Demonstration of ELM Pacing by Pellet Injection on DIII-D and Implications for ITER

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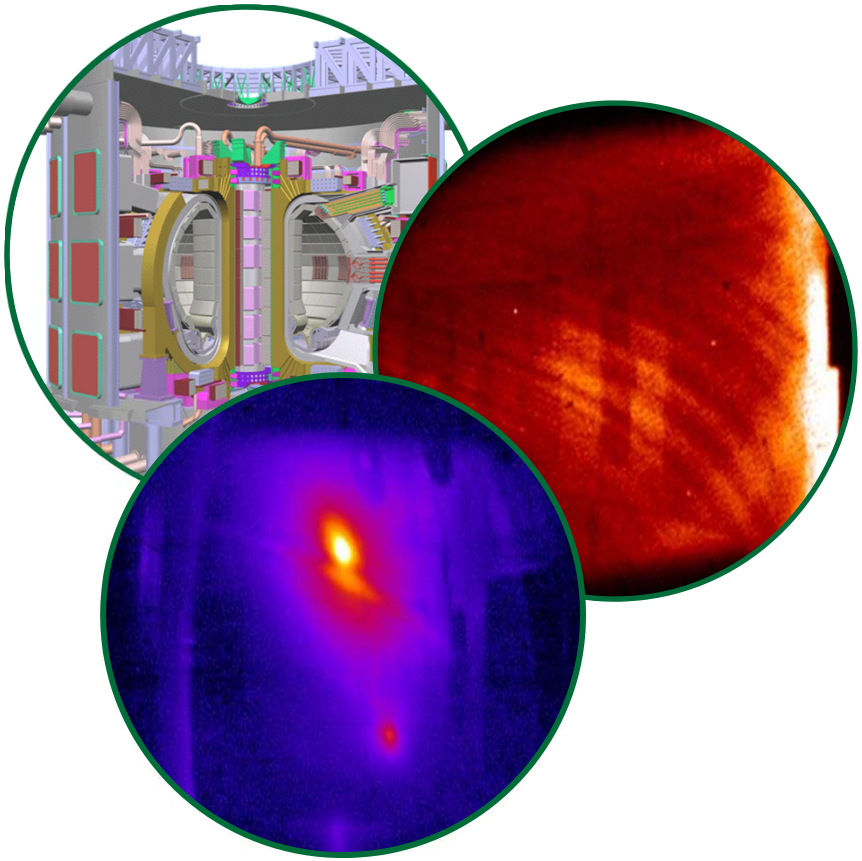

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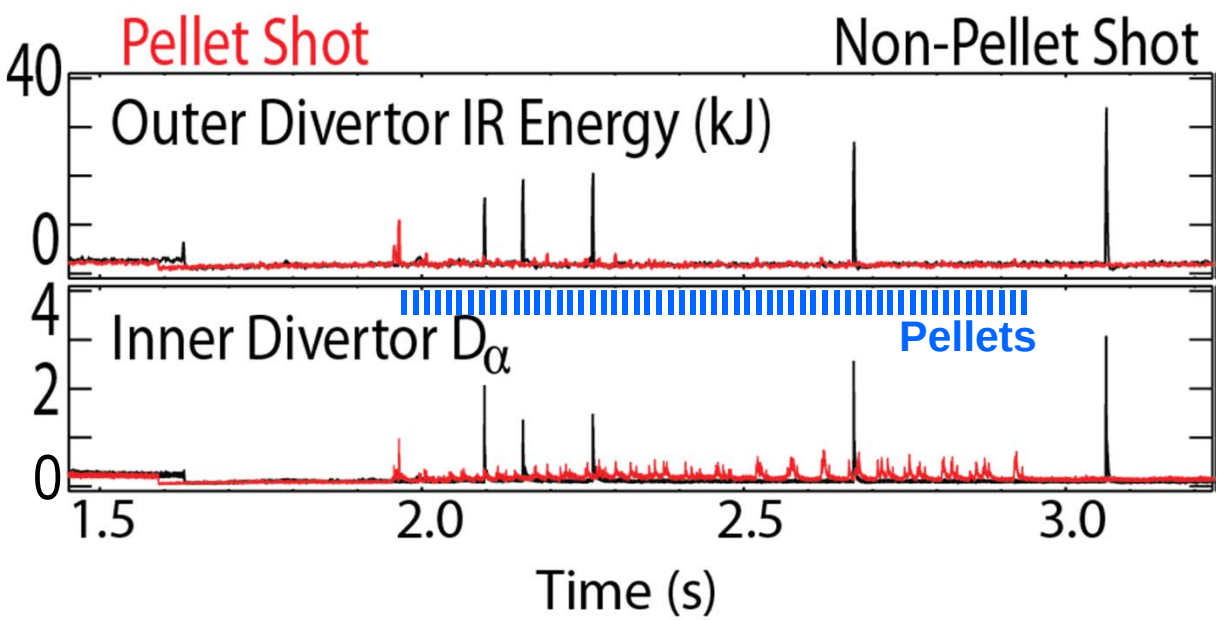
DIII-D has Demonstrated Viability of Pellet ELM Pacing Mitigation for ITER

- D_2 pellets injected in ITER configuration
- 12x increase in f_{ELM} with 12x reduction in ELM ΔW
- H factor maintained
- Impurities greatly reduced



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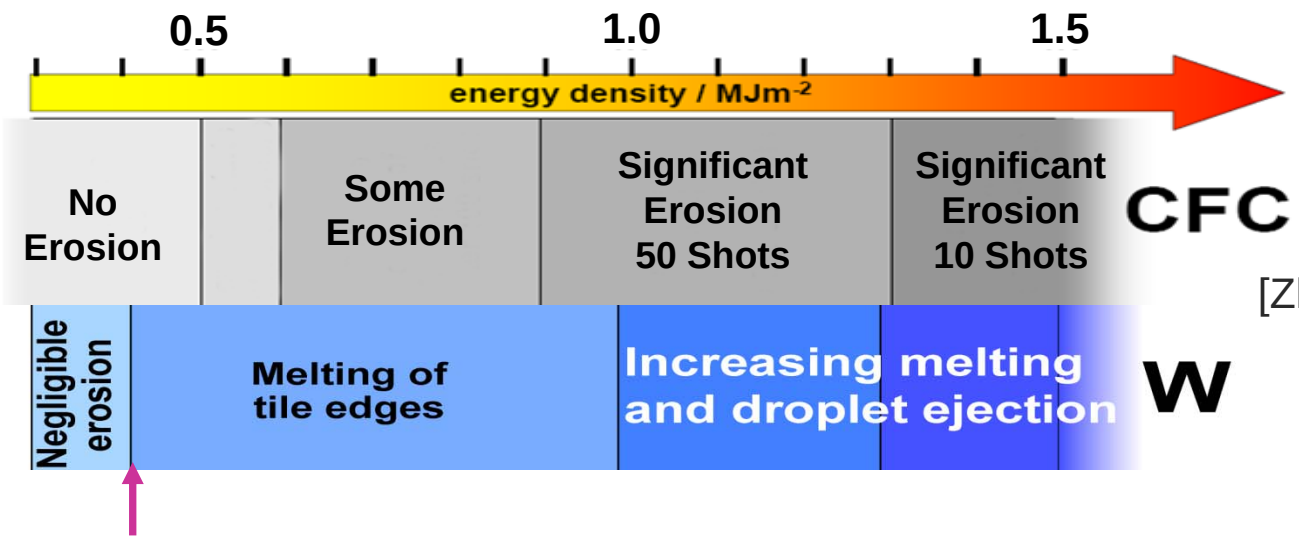
ELM Erosion of the Divertor is an Important Issue for ITER



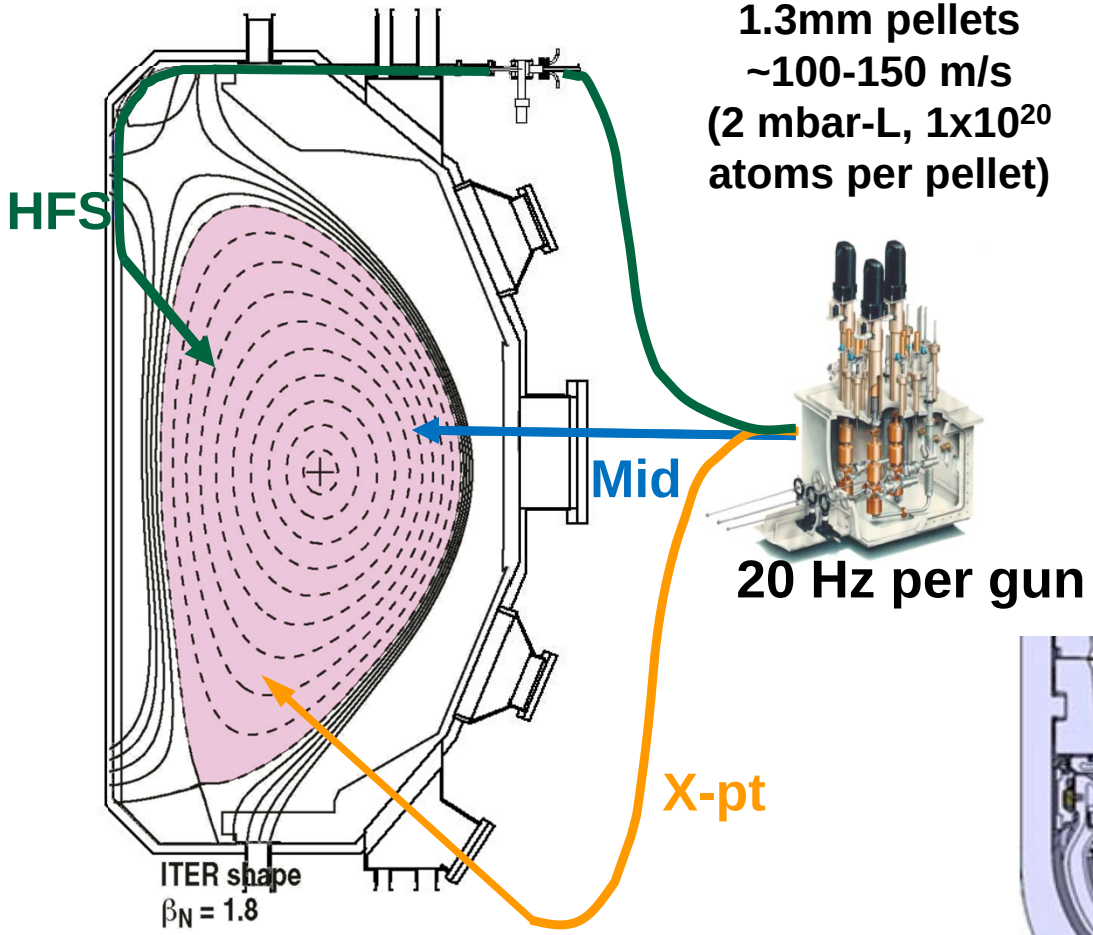
[Zhitlukhin et al., JNM, 2007]

ITER ELM size needs to be < 0.7 MJ for low erosion
Implying ELM triggering is needed > 30Hz if $f_{ELM}*\Delta W$ = **Const**
(>30x increase in natural ELM frequency)

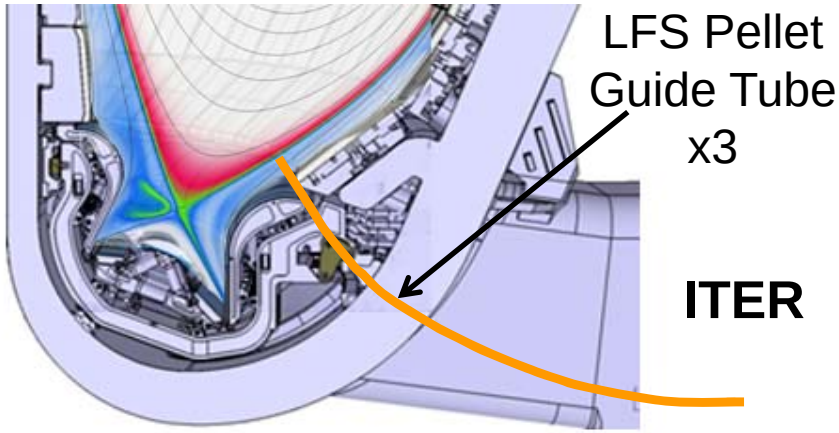
[A. Loarte, et al., IAEA 2010 and ITR/1-2 this conference]

- **Can pellets be used to trigger frequent ELMs on-demand to reduce ΔW?**

DIII-D Pellet ELM Pacing Experiment Performed with D_2 Pellets Injected from Low Field Side Midplane and X-point

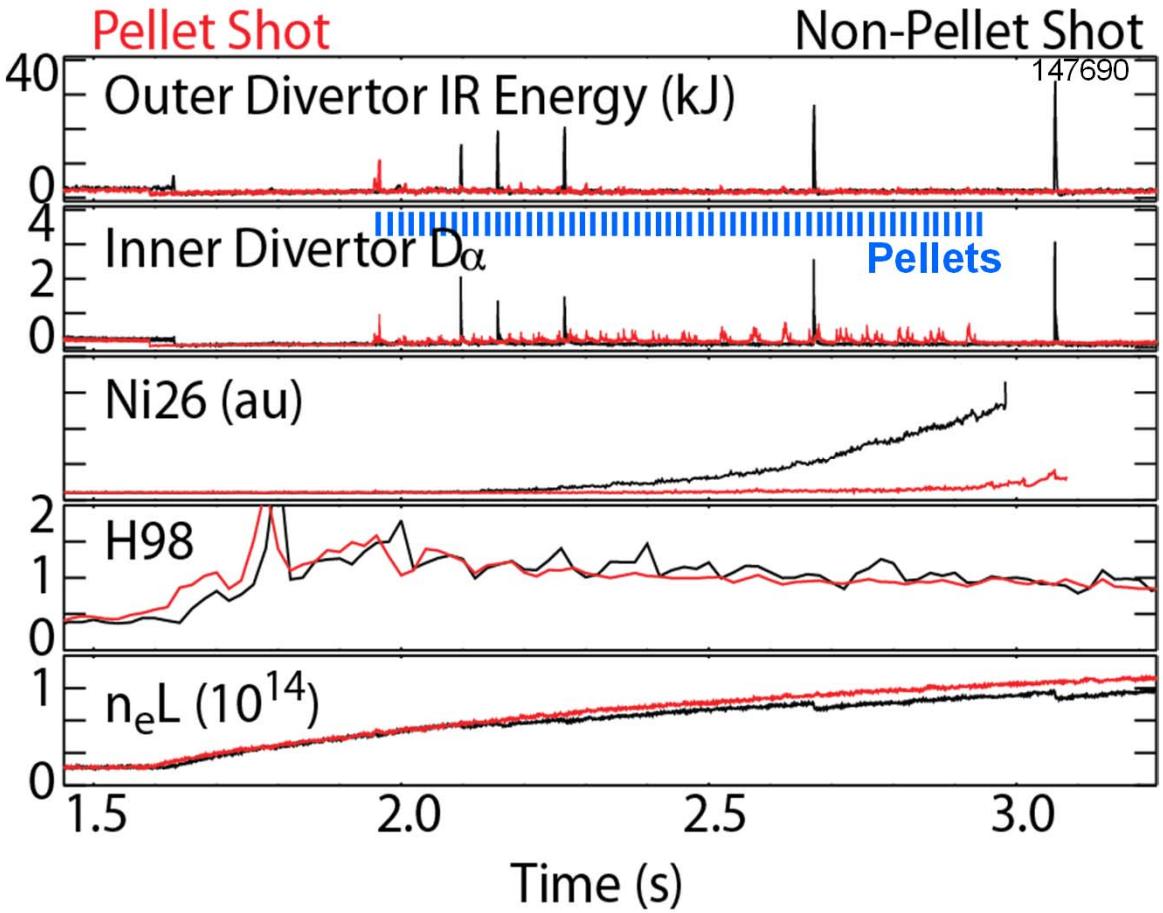


- New ITER like LFS X-point injection line installed on DIII-D.
- All 1.3mm pellets from X-point and Midplane reliably trigger ELMs – no fueling.
- HFS 1.3mm pellets trigger ELMs, but provide fueling.



[S. Maruyama, ITR/P5-24]

ELMs Triggered On-demand by 60 Hz Pellets at 12x the Natural ELM Frequency



- ITER shape, β_N~1.8, q_{95}=3.4
- ELM Pacing demonstrated 12x the natural ELM rate.
- 60 Hz 1.3mm pellets injected from LFS mid (20 Hz), X-pt (40Hz) at 100-150 m/s.
- Much lower energy loss ELMs observed with the pellets.
- Negligible fueling and reduction in H-factor observed.
- Reduced Ni in the plasma core with high rep rate pellets, $f_{ELM} * \tau_E > 15$.

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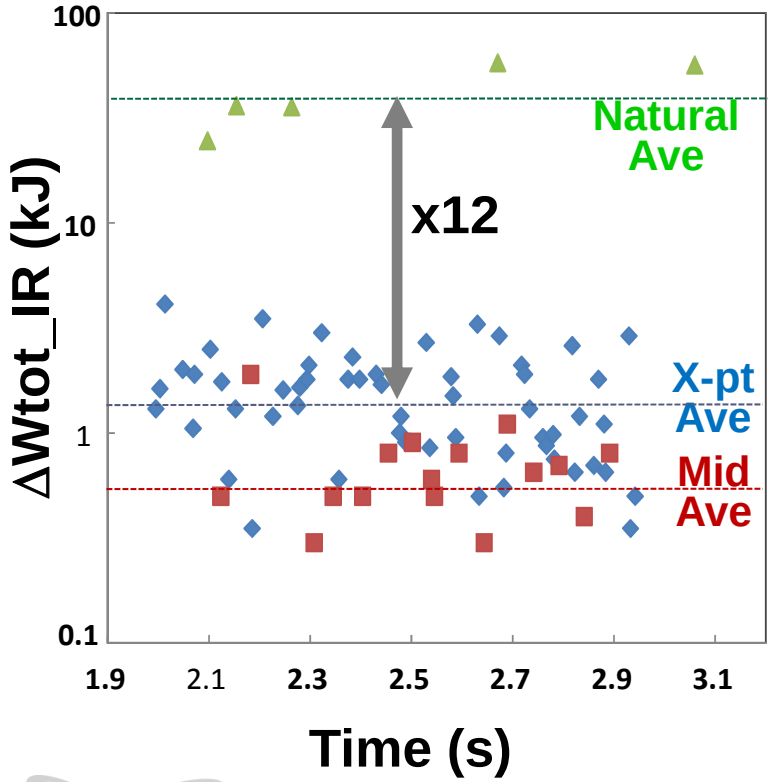
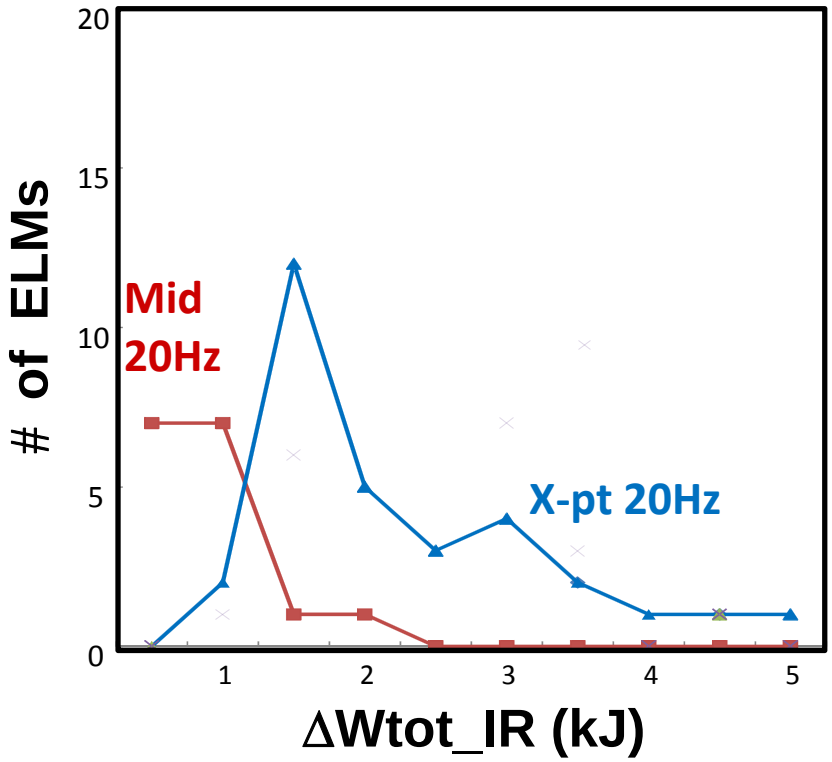
Divertor Heat Load from Pellet Triggered ELMs is Significantly Smaller than Natural ELMs

- The energy deposited (log scale) in the divertor from the IR camera data is significantly lower than the 5 Hz natural ELM case.
- The energy distribution spread is somewhat larger for the X-pt pellets.





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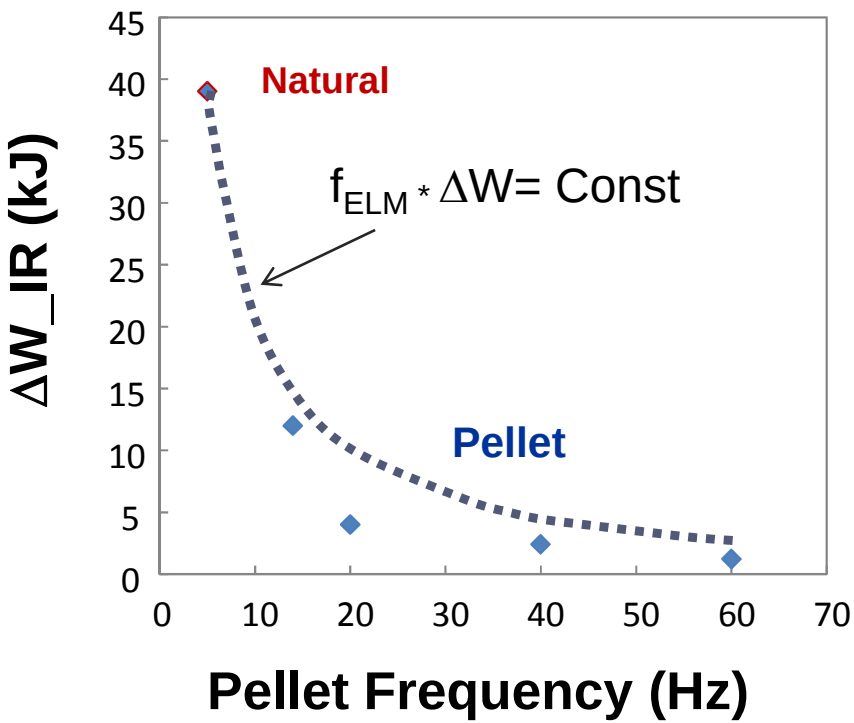
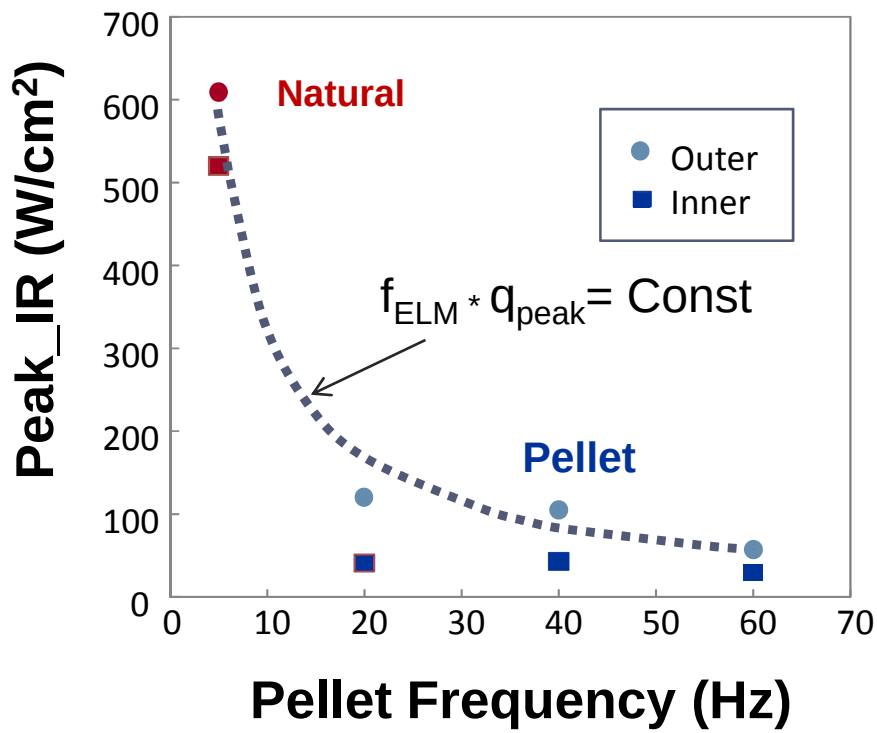
Divertor Heat Deposition per ELM Decreases as the Pellet Frequency Increases

- **The average energy deposited in the divertor per ELM decreases with increased pellet frequency.**
- **The peak heat flux in the outer divertor is greater than the inner divertor.**
  - The IR camera data is integrated assuming axisymmetric deposition





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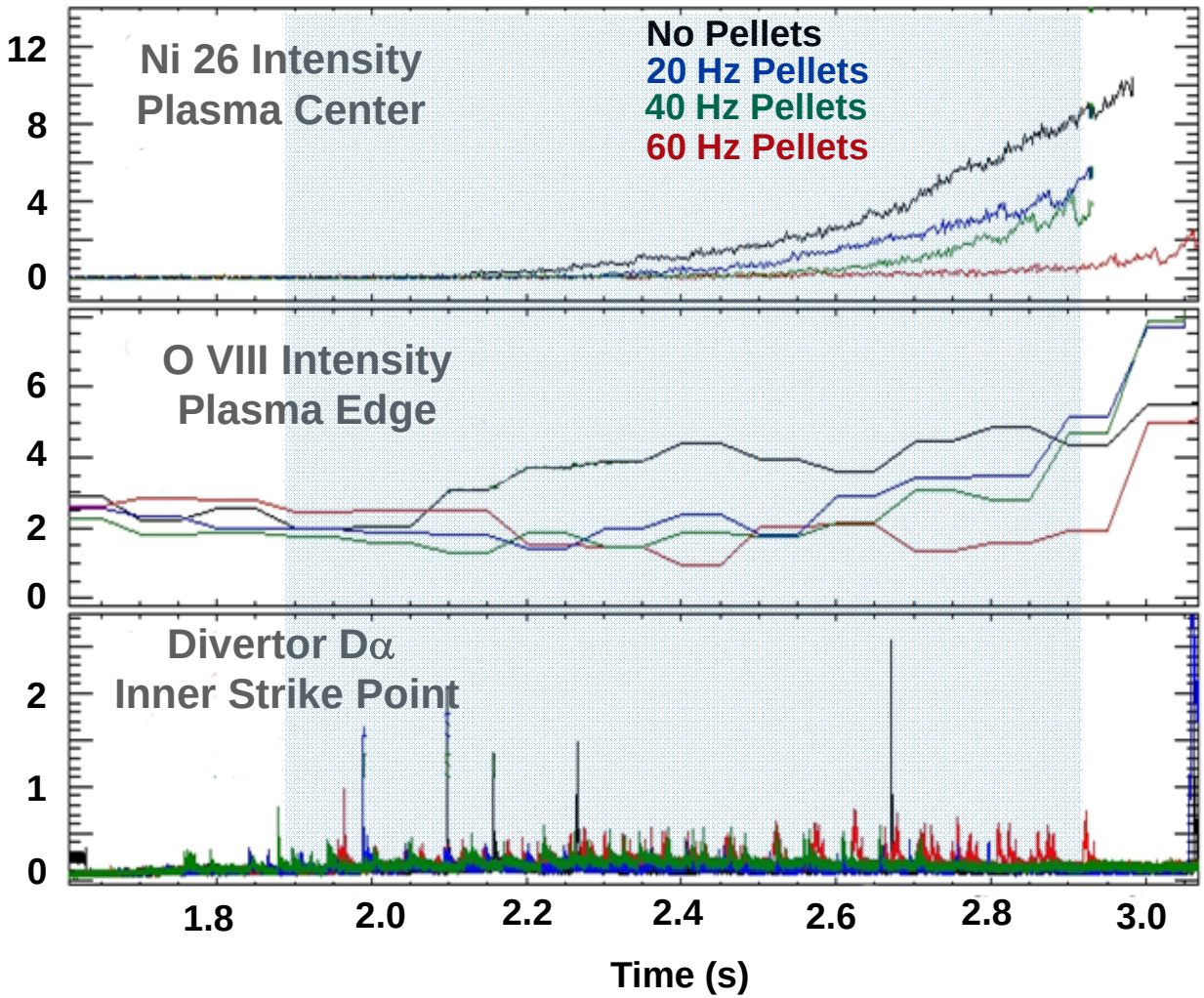
Reduction of Impurities Observed with Pellet ELM Pacing – A Function of the Pellet Frequency



- Reduced high-Z and lower Z impurities during pellet ELM pacing.
- STRAHL calculations indicate a reduced Ni density explains reduced emission.
- Higher frequency pellets reduces impurity levels.
- Impurities and natural ELMs return within τ_E.

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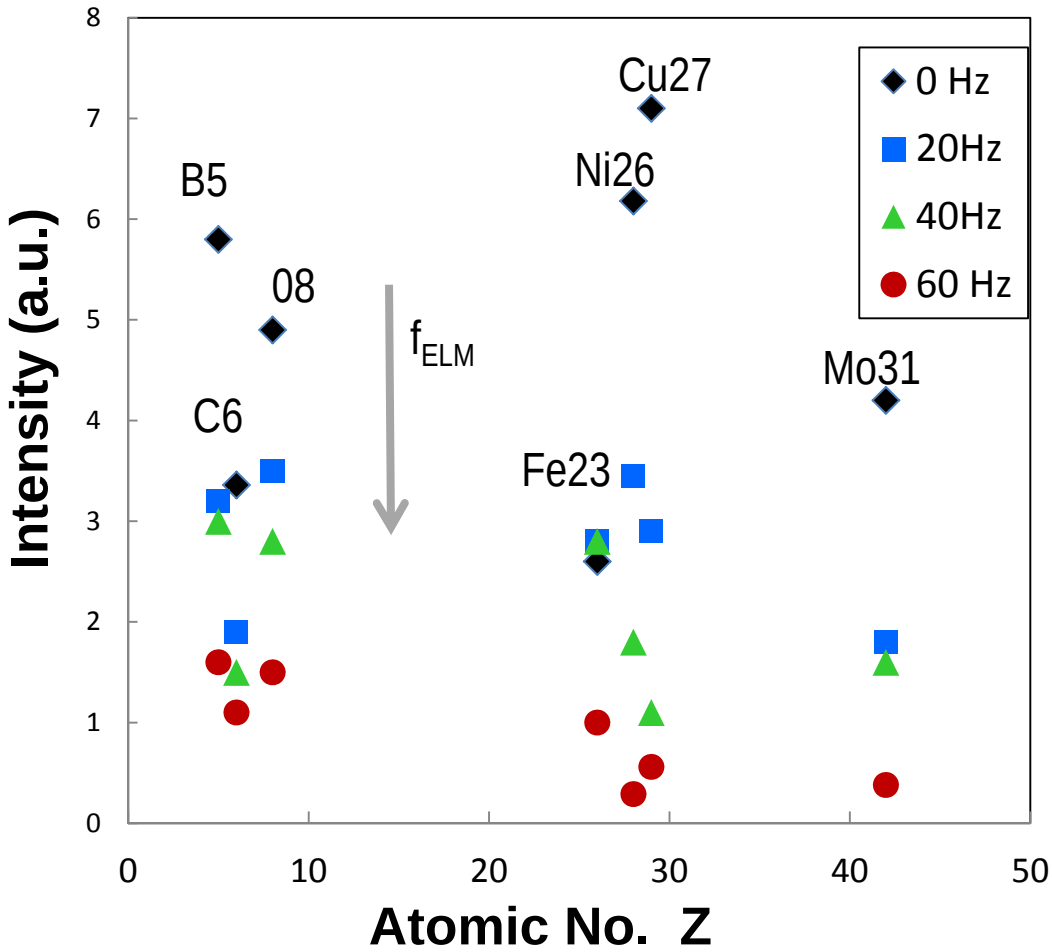
All Impurities are Reduced with Pellet ELM Pacing as a Function of the Pellet Frequency



- **SPRED and CX show a reduced impurities with pellet ELM pacing. (Data shown from 0.8s after the start of pellets)**
- **Consistent with earlier gas puffing results where impurities were entrained in the divertor with enhanced SOL flow.** [Wade, et al., JNM 1999]

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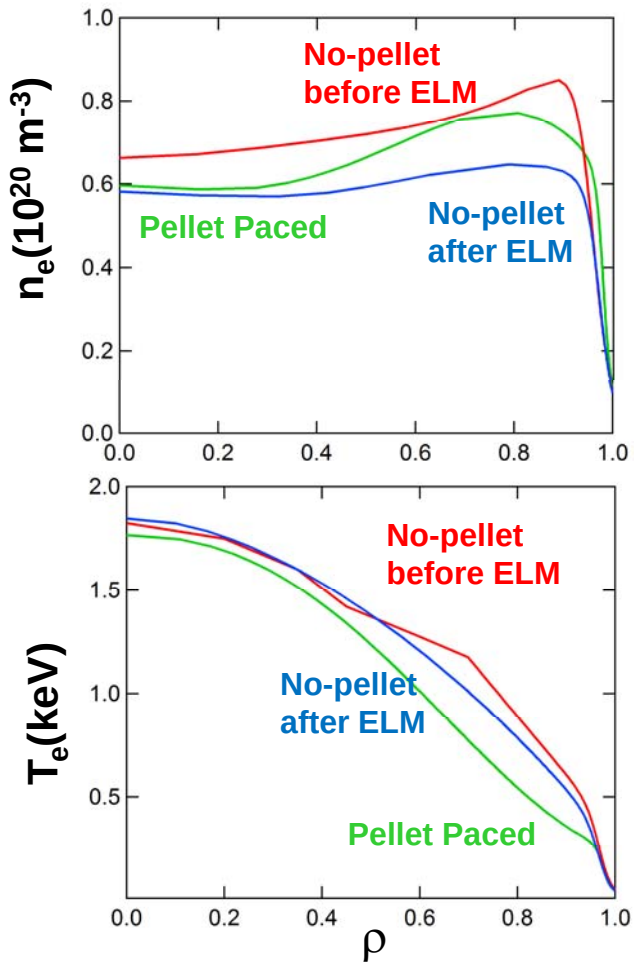
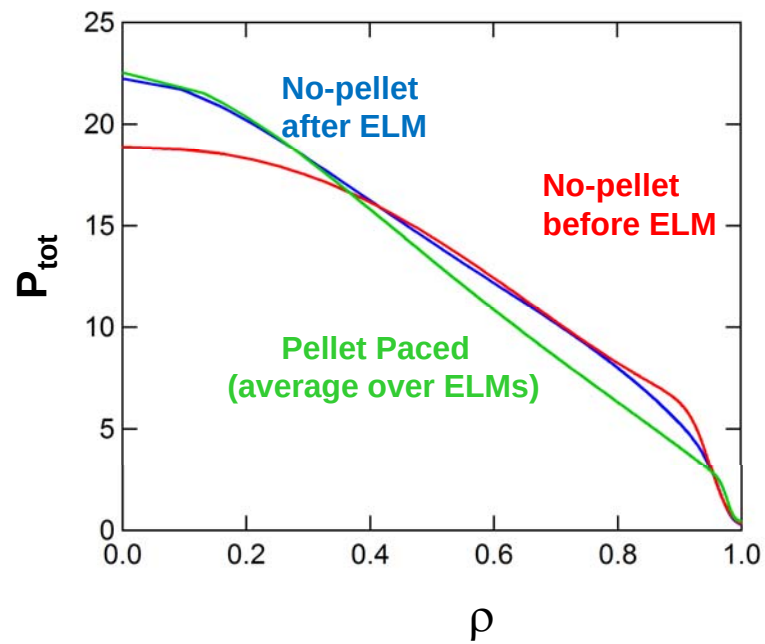
Pellet ELM Pacing Produces a Narrower Pedestal Width



- **Total pressure profile from the pellet ELM pacing has a narrower pedestal width and lower height.**

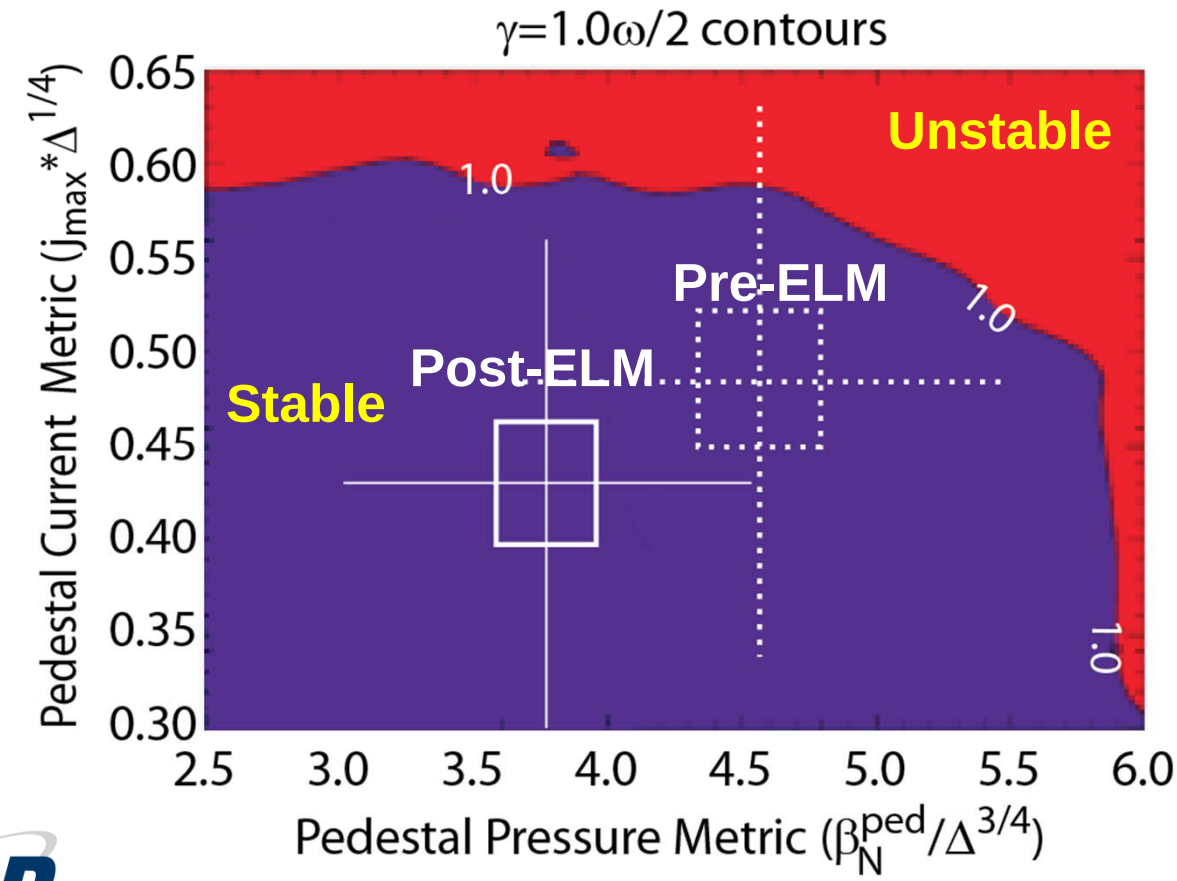
Note: Pellet case averaged over 200ms.

– Lower Z_{eff} and higher rotation shear help to compensate for lower pedestal pressure.



Natural ELMs Occur When Pedestal Width Becomes Unstable to Peeling Ballooning Modes

- **The boundary for peeling and ballooning stability in this plasma configuration is calculated by ELITE (P. Snyder, NF 2007).**



Natural ELMing Case

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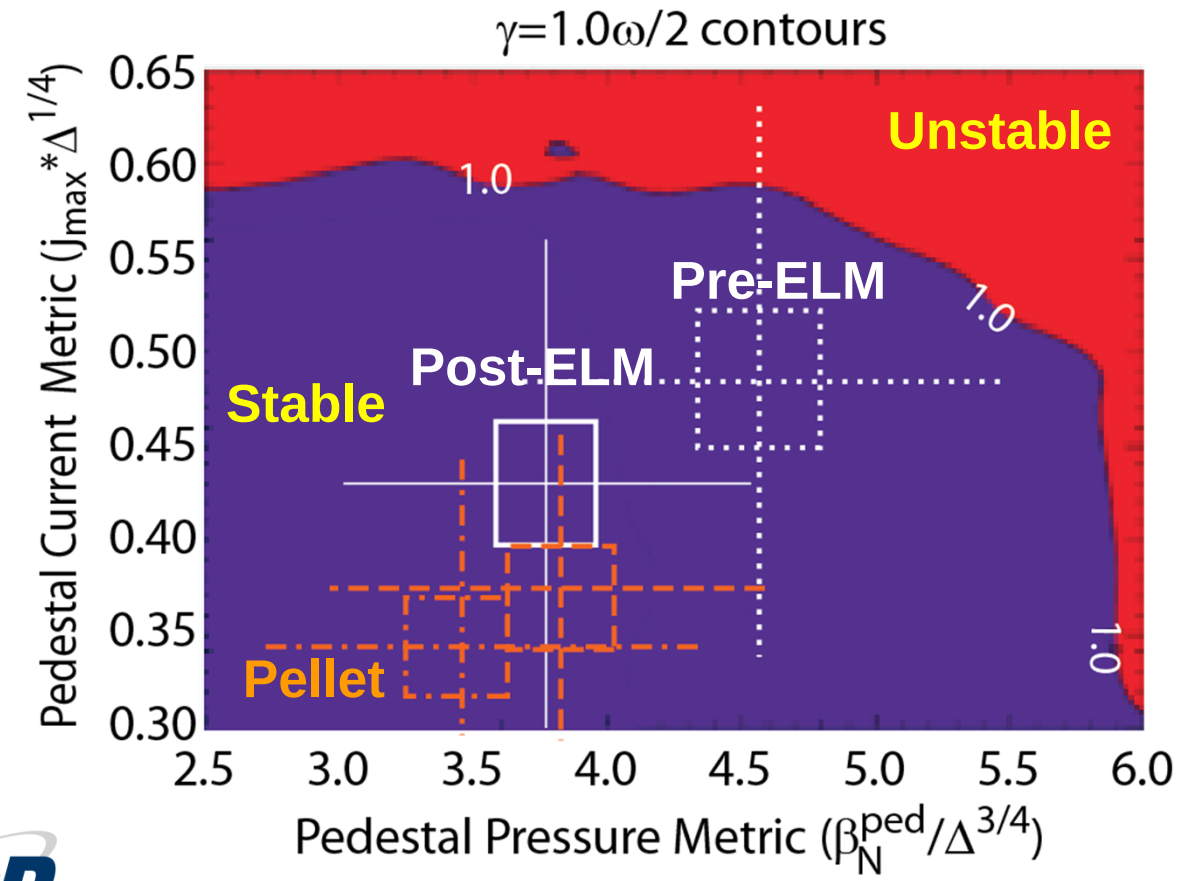
Pellet ELM Pacing Produces a Narrower Pedestal Width - Stable to Peeling Ballooning Modes

- **The boundary for peeling and ballooning stability in this plasma configuration is calculated by ELITE (P. Snyder, NF 2007).**
- **Pellet case is far in stable region, ELMs likely triggered by local effect.**



Natural ELMing Case

Pellet ELMing Case

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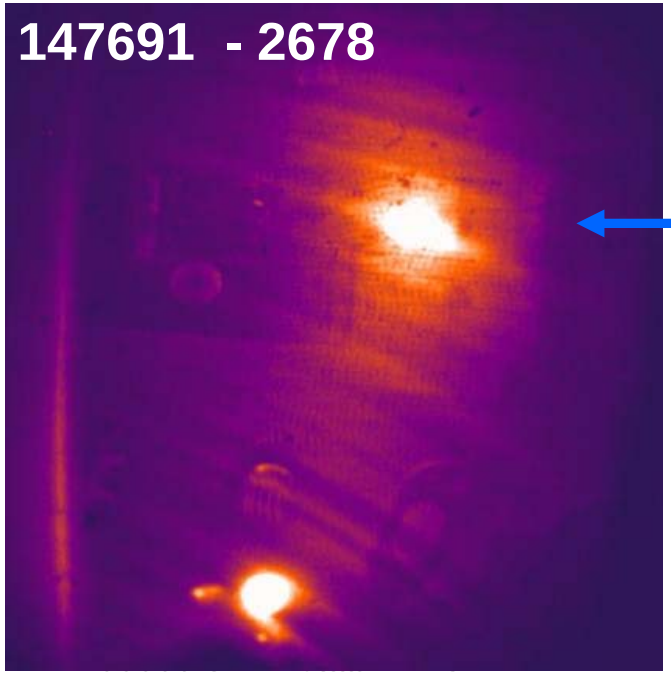
Fast Camera Images of Pellets Triggering ELMs Show Individual Filaments Being Perturbed

D_α Filter

X-pt

- X-point pellet exciting a filament as it enters the plasma. ELM is subsequently triggered.



Mid

- Midplane pellet triggers ELM while X-point pellet fragment enters plasma.

Images consistent with hypothesis of a local ballooning mode triggered by pressure gradient in pellet cloud.

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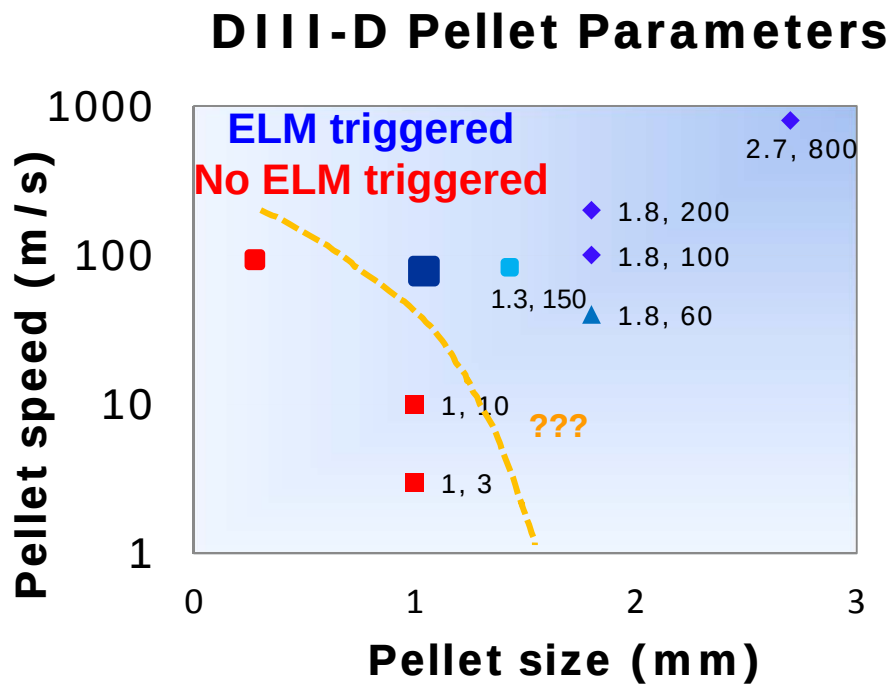
Minimum Pellet Size Needed for ELM Triggering is Under Investigation

- What are the minimum pellet size and speed requirements to reliably trigger ELMs ?
- Small fragments and 1mm slow pellets do not trigger ELMs. ≥ 1.3mm do trigger ELMs.
- New smaller 0.9x1.3mm pellets (~60% of 1.3mm size) also trigger ELMs.
- Non-linear MHD modeling is consistent with observations of local ballooning instability and minimum pellet size. [Futatani ITR/P1-22]



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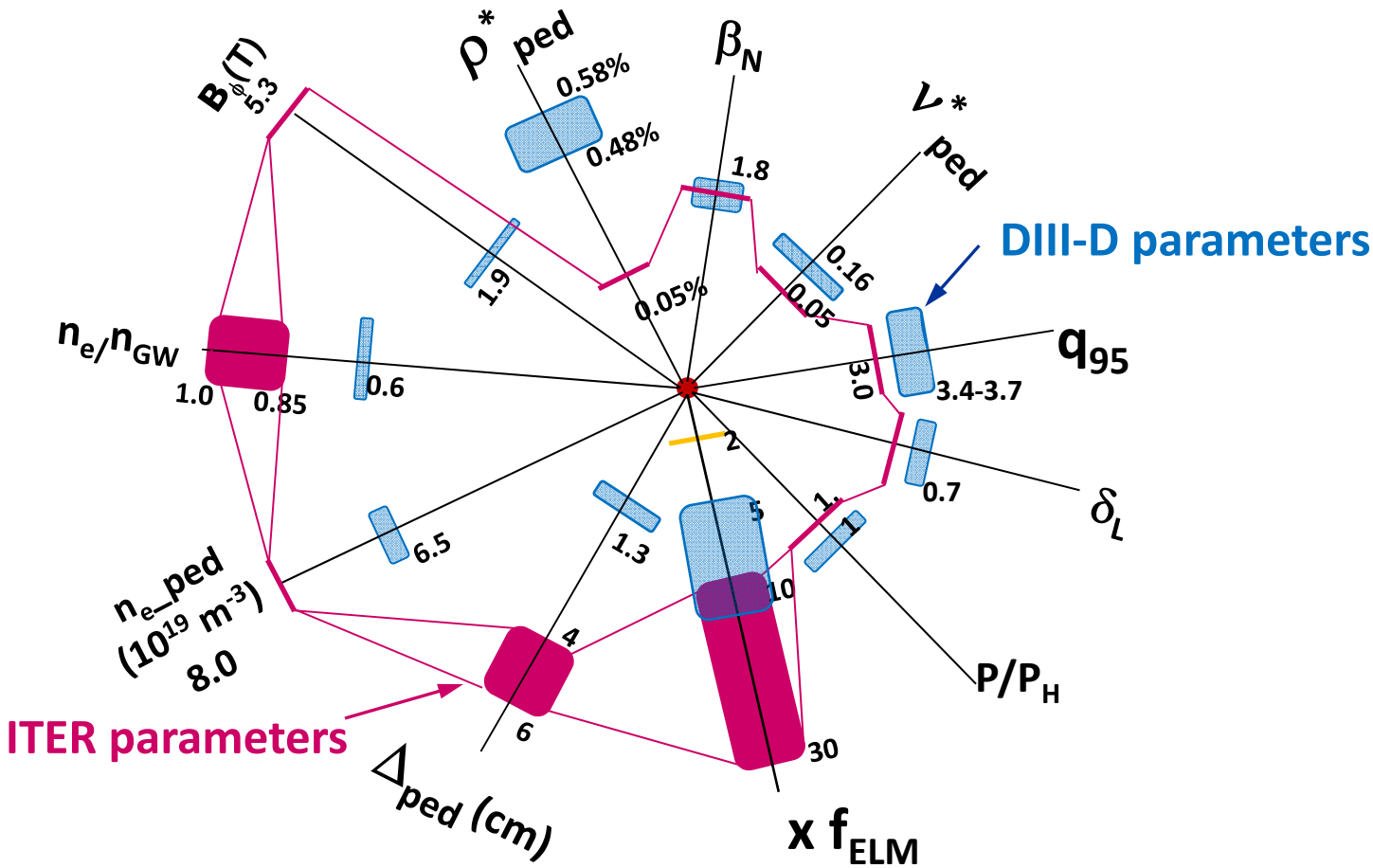
DIII-D Pellet ELM Pacing Operating Space Compared to ITER



- Except for magnetic field and ρ* the operating space on DIII-D is comparable to that expected for ITER.

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Summary – DIII-D has Tested Key Principles of Pellet ELM Pacing for ITER

- **Pellets trigger ELMs on demand with lower X-point injection.**
- **ELM frequency increase of 12x achieved with > 12x reduction in divertor ELM energy deposition.**
- **No confinement degradation**
- **Impurities screened out**
- **ELMs triggered locally before pellet reaches pedestal top**
  - enables smaller pellets and lower fueling
- **Future optimization and extension to higher frequencies with smaller pellets is planned.**