The National Center for Hypersonic Laminar-Turbulent Transition Research

Surface Roughness Effects on a Blunt Hypersonic Cone

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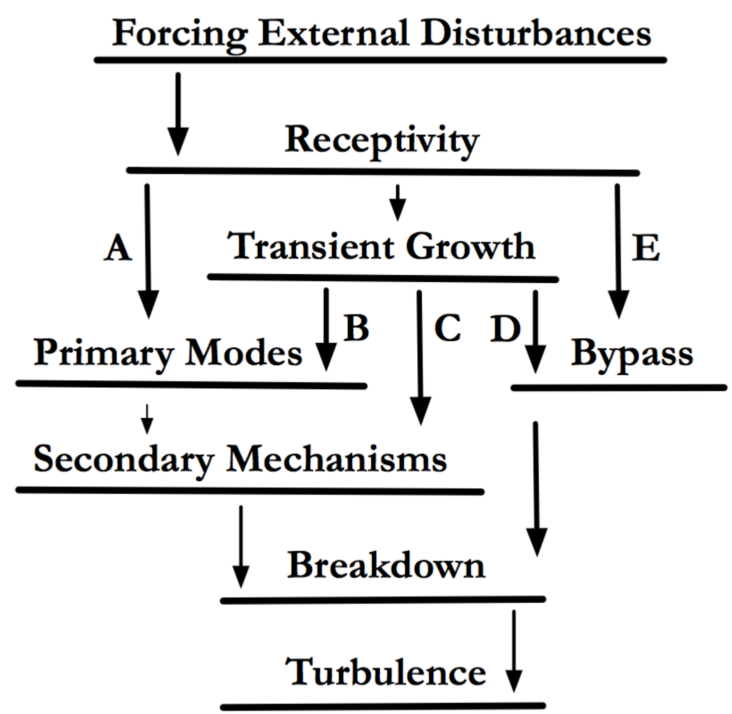
- Real hypersonic surfaces are rough.

- Isolated roughness includes:
  - Fasteners
  - Joints
  - Tripping elements
  - Gap filler

- Distributed roughness
  - Machining marks
  - Ablative heat shields
  - Thermal protection tiles

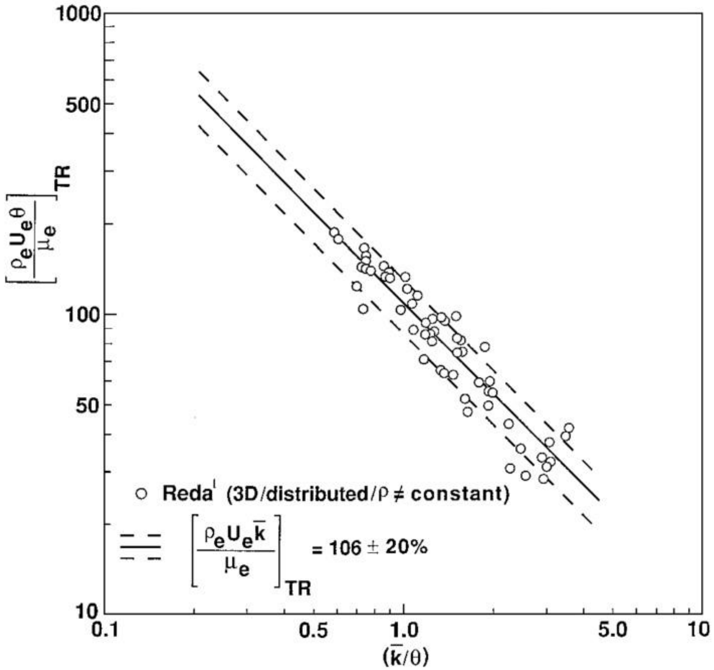
Images credits: NASA and Shannon D. Moore (OutdoorPhoto.com)

- Surface roughness introduces disturbances into the boundary layer, which may be enhanced through transient growth.
- Transient growth, being nonmodal in nature, can exist in regions subcritical to other transition mechanisms.
- The "blunt-body paradox," in which transition occurs earlier than predicted even on highly polished surfaces, may be explicable through roughness-induced transient growth.



Transition map adapted from Morkovin *et al* (1994)

- Computations of surface roughness are expensive, except in cases of isolated roughness.
- Existing literature on experimental roughness-induced transition is vast, but:
    - Focuses on empirical correlations for transition prediction
    - Often utilizes noisy, conventional wind tunnels
- Physics-based transition correlation is desirable.

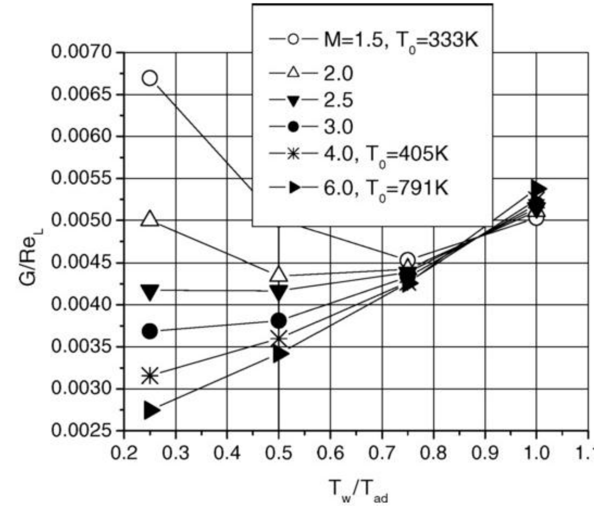


Nosetip transition data from ballistics-range experiments; three-dimensional distributed roughness, compressible flows (Reda 2002).

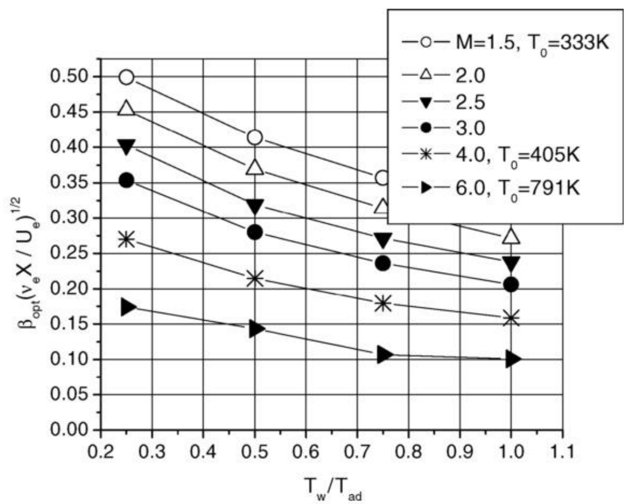
- Computations of optimal disturbances for compressible boundary layers exist:
  - Flat plate/cone, sphere (parallel): Reshotko and Tumin (2004)
  - Flat plate, sphere (non-parallel): Zuccher *et al* (2006)
  - Sharp cone (non-parallel): Zuccher *et al* (2007)

- Transient growth is destabilized by wall cooling and increasing spherical radius but stabilized by flow divergence.

- Low-speed experiments indicate roughness induces suboptimal disturbance growth (White 2002, White *et al* 2005).

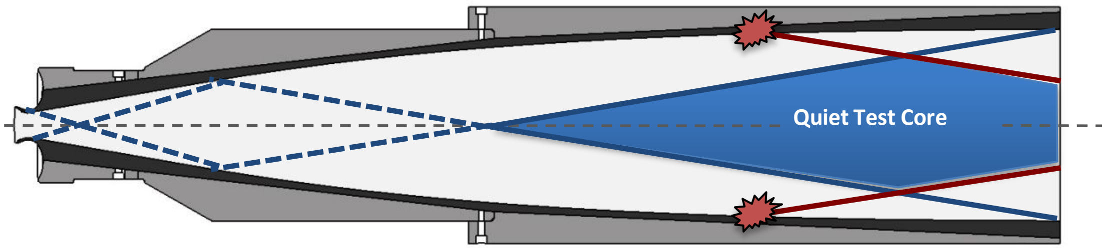


Optimal growth factors for zero pressure gradient; Re_L = 9 x 10^4 (Reshotko and Tumin 2004).



Optimal spanwise wavenumber for zero pressure gradient; Re_L = 9 x 10^4 (Reshotko and Tumin 2004).

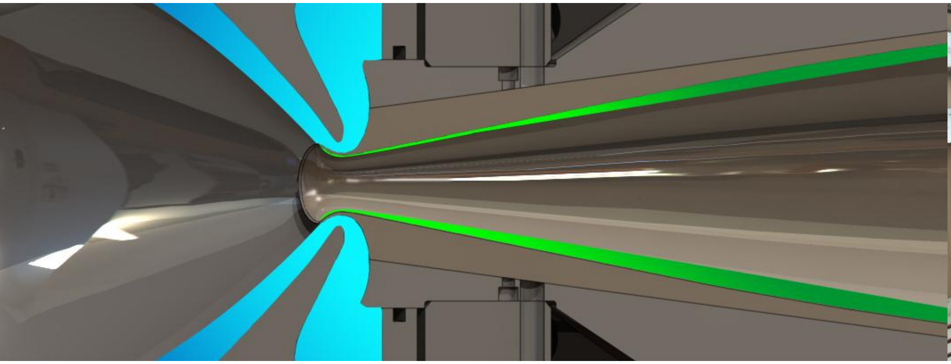
Mach 6 Quiet Tunnel (M6QT)



Straight-wall section and slow expansion contour minimizes growth of the Görtler instability

Quiet test core defined upstream by Mach 5.91 uniform flow and downstream by acoustic disturbances generated by nozzle-wall turbulent boundary-layer eddies and radiated along Mach waves

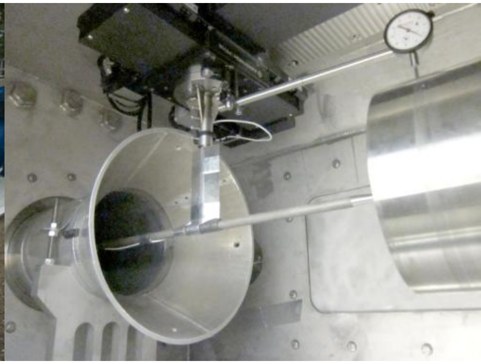
- Low-disturbance test environment up to a Re = 10 x 10^6 m^{-1}
- 40 second nominal run-time
- Hotwire anemometry used as primary diagnostic (presently uncalibrated)



Settling chamber boundary layer removed via vacuum ejectors, initiating new laminar boundary layer on nozzle

Toggling bleed valves allows quiet (0.05% Pt'/Pt) or noisy operating conditions

Vacuum-pressure blow-down configuration using a two-stage air ejector system



Enclosed free-jet test section with two-axis traverse

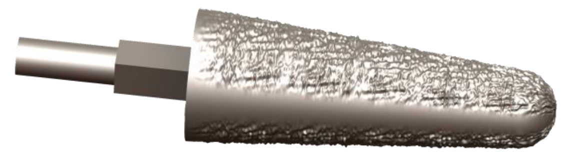
Smooth, 5-degree cone with interchangeable nosetips

6.35 mm radius, smooth

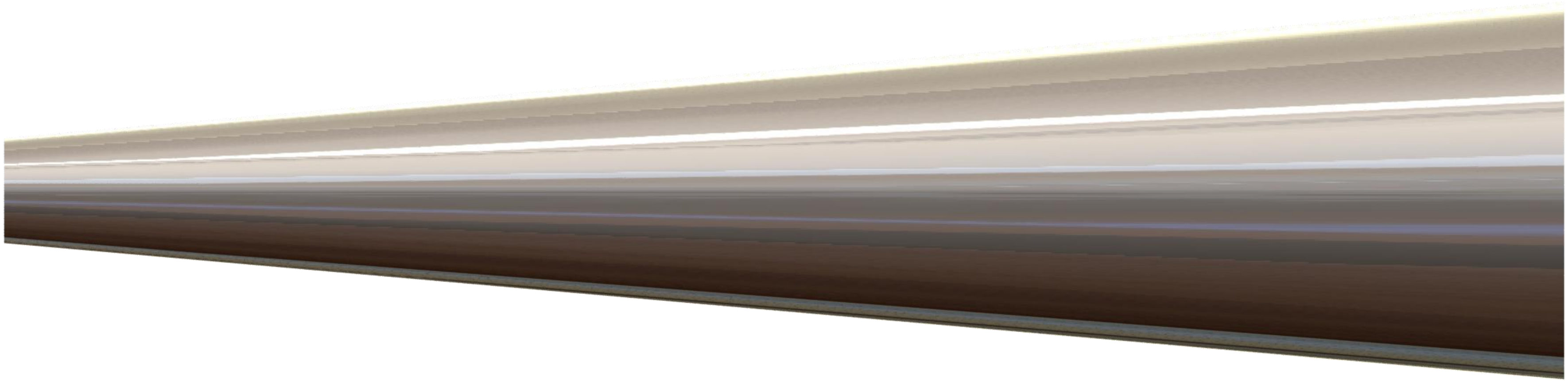
1.59 mm radius, smooth

6.35 mm radius, discrete roughness elements

1.59 mm radius, discrete roughness elements



6.35 mm radius, quasi-random distributed roughness



Quasi-random distributed roughness

6.35 mm radius nosetips, quasi-randomly distributed roughness (left) and nominally smooth (right)

- Roughness generated via Fourier series

$$h(x,\theta)=\sum_{n=1}^{N}\sum_{m=1}^{M}A_{n,m}\cos\left(\left(2\pi nx/\lambda_k\cos\gamma_c\right)+mK\theta+\phi_{n,m}\right)$$

x = axial coordinate
Θ = azimuthal angle
γ_c = half-angle = 5°
$\varphi_{n,m} \in U(0,2\pi)$

K = 12, for 30° periodicity
$N = M = 5$
λ_k = 10.16 mm
$Max(A_{n,m})$ = 0.635 mm

- Roughness repeats over two 150° arcs separated by two 30° sections of nominally smooth surface

- $A_{n,m}$ coefficients selected from a half-normal distribution and scaled

- Quasi-random distributed roughness nosetip constructed via direct metal laser sintering

Technique for quasi-random roughness adapted from Downs *et al* (2008).

Initial experiments

- Tested 6.35 mm radius smooth and distributed rough nosetips

6.35 mm radius nosetips, quasi-randomly distributed roughness (left) and nominally smooth (right)

Table 1: Experimental conditions

Parameter	Condition 1	Condition 2	Condition 3
Nominal *M*	5.9	5.9	5.9
P_0	551 kPa	689 kPa	896 kPa
T_0	430 K	430 K	430 K
Re	6.1×10^6 m^{-1}	7.7×10^6 m^{-1}	10×10^6 m^{-1}
Re_n	3.9×10^4	4.9×10^4	6.3×10^4

$$\mathrm{Re}_\theta\left(\frac{k}{\theta}\right) = \frac{U_e k}{\nu_e}$$

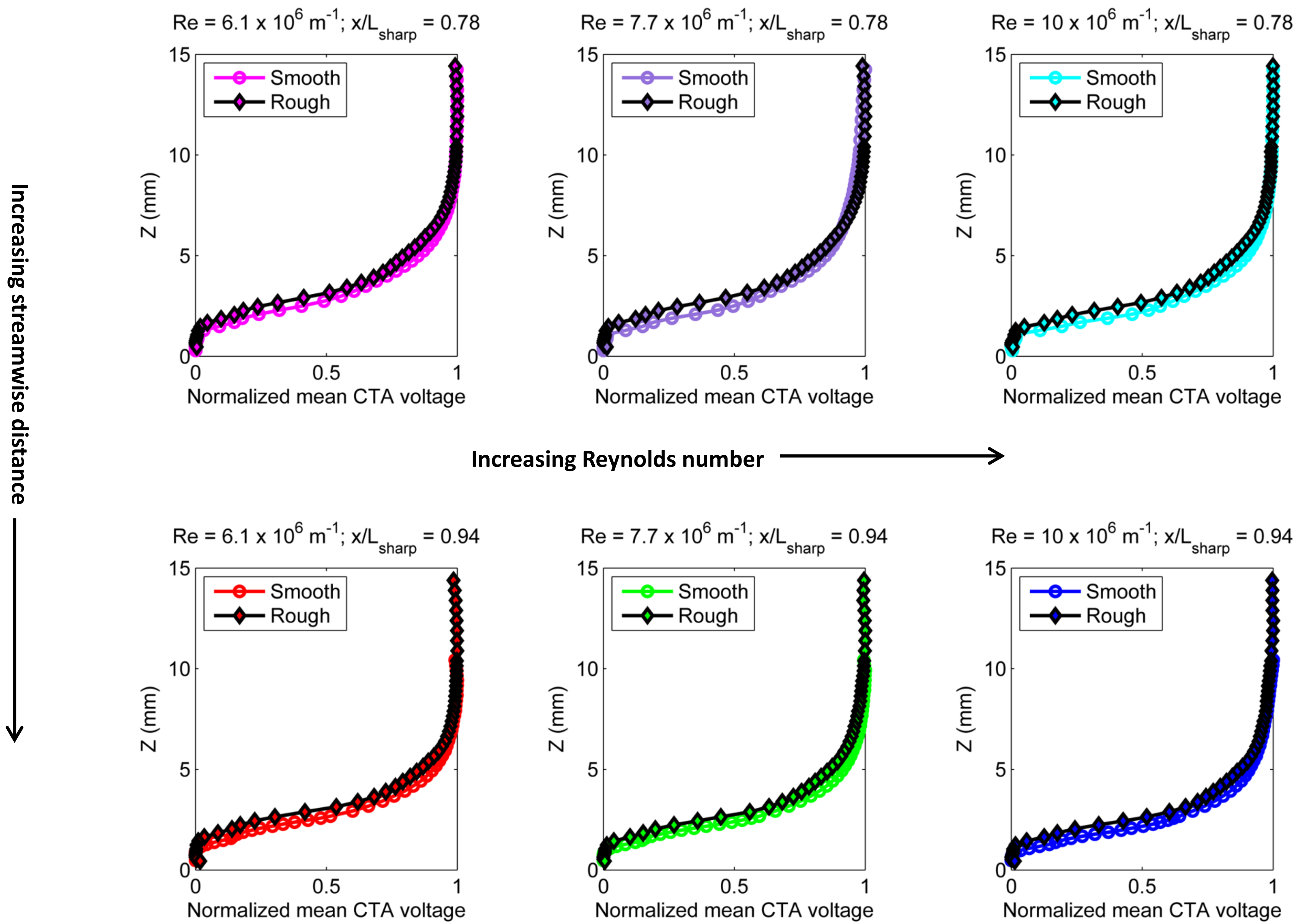
Transition predicted by Reshotko (2007) above ~250-300 (flat plate).

- For k = 0.11 mm:

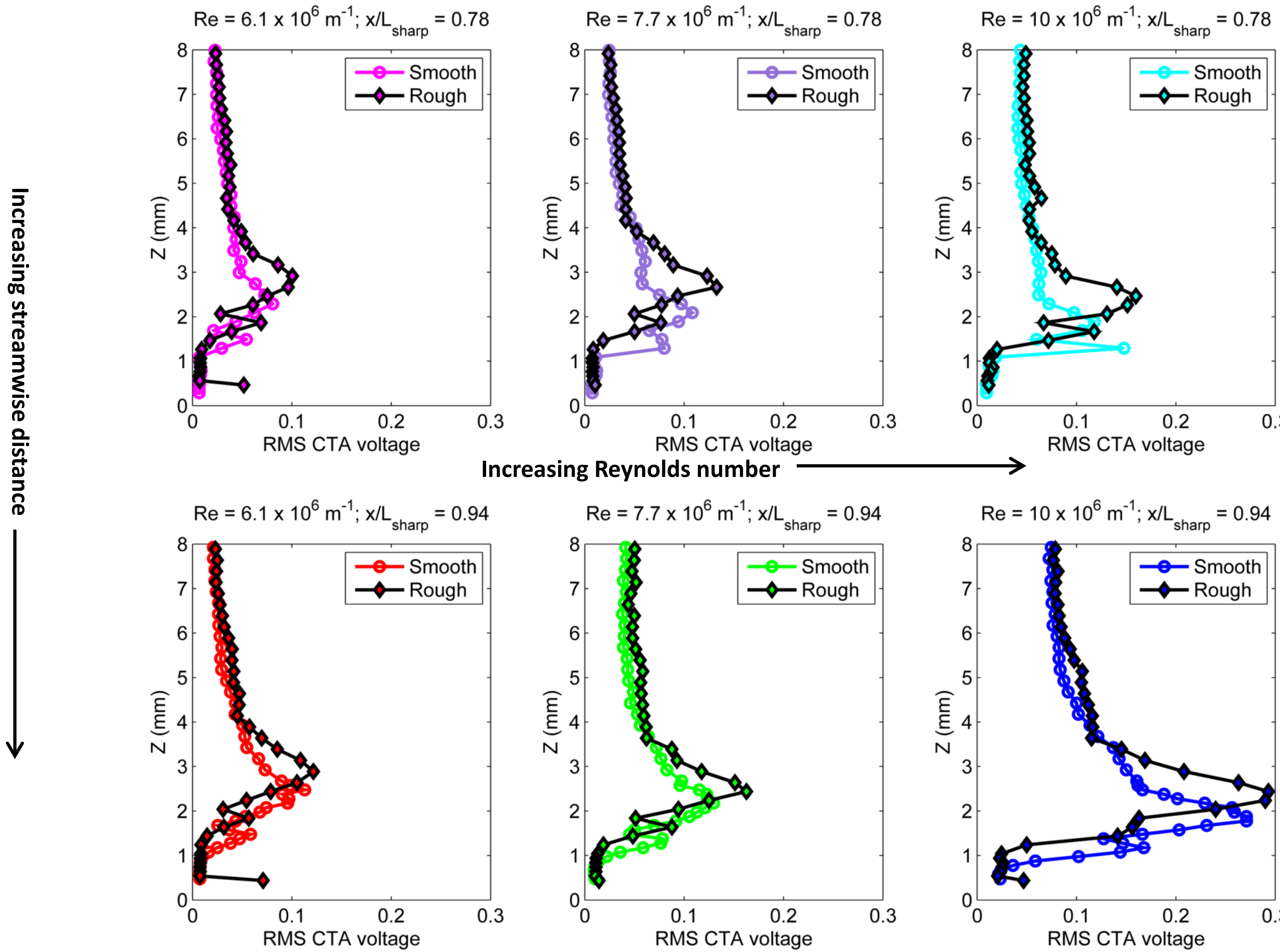
$$\frac{U_e k}{\nu_e} = 780 \; to \; 1340$$

- Wall-temperature during run is 5-8% higher than adiabatic due to subsonic preheating.

Mean boundary layer profiles



RMS fluctuation profiles



Conclusions

- Growth of fluctuation amplitudes is observed but distributed roughness only marginally increases growth compared to a smooth wall.

- The distributed roughness nosetip is insufficient to trip the boundary layer, possibly due to the bluntness of the nose.

- Future experiments will include:
    - azimuthal measurements for detection of streaky structures to confirm transient growth
    - sharper nosetips and discrete roughness elements spaced according to optimal disturbance theory

Acknowledgements