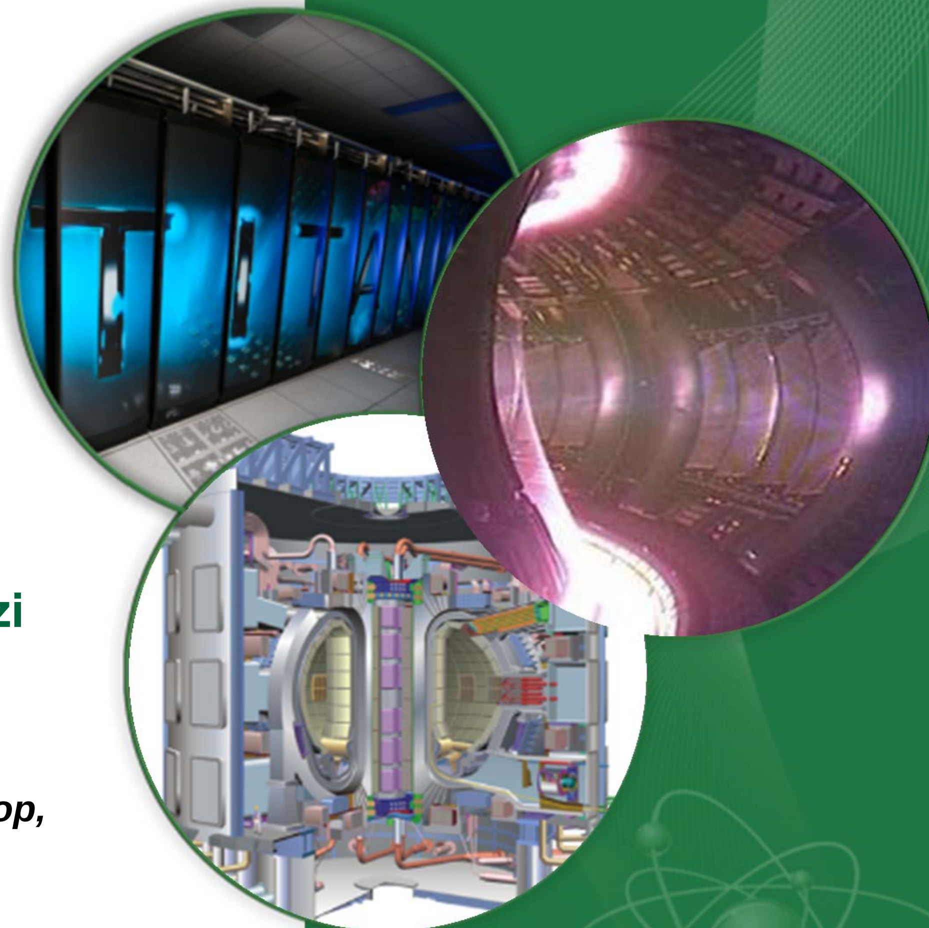
Shattered Pellet Injection Developments and Implementation on Tokamaks



L.R. Baylor, T. Gebhart,
S.J. Meitner, D. Shiraki,
D. Rasmussen*
ORNL, *USITER

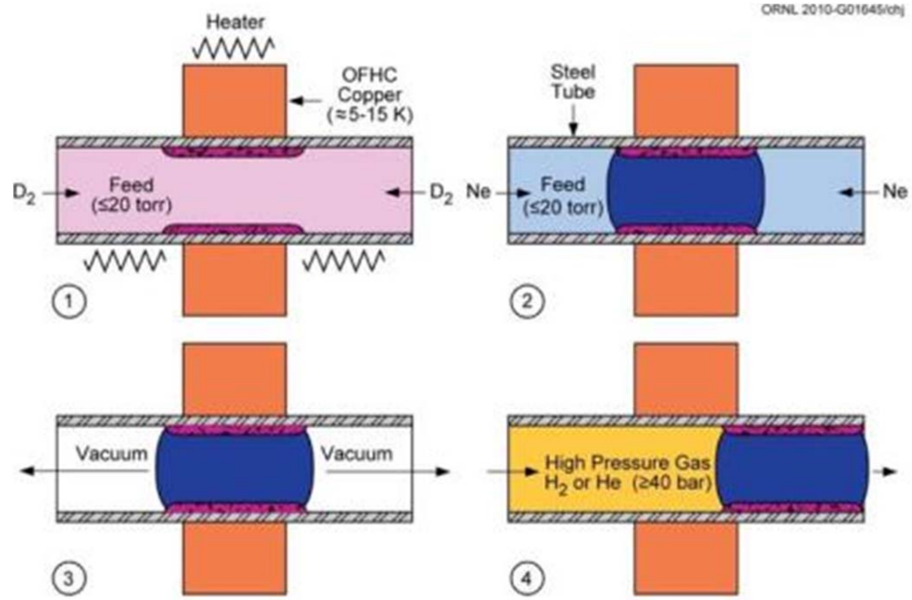
M. Lehnen, S. Maruyama, U. Kruezi
ITER

Theory and Simulation of Disruptions Workshop,
PPPL
17-July-2018

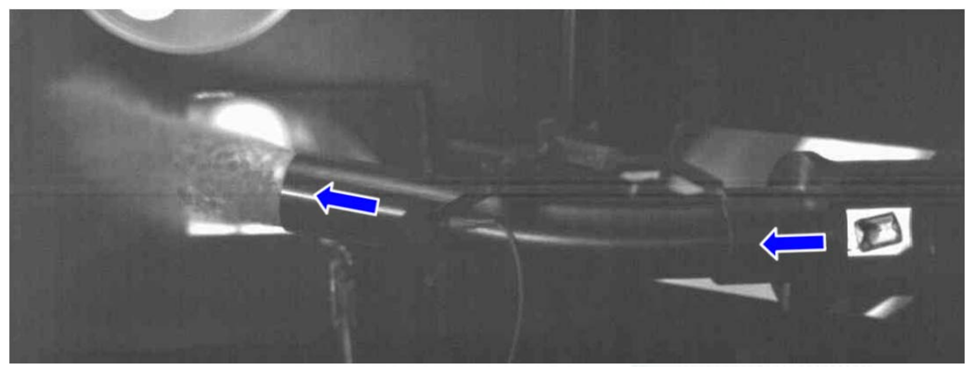
Outline

- SPI overview
- SPI Deployment on DIII-D, JET, KSTAR
- JET experimental capabilities
  - JET SPI disruption experiments to start in December
- ITER DMS Technical Issues Remaining for SPI
  - Propellant gas removal
  - Simultaneous injection
  - Shallow impact effects (Trey Gebhart)
  - Punch development and testing (Trey Gebhart)

SPI designs have been developed for ITER and deployed on DIII-D and now on JET



- **Barrel inner diameter can vary for different target plasma conditions.**
- **SPI uses MGI like gas valves to accelerate pellets.**
- **D_2, D_2/Ne, Ne*, Ar* are possible**



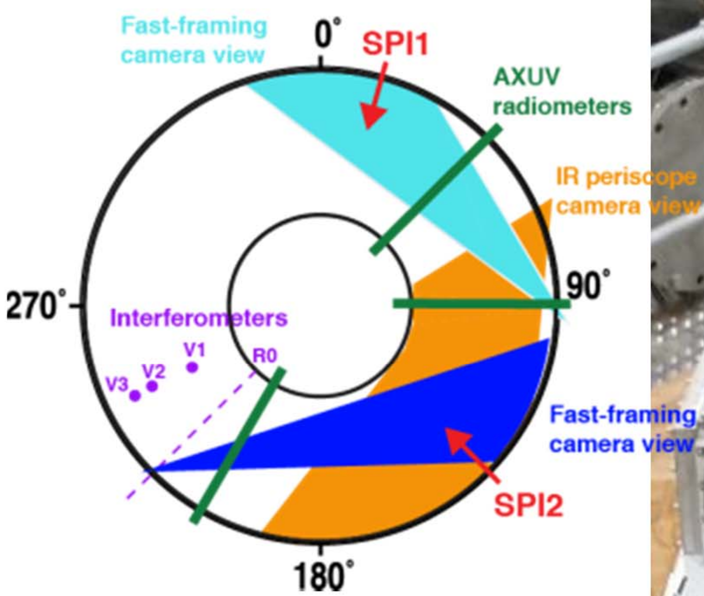
More abrupt injection than MGI, easy to reload, No possible damage and no debris

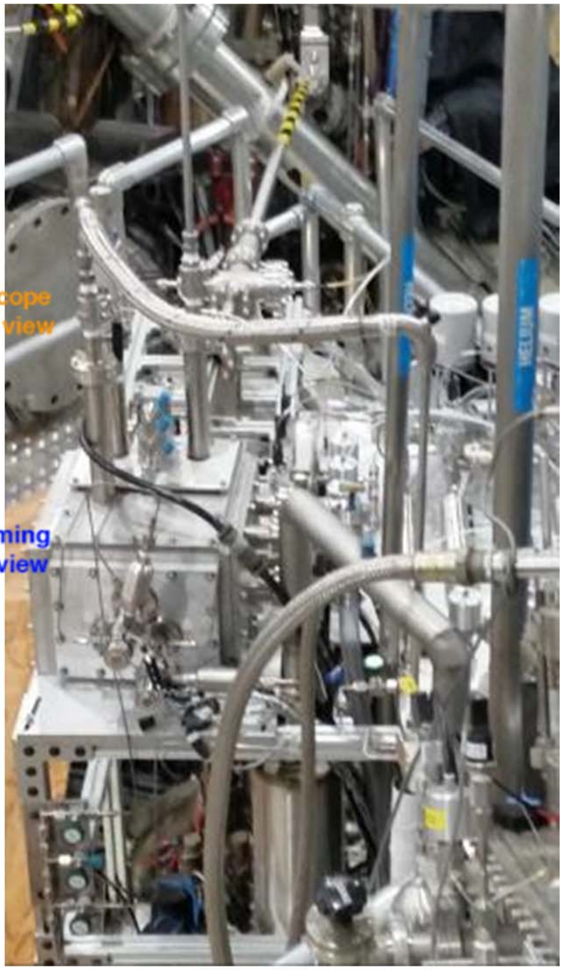
* Mechanical punch required

Outline

- SPI R&D overview
- SPI Deployment on DIII-D, JET, KSTAR*
- JET and KSTAR SPI experimental capabilities
  - JET SPI disruption experiments to start in December
- ITER DMS Technical Issues Remaining for SPI
  - Propellant gas removal
  - Simultaneous injection
  - Shallow impact effects (Trey Gebhart)
  - Punch development and testing   (Trey Gebhart)

Two SPI systems installed on DIII-D to help answer key questions for ITER





SPI1 first used in 2010.   SPI2 was installed on DIII-D in 2017.
Experiments utilizing both SPIs are under way. (N. Eidietis)

Early propellant gas in SPI2 found to be an issue to be resolved.

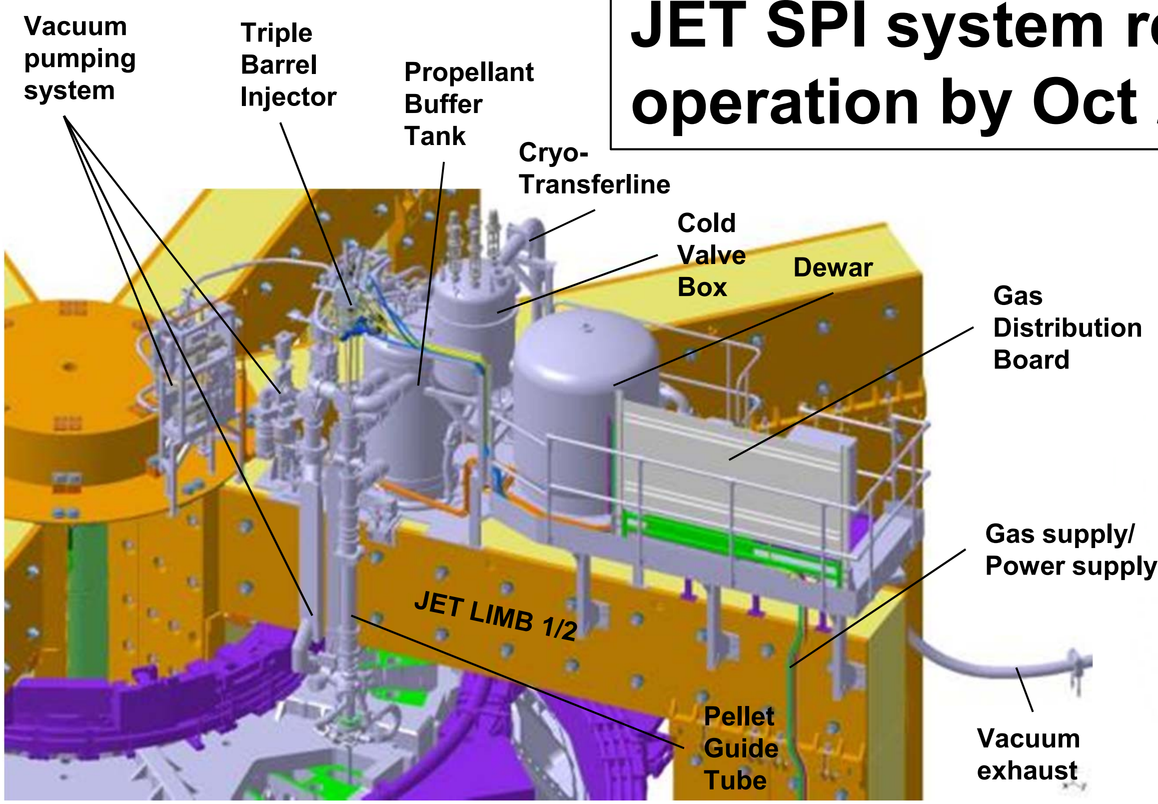
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

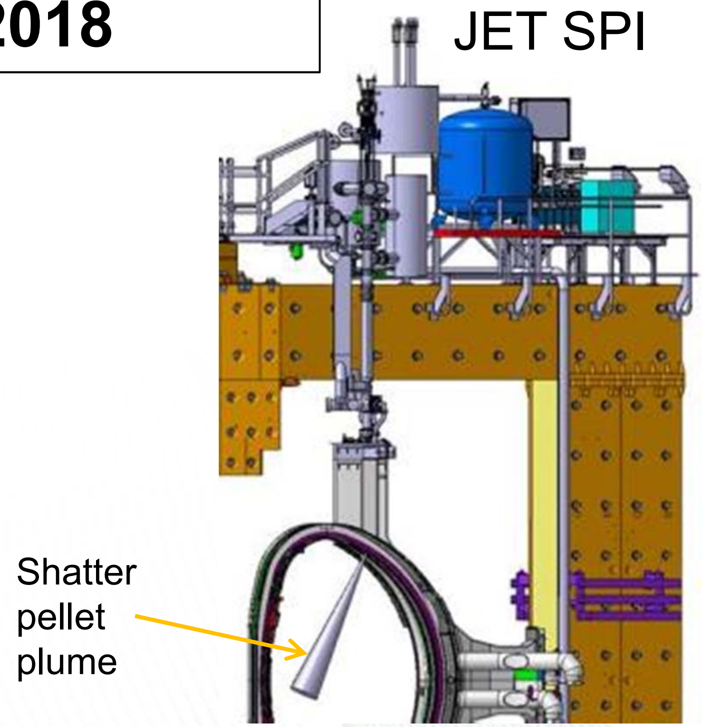
OAK RIDGE National Laboratory

SPI installation progress at JET

- Very large system with significant integration issues **(Resolved)**
- Technological difficulties (pellet punch concept etc., cryogenic infrastructure, weld verification) **(Resolved)**
- Installation ongoing, to be completed by September…

JET SPI system ready for operation by Oct 2018





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

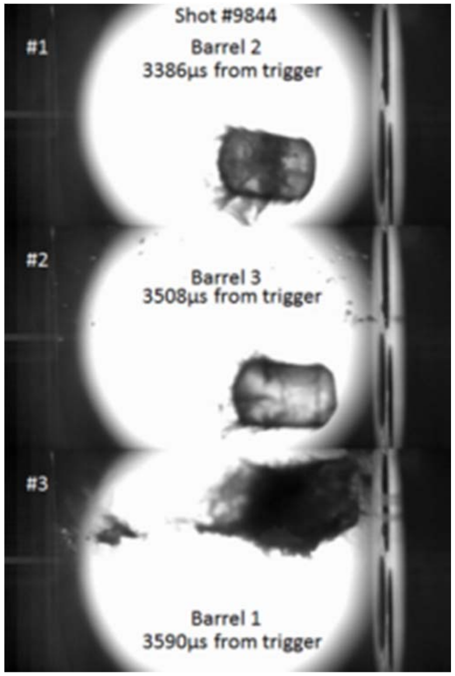
SPI Installation on JET

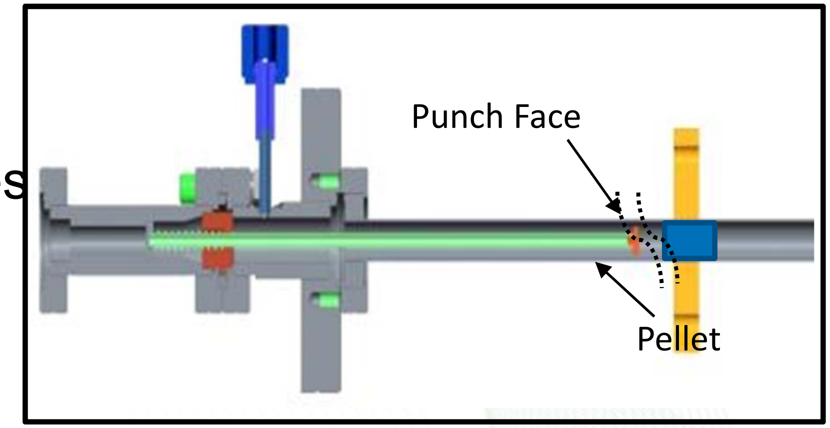
JET SPI successfully commissioned at ORNL and shipped Nov. 2017

JET SPI now mounted vertically on the machine awaiting connections to vacuum and cryogenics.

JET SPI capabilities

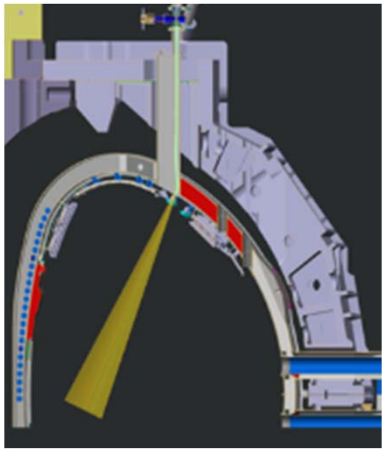
- Three pellets of different sizes
  - D_2/Ne/Ar or D_2/Ne mixture or shell
  - ~0.1 bar.L to 6 bar.L (10^{21} – 10^{23}) per pellet
  - 12.5*, 8, 4 mm sizes - *argon punch
- Independent firing
- Pellet speed ~100–250m/s (max 500m/s with pure D_2)
  - flight time ~20-50ms
  - Punches provided for large pure Ar or Ne 12.5 and 8mm sizes
  - Plasma edge arrival time predictable to <2 ms



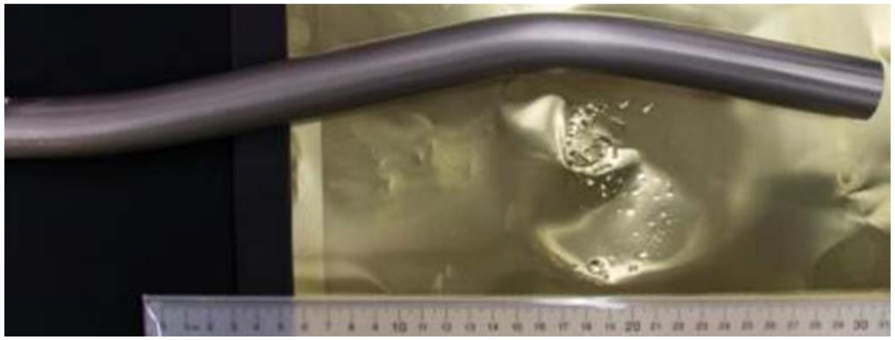


Punch Schematic

JET SPI capabilities



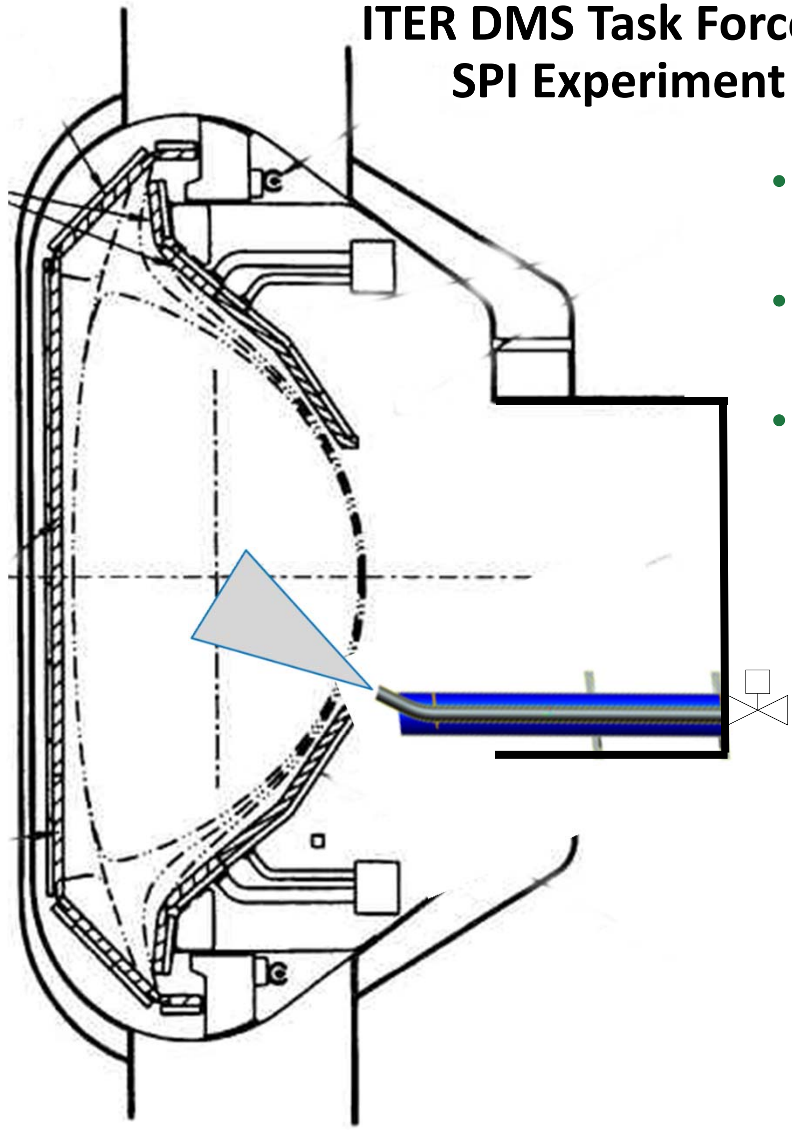
- Shatter cone facing High Field Side
  - 20 degree bend in injection tube pointed to HFS
  - Intercept/disperse REs created by DMV3
- Tube geometry: results in good collimation of ~20 degrees
  - Slow pellets with punch found to result in large fragments, useful for better penetration (T. Gebhart, to pe published).

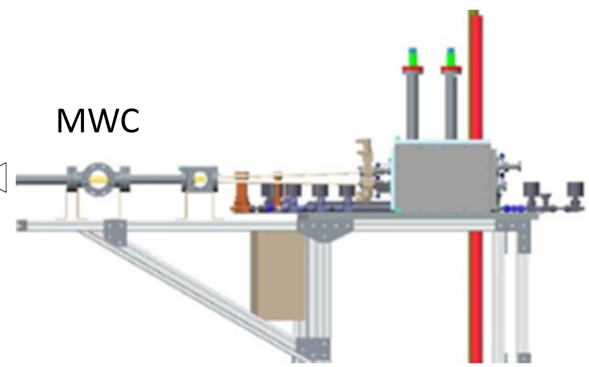


Proposed SPI Configuration on KSTAR

ITER DMS Task Force to be Involved in a KSTAR SPI Experiment that is Being Proposed

- **SPI shatter tube fits inside midplane port with bend just before entering the plasma**
- **Midplane configuration mimics the ITER equatorial port plugs**
- **Dual SPIs on opposite sides of KSTAR are proposed. (S. Park, J. Kim, NFRI)**





Outline

- SPI R&D overview
- SPI Deployment on DIII-D, JET, KSTAR
- JET SPI experimental capabilities
  - JET SPI disruption experiments to start in December
- ITER DMS Technical Issues Remaining for SPI
  - Propellant gas removal
  - Simultaneous injection
  - Shallow impact effects (Trey Gebhart)
  - Punch development and testing (Trey Gebhart)

JET SPI Experimental Plans (33 sessions to start in Dec 2018)

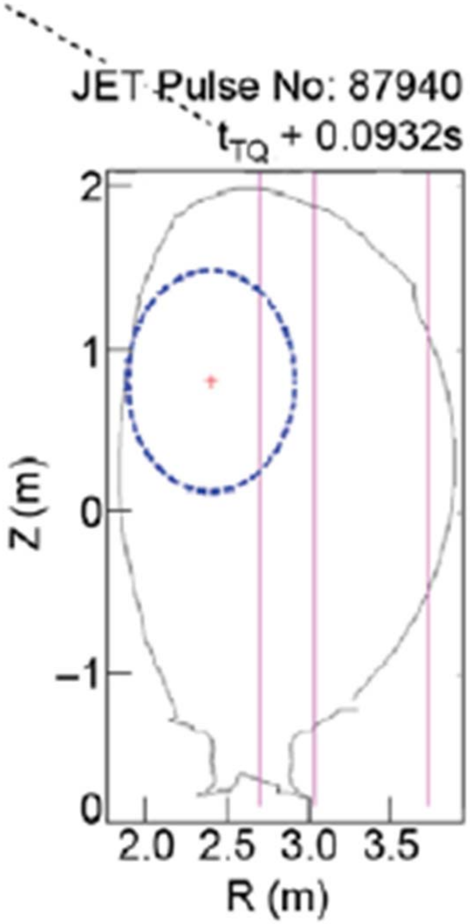
Thermal Mitigation – Small pellet sizes

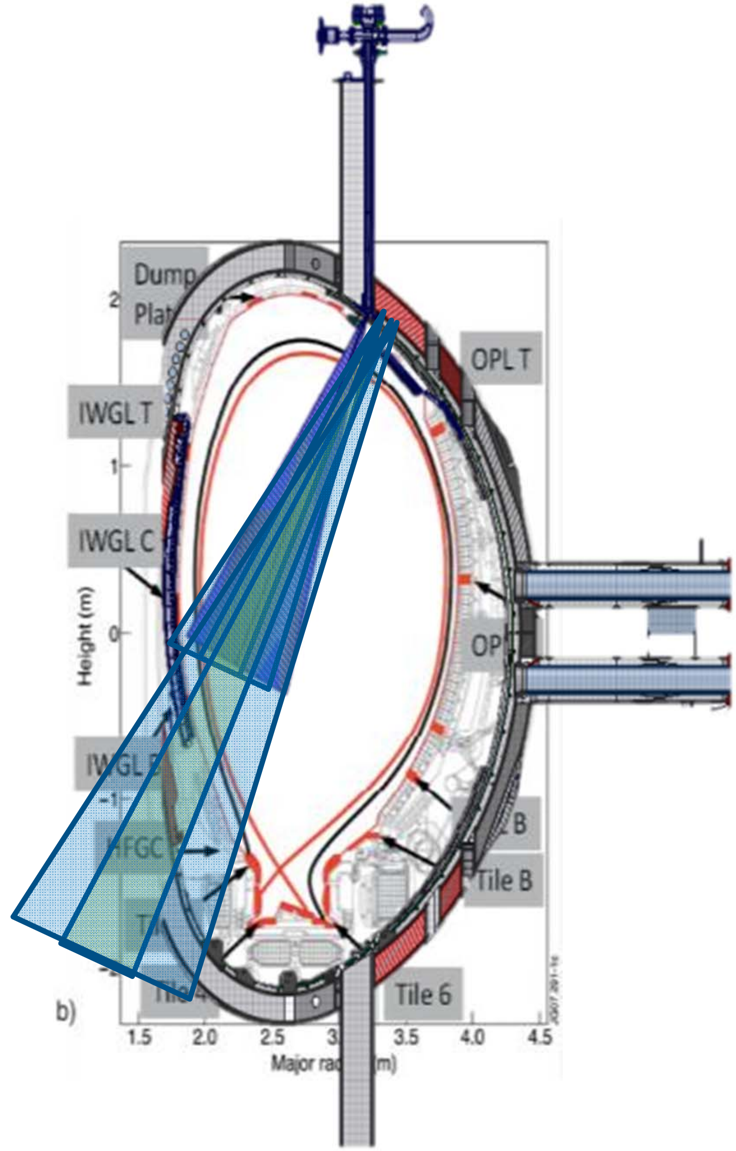
- Optimization of D2/Ne mixture
  - May need punch for small pellet size to vary pellet speed

- 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

JET SPI Aimed to Intercept Known Path of RE Beam





JET SPI Experimental Plans

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

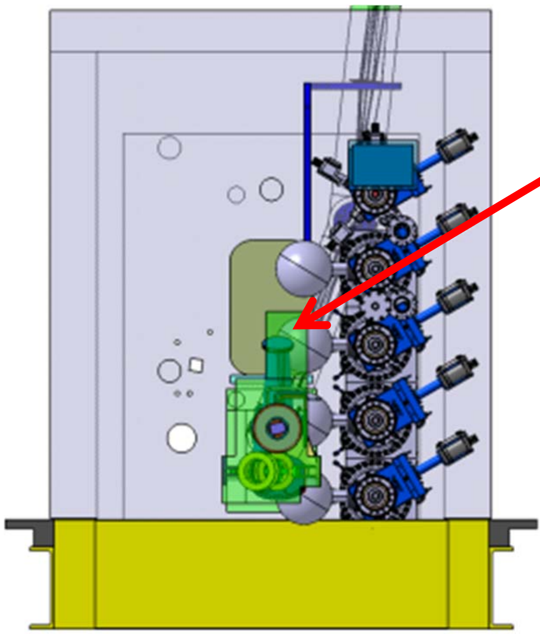
- RE Avoidance – D2/Ne mixtures, possible Ar-D2 layer pellets

Outline

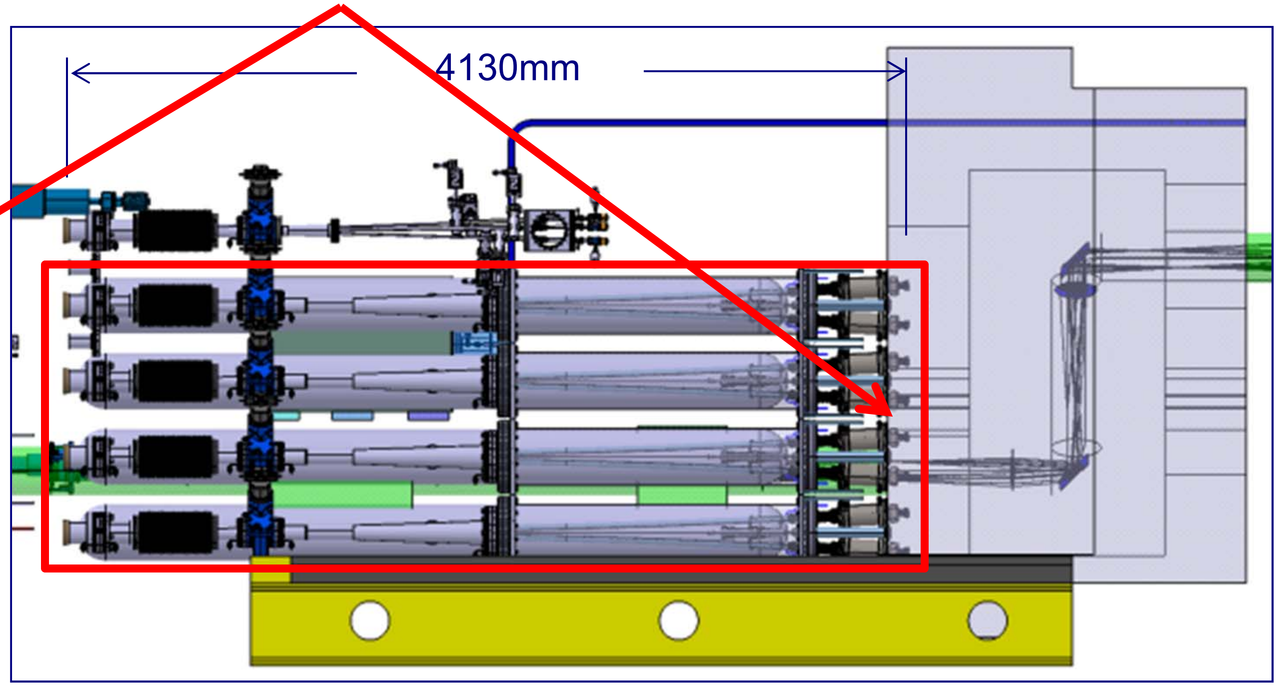
- SPI R&D overview
- SPI Deployment on DIII-D, JET, KSTAR
- JET SPI experimental capabilities
  - JET SPI disruption experiments to start in December
- ITER DMS Technical Issues Remaining for SPI
  - Propellant gas removal
  - Simultaneous injection
  - Shallow impact effects (Trey Gebhart)
  - Punch development and testing (Trey Gebhart)

Pre2018 DMS Design Equatorial Port – RE System

Pre2018 design interferes with other diagnostics and shield block – multiple funnels needed



Front View

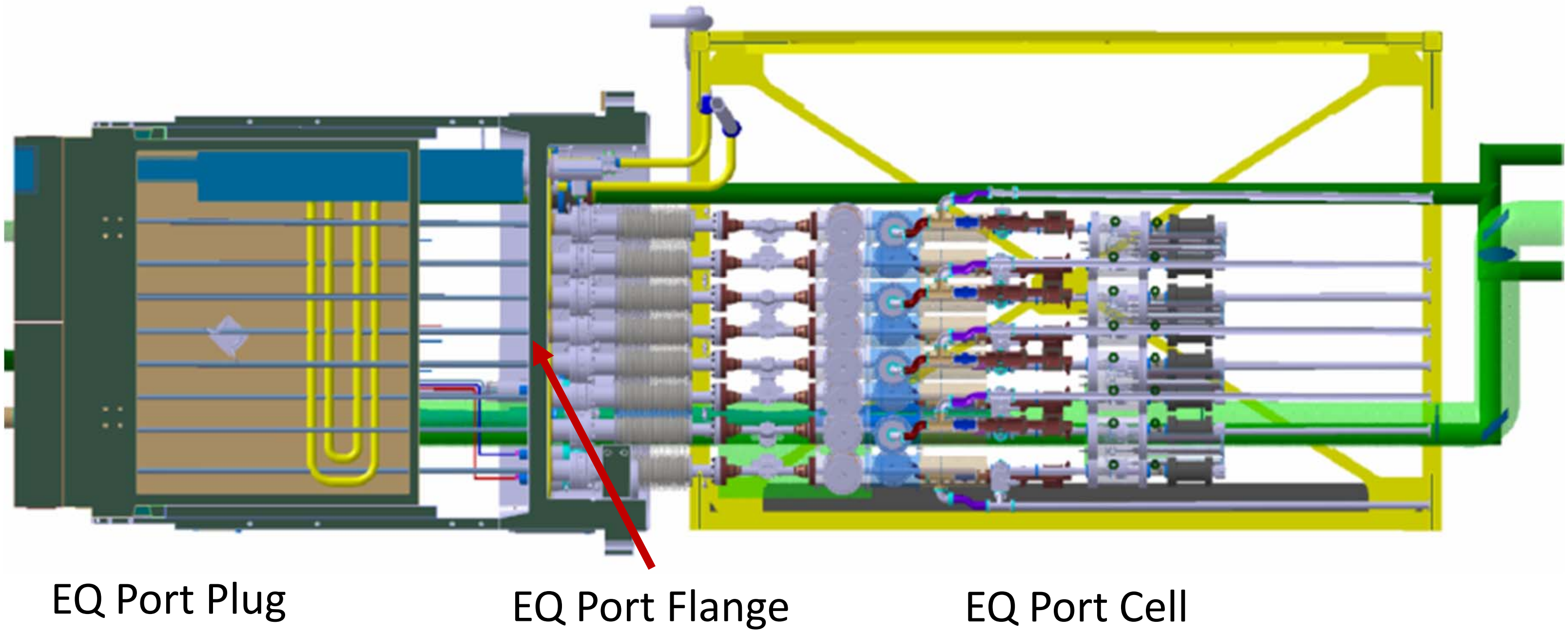


Side View

16 pellets total: 2 for TLM, 14 for RES

Not shown: transport through port plug

2018 Design Single Barrel SPI's Now Fit in EQ Port Cells



So now it fits, but only 8 barrels can be put in Port 8. Funnel still required to compensate for thermal motion.

In order to compensate for the loss of barrels more injection locations are required.

For UPPs, results in a loss of flexibility in pellet size.

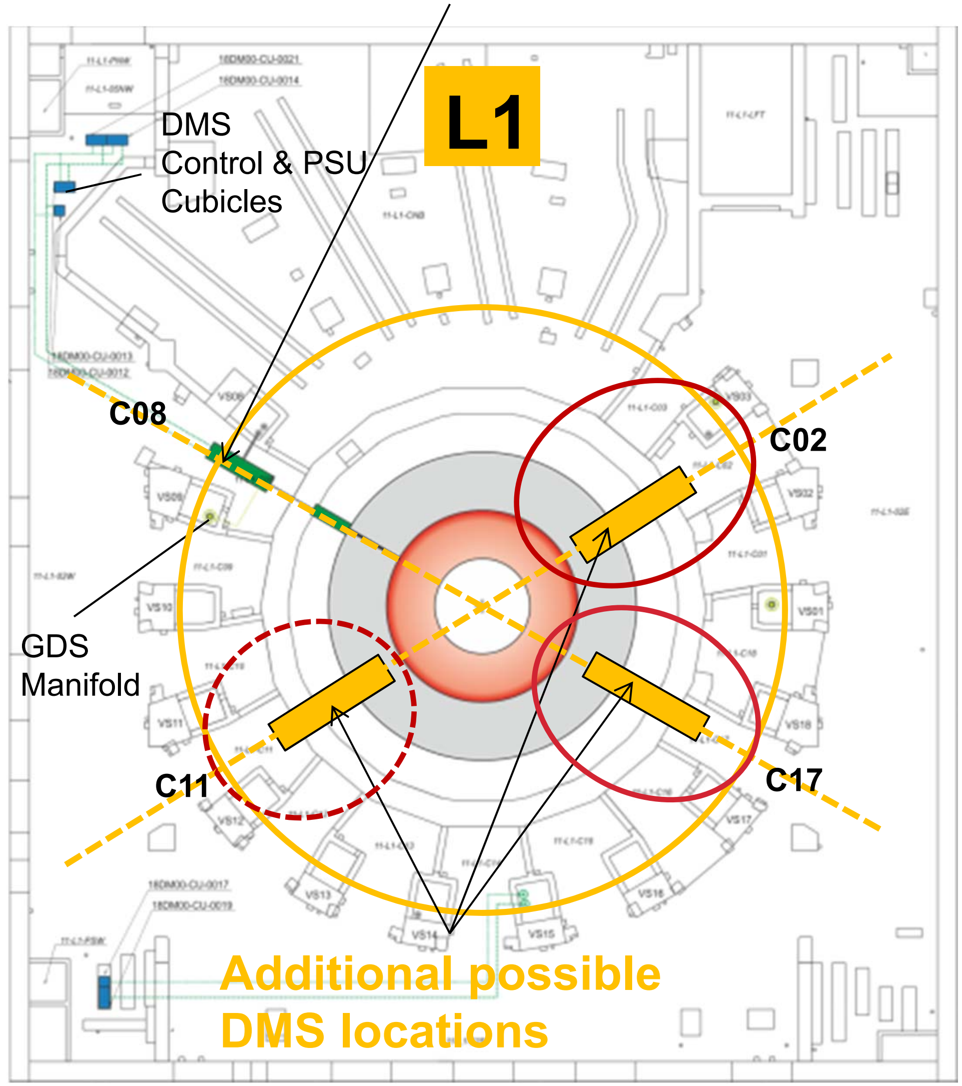
Assessment of port plug allocation

Current DMS Baseline
1 location with TLM and RES in L1 PC08 with a *total of 16 barrels*
(32 required for RE avoidance -> 4 locations)

Additional equatorial port plugs needed to ensure sufficient capability of the DMS

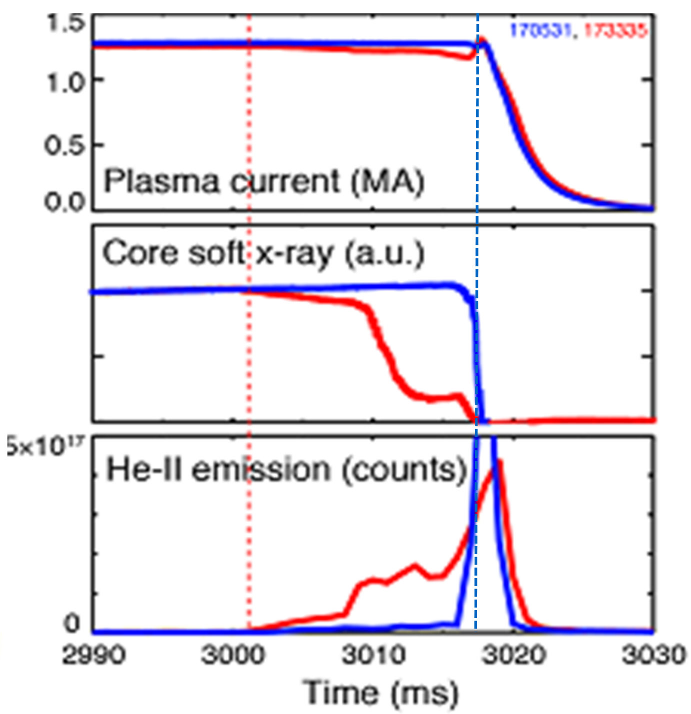
- **Requires distribution of DMS gas supply on L1 and L2 for current DMS and future DMS implementation.**
- **Requires distribution of cryogenic supply to equatorial port plugs on L1. (Urgent need to procure cryolines)**
- **Requires control cubicles and fast valve power supplies in the vicinity.**

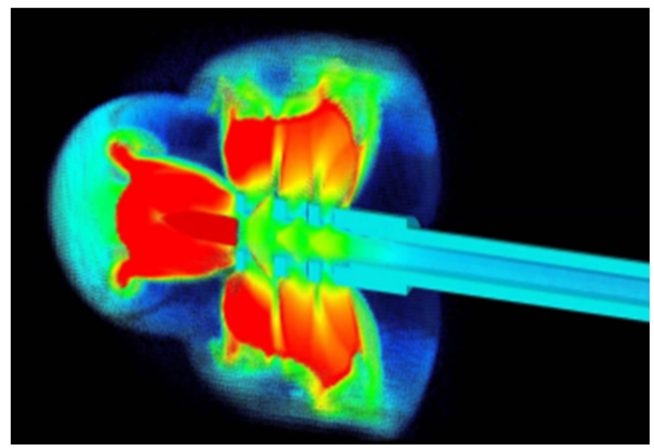
Current DMS Baseline System on L1



SPI Propellant Gas Dispersion Requires Careful Design

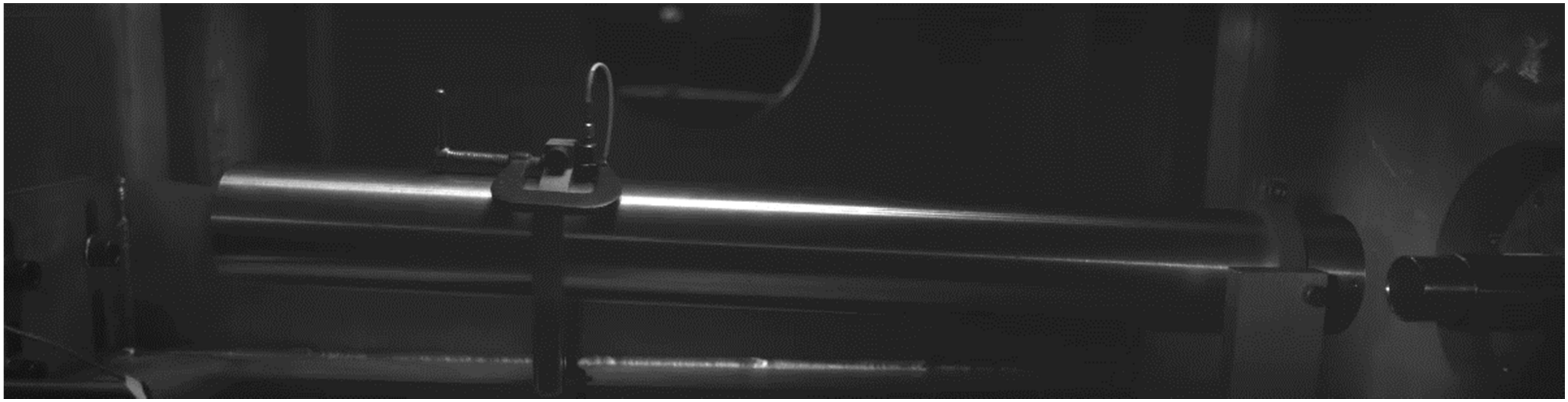
- Propellant gas is faster than the pellet – needs to be diverted and removed
  - Otherwise resulting in thermal quench before pellet fragments arrive
  - SPI2 on DIII-D has this issue, muzzle brakes being redesigned

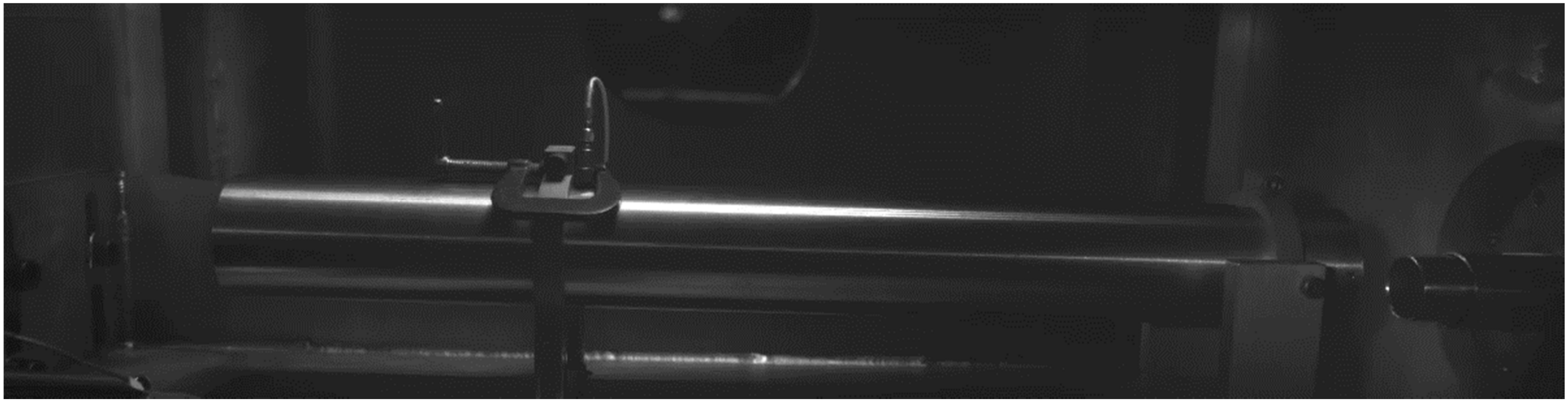




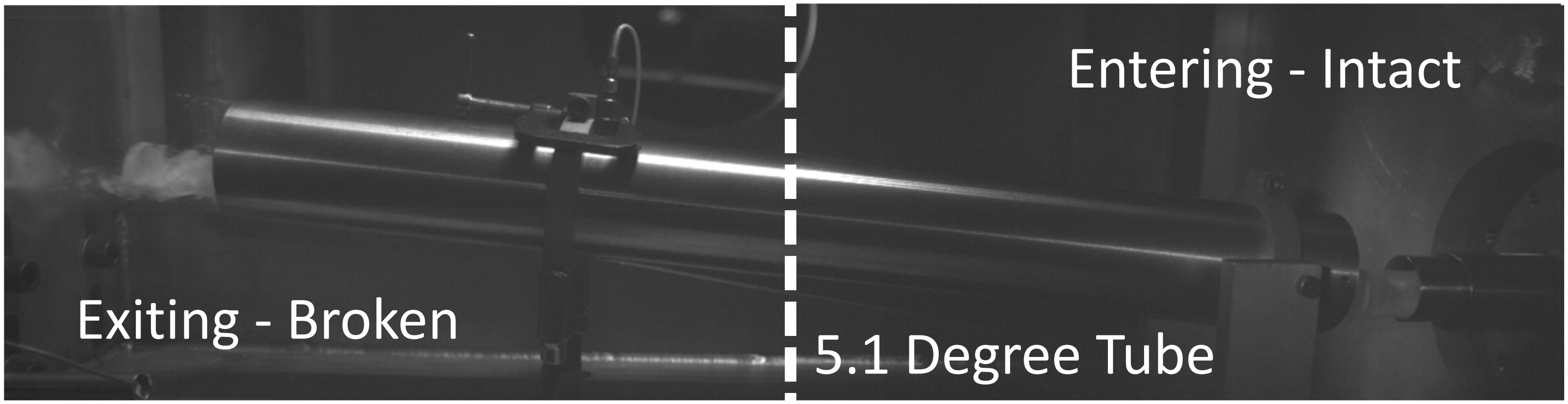
ITER design will require CFD analysis to verify brake performance

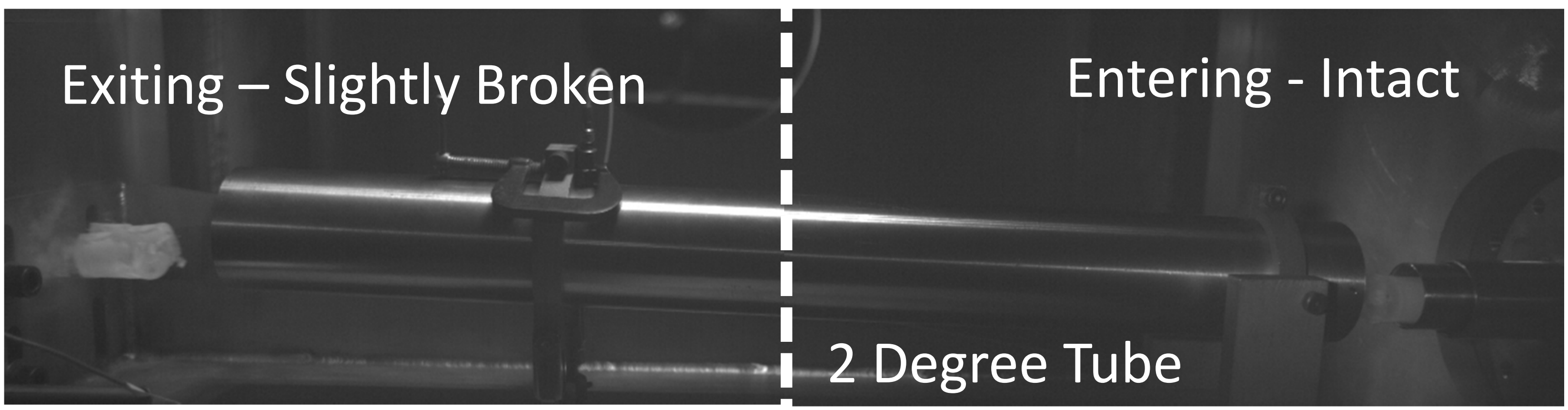
Low angle impacts of large neon pellets have been tested at ORNL.





Low angle impacts of large neon pellets have been tested at ORNL.





Shallow angle funnels required to maintain intact pellets

Dislodging and accelerating high-Z materials continues to be a challenge due to material properties at low temperatures

	Deuterium	Neon	Argon
Triple Point Temperature	18.6 K	24.6 K	83.8 K
Heat of Sublimation	1150 J/mol	2107 J/mol	7740 J/mol
Ultimate Tensile Strength (Temp)	4.4 Bar (8 K)	7.5 Bar (8 K) 5.1 Bar (20 K)	15.7 Bar (15 K) 11.4 Bar (55 K)
Crystal Structure	HCP	FCC	FCC
Density	0.2 (g/cm^3)	1.44 (g/cm^3)	1.62 (g/cm^3)
Cohesive Strength	34.7 (MPa)	93.5 (MPa)	215.7 (MPa)

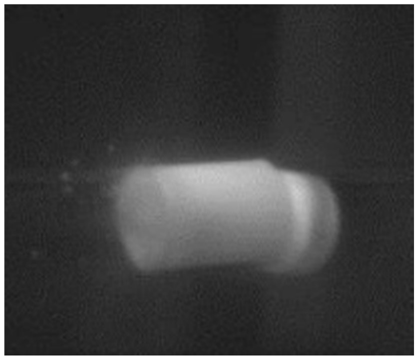
Theoretical Breakaway of 28.5 mm Pellet:

D_2 at 8 K – 35.2 bar (510 psi)

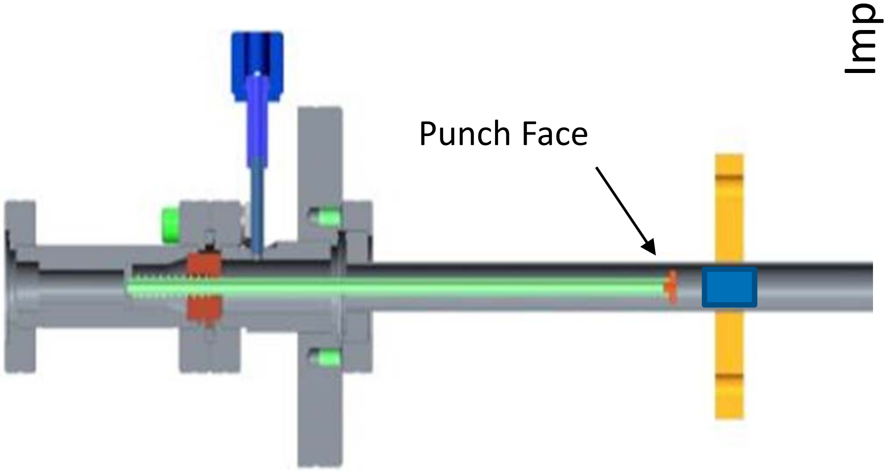
Ne at 8 K – 60 bar (870 psi)

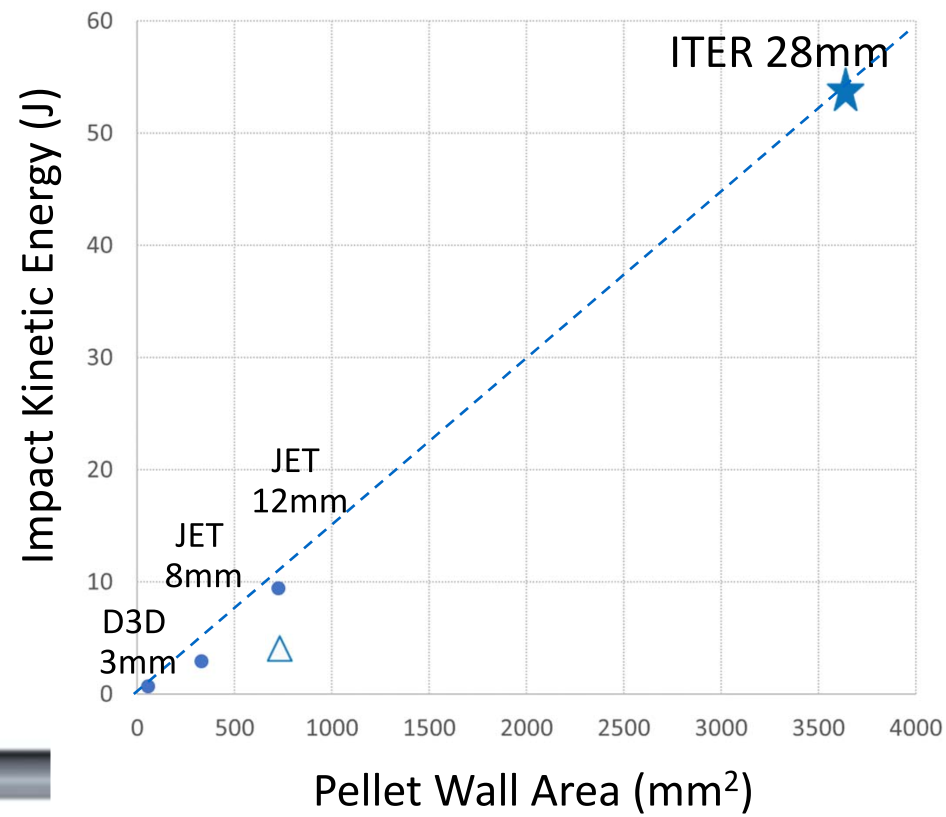
Ar at 55 K – 91 bar (1323 psi)

SPI Punch Design Critical for Argon Pellet Acceleration - RE Mitigation



Argon pellet release requires significantly more impact energy than gas alone can provide

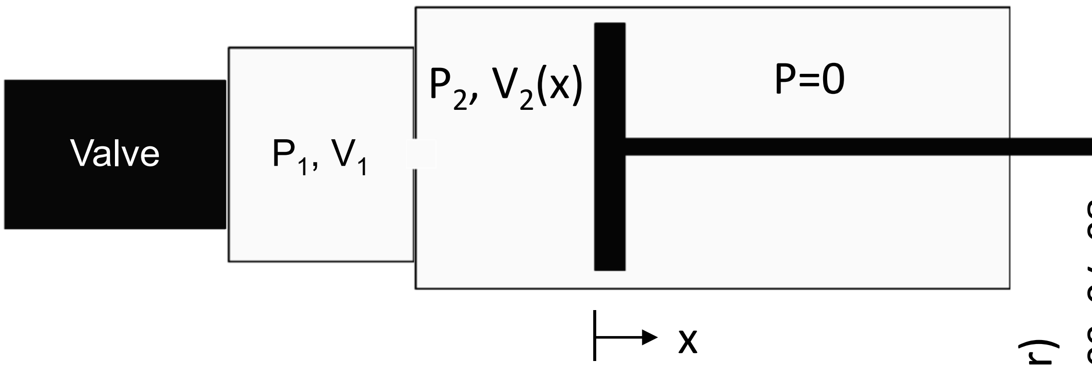


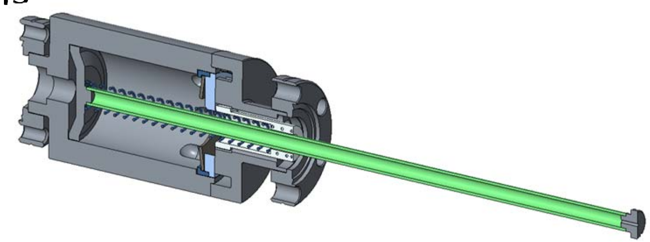


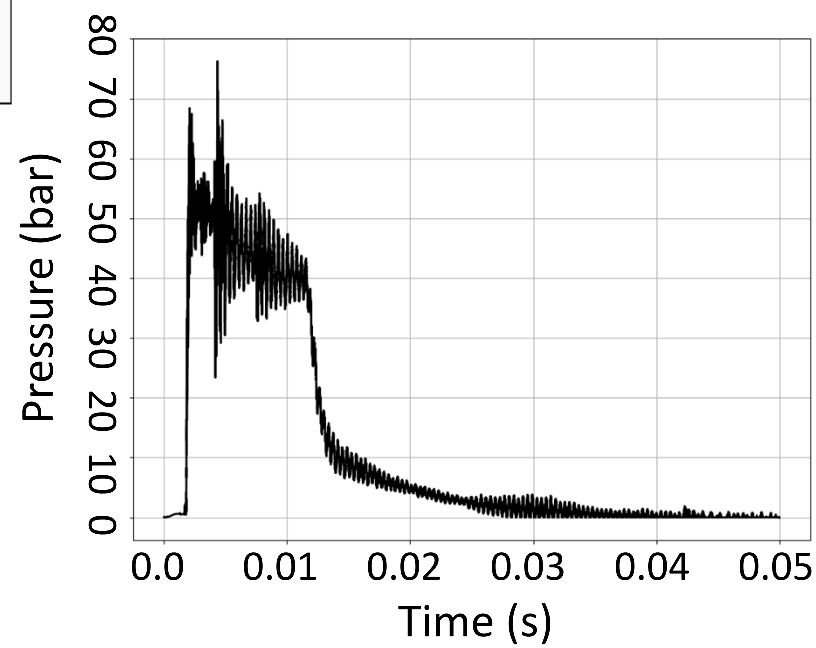
OAK RIDGE National Laboratory

Simulation of punch dynamics serves as a useful tool to estimate KE of the punch.

System dynamics approach to punch movement
- Pressure/Gas jet as main driving forces
- Spring resistance and piston leakage are main loss terms







P_1 is experimentally measured

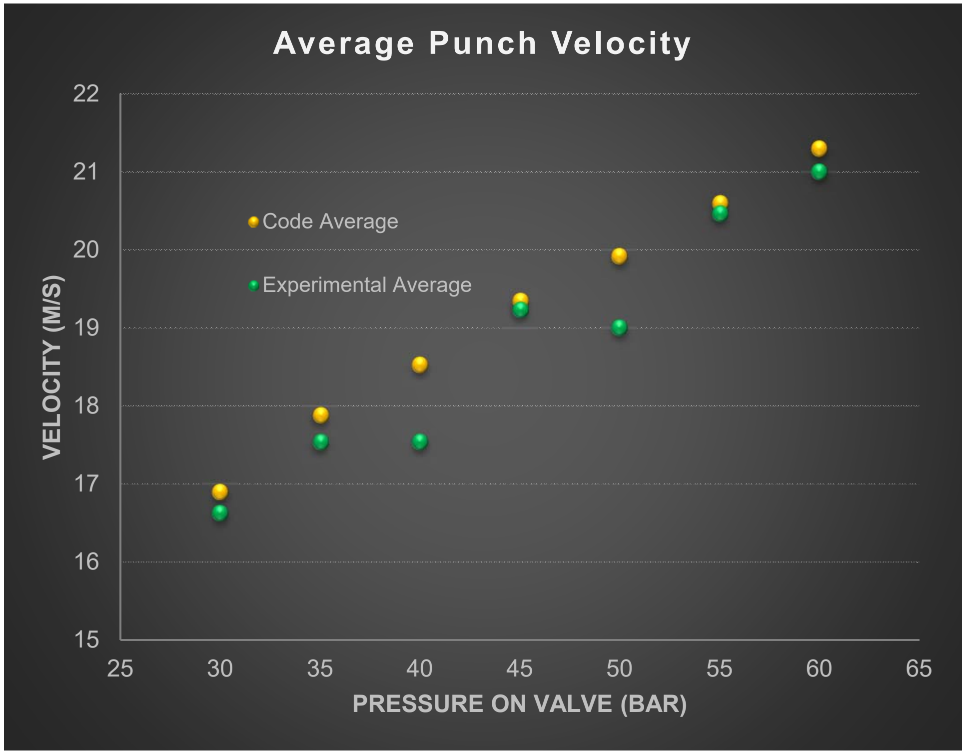
$$V_2 \frac{dP_2}{dt} = Q_{Orifice}(P_1 - P_2) - Q_{Piston\ Leakage} P_2$$

$$m_{Punch} \frac{du}{dt} = P_2(t) A_{Punch} - K(x + d) + F_{Gas\ Jet}$$

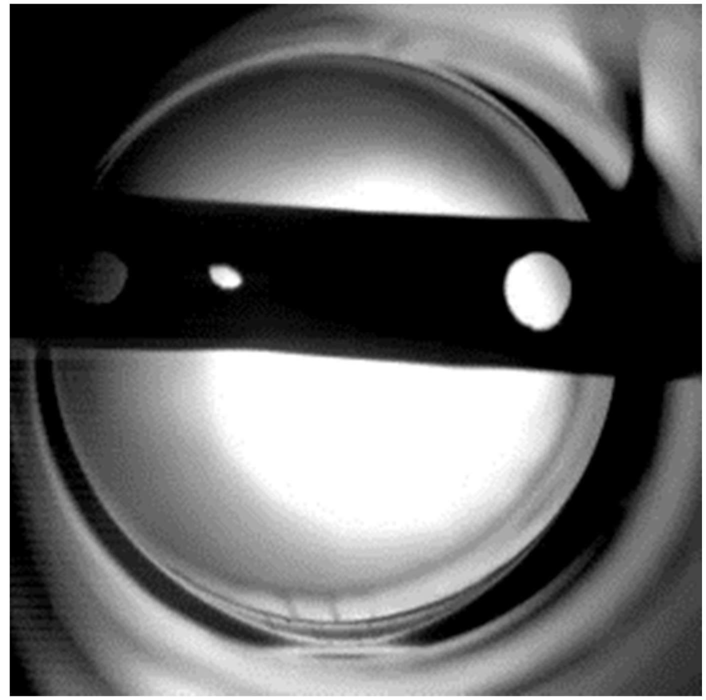
$$\frac{dx}{dt} = u$$

The code was validated using high-speed imaging of the punch in motion.

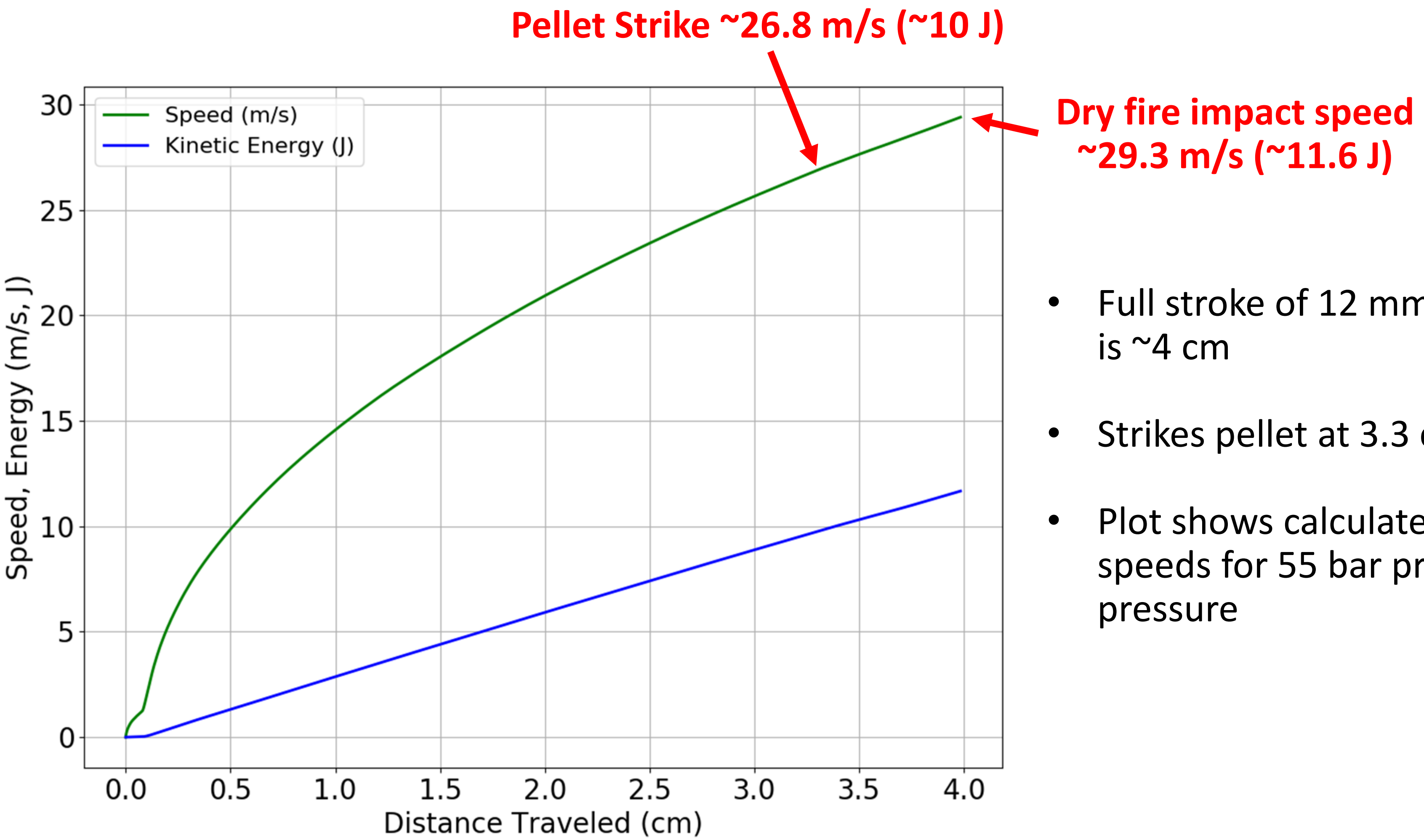
No-Pellet “Dry-Fire” Velocities



Velocities agree within 5%



The code calculates punch velocity and kinetic energy throughout the whole stroke

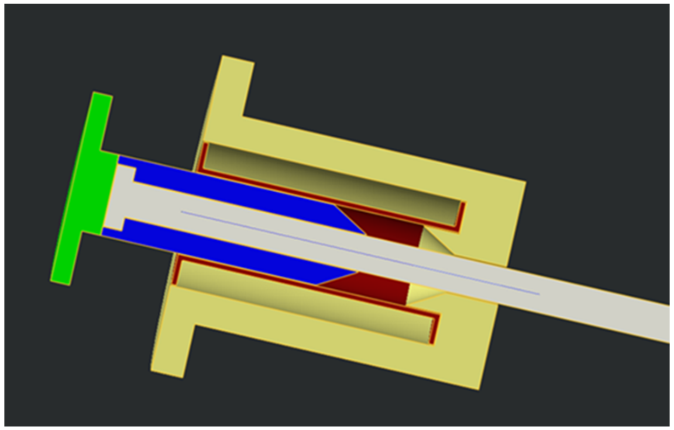


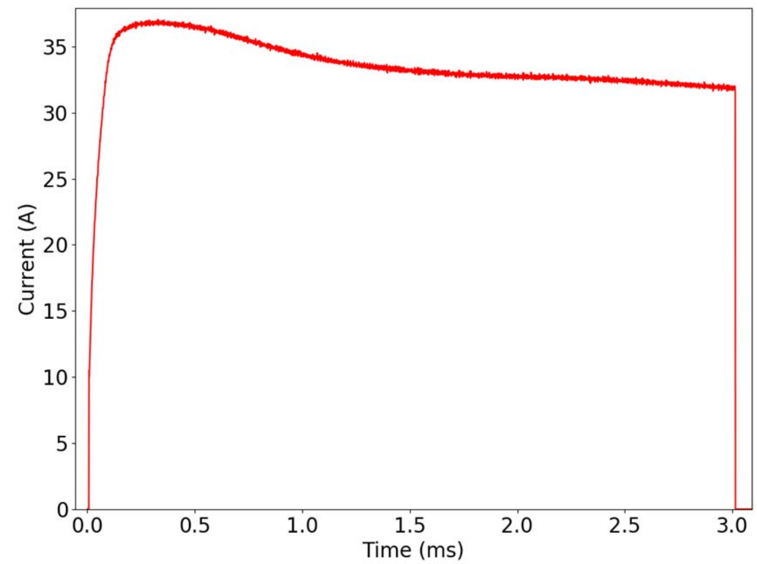
- Full stroke of 12 mm punch is ~4 cm
- Strikes pellet at 3.3 cm
- Plot shows calculated speeds for 55 bar propellant pressure

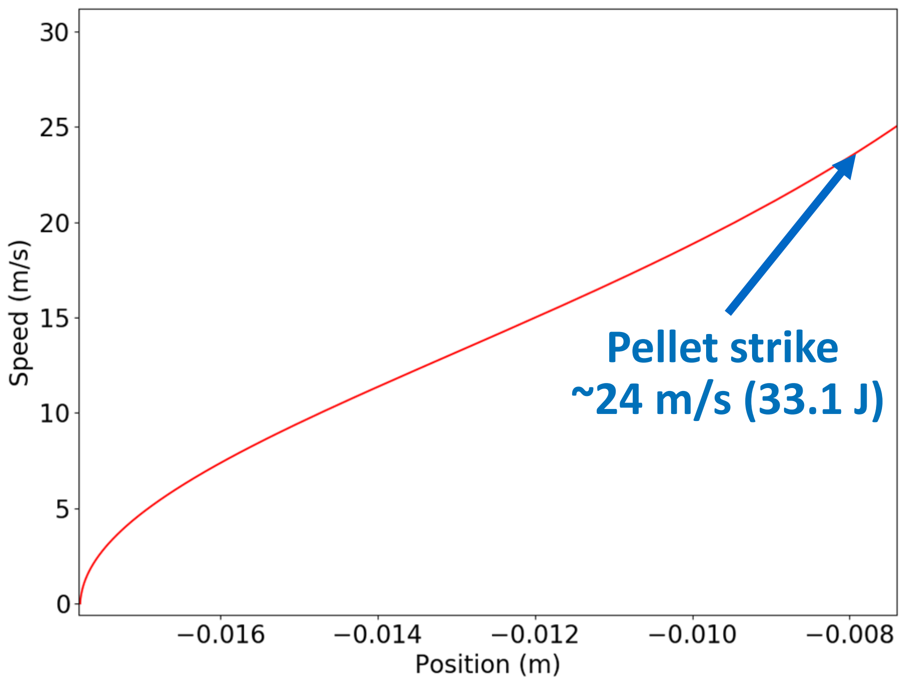
Promising results from testing most recent iteration of mechanical punch

- Punch has survived 270 shots at 50 bar propellant pressure

Solenoid operated punches are being designed to test to range of KE needed for ITER size pellets







A simulation of solenoid dynamics predicts the speed of the punch through the stroke.

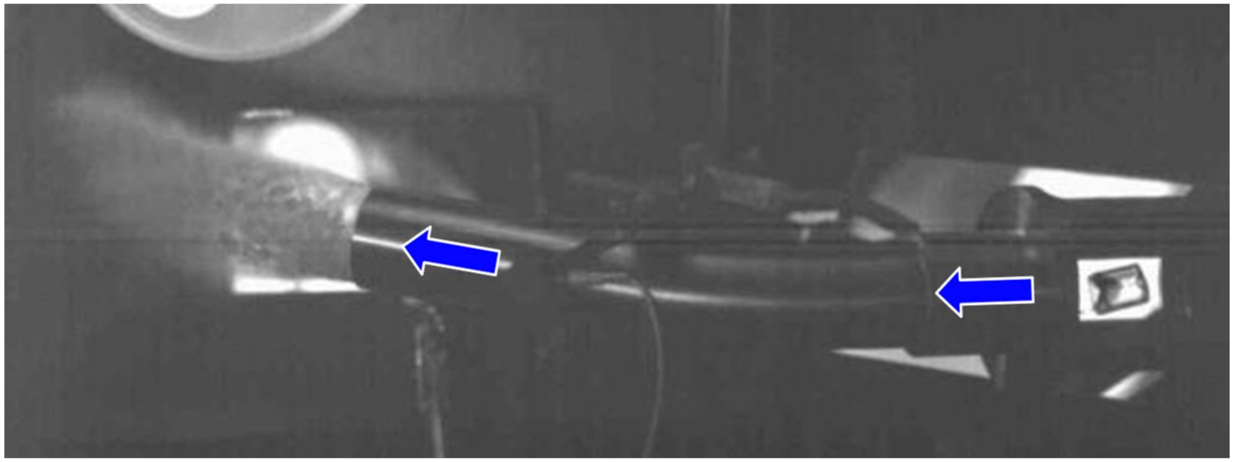
This simulation was validated using high speed imaging of an existing solenoid plunger.

Summary

- SPI now installed on JET for experiments starting in late 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
- Future KSTAR SPI collaboration under discussion now as part of ITER DMS Task Force.
- SPI R&D is needed to quantify shattering and verify capabilities for ITER configurations.

Backup Slides

Shattered Pellet Injection Developed for ITER DMS has Remaining R&D Needs



Neon Pellet in 20^{o} Shatter Tube

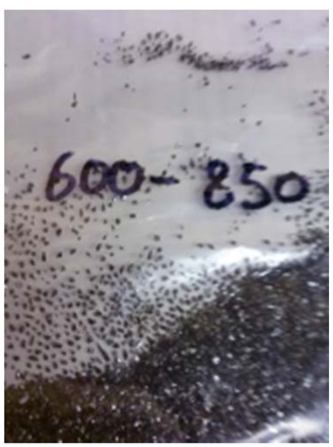
S. Combs SOFE 2015

- Shattering optimization - high solid fraction desired
- Simultaneous injection – low jitter desired
- Efficient propellant gas removal
- Shallow Impact angles from Injection line funnels
- Pellet mechanical impact release of pure argon and neon pellets

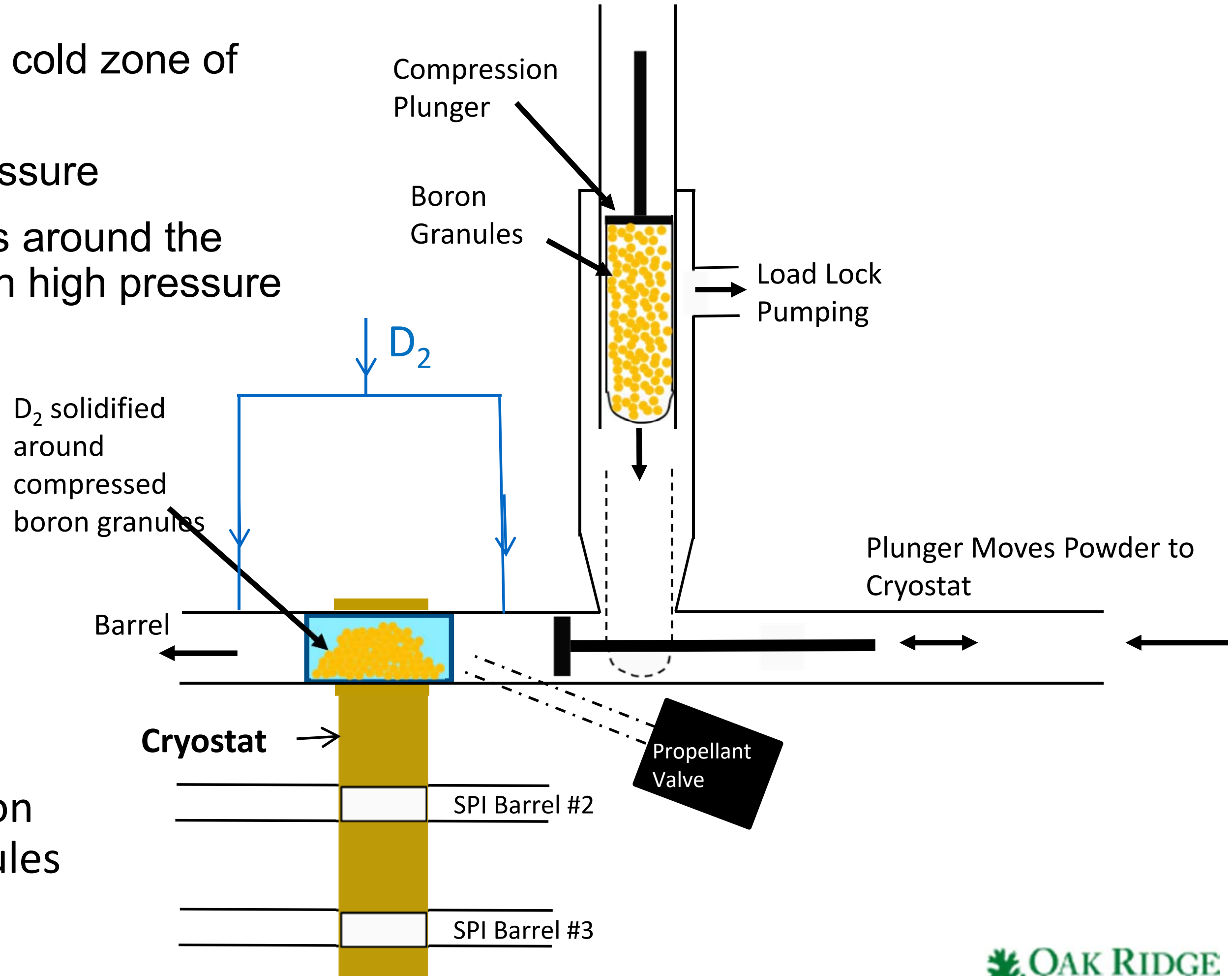
SPI Low-Z Granule Concept for KSTAR SPI RE Suppression (Avoidance) Studies

- One Barrel of the SPI is Modified to add a Boron Granule Feed Mechanism
  - Boron loaded into the cold zone of the barrel
  - D_2 is fed in at low pressure
  - A solid D_2 pellet forms around the Boron and is fired with high pressure gas

Derived from Be injection proposal by Konalov

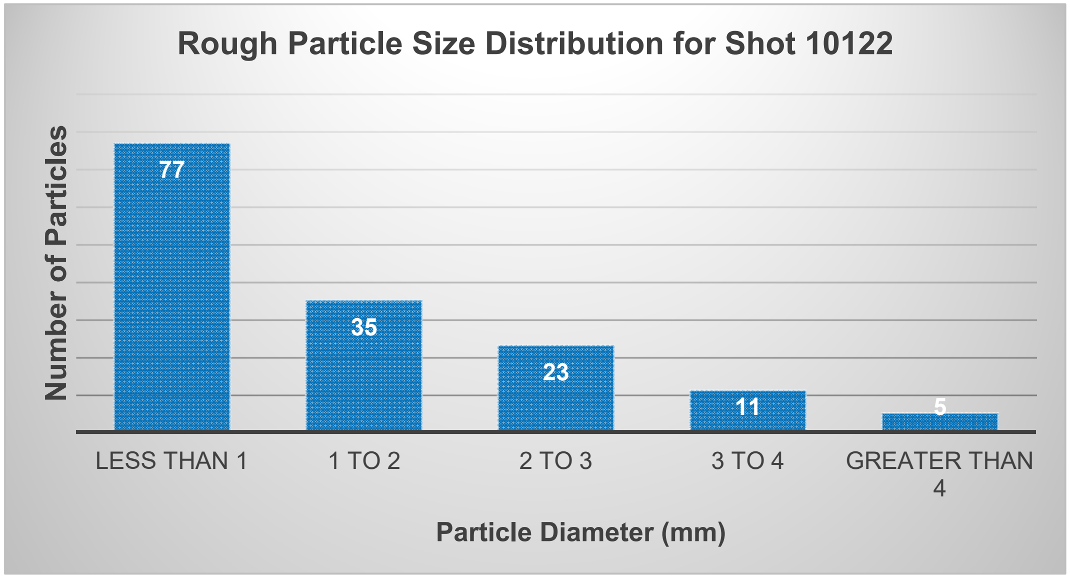


Boron Granules

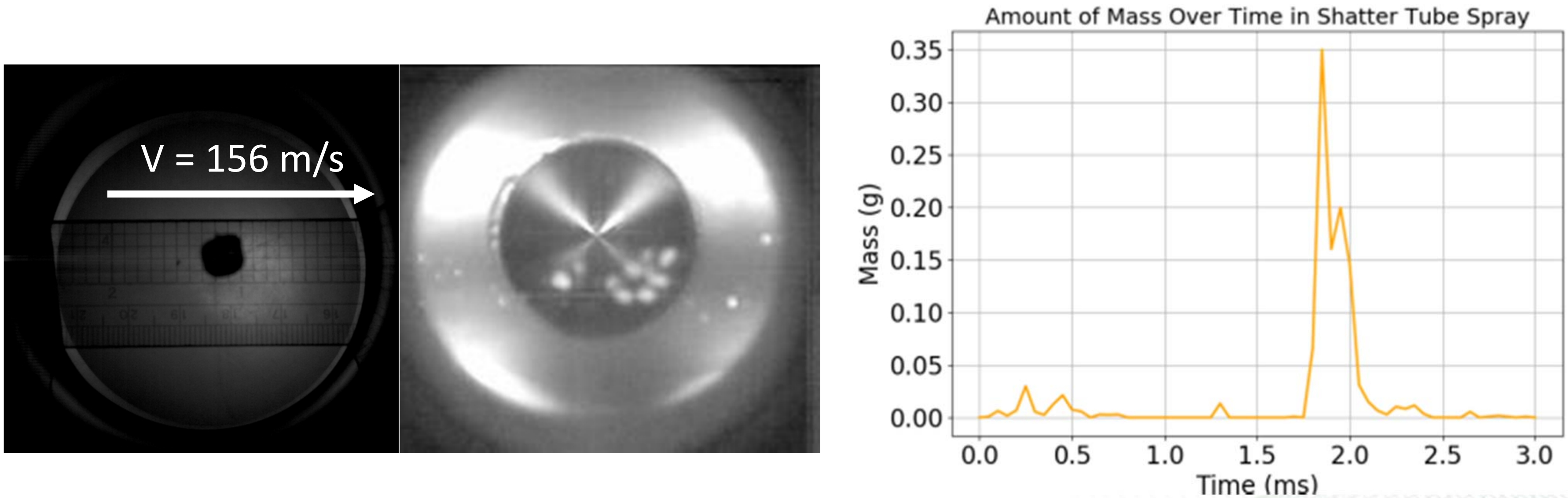


A typical Argon SPI post-shatter particle size distribution determined from the fast camera data

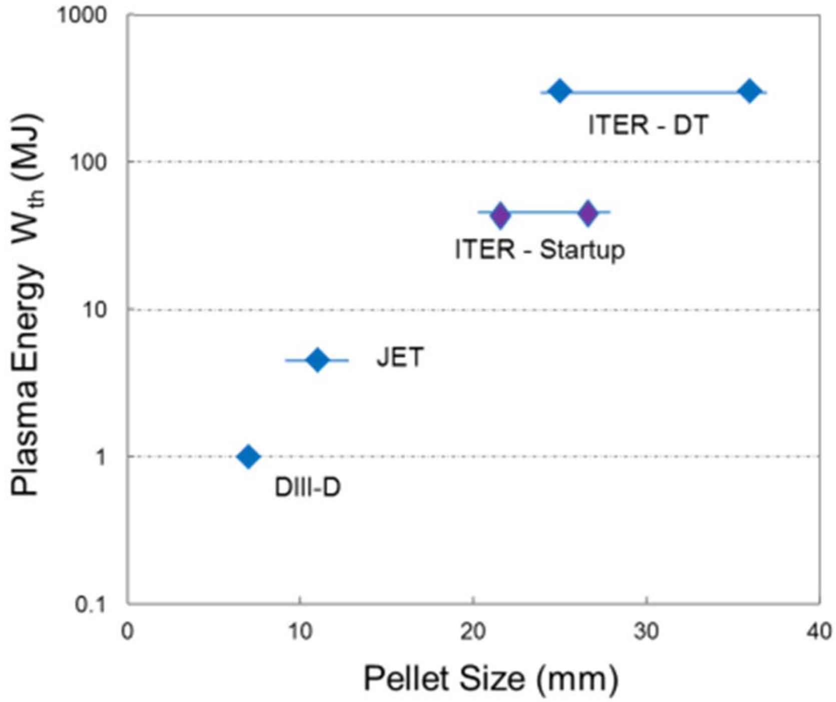
- Argon formed at 30 K
- 650 mbar L of Ar
- L/D = 1.51
- Fired at 55 K
- Speed = 156 m/s
- Mass of Pellet = 1.18 g
- Mass of Particles = 1.14 g

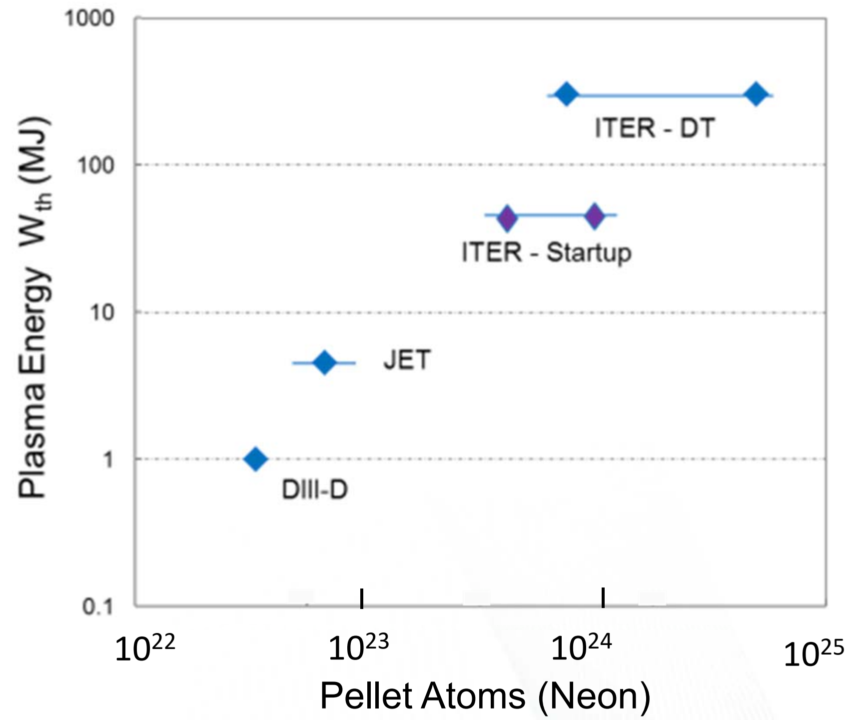


T. Gebhart, 2017

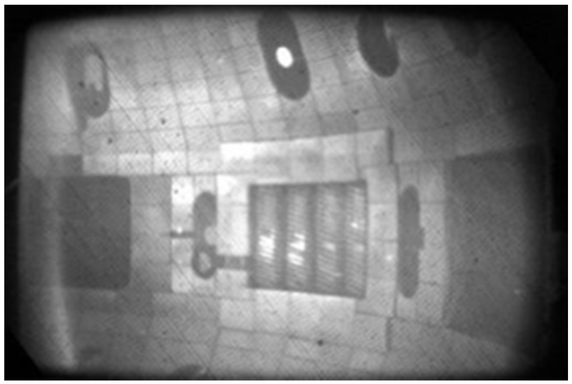


JET provides extrapolation toward ITER and future fusion system energy dissipation needs





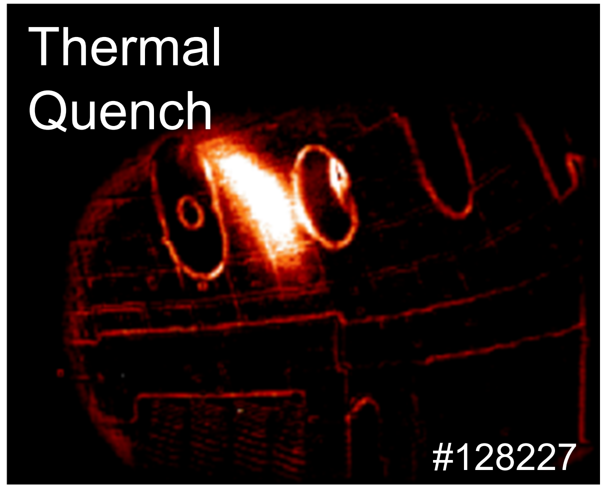
Shattered Pellet Injection (SPI) shows benefits over Massive Gas Injection (MGI) – only used on DIII-D

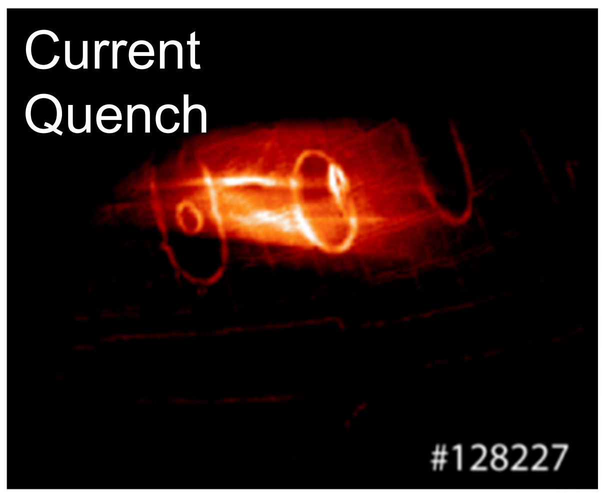


“normal” view using the fast framing camera

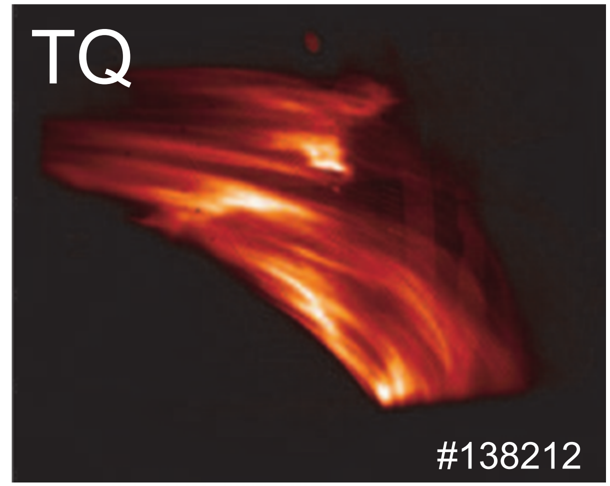
Commaux, et al., Nucl. Fus. 2011

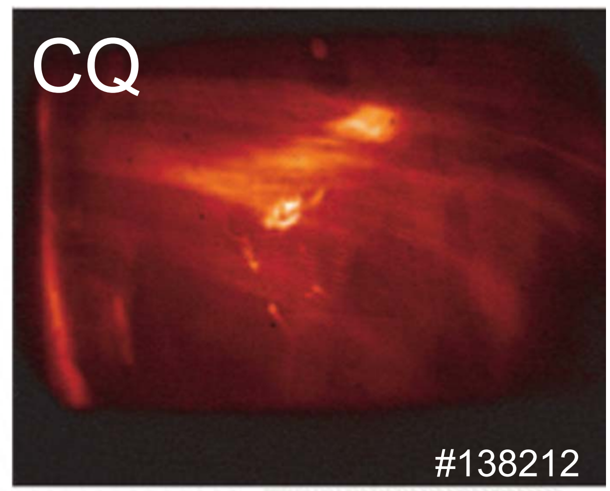
MGI





SPI





Fast visible camera images