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COMBUSTION RESEARCH FACILITY

Progress Towards In-Cylinder PIV Measurements throughout the Full Intake and Compression Strokes

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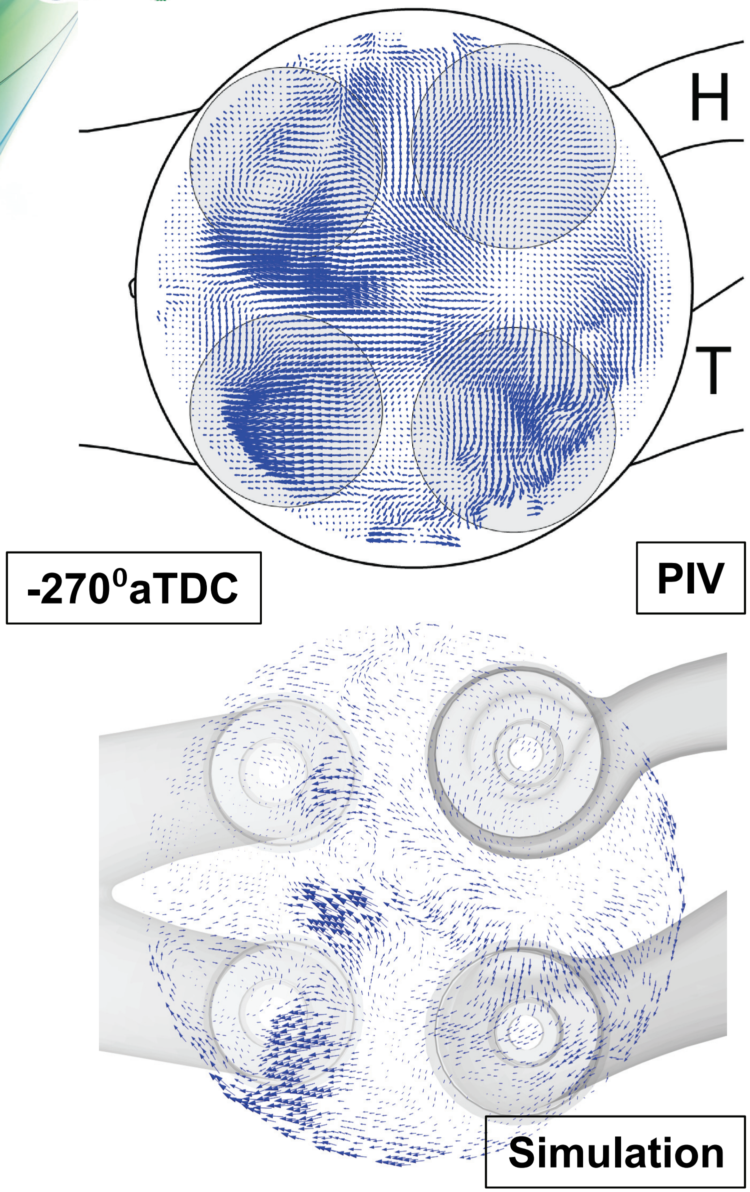
Sw=2.2, 17mm plane

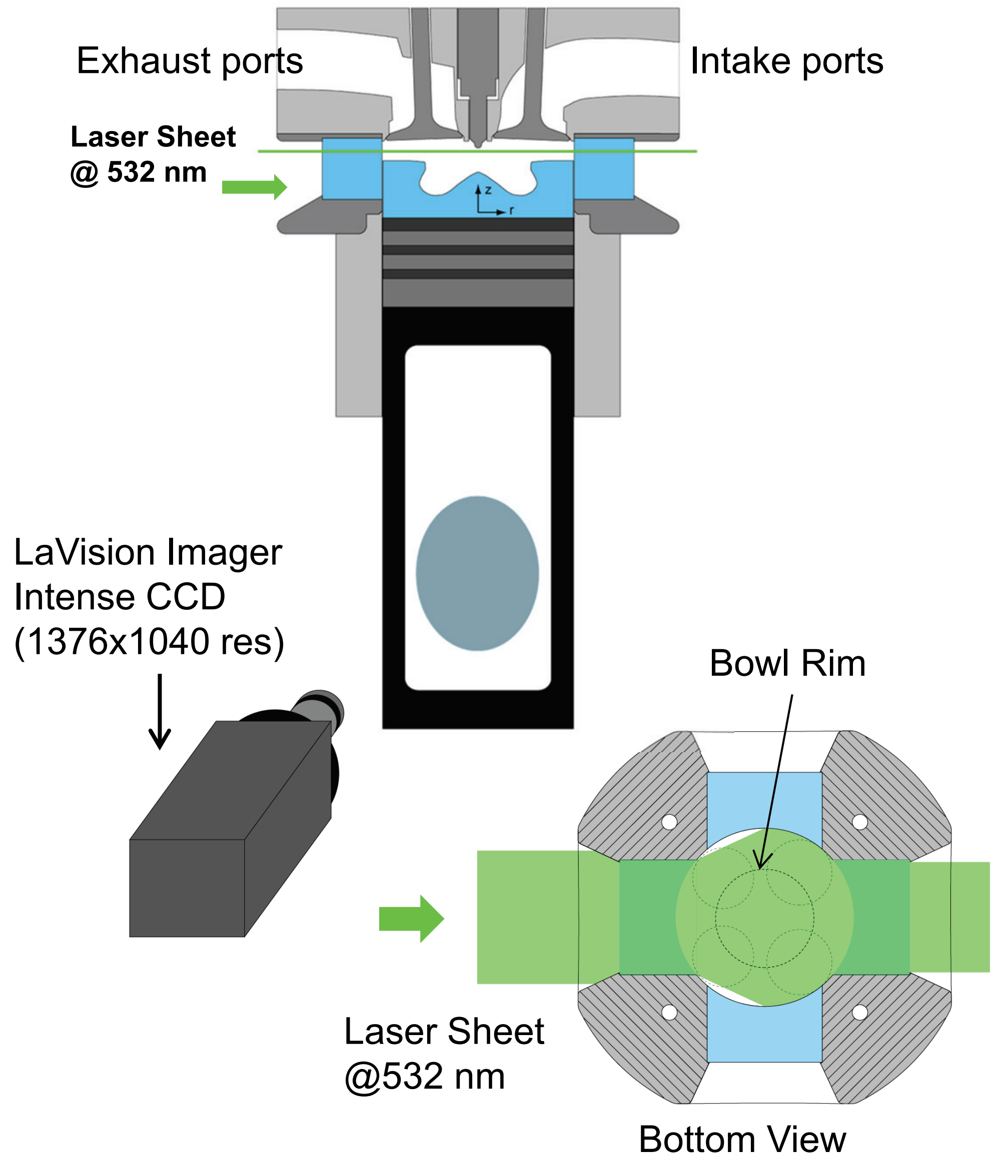


Motivation

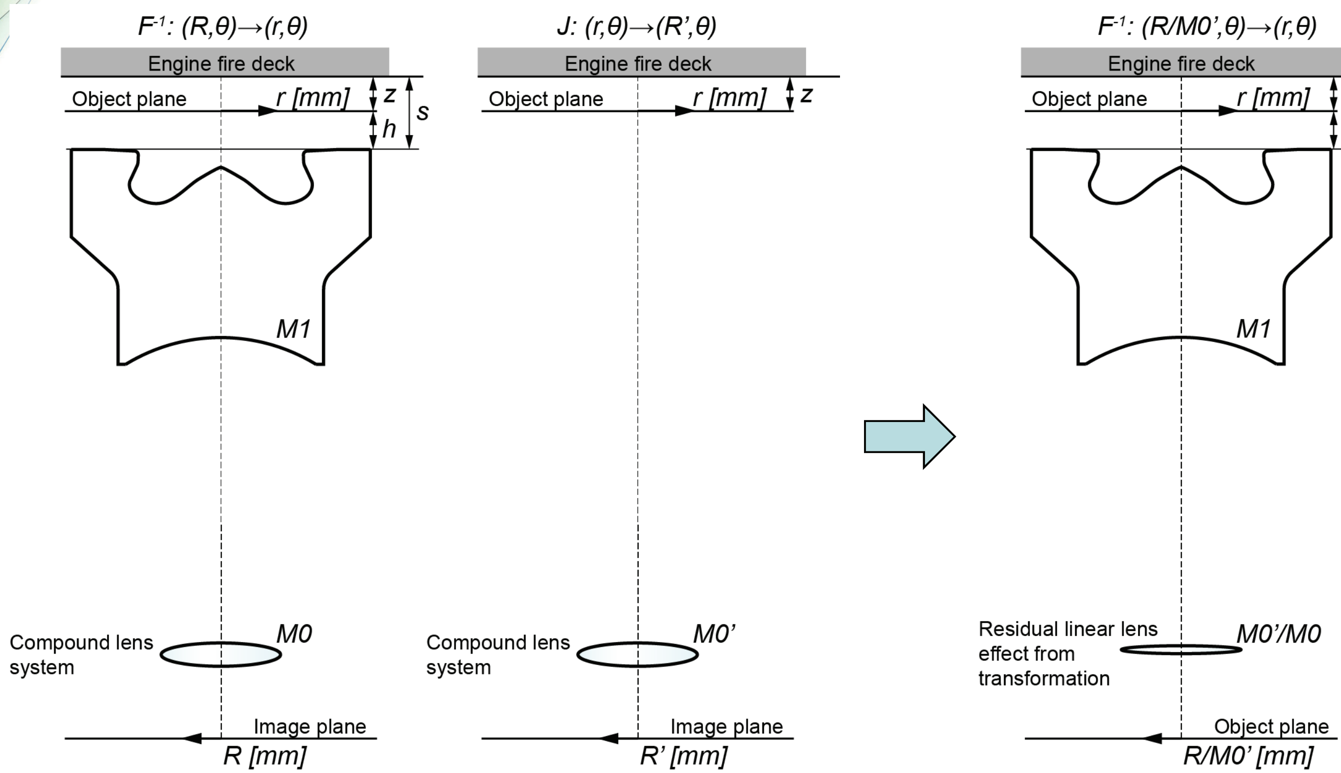
- How much error is induced by the optical distortion from the piston with reentrant bowl geometry?
  - How much error will be introduced during dewarping?
  - Is multi-pass interrogation with minimum 32x32-pixel window size the best for this application?
  - Where in the measuring plane and within what crank angle range the calculated velocities are more believable?
  - How much does the signal-to-noise ratio change with various crank angles?
- What information can be extracted from swirl-plane PIV results with this realistic piston bowl?

Experimental Setup and Swirl-plane Measurement Test Cases

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%



General Mapping Function



Undistorted Domain

$$\boldsymbol{F}: (\boldsymbol{r}, \boldsymbol{\theta}) \rightarrow (\boldsymbol{R}/\boldsymbol{M0'}, \boldsymbol{\theta})$$

$$\boldsymbol{M_0'} < \boldsymbol{M_0}$$

$$\boldsymbol{M_0'}/\boldsymbol{M_0} \approx 1$$

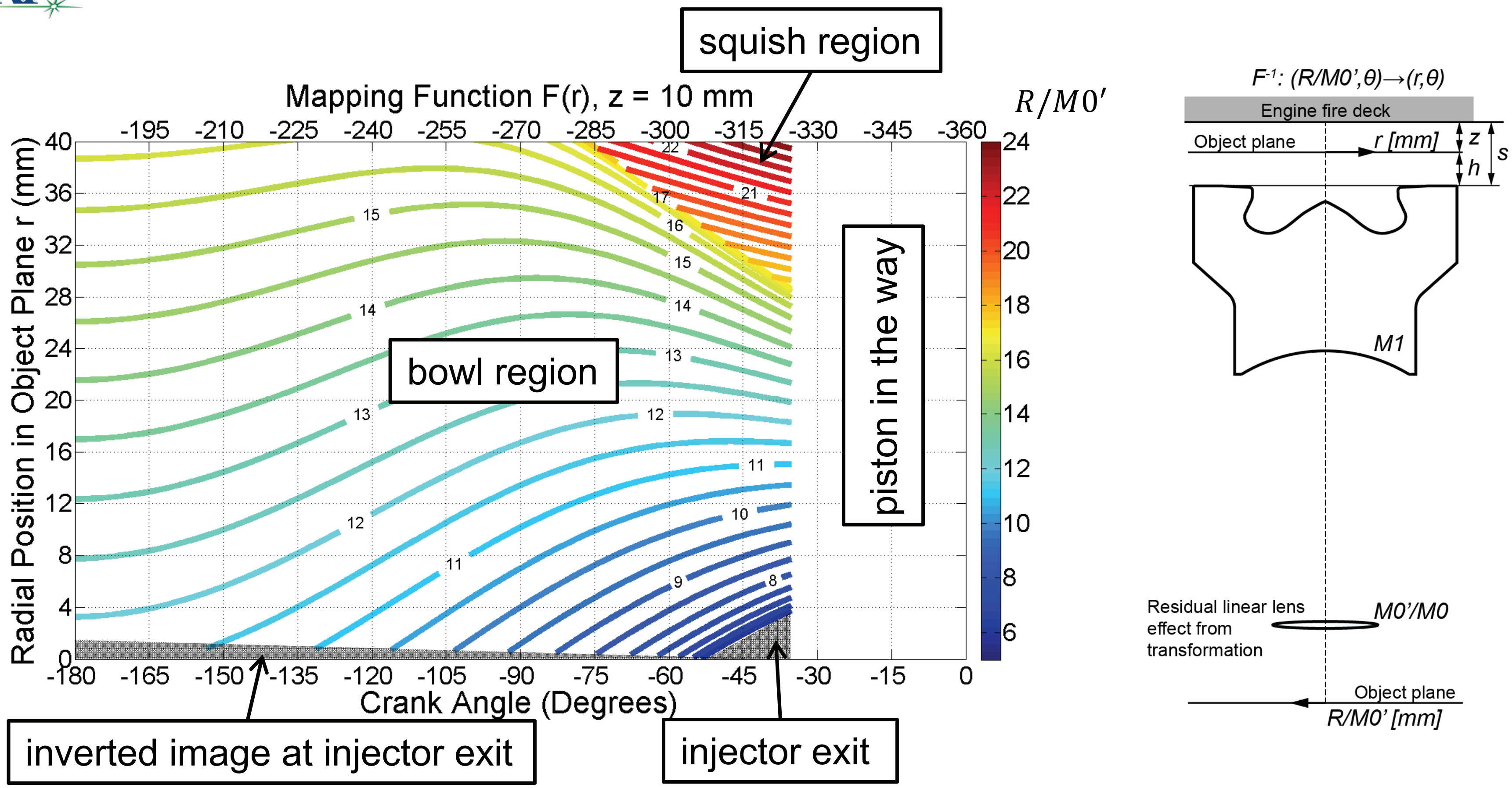
Distorted Domain

$\boldsymbol{M_1}$: magnification factor contributed to the whole optical system by the piston, which is changing with piston position.

$\boldsymbol{M_0}$: magnification factor contributed by the camera when it is focused on the object plane with piston in place.

$\boldsymbol{M_0'}$: magnification factor contributed by the camera when it is focused on the object plane without piston in place.

Radial Mapping Function



- Optical distortion induced by this piston geometry is spatially and temporally dependent.
- The mapping function is not shown when the object plane is lower than the piston top.
- The transformation pattern is different in the bowl area, squish zone, valve cut-out region and injector exit area.
- In the injector exit area, a transformation discontinuity is observed for [-335, -35] ^{o}aTDC.

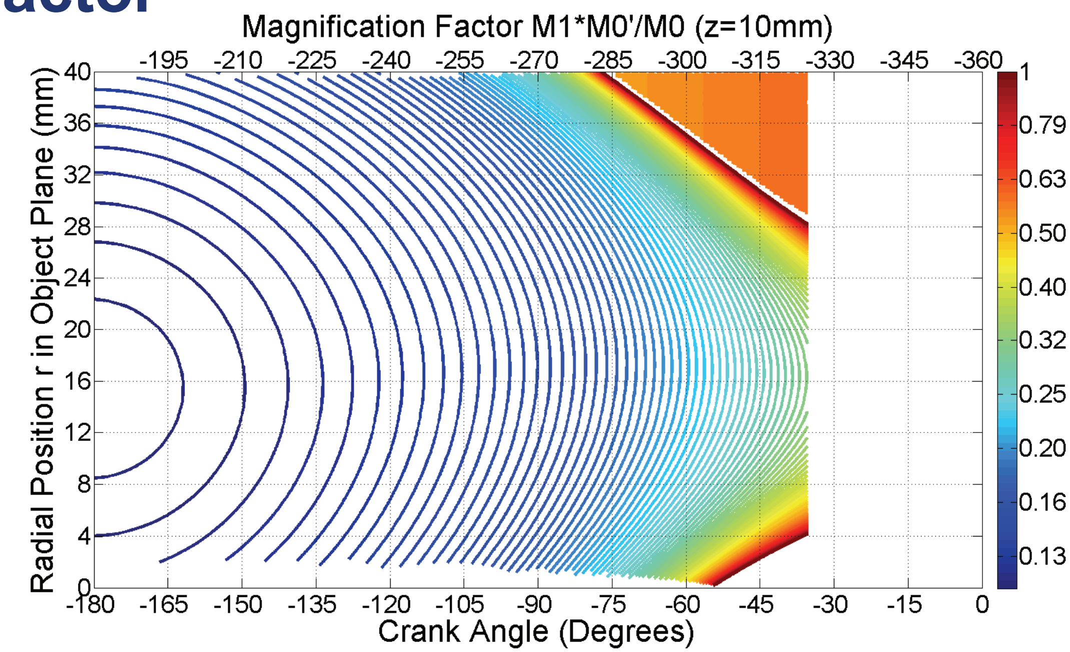
Magnification Factor

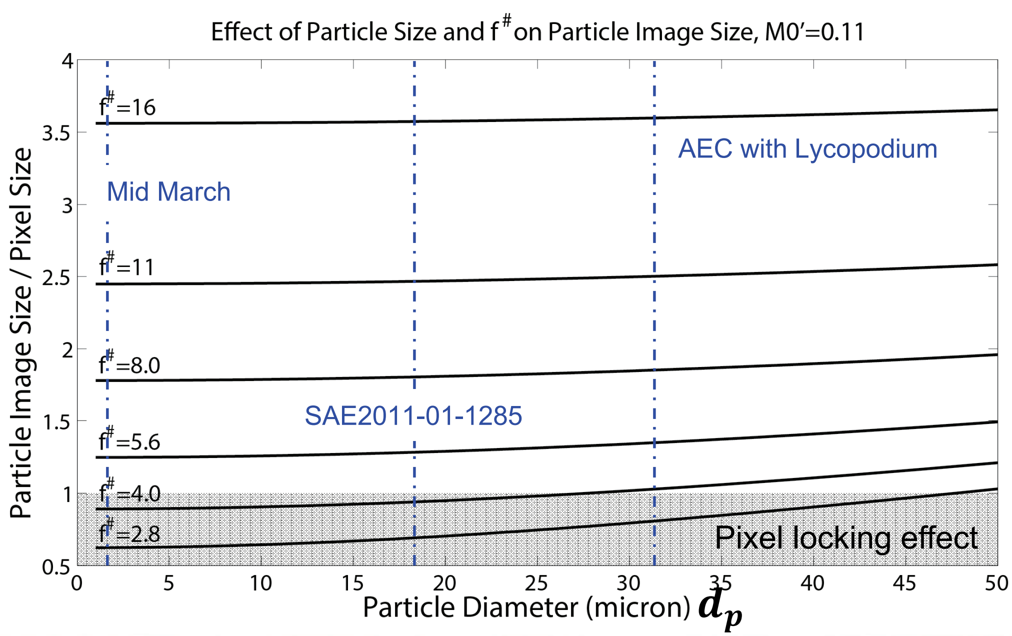
- The magnification factor in the bowl region is smaller than in the squish region.
- The farther the piston is from the fire deck, the smaller the magnification factor will be.

Particle image size d_τ

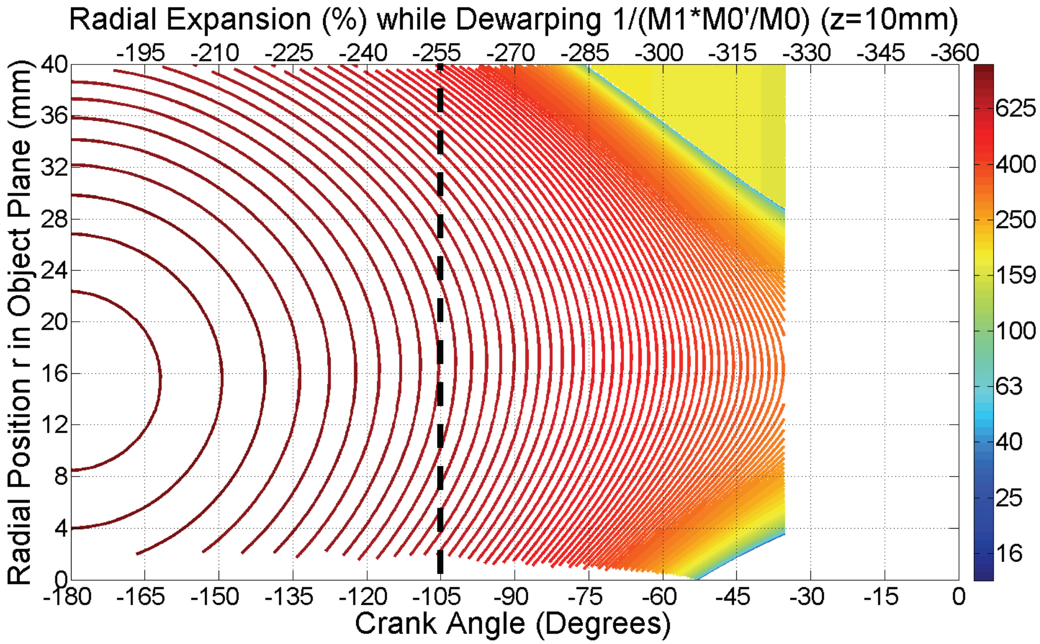
$$d_\tau = \left((M_0')^2 d_p^2 + d_s^2\right)^{1/2}$$

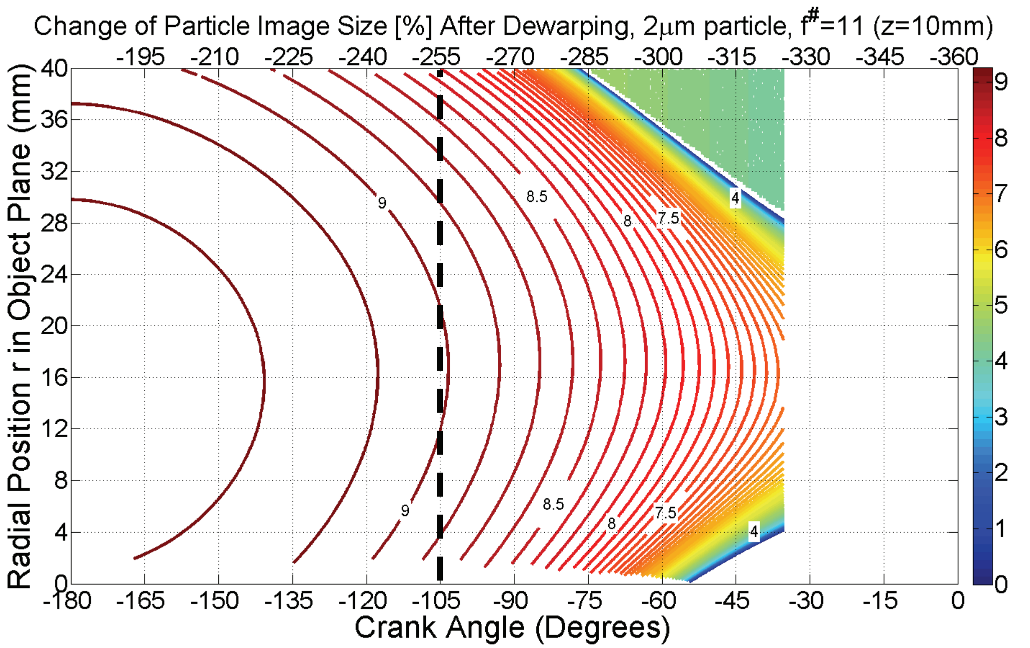
$$d_s = 2.44(M_0' + 1) f^\# \lambda$$

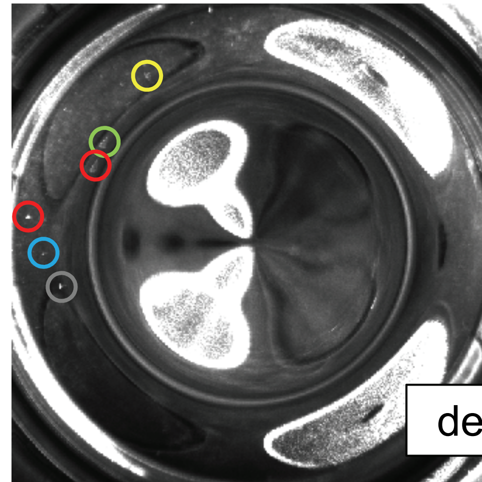




- Since M_1, M_0' are very small, particle image size is mainly diffraction limited. $d_\tau \approx d_s$
- Particle image size is dominated by camera $f^\#$ number.
- Benefits of smaller tracer particles are mainly fluid dynamic (smaller lag error).
- With the same $f^\#$, larger particle will appear in similar size on the CCD chip but brighter.

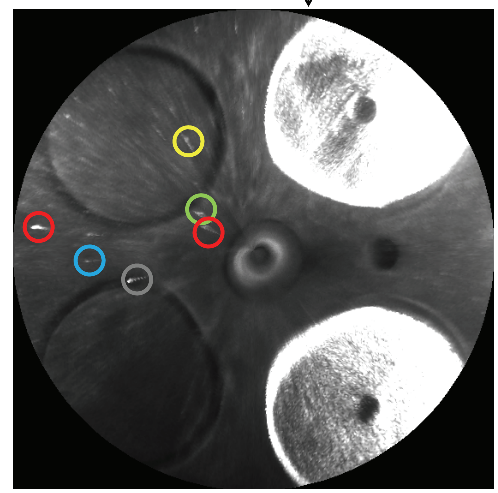






raw image

dewarped image

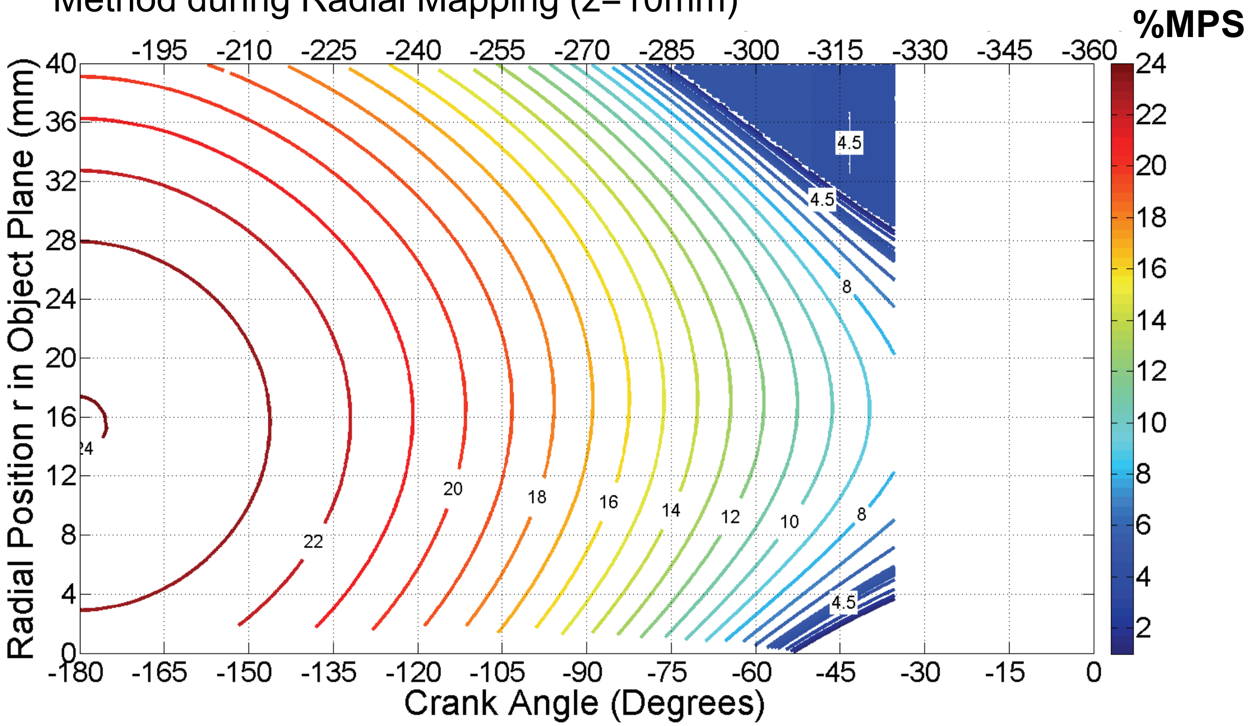


-255^{0}aTDC

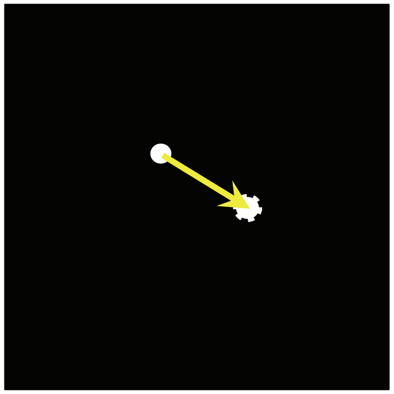
- Since M_1(with piston), M'_0(without piston) are both very small, particle image size should not experience significant change (less than 9.5%) after dewarping.
- However, radial expansion during dewarping "stretches" particles into "lines".

particle centroid radial location error $= \frac{6.45\mu m}{M1 \times M0'/M0}$ pixel size

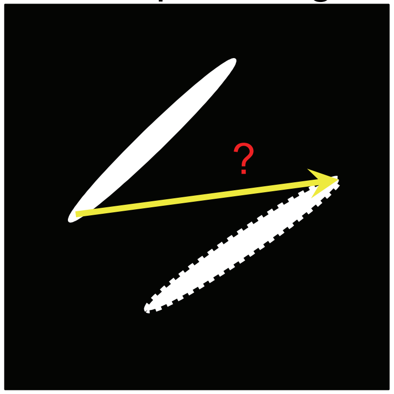
Error in Radial Velocity at Δt=55 μsec with Generic Interpolation Method during Radial Mapping (z=10mm)



Undistorted Image

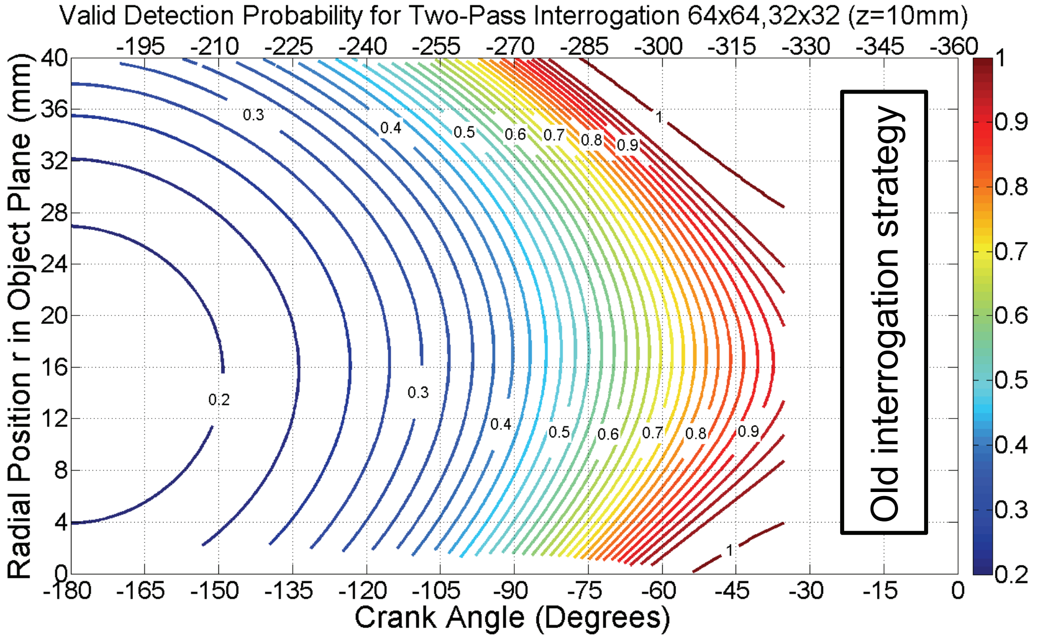


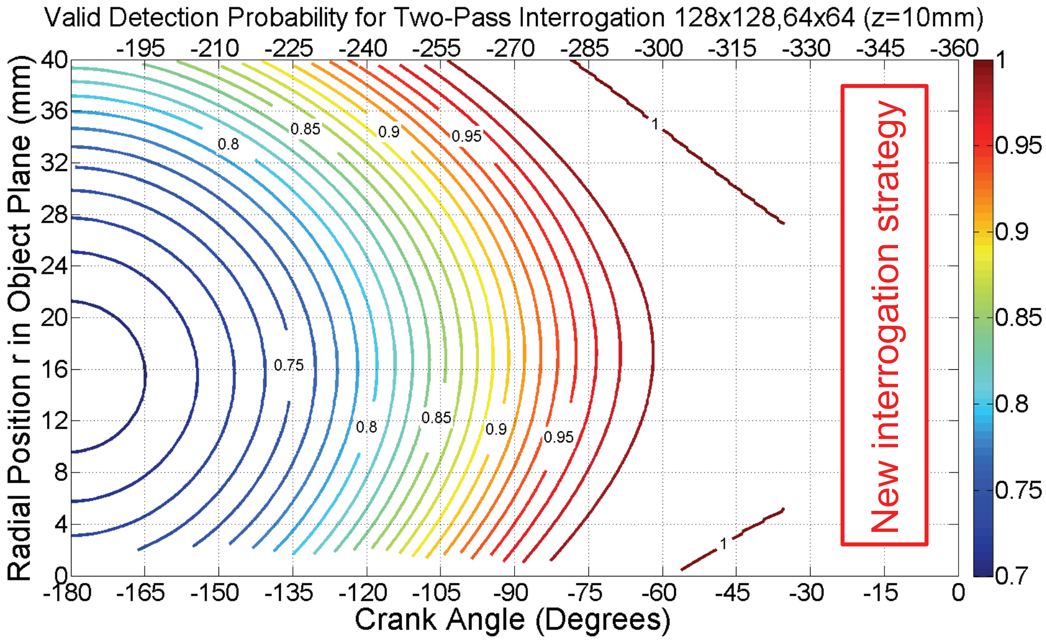
Dewarped Image



- The radial error in the squish region (4.5% of mean piston speed) is less than in the bowl region, and it is relatively independent of piston position.
- At each crank angle, there is a local maximum of error inside the bowl region.
- Radial error is inversely proportional to laser temporal interval Δt.
- The farther the piston is from the fire deck, the larger the radial error (up to 24% of MPS).
- Therefore, a new particle centroid mapping procedure is needed for this piston so as to avoid been “stretched into lines” after dewarping (future work).

Interrogation Strategy Comparison





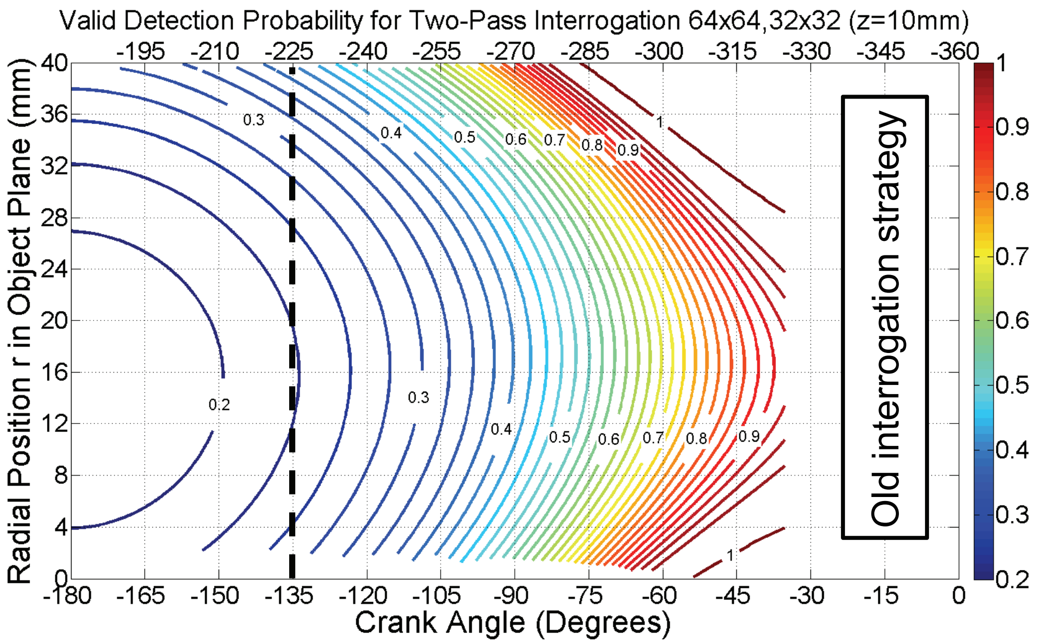
If there are no losses from in-plane F_I, out-of-plane F_O and velocity gradient $F_\Delta \cong \exp(-\frac{\frac{2}{3}a^2}{d_\tau^2})$: $F_I F_O F_\Delta = 1$

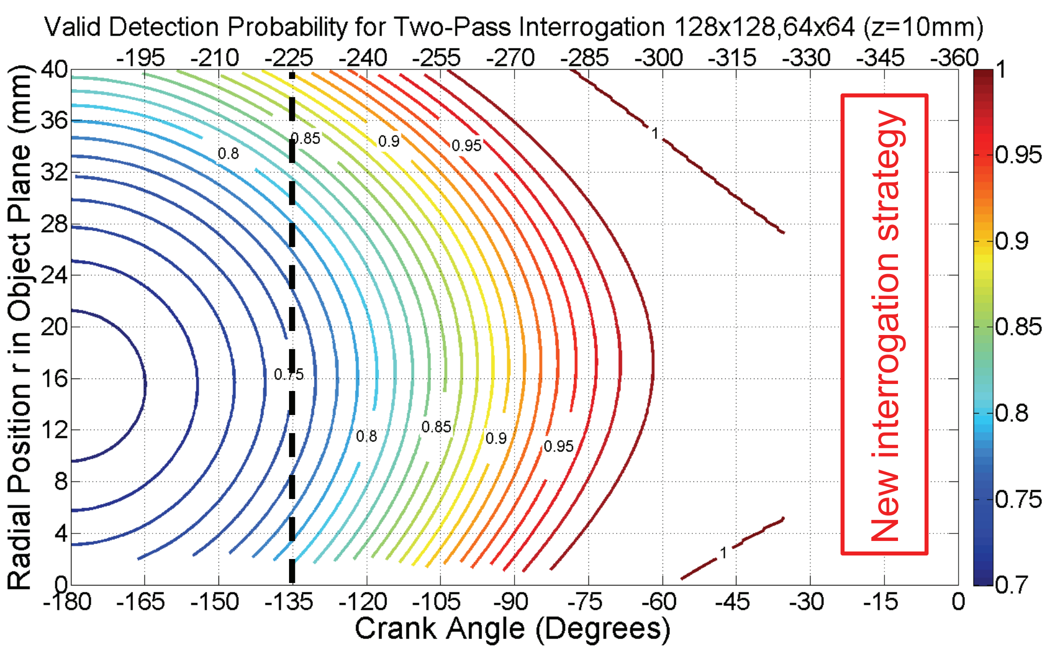
$$Prob\{valid\ peak\ detection\}$$
$$\cong 1 - \exp(-\frac{N_I F_I F_O F_\Delta}{2.5})$$
$$N_I = \left(\left|\frac{D_I}{\frac{4}{M_1 \times M_0'/M_0}}\right| + 1\right)^2$$

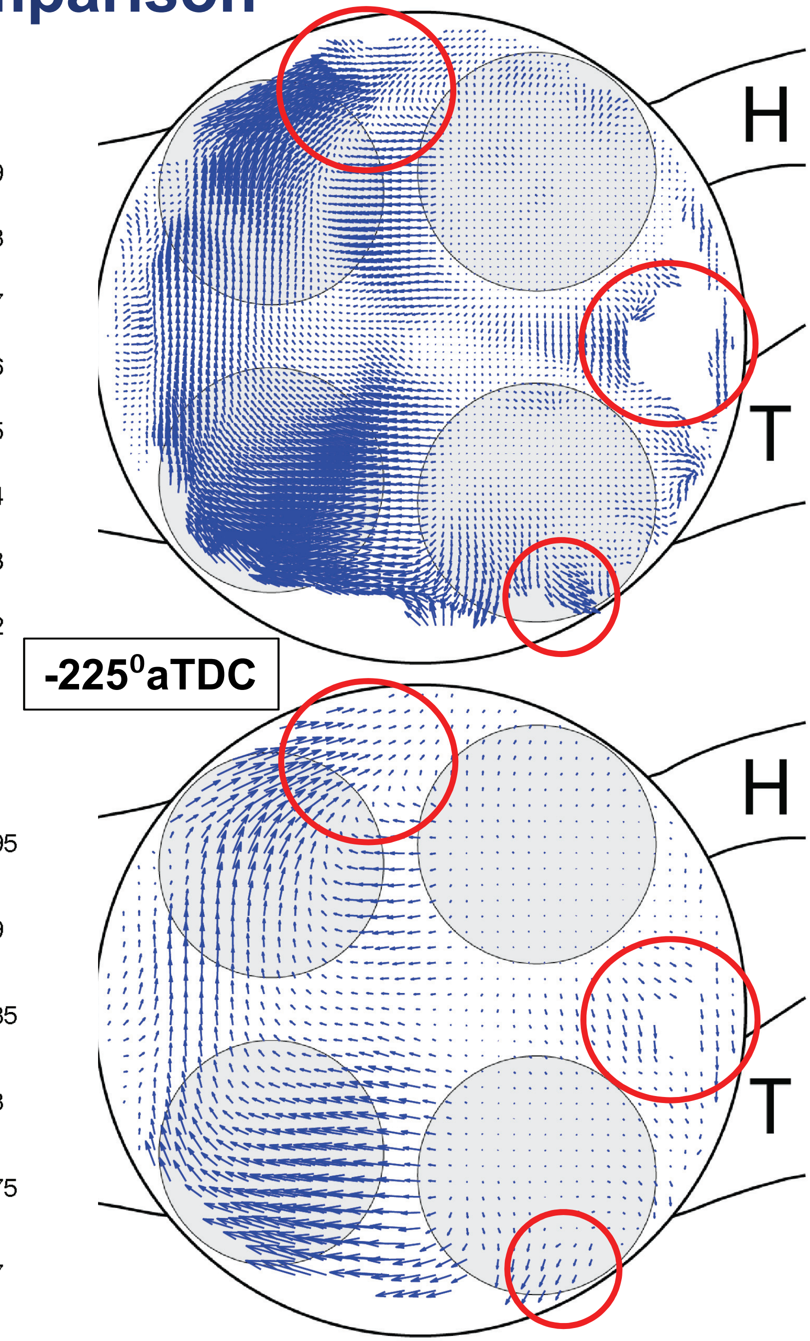
Without image overlapping, minimum distance between two particles (each cover two pixel space) for valid detection is 4 times of pixel size.

- Valid detection probability in squish region is unity.
- Multi-pass interrogation with minimum window size 64x64-pixel results in higher valid detection probability.
- Reduced velocity spatial resolution (1.95x1.95-mm) is still high enough for mean flow analysis.

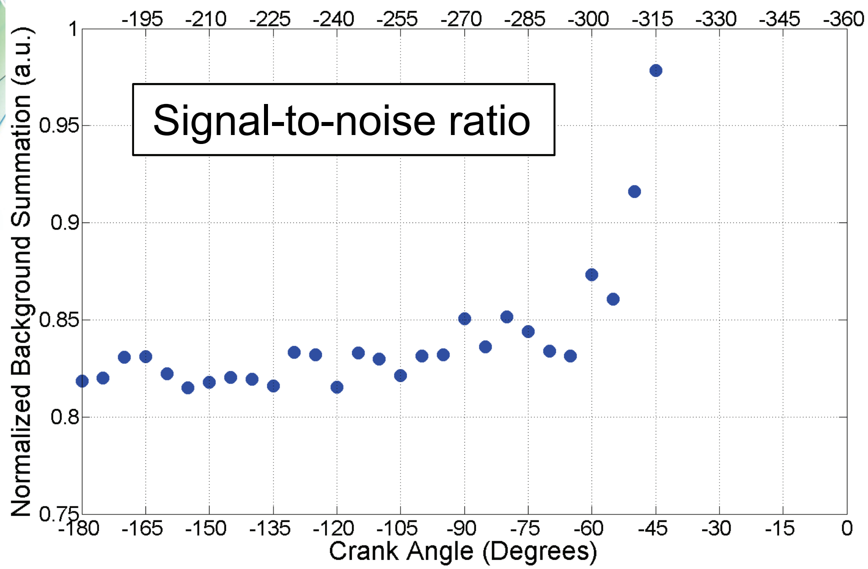
Interrogation Strategy Comparison



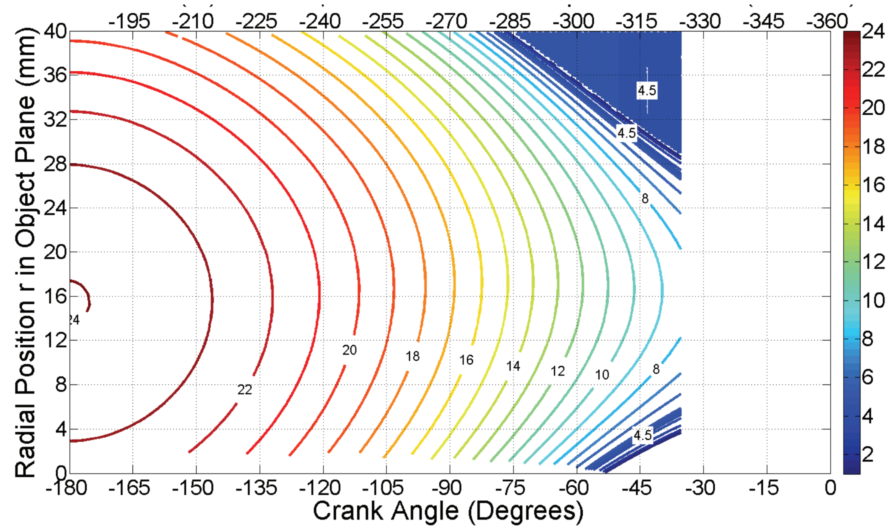




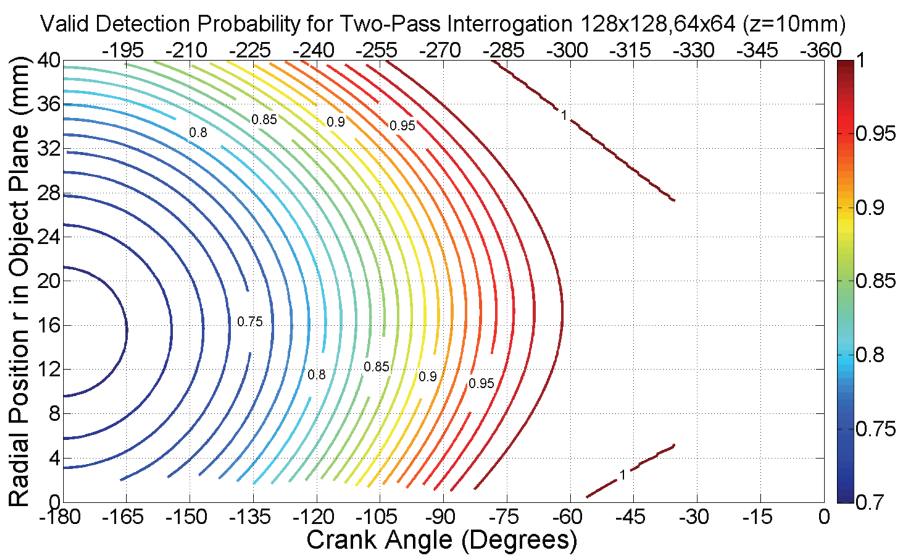
Summary



Error in Radial Velocity at Δt=55 μsec with Generic Interpolation Method during Radial Mapping (z=10mm)



New, improved interrogation strategy



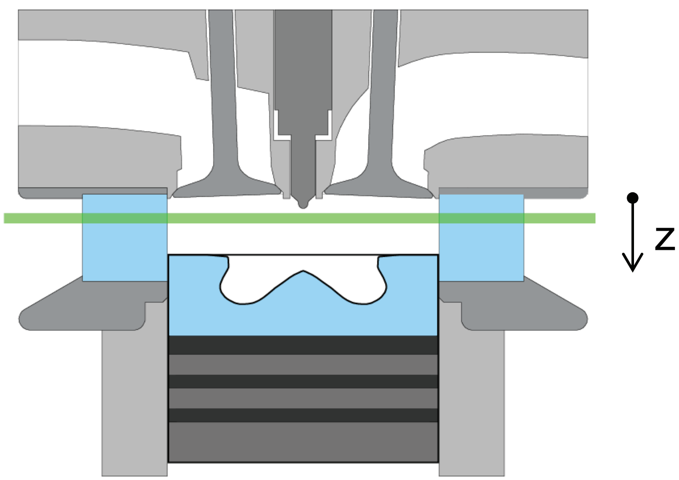
- Three sources of error are quantified by the piston with reentrant bowl geometry:

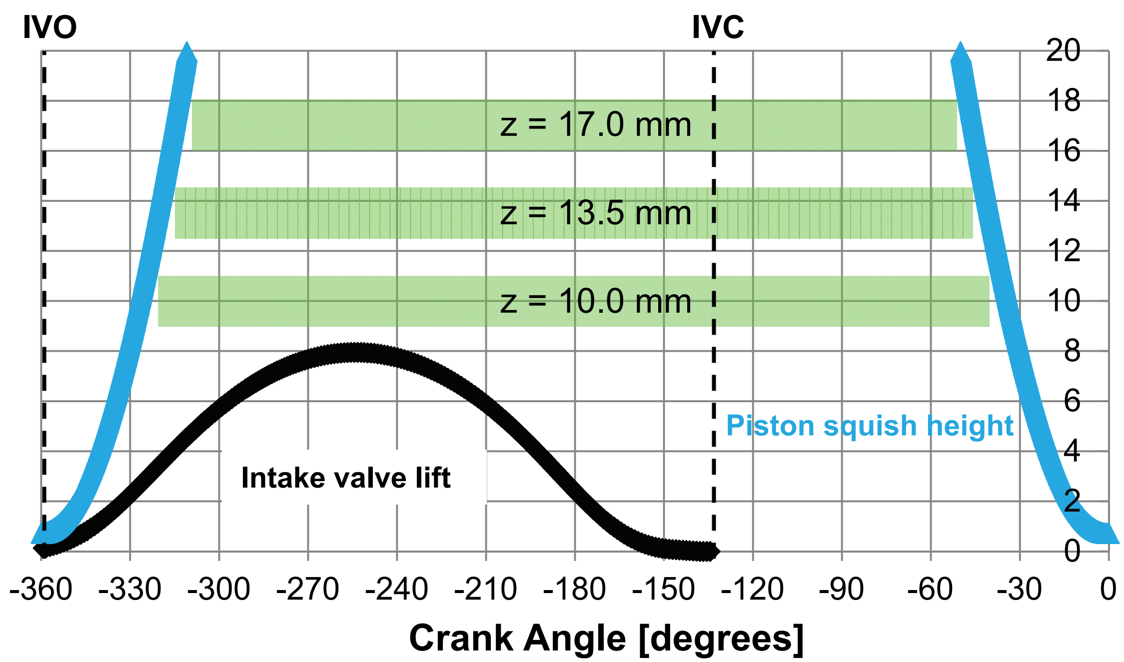
1. Signal-to-noise ratio (can be improved with higher laser fluence).
2. Error in radial velocity induced when particles are “stretched into lines” after dewarping.
3. Loss of valid peak detection from optical distortion (can be improved with bigger interrogation window size).

- Losses from in-plane F_I, out-of-plane F_O and velocity gradient F_Δ are not quantified.

Swirl-plane Measurement Test Cases

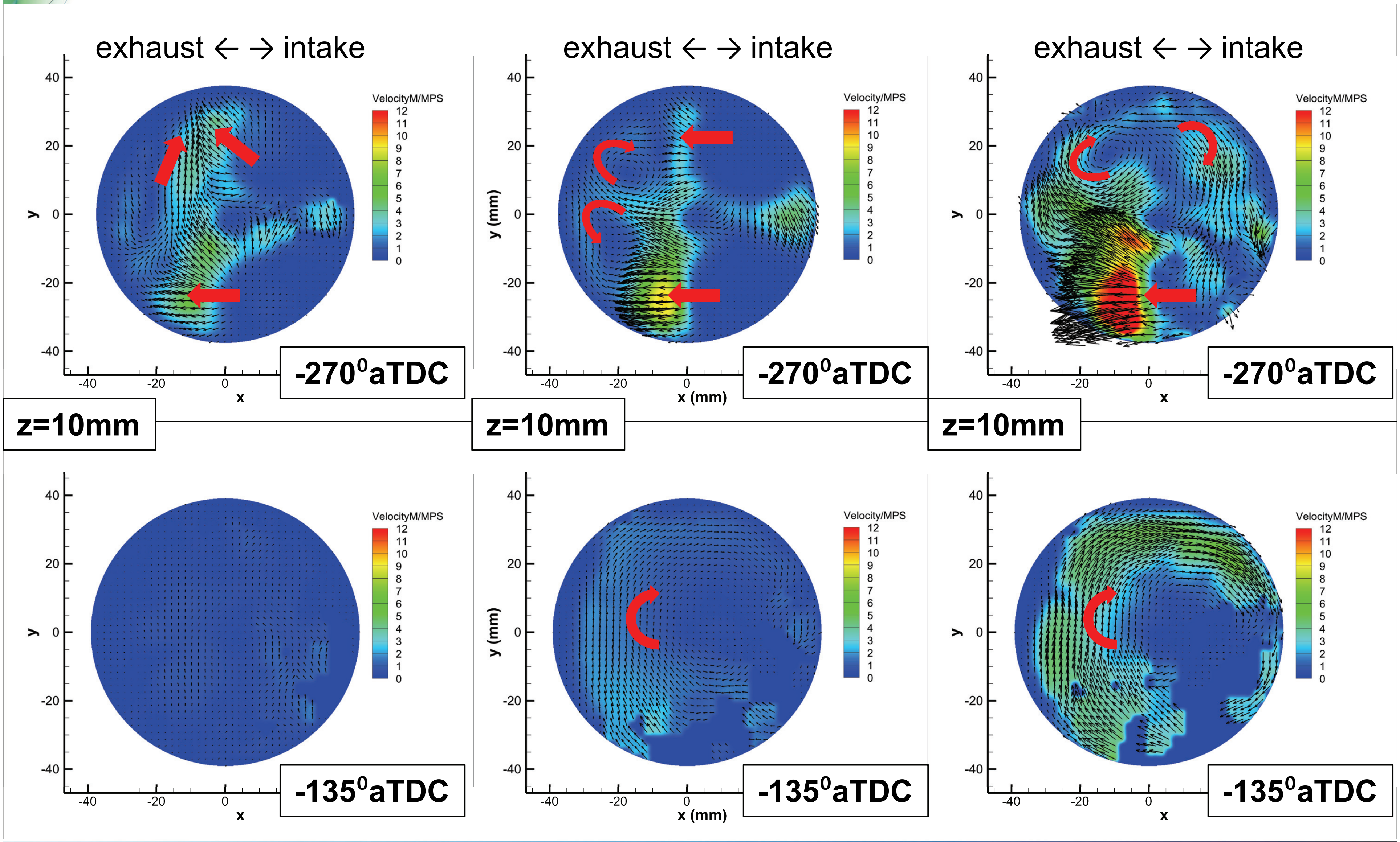
- Swirl planes are chosen to minimize laser scattering by intake valves and piston (Mid March, 2014)
- Every 15 CAD throughout intake and compression stroke (green region)
- Improved interrogation strategy (multi-pass 128x128-pixel -> 64x64-pixel minimum window size) has been implemented in the data processing.

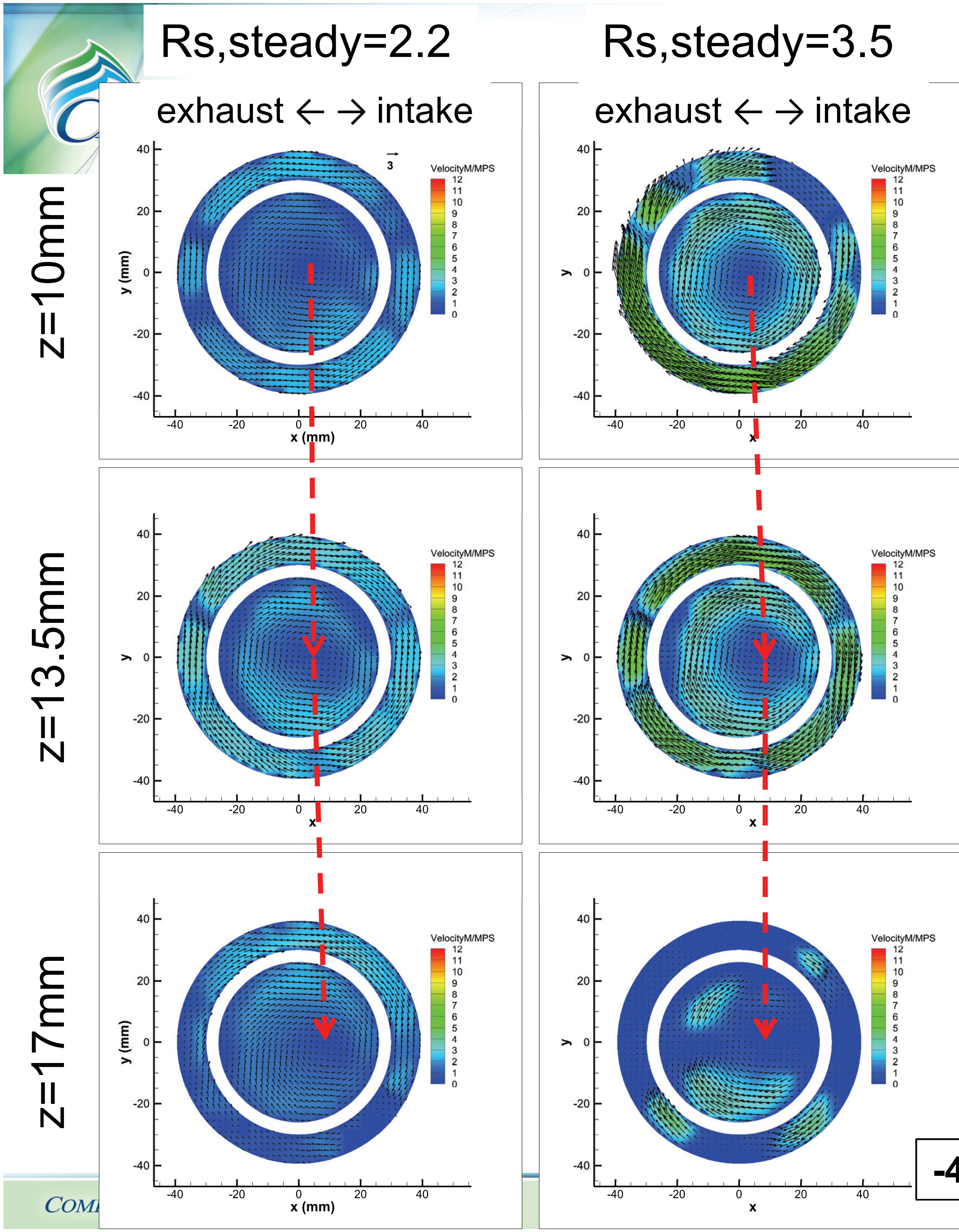




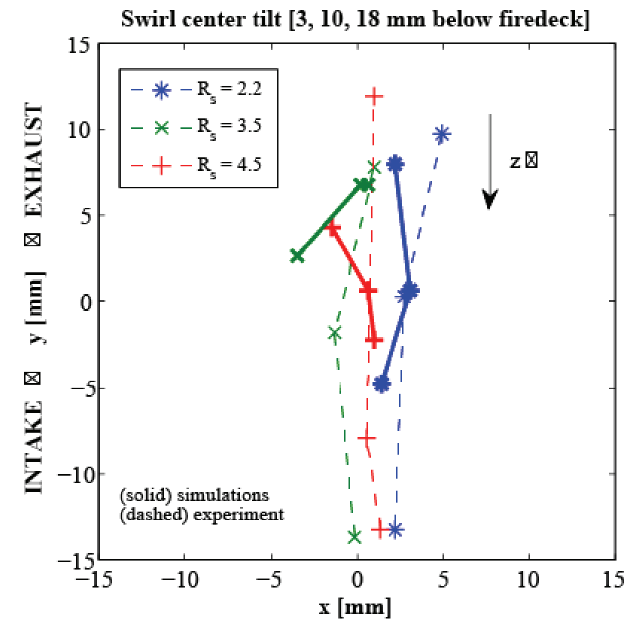
Mean Flow Topology Analysis

Rs,steady=1.5 | Rs,steady=2.2 | Rs,steady=3.5





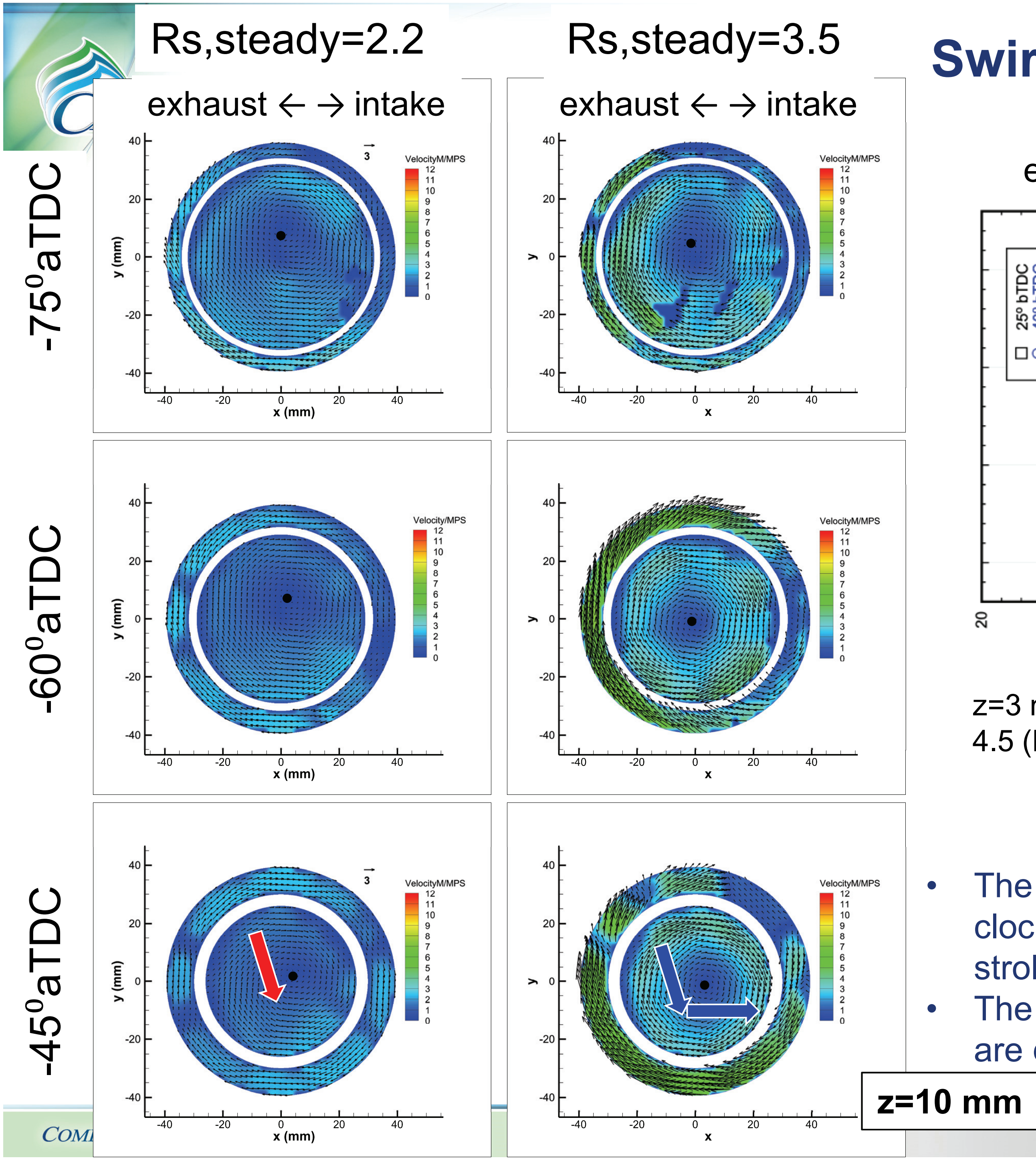
Swirl Center Vertical Tilting

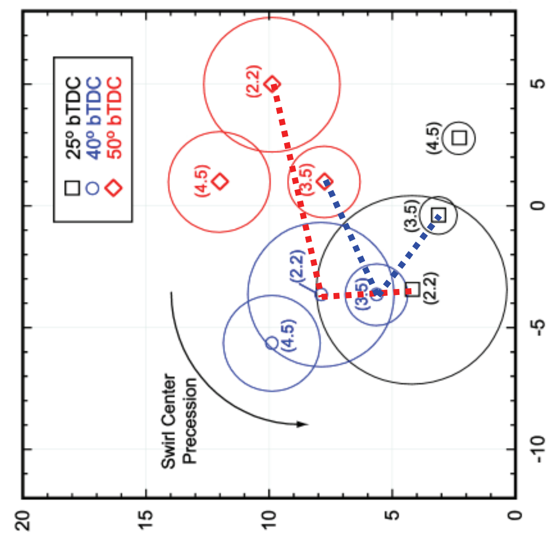


- The swirl center is located closer to the intake ports for swirl planes farther away from the fire deck.
- This behavior has also been observed in earlier experiments (Petersen, SAE2011-01-1285) and simulation (Perini, 2013, Computers & Fluids).

-45^{0}aTDC

Swirl Center Precession





z=3 mm plane @ Rs,steady=2.2, 3.5, 4.5 (Petersen, SAE2011-01-1285)

- The swirl center rotates counter-clockwise as the compression stroke progresses.
- The swirl center precession paths are different for the two swirl ratios.

Conclusions

- With the radial distortion correction, the time-dependent transformation has been quantified, which makes the quantification of errors from the optical distortion possible:

1. Although the magnification factor of this piston is temporally and spatially dependent, since it is small, the particle image size is dominated by camera $f^{\#}$, and it won't change much after dewarping. Therefore the radial mapping will "stretch particles into lines" and induce significant errors in radial velocity. A new particle centroid mapping procedure is needed in the future.
2. Quantification of valid peak detection probability allowed determination of a more optimal interrogation strategy.
3. Signal-to-noise ratio will decrease up to 20% when the piston is moving away from the fire deck. A higher laser fluence can help mitigate this problem, especially when the camera aperture opening is small ($f^{\#} = 11$) to avoid pixel locking.

- A few points need further attention:

1. The seed density should be carefully controlled so as to avoid particle image overlap.
2. The temporal interval between two laser pulses (Δt) must be optimized for particle displacement to match ~¼ of the interrogation window size at different crank angle position. (to minimize losses from in-plane F_I and out-of-plane motion F_O)

Future Work

- Finish swirl-plane, vertical-plane PIV at $R_{s,steady}$=1.5, 2.2, 3.5 with improved Mie-scattering signal and data processing in July, 2014.
- Investigate two different bowl geometries to study swirl centering and tilting.

Thanks for Your Attention!

Backup Slide

- The ignorance of transformation change during laser temporal interval Δt will result in the systematic radial velocity error up to ±55% of mean piston speed. With general mapping approach, this error can be eliminated.