Hydrogen Pellet Formation, Release, Survivability, and Shattering Research Supporting the ITER SPI System*

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

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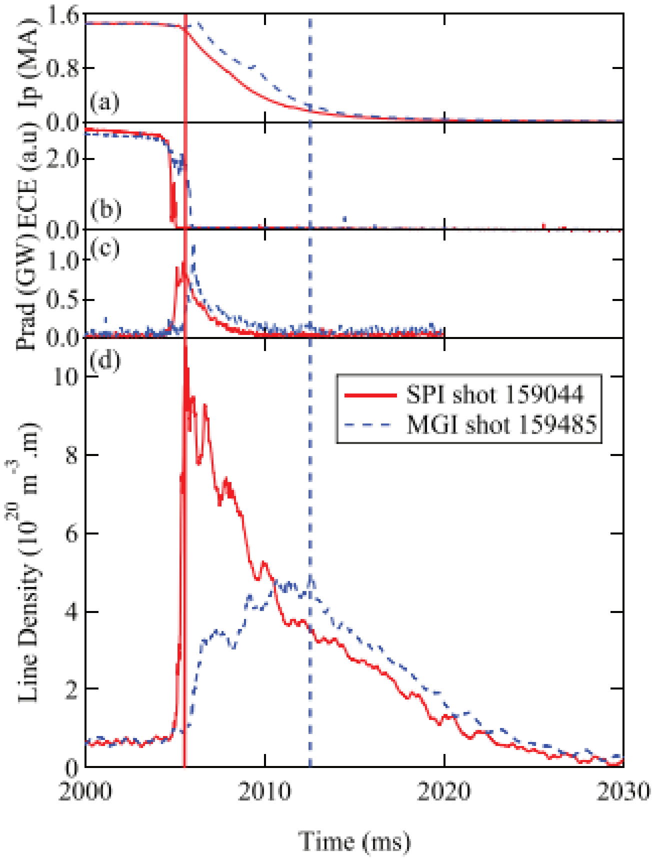
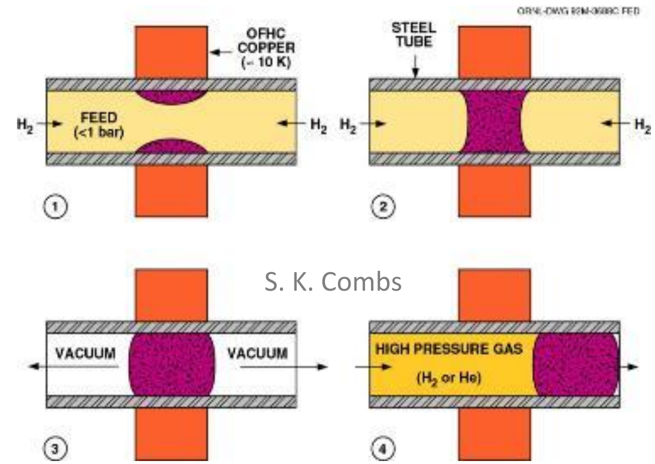
Shattered pellet injection is the baseline disruption mitigation system for ITER

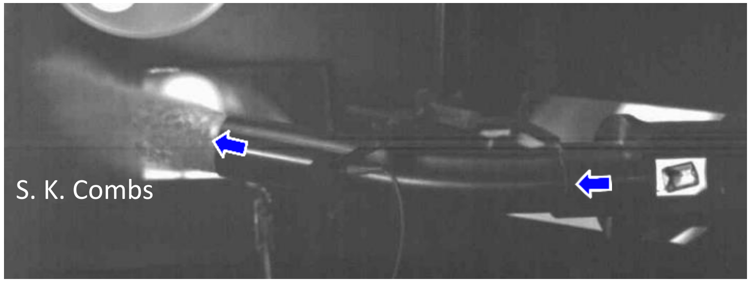
SPI is the process of firing a large solid pellet containing a small fraction of high-Z impurities

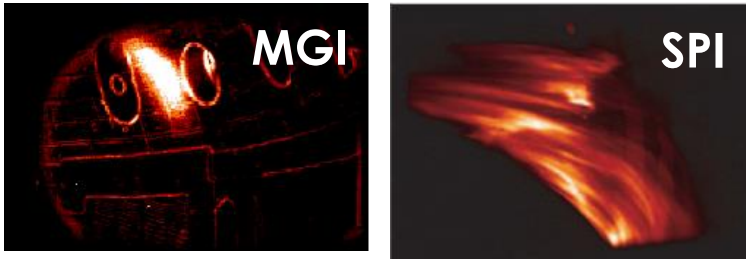


N. Commaux, et al., Nucl Fus 2016



Pellets are shattered before entering the plasma to increase surface area for ablation, and therefore increasing the assimilation rate





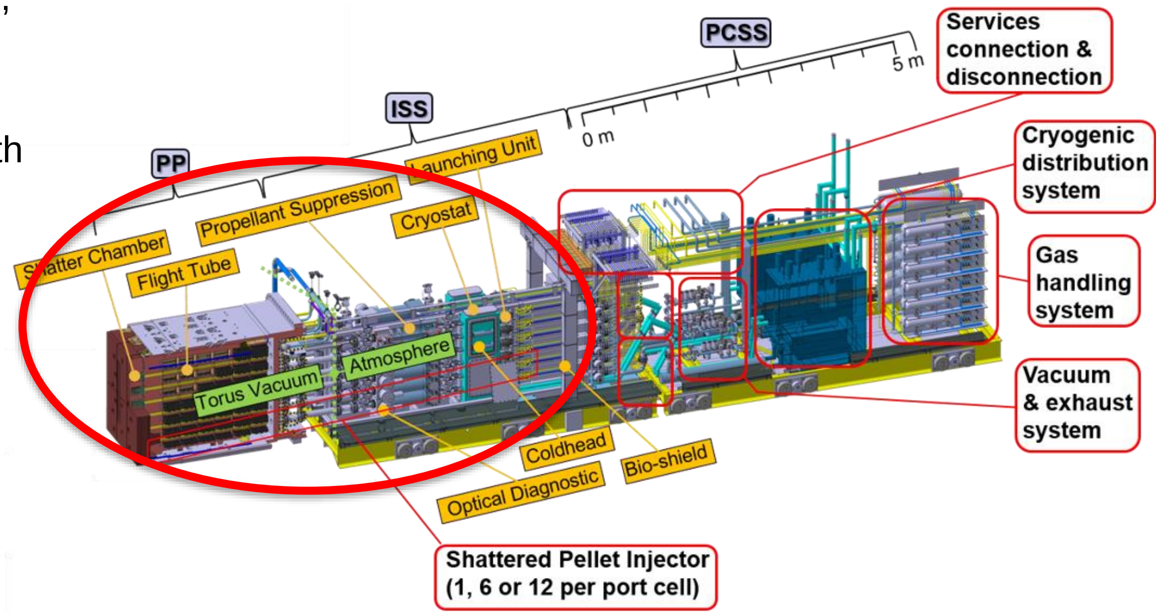
N. Commaux, et al., Nucl Fus 2010

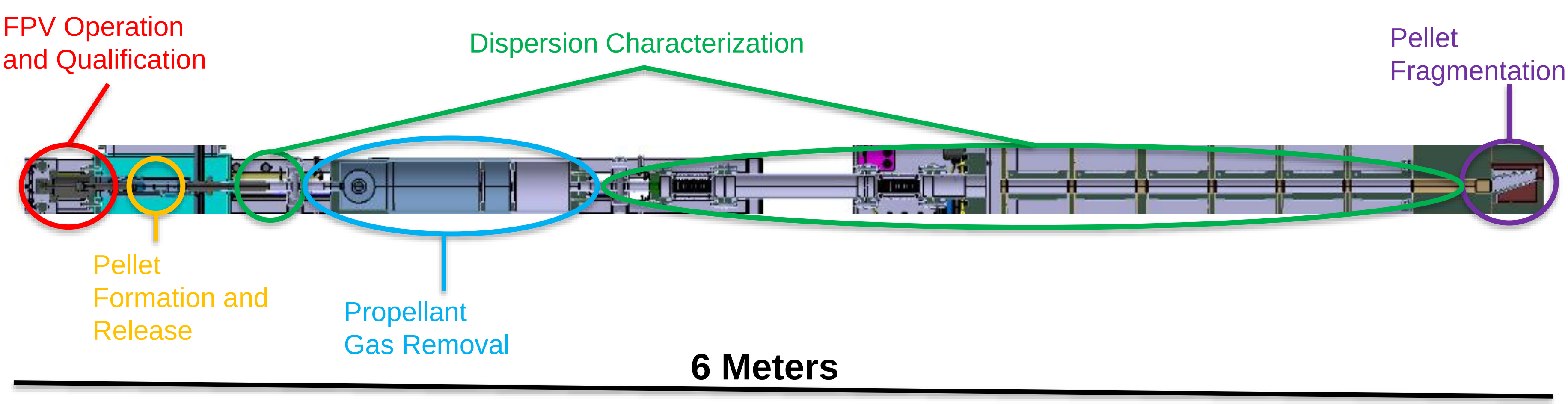
MGI is effective on machines smaller than ITER, but won't work on ITER

SPI is capable of injecting material much deeper into the plasma

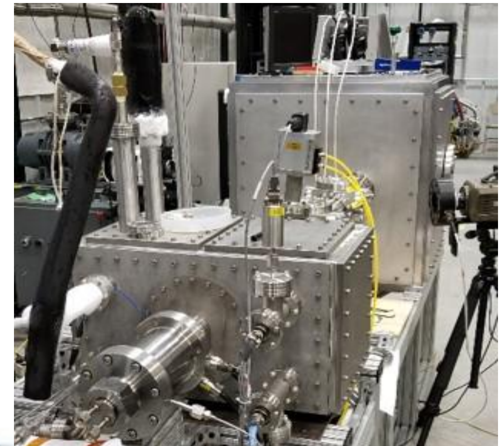
SPI is the baseline DM system on ITER

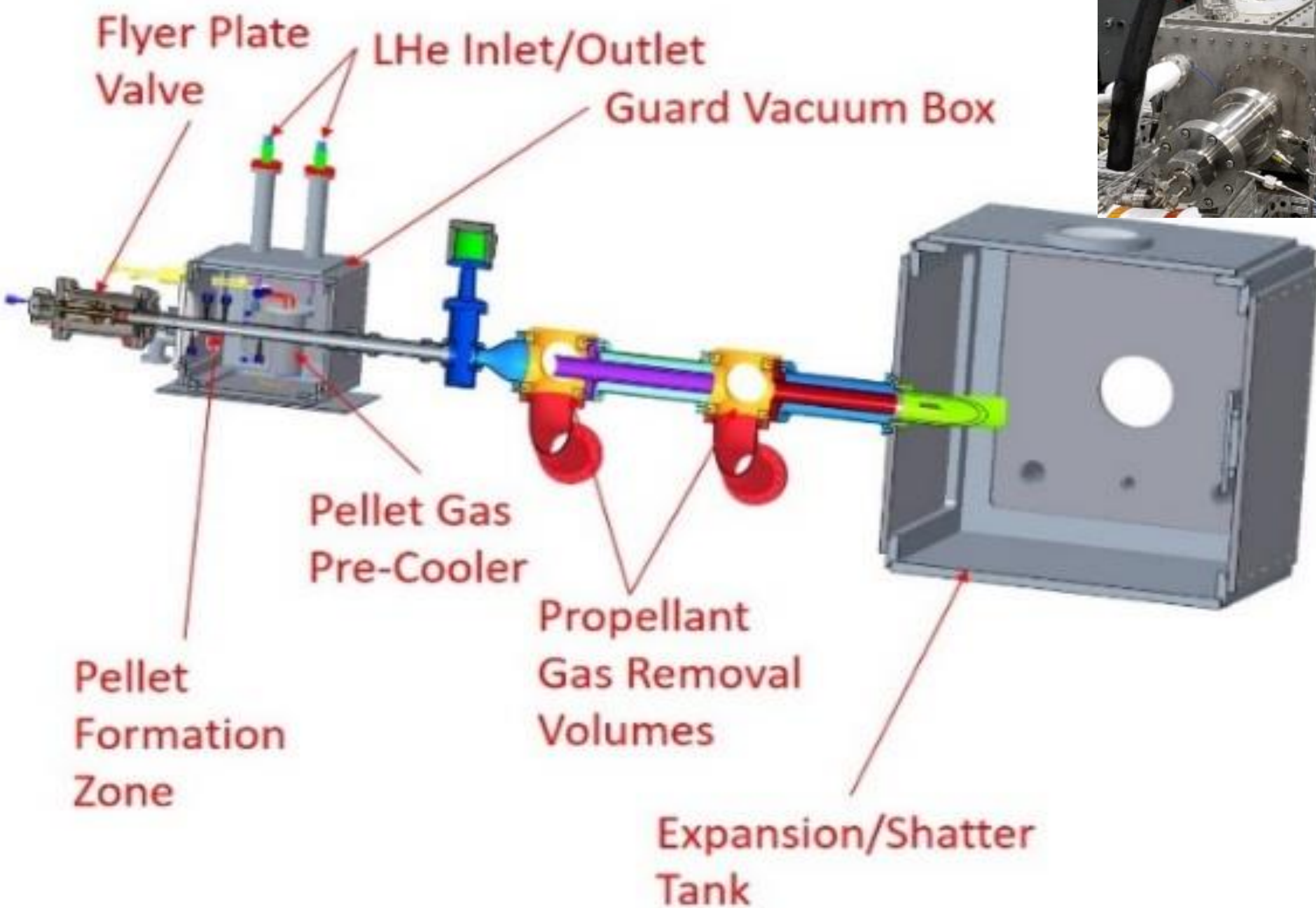
- 24 injectors on the equatorial plane, 3 injectors in upper ports
- Pellets are 28.5 mm in diameter with L/D ratio of 2
- Hydrogen will be the base pellet material
  - Deuterium will not be used in initial phases due to its classification as a nuclear material
- Pellets for TQ will likely contain a small amount of neon (~10%)



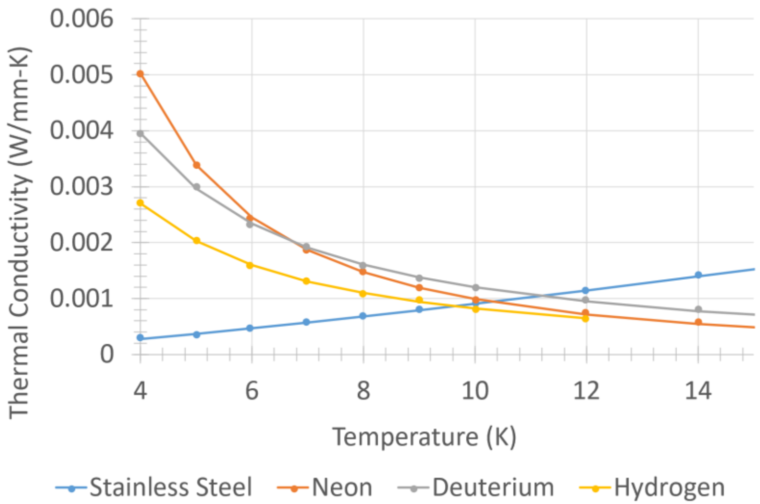


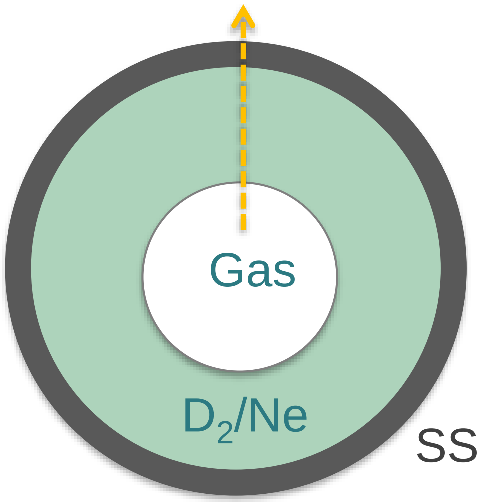
An ITER SPI test bed was designed and built at ORNL





Physical properties of hydrogen are suboptimal for formation and release of large pellets

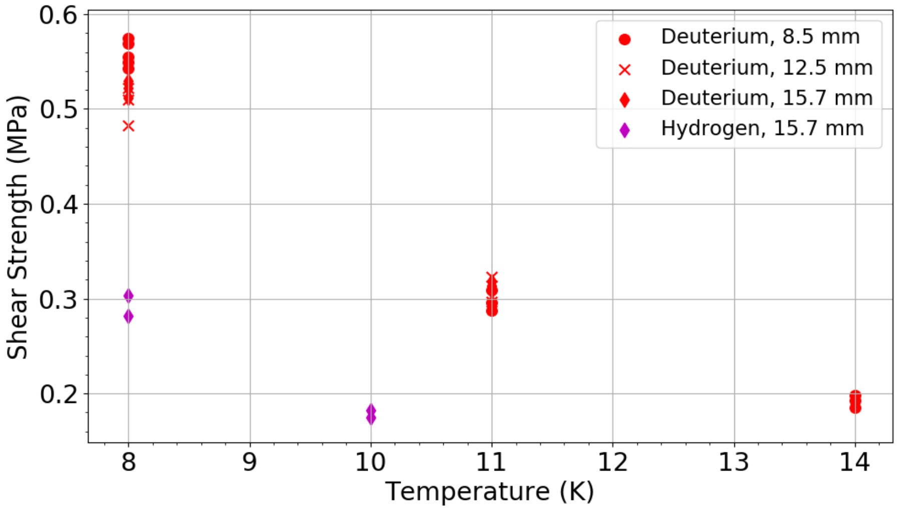




$$q = \kappa/D \, \Delta T$$

	Hydrogen	Deuterium	Neon
Triple Point Temperature	13.8 K	18.6 K	24.6 K
Heat of Sublimation	508 J/mol	1150 J/mol	2107 J/mol
Crystal Structure	FCC*	FCC*	FCC
Density	0.086 (g/cm³)	0.2 (g/cm³)	1.44 (g/cm³)

*when solid formed at low pressure



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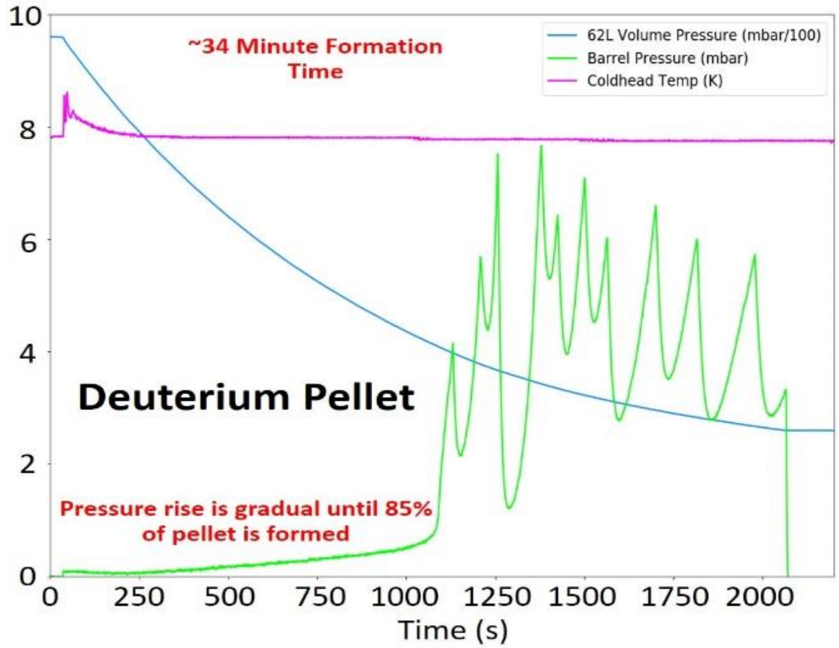
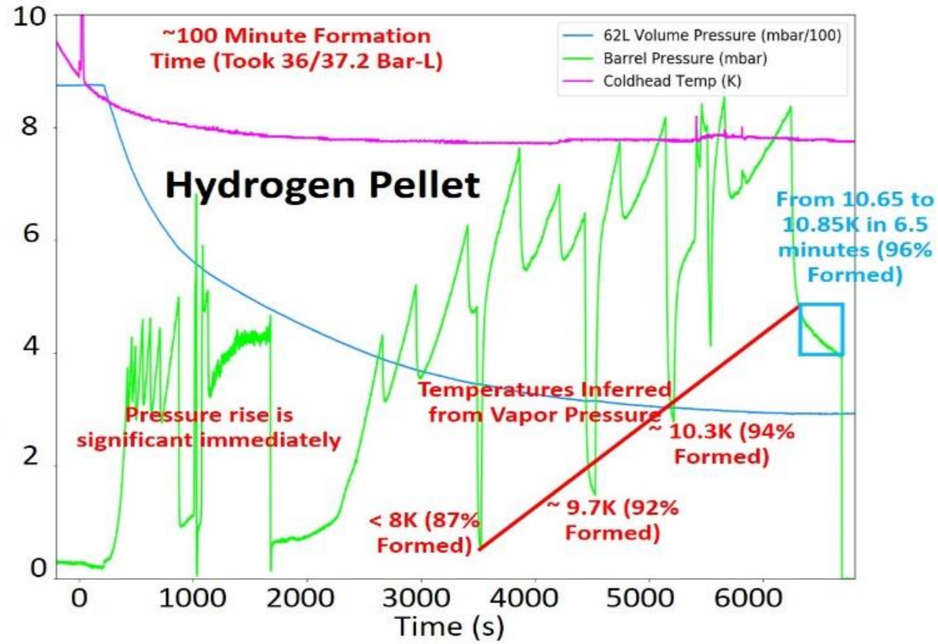
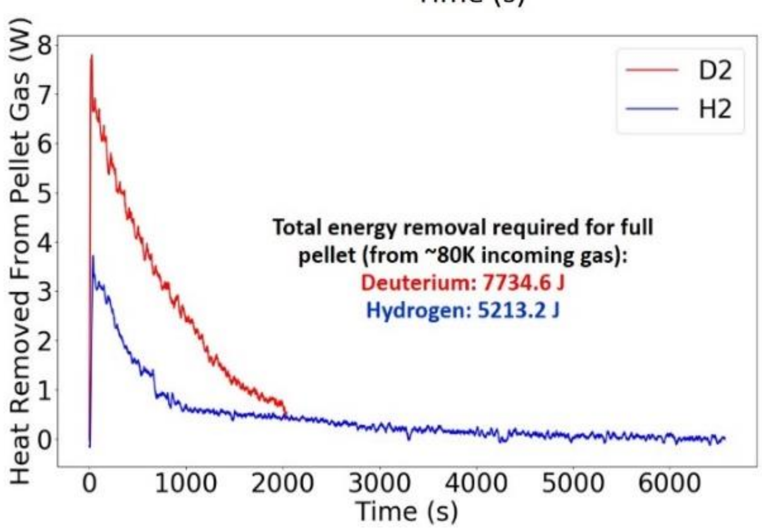
Forming a 28.5 mm H2 pellet takes ~100 minutes

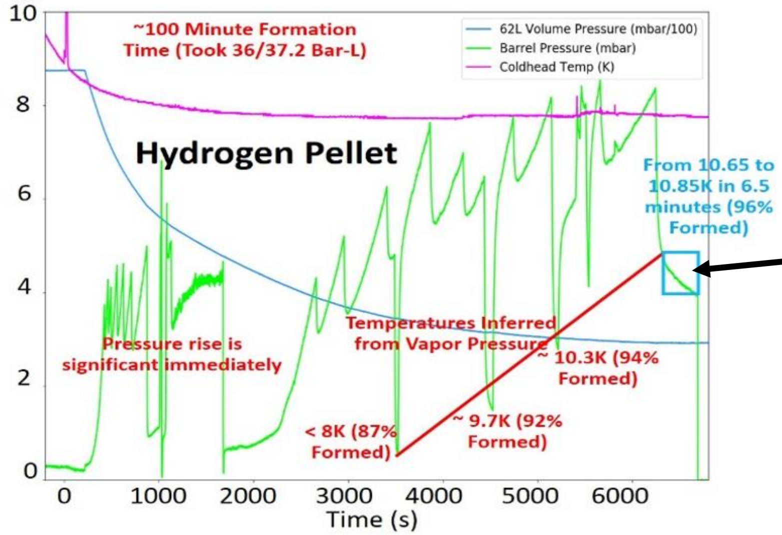




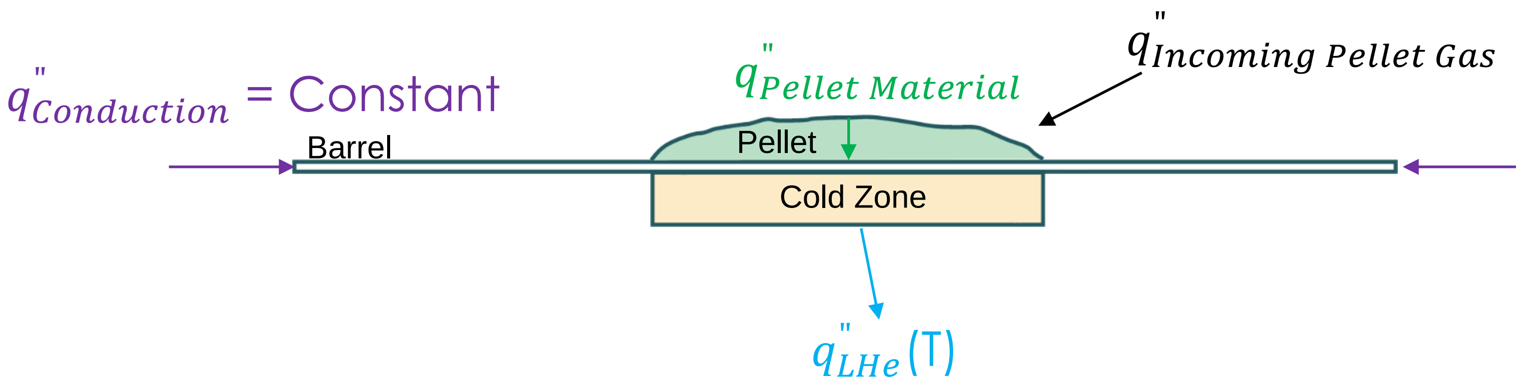


- ITER has a 30-minute constraint on pellet formation time
- Due to poor thermal conductivity and lower triple point temperature, hydrogen pellets cannot be formed in this amount of time
- One possible improvement is to reduce cold head temperature to 5-6K
  - Doing so introduces additional challenges for pellet release

The heat removal from the incoming pellet gas is dependent on the ability of the solid pellet material



- As pellets soak after formation the centers cool over time, but will take a long time to reach the same temperature as the coldhead
- The blue box to the left shows a cooling curve of a 28.5mm pellet after initial formation.
  - 6.5 minutes of cooling resulted in a 0.2K reduction in average pellet surface temperature, from 10.85 to 10.65K based on vapor pressure curves
- The material thermal conductivity is the limiting factor in heat removal from the pellet (if coldhead design is adequate)



For steady-state pellet formation → $q''_{LHe} + q''_{Conduction} = q''_{Pellet\ Material} = q''_{Incoming\ Pellet\ Gas}$

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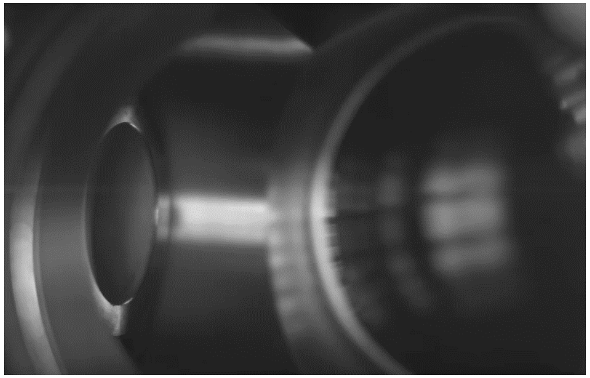
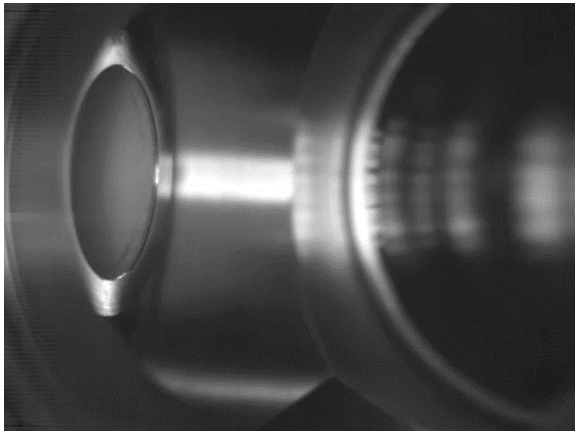
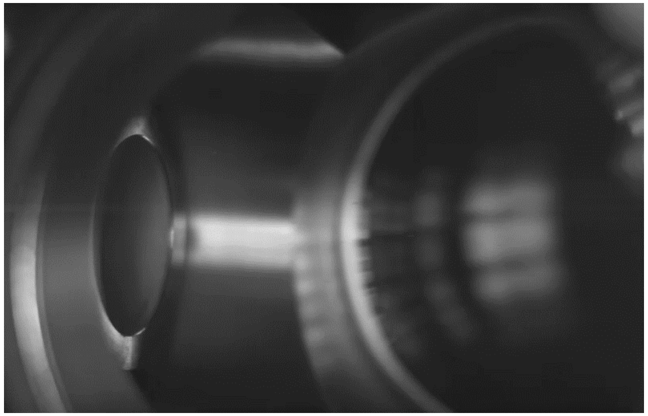
A range of hydrogen pellet sizes were formed and fired to determine the largest possible pellet that can be released intact



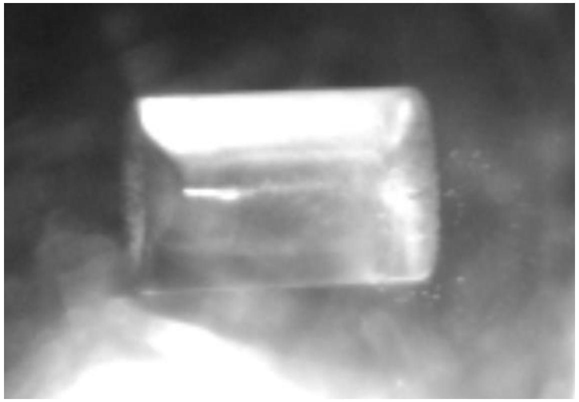
28.5 mm D2 pellet (for reference)



28.5 mm H2 pellet



23.2 mm H2 pellet

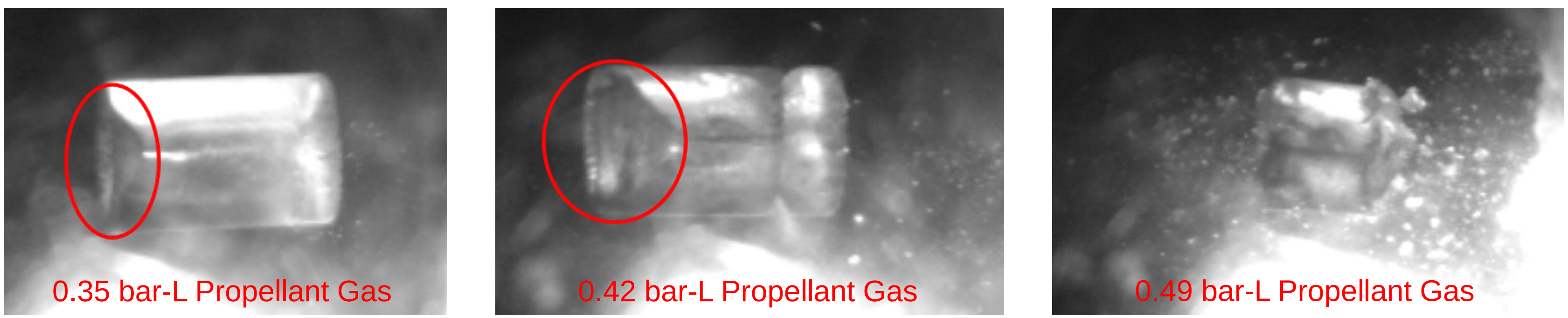


20 mm H2 pellet (success!)

Due to poor thermal conductivity, low heat of sublimation, and low material strength, the successful release of large H2 pellets is a challenge

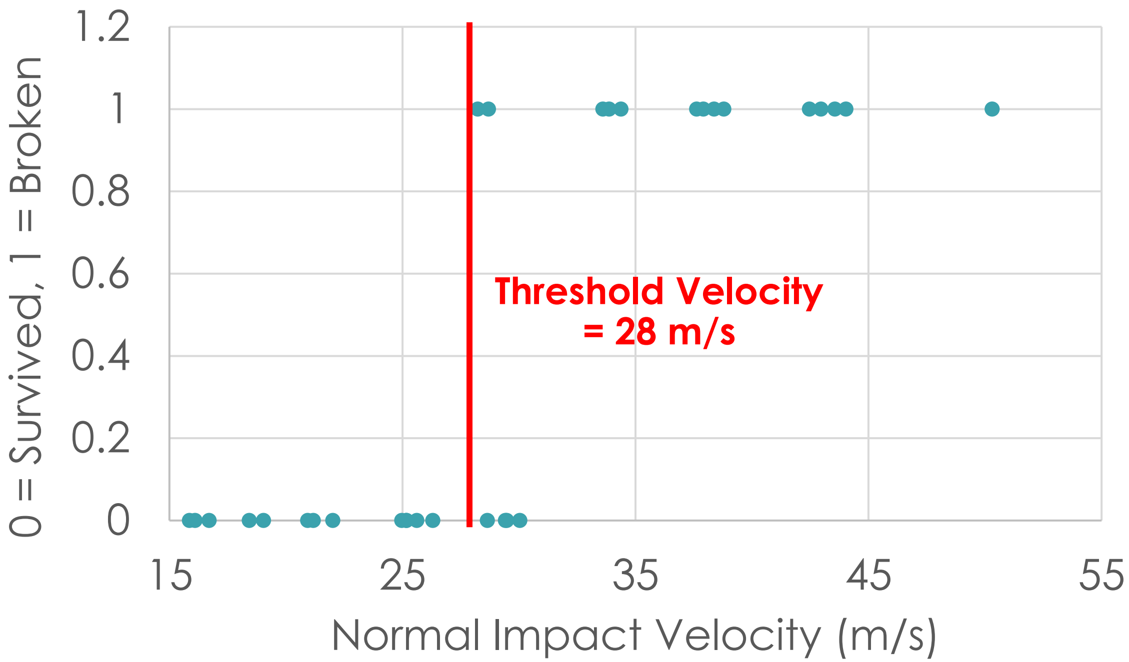
- Pellets with diameters of 28.5, 23.2, and 20 mm were formed and fired to determine the largest hydrogen pellet that can be fired reliably
- Each of these required the design and fabrication of a new, dedicated barrel
- The largest hydrogen pellets capable of withstanding the thermal load and force generated by the impacting propellant gas is ~20 mm, depending on the amount of propellant gas delivered

Similar 20mm hydrogen pellets with increasing propellant gas loads



- Each of these pellets were formed under similar conditions and fired at 7.5K with 60 bar propellant pressure
- Propellant gas amount was varied by changing the pulse width of the propellant valve

Pellet survivability is essential for the reliability of an SPI-based DM system, threshold velocity measurements were conducted via low angle impact testing



The threshold velocity is used as a design parameter to ensure pellet survivability when traversing guide tubes and potentially treacherous flight paths (fueling pellets)

It is also used in a fragmentation model to determine a fragment size distribution based on statistical fragmentation mechanics

The threshold velocity is utilized in the statistical fragmentation model to determine a relative probability function for generated fragment sizes

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

$$\alpha = X_R / D$$

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

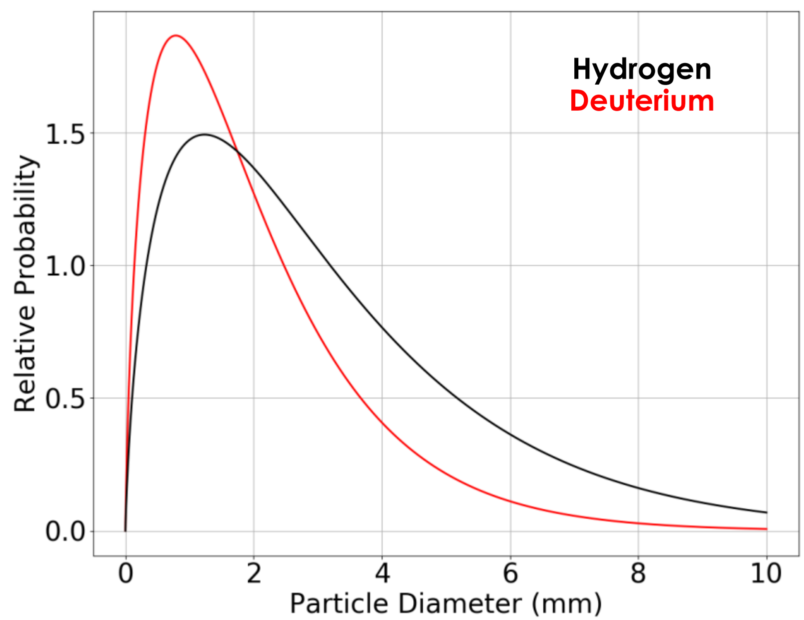
X_R can be reduced to $V^2_{Perp}/V^2_{Threshold}$

Gas	Threshold Velocity (m/s)	Constant, C
Hydrogen	**28**	**1.8***
Deuterium	**20**	**2.5**
Neon	**8**	**5**
Argon	**6**	**8**

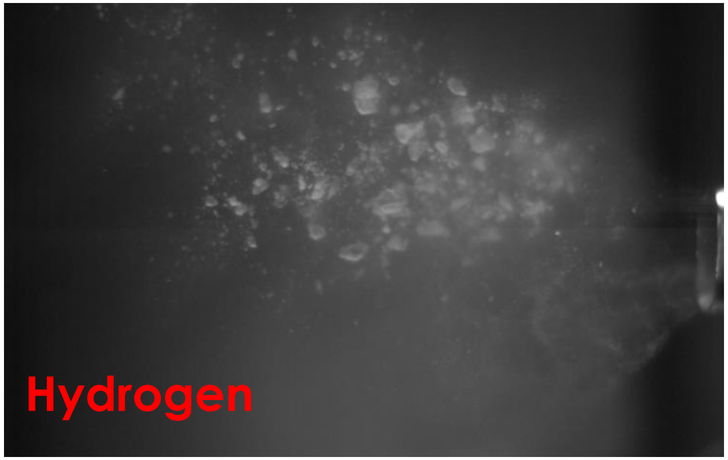
*determined with minimal statistical data

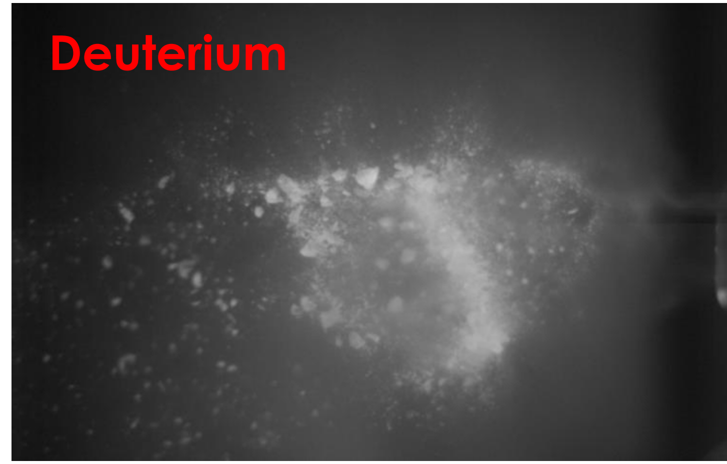
Comparison:

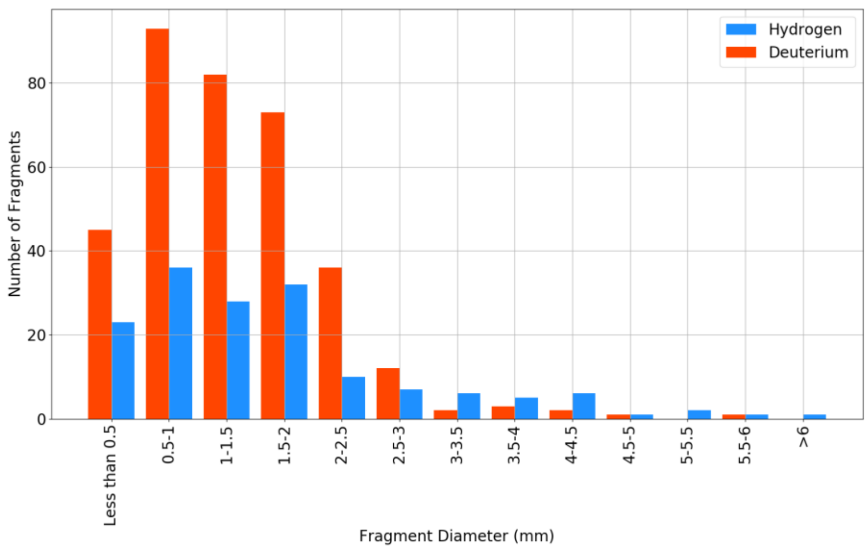
- Deuterium and hydrogen pellets
- 10mm diameter, 1.6 L/D
- 320 m/s nominal velocity
- ~20-degree impact (110m/s normal impact)

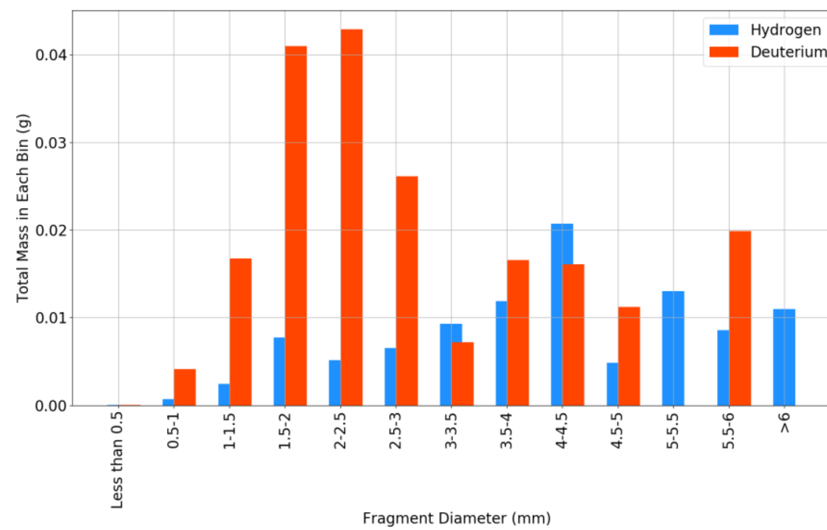


Measured fragment plumes confirm that hydrogen produces larger fragments at similar pellet velocities









Summary

- Due to the physical properties of solid hydrogen, the formation and release of large, pure hydrogen pellets is a technical challenge for the ITER DMS system
- Pellet formation, release, and survivability experiments have been conducted to determine the largest hydrogen pellet that can be reliably dislodged and accelerated from the barrel
- The threshold impact velocity measured for hydrogen is ~28m/s
- Experimental measurements supporting fragmentation models are being conducted for hydrogen pellet material

Thank you!

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Questions