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

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ELM Pacing Obtained with D₂ and Li Pellet Injection in Low-Torque ITER-Baseline Scenario (IBS)

- **D₂ 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 q₉₅, low nₑ
  - Mitigation not achieved in IBS

  *In ITER, D₂ 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$_4$C, 0.3-1.0 mm
  - Up to 300 Hz (depends on size)
  - 50-150 m/s (depends on material)
Heat Flux Mitigation Obtained with D$_2$ Pellets in ITER Baseline Scenario (IBS) at Zero Torque

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

![Graph showing ELM heat flux ISP vs. time with different pacing frequencies.](image)
Approximate $1/f_{\text{ELM}}$ Scaling of $q_{\text{peak}}$ and $\Delta W_{\text{MHD}}$ Observed

- 60 Hz injection $\rightarrow q_{\text{peak}}, \Delta W_{\text{MHD}} \sim 1/f_{\text{ELM}}$ ($f_{\text{ELM}} = 1/\Delta t_{\text{ELM}}$)
- 90 Hz injection $\rightarrow q_{\text{peak}}$ strongly reduced at all frequencies
High Frequency $D_2$ Injection Reduces Pedestal Pressure

- **Increase of $D_\alpha$ baseline by $D2P$**
  - Additional fueling from neutrals

- $p_{e,ped}$ **reduced by edge cooling**
  - At 90 Hz, $p_{e,ped} \sim 20$-$30\%$ lower
High Frequency D$_2$ Injection Reduces Pedestal Pressure

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- **$p_{e,ped}$ 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
ELM Pacing Obtained with D$_2$ and Li Pellets, in Low-torque ITER-Baseline Scenario (IBS)

- D$_2$ pellet injection up to 9X natural $f_{\text{ELM}}$ in IBS at applied torque $T_{\text{inj}} \sim 0$ 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
ELM Pacing and Mitigation Demonstrated with Li Granules

\[ \beta_N = 1.4, \; q_{95} = 4.6, \; T_{\text{inj}} = 3 \text{ Nm}, \; P_{\text{inj}} = 4 \text{ MW}, \; f_{\text{ELM}} \approx 12 \text{ Hz} \; (\text{Not IBS!}) \]

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

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

Bortolon, NF 2015
Penetration Depth of Different Materials Tested in IBS

- B$_4$C 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

- Pedestal top is 3 cm inside the LCFS
  - MHD simulations find ELM triggered when pressure peaks at pedestal top

*Parks, to be submitted*

*Futatani, NF 2014*
In IBS, Li Granules Effective in Pacing, but not Mitigation

- **IBS** $\beta_N=1.7$, $T_{inj}=2.0$ Nm, $f_{ELM} \sim 25$ Hz
- **Li** 0.7 mm, 100 m/s, 130 Hz
  - $f_{ELM} \sim 130$ Hz (~5X)
  - Triggering efficiency $>85\%$
- **Strong density pump-out**
  - $n_e$ lower by 15% ($v^*_{ped} \sim 3.5 \rightarrow 1.3$)
  - $\tau_E$ lower by 10-20%
- **Reduction of metals (Ni) in core**
- **During Li, large ELM remain**
  - $f_{LE} \sim 41$ Hz (1.6X)
  - $q_{peak,LE} \sim q_{peak}$ before and after Li
Two Classes of Li-Triggered ELMs Observed: Large & Small

- For large ELMs, $q_{\text{peak}}$ and wetted area similar to natural ELMs
  - Weakly dependent on $\Delta t_{\text{ELM}}$
- Li injection changes pedestal structure
  - Lower $n_{\text{e,ped}}$, higher $T_{\text{e,ped}}$ (dilution), $v^*_{\text{ped}} \sim 3.5 \rightarrow 1.3$
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 \( \sim 1/f_{\text{ELM}} \)
  - At higher \( f_{\text{inj}} \), mitigation correlates with lower \( p_{e,\text{ped}} \) associated with secondary fueling effects

• **ELM pacing and mitigation obtained with non-fuel pellets (Li)**
  - Ablation dynamics of C and B\(_4\)C confirm importance of tailoring deposition profile

• **In IBS, peak heat flux mitigation with Li is challenging**
  - Possibly associated with reduced \( v^*_{\text{ped}} \)

• **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
Small ELMs don't affect significantly pedestal evolution
- Consider only large ELMs ($q_{\text{peak}} > 300 \text{ W/cm}^2$)

Small changes in ELM observables, across $\Delta t_{\text{ELM}} = 5-50 \text{ ms}$
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 $\nu^*_{ped} \sim 3.5 \rightarrow 1.3$

- **Multi-machine scaling indicates larger ELM size at lower $\nu^*_{ped}$**
High frequency injection of D$_2$ and Li pellets modifies collisionality in opposite ways

- $\nu^*$ increases with 90 Hz D2P (or gas)
- $\nu^*$ decreases with 130 Hz LGI
Li-triggered ELMs show broad distribution of $q_{peak}$
ELM pacing with C spheres achieved, not mitigation

- **ITER baseline scenario, \( q_{95} = 3.2 \)**
  - \( \beta_N = 1.7 \) (feedback controlled)
  - \( P_{\text{inj}} = 4 \text{-} 5 \text{ MW}, T_{\text{inj}} = 0.6 \text{-} 1.5 \text{ N m} \)
  - \( f_{\text{ELM}} \sim 25 \text{ Hz} \)

- **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 \( \sim 50\% \)
    (including events with \( q_{\text{peak}} > 30 \text{ W/cm}^2 \))

- **For larger ELMs, \( f_{\text{ELM}} \sim 10 \text{ Hz} \)**
  - \( q_{\text{peak}} \) similar to ref. shot
  - \( q_{\text{peak}} \sim q_{\text{peak}} \) after IGI phase

- **Reduction of core Ni**
- **Similar confinement time \( \tau_e \) and \( P_{\text{rad}} \)**
**Table of relevant impurity parameters**

<table>
<thead>
<tr>
<th></th>
<th>Li</th>
<th>Li</th>
<th>D2</th>
<th>Be</th>
<th>B4C</th>
<th>C glass</th>
<th>B</th>
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<tbody>
<tr>
<td>Sublimation energy (eV)</td>
<td>1.6</td>
<td>1.6</td>
<td>0</td>
<td>3.3</td>
<td>5.3</td>
<td>7.5</td>
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<tr>
<td>Density [g/cm³]</td>
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<td>0.53</td>
<td>0.2</td>
<td>1.85</td>
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<td>Radius [mm]</td>
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<td>0.9</td>
<td>1.49</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Electrons per granule</td>
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<td>5.30E+19</td>
<td>1.04E+20</td>
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<td>4.67E+19</td>
<td>2.96E+19</td>
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<td>27.222</td>
<td>57.857</td>
<td>13.226</td>
<td>416.893</td>
<td>107.533</td>
<td>81.770</td>
<td>91.418</td>
</tr>
</tbody>
</table>

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