Reduction of Peak ELM Energy Fluence with Pellet Triggering in Low Collisionality DIII-D Plasmas

by

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with

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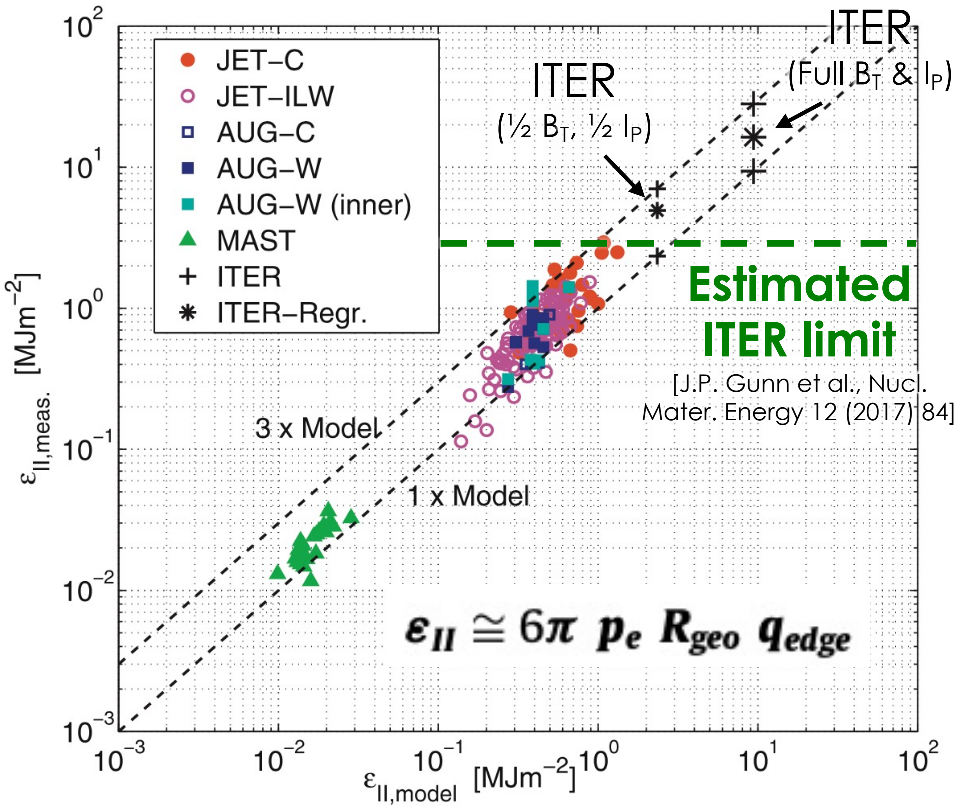
ELM energy is expected to scale with pedestal pressure, and will require mitigation or suppression in high pressure H-mode tokamaks such as ITER

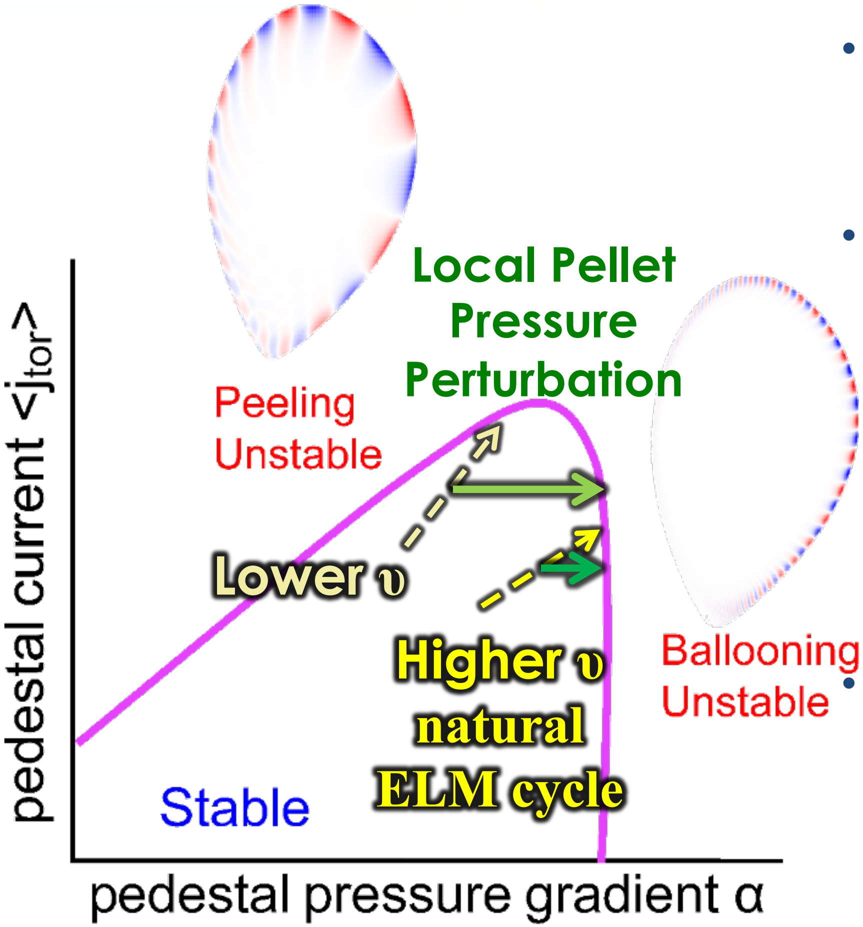
- **While tolerable in most existing devices, unmitigated ELMs in tokamaks with higher plasma pressure may be unacceptable**
  - Large ELMs ablate divertor target material, which can then contaminate the core plasma
  - Very large ELMs could cause melting or other physical damage

- **If scaling holds in ITER, even unmitigated ELMs in ½ field, ½ current non-nuclear phase may cause tile edge melting**



T. Eich et al., Nucl. Mater. Energy ***12*** *(2017) 84*

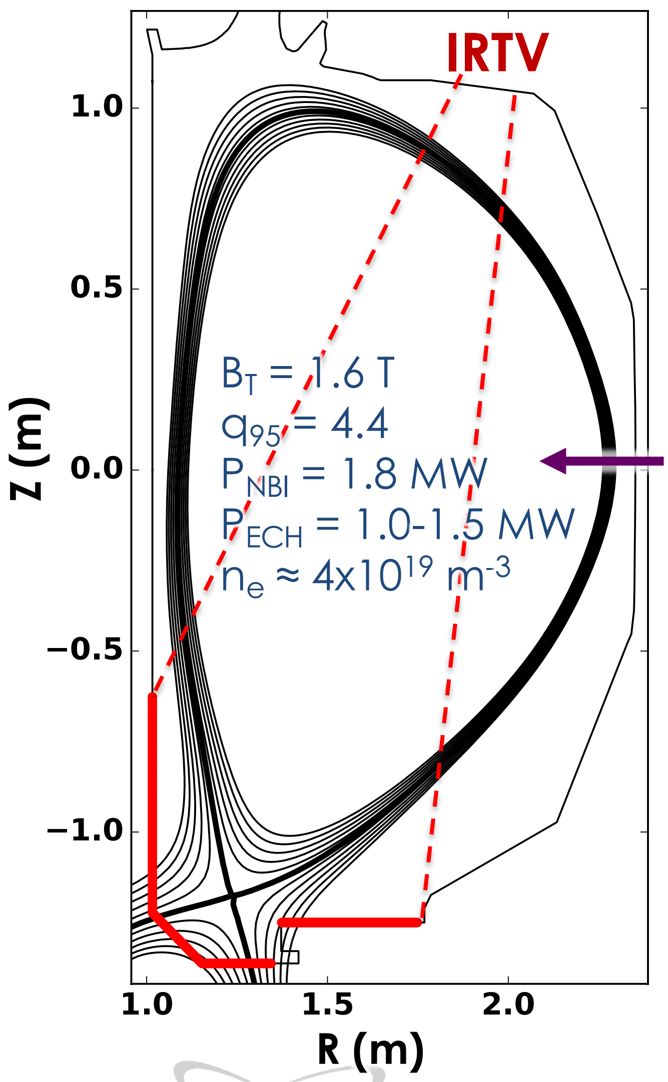
Pellets induce a 3D pressure perturbation in a finite volume flux tube in the pedestal, which destabilizes ballooning modes

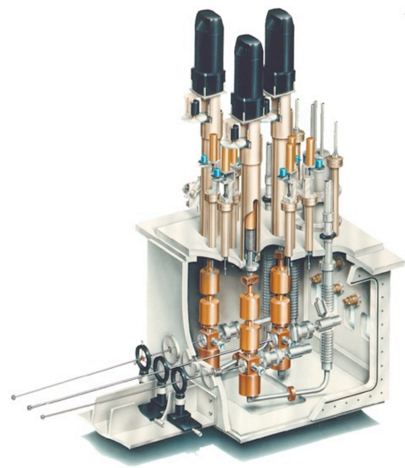


P.B. Snyder et al., Phys. Plasmas **16** (2009) 056118;
F. Laggner PhD defense, MP-IPP 2017

- **ELMs occur when coupled peeling-ballooning modes are destabilized**
- **With lower collisionality, a given pressure gradient results in more bootstrap current**
  - Pedestal growth becomes limited primarily by current density rather than by ∇P
  - ITER and other reactor-grade tokamaks are expected to operate in these low collisionality, peeling-limited conditions
- **If the perturbation is large enough, a peeling-ballooning mode is triggered**
  - For naturally peeling-limited pedestals, a larger perturbation is necessary to reach the ballooning boundary
  - Lower υ^*_{ped} → more pellet mass required
  - Most pellet ELM pacing experiments to date have operated with $\upsilon^*_{ped} > 1$
    - Always near the ballooning limit

A 3-barrel rapid pellet injector was used to inject pellets into ITER-similar shape ELMing H-mode plasmas in DIII-D



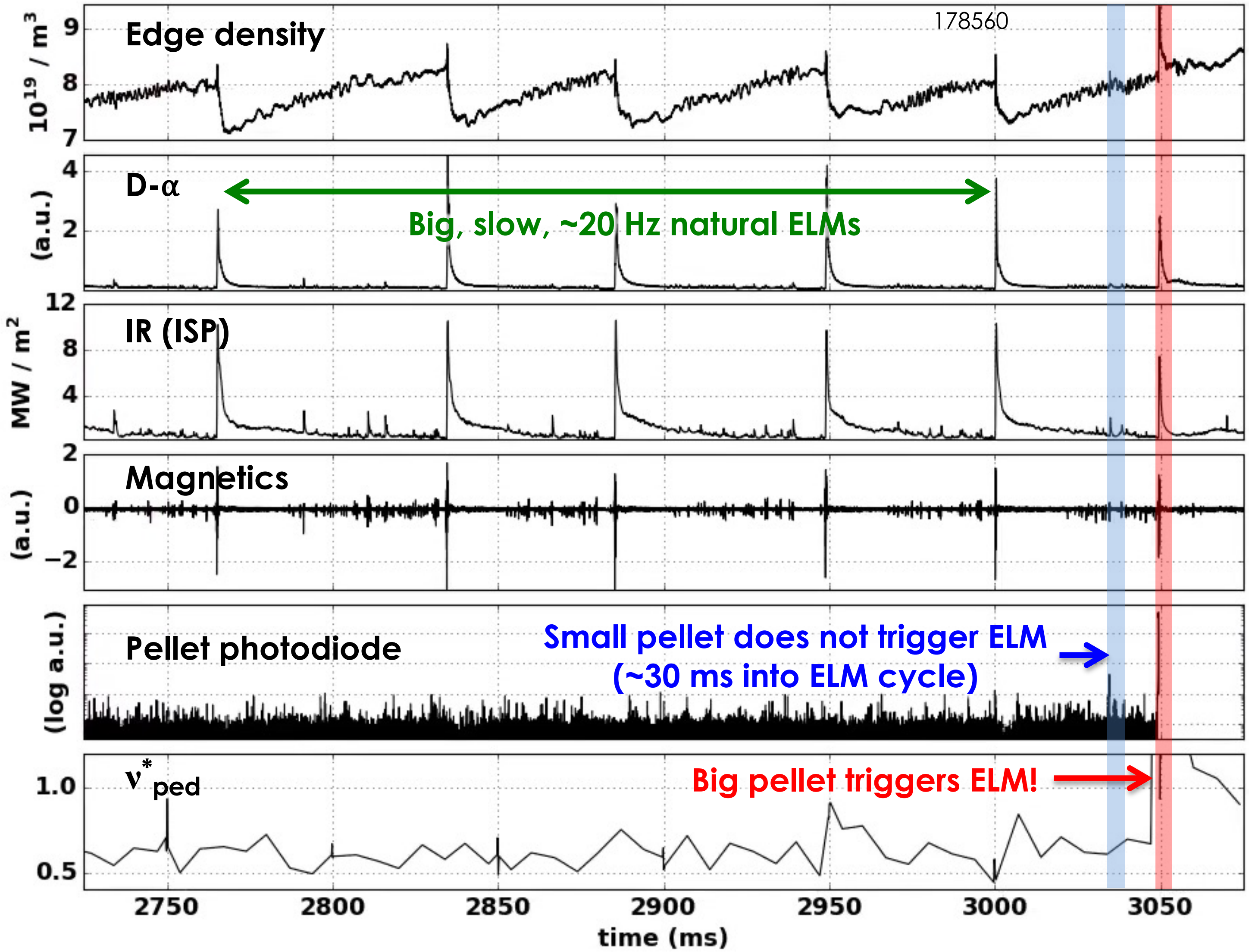


ORNL DIII-D Repeating Pellet Injector

Using 2 barrels (of 3)
5 Hz each (max 20)

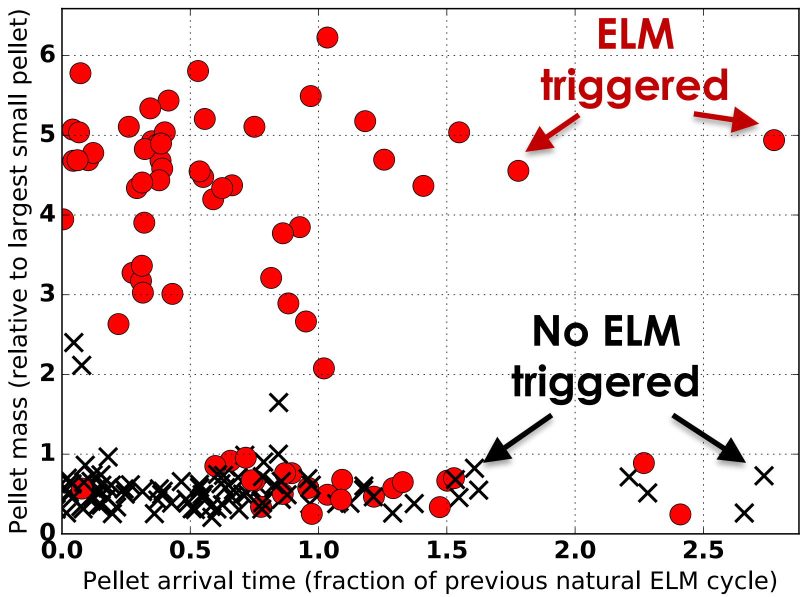
- **Inject cryogenically frozen pellets of fueling gas (D_2 here)**
  - Approximately 150 m/s
- **All experiments presented here inject pellets at outboard midplane**
  - Modified ITER-similar shape
- **Pellet mass is measured using microwave cavity detector**
  - [M.J. Gouge et al., RSI 61 (1990) 2102]
- **Heat flux to divertor targets monitored with fast infrared camera (IRTV)**
  - Line mode, 12 kHz frame rate

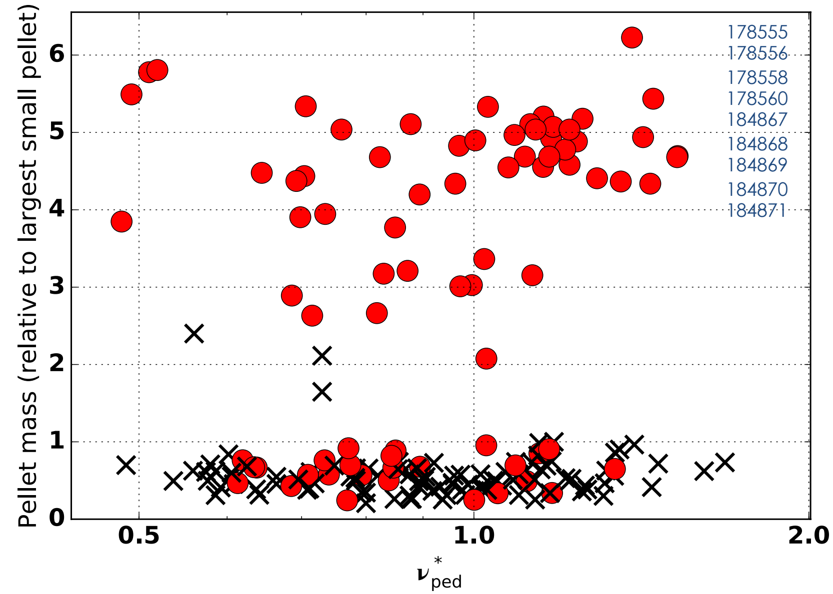
Big pellets were injected after small ones, and were more successful at triggering ELMs



DIII-D NATIONAL FUSION FACILITY

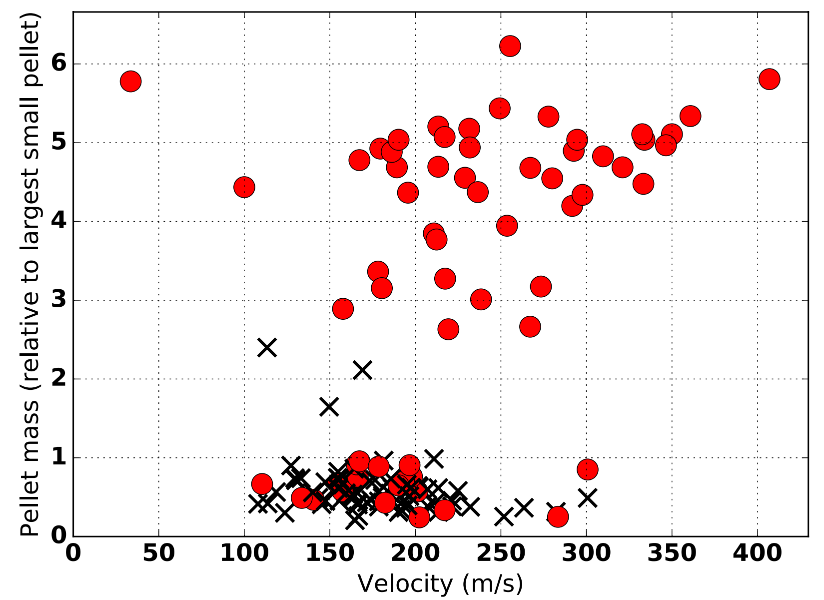
Mass threshold for triggering ELMs in these conditions was somewhere between the big and small pellet sizes



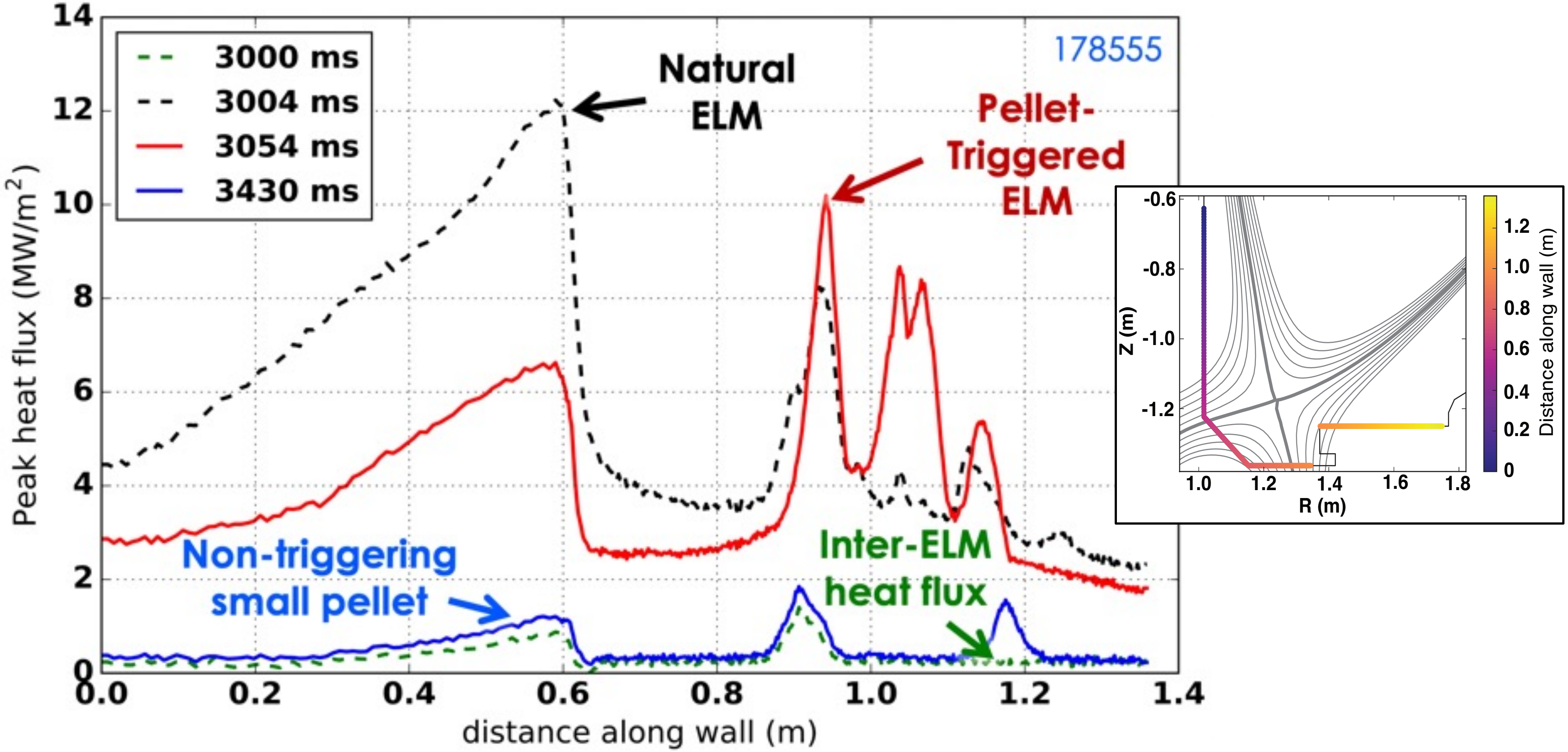


- **Fully intact big pellets clearly triggered ELMs at all values of collisionality, regardless of time since previous ELM**

- **Small pellets triggered ELMs infrequently**
  – Triggered ELMs were either very small, or pellet arrived late in the ELM cycle and triggered ELM was similar to natural ELMs

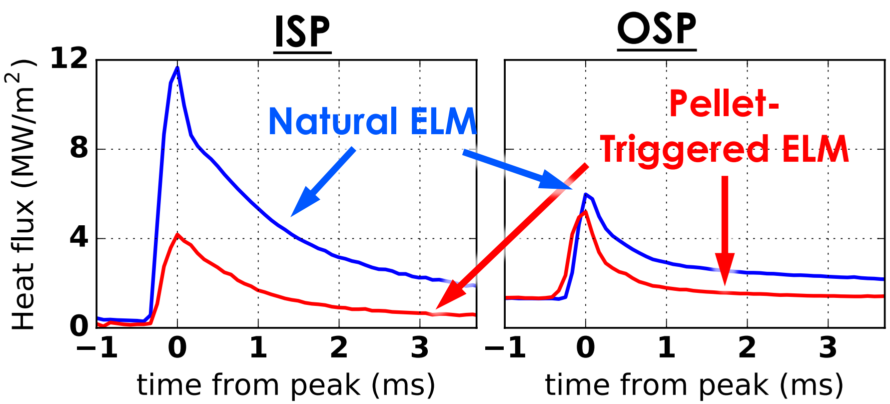


ELMs triggered with big pellets have a relative reduction in peak instantaneous heat flux to ISP and increase at OSP and far SOL

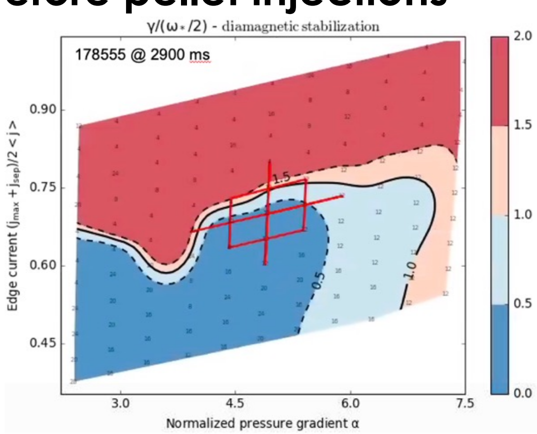


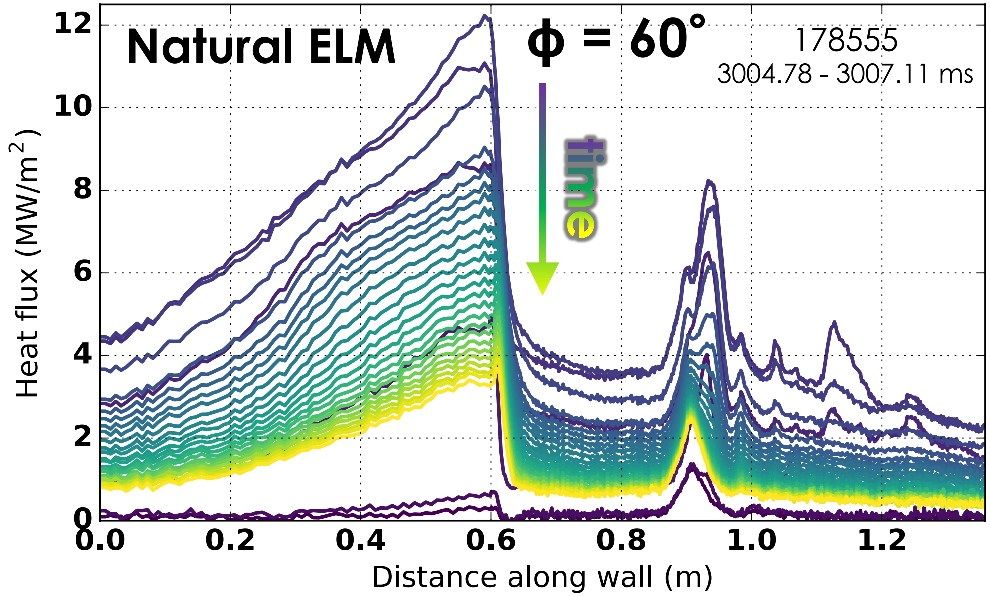
Triggered ELMs exhibit significantly reduced heat flux to ISP, larger transient striations in far SOL relative to similar sized natural ELMs

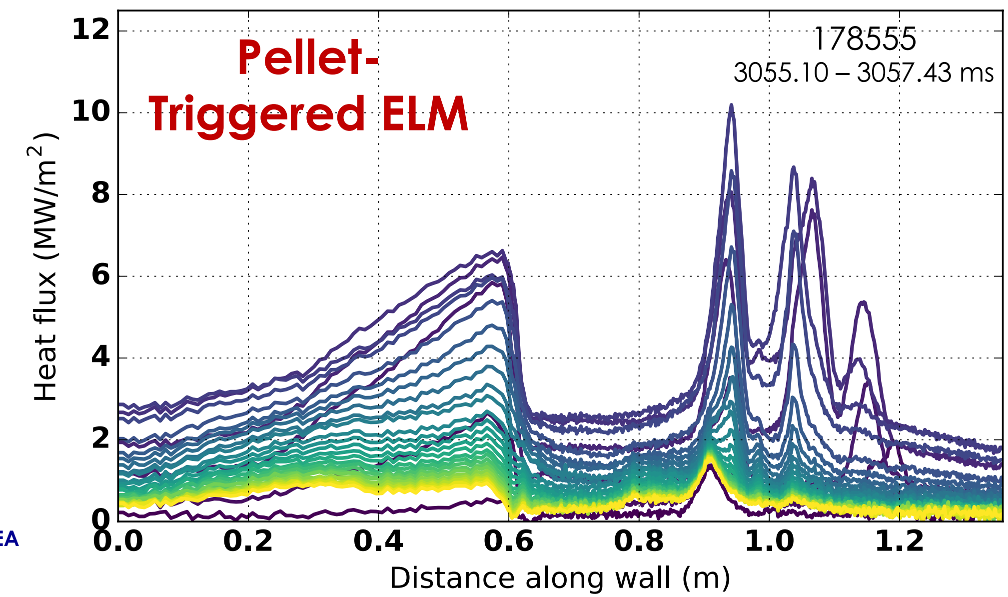
- **Big pellet arrived near the end of an ELM cycle**
  - W_{MHD} fell ~45 kJ each
  - dt since previous ELM: 53 vs 50 ms



- **Ideal stability calculations find natural ELMs are peeling-limited before pellet injections**

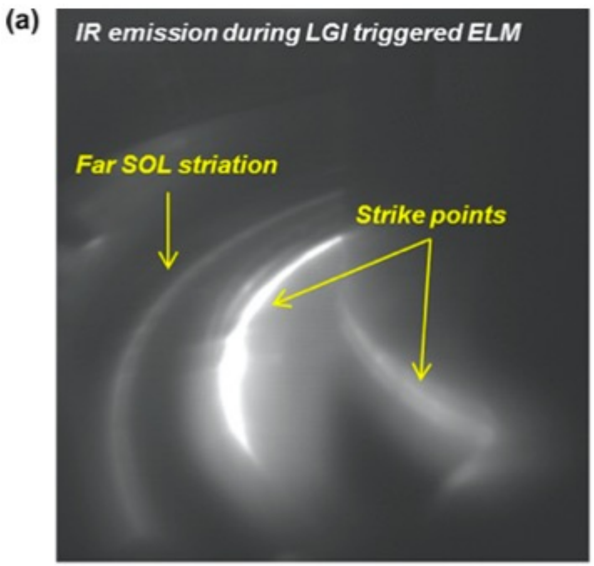




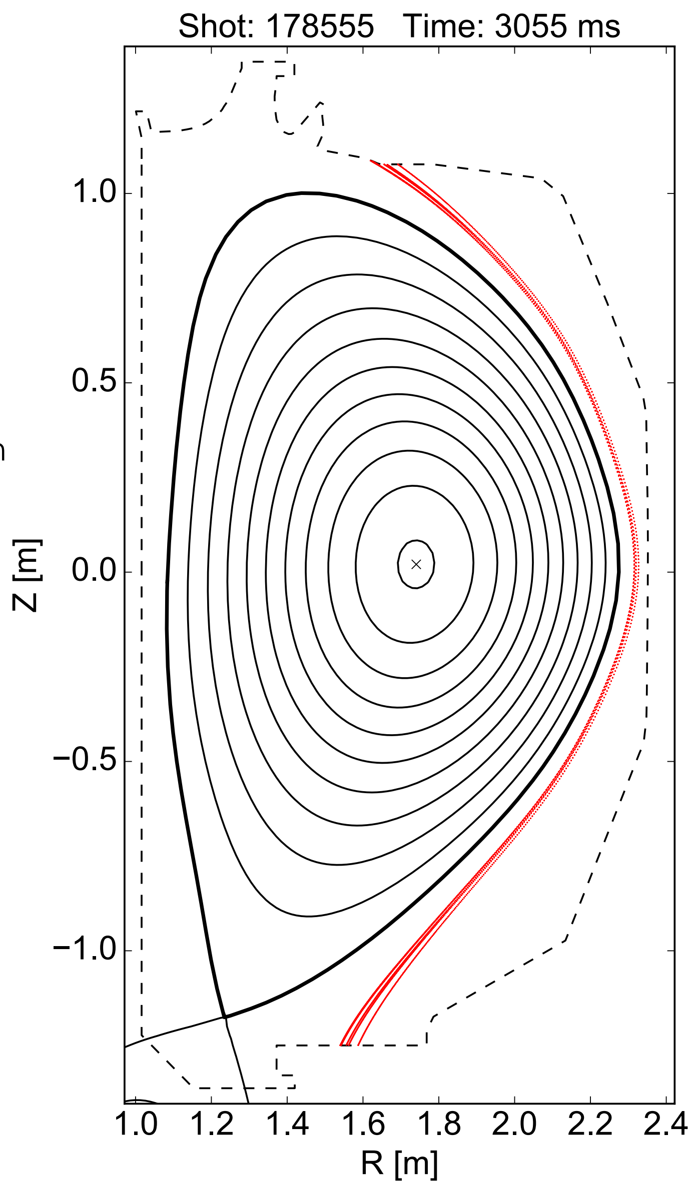


Field lines connect 3D heat flux striations in far SOL to pellet injection location

- **Field line tracing from R=1.55 m, ϕ = 60°on the shelf (IRTV striations) connect to pellet injection location at R = 2.315 m, Z = 0, ϕ = 135°**
  - ELM filament is significantly outside equilibrium separatrix
- **Triggered ELMs have reported these 3D filaments previously**
  - D pellets in JET [Wenninger PPCF 2011], Li pellets in DIII-D [Bortolon NME 2017]

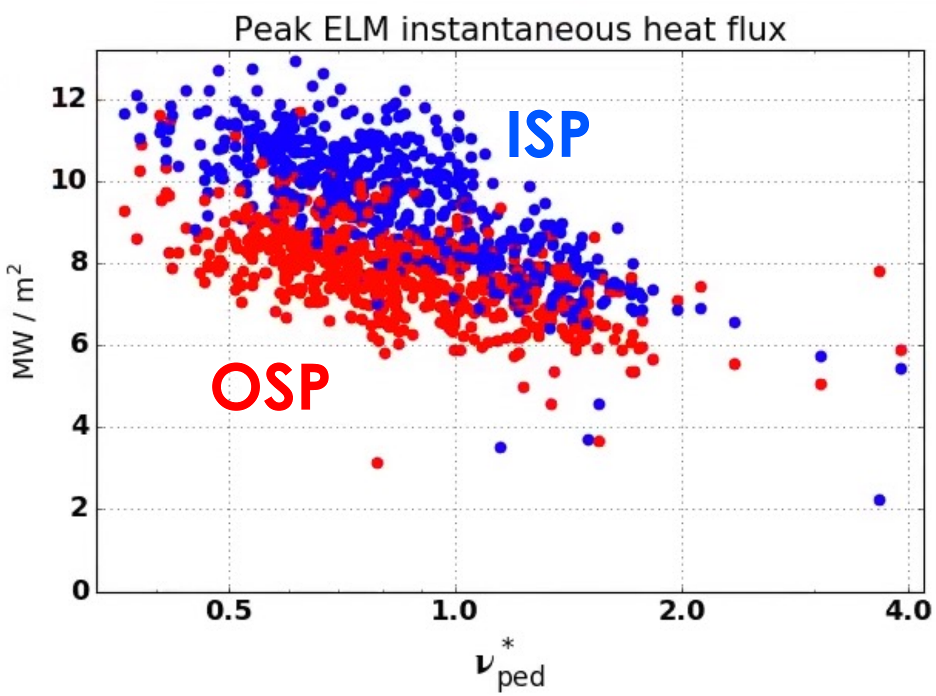


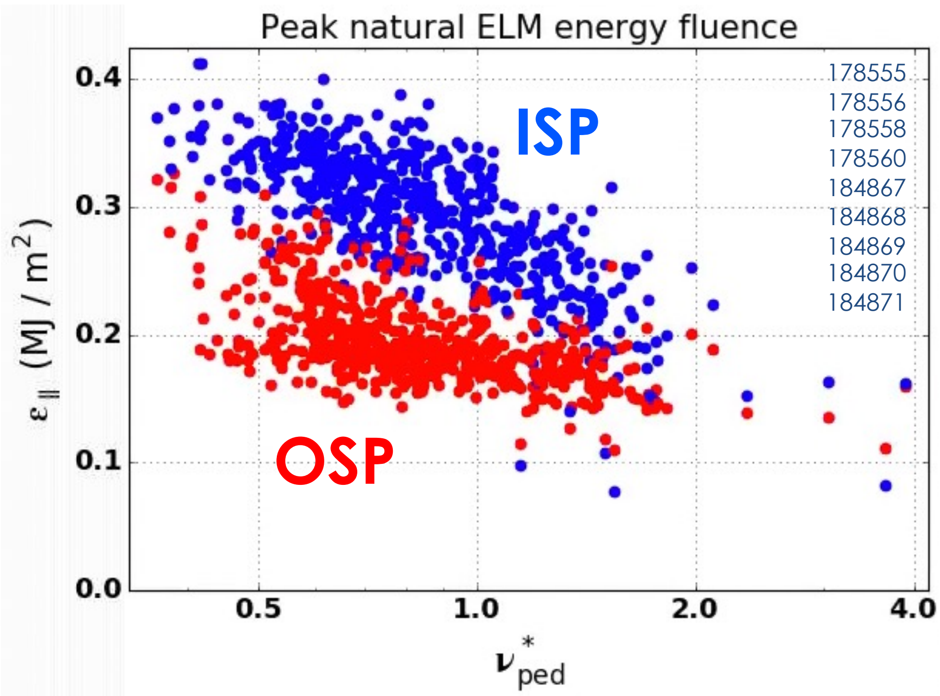
[A. Bortolon, NME 2017]



For this data set, natural ELM heat flux at ISP (both instantaneous heat flux and time-integrated fluence) increased with decreasing collisionality, as pedestal becomes more peeling-limited

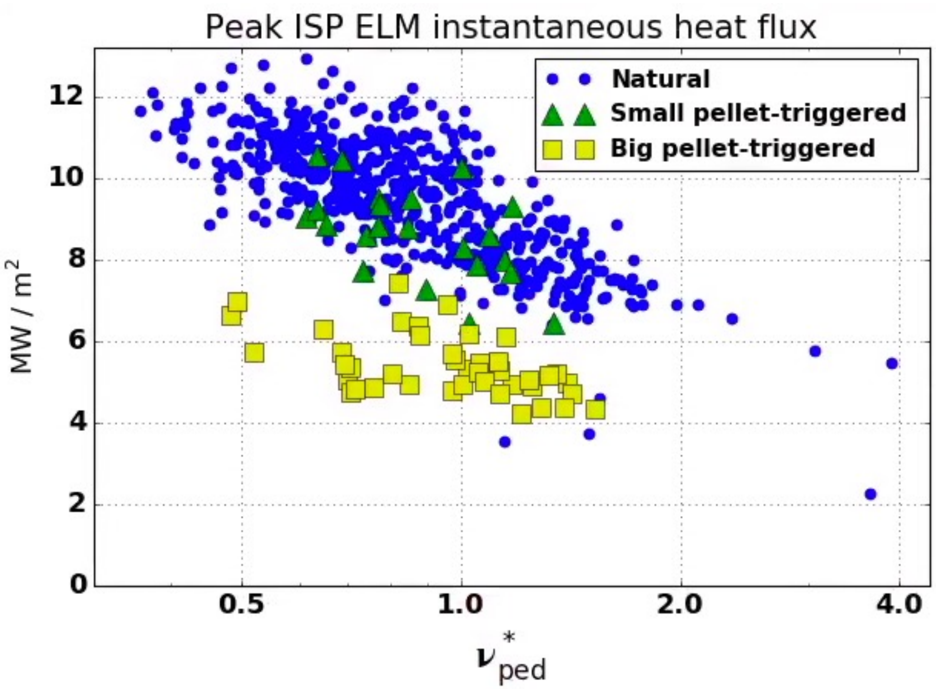
Natural ELMs

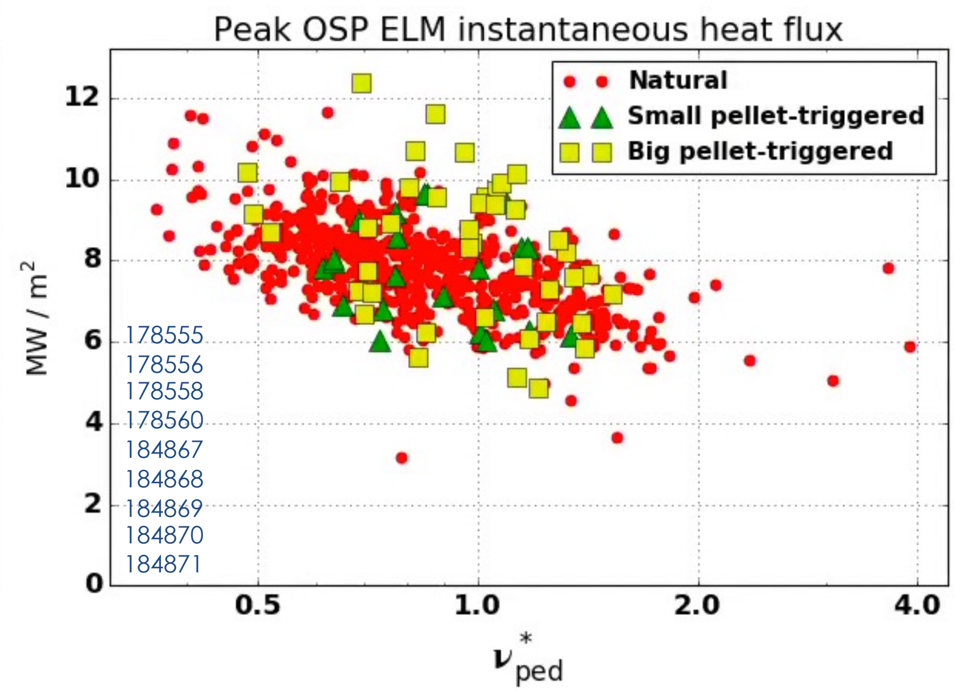




$$\varepsilon_{\parallel,peak} = \left[\frac{\int_{-0.3}^{2ms} q_{IR}\,dt}{\sin(\gamma)}\right]_{peak}$$

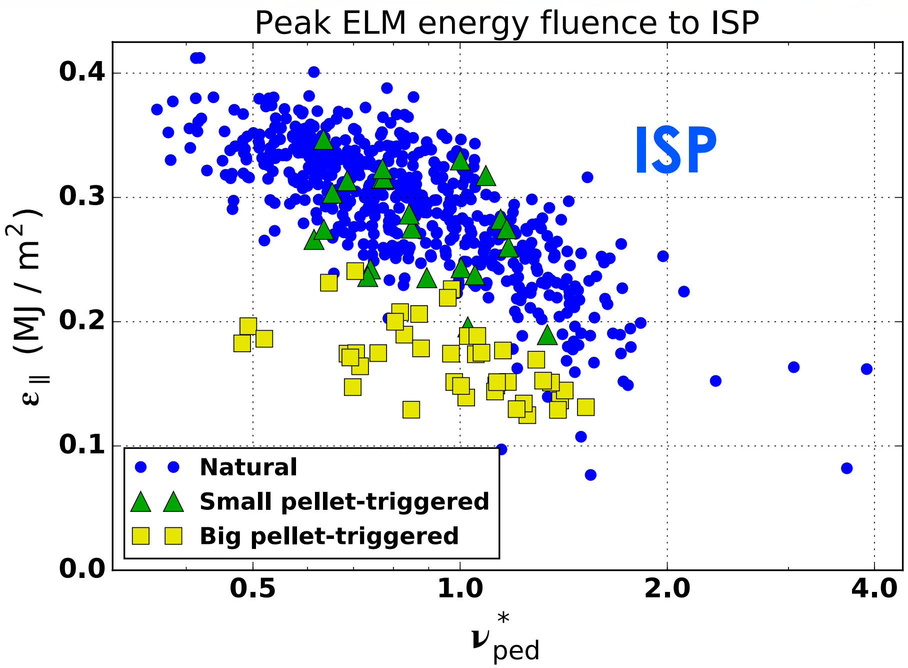
Instantaneous heat flux is consistently reduced with pellet triggering at ISP, but sometimes increased at OSP

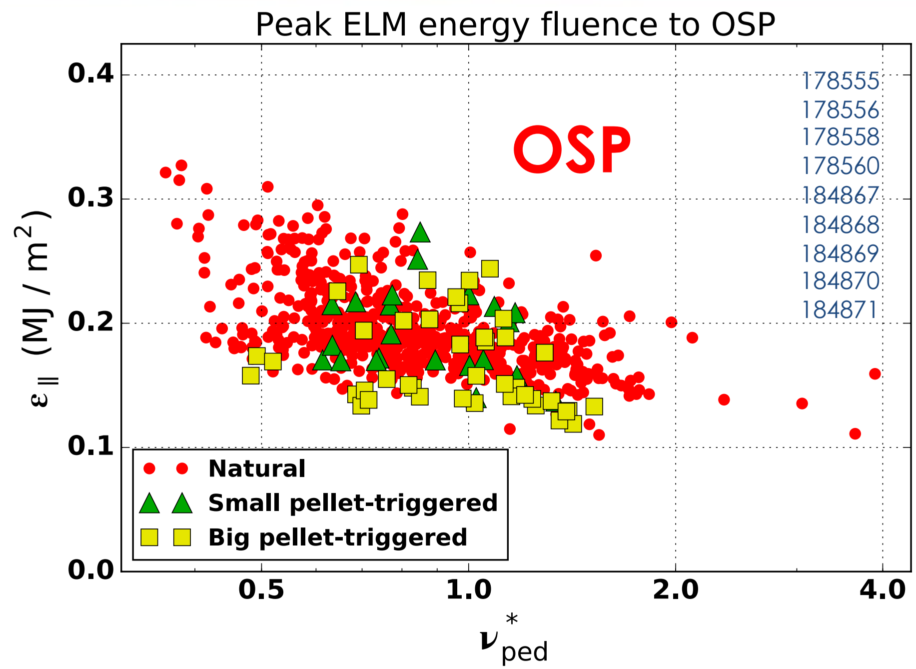




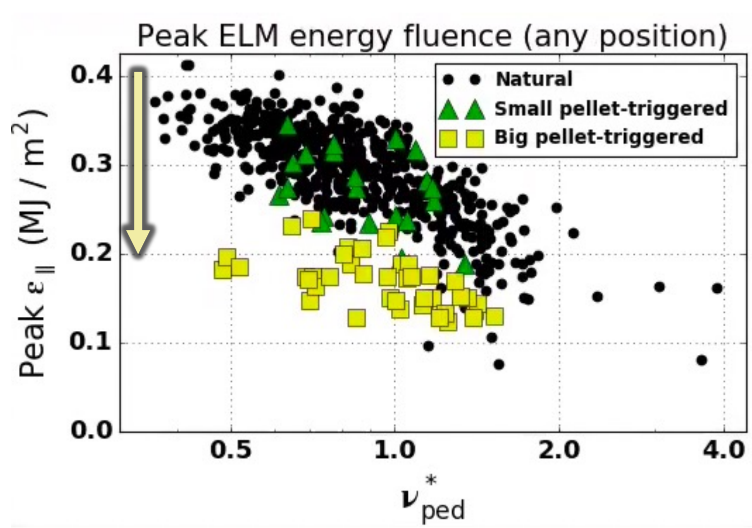
- **Instantaneous heat flux would be mitigated further by higher frequency pellet ELM pacing**
  - Some pellets here trigger ELMs late in the natural ELM cycle
  - This experiment kept $f_{pel} < f_{ELM,nat}$
    - In practice, ELM pacing would use higher frequency pellets

When big pellets trigger ELMs, both inner and outer strike point fluences are reduced relative to natural ELMs, but reduction is larger at ISP

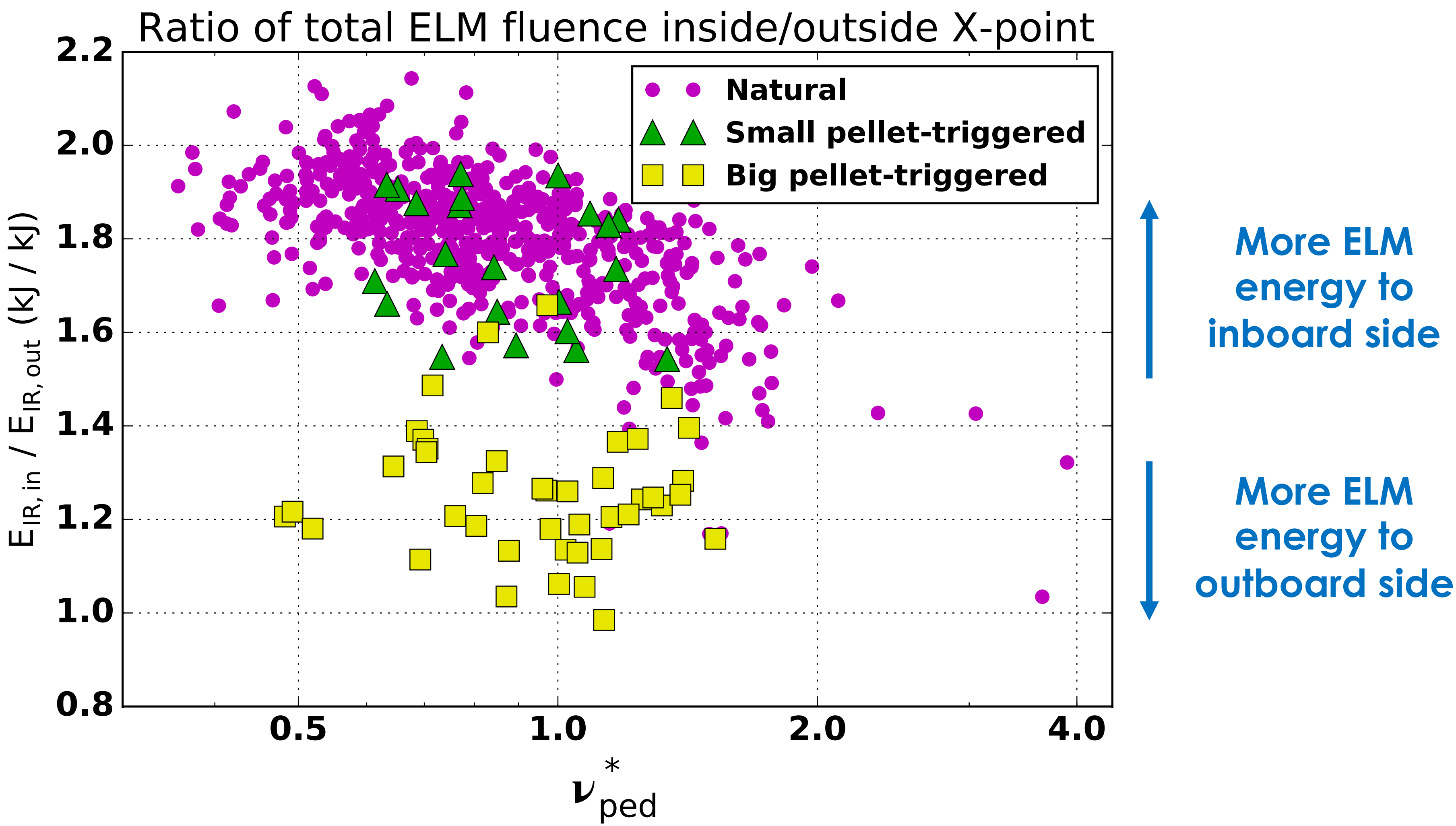




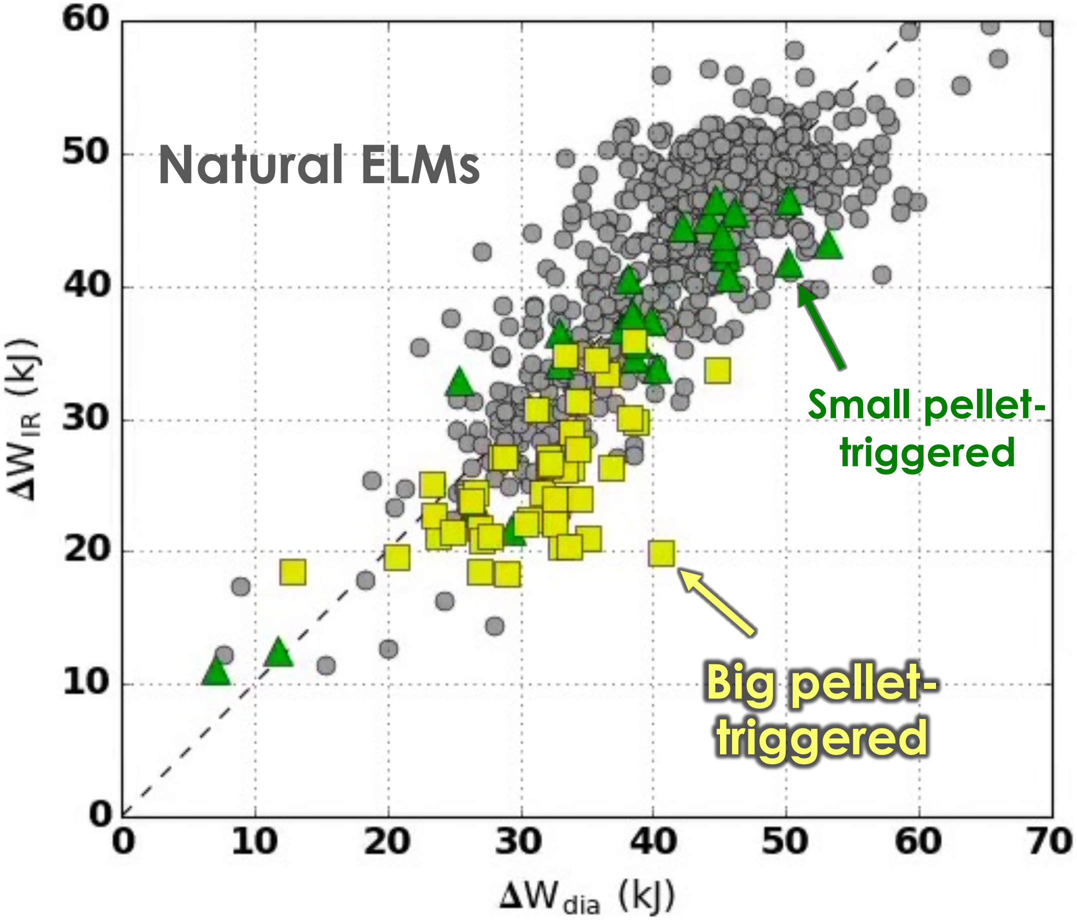
- **ELMs triggered by small pellets are generally late in the natural ELM cycle**
  - These behave like natural ELMs
- **ELMs triggered by big pellets reduce peak fluence at ISP**
  - Fluence at OSP modified less by pellet triggering
- **Net result is reduced peak fluence**



ELMs triggered by big pellets ejected higher fraction of their total energy to outboard side, regardless of collisionality (more ballooning)



Integrated IR energy lost due to ELMs is reduced by pellets more than stored diamagnetic energy, suggesting possible toroidal asymmetries in IR emission



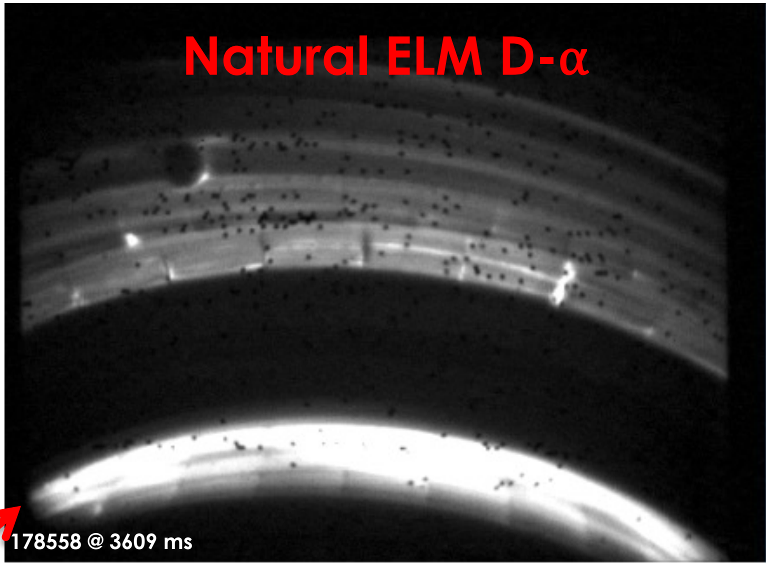
- **IRTV may be missing ELM energy more consistently in big pellet-triggered ELM cases than natural ones**
  - 3D striations in far SOL are sourced from same pellet injection location every time
  - Could also be 3D filaments conducting heat flux to ceiling
- **Toroidal asymmetries in IR are being been explored with data from a second IR camera**
  - Second IR camera view is tangential from different toroidal position
  - Calibration and analysis are in progress

D-alpha emission from fast camera shows that particle flux is shifted away from ISP, similar to heat flux

- **D-α patterns at ϕ =75° are qualitatively consistent with IR data at ϕ =60°**
  - Strong reduction of emission at ISP

- **Intense 3D structure on outboard side in triggered case**
  - Further suggests toroidal asymmetries, particularly on LFS
  - Outboard 3D filament is consistent with JOREK modeling results showing OSP splitting [S. Futatani et al., Nucl. Fusion 54 (2014) 073008]

Top-down view ϕ =75°



Reduced emission at ISP

More 3D structure in far SOL emission

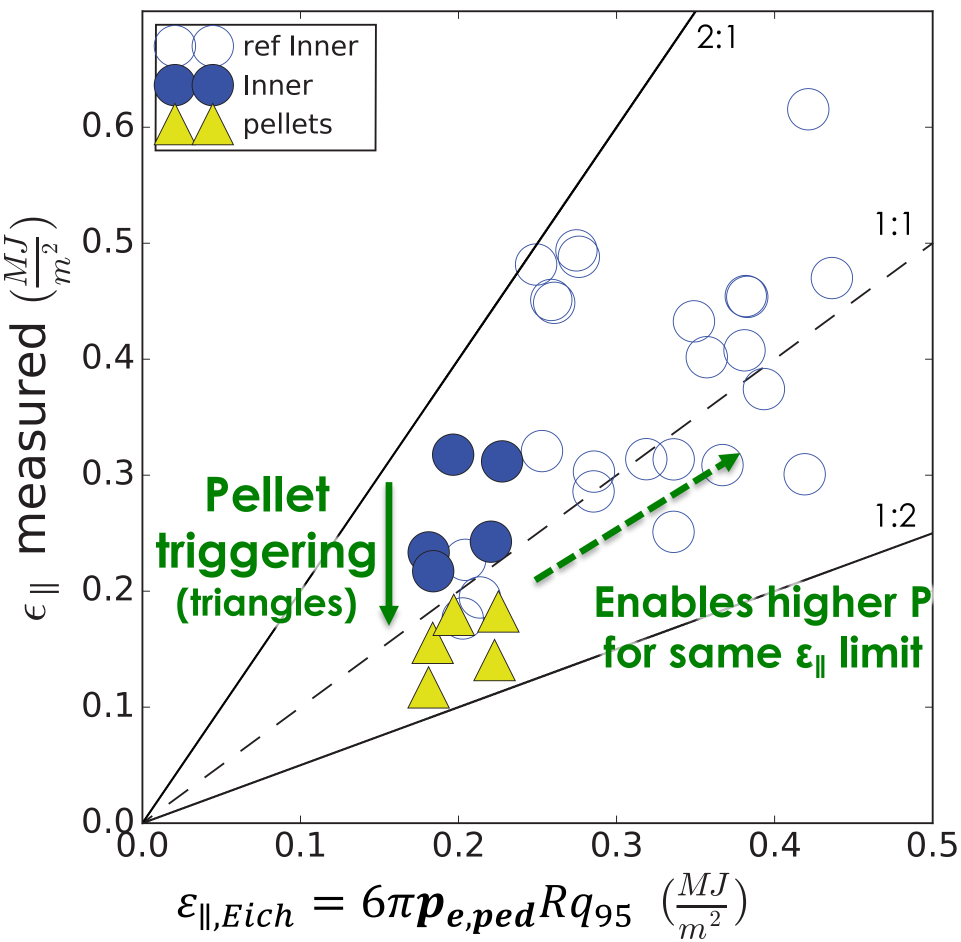
For a given allowable ELM energy fluence, maximum pedestal pressure is increased by triggering an ELM with a big pellet

- **Divertor material limits place a cap on allowable ELM energy fluence**
  - Higher P_{ped} desirable before ELM triggering

- **Eich database reported peak natural ELM fluence scattered from ~1 – 3 times scaling**

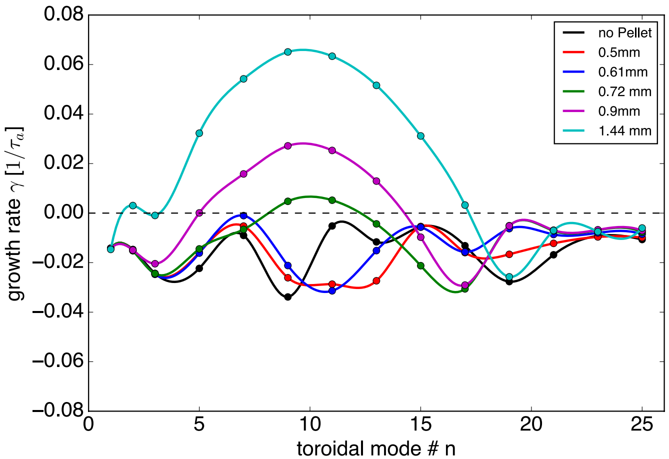
- **This (small) dataset with pellet triggering ranges from ~0.5 – 1 times the scaling**
  - Fluence from triggered ELMs in ITER at ½ field, ½ current would be tolerable
  - Pacing frequency could be set by peak heat flux / impurity flushing needs
    - Would be no need to increase f_{pel} to limit P_{ped} or ELM fluence

Peak parallel ELM energy fluence

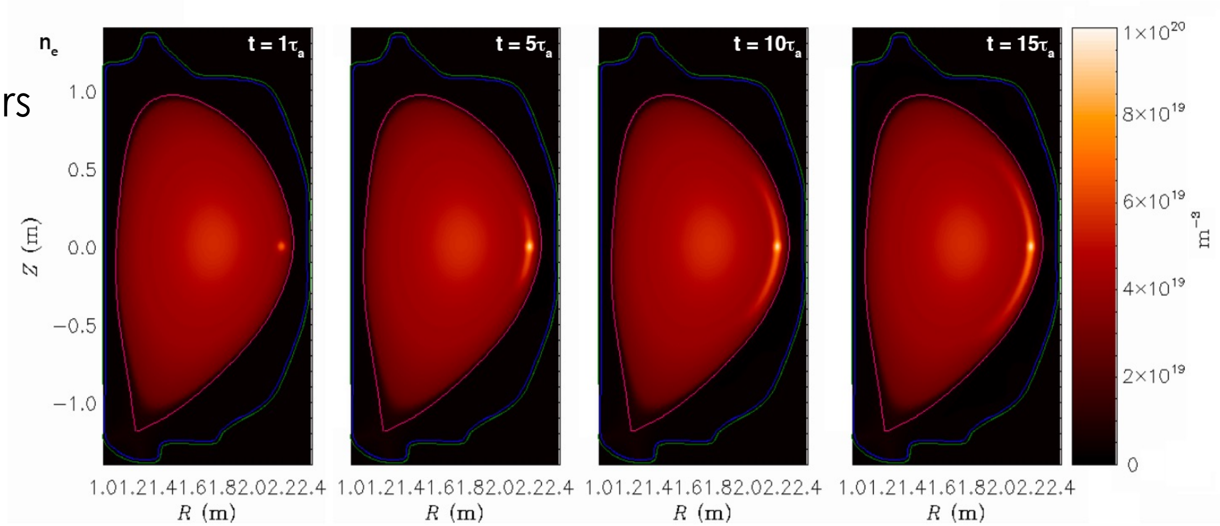


Linear 2D and non-linear 3D M3D-C1 modeling is progressing towards a validated model of critical pellet size for ELM triggering

- **Fast 2D linear growth rate simulations used to estimate critical pellet mass to trigger peeling-ballooning instability**
  - Most unstable mode numbers similar to ELITE ballooning boundary



- **Fully 3D nonlinear simulations evolve pellet ablation and mode activity in time**
  - More realistic geometry of ablation and destabilized flux tube



Summary: Pellet injection can significantly mitigate ELM heat fluxes in low collisionality conditions, but larger pellets are required

- **Larger pellets are required to trigger ELMs in low collisionality plasmas when equilibrium is farther from ballooning stability boundary, as will be the case in ITER**
  - Quantification of mass dependence will benefit from both ongoing modeling work and experiments with intermediate sized pellets

- **ELM energy fluence to ISP was reduced with pellet triggering**
  - Peak fluence is reduced by a factor of ~2 at lowest ν^* relative to natural, peeling-limited ELMs
    - Quantitative role of toroidal asymmetries is under investigation
  - Reduction of energy to ISP may enable an increase in tolerable p_{ped} before an ELM must be triggered, while keeping below $\varepsilon_{\parallel}$ threshold
    - Higher p_{ped}, lower f_{pel}