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Progress Towards Swirl-Plane PIV Measurements Throughout the Full Intake and Compression Strokes

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Abstract

Particle Image Velocimetry (PIV) has been widely utilized for in-cylinder flow measurements since 1989. In the first part of the induction stroke, in-cylinder flow is characterized by the strong interaction between valve jets and piston top. Both experiments and hybrid RANS-LES modeling approaches have identified the jet-piston interaction as one of the key factors influencing cyclic variability. Bowl-in-piston cylinder geometries can be expected to substantially change the in-cylinder flow resulting from at least the first half of the intake stroke. As an alternative way to reduce soot emissions in the light-duty diesel engines, there also exists a great interest in characterizing swirl structures and their evolution during the compression stroke prior to injection. However, severe image distortion brought by the complex piston geometries is one of the obstacles for accurate velocity measurements. This work presents an update of general mapping procedure for analytical approach of optical distortion quantification. The theoretical analysis helps the optimization of swirl-plane PIV design with re-entrant bowl geometry. The swirl-plane PIV results taken at three planes under steady-state swirl ratio at 2.2 yield in several analysis: the true swirl ratio evolution, swirl center location and the swirl center axis tilting behavior. The swirl center location exhibits clockwise motion during the compression stroke. After IVC, swirl center axis tilting towards exhaust ports becomes less as piston proceeds to -105^{0}aTDC. As the compression continues, the tilting switches to intake ports, and is getting worse until the TDC is approaching. In the end, this experiment is also used to investigate the impact of jets interaction on the swirl ratio evolution with various tangential port throttling.

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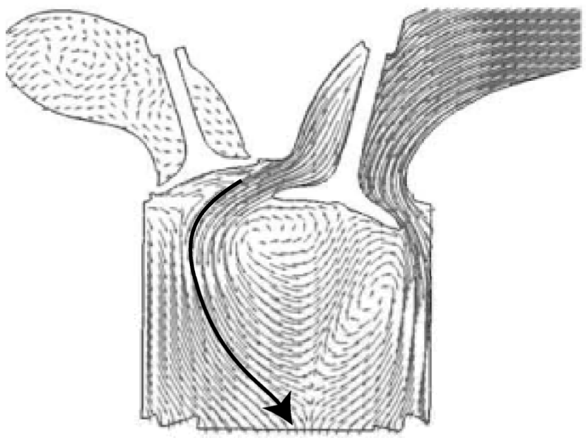
Unclassified, Unlimited Release

Outline

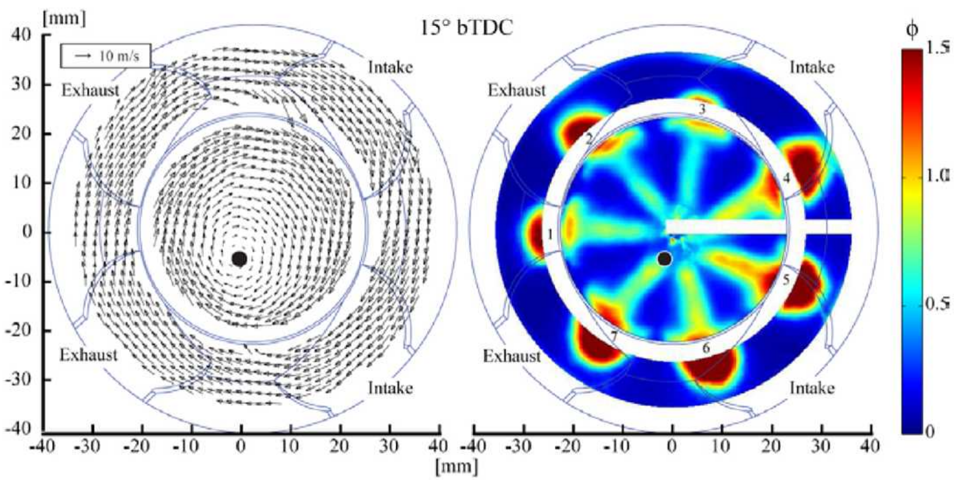
- Motivation
- Background
- General mapping procedure for optical distortion quantification
- PIV experiments design
- Results
  - Swirl ratio evolution and swirl center location
  - Study of flow asymmetry
  - Swirl ratio behavior with various intake ports throttling
- Summary
- Future Work

Motivation



Hasse, et al., Comput. Fluids, 39: 25-48

-270° aTDC



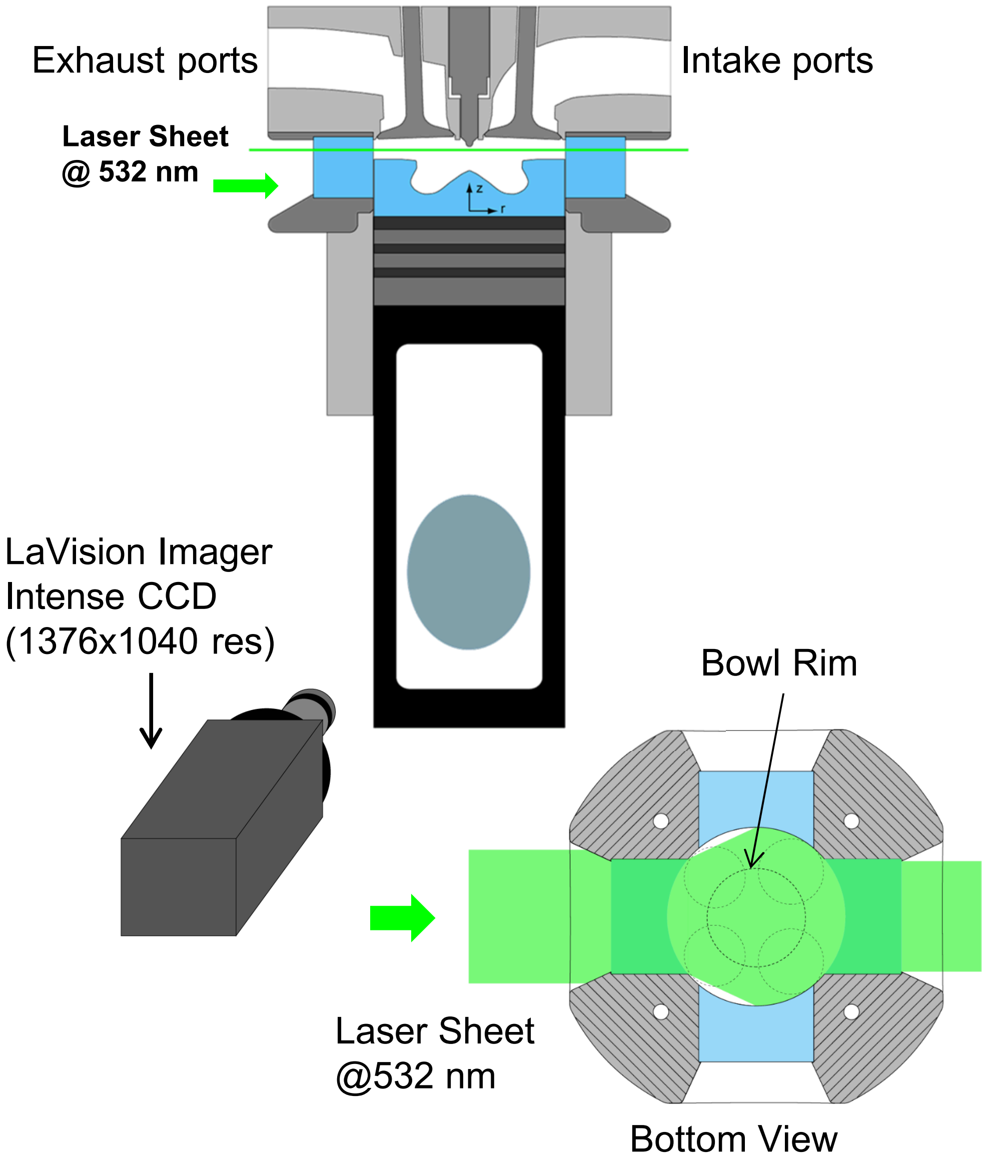
Petersen, B., Miles, P., and Sahoo, D., "Equivalence Ratio Distributions in a Light-Duty Diesel Engine Operating under Partially Premixed Conditions," *SAE Int. J. Engines* 5(2):526-537, 2012, doi:10.4271/2012-01-0692.

- Interests from industry
  - Swirl acceleration during compression
  - Swirl change with valve deactivation (4-valve)
  - Accuracy of CFD calculations

- Why use piston with conventional bowl geometry?
  - In-cylinder flow characterized by valve jets-piston top interactions in the first part of induction stroke.
  - Cyclic variability influenced by jet-piston interactions (identified by experiments and hybrid RANS-LES modeling).
  - Bowl-in-piston cylinder geometries can substantially change the in-cylinder flow.
  - Asymmetry swirl leads to the asymmetry of combustion.

Background and Swirl-plane PIV Setup

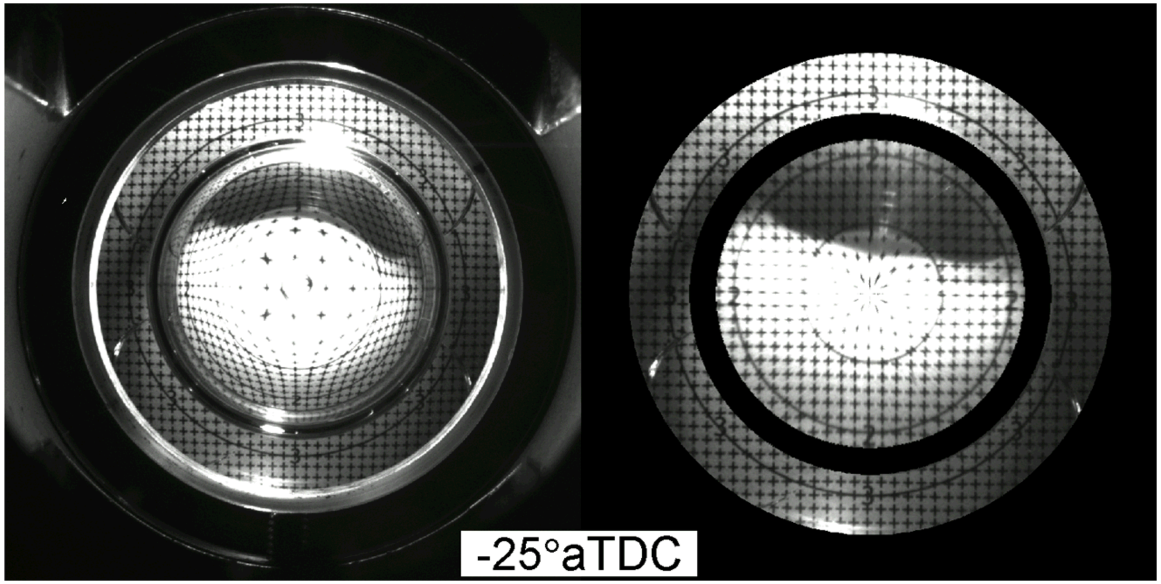
GM 1.9 L Diesel Engine	
Bore	82 mm
Stroke	90.4 mm
Displacement Volume	0.477 L
Geometries CR	16.7
Squish Height	0.78 mm
Intake / Exhaust Valves	2 / 2
Swirl Ratio	1.5, 2.2, 3.5
Engine Speed	1500 rpm
Intake Pressure	1.5 bar
Intake Temperature	99 degC
Coolant Temperature	~89 degC
O2 Mole Fraction	10%

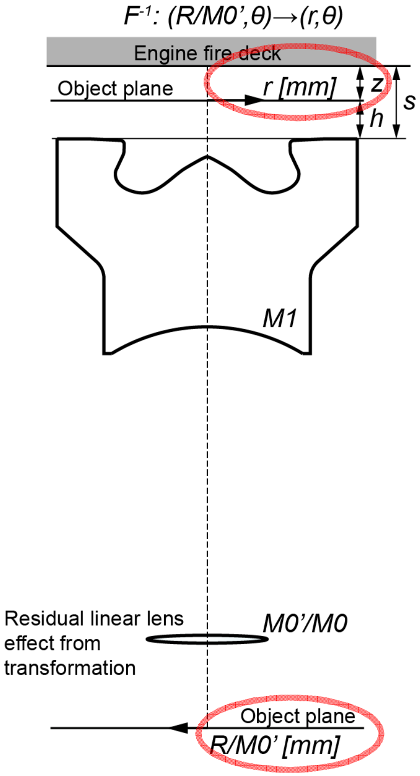


Radial Mapping Function

Raw Target Image

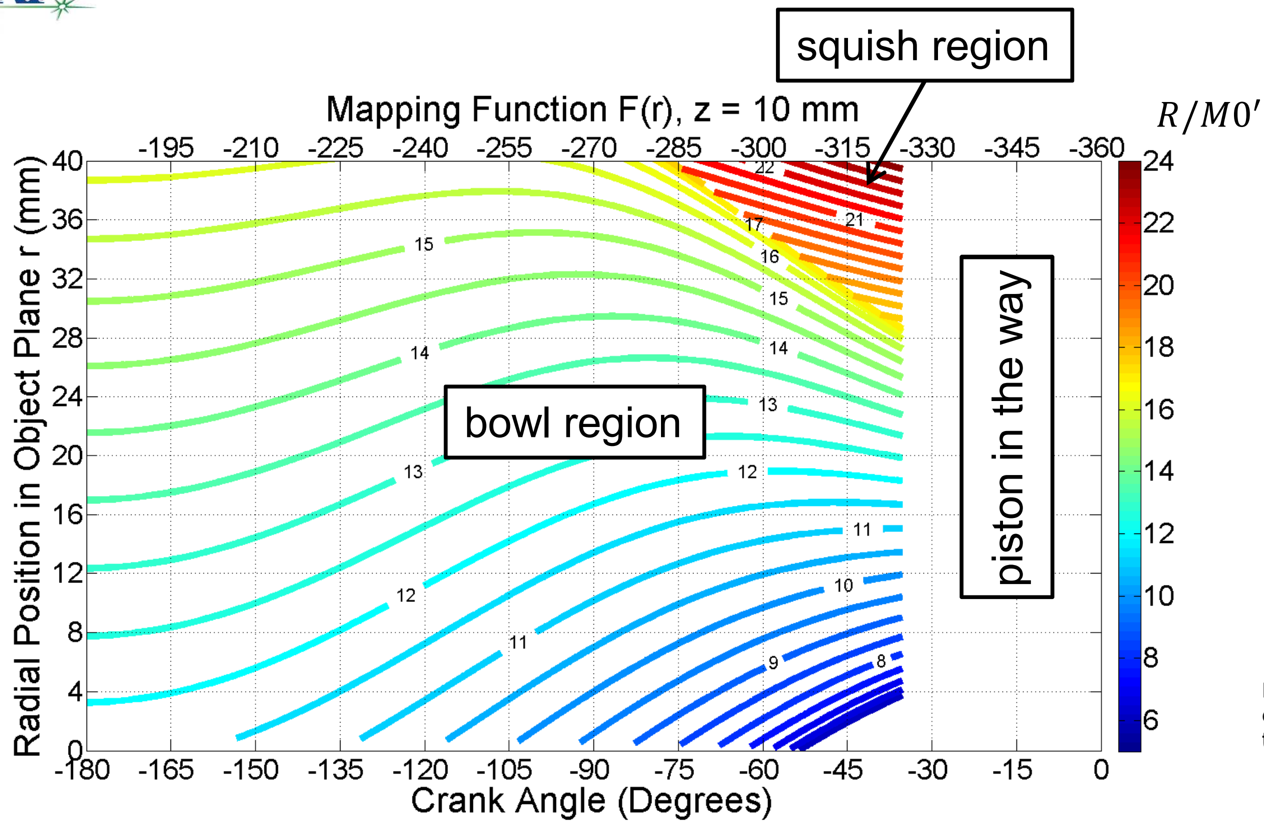
Dewarped Target Image

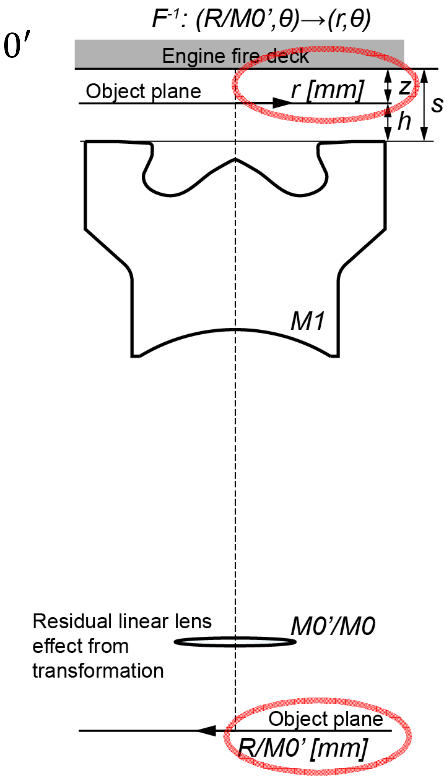




- Optical distortion induced by this piston geometry is spatially and temporally dependent.
- The transformation pattern is different in the bowl, injector exit, squish zone and valve cut-out region.

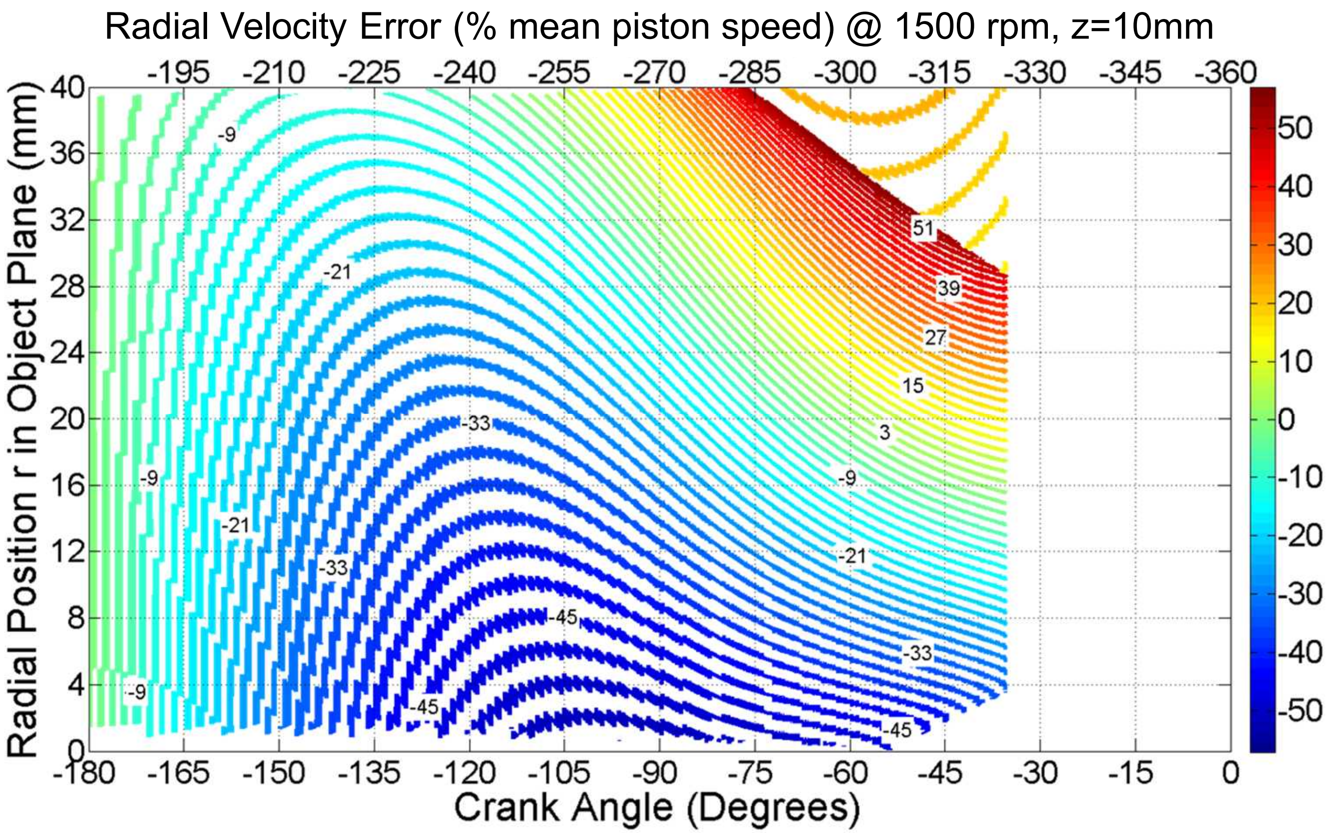
Radial Mapping Function

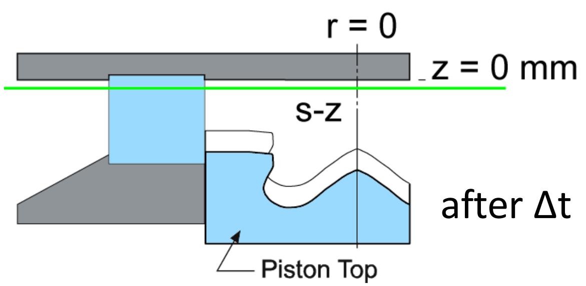




- Optical distortion quantification method:
  - Manual calibration with uniformly spacing target
  - Ray tracing (implementation is a little different, the curved virtual plane needs careful calibration with targets.)

Radial Mapping Function





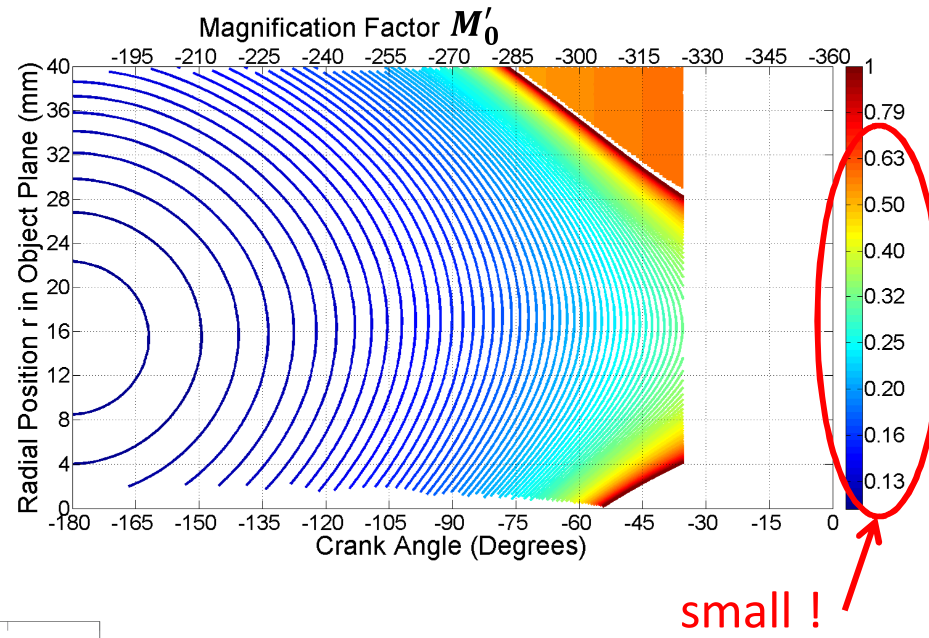
- Neglecting the transformation change during the laser pulse interval Δt can result in large error (±50%) in the radial velocity measured.

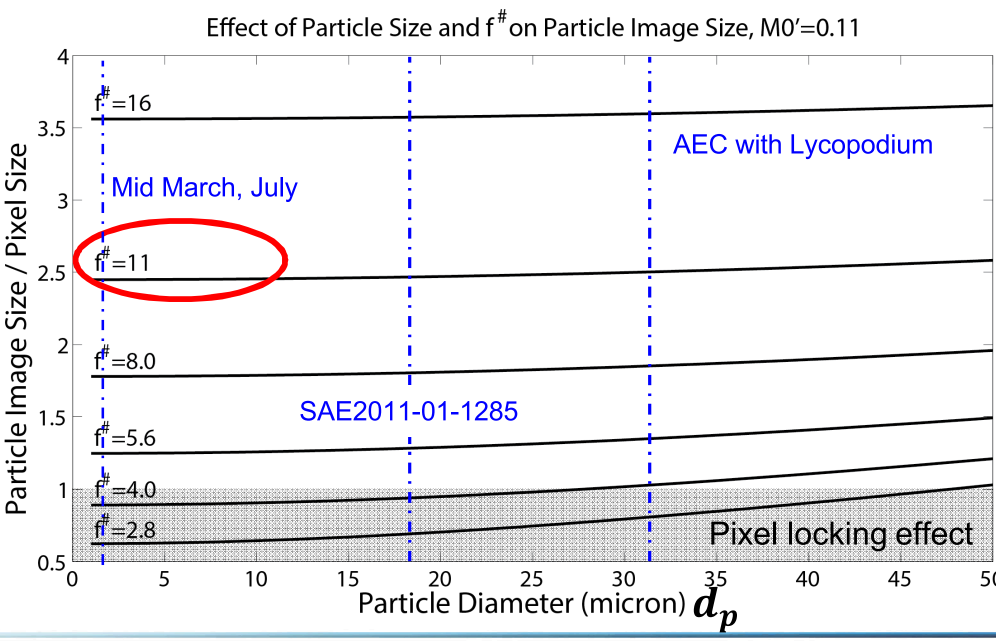
Design of PIV Experiment

- General PIV rule: particle image size d_τ ~ 2-3 pixel size.
- Since the magnification factor M'_0 of the optical setup is very small, particle image size is approximated by diffraction limited size $d_\tau \approx d_s$.

$$d_\tau = \left((M'_0)^2 d_p^2 + d_s^2\right)^{1/2}$$

$$d_s = 2.44(M'_0 + 1)f^{\#}\lambda$$





- Particle image size is dominated by camera $f^{\#}$ number.
- Benefits of smaller tracer particles are mainly fluid dynamic (smaller lag error).
- With the same $f^{\#}$, larger particle will appear to be a similar size on the CCD chip but brighter.

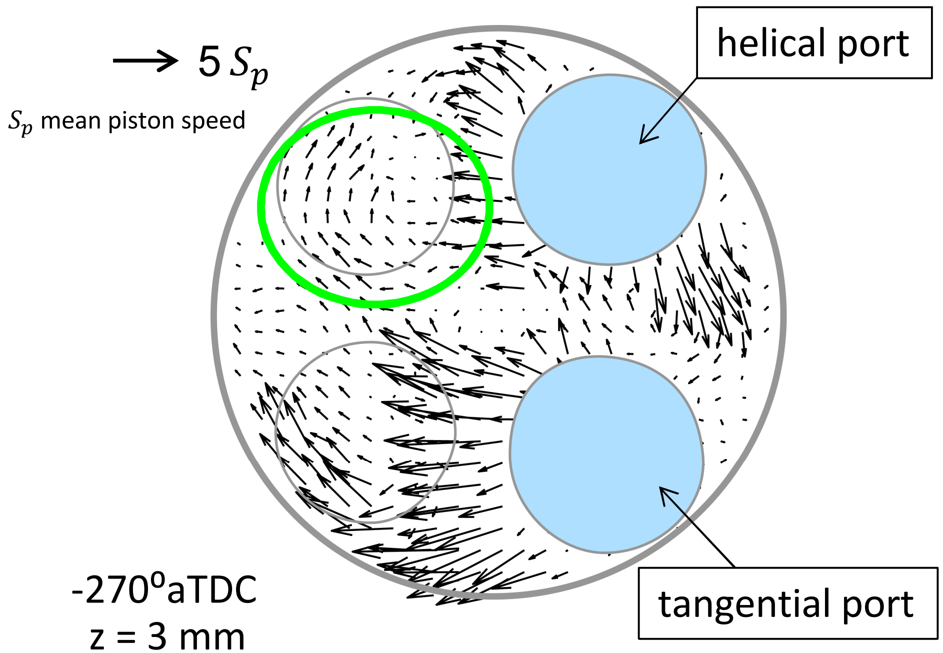
PIV Particle Tracer Selection

- Aerosol → size ~= 1 µm, Mie-scattering signal is too weak through piston
- Borosilicate glass
- 2 µm, little lag error, but induces ring torque problem
- 18 µm, lag error during early intake, and ring torque problem

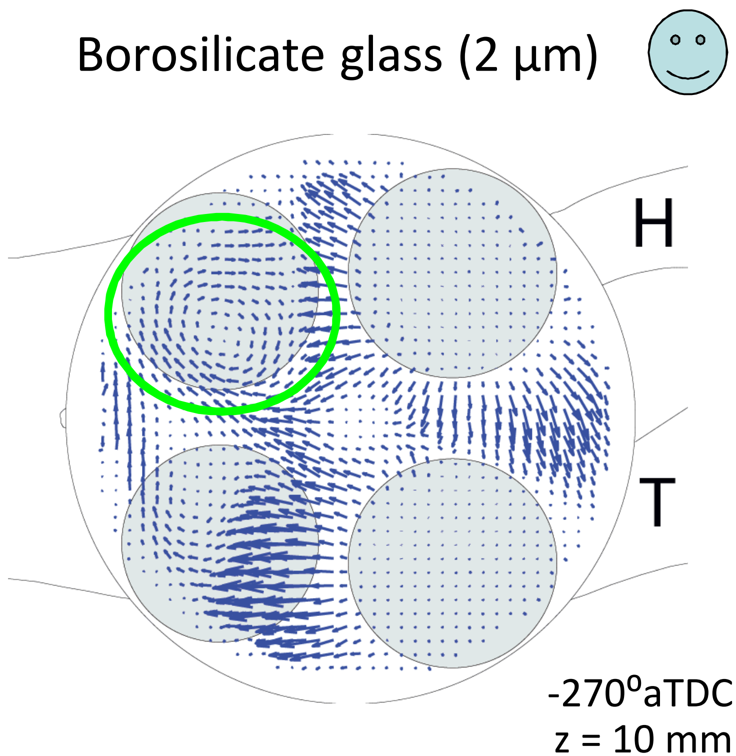
Lycopodium → size =32 µm, good ring torque, but induces large lag error

Both timescale calculation (from Converge simulation) and PIV results showed that 2µm borosilicate glass would follow more flow structures during intake stroke.

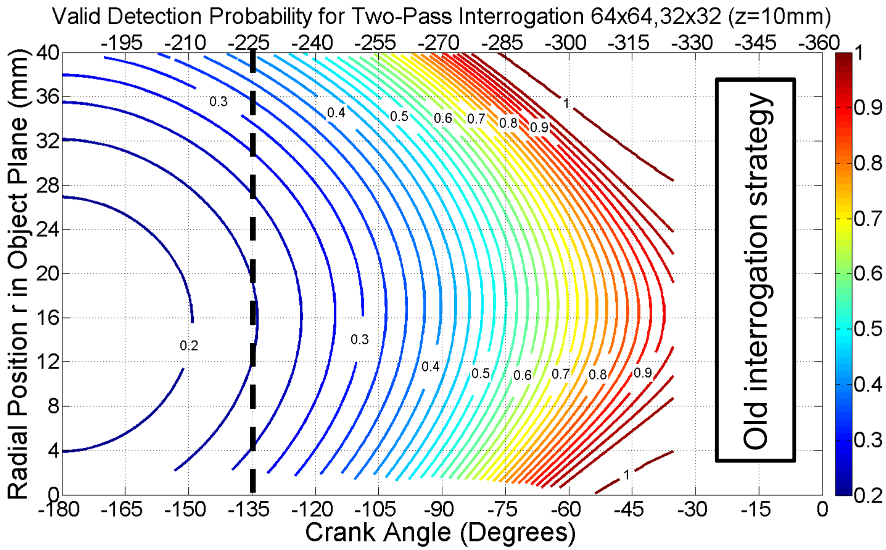
Lycopodium (32 µm)

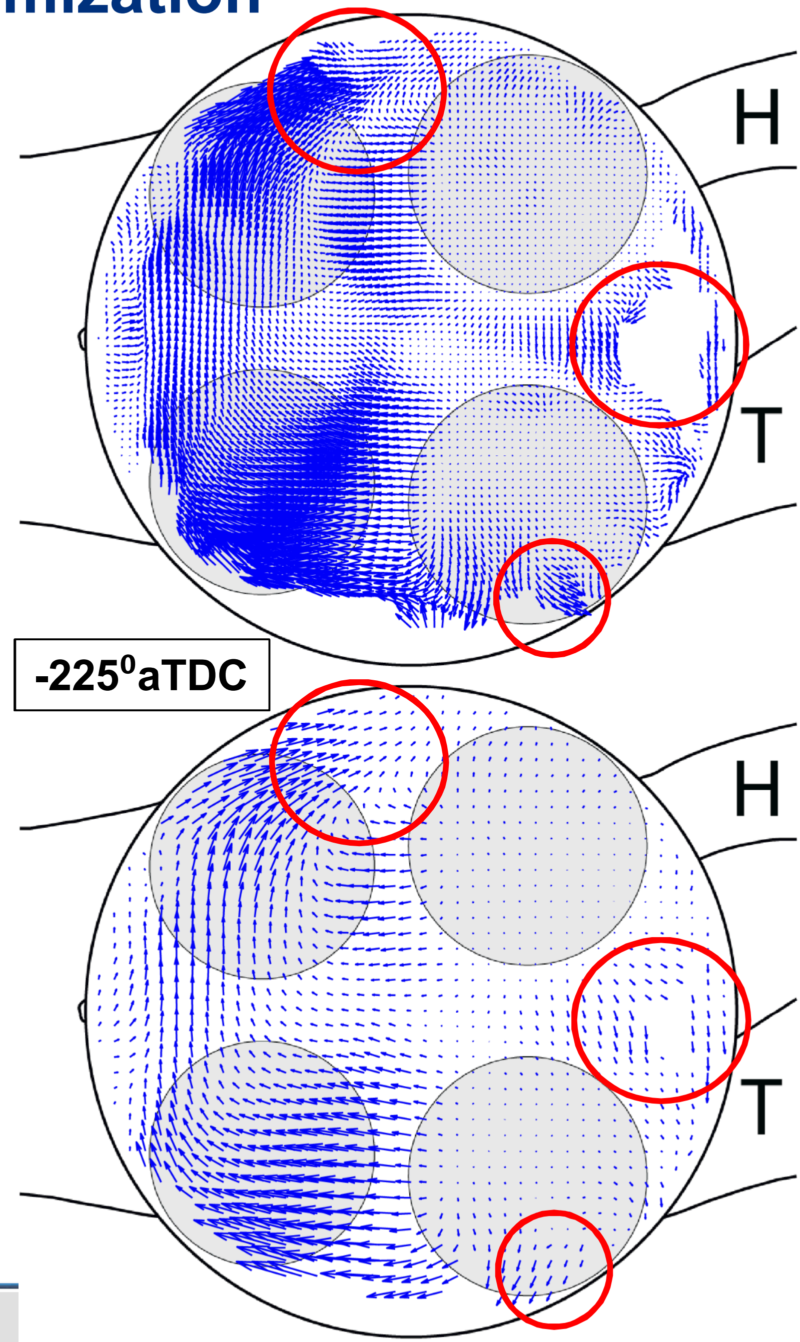


Borosilicate glass (2 µm)

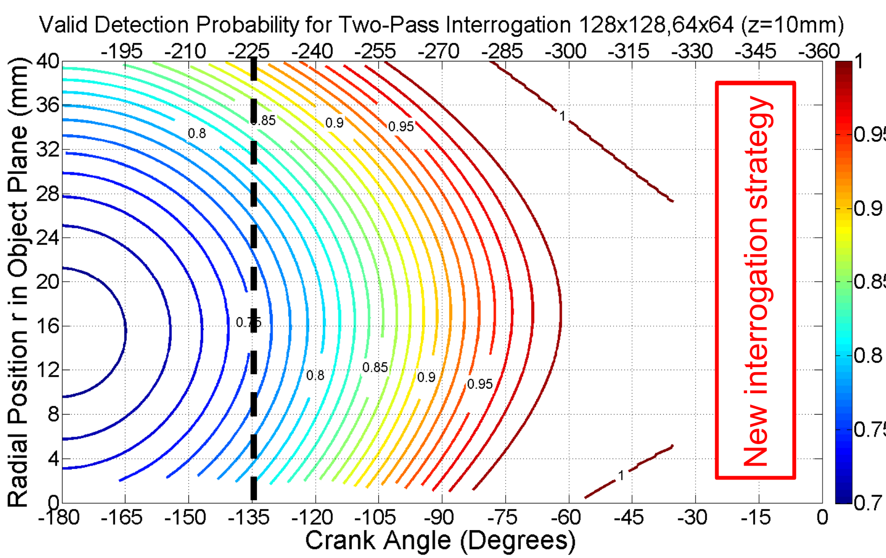


Interrogation Strategy Optimization





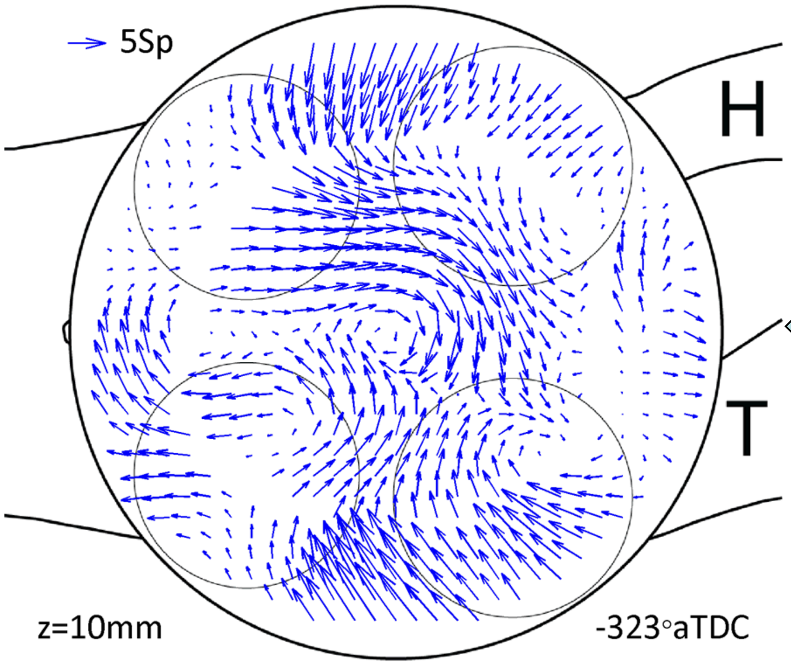
- Trade spatial resolution for a higher probability of measuring valid vectors (accuracy)

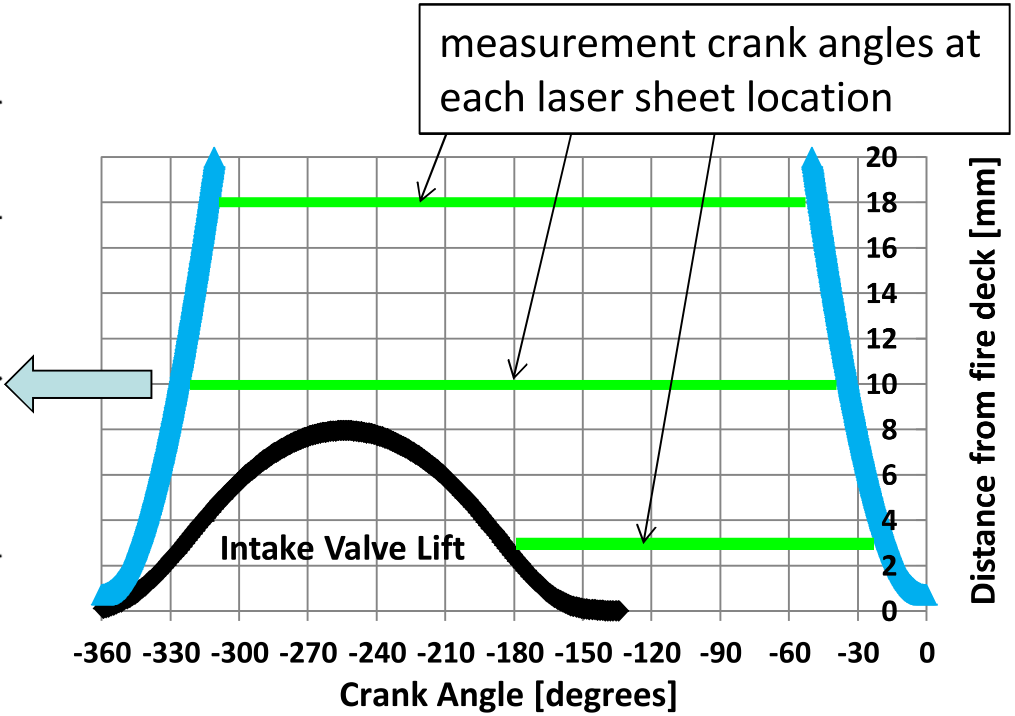


Swirl-Plane PIV Measurement Test Cases

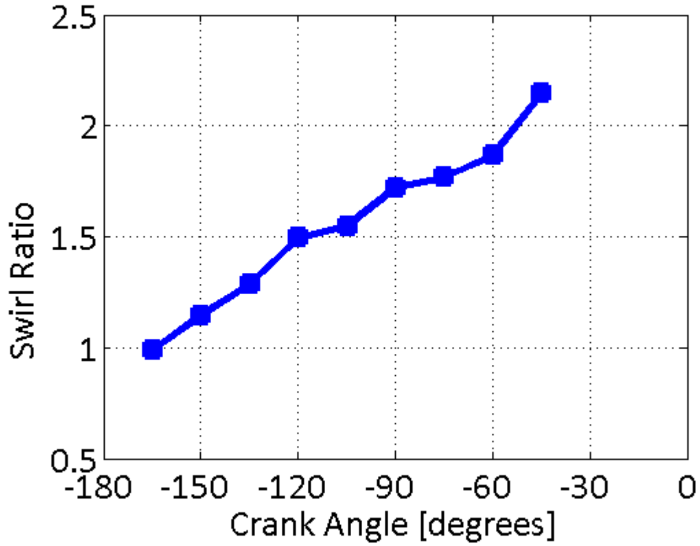
- Laser sheet minimum waist thickness around 500 µm.
- Borosilicate glass (2 µm) seeding particle.
- Camera aperture opening $f^{\#} = 11$.
- Every 15 CAD throughout intake and compression stroke (green region) for steady-state swirl ratio at 1.5, 2.2 and 3.5.
- Multi-pass interrogation strategy: 128x128-pixel window -> 64x64-pixel window.

The 1st swirl-plane PIV results!

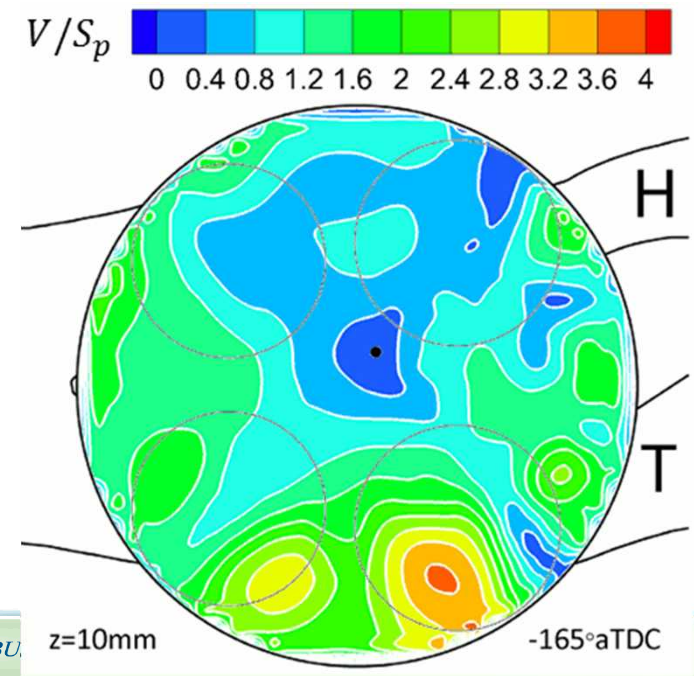


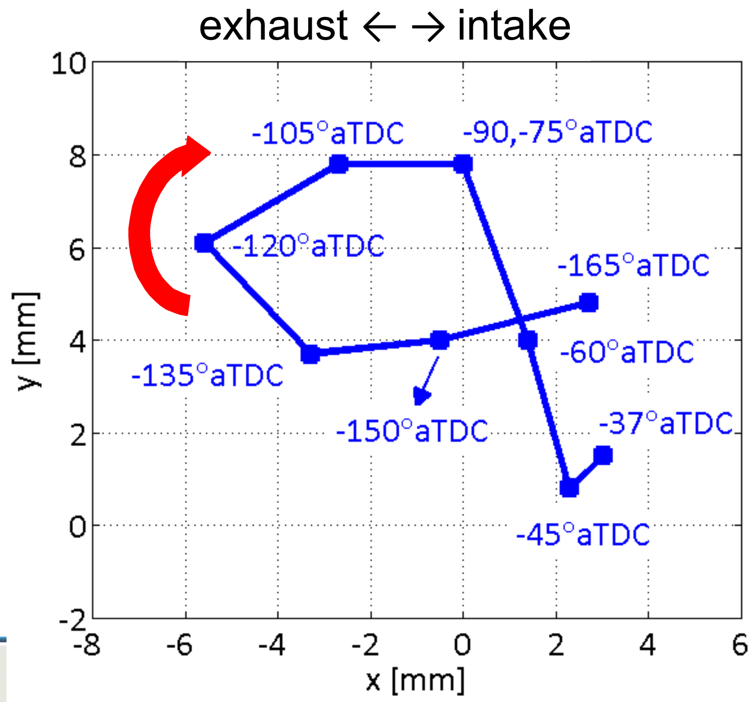


Swirl Ratio Evolution and Swirl Center Location

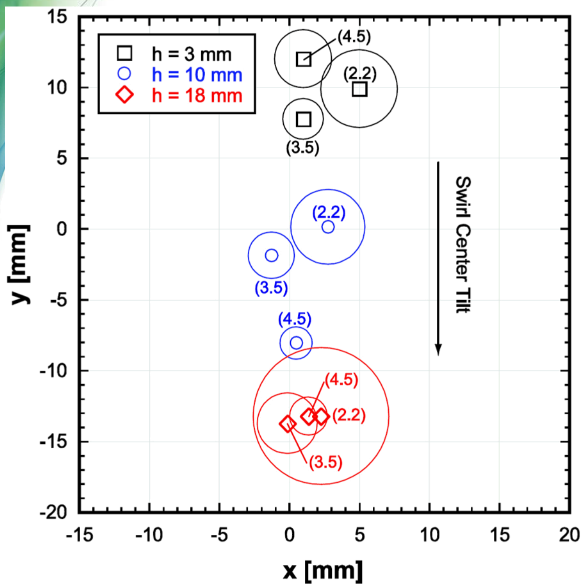


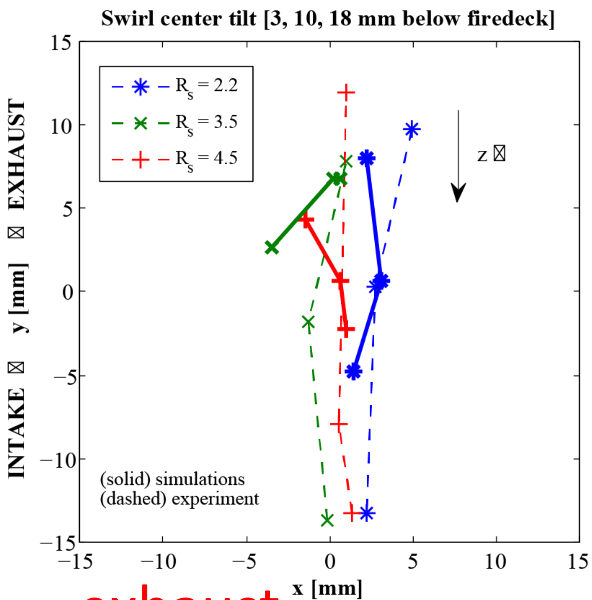
- The swirl ratio measured within each plane increases as the piston approaches the firing TDC.
- In the z=10mm plane, the swirl center precession exhibits clockwise motion in general.

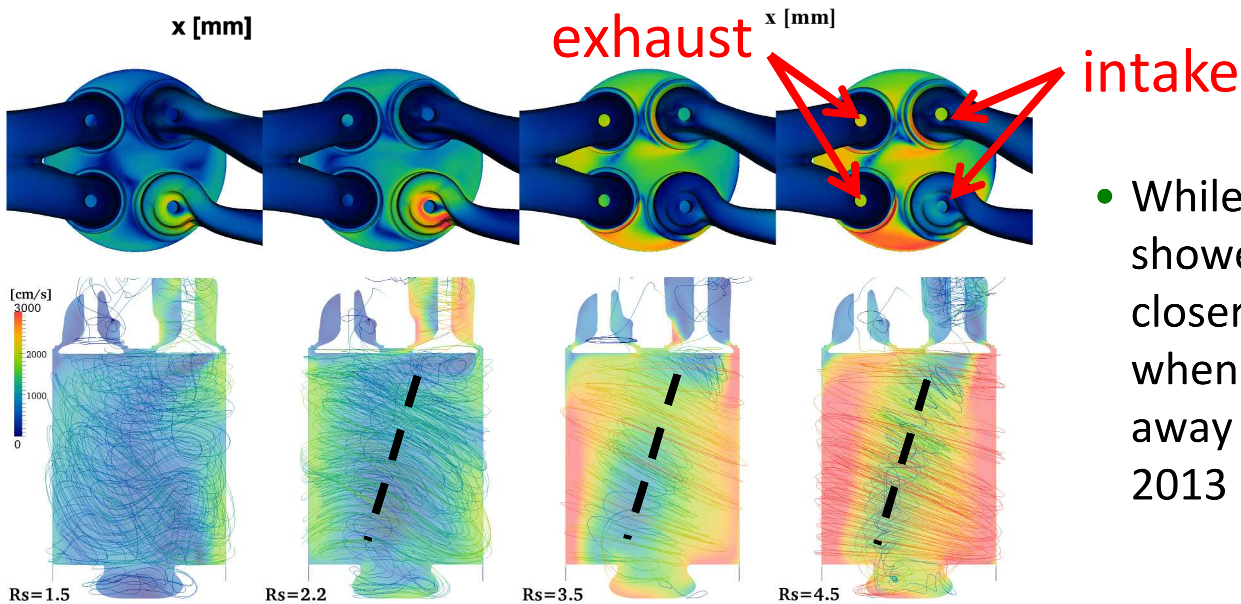




Swirl Center Location in Different Planes

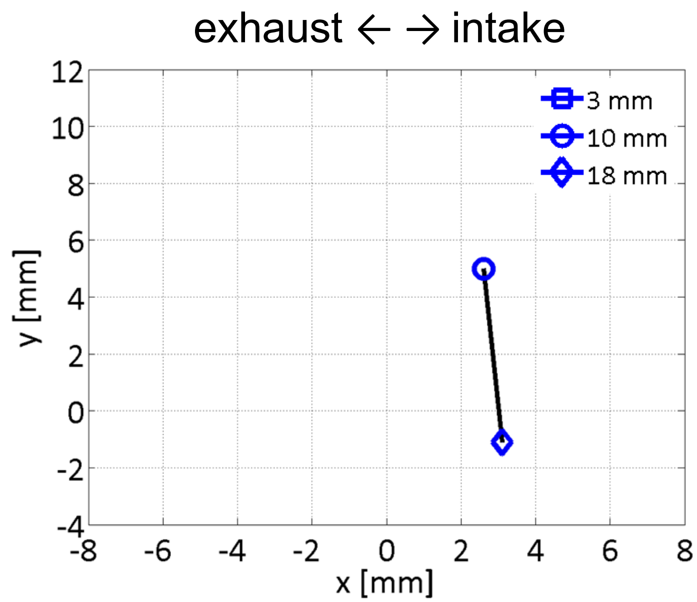


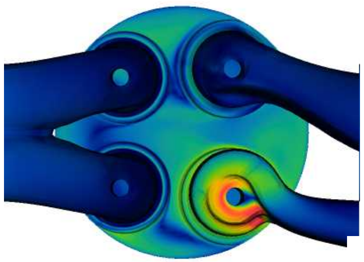


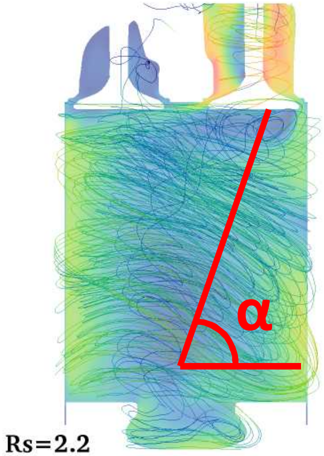


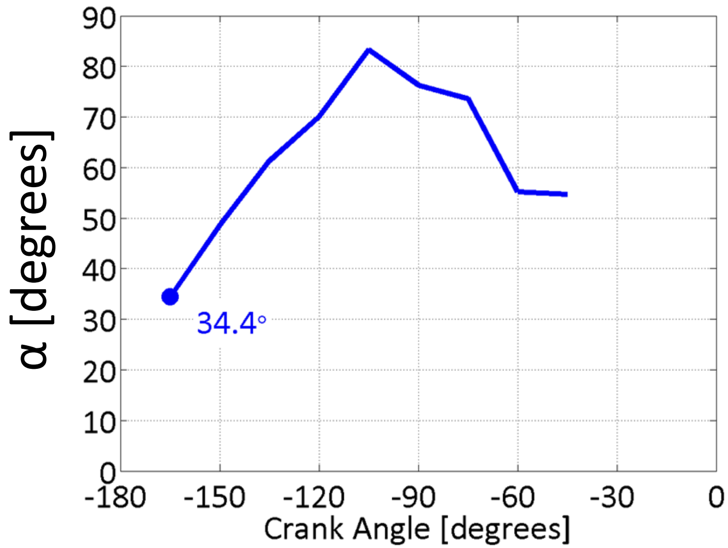
- Both experiment and simulation showed that the swirl center is closer to the intake ports when the swirl plane is farther away from the fire deck, at 50bTDC. (Petersen, SAE2011-01-1285 and Perini 2013 Computers & Fluids)
- While at BDC, simulation showed that swirl center is closer to the exhaust ports when the swirl plane is farther away from the fire deck. (Perini 2013 Computers & Fluids)

Vertical Tilting of Swirl Center Axis



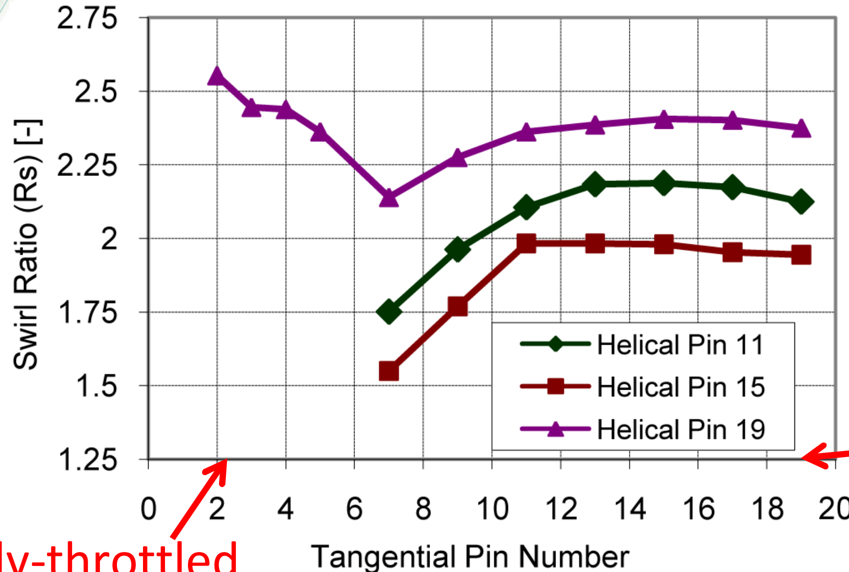






- Our current swirl-plane PIV results with Rs=2.2 confirm the previous findings (Petersen, SAE2011-01-1285 and Perini 2013 Computers & Fluids).
- With swirl center location calculated at three different plane, vertical tilting of swirl center axis is quantified.
- After IVC (-150^{o}aTDC), tilting towards exhaust ports becomes less as piston proceeds to -105^{o}aTDC.
- As the compression continues, the tilting switches to intake ports, and is getting worse until the TDC is approaching.

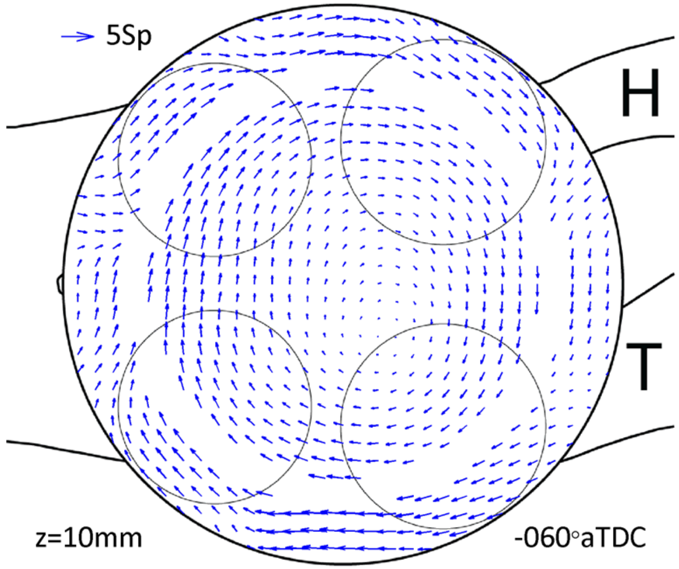
Swirl Ratio Behavior with Various Intake Port Throttling

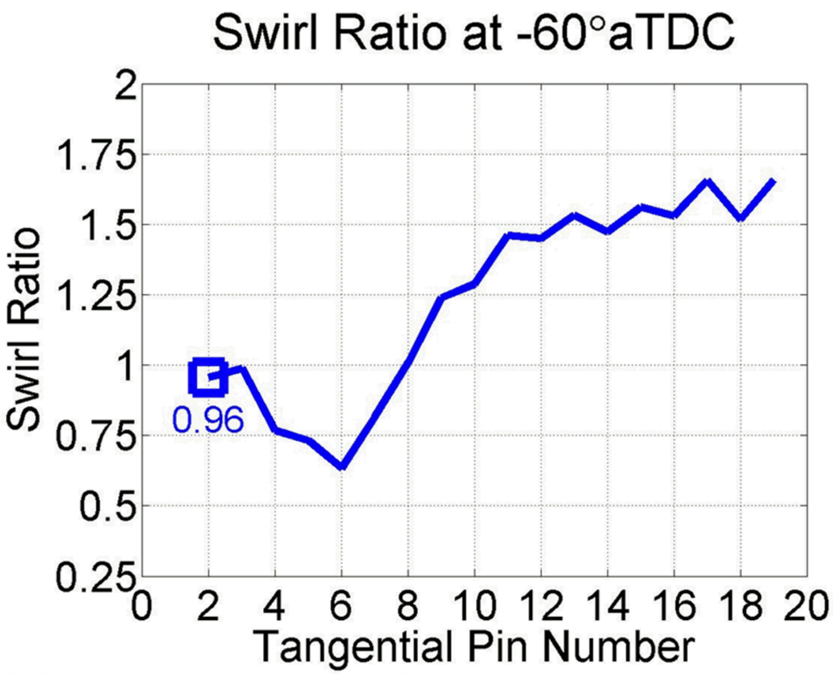


fully-throttled

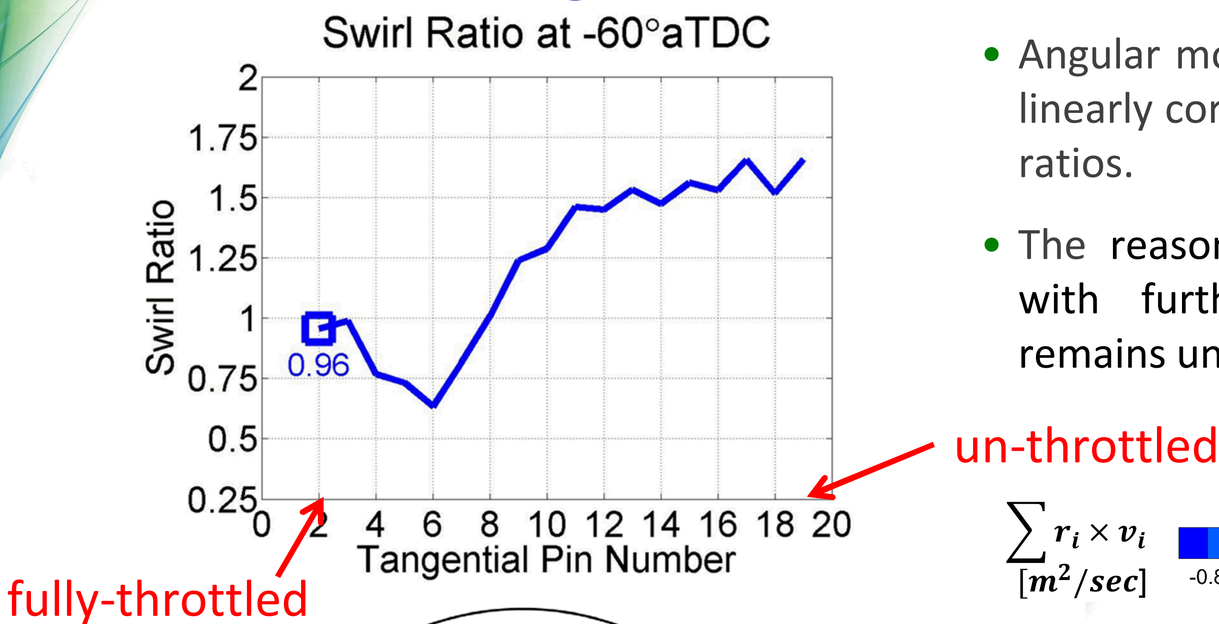
un-throttled

- A non-monotonic behavior of the swirl ratio (flow bench) with various tangential port throttling, helical port un-throttled Pin19 (SAE2009-01-1124).
- A similar trend is observed with the swirl-plane PIV measurements at -60°aTDC.

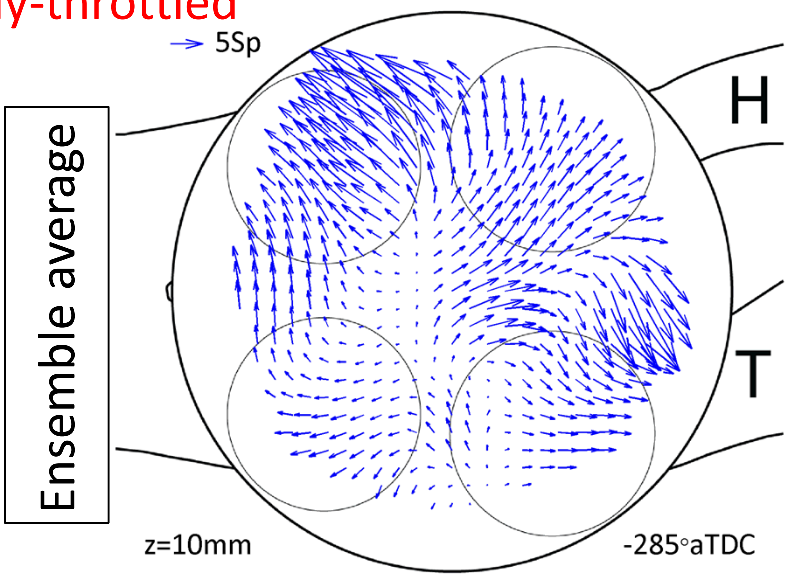


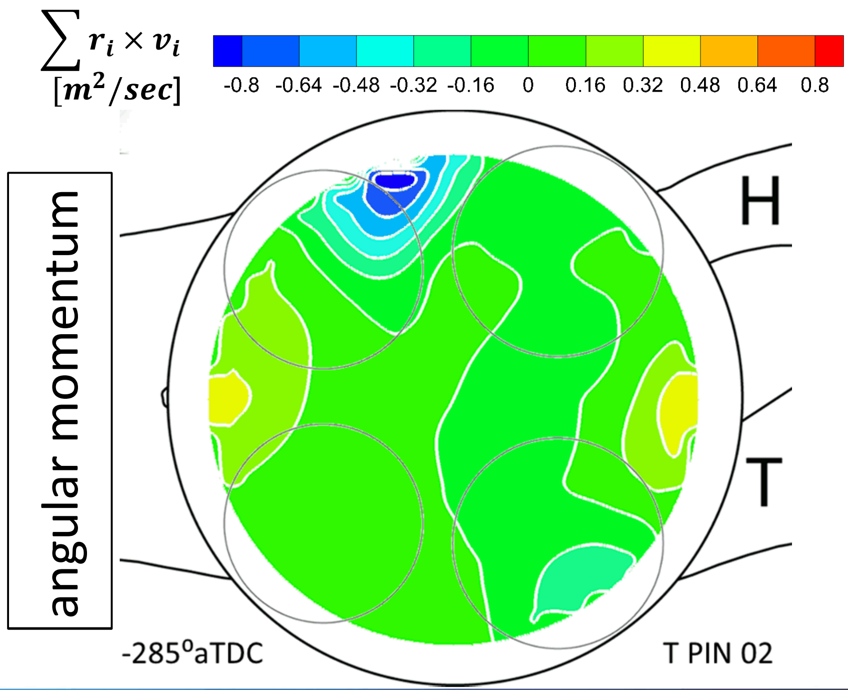


Swirl Ratio Behavior with Various Intake Port Throttling



- Angular momentum from tangential port is linearly correlated with the increase of swirl ratios.
- The reason why the swirl ratio increases with further tangential port throttling remains unclear.



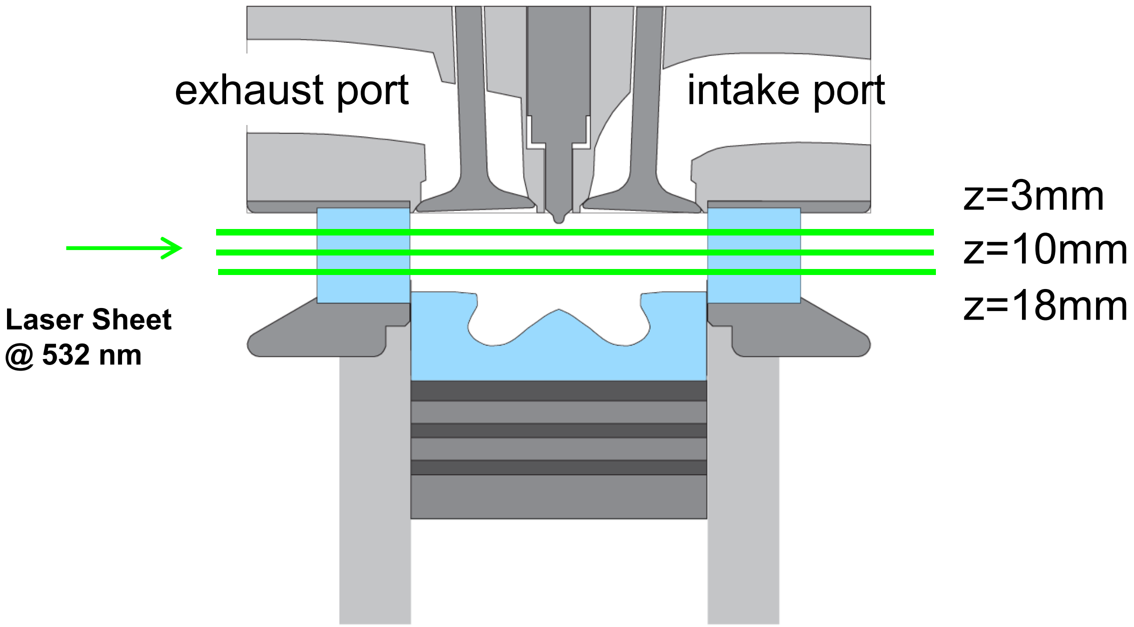


Summary

- A general mapping procedure for analytical approach of optical distortion quantification has been established.
- Theoretical analysis helps the optimization of swirl-plane PIV experimental design when severe distortion is present.
- At the z=10mm plane, with Rs=2.2, the swirl center location exhibits clockwise behavior in the compression stroke.
- After IVC (-150^{o}aTDC), swirl center vertical tilting towards exhaust ports becomes less as piston proceeds to -105^{o}aTDC. As the compression continues, the tilting switches to intake ports, and is getting worse until the TDC is approaching.
- Jets interaction visualized by PIV helps us understand the non-monotonic behavior of swirl ratio with various tangential port throttling and how port design impacts swirl ratio.

Future Work

- Investigate two different bowl geometries to study the impact of bowl geometry on the flow structure.
- Compare with CFD simulation results.



THANK YOU FOR YOUR ATTENTION !