Pellet ELM Pacing and Disruption Mitigation Impacts on the Fusion Fuel Cycle

L.R. Baylor

Oak Ridge National Laboratory

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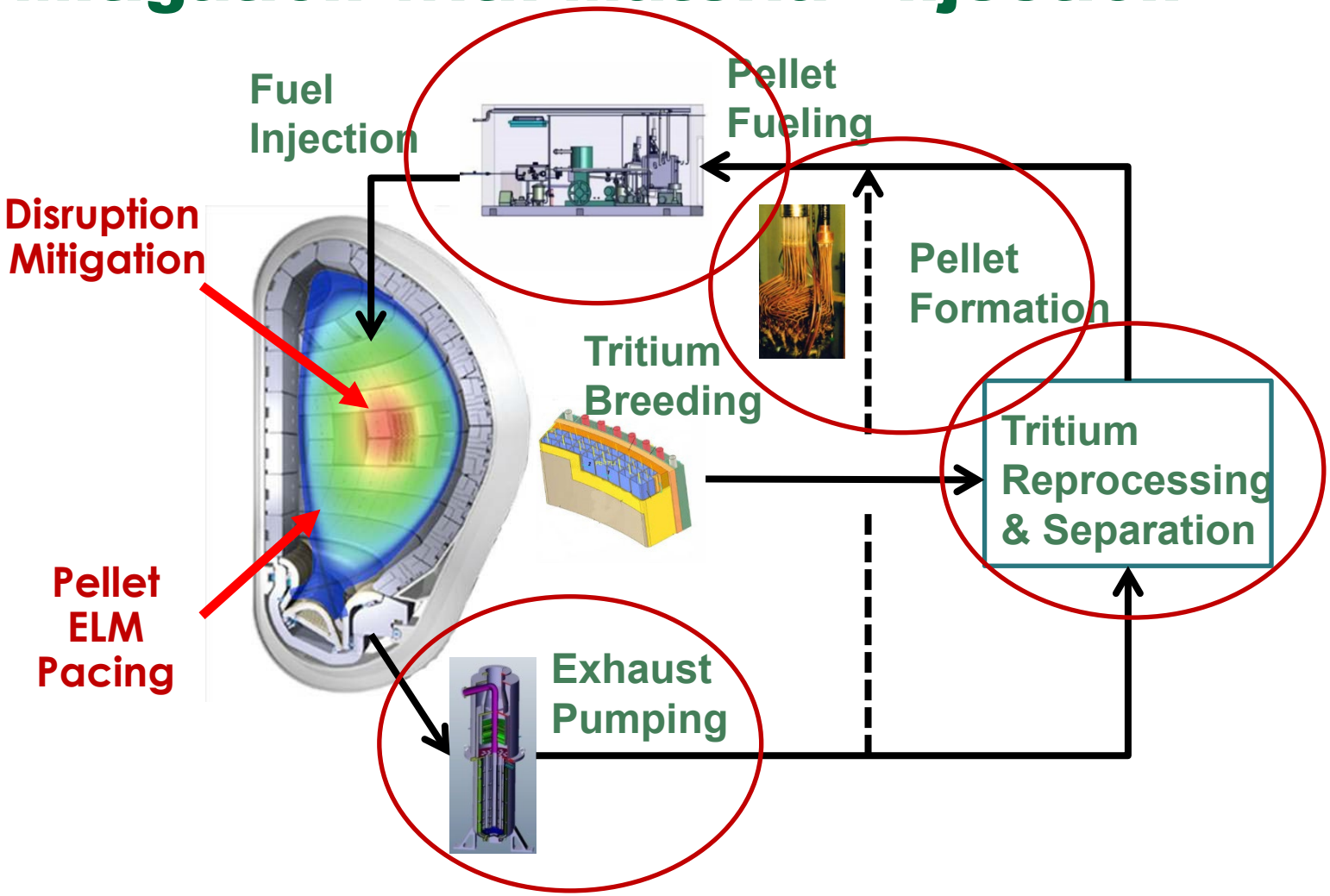
Outline

- Introduction
- Pellet ELM Pacing Technique and Impacts
- Disruption Mitigation Technology and Impacts
- Summary

Fusion Fuel Cycle Impacts from Transient Mitigation with Material Injection



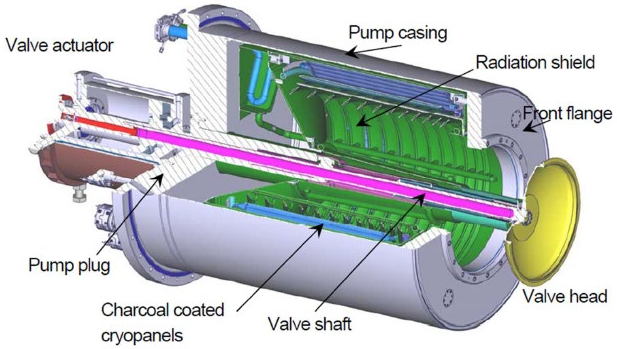
- What is the impact of material injection to mitigate ELMs and Disruptions?

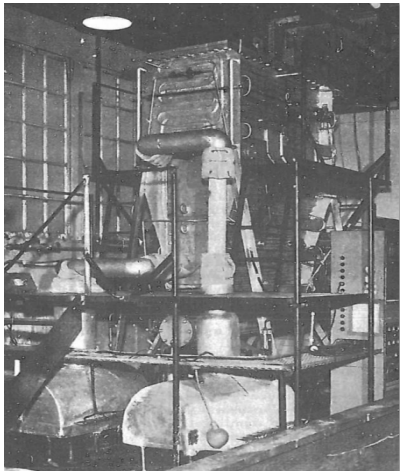
Fusion Exhaust Pumping

- Function: The torus vacuum pumping must maintain low divertor neutral pressure (~10 Pa) while removing helium ash that will be generated by the fusion burn.
  - Conductance from divertor to pumps must be high.
- Reactor requirements:
  - A Fusion Reactor will require reliable steady state pumping that can be controlled and maintained in a nuclear fusion environment.
  - It is likely that the pumping speeds and throughputs will be higher than ITER, and with a much higher duty factor.
  - Roughing pump system to pumpdown from high pressure
- Gaps: Tritium compatible pumping at fusion pressures and throughputs is a challenge

Fusion Exhaust Pumping Schemes

- Batch Cryopumps – T_2 inventory, Deflagration limit, thermal cycling, valve cycling, He pumping
- Continuous Cryopump – Snail pump prototype developed and tested
  - Mechanical scraper
  - Cryo separation
  - Helium compression for conventional pumping
- Liquid Metal Pumps (KIT): – Diffusion pump and liquid metal ring roughing pump
  - Needs separation of impurities and helium –
  - Superpermeable membrane separation
  - Promising technique proposed for EU-DEMO





Flow Rate Requirements for ITER and DEMO/FPP are a key Driver for Technology

- Fueling and exhaust flow rates for ITER are nominally 120 Pa m^3/s = $6x10^{22}$ atoms/s
- At a divertor pressure of 10 Pa, this will require pumping speeds on order of 12 m^3/s = 12000 L/s, but more like 100 m^3/s is needed.
- EU DEMO has similar fueling rates of $2x10^{22}$ (Ploeckl, et al., FST 2021) and will therefore have similar pumping needs.
- For the remainder of this talk we will use ITER flow rates and volumes as typical for a future reactor

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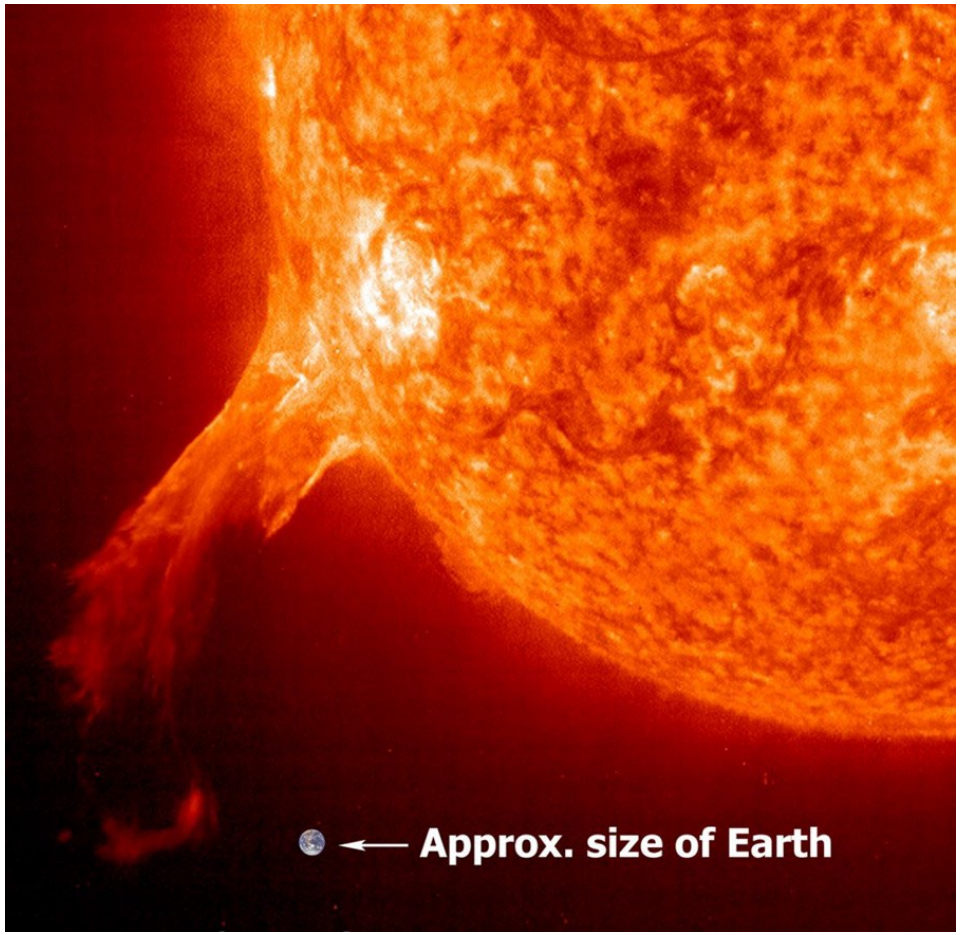
Solar Flares are the Stellar Equivalent of Edge Localized Modes (ELMs) observed in Fusion Plasmas

- Solar flares can release up to 16% of energy output in 1 second of the sun.
- Fusion plasmas can have ELMs that release up to 10% of the plasma stored energy to the plasma facing components.
- A mechanism to mitigate or eliminate ELMs are needed for fusion reactor plasmas to be controllable.



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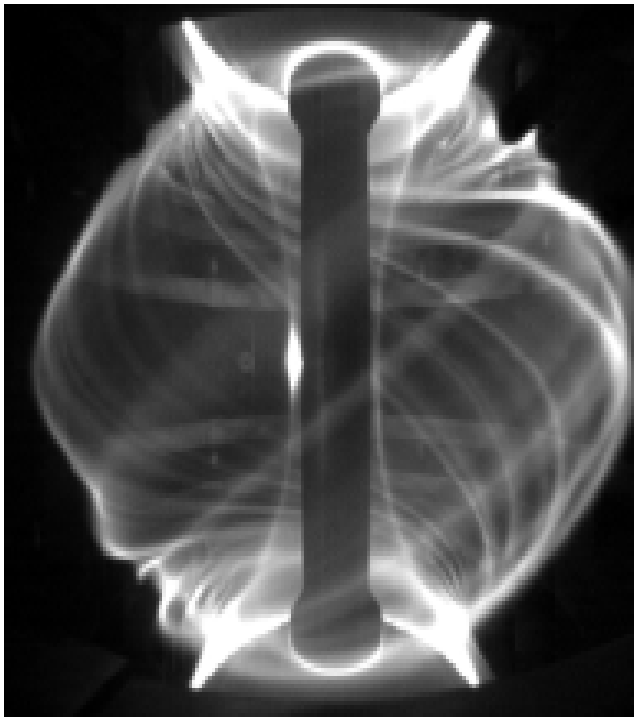
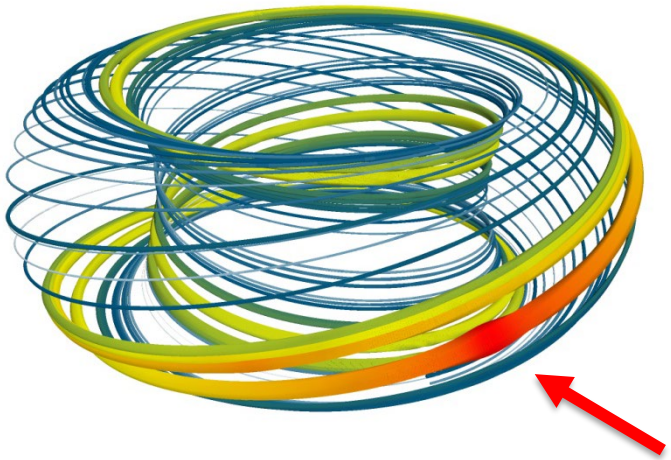
Pellets can Trigger on Demand ELMs to Increase the ELM Frequency and Reduce the Intensity

Edge Localized Mode: periodic instability located at the H-mode edge transport barrier – like solar flare



Filaments evolving during ELM on MAST. (Kirk, et al. PRL 2004.)

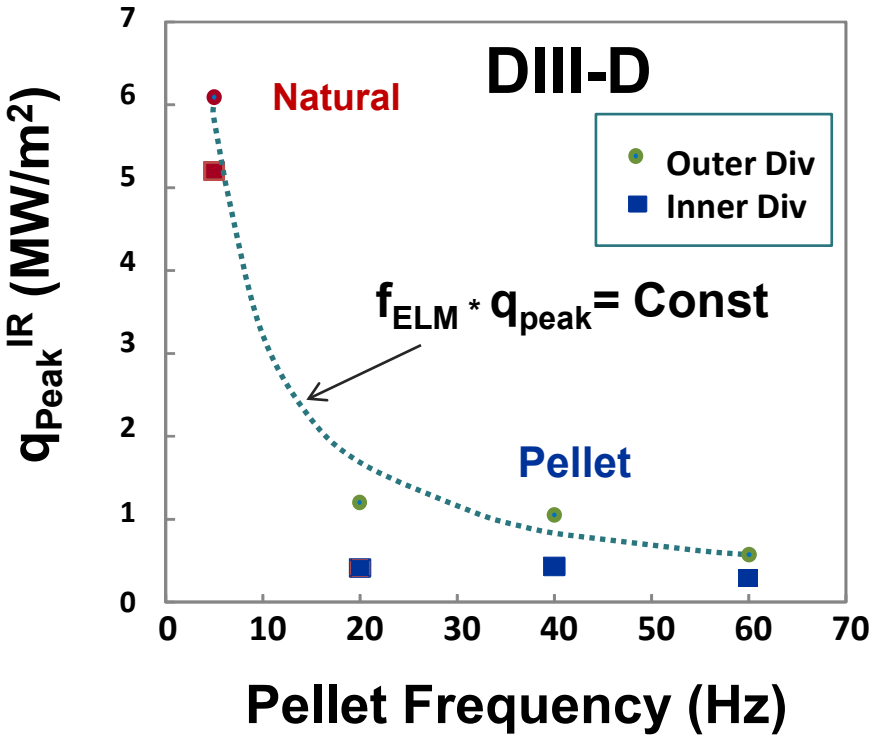


Pellets (Comets) can be used to trigger ELMs (Solar flares) before the edge pressure leads to large natural ELMs

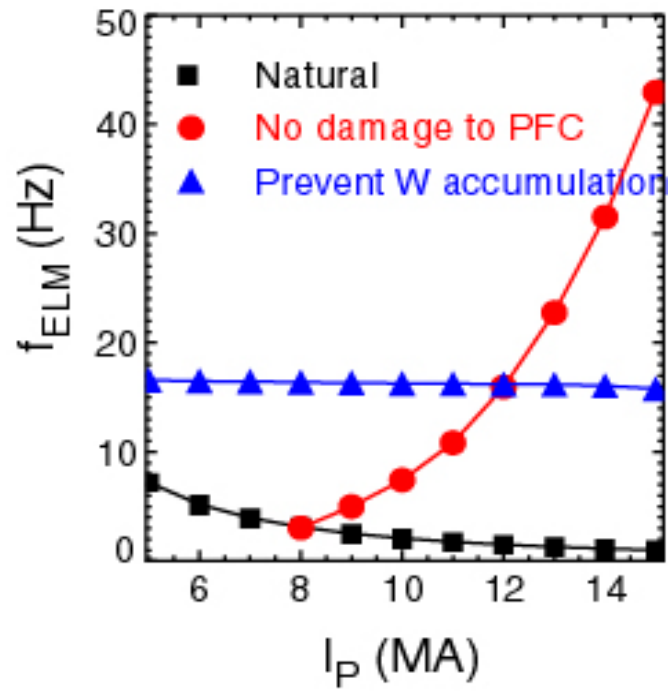
[S. Futatani, et al., Nuc. Fus. 2014]

AUG first to show pellet ELM frequency control (Lang, et al. NF 2003)

D_2 Pellet ELM Pacing Demonstrated on DIII-D at 12x, Needs to be Extended to 30x for ITER



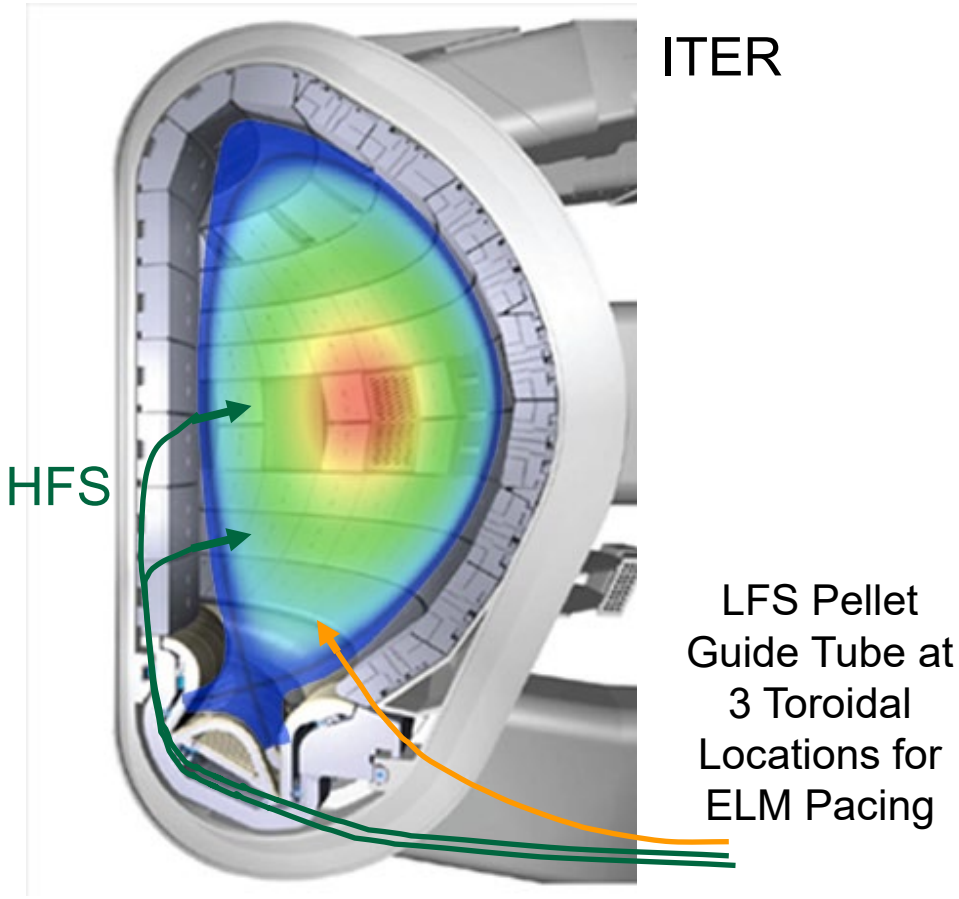
Baylor, PRL 2013



Loarte, NF 2014

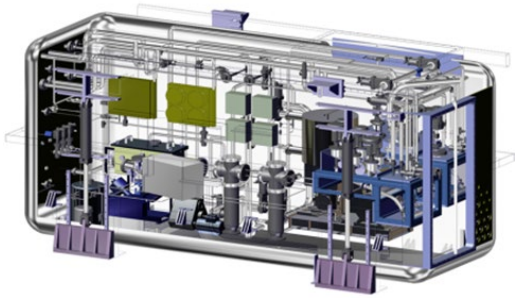
- ELM energy density must be reduced to ≤ 0.5 MJ/m^2 to prevent melting of tungsten divertor.
- Efforts to further the understanding of Pellet ELM Pacing in more ITER like conditions are underway.

Pellet ELM Pacing is Planned for ITER to Mitigate PFC Damage from ELM Bursts

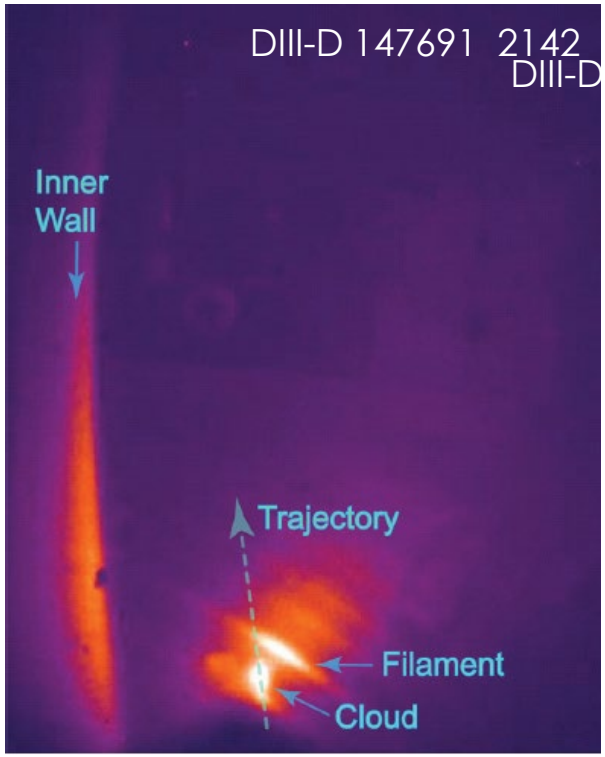


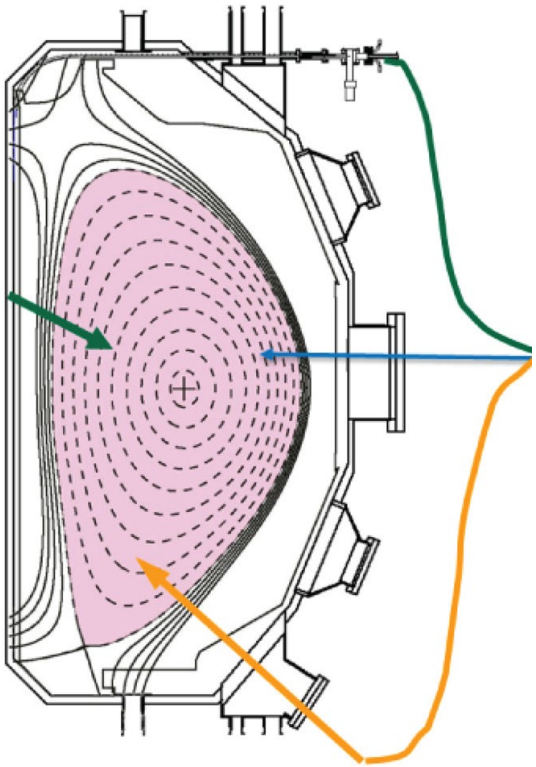
[S. Maruyama, IAEA2012]

- **Uses the same technology as for pellet fueling, but with smaller more frequent pellets**
- **Each injector to be capable of 16Hz 3 mm pellets for ELM mitigation**
- **Synchronization of multiple injectors will need a supervisory control system**



Pellets from LFS can Trigger Rapid on Demand Small ELMs to Mitigate PFC Damage

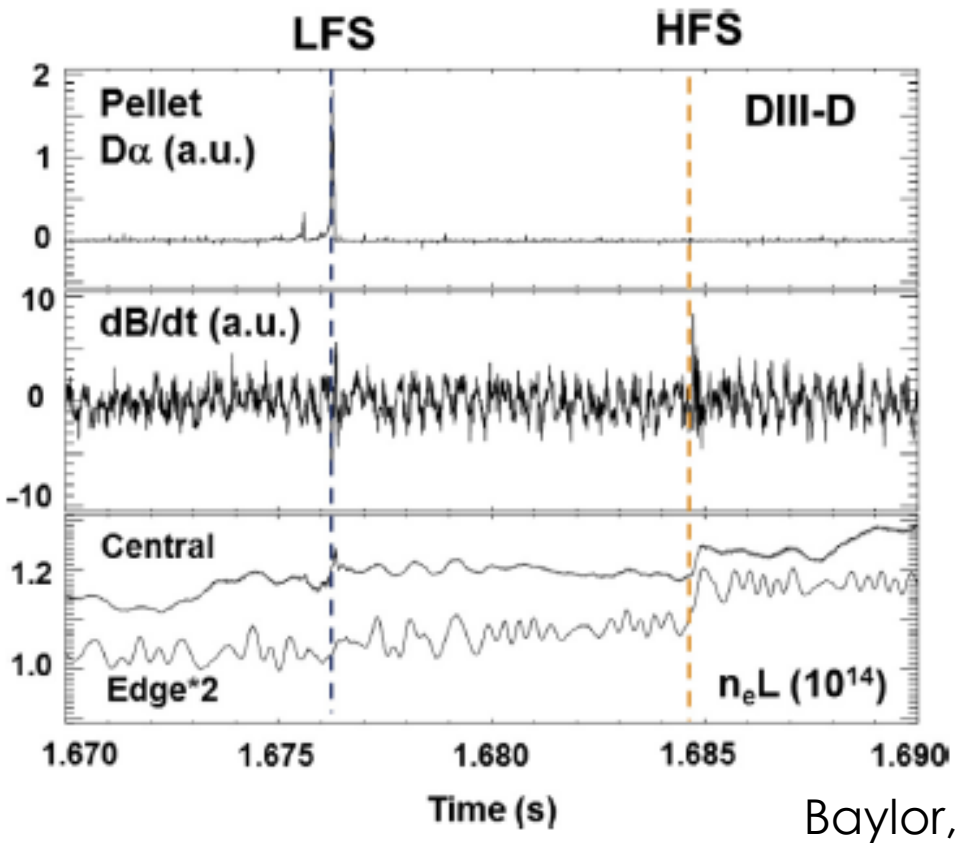




X-point pellet exciting a filament as it enters the plasma and triggers an ELM.

Baylor, et al, Phys Plasmas (2013)

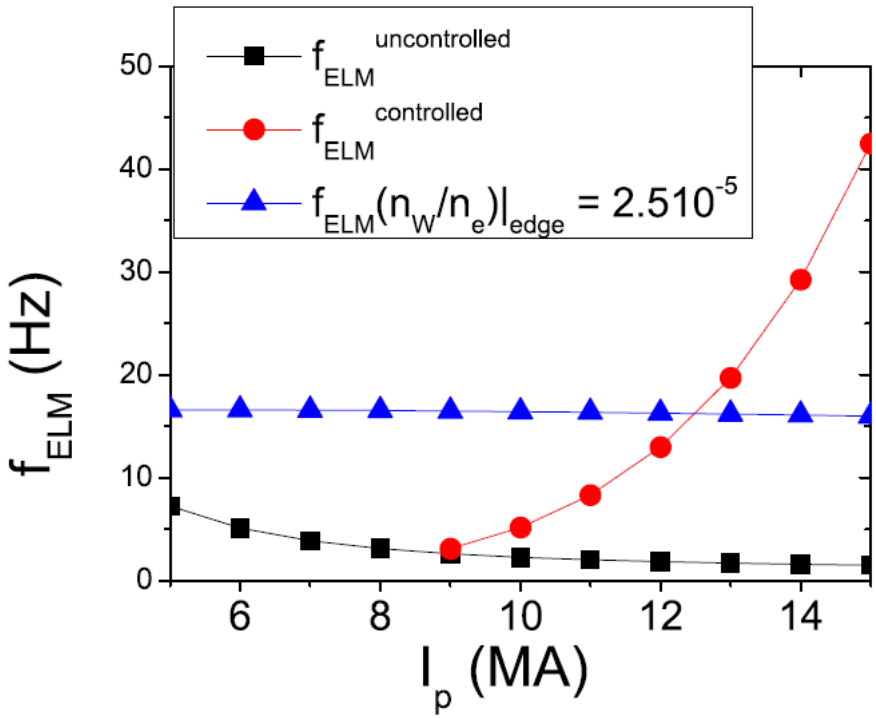
Pellets from LFS that Trigger ELMS Result in Virtually No Plasma Fueling



Baylor, et al, JNM2015

- **LFS injected pellets that trigger ELMs result in very low fueling, while HFS injected pellet do fuel and also trigger ELMs.**

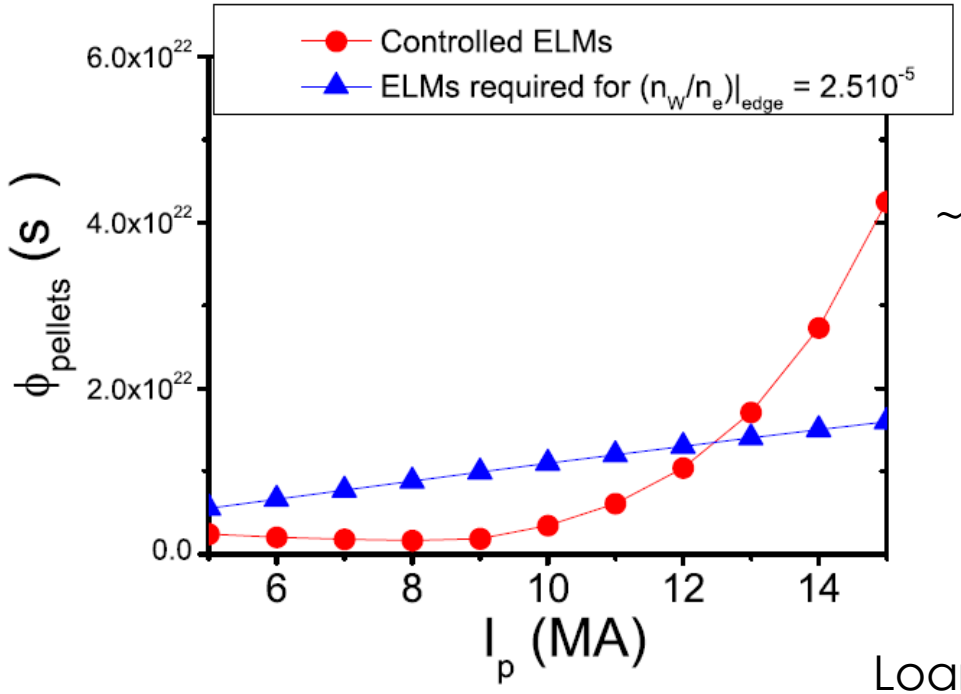
ELM Frequency Expectation to Keep W Accumulation in ITER at Tolerable Level



Loarte, et al, NF2014

- Expected ELM frequency for uncontrolled and controlled ELMs (evaluated for $(A_{ELM}/A_{inter\text{-}ELM} \sim (W_{ELM}/W_{ped})_{0.45})$ in ITER H-modes and required ELM frequency to maintain an edge W concentration of 2.5×10^{-5} for range of plasma currents.

Fuel Throughput with Pellet ELM Frequency that will Occur to Prevent W Accumulation



~(120 Pa m^3/s)

Loarte, et al, NF2014

- Required fuel throughput for pellet injection to control ELMs (evaluated for $(A_{ELM}/A_{inter-ELM} \sim (W_{ELM}/W_{ped})_{0.45})$ in ITER H-modes and for the ELMs required to maintain an edge W concentration below 2.5×10^{-5} for range of plasma currents.

Implications of Pellet ELM Pacing for ITER Requirements and Flow Rates

- Pellet ELM Pacing Flow rate can be larger than the fueling flow rate
  - ITER fueling pellet is $6x10^{21}$ – so 4 Hz rate is $2.4x10^{22}$ (70 Pa m^3/s)
- This additional input does not fuel the plasma but will end up as neutrals in the divertor and needs to be pumped away, so pumping/reprocessing requirements significantly increased.
- DIR loop in reactor needs significant T supplement
- Divertor detachment control is also complicated by this additional periodic non-axisymmetric particle source in the divertor.
- Will pellets impact a detached divertor with radiation instability (MARFE) like events?
  - AUG experiments started to examine (Valovic EPS2018)
  - DIII-D has plans for dedicated experiments.

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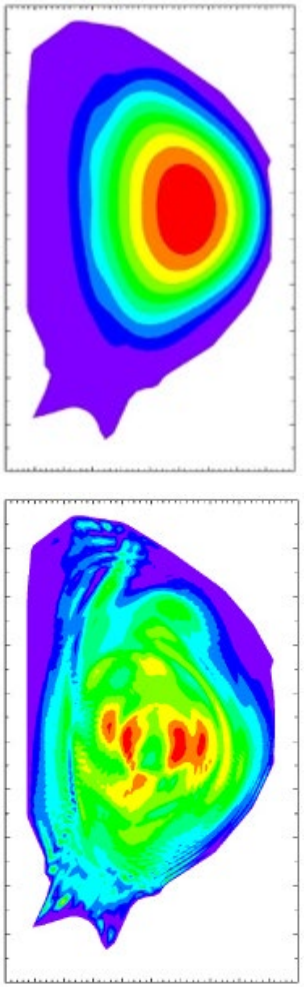
Disruptions Present a Challenge for Tokamak Fusion Devices and Must be Mitigated

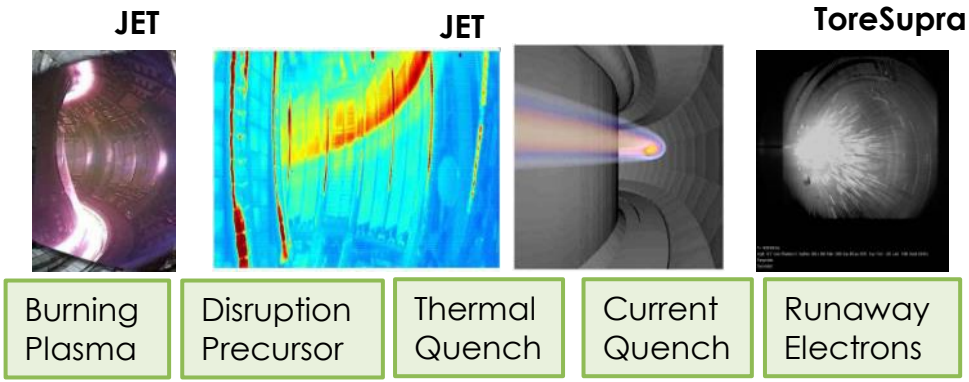
- A tokamak disruption is a sudden loss of plasma confinement on the time scale of ms, which induces a fast loss of thermal energy (by conduction and radiation) called the thermal quench (TQ) followed by a fast loss of plasma current called the current quench (CQ).
- The large toroidal electric field induced by the rapid current decline during the CQ can generate high energy (tens of MeV) runaway electron currents (RE) of many MA which can damage in-vessel components.
- Robust disruption mitigation remains a major challenge for the reliable operation of ITER and all long-pulse tokamaks

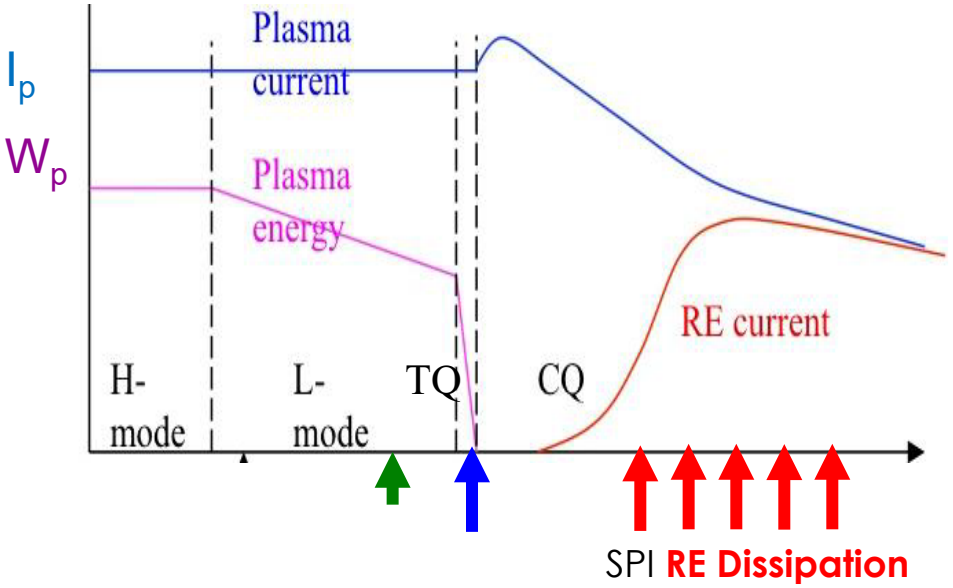


R. Paccagnella, et al., Nucl Fus 2009

Mitigation of Disruptions is a Challenge for Large Burning Plasmas

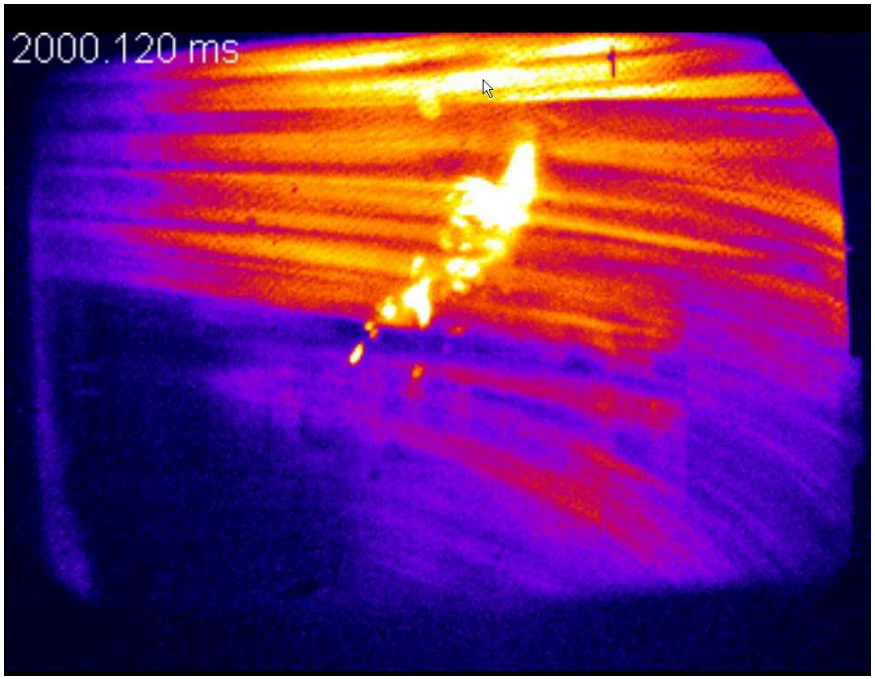
- Large Thermal Loads occur during Thermal Quench – TQ peak heat loads need reduction of > 10 X
- Large Mechanical Loads on plasma facing components and vessel during Current Quench - CQ decay time must be held within limits of 50-150 ms
- Runaway electrons can be generated during Current Quench - RE current must be suppressed or dissipated to less than 2 MA
- Mitigate with material injection of hydrogen, deuterium, and neon to radiate plasma energy
- Method developed to inject material Shattered Pellet Injection (SPI)

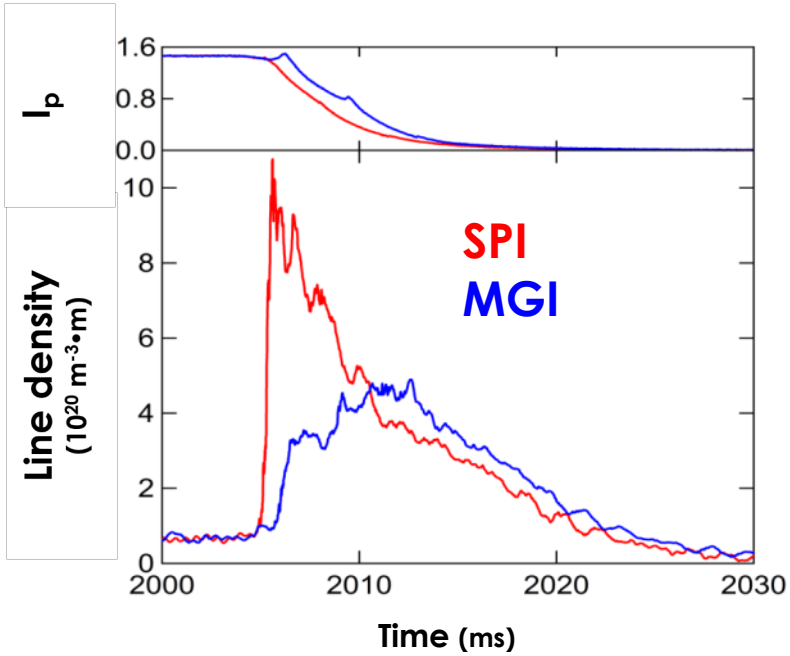




Preventive SPI of material for **Thermal Mitigation** and **Runaway Electron Suppression**

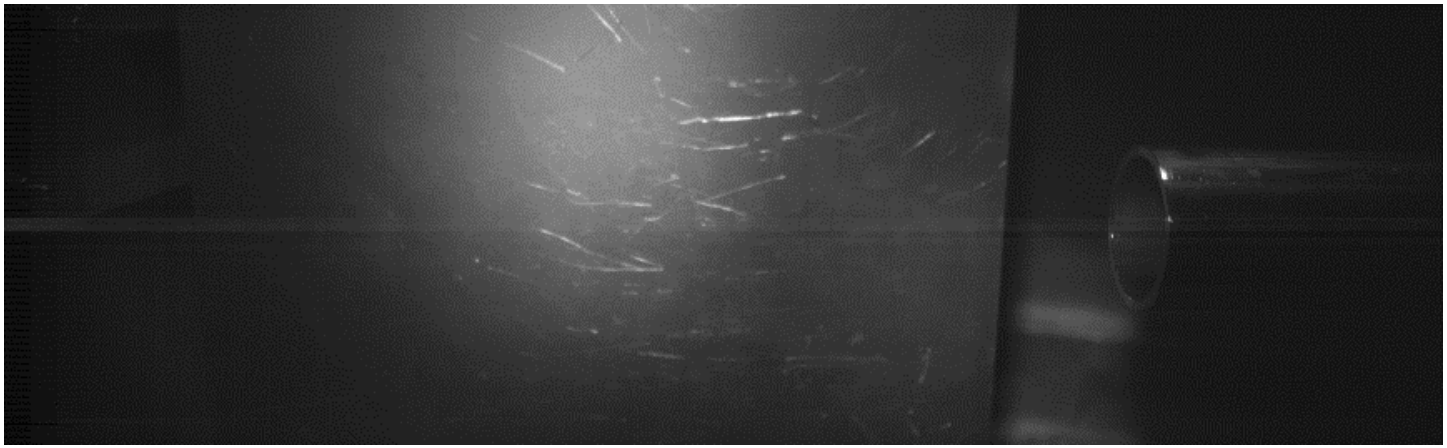
Shattered Pellet Injection has been Shown to be an Effective Disruption Mitigation Technique and is Planned for ITER





[N. Commaux, et al., Nucl. Fusion 2011, APS 2014]

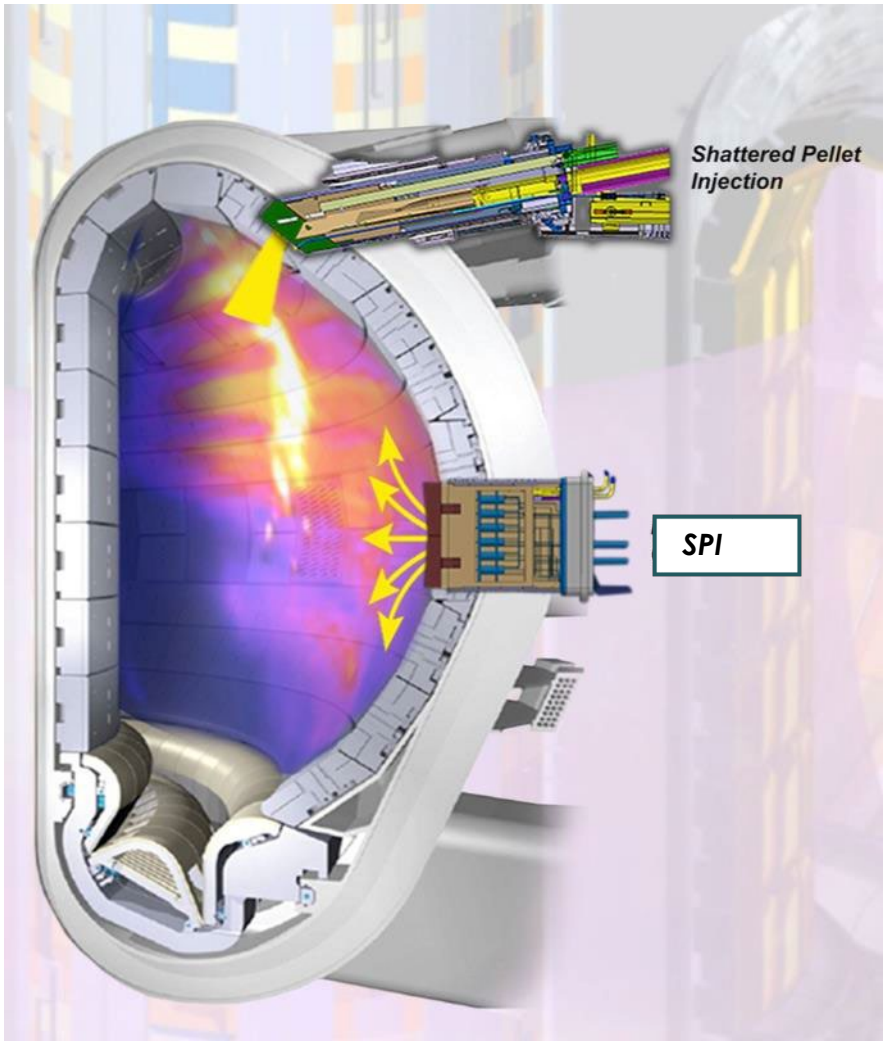
Fast Camera Movie of Pellet Shattering Allows Characterization of Fragment Size and Velocity



T. Gebhart

- **12.5mm D_2 pellet showing well collimated short duration ~1ms spray exiting the shatter tube.**
- **Shattering properties as a function of material, kinetic energy, and shatter tube design have been investigated** (T. Gebhart, et al., FST 2020)

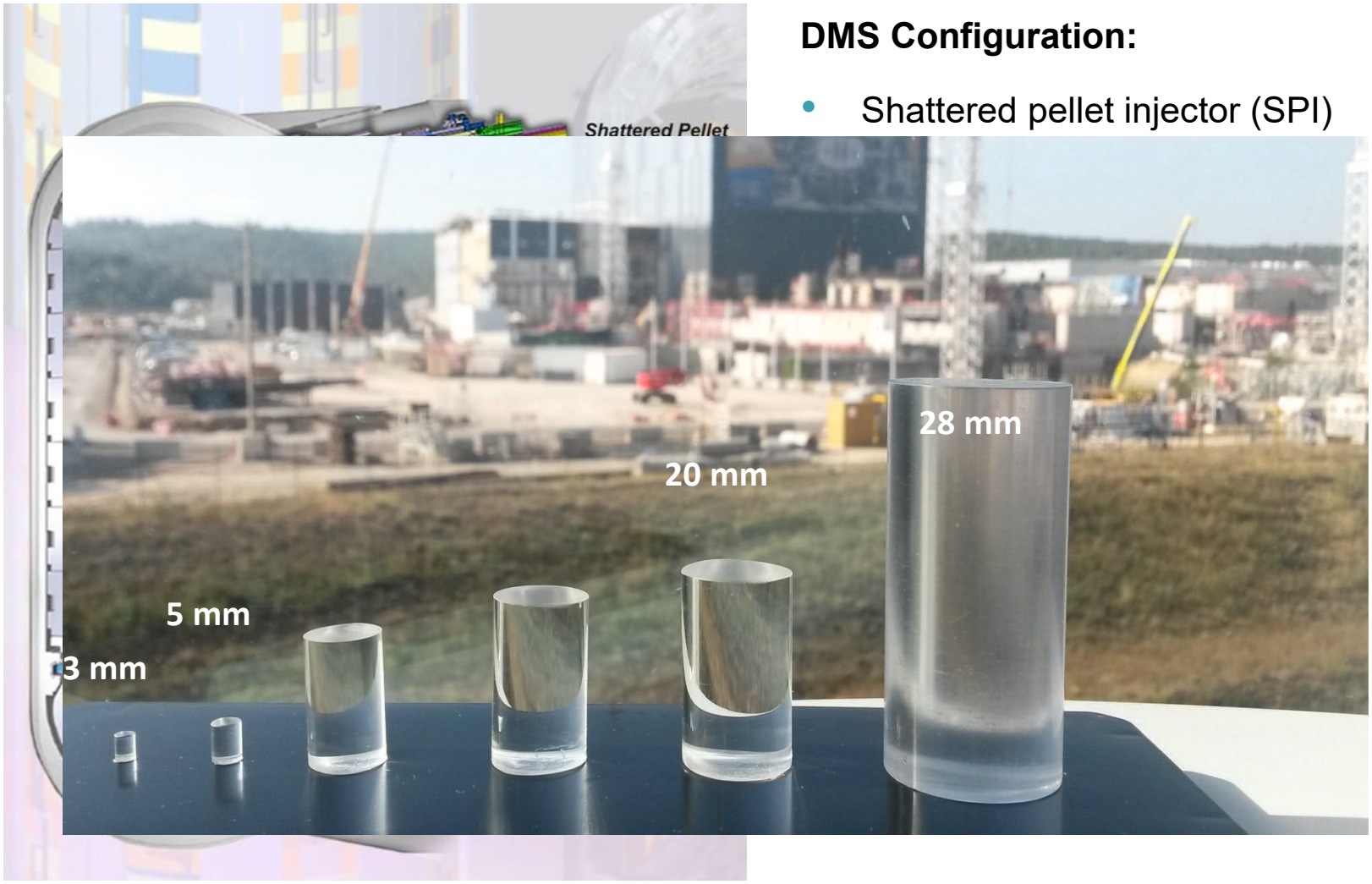
Disruption Mitigation System Configuration for ITER



DMS Configuration:

- Shattered pellet injector (SPI) located in 3 upper ports with pellet shattered near plasma edge
- Multiple SPIs to be located in each of 3 equatorial ports for runaway electron mitigation
- A total of 27 SPI pellets are available for DMS (M. Lehnen, et al., IAEA TM DM 2022)
- Space needed for injection lines will reduce breeding blanket area in a reactor

Disruption Mitigation System Configuration for ITER



DMS Configuration:

- Shattered pellet injector (SPI)

Disruption Mitigation System Material Injection is Significant

- SPI material for ITER – 27 large 28 mm size pellets, mostly H_2 with Ne
  - Lehnen, et al., IAEA TM DM 2022
  - Total amount is 1000 bar-L gas equivalent
  - If all are use, then P rises to ~ 1 mbar
- How much material for FPP/DEMO?
  - Unknown, but likely similar to or > ITER
- Likely use of H_2/D_2 with Ne, Ar unlikely
  - Low Z to densify plasma to prevent RE production
- Alternative techniques – dust implications – T retention, vacuum system contamination – filtration needed

Disruption Mitigation Impact on Fuel Cycle

- Increase in vessel pressure will impact cryopumps
  - Valves too slow to prevent regeneration
  - Impact on Hg based diffusion pumps not clear
  - If all pellets are used, then vessel pressure rises to ~ 1 mbar
- Pumpout of 0.1-1% T contained gas by T compatible roughing system
  - Technology somewhat developed for ITER (Roots backed by Scroll pump)
  - Liquid metal ring pump looks feasible if Hg allowed
- Time to pumpout gas likely multiple hours
- Up to 1000 bar-L of gas will need to be processed to remove T
  - Clearly not able to recirculate gas to fueling system

Summary

- **Pellet ELM Pacing will add to the fuel cycle recirculation and reprocessing load**
  - Pellet ELM triggering to mitigate ELMs using small high rep-rate pellets
  - Divertor detachment control issue?
  - Will lead to D_2 rich fuel in DIR loop that will need to be blended with T_2.
- **Disruption mitigation leads to gas pumping and processing**
  - Injection tube design integration with blanket modules
  - Pressure in vessel may increase quickly to ~1 mbar (100 Pa)
  - Gas must be pumped and processed to recover quickly, ~1% T
  - Alternative non pellet/gas mitigation leads to dust which must be handled somehow (T_2 retention and dust flow)
- **Significant Design and Technical Challenges to the Fuel Cycle for the Mitigation - ELM and Disruption free fusion reactor is needed**

BACKUP ONLY

Pellet Injection
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Continuous Cryopump System Coupled to Pellet Injector Demonstration