NASA/CP—2010-216112

CAVITATION, FLOW STRUCTURE & TURBULENCE IN THE TIP REGION OF A ROTOR BLADE

H. Wu
R. Miorini
F. Soranna

J. Katz

The Johns Hopkins University

T. Michael
S. Jessup

NSWC/Carderock

Sponsored by ONR, Program Officer: Ki-Han Kim

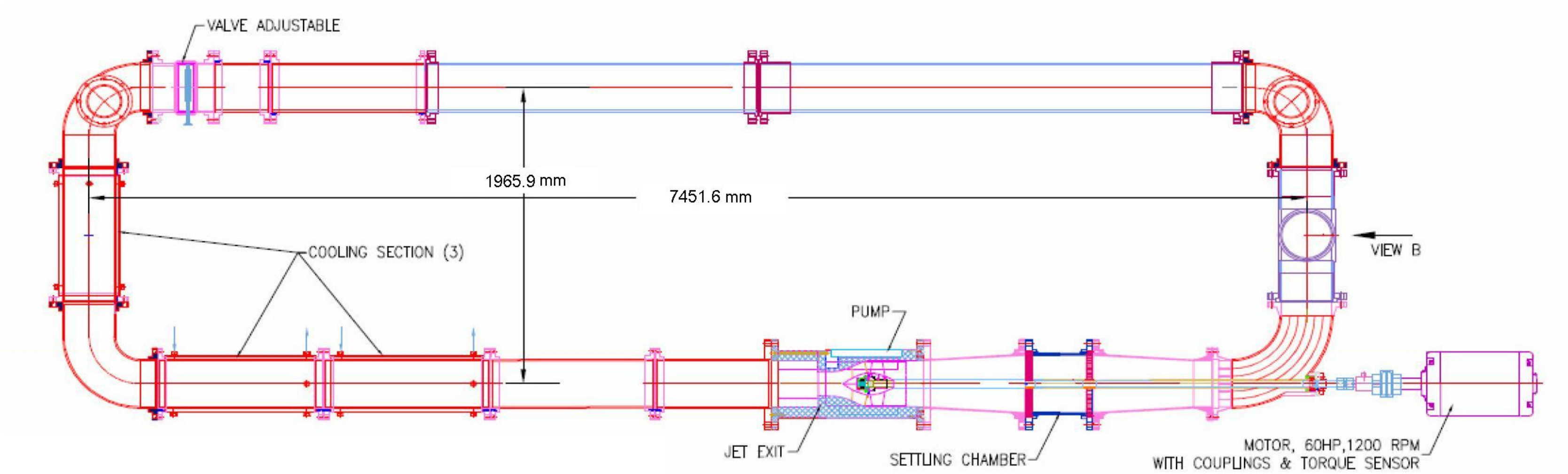
Minnowbrook, August 24, 2009

LONG TERM OBJECTIVES

- Measure the flow structure and turbulence within a Naval, axial waterjet pump.
  - Create a database for benchmarking and validation of parallel computational efforts.
  - Address flow and turbulence modeling issues that are unique to this complex environment.
  - Measure and model flow phenomena affecting cavitation within the pump and its effect on pump performance.

- This presentation focuses on cavitation phenomena and associated flow structure in the tip region of a rotor blade

FACILITY: For flow diagnostics and observations on cavitation, it is essential to have an unobstructed optical access to every section



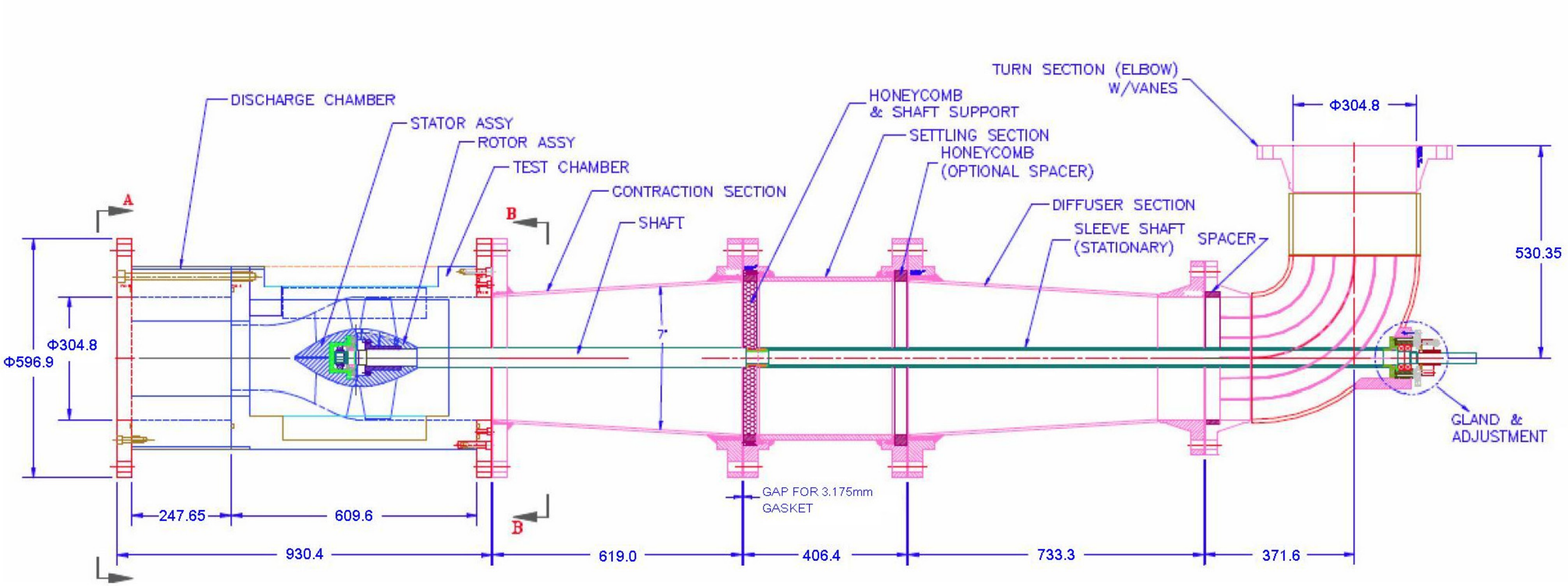
Pump blades (rotor and stator) are made of acrylic.

During PIV measurements, the test facility contains a concentrated solution of NaI in water, which has the same optical refractive index as the blades.

Blades become almost invisible

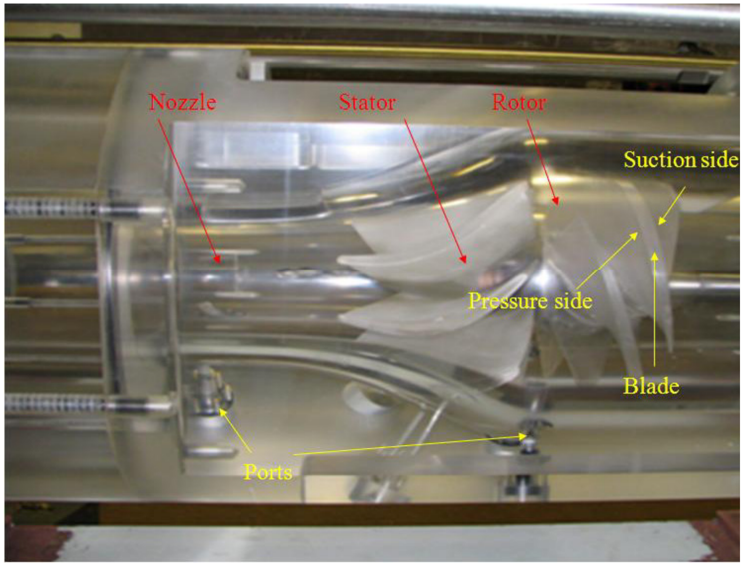
TEST SECTION

- The pump is driven by a 60HP AC motor through a 4.45cm diameter shaft. The shaft is supported by bearings at three points.
- Honeycombs (flow straighteners) are installed in the settling chamber upstream of the pump.



Unit: mm

WATERJET PUMP

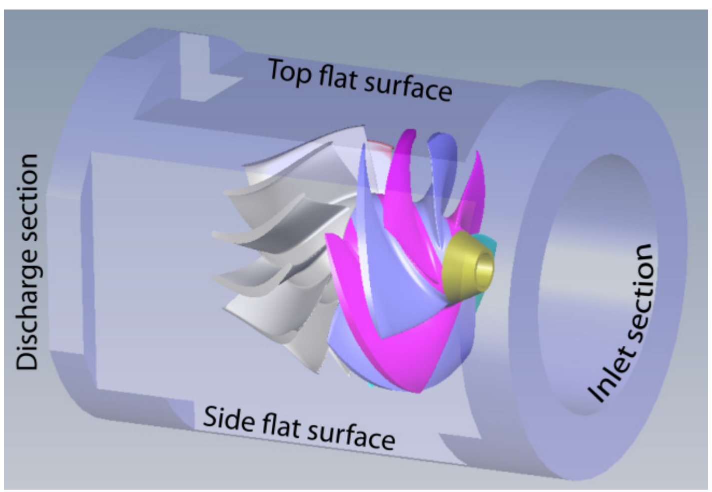


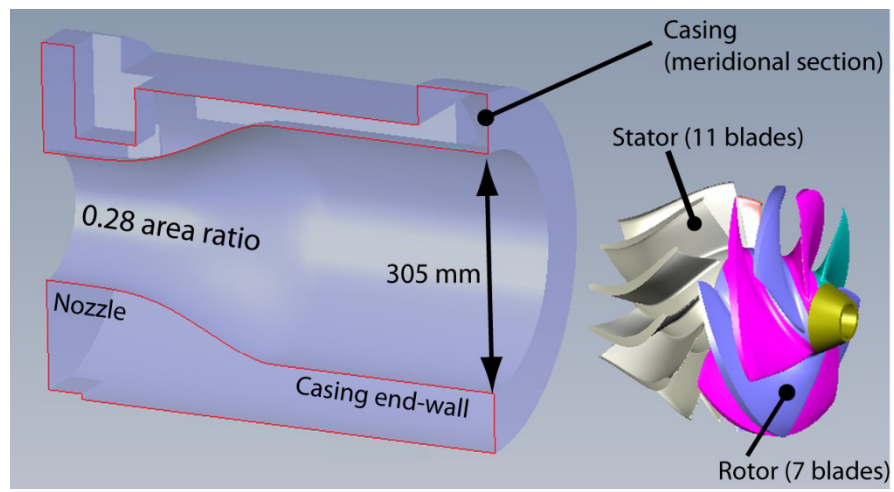
Rotor tip diameter: 305mm,
Tip clearance: 0.7mm.
Number of rotor blades: 7
Number of stator blades:11

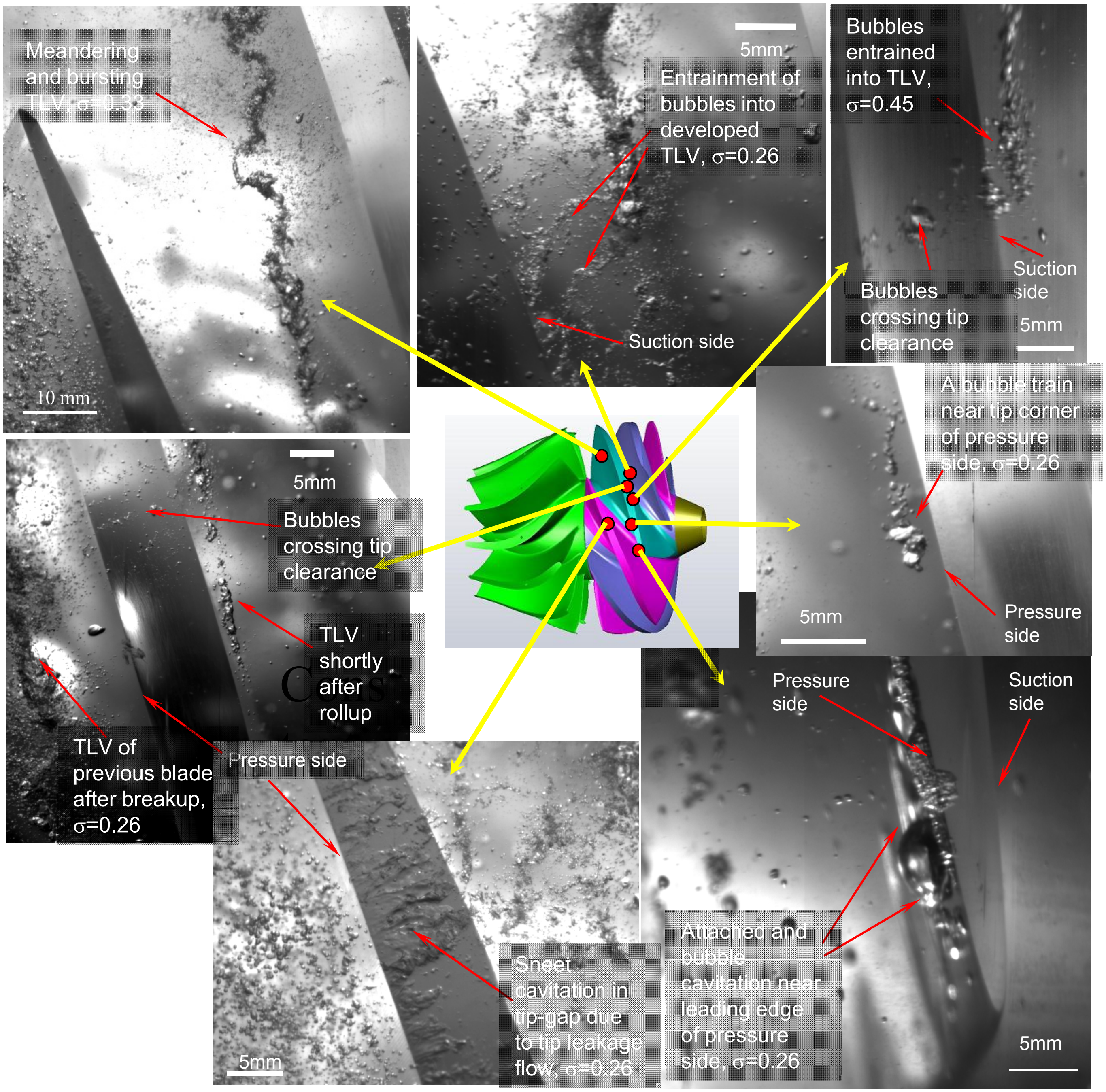
Selected flow conditions:

N=900 RPM

Flow rate [Q]	0.157 m^3s^{-1}
Flow coefficient [$\varphi = 2\pi Q\Omega^{-1}D^{-3}$]	0.37
Head coefficient [$\psi = (2\pi)^2 gH\cdot(\Omega D)^{-2}$]	1.7
Torque coef. $k_M = (2\pi)^{-2}M_e\,\rho^{-1}\,\Omega^{-2}\,D^{-5}$]	0.14







Montage of Cavitation Images

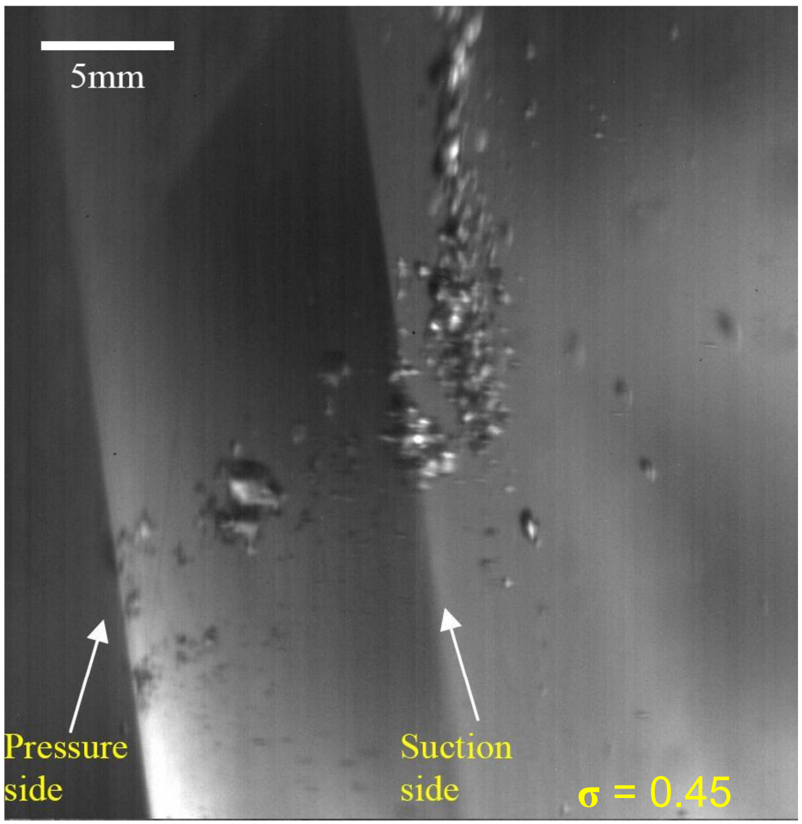
$$\sigma = \frac{p_{inlet} - p_v}{\frac{1}{2}\rho (U_{tip})^2}$$

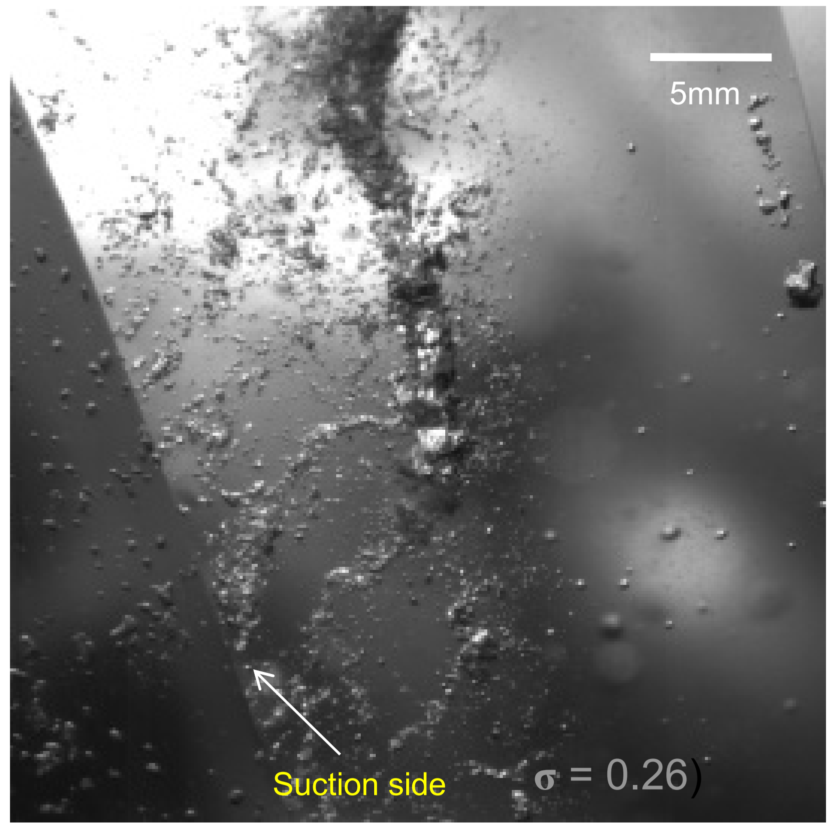
U_{tip} is the impeller tip speed
p_{inlet} is the mean pressure at the inlet plane.

Wu et al. 2008a, b

BUBBLES CROSSING TO SUCTION SIDE AT MID BLADE

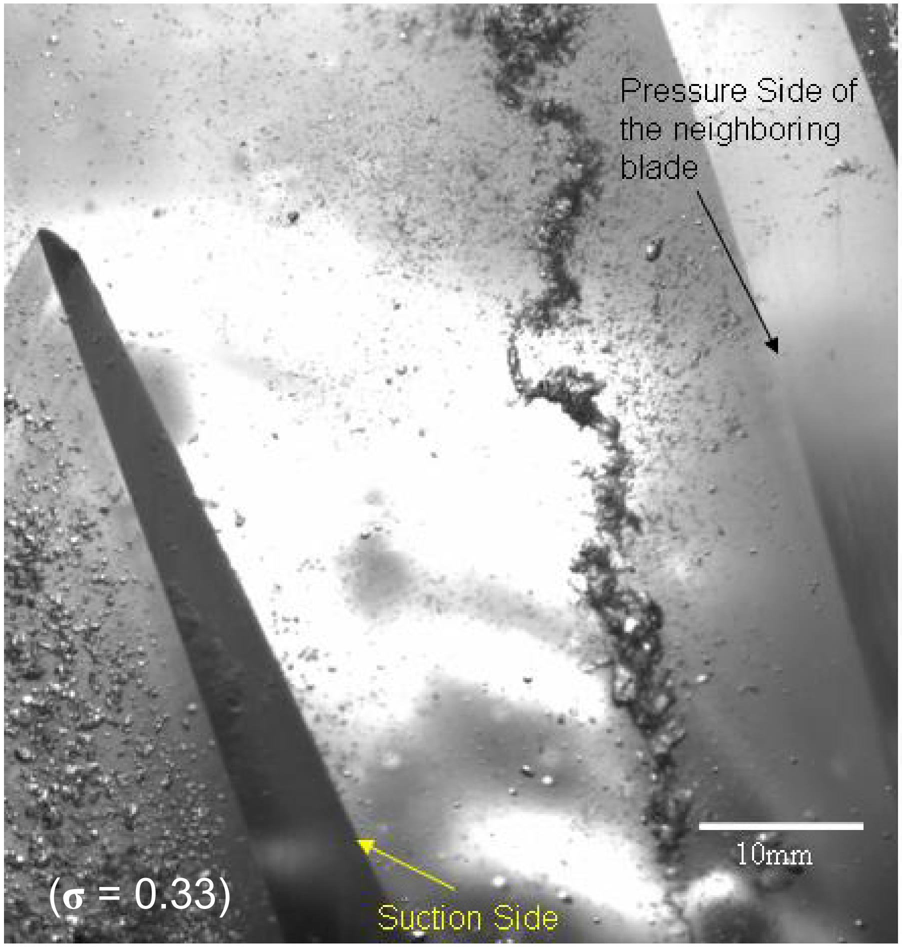
- At mid-chord, bubbles cross the tip clearance, and are entrained into the tip leakage vortex developing in the suction side

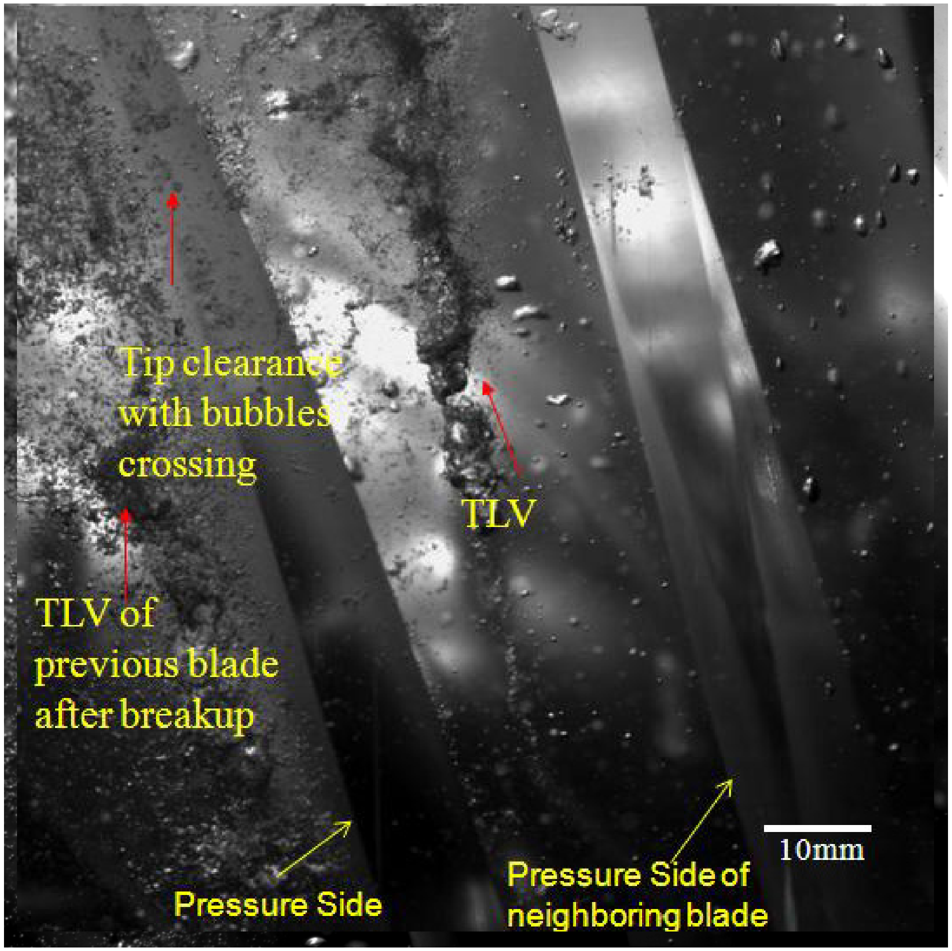




TIP LEAKAGE VORTEX MIGRATION AND BREAKUP

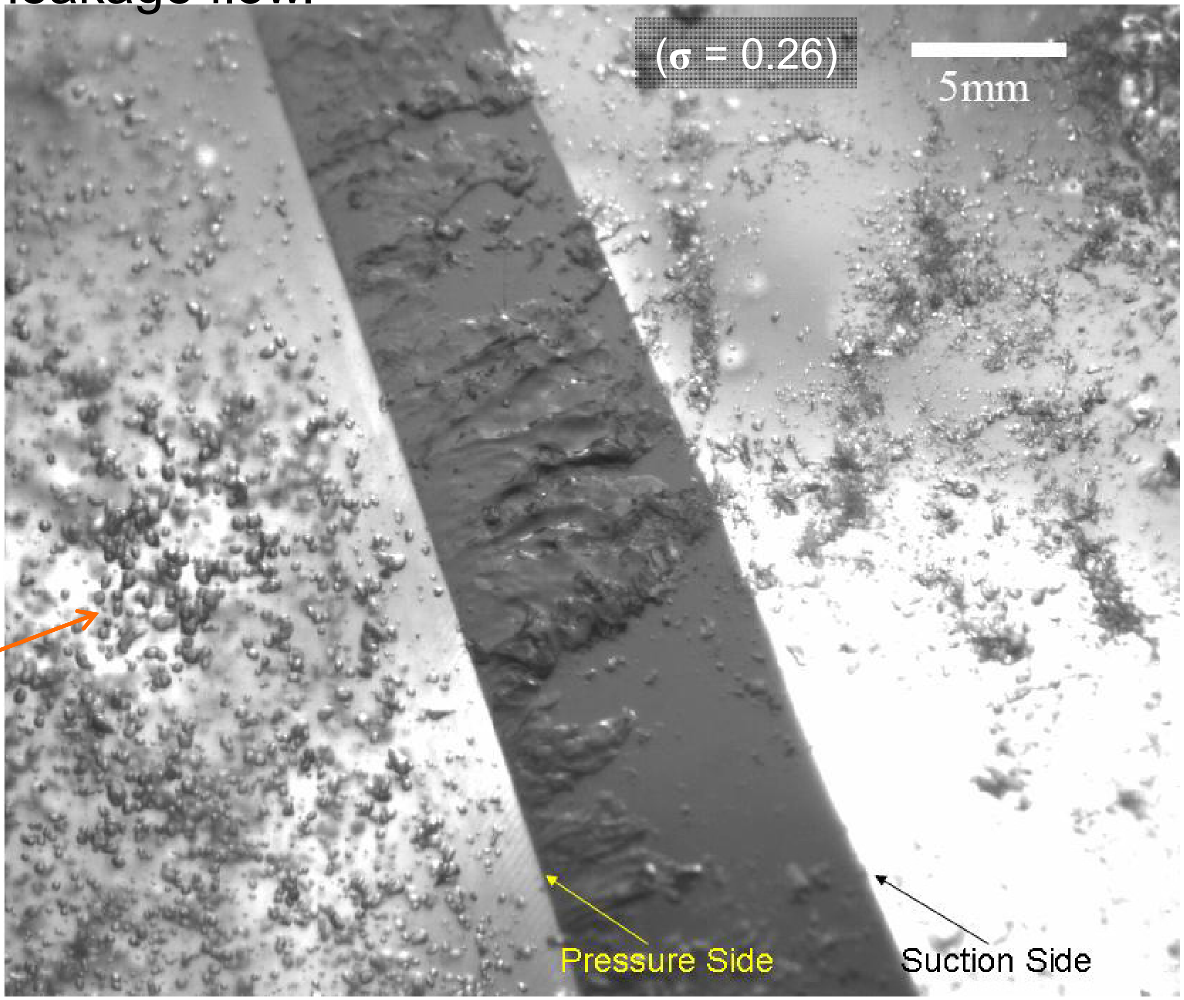
- The tip leakage vortex migrates to the pressure side of following blade.
- Adverse pressure gradient causes vortex breakup/bursting.





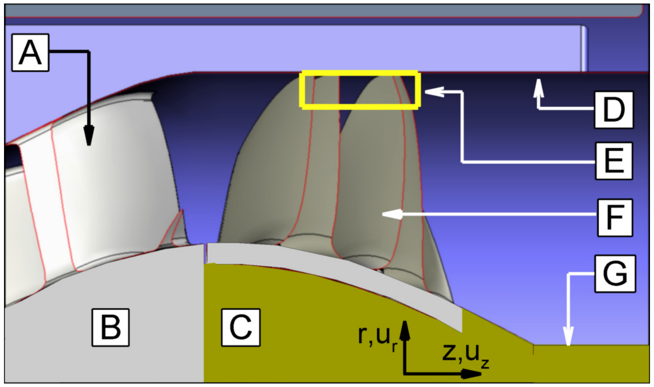
SHEET CAVITATION IN TIP GAP

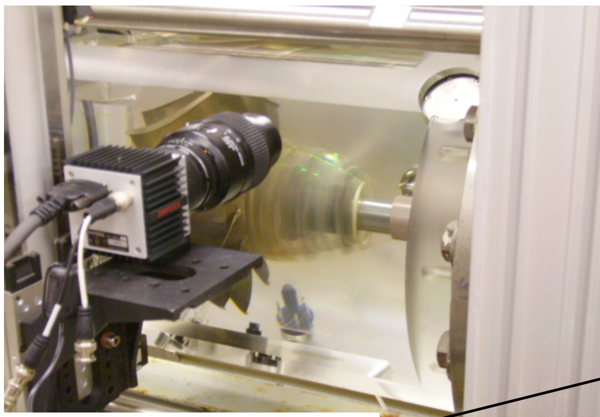
- Sheet cavitation occurs in the tip gap, demonstrating the strength of the tip leakage flow.

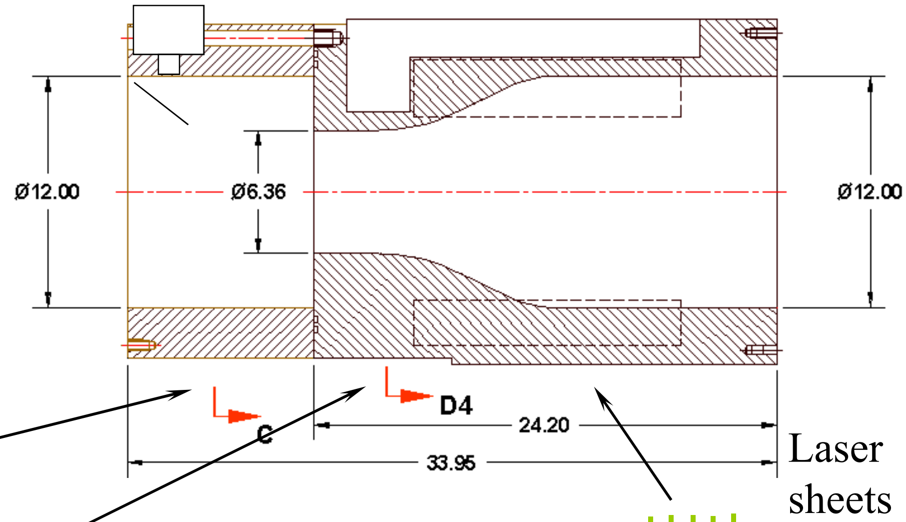


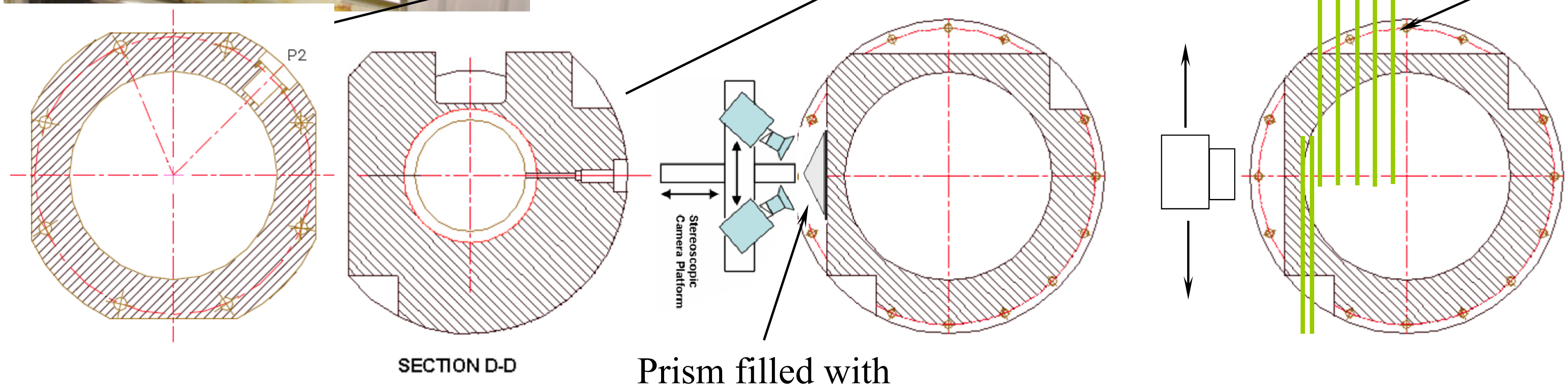
Cloud of bubbles resulting from breakup of vortex generated by previous blade

PIV MEASUREMENTS

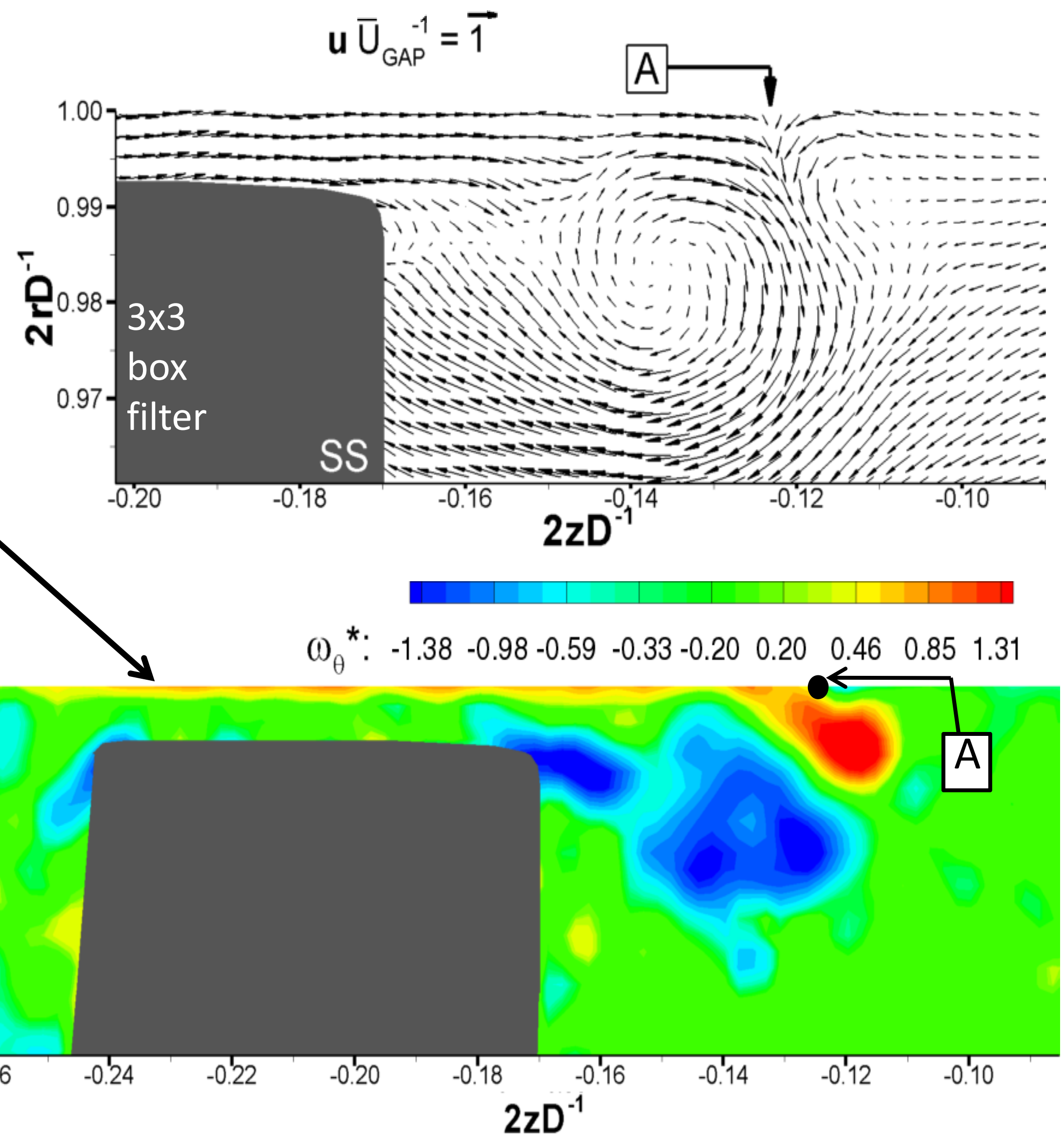








Early Stage – Instantaneous Flow – *s* = 0.56*c*



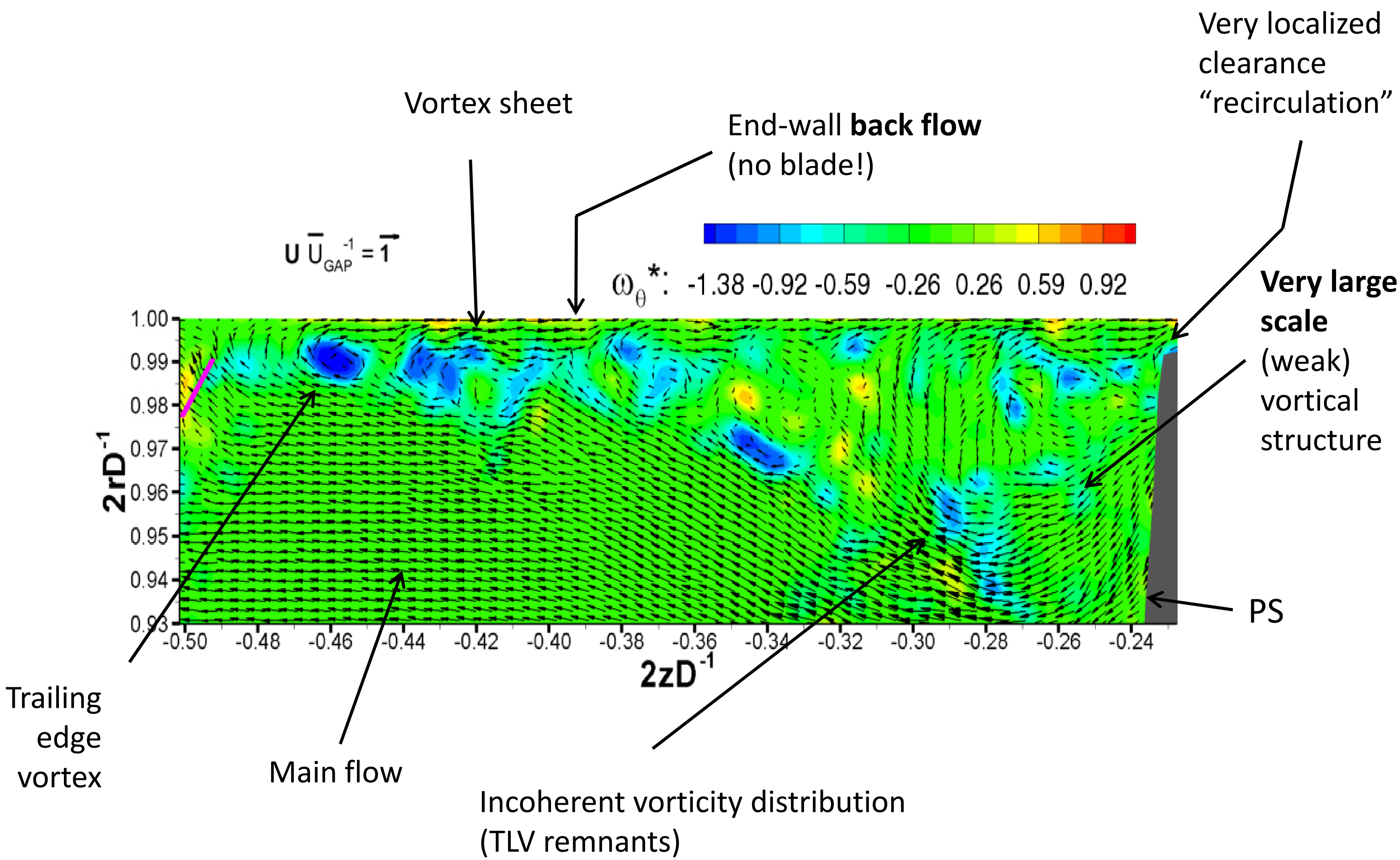
Vorticity generated at the casing by the clearance flow

Vorticity from the previous (burst) TLV

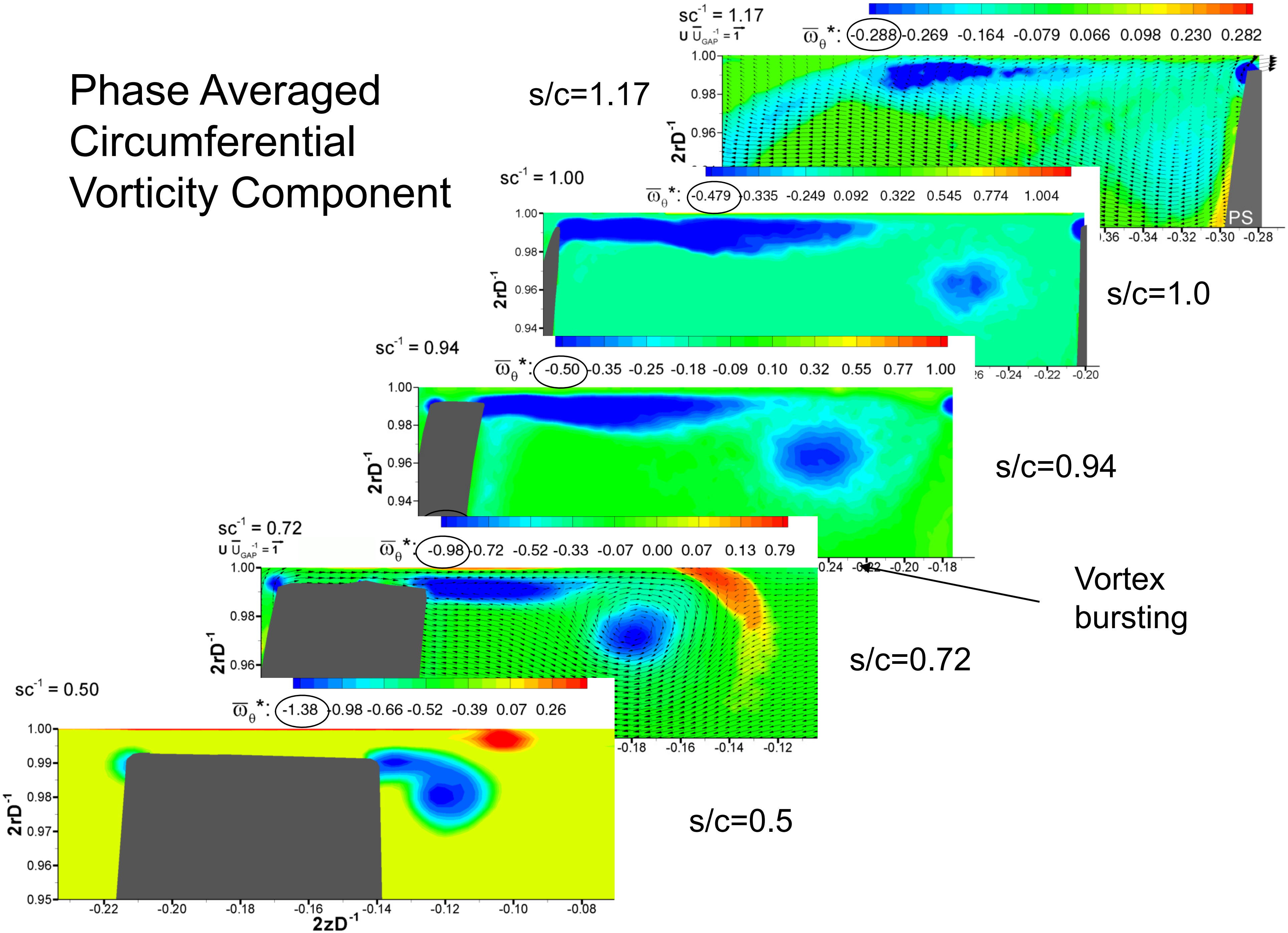
The **tip clearance backflow** collides with the main flow **[point A]** inducing a **separated flow** that follows the TLV outer branch

Miorini et al. 2009
Wu et al. 2009

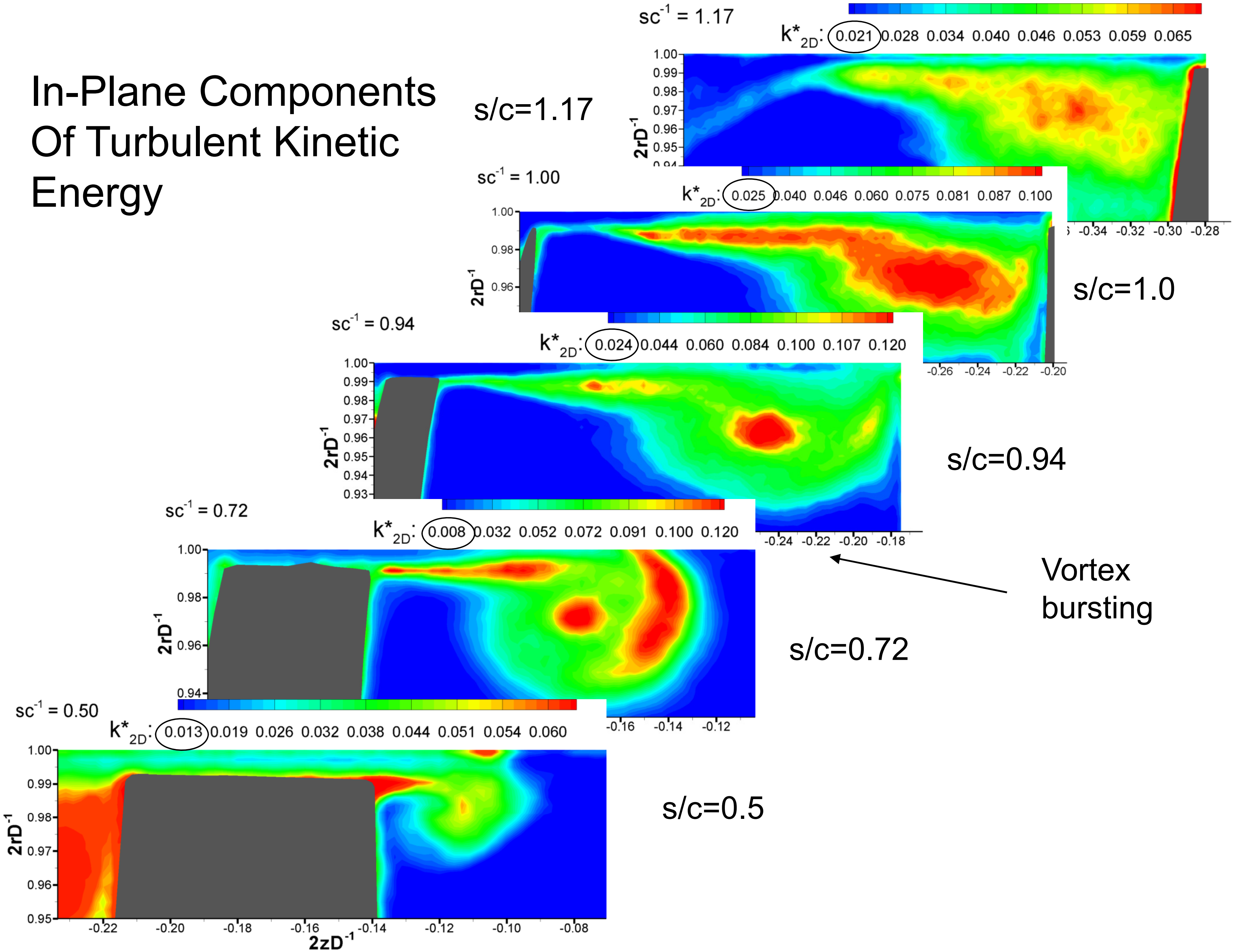
After TLV bursting – Instantaneous Flow *s* = 1.06*c*



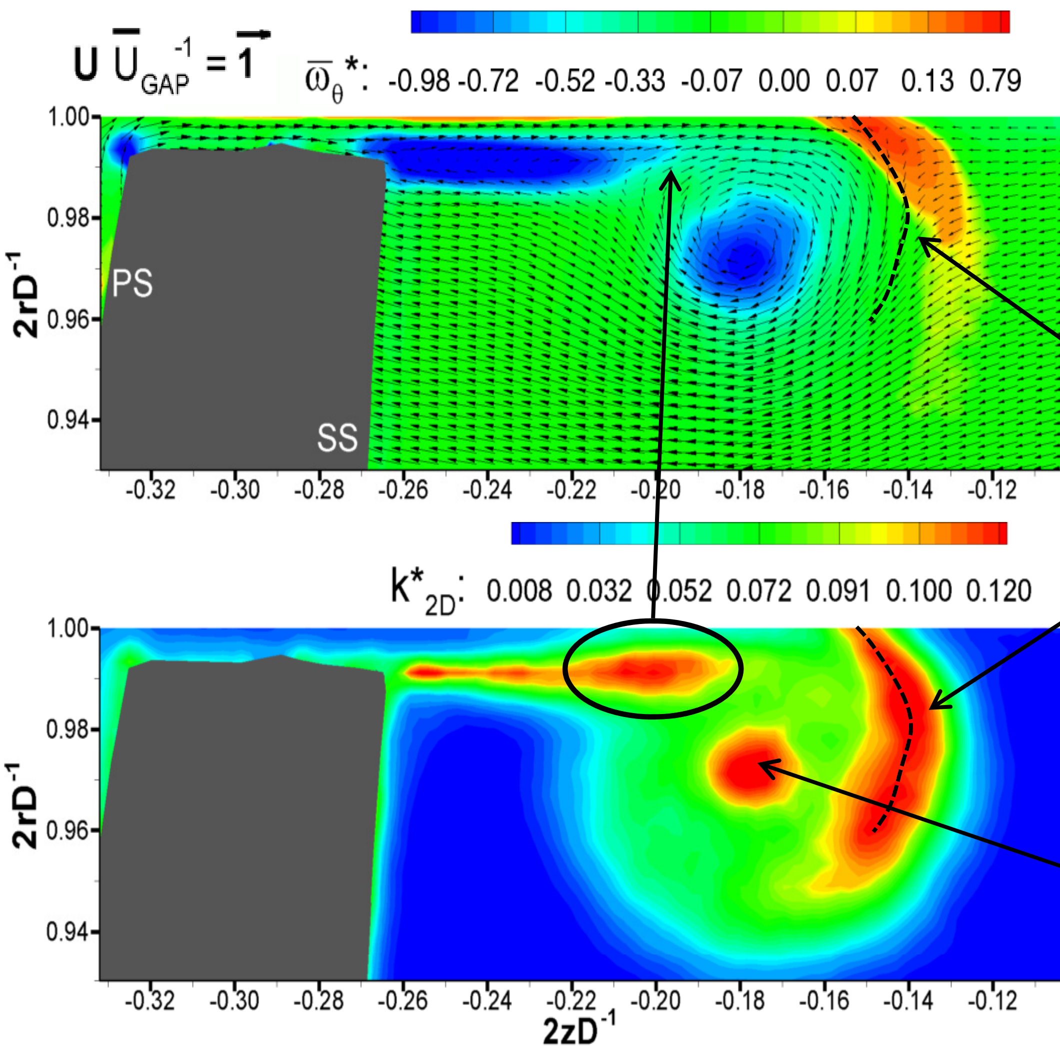
Phase Averaged Circumferential Vorticity Component



In-Plane Components Of Turbulent Kinetic Energy



Phase Averaged TLV --- Vorticity and TKE --- *s* = 0.72*c*



"Positive" vortices travel along the advancing front of the TLV generating large scale unsteadiness

TKE peaks at the **interface** between the entrained end wall vorticity and the TLV

High TKE is a direct result of vortex rope meandering

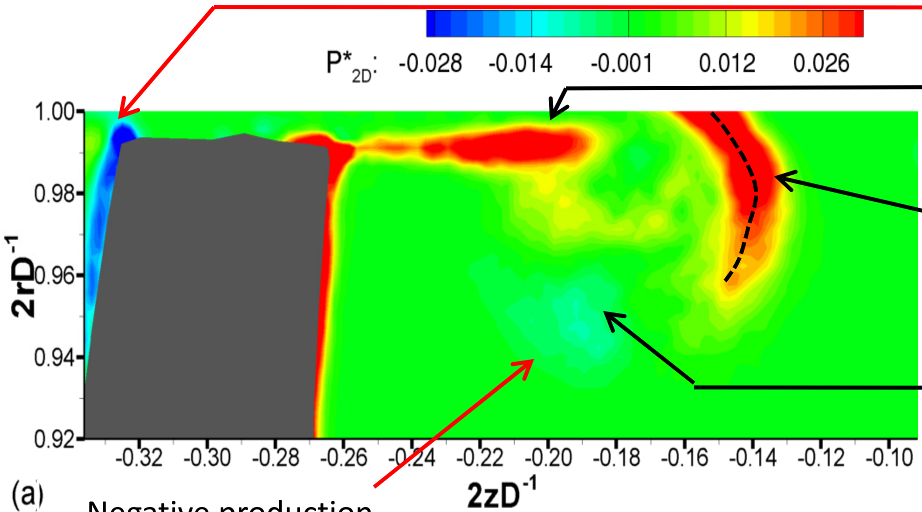
In-plane Production of 2D-TKE --- *s* = 0.72*c*

Negative production due to **rapid realignment of turbulence** (via axial "stretch") at the gap entry section **(b)**

shear production in the vorticity sheet (c)

Positive production due **to "compression" at the separation** and later due to **shear production in the advancing front of the TLV (b)**

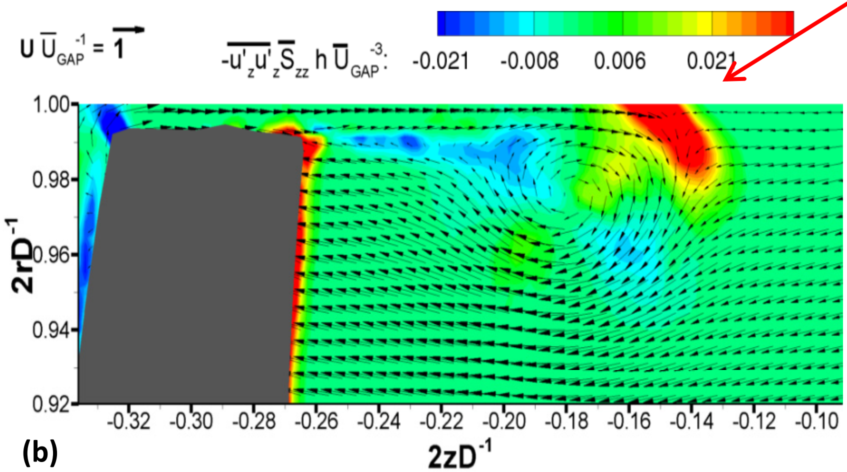
Note the absence of production in the (turbulent) core



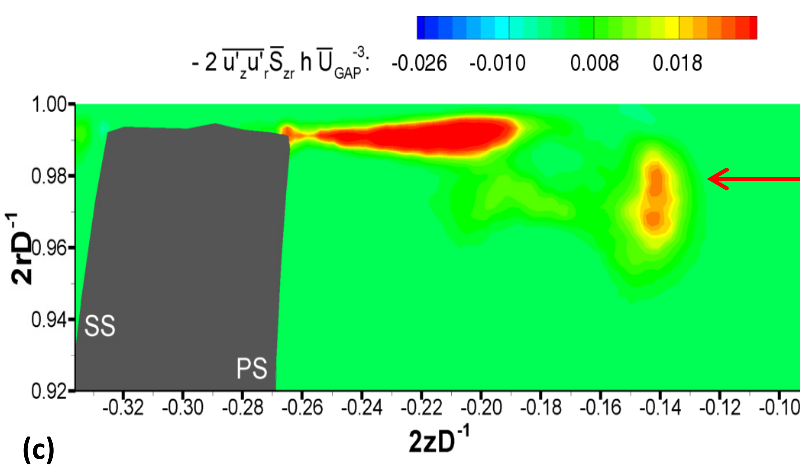
(a)

Negative production due to radial "stretch"

$$P^*_{2D} = \left[\frac{h}{\left(\bar{U}_{GAP}\right)^3}\right]\left(-\overline{u'_z u'_z}\ \bar{S}_{zz} - \overline{u'_r u'_r}\ \bar{S}_{rr} - 2\,\overline{u'_z u'_r}\ \bar{S}_{zr}\right)$$



(b)



(c)

Details can be found in

Wu, H., Soranna, F., Michael, T., Katz, J. Jessup, S., (2008), “Cavitation in the Tip Region of the Rotor Blades within a Waterjet Pump,” Paper # FEDSM2008-55170, 2008 ASME Fluids Engineering Conference, August 10-14, 2008, Jacksonville, Florida, USA.

Wu, H., Soranna, F., Michael, T., Katz, J., Jessup, S., (2008), “Cavitation Visualizes the Flow Structure in the Tip Region of a Waterjet Pump Rotor Blade,” 27th Symposium on Naval Hydrodynamics, Seoul, Korea, October 5-10.

Wu, H., Miorini, R.L. , Katz, J., (2009), “Tip Leakage Vortex Structure and Turbulence in the Meridional Plane of an Axial Pump,” 8th International Symposium on Particle Image Velocimetry - PIV09, Melbourne, Australia, August 25-28.

Miorini, R.L., Wu, H., Katz, J., (2009), “The Inner Structure and Evolution of a Turbulent Tip Leakage Vortex Within An Axial Pump, Part I: Instantaneous Results, Part II: Phase-Averaged Results,” Paper No. Fedsm2009-78534, ASME 2009 Fluids Engineering Division Summer Meeting August 2-6, 2009, Vail, Colorado.