Experimental Measurements of Shattered Pellet Injection Fragment Plume Parameters

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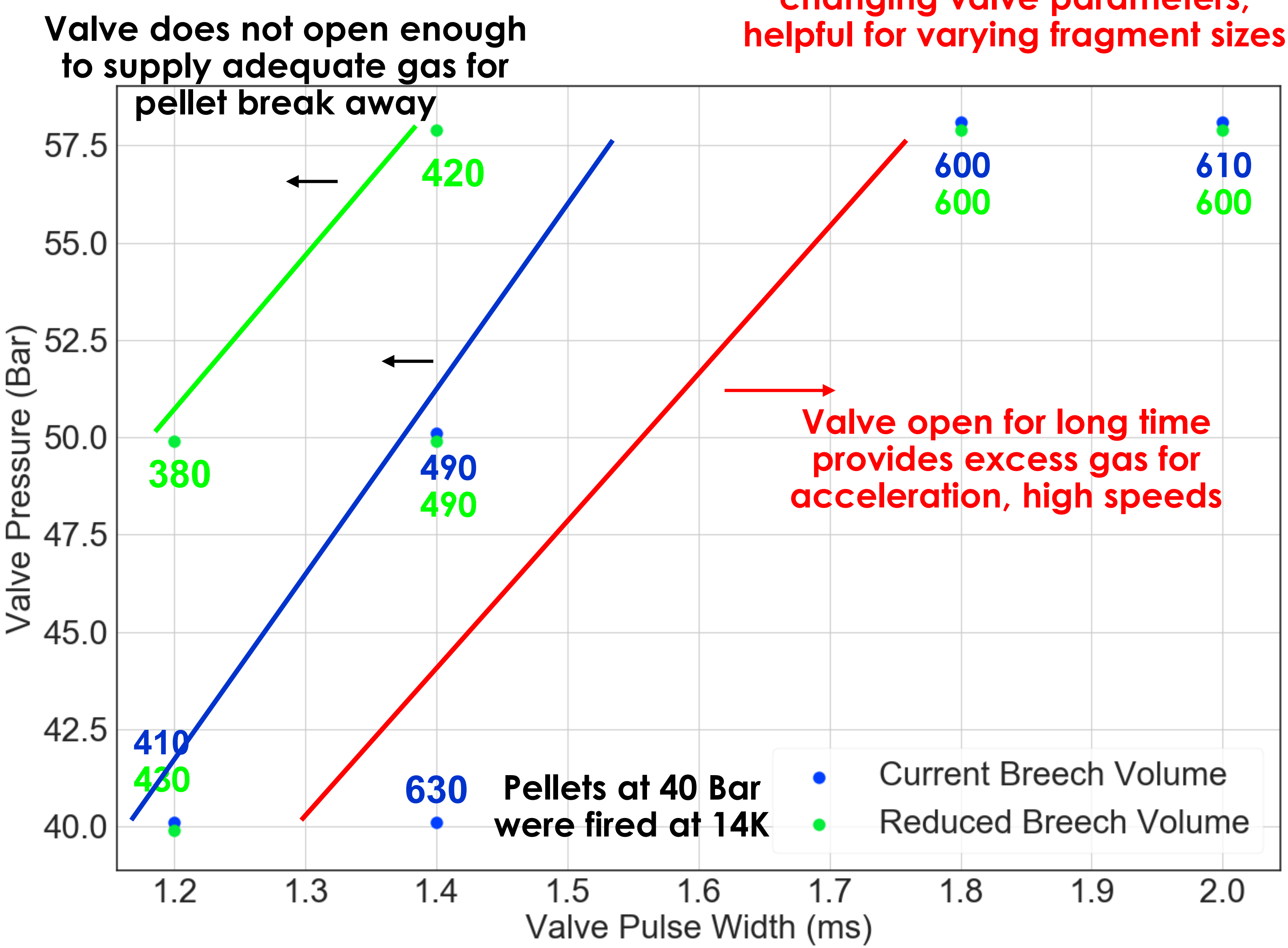
Parameters that impact the fragment plume dynamics

- Pellet speed -
- Composition – D2–Ne mixtures
- Entrained propellant gas – nominally minimal, won't be discussed here
- Shatter tube angle (normal impact velocity)

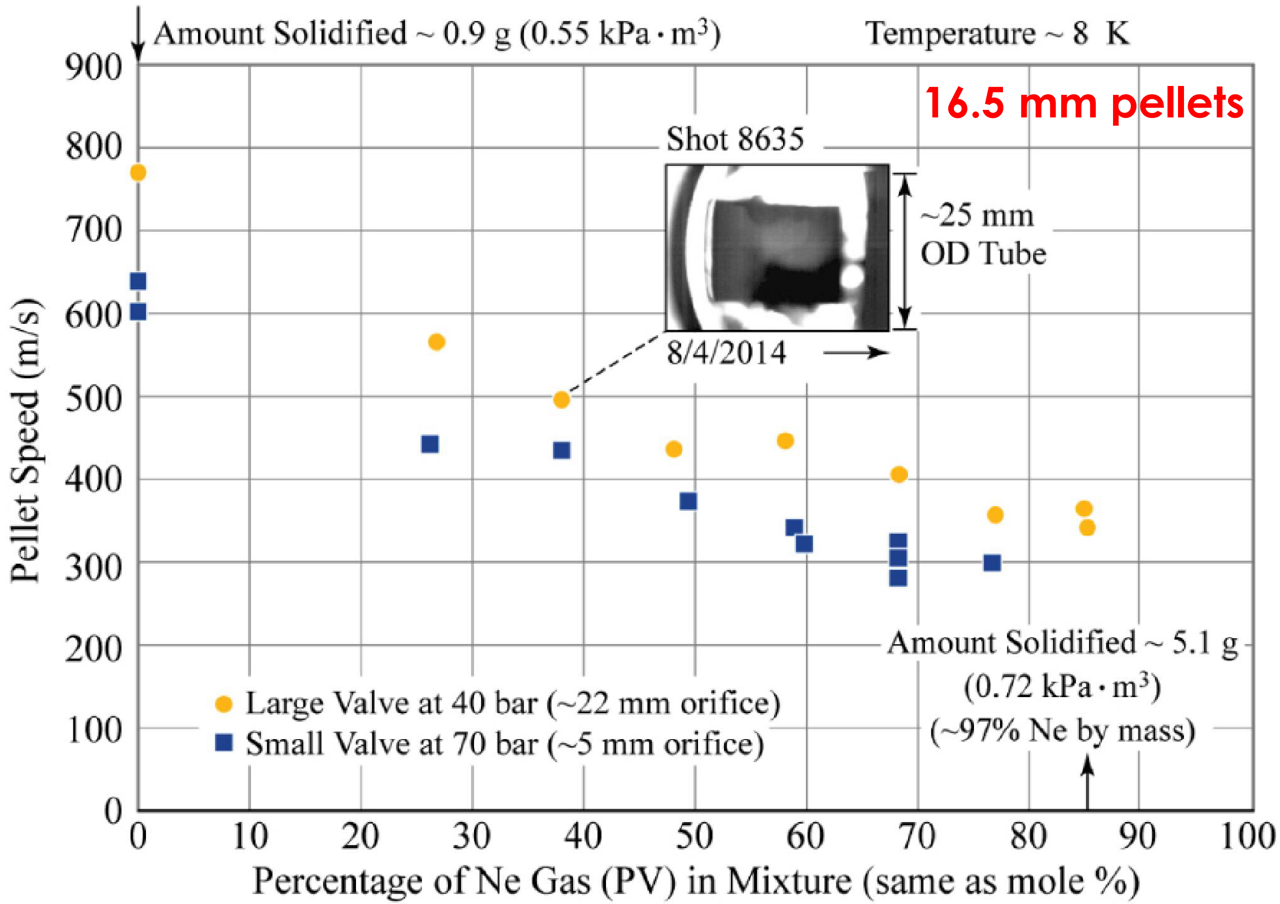
Relevant fragment plume parameters

- Fragment size distribution
- Solid/gas ratio in plume
- Plume trajectory and spread
- Temporal mass evolution
- Plume duration (length)
- Velocity distribution

Velocity variation of 8.1 mm D2 pellets relies highly on the propellant valve operation



Heavier pellets will travel slower with similar valve conditions



Fragment size distribution model

$$f(d) = \alpha d K_o(\beta d)$$

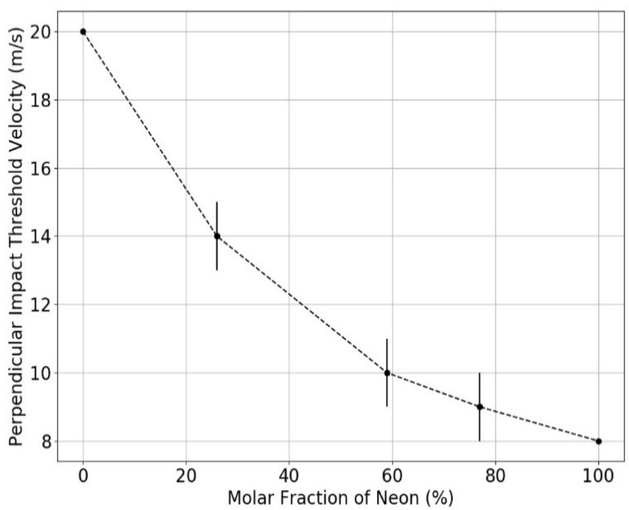
$$\alpha = X_R / D$$

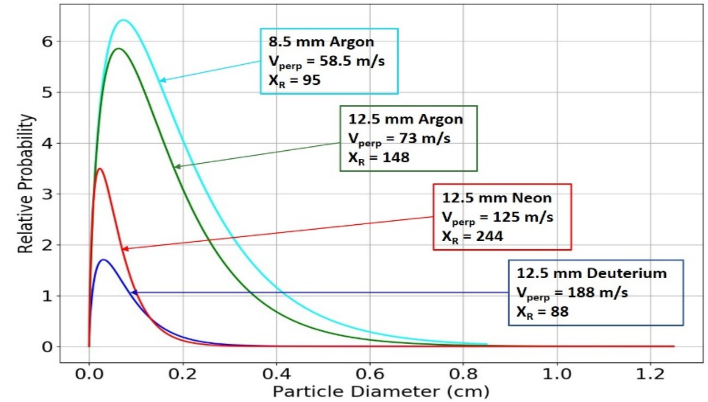
$$\beta = \frac{X_R}{L * C}$$

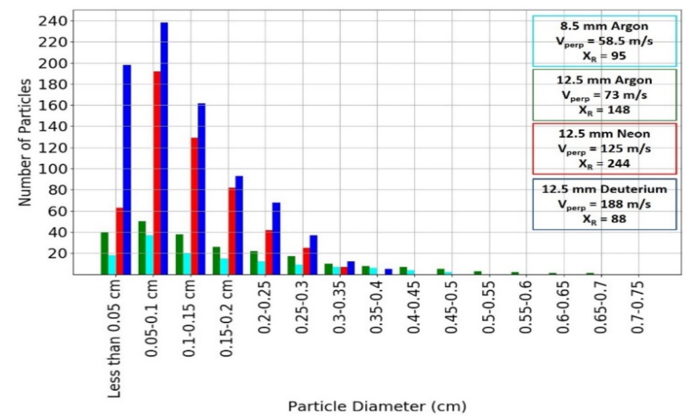
$$X_R = \frac{v_{perp}^2}{v_{threshold}^2}$$

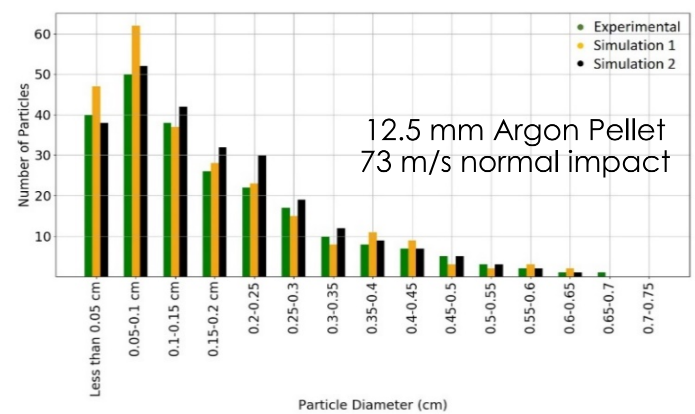
$$C_{D2} = 2.5$$
$$C_{Ne} = 5$$
$$C_{D2-Ne\ Mix} = 2.5(1 + \omega_{Ne})$$

$$v_{threshold,D2} = 20\ m/s$$
$$v_{threshold,Ne} = 8\ m/s$$



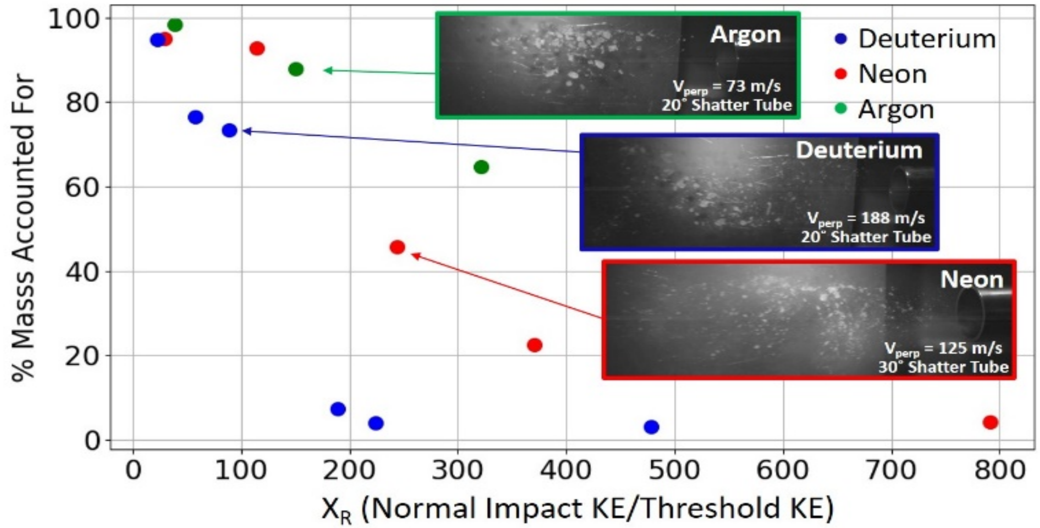




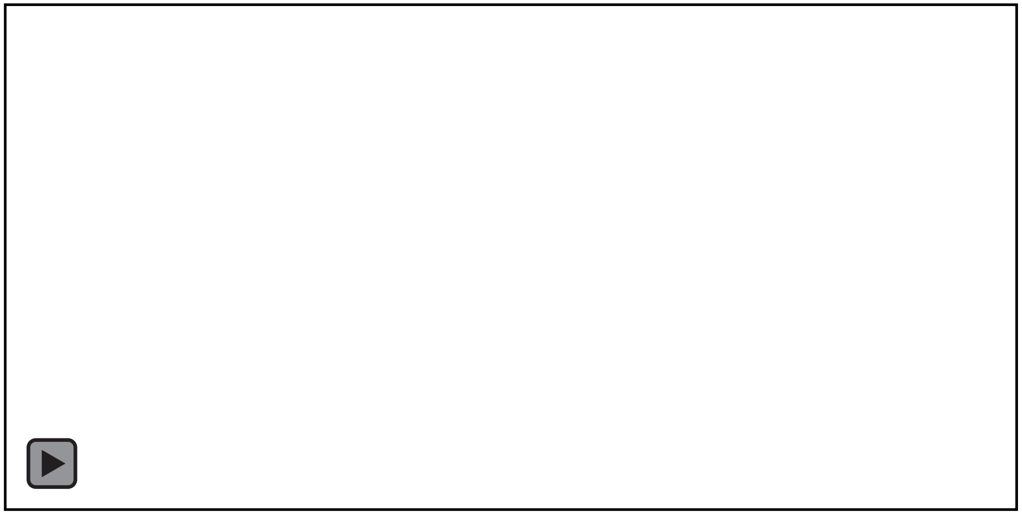


T. Gebhart et al., IEEE TPS 2019
T. Gebhart et al., FST 2020

Amount of gas produced during the fragmentation process



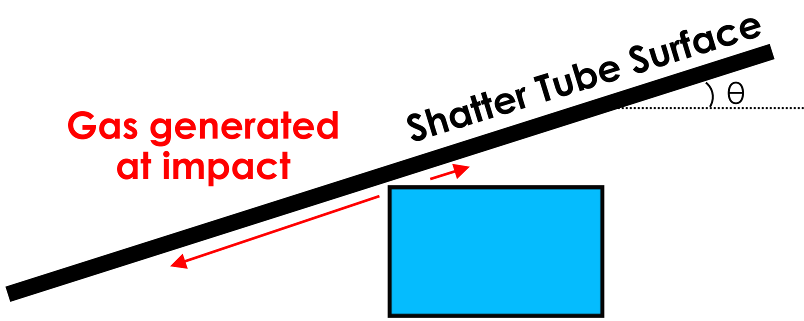
Temporal evolution of a quintessential fragment plume



28.5 mm D2 pellet

250 m/s nominal velocity

20-degree shatter surface



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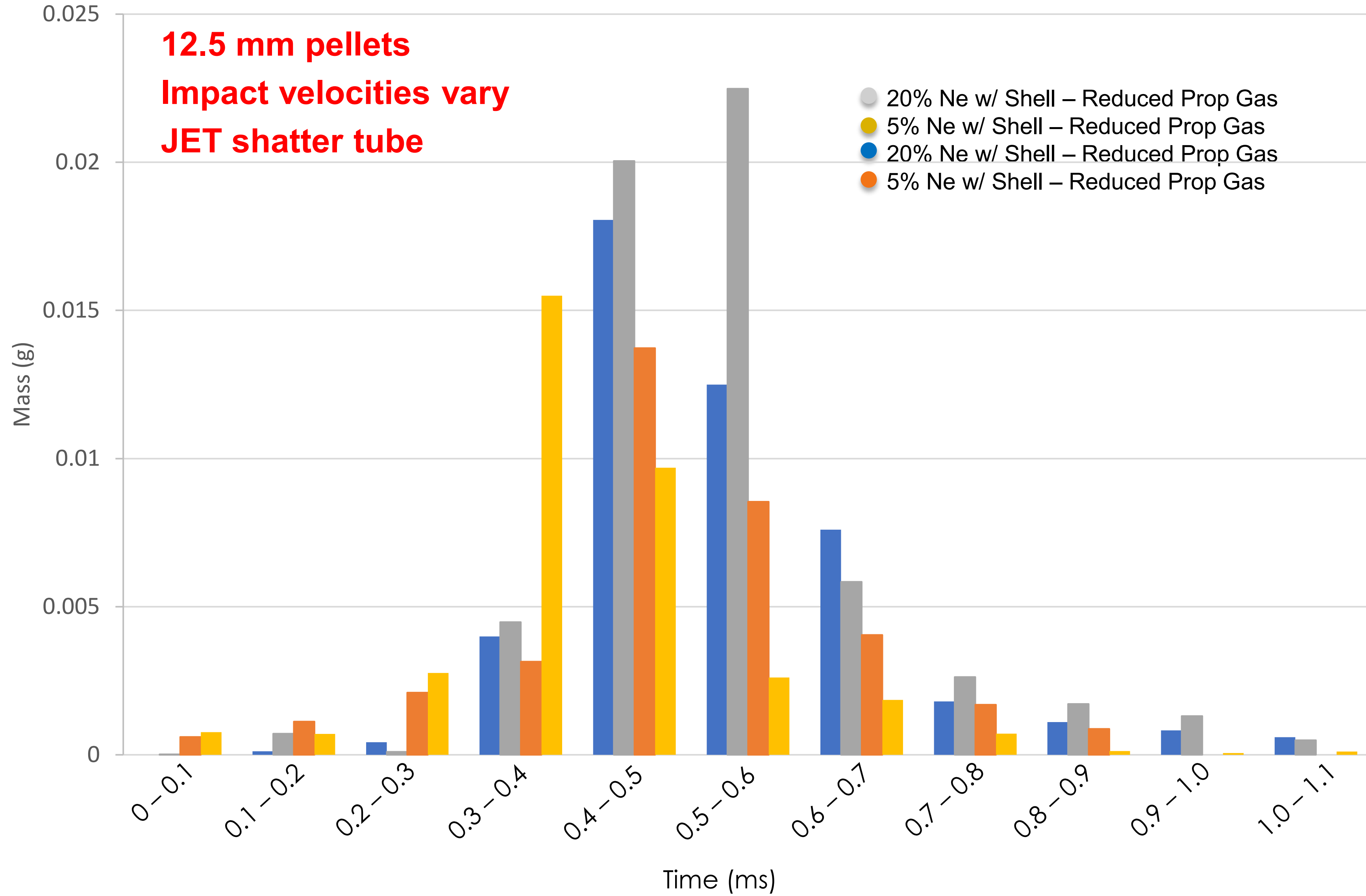
Temporal evolution of a typical fragment plume



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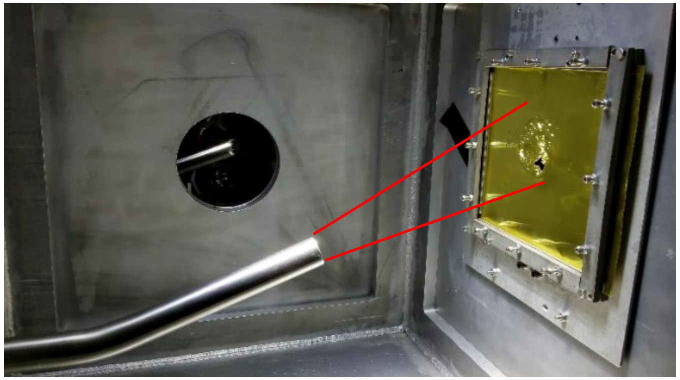
Plume trajectory is highly dependent on the shatter tube geometry

ITER 28.5 mm D2 pellets

Pellet D/Tube D = 28.5/60 = 0.475

KSTAR Shatter Tube
12.5 mm, 50-50 D2-Ne Pellets



Post-Bend Length (cm)	Distance to Target (cm)	Punch Used?	Measured Dispersion Angle
41	19	Yes	16.3
33	26.7	Yes	18.2
24	35.6	Yes	16.7
24	35.6	No	16.5

Pellet D/Tube D = 12.5/30 = 0.417

Fragment plume durations versus ST angle, pellet composition, and pellet speed

Pellet Size (mm)	Speed (m/s)	Composition	Angle & ST Type	Duration (ms)
12.5	550	Pure D2	10 Miter Bend	0.1333
12.5	875	Pure D2	10 Miter Bend	0.1666
12.5	550	Pure D2	20 Miter Bend	0.366
12.5	875	Pure D2	20 Miter Bend	0.3324
12.5	550	Pure D2	30 Miter Bend	0.466
12.5	875	Pure D2	30 Miter Bend	0.399
12.5	410	20% Ne	10 Miter Bend	0.15
12.5	760	20% Ne	10 Miter Bend	0.1
12.5	410	20% Ne	20 Miter Bend	0.35
12.5	760	20% Ne	20 Miter Bend	0.333
12.5	410	20% Ne	30 Miter Bend	0.666
12.5	760	20% Ne	30 Miter Bend	0.6998
12.5	325	50% Ne	10 Miter Bend	0.15
12.5	485	50% Ne	10 Miter Bend	0.133
12.5	325	50% Ne	20 Miter Bend	0.466
12.5	485	50% Ne	20 Miter Bend	0.433
12.5	325	50% Ne	30 Miter Bend	0.866
12.5	250	Pure Ne	10 Miter Bend	0.2666
12.5	250	Pure Ne	20 Miter Bend	0.9331
12.5	450	Pure Ne	20 Miter Bend	0.9064
12.5	250	Pure Ne	30 Miter Bend	2.163
12.5	450	Pure Ne	30 Miter Bend	1.9661

- Plume duration increases with shatter tube angle
- Pellet speed seems to not have a large impact on plume duration
- Higher neon percentage results in slightly elongated plumes
- Durations measured at the exit of the shatter tubes

12.5 mm pellets

Slower pellets fired with punch

Faster pellets fired with valve

Shatter tubes are welded miter bend tubes with an ID of 40 mm

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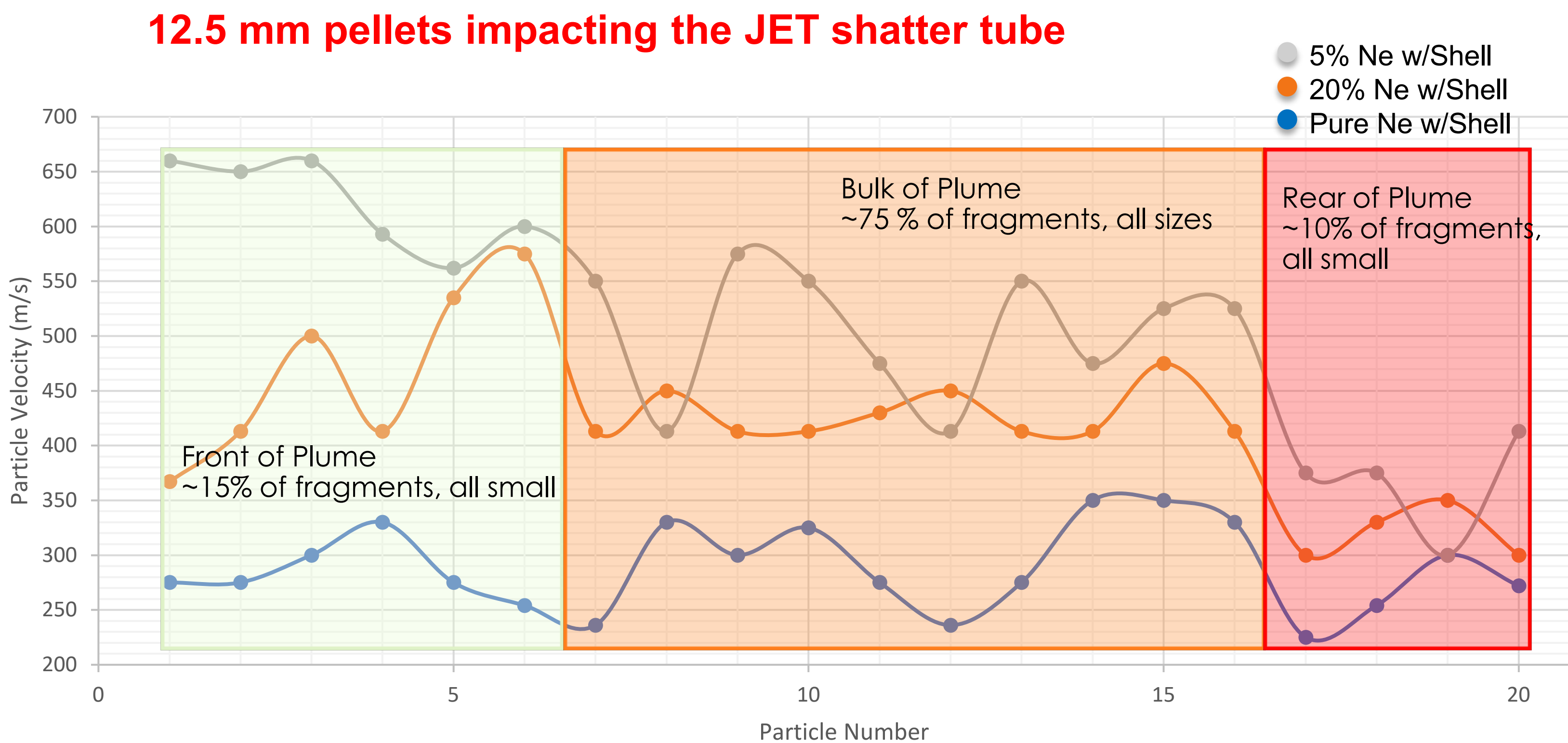
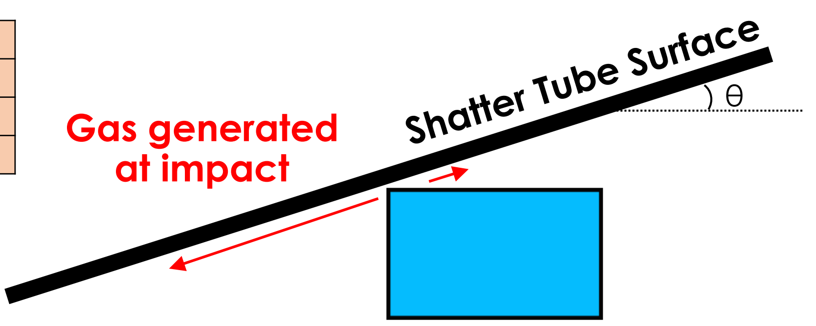
Typical fragment velocity distribution

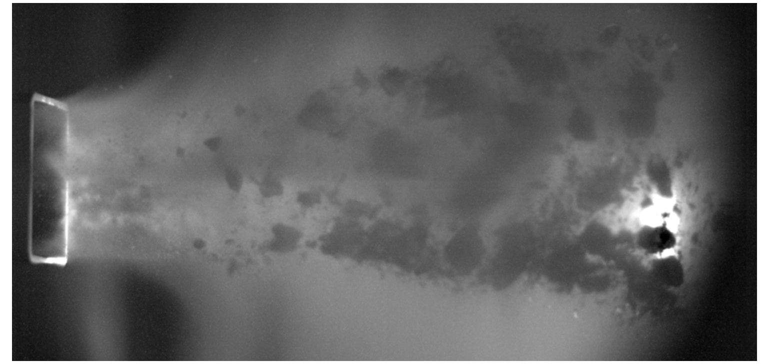


No Punch, After Mod	Pure Neon W/ Shell	20% Neon w/ Shell	5% Neon w/Shell
Max Velocity	350	575	660
Min Velocity	225	300	300
Average Velocity	288.35	418.3	511.95

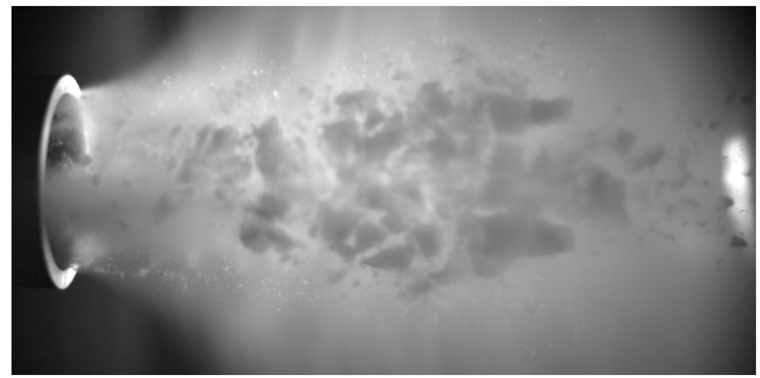


ITER deuterium pellet shattering experiments

- Shot 132 – D_2 – Square ST
  - 43.39 bar-L in pellet, 7.27 g
  - 2.7 bar-L of 60 bar He propellant
  - 255 m/s from high-speed video



- Shot 217 – D_2 – Circular ST
  - 43.52 bar-L in pellet, 7.29 g
  - 2.97 bar-L of 60 bar He propellant
  - 250 m/s from high-speed video



- Shot 218 – D_2 – Circular ST
  - 43.56 bar-L in pellet, 7.298 g
  - 3.1 bar-L of 60 bar He propellant
  - 264 m/s from high-speed video

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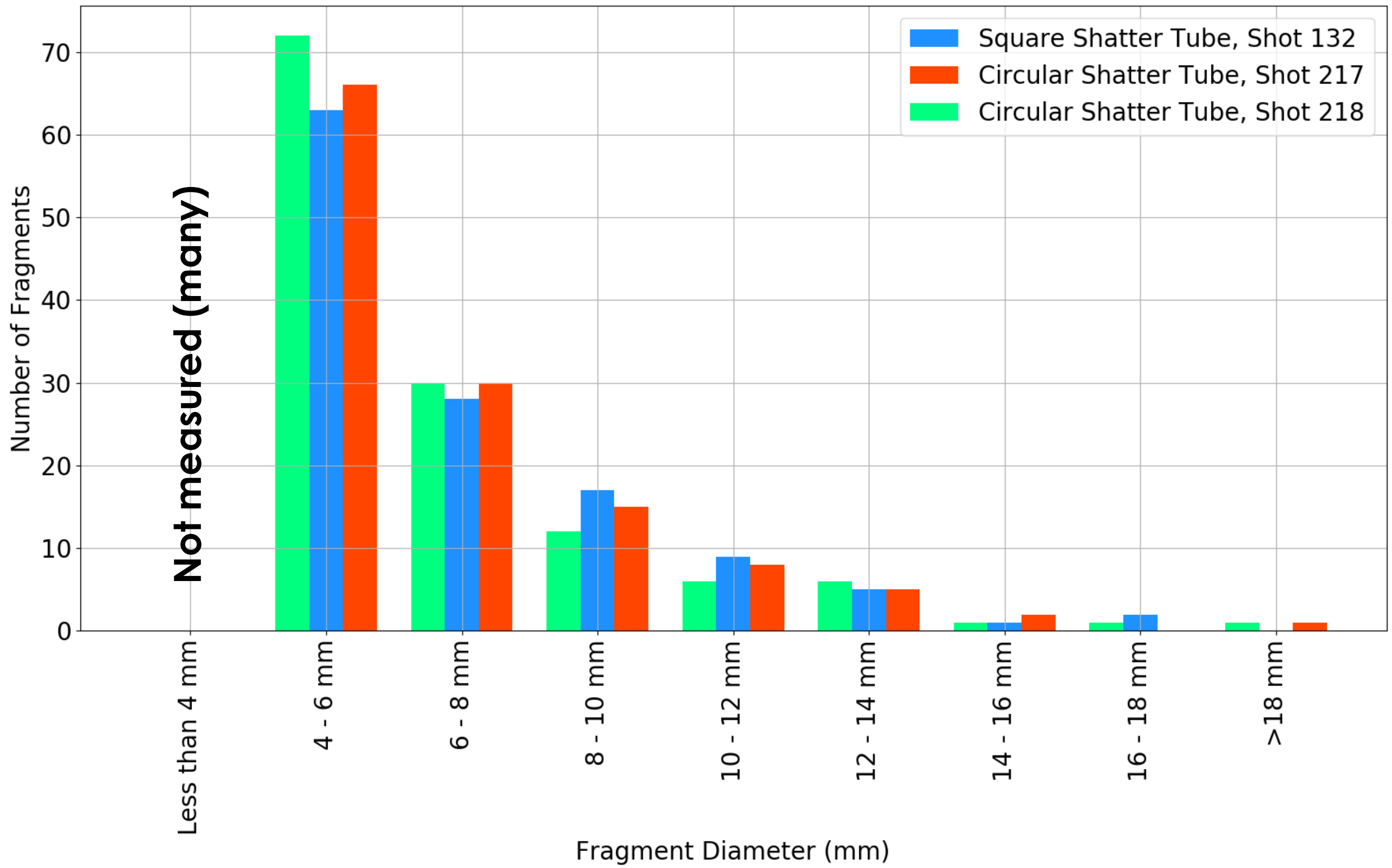
ITER deuterium pellet shattering experiments



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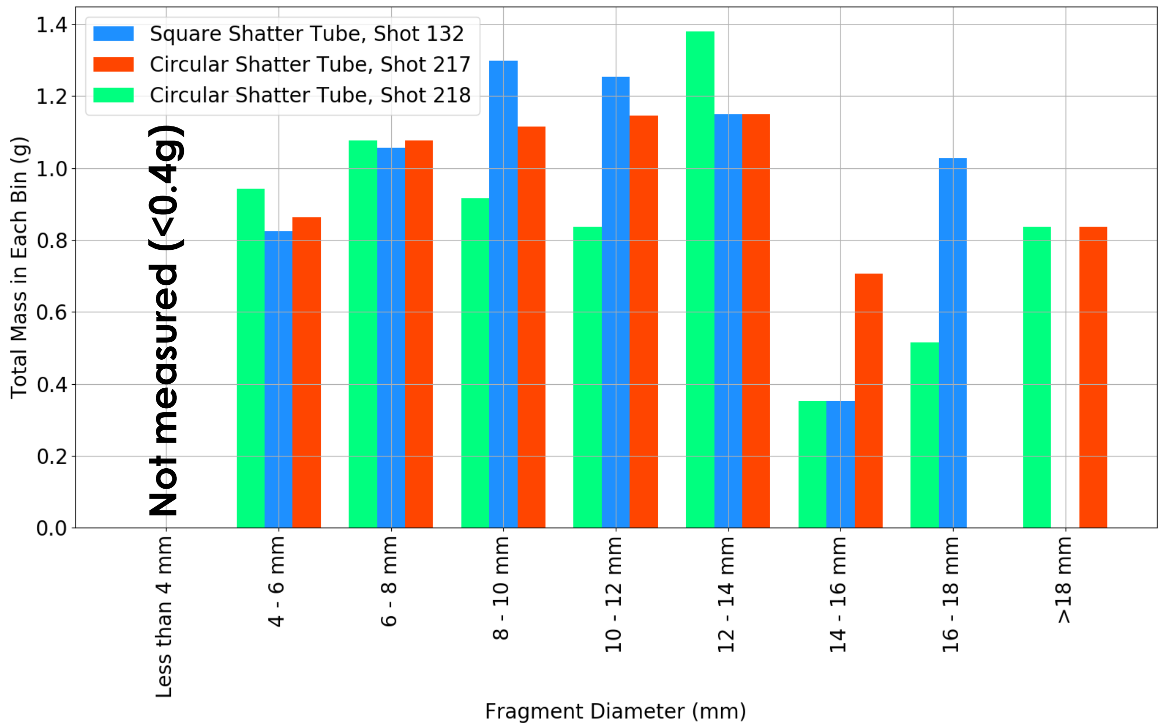
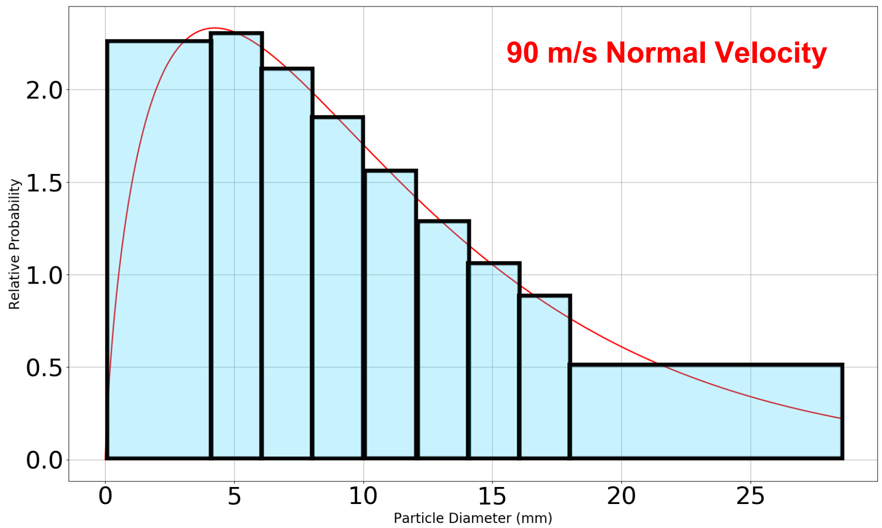
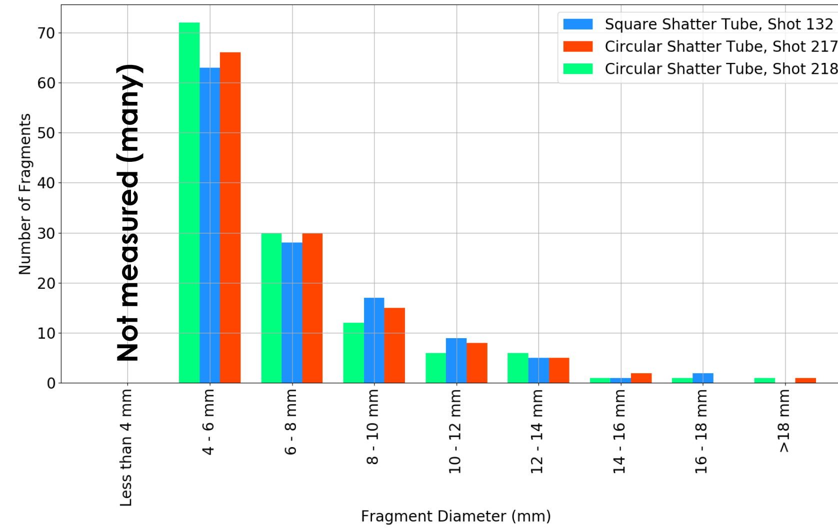
ITER deuterium pellet shattering experiments



Shot #	Total # Fragments	Total Mass (g)	Mass Based on Gas Input (g)	Difference (g)	% of mass accounted for	Plume Duration (ms) at exit of ST	Plume Duration (ms) at 0.24 m
132	125	6.915	7.270	0.355	0.951	0.739	1.608
217	127	6.897	7.297	0.400	0.945	0.782	1.695
218	129	6.859	7.298	0.439	0.940	0.826	1.608

Comparison of deuterium shattering experiments with fragmentation model





- Comparing the fragmentation model with experimental results yields a disagreement
- Frag model predicts only 4X greater chance to produce 4-5 mm fragments than ~21mm fragments (~ 4X as many 4-5 mm fragments)
- Actual results are similar to a 140 m/s impact
  - Possible scaling issue with threshold velocities for large pellets, or pellets with >1.5 L/D
  - Significant temp gradient through pellet may impact fragmentation – material strength and sublimation