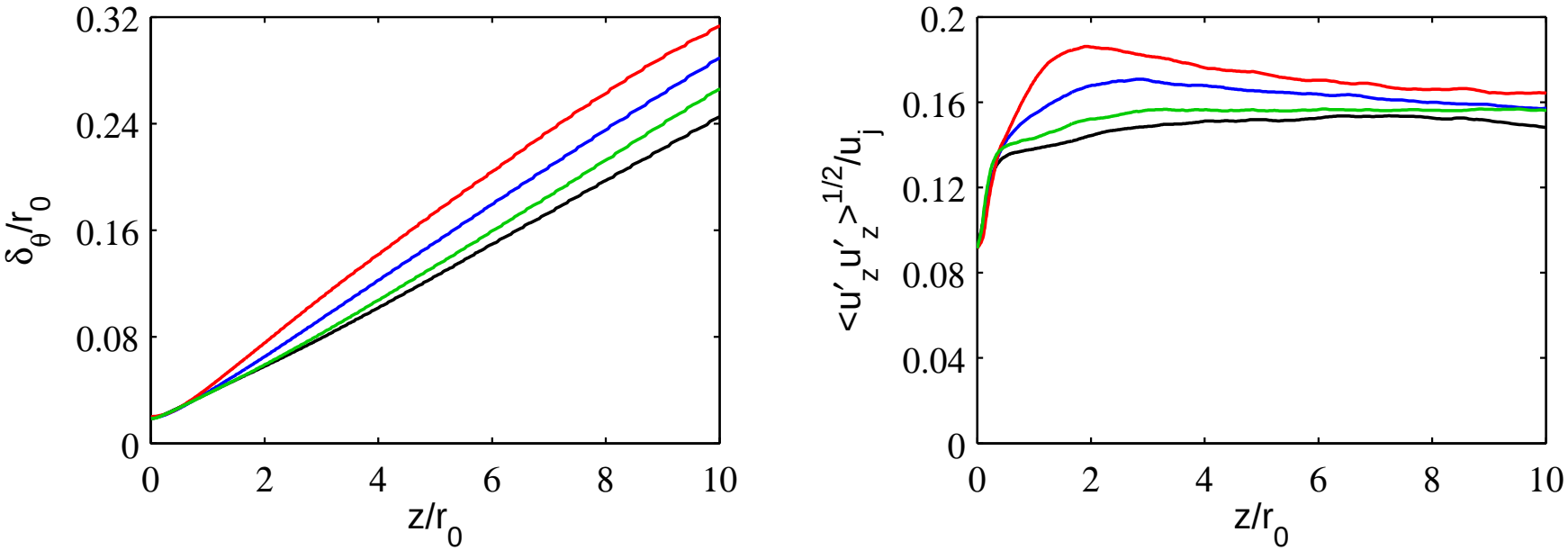
  $\rightarrow$ two hot jets at $T_j = 1.5 T_a$ and at $T_j = 2.25 T_a$ with the same diameter as the isoT jet, yielding $\mathrm{Re}_D = 5 \times 10^4$ and $\mathrm{Re}_D = 2.5 \times 10^4$ due to the variations of viscosity with T_j

  $\rightarrow$ one hot jet at $T_j = 1.5 T_a$ with the same $\mathrm{Re}_D = 10^5$ as the isoT jet

Effects of jet temperature

- **Shear-layer development**

momentum thickness δ_θ/r_0 **rms axial velocity $[u'_z]_{rms}/u_j$**



isoT, $T_j = 1.5T_a$, $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D\searrow$)

$T_j = 1.5T_a$ for the same Re_D as the isoT case

$\rightarrow$ with heating, the shear layers develop more rapidly with higher turbulence intensities for the jets at identical D, but shows much less change for a constant Re_D

... strong Reynolds nb effects

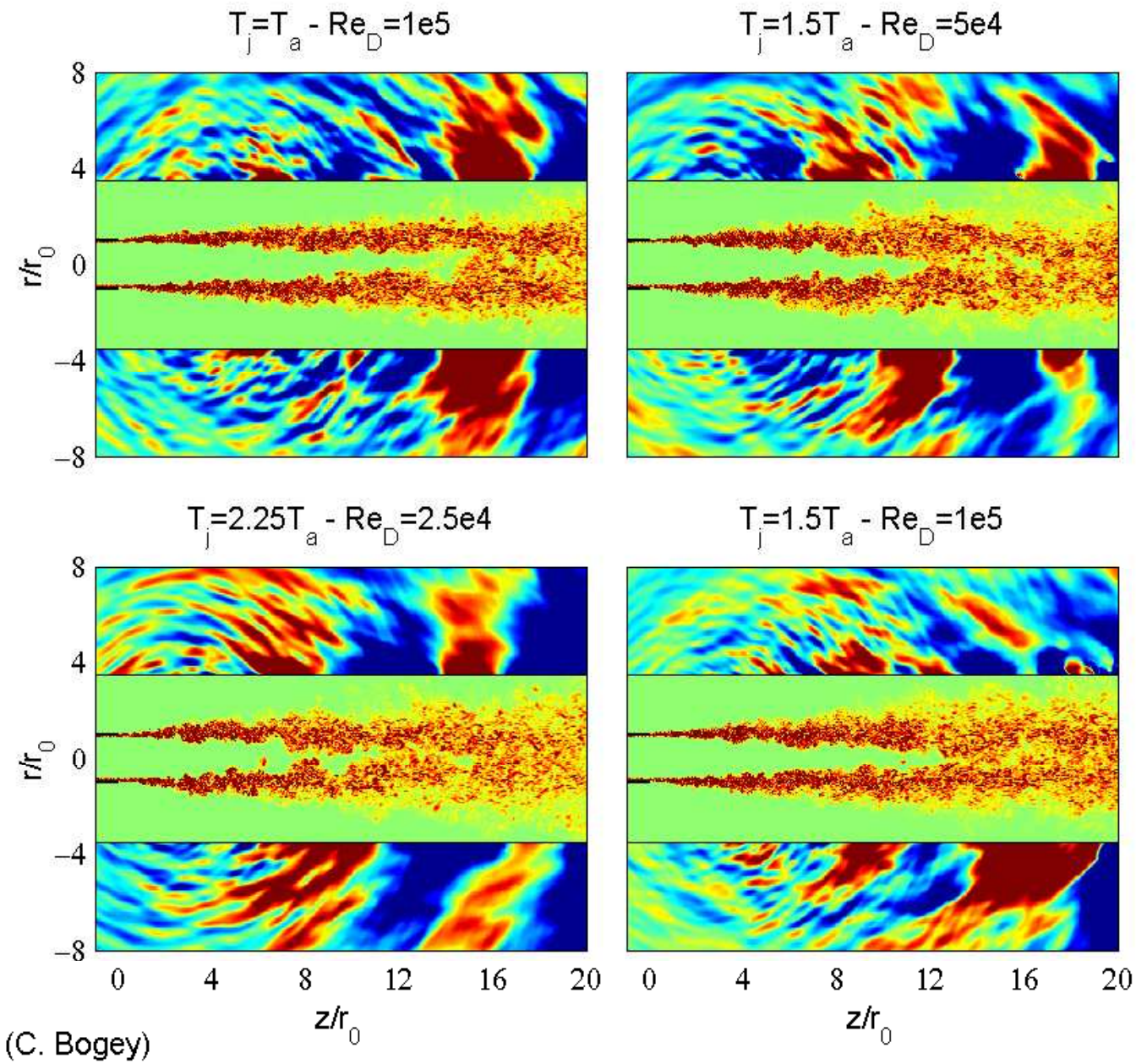
Effects of jet temperature

- **Vorticity norm in the jets and pressure outside**

with heating :

→ emission of additionnal sound waves in the mixing layers for a constant D

→ lower noise in the upstream direction at a fixed Re_D

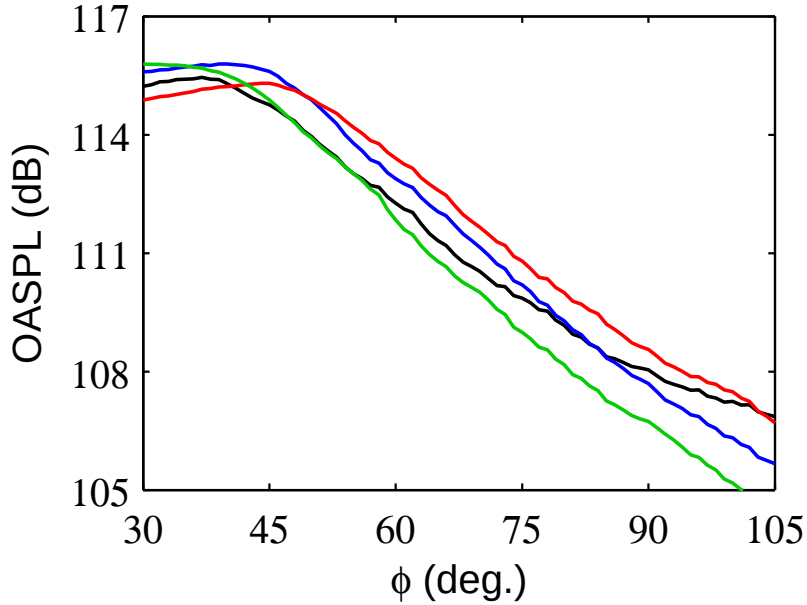


(C. Bogey)

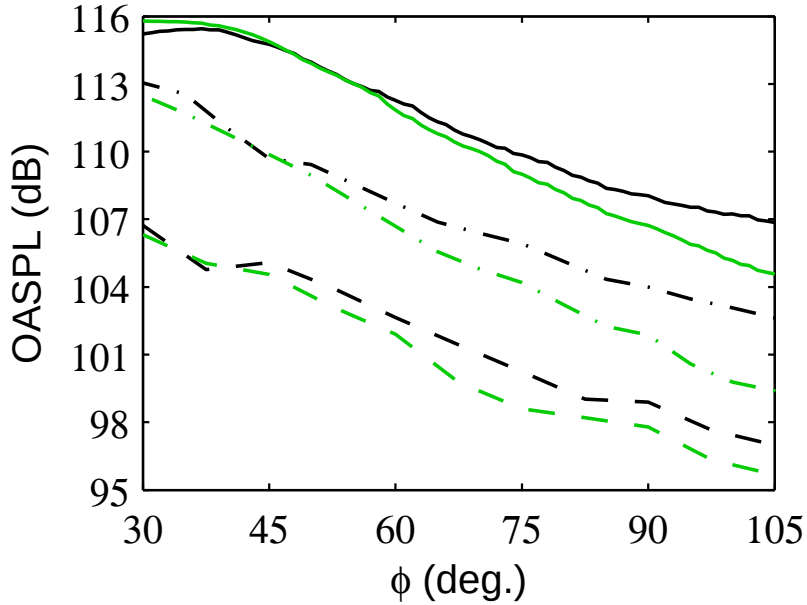
Effects of jet temperature

- **Sound levels at $d = 60r_0$** *vs* **emission angle ϕ**

OASPL



comp. with exp. data



—— isoT, —— $T_j = 1.5T_a$, —— $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

—— $T_j = 1.5T_a$ for the same Re_D as the isoT case

exp. data for M = 0.9 jets with $D = 5.1$cm from Tanna and Bridges :

– – – isoT / – – – $T_j = 2.3T_a$ at $d = 72D$, –·–·– cold / –·–·– $T_j = 1.43T_a$ at $d = 40D$

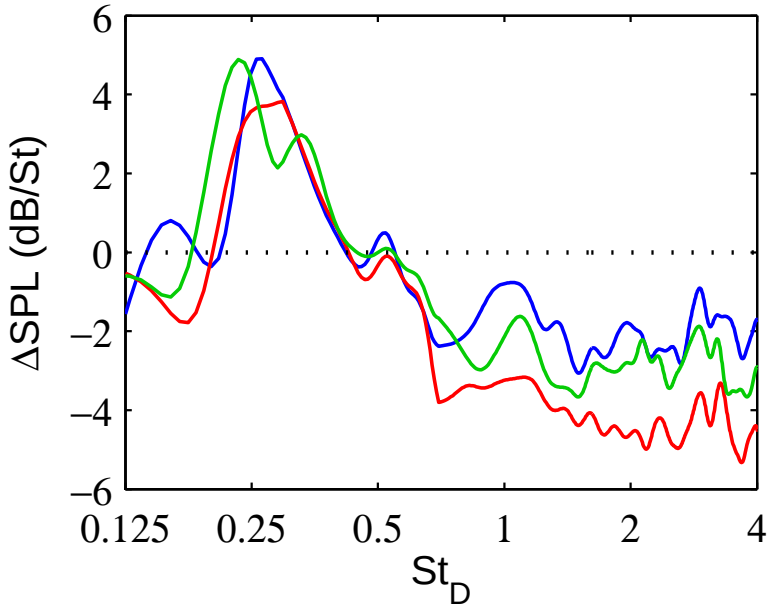
$\rightarrow$ with heating, more noise for the same D, less noise for equal Re_D

... in the latter, resemblance to exp. data for high Re_D

Effects of jet temperature

- **Difference in sound spectra wrt the isoT case** *vs* $\mathrm{St}_D = fD/u_j$

at $\phi = 30°$



— $T_j = 1.5T_a$, — $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

— $T_j = 1.5T_a$ for the same Re_D as the isoT case

$\rightarrow$ **emergence of a low-freq. component independently of Re_D**

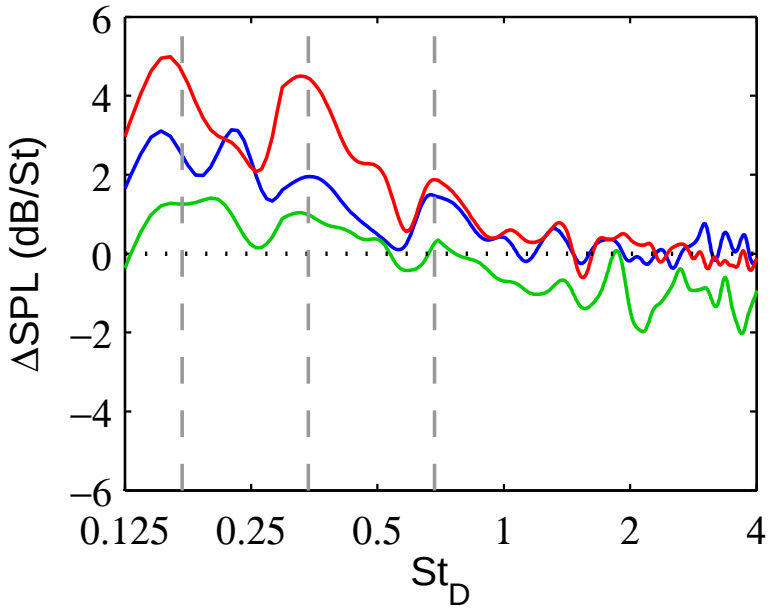
and reduction of high-freq. noise, in agreement with exp. of Tanna (1977)

... low-freq. amplification due to entropy noise sources?

Effects of jet temperature

- **Difference in sound spectra wrt the isoT case** *vs* $\mathrm{St}_D = fD/u_j$

at $\phi = 60°$



— $T_j = 1.5T_a$, — $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

— $T_j = 1.5T_a$ for the same Re_D as the isoT case

- - - 1/8, 1/4 and 1/2 of the freq. initially dominating in the mixing layers

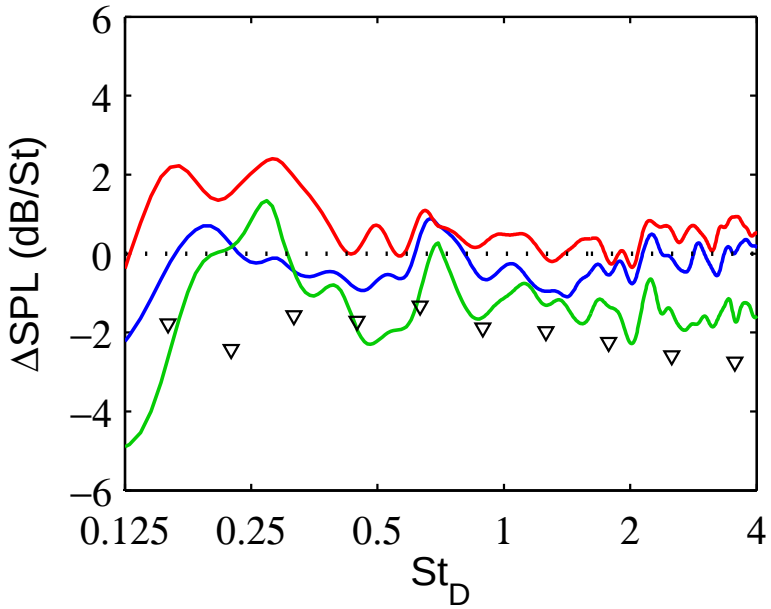
$\rightarrow$ extra noise components as Re_D decreases

... generation of vortex-pairing noise?

Effects of jet temperature

- **Difference in sound spectra wrt the isoT case** *vs* $\mathrm{St}_D = fD/u_j$

at $\phi = 90°$



— $T_j = 1.5T_a$, — $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

— $T_j = 1.5T_a$ for the same Re_D as the isoT case

exp. data for M = 0.9 jets with $D = 5.1$cm: ▽ btw cold and $T_j = 1.43T_a$ (Bridges)

$\rightarrow$ for the jet at $\mathrm{Re}_D = 10^5$, noise reduction for nearly all freq.
in line with exp. of Tanna (1977) and Bridges (2005)

Concluding remarks

- **Large-Eddy Simulations of jets**

  even still expensive, they can now allow us to carefully investigate problems encountered for laboratory-scale jets

  ... and to complement and clarify experimental results

  e.g. regarding effects difficult to distinguish, which can mutually amplify or oppose one another

  – **effects of Reynolds number ($\mathrm{Re}_D/\mathrm{Re}_\theta$) and exit turbulence levels**

  – **effects of temperature and Reynolds number**

- **They are mature enough to**

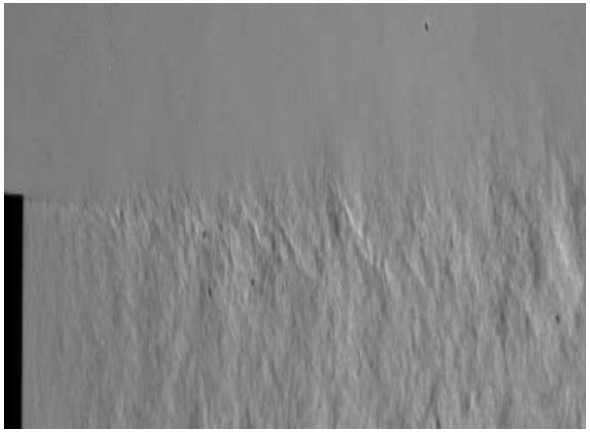
  – **provide a better understanding of noise generation mechanisms**

  – **be applied to more complex configurations**

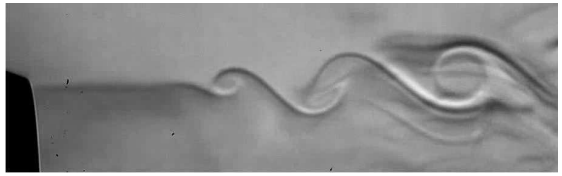
Subsonic turbulent jets

- **Shear-layer visualizations at different Re_D**

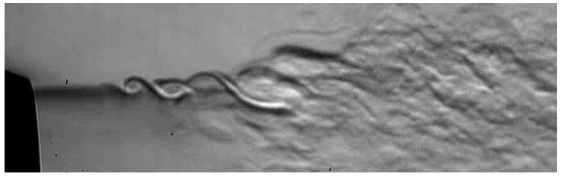
$\mathrm{Re}_D = 870,000$



$\mathrm{Re}_D = 33,000$



$\mathrm{Re}_D = 120,000$



from Castelain *et al.*, ECL

the nozzle-exit parameters vary with Re_D, including

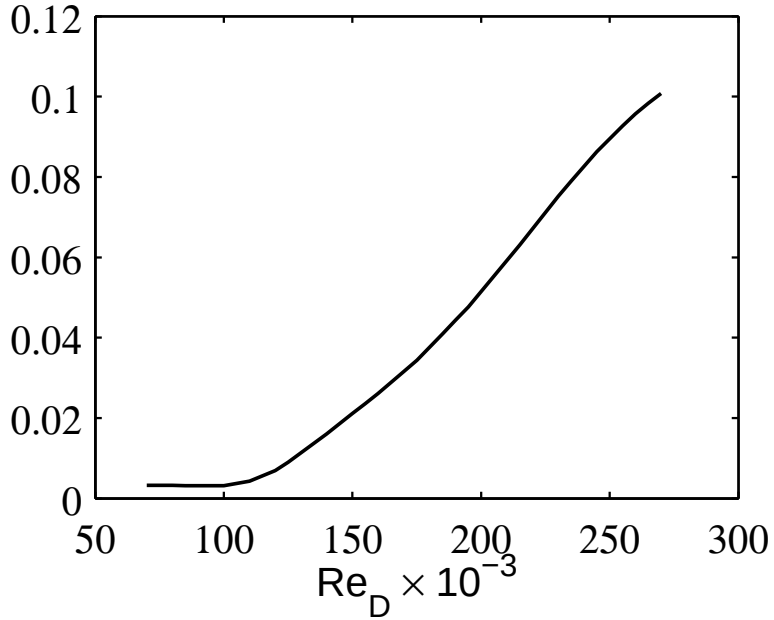
– the boundary-layer momentum thickness δ_θ/r_0 ($\sim 0.1 - 1\%$)
and its corresponding Reynolds number $\mathrm{Re}_\theta = u_j\delta_\theta/\nu$

– the peak turbulence level u'_e/u_j ($\sim 0 - 10\%$)

– the shape factor $\mathrm{H} = \delta^*/\delta_\theta$ of the mean velocity profile
($\mathrm{H} \simeq 2.5$: Blasius laminar profile - $\mathrm{H} \simeq 1.4$ turbulent profile)

Nozzle-exit conditions in subsonic jets

- **Initial flow state at the nozzle exit**



peak exit rms velocity u'_e/u_j for jets with Re_D between $50,000$ and $300,000$

from Zaman, *AIAA J.* (1985)

– **for $\mathrm{Re}_D \lesssim 100,000$: $u'_e/u_j < 1\%$ and $\mathrm{H} \simeq 2.5$**

$\rightarrow$ the jets are initially fully laminar

– **for $100,000 \lesssim \mathrm{Re}_D \lesssim 500,000$: $1\% \leq u'_e/u_j \leq 10\%$**

$\rightarrow$ the jets are initially transitional

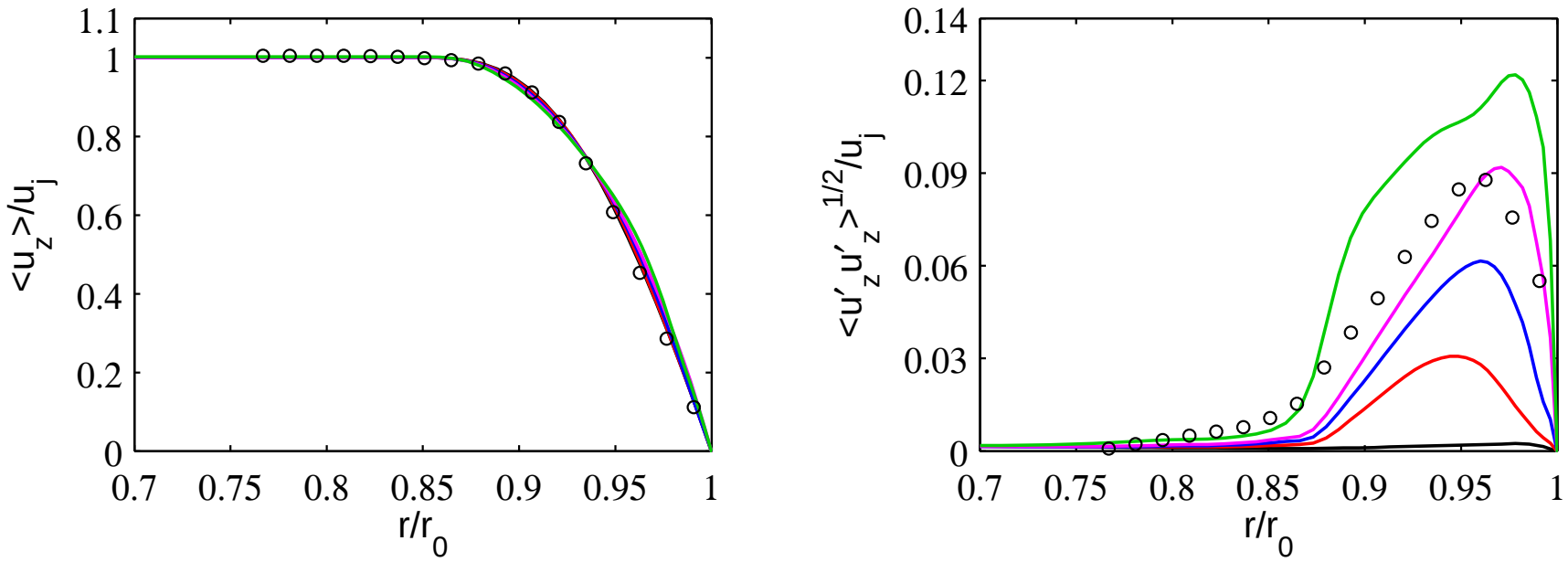
– **for $\mathrm{Re}_D \gtrsim 500,000$: $u'_e/u_j \simeq 10\%$ and $\mathrm{H} \simeq 1.4$**

$\rightarrow$ the jets are initially fully turbulent

Effects of jet initial conditions

- **Nozzle-exit flow profiles** for the jets with $\mathrm{Re}_D = 10^5$ and $u'_e/u_j \nearrow$

mean axial velocity $<u_z>/u_j$ **rms axial velocity $[u'_z]_{rms}/u_j$**



— Jet0% — Jet3% — Jet6% — Jet9% — Jet12%

○ Zaman's data for a $\mathrm{Re}_D = 10^5$ tripped jet

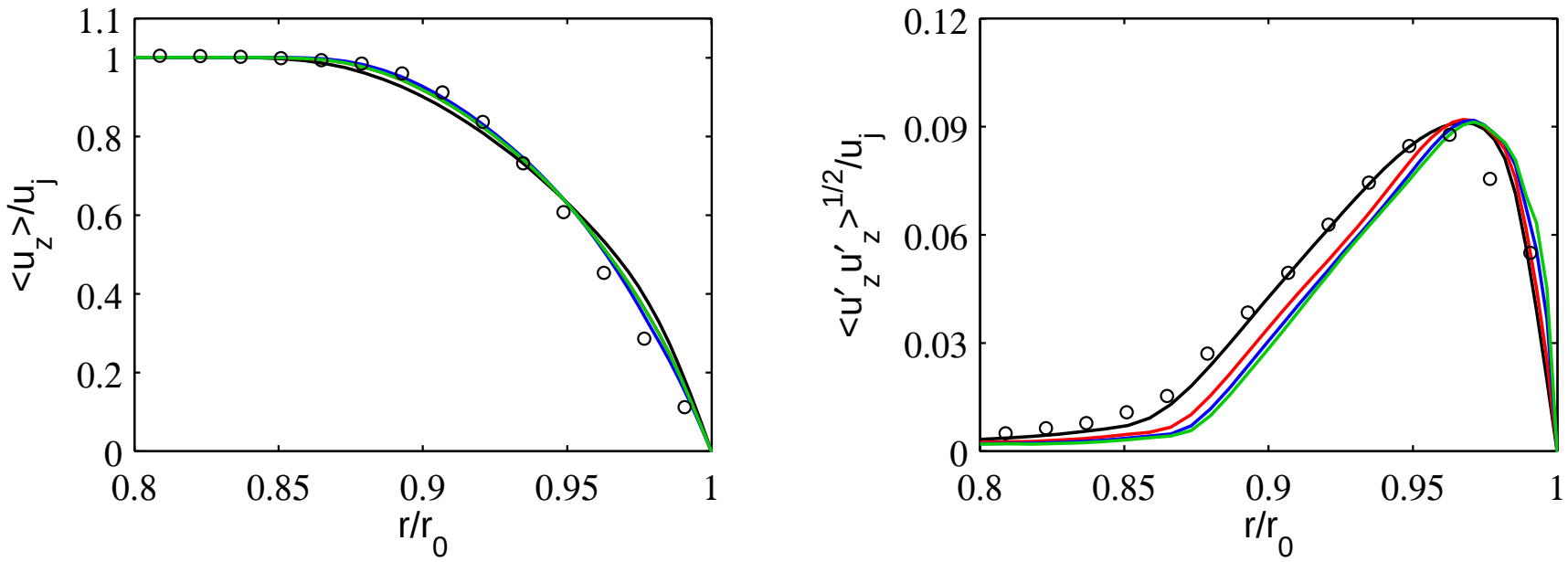
$\rightarrow$ as desired, laminar velocity profiles ($\mathrm{H} \simeq 2.3$), momentum thickness $\delta_\theta \simeq 0.018 r_0$, and rms velocity peaks $u'_e/u_j = 3, 6, 9, 12\%$

δ_θ yielding momentum Reynolds numbers $\mathrm{Re}_\theta \simeq 900$

Effects of jet initial conditions

- **Nozzle-exit flow profiles** for the jets with $u'_e/u_j = 9\%$ and $\mathrm{Re}_D \nearrow$

mean axial velocity $<u_z>/u_j$ rms axial velocity $[u'_z]_{rms}/u_j$



JetRe25e3 JetRe50e3 JetRe100e3 JetRe200e3

○ Zaman's data for a $\mathrm{Re}_D = 10^5$ tripped jet

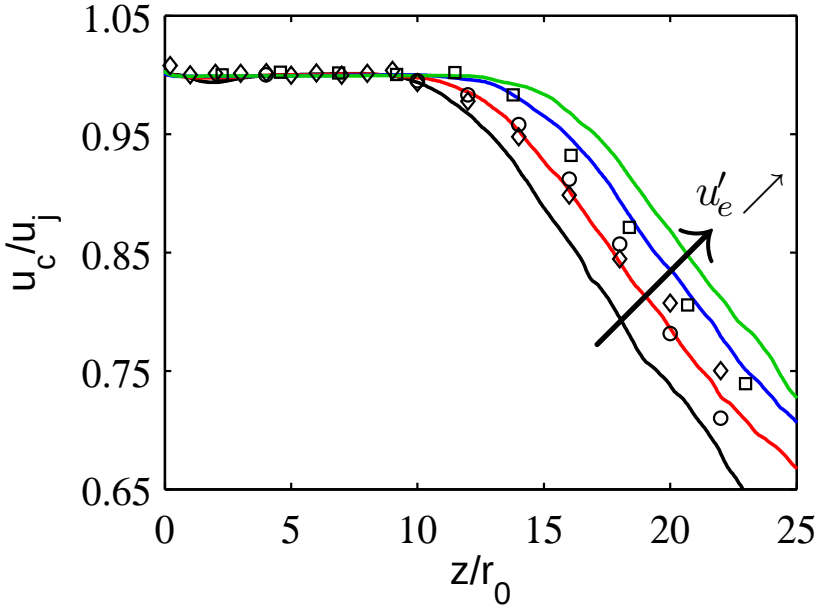
→ as desired, laminar velocity profiles (H $\simeq$ 2.3), momentum thickness $\delta_\theta \simeq 0.018 r_0$, and rms velocity peaks $u'_e/u_j \simeq 9\%$

δ_θ providing momentum Reynolds numbers $\mathrm{Re}_\theta = 251$, 477, 925 and 1830

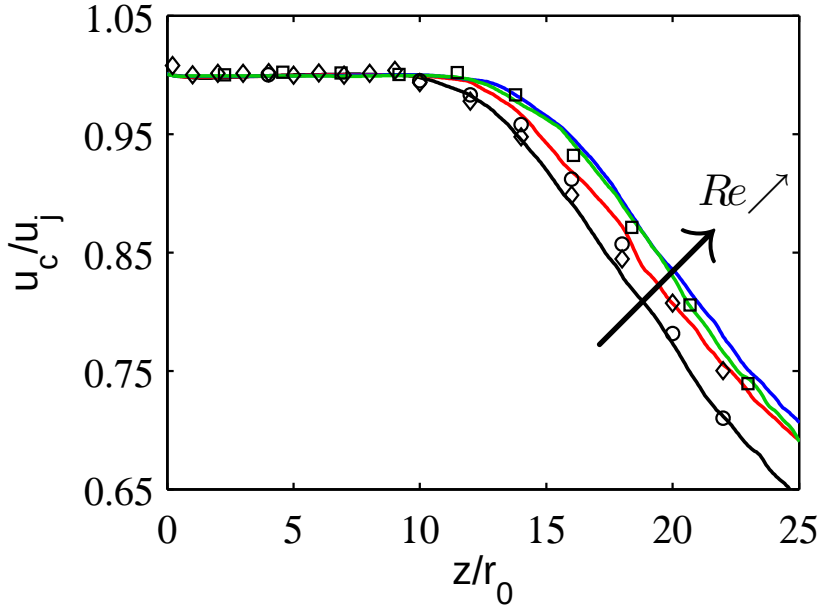
Effects of jet initial conditions

- **Centerline mean axial velocity**

$u'_e/u_j = 3\% \nearrow 12\%$



$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$



o, ◇, □ measurements for Mach 0.9 jets at $\mathrm{Re}_D \geq 5 \times 10^5$

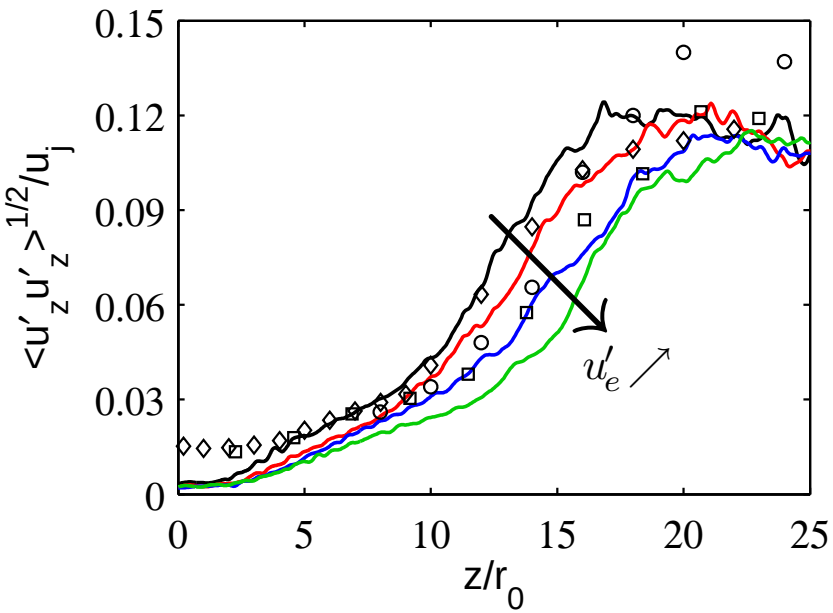
$\rightarrow$ with rising u'_e/u_j or Re_D, the jet spreads farther downstream

... fair agreement with high Re_D data

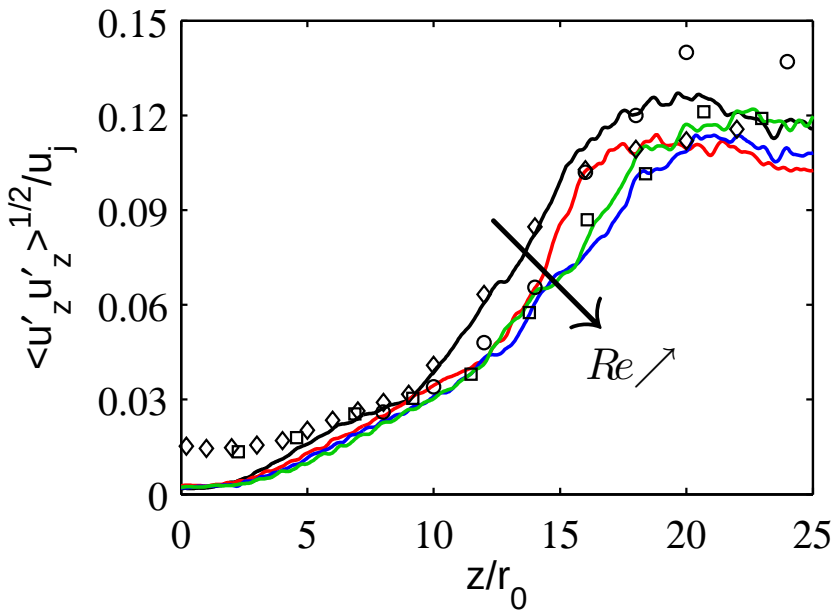
Effects of jet initial conditions

- **Centerline axial turbulence intensities**

$u'_e/u_j = 3\% \nearrow 12\%$



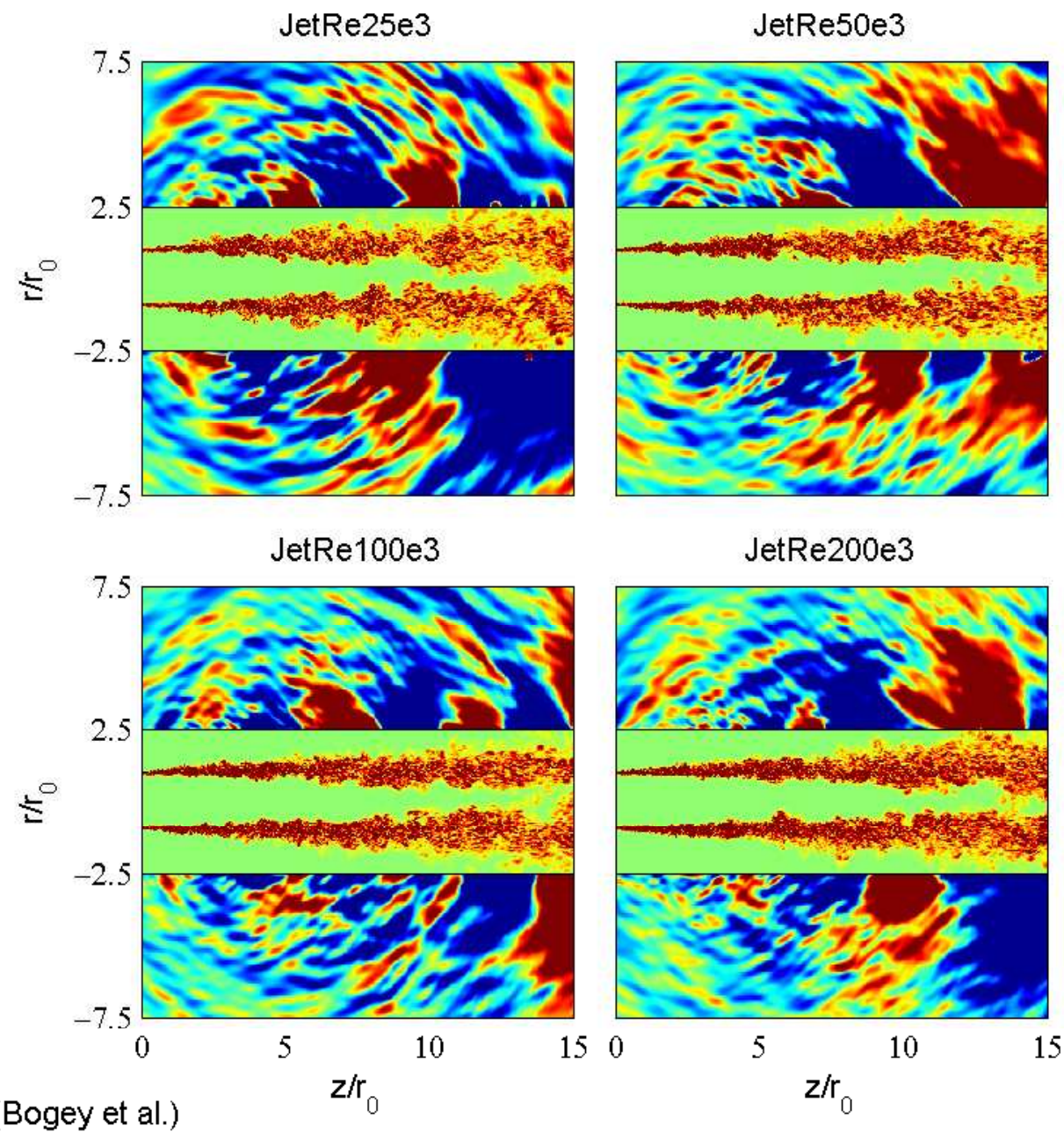
$\mathrm{Re}_D = 2.5 \times 10^4 \nearrow 2 \times 10^5$



o, ◇, □ measurements for Mach 0.9 jets at $\mathrm{Re}_D \geq 5 \times 10^5$

$\rightarrow$ as u'_e/u_j or Re_D increase, rms velocity peaks are reached farther downstream but do not differ much

Effects of jet initial conditions



(Bogey et al.)

pressure fields

for the jets with $u'_e/u_j = 9\%$ and $\mathrm{Re}_D \nearrow$

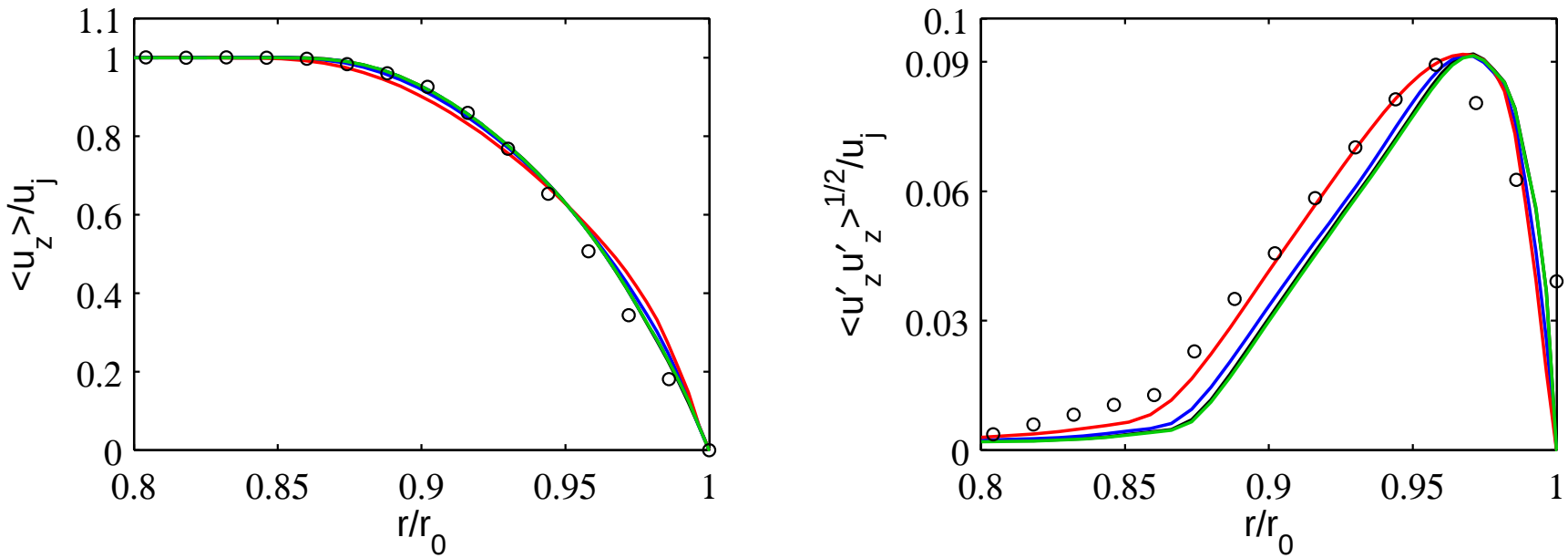
$\rightarrow$ strong waves emitted between $z = 2r_0$ and $z = 5r_0$ at lower Re_D,

attenuated at higher Re_D

Effects of jet temperature

- **Nozzle-exit profiles**

mean axial velocity $<u_z>/u_j$ **rms axial velocity $[u'_z]_{rms}/u_j$**



— isoT, — $T_j = 1.5T_a$, — $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

— $T_j = 1.5T_a$ for the same Re_D as the isoT case

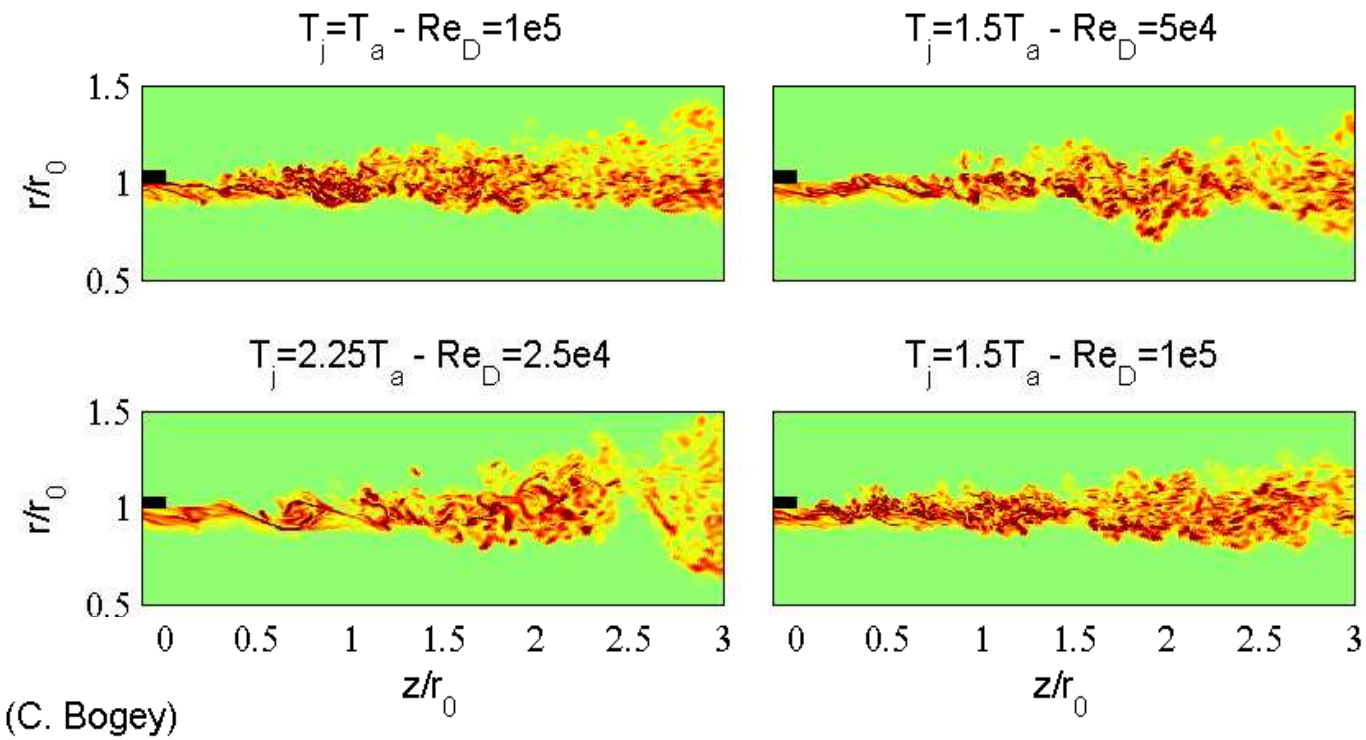
∘ exp. data for a $\mathrm{Re}_D = 10^5$ tripped jet

$\rightarrow$ as desired, (laminar) Blasius velocity profiles (shape factor $H \simeq 2.3$), momentum thickness $\delta_\theta \simeq 0.019 r_0$, and rms velocity peak $u'_e/u_j \simeq 9\%$

... δ_θ providing $\mathrm{Re}_\theta = 943$, 485, 254 and 941

Effects of jet temperature

- **Vorticity norm in the shear layers up to $z = 3r_0$**



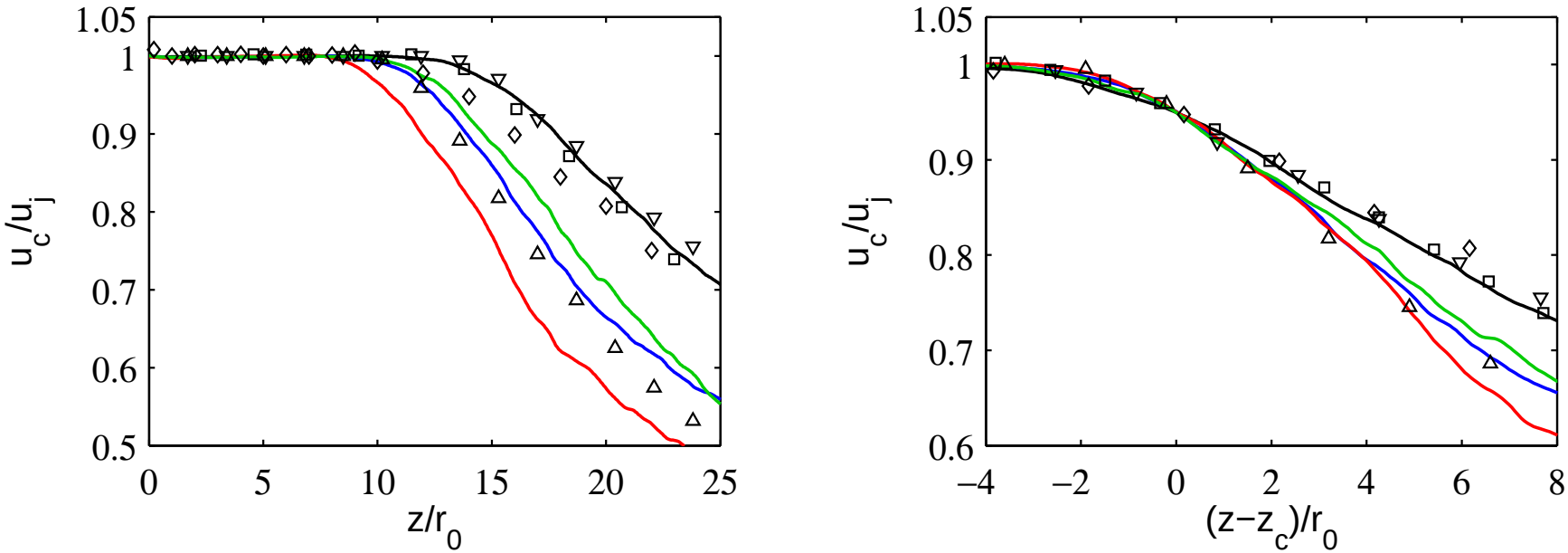
$\rightarrow$ stronger large-scale structures in the hot jets with equal diameter and decreasing Re_D

$\rightarrow$ similar vorticity fields for a constant Re_D

Effects of jet temperature

- **Centerline mean axial velocity u_c/u_j**

variations with z/r_0 **with $(z - z_c)/r_0$**



isoT, $T_j = 1.5T_a$, $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

$T_j = 1.5T_a$ for the same Re_D as the isoT case

exp. data at M = 0.9 and $\mathrm{Re}_D \geq 4 \times 10^5$: $\triangledown$, $\diamond$, $\square$ $T_j \simeq T_a$, $\triangle$ $T_j = 1.76T_a$

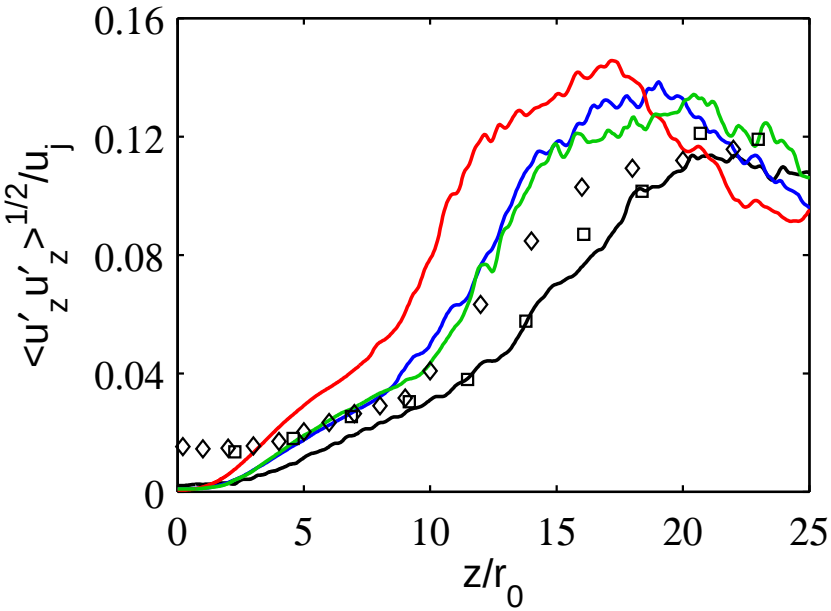
$\rightarrow$ in all cases, the potential core shortens and the velocity decay is faster with heating, in good agreement with exp. data

... temperature effects are predominant

Effects of jet temperature

- **Centerline turbulence intensities**

rms axial velocity $[u'_z]_{rms}/u_j$



—— isoT, —— $T_j = 1.5T_a$, —— $T_j = 2.25T_a$ for the same D (and $\mathrm{Re}_D \searrow$)

—— $T_j = 1.5T_a$ for the same Re_D as the isoT case

exp. data at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D \geq 4 \times 10^5$: $\diamond$, $\square$ $T_j \simeq T_a$

$\rightarrow$ with rising temperature, the peak turbulence intensities increase, in agreement with exp. findings of Bridges (2006)

LES of jet noise carried out since 2000

- **Simulations without nozzle**

  of subsonic jets at Mach M = 0.9 :

  – **feasibility (JEAN)** *TCFD*, **2003, 16(4)-** *C&F*, **2006, 35(10)**

  – **influence of forcing** *AIAA J*, **2005, 43(5)**

  – **influence of subgrid-scale model (Smagorinsky *vs* filtering)**

  AIAA J, **2005, 43(2) -** *PoF*, **2006, 18(6) -** *IJHHF*, **2006, 27**

  – **analysis of two noise components for Reynolds $\mathrm{Re}_D \leq 10,000$**

  TCFD, **2006, 20(10) -** *JFM*, **2007, 583**

- **Simulations with pipe nozzle**

  preliminary simulations :

  – **single-stream subsonic jet** *IJA*, **2008, 7(1)**

  – **supersonic screeching jet** *PoF*, **2007, 19(7)**

  – **dual-stream jet (CoJeN)** *PoF*, **2009, 21(3)**

LES of jet noise carried out since 2000

recent simulations with pipe nozzle :

- **jet at $\mathrm{M} = 3.3$ and $\mathrm{Re}_D = 100,000$** *AIAA J*, 2011, 49(10)
- **initially laminar jets at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D = 100,000$**

  JFM, 2011, 23(3)
- **initially turbulent jets at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D \simeq 100,000$**

  $\rightarrow$ **grid convergence and investigation of exit turbulence**

  PoF, 2011, 23(3) - *PoF*, 2011, 23(9)

  $\rightarrow$ **effets of initial turbulence** *JFM*, 2012, 701

  $\rightarrow$ **effets of Reynolds number** *PoF*, 2012, 24(10)

  $\rightarrow$ **effets of exit-boundary-layer thickness** *PoF*, 2013, 25(05)

ongoing work :

- **heated jets at $\mathrm{M} = 0.9$ and $\mathrm{Re}_D \simeq 100,000$** **AIAA-2013-2140**

papers available at http://acoustique.ec-lyon.fr/caapubli_fr.php

About grid resolution in jet LES

- **Highest resolutions in recent LES of subsonic single jets**

  → **jet conditions**

	Re_D	Re_θ	δ_{BL}/r_0	BL trip	u'_e/u_j	initial state
Bogey & Bailly (JFM, 2010)	10^5	1200	0.2	no	$< 1\%$	fully laminar
Bogey *et al.* (PoF, 2011)	10^5	900	0.15	yes	$\sim 9\%$	nominally turbulent
Shur *et al.* (JSV, 2011)	1.1×10^6	550	0.016	DES	na	na

  → **grid resolutions wrt δ_{BL}**

	$n_r \times n_\theta \times n_z$	$\delta/\Delta r_{min}$	$\delta/(r_0\Delta\theta)$	$\delta/\Delta z_e$	remarks
Bogey (2010)	$173 \times 256 \times 505$	7	8.1	3.5	similar results when Δr & $\Delta z/2$
Bogey (2011)	$256 \times 1024 \times 962$	41	24	21	very close mixing layer solutions when $\delta/\Delta r$, $\delta/(r_0\Delta\theta)$ & $\delta/\Delta z \times 2$
Shur (2011)	$158 \times 240 \times 601$	4.4	0.6	1.6	

in Bogey (2011) : integral length scales shown to be well discretized and affected by molecular viscosity rather than by the sgs model