CCGEx

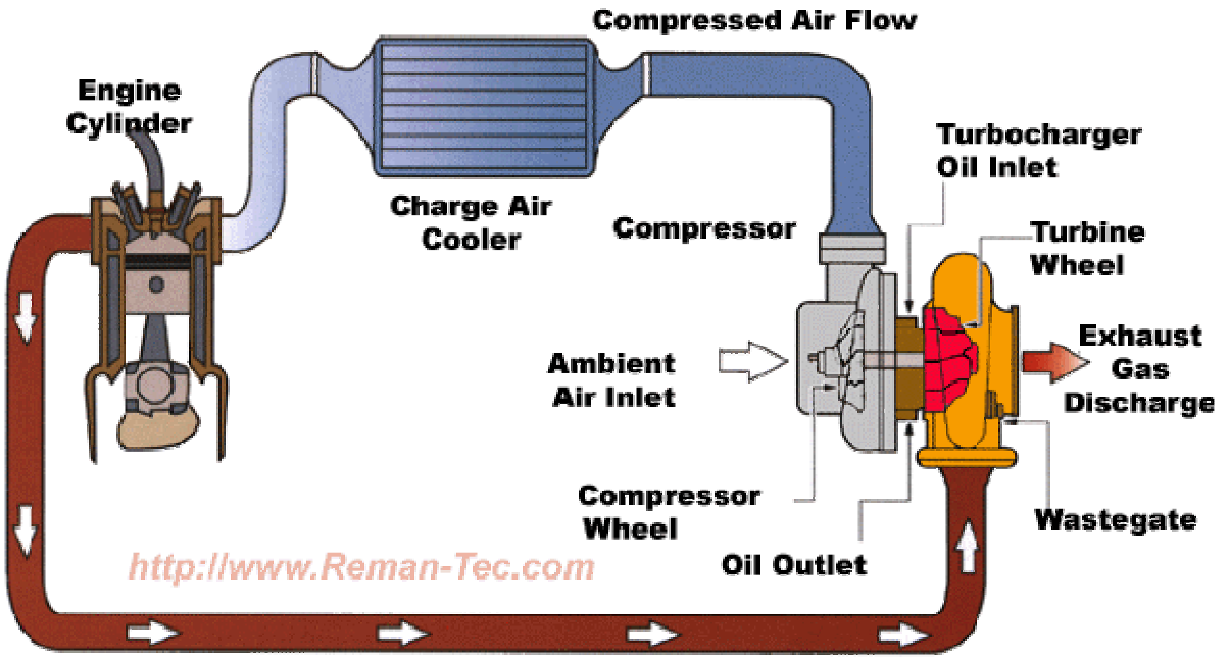
Similarities and Differences in Flow Characteristics in Centrifugal Compressors of Different Size

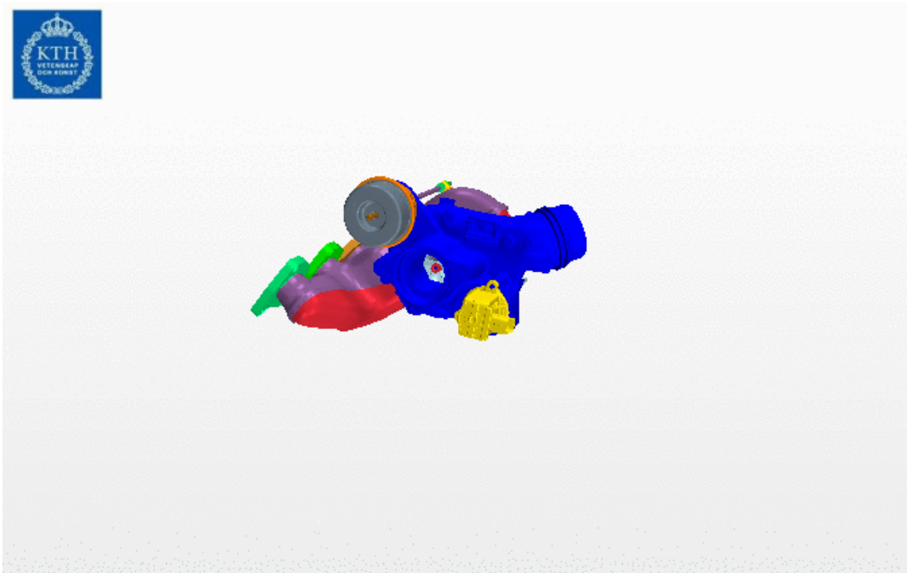
E. Sundström, M. Mihaescu
Royal Institute of Technology (KTH)
Department of Mechanics
Project duration: Nov 2013 – Nov 2017 (est)

Turbocharging & ICE

CCGEx

- Downsize the ICE and use turbocharging for keeping the same maximum power output
    - to control emission
    - to improve fuel economy

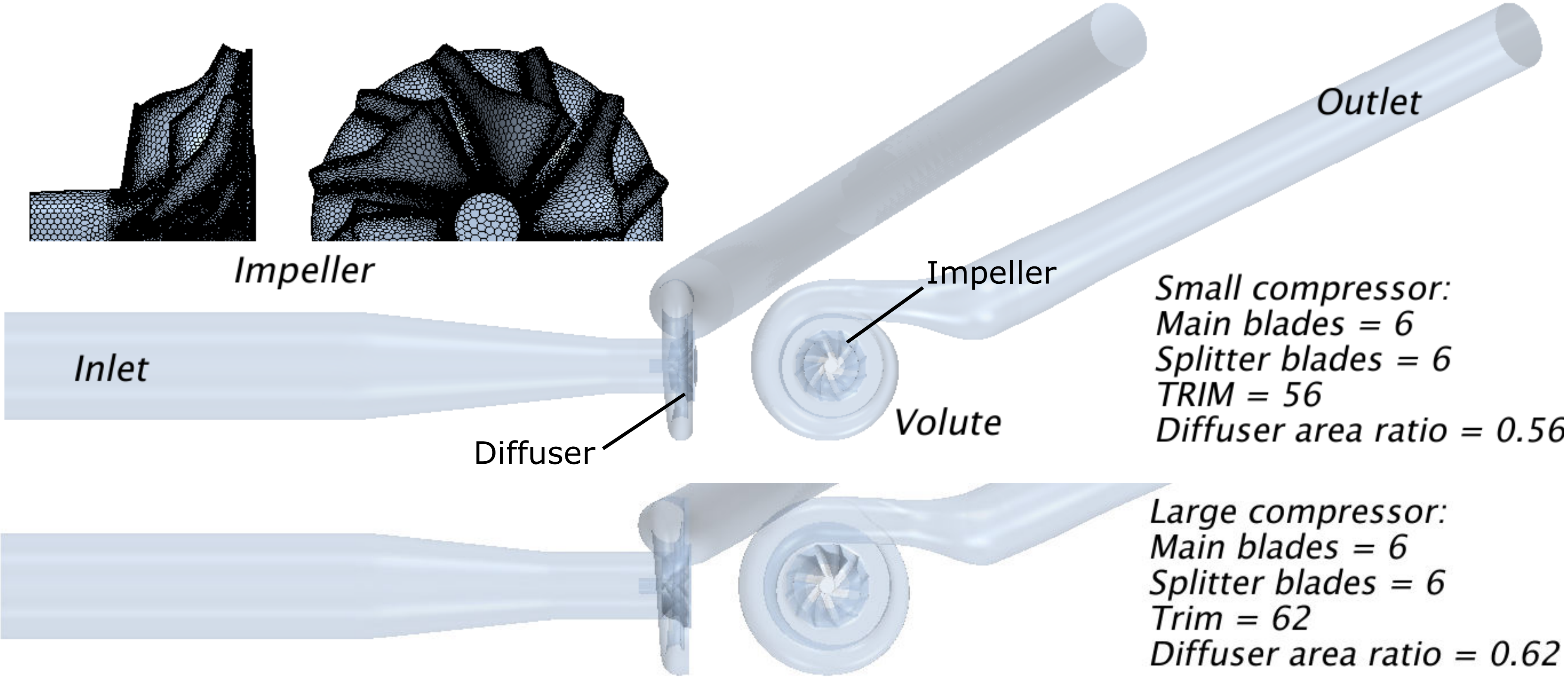




BorgWarner: Computational Approach

CCGEx

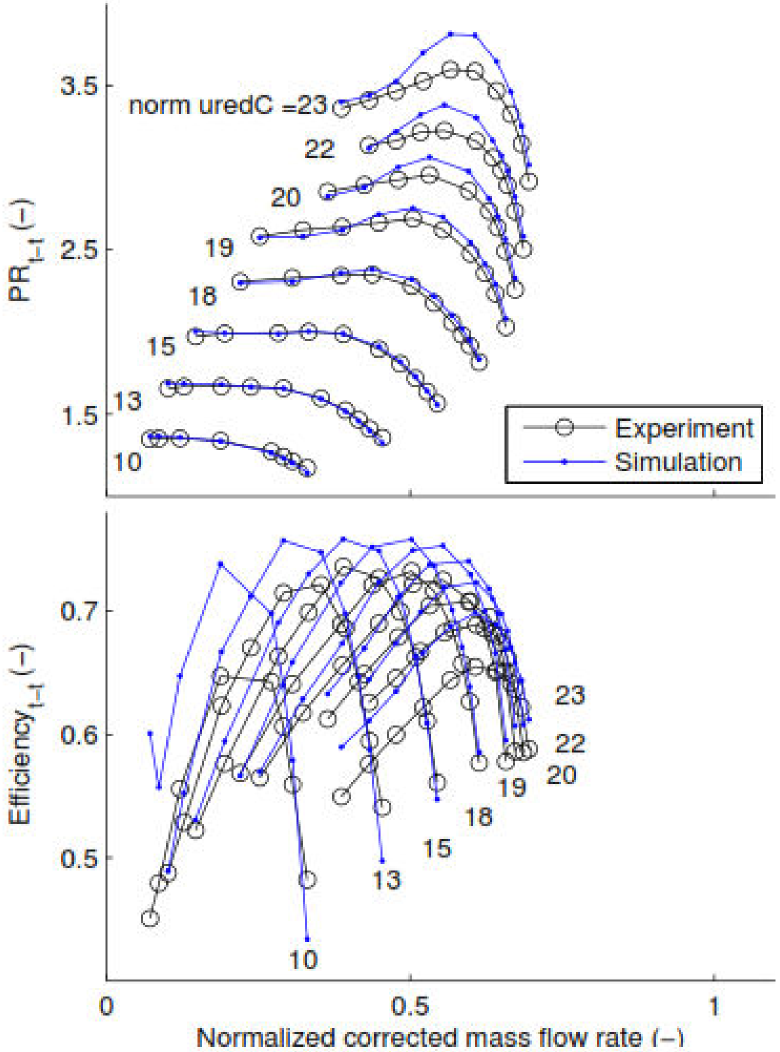
Governing Eqs:	Continuity, Momentum, Energy & Equation of state
RANS:	SST k-w
Solver:	Coupled Flow (density based)
Discretization:	2^{nd} order upwind
Polyhedral Mesh:	~1 million (MRF with circumferential averaged interface)



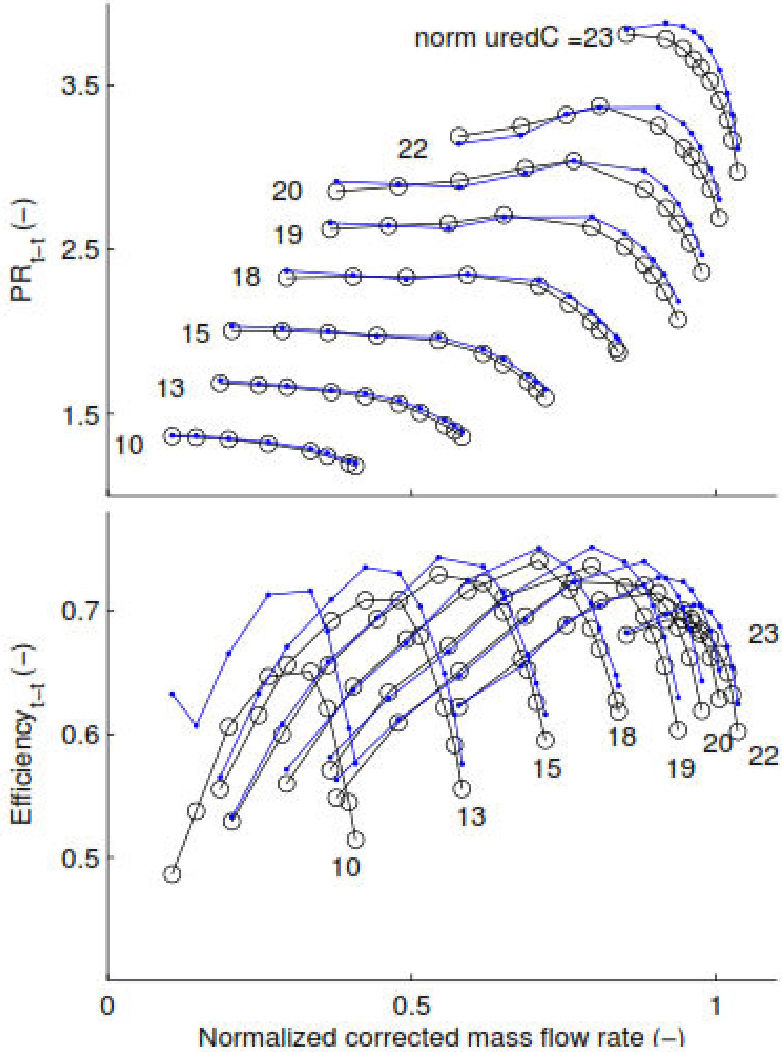
CCGEx

Performance parameters

- Fast compute steady-state RANS
- coarse grid (~1M cells)
- PR shows good trend with exp for a range of operating conditions
- A large number of operating conditions need to be simulated!
- The larger compressor is operating at higher mass-flow rates towards its surge line



Small compressor



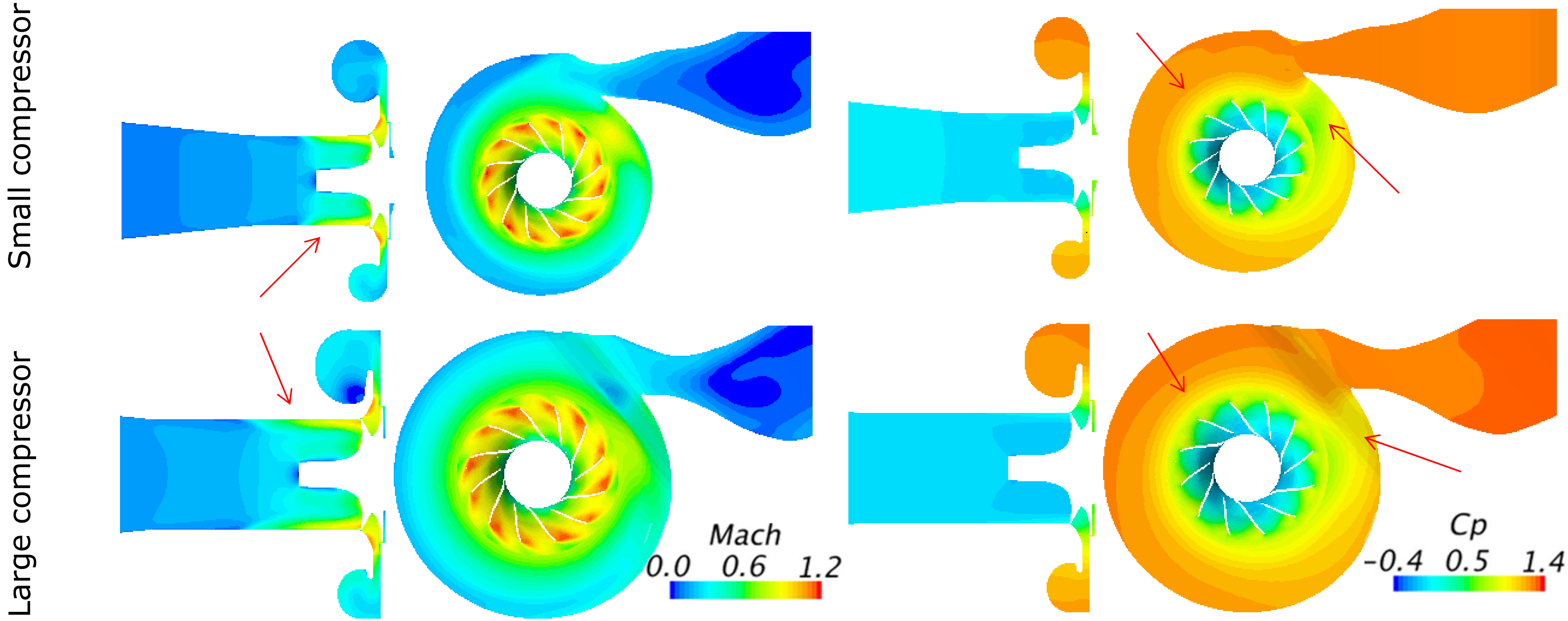
Large compressor

Pressure ratio (PR) = P_{02}/P_{01}
Efficiency = $((P_{02}/P_{01})^{(\gamma-1)/\gamma}-1)/(T_{02}/T_{01})$

Mach & Pressure (last stable operating point)

CCGEx

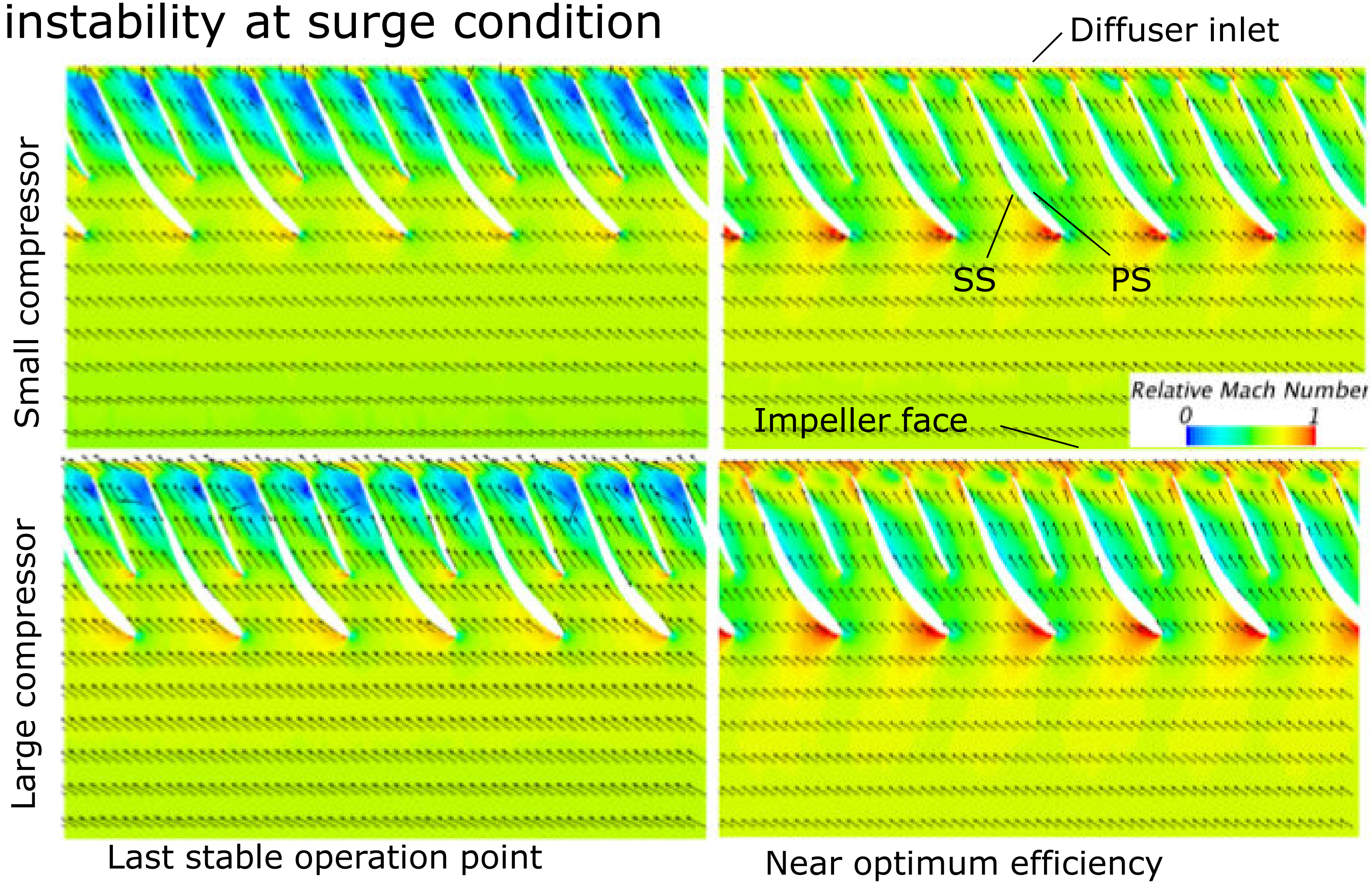
- At near surge the flow is pushed from the diffuser through the tip leakage and reaches further upstream for the larger compressor.
- Towards near surge (lower mass-flow rates) an adverse pressure gradient develops under the volute tongue at 2 o’clock.
- Flow directed towards this area
- Pressure gradient in radial direction increases towards surge
- At critical back pressures local blade separation occurs



CCGEx

Relative Mach number

- Similar flow field at near optimum efficiency for both designs
- At near surge (lower mass-flow rates) prediction of boundary layer separation on the blade suction side at 50% span. Source for onset of flow instability at surge condition

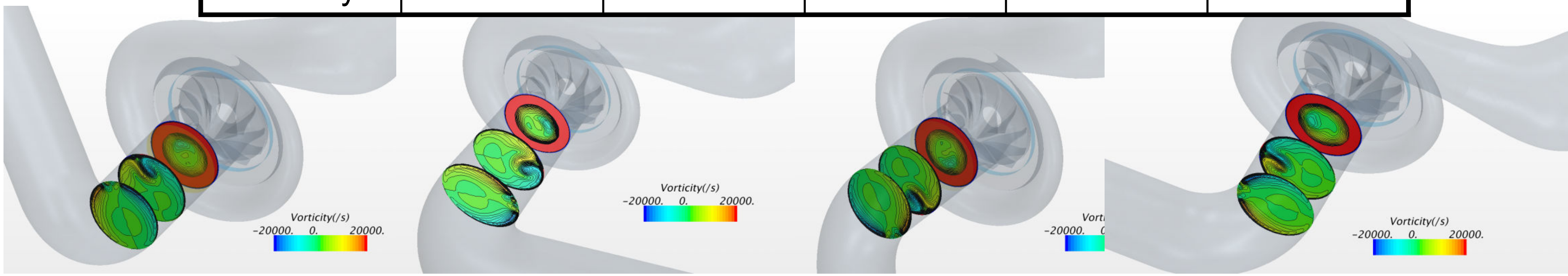


CCGEx

Outlook: Installation effects

- Two counter-rotating Dean vortices introduced after the bend inlet pipe
- Performance parameters depends on shape and orientation – clocking
- Structures introduced may be used to mitigate effect of strong swirling backflow at near surge.

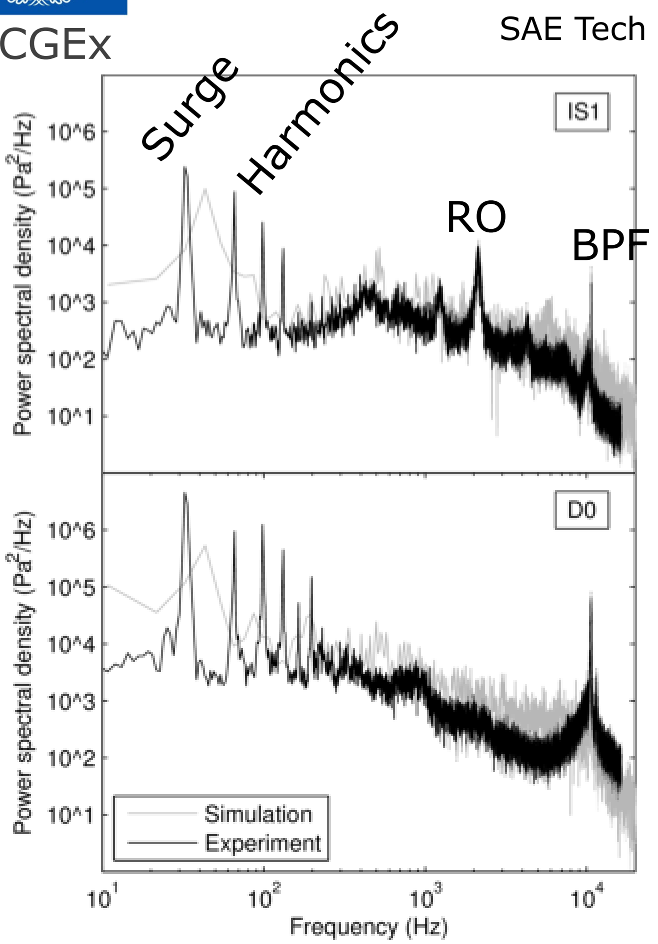
	Straight inlet	Curved inlet 0°	Curved inlet 90°	Curved inlet 180°	Curved inlet 270°
Pressure ratio	2.33	2.30	2.35	2.30	2.35
Efficiency	0.57	0.55	0.59	0.55	0.59

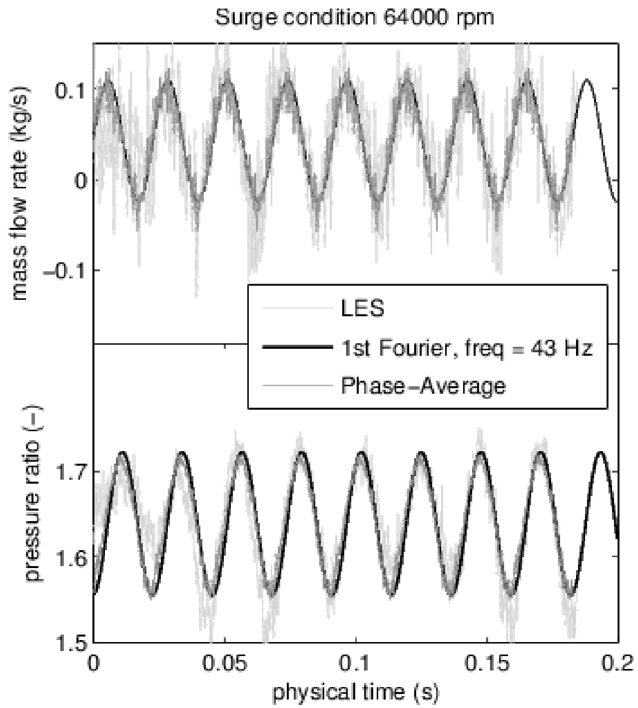


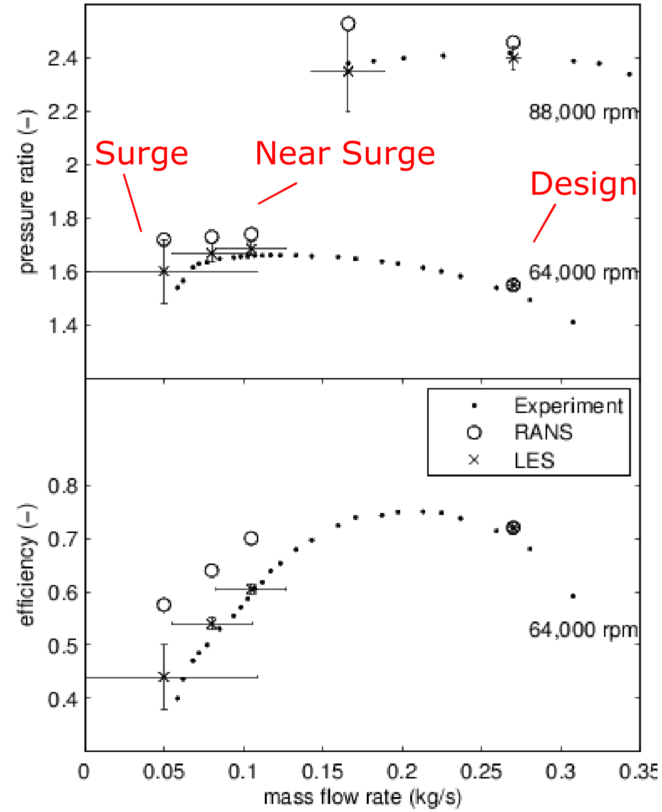
Outlook: Surge prediction (LES)

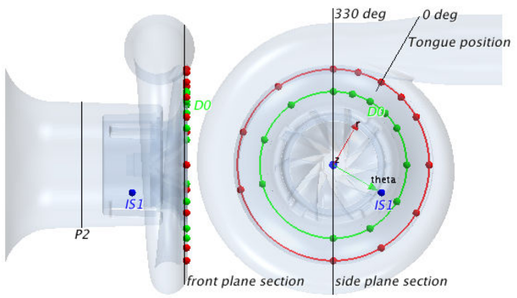
CCGEx

SAE Tech Paper 2014-01-2856









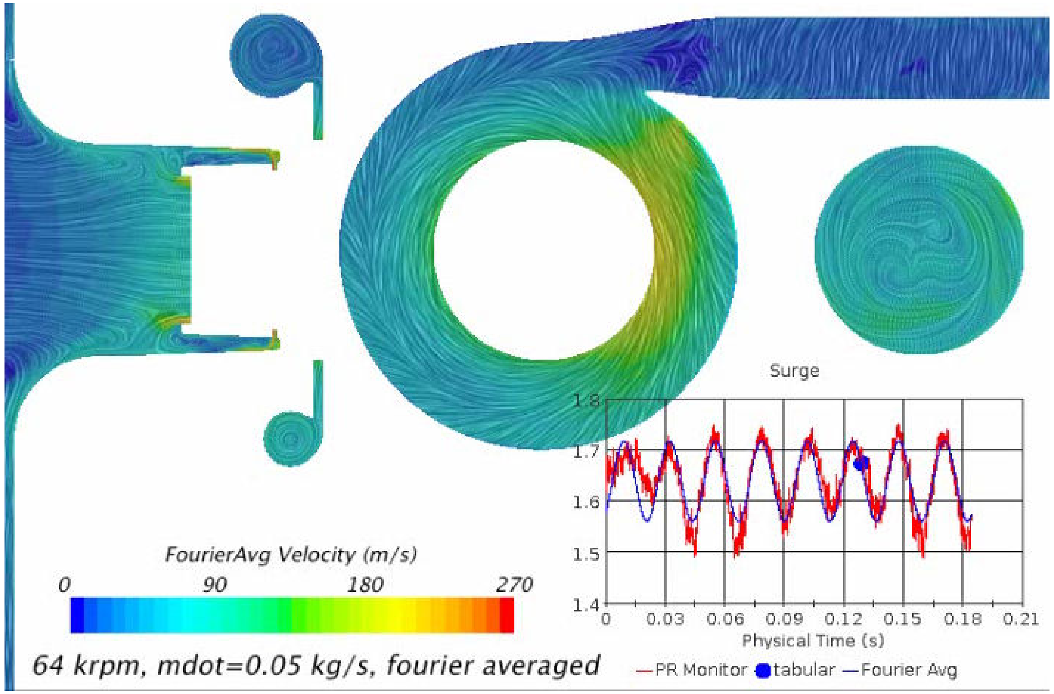
- Broadbanded PSD in mid frequency range
- Tonality at 43 Hz, 1st surge cycle harmonic, blade passing frequency and rotating order
- Narrowband at 0.5RO (~500 Hz)
- 8 cycles: under-resolved at low frequency range
- HOWEVER, surge frequency captured!
- Exp data thanks to Dr. Gutmark and his team at University of Cincinnati

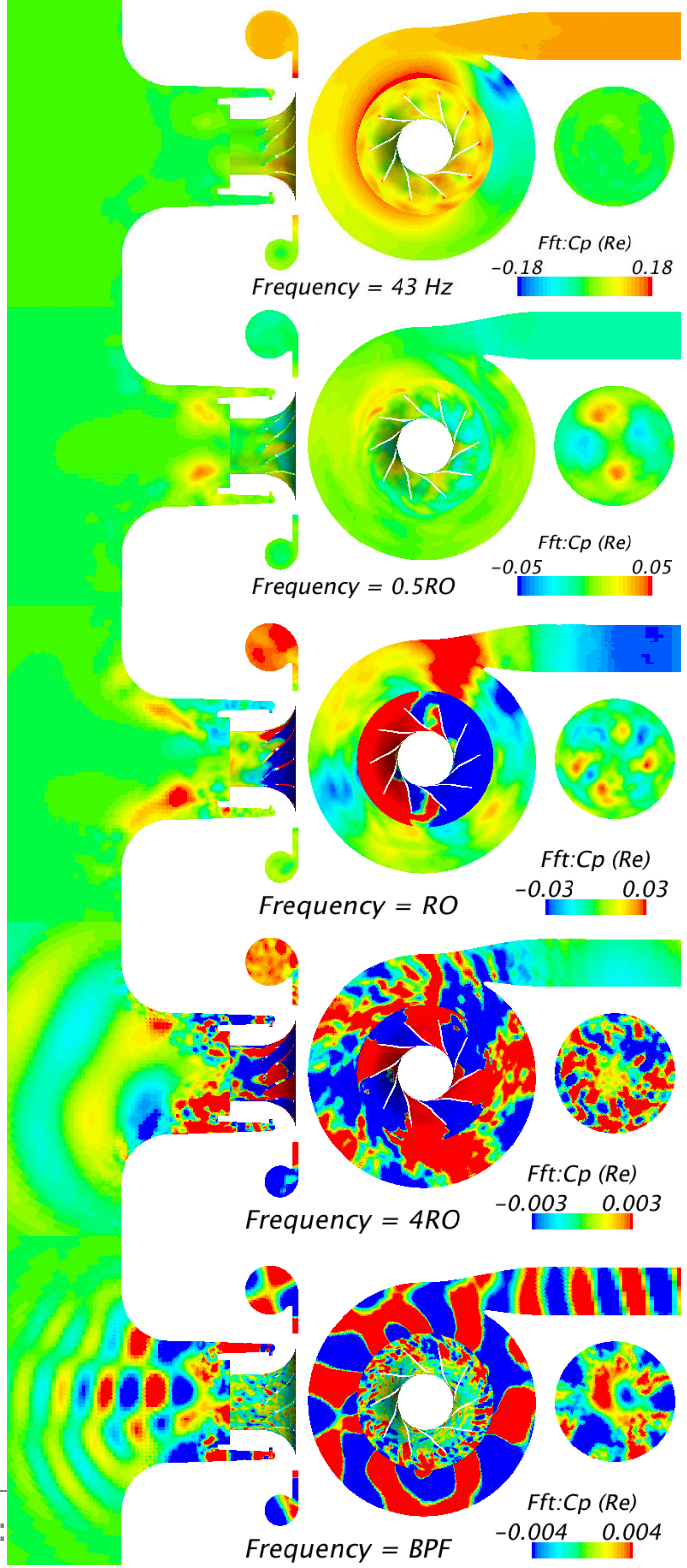
CCGEx

Outlook: LES

- Flow instability at surge condition with broadband and narrowband features motivates transition to LES
- Use of Flow Decomposition techniques to assess instability modes at off-design conditions: Fourier spectra, POD & DMD
- Assessment of amplified noise

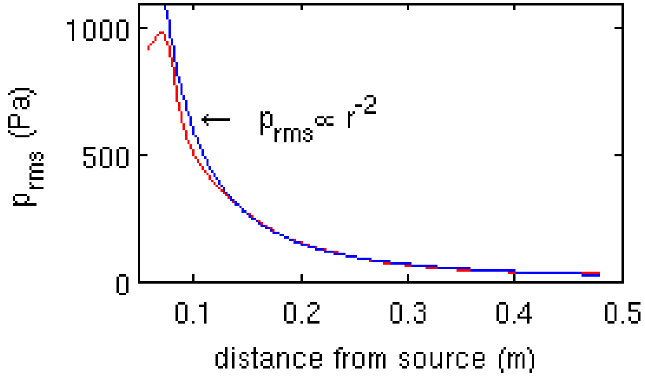
AIAA 2015 - 2674 at 21st AIAA/CEAS Aeroacoustics 2015, June 22-26, 2015, Dallas, TX, USA



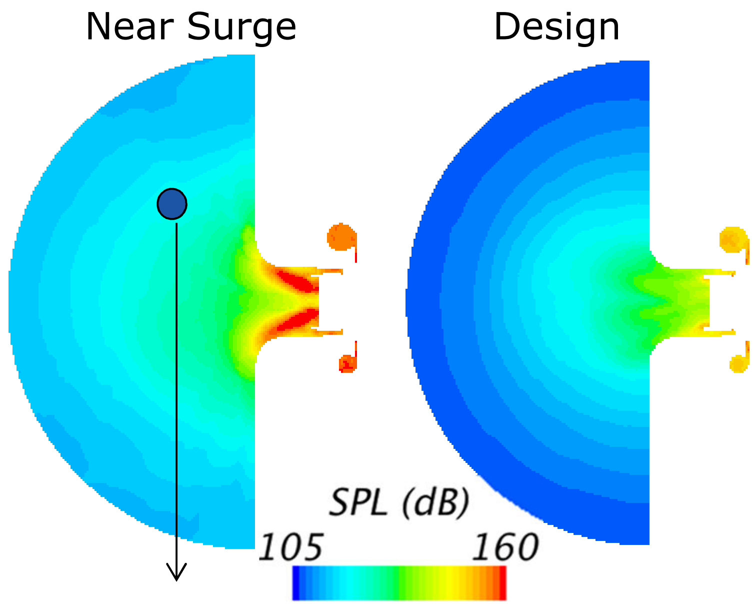


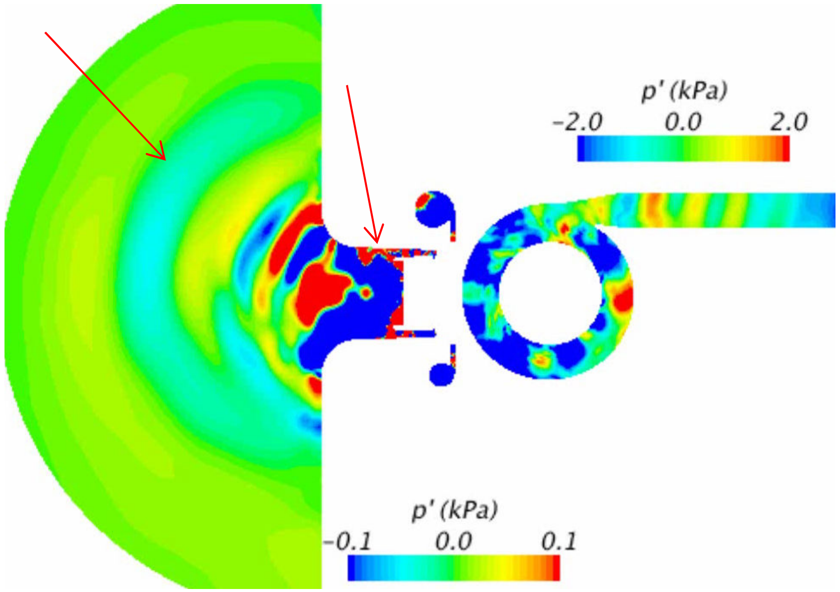
Outlook: noise (LES)

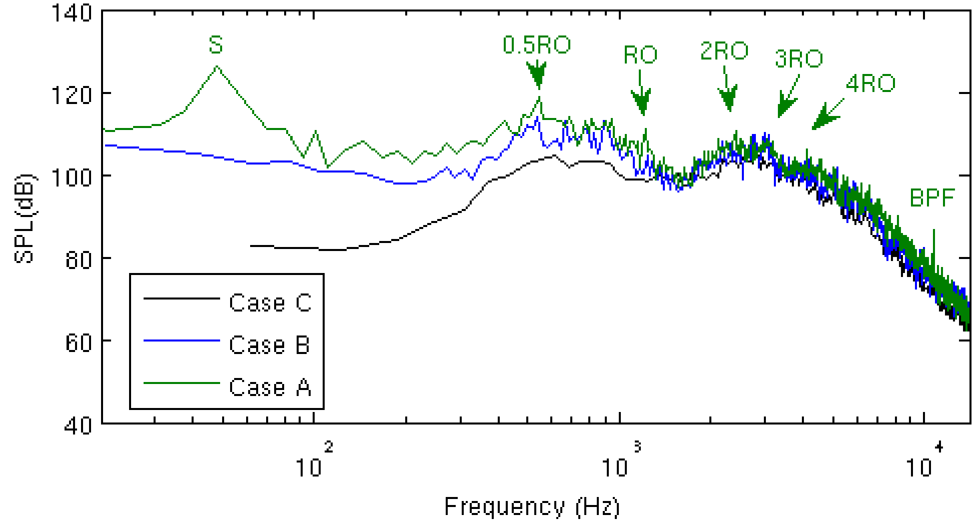
CCGEx



- Acoustical fluctuation in the upstream near field
- Turbulent(hydrodynamic) fluctuation in the impeller and volute
- Amplitude amplifies towards surge
- The intensity of pressure fluctuations fall of like the inverse of the distance from the source (Lighthill, M. J. and Ffowcs Williams, J. E, Fluid Mechanics 1974)
- Broadbanded features around 0.5*RO and 3*RO, whoosh noise or surge noise (Evans D. and Ward A., SAE2005-01-2485, and Teng C. and Homco S., SAE2009-01-2053)



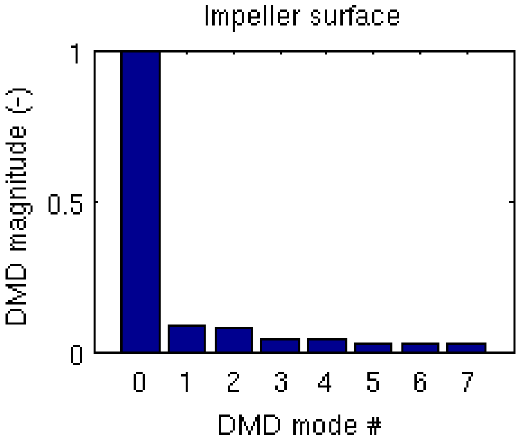


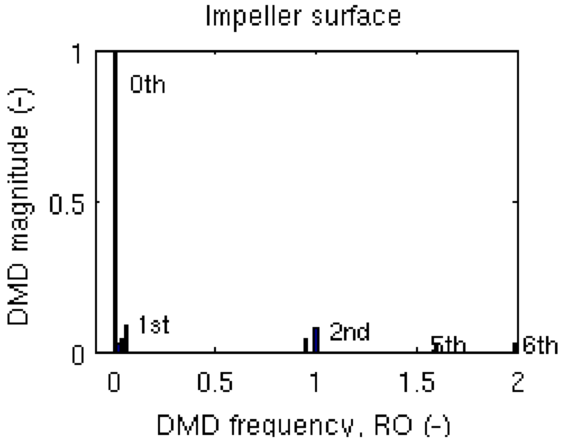


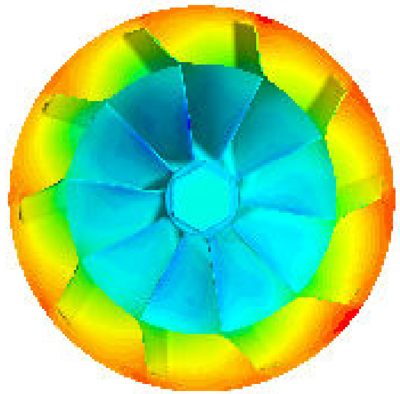
CCGEx

Outlook: DMD modes at Surge

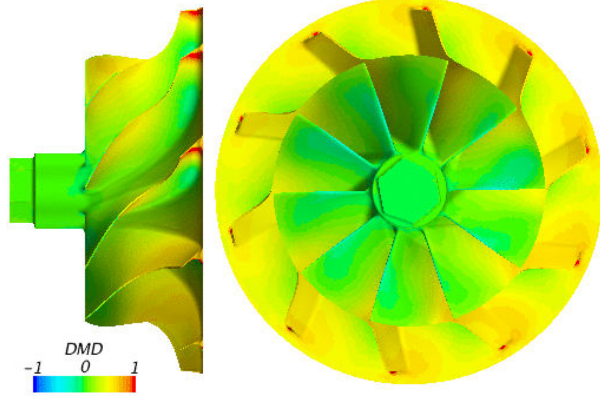
- Dynamic Mode Decomposition (DMD) based on pressure field for dominant mode shapes.
- Wave generating mechanisms captured at surge; pulsating mode, spinning modes (Pastuhoff M., Doctoral thesis, similar modes found with PSP)



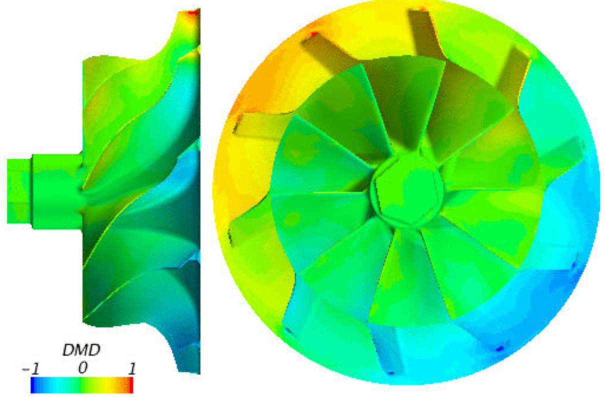




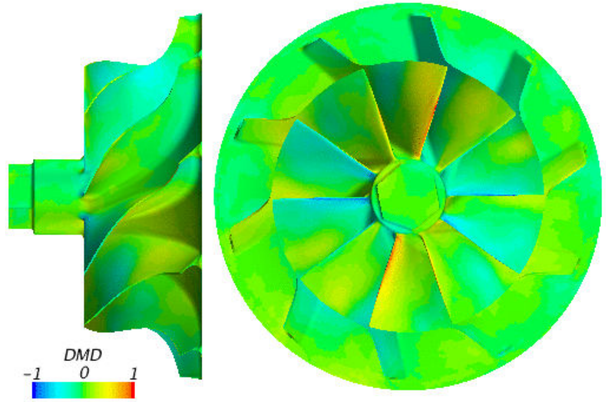
0th Mean (0 Hz)



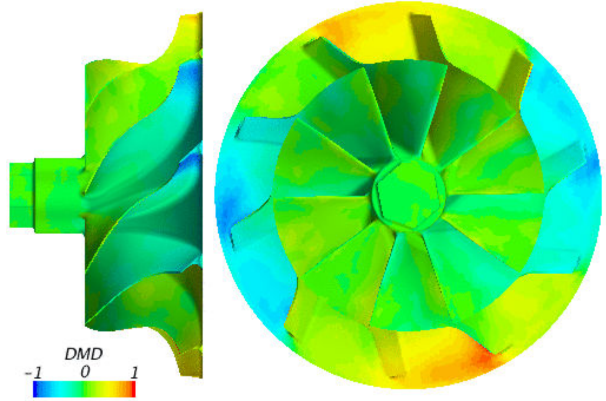
1st Surge (43 Hz, pulsating)



2nd RO (1069 Hz, spinning mode)



5th 1.5*RO (spinning mode)



6th 2*RO (spinning mode)

CCGEx

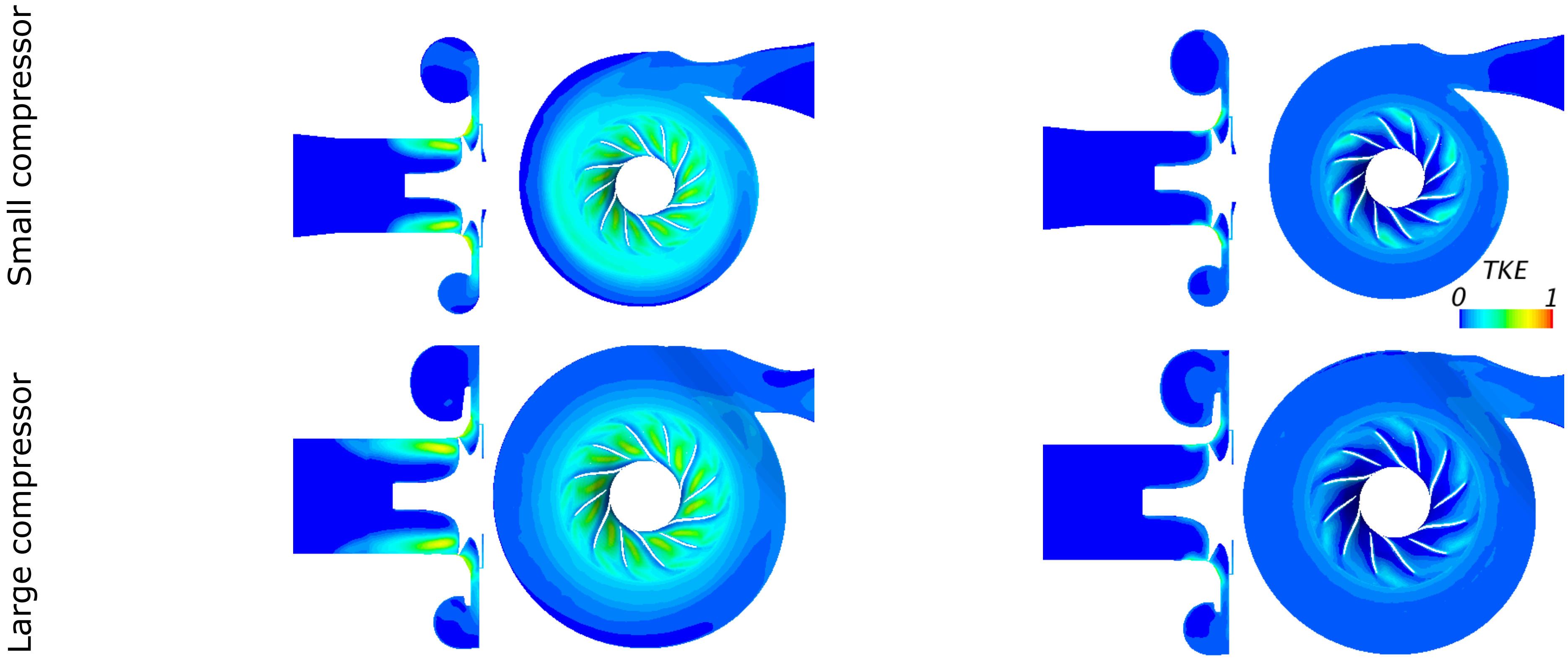
Summary/Conclusions

- Similar flow field at near optimum efficiency for both designs
- At near surge (lower mass-flow rates) the flow is pushed from the diffuser through the tip leakage and reaches further upstream for the larger compressor
- Larger compressor operates at higher mass-flow rates towards its surge line
- The interaction between the reversed flow and incoming flow triggers surge occurrence at different locations in the map
- Adverse pressure gradient under the volute tongue
- Pressure gradient in radial direction increases towards surge
- At critical back pressures local blade separation occurs

Turbulent Kinetic Energy

CCGEx

- Similar flow field at near optimum efficiency for both designs
- Towards near surge (lower mass-flow rates) increased TKE at the tip leakage and reaches further upstream for larger compressor



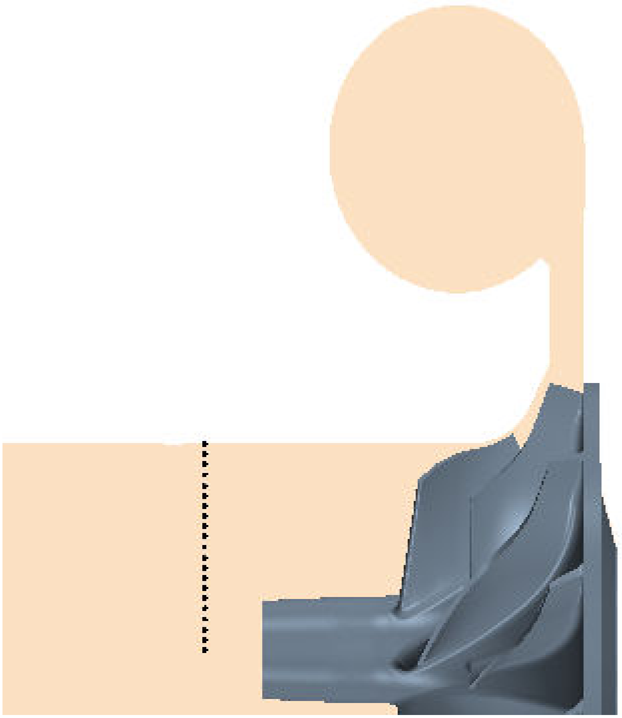
Last stable operation point

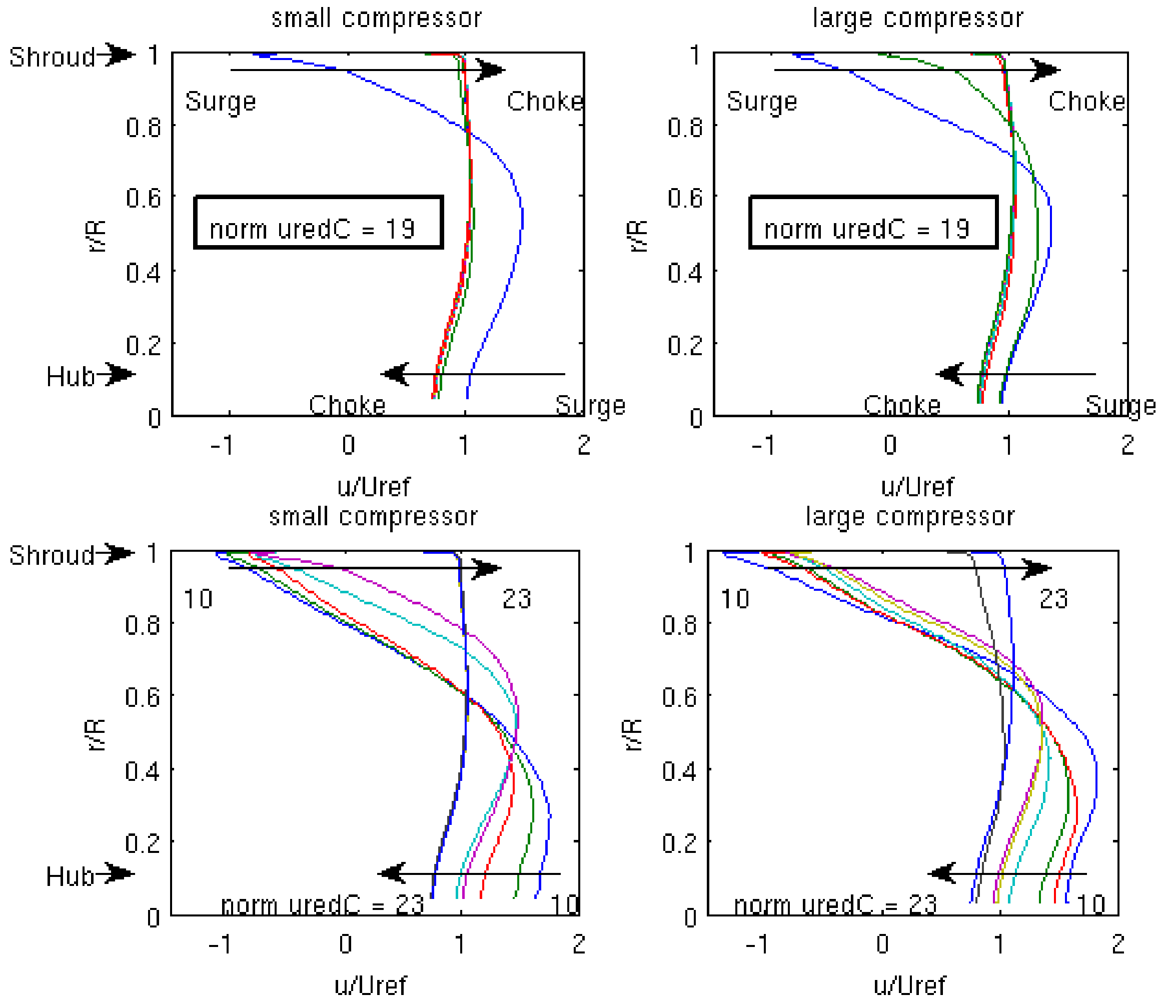
Near optimum efficiency

CCGEx

Velocity profiles

- Similar flow field at near optimum efficiency for both designs
- Towards near surge (lower mass-flow rates) flow reverses through tip leakage near the shroud and reaches further upstream for larger compressor

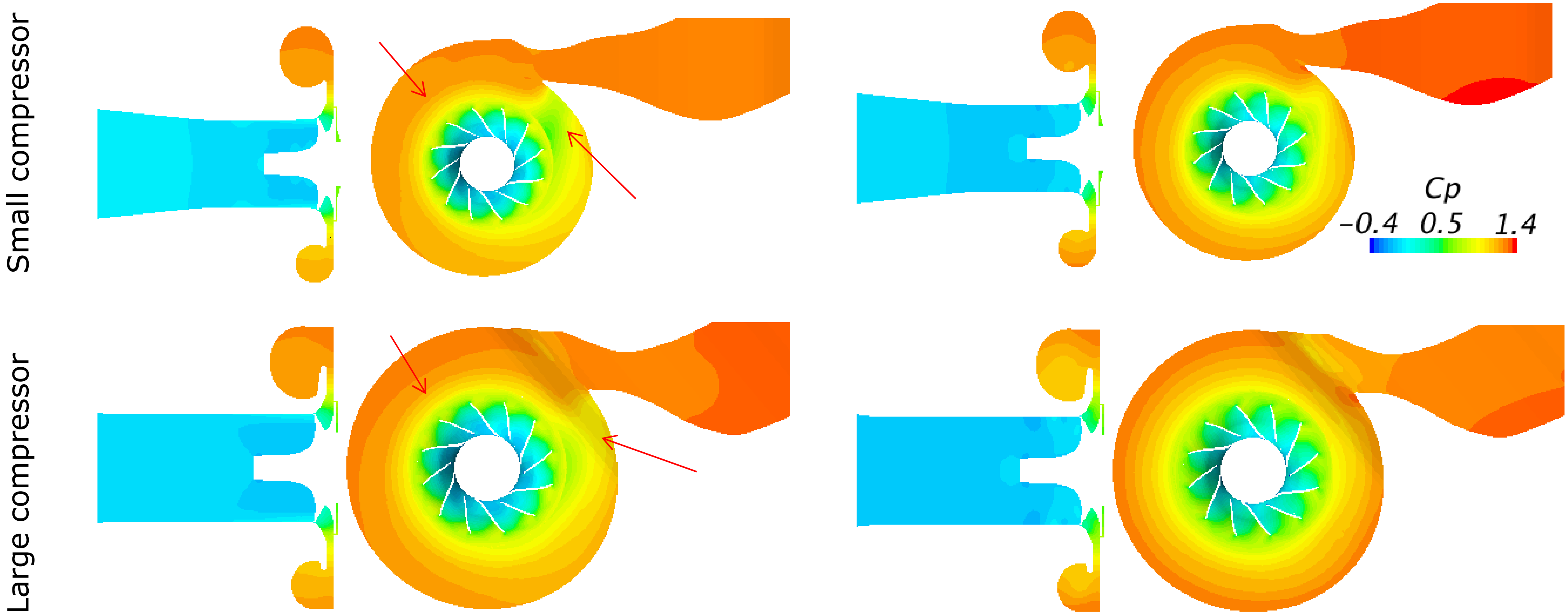




Pressure coefficient

CCGEx

- Similar flow field at near optimum efficiency for both designs
- Towards near surge (lower mass-flow rates) an adverse pressure gradient develops under the volute tongue at 2 o'clock.
- Flow directed towards this area
- Pressure gradient in radial direction increases towards surge
- At critical back pressures local blade separation occurs



Last stable operation point

Near optimum efficiency

CCGEx

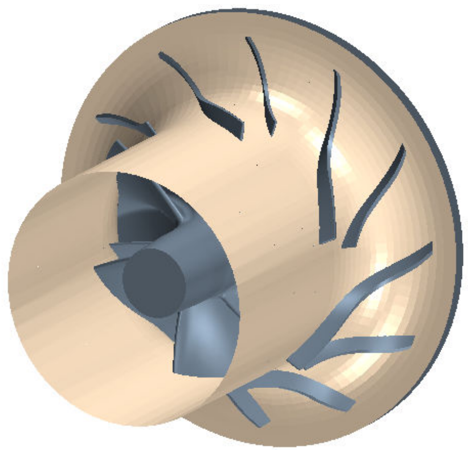
Motivation

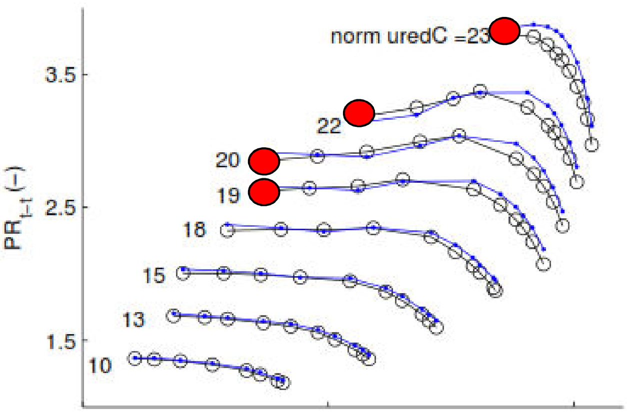
- Unsteady pressure loads associated with off-design operation can damage the centrifugal compressor
  - May also generate an amplified whoosh or surge noise, resulting in a notable discomfort
- Experimental assessment of flow instabilities inside the centrifugal compressor is challenging:
  - Confinement of the geometry complicates flow visualization
  - Sophisticated setups required to deliver high quality images
  - Tight spaces where dynamic pressure transducers cannot be mounted
- Numerical simulations ideally suited to elucidate the 3D flow inside the centrifugal compressor
  - What are the difference in the flow field between design (near maximum efficiency) condition and off-design condition near surge?
  - Which flow phenomena(s) is/are causing surge?
  - Are the mechanism for the on-set of flow instabilities the same for different operating conditions (e.g. different speed-lines)?
  - Are there similarities/differences in flow characteristics in centrifugal compressors of different size?

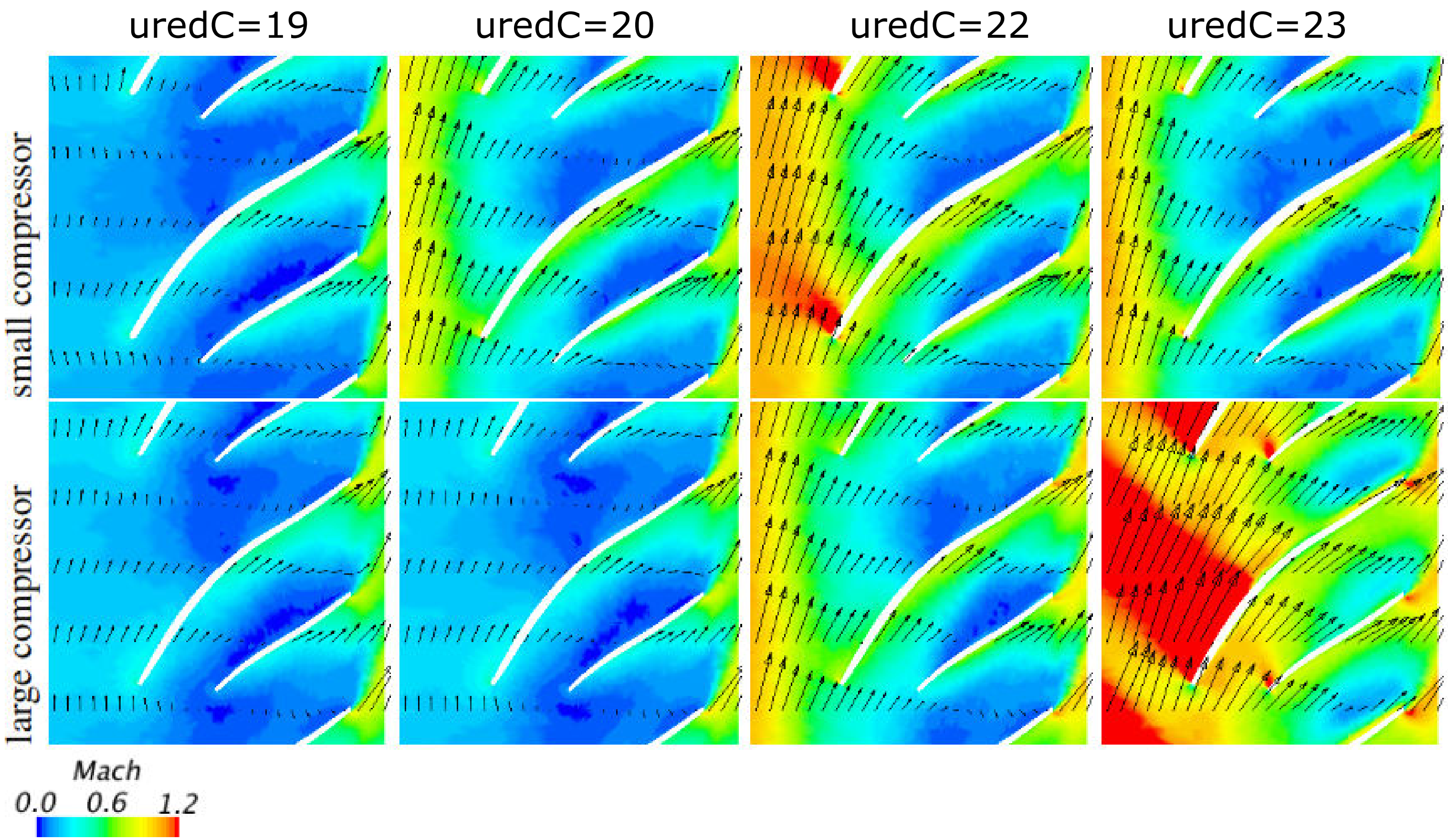
CCGEx

Relative Mach number

- Velocity vectors and Mach number contours for last stable operating point. Increasing speed-lines from left to right
- Boundary layer separation suction side at 85% span.
- Source for onset of flow instability at surge condition



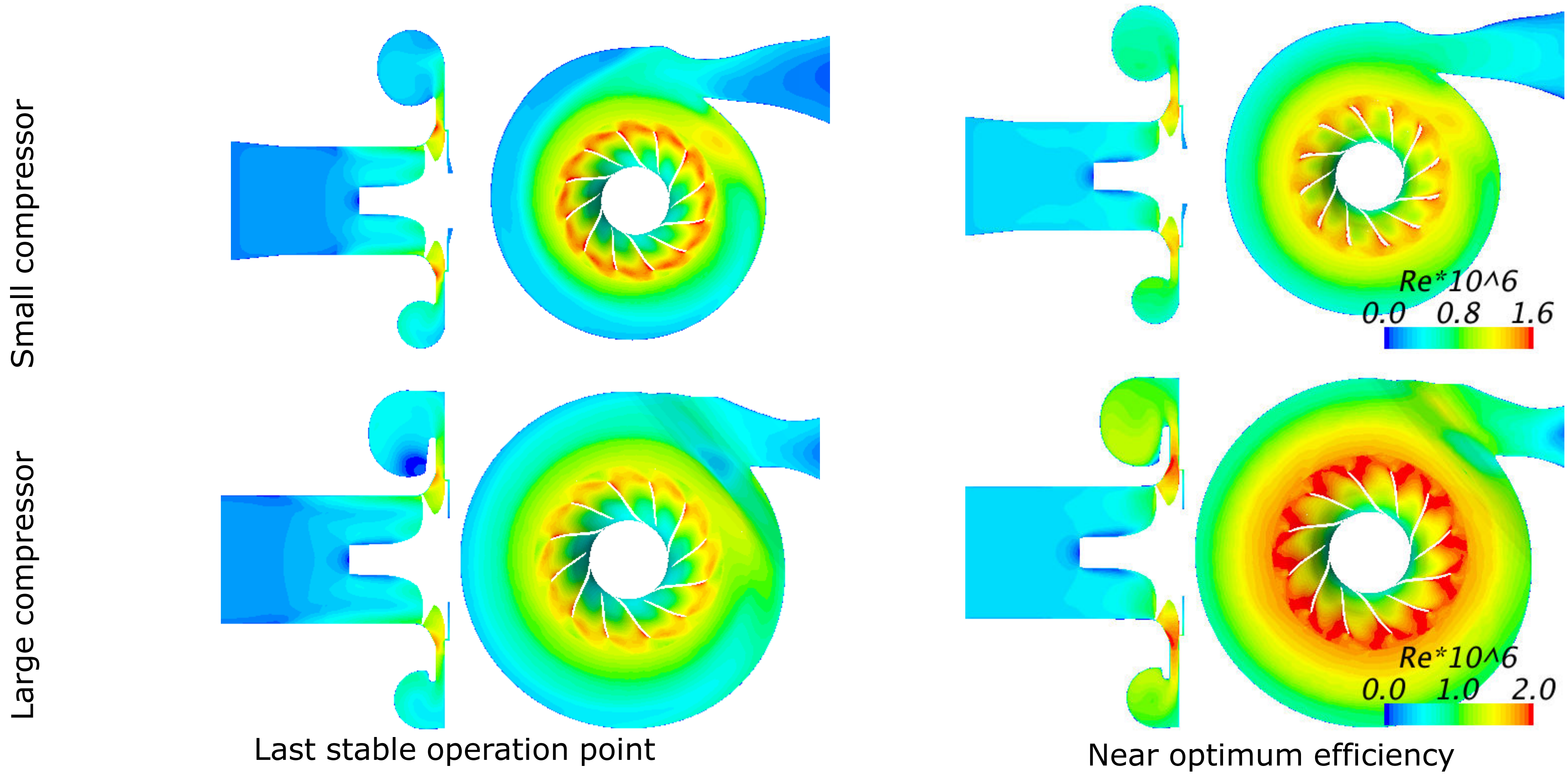




CCGEx

Reynolds number

- Similar flow field at near optimum efficiency for both designs
- Towards near surge (lower mass-flow rates) increased TKE at the tip leakage and reaches further upstream for larger compressor



CCGEx

Background: Surge prediction (LES)

Gutmark et al., 2010. Experimental data (PIV)
Hellström et al., 2012. LES frozen rotor
Jyothishkumal et al., 2013. LES sliding mesh
Semlitsch et al., 2013. POD/DMD
Sundström et al., 2014. LES sliding mesh, POD/DMD, surf spectra

- Beginning of surge cycle: high pressure rising in the volute/outlet
- Adverse pressure gradient develops in the tongue region
- Flow towards the low pressure region under the tongue
- Flow pushed back towards diffuser (between 5-12 o’clock)
- Swirling back-flow (same direction as impeller’s rotation) through the tip leakage affecting the incoming flow
- At the end of surge cycle PR drops, the compressor is empting
- Jets of fluid through the open ports
- Recirculation of fluid from shroud-cavity to impeller
- Rotating vortical structures upstream of impeller face