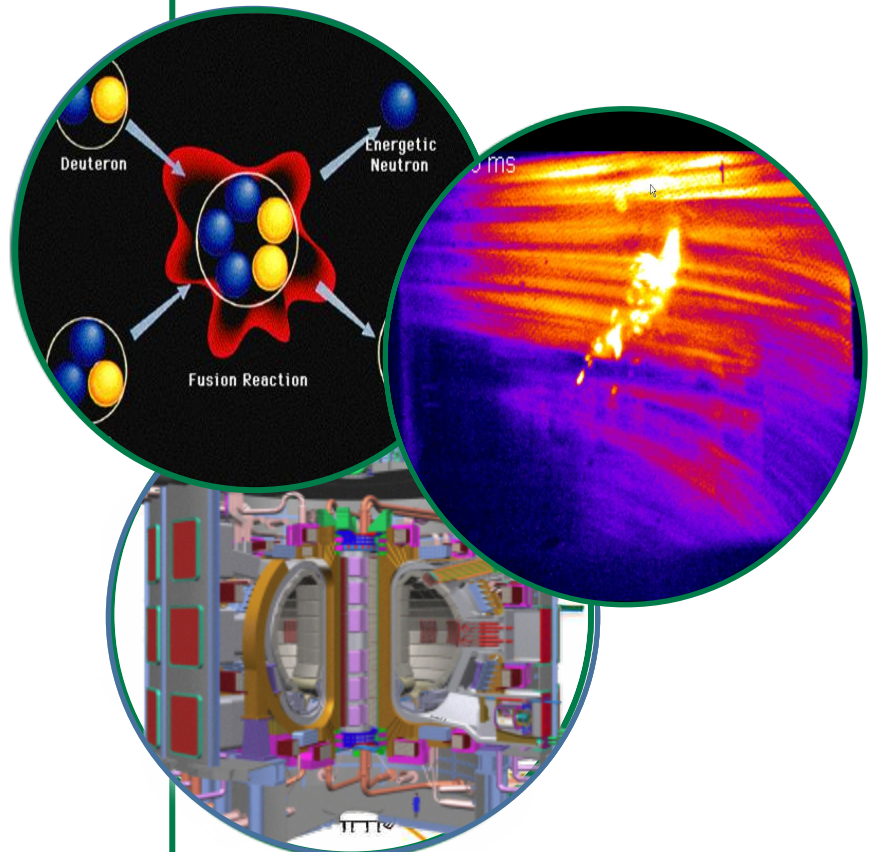
R&D in Support of the Shattered Pellet Technique for Disruption Mitigation

S.K. Combs, L.R. Baylor, S.J. Meitner, N. Commaux, T.J. Jernigan, D.A. Rasmussen, S.L. Milora, and T.R. Younkin*

Oak Ridge National Laboratory, Oak Ridge, Tennessee
***University of Tennessee, Knoxville, Tennessee**



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U.S. DEPARTMENT OF ENERGY

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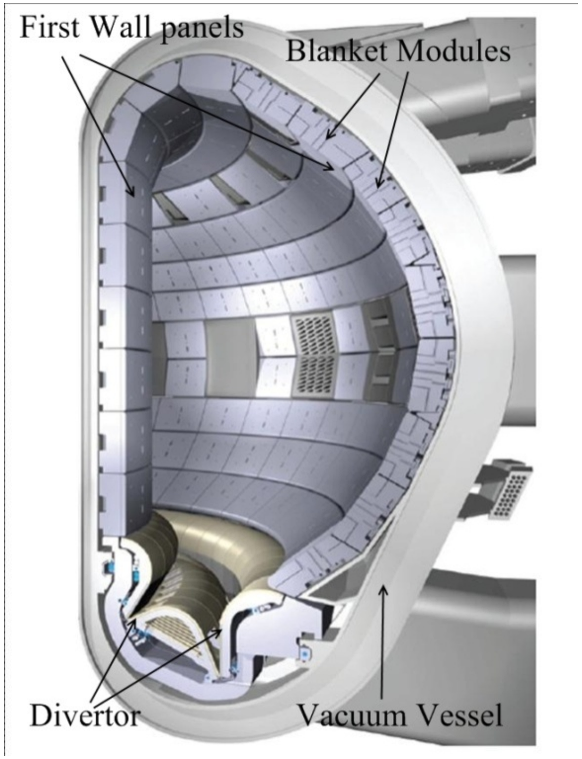
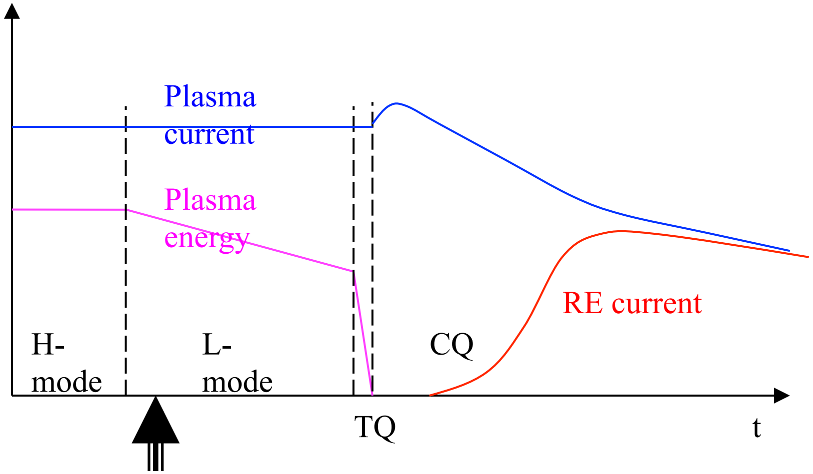
Mitigation of Disruptions Is a Challenge for ITER

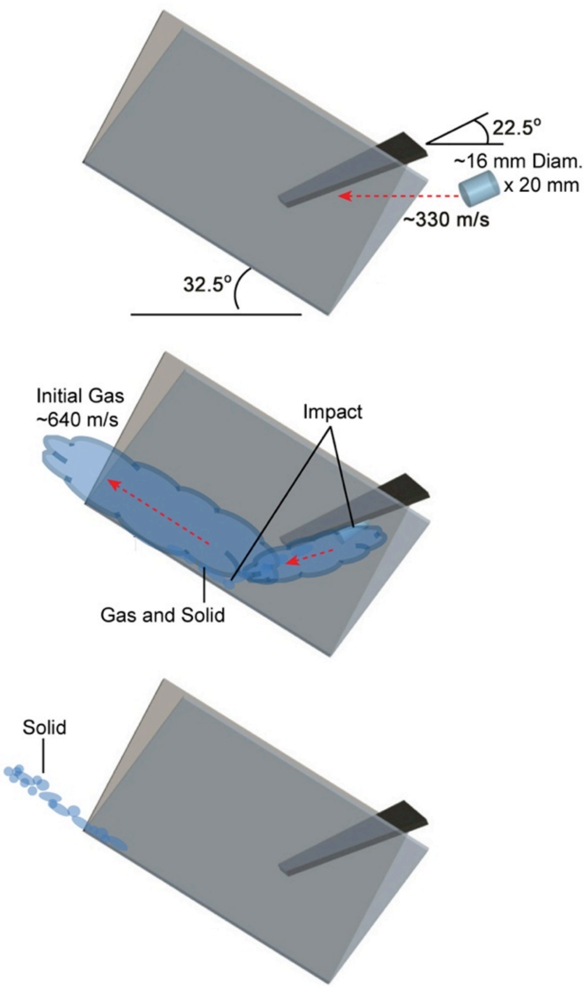


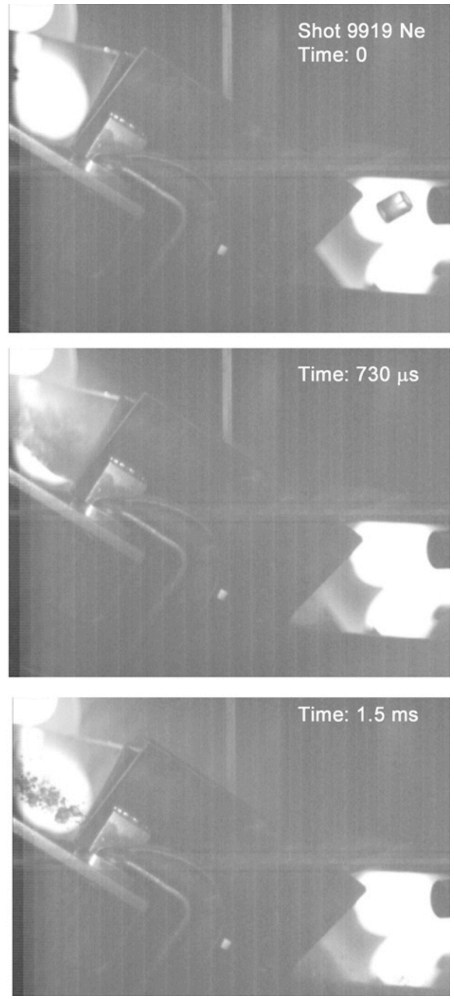


Typical chain of events during plasma disruption

- The largest thermal loads occur during Thermal Quench (must be reduced by factor of 10 by preventive MGI)
- Major mechanical forces act on plasma facing components during Current Quench (CQ time shall be controlled by DMS within limits 50-150 ms)
- Runaway electrons can be generated during Current Quench (RE current must be suppressed to less than 2 MA)

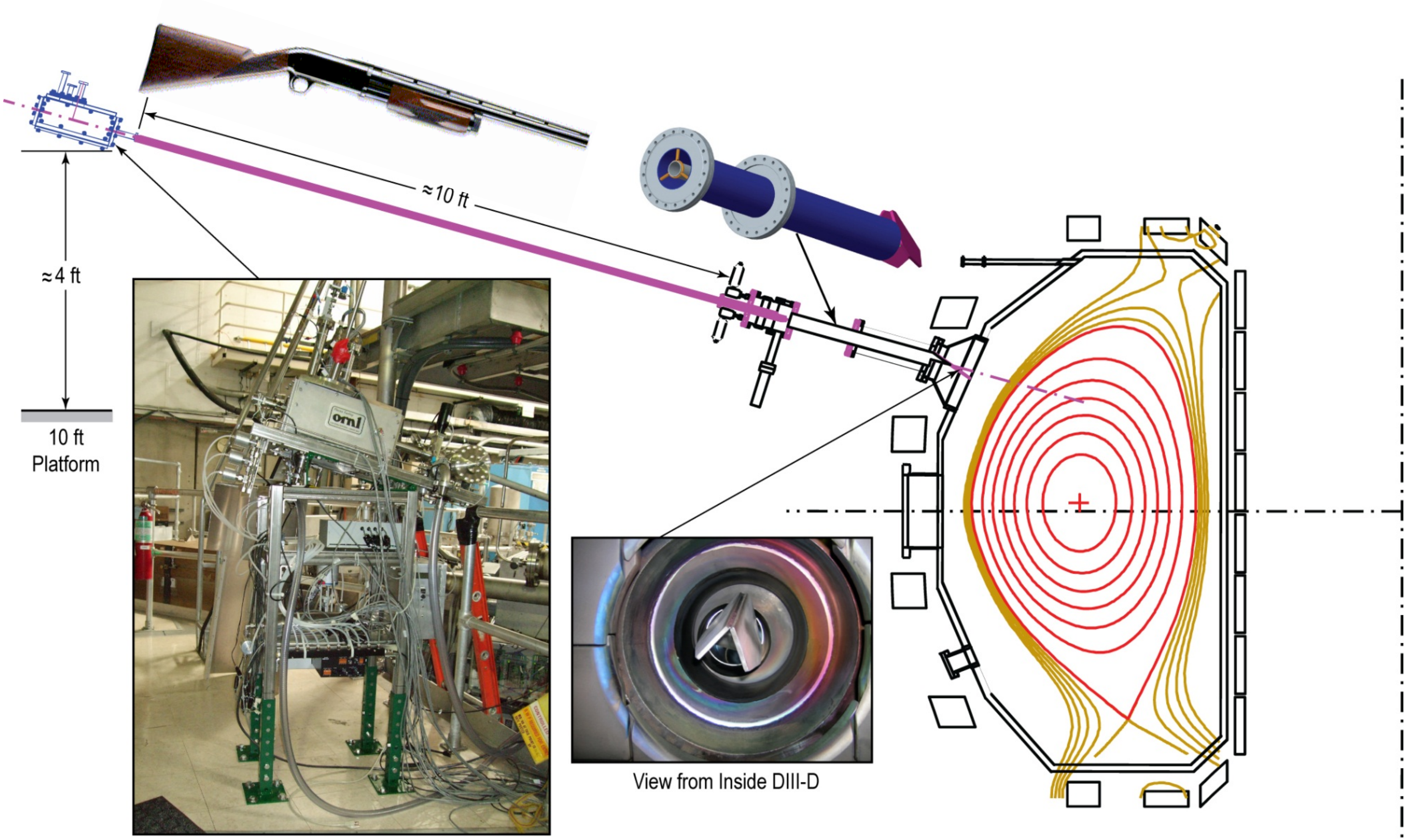
Shotgun Pellet Injector – Technique of Injecting Large Shattered Pellets for Disruption Mitigation Has Been Pioneered by ORNL



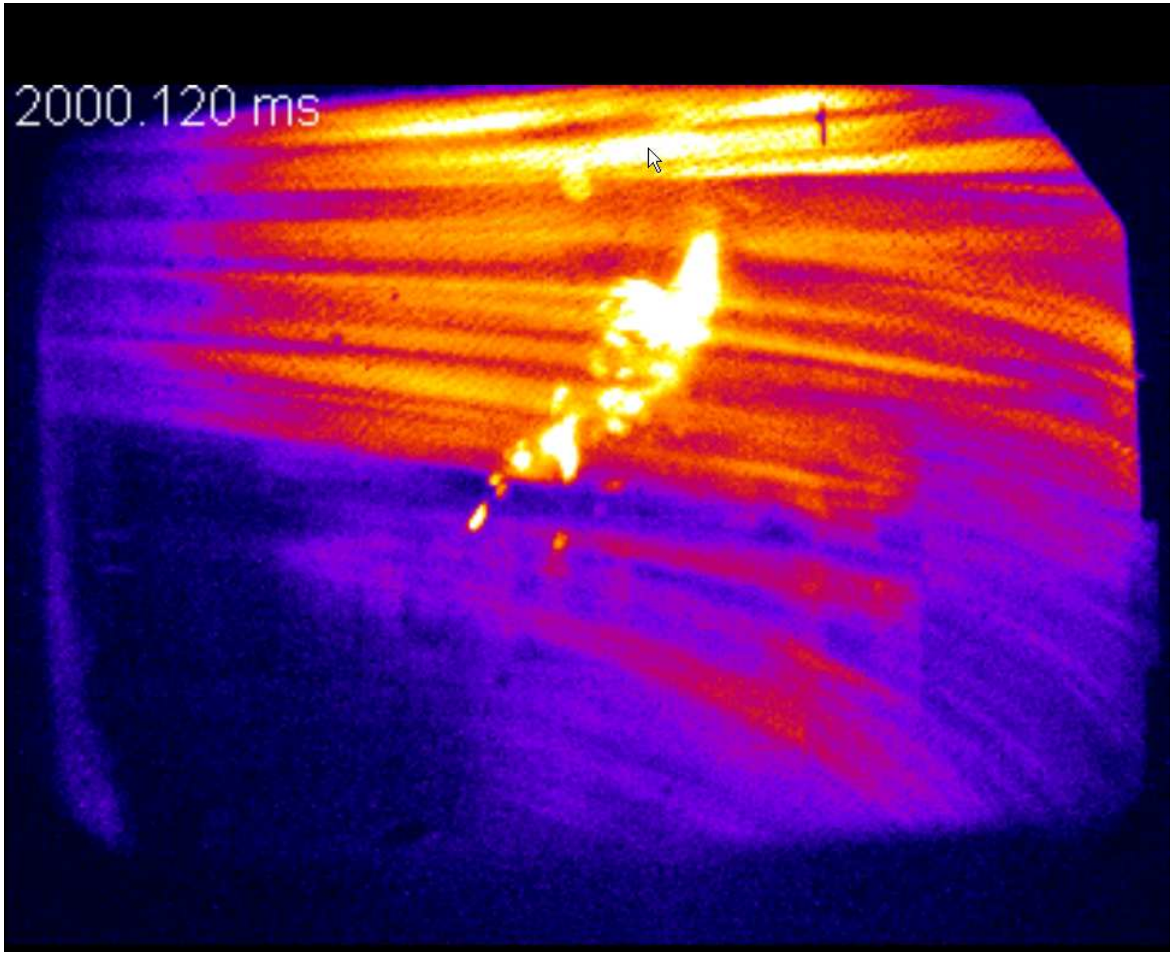


- Double-impact V-groove target was used in the prototype to effectively shatter the large pellets
  - Some limited analysis of fast video and impacts on target foils suggest that ~half of the mass exits the V-plate as solid material
  - It also showed that the initial gas burst exiting the V-plate is traveling at ~640 m/s with some very small debris (≤0.5 mm)
  - Particles tend to get larger and slower as the event progresses, with moderate size particles (~0.5 to 2 mm) at ~225 m/s and large particles (≥2 mm) at ~90 m/s.
  - Also, the amount of blowback in this setup was minimal, which was an issue with the nozzle target described later
- A system (shotgun pellet injector) was installed on DIII-D in 2009 and has since been used successfully in disruption mitigation experiments

Shotgun Pellet Injector Developed and Used on DIII-D for Disruption Mitigation Studies



Shotgun Pellet Terminating a 1.5 MA Plasma on DIII-D



[N. Commaux, et al., Nucl. Fusion 2011]

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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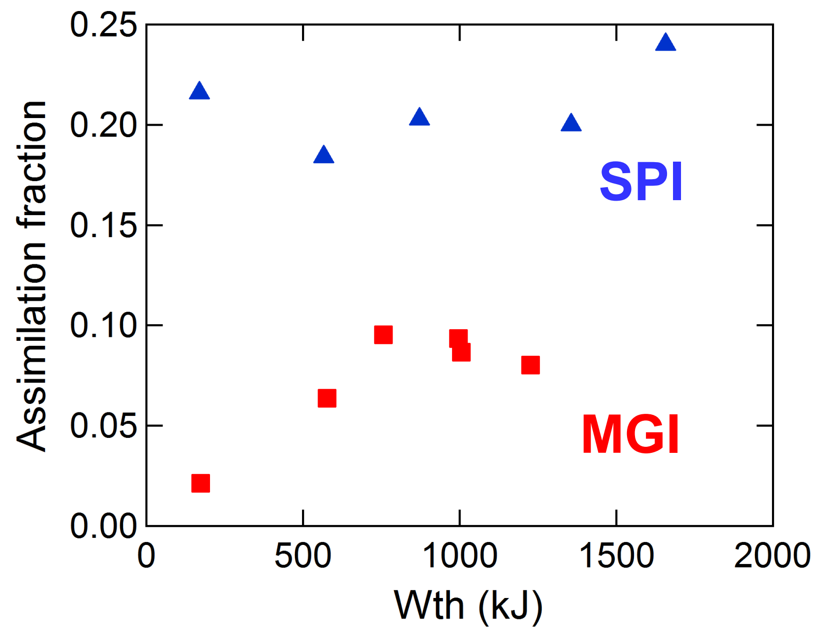
Shattered Pellet Injection Achieves Faster and Higher Density Assimilation

- **Shattered pellet injection developed by ORNL is a leading candidate for disruption mitigation on ITER**
- **Encouraging results:**
  - SPI shutdown mechanism different from massive gas puff: no sign of inward propagation triggering a 2/1 mode
- **Faster and greater particle assimilation for SPI compared to MGI**
- **Unlike MGI, the assimilation fraction of SPI does not depend on the thermal energy content of the plasma**
- **Research planned on assimilation mechanism and radiation asymmetry**



Gas Properties Relevant for Pellet Formation/Acceleration

Gas Species	Molecular Weight (g/mol)	Critical-point temperature (K)	Triple-point temperature (K)	Triple-point pressure (bar)	Solid parameters: Density (g/cm^3)	Solid parameters: Ultimate yield strength (bar)
H_2	2.016	33.2	13.9	0.072	0.087	2.3 (8 K)
D_2	4.028	38.3	18.7	0.172	0.20	4.3 (8 K)
T_2	6.032	40.4	20.6	0.216	0.32	10.3 (8.0 K) 11.7 (9.0 K)
Ne	20.18	44.4	24.6	0.434	1.44	2.03 (8.0 K) 1.72 (21 K)
Ar	39.95	150.8	83.8	0.688	1.66	13.3 (10.0 K) 4.81 (50 K)

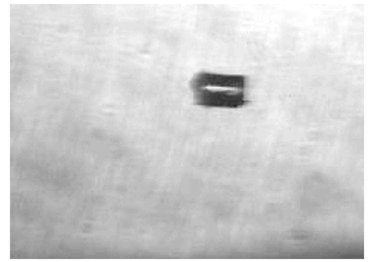
Material of choice for DM on ITER

This appears to be much too low – it is probably dynamic shear which does not necessarly correlate with ultimate tensile strength

Large Pellet Size Needed for Disruption Mitigation

- Small pellets for TJ-II

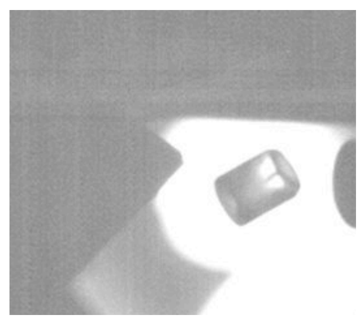
H_2

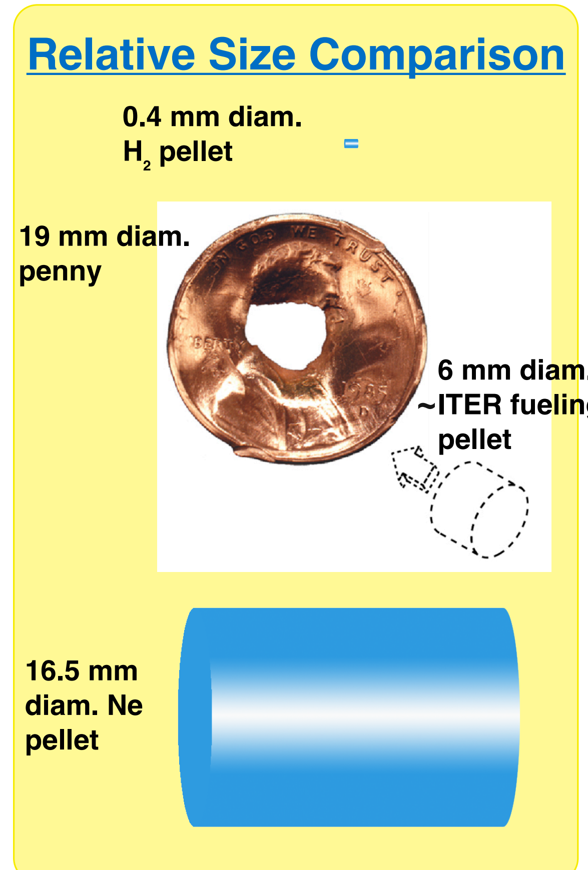


Pellet	Diameter (mm)	Volume (mm^3)	Mass (mg)
H_2	0.4	0.065	0.006
Ne	16.5	5000	7000
Ratio Ne/H2	~41	~75000	~$1.2x10^6$

- Large pellets for disruption mitigation on DIII-D and ITER (injection of shattered pellets)

Ne





Testing with ~25 mm Ne pellets are planned for the future since ITER might need some even larger pellets for disruption mitigation

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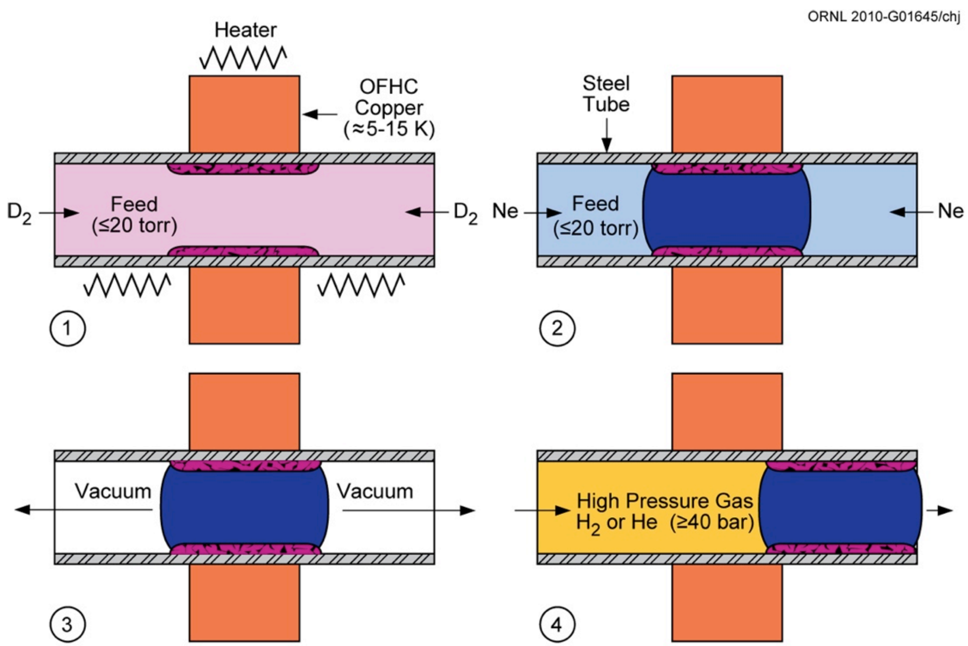
Dual Layer Pellets Offer Some Distinct Advantages Over Pure Ne Pellets for Reliable Operations



- **Sequence of events for forming dual-layer pellet: (1) freeze D_2 shell, (2) freeze Ne core, (3) evacuate gas, and (4) fire with high-pressure gas**

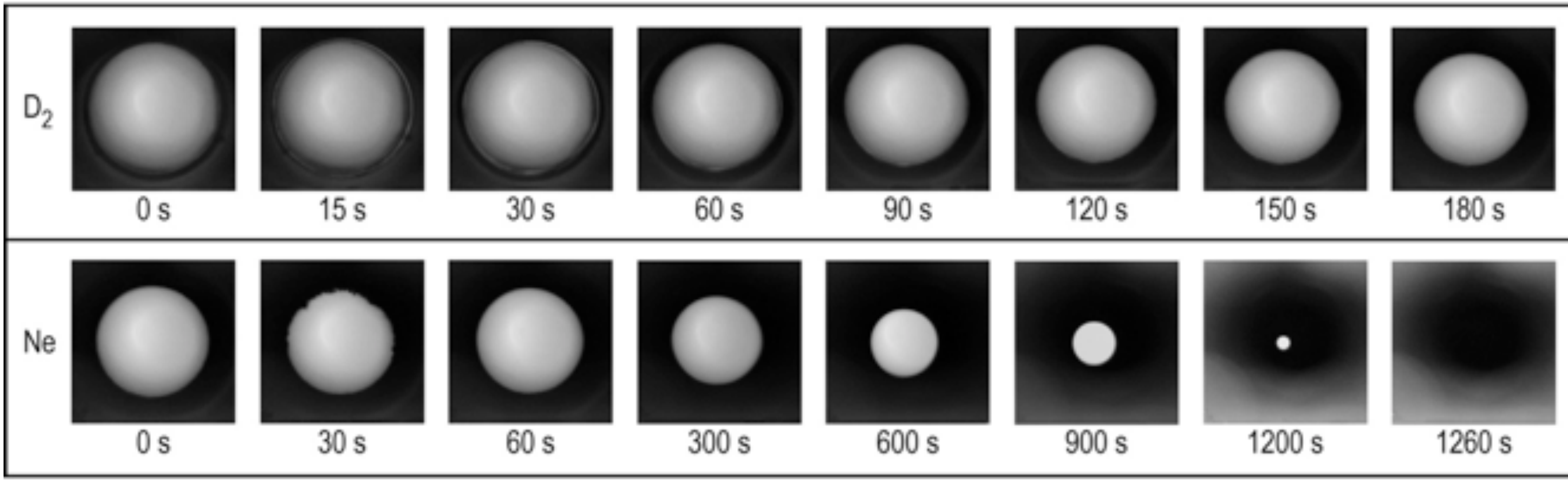
- Solid Ne is significantly stronger (?) than D_2 at ~10 K and will not breakaway from the wall with typical propellant gas pressures (≤ 70 bar)
- With a D_2 shell, pellet breakaway pressure is the same as if it was a solid D_2 pellet – thus, the gun can operate at lower temperatures and vapor pressures
- It is desirable to operate the pipe gun at the coldest temperature possible (≤ 8 K) to minimize the vapor pressure – the large pellets could then probably be maintained for relatively long periods (24 hrs or longer?)
- With this technique, the bulk of the material is still Ne which is more desirable for the disruption mitigation application

Photo Sequences of Formation for a Shell Pellet

(1) 1-mm layer of D_2 freezes on the pipe-gun inner wall (16.5 mm diam)
(2) Core is filled with solid Ne (temperature ~12 to 13 K for both phases)
(3) Pellet can be easily shot with gas at 70 bar

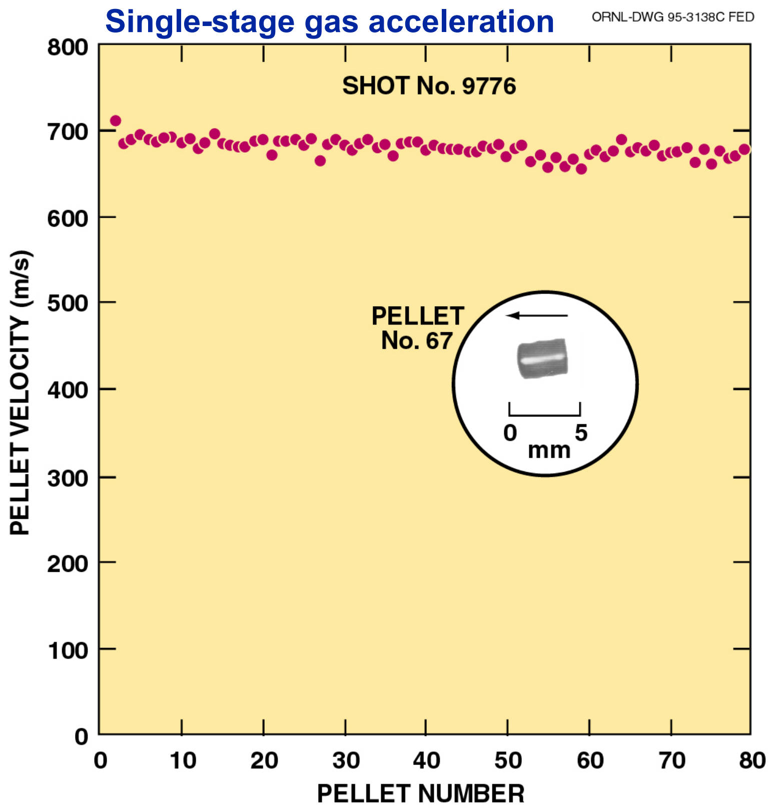
ORNL 2010-G001685/chj

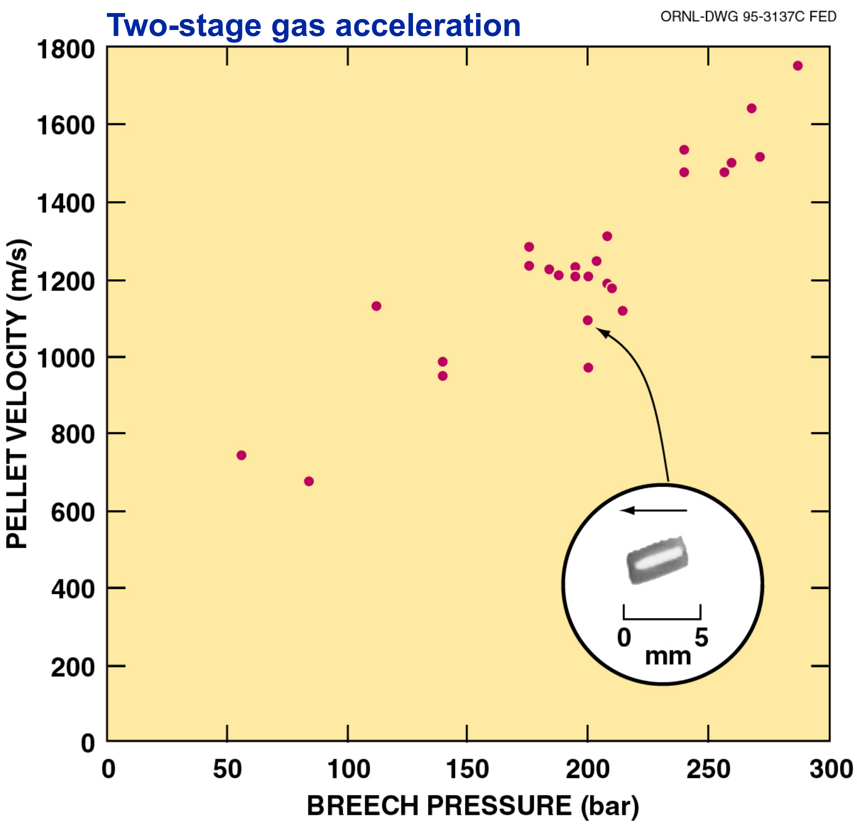
4/1/2010 View is looking down the gun barrel from the breech



- Shell thicknesses from ~0.1 to 1.0 mm were tested – performance not affected
- With a pure Ne pellet, the temperature had to be raised to ~20 K (~30 Torr vapor pressure) to reliably break the pellet away from the wall with the available fast valve and supply pressure
- Standard ORNL fast propellant valve with a 70-bar supply pressure was used for the experiments, and the orifice is actually too small (~5 mm) for this application

Speed Data for 2.7-mm Ne Pellets from Previous Testing

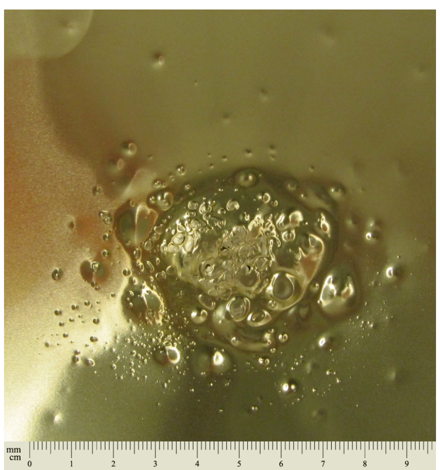




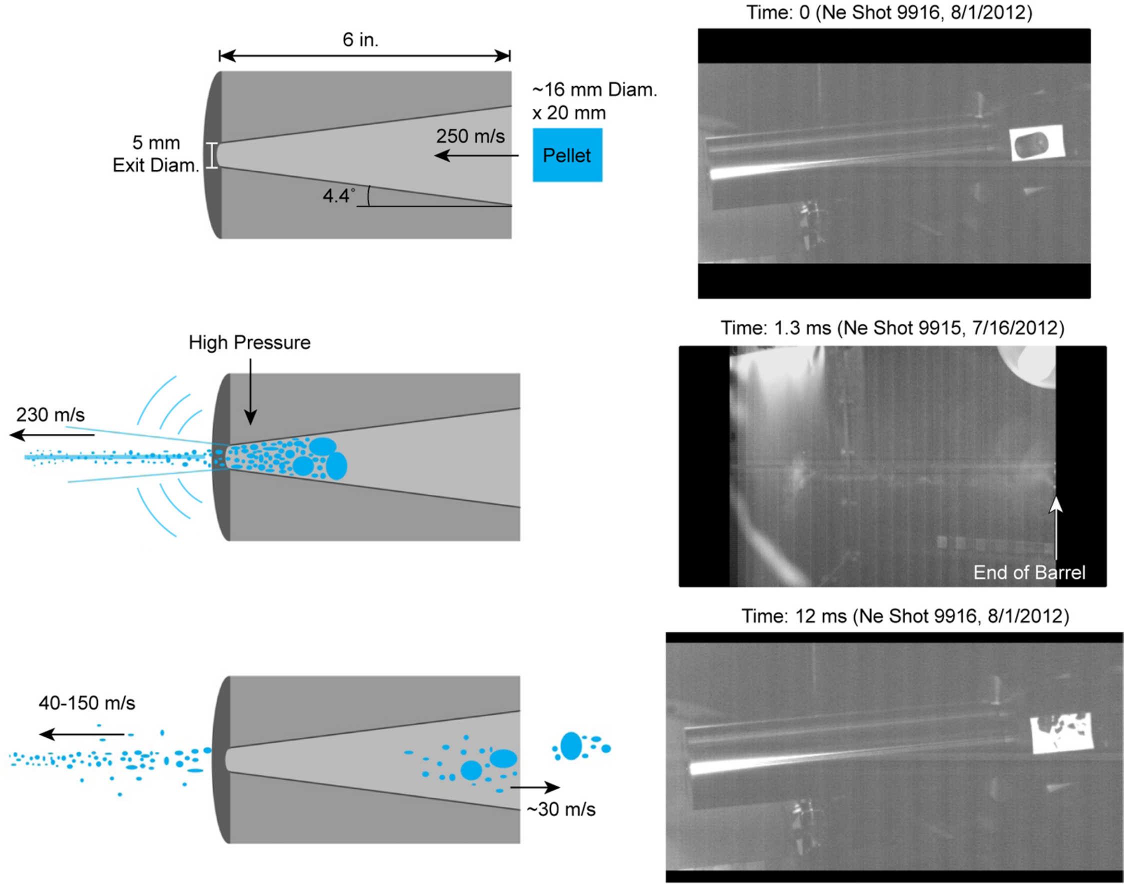
- It is likely that the speed of the large Ne pellets would approach 700 m/s with a larger propellant valve (bigger orifice and greater flow rates) that could keep the acceleration pressure higher on the base of the pellet – plan to test with a larger valve (22 mm orifice vs 5 mm presently used) in the very near future
- Faster pellet speed is desirable since material needs to be injected into plasma very shortly after "precursor" for effective disruption mitigation

Tested Other Concepts in LAB for Shattering Large Pellets

- Video data suggested that a significant fraction of the pellet is vaporized upon impact with the funnel, and that the output is like a high-pressure gas jet with a stream of relatively small debris
- Using the front and back of a brass foil target (back not shown) for analysis of particle size, results suggested that only ~25% of the mass of the original pellet reached the target as solid and that most particles were less than 1 mm in size
- Significant blowback was observed
- Abandoned concept after limited testing

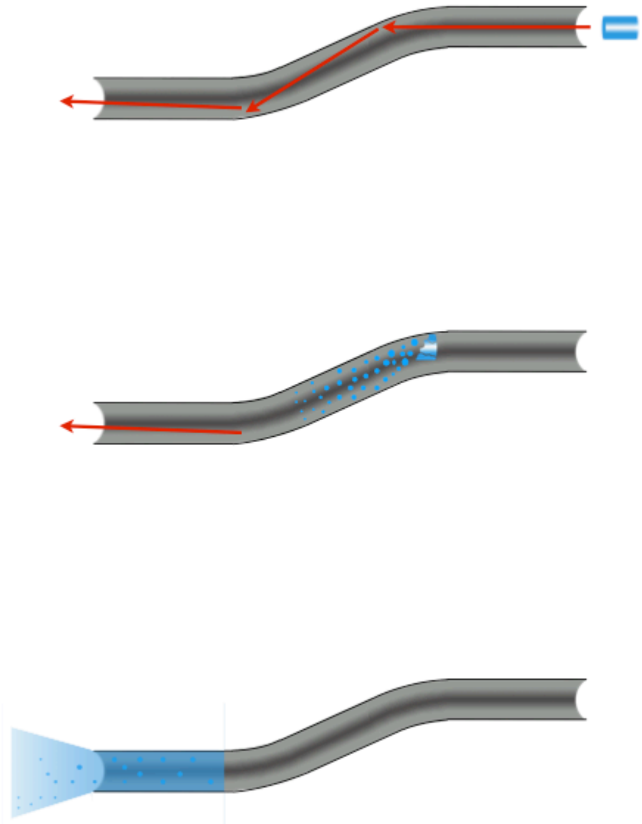


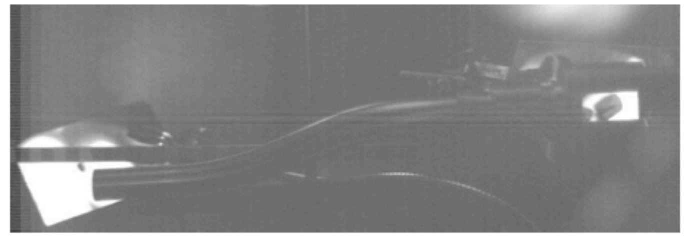
Photos/illustrations of pellet shattering in a nozzle

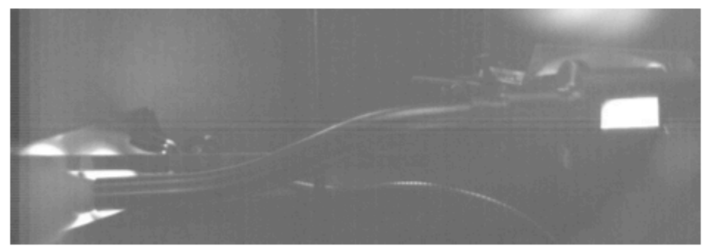


Significant blowback and direct line of sight are disadvantages

Limited Testing Was Carried Out in Lab with Large Ne Pellets and Tube with an S-Bend







S-Bend proved to be too extreme with pellets mostly vaporized and only a small fraction of solid observed exiting the tube

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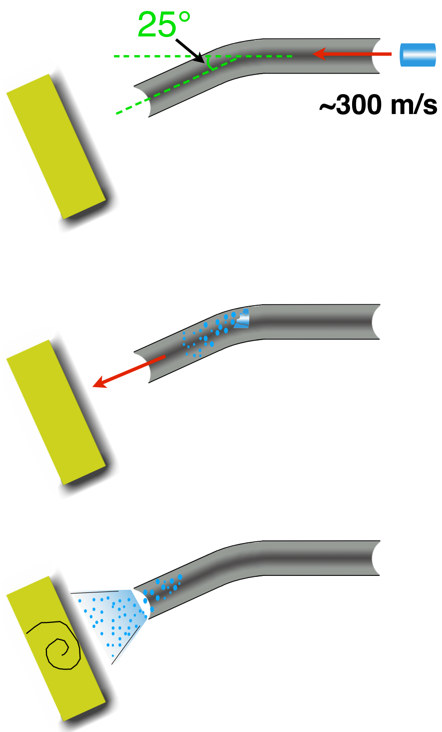
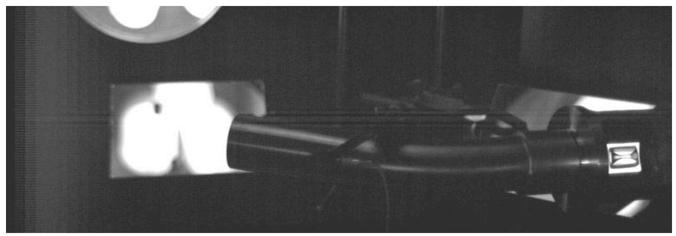
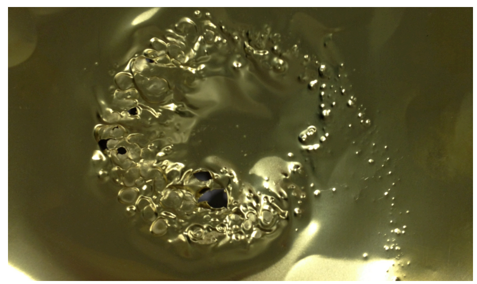
Simple Breaker Tube with Single Bend Proved Quite Effective in Shattering the Large Pellets







- Video data suggested that a significant fraction of the pellet exits as relatively small pieces (most less than a few mm)
- No blowback was observed
- No line of sight is big advantage for neutron activation issues
- Footprint required is much less than that for original double-bounce target apparatus
- Simple and attractive technique for installation on fusion experiments (DIII-D and ITER)

A breaker tube with a single bend (R=160 mm & included angle=25º) was fabricated at ORNL and will be installed on DIII-D in the very near future

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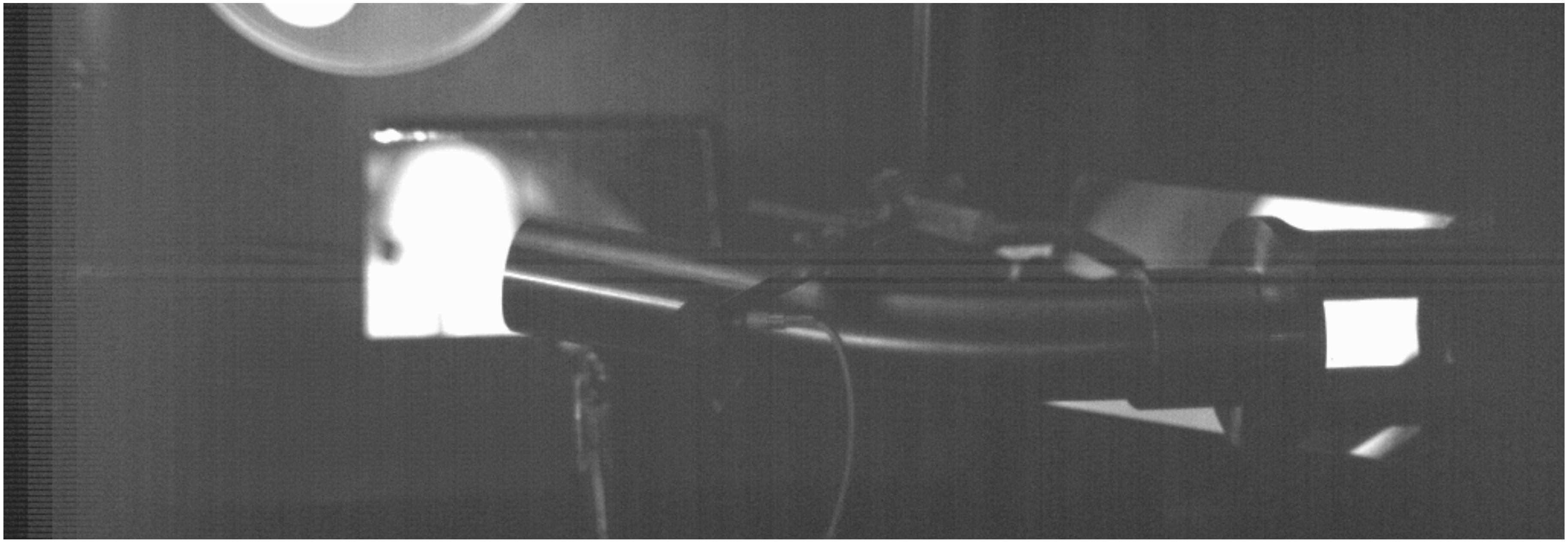
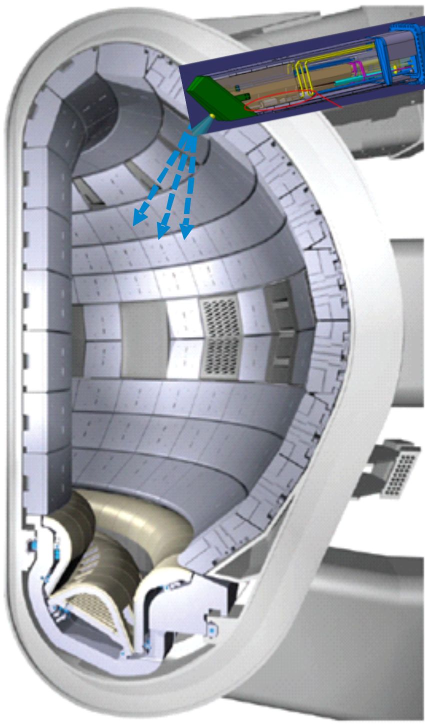
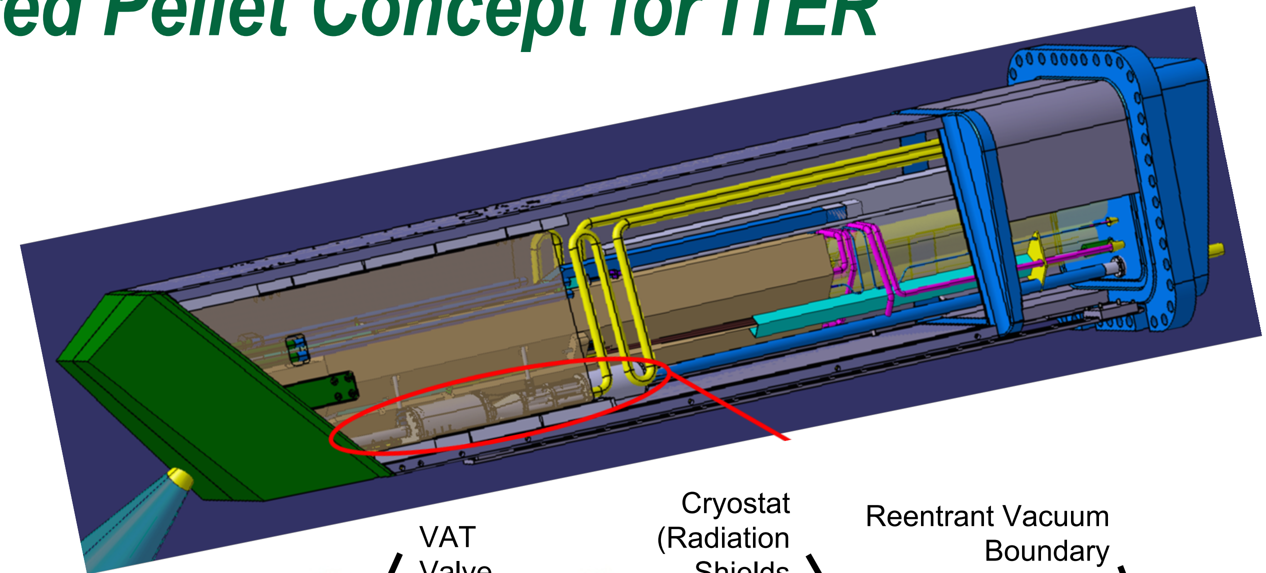
Video from High-Speed Camera of Large Ne Pellet Shattering in Breaker Tube

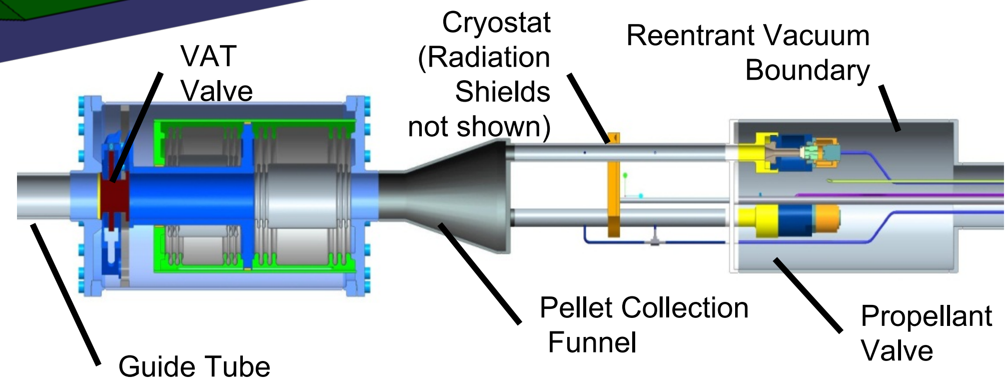


- Camera operating at 18000 frames/s & shutter speed of 2 us
- Duration of video is 2.83 ms with 51 frames (55 us between frames)
- Actual event is 9000 times faster than shown

Shattered Pellet Concept for ITER







G. Kiss – Poster ThPO-104 (SOFE 2013)

- **SPI located in upper port plug(s) with pellet ~1.5m from plasma edge**
- **Injector has multiple barrels for redundancy and adjusting amount injected – combination of MGI and SPI is possible**
- **Bent tube for shattering located inside shield block**