Modeling of shell pellet injection for disruption mitigation on DIII-D

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PPPL Theory and Simulation of Disruptions Workshop

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Outline

- Disruption mitigation with shell-pellets: concept and motivation
- DIII-D experiments and questions for modeling
- Summary of findings from previous NIMROD "shell pellet" modeling
- Description of present NIMROD shell pellet model
- Results: TQ, I_p spike, and RE confinement
- Summary
- Future Plans

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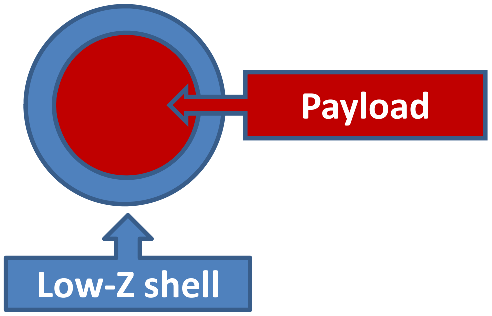
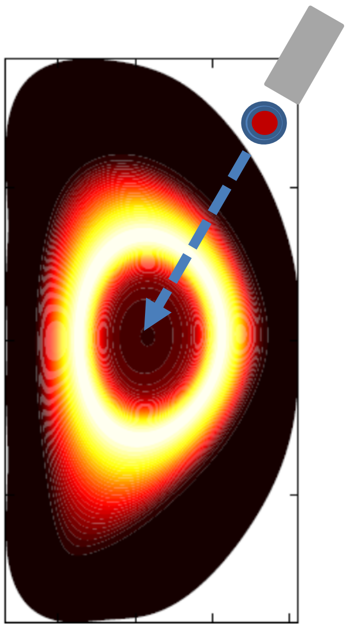
Shell Pellet Concept Seeks to Deliver Radiating Payload Directly to Center of Plasma



- Low-Z shell ablates, breaks open in the plasma center, delivering payload [1,2]
- DIII-D experiments have sought to demonstrate this concept for some years [3,4]



Potential Advantages:

- Outer flux surfaces retained→ less core heat conducted to the divertor
- High assimilation efficiency of impurities → runaway suppression, faster recovery

[1] P.B. Parks and W. Wu , Nucl Fusion 54 (2014) 023002

[2] METHODS AND APPARATUS FOR DISRUPTION MITIGATION IN FUSION DEVICES by P. B. Parks U.S. Patent Application Attorney Docket No.: 074915-8030.US00

[3] E. M. Hollmann, N. Commaux, N. W. Eidietis, T. E. Evans, D. A. Humphreys, A. N. James, T. C. Jernigan, P. B. Parks, E. J. Strait, J. C. Wesley, J. H. Yu, M. E. Austin, L. R. Baylor, N. H. Brooks, V. A. Izzo, G. L. Jackson, M. A. van Zeeland, and W. Wu Physics of Plasmas 17, 056117 (2010)

[4] N. Commaux, L.R. Baylor, S.K. Combs, N.W. Eidietis, T.E. Evans, C.R. Foust, E.M. Hollmann, D.A. Humphreys, V.A. Izzo, A.N. James, T.C. Jernigan, S.J. Meitner, P.B. Parks, J.C. Wesley and J.H. Yu, *Nucl. Fusion* **51**, 103001 (2011).

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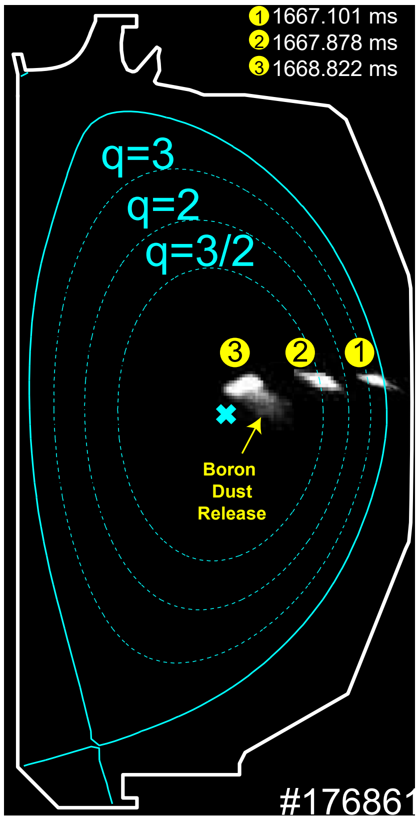
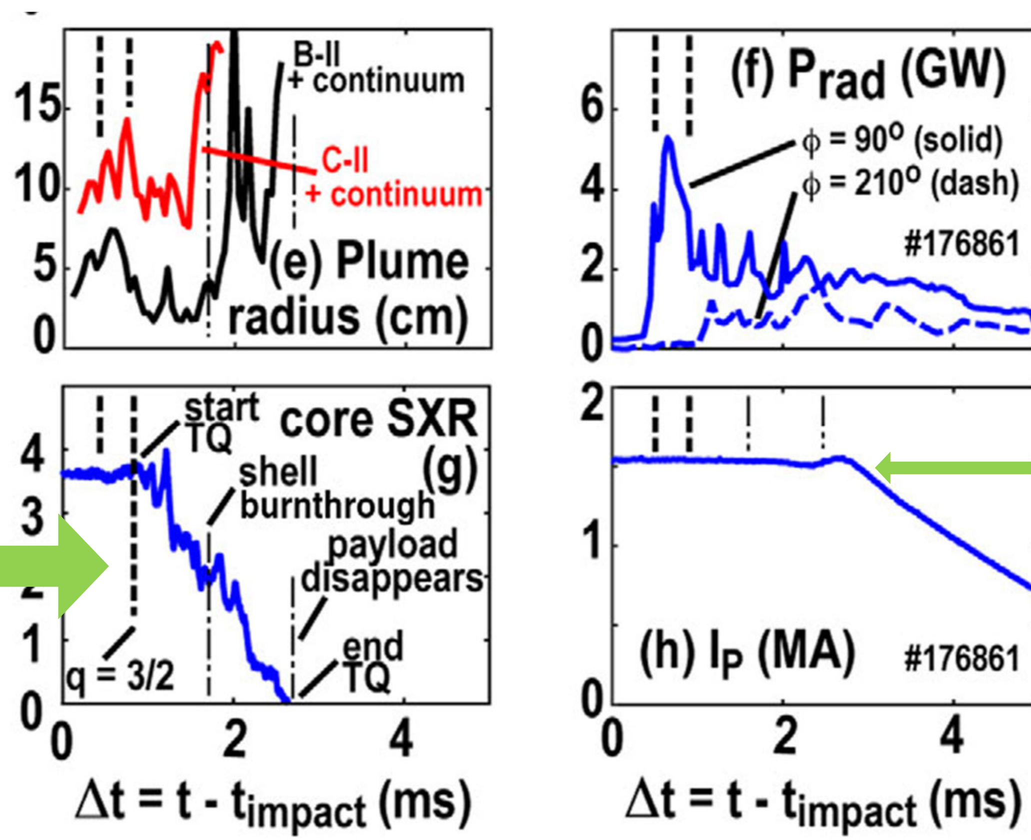
DIII-D experiments demonstrated successful mitigation with B-filled diamond shells



Drop in core SXR before payload delivery



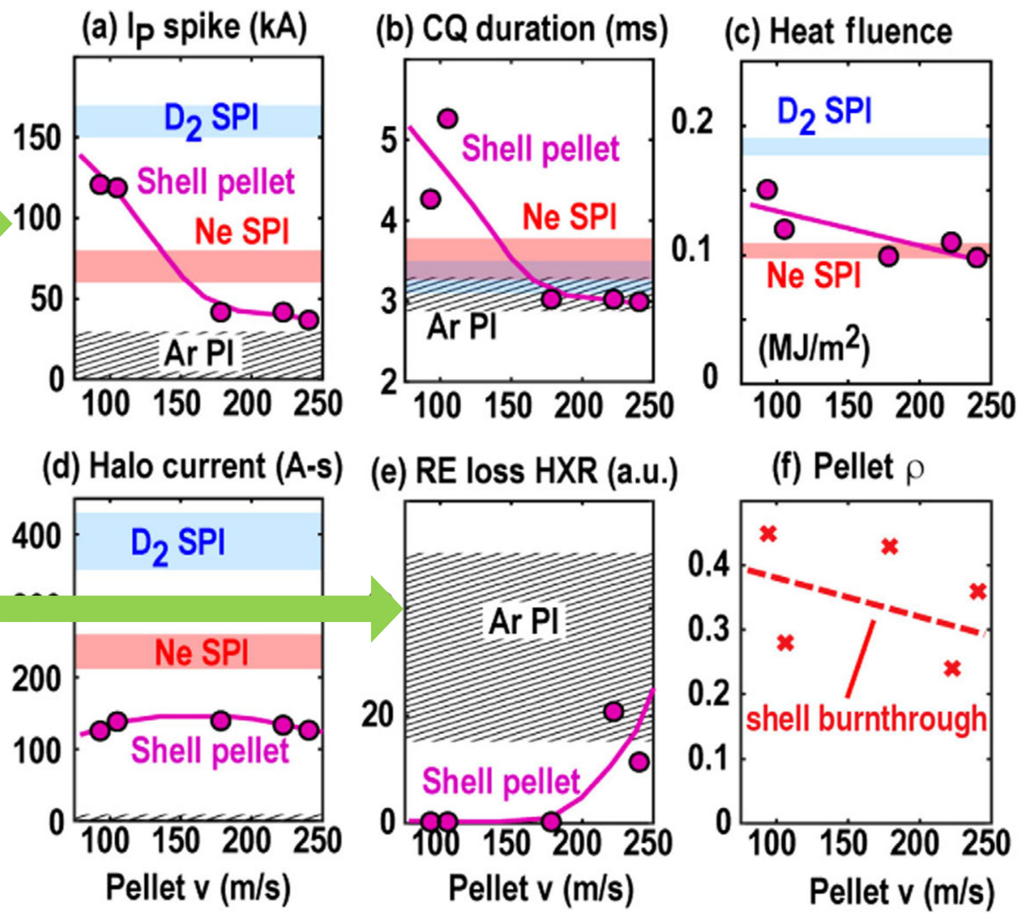
I_p spike

Hollmann, E., et al, *Physical review letters* **122** (2019): 065001.

Mitigation metrics dependent on pellet speed

Threshold like behavior for Ip spike?

RE seed production and prompt loss observed



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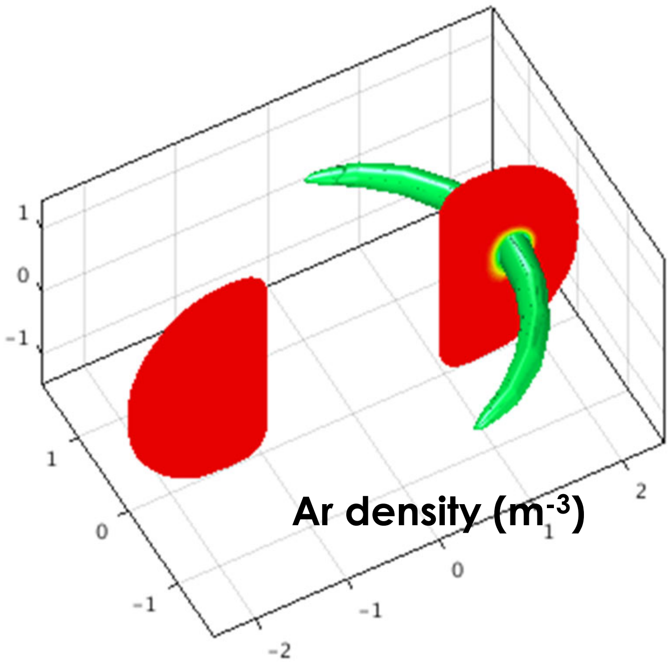
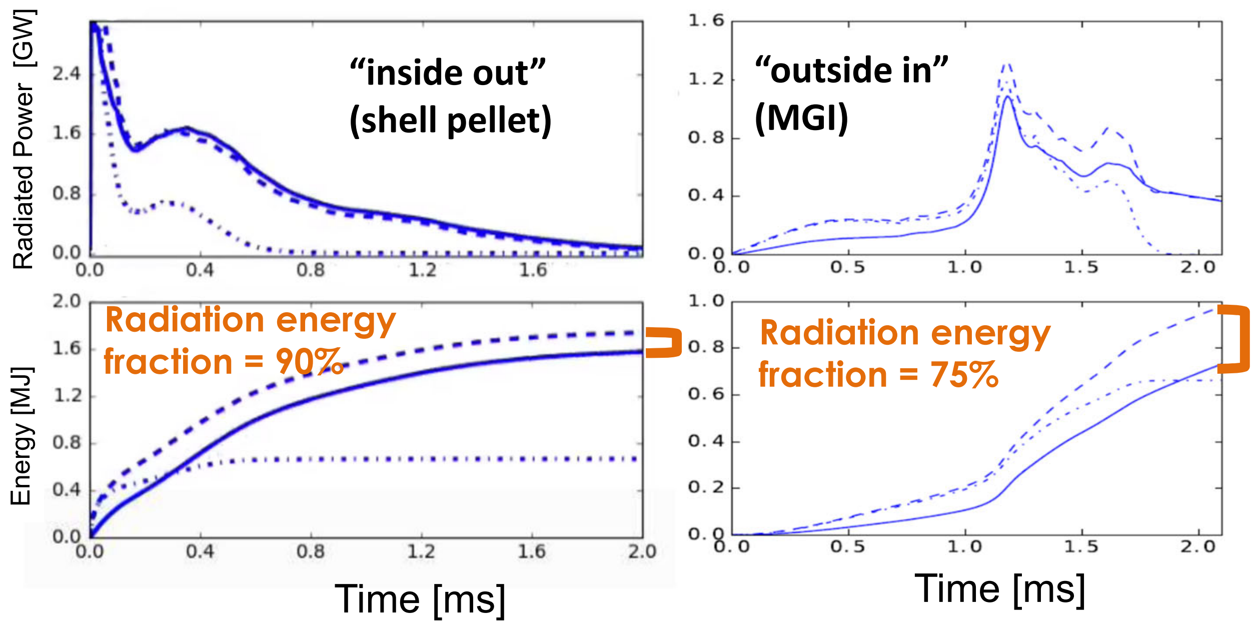
Prior "shell pellet" modeling neglected the shell

Modelled "inside-out" TQ by depositing radiating payload directly in the core



Higher radiated energy fraction than outside-in TQ (MGI) modeling



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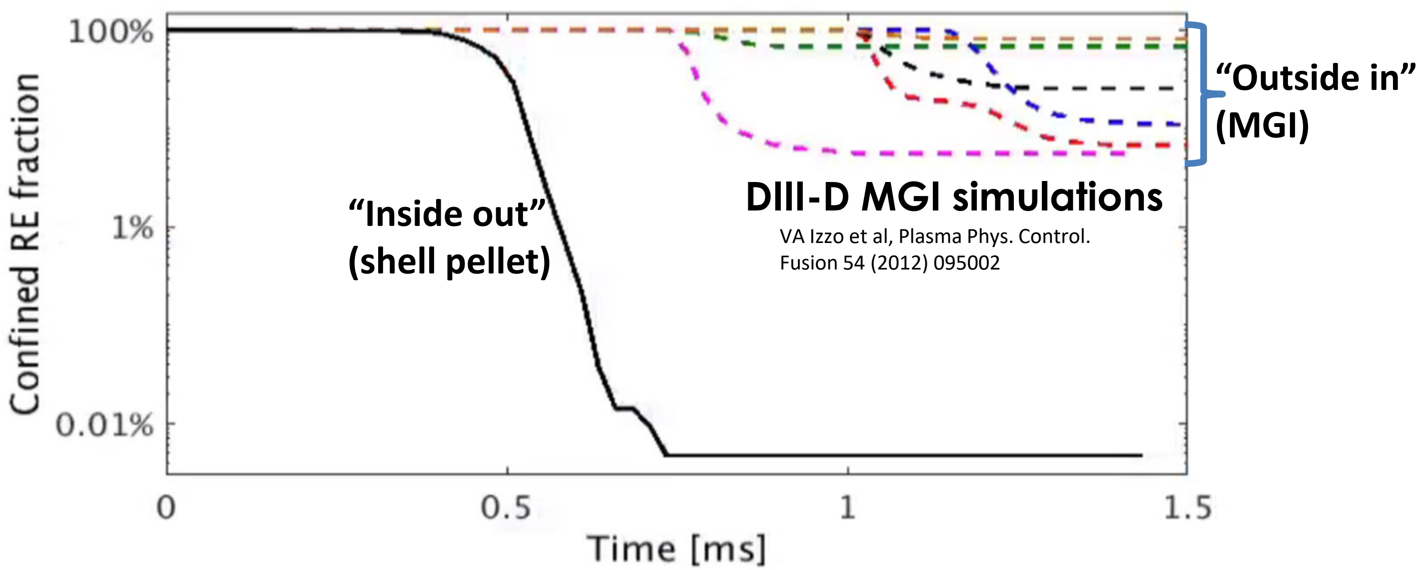
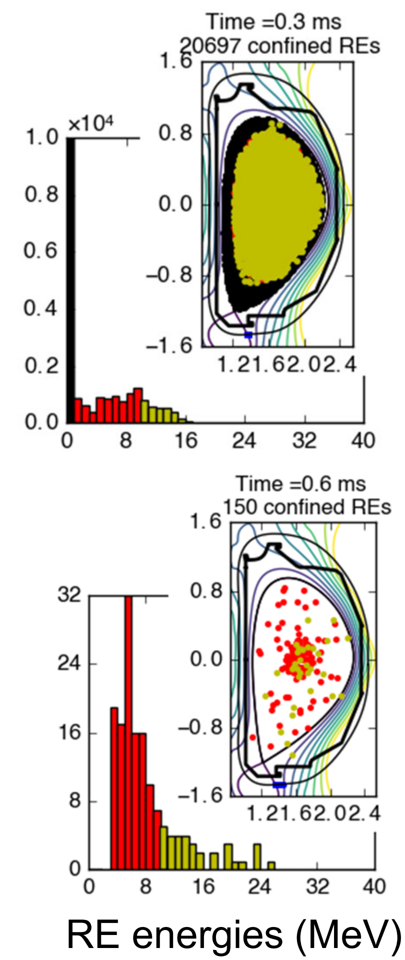
Inside out TQ also produces larger "prompt-loss" of REs

NIRMOD MGI simulations retained 5-80% of REs after TQ, compare with <0.01% retained in ShPI simulation

Aim: lose seed REs to divertor w/o conducting e-heat to divertor





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Goal of the updated shell pellet model in NIMROD

- Model does not include any physics based ablation rates. Not an attempt to predict when the shell will break open

- Model assumes that the shell ablation rate is constant as the shell travels through the plasma (rate is determined by free parameters– see next slides)

- Model allows for independent variation of pellet speed, penetration depth, ablation rate, can be used to investigate:

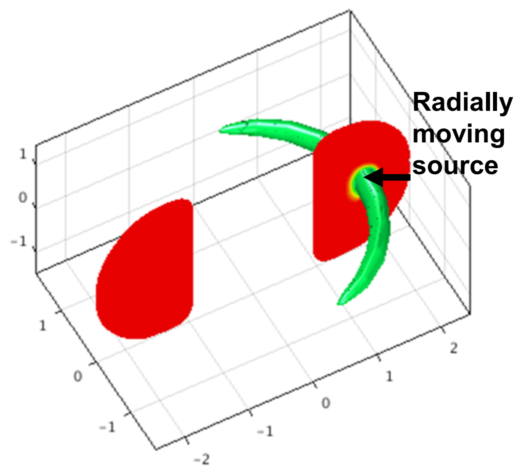
    - Requirements for “ideal shell”-like case
    - Effects of penetration depth on plasma current spike
    - Separate significance experimentally of inter-dependent parameters

Simple model to include effects of shell and consider off-center pellets

- Unlike previous model:

  Centroid of source moves inward from edge to core as a function of time

  Source delivery rate changes at specified location (when shell breaks open)



Seven free parameters:

N_{shell} = total number of atoms in the shell

$N_{payload}$ = total number of atoms in the payload

f_{ablate} = location at which shell breaks open (fraction of r/a)

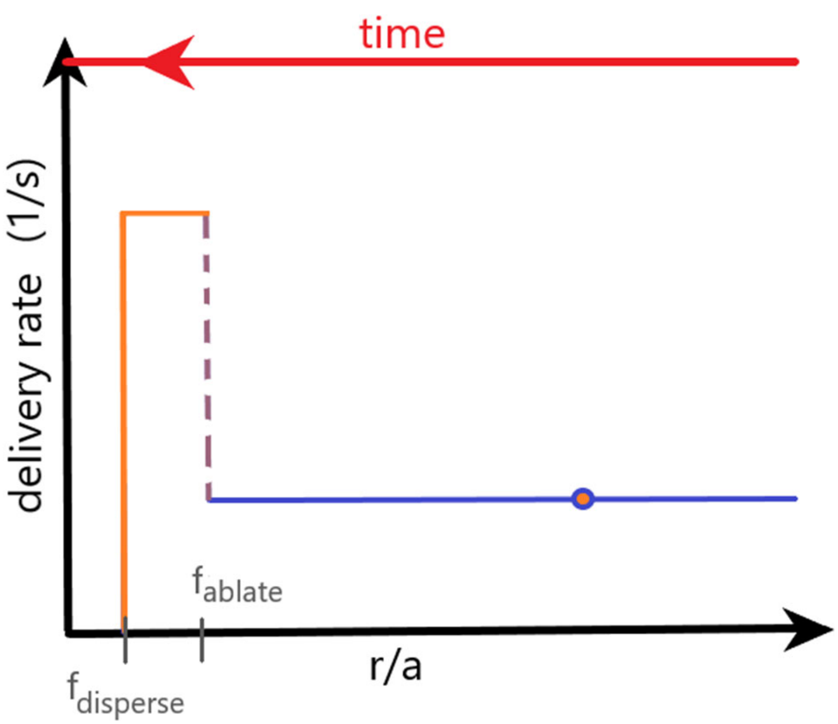
$f_{disperse}$ = location at which payload dispersal is complete (fraction of r/a)

v_{pellet}= velocity of pellet

r_d=radius of source deposition (gaussian half width)

L_d=toroidal length of source deposition (gaussian half width)

Two-source-rate model for shell/payload



Shell delivery rate (1/s) = $N_{shell}v_{pellet}/(af_{ablate})$

Payload delivery rate (1/s) = $N_{payload}v_{pellet}/(a(f_{disperse}-f_{ablate}))$

Regardless of pellet speed, integrated total material delivered over a certain region remains fixed, must deposit faster if speed is faster

Because it is not straightforward to include more than one impurity species in NIMROD, for now the shell and payload must be treated as the same. C is used for both.

Summary of Simulation Parameters

- Injection quantities are based on nominal shell and payload quantities of 3.01×10^{20} atoms and 1.17×10^{21} atoms, respectively. Cases have either 100% of shell quantity or 25%. All have 100% payload quantity
- Pellet speed in all cases here is 200m/s. A few faster cases have been run.
- Start of payload delivery ranges from 60%-90% of the way in (r/a=0.4-0.1), and always have a delivery window of r/a=0.2.
- Two sets of simulations: $\chi_{\parallel}\propto T^{5/2}$ (run only to near end of TQ) and $\chi_{\parallel}$=const. (run through early CQ)

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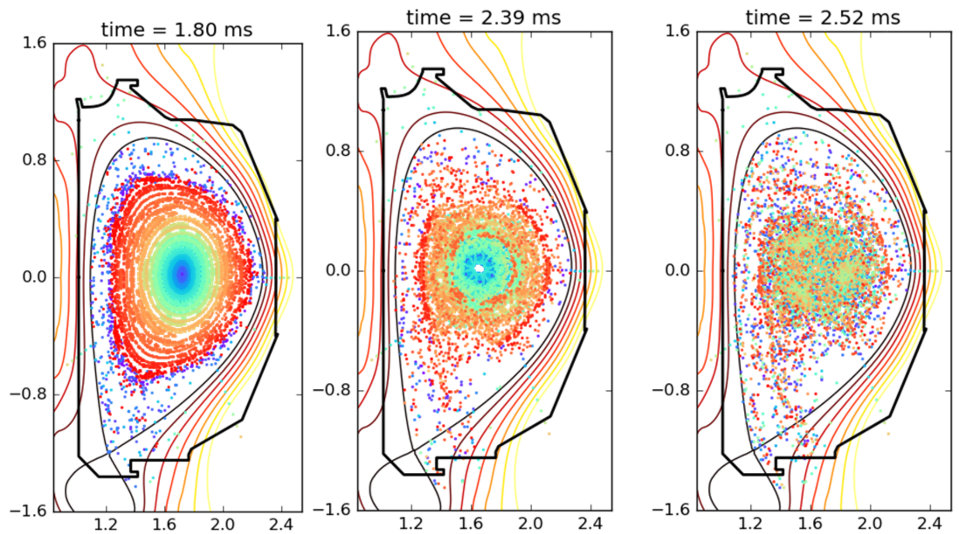
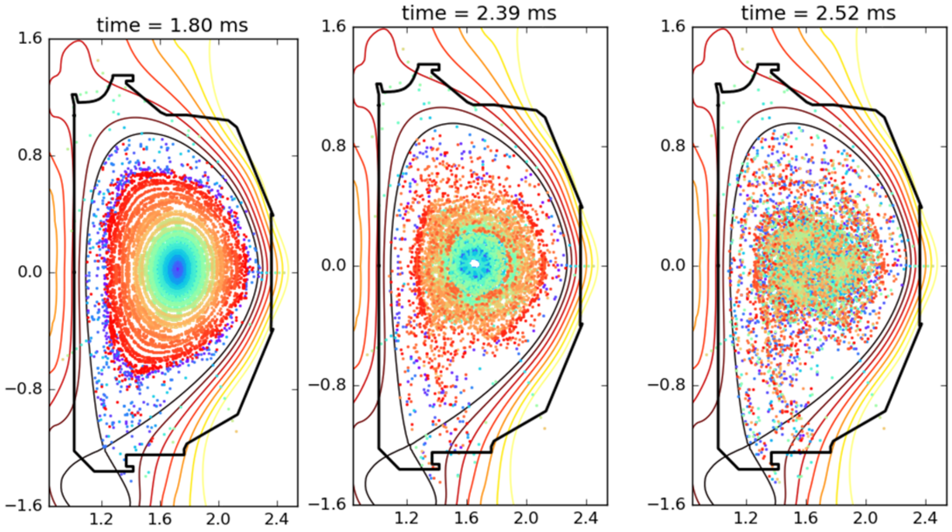
Pre-TQ: ideal-like flux surface retention shell quantities in ballpark of experimental quantities



Case 1:100% of experimental shell material ablated before payload delivery at r/a=0.4 → purely outside-in flux surface destruction

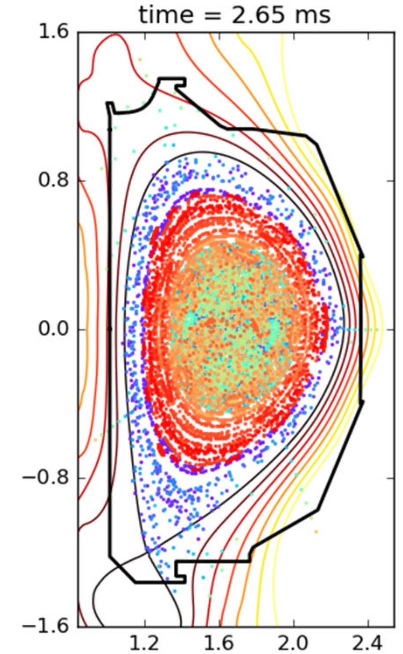
	Ablated shell material	Payload delivery location (r/a)
Case 1	100 %	r/a = 0.4
Case 2	100 %	r/a = 0.2
Case 3	25 %	r/a = 0.2

Pre-TQ: ideal-like flux surface retention shell quantities in ballpark of experimental quantities



Case 1:100% of experimental shell material ablated before payload delivery at r/a=0.4 → purely outside-in flux surface destruction

Case2: 100% of experimental shell material ablated before payload delivery at r/a=0.2 → some mid-range flux surfaces retained



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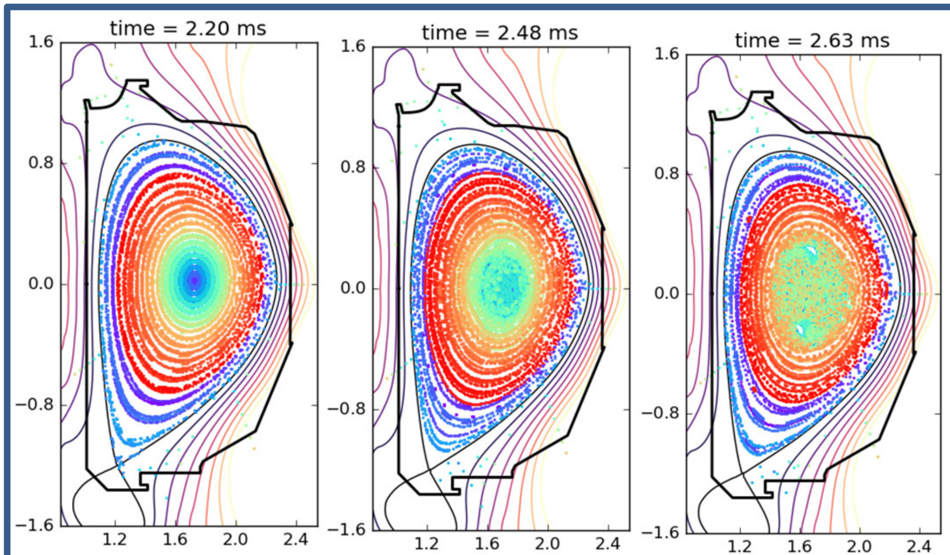
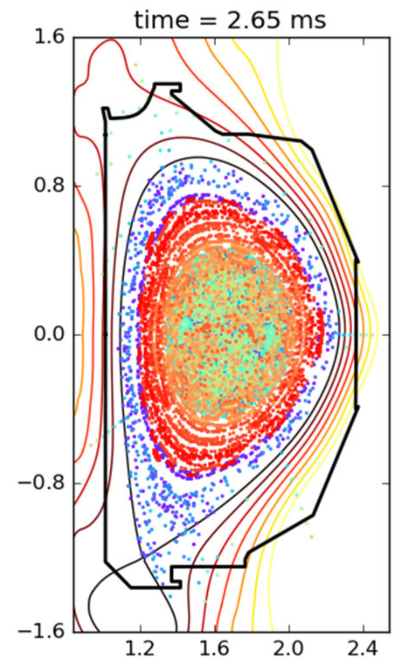


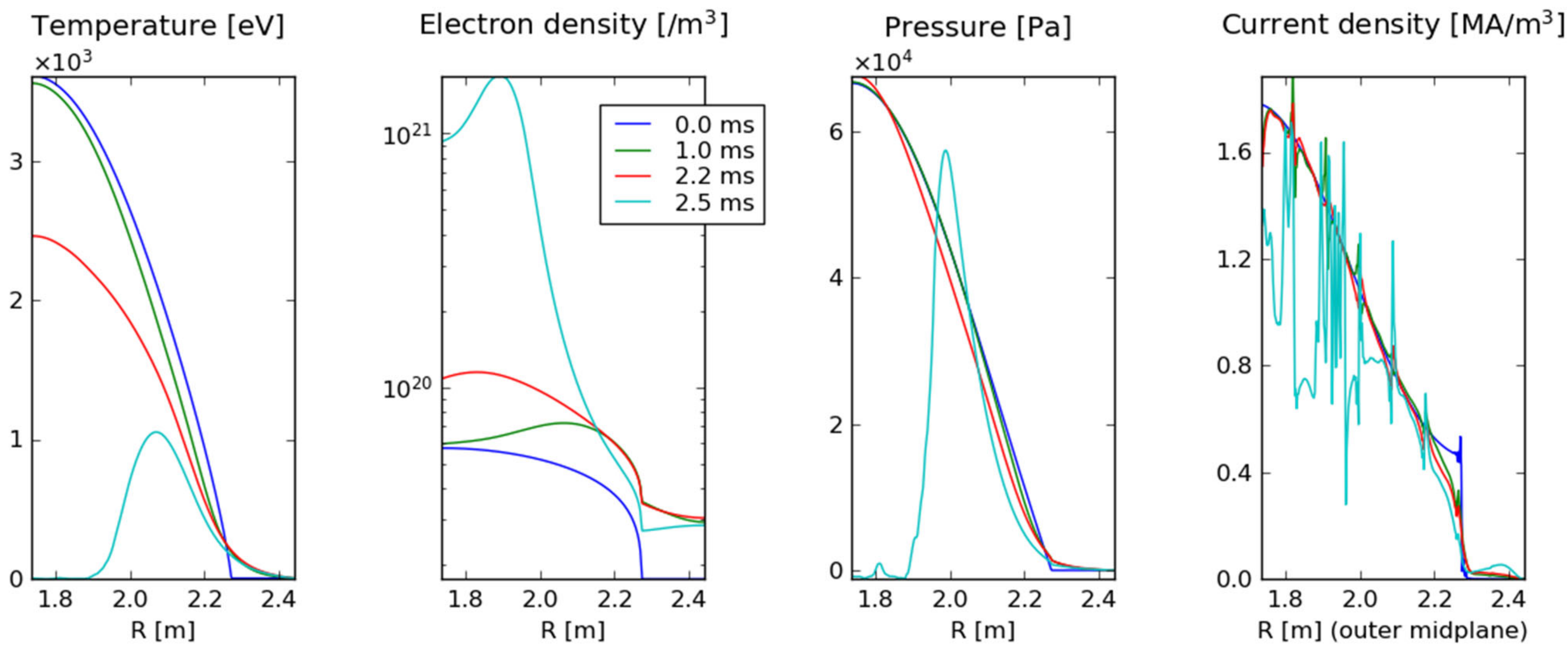
Case3: 25% of experimental shell material ablated by payload delivery r/a=0.2 → purely inside-out flux surface destruction

Case2: 100% of experimental shell material ablated before payload delivery at r/a=0.2 → some mid-range flux surfaces retained

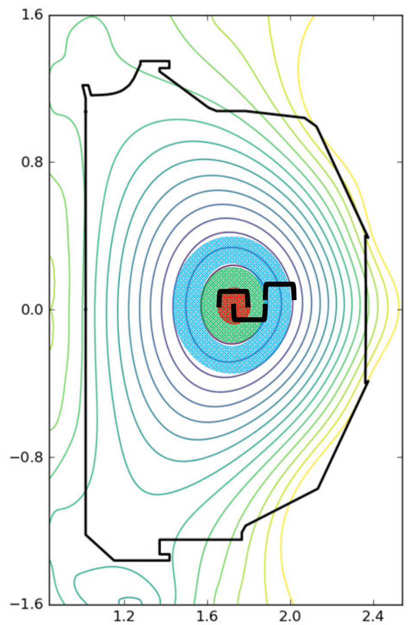


Measurable change in core T_e in pre-TQ is not associated with loss of thermal energy

Ideal-like case: payload delivery begins at 2.24 ms



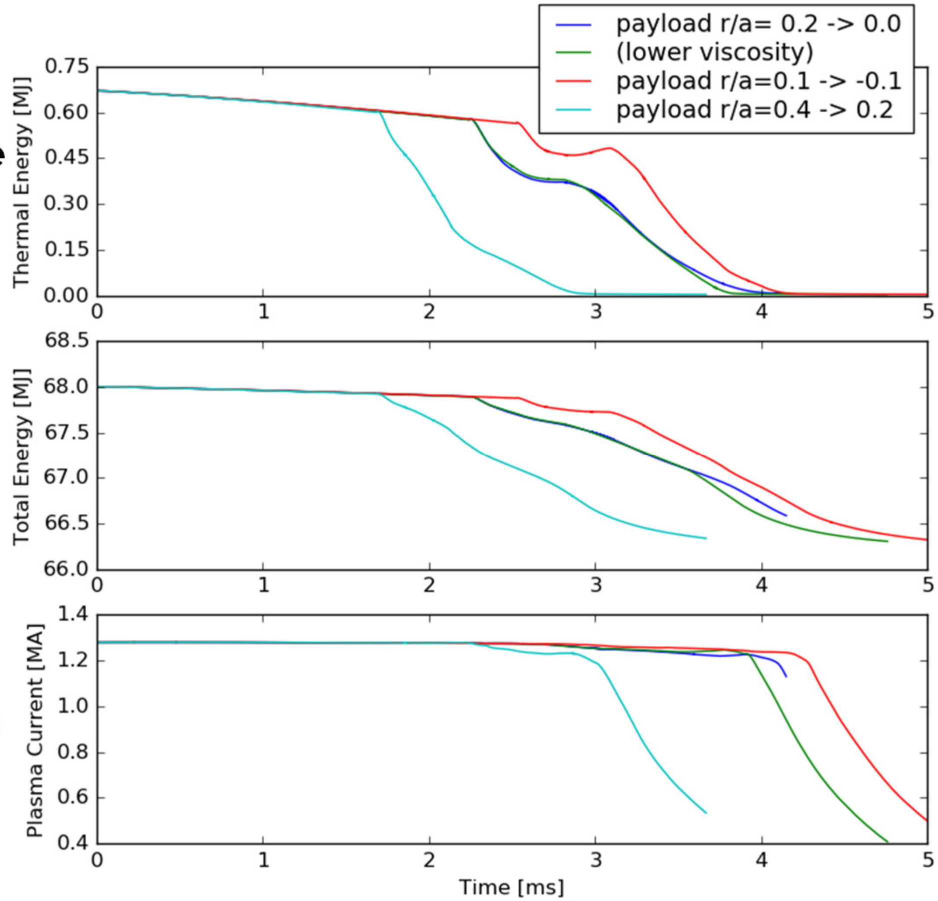
TQ characteristics depend on payload delivery location



Payload delivery at largest r/a intersects largest volume of flux surfaces → fastest cooling

Core-centered case delivers payload in region only half as wide in minor radius

Core localized payloads produce pause or brief increase in thermal energy after initial inverted profile is formed.



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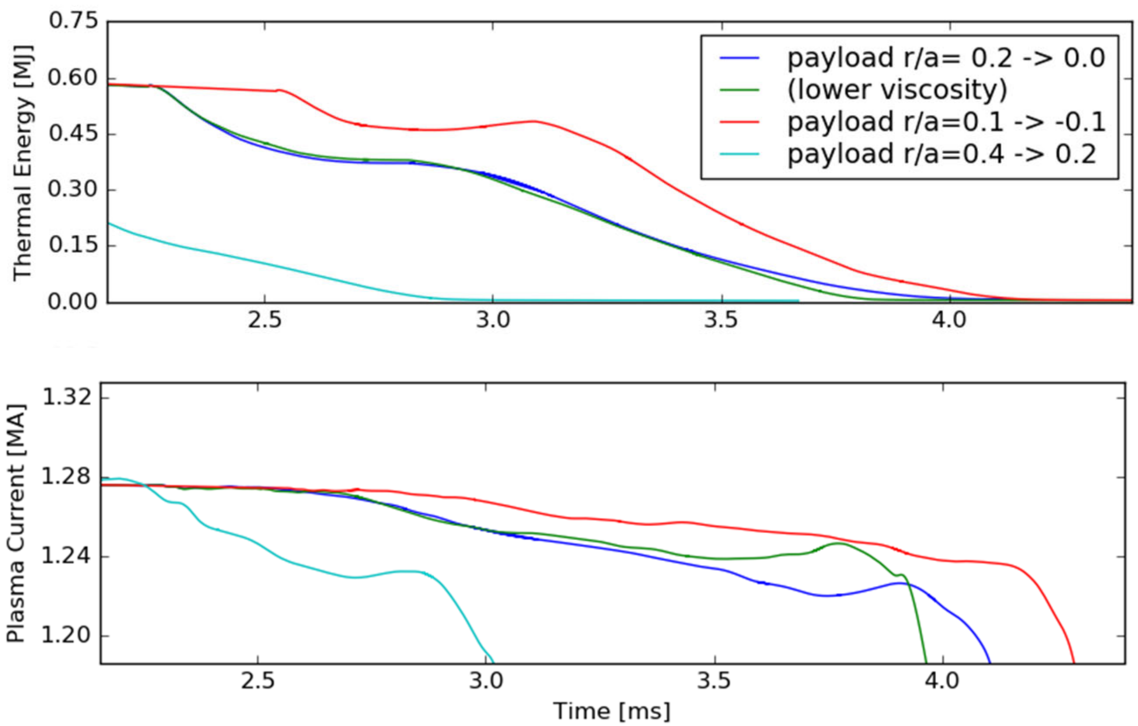
Very small "Ip spikes" seen in off-center cases, investigating relevant simulation parameters

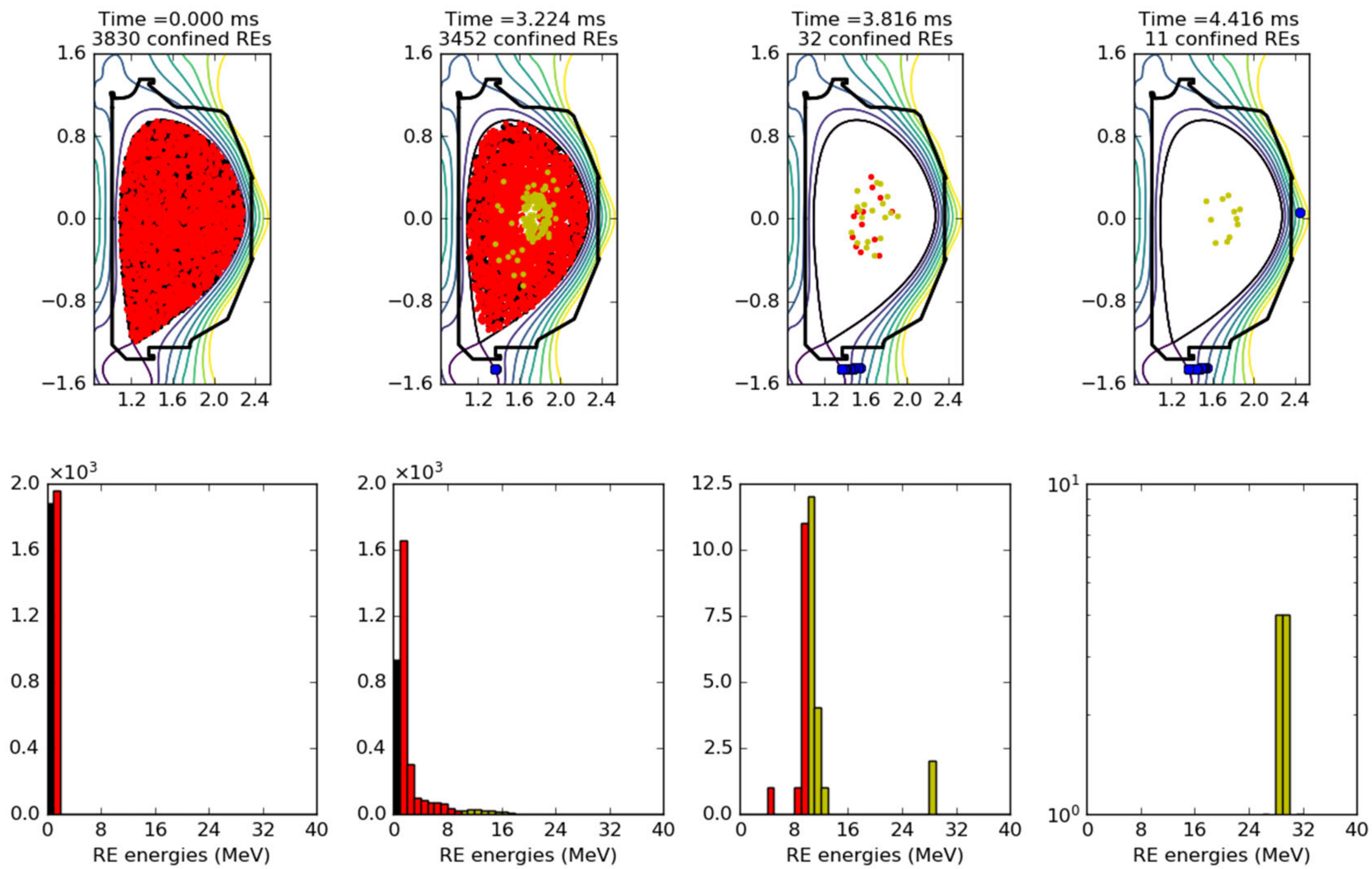


Few kA increase in current seen in cases with off-axis payload delivery (compared with 100 kA experimental I_p spikes)

10x decrease in viscosity makes only a small difference. Effect of other simulation parameters will be investigated

Mini-I_p spike is seen to disappear for on-axis payload

RE test particle orbits are tracked, significant “prompt-loss” at end of TQ

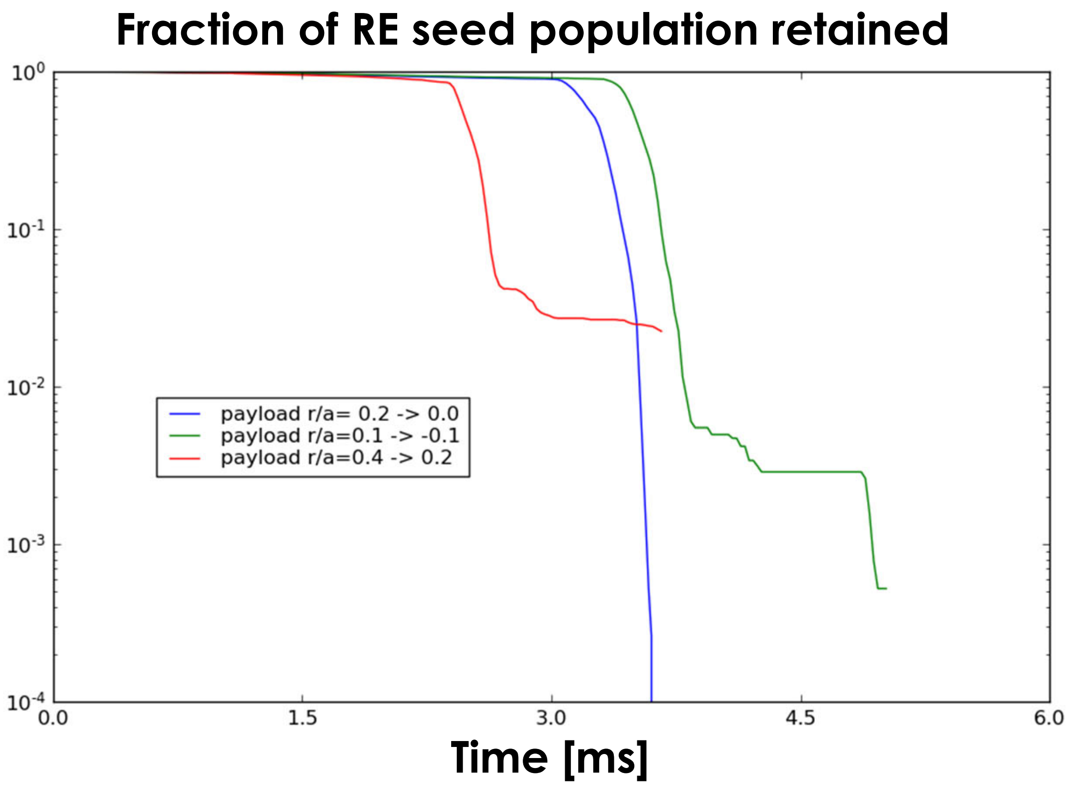


Differences in loss fraction vs. payload release location are seen

Most off-axis simulation retains a few percent of the initial seed population post-TQ

Most on-axis simulation retains only 10ths of a percent of the seed

Nearly on-axis simulation dumps entire RE seed population



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- Simple shell pellet model in NIMROD finds ideal-like (non-perturbative) shell interaction near (just below) experimental quantities
- In simulations, significant pre-TQ Te drop is not associated with significant pre-payload loss of thermal energy
- Very small I_p spikes are seen in some cases, but further work needed to produce ~100kA spike observed
- Fast loss of runaway electrons at the end of the TQ, with variation dependent on payload delivery location

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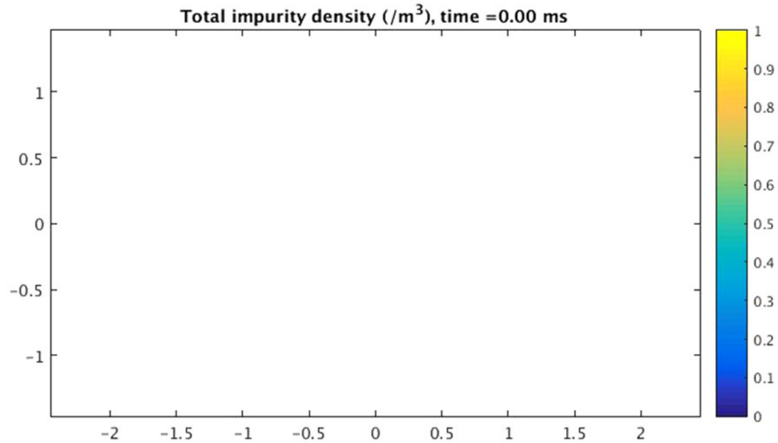
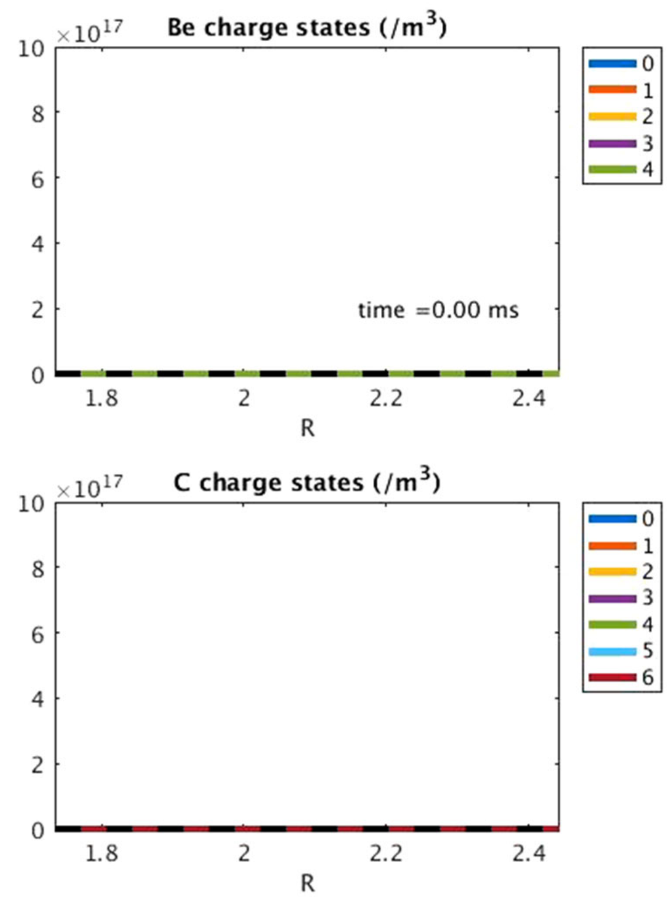
Plans for existing model and new model development

- Using the existing simple model
  - Focus on reproducing larger I_p spike by examining effects of various dissipation parameters
  - Examine toroidal source localization and effects on radiation peaking
  - Model HFS payload release
- Upgrades to the model
  - **Inclusion of different impurity species for shell and payload– Next slide**
  - Non-constant/physics-based ablation rates

Test of multi-species impurity model in NIMROD

Initial test is done with C shell and Be payload… because B data presently not available in NIMROD





References

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[2] METHODS AND APPARATUS FOR DISRUPTION MITIGATION IN FUSION DEVICES by P. B. Parks U.S. Patent Application Attorney Docket No.: 074915-8030.US00

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[5] Eidietis, N., Hollmann, E., Parks, P., Moyer, R., Herfindal, J., Lvovskiy, A., & Shiraki, D. (2018). First demonstration of disruption mitigation using shell pellets for core impurity deposition on DIII-D. *Bulletin of the American Physical Society*.

[6] Izzo, V. A., & Parks, P. B. (2017). Modeling of rapid shutdown in the DIII-D tokamak by core deposition of high-Z material. *Physics of Plasmas* **24**, 060705.

[7] Hollmann, E. M., P. B. Parks, D. Shiraki, N. Alexander, N. W. Eidietis, C. J. Lasnier, and R. A. Moyer. "Demonstration of Tokamak Discharge Shutdown with Shell Pellet Payload Impurity Dispersal." *Physical review letters* **122** (2019): 065001.