Topic 1.1: In-Nozzle Experiments

- Measurements of Nozzle Geometry
  - Spray A
  - Spray B
- Evidence for Gas in Sac
- Rate of Injection, Spray B

Nozzle Geometry of Spray A – Resources Available

Kastengren et al, Atomization & Sprays **22** (12), pp 1011-1052 (2012).

Proceedings from ECN1, ECN2 web site

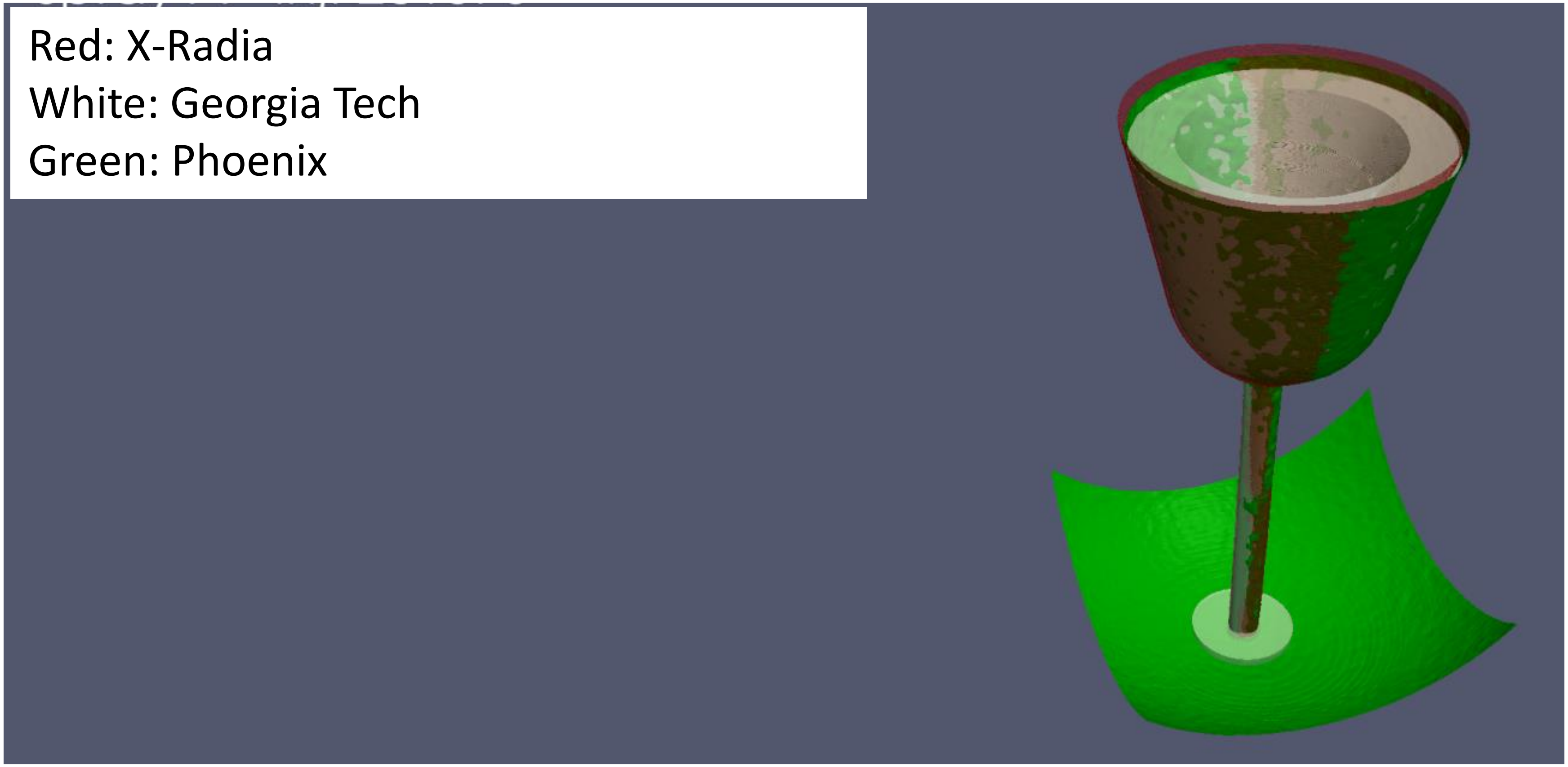
Geometries Available: Spray A #210675

Injector 675 is the Target Injector for Internal Flow Simulations

Name	Supplier	Method	Size (MB)	Num. Points	Resolution
Phoenix	Caterpillar	Benchtop CT	32	1 M	16 μm
Georgia Tech	Georgia Tech	*Smoothed Phoenix*	66	2.1 M	2 μm (based on 16 μm data)
X-Radia	CNRS	Benchtop CT	41	1.3 M	2 μm
ESRF	Infineum, ESRF	*Synchrotron CT*	Not yet available		

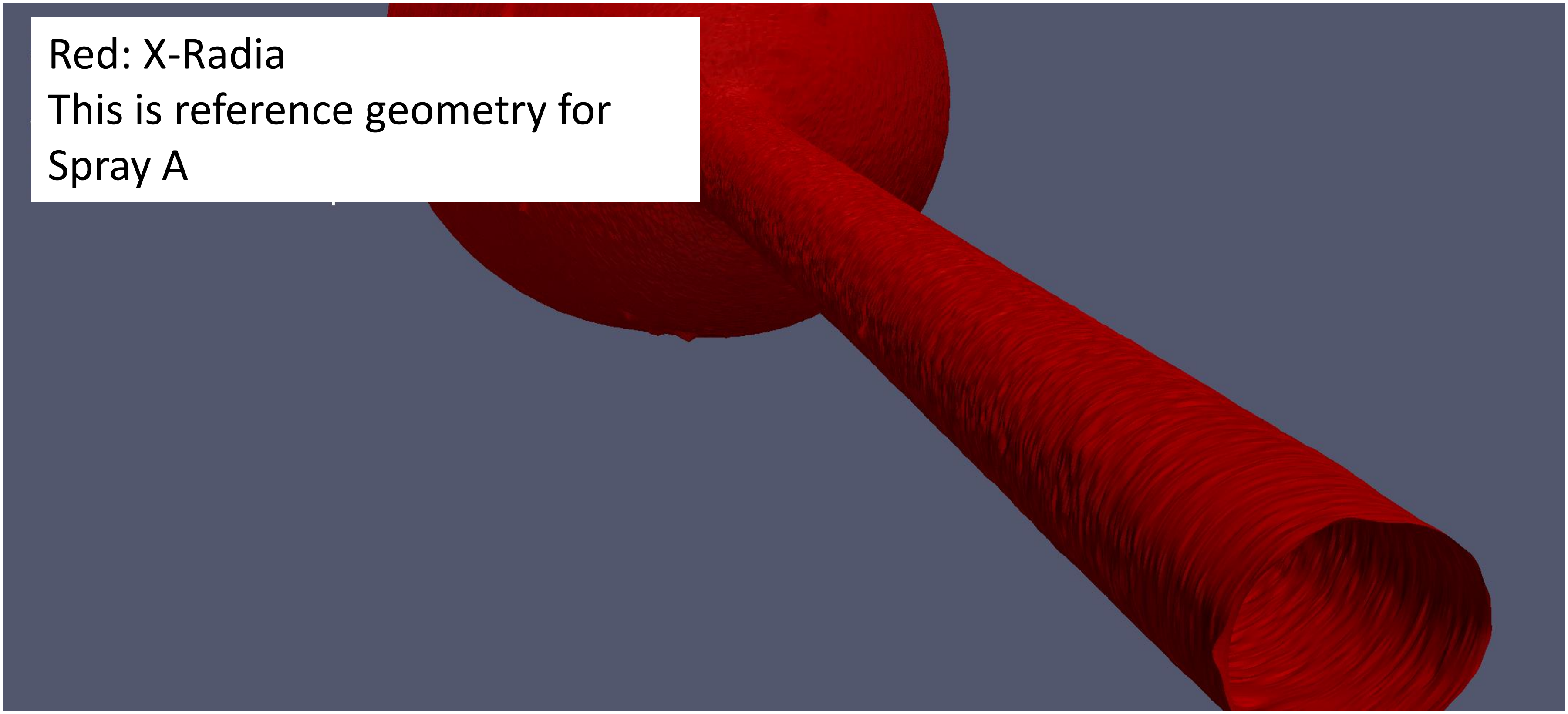
- All STL format
- Quoted Resolution is 2x the vertex spacing

- Phoenix, X-Radia, and Georgia Tech geometries all overlay very well once the nozzle hole inlets were aligned to the same origin and meshes were rotated to same alignment.



Spray A Injector 675

- X-Radia data show ridges around the circumference of the orifice
- These may be real, based on ESRF data of Spray B
- They are smoothed out in Phoenix and Georgia Tech geometries

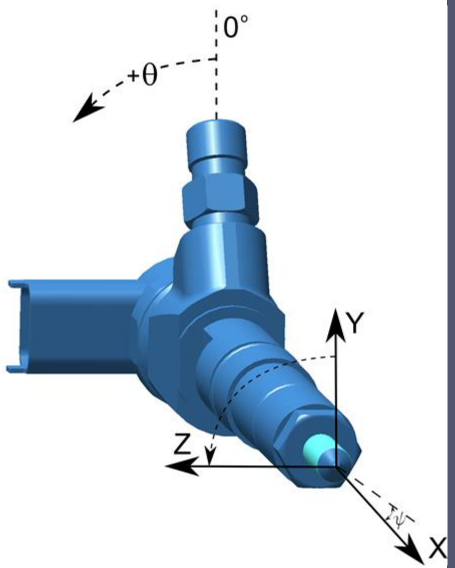


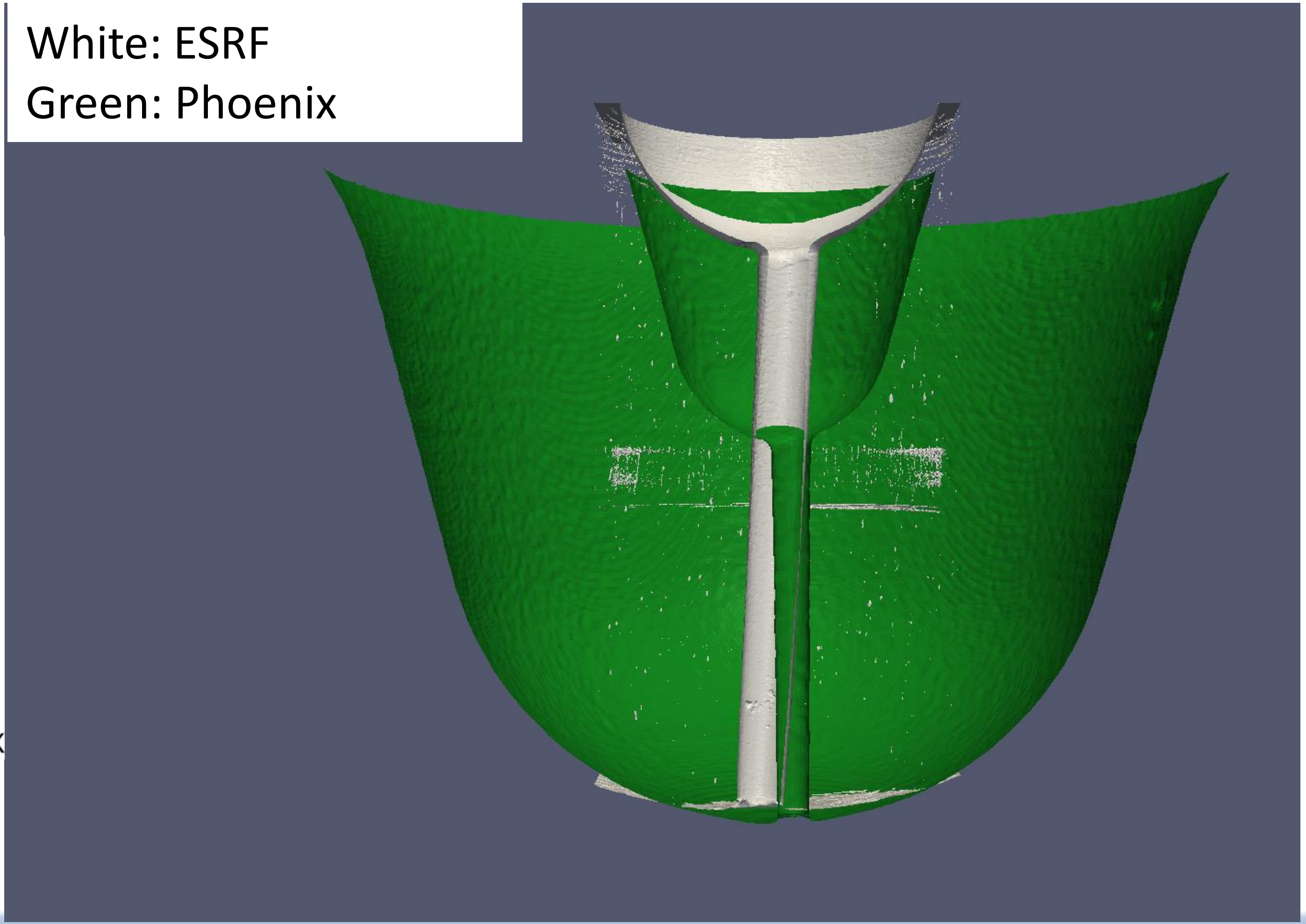
Validation of Nozzle Geometries

- Geometries do not all agree (more later)
- Need to verify calibration with other measurements
  - Optical microscopy of hole exit
  - Calibrated X-ray phase contrast images
- Best available data for comparison: Nozzle 210677

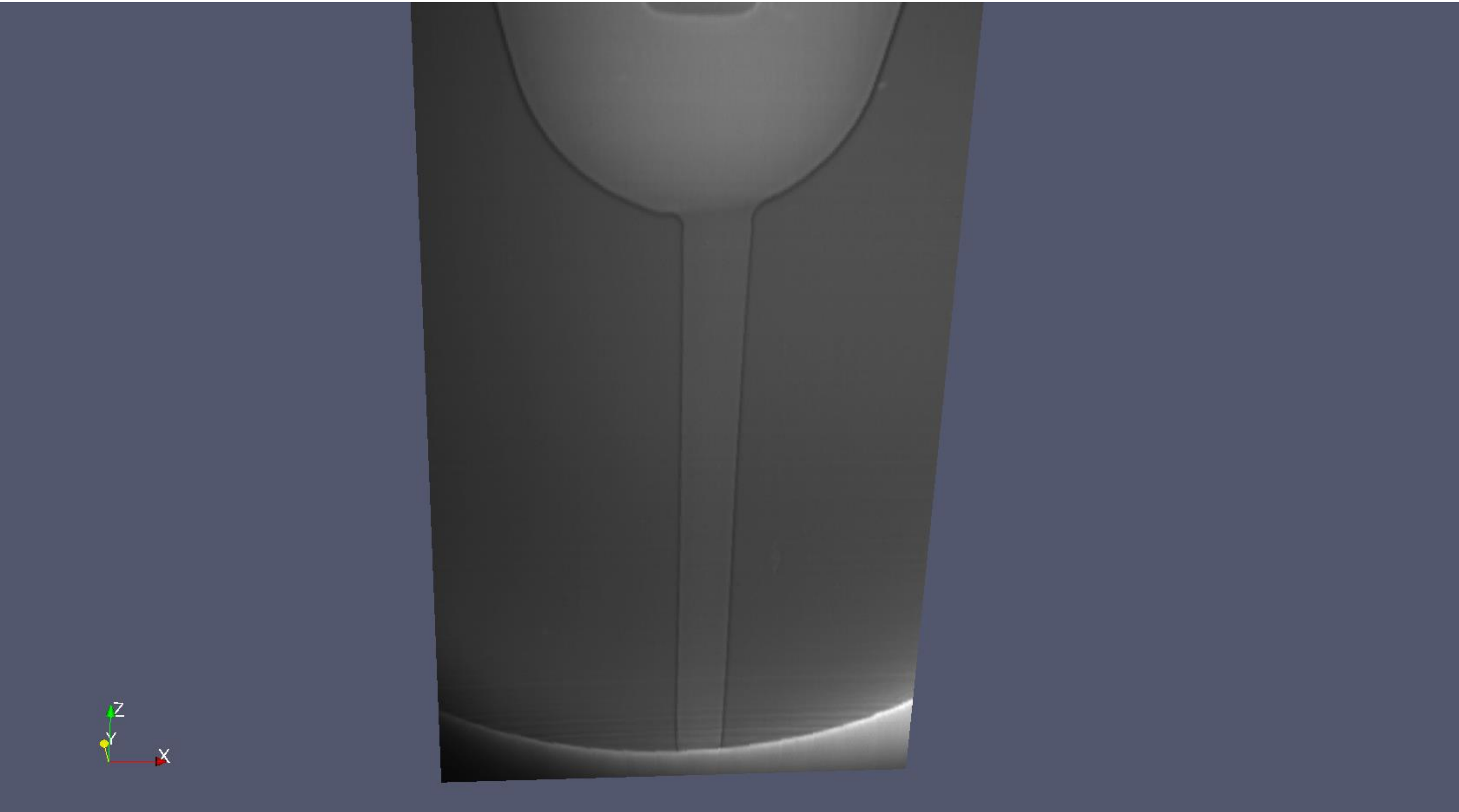
Scaling Errors Between Geometries

- Geometries are not aligned: ECN Coordinate system defined on web site
- Phoenix and X-Radia data have very similar scaling
- For 210677, ESRF data is exactly 50% oversized



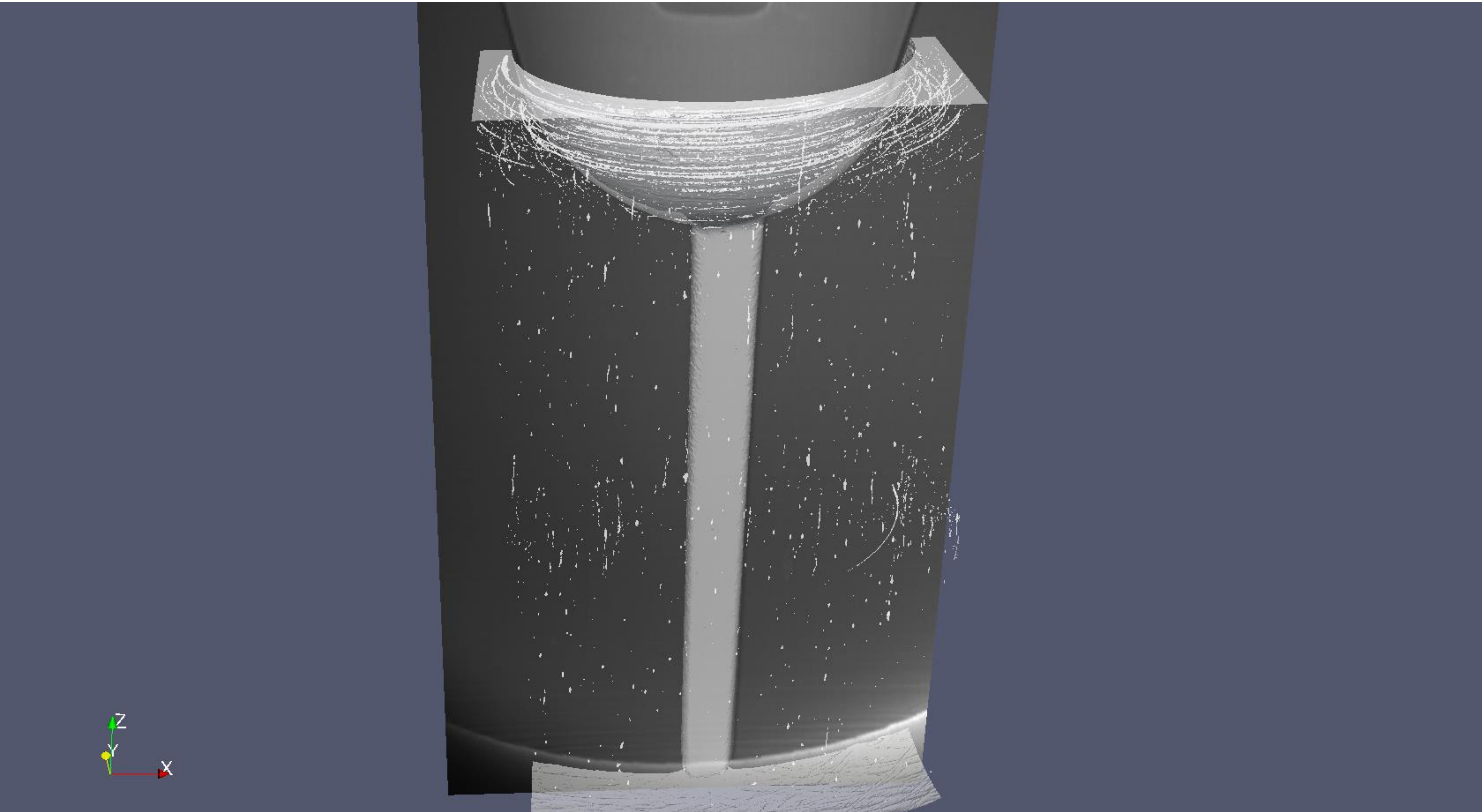


Verification with X-ray phase contrast

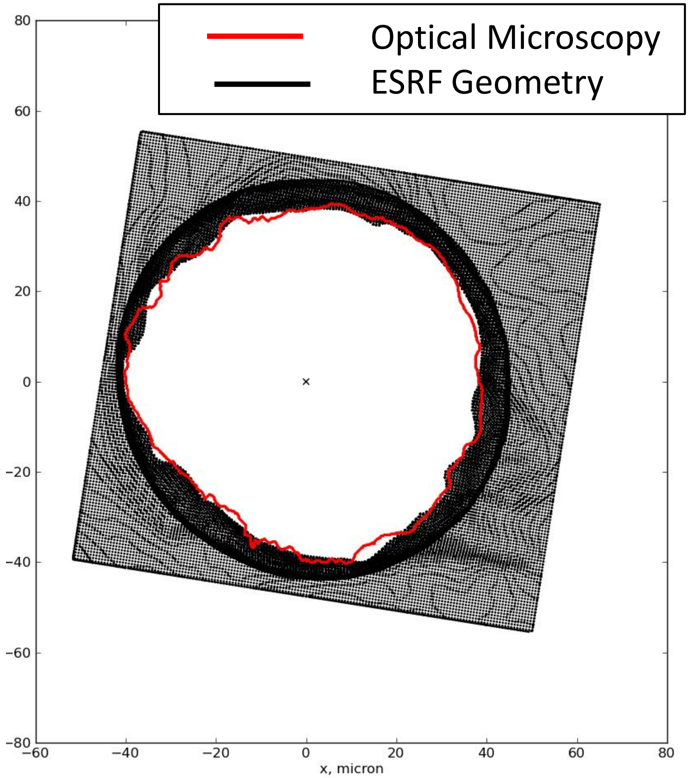


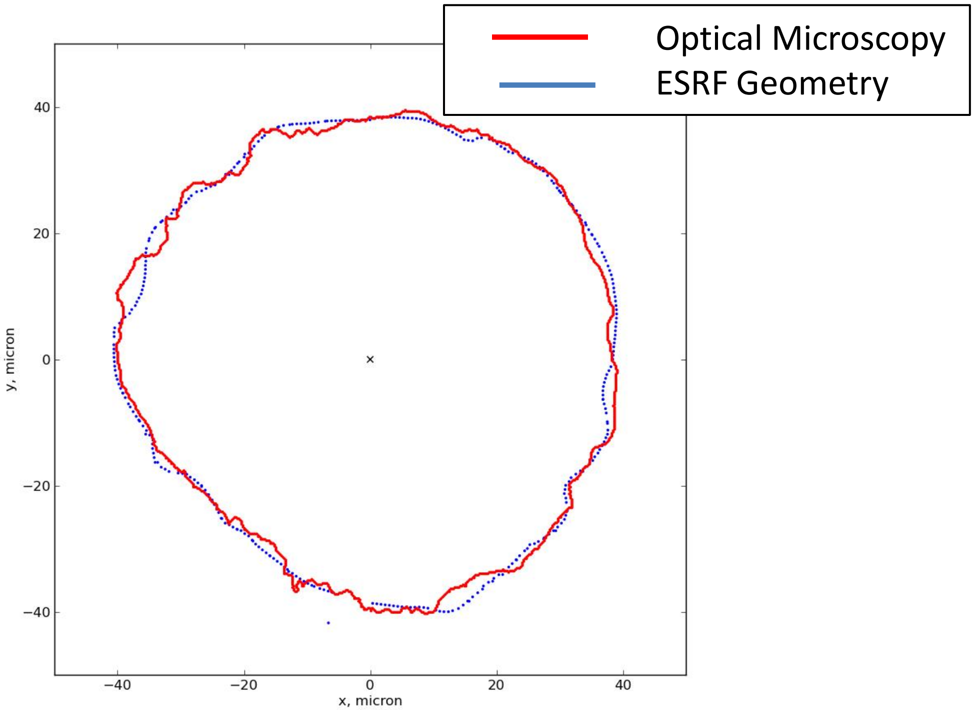
Verification with X-ray phase contrast

- Once the 2/3 scaling correction is applied, ESRF mesh aligns very well with phase contrast data



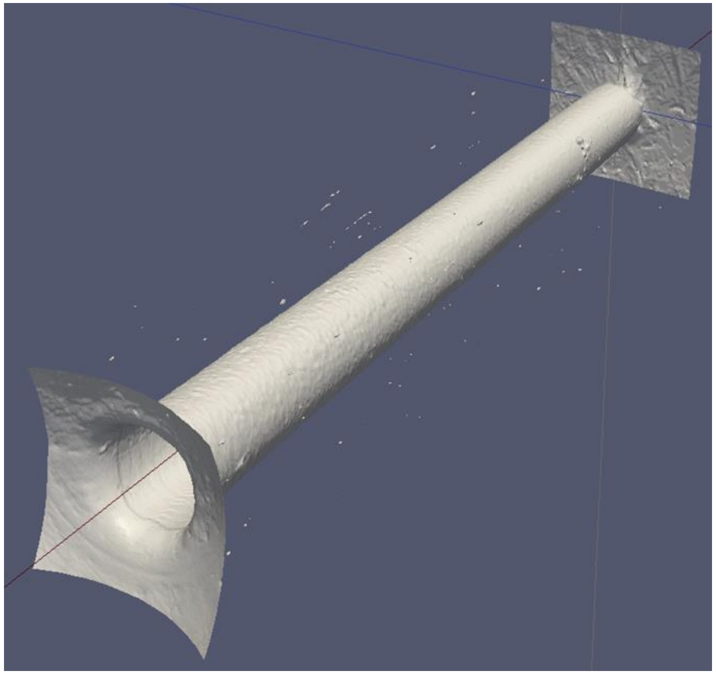
- Nozzle 677
- Microsopy measurement of hole exit has depth of field of 10-20 μm
- Project hole exit of ESRF geometry onto a plane
- Compare the inner diameter of projection with optical microscopy
- Great agreement
- ESRF Geometry matches all available reference data

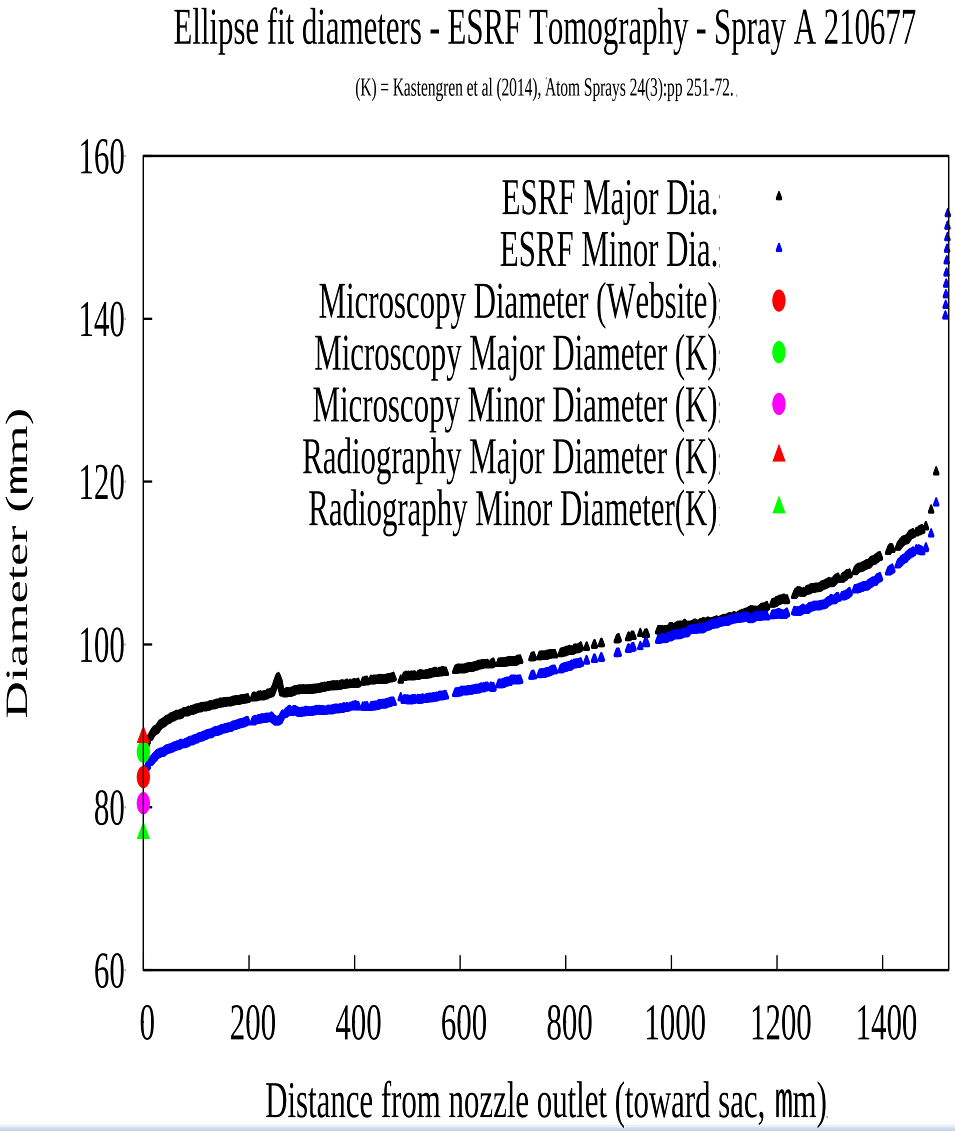




Analysis of nozzle hole geometry – Spray A 210677

- Eliptical Fit to nozzle profile
- Hole slightly elliptical
- Taper profile revealed by elliptic fit

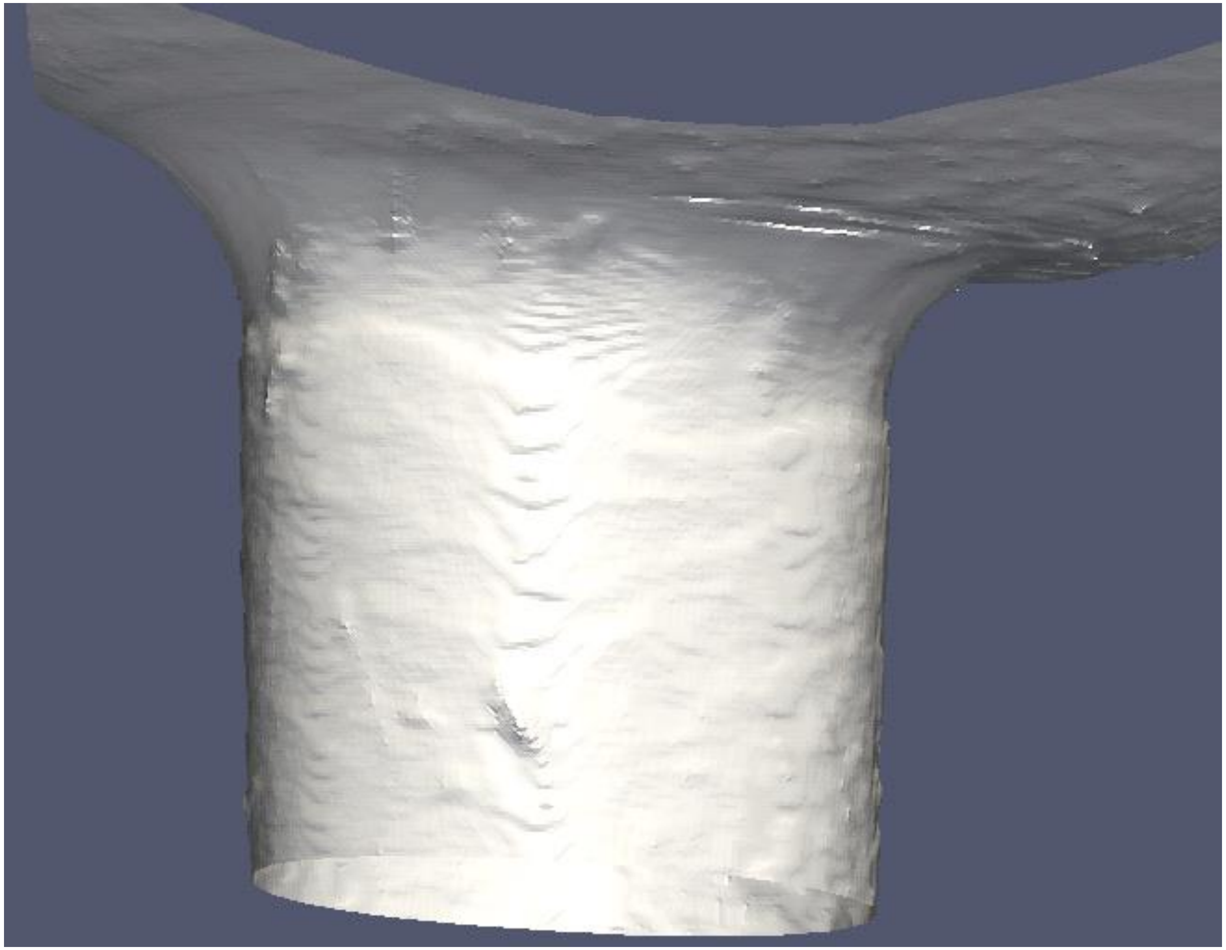




Geometry Analysis for 677

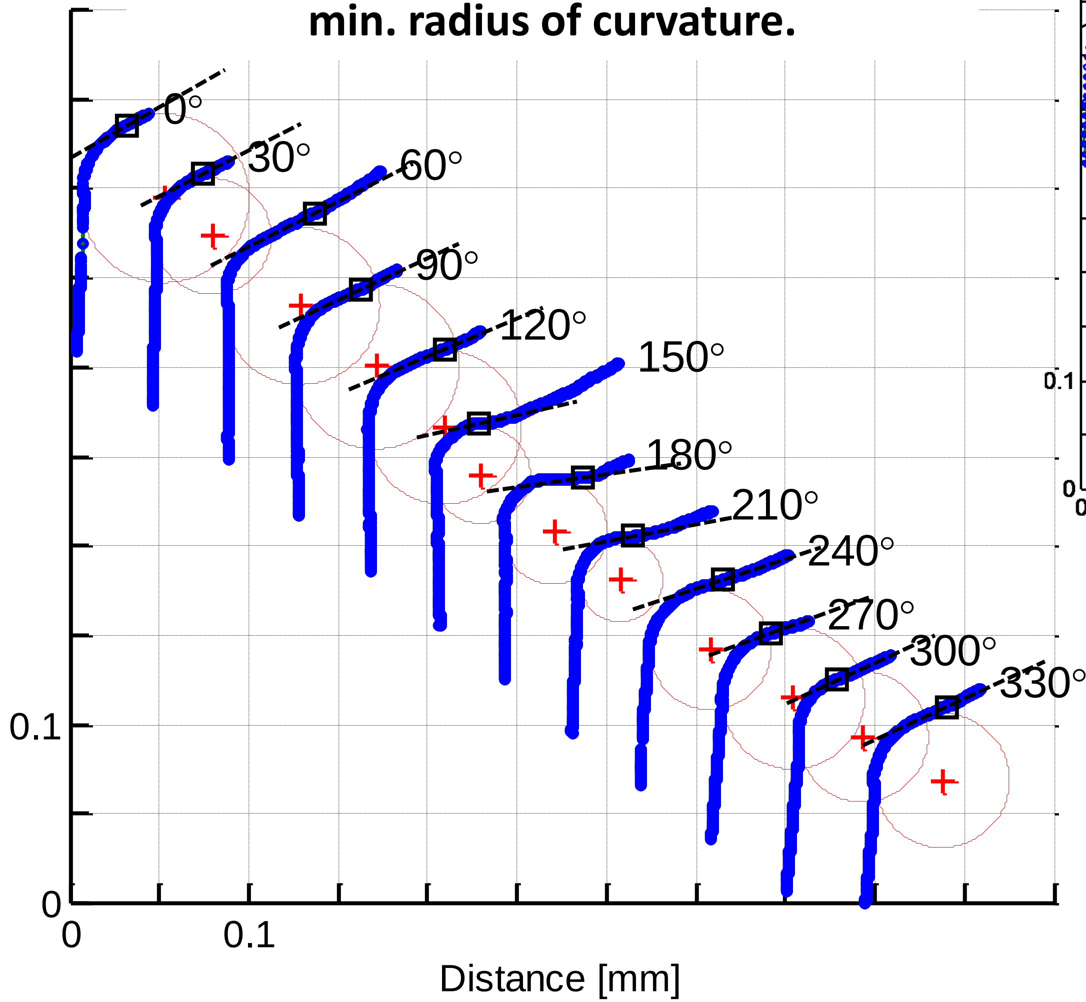
Extract for Simulations:

- Radius of curvature
- Turning angle

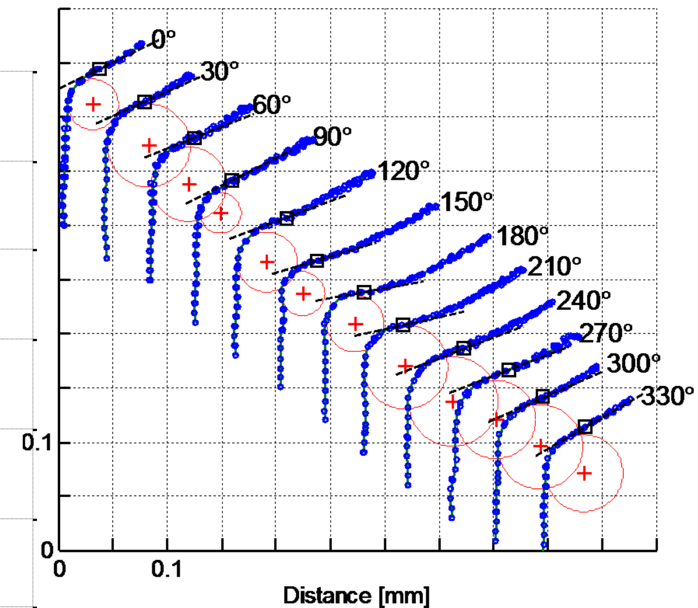


Geometry Analysis for 677

ESRF synchrotron x-ray tomography: Better resolution to extract inlet turn angle and rad curve. Routine detects min. radius of curvature.

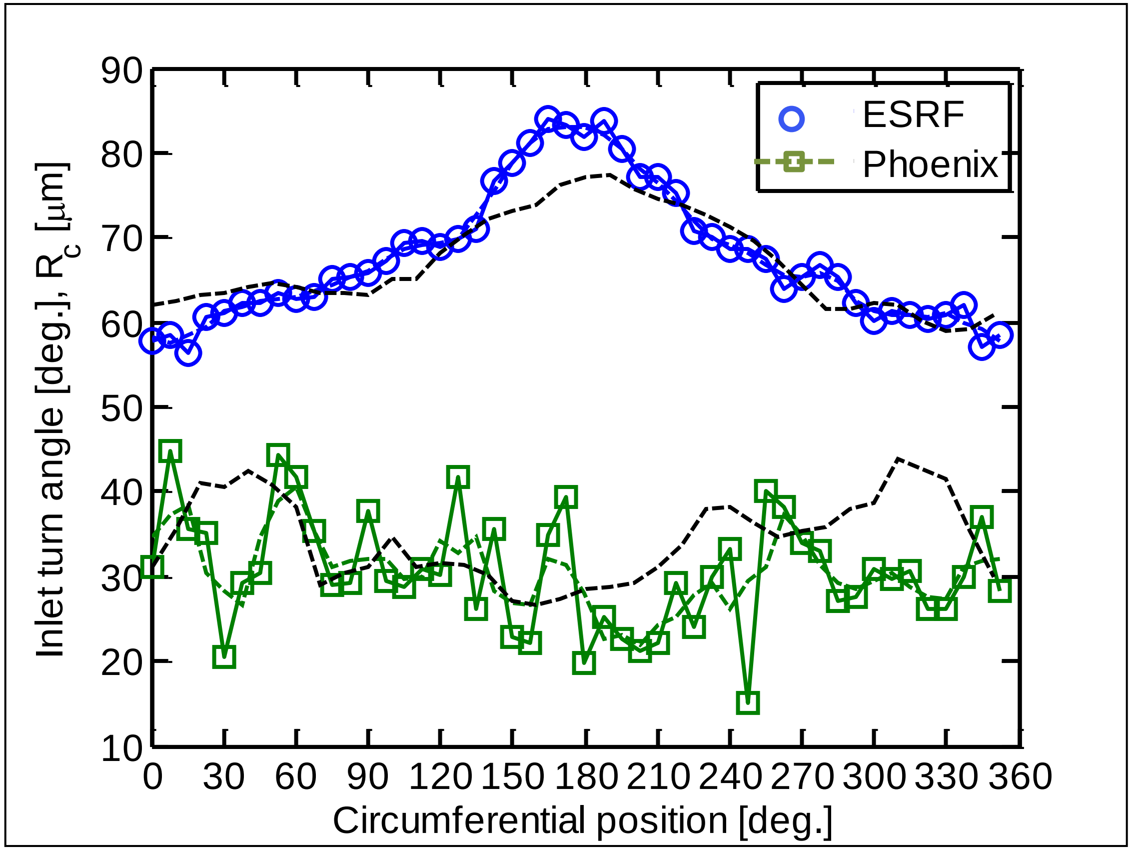


Phoenix commercial x-ray tomo stl: Fig.9 Kastengren 2012



Evolution of geometry analysis for 677

More accurate determination of inlet turn angle and Radius of curvature



Summary of Spray A Geometry

- **Nozzle 210677 – Used to Check Calibration**
  - ESRF Geometry compares very well with microscopy of hole exit, calibrated phase contrast images (after 50.0 % correction)
  - Phoenix, X-Radia geometries show distortions from ESRF geometry
  - Eliptical fits to nozzle profile are available
  - Improved measurements of radius of curvature, turning angle

- **Nozzle 210675 – ECN3 Reference Nozzle**
  - ESRF geometry not yet available
  - X-Radia geometry is the best currently available

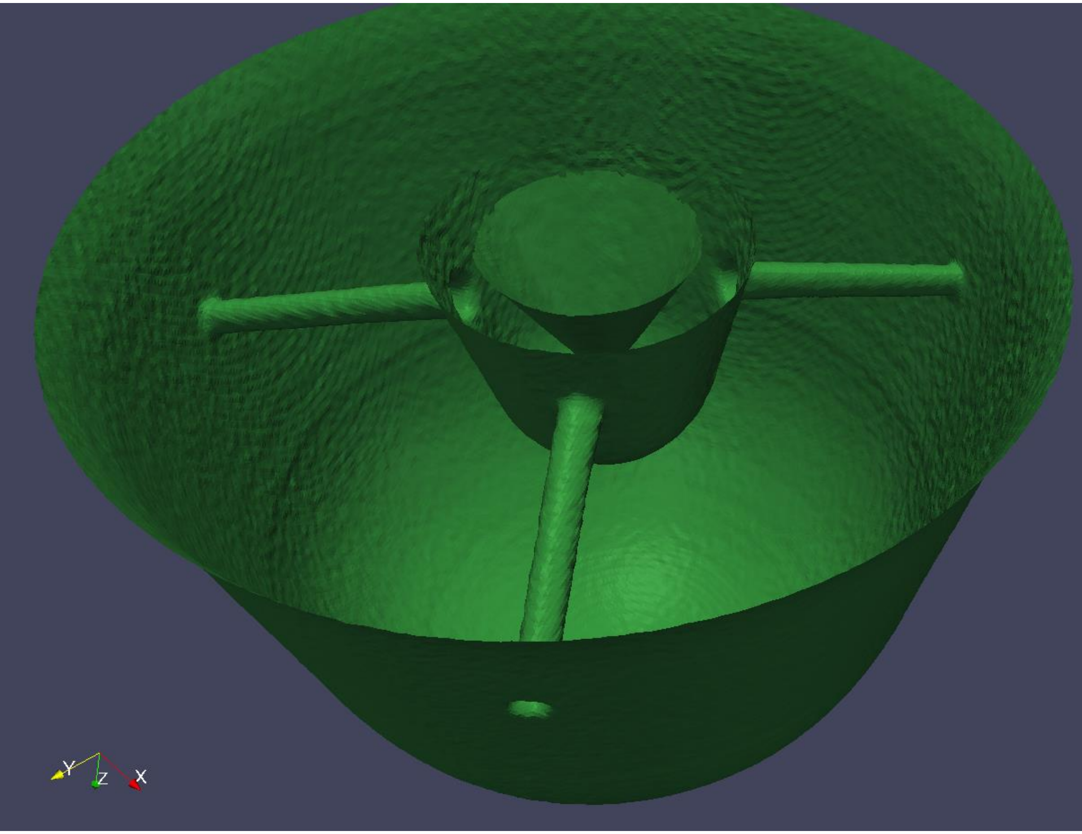
Geometries Available: Spray B #211201

Injector 201 is the Target Injector for Internal Flow Simulations

Name	Supplier	Method	Size (MB)	Num. Points	Resolution
Phoenix	Caterpillar	Benchtop CT	31	260 k	16 μm
ESRF	Infineum, ESRF	Synchrotron CT	4128	34 million	1.5 μm
Converge	Convergent Science (ESRF)	*Downsampled ESRF*	23	290 k	≥ 10 μm

- All STL format
- Resolution is 2x the vertex spacing

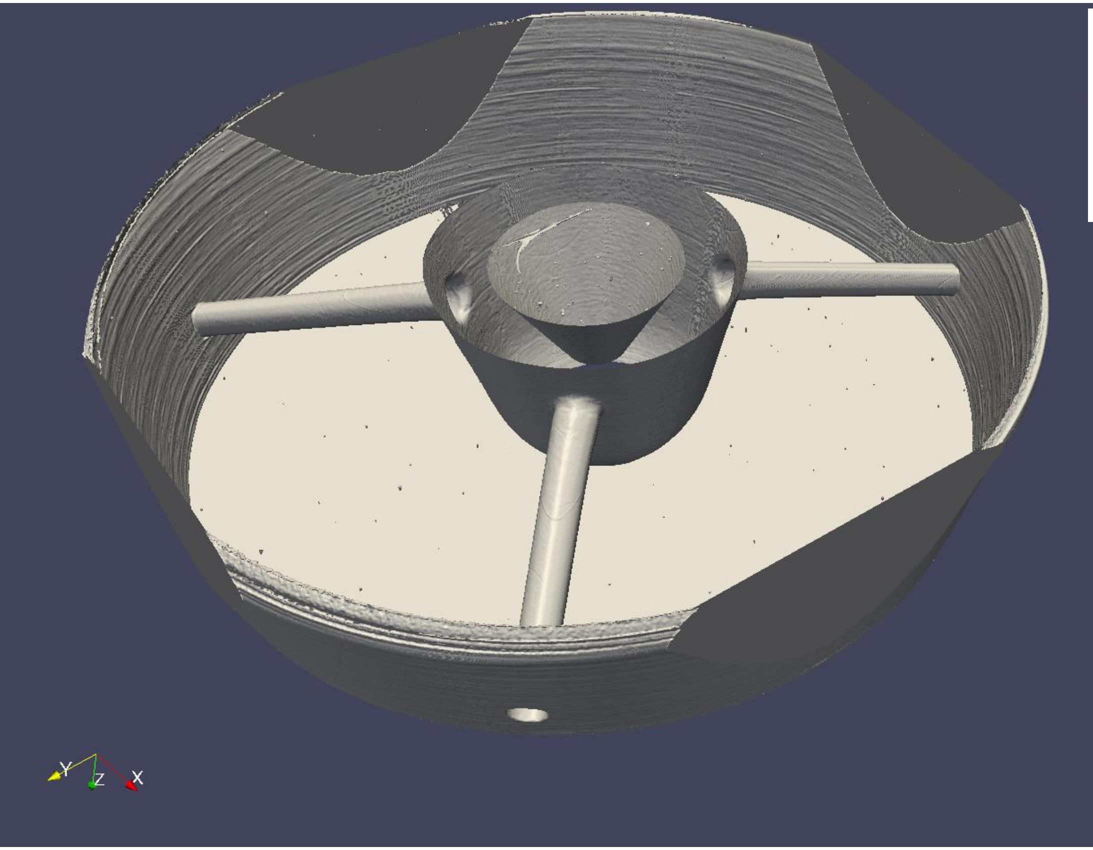
- Whole nozzle tip, truncated above nozzle inlet holes



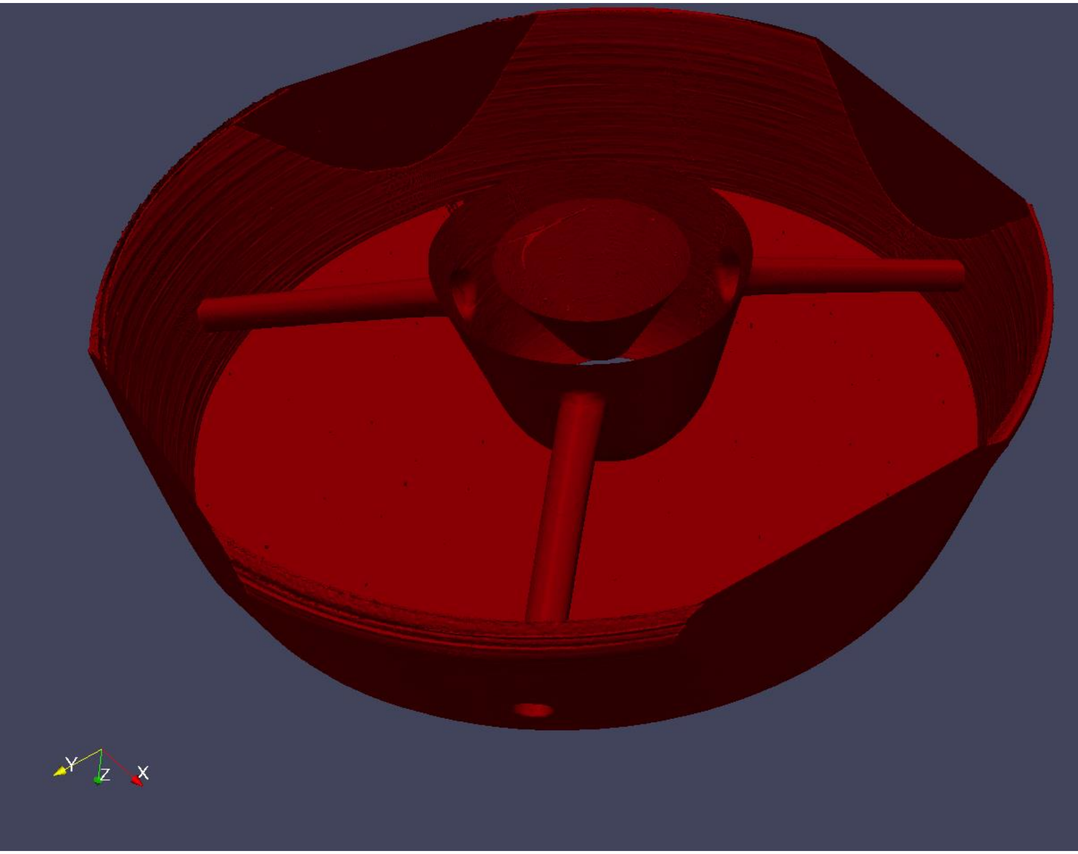
White: ESRF
Red: Converge/ESRF
Green: Phoenix

- Truncated above nozzle inlet holes and near the bottom of the sac (hole in sac)

White: ESRF
Red: Converge/ESRF
Green: Phoenix



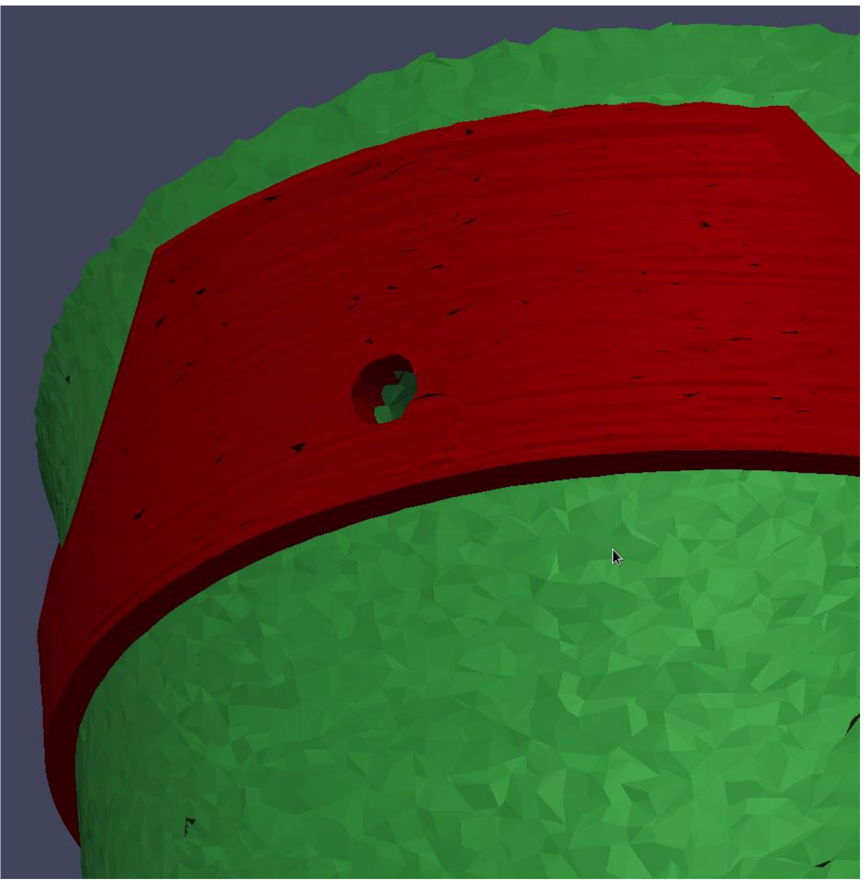
- Downsampled version of Infineum ESRF
- Same x,y,x extents as original ESRF data.
- Coarser spatial resolution

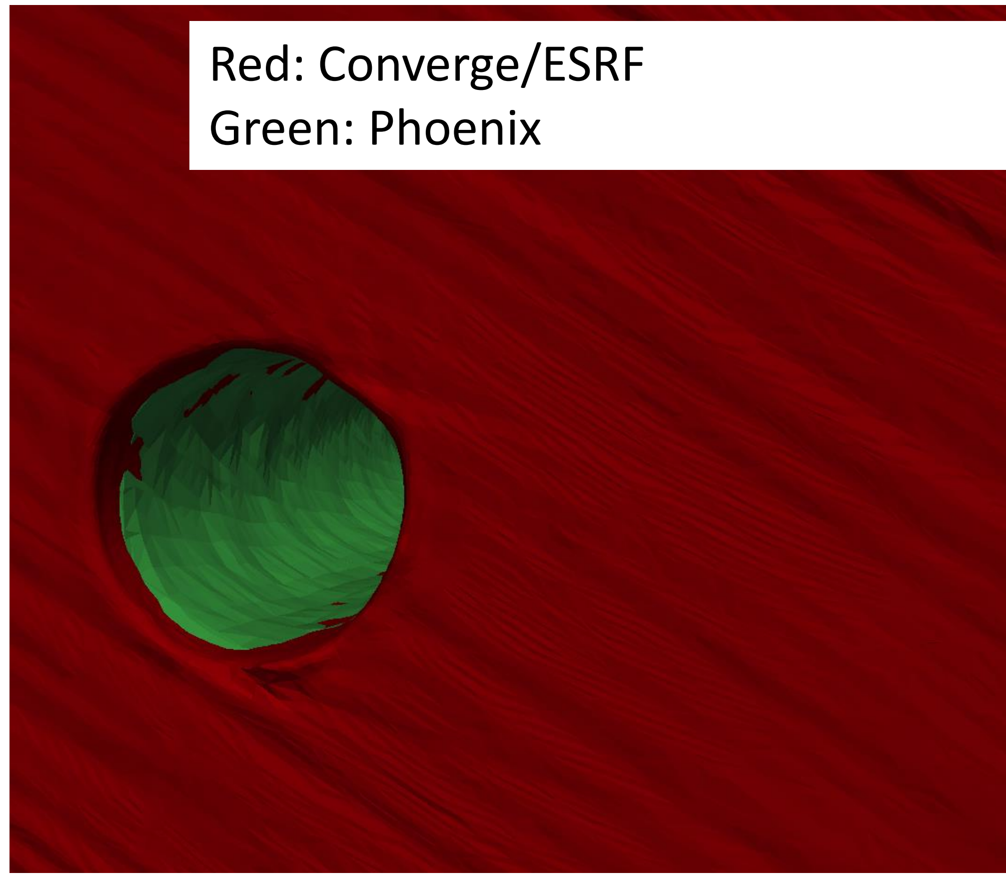


White: ESRF
Red: Converge/ESRF
Green: Phoenix

Comparison of Phoenix and ESRF Geometries

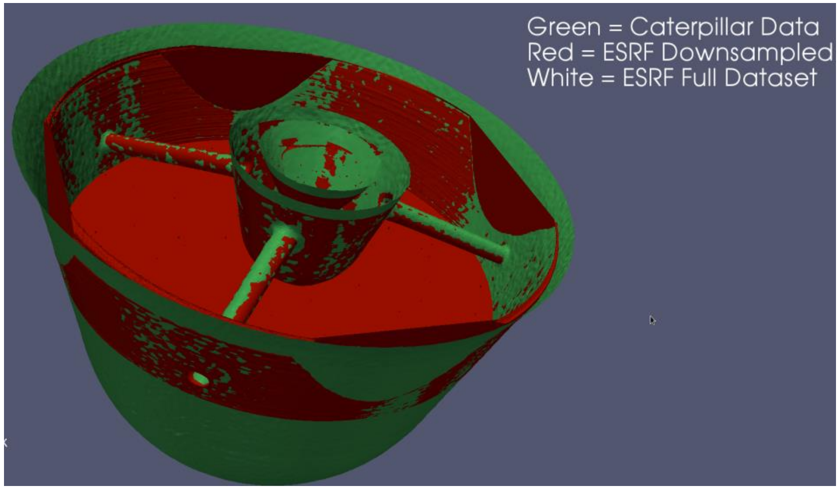
- The ESRF geometry is larger than the Phoenix geometry





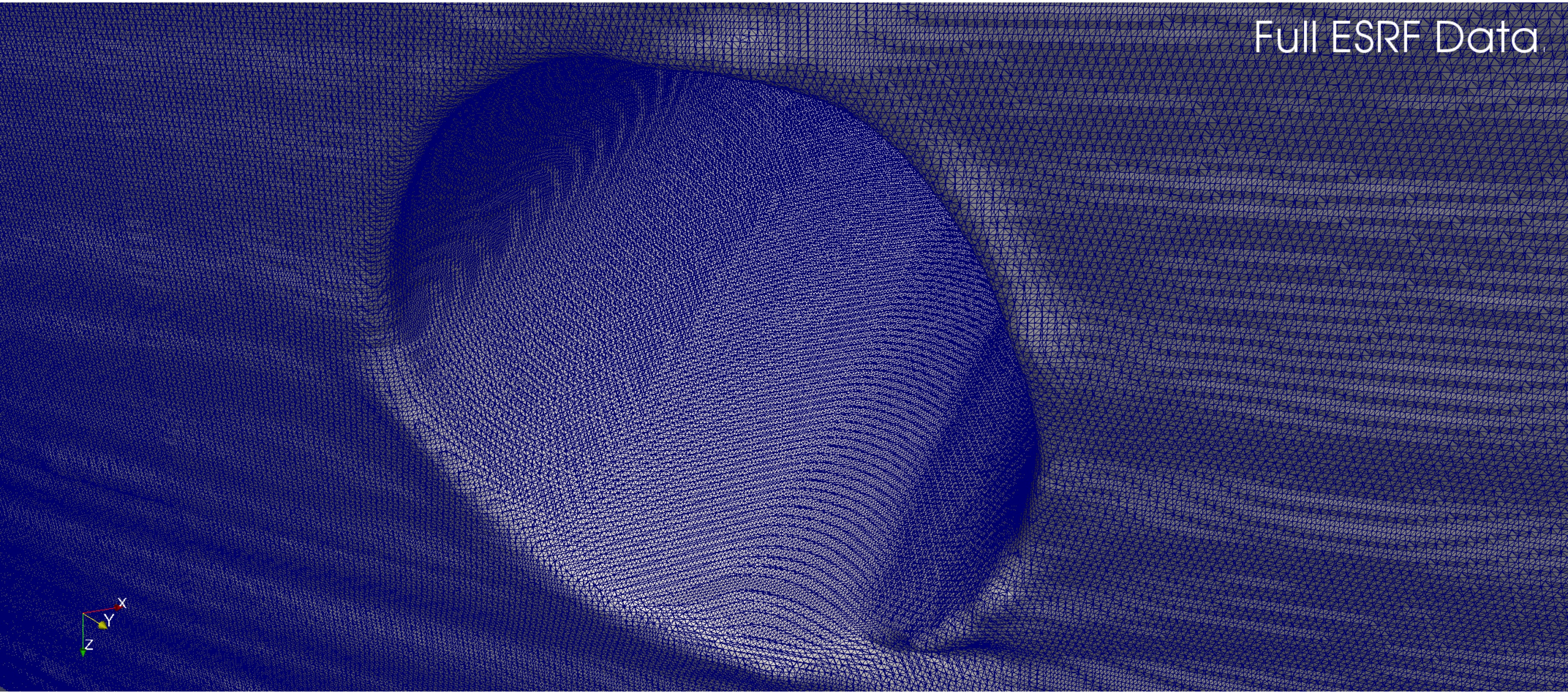
Comparison of Phoenix and ESRF Geometries

- To achieve overlap between the Phoenix and ESRF geometries, we must:
  - Rotate Phoenix data 123 degrees in Z
  - enlarge Phoenix data in every direction by about 3%
- ESRF geometry agrees with outlet diameter measured using optical microscopy
- Why is Phoenix geometry too small?
  1. Tomography generates a 3D density field
  2. All measurement methods show a gradient in density at the boundaries: must pick a threshold to define as a "wall"
  3. Beam hardening is more pronounced with benchtop x-ray sources, makes this more difficult
  4. X-ray source size, divergence, detector broadening are much larger for benchtop x-ray source

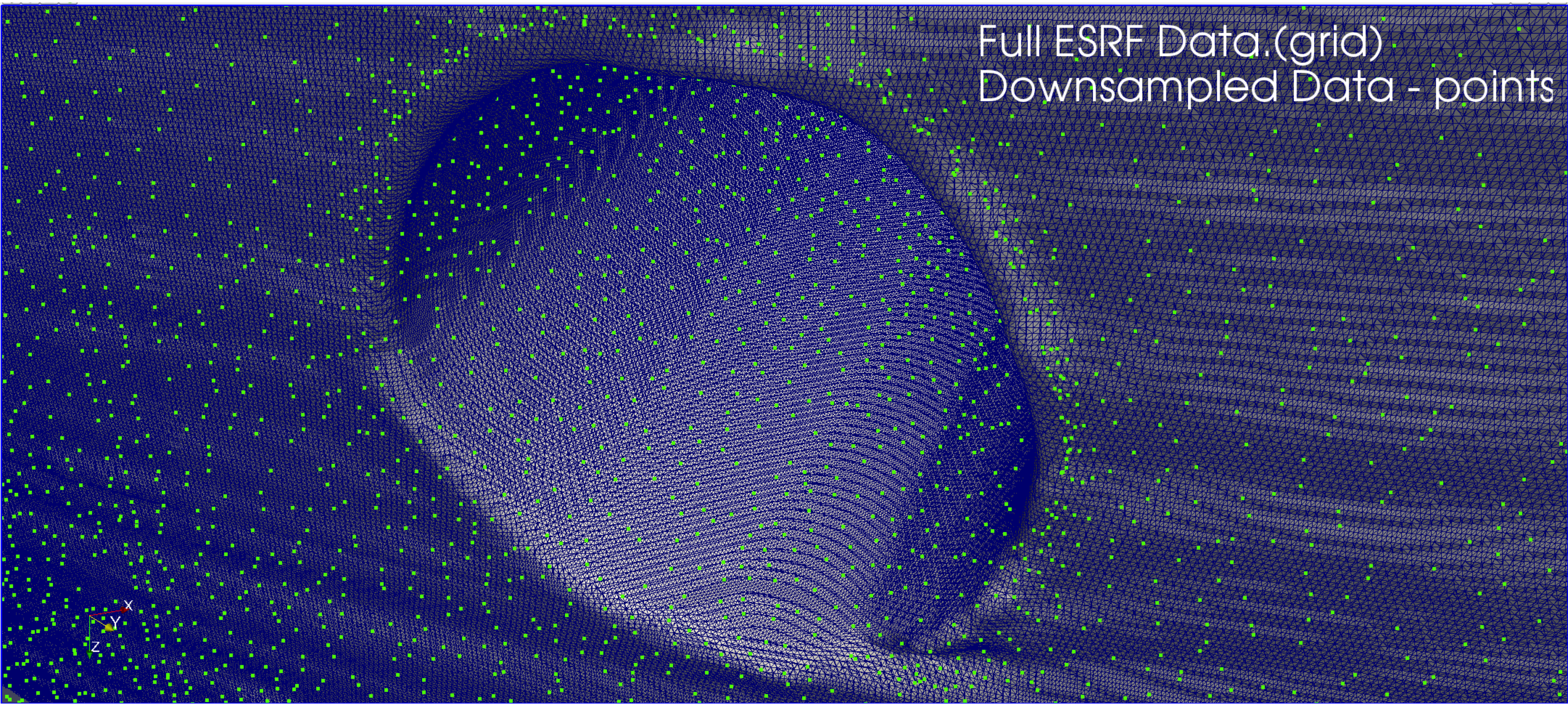


Expand Phoenix data by 3%, overlay, still not quite right

View of Nozzle Hole Outlet



View of Nozzle Hole Outlet

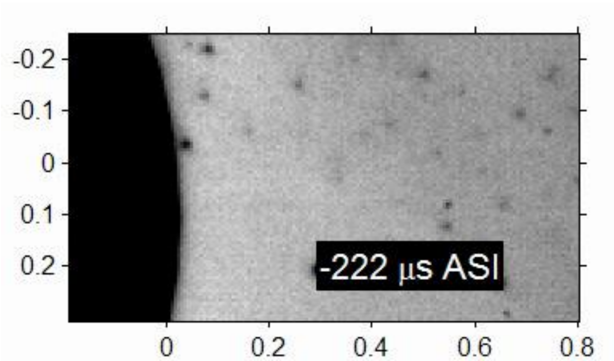


Summary of Spray B #211201 Geometries

- **The Phoenix data is distorted and should preferably not be used**
- **ESRF and Converge geometries match calibration data**
- **The ESRF: 1.5 microns**
- **Converge : 5 microns**
- **Converge geometry is probably suitable for CFD meshing but not for geometry studies**
- **The nozzles have changed over time!**
  - Discussed in Topic 1.2
  - We need to come up with a plan to deal with this

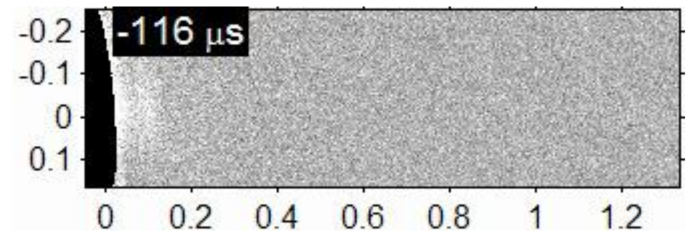
- **Advice for reading the large ESRF STL data…**
  - Paraview is the recommended software
  - You will need at least 8 GB of RAM per node (advise to run in serial if using desktop PC)
  - Very high end graphics card needed for rendering (otherwise 30 sec+ per frame!)
  - If you do not have a high end 3D card, advise loading the Converge downsampled data to navigate the mesh, then switch on the full ESRF data set when ready. Both identically scaled and aligned.
  - Paraview is smart: Zooming in allows faster rendering of image
  - We have software that can chop STL files, we are willing to share

Evidence for Gas in Sac at SOI

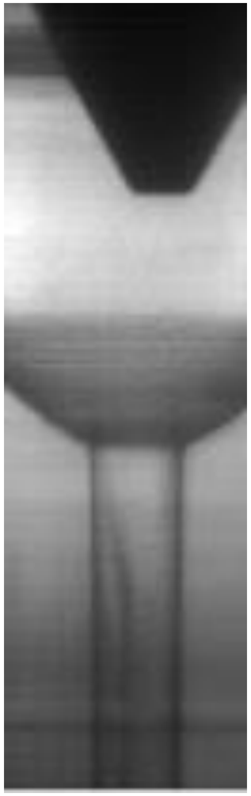


Courtesy of Lyle Pickett

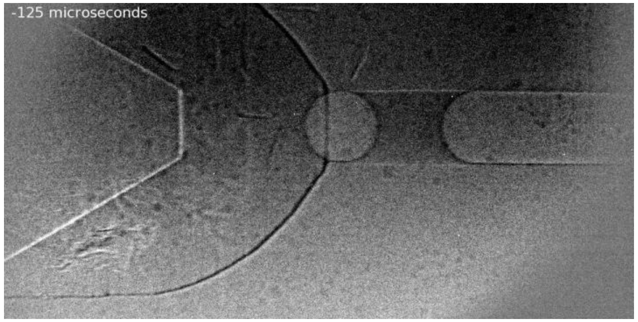
Courtesy of Lyle Pickett

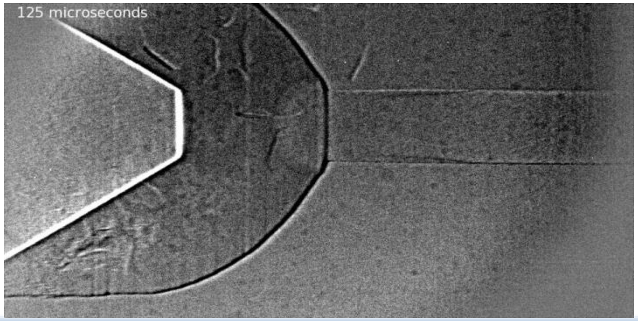


- Sandia: Spray imaging shows droplet pulled into the nozzle just before spray
- Leibniz Universität Hannover: Imaging in transparent nozzle shows fuel pulled into nozzle just before spray
- X-ray imaging: Bubble in nozzles is pulled toward sac just as needle begins to lift



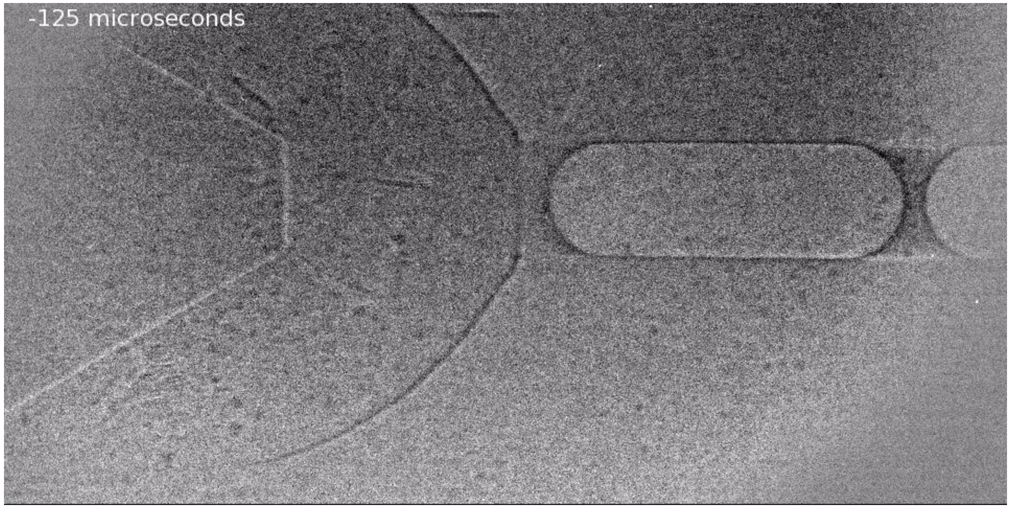
Courtesy of Ansgar Heilig





Evidence for Gas in Sac at SOI (continued)

- At EOI, gas is pulled from the orifice into the sac
- Simulations by Arienti and Battistoni have showed low pressure in sac at needle closure
- Particularly significant in multi-hole nozzles



Note: NOT an ECN injector

Conclusions

- Likely to have an effect on SOI transient
  - Takes time to flush gas from sac, or to dissolve gas in fuel
  - Bubbly mixture during SOI transient?
- Important to simulate this, particularly for Spray B Multi-Hole

Engine Combustion Network (ECN): Measurements of Nozzle Geometry and Hydraulic Behavior

Alan L. Kastengren

F. Zak Tilocco, Christopher F. Powell

Julien Manin, Lyle M. Pickett

Raul Payri

Tim Bazyn

Abstract

Manin, Payri, Kastengren,
Journal of Engineering for Gas Turbines and Power,
December 2012,
Vol. 134 / 122801-1

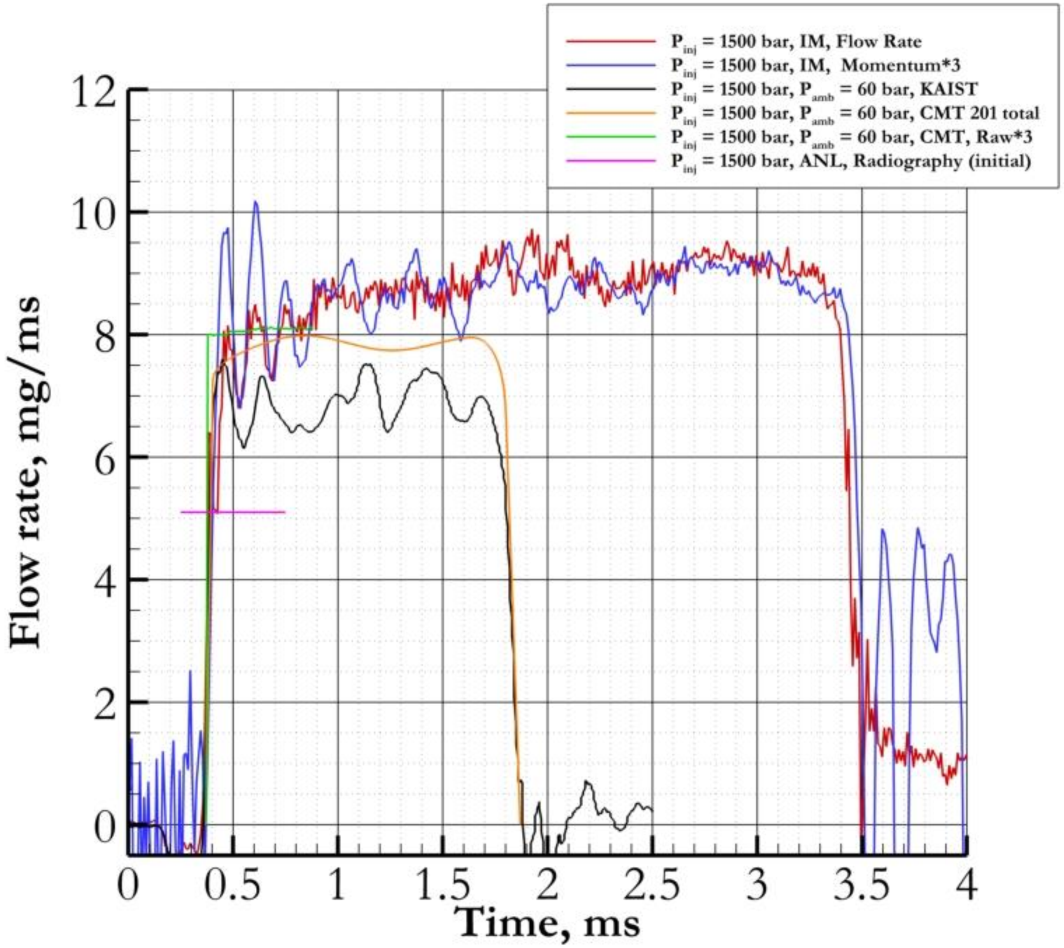
Payri et al,
SAE 2013-24-0001

Proceedings from ECN1, ECN2
ECN web site

Recording of ECN2.3 web meeting
Juan Pablo Viera, CMT
Location: 1h 42m
ECN web site

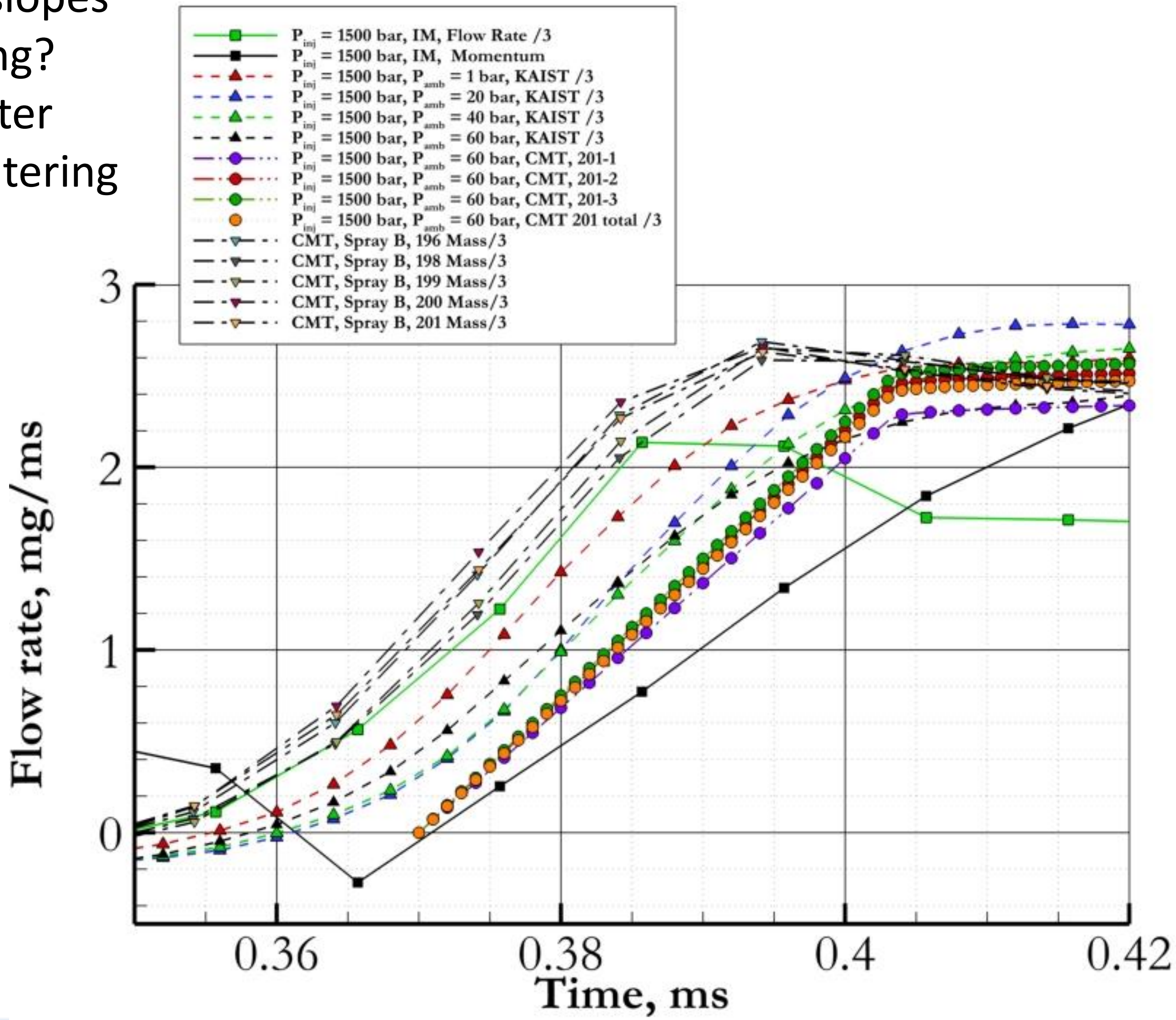
All Institutions, Spray B Standard

- Significant differences between institutions
- Possibly due to differences in analysis:
  - Long-tube method requires calibration of total injected quantity
    1. Calculating based on time of reflected wave. Requires knowledge of speed of sound in fuel, temperature
    2. Measurement by weight
  - CMT used method 2, KAIST used method 1, IM used both

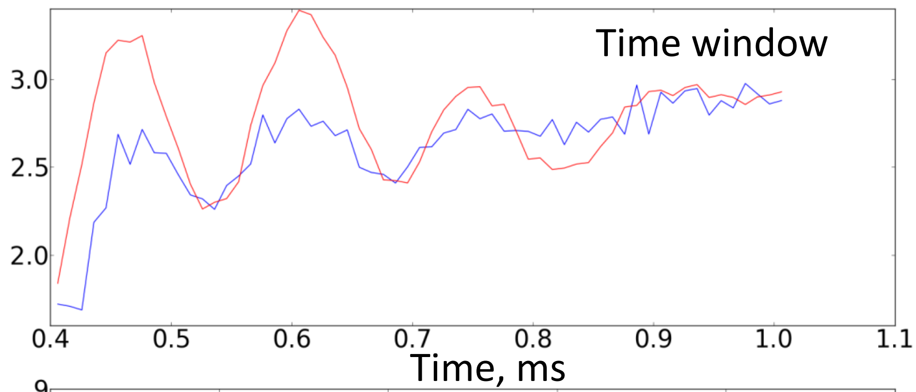


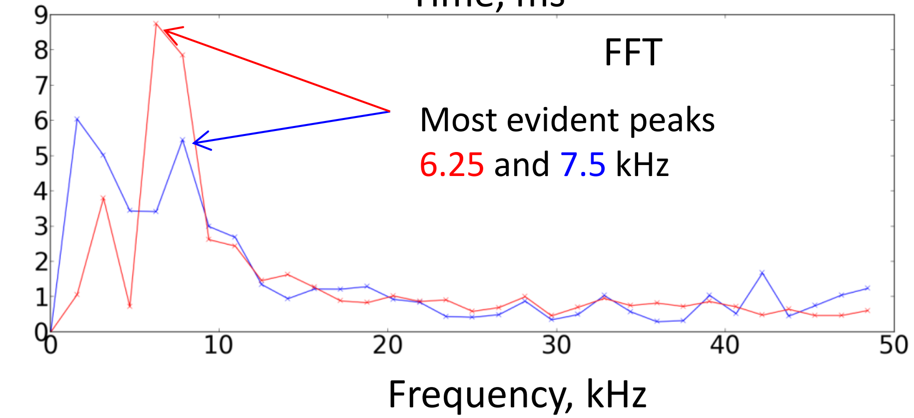
Spray B - Start of Injection Transient

- Very good agreement in slopes
- Possibly a result of filtering?
  - KAIST used 30 kHz filter
  - IM, CMT report no filtering



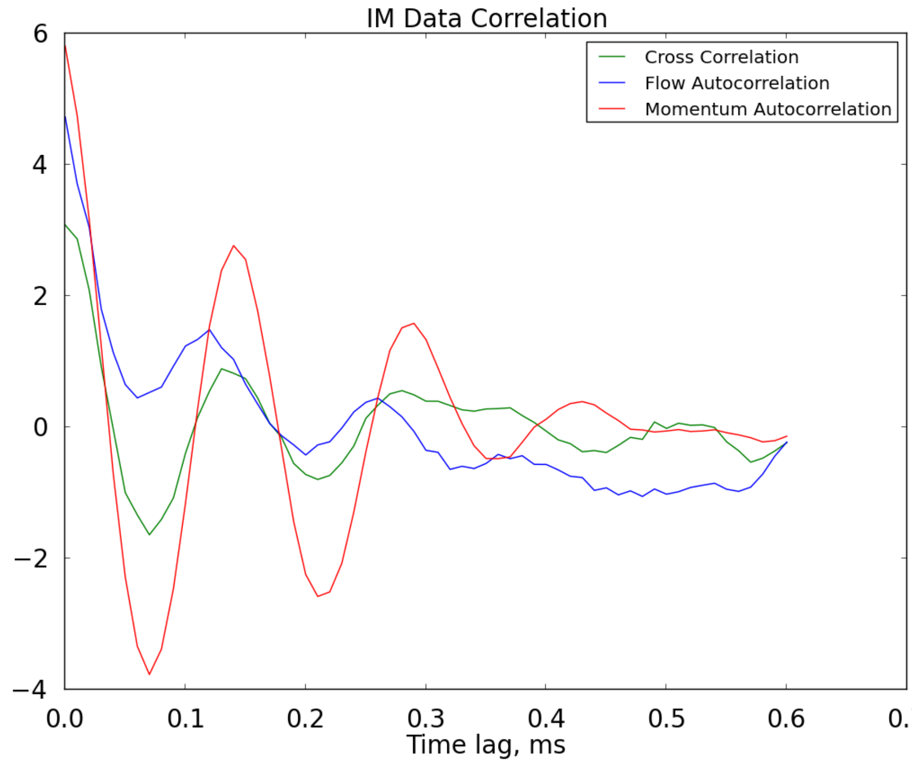
Frequency Analysis – Istituto Motori





Momentum Data
Flow Data

Fluctuations at spray are analyzed (not shown) from momentum data. Peaks at 2.5, 6.6, 8.9 kHz



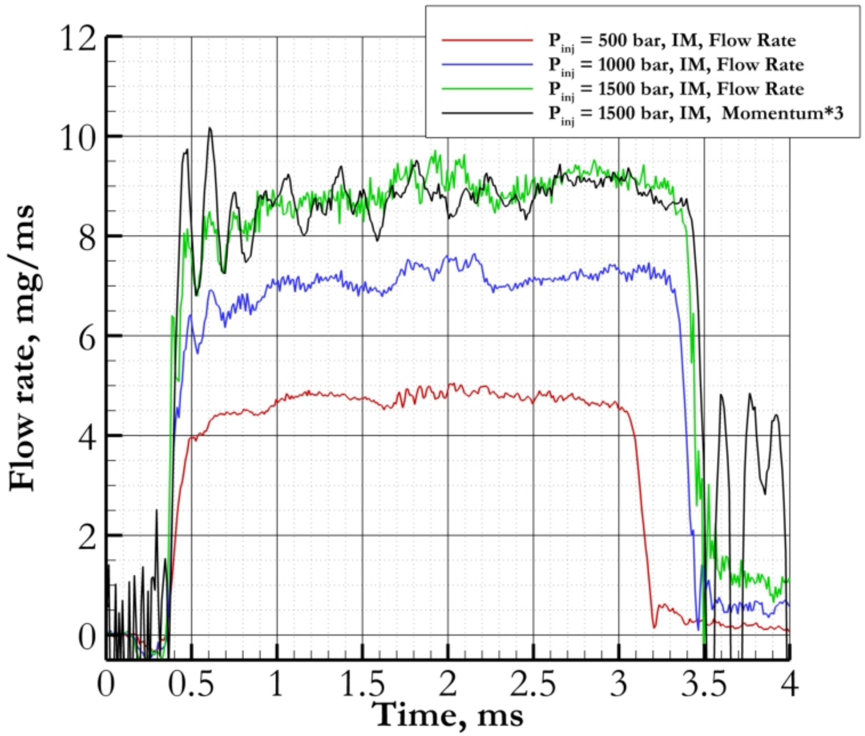
First evident positive peaks :
0.14 ms (7.14 kHz)
0.12 ms (8.33 kHz)

Lag between signals is not detectable with point resolution (<0.010 ms), could fit with Gaussian. Momentum signal appears to lag though from the flow signal.

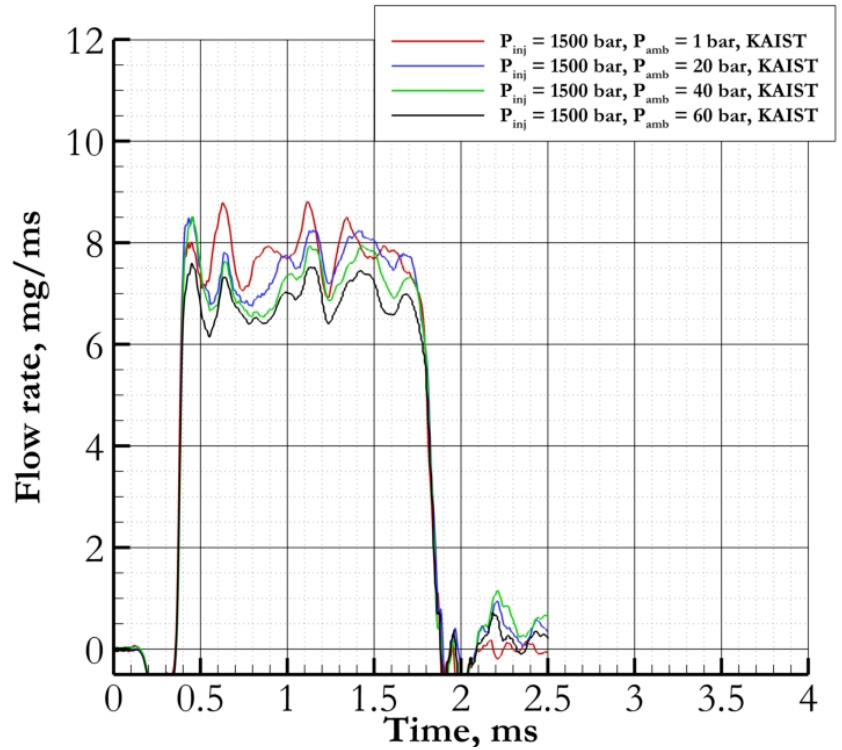
Summary of Frequencies in ROI

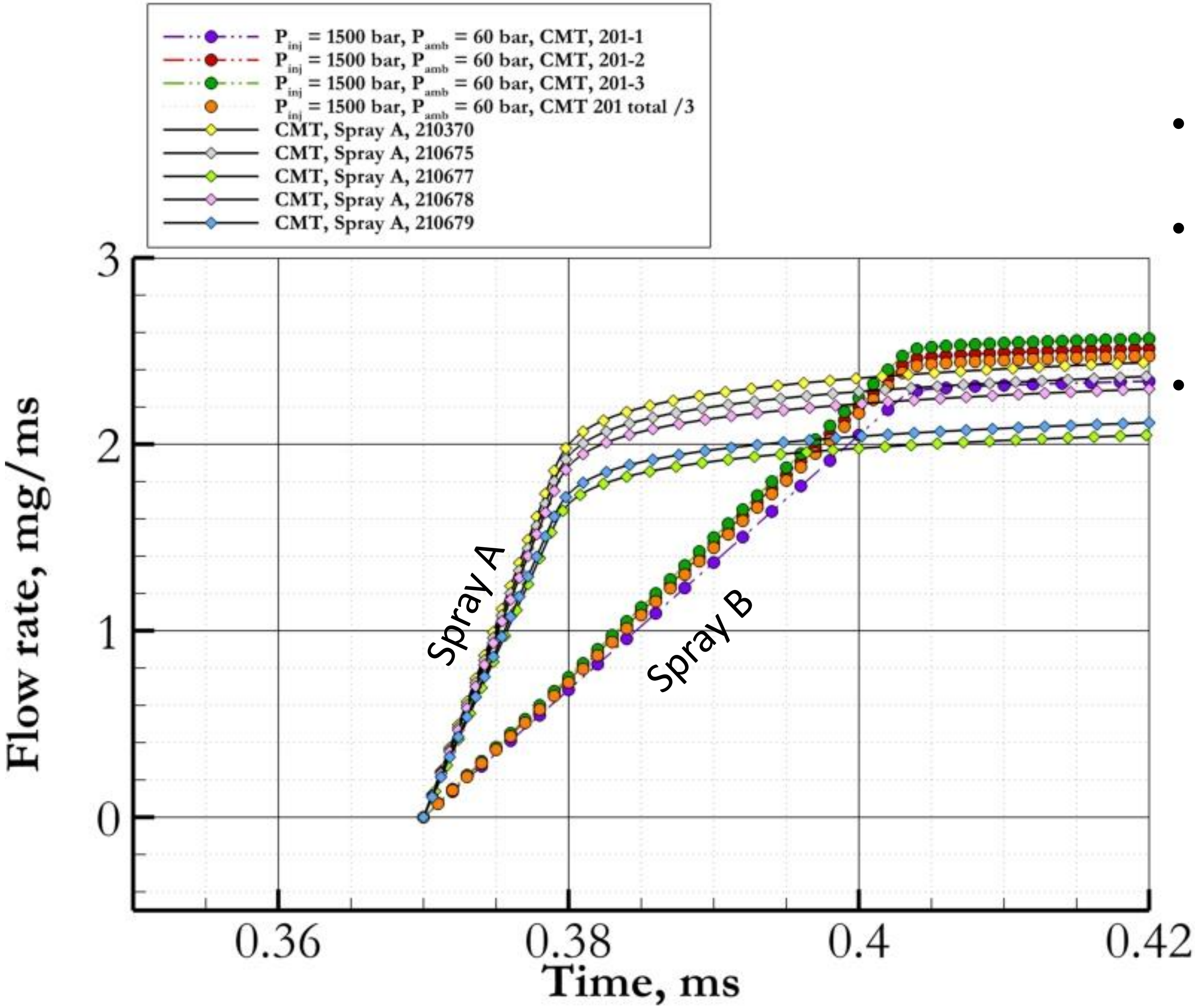
Data Set	FFT frequencies [kHz]	First Autocorrelation Peak [ms]/[kHz]
IM Momentum Data	6.25	0.14/7.1
IM Flow Data	7.5	0.12/8.3
KAIST 1 bar ambient	4.4	0.232/4.3
KAIST 20 bar ambient	0.91, 3.9, 5.9	0.192/5.2
KAIST 40 bar ambient	0.9, 3.0, 3.9, 5.9	0.182/5.5
KAIST 60 bar ambient	0.9, 2.8, 3.8, 5.8	0.196/5.1

Injection Pressure by Istituto Motori

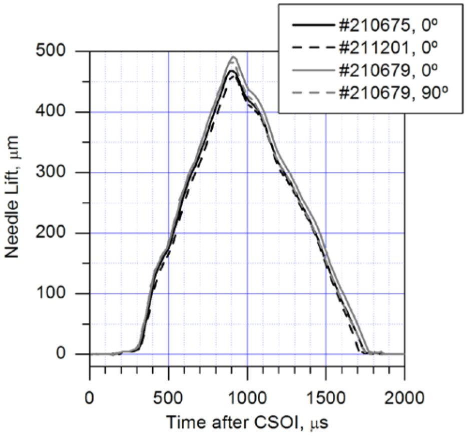


Ambient Pressure by KAIST





- Spray A shows increased ROI at SOI
- Correlates with significantly faster penetration (Topic 1.2)
- Needle lift identical



Summary – Rate of Injection

- Significant difference in steady-state flow across institutions
  - Possibly due to diffferent analysis techniques
- Similar start-of-injection transient
- If oscillations are smoothed, steady state flow is nearly flat
  - Differs from TIM measurements, see topic 1.2
- No common oscillation frequencies between institutions
- Parametric variations on Spray B are available

- Should standardize measurement and analysis techniques
  - Recommend Payri SAE Paper as a starting point

Acknowledgements

- Measurements of Nozzle Geometry
  - Tim Bazyn (Caterpillar)
  - Peter Hutchins (Infineum)
  - Convergent Science
  - Caroline Genzale (Georgia Tech)
  - Lyle Pickett (Sandia)
  - Ali Chirazi (CNRS)
  - Daniel Duke (Argonne)
- Evidence for Gas in Sac
  - Lyle Pickett (Sandia)
  - Alan Kastengren (Argonne)
  - Ansgar Heilig (Leibniz University Hanover)
- Rate of Injection
  - Raul Payri (CMT Motores Termicos)
  - Luigi Allocca, Alessandro Montanaro (Istituto Motori)
  - Jaeheun Kim, Cheongsik Bae, Kihyun Kim (KAIST)
  - Julien Manin (Sandia)
  - Andrew Swantek (Argonne)