Dispersive shell pellet modeling and comparison with experimental trends*

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Theory and Simulations of Disruptions Workshop

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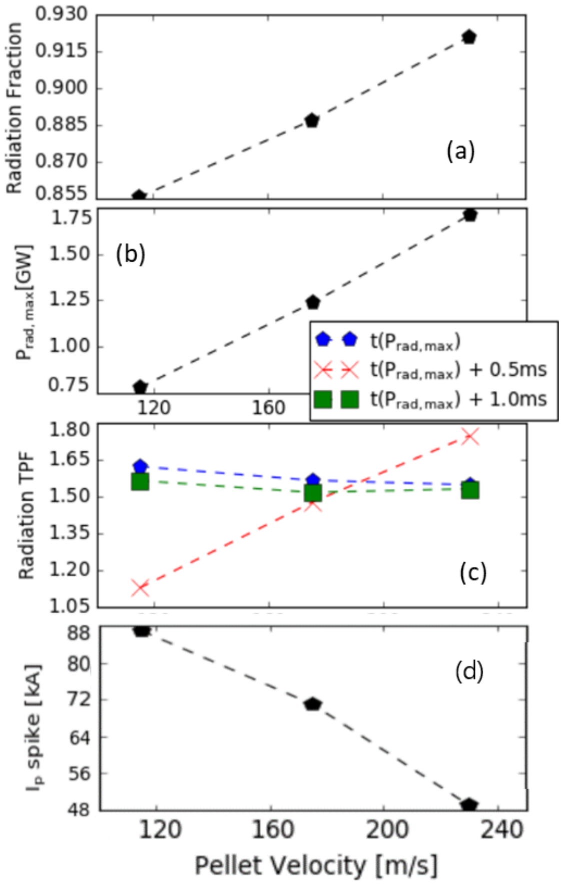
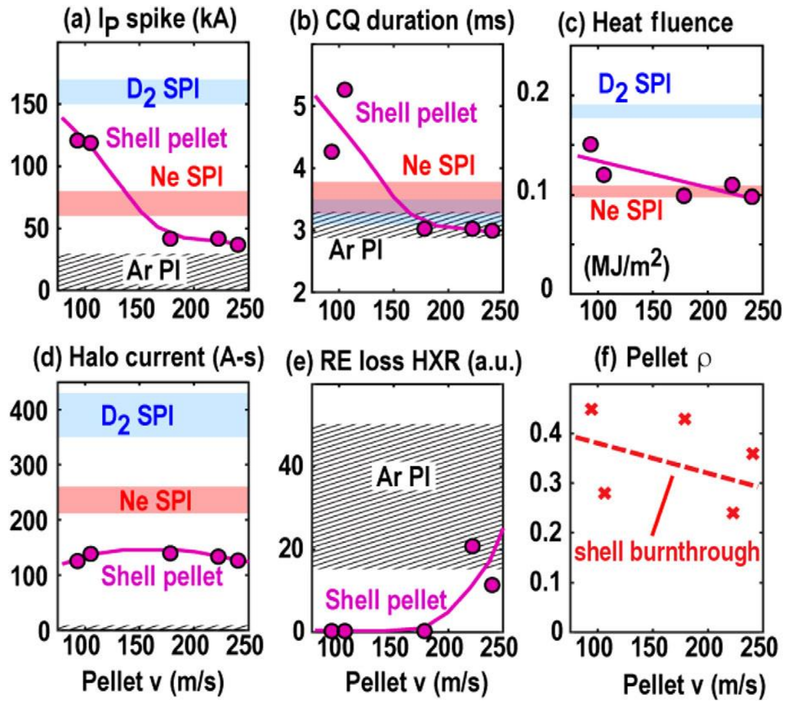
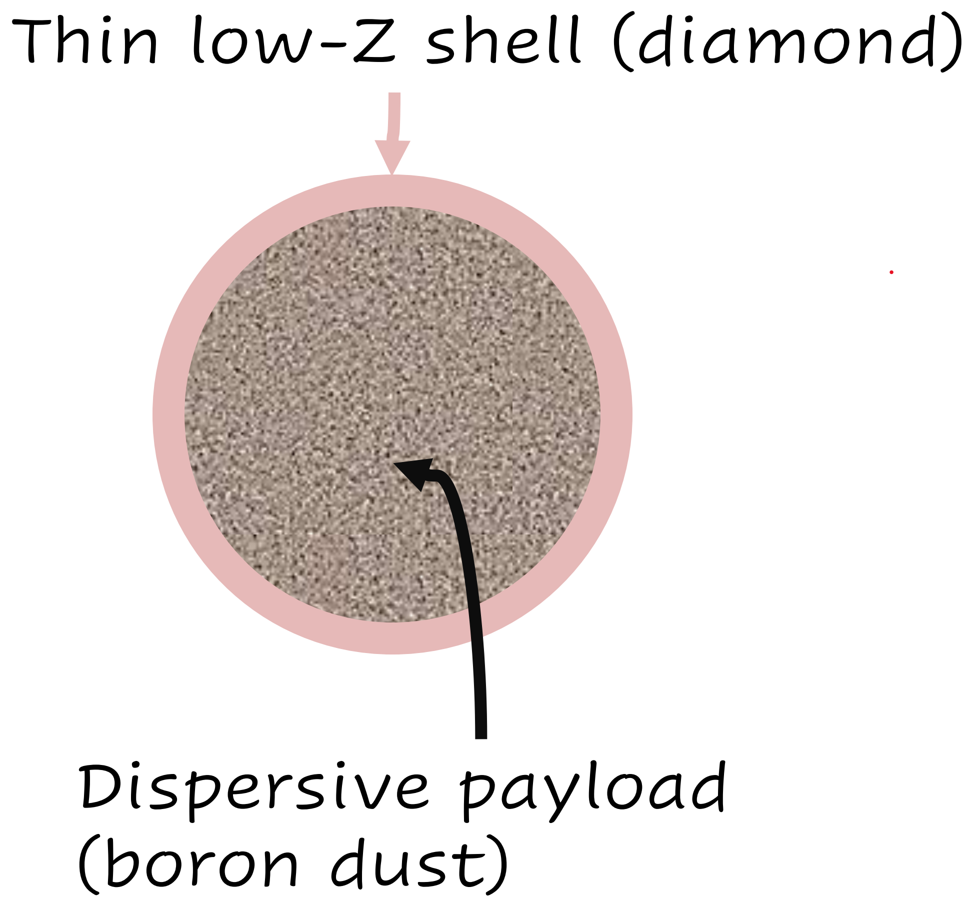
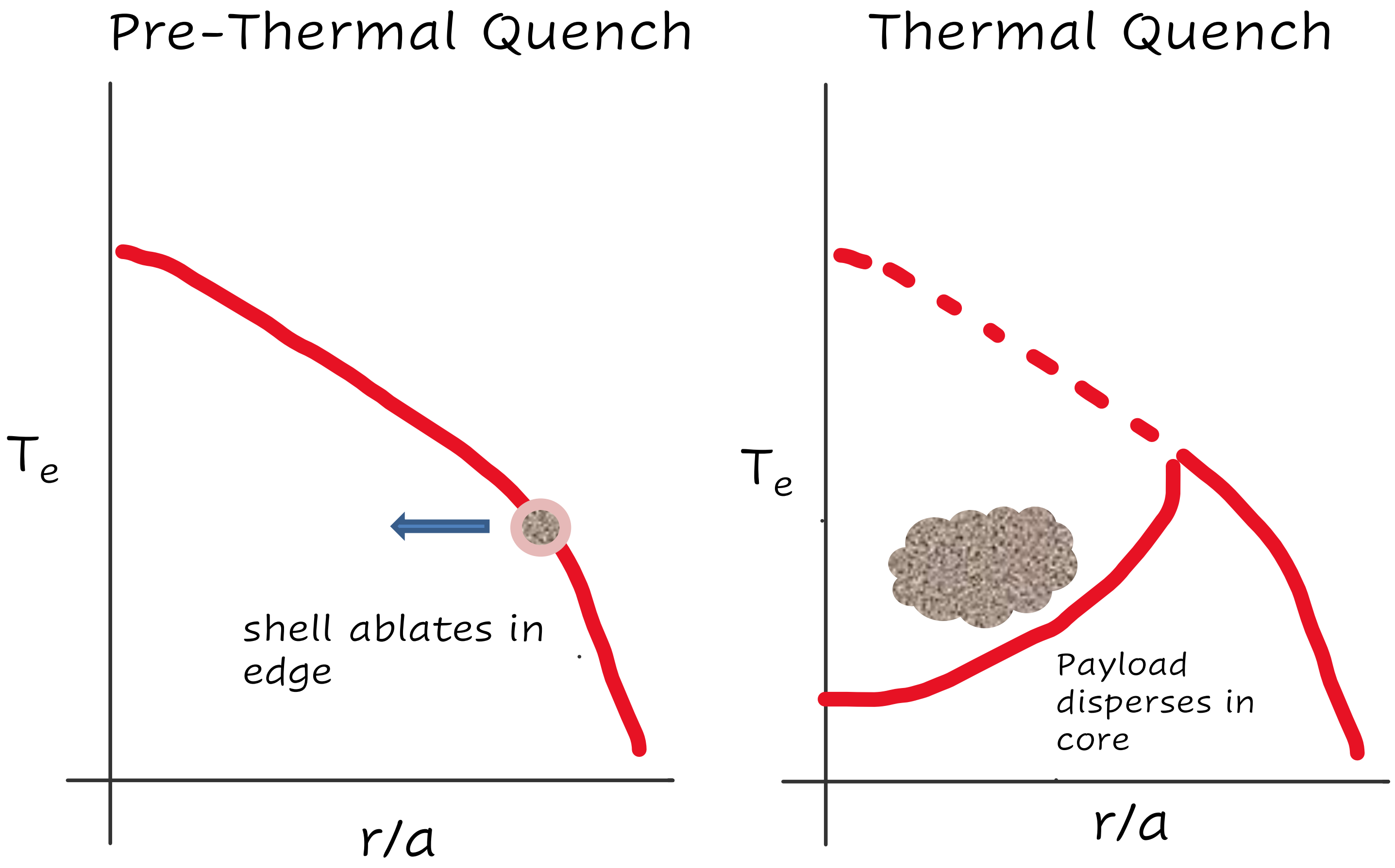




Hollmann, PRL **122**, 065001 (2019)

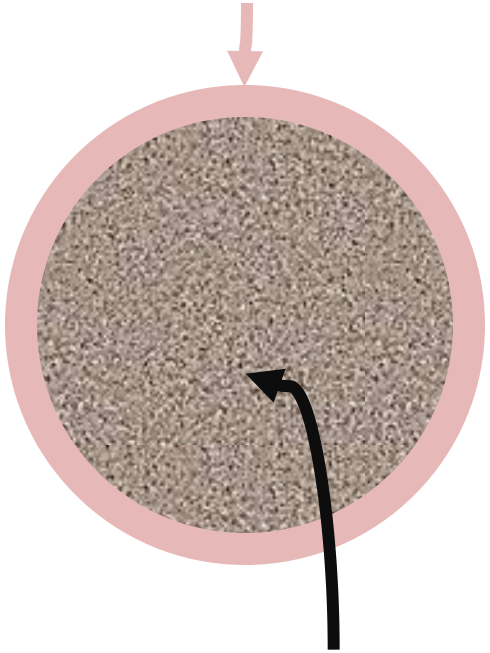
The DSP Concept for disruption mitigation cools the plasma from the inside out



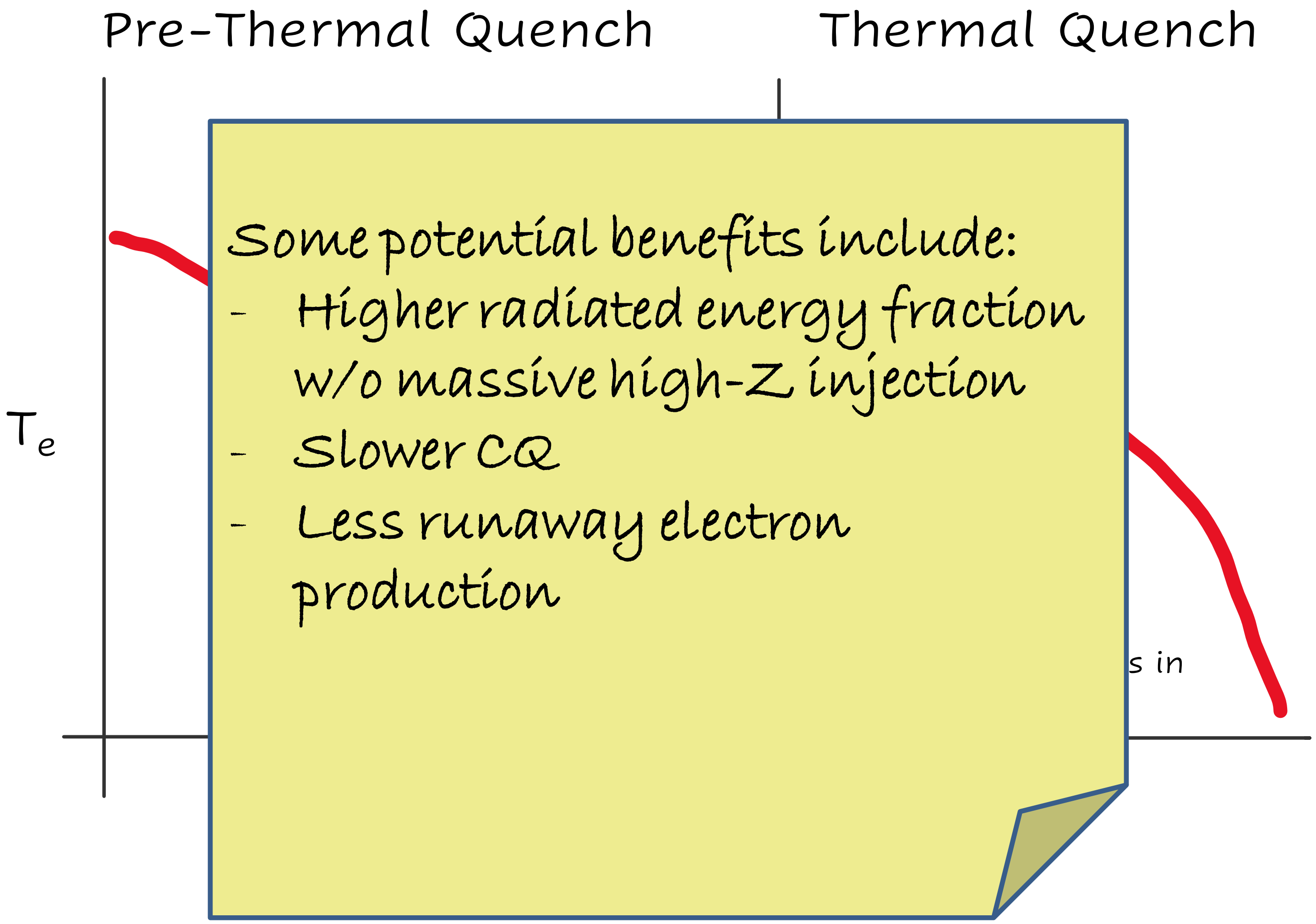


The DSP Concept for Disruption Mitigation cools the plasma from the inside out

Thin low-Z shell (diamond)



Dispersive payload (boron dust)

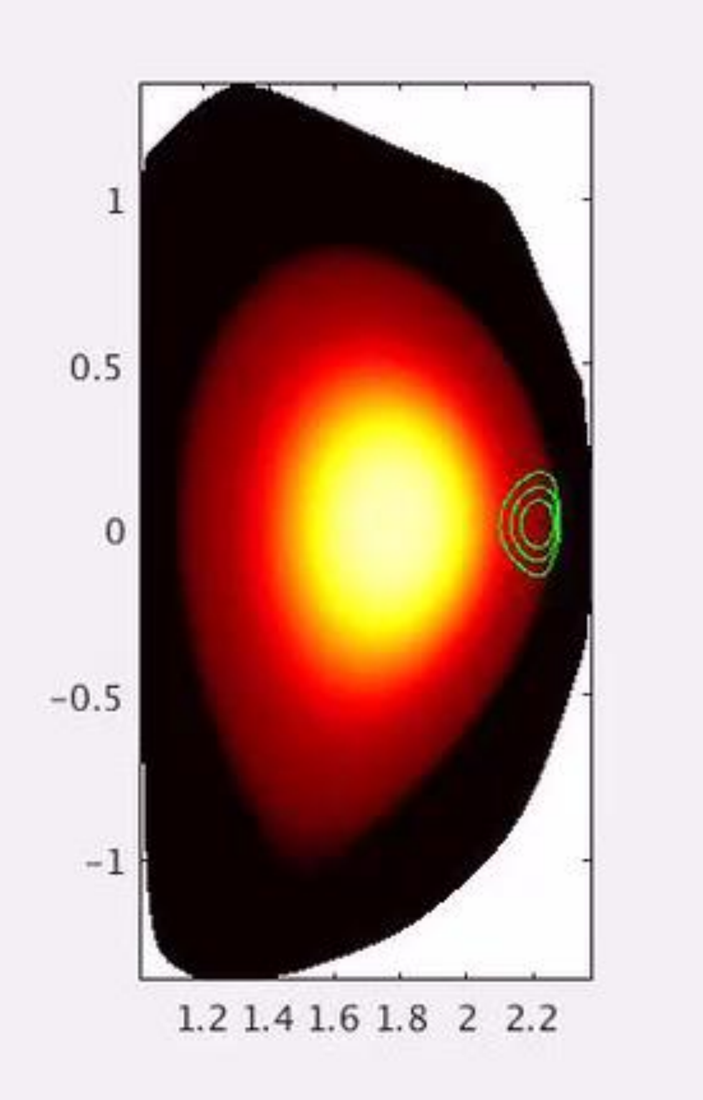


Some potential benefits include:

- Higher radiated energy fraction w/o massive high-Z injection
- Slower CQ
- Less runaway electron production

In NIMROD simulations, the pellet is modeled as a moving source of neutral impurities

- Poloidal distribution is circular Gaussian
- Toroidal is periodic normal distribution (approximately Gaussian)



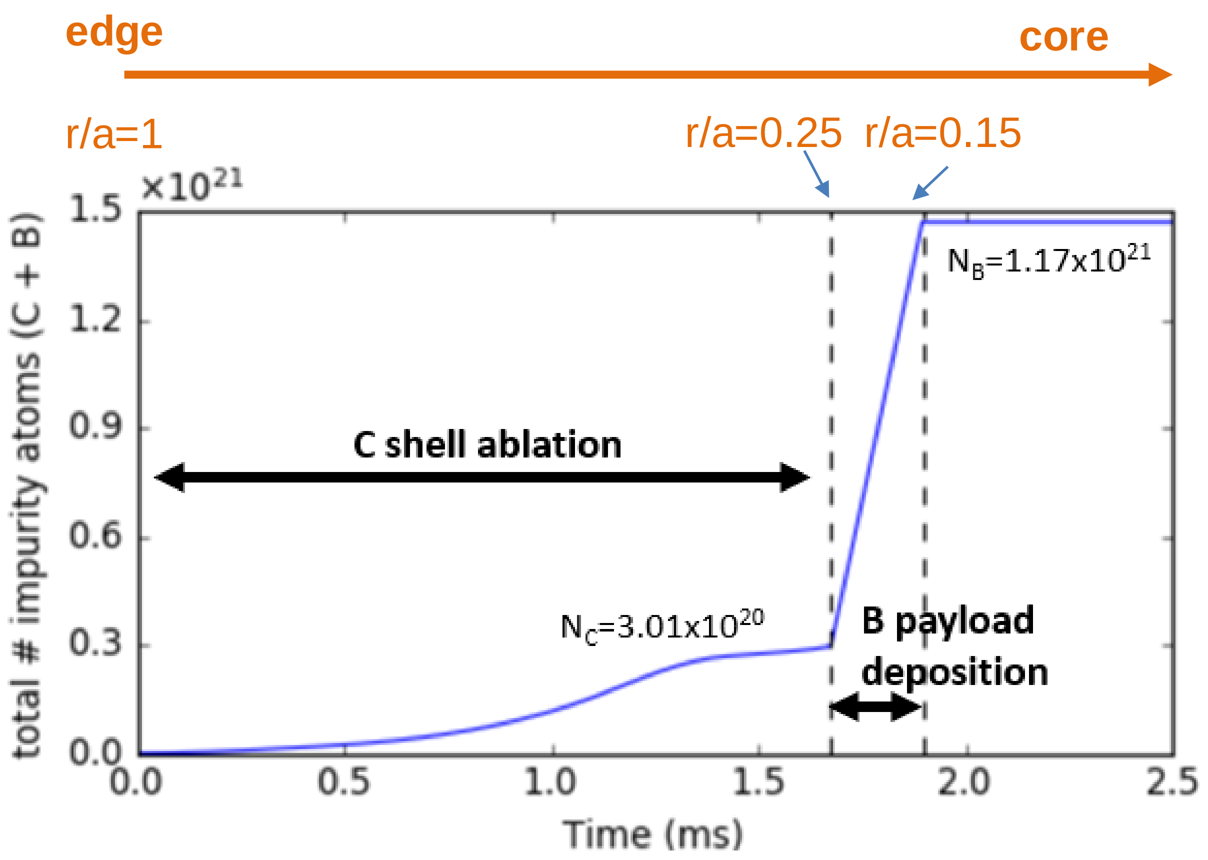
- Spatial distribution, pellet speed do not change
- Species (carbon →boron) and delivery rate do change

Non-constant shell ablation partially based on theory, calibrated to one experimental data point

Shell ablation (calibrated to one experimental data point at 230 m/s):

$$G(atoms/\sec) = 1.44 \times 10^{11} T^{5/3} n^{1/3}$$

Payload delivery width of r/a=0.1 also matched to experiment. (Constant rate is backed out based on total quantity, pellet speed.)



Conclusions

- NIMROD modeling **reproduces three major trends** vs. pellet speed seen in DIII-D DSP experiments: TQ mitigation efficiency, RE production, and I_p-spike amplitude.

- For an inside out TQ, the plasma current spike is produced by **a double tearing mode** that produces stochasticity over a wide region of the plasma.

- In the presence of pre-TQ MHD, payload delivery can be unpredictable and sensitive to numerical parameters in pellet model… but **predictive modeling should be feasible** in a more ideal DSP scenario

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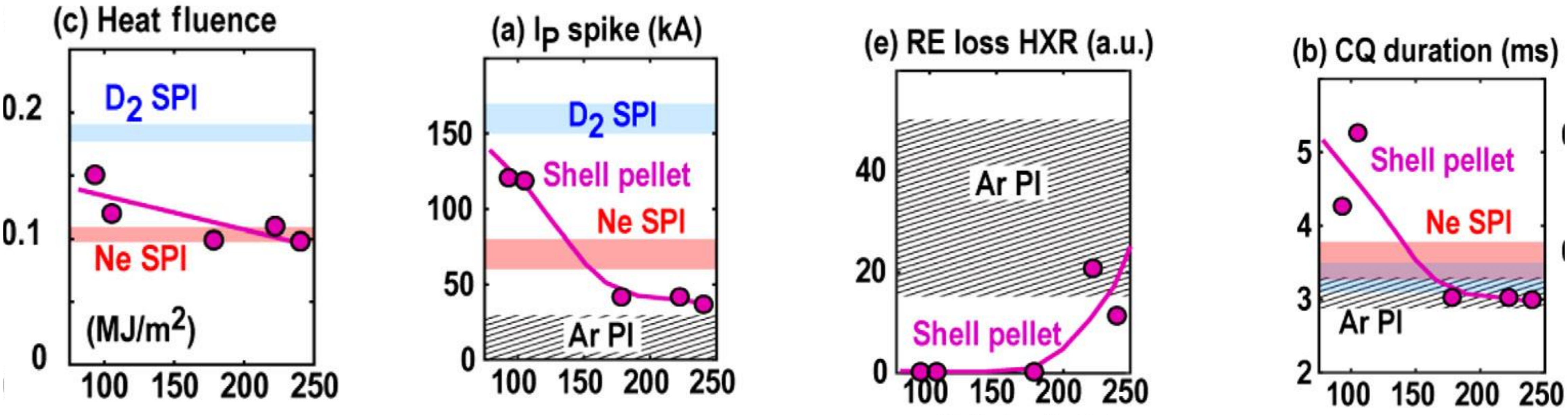
First successful demonstration on DIII-D* showed various trends versus pellet velocity

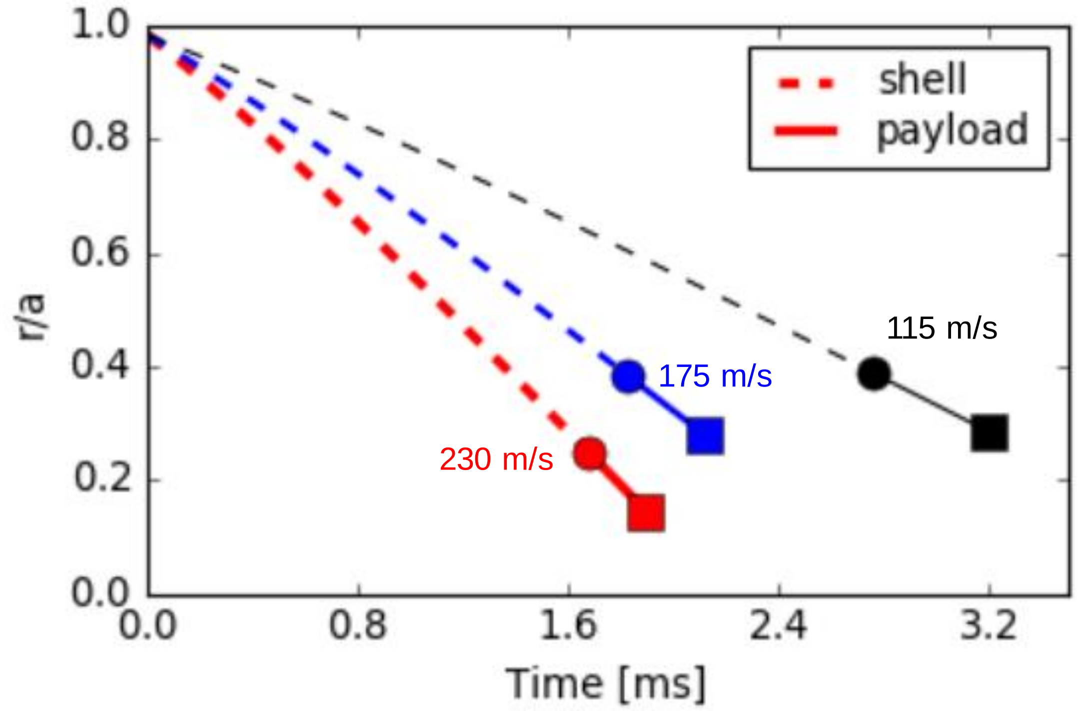
Better TQ mitigation,… Smaller I_p spike,… more RE production,… faster CQ…

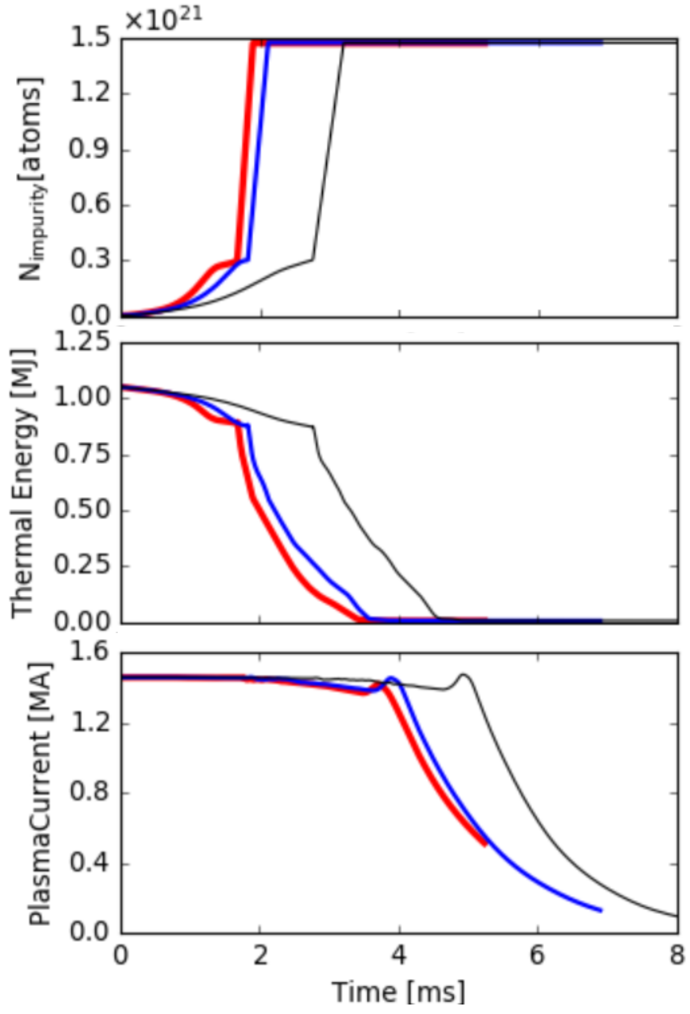


as pellet velocity is increased.

*Hollmann, et al, *PRL* **122**, 065001 (2019)

Three pellet speeds are compared in NIMROD modeling



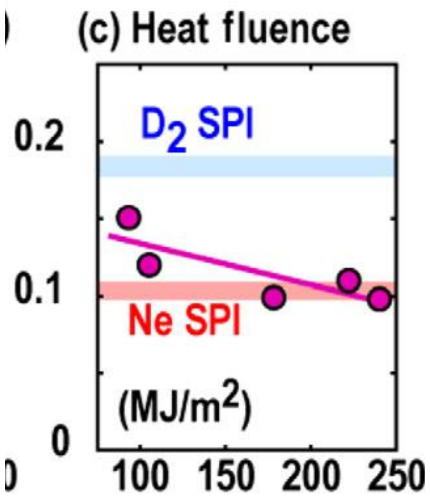


Impurity Quantity

Thermal Quench

Current Quench

Trend 1: Better TQ Mitigation with Faster Pellet



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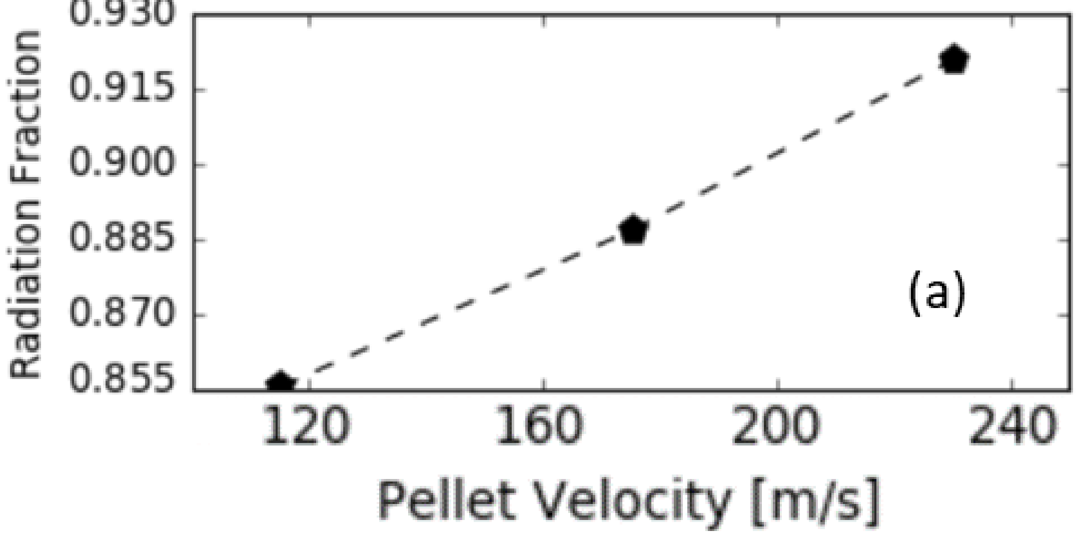
- **Radiation fraction is large (>85%) in all simulations**
- **Increases (pretty linearly) with pellet speed (less perturbation of the edge, faster radiation of the core thermal energy)**
- **Only 230 m/s case exceeds 90% (ITER target)**

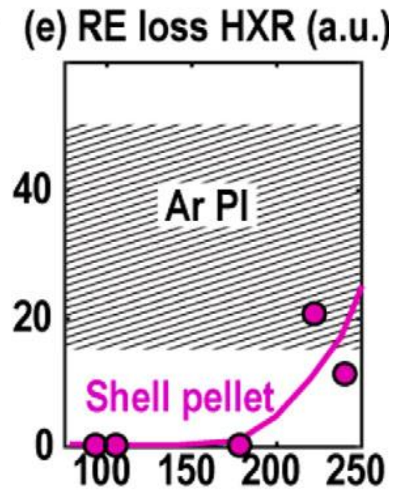
NIMROD Modeling



Trend 2: RE seed production only for fast pellet

- No RE generation model in NIMROD, but T-profile evolution consistent with hot-tail RE production only for fast pellet

- Fast cooling phase ends at lower T for 230 m/s pellet
- $E/E_c > 1$ at end of fast cooling phase only for 230 m/s case



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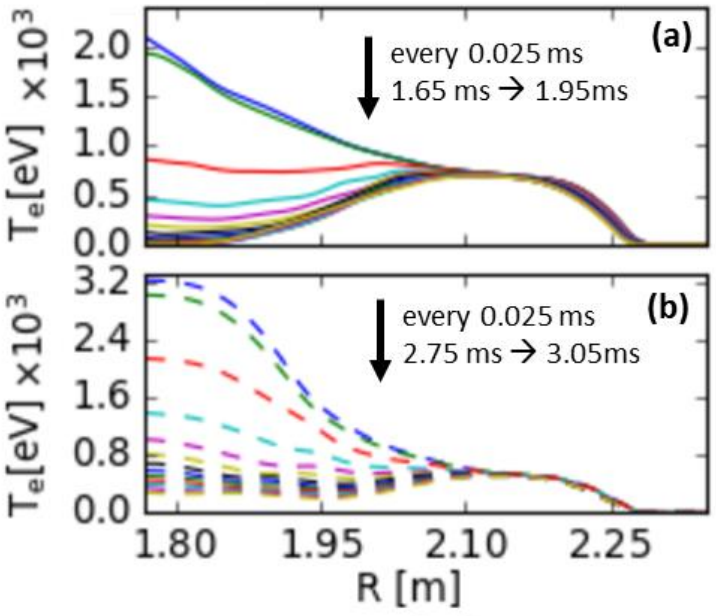
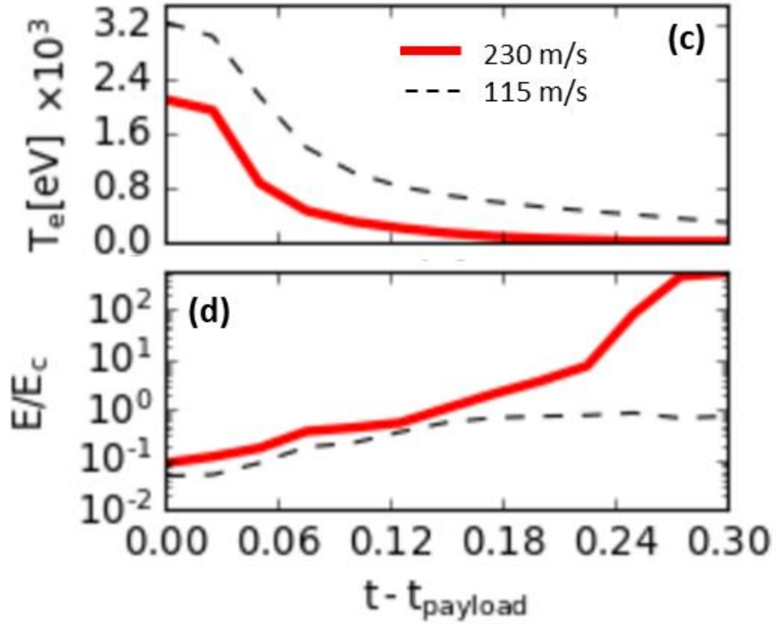
Profiles beginning at payload release

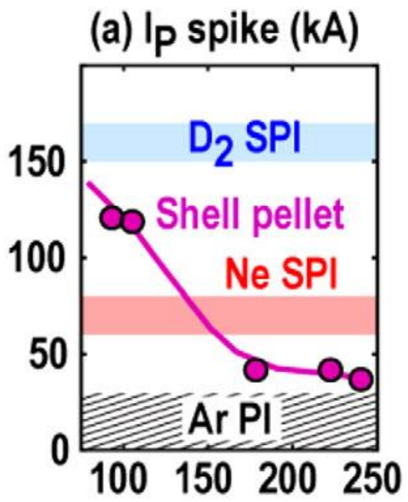
230 m/s pellet

115 m/s pellet





Trend 3: Smaller I_p spike for faster pellets



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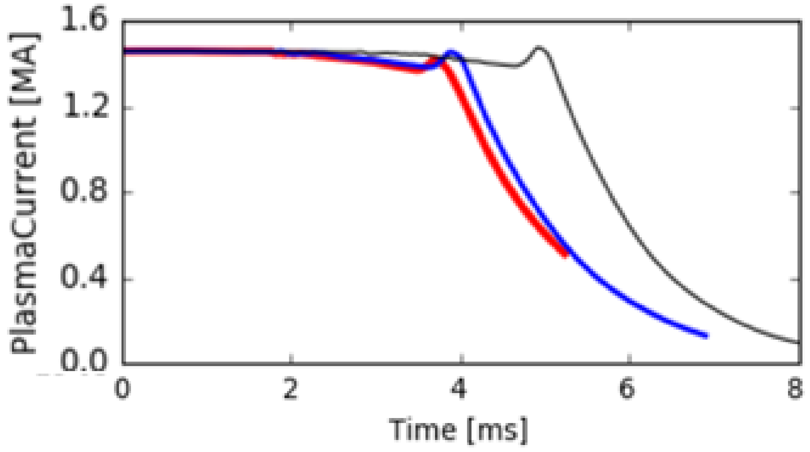
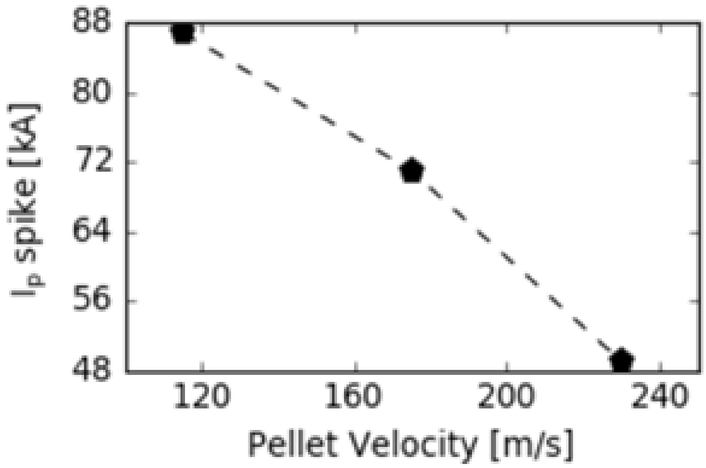
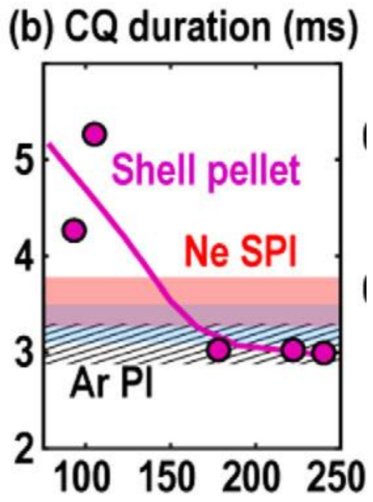
- Trend is in the same direction in each case, although step-like behavior not seen in simulations (once again pretty linear)
- Smaller values similar to experiment, larger values a little lower





- Much more discussion on this in part 2 of talk …

Discrepancy: Faster CQ for faster pellet



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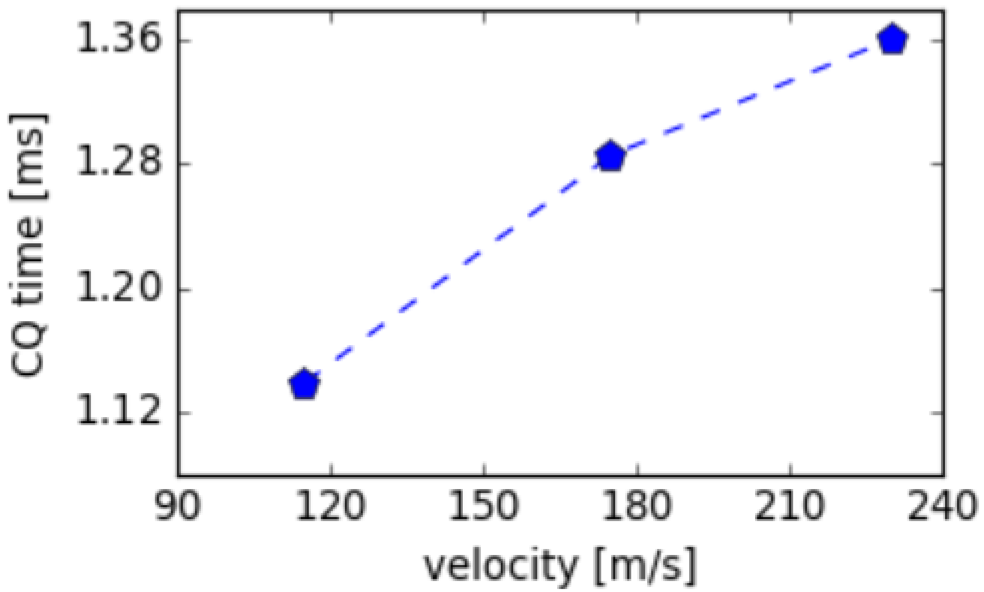
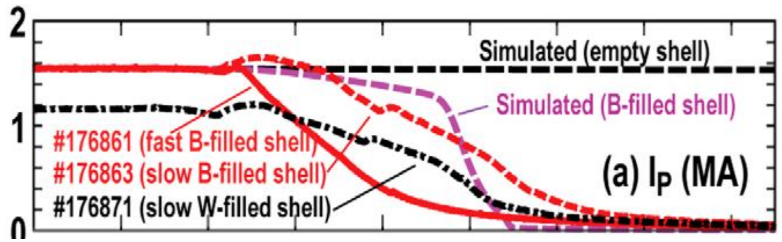
- **Trend in CQ times in the simulations is the opposite**
- **Longest CQ cases in experiment look to have series of MHD events during CQ?**





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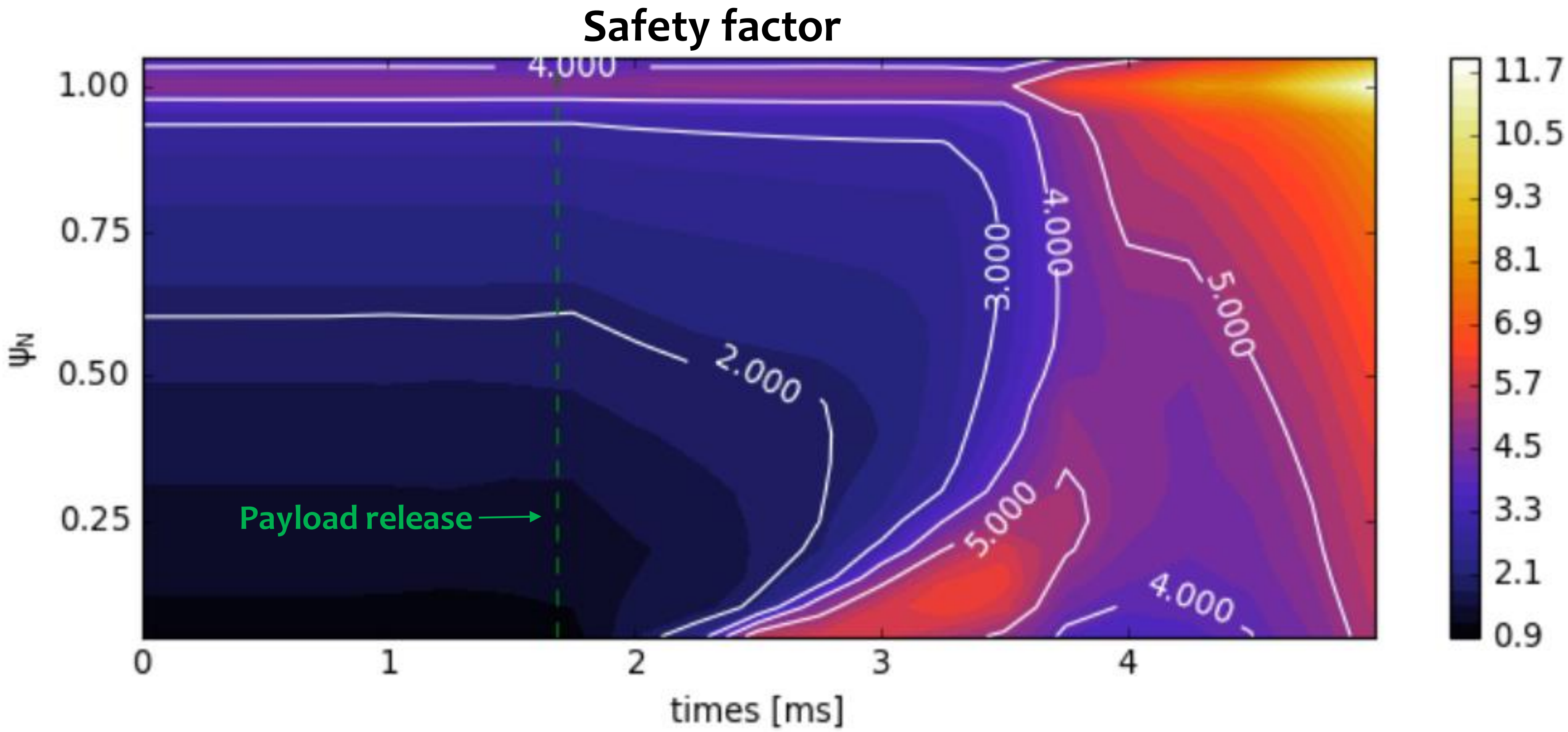
Conclusions

- NIMROD modeling **reproduces three major trends** vs. pellet speed seen in DIII-D DSP experiments: TQ mitigation efficiency, RE production, and I_p-spike amplitude.

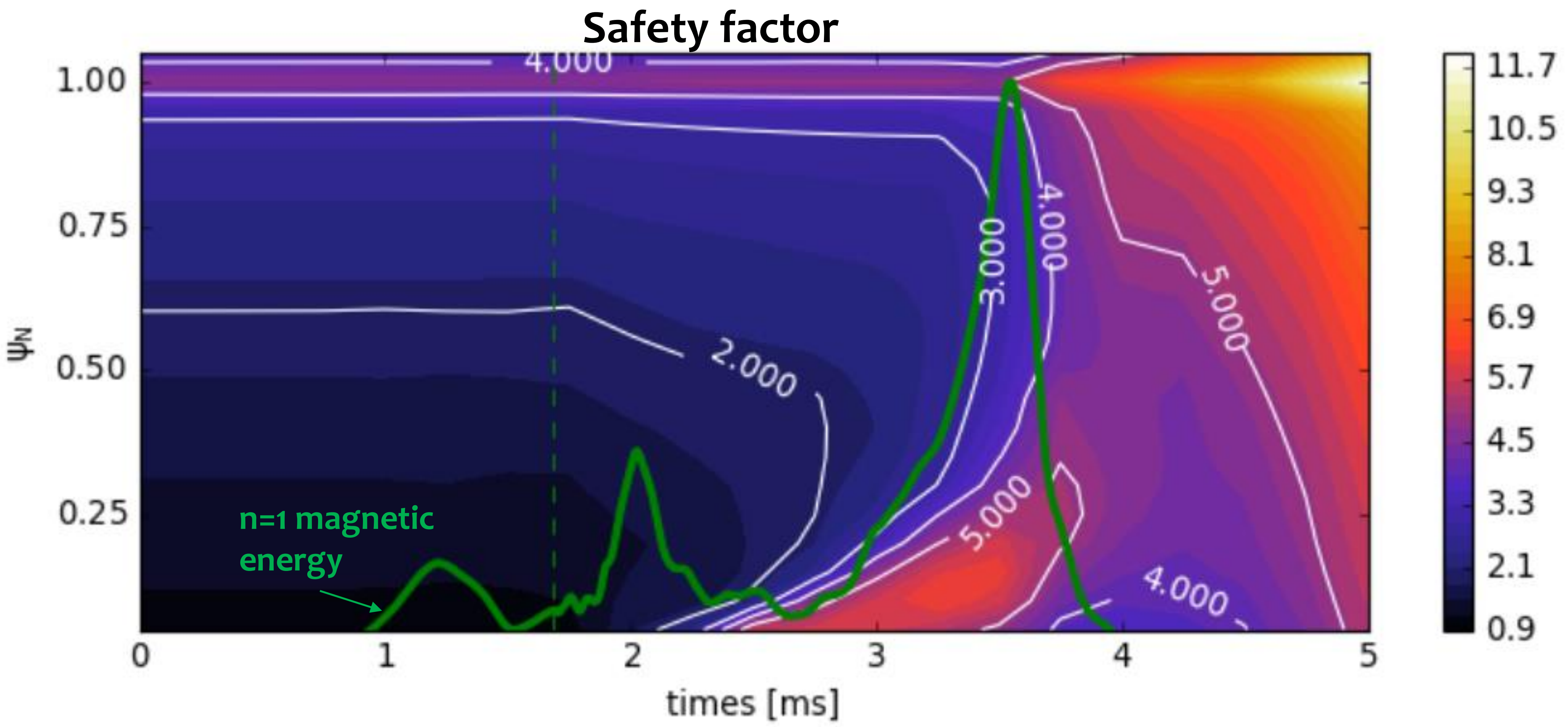
- For an inside out TQ, the plasma current spike is produced by **a double tearing mode** that produces stochasticity over a wide region of the plasma.

- In the presence of pre-TQ MHD, payload delivery can be unpredictable and sensitive to numerical parameters in pellet model… but **predictive modeling may be feasible** in a more ideal DSP scenario

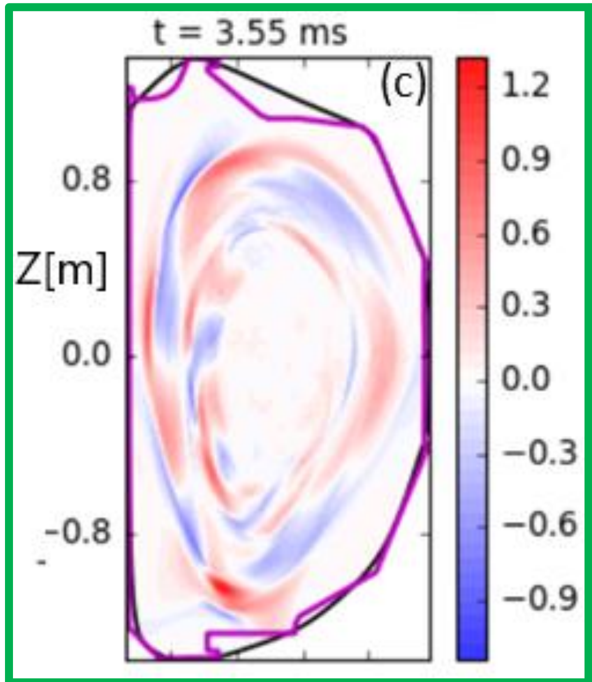
Release of the payload forces current out of the center, increases q on-axis

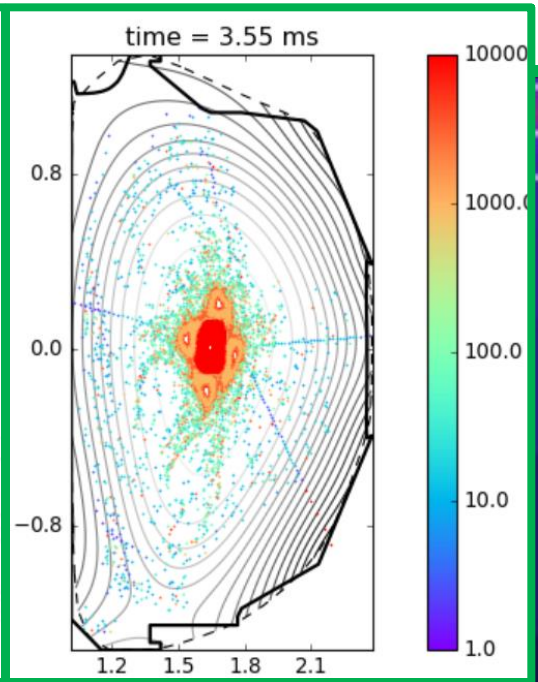


Largest n=1 mode begins to grow after disappearance of the q=2 surfaces

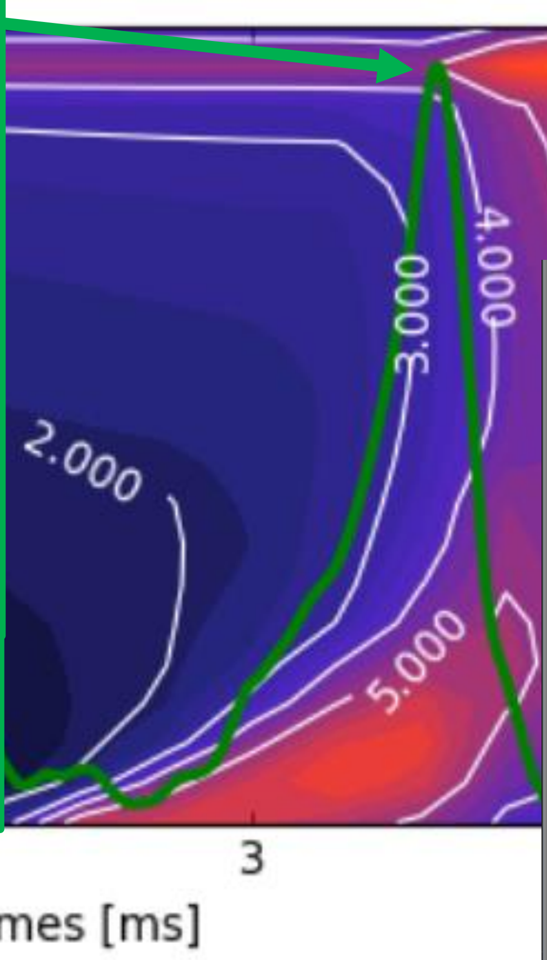


Mode has predominantly m=3 structure with a radially broad structure characteristic of a double tearing mode





Broad region of stochasticity in the edge allows for flattening of the current profile across much of the plasma



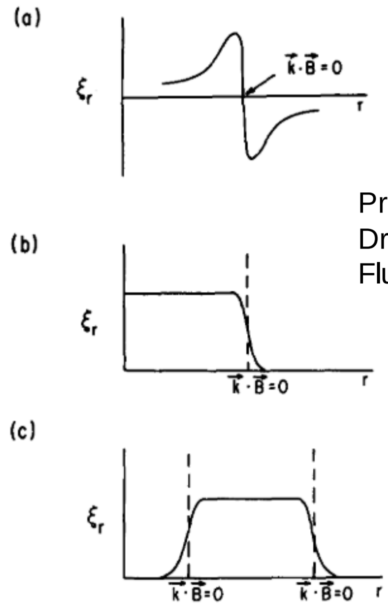
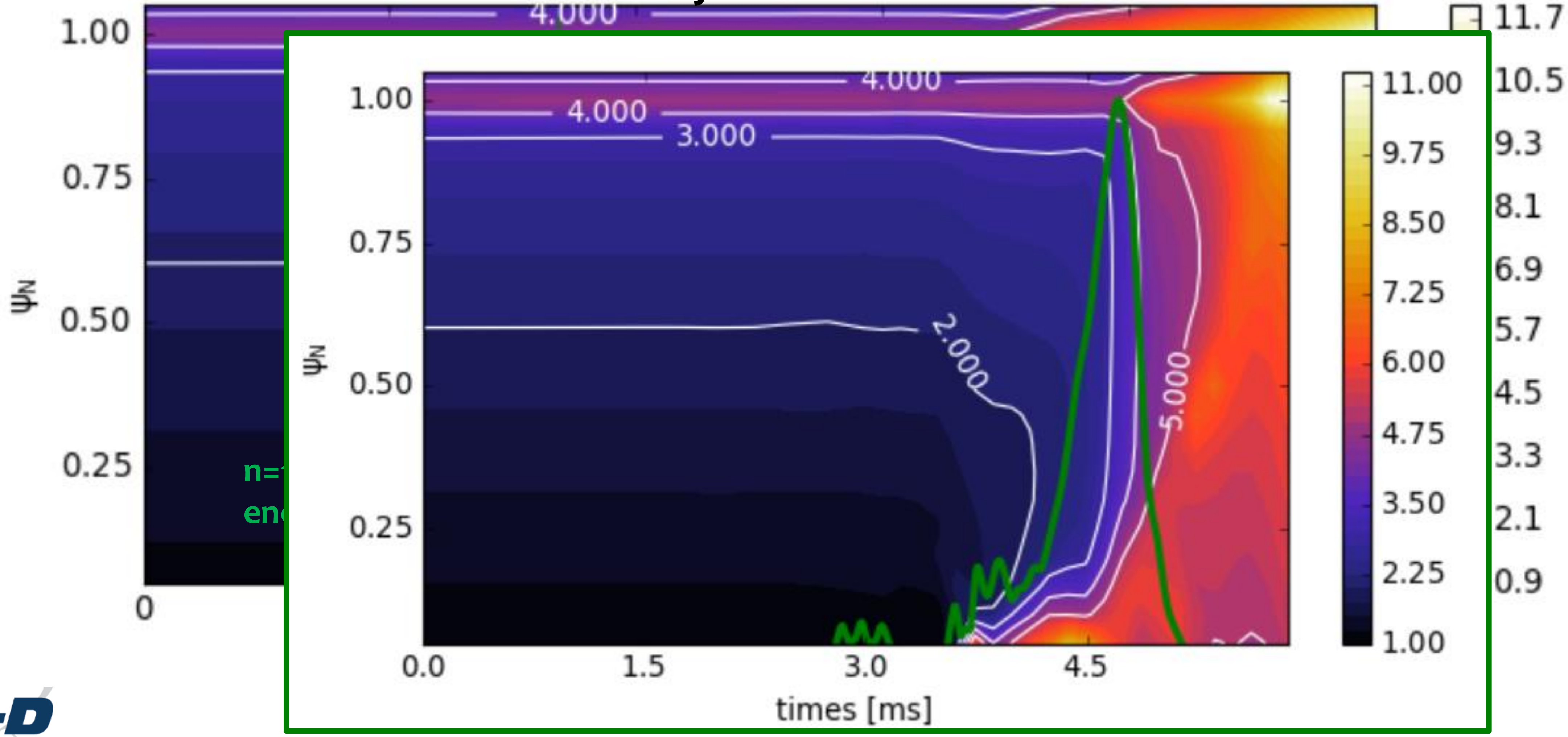


FIG. 2. Typical radial displacement $\xi_r(r)$ for (a) the standard tearing mode, (b) the $m=1$ tearing mode, and (c) the double-tearing mode.

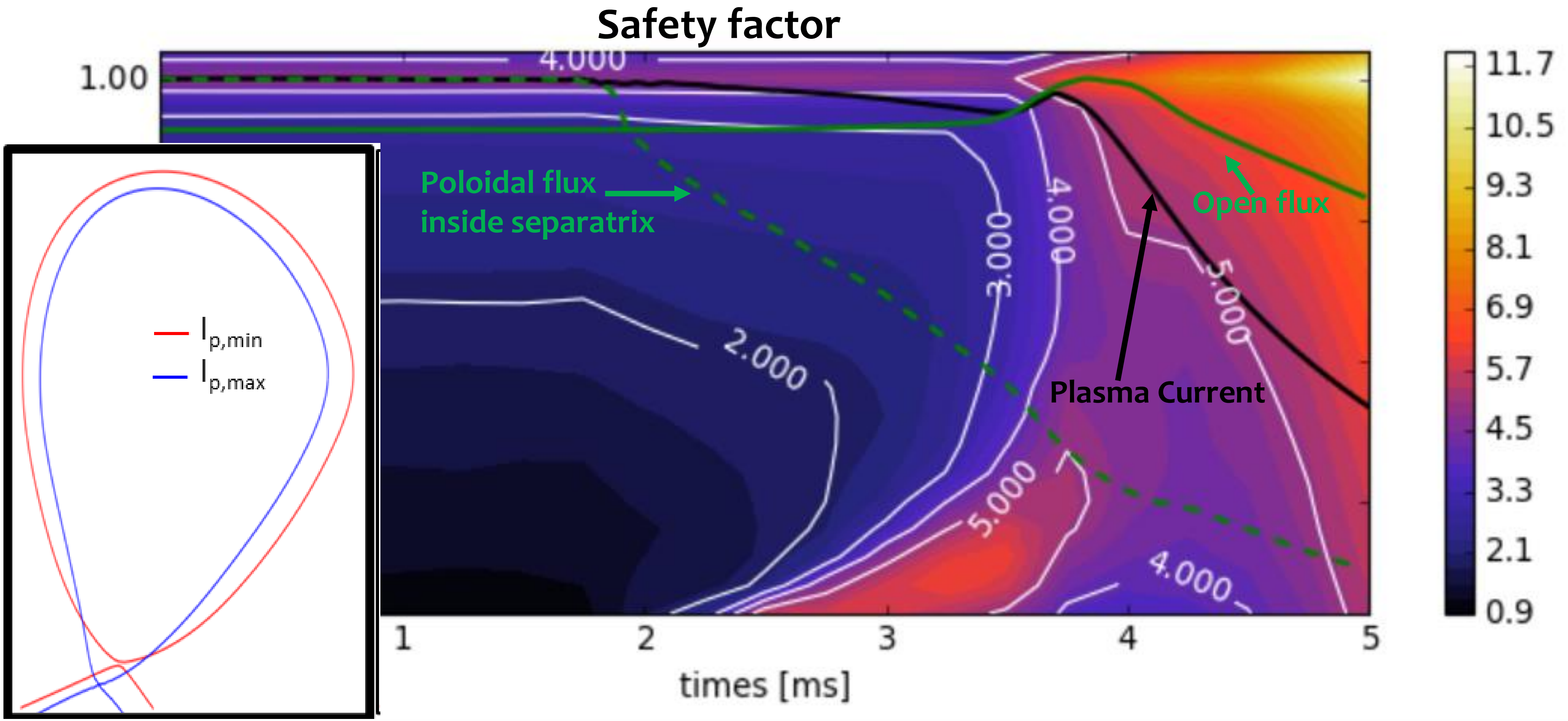
Pritchett, Lee, Drake, Phys Fluids **23** (1990)

Growth of 3/1 after q_{min} exceeds 2 is true in every case

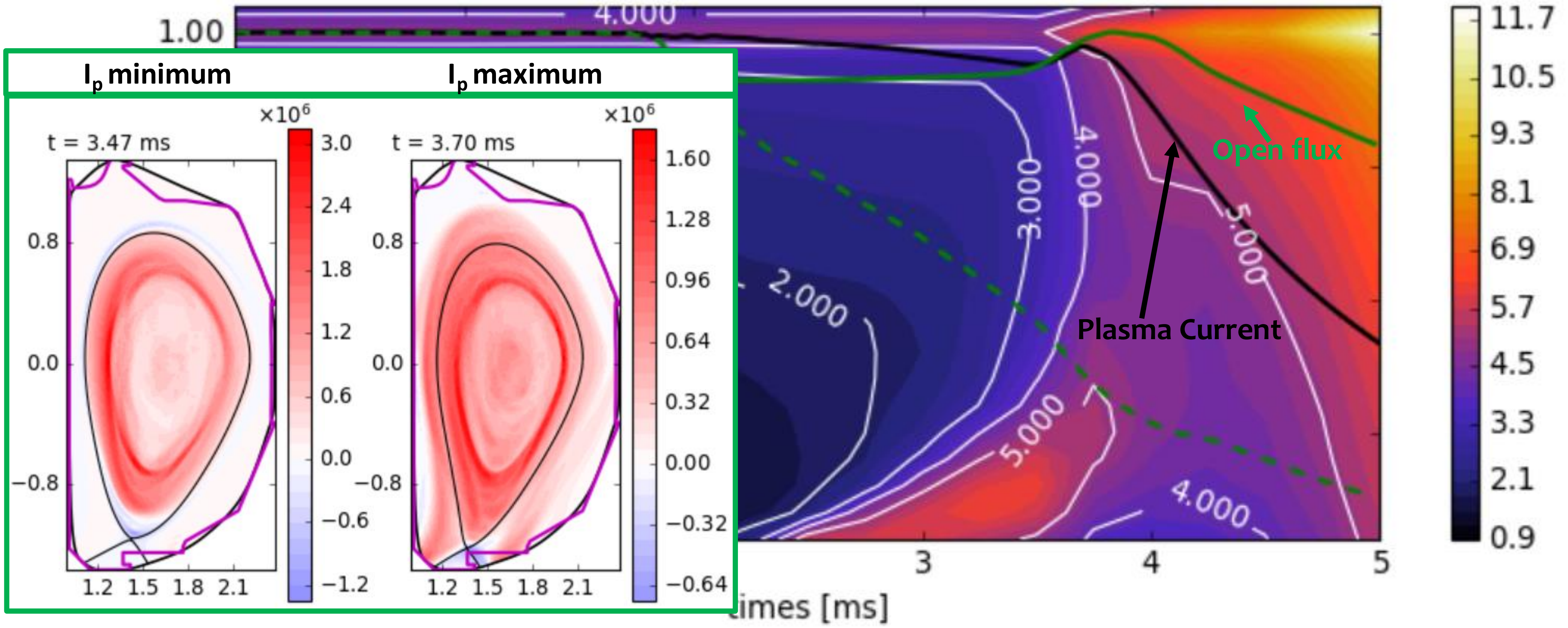
Safety factor



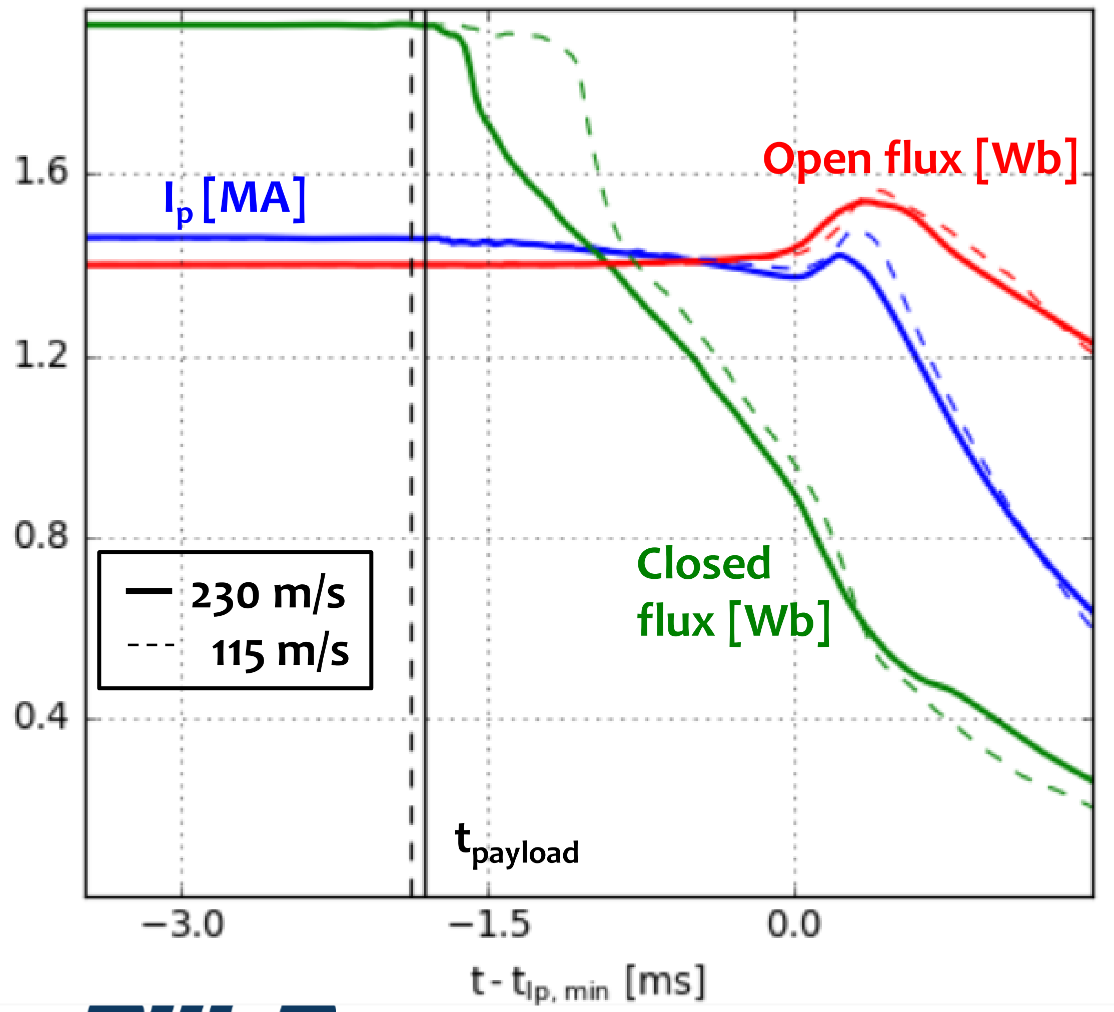
I_p-spike coincides with reconnection at the x-point, reduction of closed flux volume

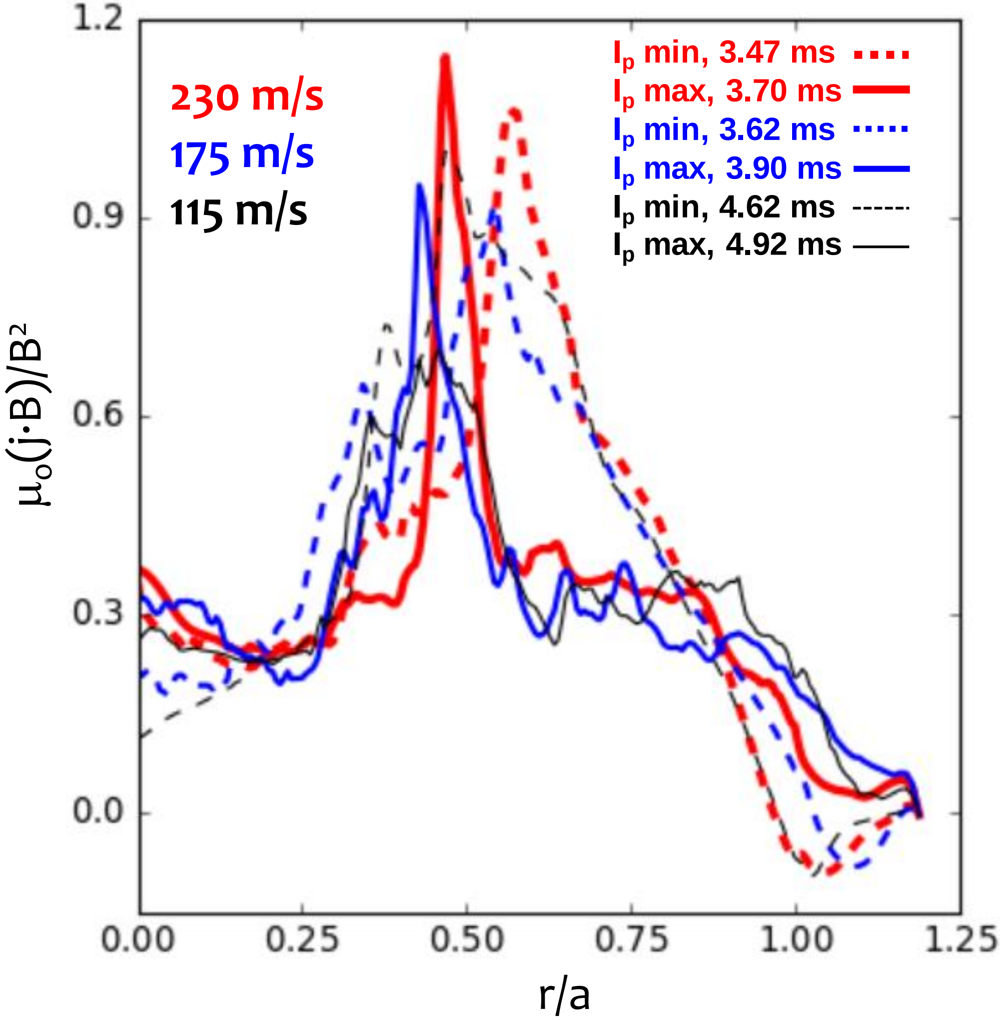


Halo current region appears after reconnection



Smaller I_p spike: less reconnected flux and less relaxed current profile

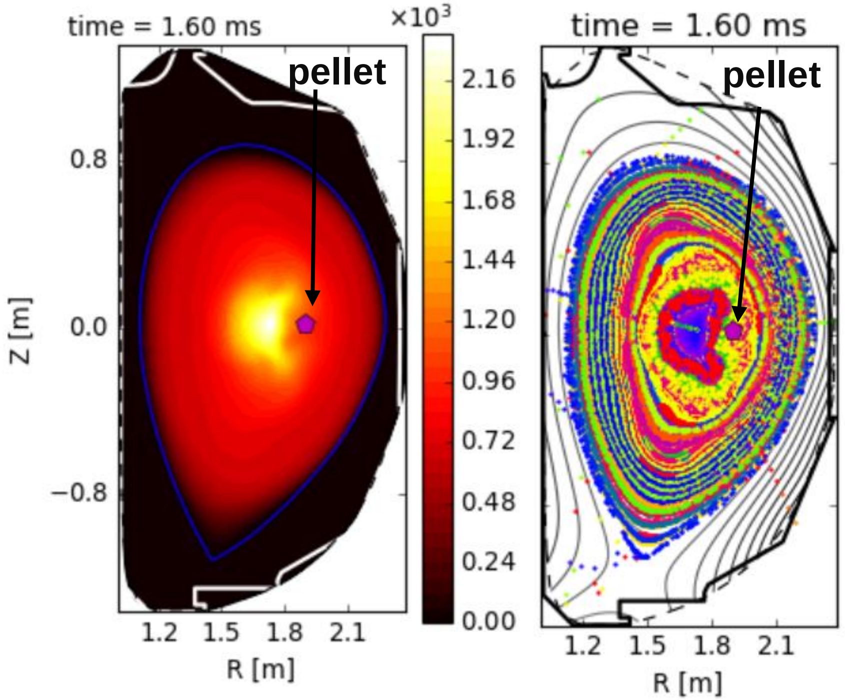




Conclusions

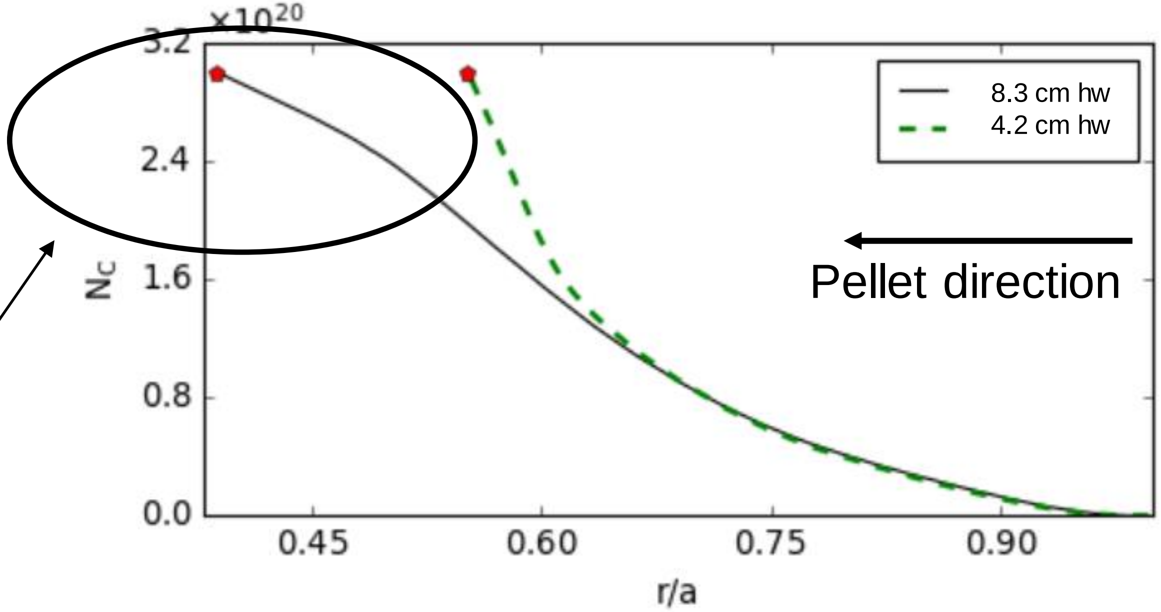
- NIMROD modeling **reproduces three major trends** vs. pellet speed seen in DIII-D DSP experiments: TQ mitigation efficiency, RE production, and I_p-spike amplitude.
- For an inside out TQ, the plasma current spike is produced by **a double tearing mode** that produces stochasticity over a wide region of the plasma.
- In the presence of pre-TQ MHD, payload delivery can be unpredictable and sensitive to numerical parameters in pellet model… but **predictive modeling may be feasible** in a more ideal DSP scenario

Every case modeled has some pre-TQ MHD

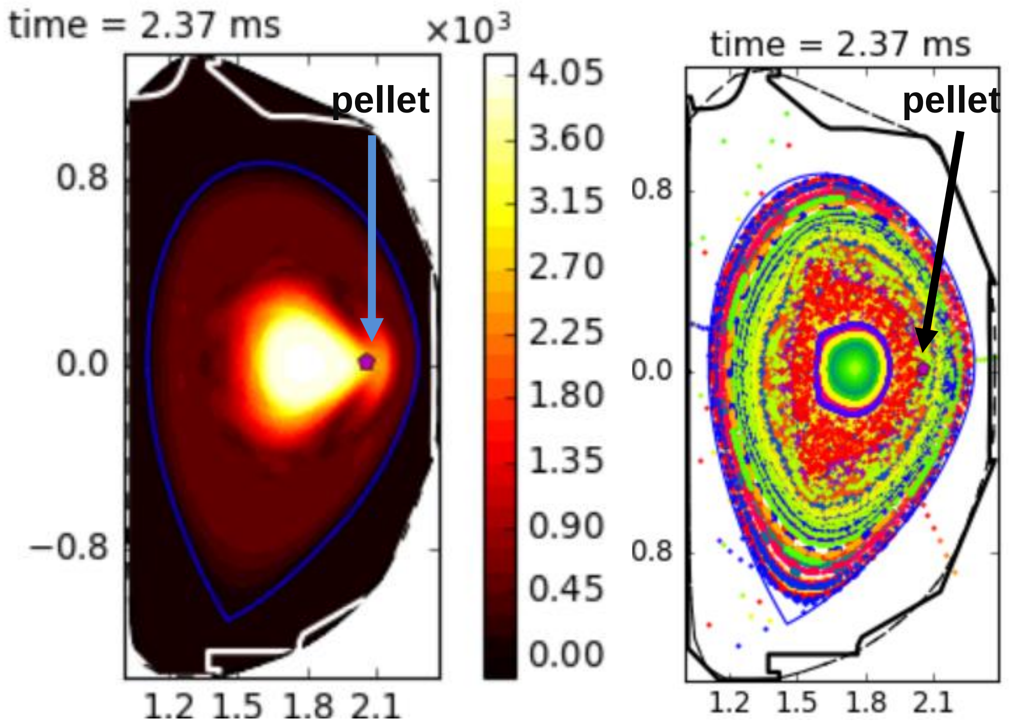


In most cases, the onset of a 1/1 mode in the core reduces the shell ablation rate prior to payload release

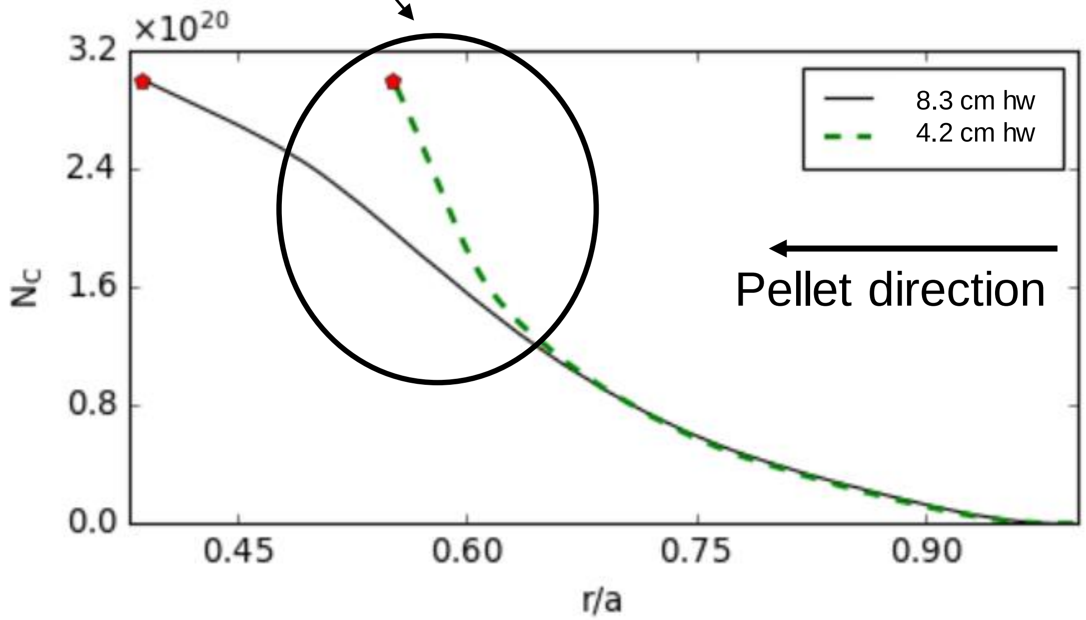
Two 115 m/s cases with different Gaussian deposition width in the poloidal plane



Neutral deposition width significantly impacts pre-TQ MHD



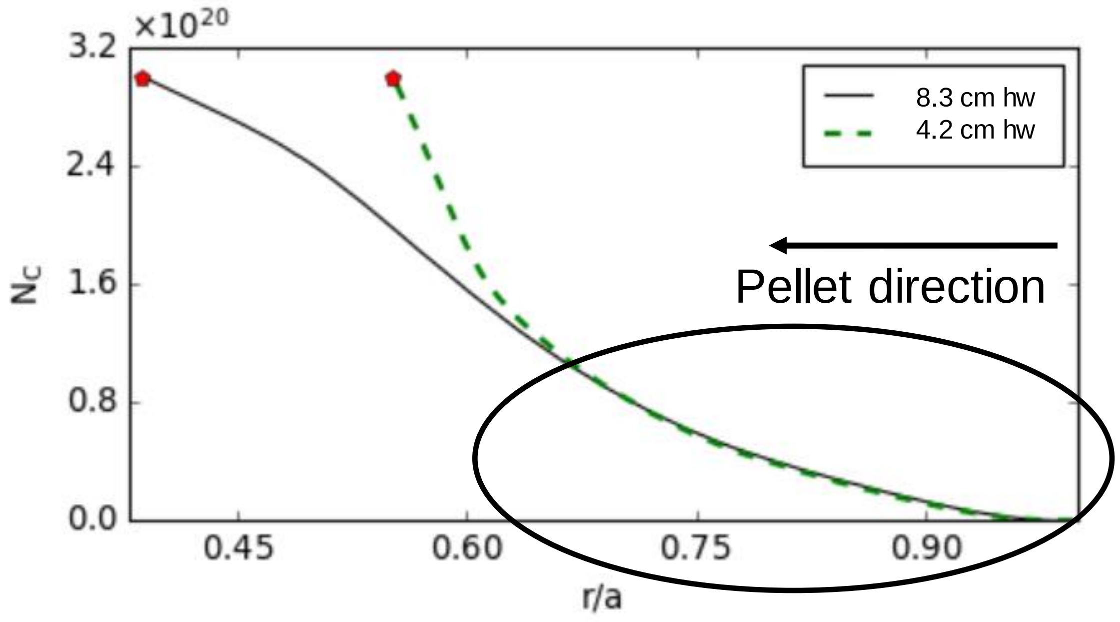
When the impurity source is more localized, 2/1 mode is destabilized, ablation accelerates due to enhanced parallel heat transport



Good news: w/o pre-TQ MHD, ablation is not sensitive to deposition width

- Goal of DSP is to avoid pre-TQ MHD; simulation results are more optimistic for a predictive model in that case.

- Scaling to ITER may be favorable to a non-perturbative shell, due to reduced surface to volume ratio for larger DSPs-- **assuming** pellet speed can be increased significantly



Conclusions

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  → Ablation model calibrated to one data point; modeling predicts very high radiation fraction ~90%
- For an inside-out TQ, the plasma current spike is produced by **a double tearing mode** that produces stochasticity over a wide region of the plasma.
  → Grows once q_{min} exceeds 2; similar to the m=1 mode responsible for I_p spike during an outside-in TQ
- In the presence of pre-TQ MHD, payload delivery can be unpredictable and sensitive to numerical parameters in pellet model… but **predictive modeling should be feasible** in a more ideal DSP scenario
  →Scaling to ITER could be favorable in this regard… if higher velocity is achieved

Initial Simulations to assess scaling to ITER

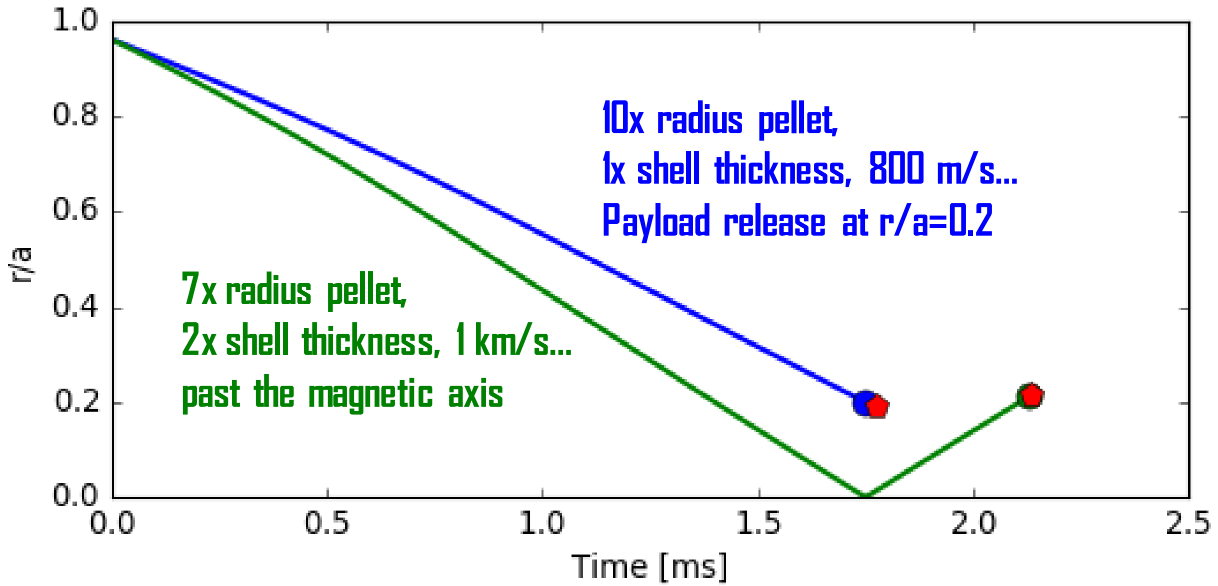
- Have carried out some 2D scoping studies (just started 3D cases) to address some questions:
  1) What payload quantity (assuming Be rather than B) is needed to achieve TQ in ITER?
  2) What shell thickness and speed is needed to reach the core?

→ Scaling payload up from DIII-D by stored thermal energy ~ 360x does not by itself produce a TQ in ITER
  - ➢ Can get TQ with a small amount of high-Z, 0.1% W for instance

→ Pure Be payload increase 1000x DIII-D does produce a TQ by itself

→ Considered pellets 7x increase in radius and 10x in radius with 1x-2x shell thickness (50x – 100x surface area)

Ablation rate is scaled with pellet radius as $r^{4/3}$



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