ELM Mitigation using Pellet Injection and Plans for ITER*

by

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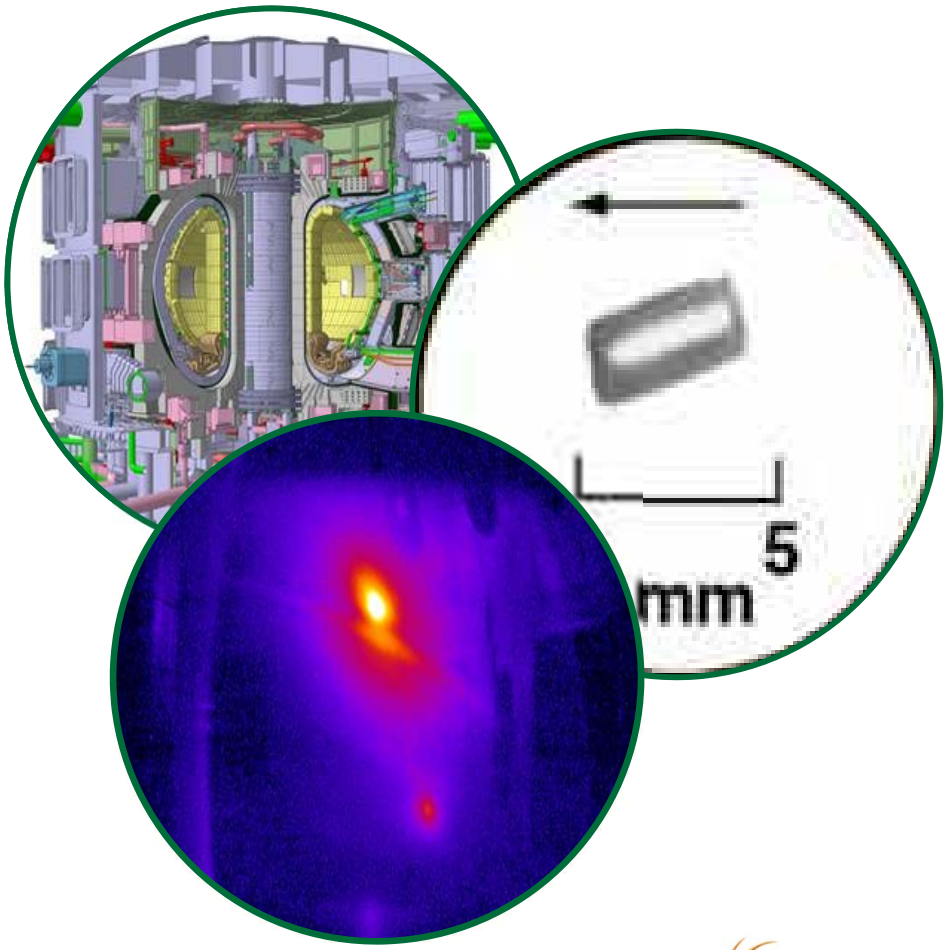

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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Summary – Pellet ELM Pacing has been Shown to Mitigate ELMs and is Planned for ITER

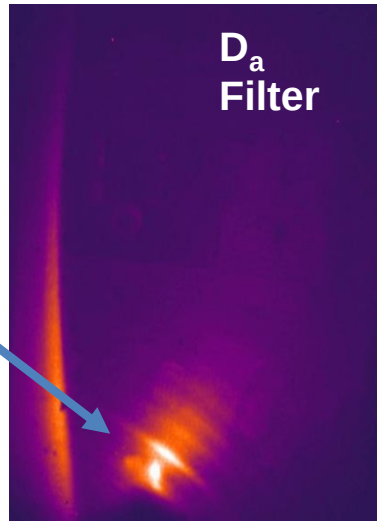
- **Experiments on AUG, DIII-D, and JET have shown that pellets can trigger small ELMs on demand**
- **ELM frequency increase of up to 12x achieved with > 12x reduction in divertor ELM energy and peak heat flux in DIII-D**
  - JET has achieved 4.5x increase with ITER like wall
- **ELMs triggered locally by pressure perturbation in pedestal gradient region**
  - Pellet size and speed determined for trigger to compare with 3-D MHD Modeling
- **Design of ITER pellet system is underway - injection line and pellet size based on extrapolated results**

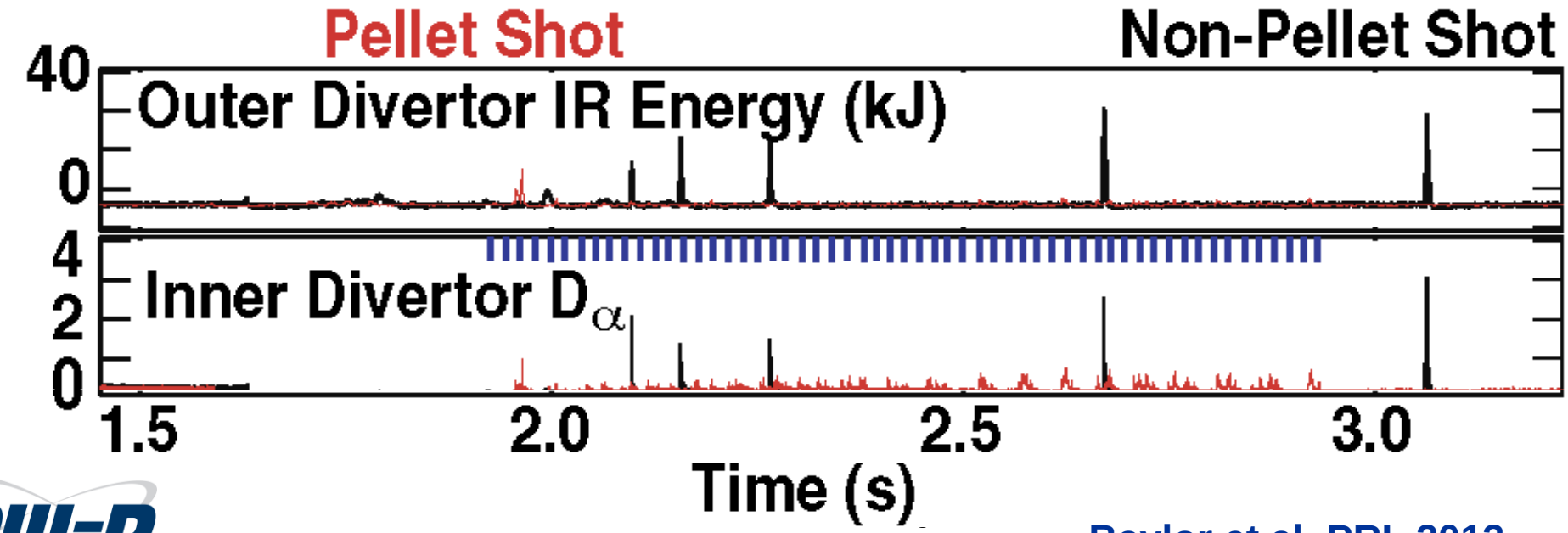
Pellet ELM Pacing Mitigation Approach

- Small slow pellet injection localized at plasma edge
- ELM triggered despite peeling-ballooning stable pedestal
- Increases the ELM rate to >12X natural rate
- Corresponding reduction of ELM intensity >12X
- Edge pellet injection reduces impurity accumulation
- Also demonstrated with metal wall on AUG & JET

Pellet excites a filament as it enters the plasma

ELM is subsequently triggered





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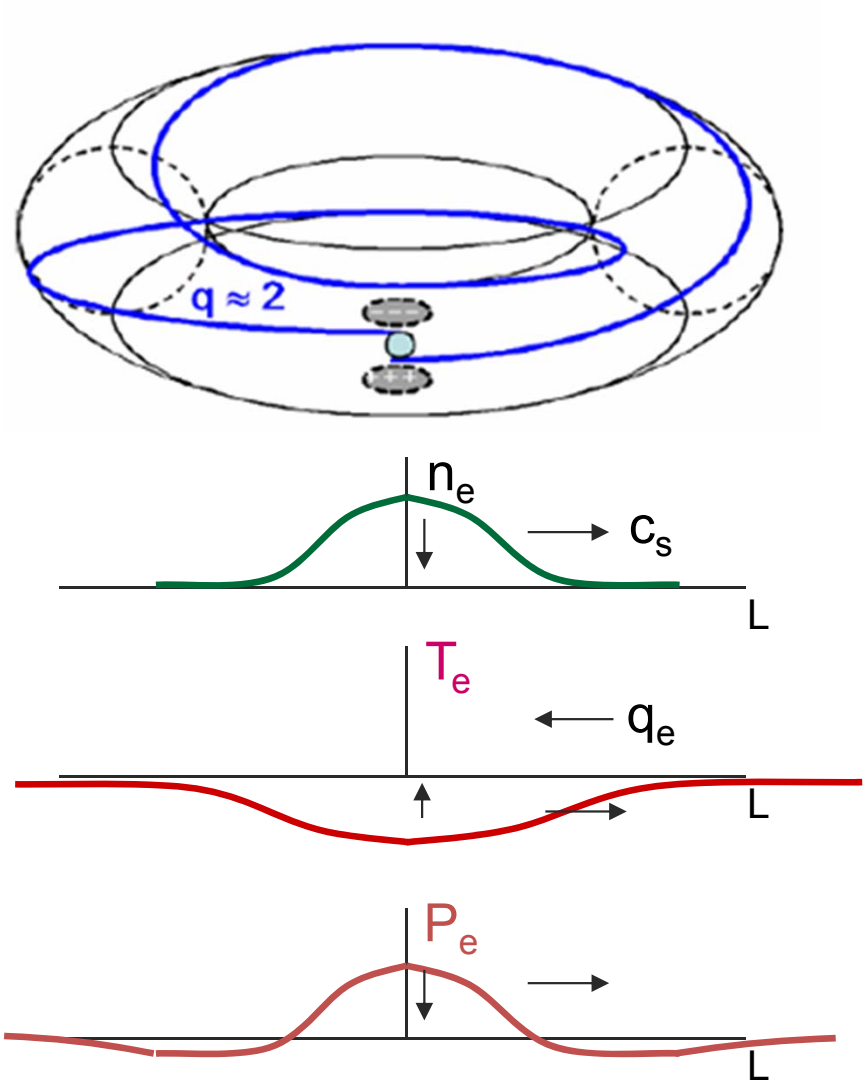
How Does a Pellet Trigger an ELM?



- **Pellet cloud releases from pellet and expands along a flux tube at the sound speed c_s**
- **Temperature 'cold wave' travels along the flux tube at the thermal speed. Heat is absorbed in the cloud resulting in a local pressure increase in the cloud**
- **Strong local cross field pressure gradients produced along the flux tube in μs**
- **The pellet ablates with a rate given by:**

$$dN/dt \propto r_p^{4/3} T_e^{11/6} n_e^{1/3}$$

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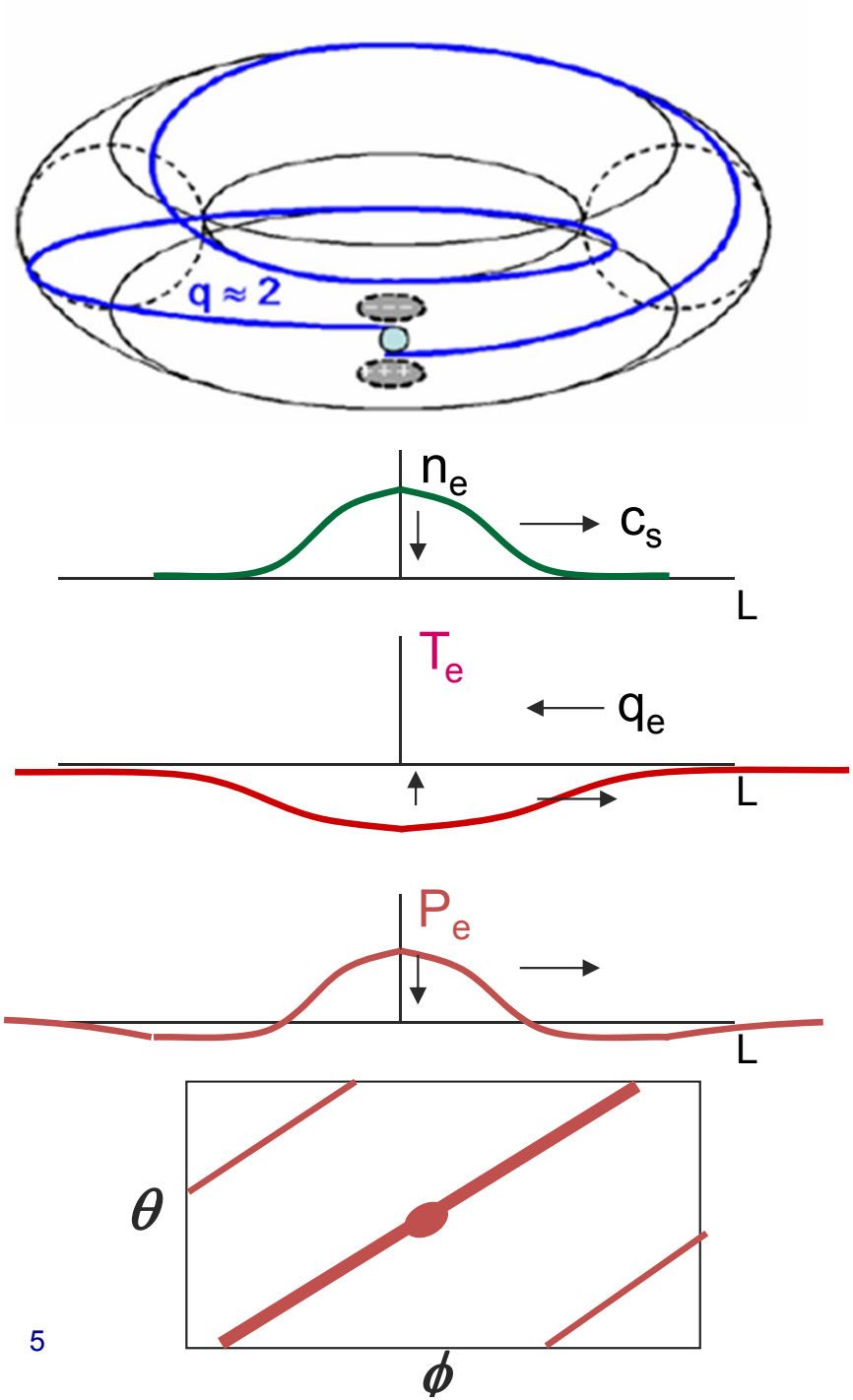

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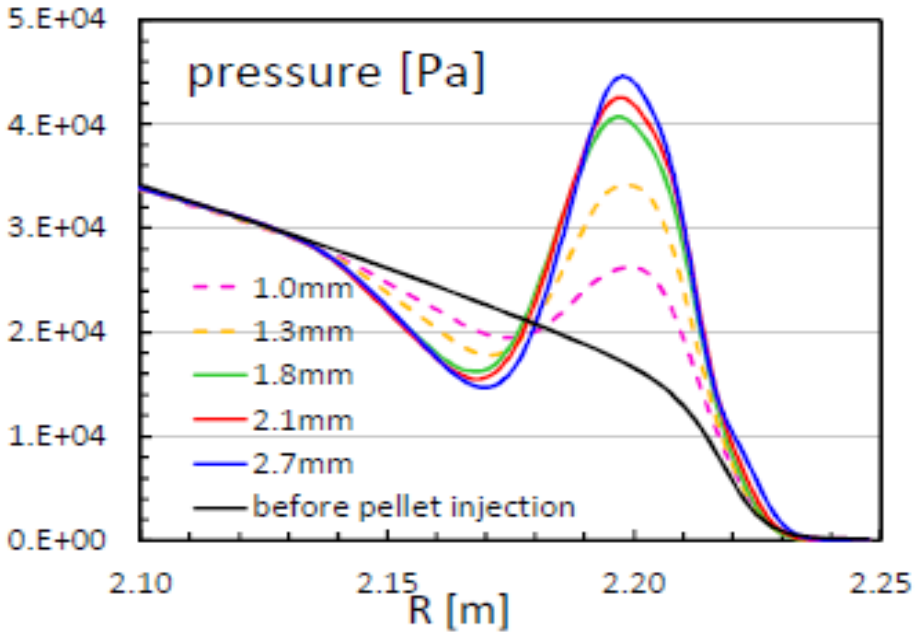
- **The local ∇P is proportional to the ablation rate. Once sufficient ablation occurs, the local ∇P can trigger a ballooning instability at that location.**

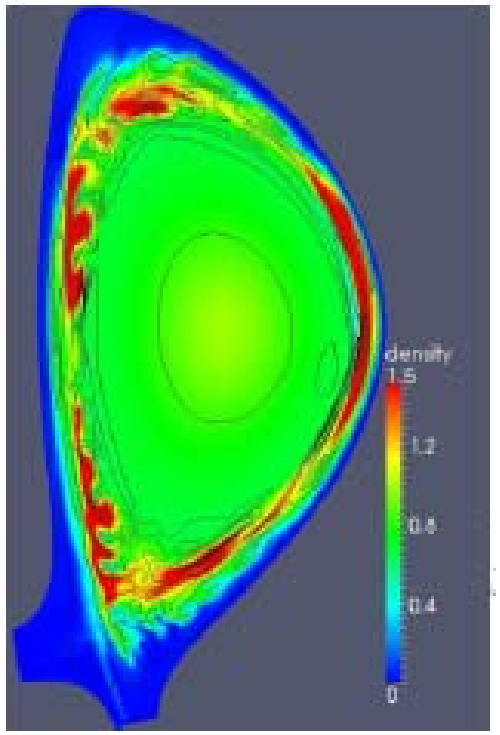
Modeling with JOREK Non-linear MHD Code Consistent with Experiment and Hypothesis

JOREK modeling of DIII-D shows that the key parameter for ELM triggering is the local plasma pressure perturbation by the pellet. It is similar at ELM onset for all pellet sizes triggering ELMs.
(Futatani, et al., IAEA2012)

Critical pressure perturbation of 2x is needed to trigger ballooning instability

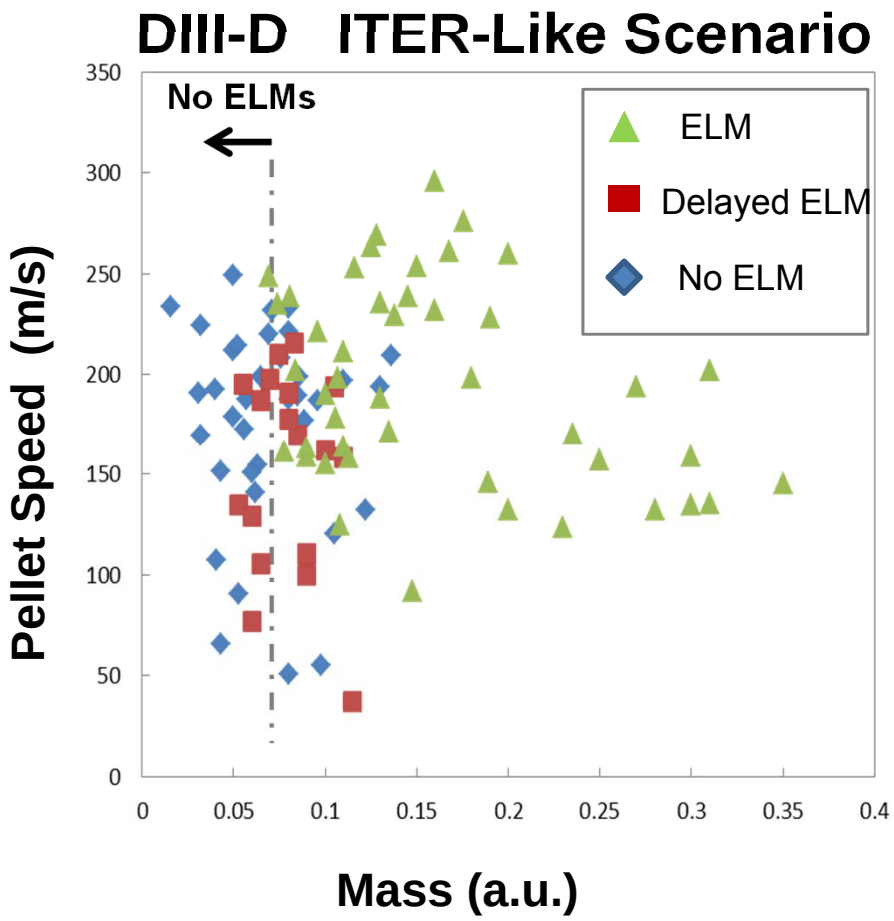


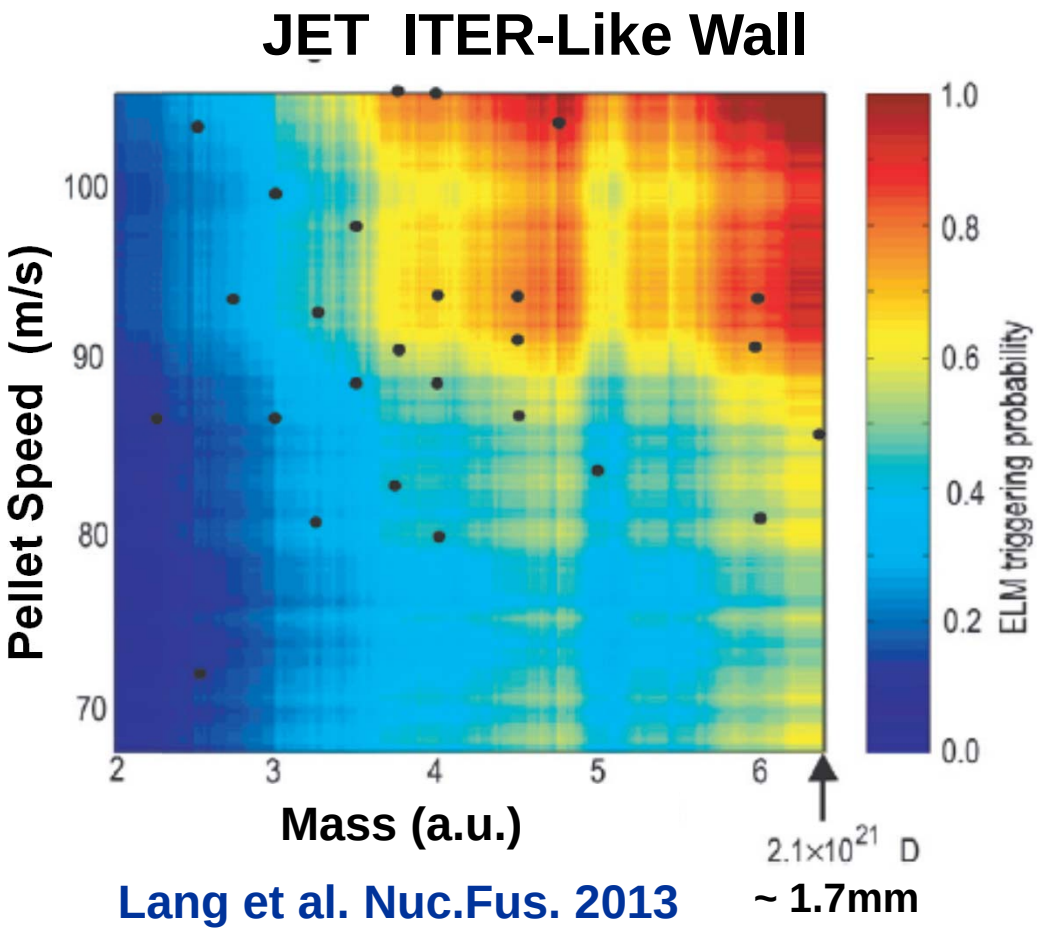
Local Pressure Profile Near Pellet



Density and flow contours after pellet instability generated

Pellets of Insufficient Size/Speed Do Not Trigger ELMs





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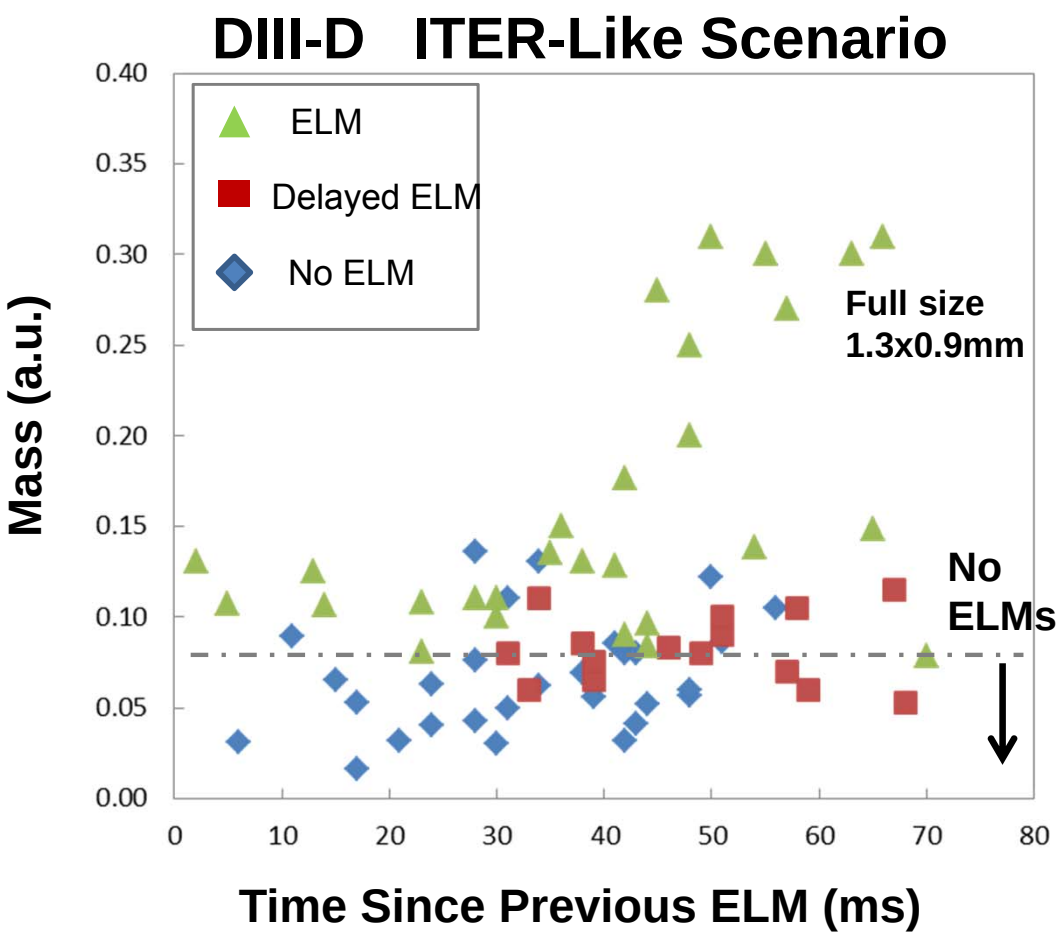
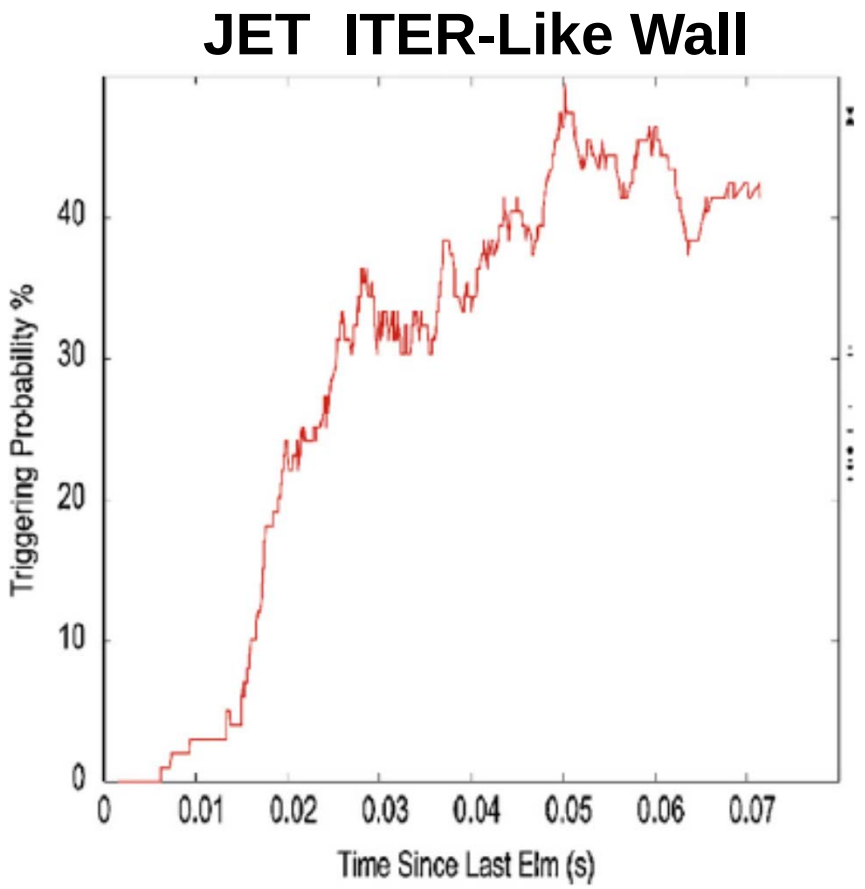
- **Pellets that are < 30% of a full size 1.3mmx0.9mm pellet do not trigger ELMs on DIII-D. Pellet speeds above 100m/s are more likely to trigger ELMs.**

Pellets of Sufficient Size Do Not Depend on Time During ELM Cycle to Trigger an ELM





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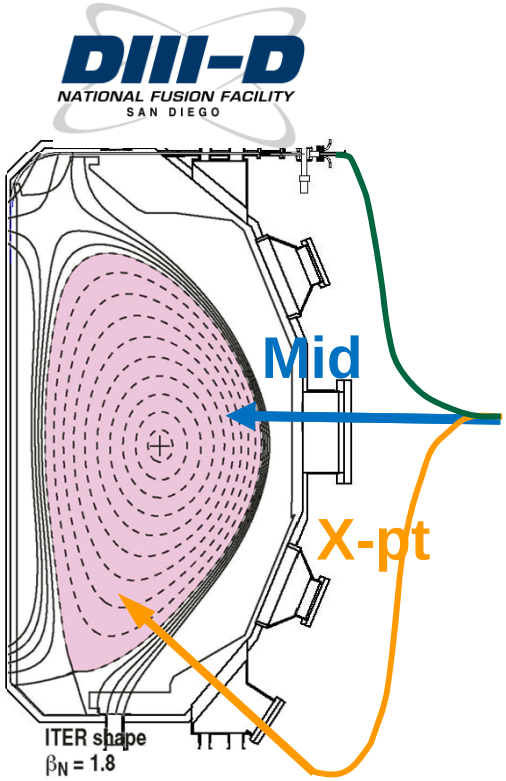
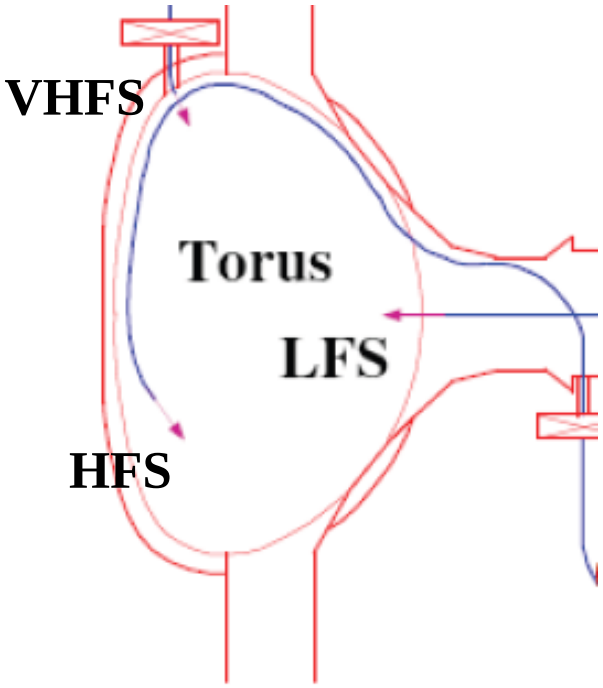
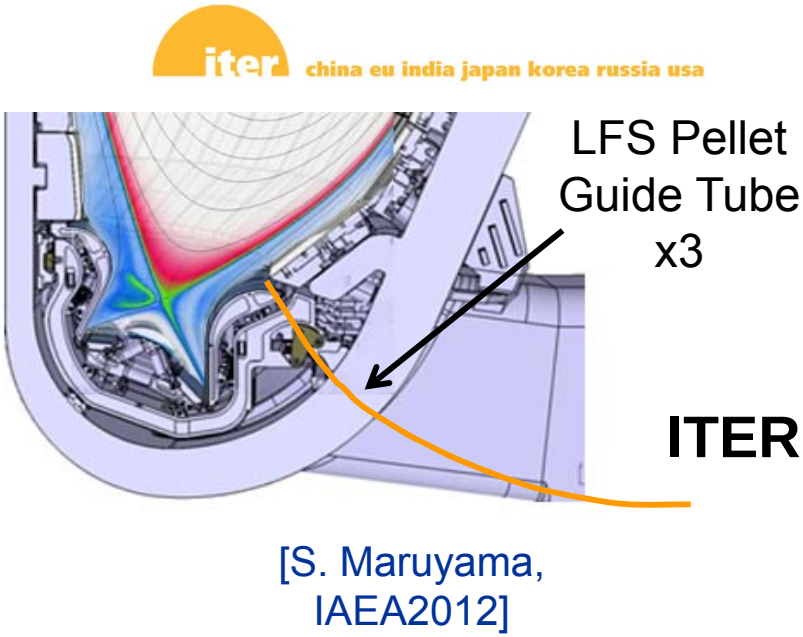
- **Pellets that are sufficiently large can trigger ELMs even very early in the natural ELM cycle.**

Pellet ELM Experiments Performed with D_2 Pellets Injected from LFS Trigger ELMs without Fueling





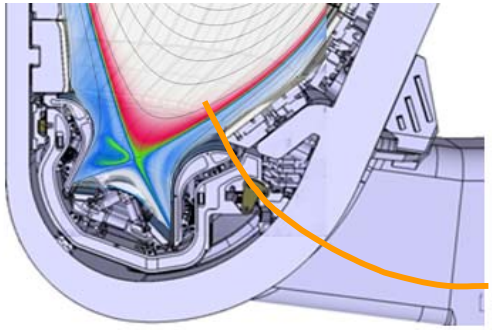


[S. Maruyama, IAEA2012]

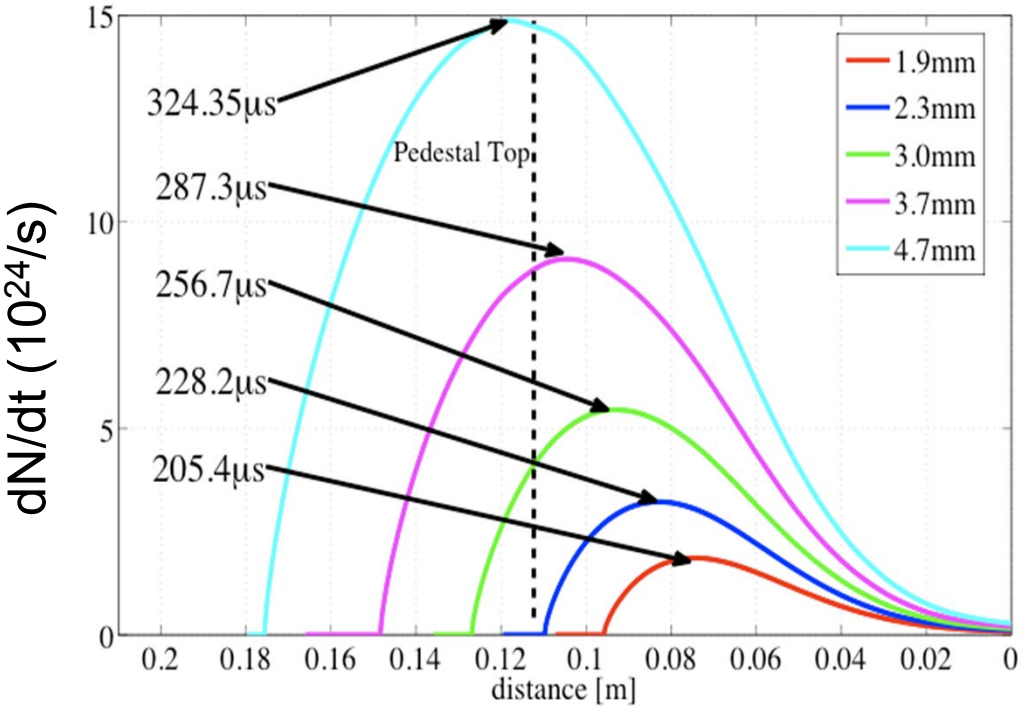
- **LFS and HFS injection have been used to trigger ELMs. HFS on AUG and JET were shown to increase density.**
- **X-point LFS injection takes advantage of flux expansion to localize pellet ablation and reliably trigger ELMs – with no fueling.**

ITER Q=10 Scenario JOREK Modeling Shows 3.7mm Size Pellets Needed to Trigger ELMs

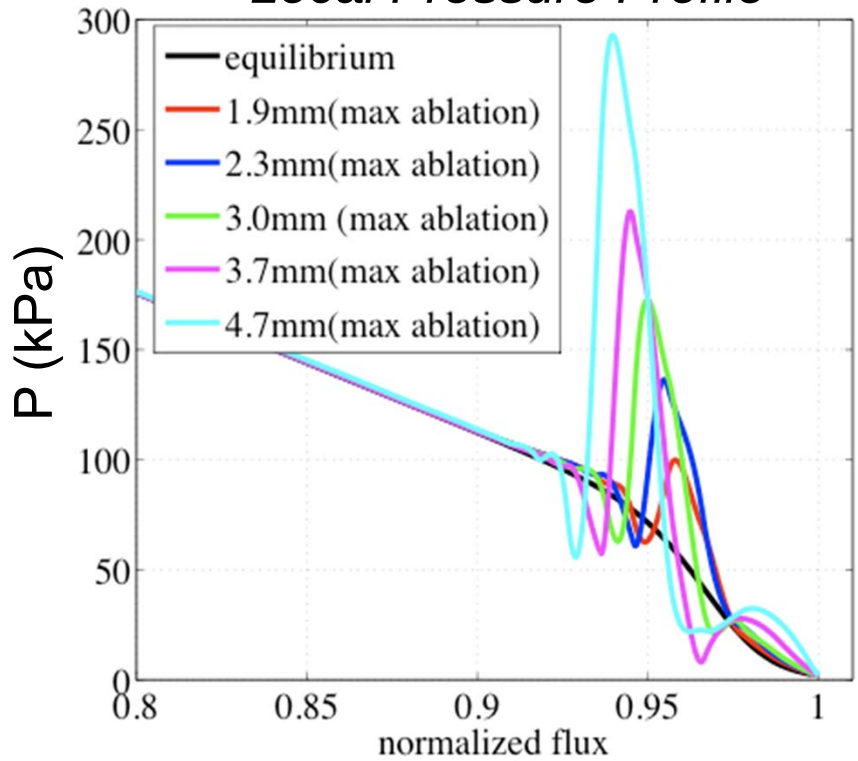
- Q=10, 15MA/5.3T, H-mode, P_{ped}=80kPa
  - Stable equilibrium
- LFS X-pt Pellet Injection Location
  - Pellet speed 350m/s



Pellet Ablation Profiles

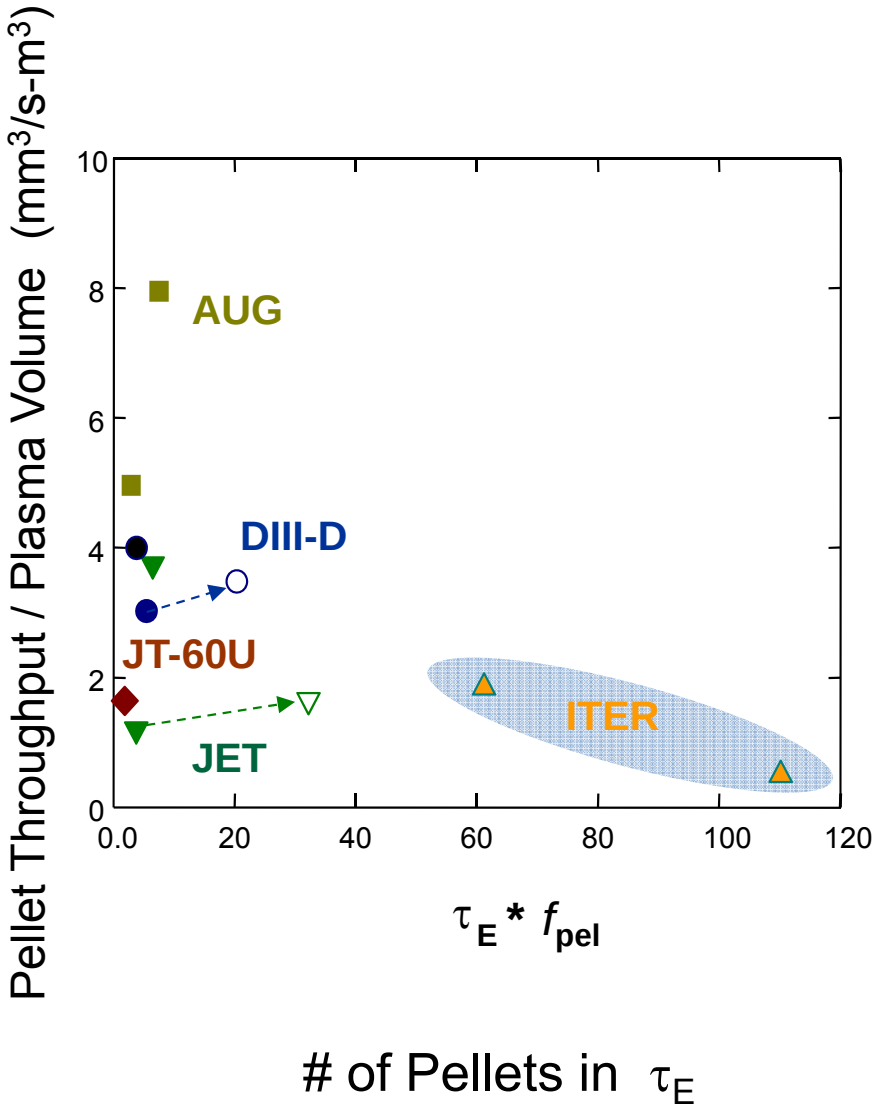


Local Pressure Profile

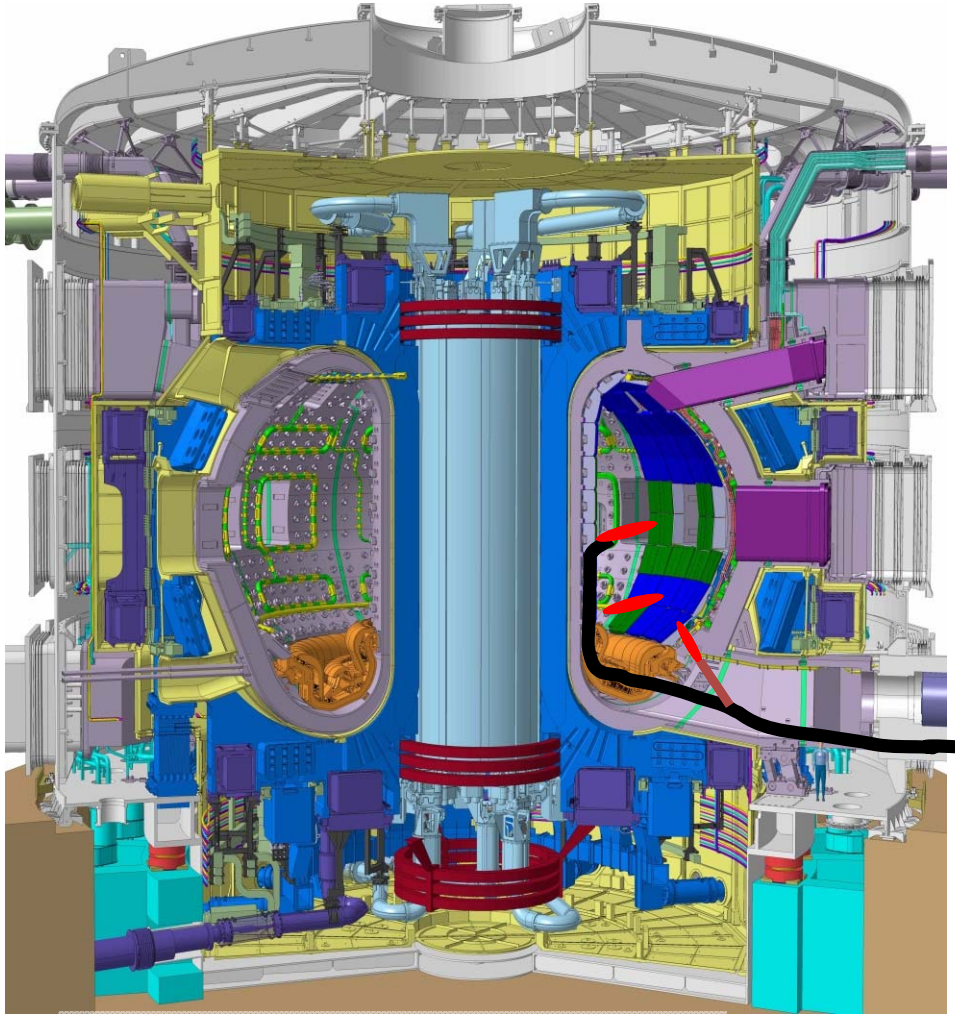


Pellet Mass Throughput for ELM Triggering Approaching that Expected for ITER

- **The DIII-D 60 Hz 1.3mm pellet experiments demonstrated ELM pacing at ~15 pellets per energy confinement time**
- **DIII-D has thus far demonstrated the closest normalized throughput and pellet ELM frequency as compared to ITER**
- **JET can potentially reach a very ITER relevant scenario**
- **Uncertainties for ITER include confinement, heat flux asymmetry, fueling and pumping at these high pellet rates.**



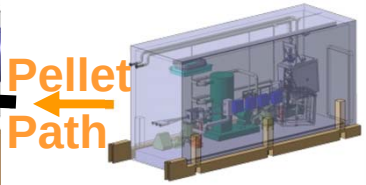
Pellet Fueling and Pellet ELM Mitigation are Functions of the ITER Pellet Injection System



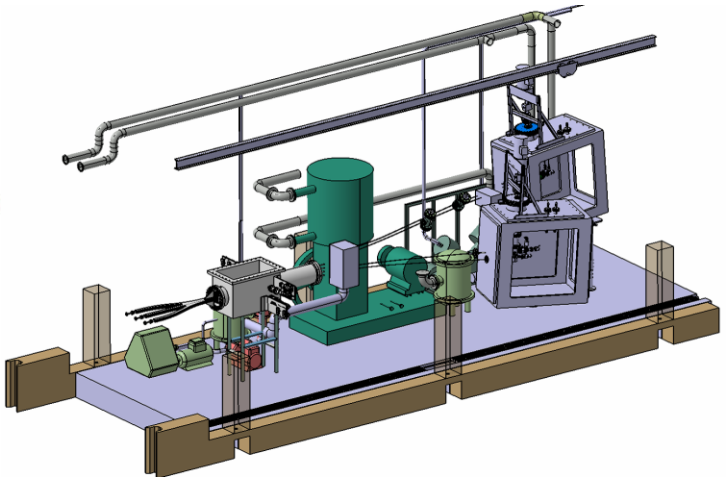
6 HFS & 3 LFS Pellet Guide Tubes

Up to 6 injectors deliver H, D, or DT pellets to

- **Provide a steady supply of deuterium and tritium fuel via HFS injection (~5mm DT pellets at 4 Hz)**
- **Mitigate the impact of ELMs via LFS or HFS (~3mm D_2 pellets at 45 Hz)**
- **Pellet speed = 300 m/s to survive the curved guide tubes**



PIS cask

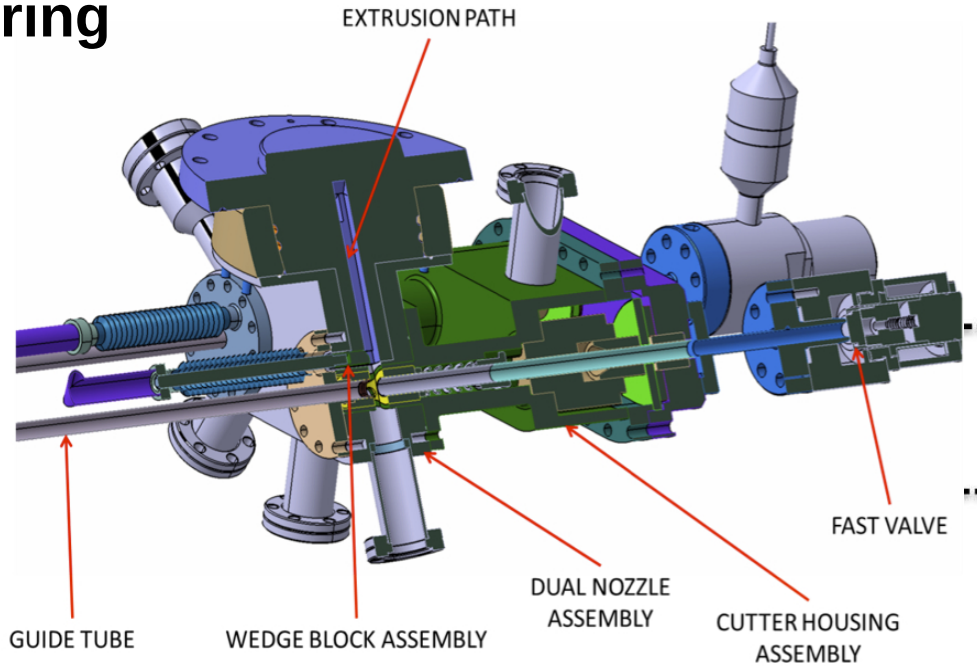


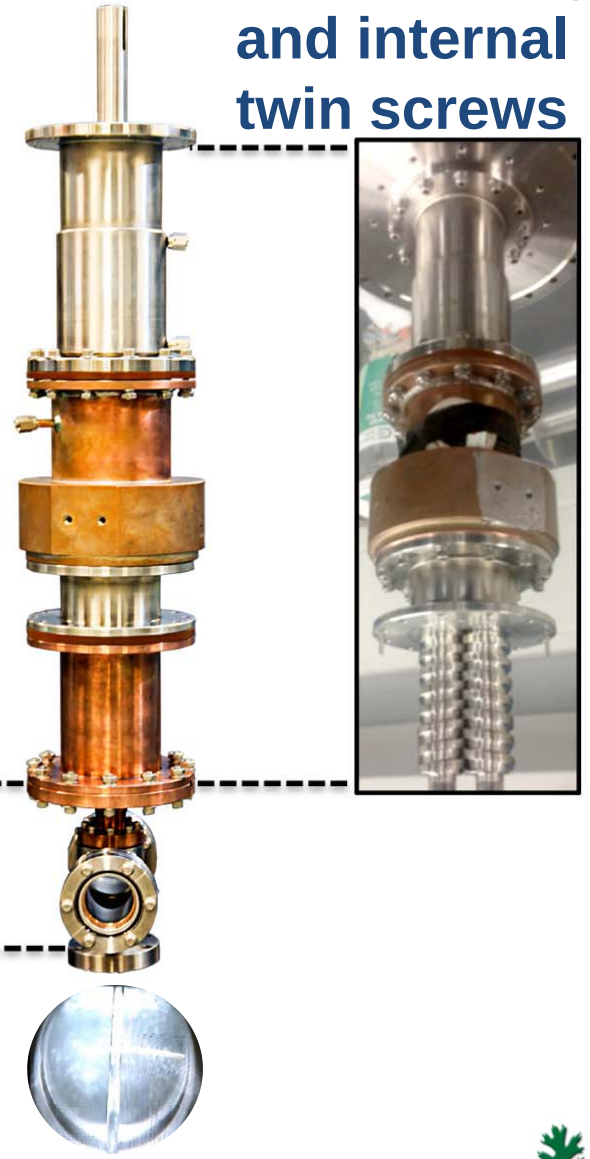
PIS cask internal subsystems

Pellet Injector Continuous Twin-Screw Extruder and Gas Gun are Under Development

- **Continuous D/T ice stream using twin-screw extruder**
- **Pellets accelerated by high- pressure gas**
- **Extruder nozzle produces adjustable length pellets for fueling or ELM triggering**

Extruder body and internal twin screws





Gas gun and pellet cutter

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