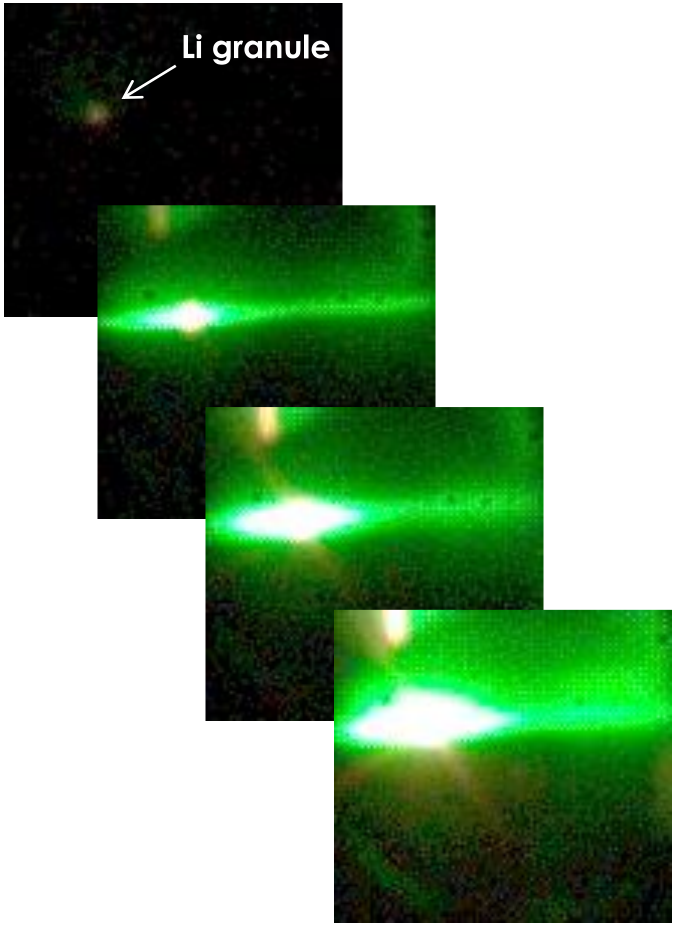
Effectiveness of High-Frequency ELM Pacing with Deuterium and Non-fuel Pellets in DIII-D

A.Bortolon[1], L.R. Baylor[2], N.Commaux[2], R.Maingi[1], D.K.Mansfield[1], A.L.Roquemore[1], R.Lunsford[1], A.Nagy[1], D.Shiraki[2], M.Vorenkamp[1], I.Bykov[3], G.L.Jackson[4], R.A.Moyer[3], T.Osborne[4], C.J.Lasnier[5], M.J.Makowski[5], P.B Parks[4], R.Groebner[4], R.Nazikian[1] and the DIII-D team

[1]PPPL, [2]ORNL, [3]UCSD, [4]GA, [5]LLNL



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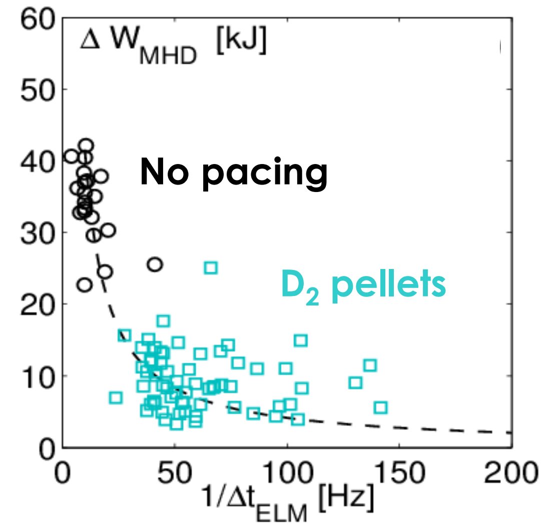
ELM Pacing Obtained with D_2 and Li Pellet Injection in Low-Torque ITER-Baseline Scenario (IBS)

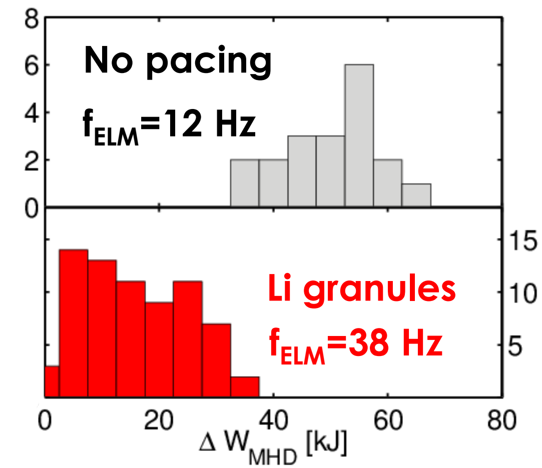
- **D_2 pellet injection up to 9X natural f_{ELM} in IBS at applied torque T_{inj} ~0 Nm**
  - ELM pacing and mitigation observed

ITER operation at 15MA may need up to 30X reduction of ELM heat flux



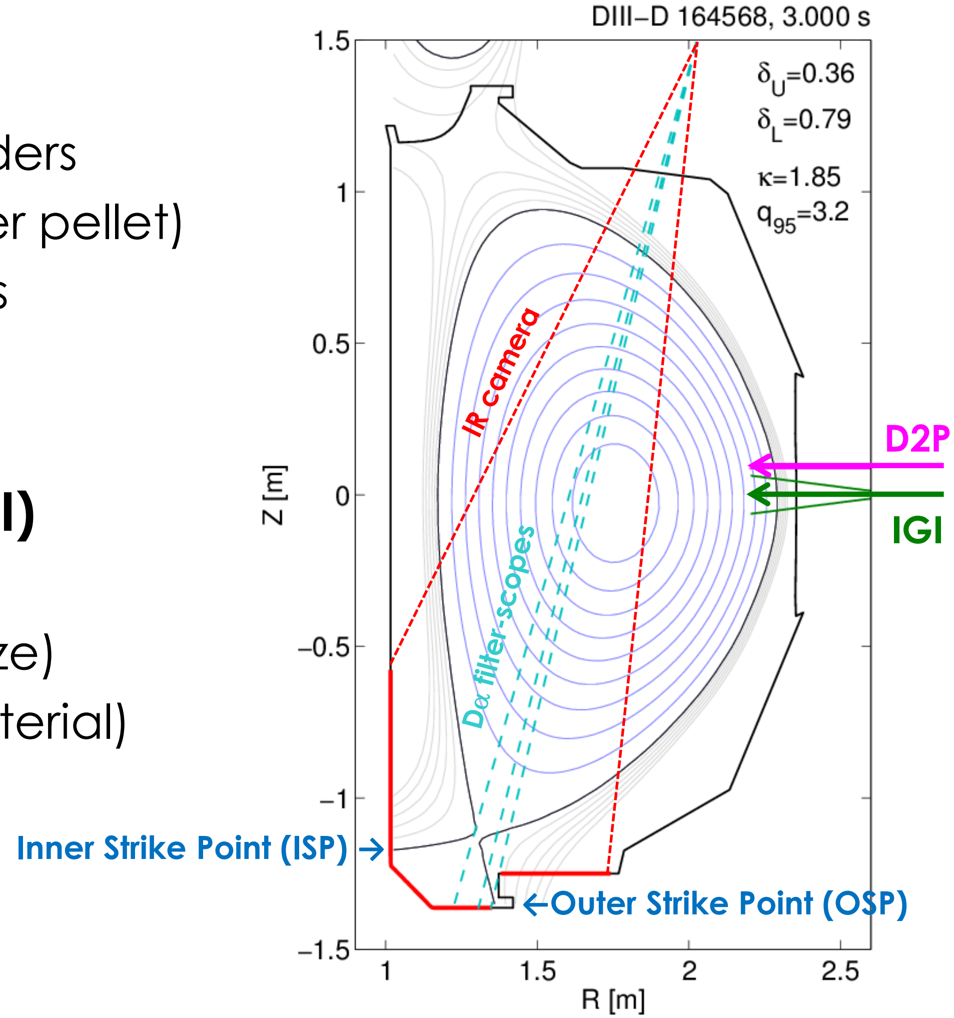
- **ELM pacing obtained with non-fuel granule injection (lithium)**
  - Effective mitigation at high q_{95}, low n_e
  - Mitigation not achieved in IBS

In ITER, D_2 pellets for ELM control might use up to 40% of total allowed fuel throughput



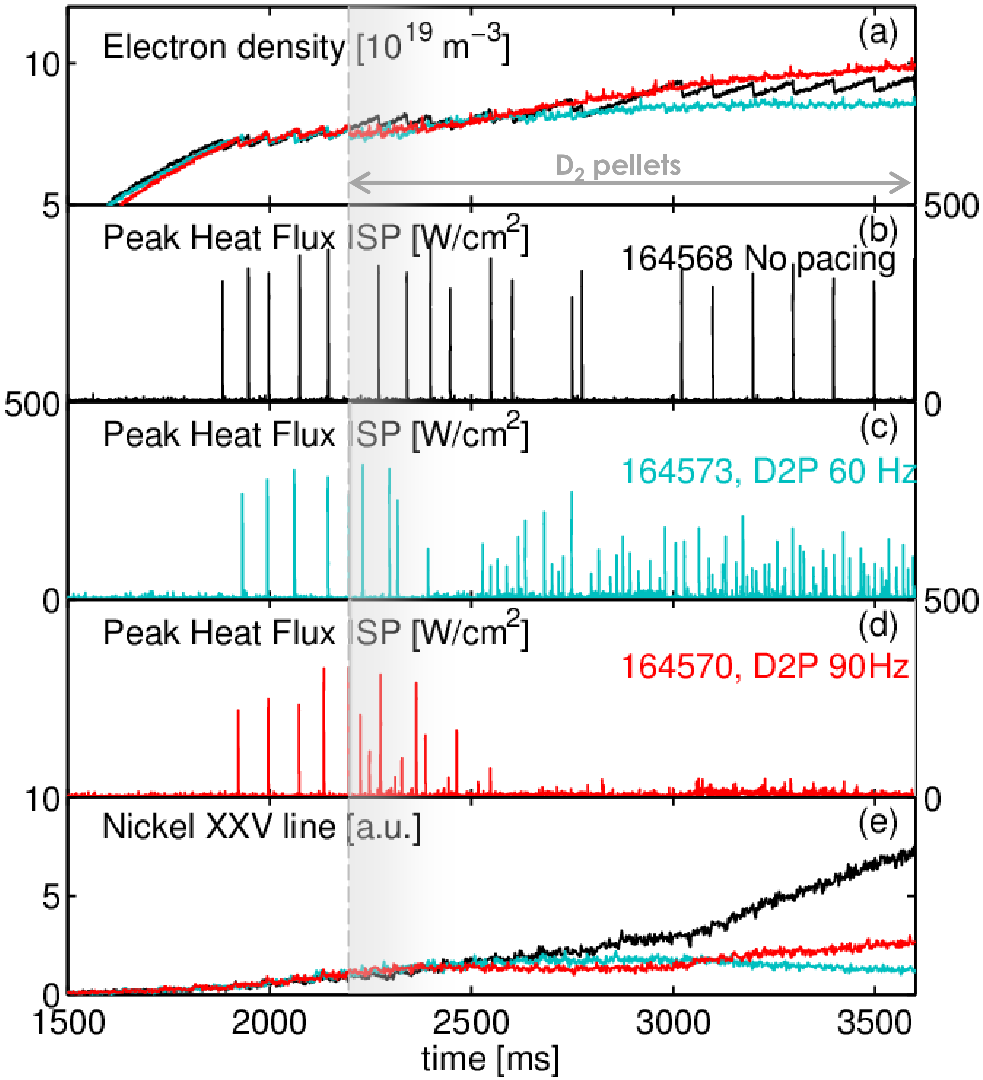
Upgrades of Injection Systems Enable Faster Injection Rates with D_2 and Non-fuel Pellets

- **D_2 pellet injector (D2P)**
  - 3 guns, 90Hz with new extruders
  - 1.3x0.9 mm ($7x10^{19}$ atoms per pellet)
  - Injection speed~100-150 m/s
- **Impurity Granule Injector (IGI)**
  - Li, C, B_4C, 0.3-1.0 mm
  - Up to 300 Hz (depends on size)
  - 50-150 m/s (depends on material)



Bortolon / IAEA-FES, Kyoto/ 21 October 2016

Heat Flux Mitigation Obtained with D_2 Pellets in ITER Baseline Scenario (IBS) at Zero Torque



- β_N=1.7, q_{95}=3.2, T_{inj}~0.0 Nm
- Reference no D2P, f_{ELM}~10 Hz
  - q_{peak}~350 W/cm^2
- D2P 60 Hz → f_{ELM}~60 Hz
  - q_{peak}~50-100 W/cm^2
- D2P 90 Hz → f_{ELM}~90Hz
  - q_{peak} <30 W/cm^2
- No Ni accumulation with D2P

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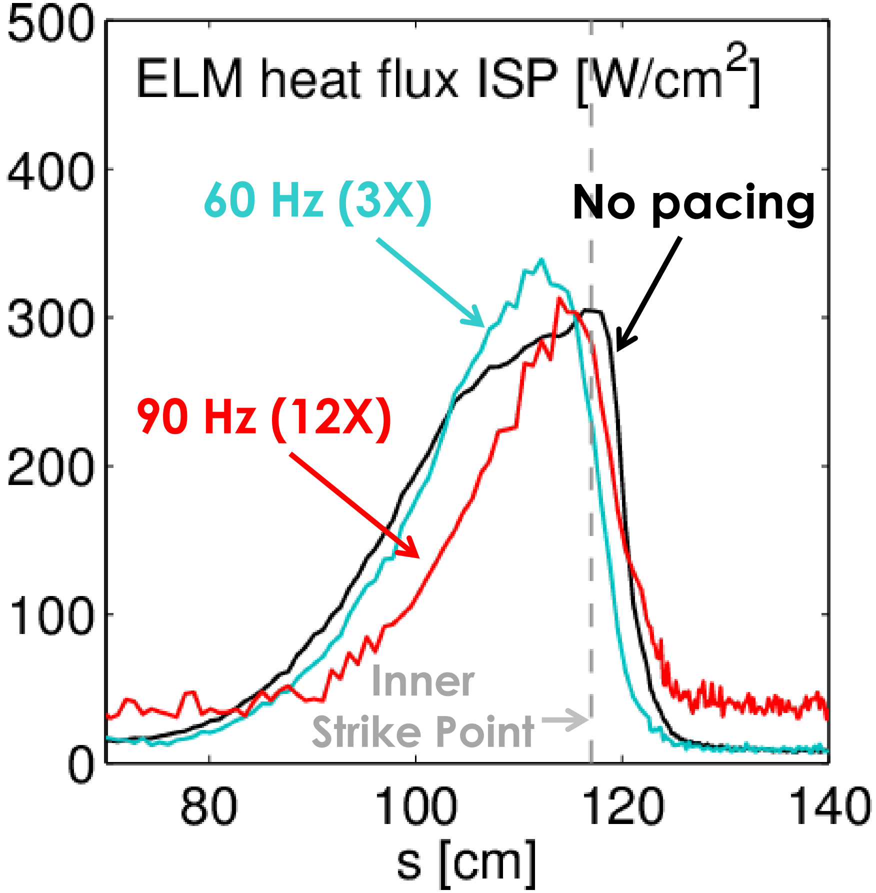
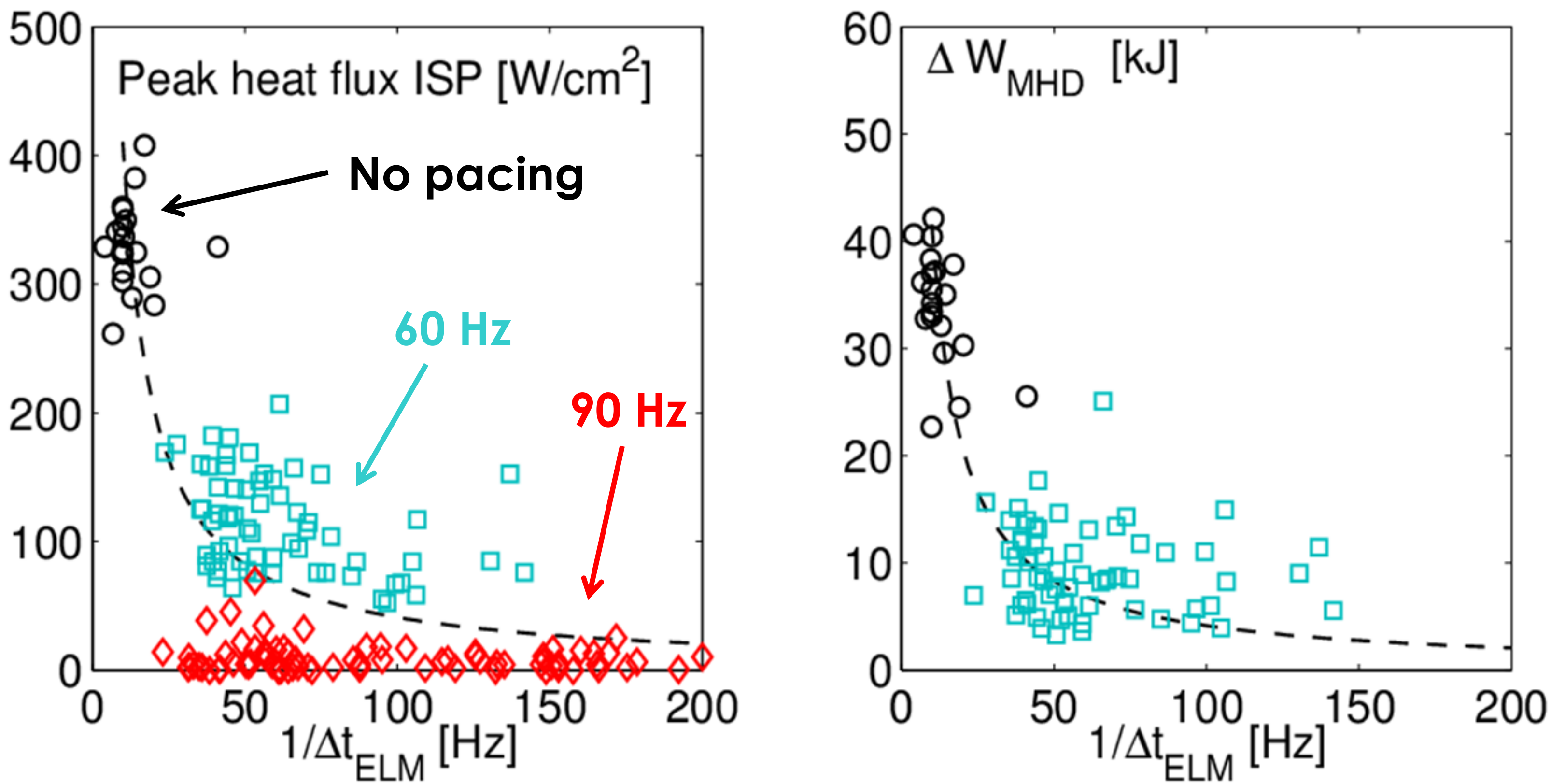
Moderate Reduction of ELM Footprint Observed During ELM Mitigation by D_2 Pellet Injection



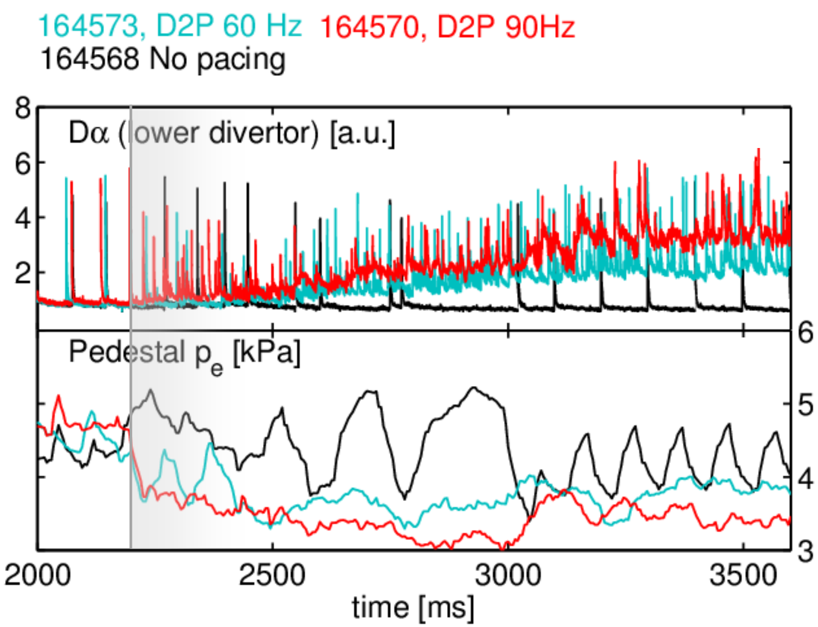
- **D2P 60 Hz**
  ELM heat flux footprint width similar to natural ELMs
- **D2P 90 Hz**
  Footprint ~20% narrower

Approximate $1/f_{ELM}$ Scaling of q_{peak} and ΔW_{MHD} Observed



- **60 Hz injection → q_{peak} , ΔW_{MHD} ~ $1/f_{ELM}$** ($f_{ELM} = 1/\Delta t_{ELM}$)
- **90 Hz injection → q_{peak} strongly reduced at all frequencies**

High Frequency D_2 Injection Reduces Pedestal Pressure



- **Increase of Dα baseline by D2P**
  - Additional fueling from neutrals
- **$p_{e,ped}$ reduced by edge cooling**
  - At 90 Hz, $p_{e,ped}$ ~20-30% lower

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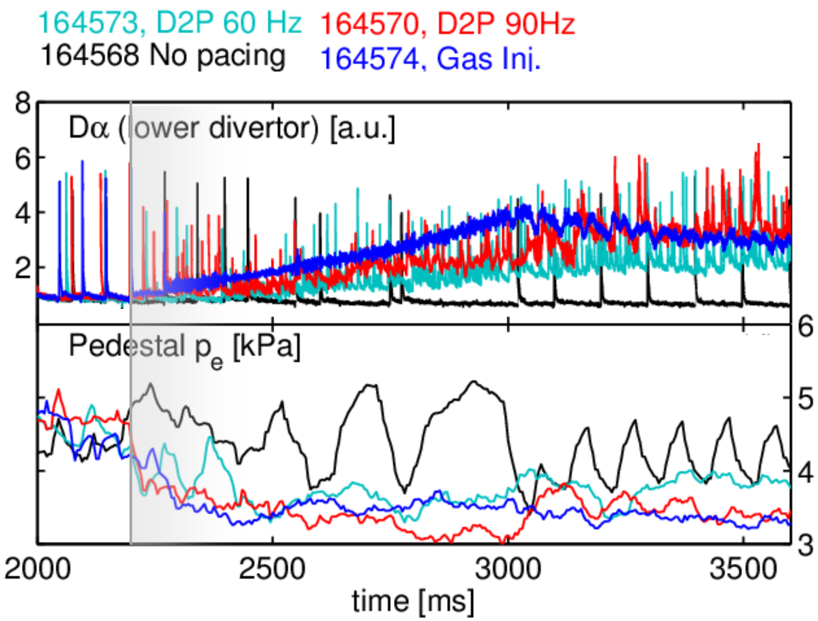

- **Increase of Dα baseline by D2P**
  - Additional fueling from neutrals
- **$p_{e,ped}$ reduced by edge cooling**
  - At 90 Hz, $p_{e,ped}$ ~20-30% lower
- **Similar pedestal parameters with 90Hz D2P and equivalent D_2 gas**
  - Discharge free from type-I ELMs

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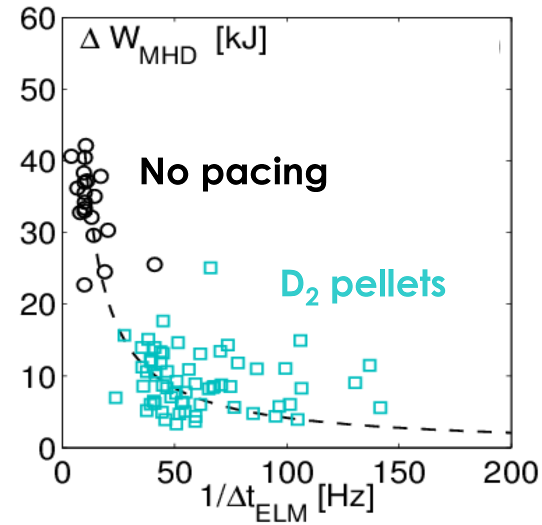

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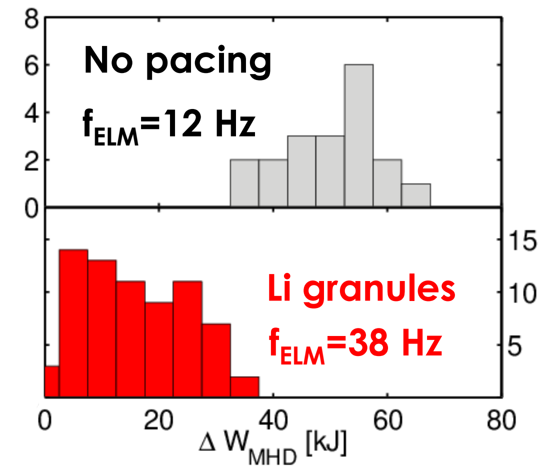
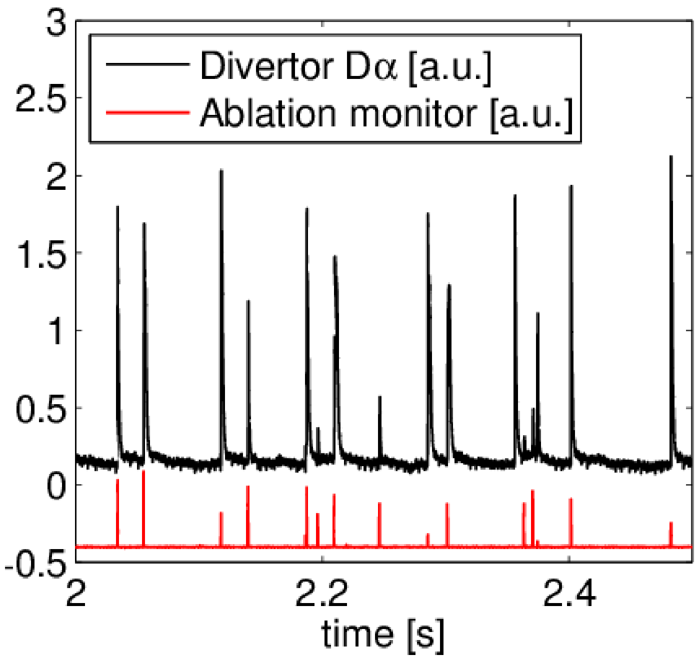
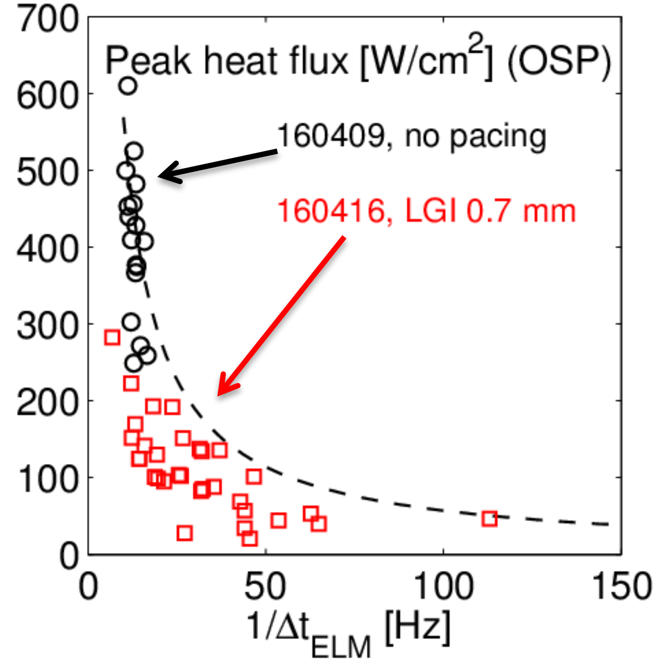


ELM Pacing and Mitigation Demonstrated with Li Granules

β_N=1.4, q_{95}=4.6, T_{inj}=3 Nm, P_{inj}=4 MW, f_{ELM}~12 Hz (***Not IBS!***)



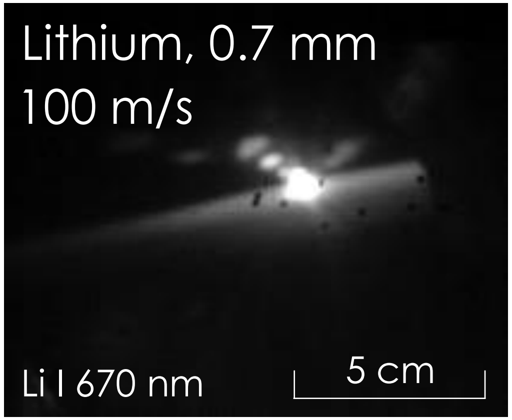


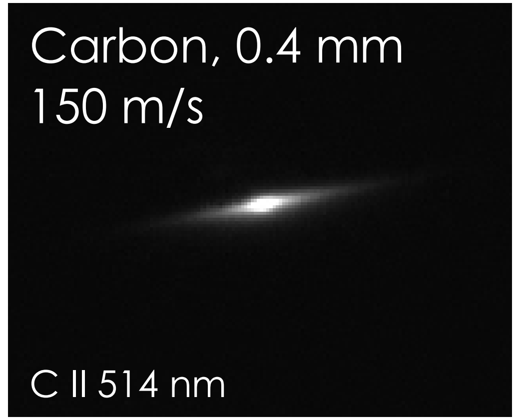
- **ELM triggering efficiency increases with granule size**
  - Pacing f_{ELM}~38 Hz (3X)
  - Transiently f_{ELM}~100 Hz (8X)

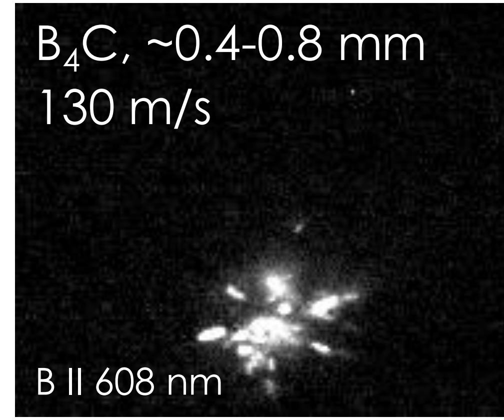
- **At OSP q_{peak} < 1/f_{ELM}**
  - At ISP, $q_{peak} \geq 1/f_{ELM}$

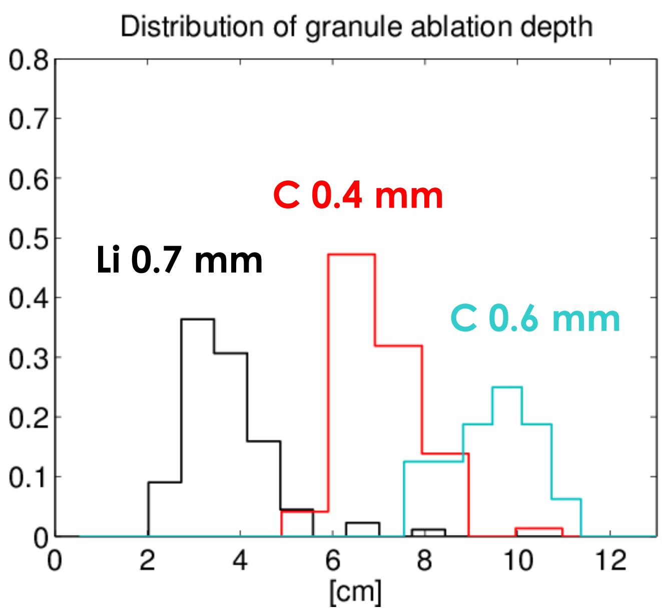
Bortolon, NF 2015

Penetration Depth of Different Materials Tested in IBS



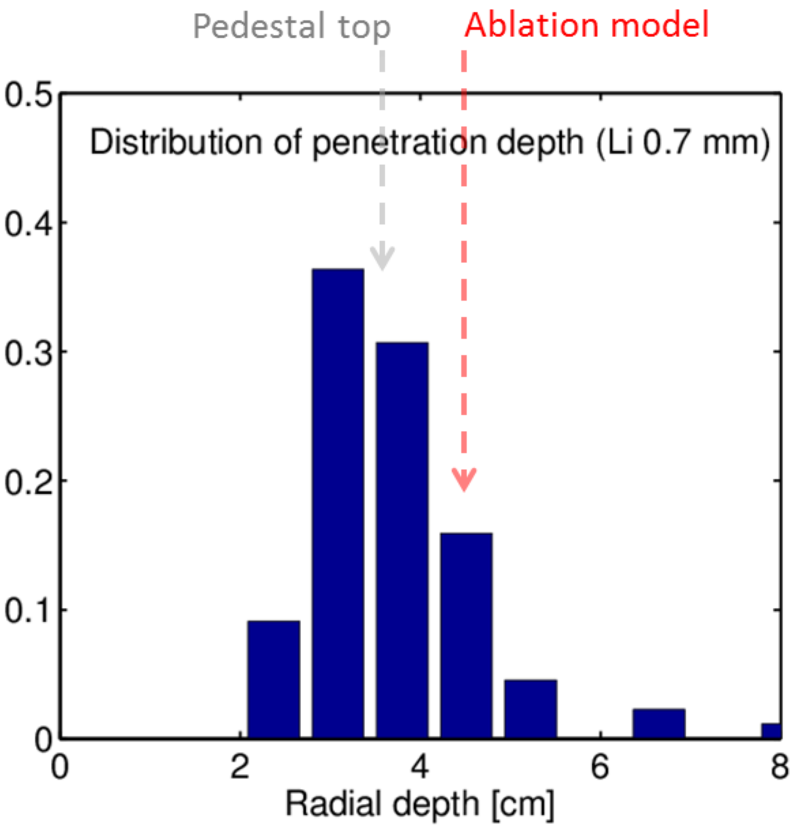






- **B_4C tends to shatter at LCFS due to thermal stresses on sharp edges**
- **C deepest penetration (5-12 cm)**
  - From measured ablation times and injection velocity, assumed constant

Li 0.7mm Granules Optimize Deposition at Pedestal Top

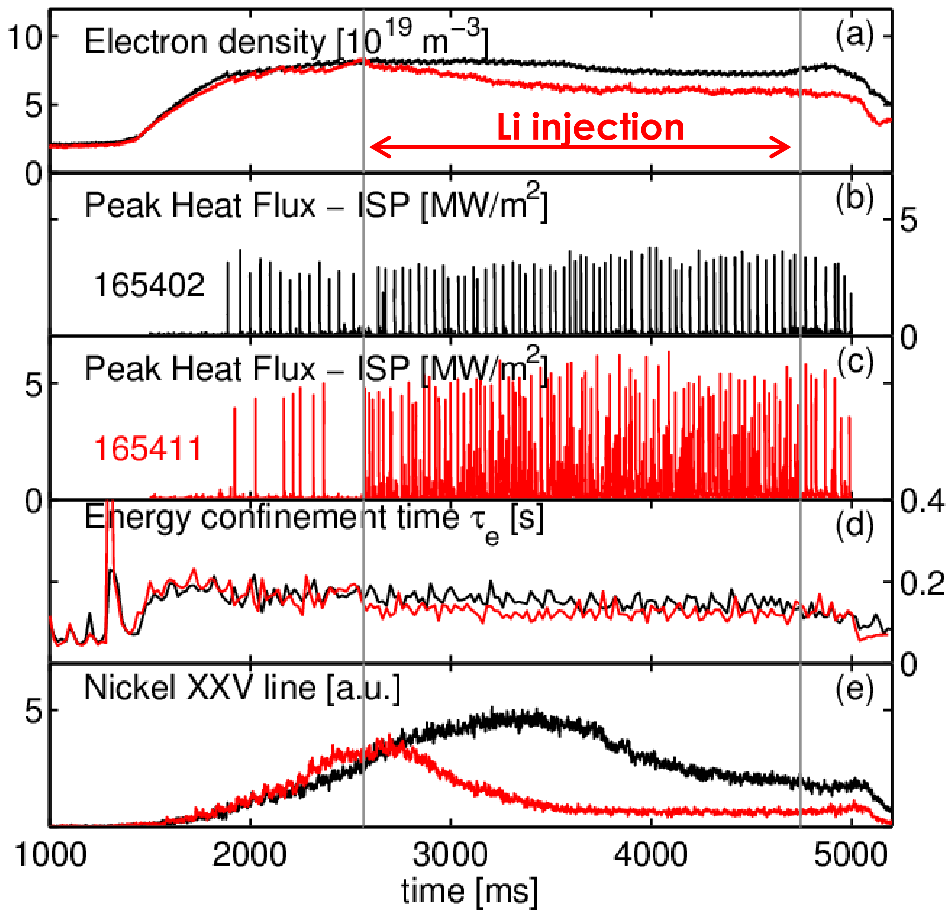


- **Most of 0.7mm Li granules reach 3-4 cm inside the LCFS**
- **New ablation model for Li predicts moderately deeper penetration than observed**

  Parks, to be submitted
- **Pedestal top is 3 cm inside the LCFS**
  - MHD simulations find ELM triggered when pressure peaks at pedestal top

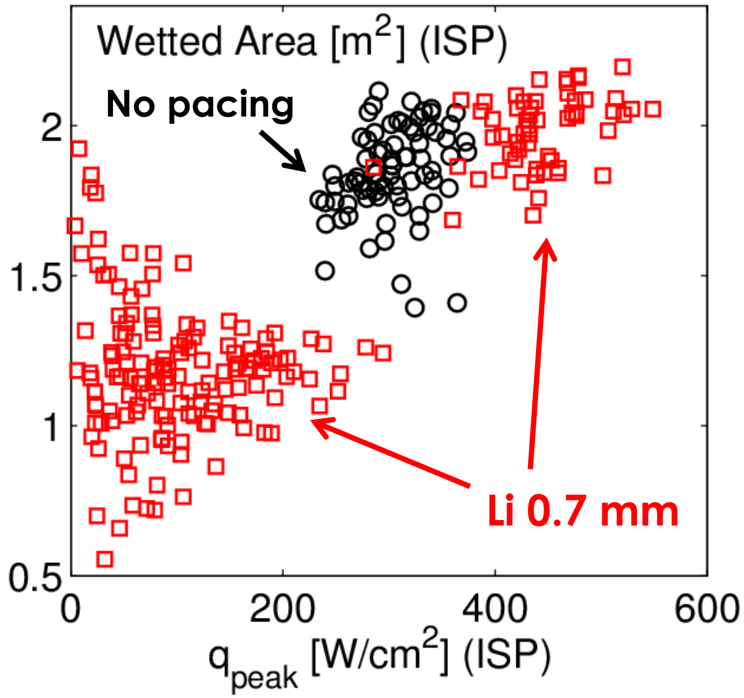
  Futatani, NF 2014

In IBS, Li Granules Effective in Pacing, but not Mitigation



- **IBS β_N=1.7, T_{inj}=2.0 Nm, f_{ELM} ~ 25 Hz**
- **Li 0.7 mm, 100 m/s, 130 Hz**
  - f_{ELM}~130 Hz (~5X)
  - Triggering efficiency >85%
- **Strong density pump-out**
  - n_e lower by 15% (ν^*_{ped} ~3.5→1.3)
  - τ_E lower by 10-20%
- **Reduction of metals (Ni) in core**
- **During Li, large ELM remain**
  - f_{LE}~41 Hz (1.6X)
  - $q_{peak,LE}$ ~ q_{peak} before and after Li

Two Classes of Li-Triggered ELMs Observed: Large & Small



- **For large ELMs, q_{peak} and wetted area similar to natural ELMs**
  - Weakly dependent on Δt_{ELM}
- **Li injection changes pedestal structure**
  - Lower $n_{e,ped}$, higher $T_{e,ped}$ (dilution) , ν^*_{ped} ~3.5→1.3

Changes of Pedestal Affect Effectiveness of Mitigation

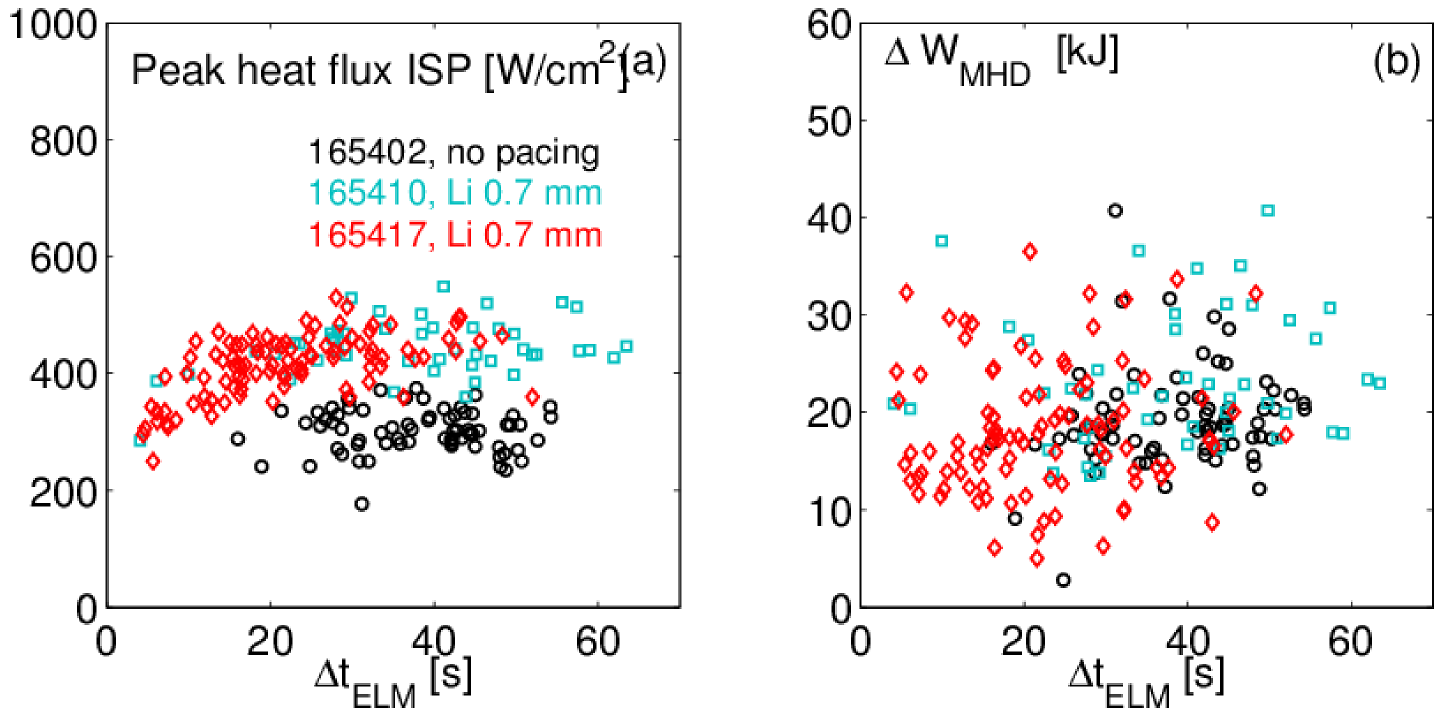
- **ELM pacing and mitigation with D2P obtained in zero-torque IBS**
  - Up to 6X increase of frequency with mitigation $\sim 1/f_{ELM}$
  - At higher f_{inj} , mitigation correlates with lower $p_{e,ped}$ associated with secondary fueling effects
- **ELM pacing and mitigation obtained with non-fuel pellets (Li)**
  - Ablation dynamics of C and B_4C confirm importance of tailoring deposition profile
- **In IBS, peak heat flux mitigation with Li is challenging**
  - Possibly associated with reduced ν^*_{ped}

Fil, TH/P1-10

- ***M3D-C[1] simulations in progress to study conditions for ELM triggering***
  - *Accurate extrapolation to ITER requires predicting changes to pedestal profiles under repetitive pellet injection*

Back up slides

For large ELMs, size depends weakly on pre-ELM period



- **Small ELMs don't affect significantly pedestal evolution**
  - Consider only large ELMs (q_{peak} > 300 W/cm^2)
- **Small changes in ELM observables, across Δt_{ELM} =5-50 ms**

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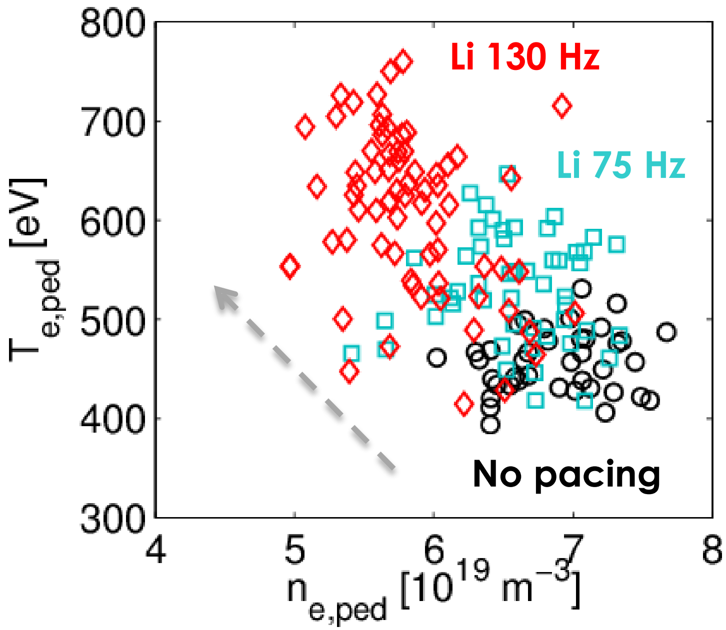
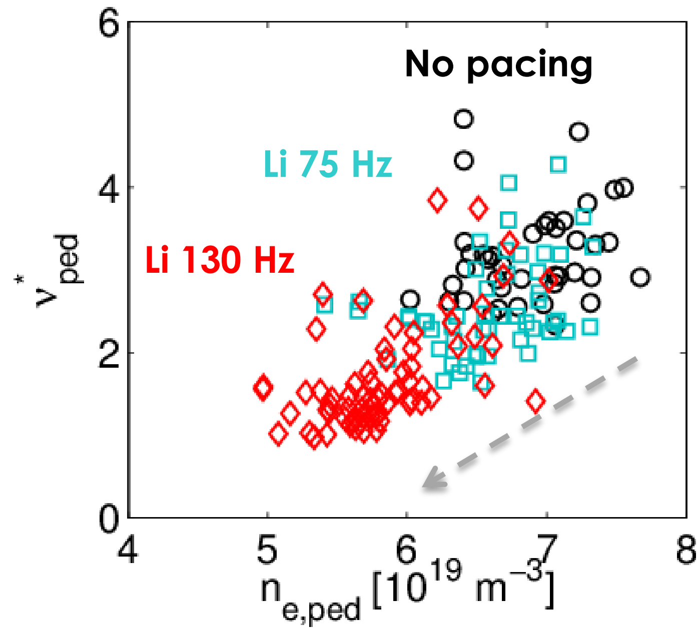
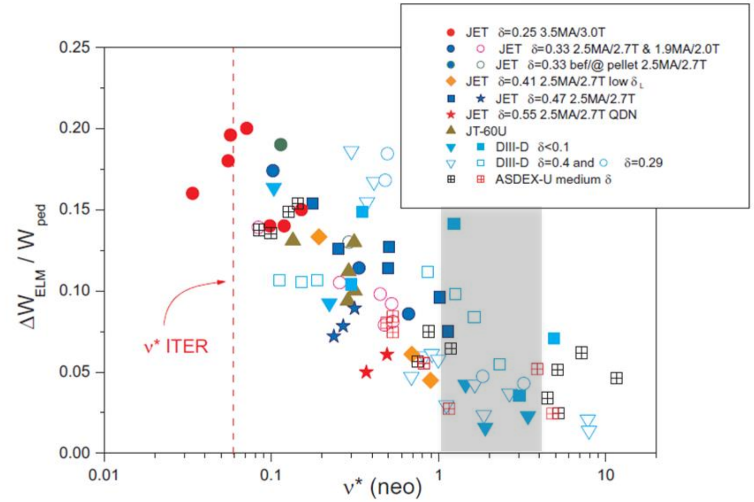
Pedestal changes observed during Li injection can lead to larger ELMs



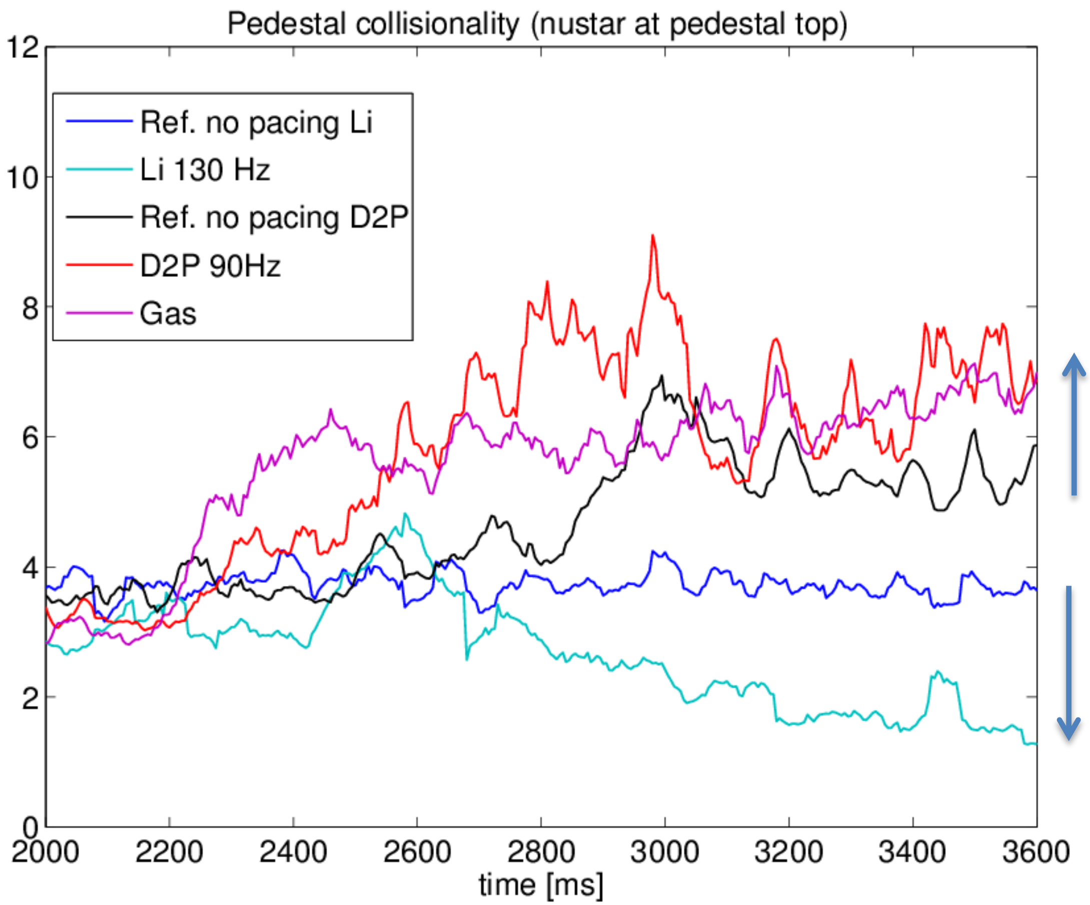


- **Li injection changes pedestal structure**
  - Lower $n_{e,ped}$, higher $T_{e,ped}$ (dilution)
  - Collisionality ν^*_{ped} ~3.5→1.3

- **Multi-machine scaling indicates larger ELM size at lower ν^*_{ped}**



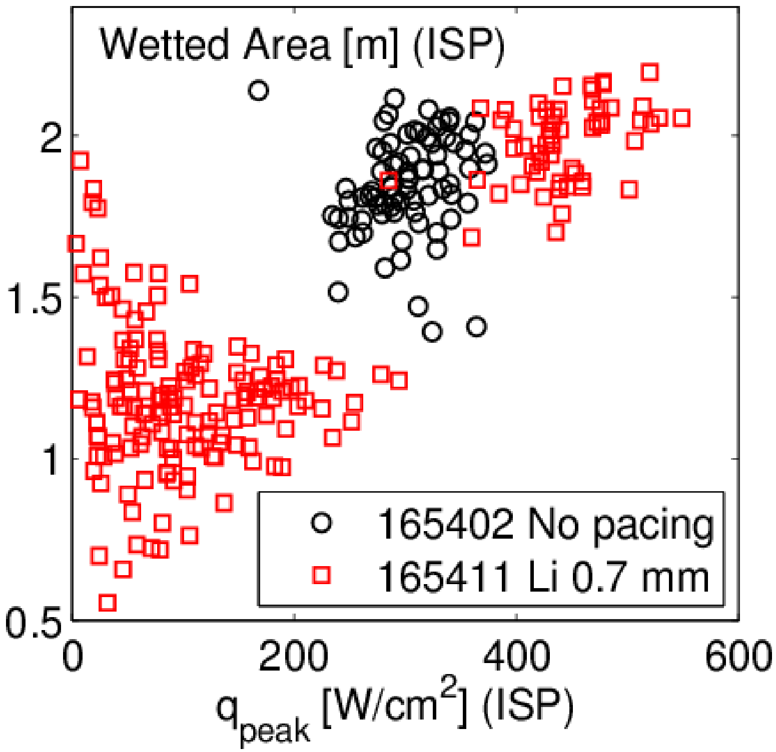
High frequency injection of D_2 and Li pellets modifies collisionality in opposite ways

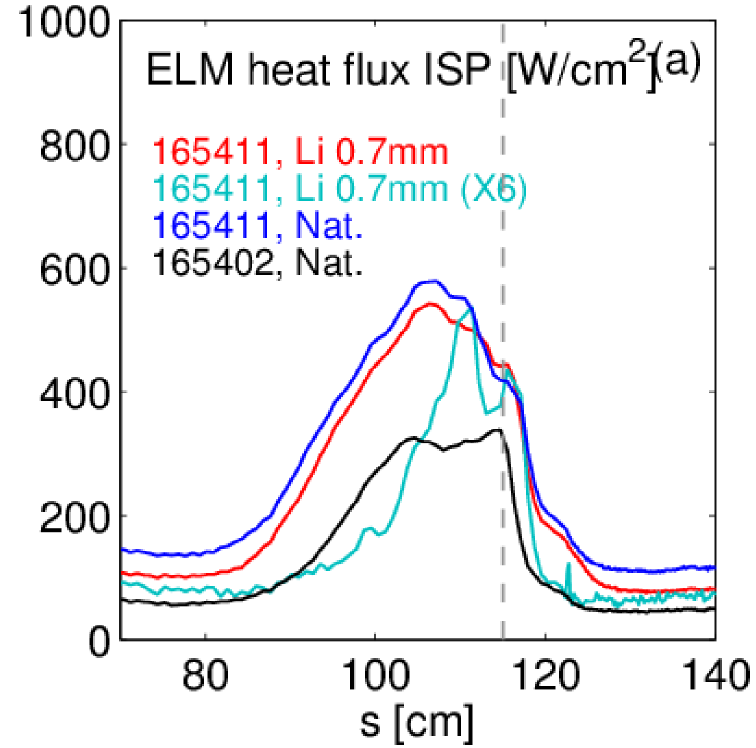


ν^* increases with 90 Hz D2P (or gas)

ν^* decreases with 130 Hz LGI

Li-triggered ELMs show broad distribution of q_{peak}





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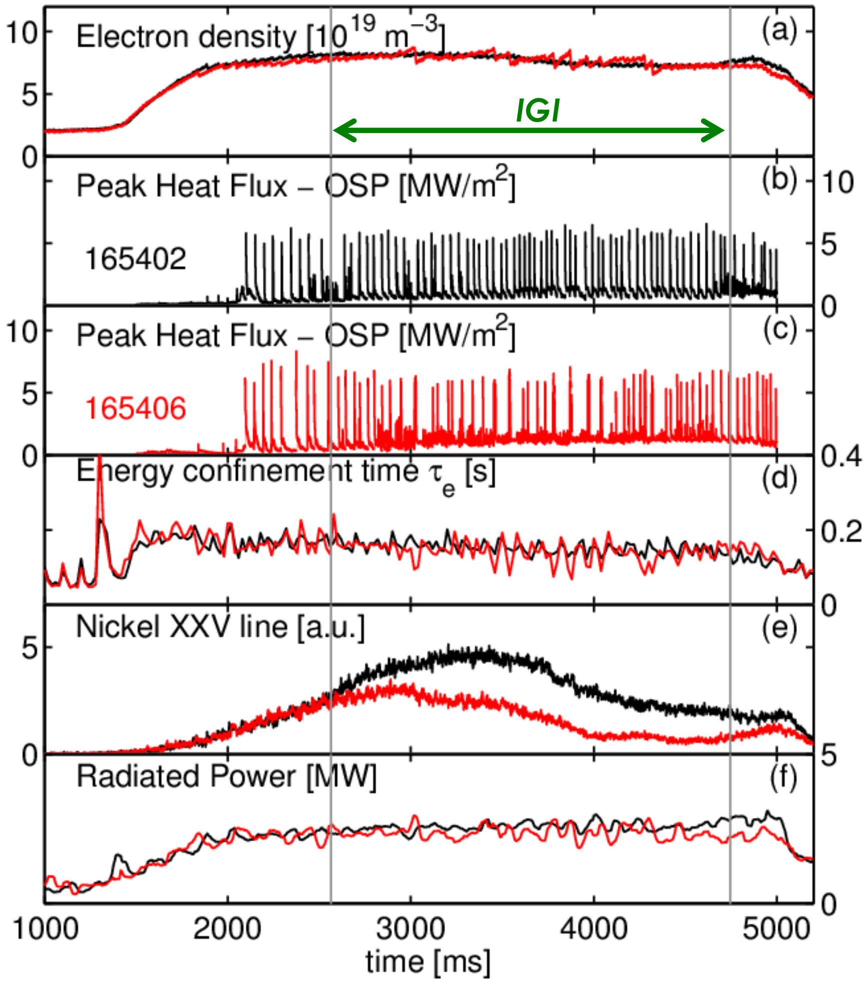
ELM pacing with C spheres achieved, not mitigation



- **ITER baseline scenario, q_{95}=3.2**
  - β_N=1.7 (feedback controlled)
  - P_{inj}=4-5 MW, T_{inj}=0.6-1.5 N m
  - f_{ELM} ~ 25 Hz
- **C sphere injection 2.6-4.8 s**
  - 0.4 mm, 130 m/s, 60 Hz
- **C injection results in a combination of large and small ELMs**
  - Overall triggering efficiency ~50% (including events with q_{peak} >30 W/cm^2)
- **For larger ELMs, f_{ELM}~10 Hz**
  - q_{peak} similar to ref. shot
  - q_{peak} ~ q_{peak} after IGI phase
- **Reduction of core Ni**
- **Similar confinement time τ_e and P_{rad}**

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Table of relevant impurity parameters

	Li	Li	D2	Be	B4C	C glass	B
Sublimation energy (eV)	1.6	1.6	0	3.3	5.3	7.5	5.8
Density [g/cm3]	0.53	0.53	0.2	1.85	2.52	1.5	2.37
Radius [mm]	0.7	0.9	1.49	1	0.5	0.5	0.5
Electrons per granule	2.49E+19	5.30E+19	1.04E+20	2.59E+20	4.67E+19	2.96E+19	4.22E+19
	27.222	57.857	13.226	416.893	107.533	81.770	91.418

- **Carbon, B4C, Boron, have higher sublimation energy than Li/D2**
  - Deeper penetration
  - Larger impact on energy balance (might induce H-L back transitions