TOPIC 8

Spray G Nozzle Geometry and Internal Nozzle Flow

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1. Nozzle geometry and near-nozzle experiments
2. Internal and near-nozzle flow modeling

Contributors / Acknowledgements

- Scott Parrish, Ron Grover (GM R&D)
  - Near nozzle-tip imaging, Rate of Injection, PDA
- Lee Markle (Delphi)
  - Patternation
- Julien Manin, Lyle Pickett (Sandia)
  - Microscopy, Tomography, geometric analysis
- Raul Payri, Jaime Gimeno, Pedro Marti-Aldaravi, Daniel Vaquerizo (CMT)
  - ROI, ROM, Silicone mold
- Alan Kastengren, Daniel Duke, Andrew Swantek, Nick Sovis, Chris Powell (ANL)
  - Radiography & Tomography

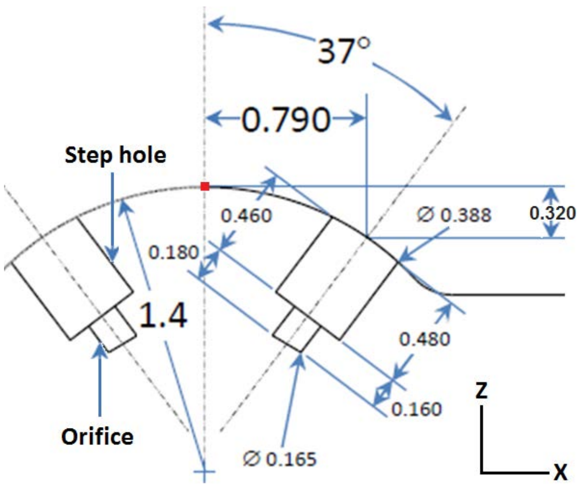
Outline

- Nozzle Geometry
  - X-ray tomography
  - Microscopy
  - Meshes used for simulation contributions
  - Deviation of actual injector geometry from ideal
- Internal & near nozzle experiments
  - Rate of injection & rate of momentum
  - Patternation
  - Near tip microscopic imaging
  - X-ray radiography
- Internal flow modeling contributions

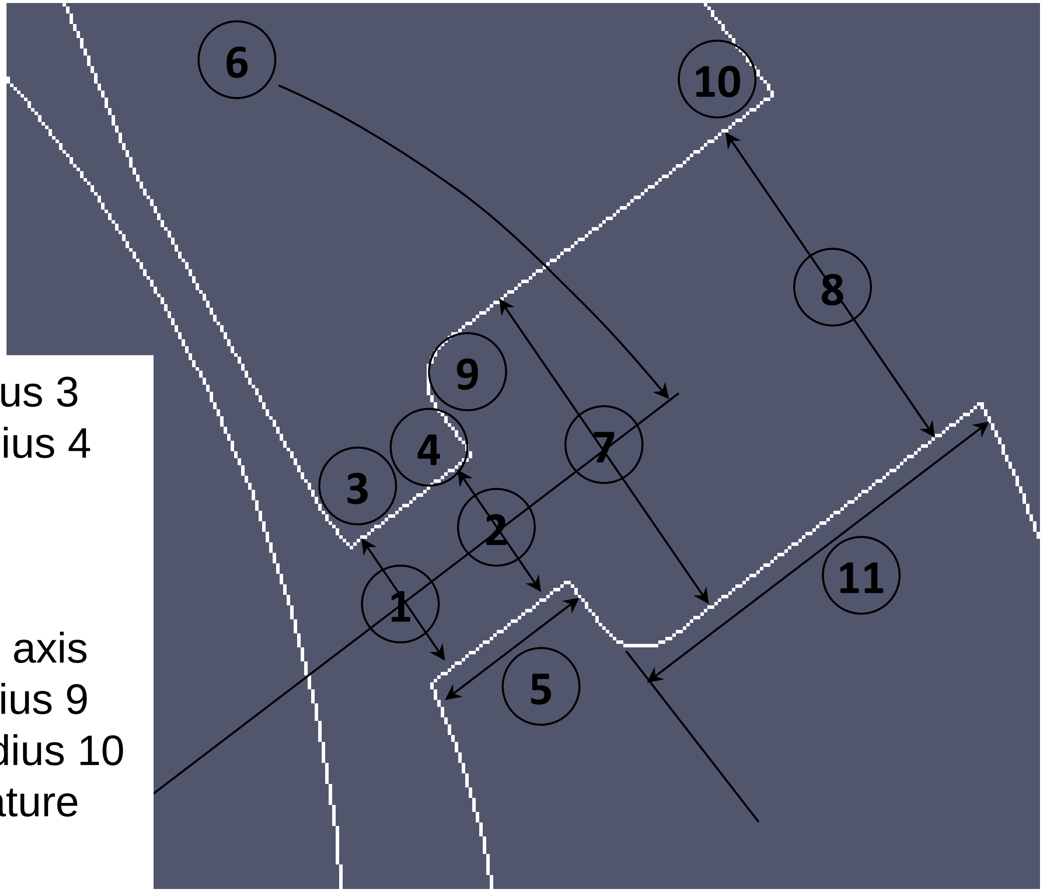
Goals of Topic 8

- Characterize the geometry of the Spray G injectors
- Evaluate the available measured geometries in terms of accuracy and precision
- Decide on a “reference” geometry
- Experimentally characterize the internal flow of Spray G nozzles
- Co-ordinate simulations of the internal flow
- If possible, determine best practices for nozzle flow simulations

Critical Features



"Specified" geometry with "open" pintle/ball



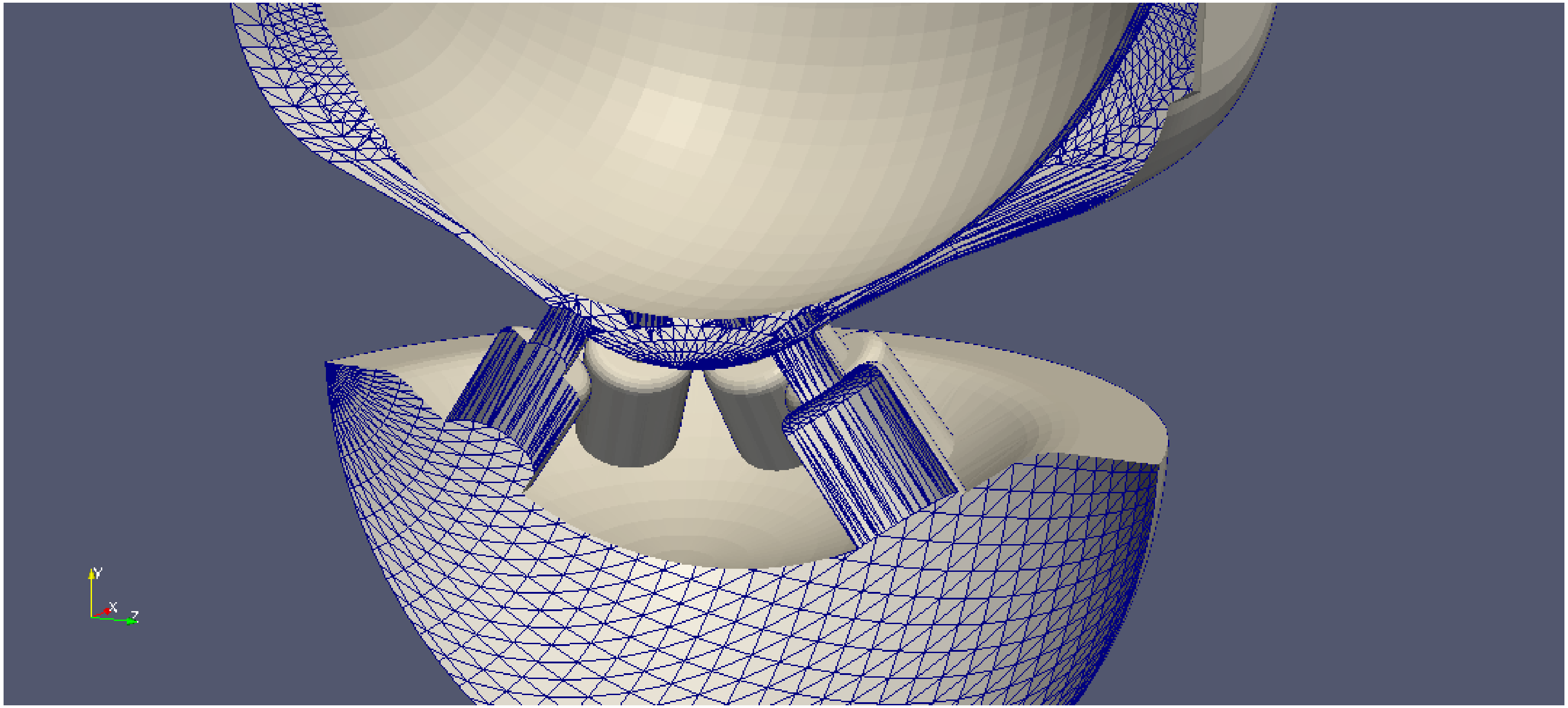
1. Inner hole inlet diameter after inlet radius 3
2. Inner hole exit diameter before exit radius 4
3. Inner hole inlet radius of curvature
4. Inner hole exit radius of curvature
5. Inner hole length
6. Inner hole drill angle relative to injector axis
7. Outer hole inlet diameter after inlet radius 9
8. Outer hole exit diameter before exit radius 10
9. Outer hole inlet reverse radius of curvature
10. Outer hole exit radius of curvature
11. Outer hole length

Spray G geometries

Name	Source	Resolution	Format	*Note*
Northstar X-ray	Benchtop x-ray tomography	5.07 micron	STL	*Available online*
Sandia Microscopy	Optical microscopy of hole diameters	2 micron	Powerpoint slides	*Presented at ECN web meeting*
ESRF Tomography	Synchrotron x-ray tomography	1.325 micron	Volume images	*Wall isosurface not available*
ANL Tomography	Synchrotron x-ray tomography	1.845 micron	Volume images	*Wall isosurface not available (yet)*
GridPro "Ideal"	Ideal geometry		OpenFOAM Mesh	*All holes same dimensions.* ***Used for simulation contributions***
GridPro "Informed"	Ideal geometry, key features adjusted		OpenFOAM Mesh	*All holes same dimensions*

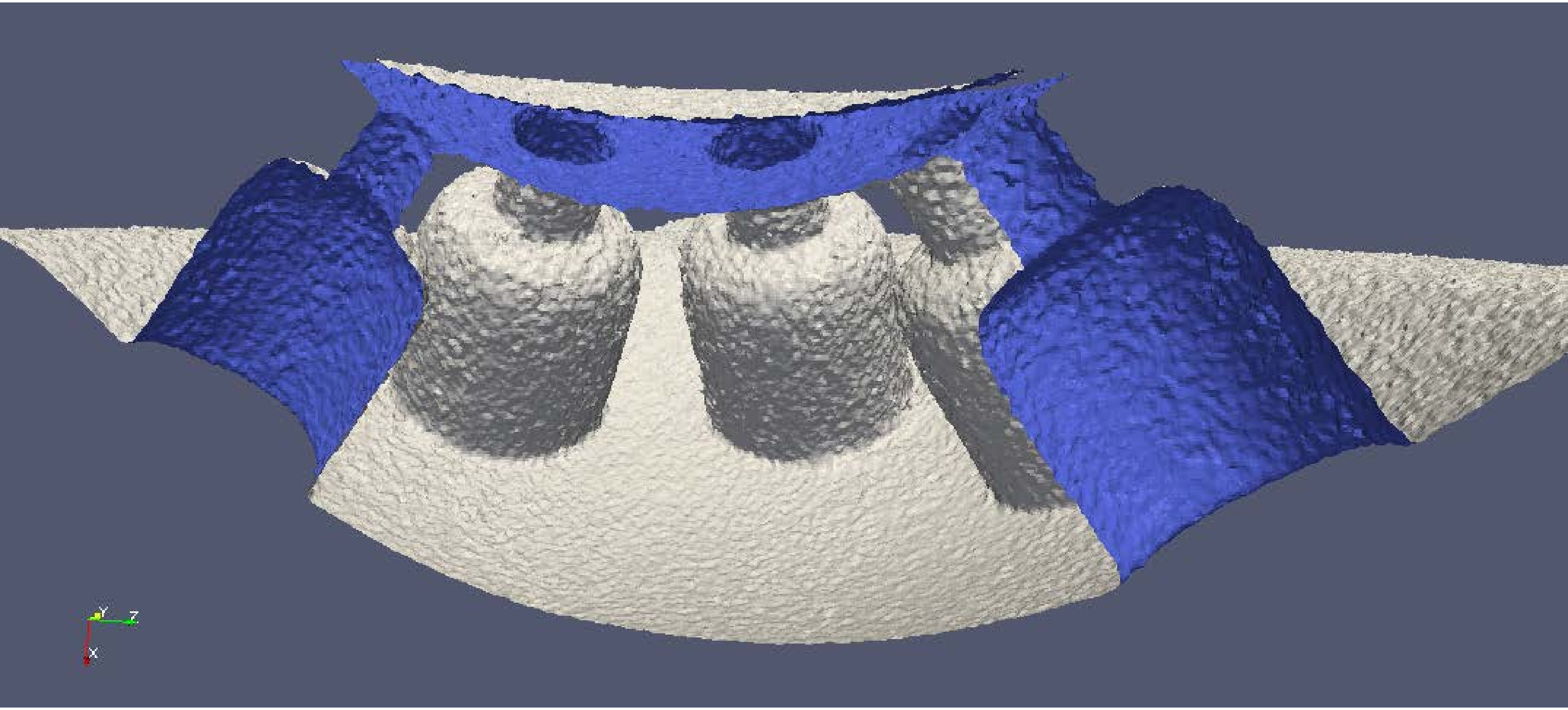
Short history of the Spray G geometry

- Original ideal geometry from injector design dimensions

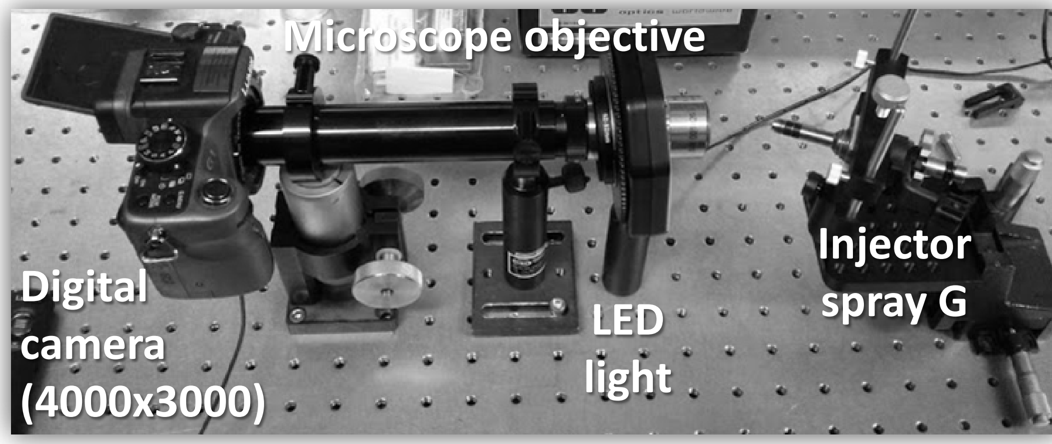


Short history of the Spray G geometry

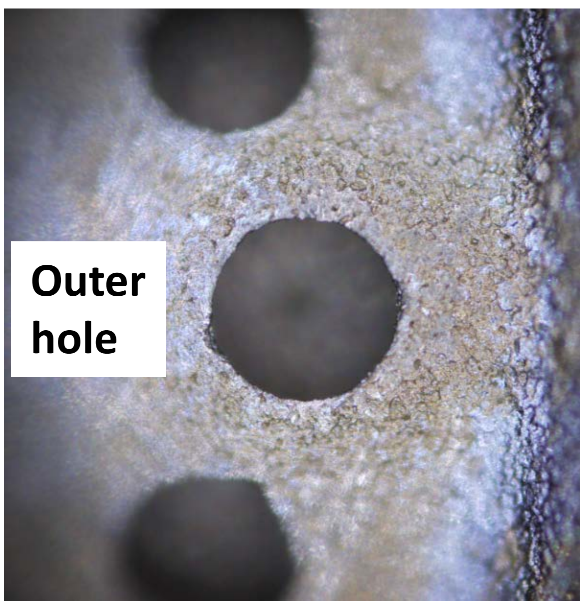
- Measurements from Northstar & Sandia used to update "informed" mesh – all holes same

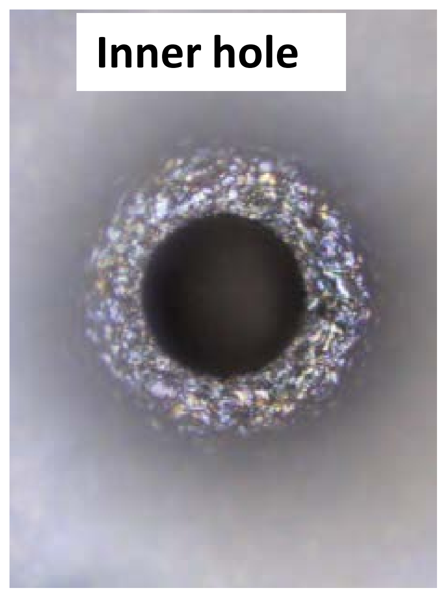


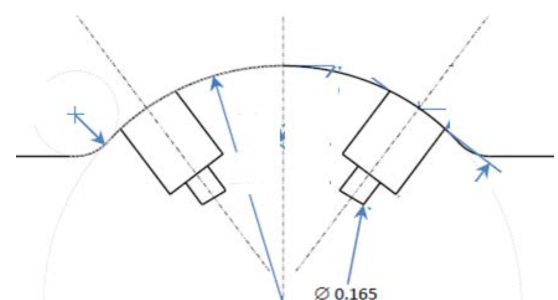
Sandia microscopy



- Lens: Plan Apochromat Objective (Edmund), 10X
- Spatial resolution : ≈ 2.34 pixel/µm

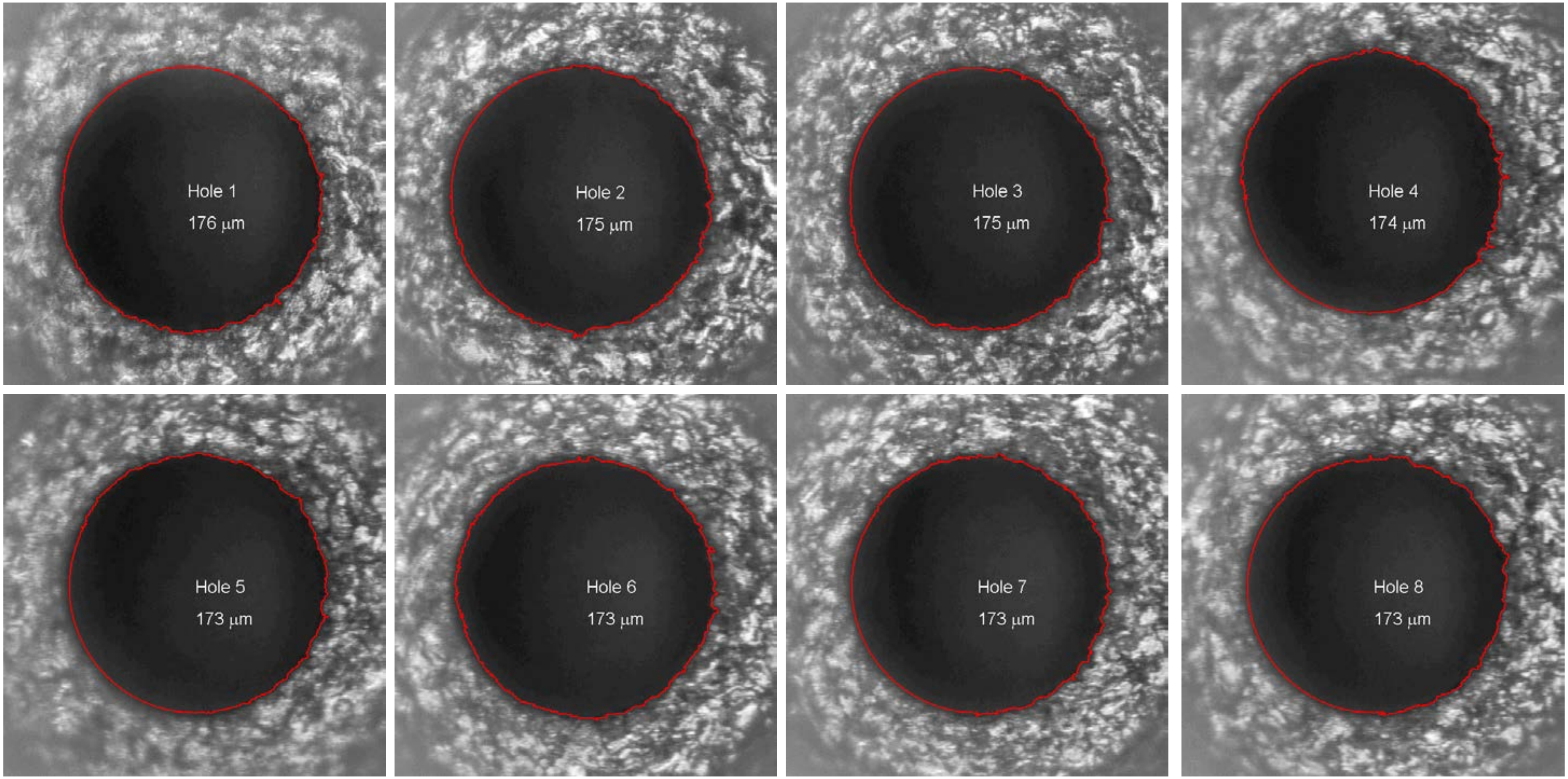






Schematic of cross sectional area

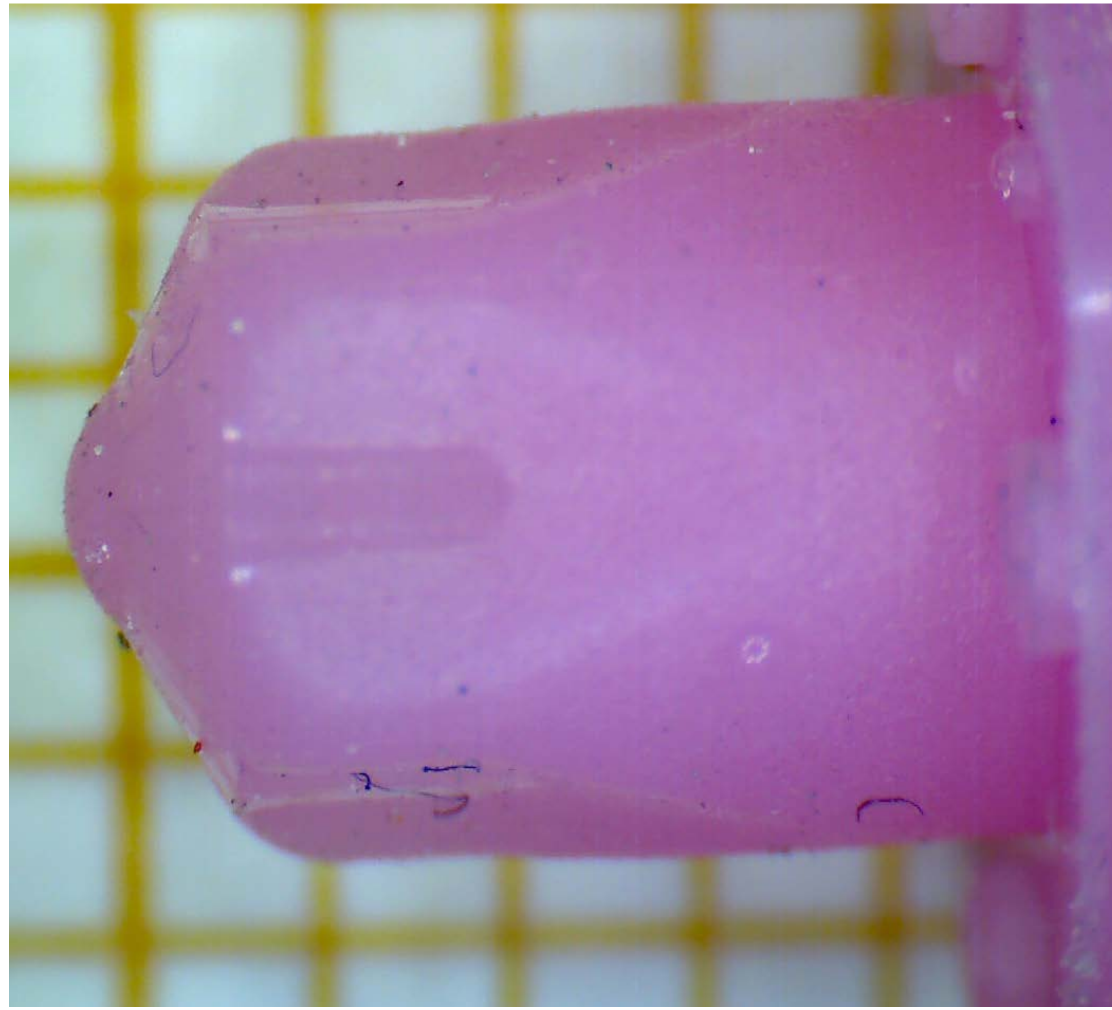
- Measurements from Northstar & Sandia used to update “informed” mesh – all holes same



GridPro Ideal vs. Informed

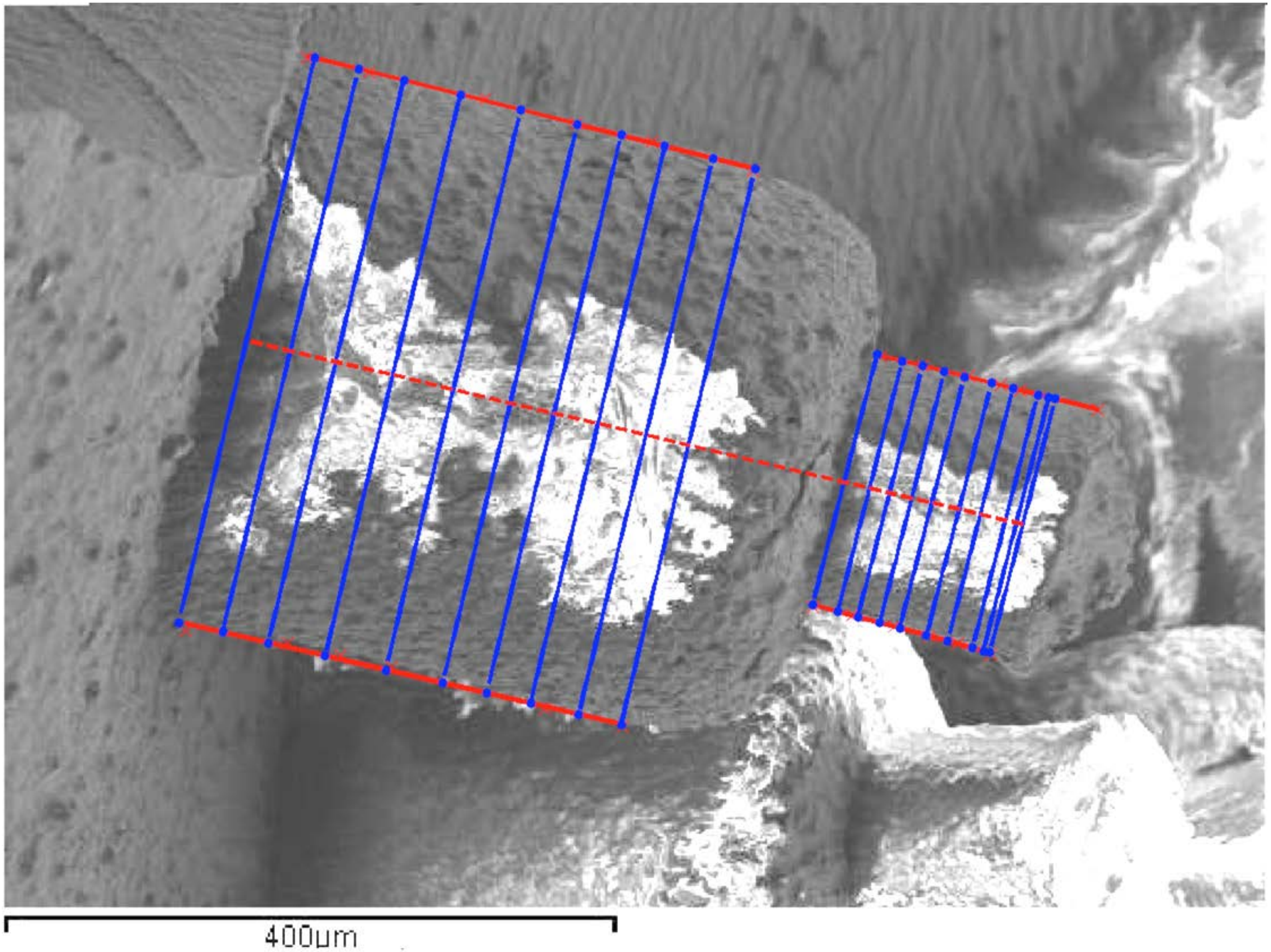
	Specification	Recommendation	Justification comment
1.Inner hole inlet diameter after inlet radius 3	0.165 mm	0.170 mm, all holes	The 5 um increase is justified based on the optical to Northstar comparison at 2. The 3 um divergent taper to 2 is based on the mean profile from the stl. Even though the exact size may not be accurate in the stl, the slight divergent taper is consistent for all holes, so we include it. Any hole by hole adjustment is premature.
2.Inner hole exit diameter before exit radius 4	0.165 mm	0.173 mm, all holes	We believe the Northstar stl method finds a surface that is too small because the metal-air gradient is poorly resolved. Optical microscopy measurements comparable to 2 are greater than 175, and easily 5 um higher than the stl boundary at 2. 173 um is reasonable accounting for uncertainty in the microscopy
3.Inner hole inlet radius of curvature	0 mm	0.005 mm, all holes	The Northstar data is unresolved for this, and cannot be used. ESRF data still shows some radius. Measurements of ESRF data show even 0.010 mm radius, but we estimate low at 0.005 mm because ESRF data also may suffer from noise. More hole by hole analysis is needed.
4.Inner hole exit radius of curvature	0 mm	0.005 mm, all holes	Same comments above.
5.Inner hole length	0.160 - 0.180 mm	no change	No conclusive data. Complicated because one value does not work for both sides of hole.
6.Inner hole drill angle relative to injector axis	37.0 degrees	37.0 degrees	Analysis of Northstar .stl shows 2 degrees variation from specification, but fit is made over only very short hole length. Need more confidence in the stl shape to go further.
7.Outer hole inlet diameter after inlet radius 9	0.388 mm	0.388 mm	Fair agreement in stl and optical microscopy. No change is warranted.
8.Outer hole exit diameter before exit radius 10	0.388 mm	0.388 mm	measurements show a only a very slight taper, 4 um over 0.3 mm, so change likely not important.
9.Outer hole inlet reverse radius of curvature	0.040 mm estimate	0.080 mm	Just put a circle on slide 8 on both sides of the hole and calculated its size. Double the specification. A needed change.
10.Outer hole exit radius of curvature	0 mm	0 mm	Edge looks sharp in ESRF and Northstar tomography. No change.
11.Outer hole length	0.460 - 0.480 mm	no change	Not analyzed

- Silicon mold from CMT

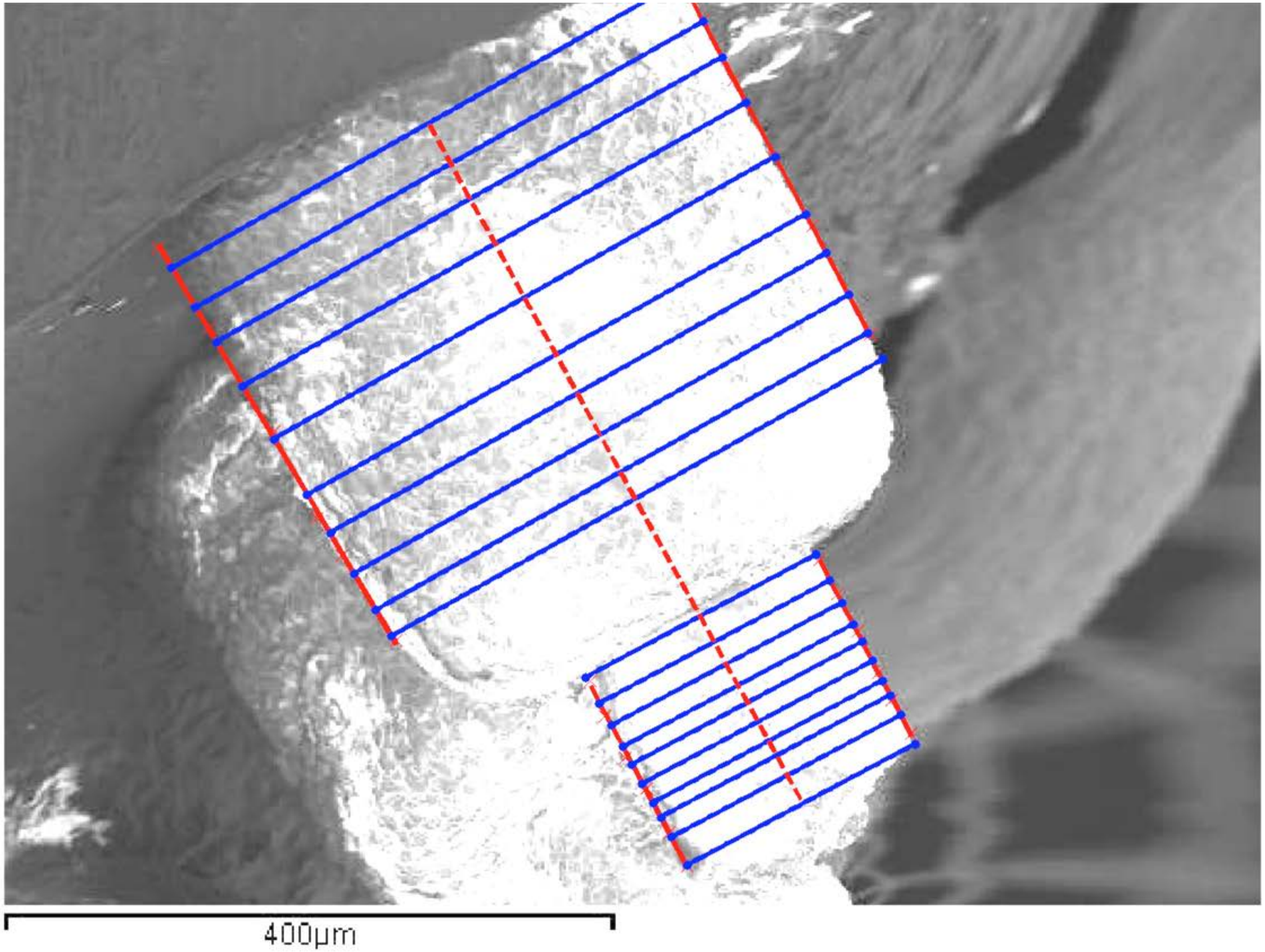
Further investigation of Spray G geometry

- Silicon mold from CMT

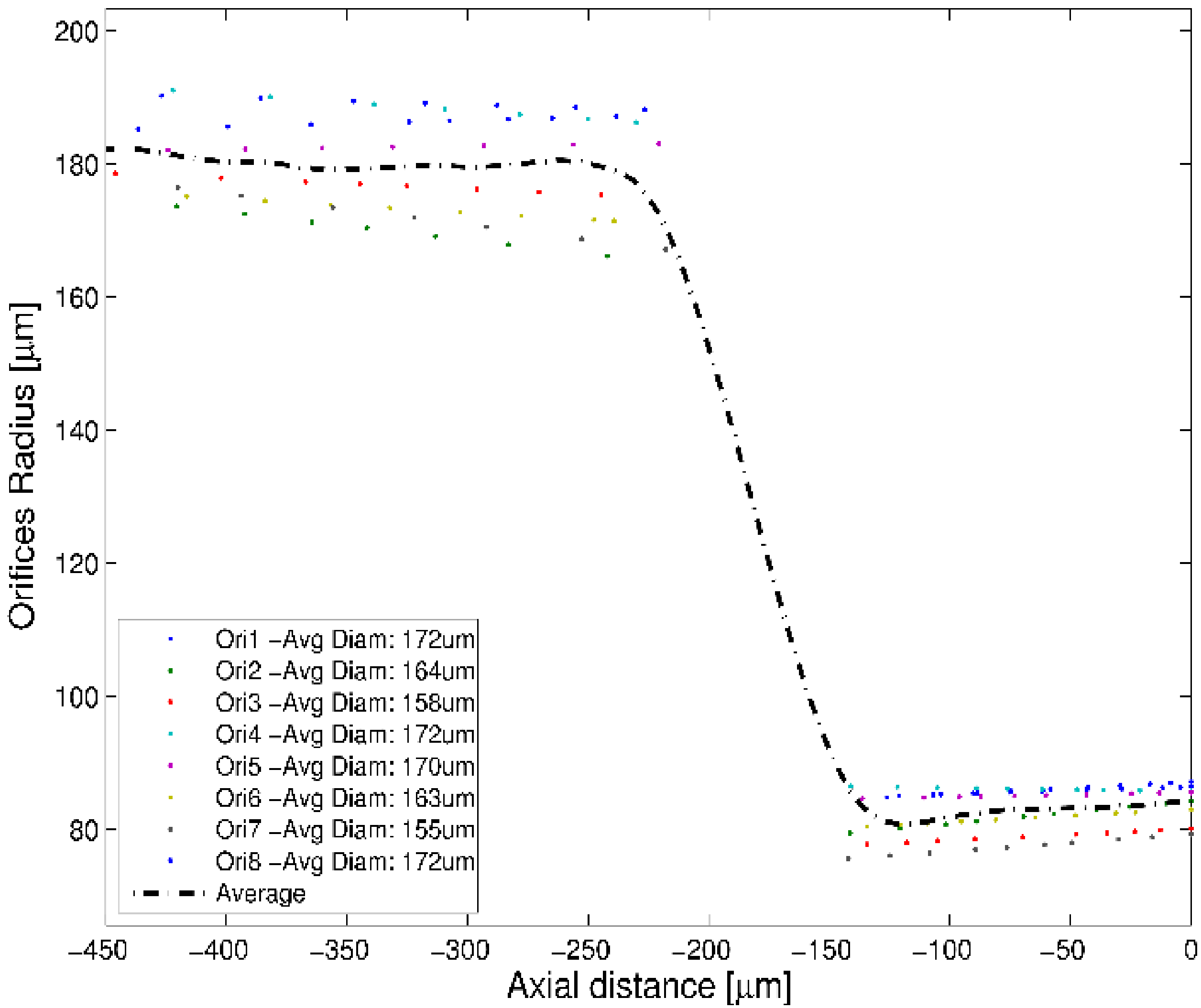


Further investigation of Spray G geometry

- Silicon mold from CMT

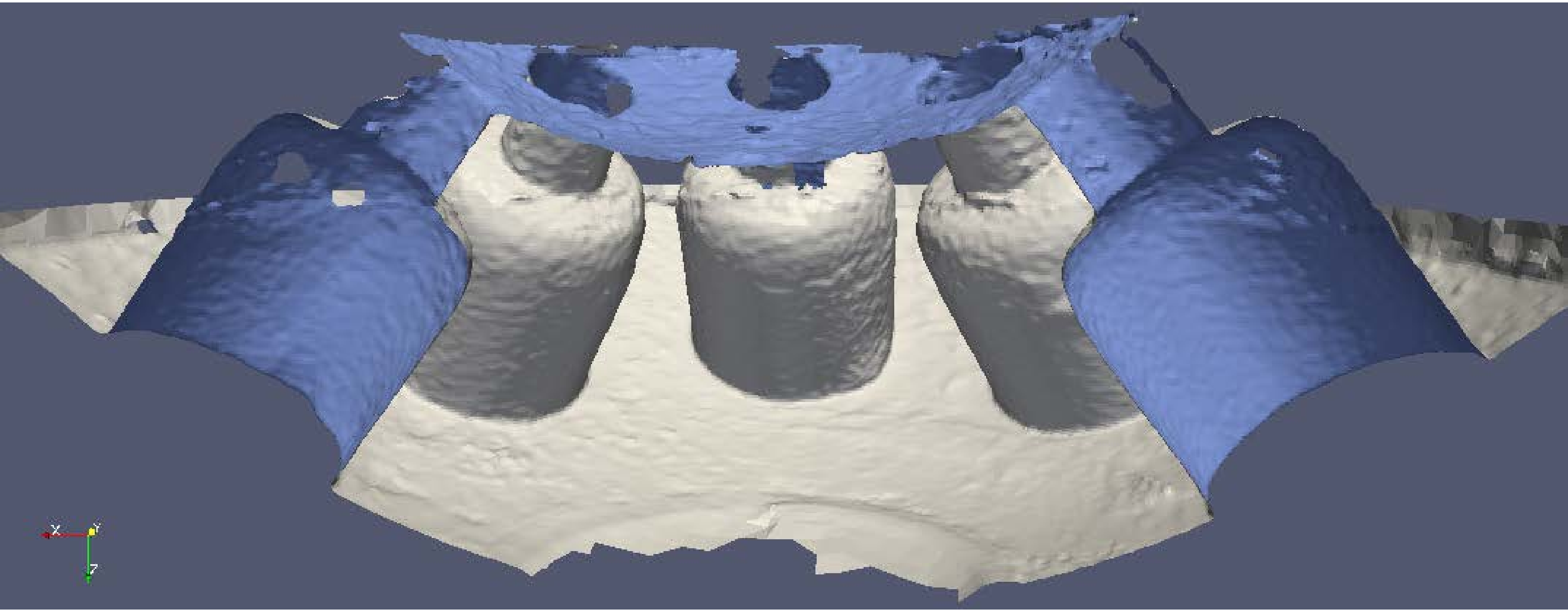


CMT Silicon mold



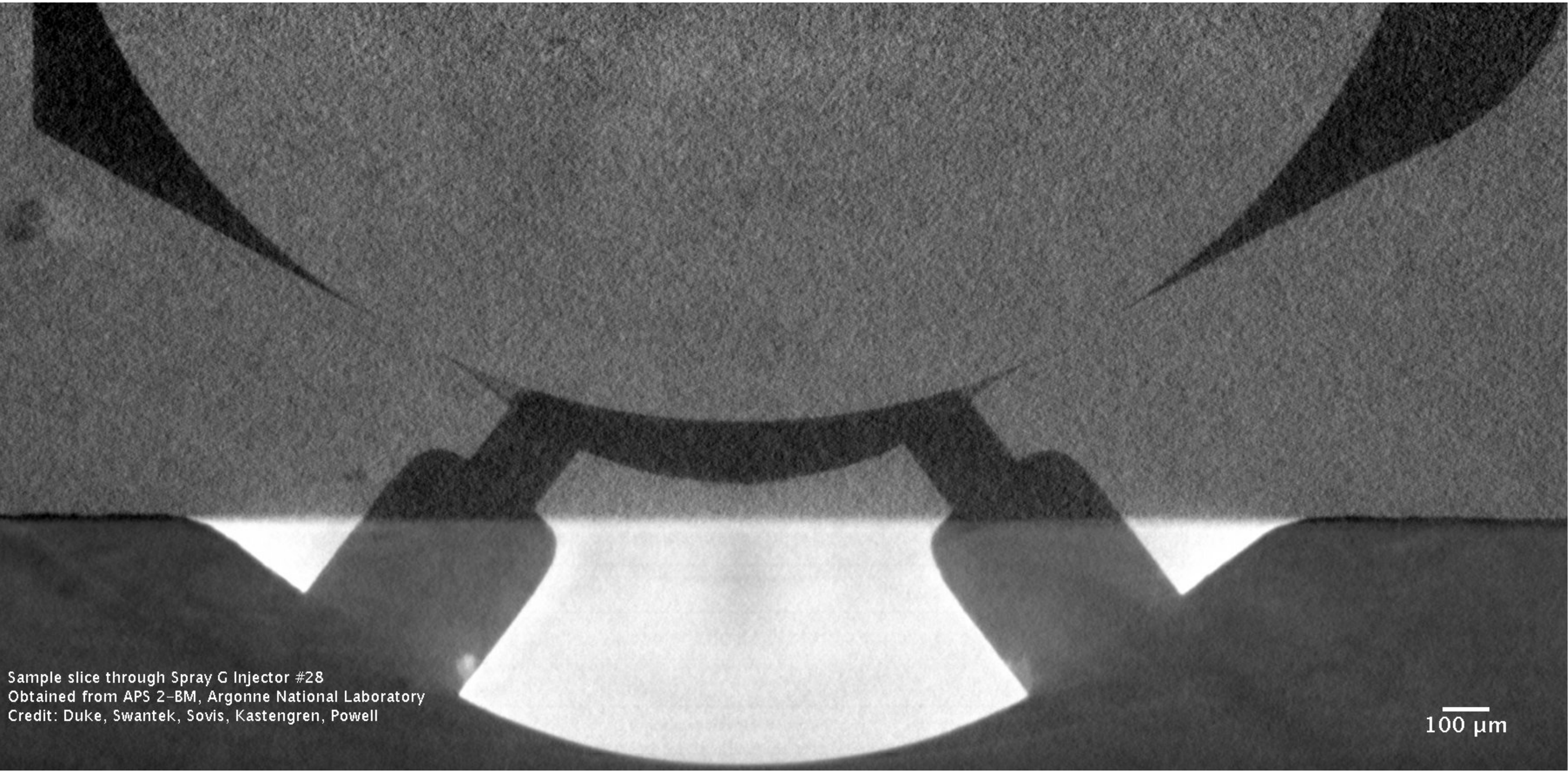
Short history of the Spray G geometry

- ESRF tomography data
  (Peter Hutchins, Chris Powell & Alan Kastengren)
- Data was too large to be easily analyzed
- Iso-surface too noisy for direct meshing
- Measurements now available of key features for cross-check

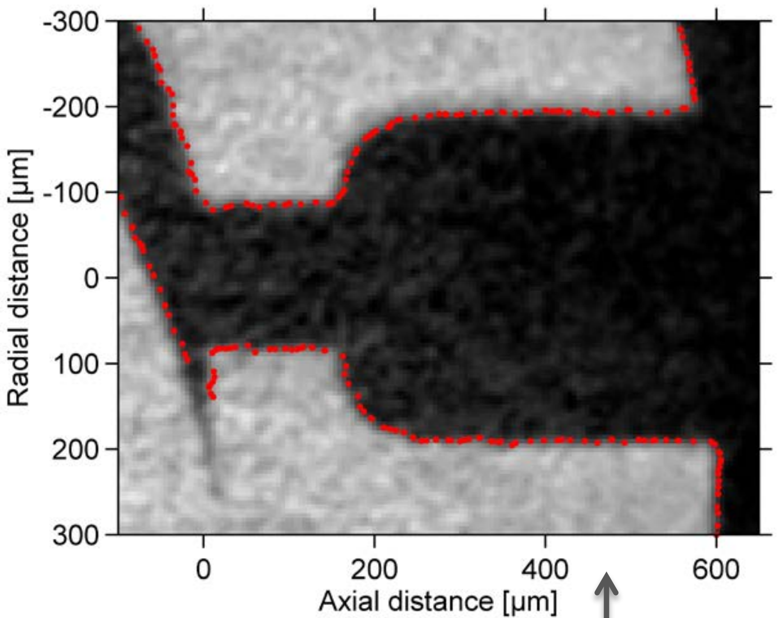


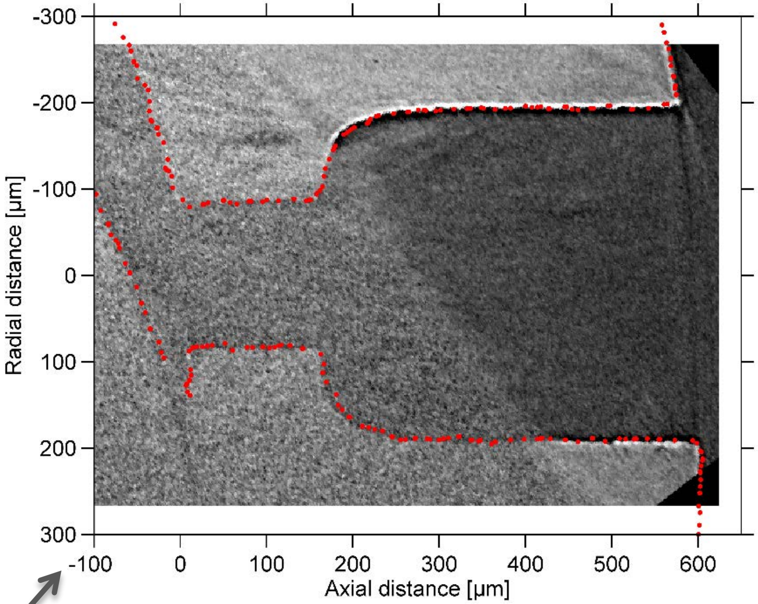
Short history of the Spray G geometry

- New tomography data from APS available, which can be used to make a 3rd generation mesh (next round of Spray G)

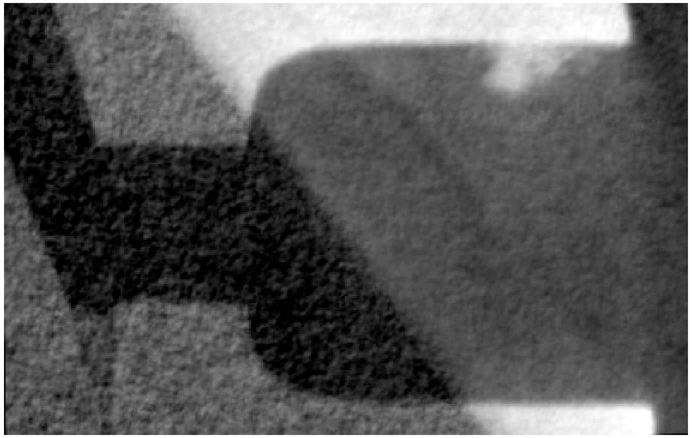


Comparing X-ray Tomography Datasets





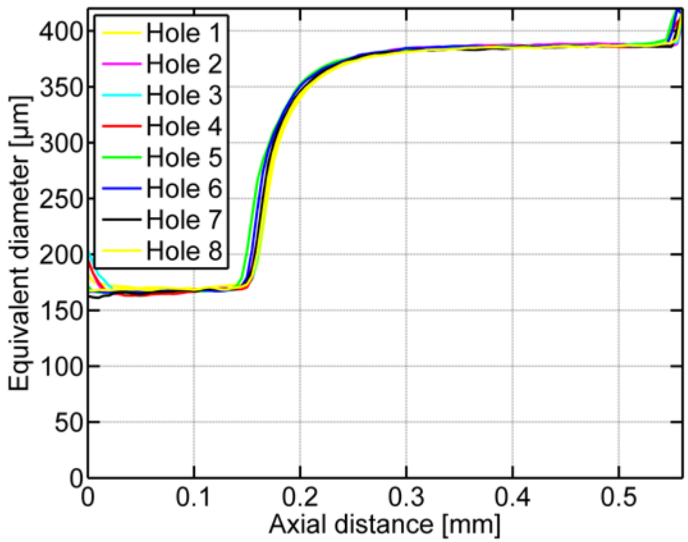
- Northstar tomography (5.07 micron)
  - Low resolution
- ESRF tomography (1.325 micron)
  - Poor SNR, big dataset
- ANL tomography (1.845 micron)
  - *Open source reconstruction code*
  - Less resolution, better SNR
  - Currently too large to isosurface

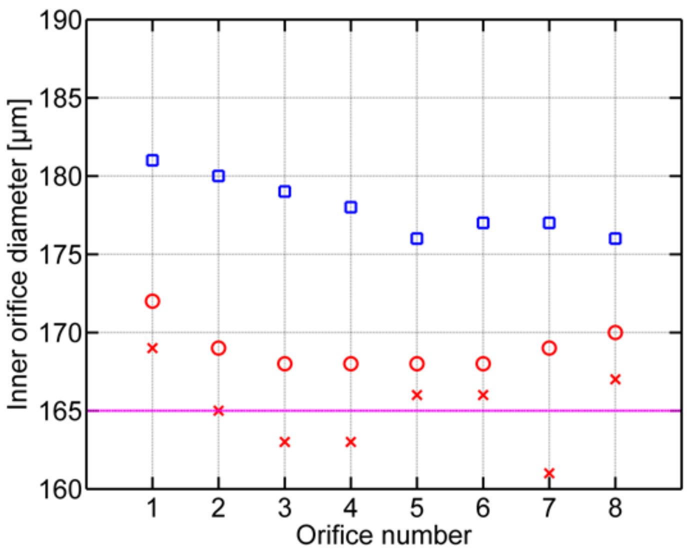


Comparison to Microscopy

Manin et al, SAE Paper 2015-01-1894

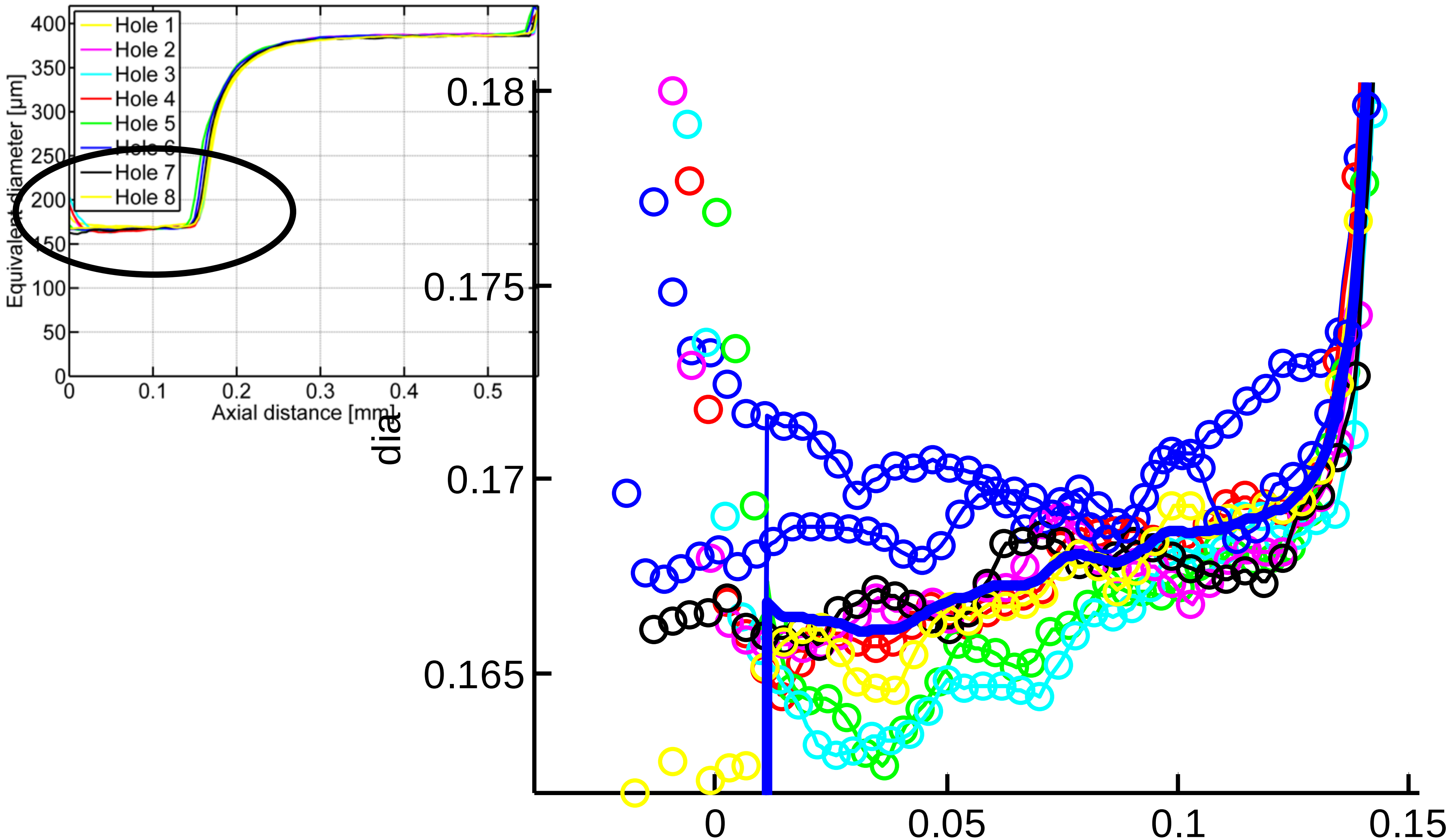
- Optical microscopy provides relatively accurate measurement of outlet equivalent diameter
- But the measurements only consider the very exit of the orifice
  - Problematic when the orifice is cylindrical or inversely tapered



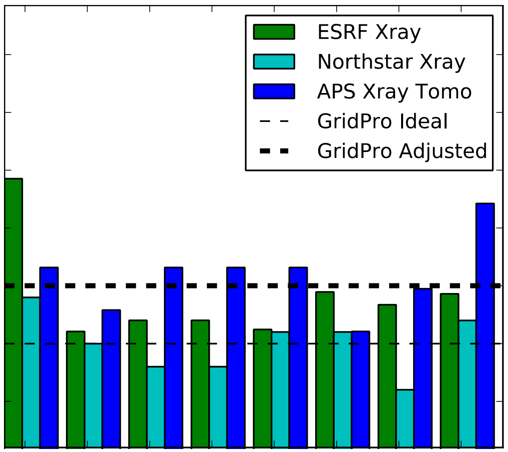


- The optical microscopy measurements show larger diameters than the x-ray-derived STL data
- X-ray tomography shows that the minimum hole diameter is slightly smaller than the value measured near the exit

Northstar X-ray: Divergence of holes

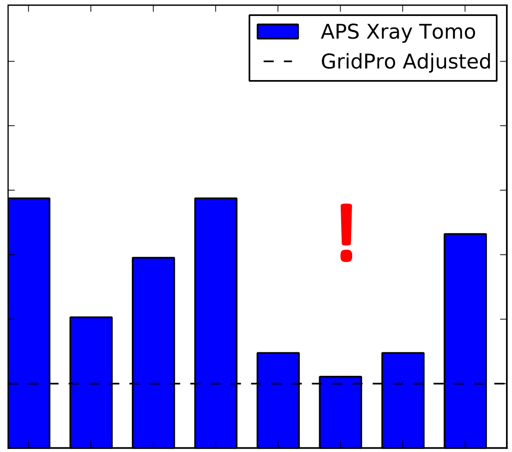


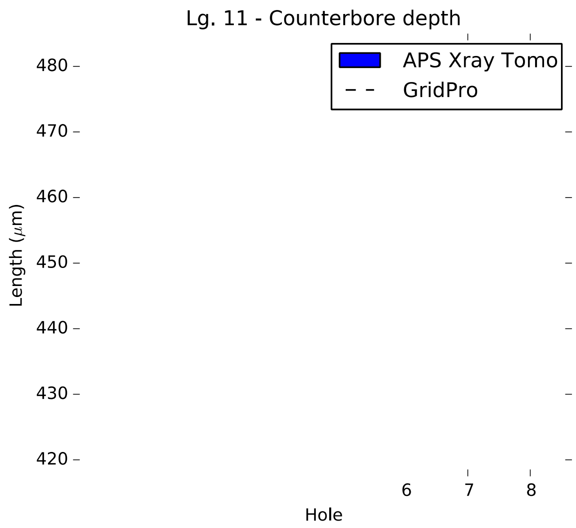
Injector 28 – deviation from ideal geometry



- Diameters improved but need more adjustment
- Drill angle ok
- Counterbore dia. probably ok

Injector 28 – deviation from ideal geometry





Geometry – conclusions / discussion points

- Hole diameters vary by 11 um (6%)
  - Correlated with plume mass variation (discussed next)
- Hole entrance radius of curvature varies from 6-17 um
  - May have strong effect on cavitation in the hole at low ambient pressure conditions
- Holes are slightly divergent
- Need for new geometry with hole to hole variations included
  - Need to separate effect of geometry and flow physics in deviations between models, and experiments
  - Can we capture the hole to hole variation with geometric variation alone?
- ANL/APS tomography data of #28 is recommended reference
- Practical route – **gen. 3 mesh** informed by individual hole dimensions
- Next year – full STL from the x-ray tomography data **(gen 4?)**

Outline

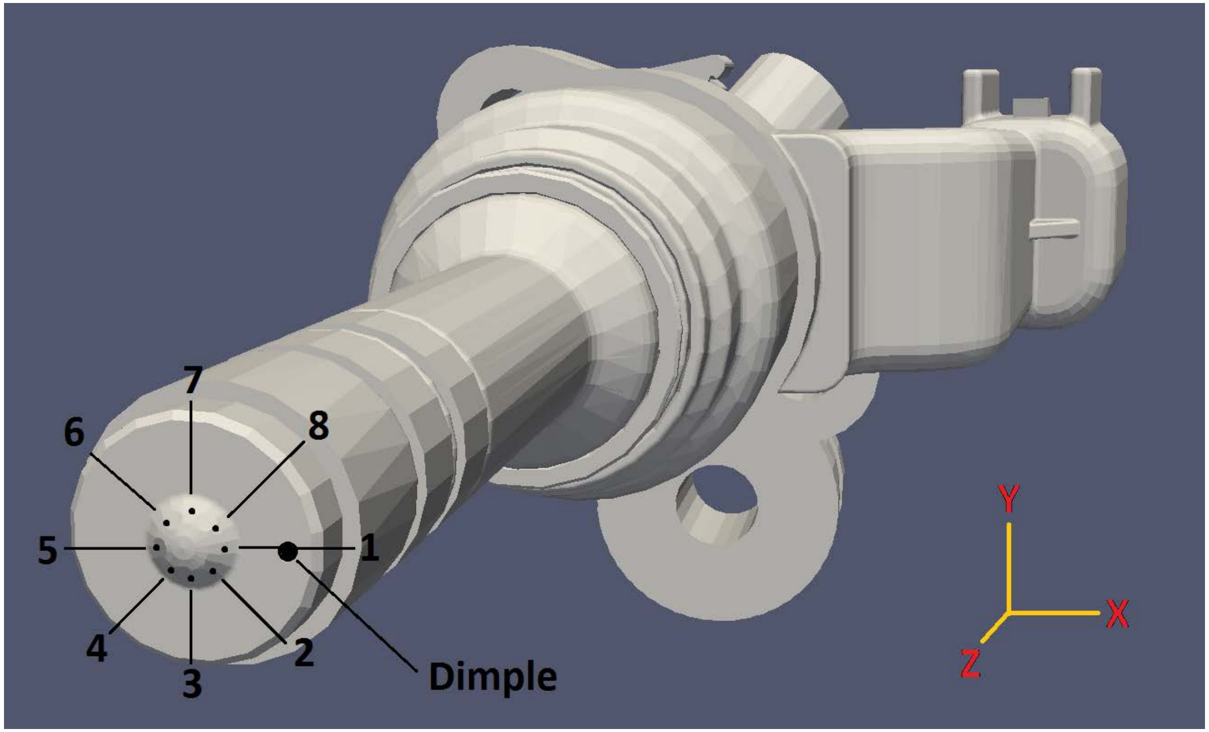
- Nozzle Geometry
  - X-ray tomography
  - Microscopy
  - Meshes used for simulation contributions
  - Deviation of actual injector geometry from ideal
- Internal & near nozzle experiments
  - Rate of injection & rate of momentum
  - Patternation
  - Near tip microscopic imaging
  - X-ray radiography
- Internal flow modeling contributions

Near-nozzle experiments

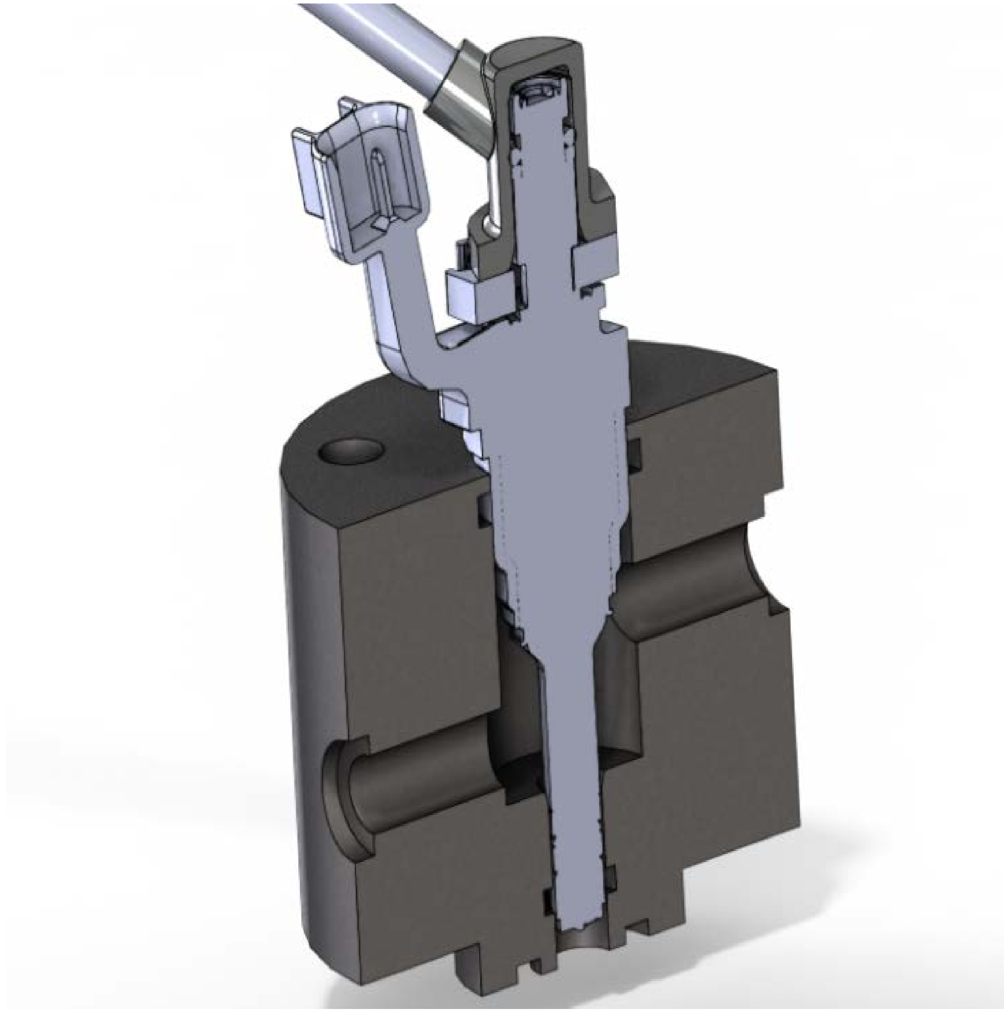
- Results will be presented in a comparative order, rather than individually
- Methodologies will be discussed as each experiment is introduced

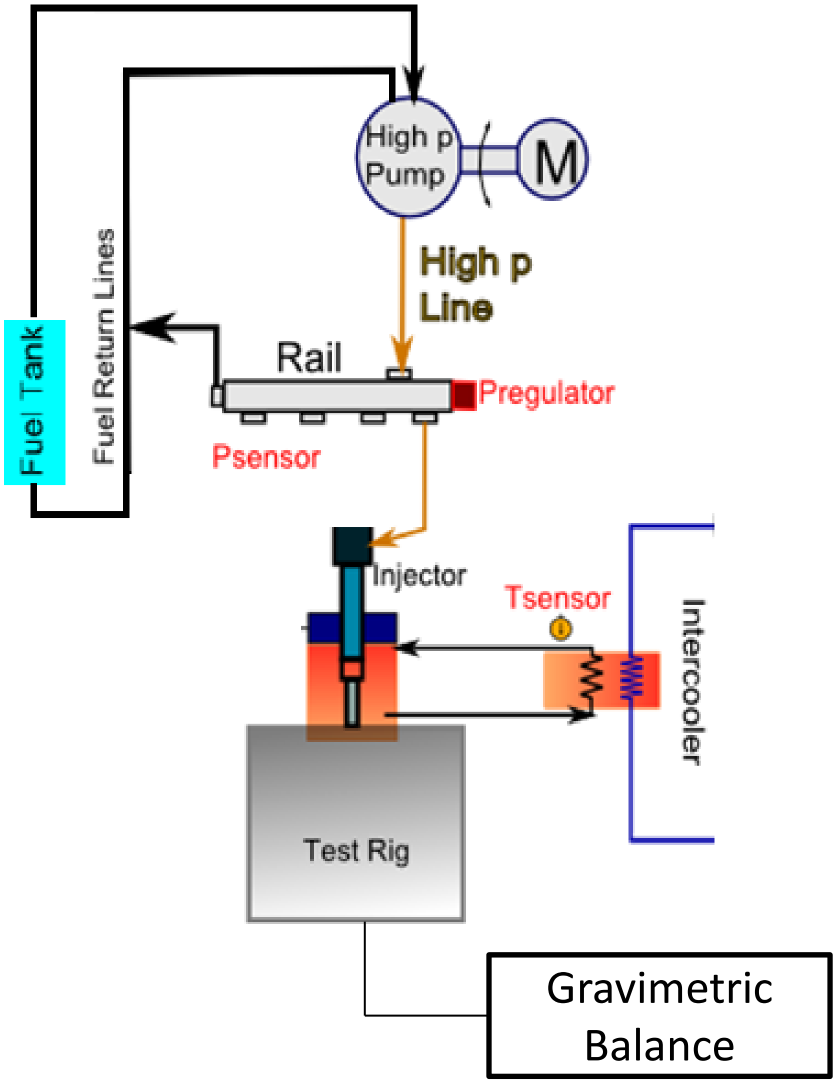
Hole Numbering Convention

- We decided to use the SAE J2715 as guidelines for the orientation of the Spray G injector (Different from Spray A)
- The hole numbering is done clockwise from the front view of the injector (facing the spray tip)



CMT Rate of Injection & Momentum

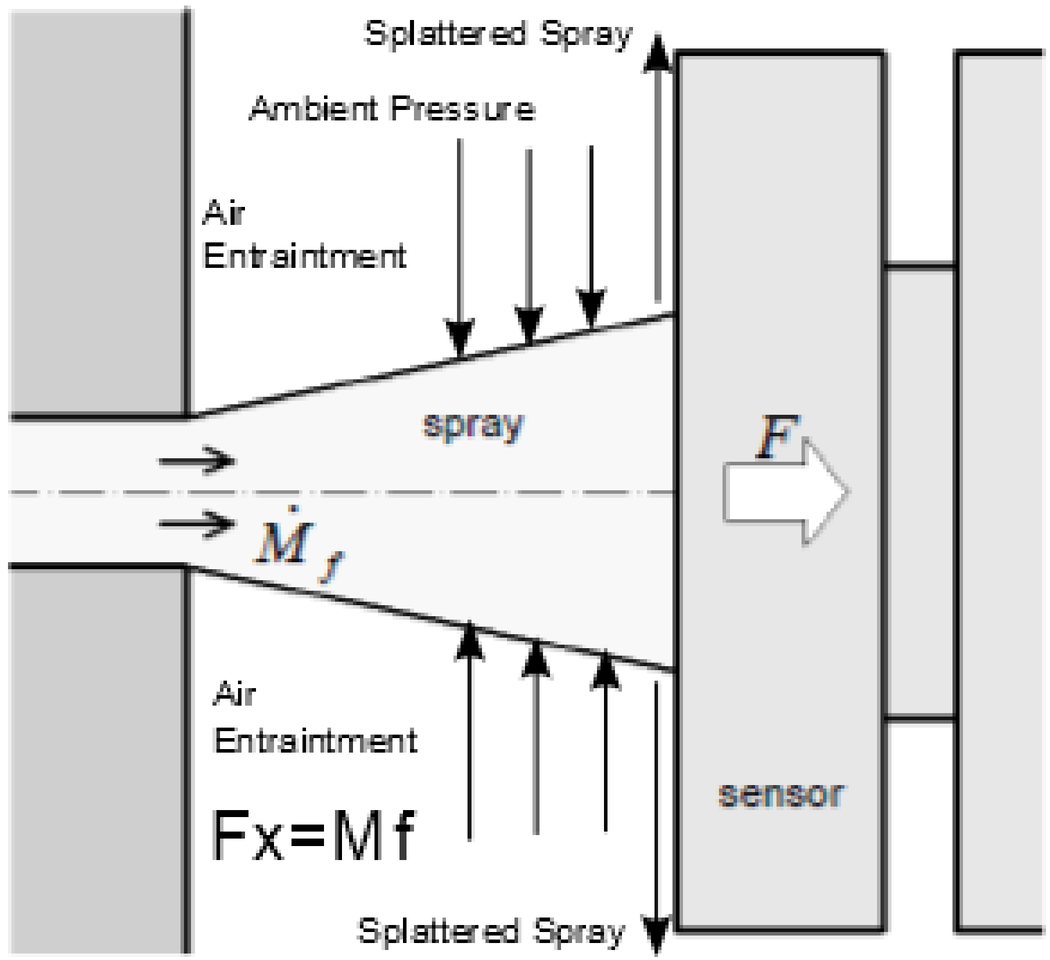




Ref: SAE Paper 2015-01-1893

CMT Rate of Injection & Momentum

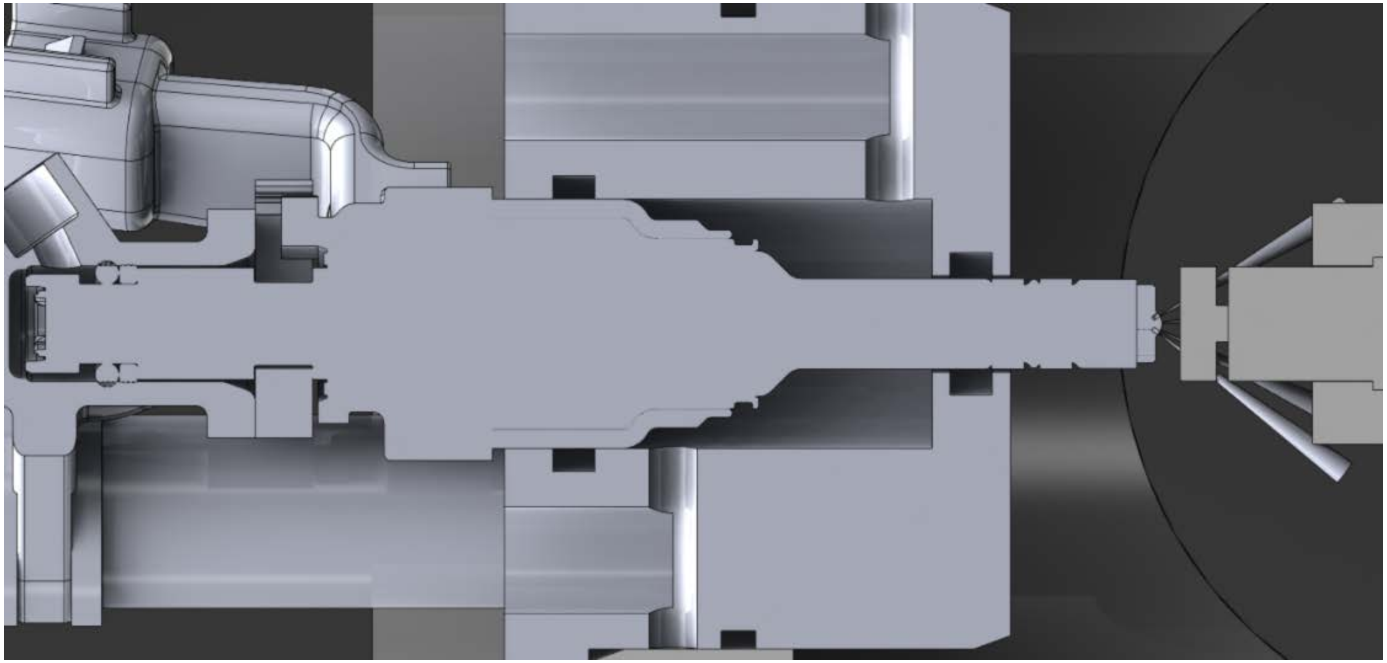
- Spray Impacts perpendicularly to the sensor
- The splattered spray is perpendicular to the original direction of the spray
- Air entrainment perpendicular to spray direction
- With previous hypothesis momentum is conserved in axial direction



Ref: SAE Paper 2015-01-1893

Ref: SAE Paper 2015-01-1893

- Two Configurations:
- Frontal Configuration:
  - All Sprays collected simultaneously
  - Hypotheses are not met
  - Transfer of momentum to the ambient can play a role
  - Correction to the measurement is necessary



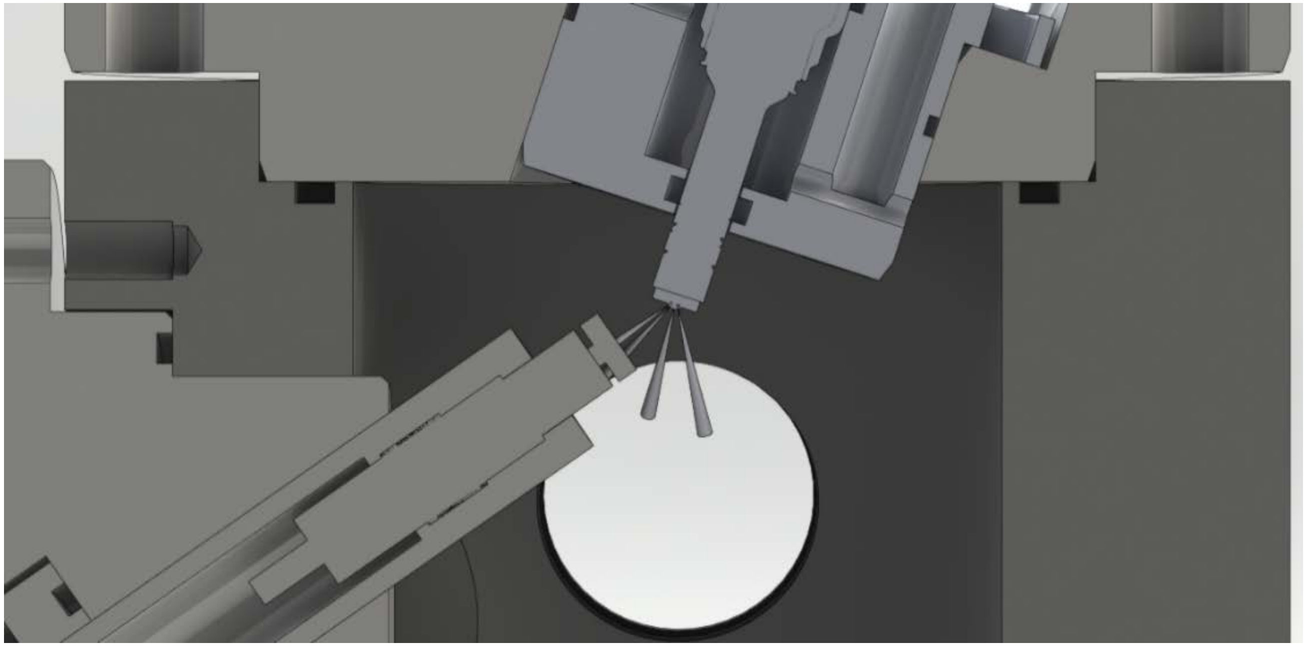
CMT Rate of Injection & Momentum

Ref: SAE Paper 2015-01-1893

- **Two Configurations:**
- **Lateral Configuration**
  - Only one spray impacts perpendicularly
  - Hypotheses are met

- But…

Plumes are very close together
Sensor has to be put very far away
Plumes can get wider than the target
Interactions within the plumes

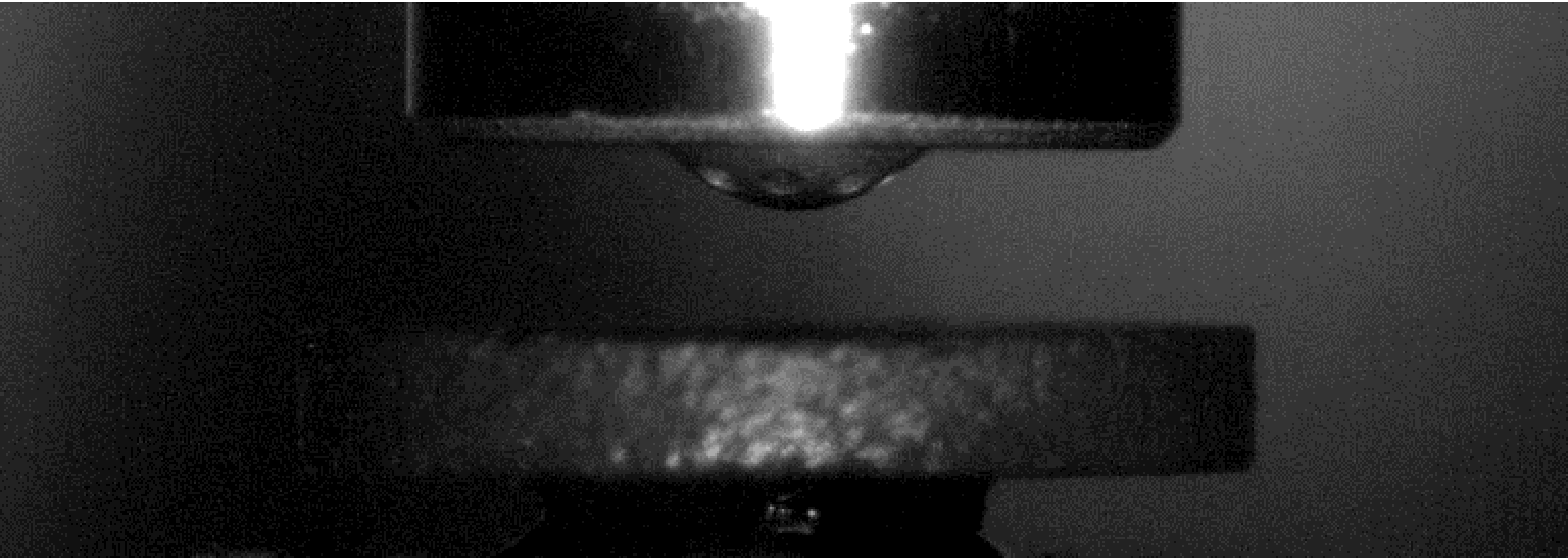


CMT Rate of Injection & Momentum

Ref: SAE Paper 2015-01-1893

- **Frontal Configuration: High speed camera was used to check if the spray was impacting properly and to try to assess the impacting angle**

Injection Pressure: 200 bar. Back Pressure: 7 bar. Ambient Temperature: 25ºC

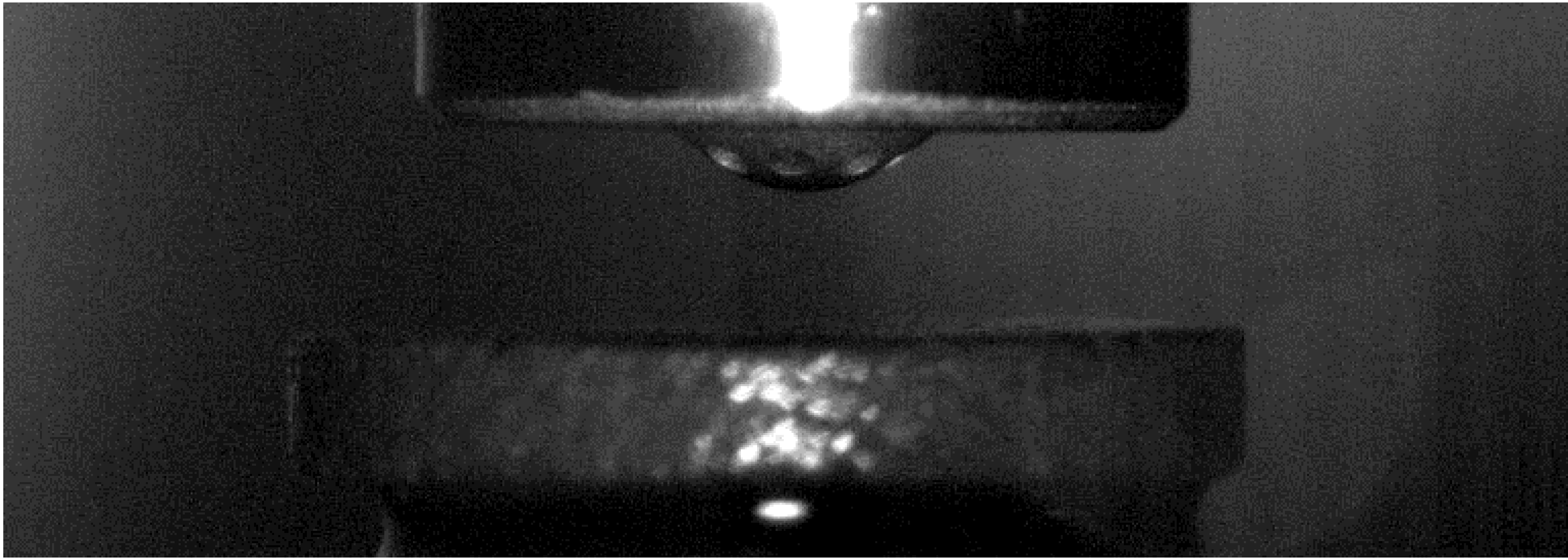


CMT Rate of Injection & Momentum

Ref: SAE Paper 2015-01-1893

- **Frontal Configuration: High speed camera was used to check if the spray was impacting properly and to try to assess the impacting angle**

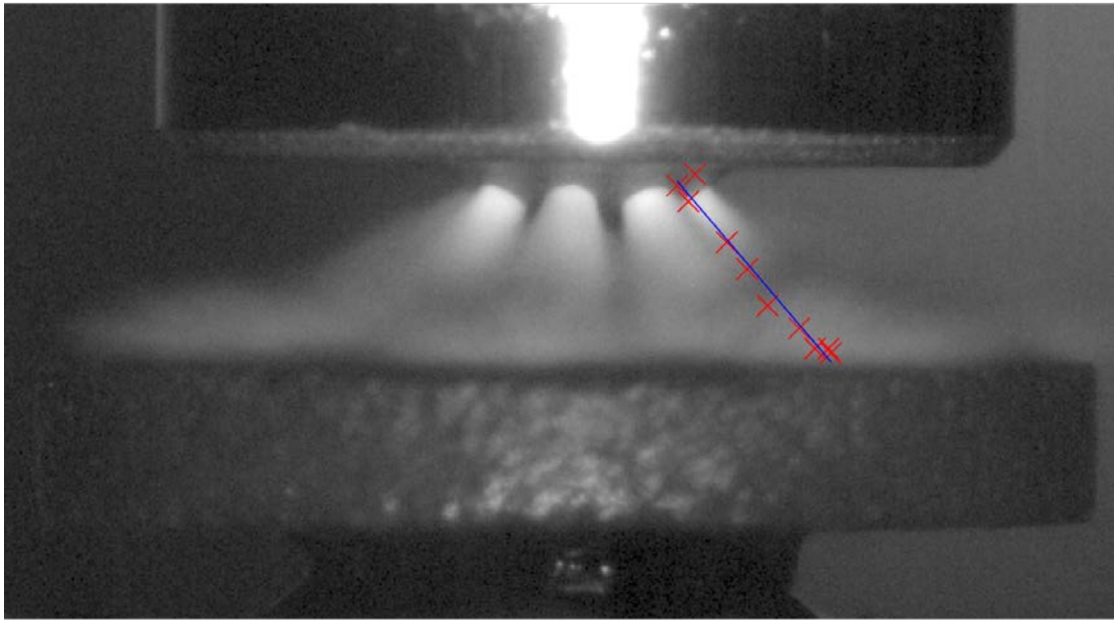
Injection Pressure: 200 bar. Back-Pressure: 31 bar. Ambient Temperature: 25ºC



CMT Rate of Injection & Momentum

Ref: SAE Paper 2015-01-1893

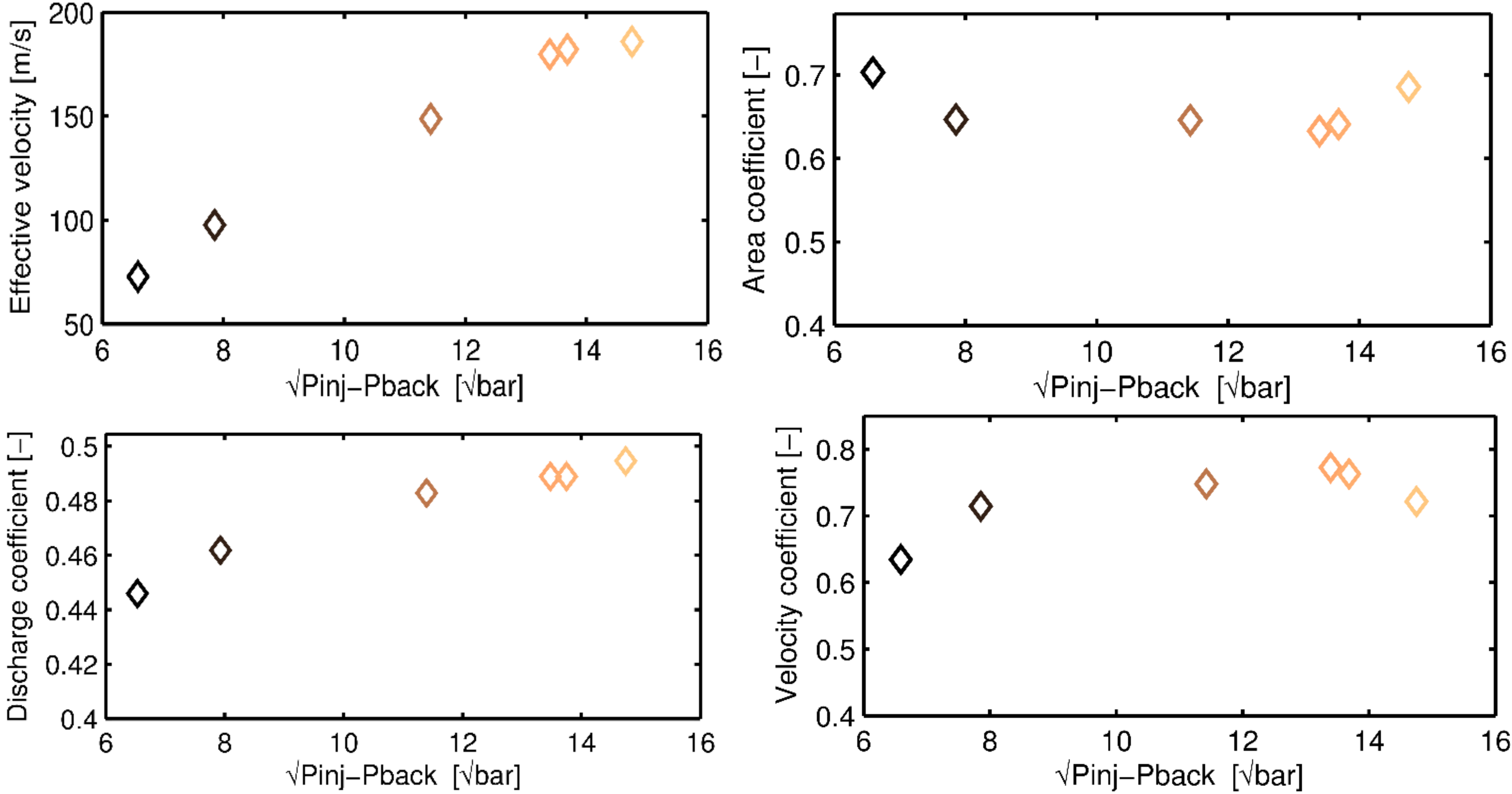
- **Frontal Configuration:**
  - A correction is necessary to transform the momentum registered by the sensor (y-axis) and the one from the combination of all the sprays
  - A line was fitted to calculate the angle of the right plume
  - An angle of 40 degrees was selected to make the correction (value in agreement with drawing)



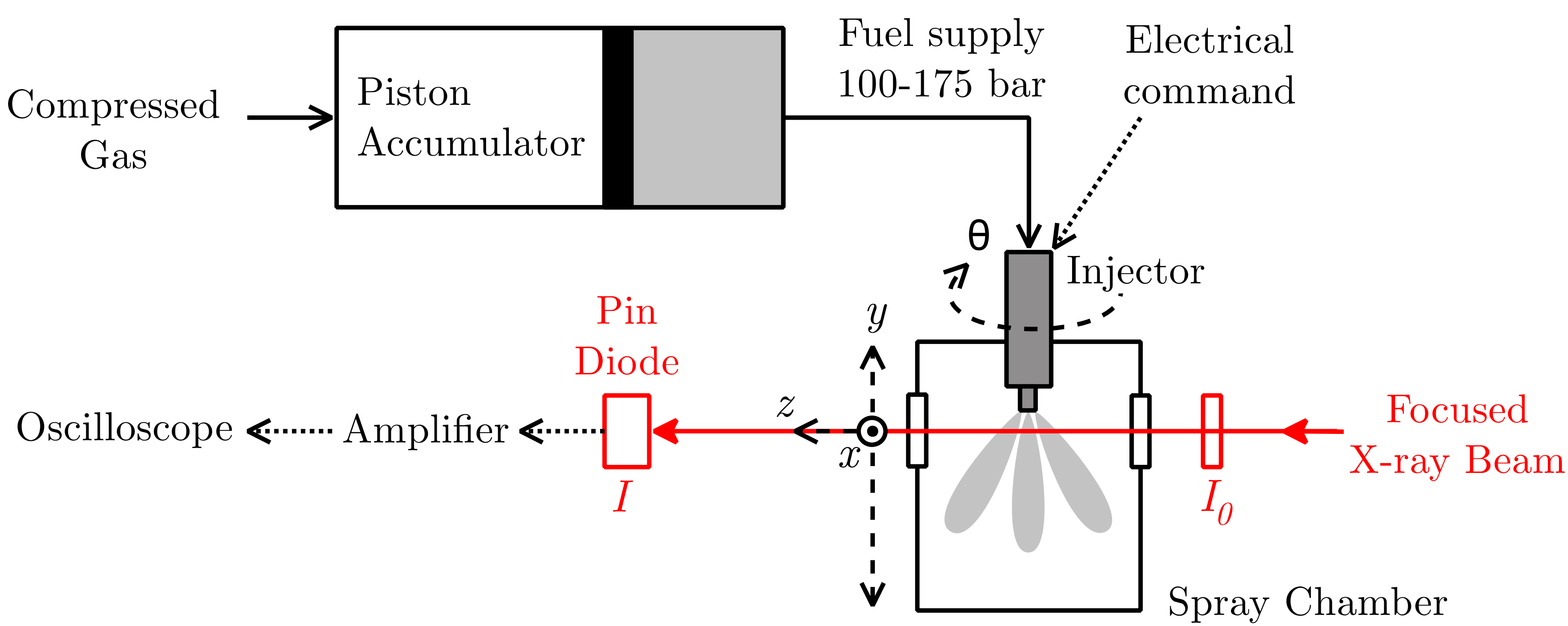
CMT Rate of Injection & Momentum

Ref: SAE Paper 2015-01-1893

Hydraulic Coefficients (using frontal configuration data)

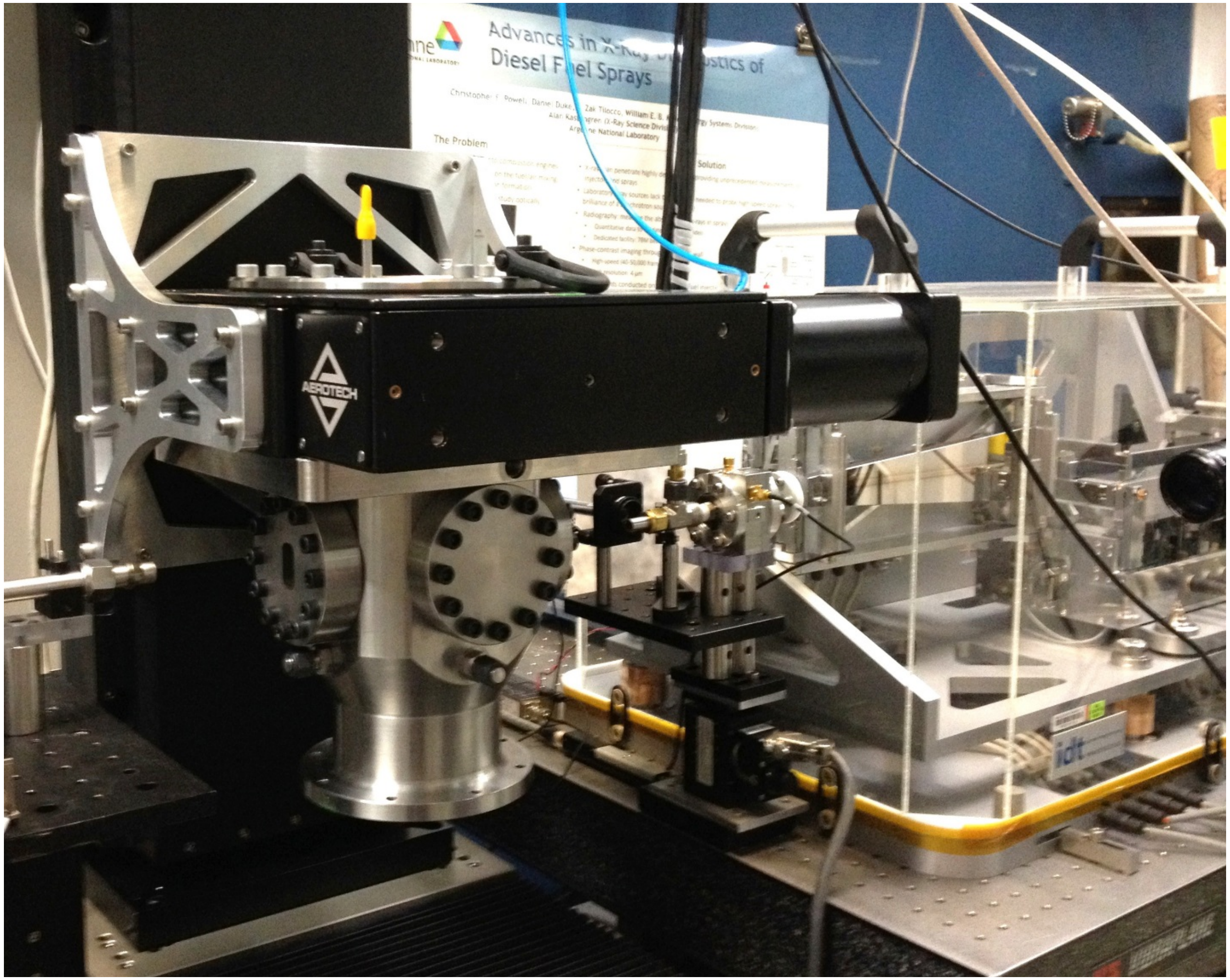


X-ray Radiography



- Purge flow of N_2 through the chamber at 4 L/min

- High pressure x-ray tomography chamber



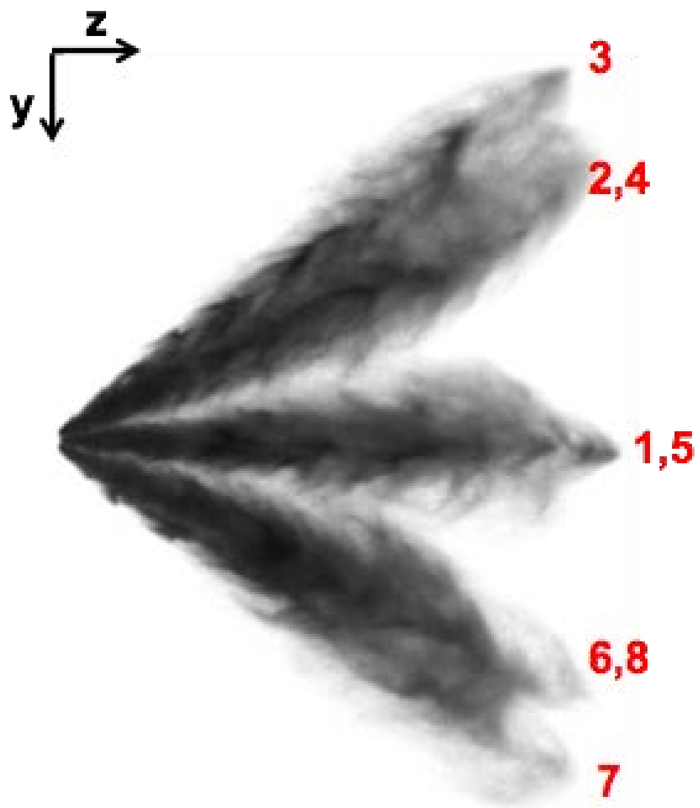
Spray G Target Condition #1 vs. APS Conditions

- **Iso-Octane Fuel**
  - pressure 20 MPa
  - fuel temperature 90° C / 363 K
  - injector temperature 90° C / 363 K
  - density 0.7811 g/cc
  - viscosity 5.44 cSt
  - surface tension 18.77 dyn/cm
  - vapor pressure 75 kPa (est.)
- **Ambient conditions**
  - temperature 300° C (573 K)
  - pressure (N_2) 5.97 bar
  - density 3.5 kg/m^3

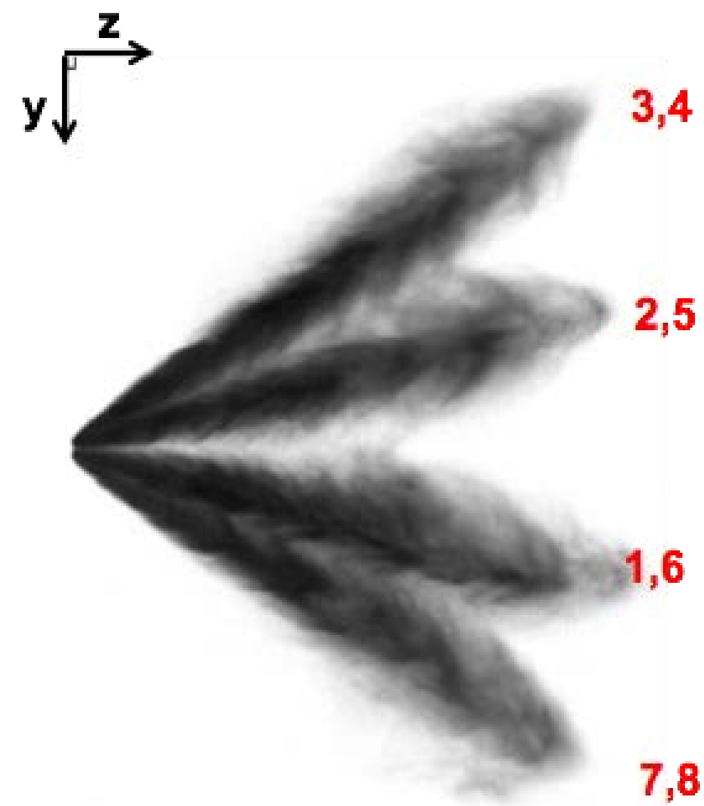
- **Viscor gasoline calibration fuel with DPX9 Cerium additive at 9:1 vol. ratio**
  - pressure 19 MPa
  - fuel temperature 25° C / 298 K
  - injector temperature 25° C / 298 K
  - density 0.8379 g/cc
  - viscosity 1.15 cSt
  - surface tension -
  - vapor pressure 0.6 kPa
- **Ambient conditions**
  - temperature 25° C (298 K)
  - pressure (N_2) 3.15 bar
  - density 3.56 kg/m^3

Rotation views for planar radiography

Theta = 0
View from electrical conn. / hole 1



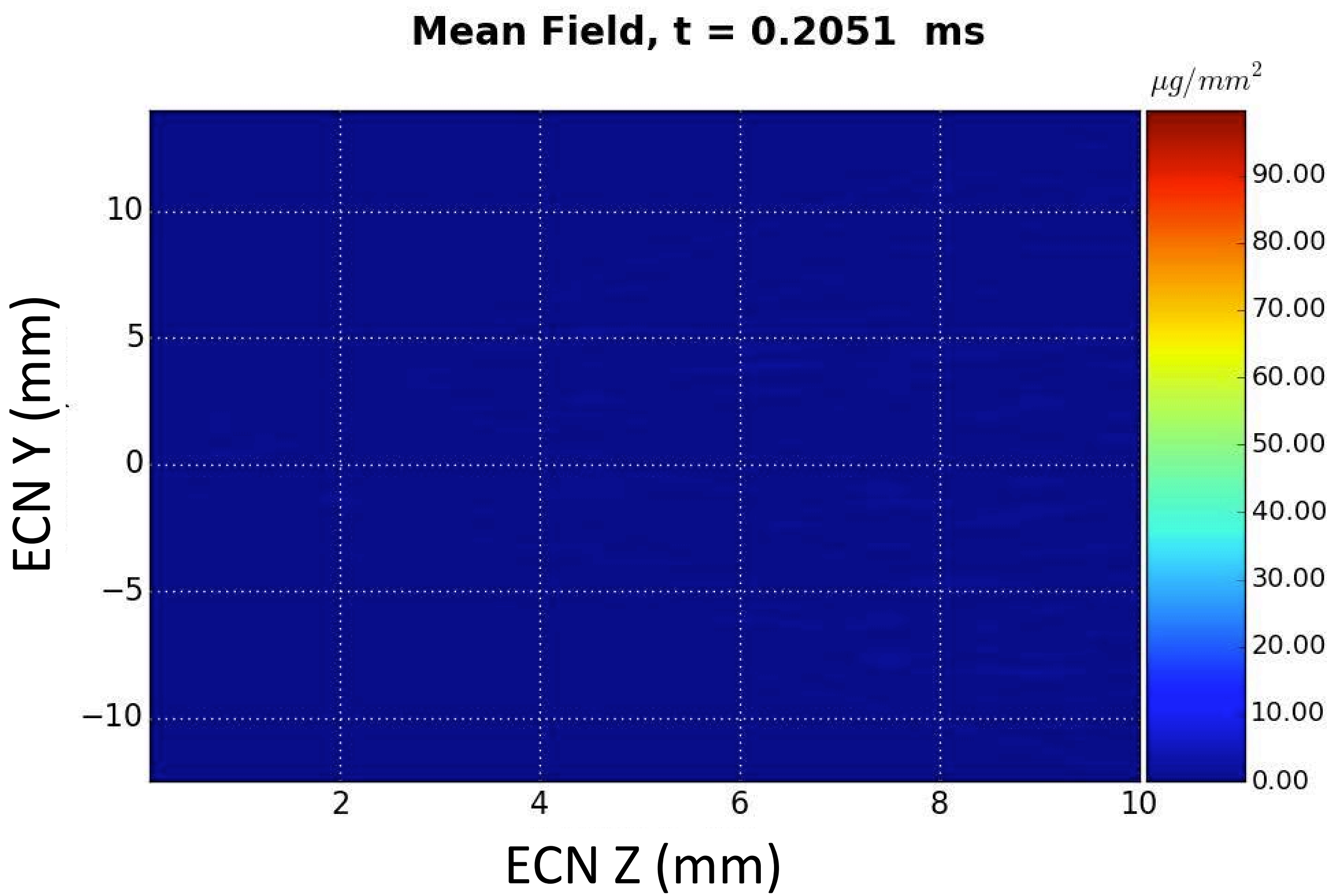
Theta = -22.5
Rotated CCW, plumes 1 and 6 aligned



J2715: 1 atm, room T imaging
spray back illumination imaging
Lee Markle, Delphi

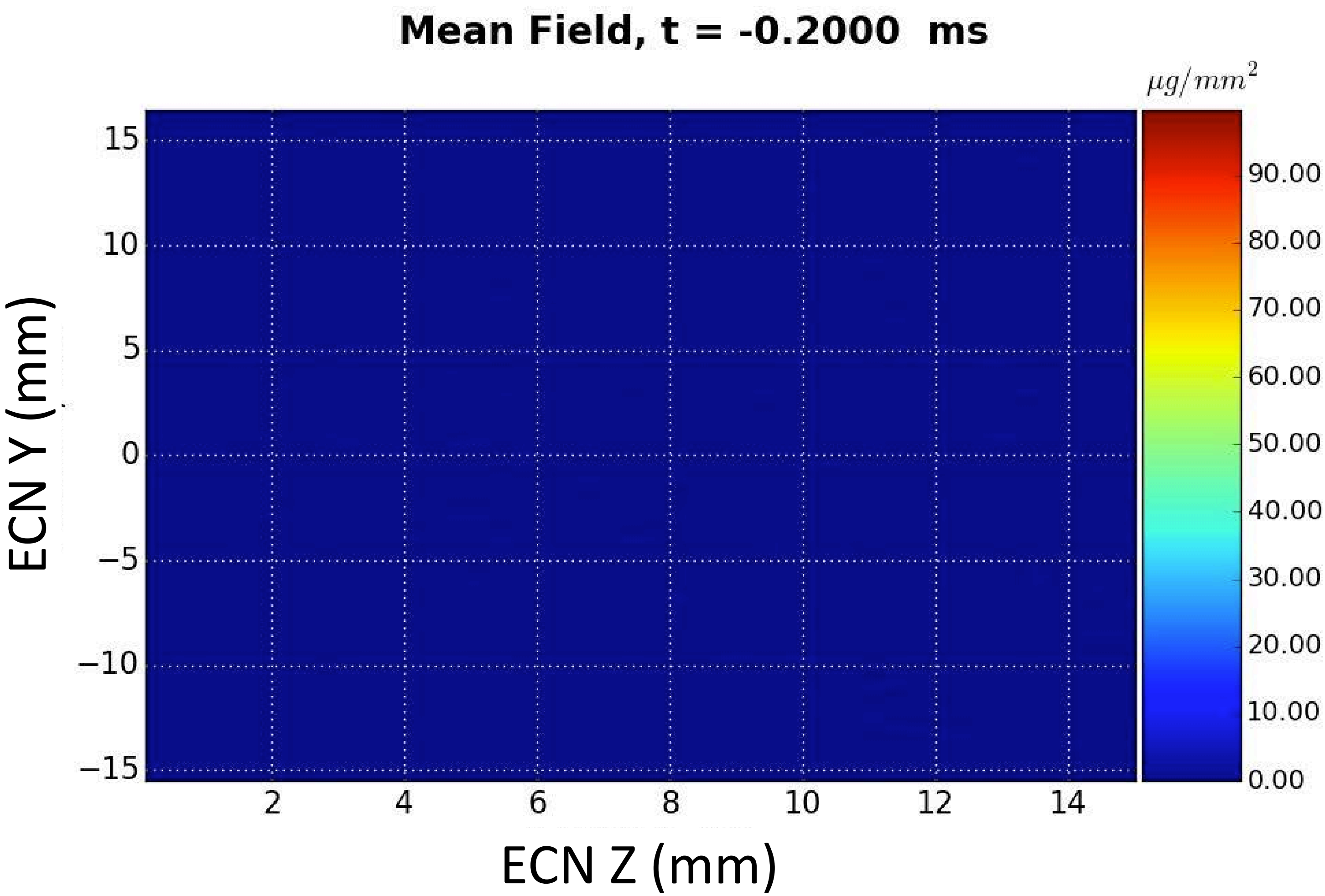
Radiography (theta = 0)

Injector command at T_0+200µs, average of 30 injections per point



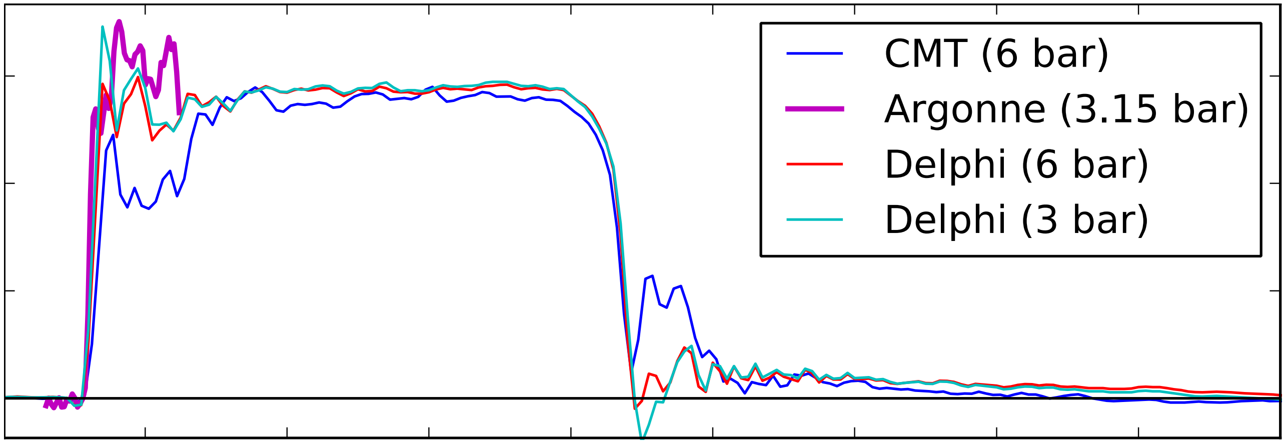
Radiography (theta = -22.5 degrees)

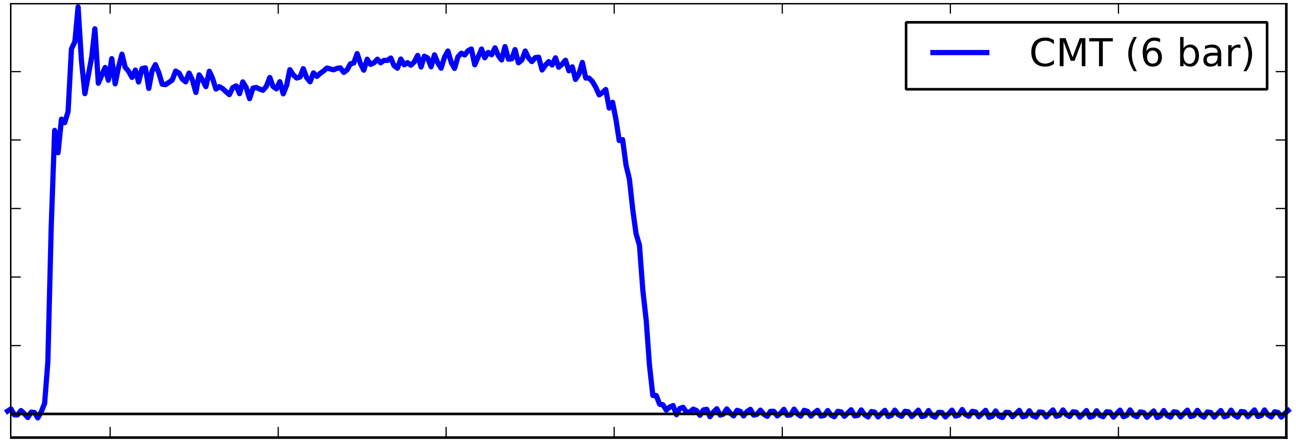
Injector command at T_0+200µs



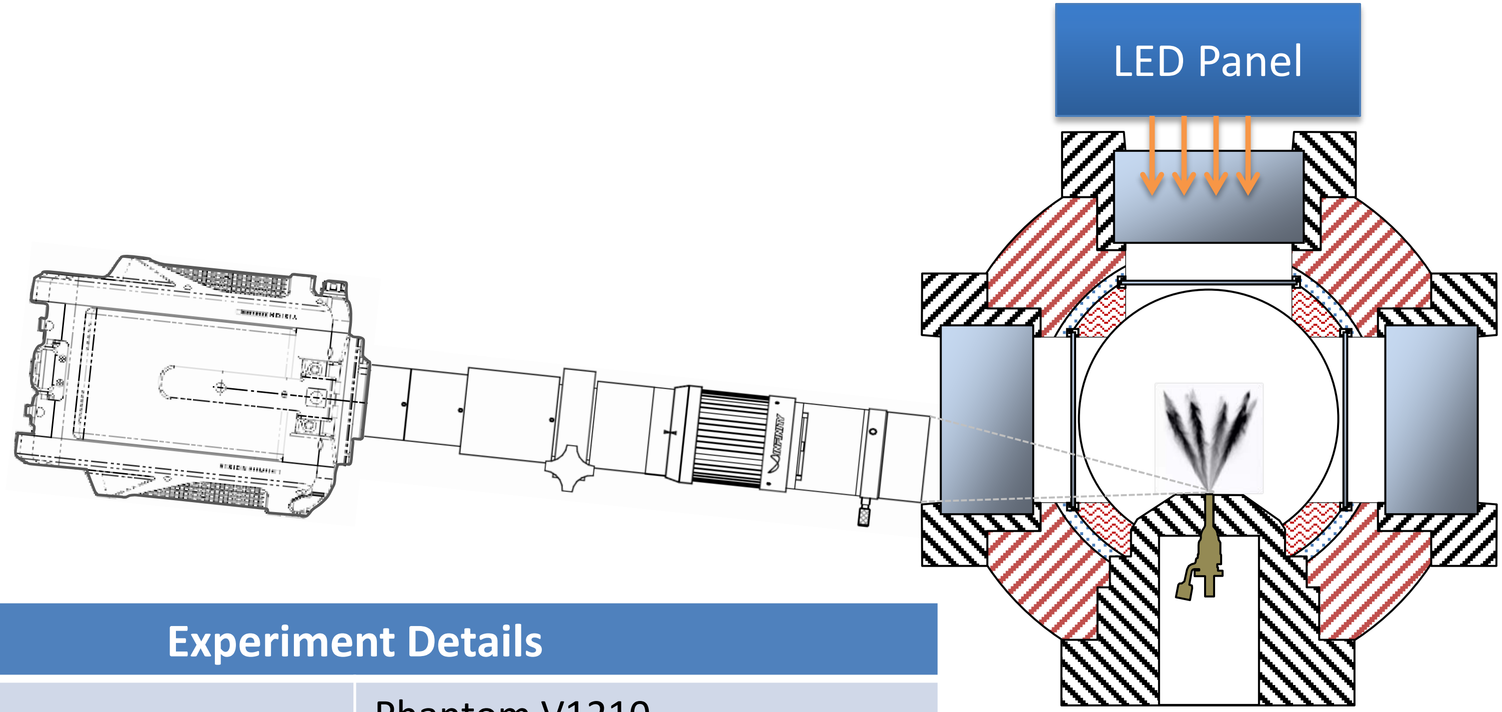
Rate of Injection & Momentum

- CMT & Delphi rate meter data
- Argonne data from planar radiography (average of 2 views). Valid while spray tip inside axial domain (SOI only)
- Argonne & Delphi ROI match very well
- Daniel Vaquerizo suggests that lower CMT ROI may be due to a sealing issue
- ROM from CMT with longer injection duration.



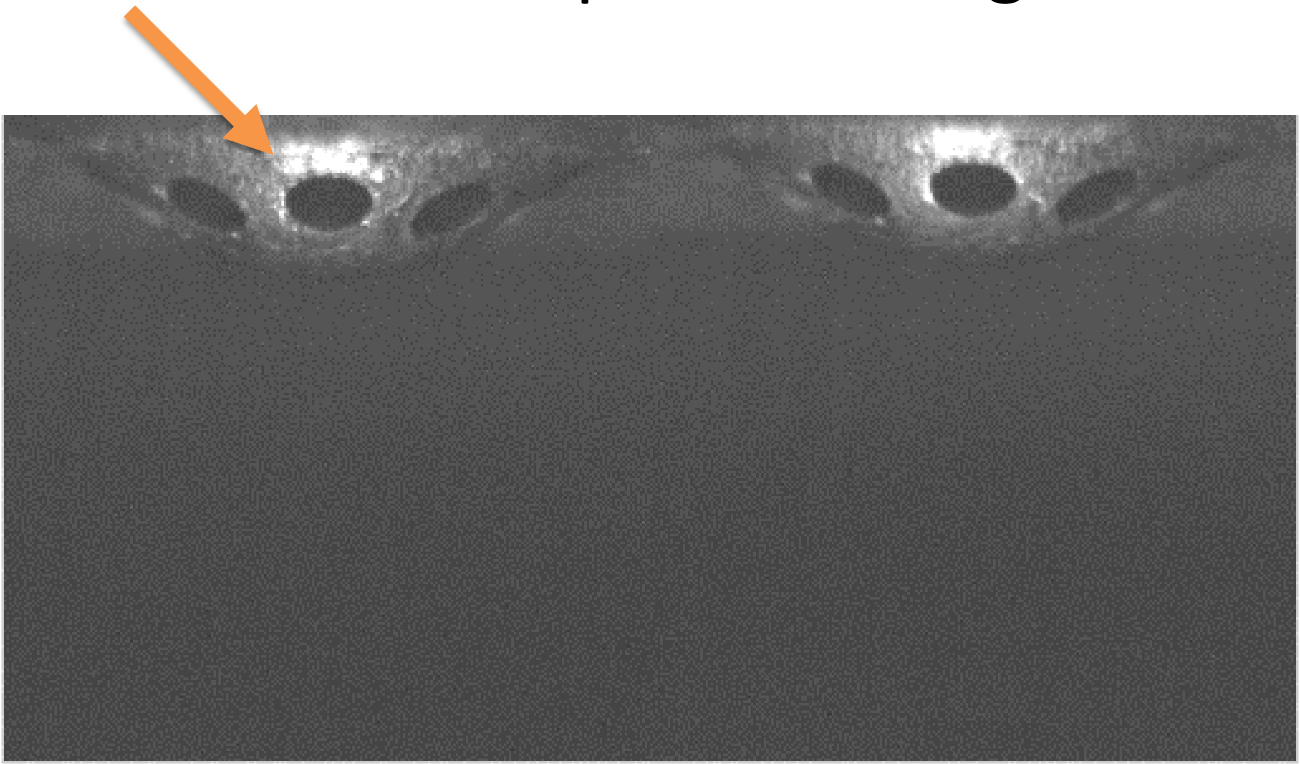


Spray G – Near-tip Imaging (GM)



Experiment Details	
Camera	Phantom V1210
Lens	Infinity K2 (CF2)
Frame Rate	100 kHz
Spatial Resolution	256 X 256
Exposure Time	9 µs
FOV	≈ 2.9 mm X 2.9 mm
Light Source	VIC LED Panel (continuous)

- Fuel film on nozzle tip for flashing condition G2*



Spray G2*
20 C, 0.6 kg/m^3 (53 kPa)*
60 C, 0.5 kg/m2 (50 Kpa)

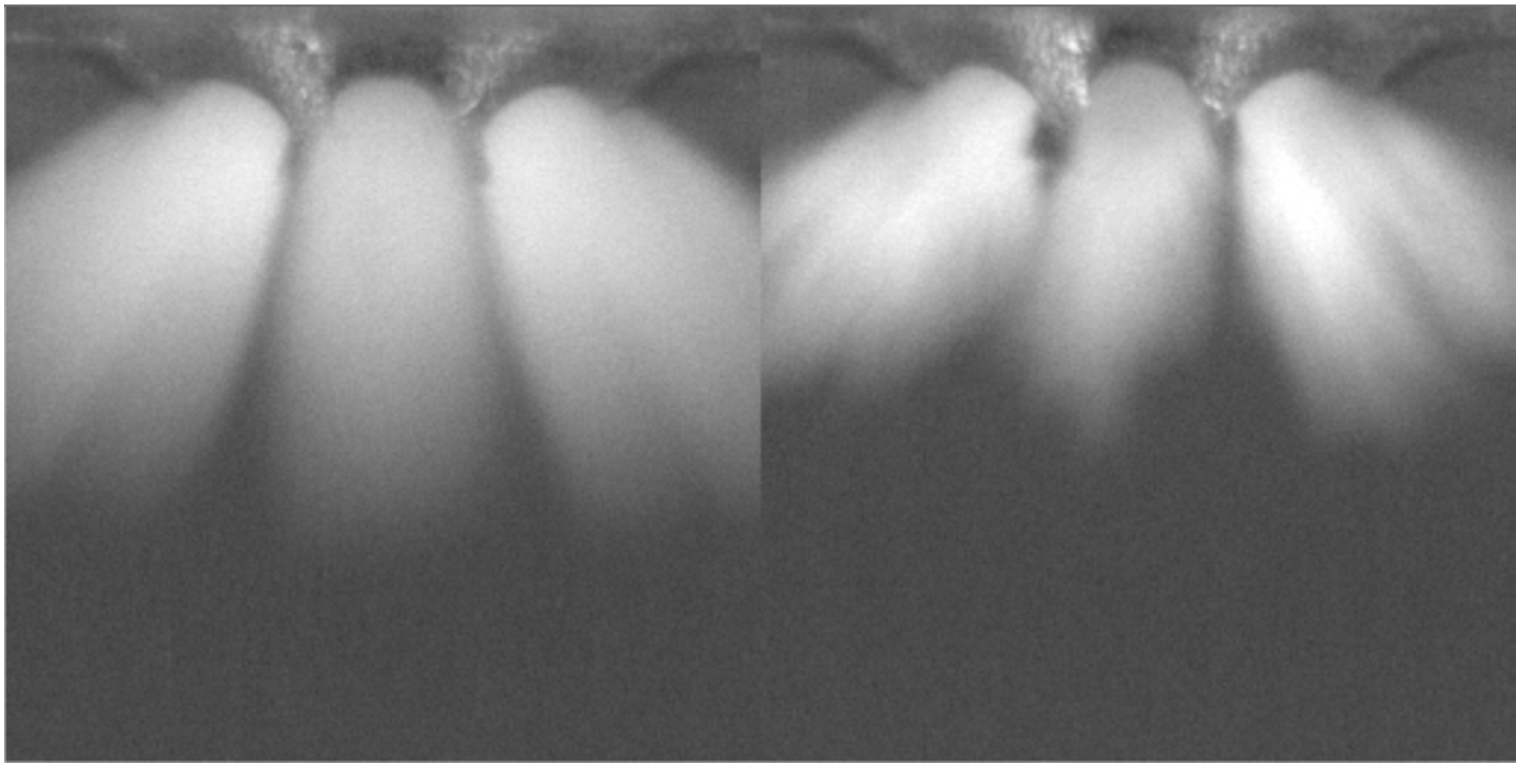
Spray G
300 C, 3.5 kg/m^3 (6 Bar)

SAE 2015-01-0944, “Internal and Near-Nozzle Flow in a Multi-Hole Gasoline Injector Under Flashing and Non-Flashing Conditions”

Spray G – Near-tip Imaging (GM)

- Plumes merge shortly after SOI for Spray G2*

t = SOI + 10 μs



Spray G2*
20 C, 0.6 kg/m^3 (53 kPa)*
60 C, 0.5 kg/m2 (50 Kpa)

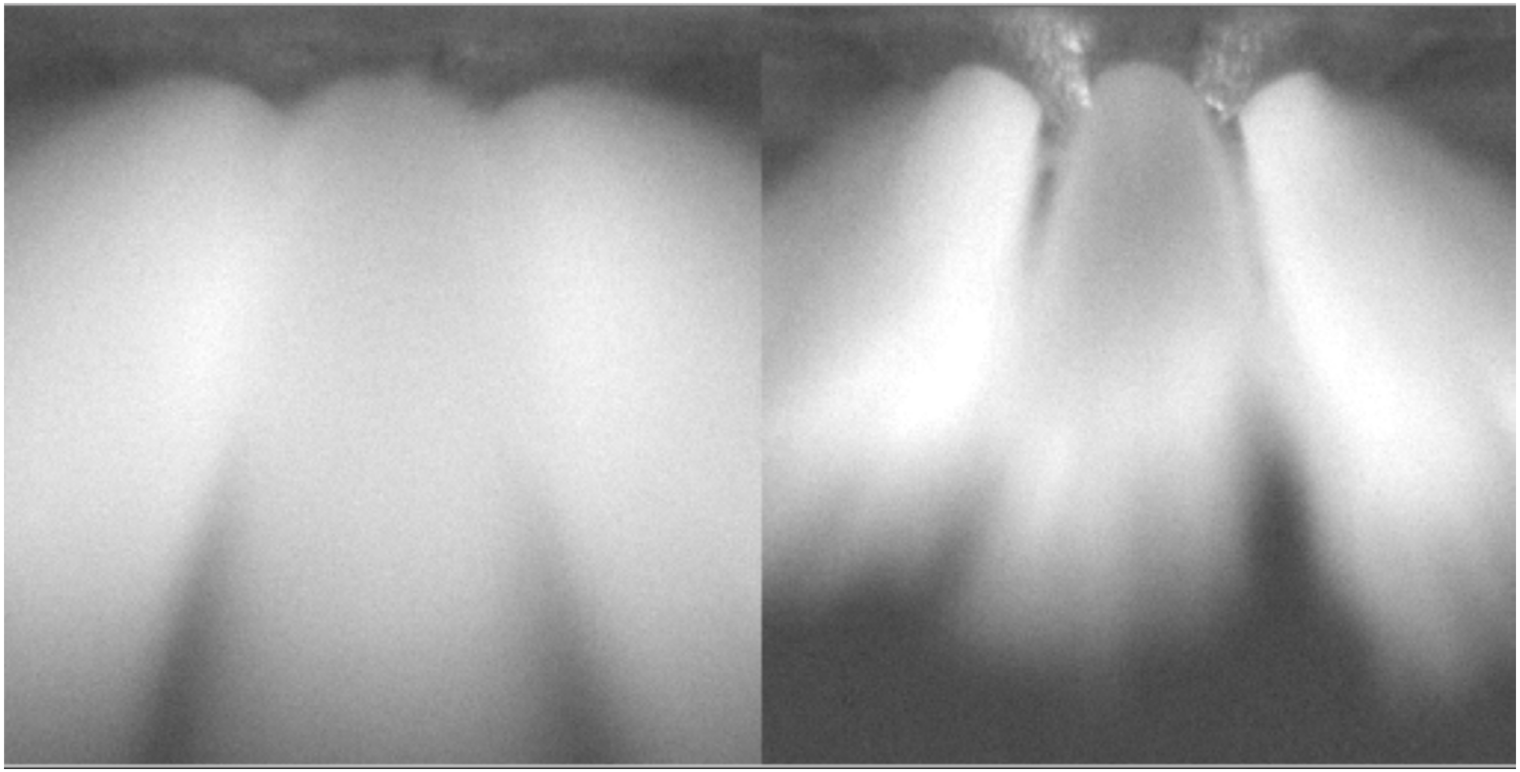
Spray G
300 C, 3.5 kg/m^3 (6 Bar)

SAE 2015-01-0944, "Internal and Near-Nozzle Flow in a Multi-Hole Gasoline Injector Under Flashing and Non-Flashing Conditions"

Spray G – Near-tip Imaging (GM)

- Plumes merge shortly after SOI for Spray G2*

t = SOI + 20 μs



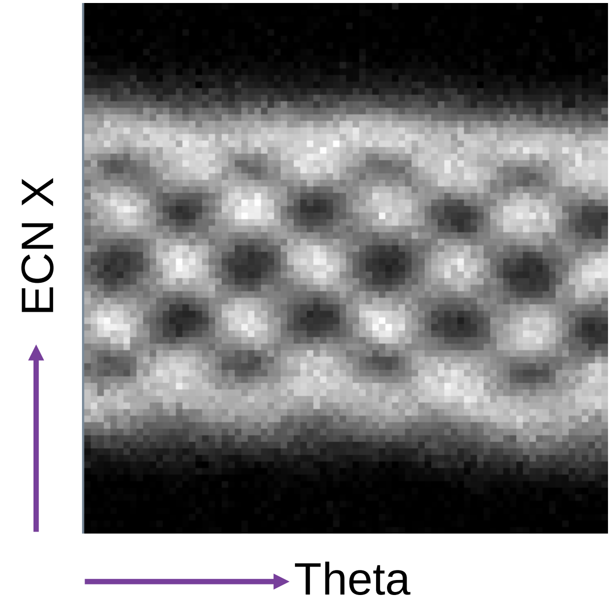
Spray G2*
20 C, 0.6 kg/m^3 (53 kPa)*
60 C, 0.5 kg/m2 (50 Kpa)

Spray G
300 C, 3.5 kg/m^3 (6 Bar)

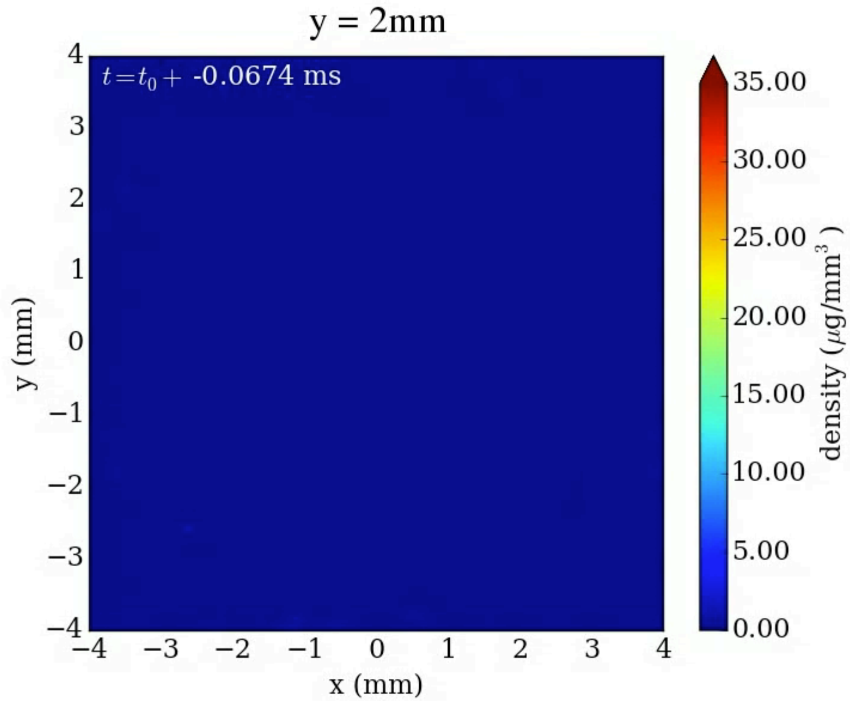
SAE 2015-01-0944, "Internal and Near-Nozzle Flow in a Multi-Hole Gasoline Injector Under Flashing and Non-Flashing Conditions"

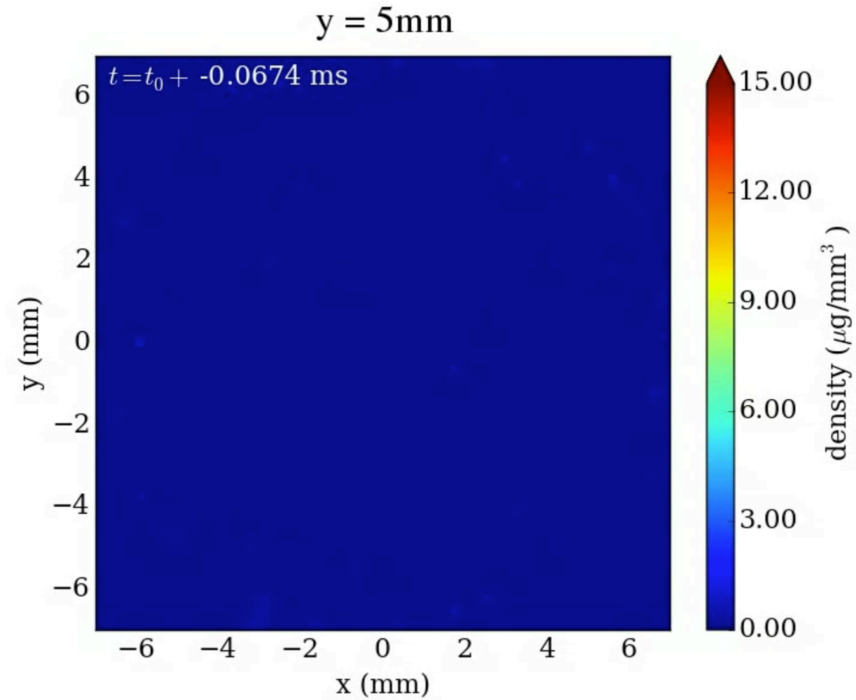
Radiography – Tomography method

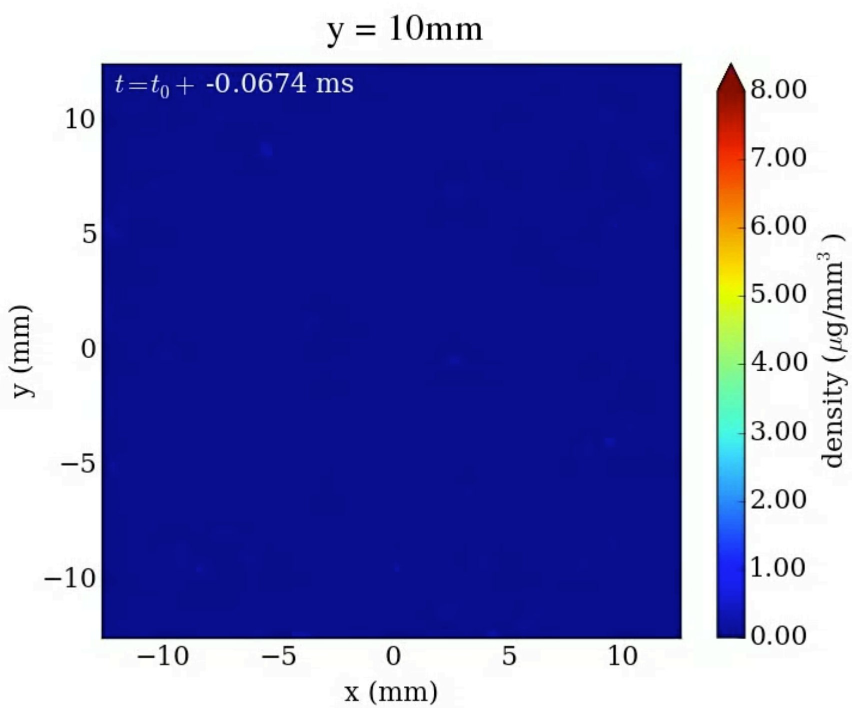
Sinogram at Z = +2mm
$T = T_0 + 2.1$ ms



- Three slices at ECN Z = 2, 5 and 10 mm
- Raster-scan and rotate method
- Same conditions as 2D radiography
- 80 view angles (every 2.25 deg.)
  x 81 transverse points
  x 16 repeat injections per point
  x 3 slices
  x 1300 time-steps
- Each slice requires 24 hours to complete
- Reconstruction is done using penalized maximum likelihood (PML-3D) algorithm
- Spatial and temporal smoothness parameters using 8 nearest neighbour points (penalizes strong temporal and spatial gradients, requires always positive density)
- Gives superior results compared to FPB or ART with few data points
- The code is *TomoPy*, developed in-house at APS and available as open source
- SEE JSAE PAPER 20159213







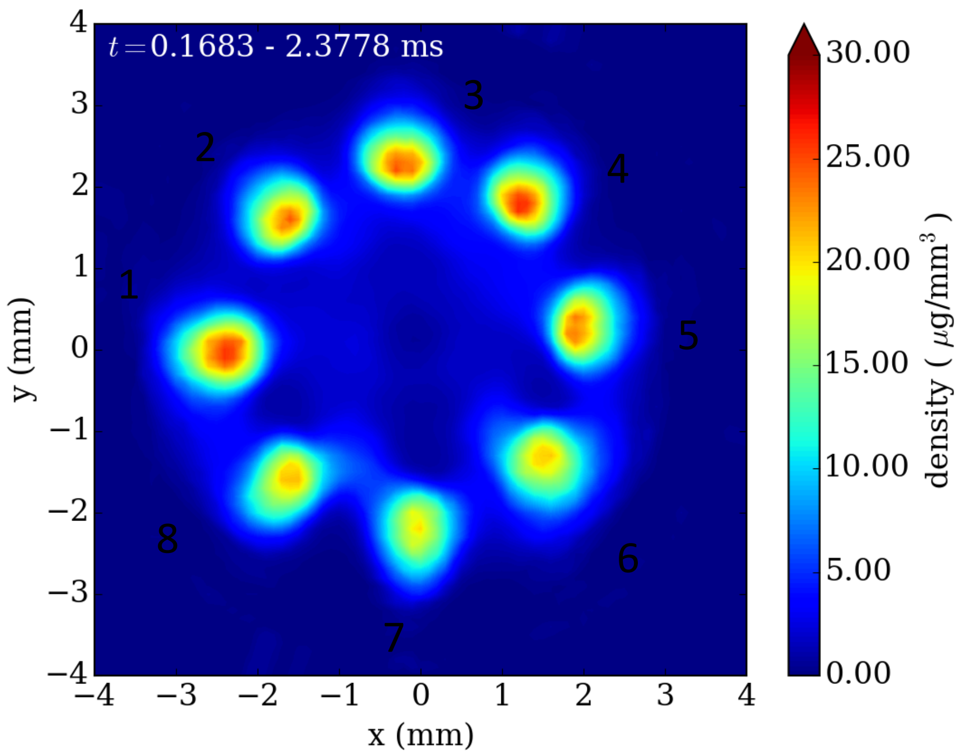
Injector command at T_0

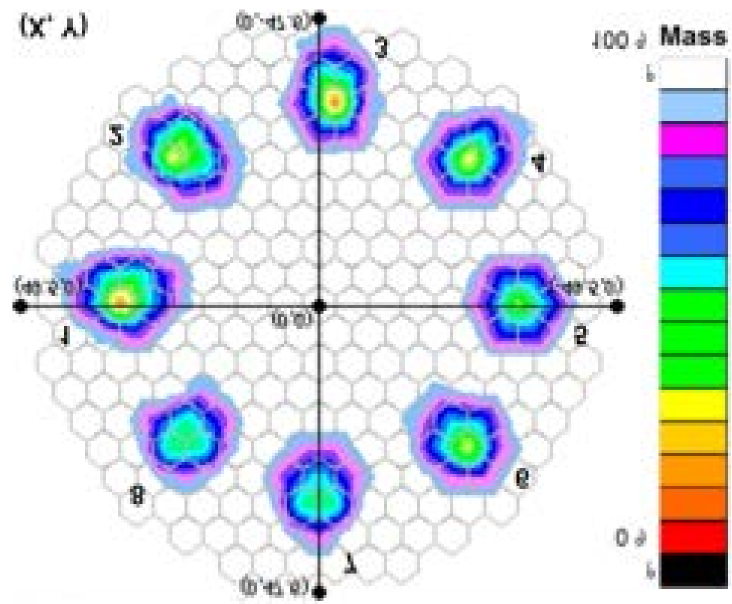
No large-scale unsteady features

Accumulation of fuel at center for Z=10mm

Time-average during steady-state

Z=+2mm

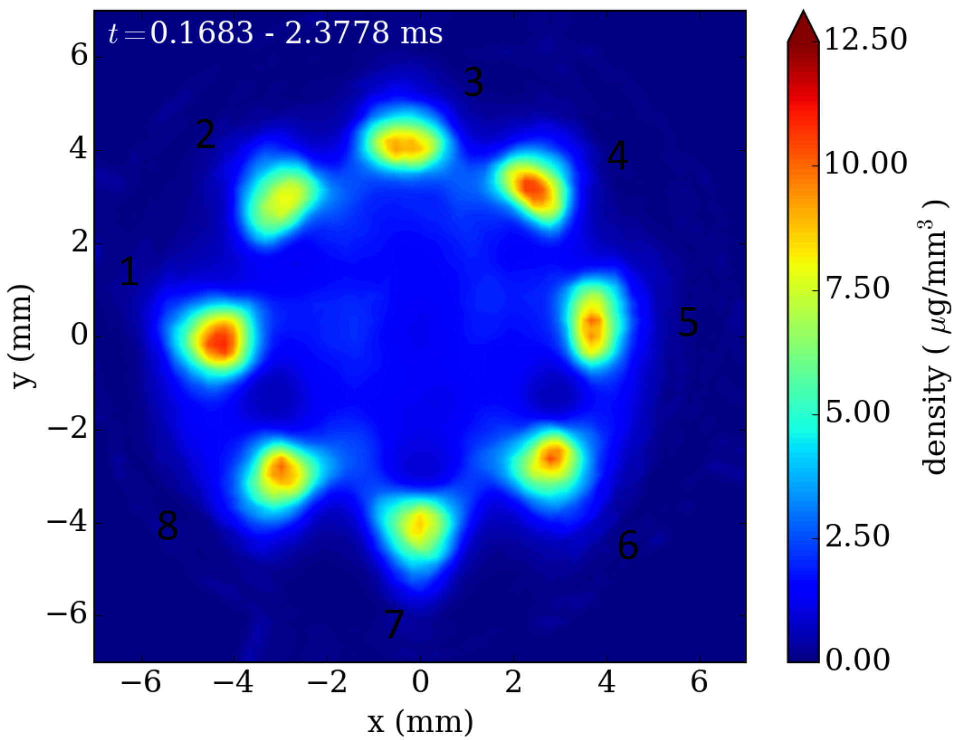


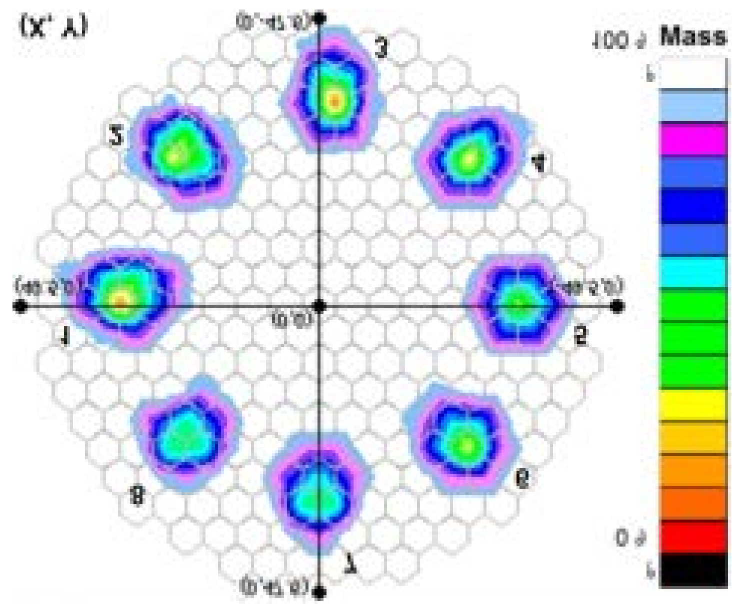


Hole #	1	2	3	4	5	6	7	8
Mass [%]	15.0	13.9	13.3	11.9	11.6	11.9	11.2	11.2

Time-average during steady-state

Z=+5mm (note change of color bar scale)





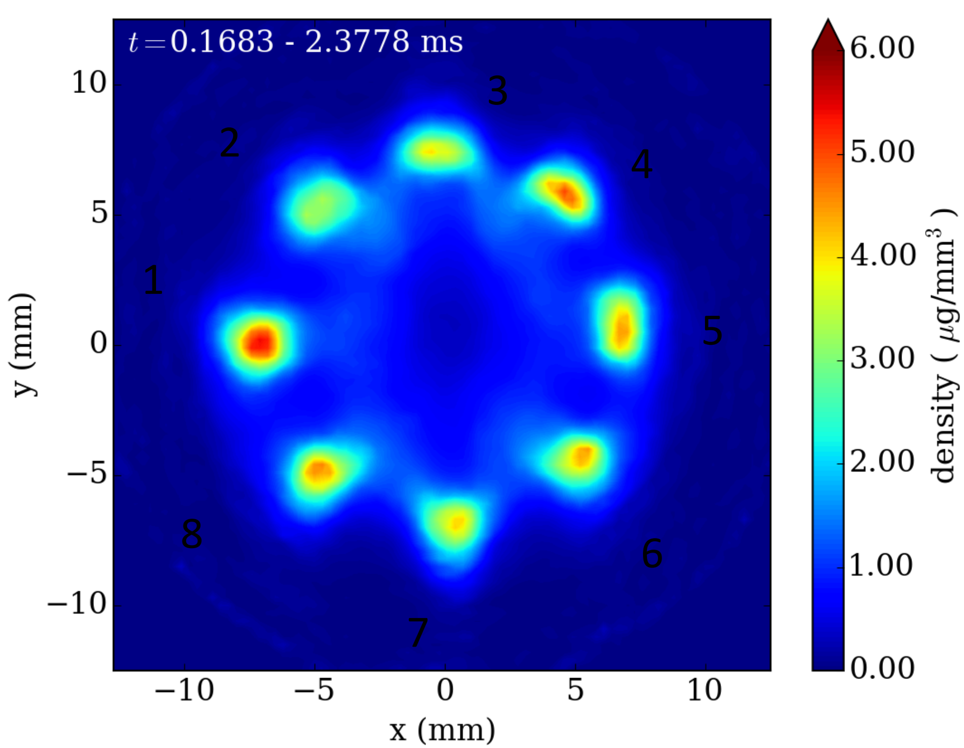
Hole #	1	2	3	4	5	6	7	8
Mass [%]	15.0	13.9	13.3	11.9	11.6	11.9	11.2	11.2

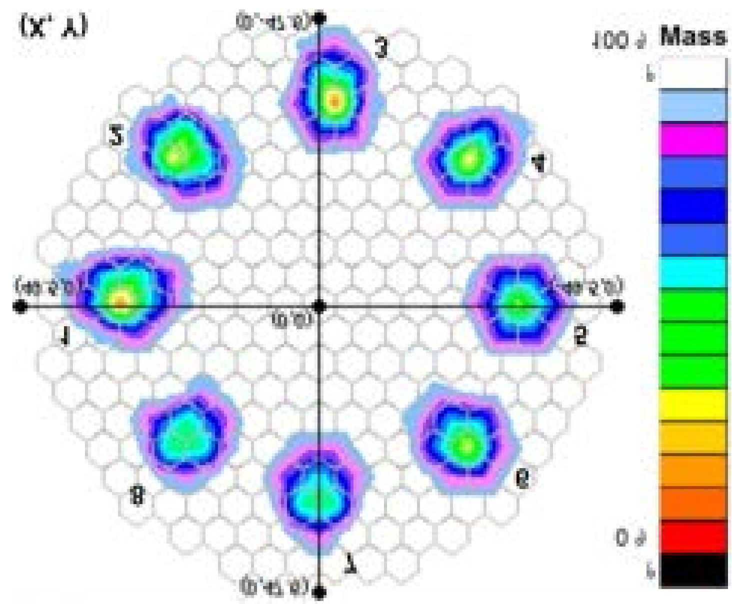
Structure of plumes 2-4,6-8 changes

X-ray tomography & patternation

Time-average during steady-state

Z=+10mm (note change of color bar scale)



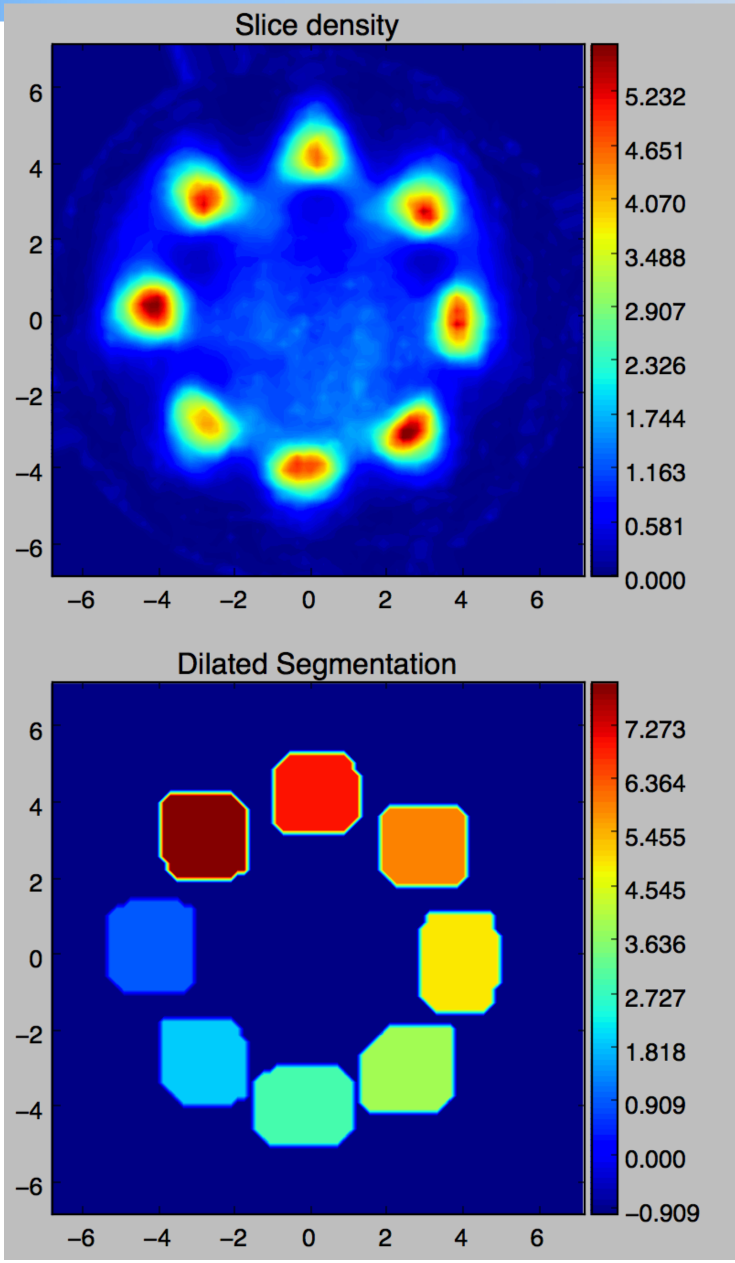


Hole #	1	2	3	4	5	6	7	8
Mass [%]	15.0	13.9	13.3	11.9	11.6	11.9	11.2	11.2

Interactions between plumes 2-4,6-8

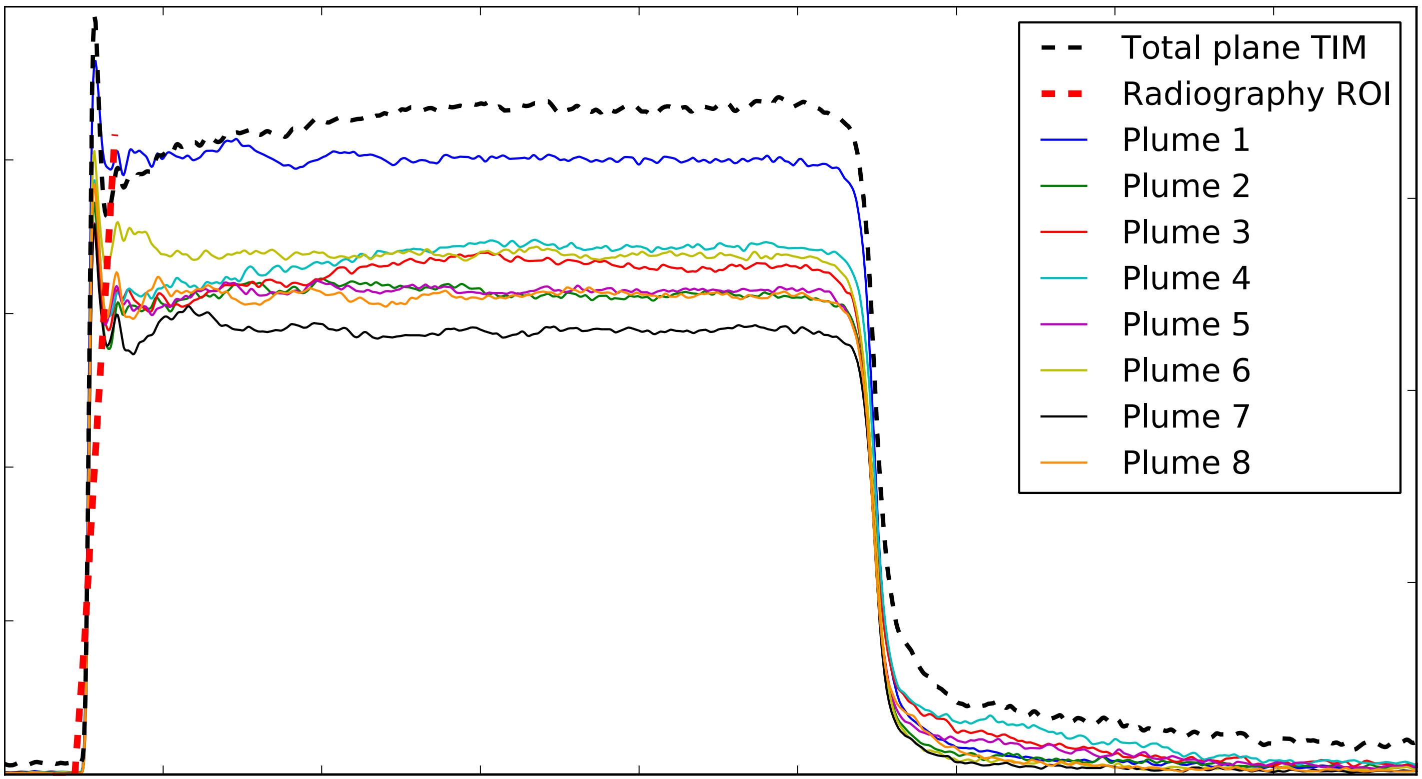
Per-plume mass analysis

- Segmentation of tomography plane to separate plumes
- Integrate density; TIM = mass per unit thickness of plane
- Compare temporal evolution

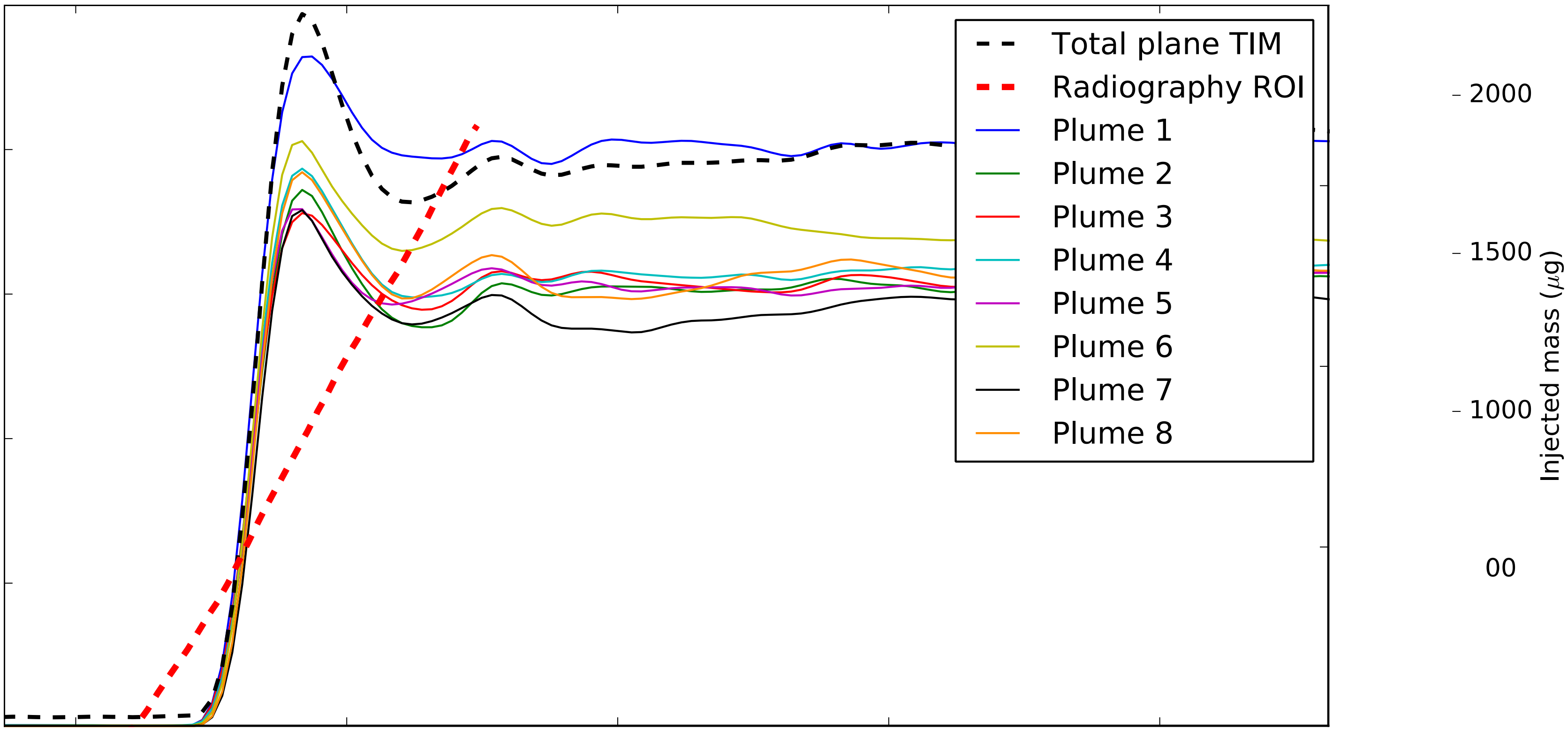


Transverse Integrated Mass

Z = +2mm



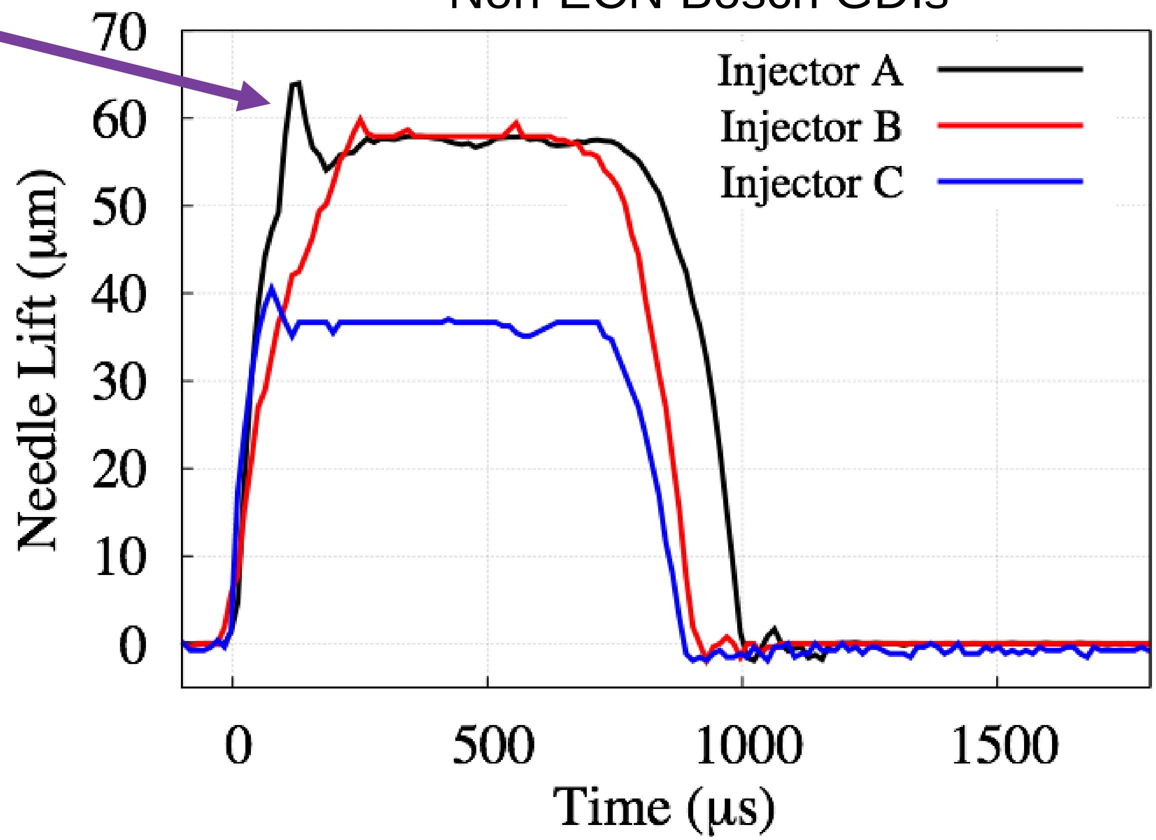
Z = +2mm


Total plane TIM
Radiography ROI
Plume 1
Plume 2
Plume 3
Plume 4
Plume 5
Plume 6
Plume 7
Plume 8
2000
1500
1000
00
Injected mass (μg)

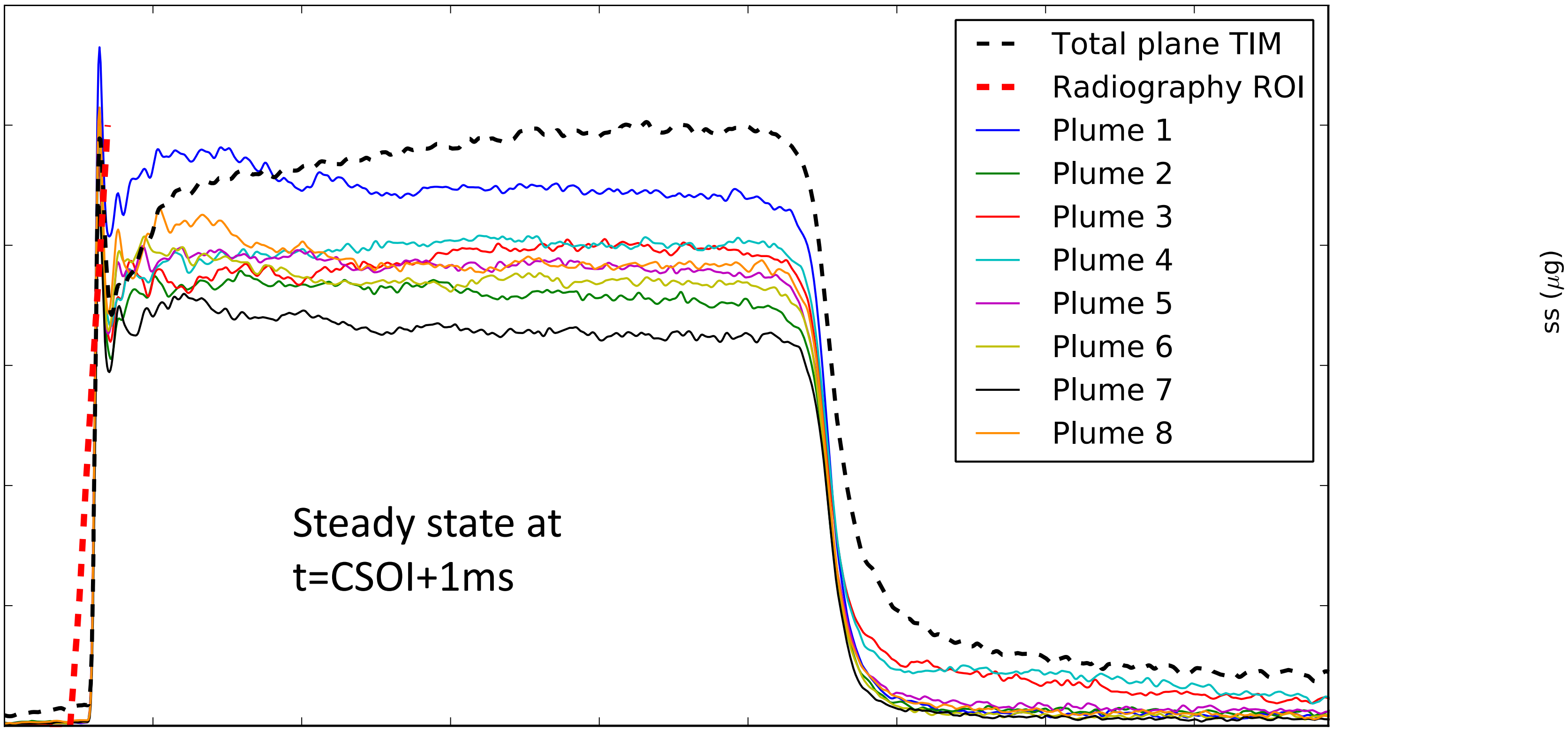
Needle Lift

- Needle Lift data not yet available
- Does Spray G have lift profiles like these Bosch GDIs?
- Checkball bounce? (caveat: no experimental evidence yet for this in Spray G injectors)

Non-ECN Bosch GDIs

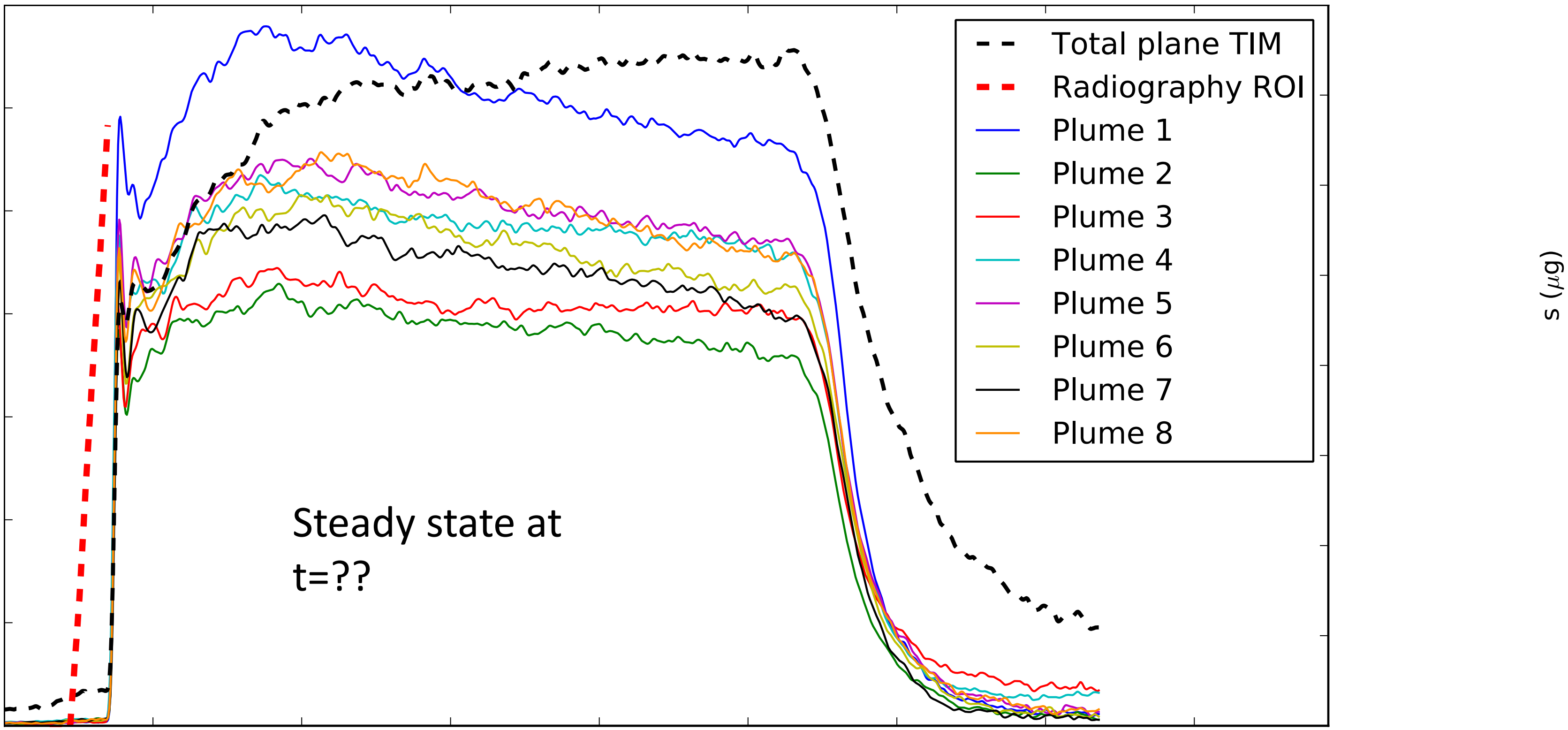


Z = +5mm


Total plane TIM
Radiography ROI
Plume 1
Plume 2
Plume 3
Plume 4
Plume 5
Plume 6
Plume 7
Plume 8
Steady state at
t=CSOI+1ms
ss (μg)

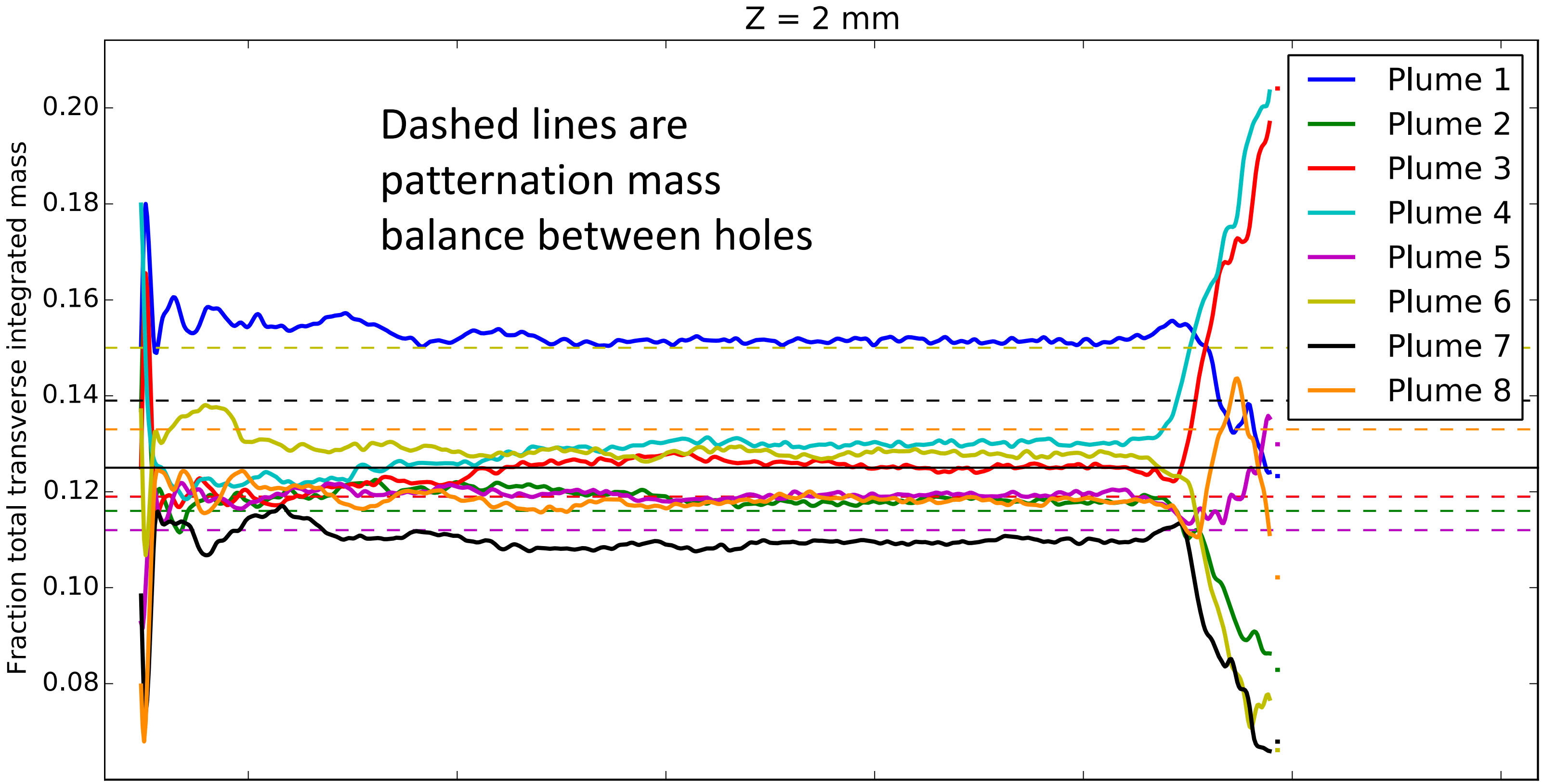
Transverse Integrated Mass

Z = +10mm



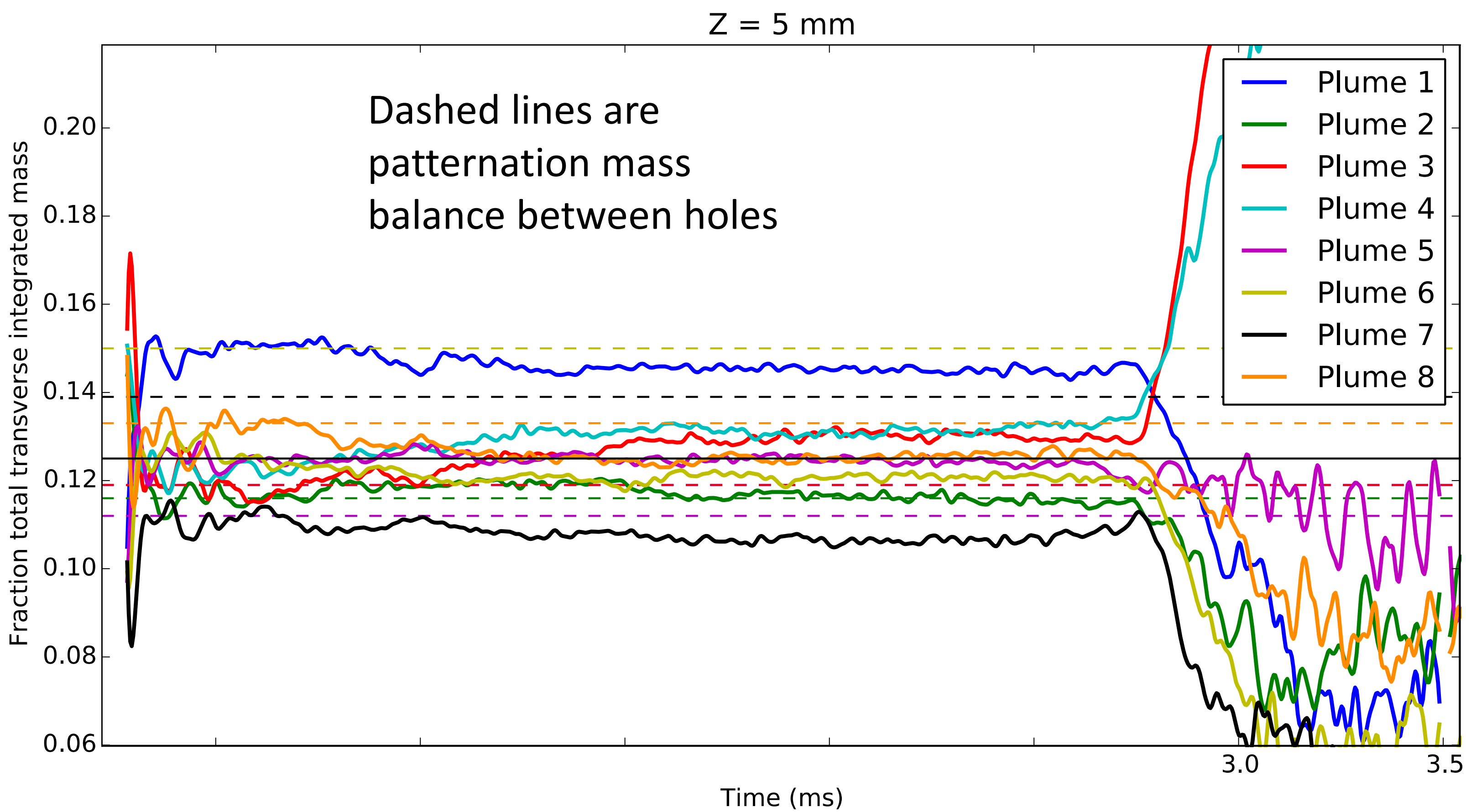
Transverse Integrated Mass

Z = +2mm
Fraction of total TIM

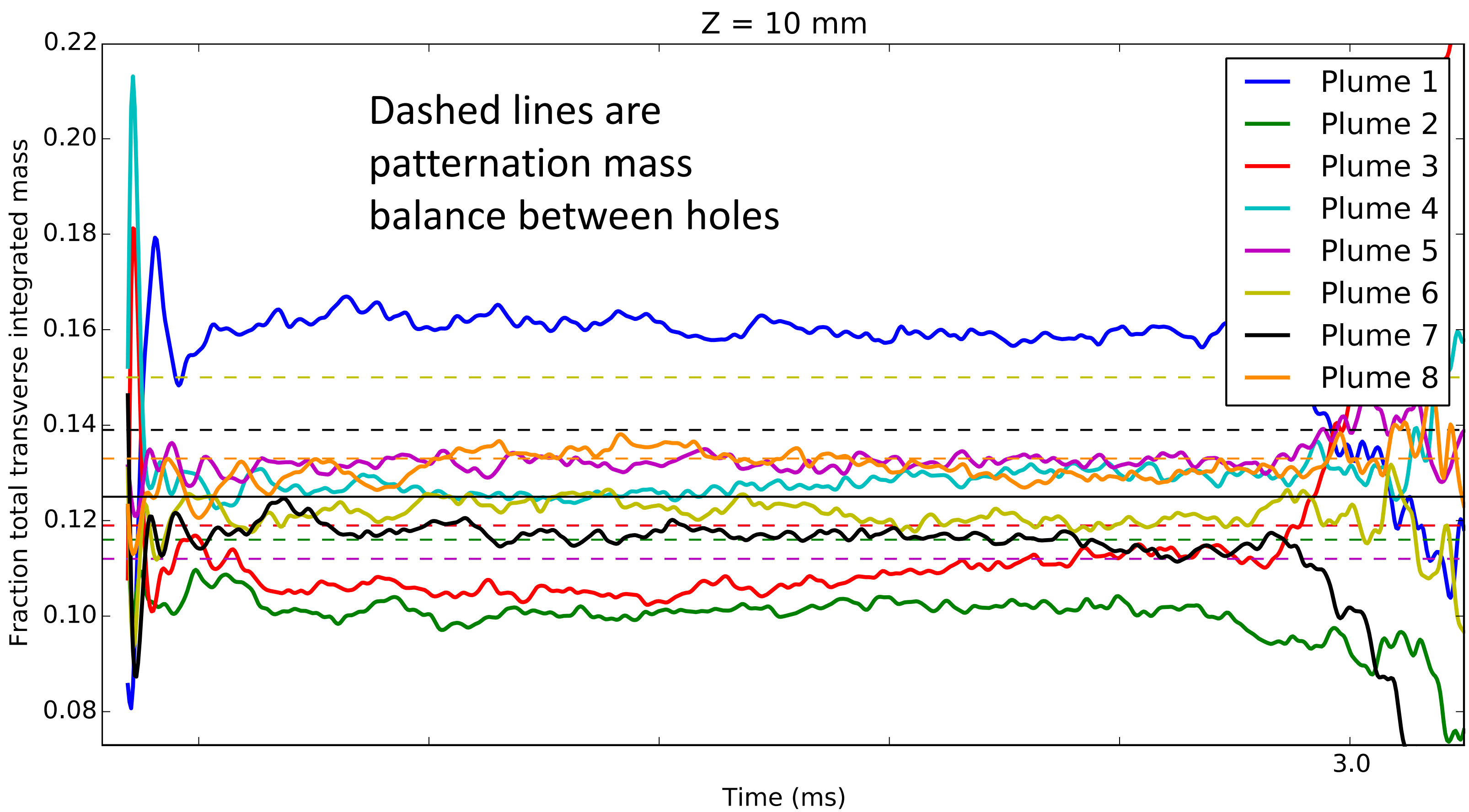


Transverse Integrated Mass

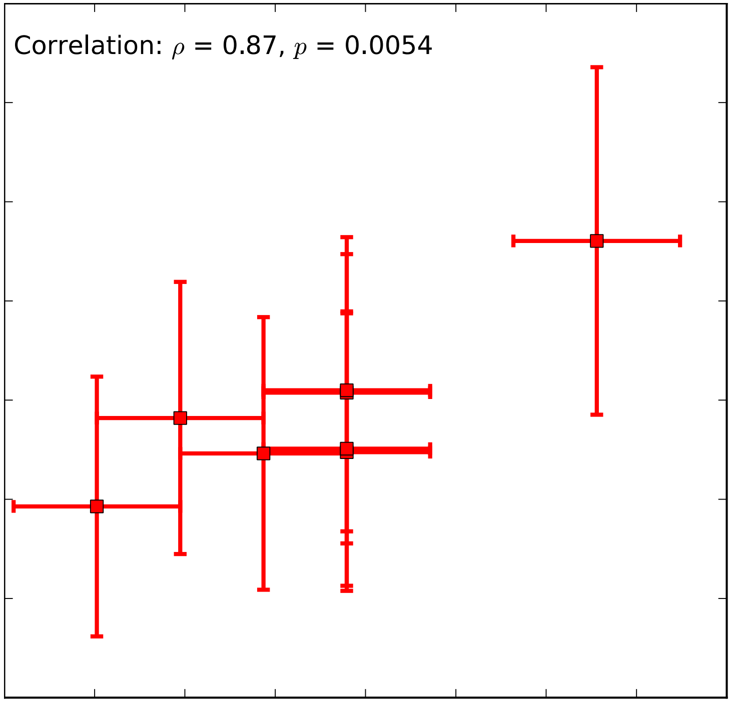
Z = +5mm
Fraction of total TIM

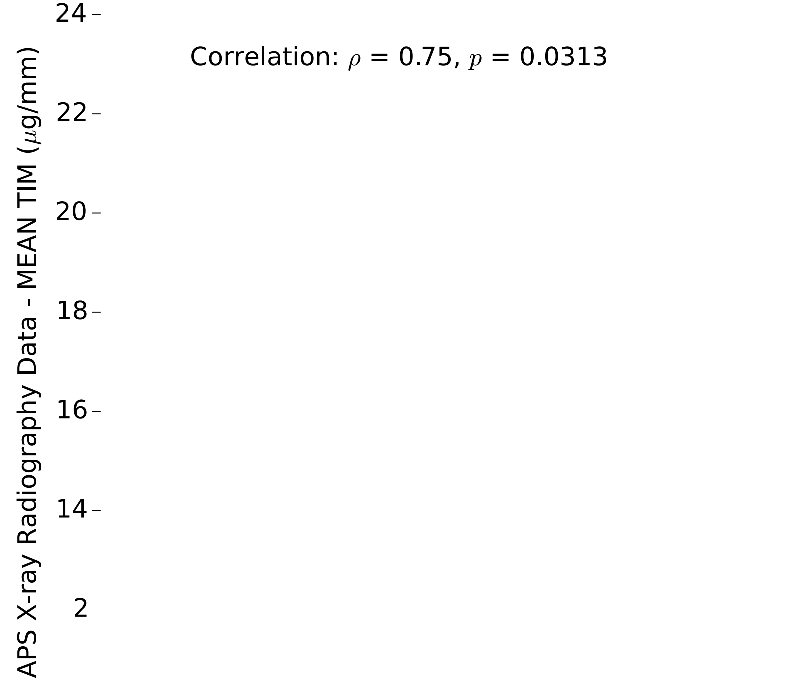


Z = +10mm
Fraction of total TIM



What geometric parameter correlates most strongly with the variations in TIM?

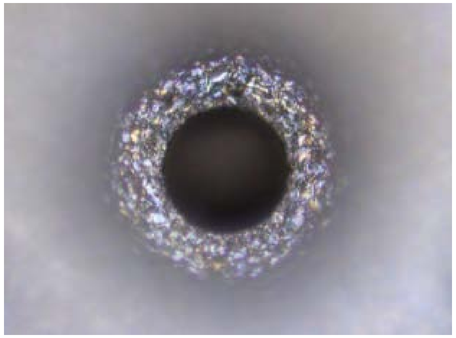




Statistically significant correlation of x-ray radiography TIM with small hole inlet & outlet diameters.

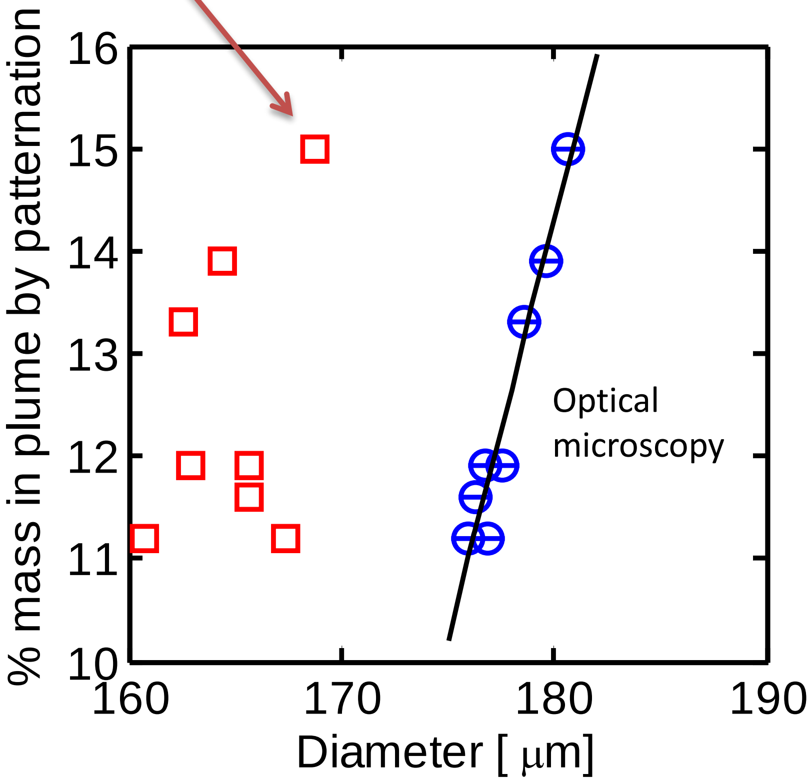
Other variables not statistically significant.

Effect of hole size on plume mass



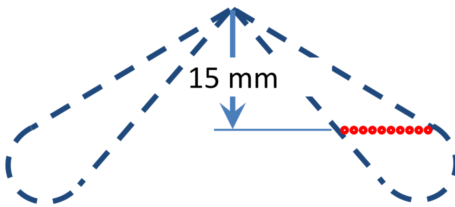
Similar result found by Sandia.

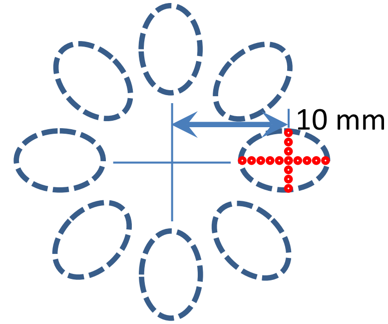
Minimum diameter inside nozzle measured via x-ray



Spray G – Drop Sizing (GM)

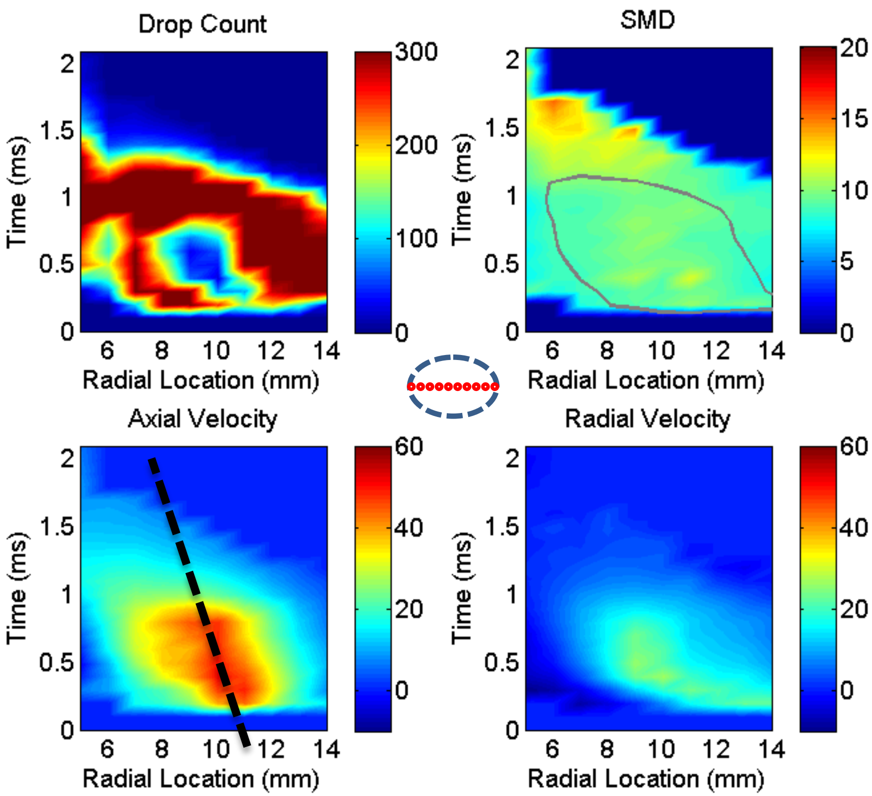
COVERED IN TOPIC 9



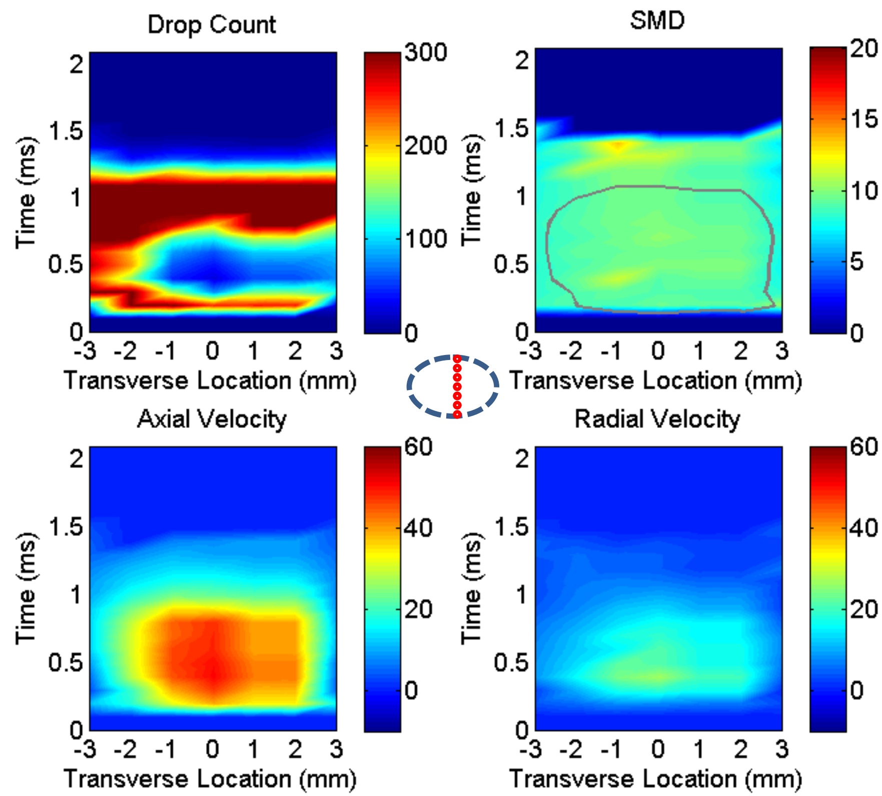


Scott Parrish
GM R&D

Radial Scan



Transverse Scan



Sandia Schlieren measurements

JSAE Paper 20159153

Julien Manin, Scott Skeen,
Lyle Pickett (Sandia),
Yongjin Jung (KAIST),
Scott Parrish (GM) and
Lee Markle (Delphi)

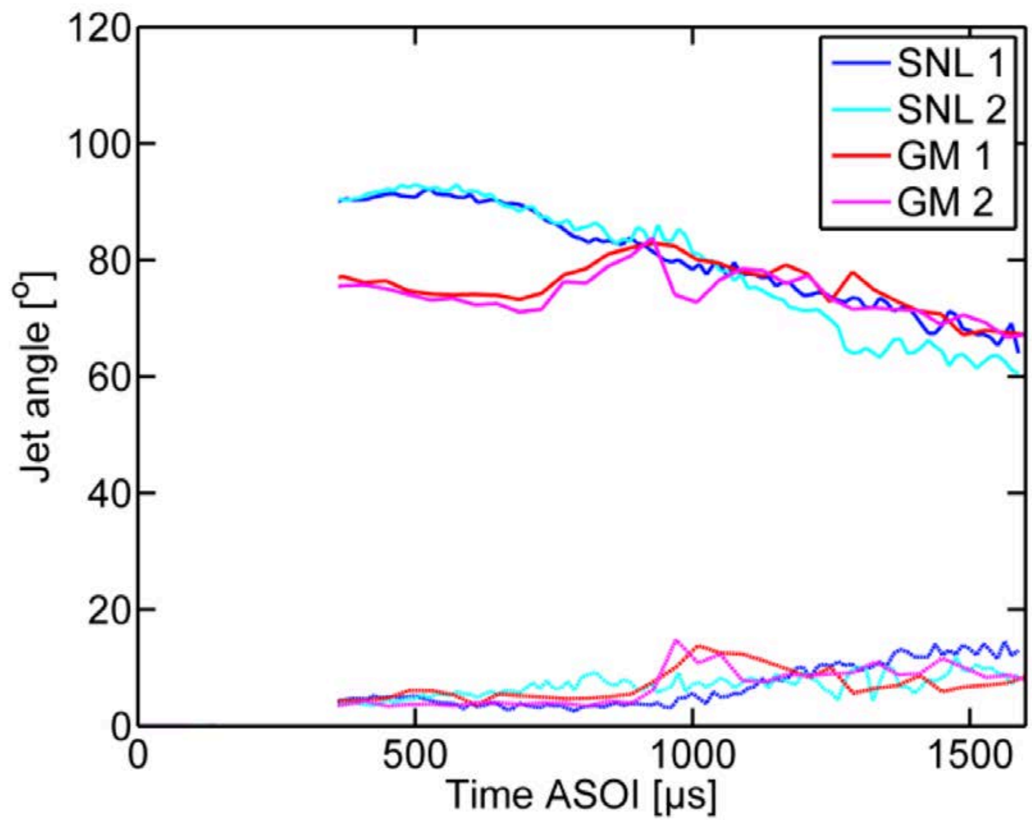
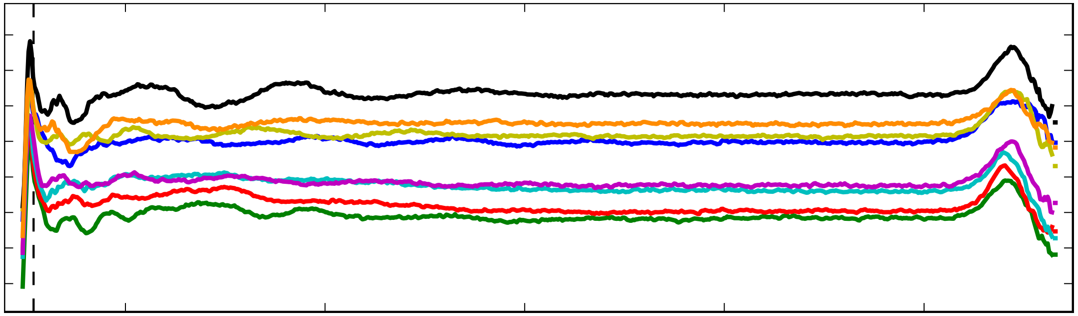


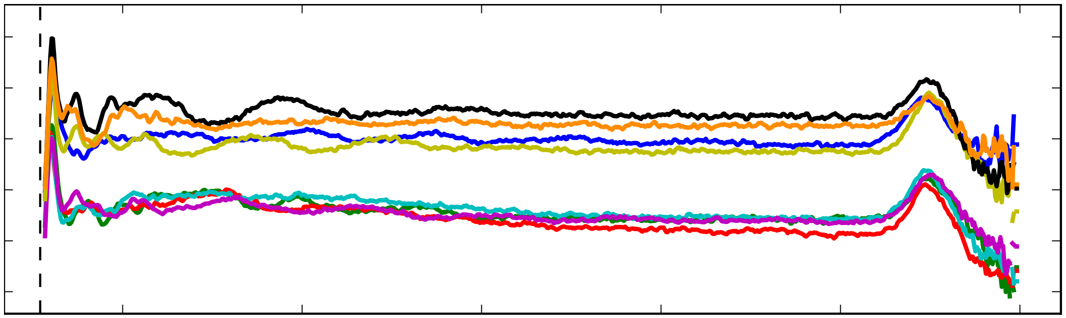
Figure 10. Full included angle of the jet as a function of time measured with schlieren imaging for the two injector orientations (1 & 2) at SNL and GM. The dashed lines at the bottom of the graph represent the standard deviation of the experiments.

Plume centers : Z=+2mm

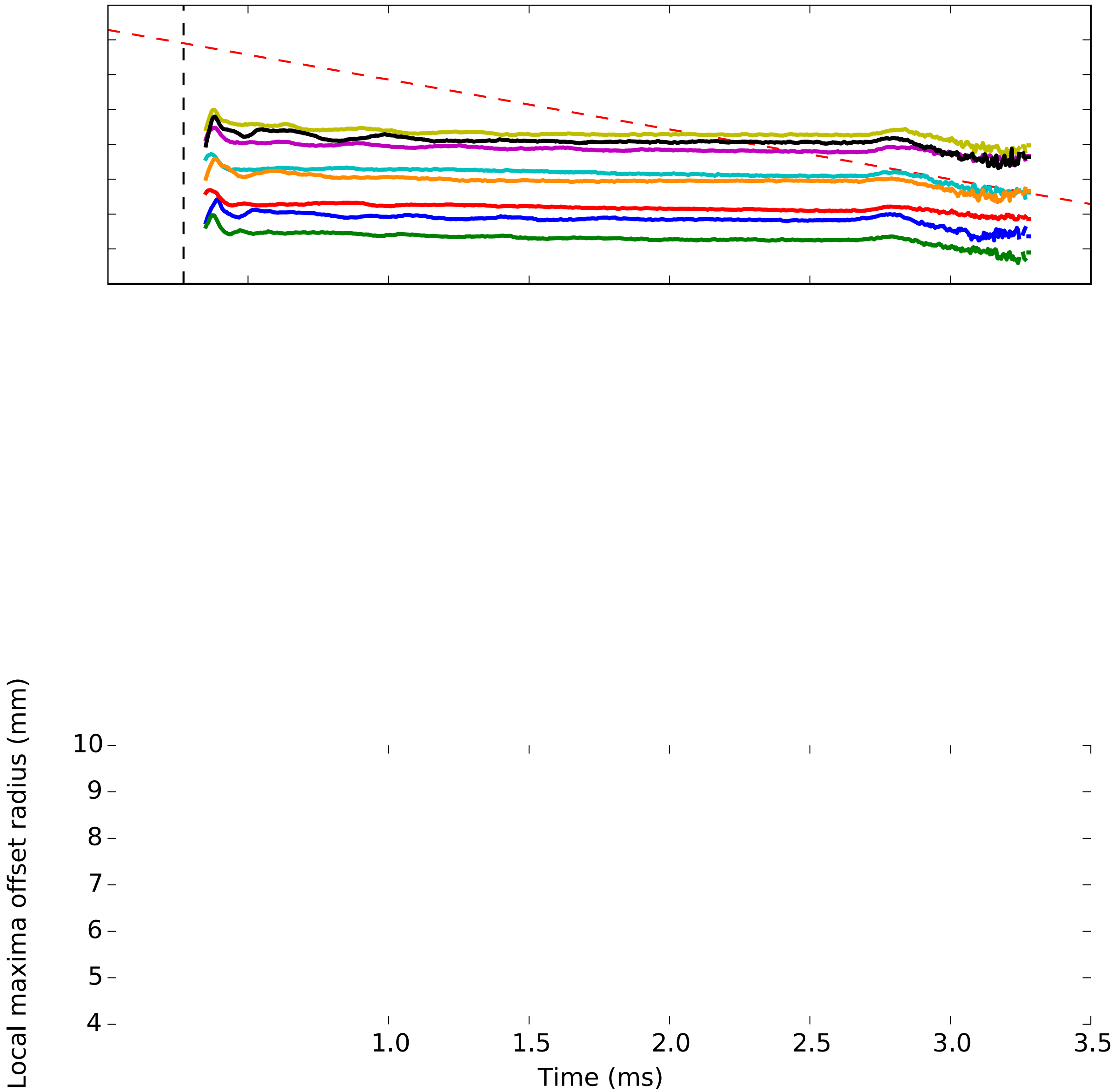


Threshold captures
80% of mass
(no entrainment field)

Plume centers : Z=+5mm

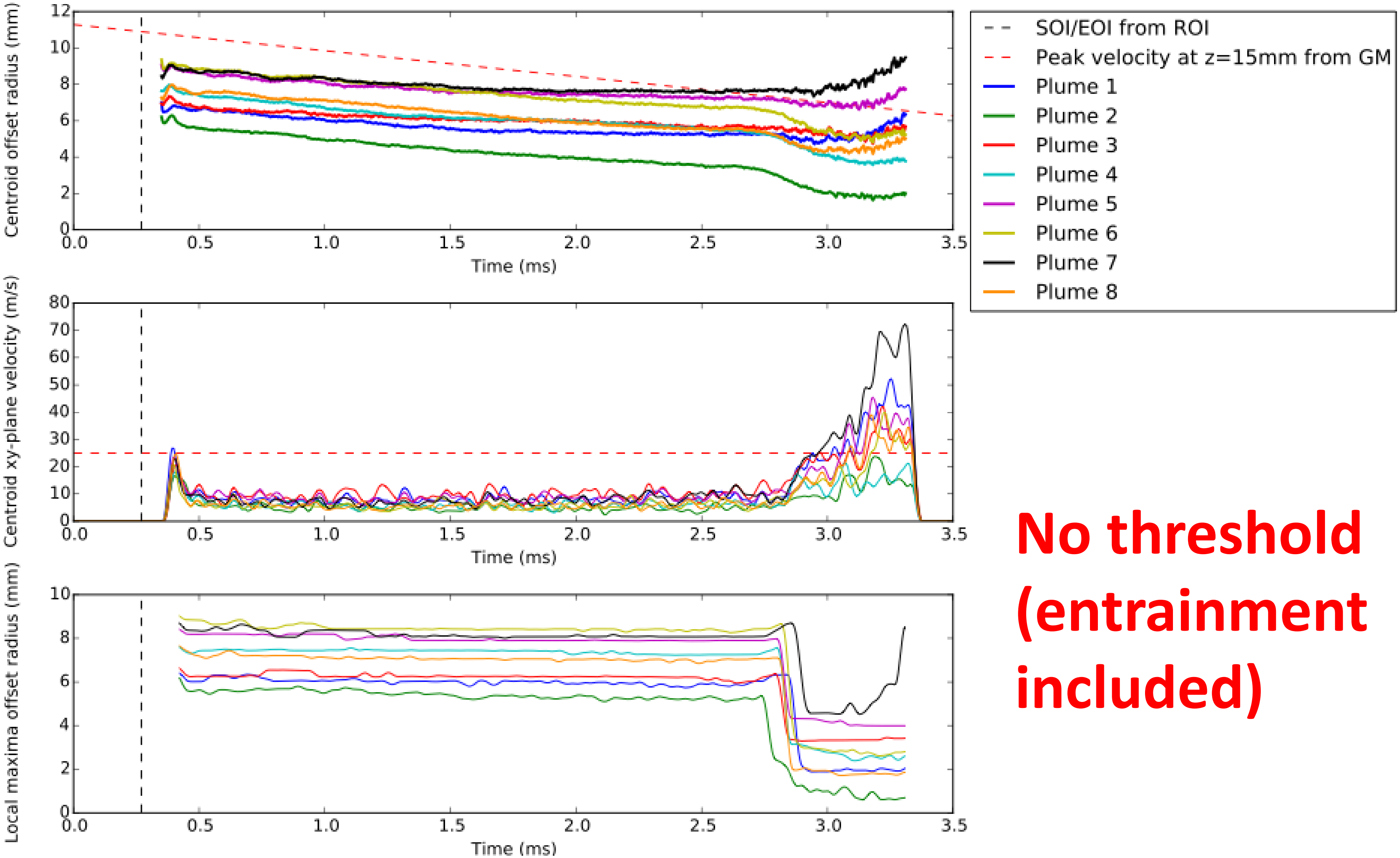


Threshold captures
80% of mass
(no entrainment field)



Threshold captures
80% of mass
(no entrainment field)

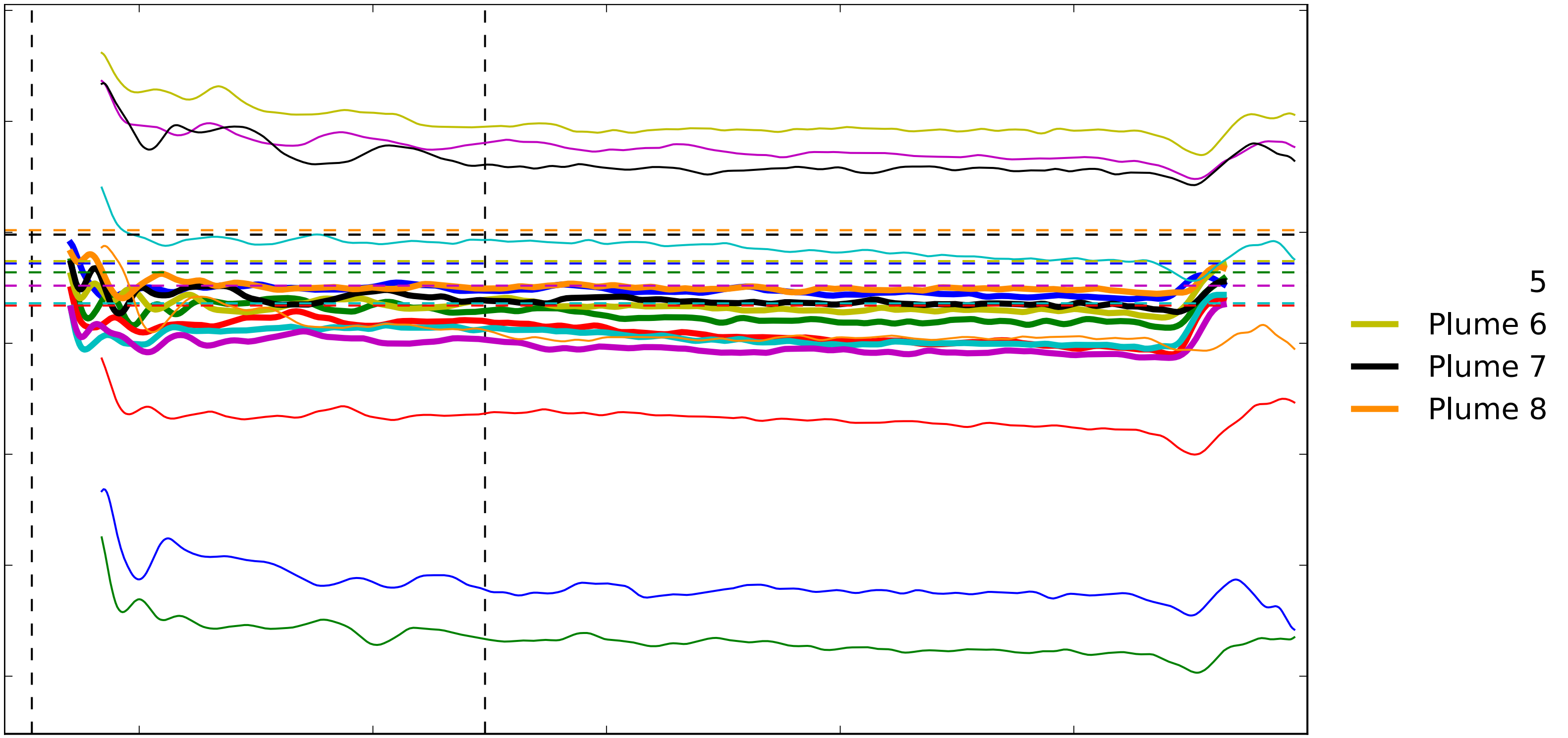
Plume centers : Z=+10mm



No threshold (entrainment included)

Plume vectoring

Spray G 028 plume vectoring - bold lines are z=2-5mm, thin lines are z=5-10mm, dashes from patternation at z=50mm



- Hole drill angles are all between 36 – 37 degrees
- Patternation data taken at z=50mm
- Entrainment can cause sprays to bend inwards
- We find that the plume vectoring remains constant with time, with an 80% total mass threshold (excluding entrainment field)

Conclusions – internal & near nozzle meas.

- Sprays take ~ 1ms to reach steady state at 10mm (longer than desired injection duration)
- **Do the short injections ever reach steady state?**
- Large variation (50%) in plume to plume mass distribution
- Correlates with hole inlet diameter ($p < 0.005$)
- **Do we need to capture this in future modeling?**
- Mass distribution consistent as distance from nozzle increases. Consistent between patternation and radiography.
- nb. More discussion and data on plume angles and collapse in Topic 8.2 & 9.

Q&A

- Hole diameters vary by 11 um (6%)
  - Correlated with plume mass variation (discussed next)
- Hole entrance radius of curvature varies from 6-17 um
  - May have strong effect on cavitation in the hole at low ambient pressure conditions
- Need for new geometry with hole to hole variations included
  - Need to separate effect of geometry and flow physics in deviations between models, and experiments
  - Can we capture the hole to hole variation with geometric variation alone?
- ANL/APS tomography data of #28 is recommended reference
  - Practical route – gen. 3 mesh informed by individual hole dimensions
  - Later – full STL from the x-ray tomography data
- Sprays take ~ 1ms to reach steady state at 10mm (longer than desired injection duration)
  - Do the short injections ever reach steady state?
- Large variation (50%) in plume to plume mass distribution
  - Correlates with hole inlet diameter ($p < 0.005$)
  - Do we need to capture this in future modeling?
- Mass distribution consistent as distance from nozzle increases. Consistent between patternation and radiography.
- More discussion and data on plume angles and collapse in Topic 8.2 & 9.