Preliminary results of recent impurity granule injection experiments on DIII-D

by
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Impurity Granule Injector upgraded to allow injection of granules of materials other than Lithium (e.g. C, B$_4$C)

- **Top part: piezo-electric granule dropper**
  - Average drop rate function of applied voltage (0 – 1000 granules/s)
  - Four separate reservoirs, 0.3 – 0.9 mm
  - Inter-shot manual selection

- **Bottom part: rotating granule impeller**
  - Two-paddle impeller, $f_{\text{rot}} < 250$ Hz
  - $f_{\text{inj}} < 500$ Hz, $v_{\text{inj}} \sim 40$-150 m/s
  - Adjustable drop location accounts for elastic VS inelastic impacts
  - Max $v_{\text{inj}}$ depends on material (100 m/s for Li)

- **Asynchronous coupling**
  - Injection frequency fluctuates
  - Multi granule injection events can happen (at lower velocity/higher drop rates)
Summary ELM pacing with impurity granules in DIII-D

- Oct 2014: Lithium granule injector installed on DIII-D
- Nov-Dec 2014: Experiments on ELM pacing with Li granules
  - Hybrid plasma scenario (NF in press)
  - ITER baseline at low torque (presented at H-mode WS and APS2015)
- Oct 2015: Upgraded Injector installed on DIII-D
  - Handles different species without major hardware re-configuration
- Feb 2015: Experiment on ELM pacing with impurity granules
  - Study effectiveness of using Lithium, Carbon, Boron Carbide
  - Combined operation of pellet ELM pacing and pellet fueling
Outline of the talk

• Overview of previous results of Li granule injection in DIII-D

• Preliminary results on ELM pacing with different materials
  – Glassy carbon spheres (0.4-0.6mm diameter)
  – Lithium spheres (0.7mm diameter)
  – Boron Carbide (B\textsubscript{4}C, irregularly shaped granules, 0.6-0.8mm)

• D2 pellet fueling in IGI paced discharges
Robust ELM pacing achieved with 0.4-0.9 mm granules

- **ELM pacing tested varying granule size, injection frequency and speed**
  - Triggered ELMs occur within 1 ms from start of granule ablation
  - Close to 100% of ELMs are result of granule injection

- **Triggering efficiency increases with granule size**
  - Averaged ELM frequency up to 100 Hz achieved  \( (f_{ELM}=200 \text{ Hz transiently!}) \)

\[
\begin{align*}
0.4 \text{ mm}, 105 \text{ m/s} & \quad f_{LGI}=140 \text{ Hz}, f_{ELM}=38 \text{ Hz} \\
0.7 \text{ mm}, 100 \text{ m/s} & \quad f_{LGI}=30 \text{ Hz}, f_{ELM}=30 \text{ Hz} \\
0.9 \text{ mm}, 120 \text{ m/s} & \quad f_{LGI}=95 \text{ Hz}, f_{ELM}=80 \text{ Hz}
\end{align*}
\]
Divertor peak heat flux scaling with ELM frequency

- **Test** $q_{\text{peak}} = \text{const}/f_{\text{ELM}}$ with statistical approach
  - Consider sets of single LGI-induced ELMs
  - $f_{\text{ELM}} = 1/(t_{\text{ELM},n} - t_{\text{ELM},n-1})$

- **Reduced $q_{\text{peak}}$ at higher $f_{\text{ELM}}$**
  - Data scatter at const. $f_{\text{ELM}}$
  - Independent on actual pre-ELM period

- **Outer Strike point**
  - $q_{\text{peak}} < 1/f$

- **Inner Strike Point**
  - $q_{\text{peak}} > 1/f$ (for 0.4 mm)

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- **0.4 mm granules**
  - Peak heat flux ISP [W/cm²]
  - Peak heat flux OSP [W/cm²]

- **0.7 mm granules**
  - Peak heat flux ISP [W/cm²]
  - Peak heat flux OSP [W/cm²]
In low-torque ITER baseline Li granules trigger different classes of ELMs: large and small.

**Hybrid scenario**
- $f_{\text{ELM}} = 38 \text{ Hz (X3)}$
- Peak Heat Flux $q_{\text{peak}}$ is reduced (X0.5)
- ELM amplitude varies by 50%

**ITER baseline**
- $f_{\text{ELM}} = 98 \text{ Hz (X4)}$
- Granule speed $v_g = 50 \text{ m/s}$
- Clear separation of ELM amplitude
- $q_{\text{peak}}$ can be larger than natural ELMs!
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  - Lithium spheres (0.7mm diameter)
  - Boron Carbide ($B_4C$, irregularly shaped granules, 0.6-0.8mm)

- D2 pellet fueling in IGI paced discharges
Fast multi-spectral imaging of ablation region provides estimates of penetration depth and ablation cloud size.

<table>
<thead>
<tr>
<th>Material</th>
<th>Diameter (mm)</th>
<th>Speed (m/s)</th>
<th>Time (ms)</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glassy Carbon</td>
<td>0.4</td>
<td>140</td>
<td>0.6</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>1.1</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Solid Lithium</td>
<td>0.7</td>
<td>100</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Boron Carbide B$_4$C</td>
<td>~0.7</td>
<td>Granules tend to shatter upon contact with the LCFS. Possibly due to thermal stresses due to the hardness and sharp edges.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Granules tend to shatter upon contact with the LCFS. Possibly due to thermal stresses due to the hardness and sharp edges.
ELM pacing with C spheres achieved, not mitigation

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

- C sphere injection 2.6-2.8 s
  - 0.6 mm, 130 m/s, 60 Hz

- C injection results in a combination of large and small ELMs
  - Overall triggering efficiency $\sim 50\%$

- For larger ELMs, $f_{ELM} \sim 10$ Hz
  - $q_{peak} \sim q_{peak}$ after IGI
  - $q_{peak}$ similar to ref. shot

- Reduction of core Ni
- Similar confinement time $\tau_e$ and $P_{rad}$
Carbon granules are effective in pacing small ELMs

- Small natural ELMs appear in the reference discharge
  - Occurrence of type-I ELMs delayed

- Carbon granule injection promotes natural small ELMs
  - Fast pacing of small ELMs observed
Larger C and B\textsubscript{4}C granules trigger ELMs but with detrimental effects on discharge evolution

• **IGI, Carbon 0.6mm**
  – 60-130 m/s

• **Large low frequency ELMs**
  – Collapse of density pedestal
  – Followed by L-mode transients
  – 2/1 mode locks, leading to disruption

• **IGI Boron Carbide**
  – $f_{ELM} \sim 60\text{Hz}$, but likely most are natural
  – Peak heat flux remains high
  – Strong 3/2 mode perturbs plasma evolution (and ELMs)
Lithium granules effective in pacing, but not mitigation

- **ITER baseline scenario**
  - $\beta_N = 1.7$, $f_{ELM} \sim 25$ Hz

- **Li injection 2.6-4.8 s**
  - 0.7 mm, 100 m/s, 130 Hz
  - $f_{ELM} \sim 130$ Hz (~5X, small + large)
  - Triggering efficiency ~85%

- **Large events remain**
  - $f_{ELM} \sim 35$ (1.5X)
  - $q_{peak} \sim q_{peak}$ after IGI
  - $q_{peak}$ larger than in ref. shot

- **Strong density pump-out**
  - Stationary $n_e$ decreased by 15%
  - $\tau_e$ lower by 10-20% ($n_e$ effect?)

- **Reduction of core Ni**

- **$P_{rad}$ reduced by 20%**
Distribution of divertor $q_{\text{peak}}$ shows two classes of ELMs

- In IGI shots the peak heat flux is larger than reference shot
- Effect of impurity in the pedestal? (dilution, $j_{\text{BS}}$, resistivity, …)
Outline of the talk

- Overview of previous results of Li granule injection in DIII-D

- Preliminary results on ELM pacing with different materials
  - Glassy carbon spheres (0.4-0.6mm diameter)
  - Lithium spheres (0.7mm diameter)
  - Boron Carbide ($B_4C$, irregularly shaped granules, 0.6-0.8mm)

- D2 pellet fueling in IGI paced discharges
Combining ELM pacing (IGI) with pellet fueling (D2PF)

- ELM pacing: Li, 100 m/s, 130 Hz
  - $f_{\text{ELM}} \sim 130$ Hz ($\sim 5X$), 85% efficiency
- $n_e$ pump-out affects pedestal
  - $n_{e,\text{ped}}$ reduced by $\sim 15\%$
  - $T_{e,\text{ped}}$ increased by $\sim 20\%$
Combining ELM pacing (IGI) with pellet fueling (D2PF)

- ELM pacing: Li, 100 m/s, 130 Hz
  - \( f_{\text{ELM}} \approx 130 \text{ Hz (~5X)} \), 85% efficiency
- \( n_e \) pump-out affects pedestal
  - \( n_{e,\text{ped}} \) reduced by ~15%
  - \( T_{e,\text{ped}} \) increased by ~20%
- Add D\(_2\) pellet fueling for \( t>3 \) s
  - 5 Hz, 1.8x1.8mm, HFS injection
- ELM pacing: Li, 100 m/s, 120 Hz
  - \( f_{\text{ELM}} \approx 100 \text{ Hz (~4X)} \), 75% efficiency
- Density matched target value
  - Pedestal \( T_e, n_e \) as in reference shot
  - Confinement recovers (partially)
  - Radiative losses remain low
Summary and outlook

• ELM pacing by injection of Li, C and, B$_4$C granules in DIII-D

• Preliminary results indicate that Li and C can effectively trigger ELMs in this scenario. However:
  – A combination of small and large ELMs is typically obtained
  – ELM size (natural and paced) in IGI shots appears to be larger than in reference shots, with a weak dependence on ELM frequency (effect of $Z_{\text{eff}}$ / dilution or plasma resistivity in the pedestal?)
  – Small ELMs appear to delay large ELM: can we use well tailored periodic injection to control the pedestal working point and prevent large events?

• Data from ablation camera provide opportunities (and few surprises) for validating and advancing ablation models

• The optimized density control has been obtained with combining high frequency pacing with IGI ELM and D2P fueling
  – Initial step towards a demonstration at ITER relevant $f_{\text{ELM}}$ multipliers
Back up slides
Boron granule can pace fast ELMs
Small ELMs delay occurrence of Large ELMs

- In reference discharge the occurrence of small ELMs delays the onset of a large ELMs
- PHF of large events does not change
- Provoking thought:
  - Use periodic trig of small ELMs for delaying large events indefinitely
  - In other words, utilize small ELMs (that we can trigger reliably) to control the “working point” in the stability diagram
Li 0.7mm effective in pacing big and small ELMs

Pacing frequencies up >350 Hz (transiently)
Frequency of large ELMs ~X2, similar PHF
Back up slides
With small ELMs a pedestal collapse is not observed

- Measurement profile changes is challenging
  - For 0.9 mm granule full ablation takes <1ms

- Line integrated $n_e$ from double-pass CO$_2$ interferometer
  - Vertical chord at $r/a$~0.7
  - Sampled at 100 kHz

- Granule injection causes 10% increase for 1 ms
  - Small ELMs are not followed by $n_e$ drops
  - “Fueling” effect observed
30% increase of maximum ELM peak heat flux observed

- Considering average $q_{peak}$ due only to large ELMs
  - Increase by 30% at ISP
  - Unchanged at OSP

- Possible scaling of $q_{peak, large}$ with $1/f$
- Weak dependence on frequency of small ELM events
Granule injection captured by fast imaging camera

- 0.4 mm granule at 105 m/s
- ~250 μs ablation time

More on granule ablation
R. Lunsford, Tue 12:30
High triggering efficiency with deeper penetration

- **Granule diameter >0.7 required for ~80-100% efficiency**
  - Weak improvement with higher injection velocity
- **Larger granules penetrate beyond the pedestal top**
  - Smaller granules ablated in the pedestal region
  - Assumes constant velocity → possible overestimate
Increased ELM frequency reduces ELM size

- ELM stored-energy drop $\Delta W_{\text{ELM}}$ and peak heat flux $q_{\text{peak}}$ decrease
- Broader distributions observed
  - Variability in granule size? Fluctuating injection frequency?
Global effects on kinetic plasma profiles observed

- **160409, Ref.** $f_{\text{ELM}} = 12 \text{ Hz}$
- **160414, LGI** $f_{\text{ELM}} = 38 \text{ Hz}$

- **Reduced $N_e$ at pedestal top**
  - Unchanged $T_e, T_i$
- **25% increase in core $T_e$ & $T_i**
  - Due to increased peaking
  - Transport?

- **Lithium dominant core impurity**
  - Flat Li$^{3+}$ density profile
  - C$^{6+}$ density reduced by 50%
  - Metal impurities (Nickel) strongly reduced in the core
In IGI shot the peak heat flux is larger than reference shot

Distribution of divertor $q_{\text{peak}}$ shows two classes of ELMs
Summary and outlook

- **The LGI has been successfully installed and operated on DIII-D**
  - Flexible granule injection possibilities (granule material, size, velocity)
  - Ongoing development for improving injection periodicity

- **ELM triggering and pacing demonstrated in ITER-like scenarios**
  - Trig efficiency improves with granule size
  - LGI pacing compatible with high performance (to be extended to low torque scenarios)
  - Need to understand ELM size distribution and violations to $q_{\text{peak}} \propto 1/f_{\text{ELM}}$

- **Future focus for analysis / modeling**
  - Validation of ablation models (ablation imaging camera)
  - Dynamic of the LGI induced ELMs (MHD stability)
Full shot ELM pacing obtained with 0.4 mm granules

- **Reference ELMy H-mode**
  - 1.2 MA, $\beta_N = 1.4$,
  - $P_{\text{NBI}} = 2.3$ MW, $T_{\text{NBI}} = 0.6$ N m
  - “Natural” $f_{\text{ELM}} = 12$ Hz
  - MHD mode for $t > 350$ ms

- **LGI pacing ($1.5 < t < 5$ s)**
  - Granule diam. **0.4 mm**
  - Granule velocity **105 m/s**
  - $f_{\text{ELM}} = 38$ Hz (3X)
  - $n_e$ reduced by ~15%
  - Small or no change in confinement
  - No MHD modes
  - Metal impurities reduced
LGI and natural ELMs have similar heat flux footprint

- ELM heat flux from fast IR camera
  - 12 kHz, array mode
  - THEODOR analysis for thermography

- OSP double peak observed for natural ELMs
  - Most heat goes 5 cm from the strike point

- LGI trigger does not modify ELM footprint
  - Two peaks have comparable amplitude
Summary of the experimental activities

- **Two full experimental days**
  - Total 50 plasma shots (~ 550 mg of Li injected)

- **Injection frequency ~ 100-500 Hz,**
- **Granule speed ~ 50-150 m/s**
- **4 granule sizes (0.3, 0.5, 0.7, 0.9 mm)**

- **Low power H-modes**
  - Minimize natural ELM frequency
  - ITER-like shape

- **Comparison with D$_2$ pellets within the same discharges**
Toroidal location of LGI and IR camera
Pacing efficiency depends weakly on granule velocity

- Shot by shot velocity scan
  - 0.9 granule size
  - Constant piezo drive (30V)
  - Approximately constant drop frequency (100 Hz)
  - Impeller speed varied
- Granule speed varied within a factor ~2
  - 60 – 110 m/s
- 5% increase of average ELM frequency
- Pacing efficiency increases from 88% to 92%
High triggering efficiency obtained with large granules

- **Super H-mode attempt**
  - 1.2 MA, $\beta_N \sim 2$
  - $P_{\text{NBI}} = 8$ MW

- **LGI on 1.5<$t<$3.5 s**
  - Granule diam. 0.9 mm
  - Granule velocity 120 m/s
  - Average injection frequency 95 Hz
  - Average $f_{\text{ELM}} = 80$ Hz
  - Triggering efficiency $\sim 100\%$ in selected time windows
Lithium granule injector implemented on DIII-D

- Equatorial plane port
- Radial, horizontal injection
- Linear step motor for TIV shield
- TIV valve
- Drift tube
- Impeller Chamber
- Top view of dropper in its housing (loaded with granules)
- Lithium granules stored in Argon atmosphere