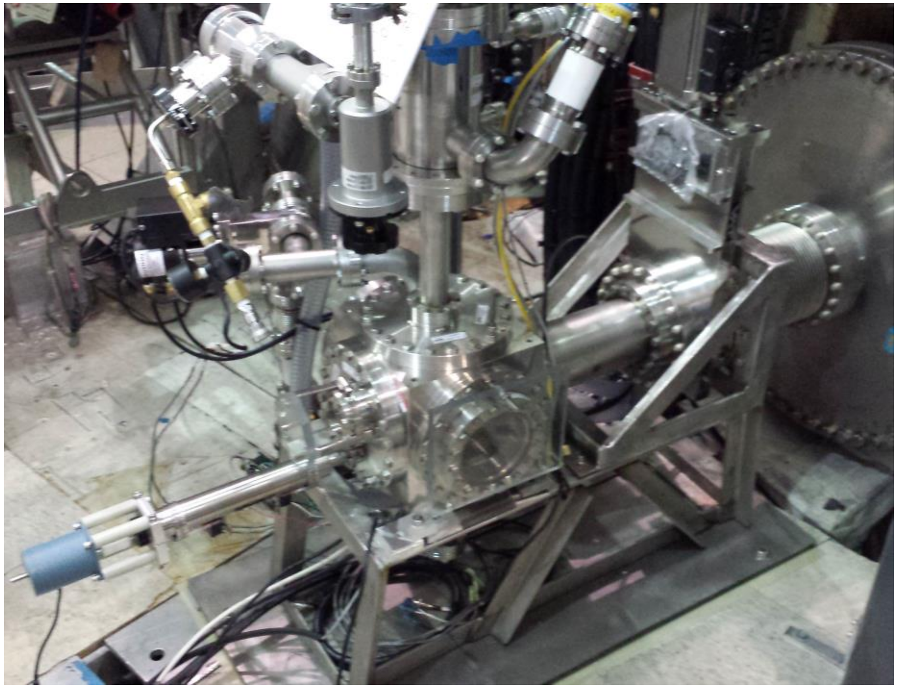
ELM pacing experiments on DIII-D using Lithium Granule Injector (LGI)

by
A.Bortolon for the LGI team

(A.Bortolon, W.Brown, E.Gilson, G.Jackson (GA), R.Lunsford, R.Maingi, D.Mansfield, A.Nagy, A.Roquemore, …)



Presented to
NSTX-U group at PPPL

Jan 5th 2015

Introduction and motivation

- **Control / pacing of ELMs required in ITER** *[Loarte, NF 2014]*
  - Peak Heat Flux tolerable by PFC
  - Counteract impurity contamination (W)
  - ELM frequency much larger that "natural" are required(50X)
- **Pellet injection (D_2) proved to be effective ELM pacing tool**
  [Baylor, IAEA 2012]
- **It is desirable to decouple fueling and ELM control**
  - Avoid interference with density control
  - Exhaust fuel processing capabilities limits fuel throughput
- **ELM pacing by Lithium Granule Injection was demonstrated on EAST** *[Mansfield NF 2013]*
  - The LGI (developed by D.Mansfield and L. Roquemore) has potential for high injection rates

Assessing LGI potential for ELM control at DIII-D

- **Program goals (following ITPA needs) includes:**
  - Measure minimum size, speed, and penetration depth to trigger ELMs, compare with D_2 pellets
  - Assess triggering and pacing efficiency
  - Characterize impurity-triggered ELMs
  - Determine the achievable multiplication of natural ELM frequency
  - How do heat flux peak and footprint width respond?

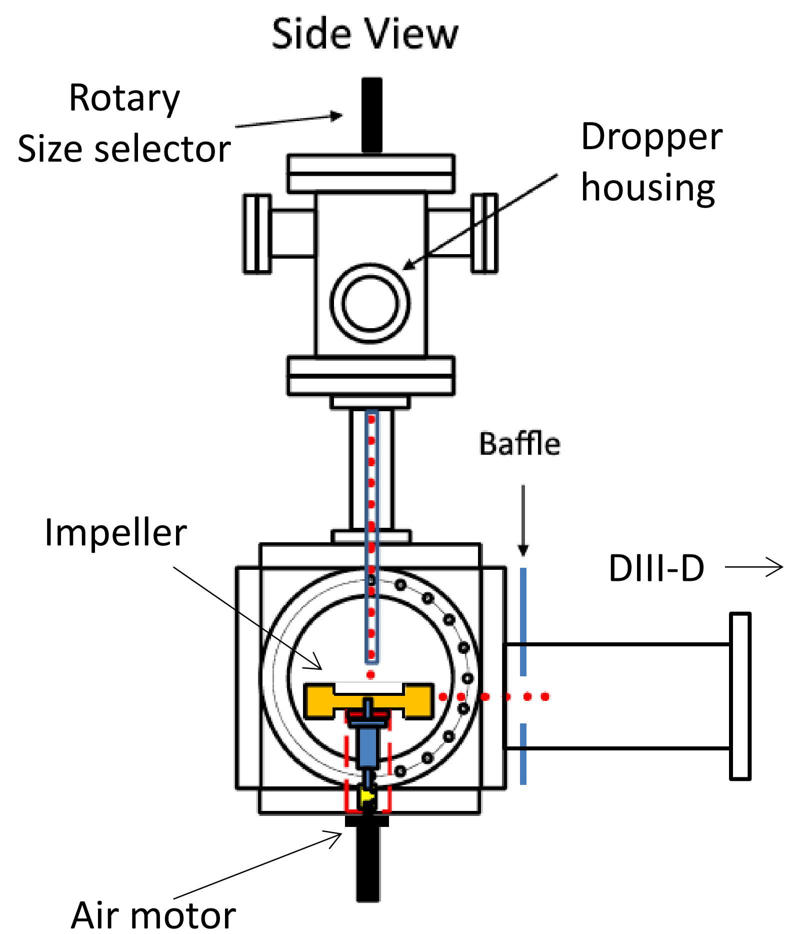
- **LGI assembled at PPPL, installed on DIII-D during Sep-Oct 2014**
- **Experiments on DIII-D plasmas performed on Nov-Dec 2014**

Outline of the talk

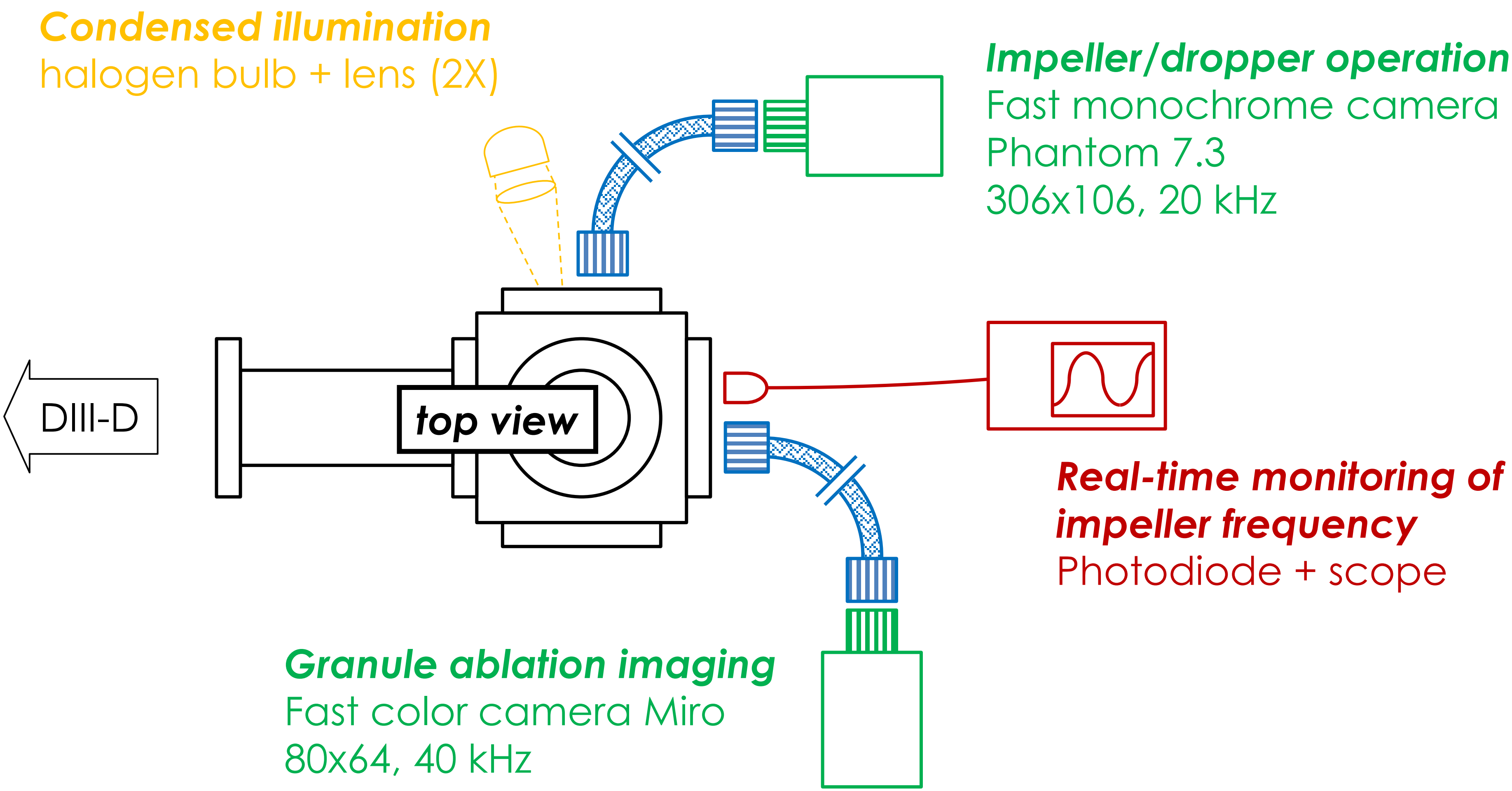
- **Description of the Lithium Granule Injector**
  - Concept and DIII-D implementation
- **Experiments on DIII-D**
  - Effectiveness of ELM triggering and pacing
  - Different granule size
  - Effect of granule velocity
- **Characterization LGI paced ELMs and effect on plasmas**
  - Peak heat flux dependence on f_{ELM}
  - Impurity accumulation
  - Neutron production rates

Lithium granule injector concept

- **Top part: granule dropper**
  - four separate reservoirs, 0.3 – 0.9 mm
  - vibrating piezoelectric disk
  - Average drop rate function of applied voltage (0 - 1000Hz)
- **Bottom part: granule impeller**
  - rotary motor + ferro-fluidic feed-though, f_{rot} < 250 Hz
  - Two-paddle impeller imparts 10-100 m/s (at f_{inj}=500 Hz)
- **Asynchronous coupling**
  - Injection frequency fluctuates
  - Multi granule injection events (at lower velocity/higher drop rates)



LGI equipped with diagnostics to monitor operation



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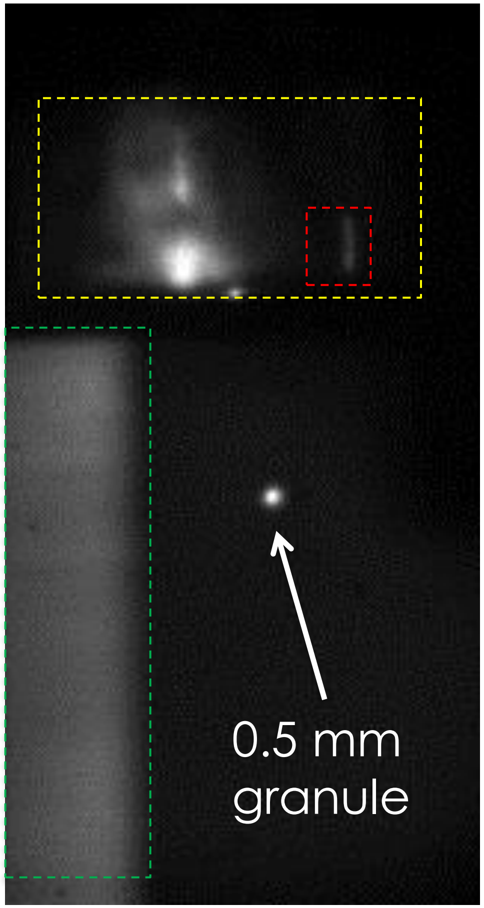
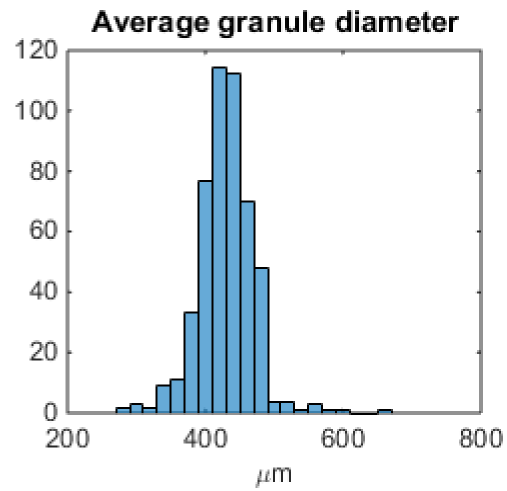
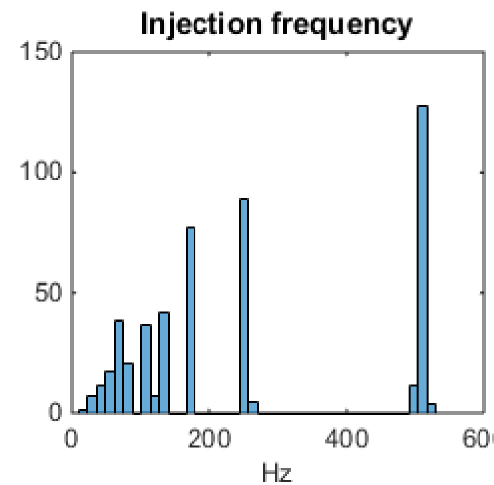
Fast imaging provides useful data for interpretation

Side camera frame



- **Image processing of frames preceding impeller hit provides history of hit events (injections)**





- **Light from pellet ablation reflected on the dropper nozzle provides ablation time line**
- **Cross-correlating hits and ablations provides and estimate of pellet velocity**

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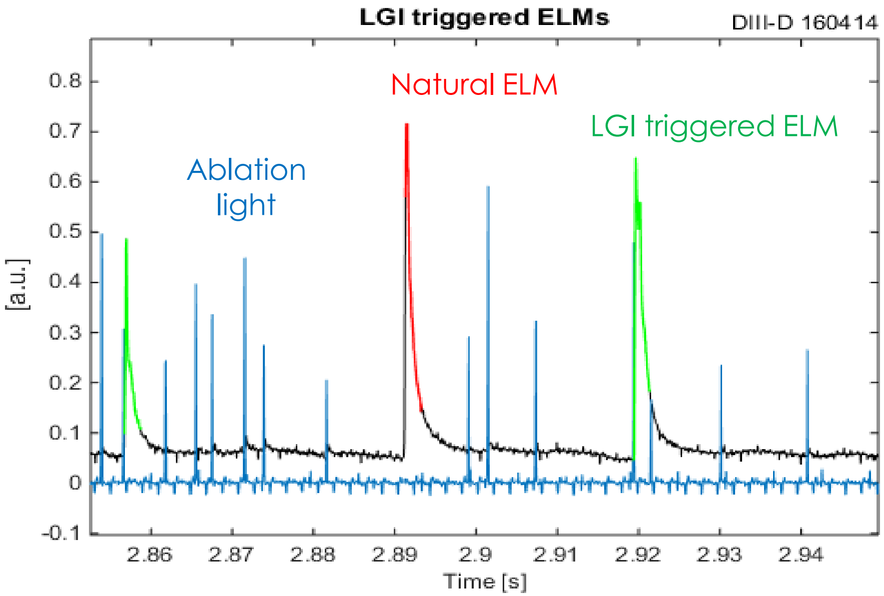
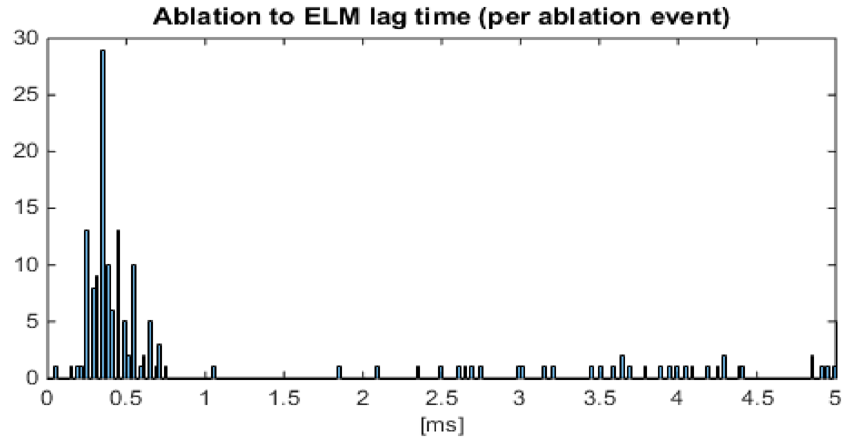
LGI triggered ELMs destabilized within 1 ms from ablation





- **Its key to identify which ELMs are associated with LGI**
  - Not all ablations are followed by ELMs
  - ELMs can occur naturally during LGI phases
- **Ablation history used to distinguish natural and LGI ELMs**
  - Distribution of ablation-ELM lag-time shows a peak at 0.5ms
  - Indicative of causal effect
  - Trigger on single ablations
- **Lag time<1ms → *LGI ELMs***

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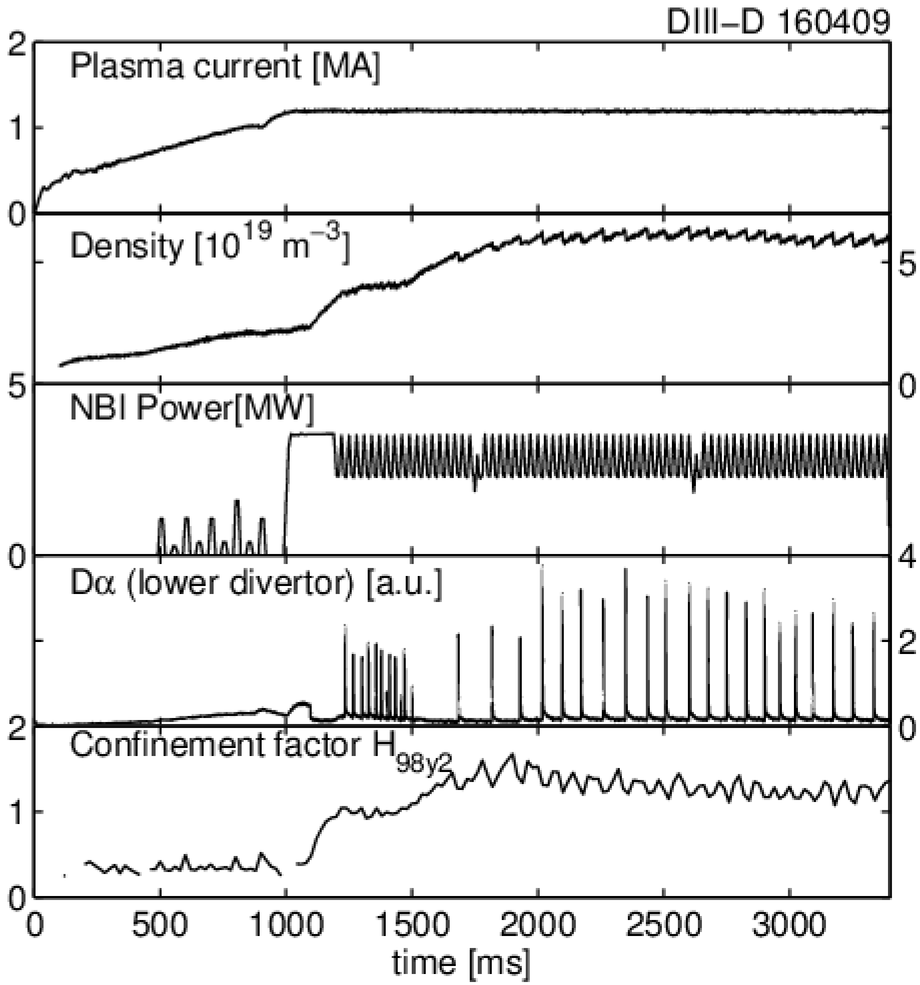
- **Characterization LGI paced ELMs and effect on plasmas**
  - Peak heat flux dependence on f_{ELM}
  - Impurity accumulation
  - Neutron production rates

Summary of the experimental activities

- **Two full experimental days (Nov 21, Dec 17)**
  - 2 hours evening session for commissioning
  - Total 50 plasma shots
- **In between shot analysis of fast camera data**
  - Characterization of injection history and ELM triggering efficiency
  - Data stored in dedicated MDS+ trees, available on scopes/ReviewPlus

- **Injection frequency ~ 100-500 Hz, pellet speed ~ 50-150 m/s**
- **Tested 4 granule sizes (0.3, 0.5, 0.7, 0.9 mm)**
- **Standard low power H-mode and ITER relevant scenarios**
- **Comparison with D_2 pellets in same discharges**
- **Injected F + Cl to assess impurity confinement time**

Day 1: ELM pacing obtained with small granules (0.3,0.5mm)



- **Reference ELMy H-mode**
  - 1.2MA, $\beta_N = 1.4$
  - P_{NBI}=2.3MW for low ELM frequency
  - f_{ELM} = 12 Hz
  - No MHD for t<350ms

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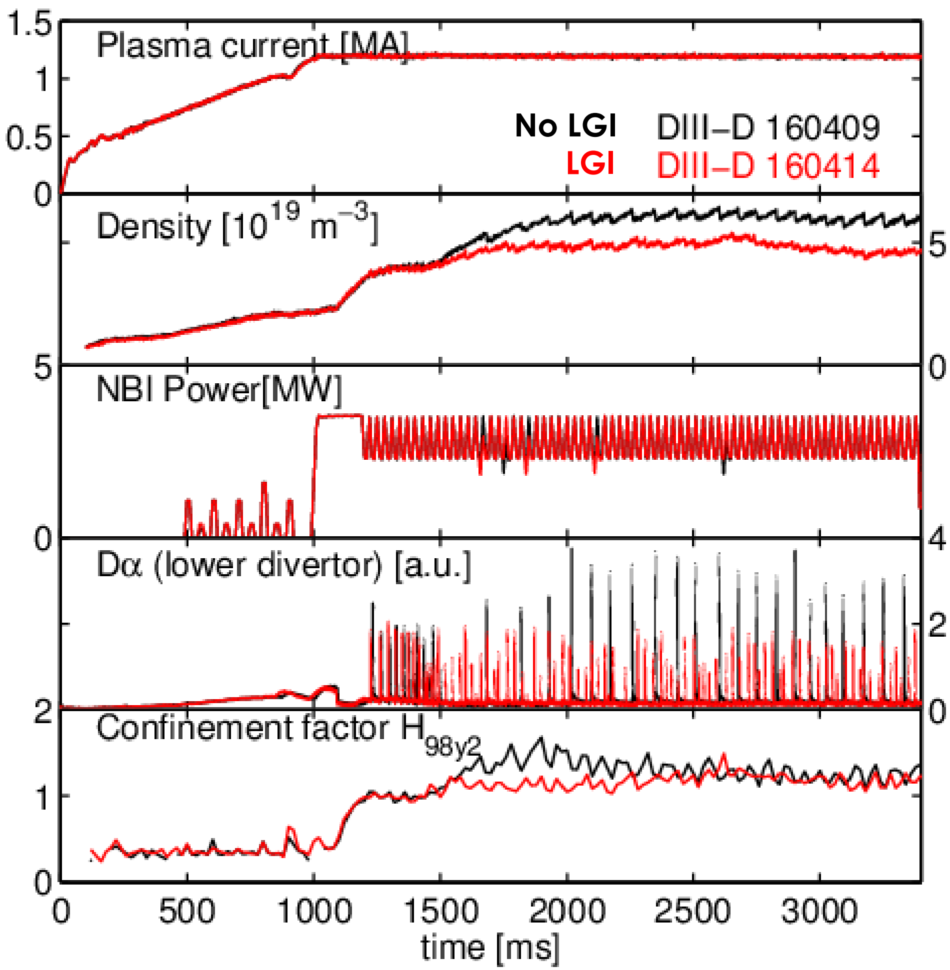

- **Reference ELMy H-mode**
  - 1.2MA, β_N = 1.4
  - P_{NBI}=2.3MW for low ELM frequency
  - f_{ELM} = 12 Hz
  - No MHD for t<350ms
- **LGI phase 1.5 < t < 5 s**
  - Granule diam. **0.5 mm**
  - Granule velocity 105m/s
  - Average injection frequency 140 Hz
  - f_{ELM} = 38 Hz (average, 3X)
  - Small or no confinement degradation
  - ,

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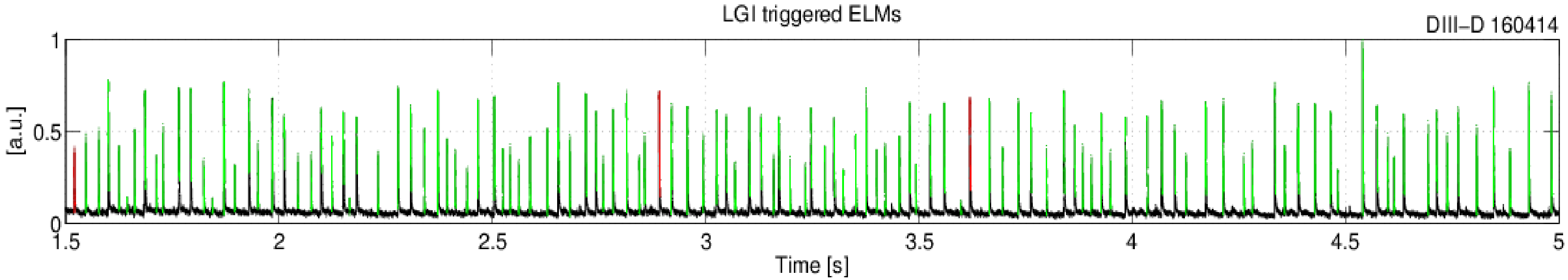
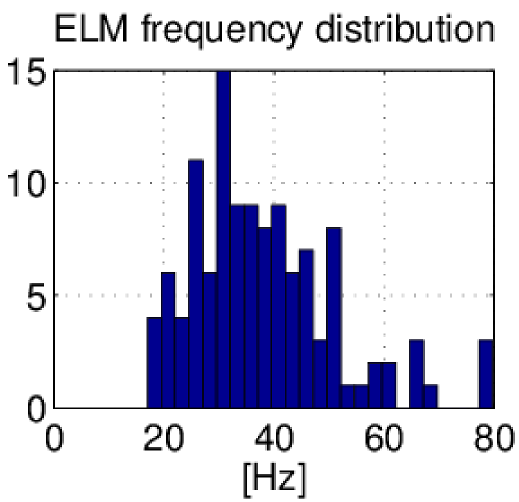
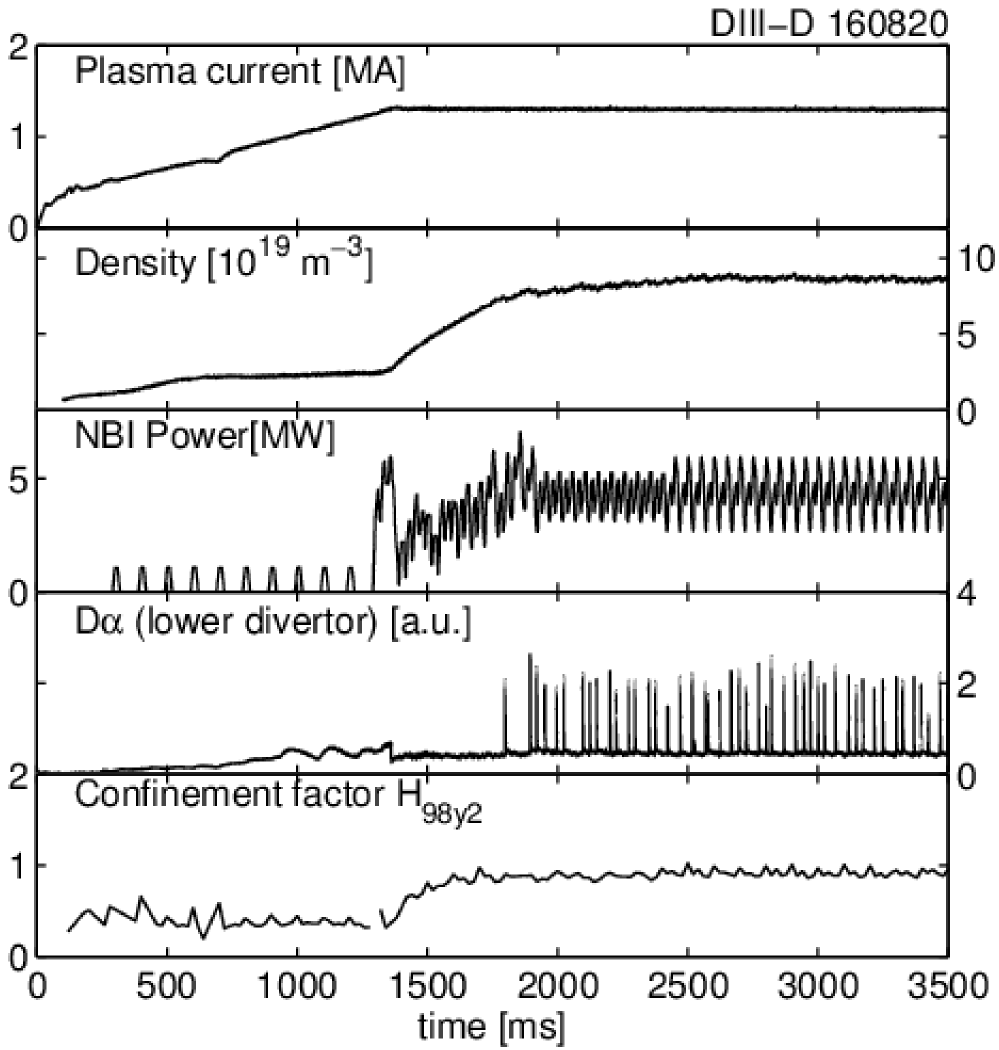
Smaller granules show relatively low pacing efficiency





- **During the LGI time window of 3.5 s :**
  - 570 granules hit, 520 single ablations
  - 90% injection efficiency
- **119 ELMs (3 natural)**
  - 97% ***trig efficiency*** (probability that an results from an ablation event)
  - 23% ***pacing efficiency*** (probability that an ablation event results in an ELM)
- **Similar results obtained for 0.3 mm**

Day 2: ELM pacing obtained with 0.7 and 0.9 mm granules



Reference: low torque ITER baseline scenario

- 1.2MA, $\beta_N = 1.9$
- P_{NBI}=4 MW, 0.5 N m
- f_{ELM} = 25 Hz

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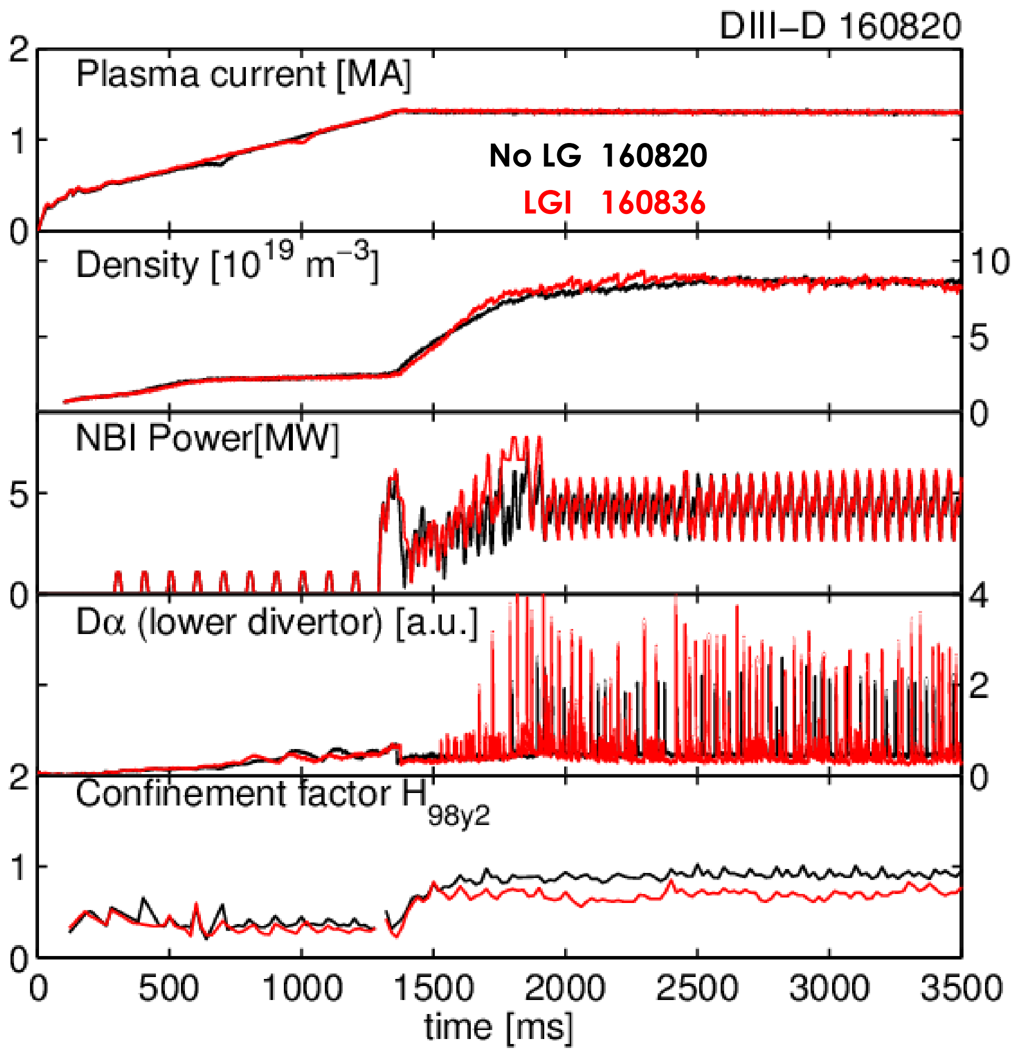
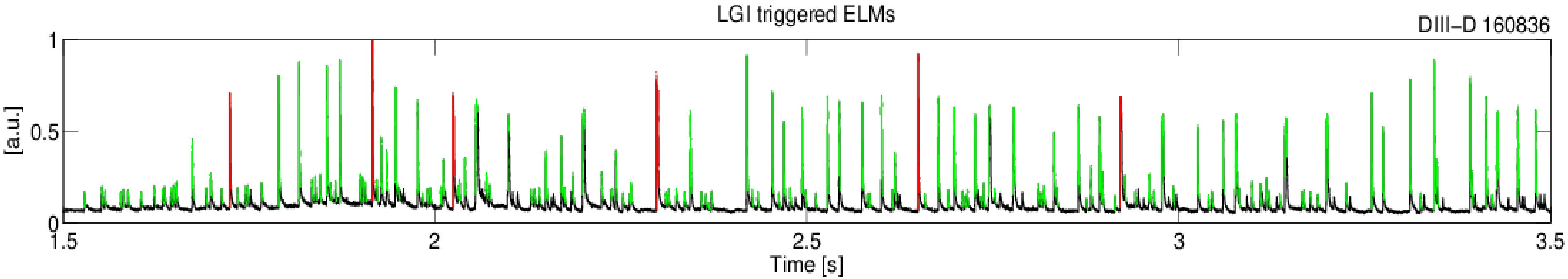
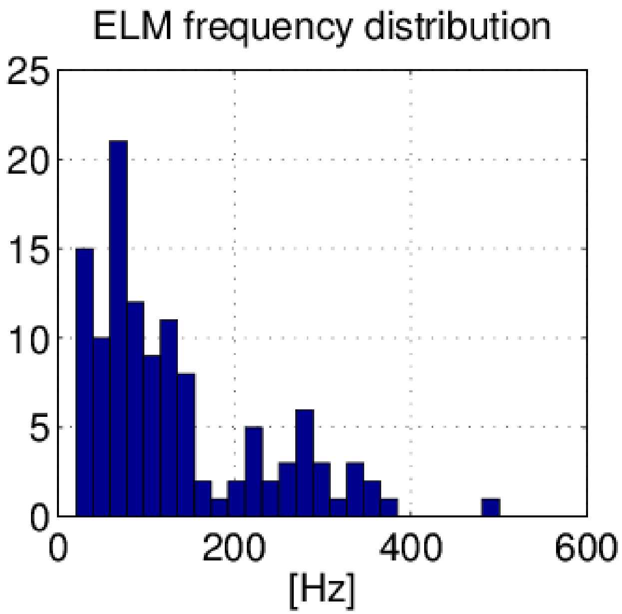
Day 2: ELM pacing obtained with 0.7 and 0.9 mm granules



- **Reference: low torque ITER baseline scenario**
  - 1.2MA, β_N = 1.9
  - P_{NBI}=4 MW, 0.5 N m
  - f_{ELM} = 25 Hz
- **LGI on 1.5<t<3.5 s**
  - Granule diam. 0.9 mm
  - Granule velocity 45 m/s
  - Average injection frequency 114 Hz
  - f_{ELM} = 90 Hz (average, 4X)
  - 25% degradation of energy confinement

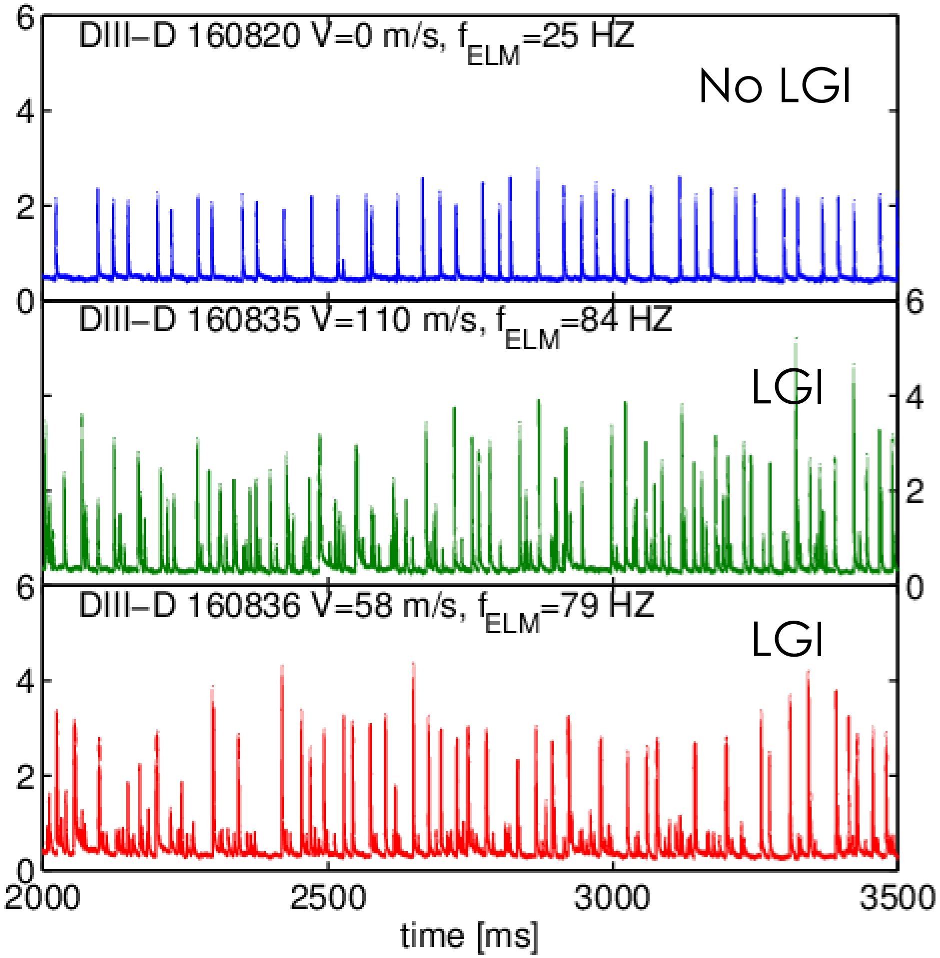
Larger granules show high pacing efficiency





- **During the LGI time window of 2 s**
  - 290 granules hit, 227 single ablations
  - 78% injection efficiency
- **206 ELMs (6 natural)**
  - 96% ***trig efficiency*** (probability that an results from an ablation event)
  - 88% ***pacing efficiency*** (probability that an ablation event results in an ELM)
- **Similar results for 0.7 mm**

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%**

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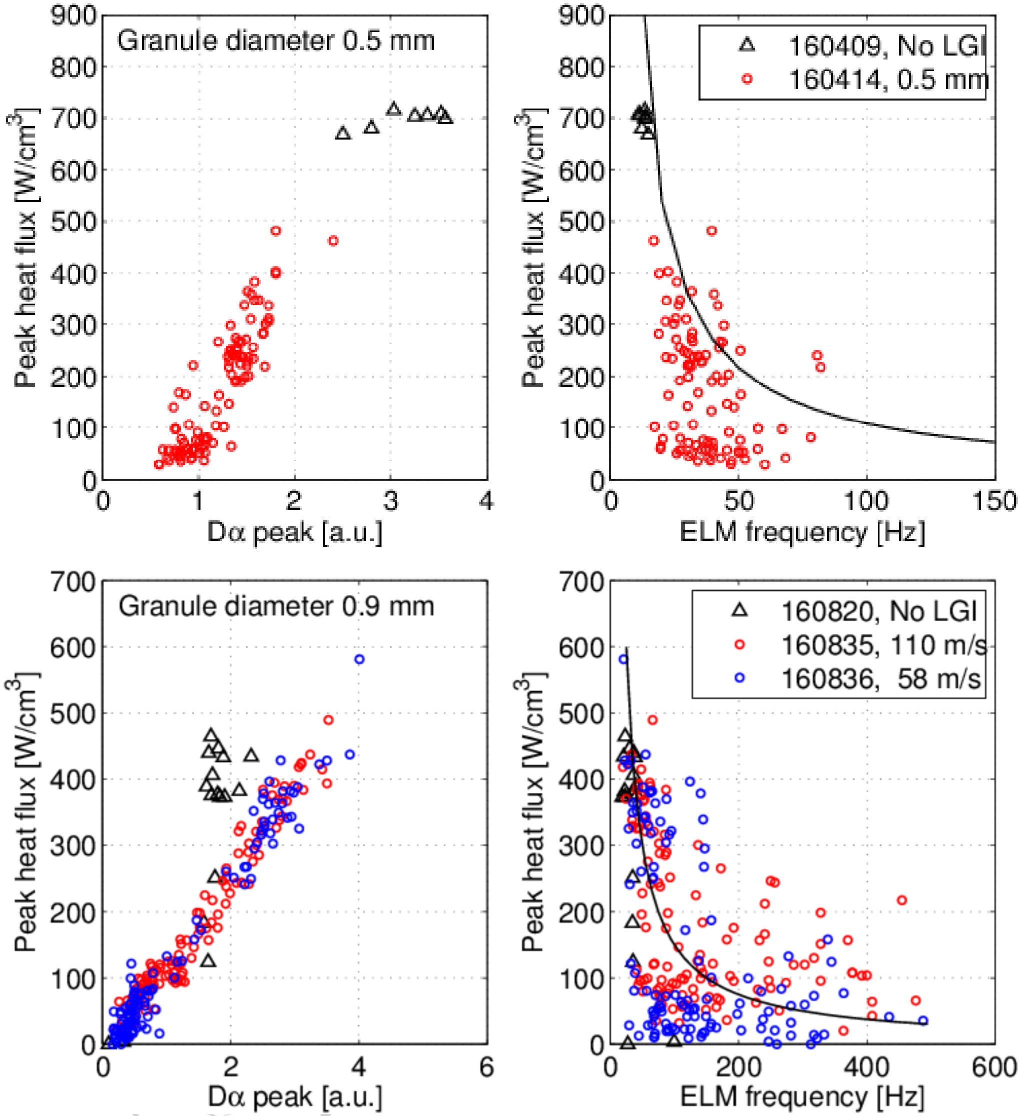
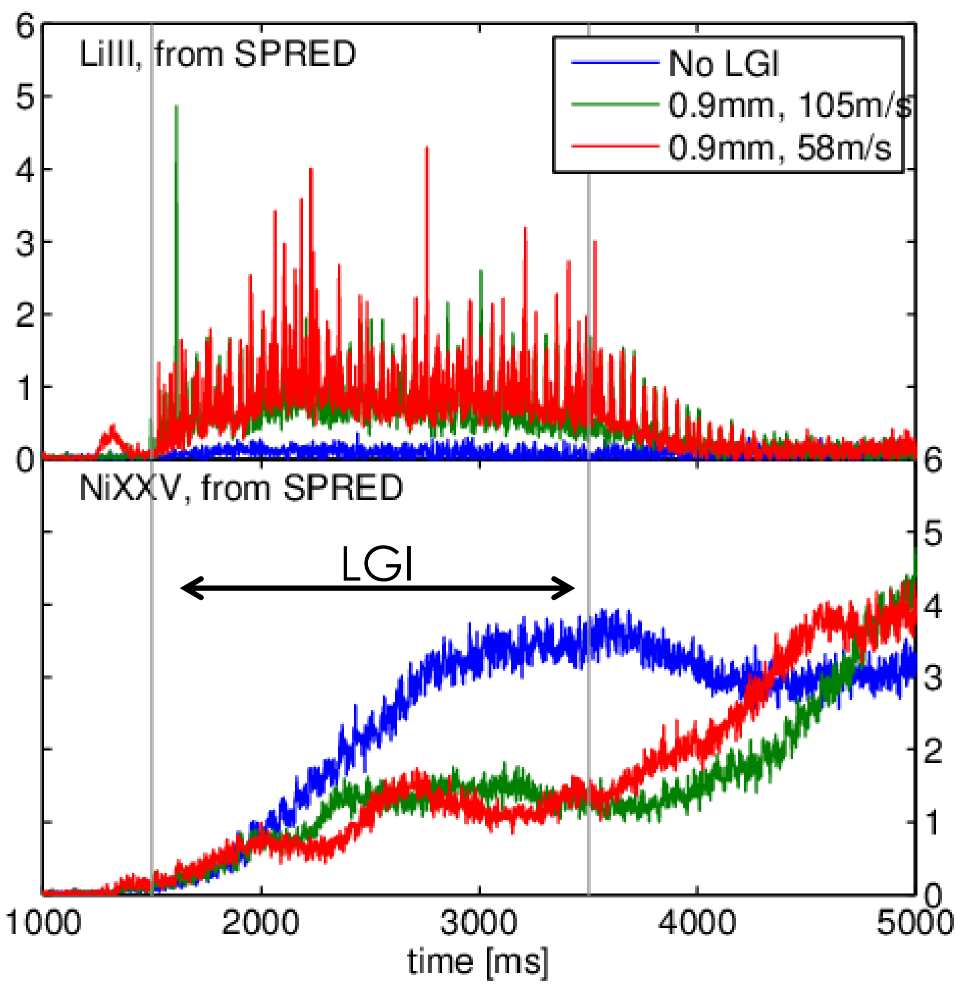
Peak heat flux dependence on ELM frequency



- **Peak heat flux q_p at the outer strike point from IR imaging (IRTV)**
- **Test $q_p = const/f_{ELM}$ with statistical approach**
  - Consider sets of single LGI-induced ELMs
- **General trend: reduced q_p with higher f_{ELM}**
- **Two classes of ELMs!**
  - Small ELMs: $q_p < const/f_{ELM}$
  - Distinction found with all granule sizes
  - Lower velocity appears to favor the distinction

Nickel contamination clamped during LGI operation



- **Charge exchange emission from Li III indicates Li reaches the core**
  - Previously observed in dropper discharges
  - Potential for dilution effect
- **Nickel "intrinsic" impurity tends to accumulate**
  - During LGI operation the Ni density is clamped to low values
  - Accumulation resumes as LGI turns off

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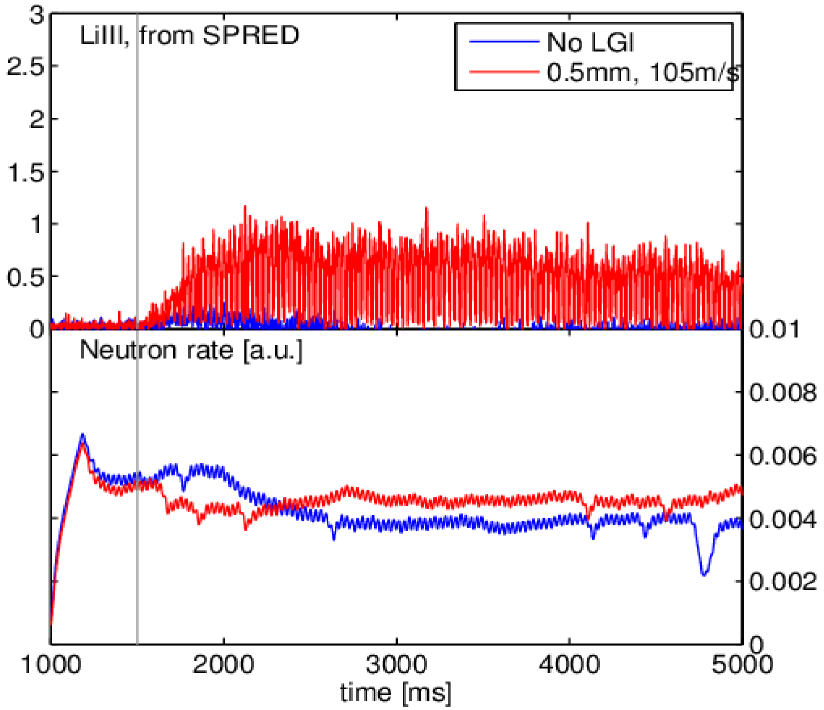
Neutron rate improvement with 0.5 mm granules. But…



- **Possibly associated with:**
  - Good energy confinement
  - Peaking of ion temperature

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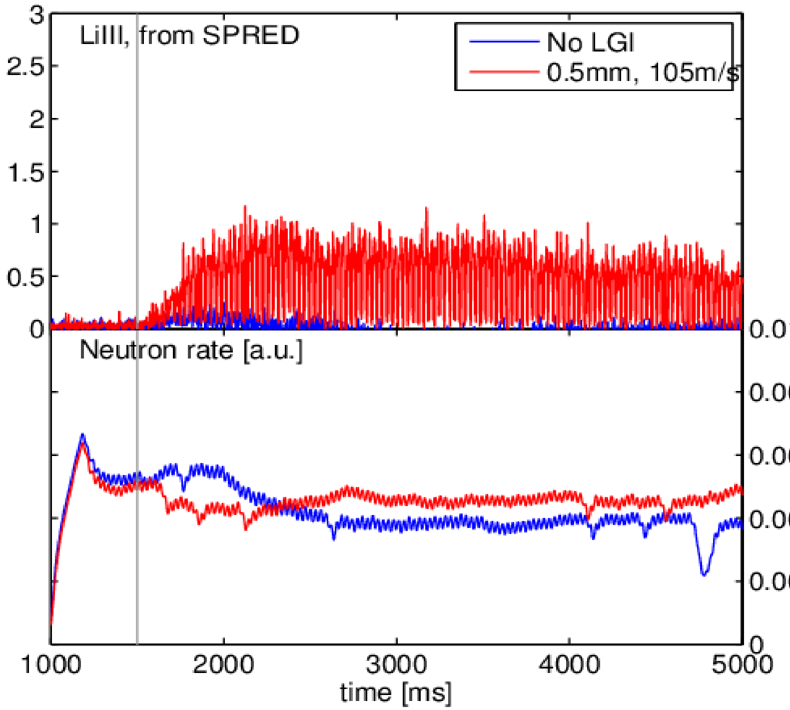

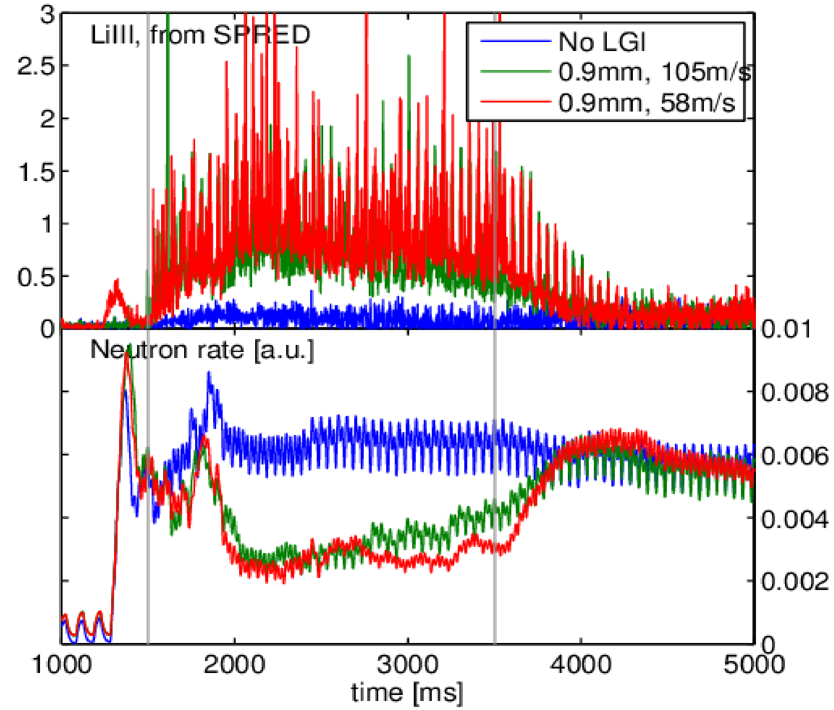

- **Possibly associated with:**
  - Good energy confinement
  - Peaking of ion temperature

- **Possibly associated with:**
  - Deteriorated confinement decrease
  - Core main ion dilution

Summary and outlook

- **The LGI has been successfully installed and operated on DIII-D**
  - As for any new system, it required some extra care ("what could possibly go wrong?")
  - Support from the LGI has been requested for upcoming experiments on advanced H-mode scenarios

- **The effectiveness of LGI pacing has been assessed for different H-mode scenarios**
  - 4 nominal granule sizes
  - Spanning a factor of 2 in injection velocity
  - This completes a PPPL notable outcome goal

- **Scientific opportunities to come:**
  - Study of the dynamic of the LGI induced ELMs (MHD stability)
  - Study of the ablation physics (back viewing camera)