

Comparison of Non-Combusting Spray Fields in a Model Combustor using Shadowgraphy

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Motivation

- Lean direct injection (LDI) for gas turbine engines capable of reducing NOx emissions in the lean overall combustion regime
- Multi-point fuel injection and rapid fuel-air mixing create more uniform combustible mixture for lower NOx
- Many iterations of LDI but this study focuses on an early generation, swirl-venturi LDI (LDI-1)
- This presentation will provide mass fluxes, droplet sizes, and droplet velocity data with non-reacting water spray

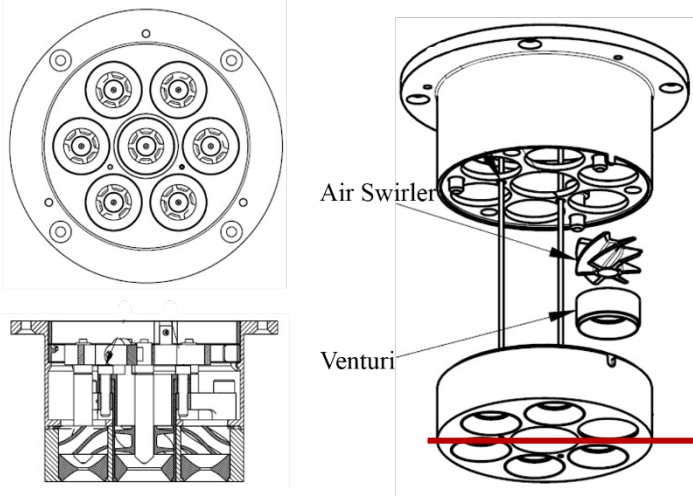
Combustion and dynamics facility



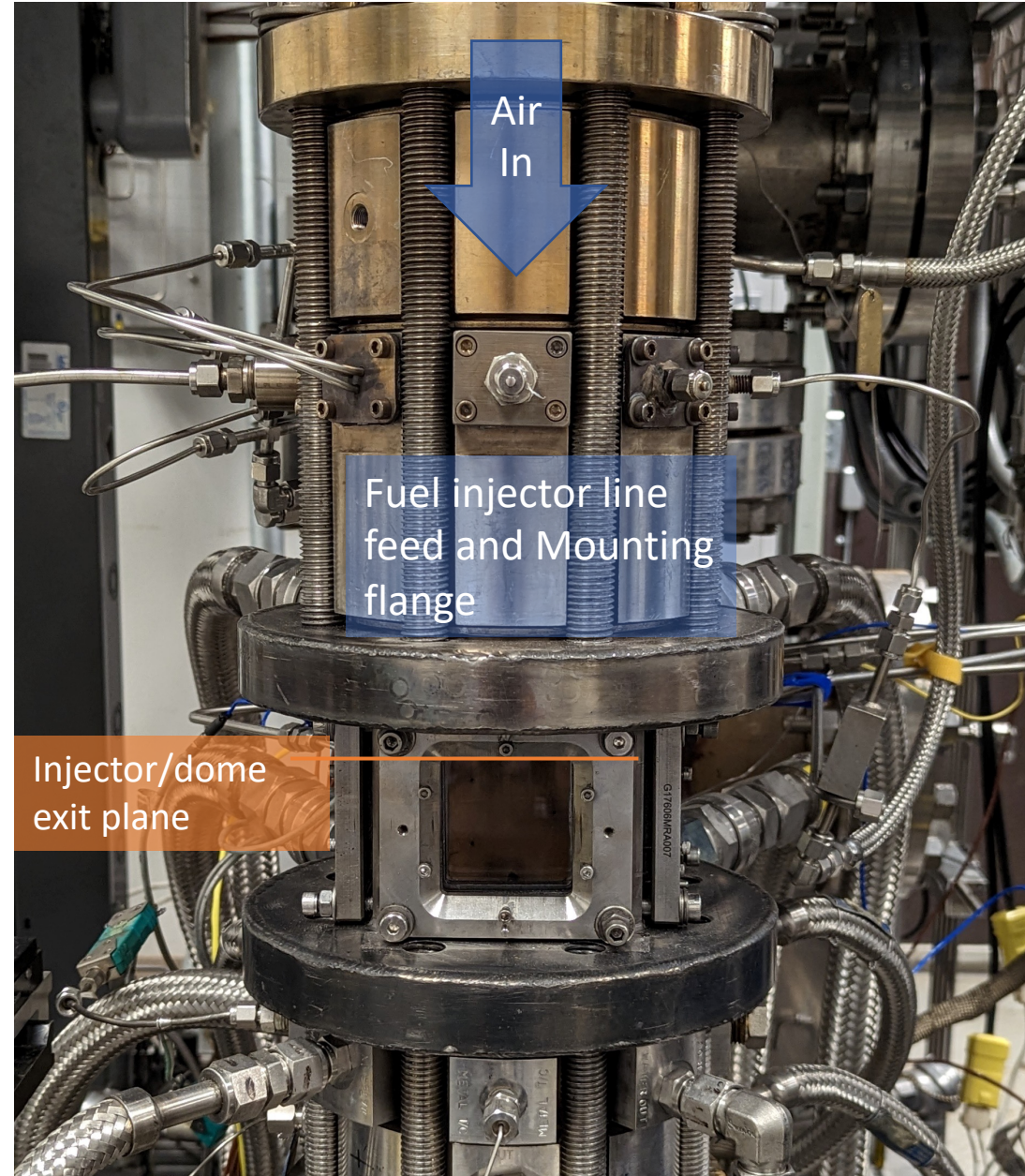
Facility Setup

- Circular cross-section
- Diameter of 7.62-cm (3-in)
- Flow is downward. Dome at $z = 0$
- Combustor section has 3 windows, each 5.8-cm $\times$ 6.1-cm (2.3-in $\times$ 2.4-in)

7-point Lean Direct Injection Hardware



$z = 0$
Dump plane



NASA 7-point LDI hardware



- 7 identical elements, equally spaced neighbors
- Converging-diverging venturi
- Simplex atomizer, tip at venturi throat
- Axial air swirler
- Flow through center nozzle only, air through all 7 elements

Component Description	Dimensions mm
Combustor diameter	76.2
LDI diameter	
Element center-to-center spacing	23.8
Element axial length	20.83
Element diameter	22.17
Venturi throat diameter	13.0
Venturi throat length	1.55
Diffuser length	4.37
Diffuser diameter at dump plane	20.32

Shadowgraph Setup and Procedure

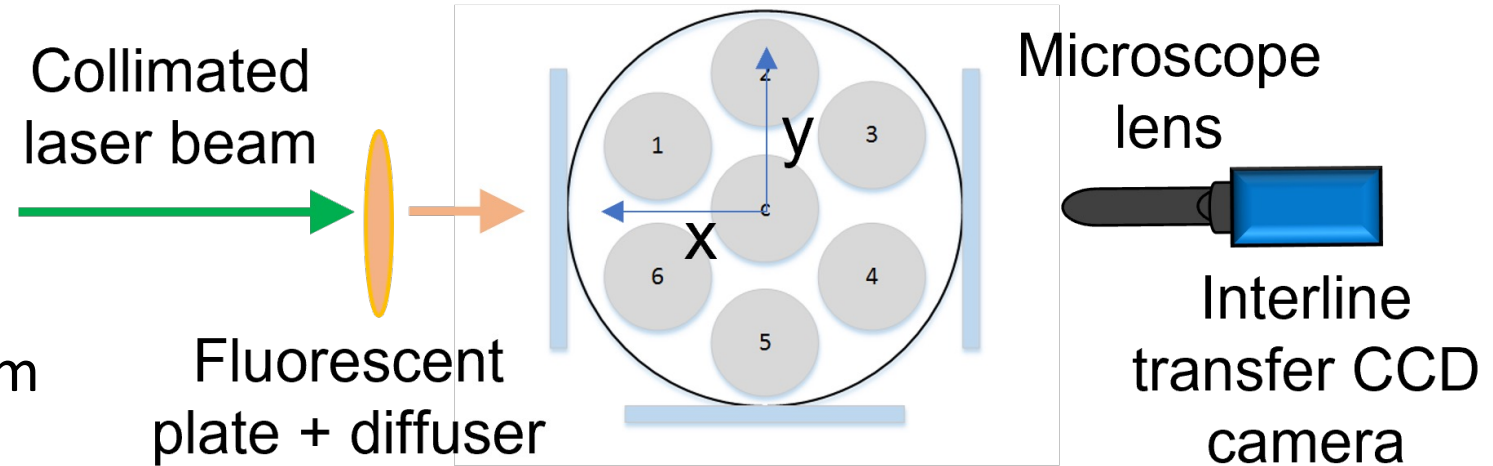
Imaging Setup

Backlight optics:

- 15 Hz dual head Nd:YAG laser, collimated beam incident on fluorescent plate and diffuser to produce orange backlight

Receiving optics:

- Navitar 12x zoom system with 12mm fine focus zoom lens, 2x standard adapter, 0.5x lens attachment.
- Imager Pro 2M CCD camera (LaVision), 1600 x 1200 pixel resolution
- Magnification $1.32 \mu\text{m}/\text{pixel}$



Procedure

- Optics set up on 3-axis traversing stages to allow for measurement throughout the combustor
- 500 image pairs were collected at each position



Test matrix

test point	Reference velocity, u _{ref}	Air flow rate	water flow rate	water/air ratio	ALR	line + nozzle ΔP_L
	m/s	kg/s	kg/h			Bar
300L	7.6	0.089	1.6	0.0050	202	2.1
300N	7.6	0.089	2.1	0.0066	150	3.7
300H	7.6	0.089	2.7	0.0086	117	6.1
500L	15.2	0.179	2.5	0.0039	254	5.2
500N	15.2	0.179	2.9	0.0044	225	6.6
500H	15.2	0.179	3.5	0.0054	184	10.3
700L	22.8	0.269	2.8	0.0029	342	6.4
700N	22.9	0.269	4.0	0.0041	241	12.8
700H	22.9	0.269	5.1	0.0053	190	20.3

- Three test point series: 300, 500, 700
- Each test point series indicates air reference velocity
- Each reference velocity with a nominal (N), high (H), and a low (L) liquid flow rate excursion
- Inlet air temperature and pressure, 700 K and 5 bar

$\Delta P = 4.8$ bar



$\Delta P = 7.9$ bar



$\Delta P = 11.3$ bar



$\Delta P = 14.8$ bar



$\Delta P = 18.2$ bar



$\Delta P = 21.7$ bar



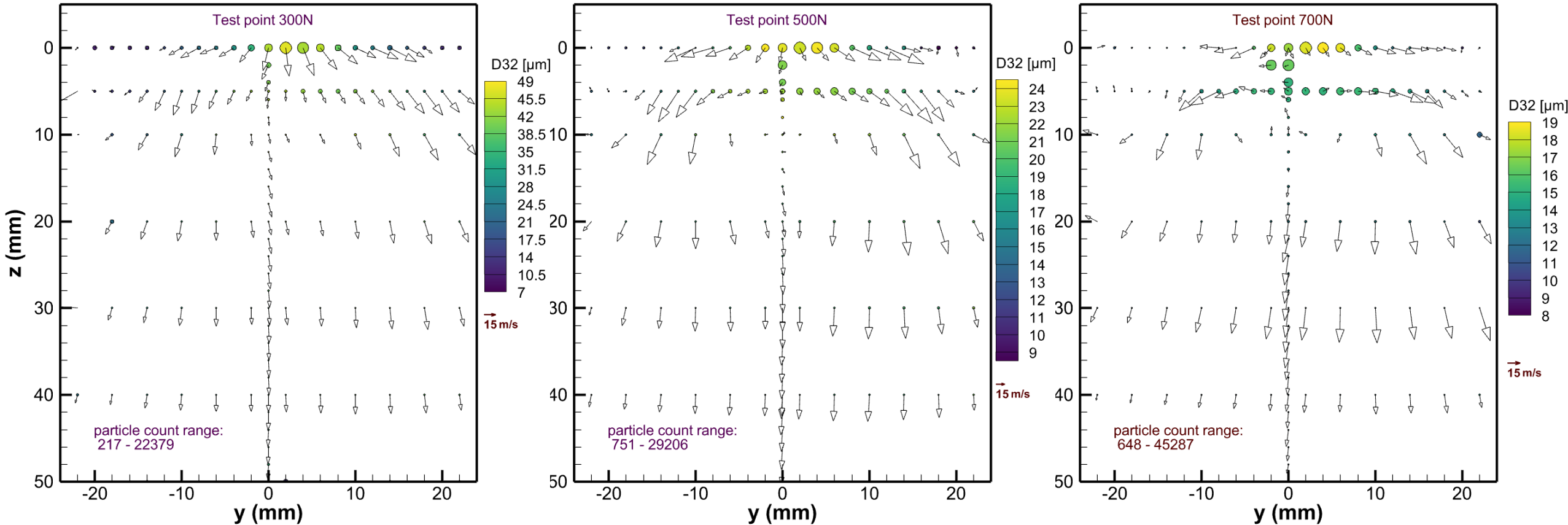
Pressure atomizer spray from a simplex nozzle to highlight effect of nozzle ΔP_L

Water spray patterns into still air

- Illuminated with a cw laser sheet
- Ambient air temperature and pressure
- Ambient water temperature
- Water flow through center nozzle only
- No air flow through array
 - Pattern a result of flow and pressure drop through pressure-swirl (simplex) nozzle
- Lowest pressure drop has worst quality atomization

Results

Results in x=0 plane: SMD, number of drops, and y-z velocity

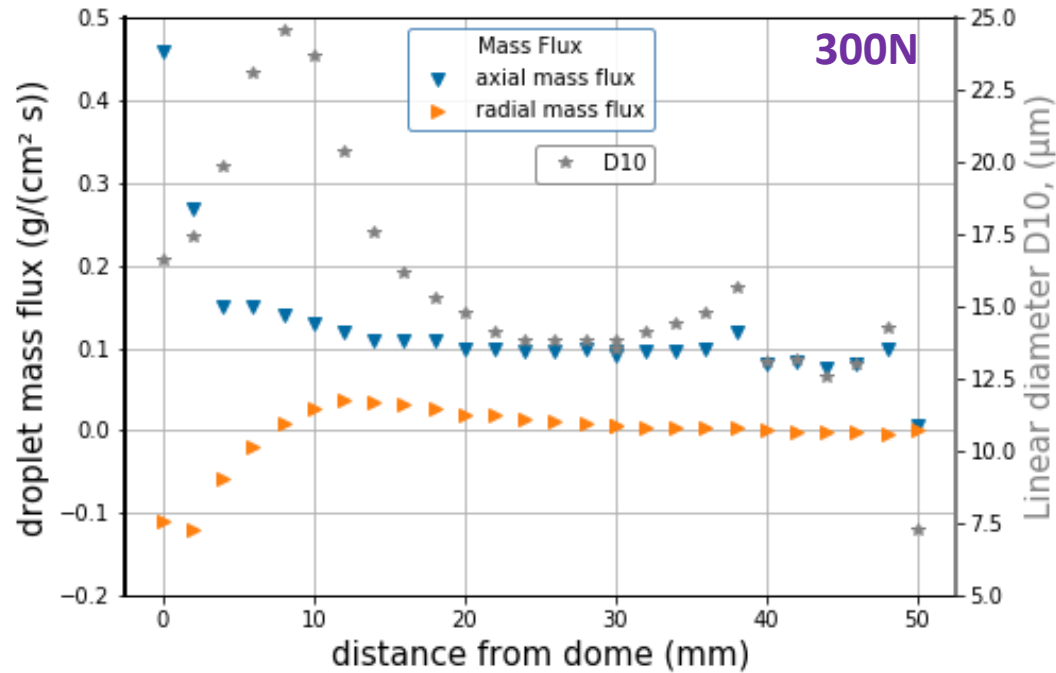


Highest particle count within 5 mm axially and 10 mm radially

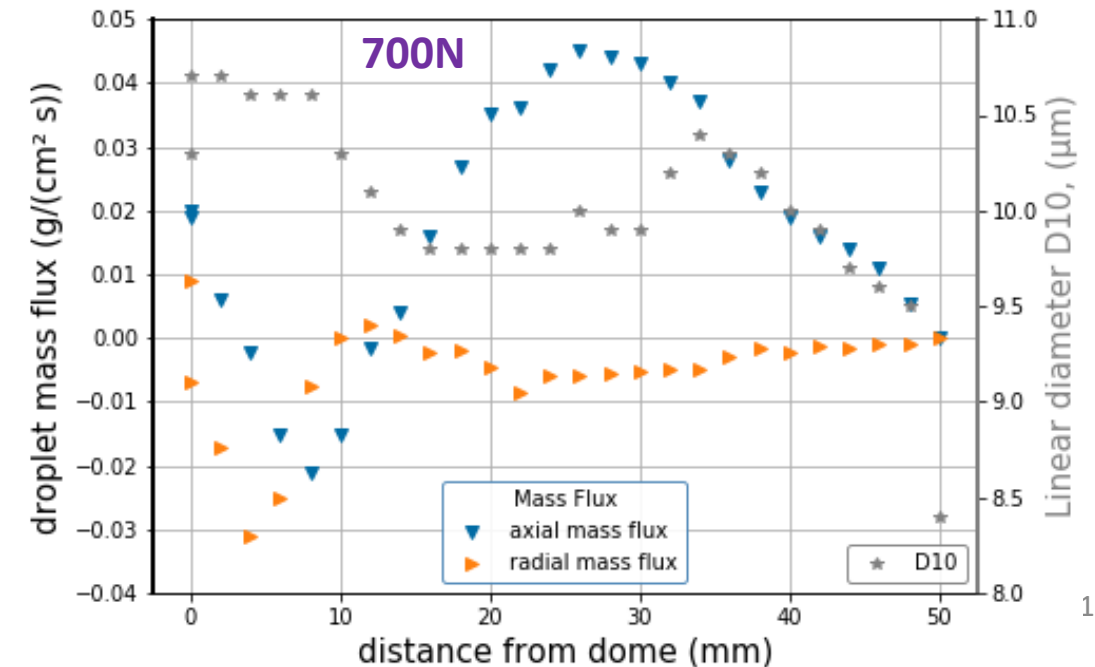
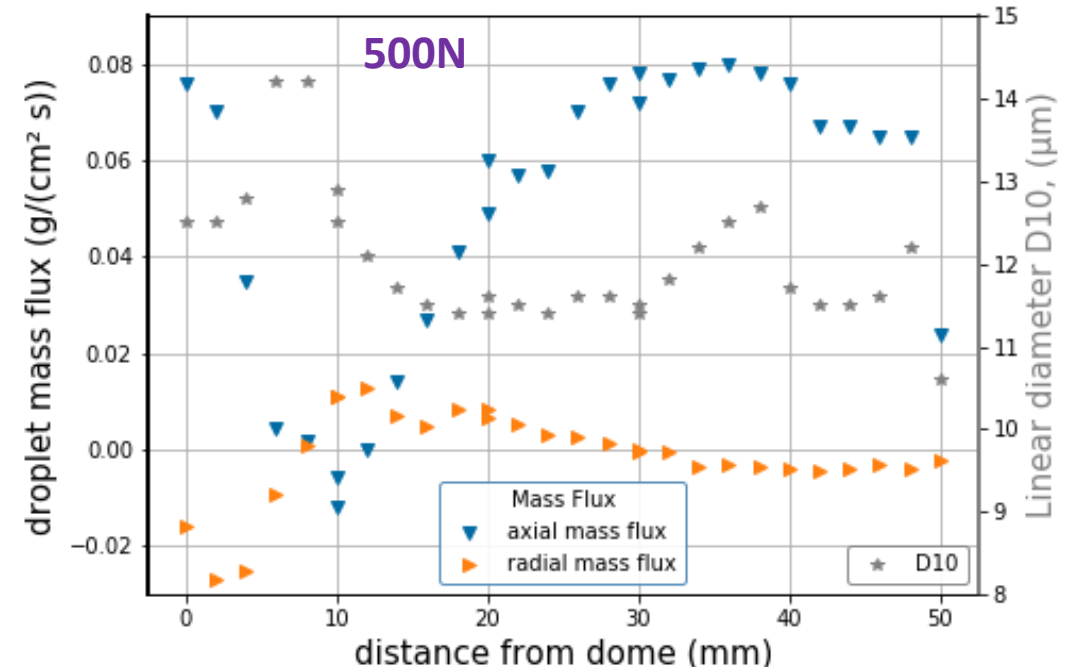
As nozzle ΔP_L increased, total number of drops increased and SMD decreased

No reverse flow at 300N, small region of recirculation at 500N and 700N

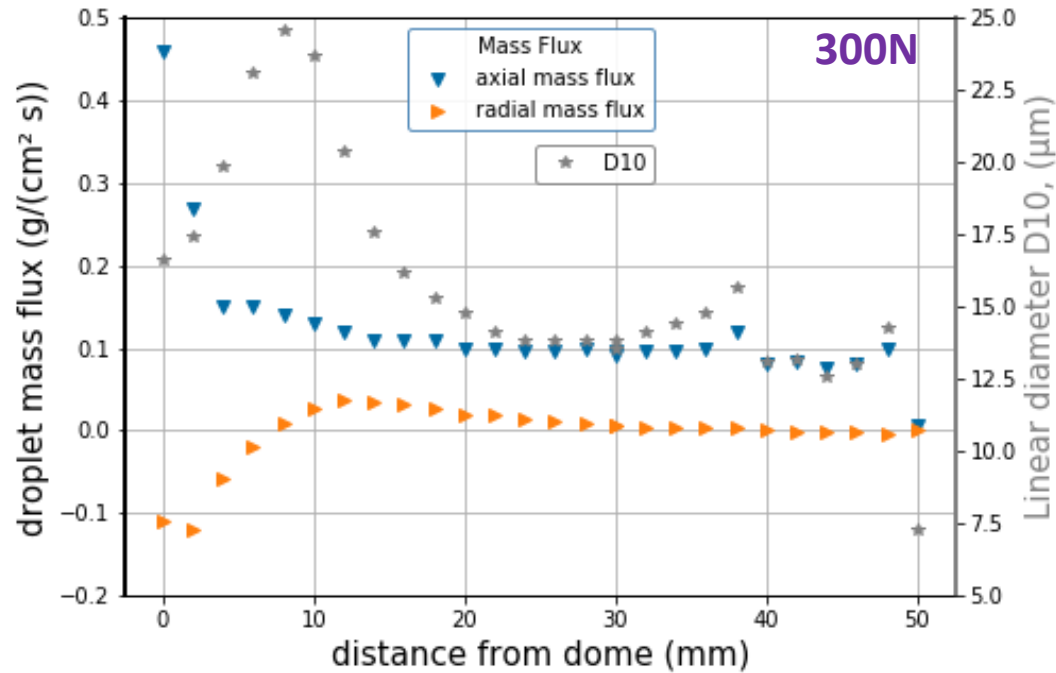
Axial and radial mass flux and average linear diameter along centerline as a function of distance from dome



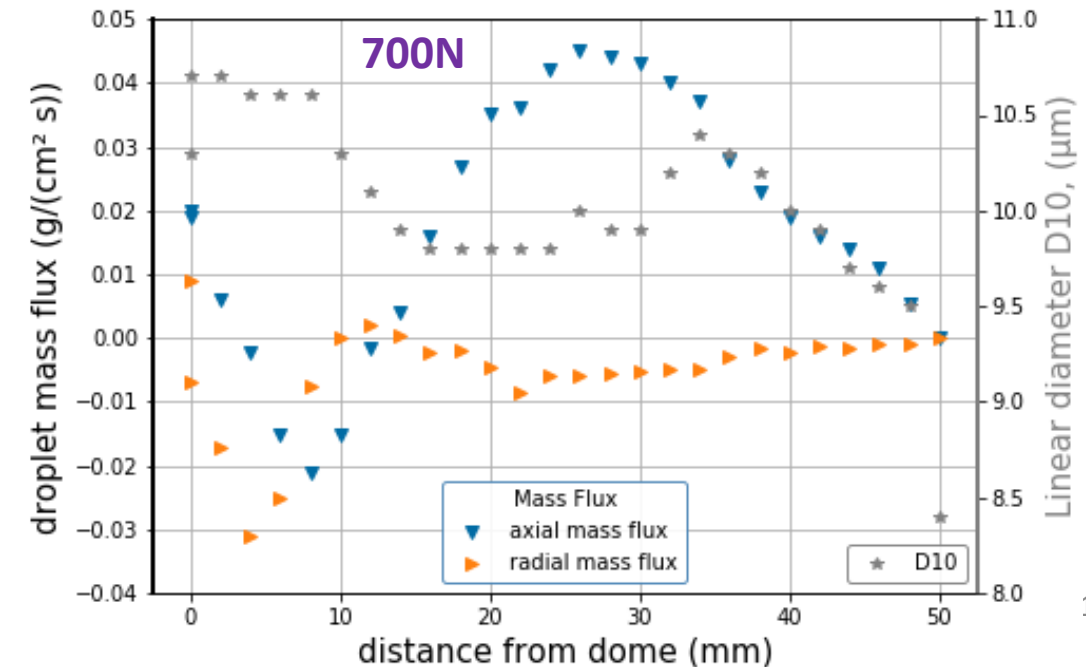
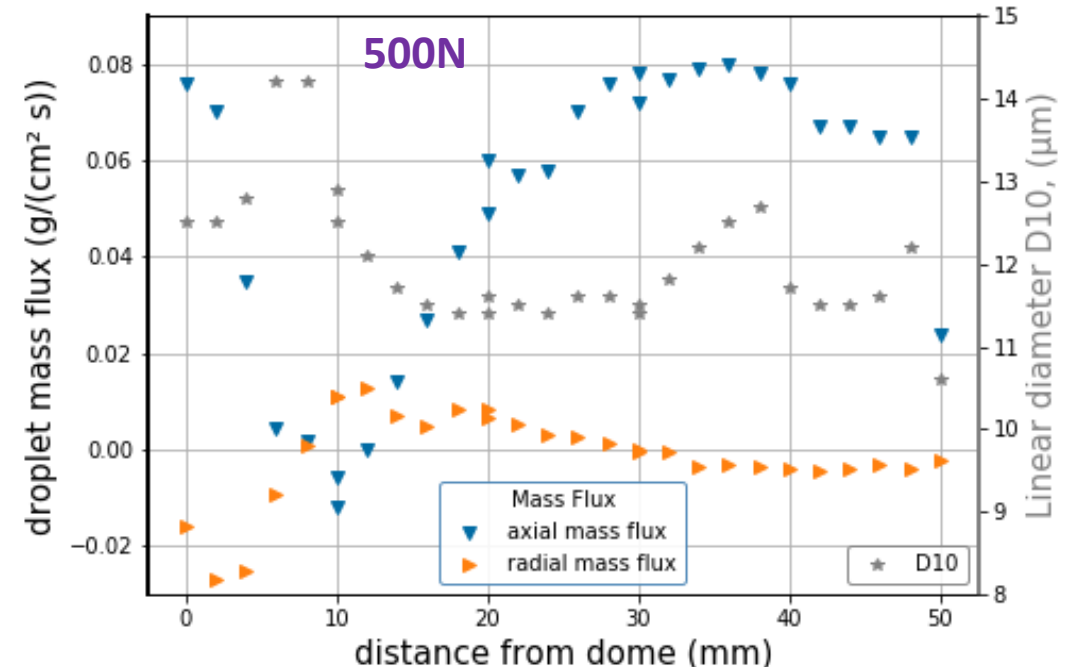
Point 300N: drops do not recirculate
Increase in droplet diameter close dome due to droplet recombination where axial velocity slows, larger initial drop, narrower spray angle



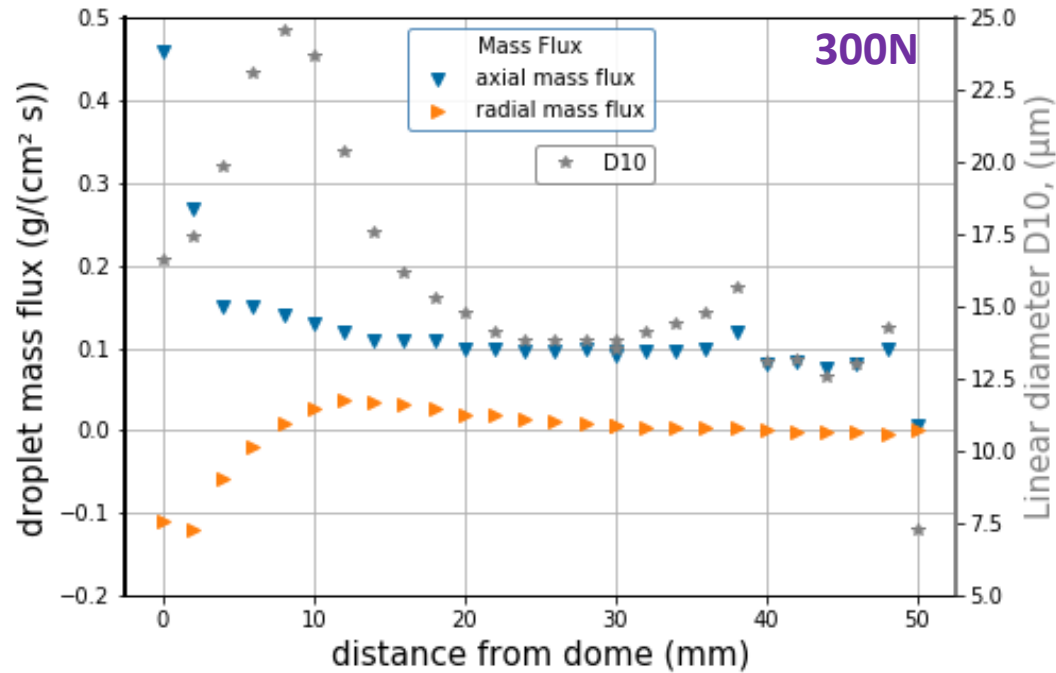
Axial and radial mass flux and average linear diameter along centerline as a function of distance from dome



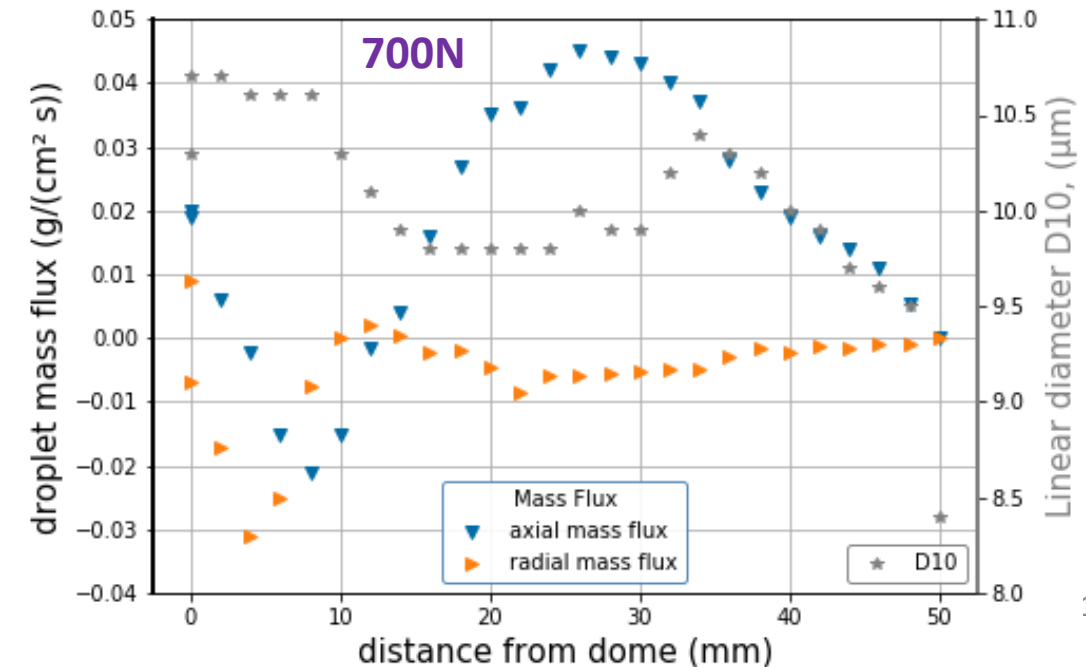
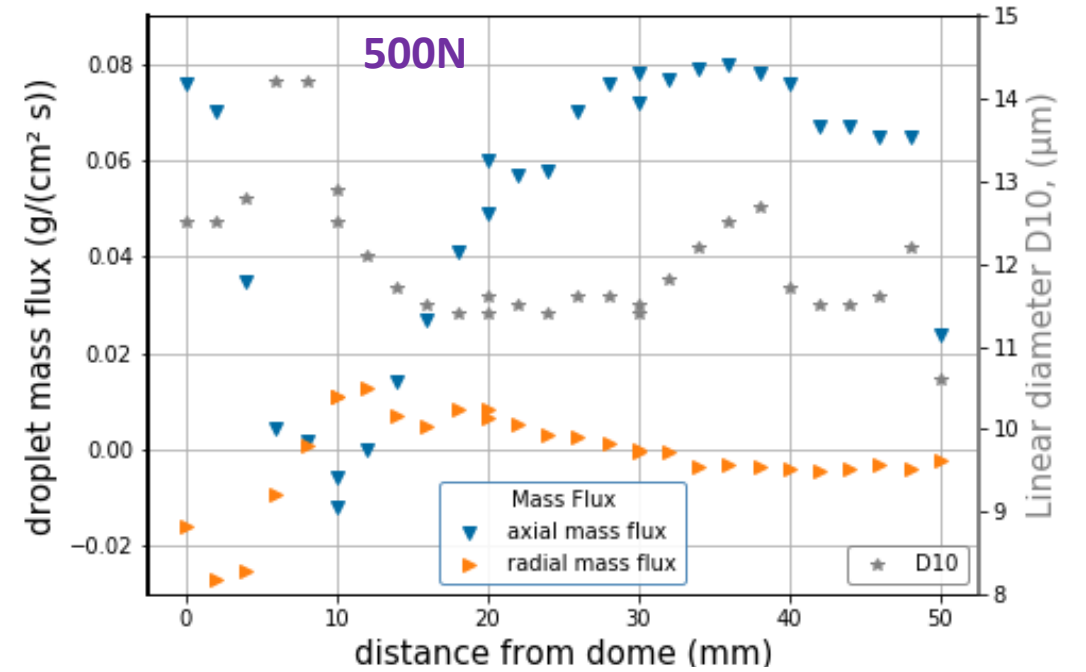
Point 500N: region of small negative axial mass flux
Smaller increase in droplet diameter close dome due to droplet recombination where axial velocity reverses, smaller initial drops, wider spray angle



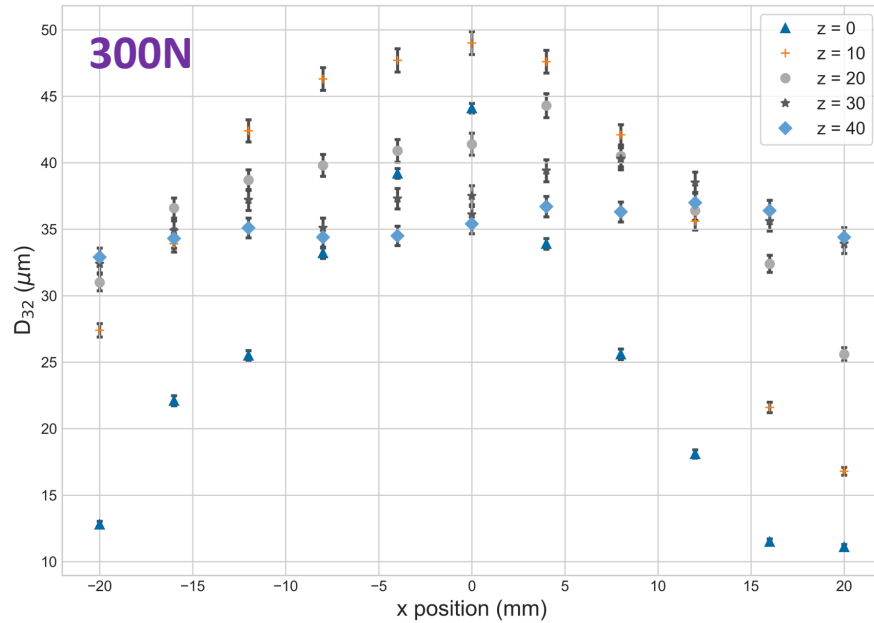
Axial and radial mass flux and average linear diameter along centerline as a function of distance from dome



Point 700N: region of largest negative axial mass flux
 Droplet diameter steadily decreased with downstream distance with smallest generated drops more likely to vaporize quickly



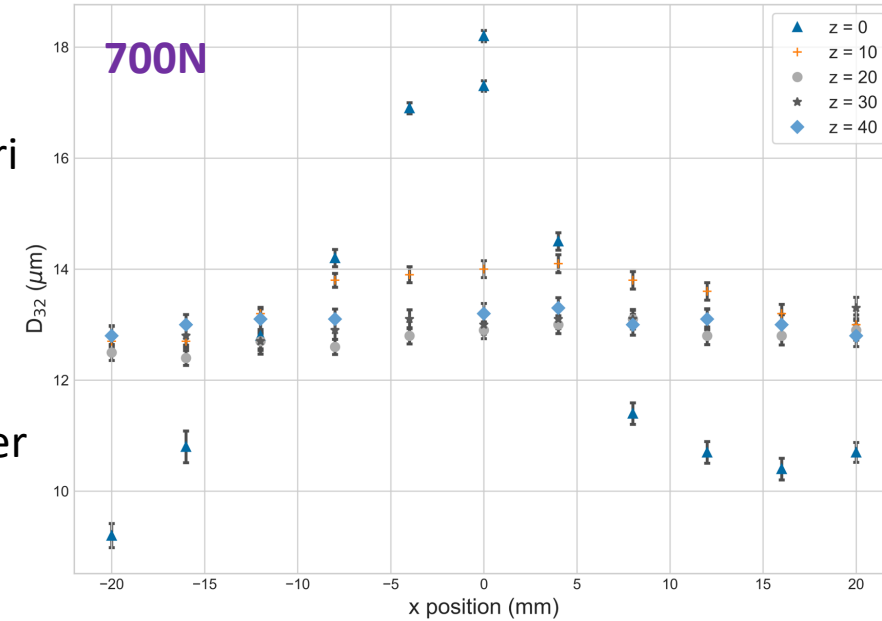
SMD at $y=0$ for various downstream positions at the three nominal flow conditions shows symmetric distribution for all axial locations



Points 300N, 500N, 700N

Near the dome at $-10 \text{ mm} < x < 10 \text{ mm}$ within venturi diffuser diameter, larger droplets observed

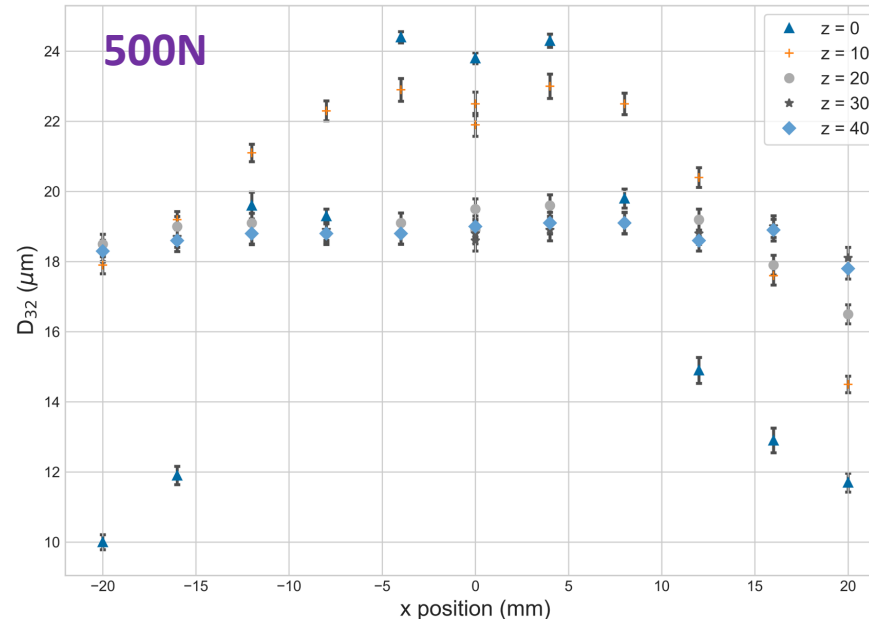
Near the dome at $x > 10 \text{ mm}$ and $x < -10 \text{ mm}$, smaller droplets from downstream mixing or spray cone periphery



Point 300N

SMD at $z = 10 \text{ mm}$ larger than SMD at $z = 0 \text{ mm}$, droplet recombination

Size uniformity across x, observed at $z = 40 \text{ mm}$



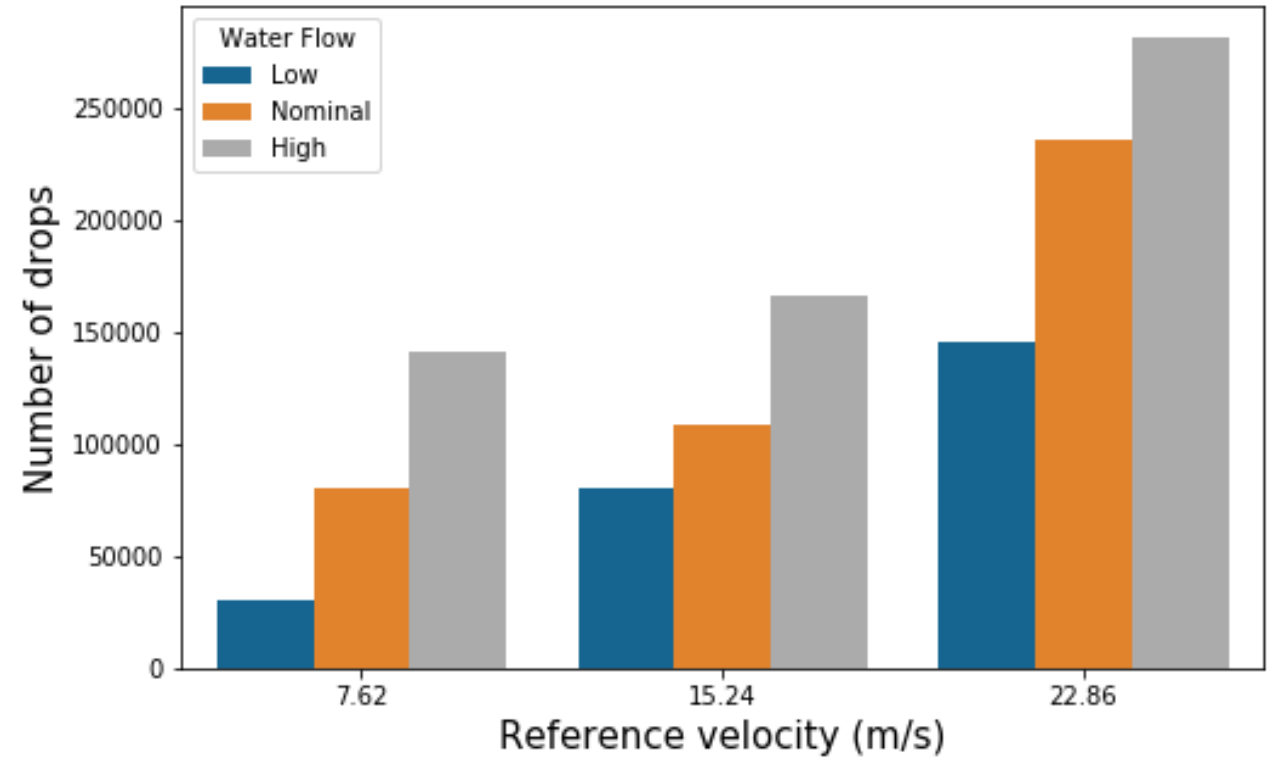
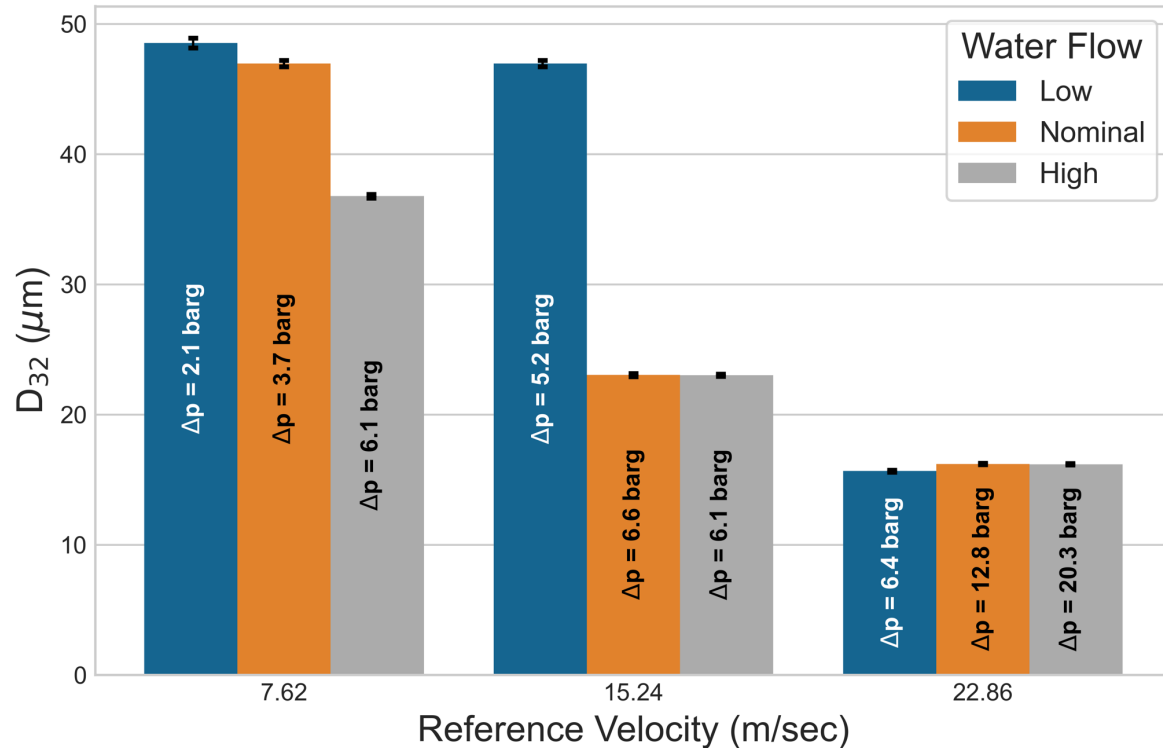
Point 500N and 700N

Size uniformity around $z = 20 \text{ mm}$ downstream

No further significant droplet breakup beyond 20 mm

Further mixing at $z > 20 \text{ mm}$ is more influenced by evaporation

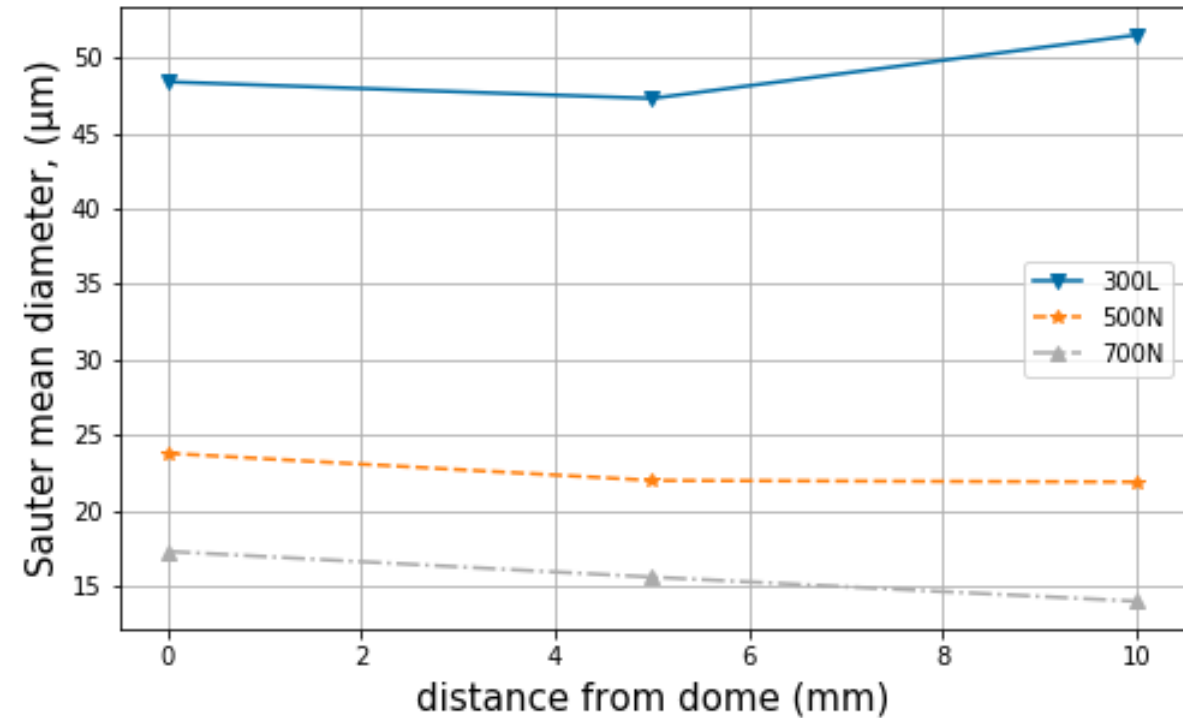
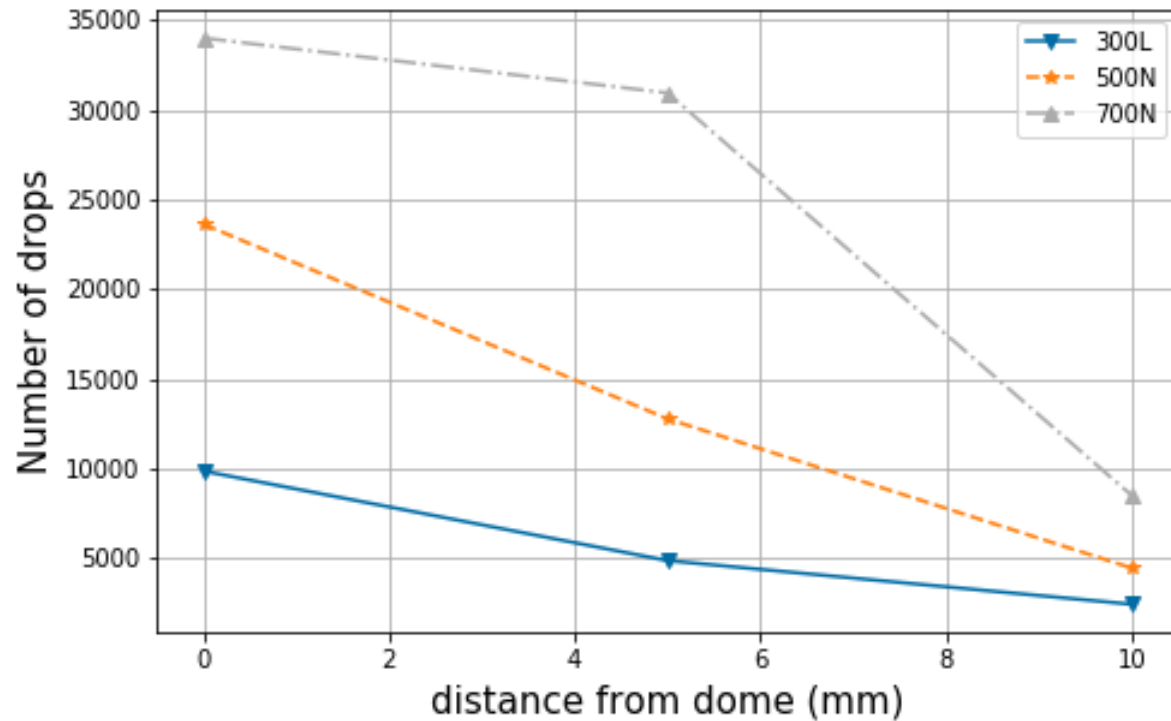
Effect of nozzle ΔP_L (water flow) on droplet number and size for the three reference velocities



- SMD decreased with increased reference velocity
- SMD decreased with increased nozzle ΔP_L (water flow) at 300 test series
- 300L vs 500L SMD: nozzle ΔP_L (water flow rate) at 500L in between 300N and 300H
- From 500 and 700 series, apparent critical nozzle $\Delta P_L \geq 6.4$ bar generates small drops
- Nozzle ΔP_L (water flow rate) increased number of drops for 300, 500, and 700 test series

A look at droplet count and SMD moving downstream along centerline

Roughly same air-liquid ratio



- Large number of drops at dump plane compared to downstream locations
- Monotonic decrease in number of drops as liquid break up and vaporize
- SMD decreased with increasing nozzle ΔP_L (water flow rate)

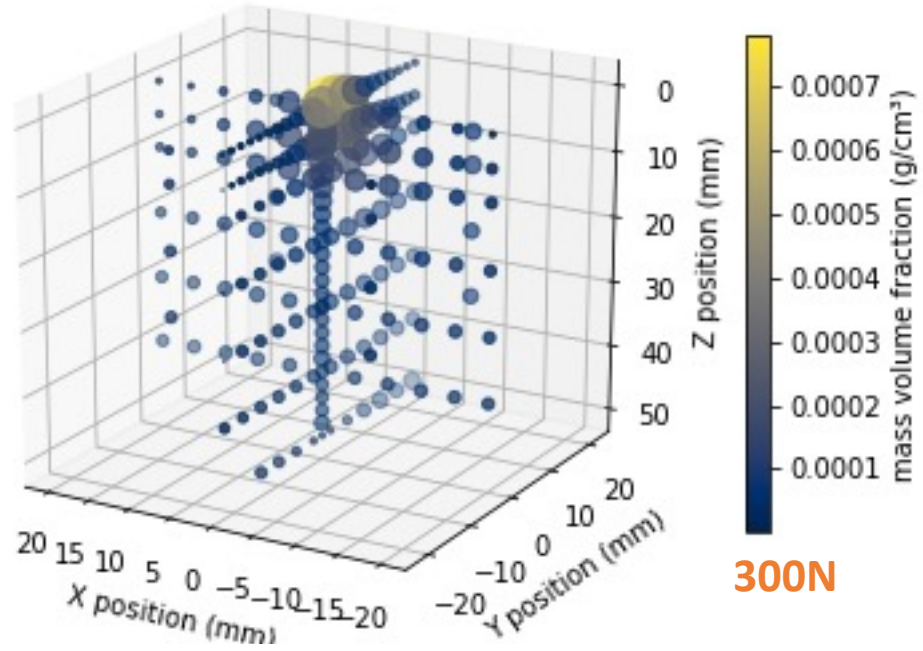


Summary

- Presented non-combusting water spray data from shadowgraph using NASA 7-point LDI
- Mass fluxes, droplet velocities, and droplet diameters at multiple air reference velocities and water flow rates analyzed
- Data consistent with pressure atomizer theory: increasing nozzle ΔP_L increased number of drops and decreased droplet diameter
- Poorer atomization at lower nozzle ΔP_L (water flow rates)

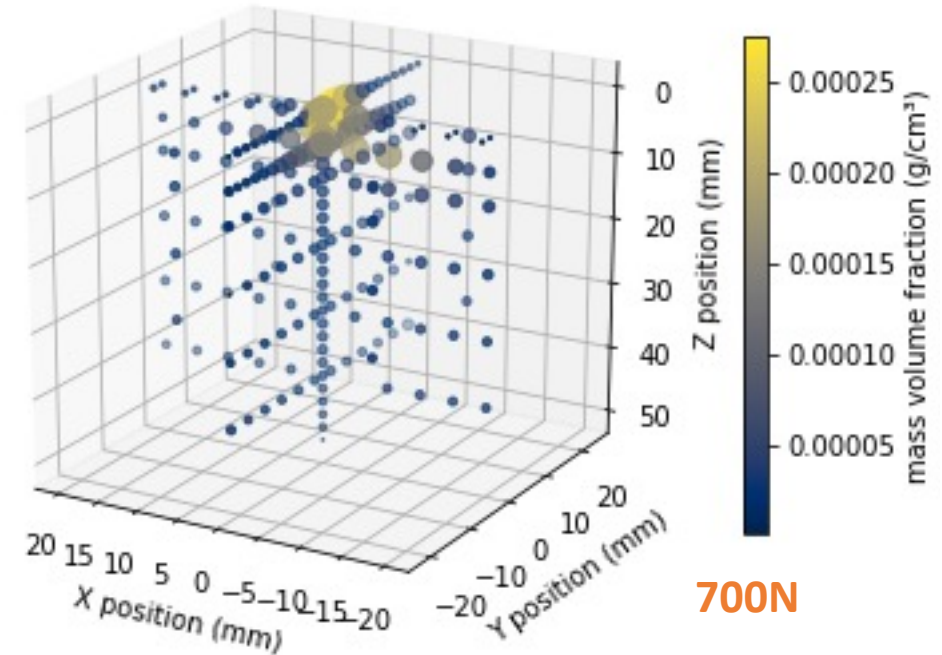
Extra Slides

Mass volume fractions at each location

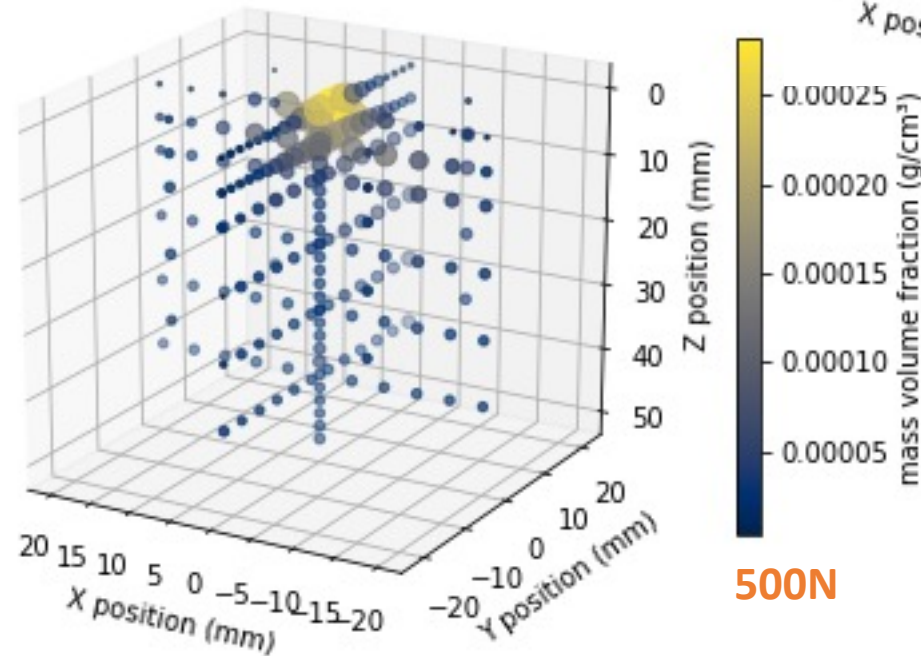


300N

- MVF highest at dump plane and near centerline
- MVF reduces with downstream distance
- 300N MVF has nearly 3x compared to 500N, 700N due to nozzle ΔP_L

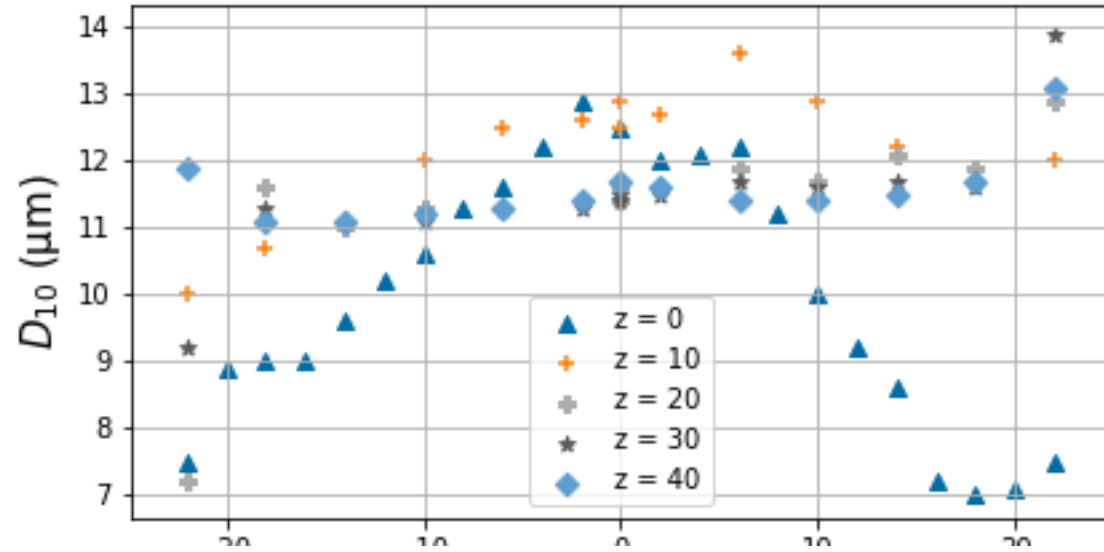


700N

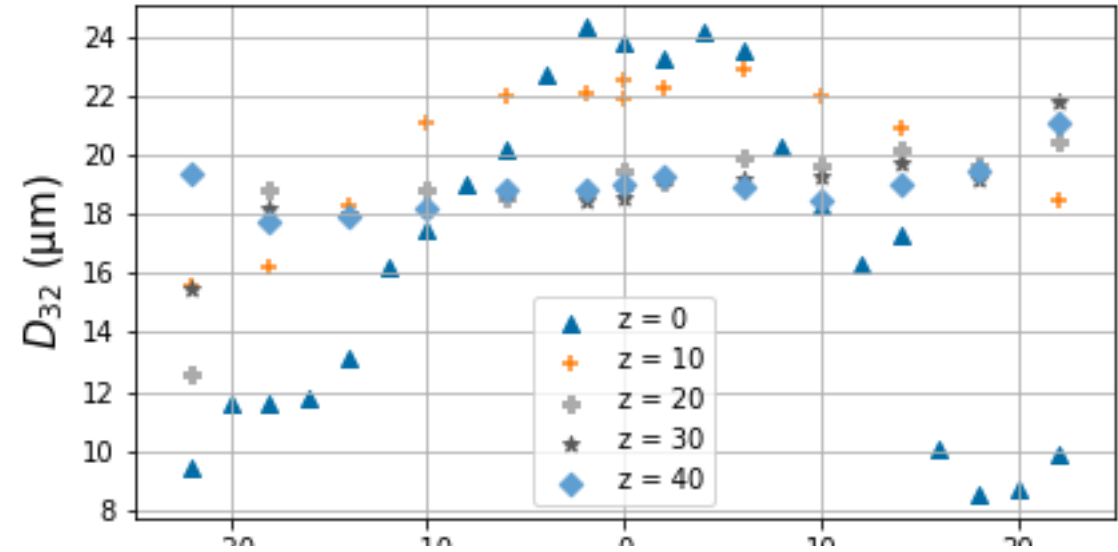


500N

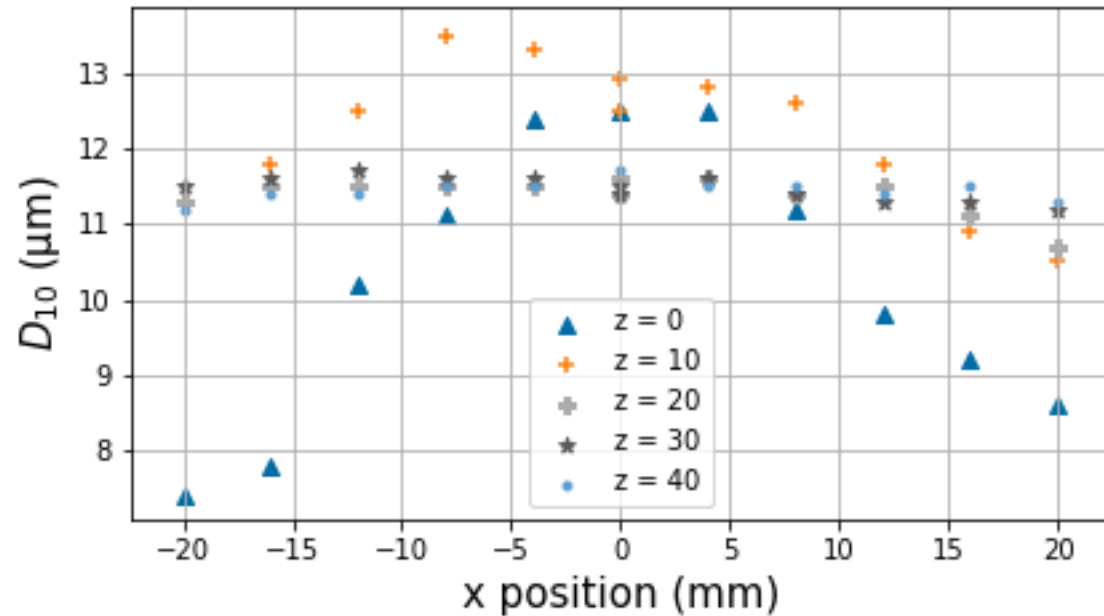
point 508 D10 at $x=0$ for y and downstream position, z



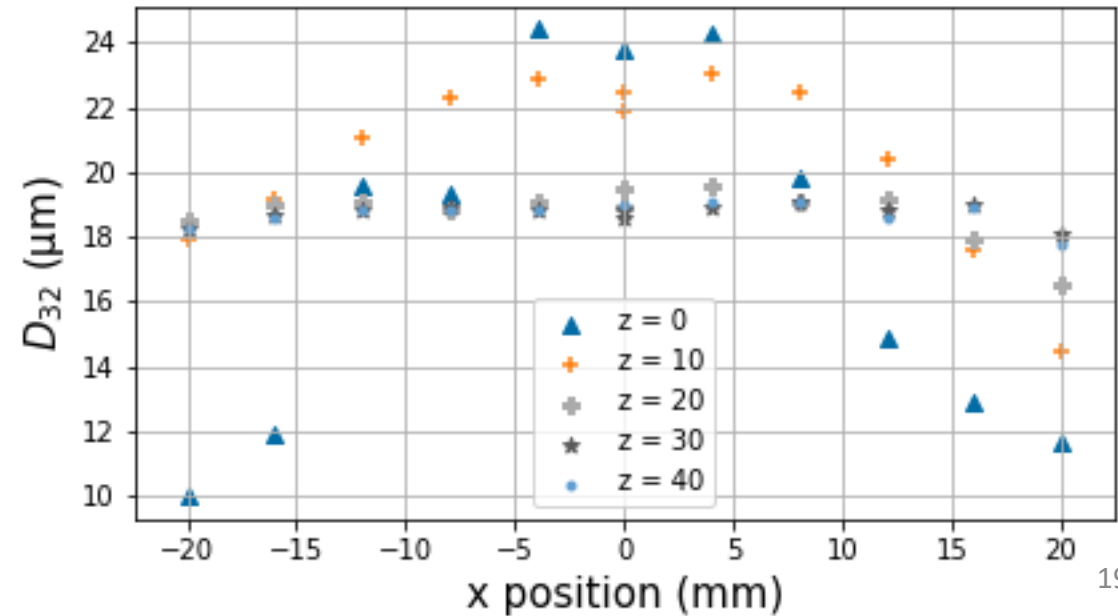
point 508 SMD at $x=0$ for y and downstream position, z



point 508 D10 at $y=0$ for x and downstream position, z

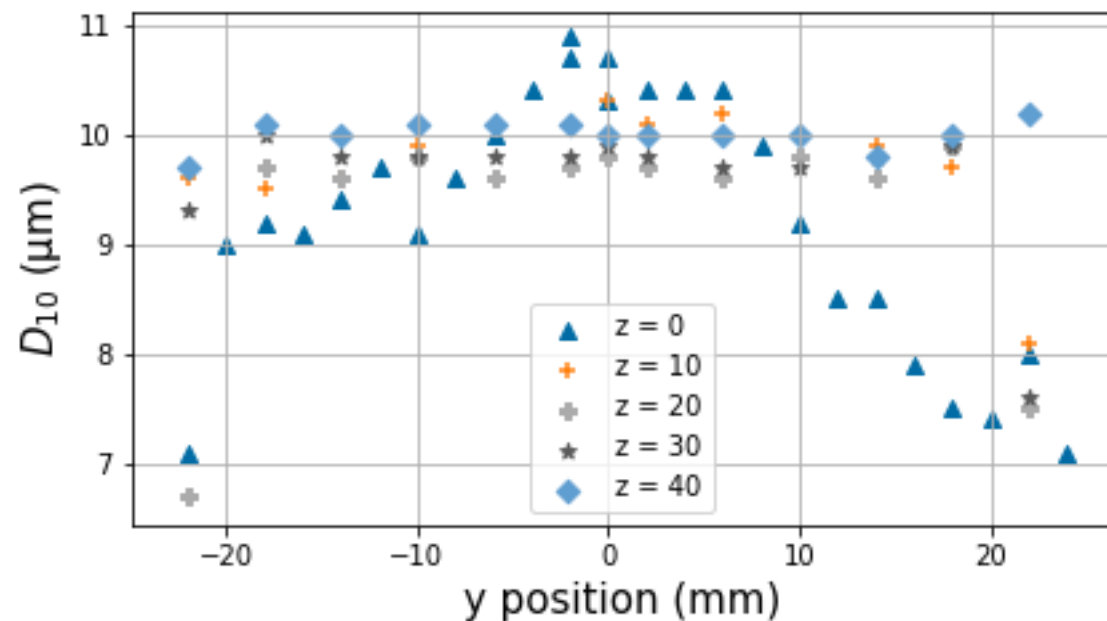


point 508 SMD at $y=0$ for x and downstream position, z

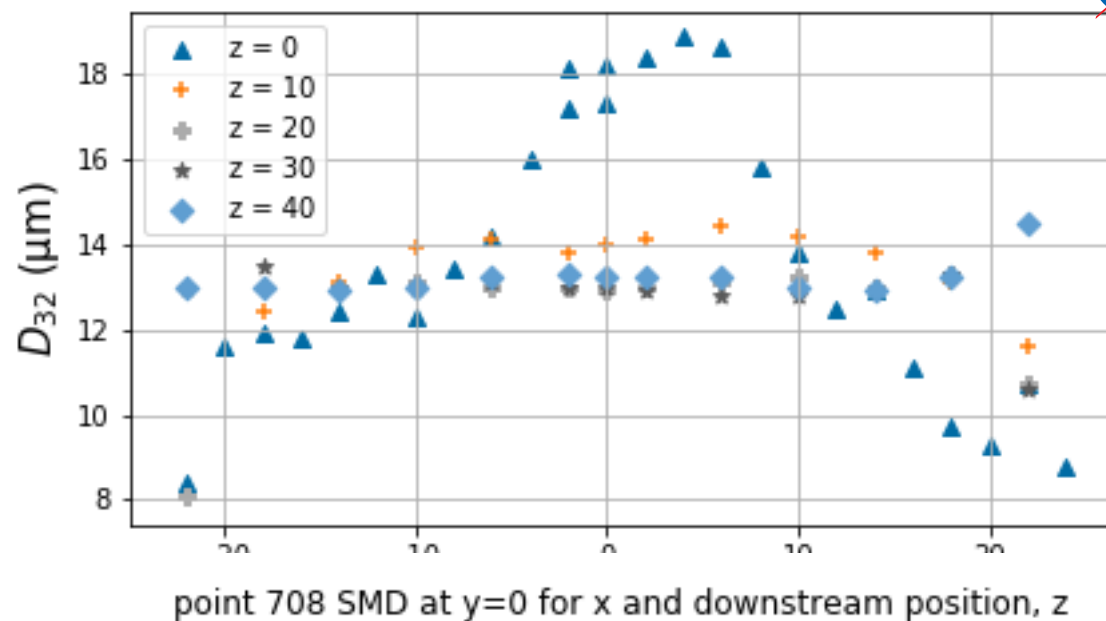




point 708 D10 at $x=0$ for y and downstream position, z



point 708 SMD at $x=0$ for y and downstream position, z



point 708 SMD at $y=0$ for x and downstream position, z

