# Developments in Shattered Pellet Technology and Implementation on JET and ITER


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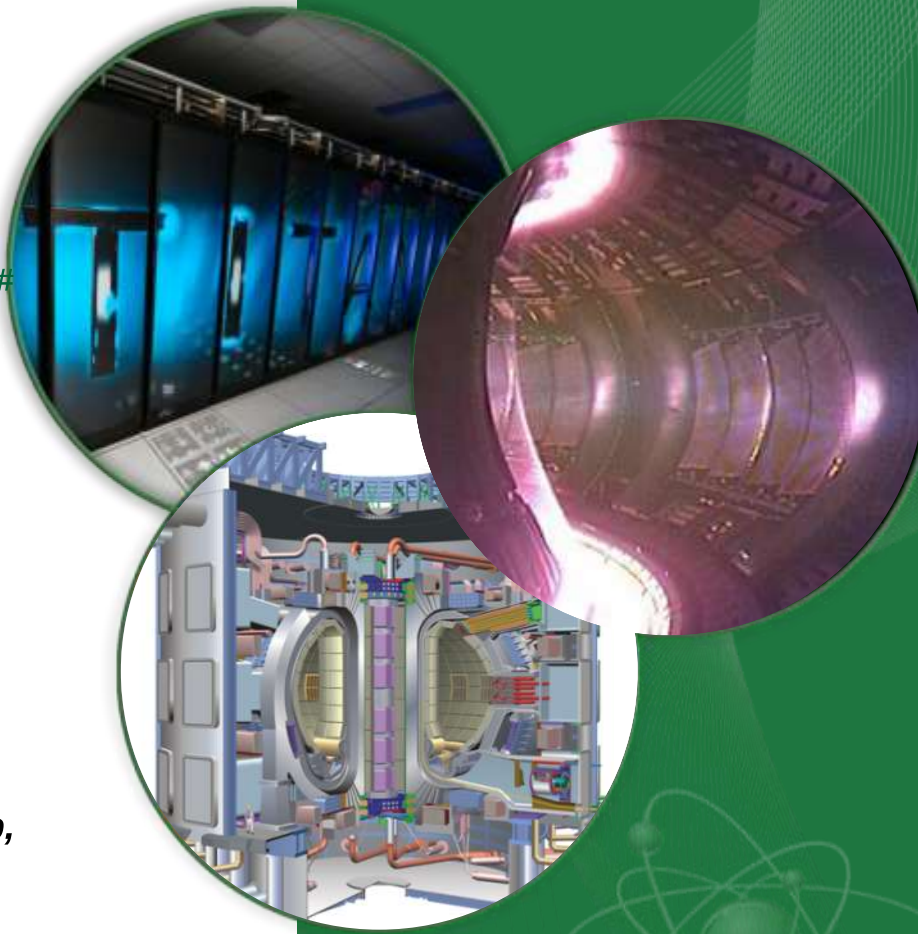


***Theory and Simulation of Disruptions Workshop, PPPL***
***17-July-2017***

# Outline

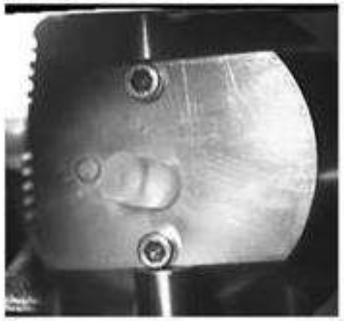
- SPI  R&D overview
- SPI Deployment on JET
- ITER DMS Issues for SPI
- JET SPI experimental opportunities
  - U.S. input to the JET disruption taskforce:   proposal titles due Aug. 4, full proposals in Sept.

# SPI: History

**Pellets are known to shatter when hitting a surface with enough perpendicular velocity**

- $D_2$ fueling pellets hitting an inclined plate shatter when the normal velocity >30 m/s.
- This motivated the development of shatter plates and tubes to form collimated sprays of pellet material that penetrate deeply in a short duration.
- The shattered material prevents impact damage to the first wall and increases ablation.
- Mixed species $D_2$/Ne SPI allows control of mitigated disruption properties

Shot 1069



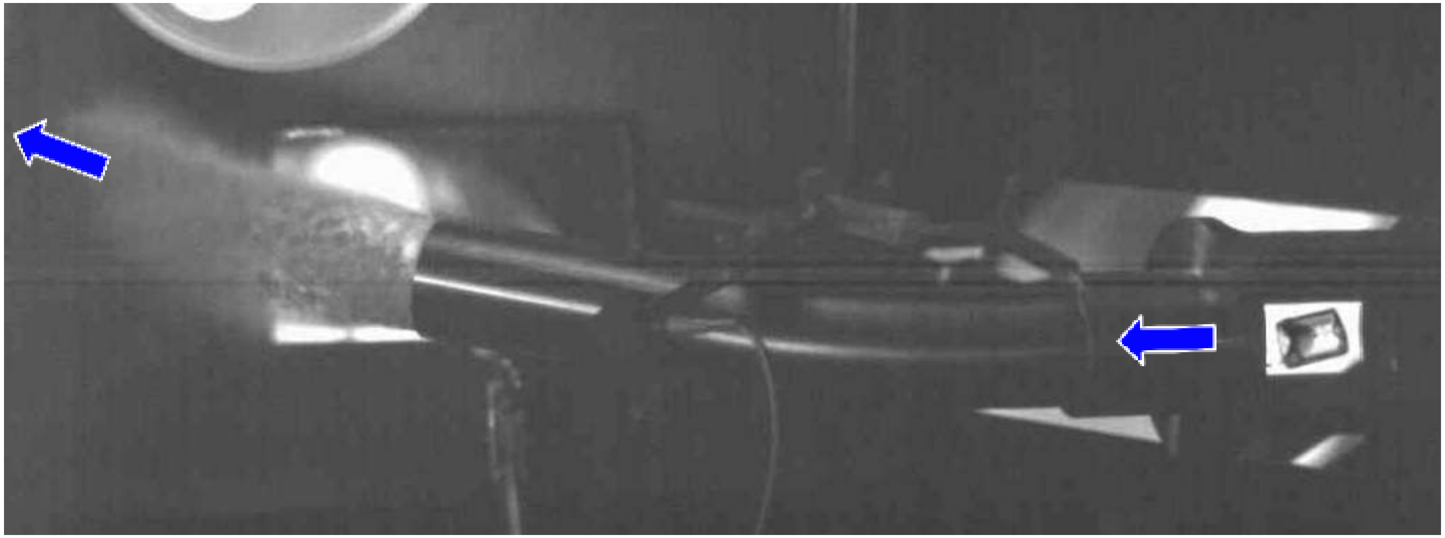
Pellet Speed = 77 m/s
Impact Angle = 15°
Normal Velocity = 20 m/s

Shot 1074

Pellet Speed = 61.5 m/s
Impact Angle = 30°
Normal Velocity = 30.8 m/s

Combs, et al.

# Shattering Occurs from Transit Through Bent Tube Resulting in ~15$^{o}$ Dispersion



**Neon Pellet in 20$^{o}$ Shatter Tube**

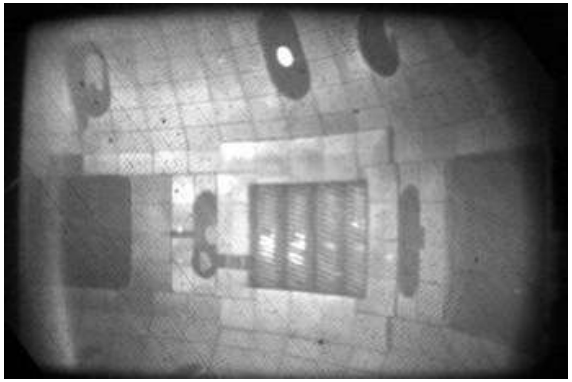
**Foil Impacts**

*S. Combs SOFE 2015*

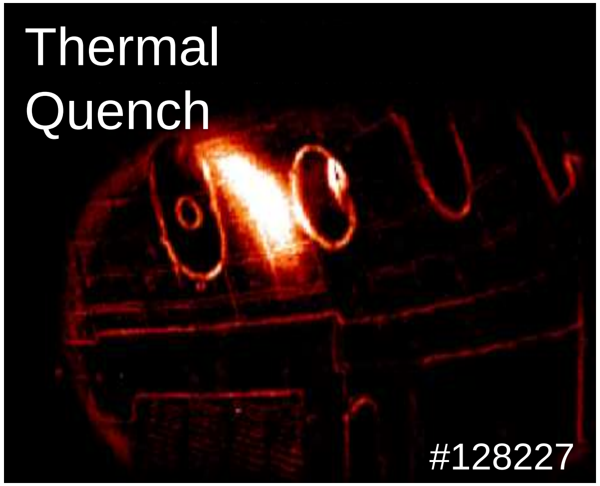
# Shattered Pellet Injection (SPI) shows benefits over Massive Gas Injection (MGI) – only used on DIII-D

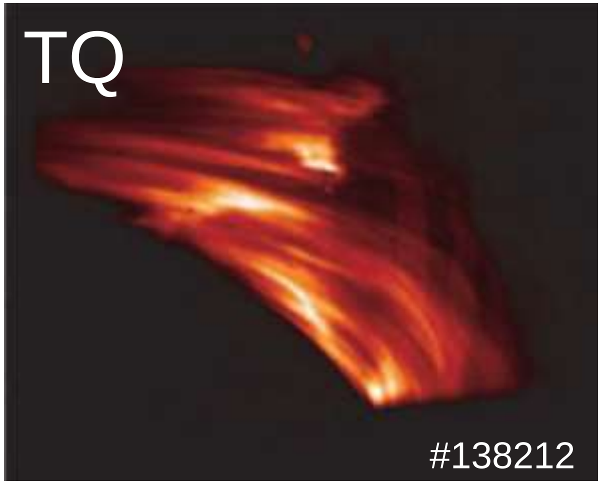
MGI

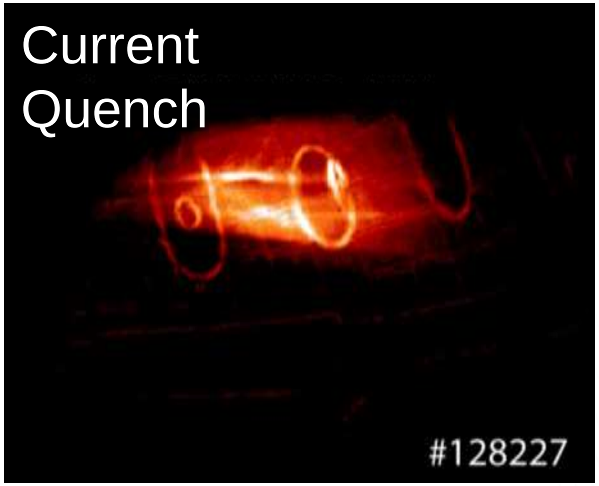
SPI

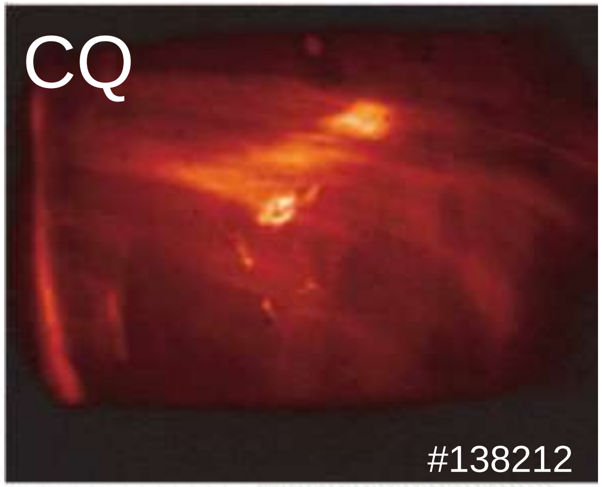


“normal” view using the fast framing camera



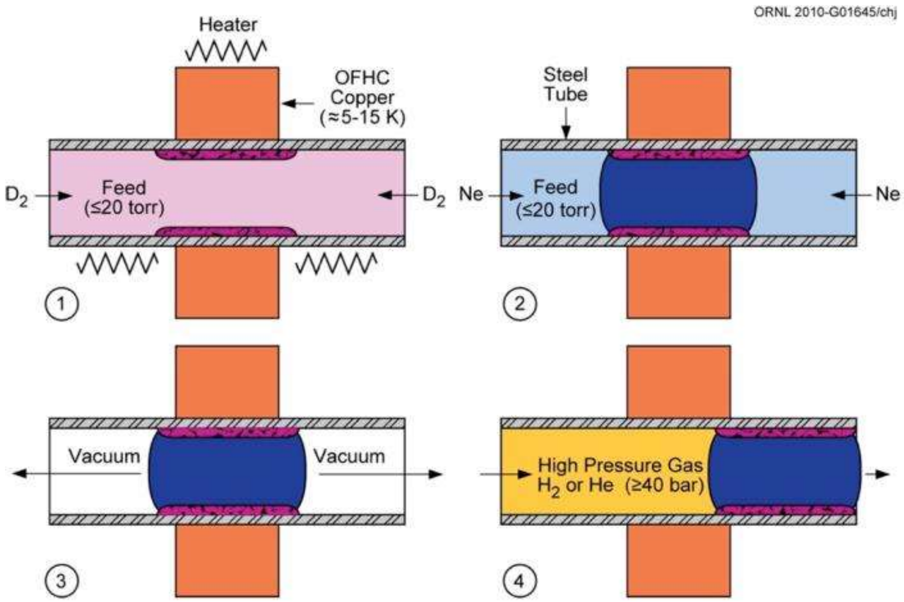



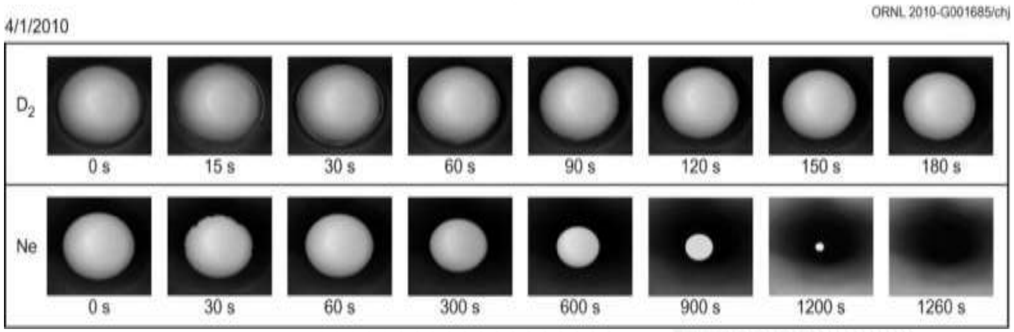




*Commaux, et al., Nucl. Fus. 2011*

Fast visible camera images

# 3-Barrel SPI design has been developed for ITER and deployed on DIII-D and soon on JET



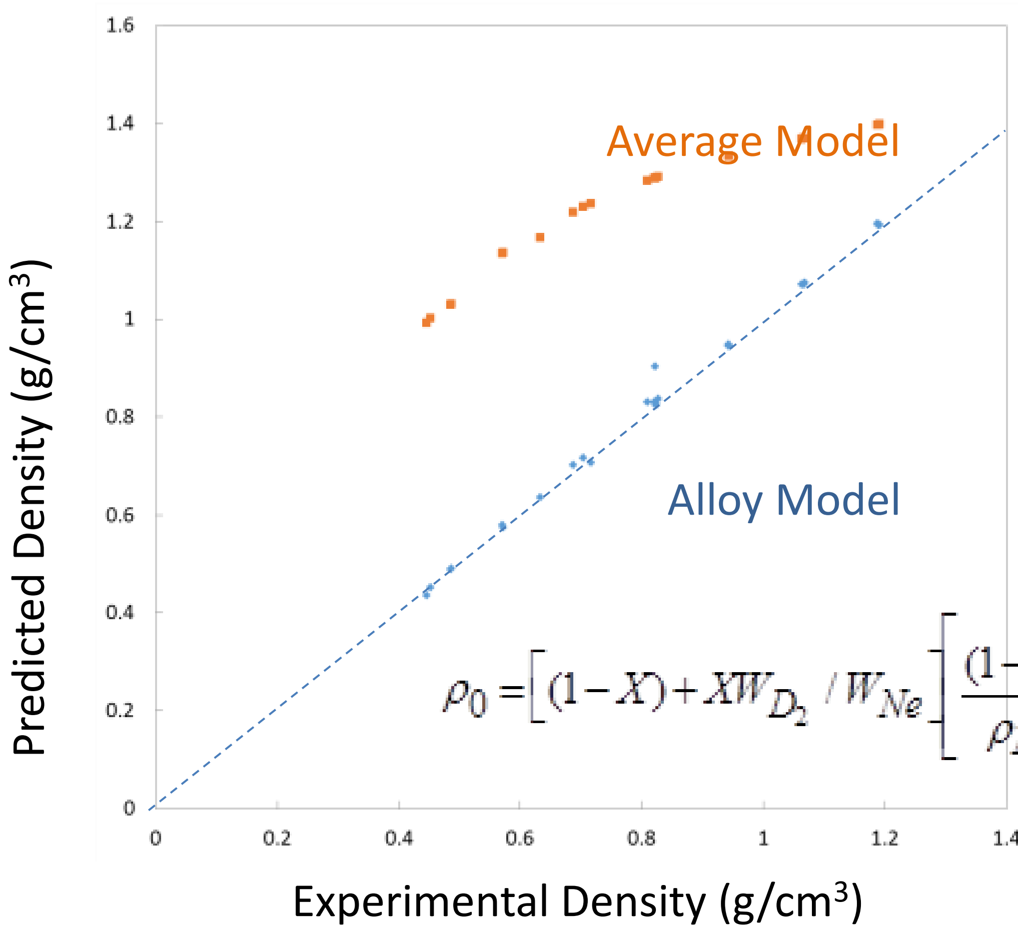




View of freezing process from end of barrel

- **Barrel inner diameter can vary in order to study scaling of $D_2$ and neon SPI**
- **SPI uses MGI like valves to accelerate pellets and can be used as MGI system when no pellet is formed.**
- **$D_2$, $D_2$/Ne, Ne, Ar* are possible**

OAK RIDGE National Laboratory

# Mixed $D_2$/Neon Pellet Density Agrees with the Alloy-Based Model




$$\rho_0 = \left[(1-X) + XW_{D_2}/W_{Ne}\right]\left[\frac{(1-X)}{\rho_{Ne}} + \frac{XW_{D_2}/W_{Ne}}{\rho_{D_2}}\right]^{-1}$$

The required SPI pellet size for a given mixture ratio and quantity of material is now well understood. (Parks 2017)

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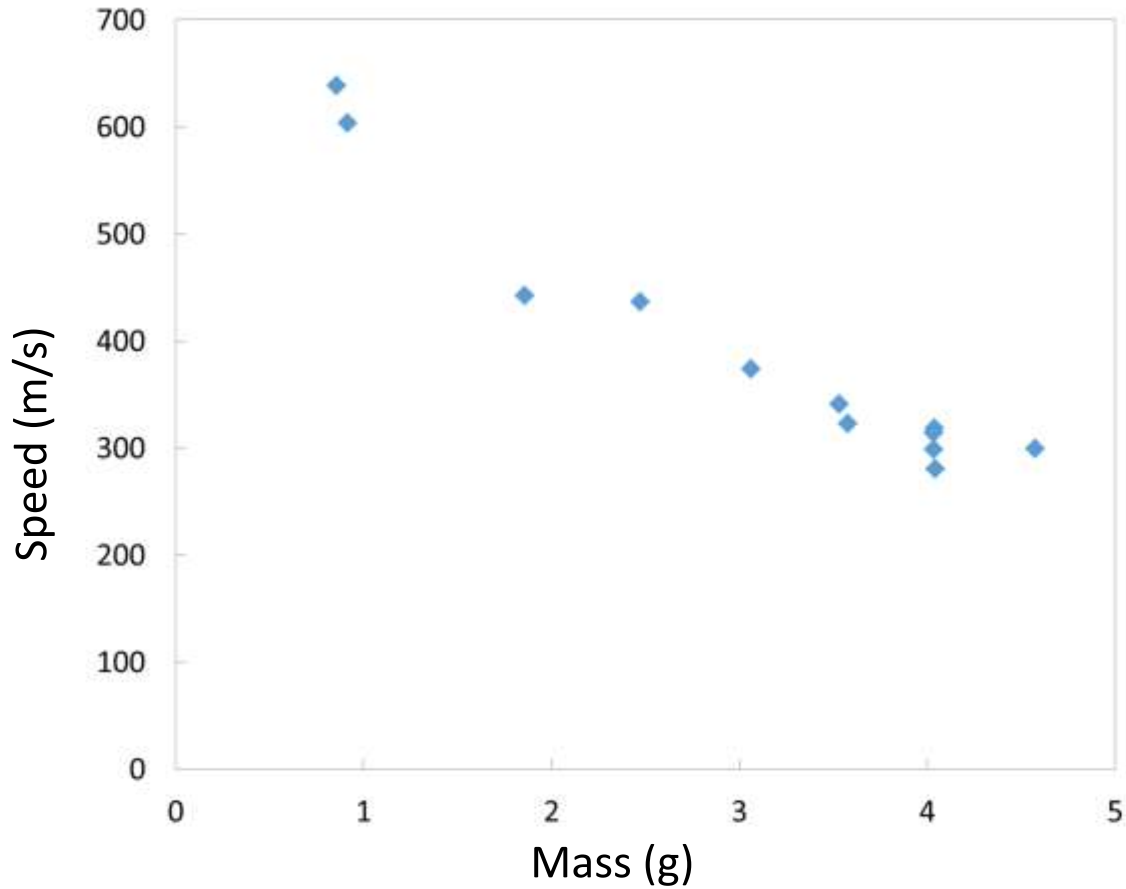
# Mixed $D_2$/Neon Pellet Speed Decreases as the Neon Fraction and Pellet Mass Increases




The SPI pellet speed is a strong function of the mass for a given pellet size and gas valve pressure as expected from ideal gun theory.   A factor of 2 range in speed is expected for SPI  D2/Ne mixtures.

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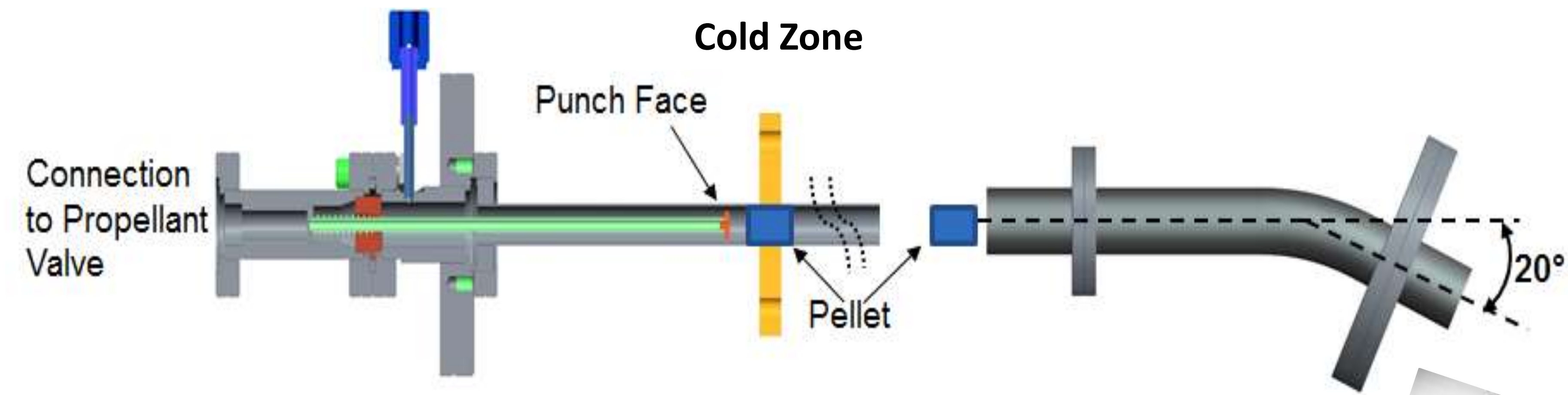
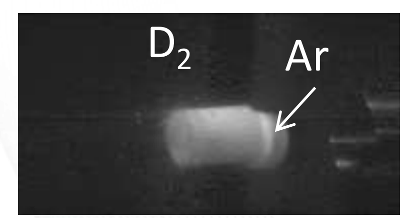
# Argon SPI pellets have now been made and shot with the use of a gas driven mechanical punch





- Argon  and pure neon (with no D2 shell) are difficult to break free from the cold barrel with gas.  A mechanical punch is employed to break the pellet free, then gas accelerates it.

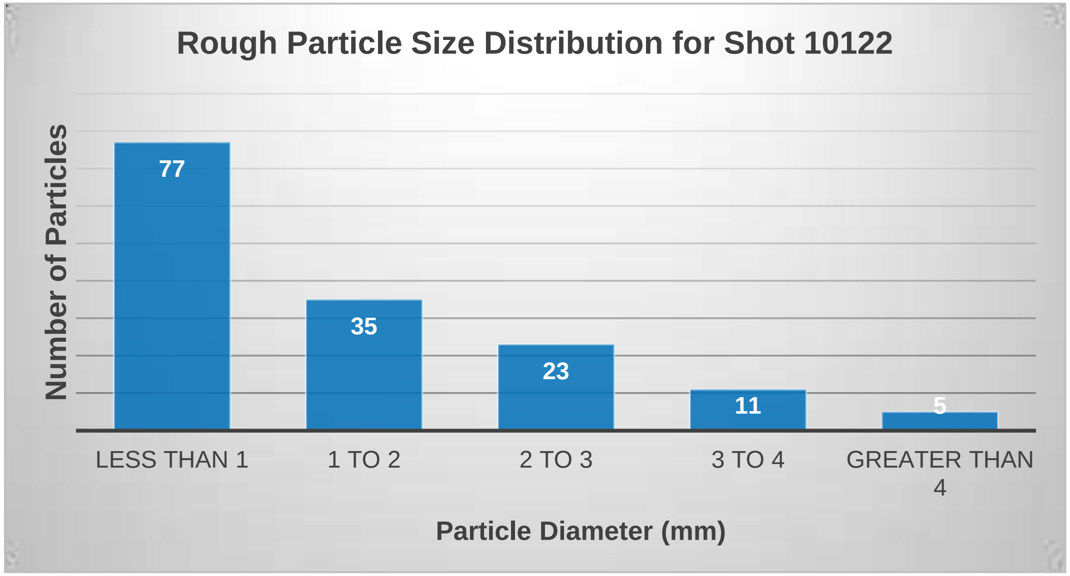
- The argon triple point of 87K is much higher than that of Ne (24.5K) and D2 (18.7K). Mixtures with Ar are therefore not possible.  Layered pellets with Ar in front or rear are possible.



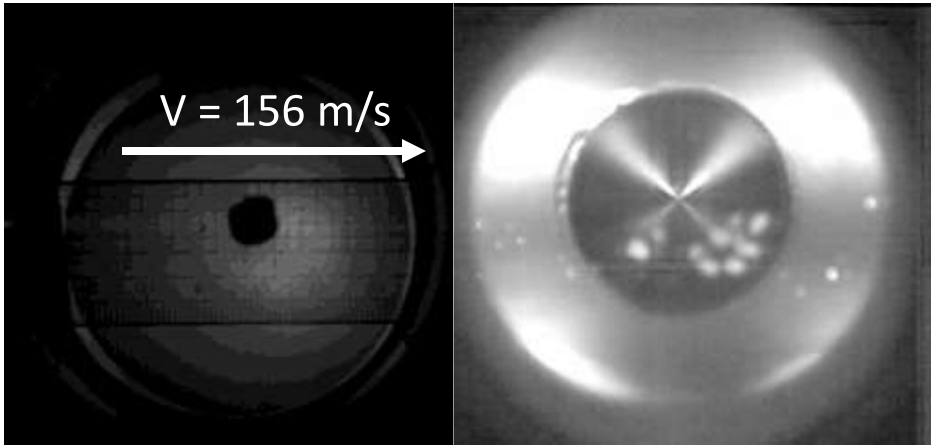

Combs, 2015

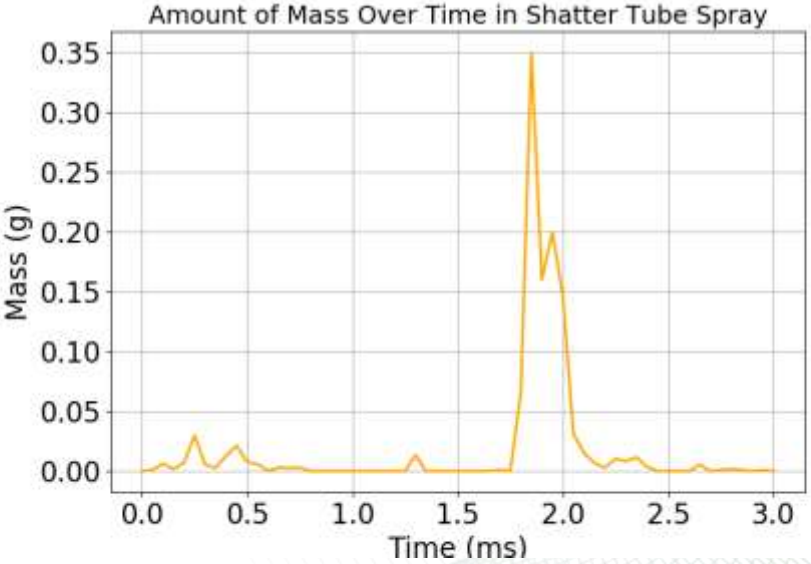
# A typical Argon SPI post-shatter particle size distribution determined from the fast camera data

- Argon formed at 30 K
- 650 mbar L  of Ar
- L/D = 1.51
- Fired at 55 K
- Speed = 156 m/s
- Mass of Pellet = 1.18 g
- Mass of Particles = 1.14 g

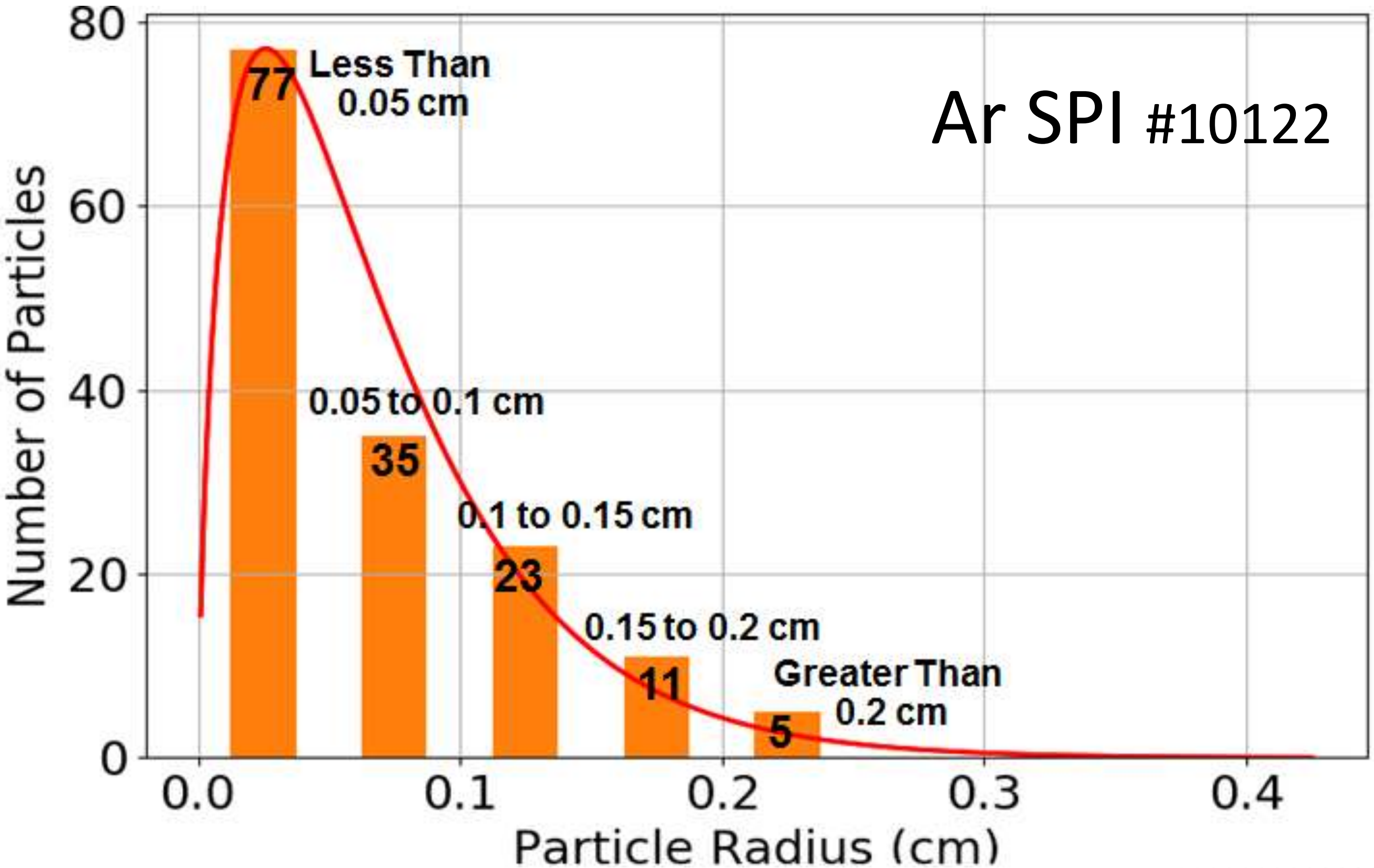



T. Gebhart, 2017



# The particle size distribution compares favorably to a Statistical Fragmentation Model by Parks




$$f(r) = \alpha r K_0(\beta r)$$

- $\alpha = 3800$
- $\beta = 23$
- Fits data better than other two models based on Energy and Maximal Entropy





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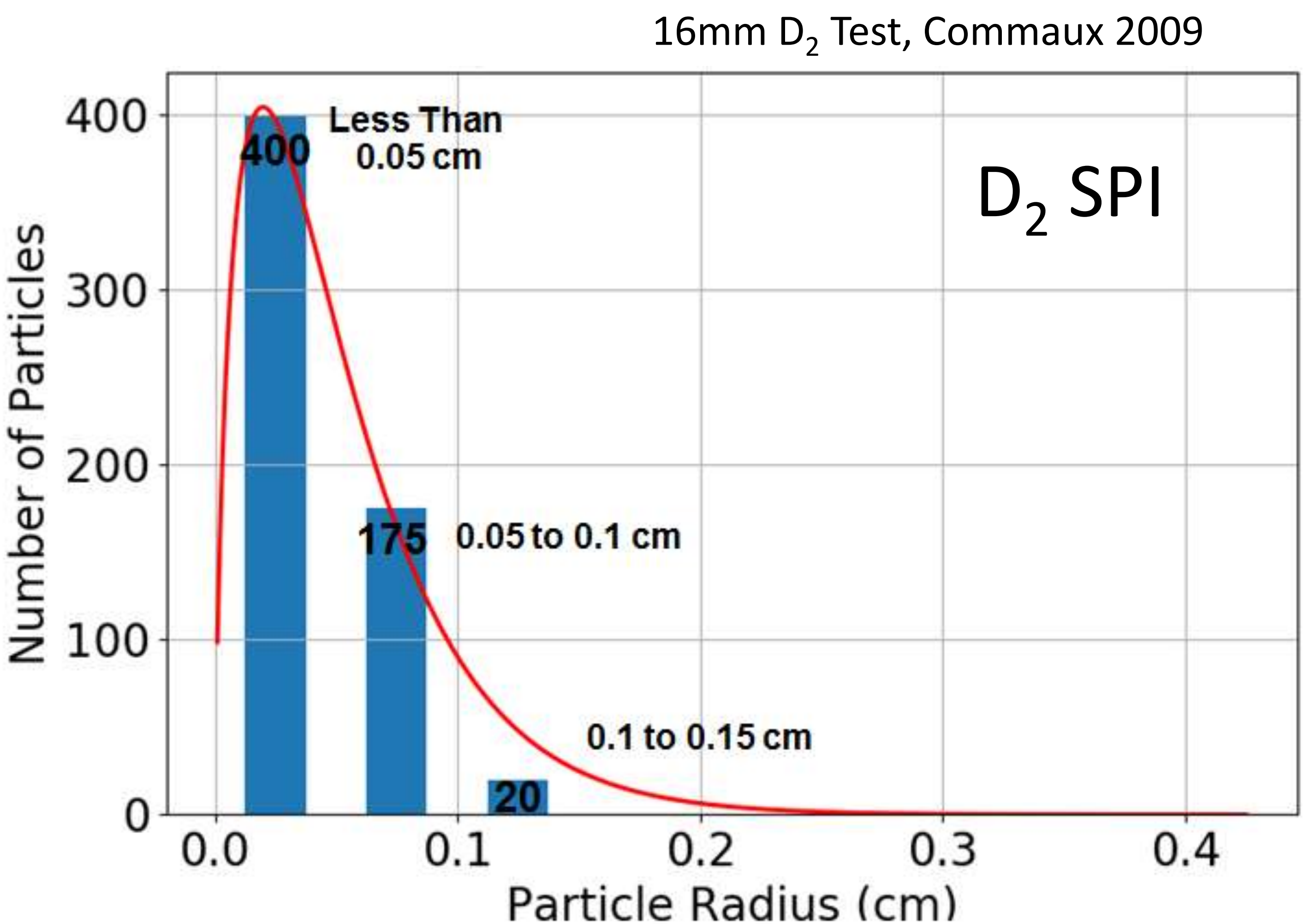
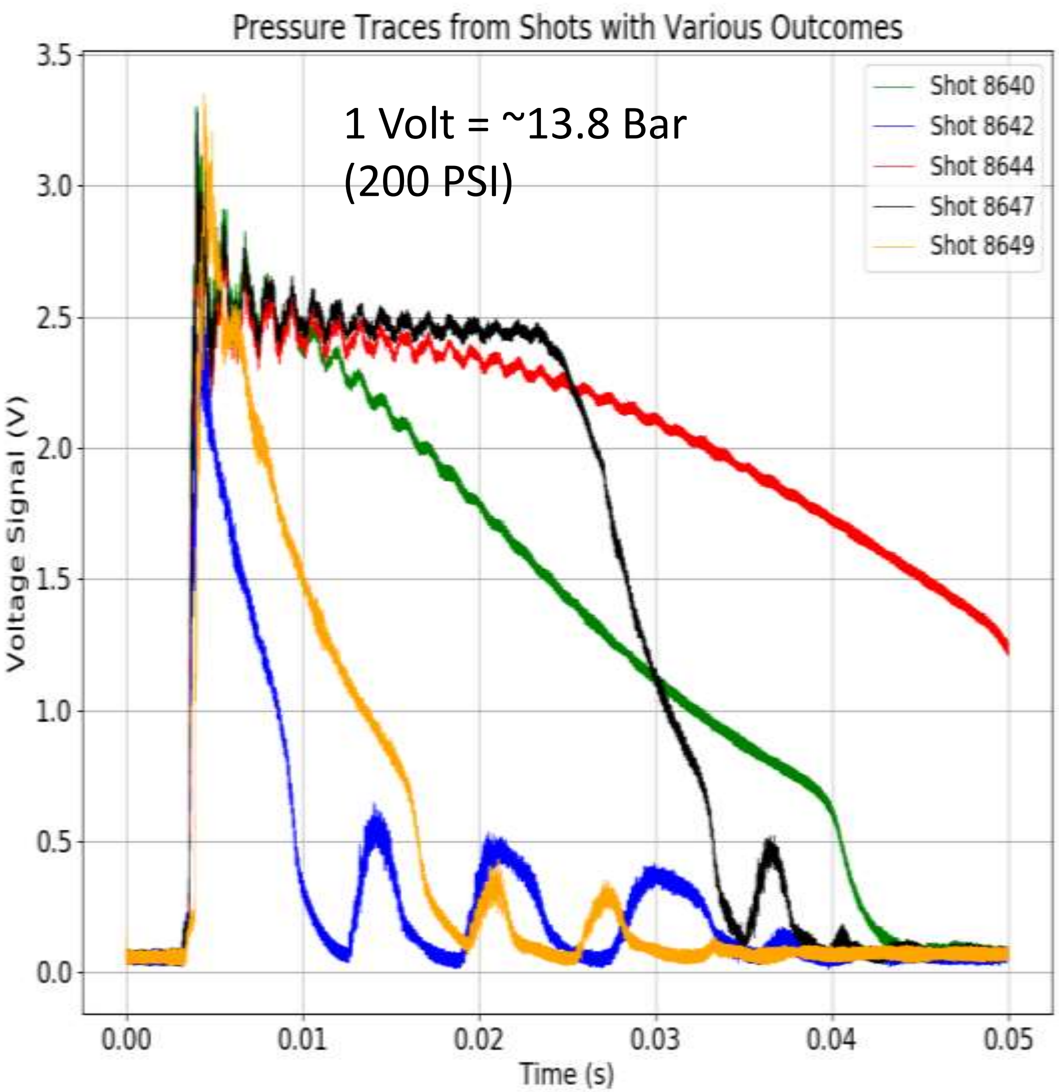
# The particle size distribution for $D_2$ pellets also compares favorably to the Statistical Fragmentation Model




$$f(r) = \alpha r K_0(\beta r)$$

- $\alpha = 26000$
- $\beta = 30$

# Pressure in the valve can be used to determine whether or not the pellet was successfully fired




**System Parameters:**

- 16.5 mm Barrel ID (16.5mm diameter pellets)
- Large Orifice Valve Operated at 600 PSI , 0.85 L

**Explanation of Shots:**

Shot 8640 (**Green**) – Pellet stuck and gas penetrated through center.

Shot 8642 (**Blue**) – Valve shot with no pellet or mass in barrel.

Shot 8644 (**Red**) – Pellet stuck and pressure slowly released.

Shot 8647 (**Black**) – Pellet fired after sticking in the barrel for 25 ms.

Shot 8649 (**Yellow**) – Good shot, 50-50 $D_2$-Ne mix, 405 m/s.

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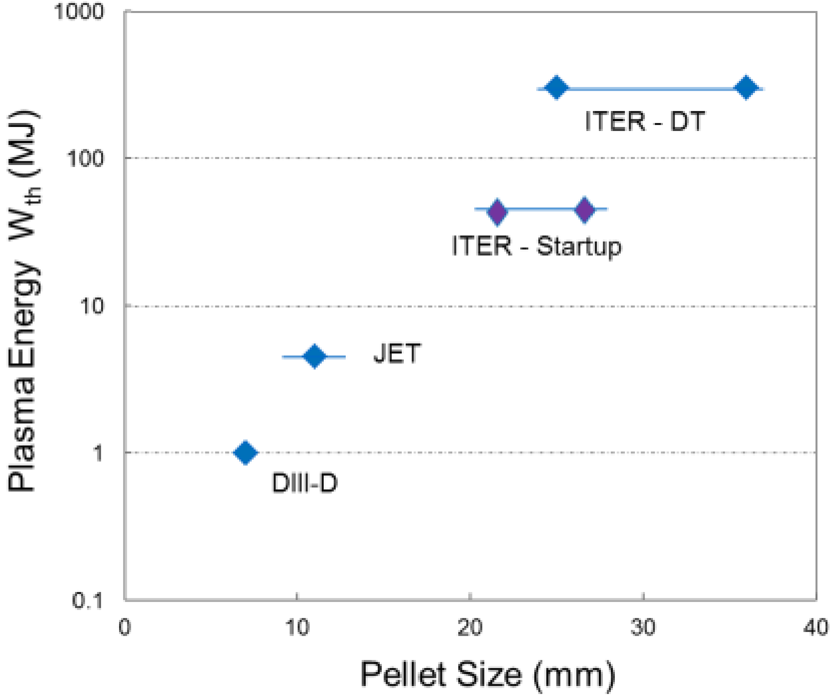
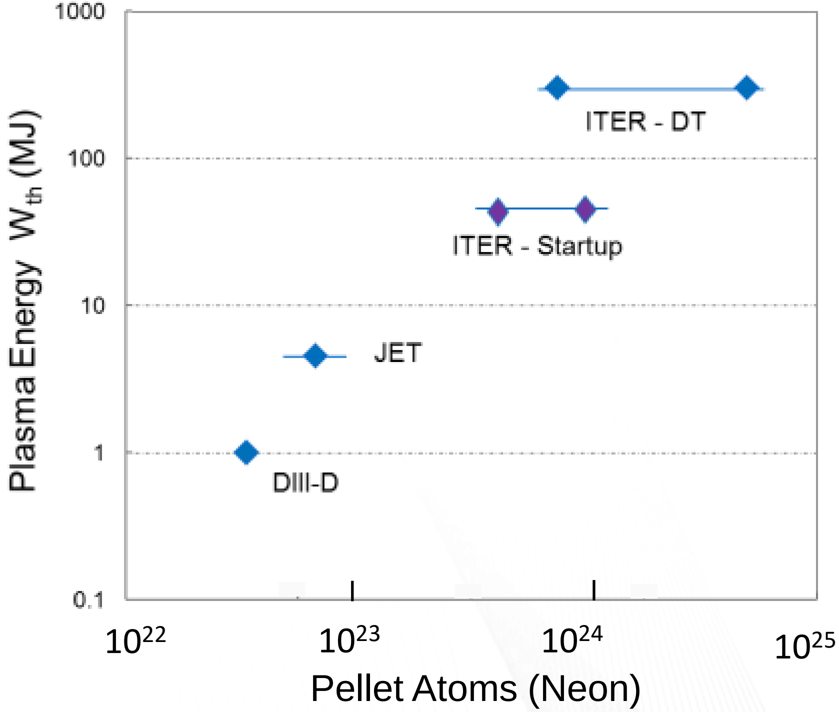
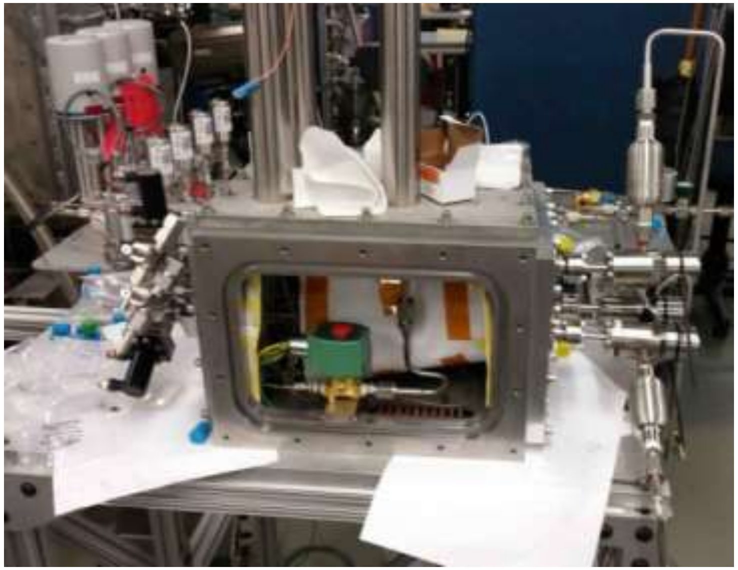
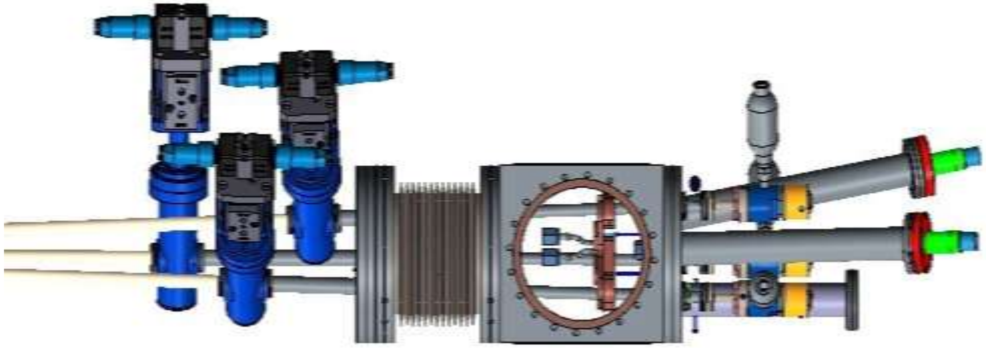
# JET provides extrapolation toward ITER and future fusion system energy dissipation needs



# SPI 3-barrel concept for ITER to be deployed on DIII-D and JET to help answer key questions for ITER





SPI2 has been installed and on DIII-D in February 2017– initial experiments under way.  (D. Shiraki, N, Eidietis)

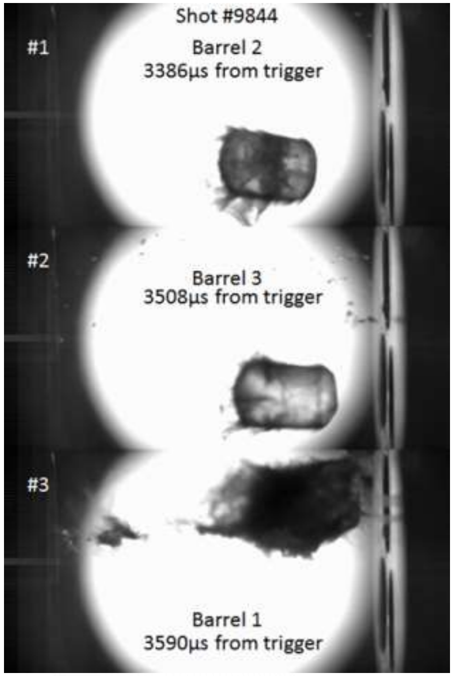
3 pellets can be fired together or serially.

An SPI for JET has been designed based on the same design. Limits
pellet size to 12.5mm (6 bar-L of neon).

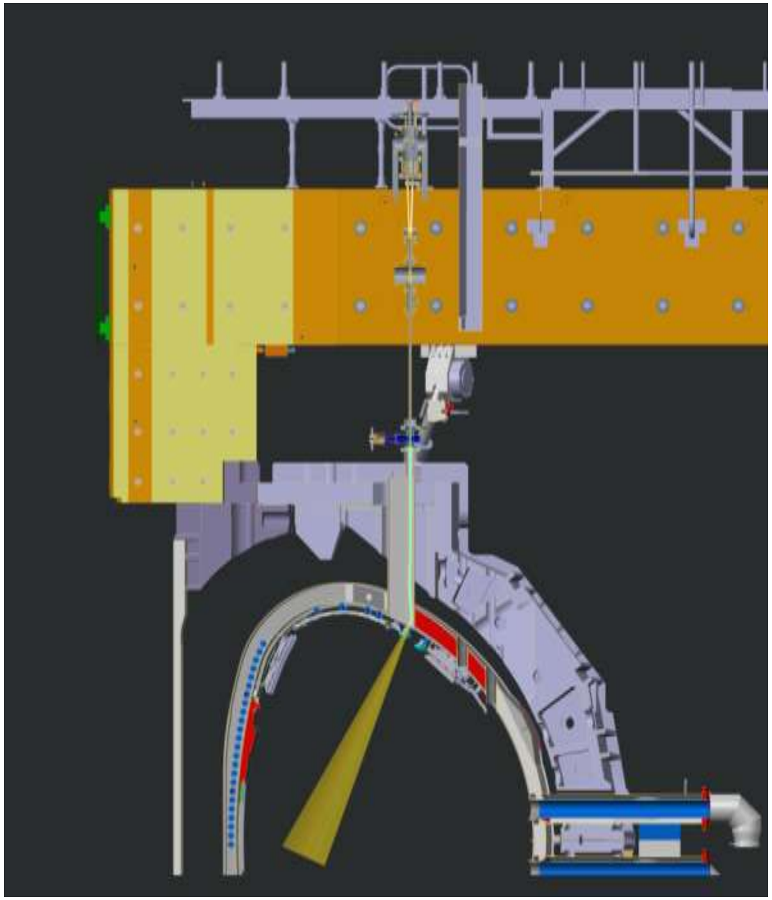
Major difference is Tritium compatibility requiring  more  rigorous QA. Good practice for ITER.

# JET SPI capabilities

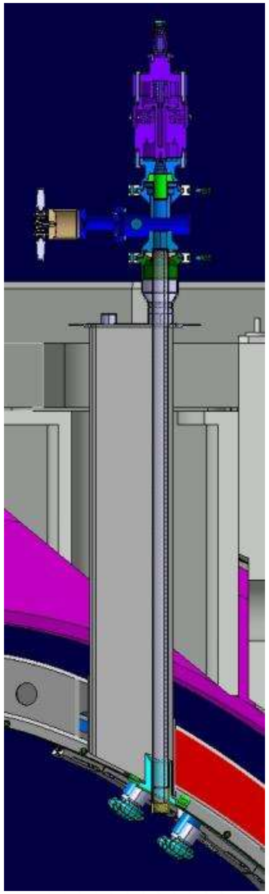
- Three pellets of different sizes
  - $D_2$/Ne/Ar or $D_2$/Ne mixture
  - ~0.1 bar.L to 6 bar.L ($10^{21}$ – $10^{23}$) per pellet
  - 12.5*, 8, 4 mm sizes - *argon punch
- Independent firing
  - timed or simultaneous (±0.2ms)
  - (signal delay TBC)
- Pellet speed ~100–250m/s (max 500m/s with $D_2$)
  - flight time ~20-50ms
  - Plasma edge arrival time known to <2 ms



# SPI Configuration on JET



JET SPI to be located where DMV1 was installed for vertical injection

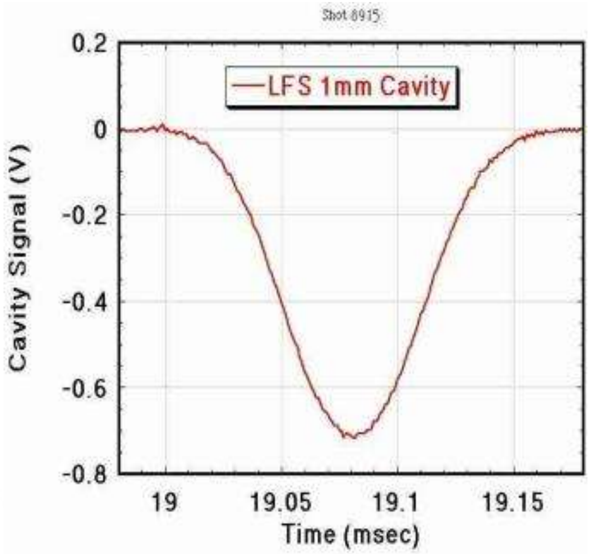


The 40mm opening constrains the shatter tube geometry that can be employed.

# JET SPI capabilities

- Microwave cavity diagnostic
  - Pellet mass* (amplitude ~ mass)
  - Velocity ± 10% (perturbation width)
  - Pellet integrity (early/late peaks)

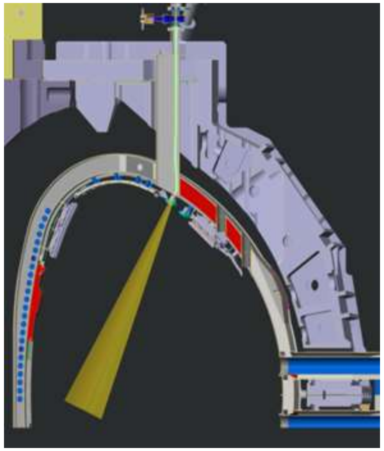
- *Pellet mass determined by reservoir ΔP during formation



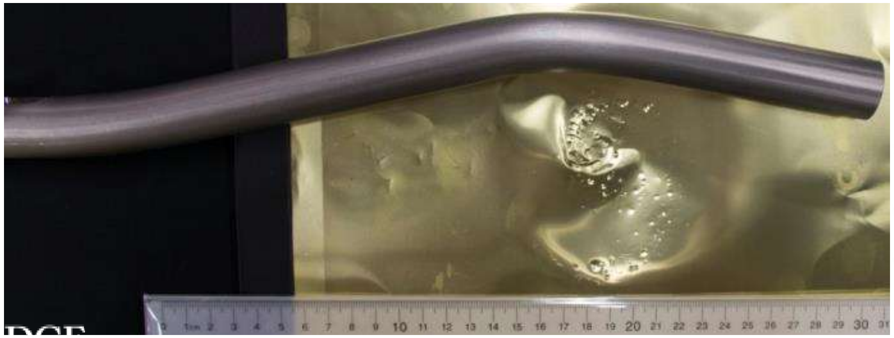

J. Caughman, 2017

# JET SPI capabilities

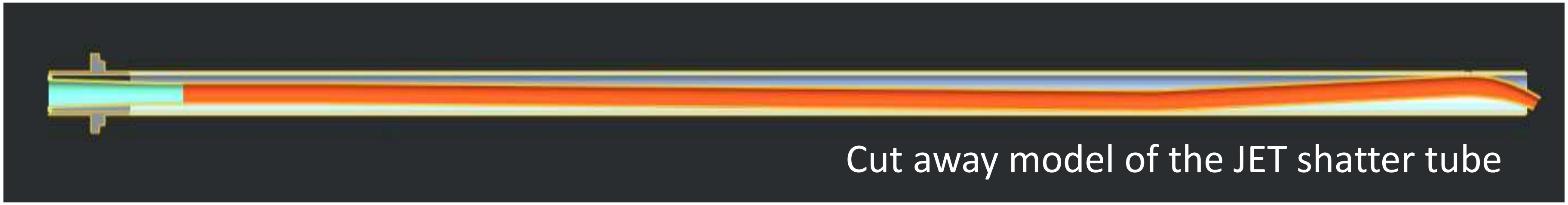
- Shatter cone facing High Field Side
  - 20 degree bend in injection tube pointed to HFS
  - Intercept/disperse REs created by DMV3



- Tube geometry: good collimation
  - Fragments too small to damage PFCs
  - Large enough for good penetration

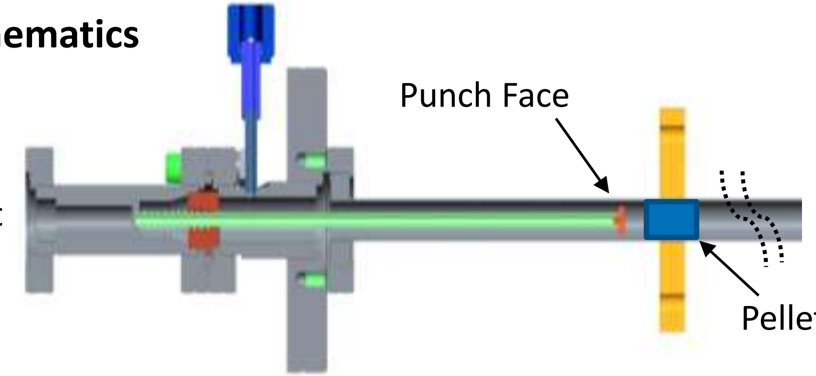


# The JET shatter tube was tested at ORNL using argon pellets launched with a prototype mechanical punch



Cut away model of the JET shatter tube

**Punch Schematics**

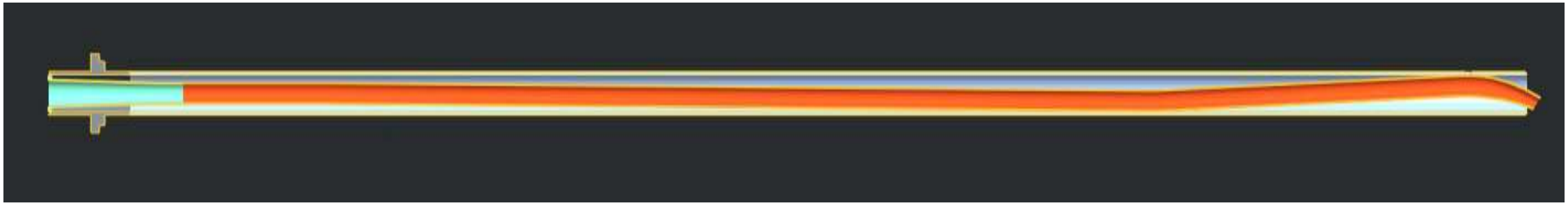



JET shatter tube installed on test stand in Pellet Lab

S. Meitner,

Exit of shatter tube as viewed by the fast camera

# JET SPI capabilities



- Pellets of <15 m/s survived the shatter tube intact
  - 12.5mm argon pellet of 6g has only 1 J of kinetic energy – no danger to JET inner wall

- Largest pellet could have up to 180J of kinetic energy, must be interlocked to prevent hitting the closed TIV

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# ITER SPI Configuration

- Pellet sizes chosen based on IO requirements, available space, and lab results

| Pellet | OD (mm) | L/D | Qty | Location |
| --- | --- | --- | --- | --- |
| Size 1 | 13.39 | 1.5 | 3 | One each UPP 2, 8, 14 |
| Size 2 | 16.56 | 1.5 | 4 | One each UPP 2, 8, 14<br>EPP 08 |
| Size 3 | 19.74 | 1.5 | 4 | One each UPP 2, 8, 14<br>EPP 08 |
| Size 4 | 28.45 | 2.0 | 14 | All in EPP08 |

Injectable amounts for Ne shell pellet
TLM: up to 9.6 kPa*m$^3$
RES: up to 76.6 kPa*m$^3$

Requires ~90 kPa*m$^3$ of He propellant gas required to maximize speed (challenges vacuum system)

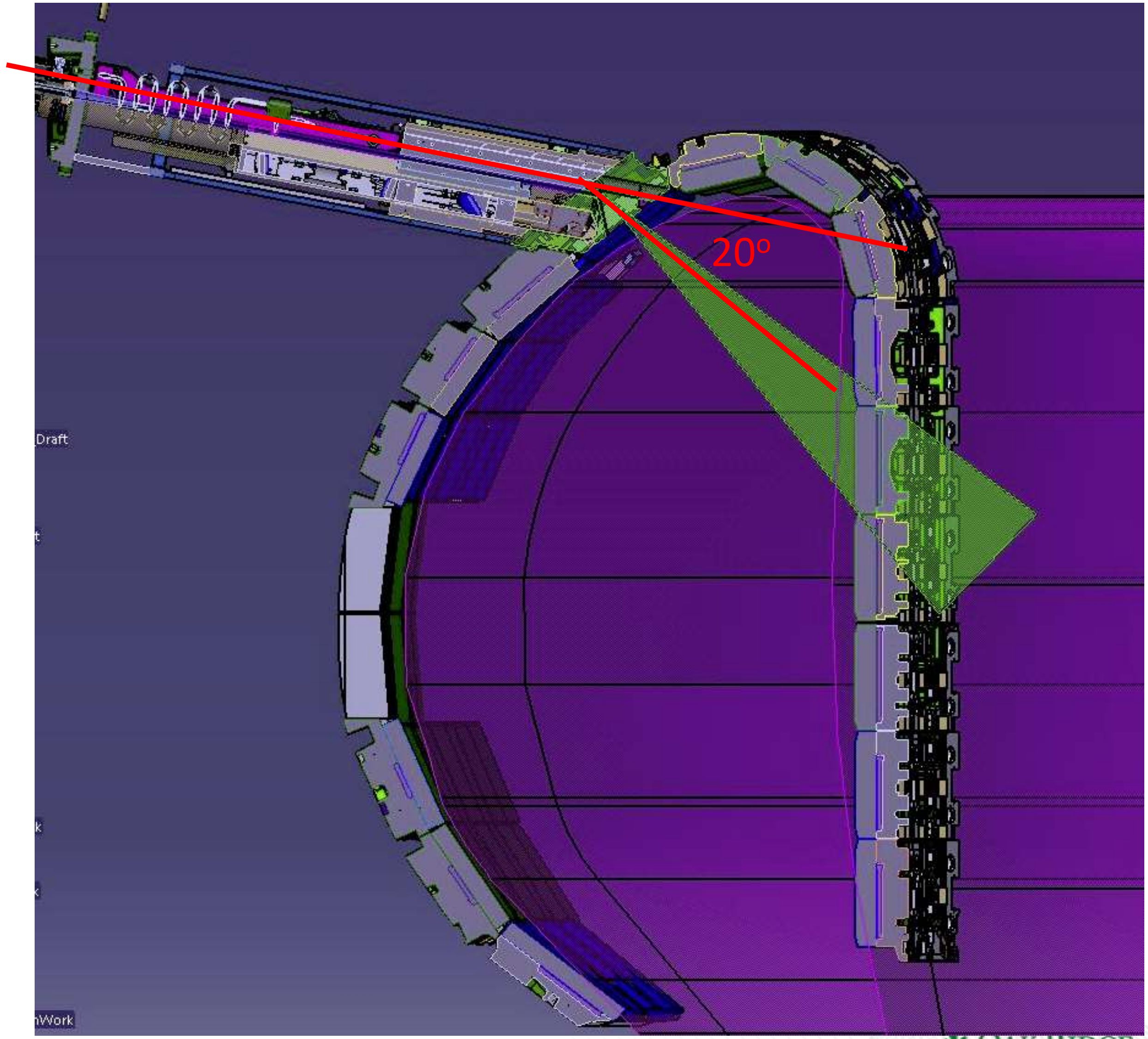
# Design Issue #1 - Upper Port Exit Angle

Upper ports do not aim towards center of plasma

SPI requires 20 degrees or less for proper shattering

This angle only hits the top of the plasma

Experiment is planned on DIII-D to determine if UPP SPI geometry is viable

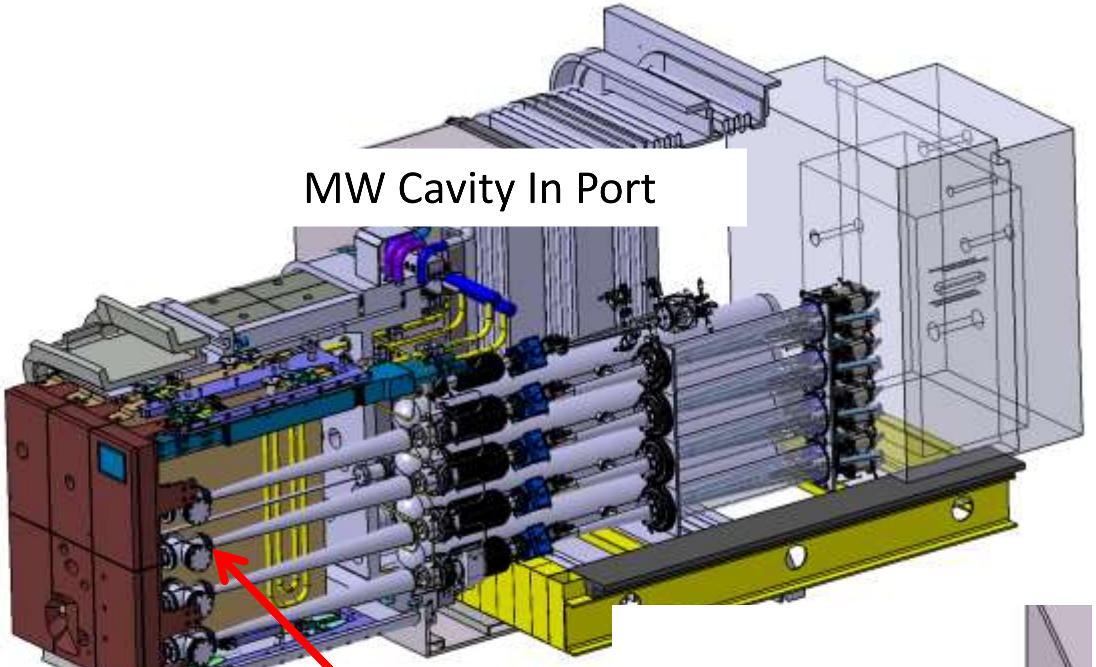


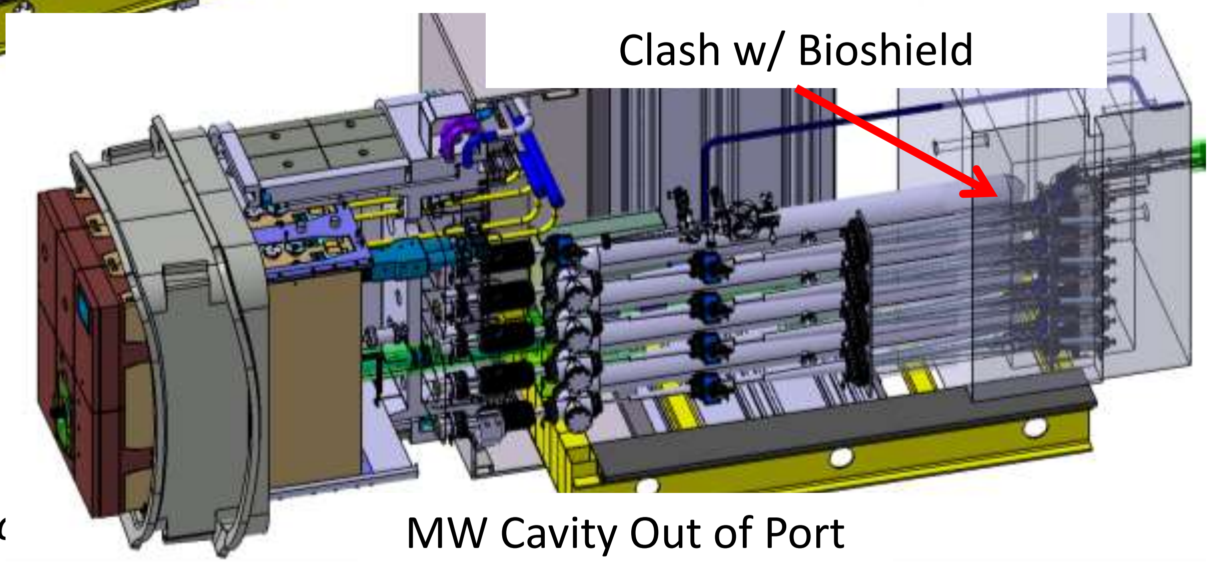
# Design Issue #2 – No space for Microwave Cavity

MW Cavity causes clashes

MW Cavity not included in the baseline design

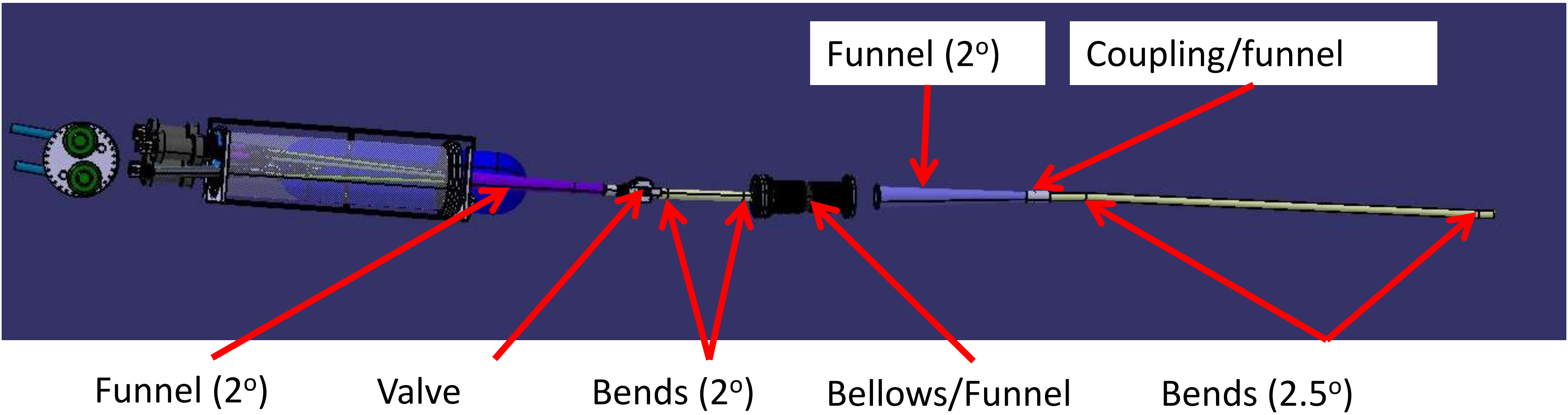
Other diagnostics are needed (e.g. pressure trace, Vis-IR plasma view)




*Not sh*

# Design Issue #3 – Upper Port Path




***Pellet speed and/or pellet survivability are likely to be limited by this configuration***

- Previous testing at ORNL shows bends over 2° are likely to break pellets
- New tests underway to expand on previous testing and to verify ITER geometry

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# JET SPI Experimental opportunities

## RE Studies

- RE dissipation with Ar/Ne SPI using punch
  - Working on variation of particle size as function of speed – possible knob
  - Multiple pellets possible – Ar, Ne
  - JET is working on vertical position control to allow results
- RE Avoidance – D2/Ne mixtures, possible Ar-D2 layer pellets
  - High current operation?

# JET SPI Experimental opportunities

**Thermal Mitigation** – Small pellet sizes

- Optimization of D2/Ne mixture
  - May need punch for small pellet size to vary pellet speed

- TM with fixed amount of Ne and different amounts of D2 (vary pellet size)

- Mitigation of a near disrupting plasma – wounded duck
  - Dependence on locked mode location WRT SPI location

# Summary

- SPI  R&D is ongoing to quantify shattering and capabilities for ITER configurations.
- The need for a reliable DMS on ITER have motivated a strong international effort on JET (ITER, USITER, USDOE, EUROfusion, CCFE all working well together)
- SPI will be installed on JET in Sept. for experiments starting in 2018, and could with further development be integrated into JET DMS in future.
- JET SPI Benefits to ITER
  - Commissioning and Operational Experience
  - Data on TM heat loads, halo currents,  and RE mitigation
  - Modeling, simulation, extrapolation to ITER
- U.S. input to the JET disruption taskforce: proposal titles due Aug. 4, full proposals in Sept.