Direct Numerical Simulation of Transition Mechanisms at Mach 6.8 on the flat plate and the cone

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Overview

- **Introduction and Issue**
- **Numerical Method**
- **Stability Properties using Linear Stability Theory (LST)**
- **Results of Direct Numerical Simulations (DNS)**
  - Flat plate / sharp cone
  - Fundamental-type / oblique-type breakdown
  - Wind-tunnel / flight conditions
- **Simulation of Harmonic Point Source Experiment**
  - Comparison with controlled experiments at ITAM
  - Sharp cone, M_∞=5.92
- **Conclusions**

Introduction and Issue

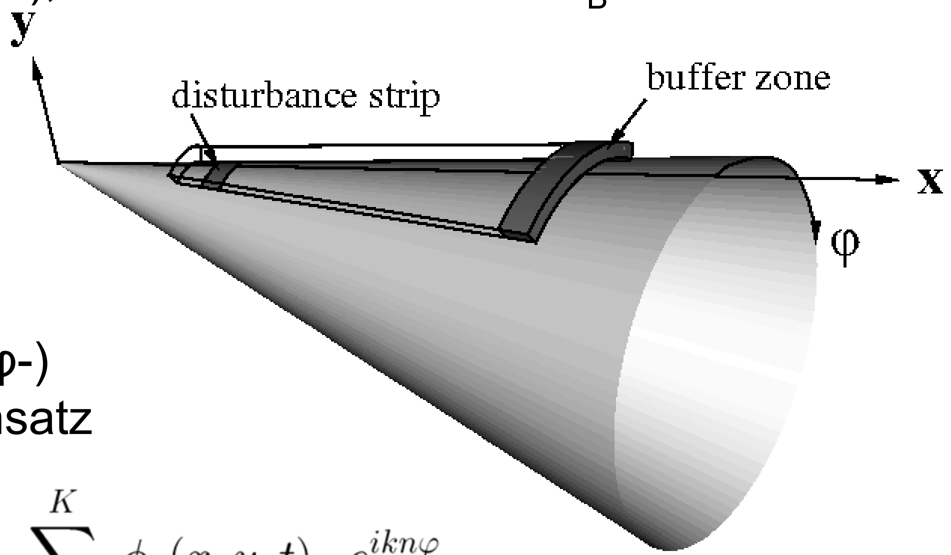
- **Complexity of physical mechanisms at „compressible“ transition**
  - Examination of simple, but generic bodies → flat plate, sharp cone
- **Investigation of boundary-layer transition with highly accurate Direct Numerical Simulations (DNS)**
  - Simulation of disturbances controlledly excited on the body surface
- **Flow properties for simulations at Ma=6.8**

Wind-tunnel conditions (WT)	Flight conditions (FC)
Cold flow (T_∞=50 K),	Hot flow (T_∞= 220 K)
Adiabatic wall ($T_w = T_{rec} \approx 435$ K)	Radiation-adiabatic cooled wall ($T_w \approx 0.5\ T_{rec} \approx 950$ K)

- **Issues**
  - Instabilities / transition mechanisms at these conditions?
  - Influence of geometry and flow properties?

Numerical method

- **Complete 3-d compressible unsteady Navier-Sokes equations**
  - Conservative in (ρ,ρu,ρv,ρw,E), disturbance form. $\Phi = \Phi_B + \Phi'$
- **Spatial discretization**:
  - Compact finite differences of 6th-order accuracy in flow- (x-) and wall-normal (y-) direction
  - Spanwise (z-) / transversal (φ-) direction: Spectral Fourier ansatz

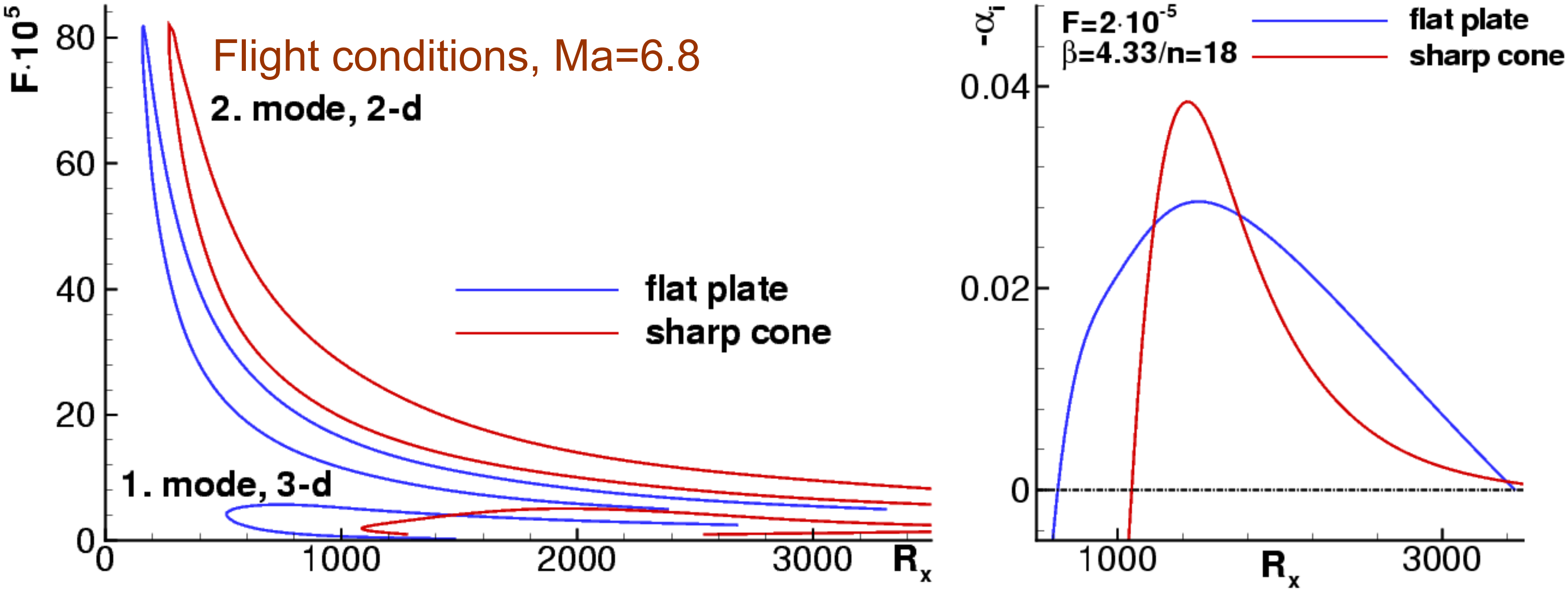


$$\phi = \sum_{k=-K}^{K} \phi_k(x,y,t) \cdot e^{ik\beta z} \quad \text{or} \quad \phi = \sum_{k=-K}^{K} \phi_k(x,y,t) \cdot e^{ikn\varphi}$$

with $n = \beta \cdot r = \beta_0 \cdot R_0 = \text{const.}$

- **Time discretization**: 4-step Runge-Kutta scheme of 4th-order accuracy
- **Method** carefully verified with LST/PSE/DNS (Pruett&Chang, Chang&Malik)

Stability properties – LST (1)

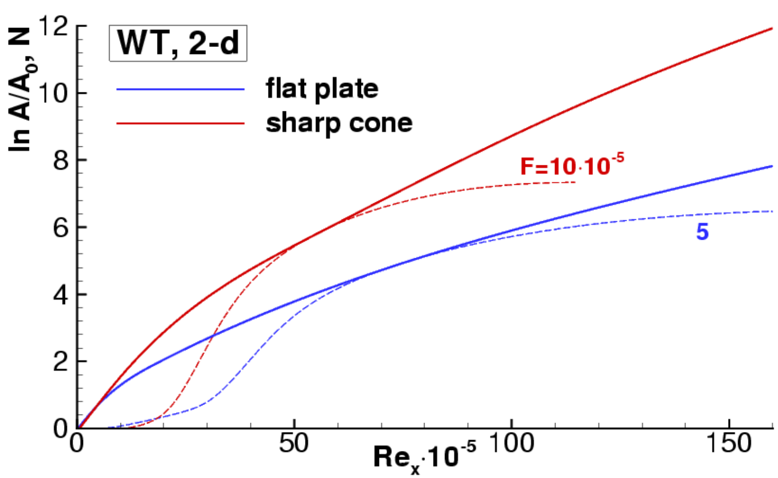


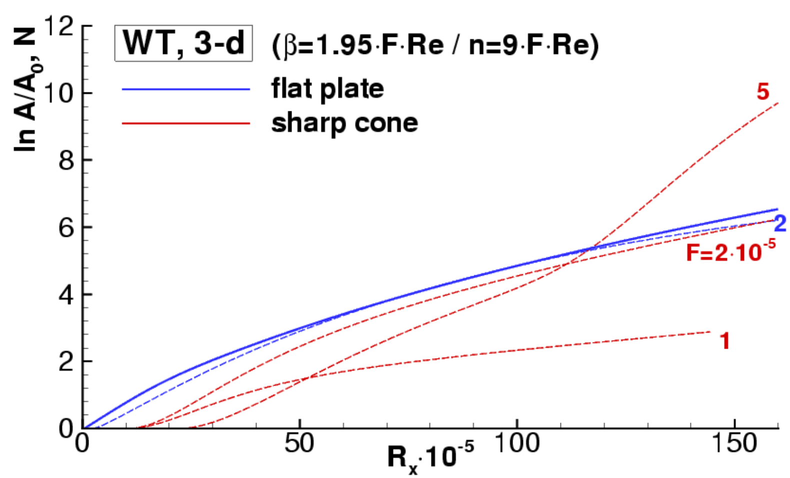
- **Mangler-Levy-Lees transformation:** $x_{cone} = 3 \cdot x_{plate}$
- **Cone vs. flat plate (2-d disturbances):**
  - Unstable region three times later, but 3 times longer (for each F)
  - Same unstable frequencies, but relevant frequencies higher
  - Same max. amplification rates, but integral amplification higher
- **Cone vs. flat plate (3-d disturbances):** decreasing propagation angle θ

Stability properties – LST (2)

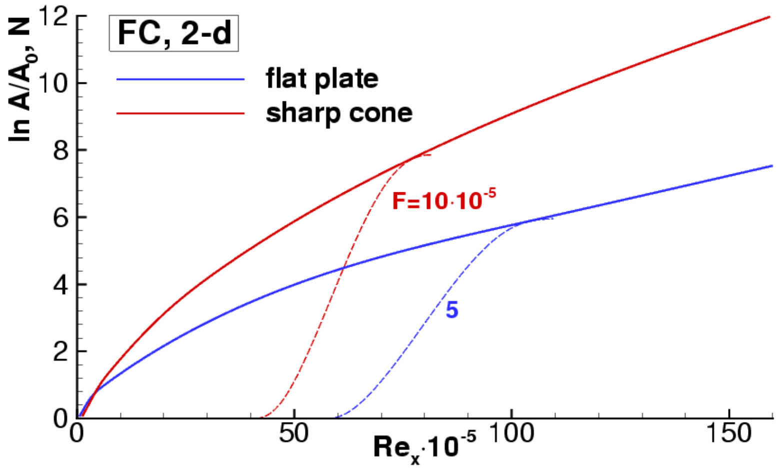
2-d, acoustic (2nd) mode | 3-d, vorticity (1st) mode

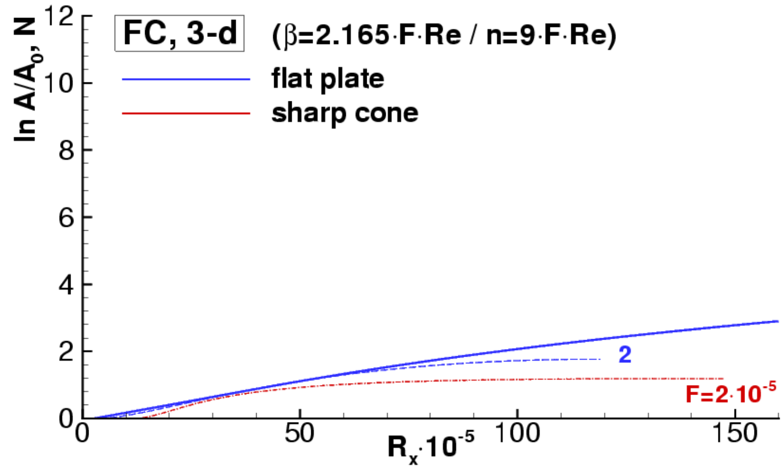
Wind-tunnel cond.



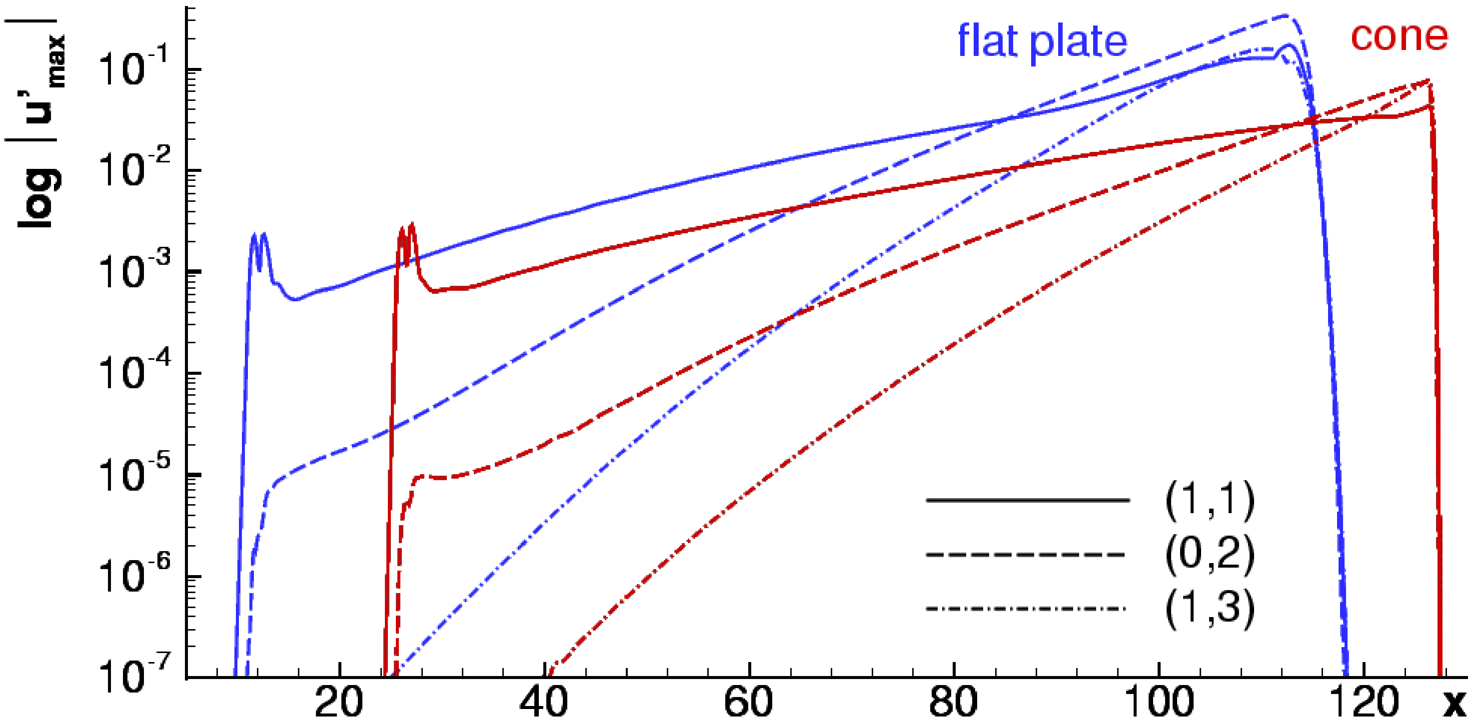


Flight conditions



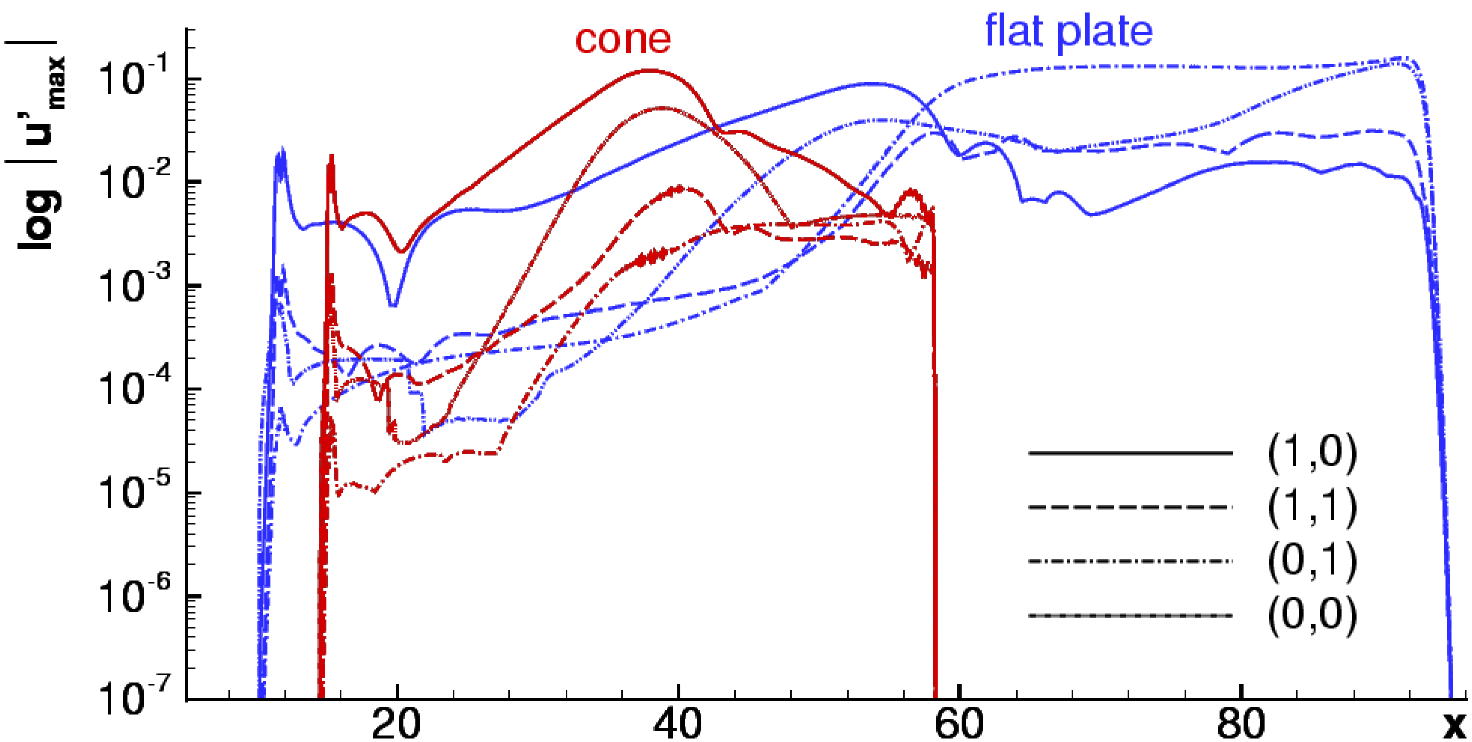


Results of DNS – Oblique Breakdown, WT



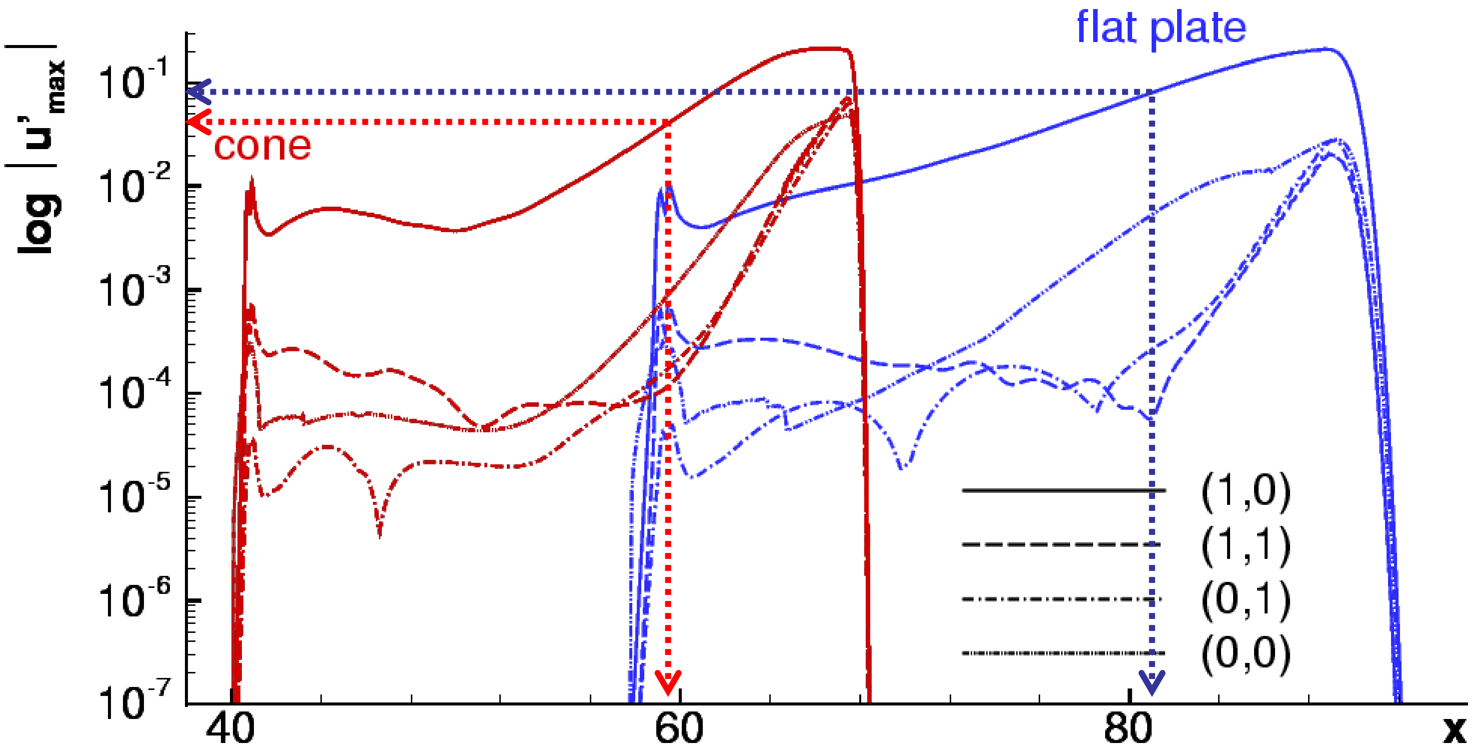
- **(h,k)**: disturbance wave with h·F and ±k·β / ±k·n
- Robust transition mechanism in both cases, no phase correlation process and no threshold amplitude required
- Mode development and physical structures quite similar

Results of DNS – Fundam. breakdown, WT



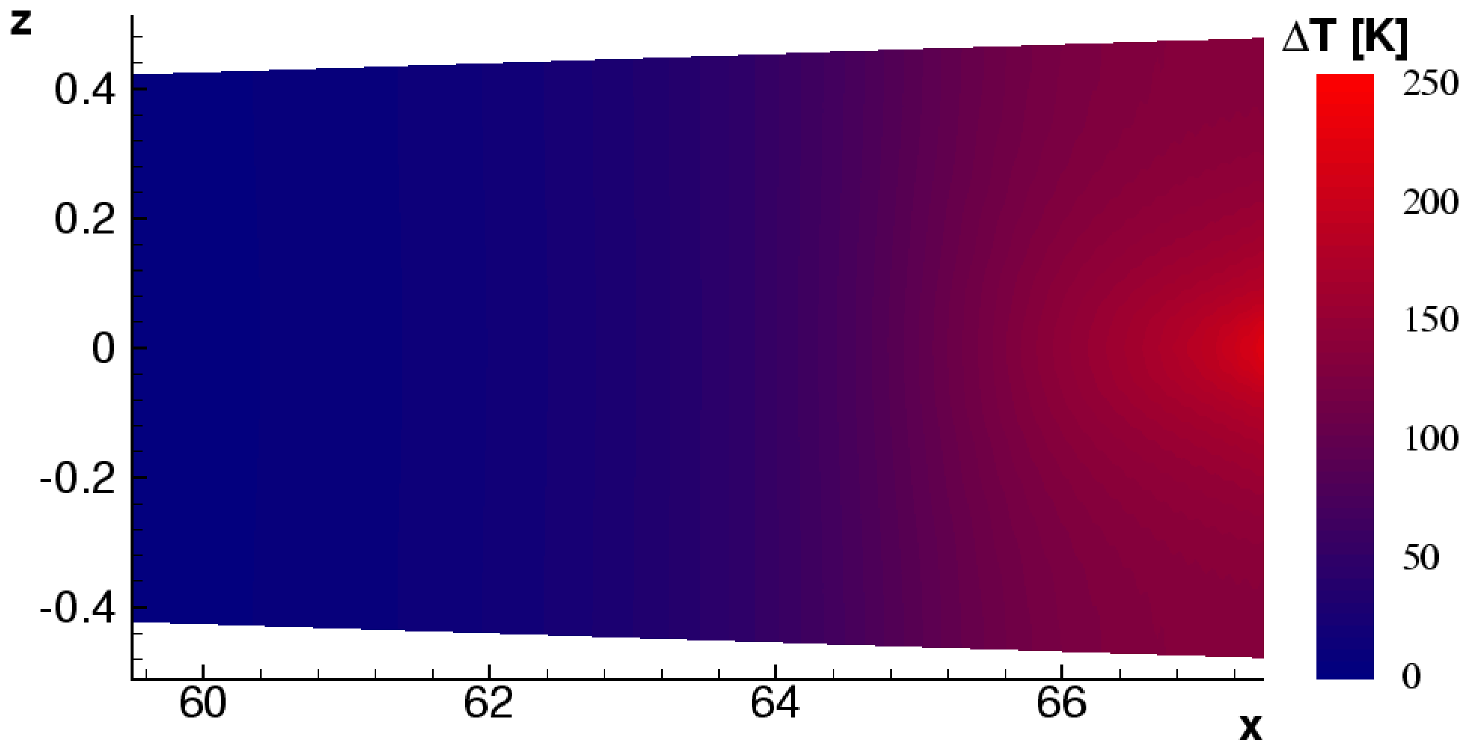
- Threshold amplitude for resonance reached earlier (stability properties) and smaller on the cone
- Considerable damping of the 2-d mode caused by decreasing phase speed → suppression of the transition process

Results of DNS – Fundam. breakdown, FC (1)



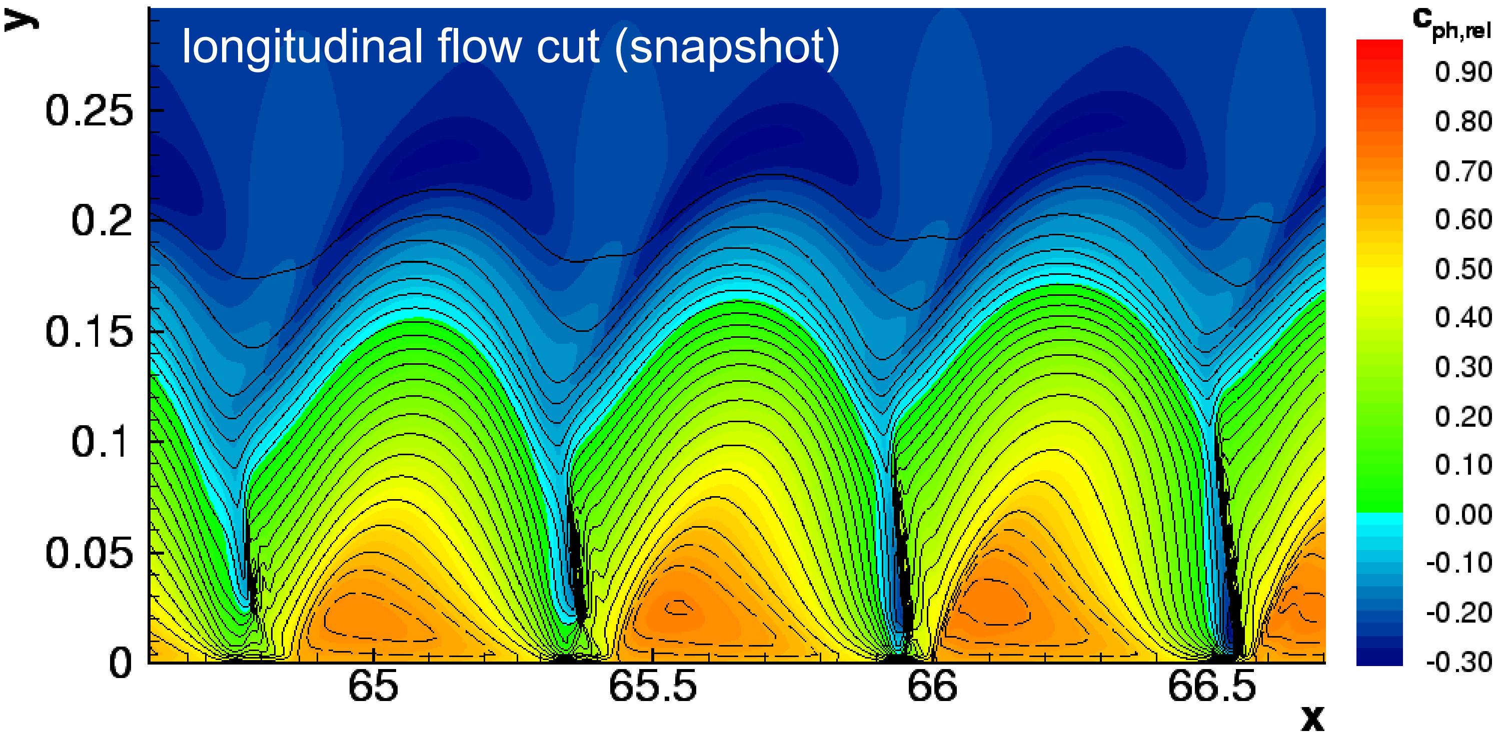
- Threshold amplitude for resonance reached earlier on the cone (because of instability properties)
- Threshold amplitude halved on the cone (4% compared to 8% at the plate) → resonance process favoured by decreasing propagation angle of 3-d wave

Results of DNS – Fundam. Breakdown, FC (2)



- **Specialties of fundamental breakdown**
  - Caused by acoustic disturbances with near-wall maximum
  - Heating and shear stresses at the wall much higher

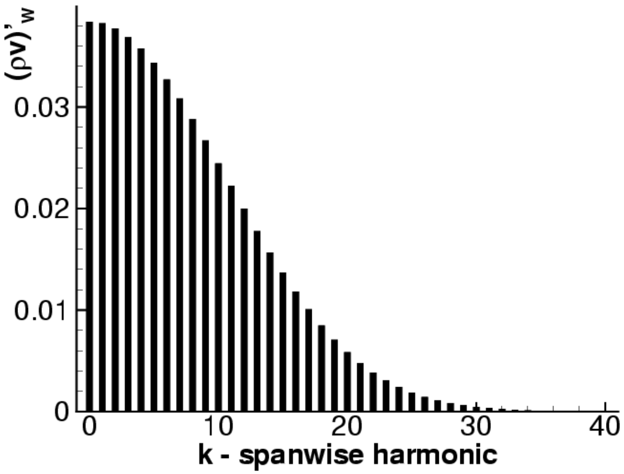
Results of DNS – Fundam. Breakdown, FC (3)

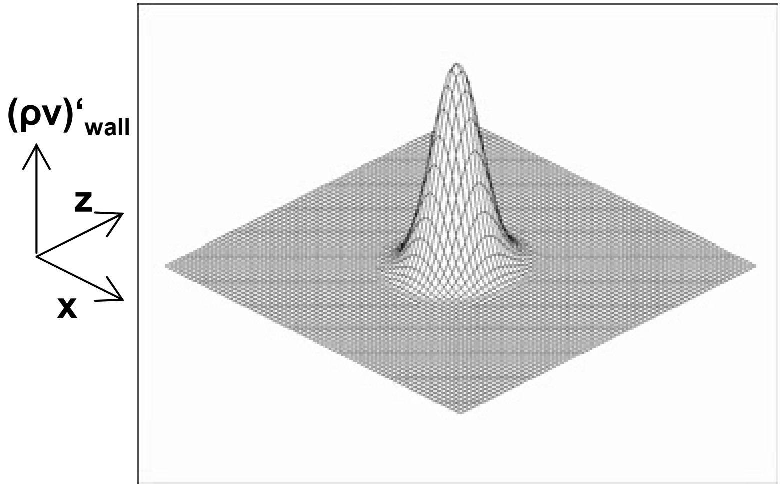


- **Complex phenomena caused by high-ampl. acoustic modes**
  - rel. supersonic region at wall: $c_{ph,x} > u+a$ or $c_{ph,rel} = c_{ph,x} - u - a > 0$
- **Isolines of total velocity u:** formation of shocklets at nonlinear disturbance ampl.; strong local separation zones caused by large near-wall maxima

Simulation of Harmonic Point Source Exp. (1)

- **Cone transition experiments at ITAM, Novosibirsk, Russia; Ma=5.92**
  - A.A. Maslov, A.N. Shiplyuk, A.A Sidorenko (2000), Study of hypersonic boundary-layer instability on a cone using artificial disturbances. Proc ICMAR, Novosibirsk-Tomsk, July 2000.
  - Controlled transition experiment, spark ignition actuator
  - Transversal amplitude distributions and wave number spectra measured by cone rotation
  - 1st mode (78 kHz) and 2nd mode (269 kHz) disturbances
- **DNS:** Disturbances excited by harmonic point source

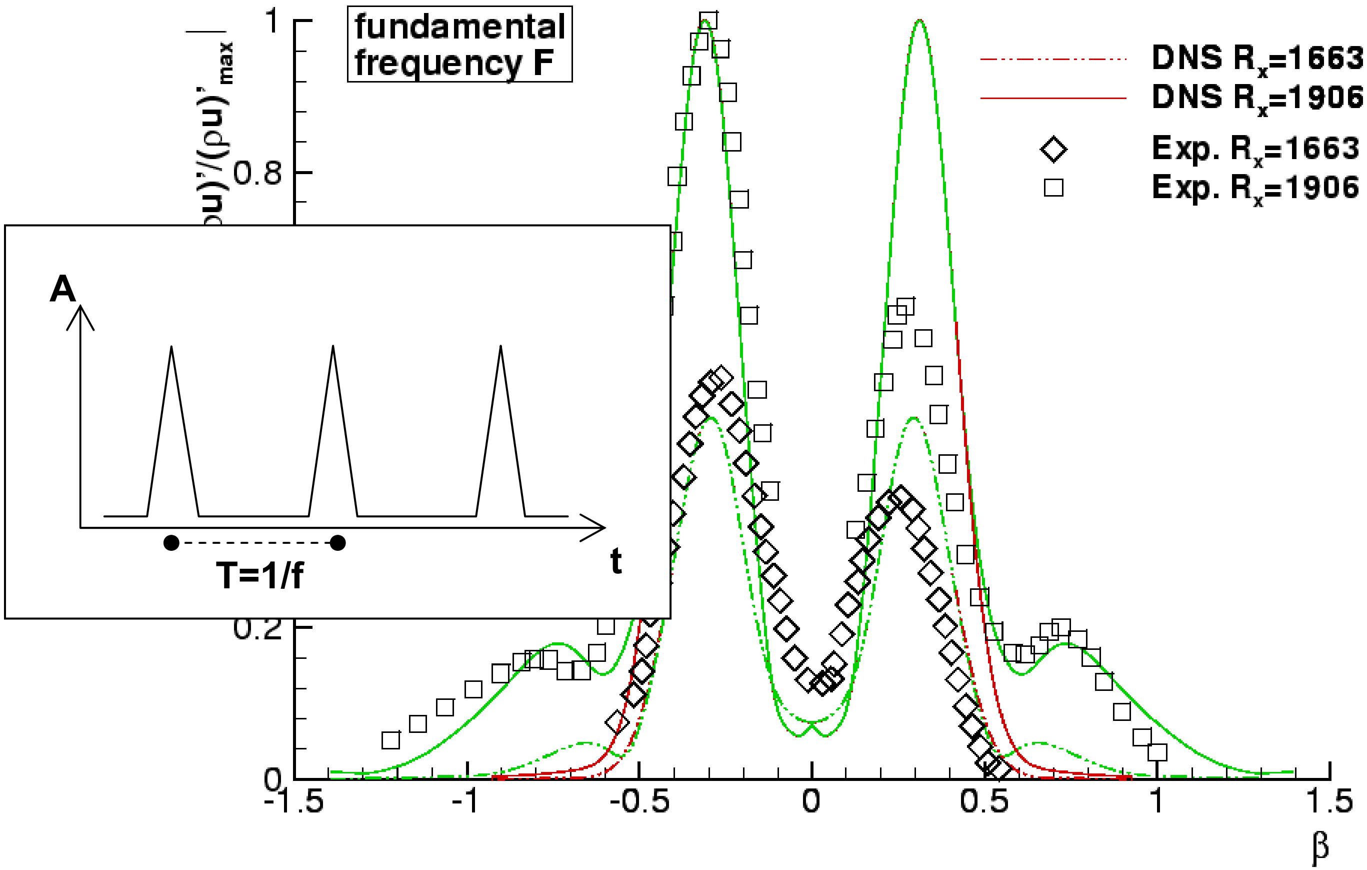




Simulation of Harmonic Point Source Exp. (2)

- **Transversal wave number spectra, 1st mode disturbances** (78 kHz)

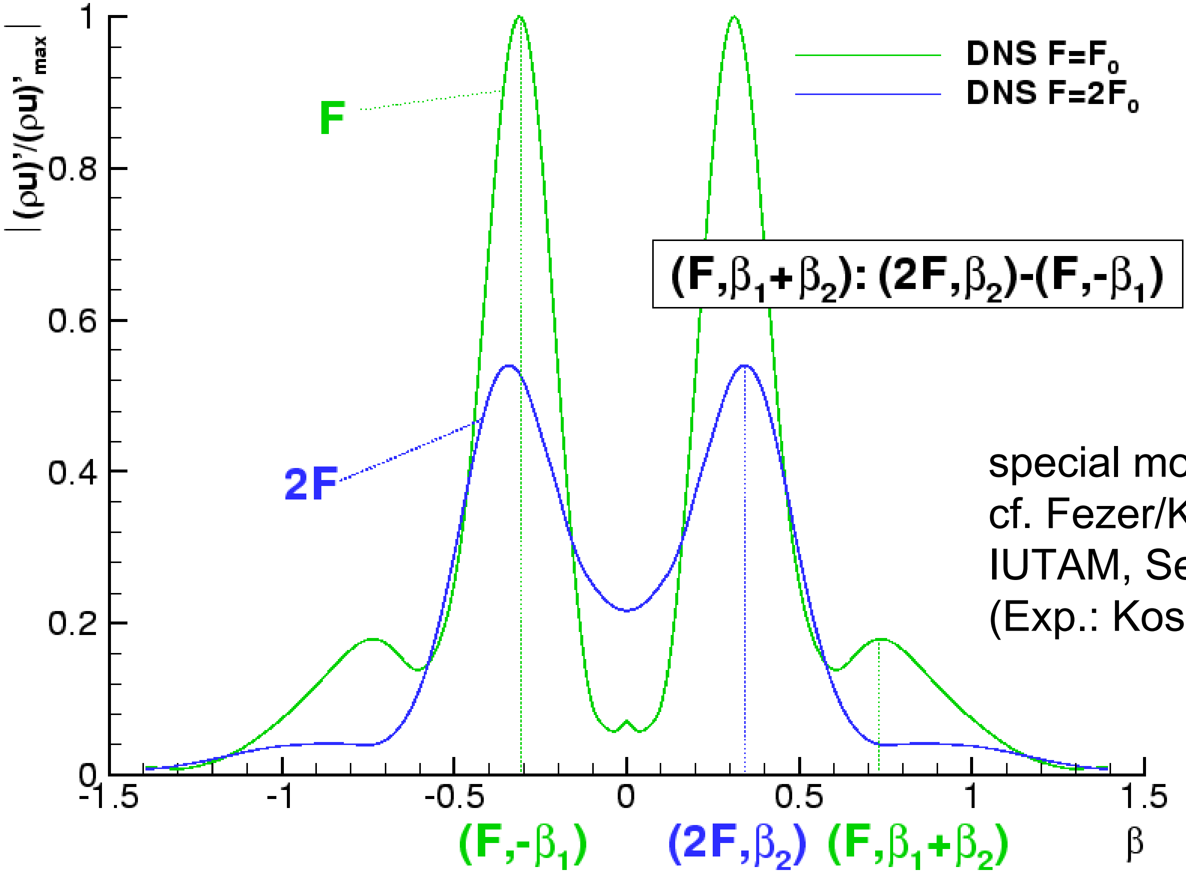
Monofrequent disturbance F   Bifrequent disturbance F+2F



Simulation of Harmonic Point Source Exp. (3)

- **Transversal wave number spectra, 1st mode disturbances** (78 kHz)

Bifrequent disturbance **F**+**2F**

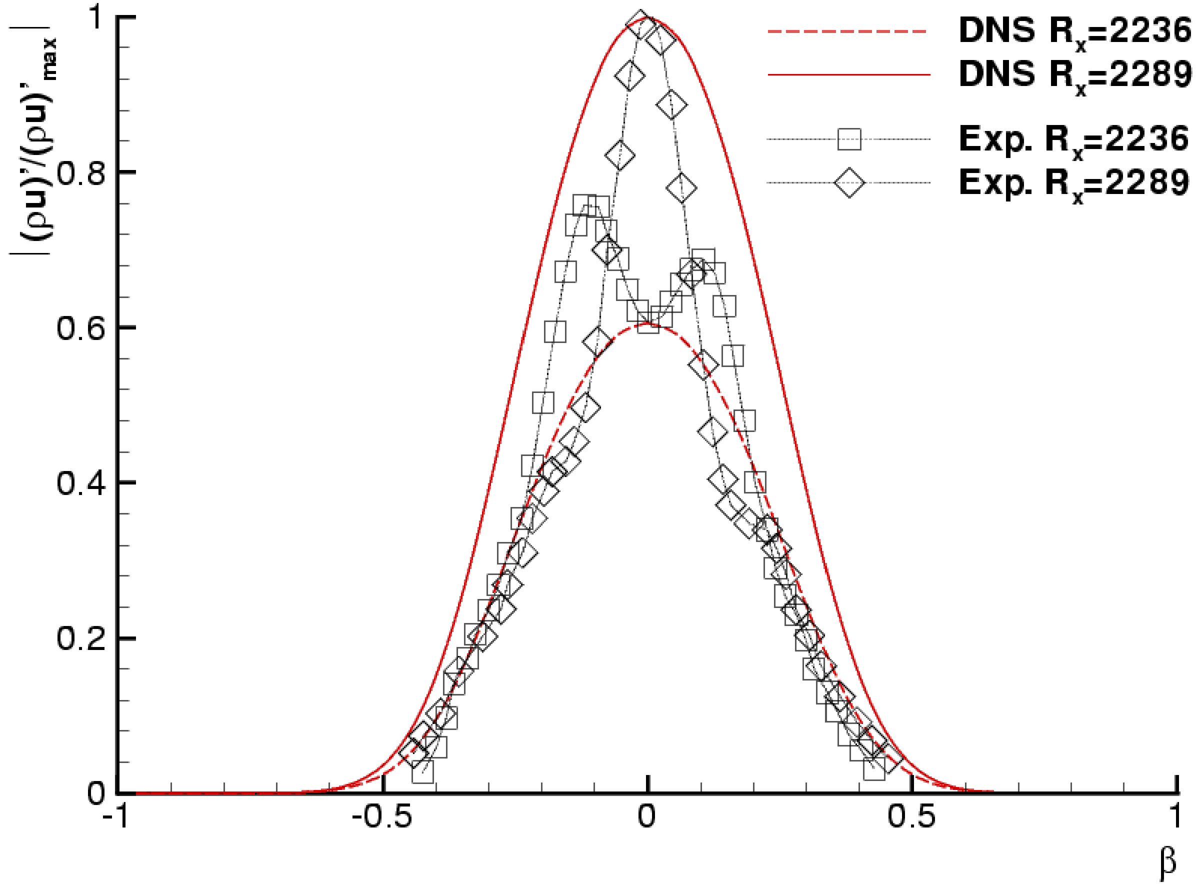


special mode interaction
cf. Fezer/Kloker
IUTAM, Sedona 1999
(Exp.: Kosinov et al.)

Simulation of Harmonic Point Source Exp. (4)

- **Transversal wave number spectra, 2nd mode disturbances** (269 kHz)

  Bifrequent disturbance F+2F



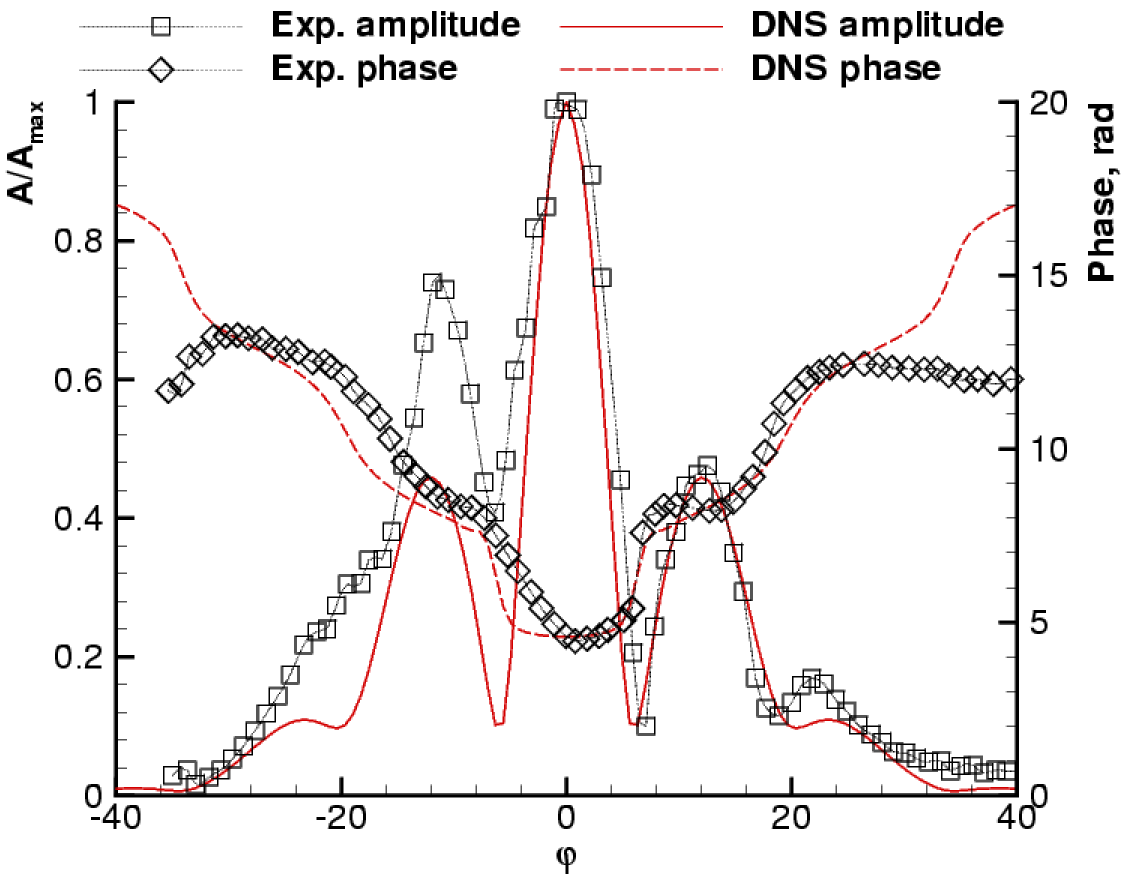
Conclusions

- **Wind-tunnel conditions vs. flight conditions:**
  - At WT oblique breakdown favoured; fundamental breakdown suppressed by damping of 2-d mode (decreasing phase speed)
  - At FC 2-d acoustic waves destabilized compared to 3-d vorticity modes
    → fundamental breakdown favoured
    → nevertheless oblique breakdown robust mechanism
- **Cone vs. flat plate:**
  - Fundamental breakdown favoured on the cone by instability properties and decreasing propagation angle of 3-d waves
  - Oblique breakdown delayed by weaker-growing vortex mode
- **At FC sharp cone geometry less favourable than sharp wedge**
  (as for transition)
- **DNS of harmonic point source**
  - Excellent agreement to ITAM experiment for 1st mode frequency
  - Unexpected details in transversal wave number spectra could be identified as special subharmonic 3-d nonlinear mode interaction
  - 2nd-mode case: not fully clear yet

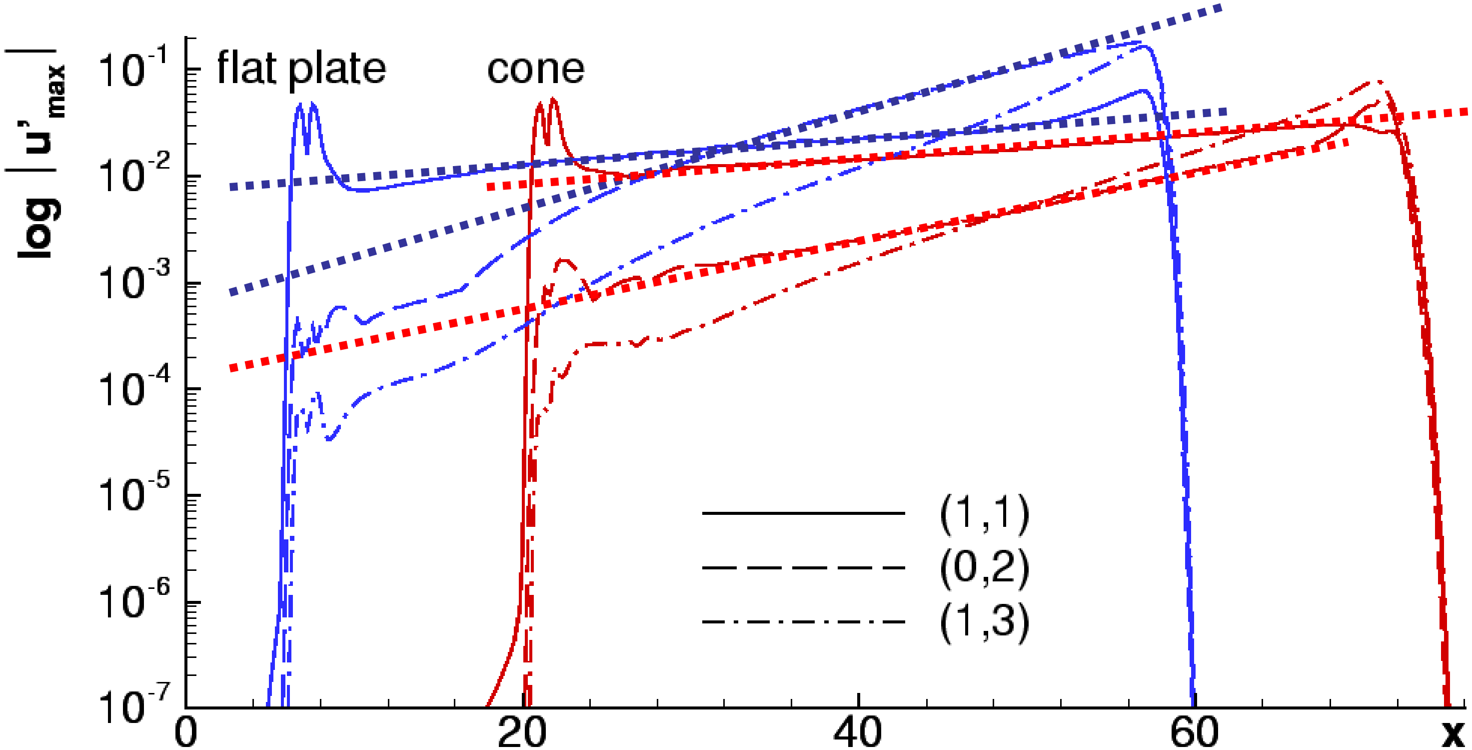
Simulation of Harmonic Point Source Exp. (5)

- **Transversal ampl. + phase distr., 1st mode disturbances** (F=78 kHz)

  Bifrequent disturbance F+2F



Results of DNS – Oblique breakdown, FC



- High disturbance amplitudes required (stability properties)
- Smaller growth rates of nonlinearly generated vortex mode (0,2) on the cone (effect of slower-growing boundary layer?)
- Mode development and physical structures quite similar