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

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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

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

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

Radiation energy fraction = 90%

Radiation energy fraction = 75%
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

“Inside out” (shell pellet)  “Outside in” (MGI)

DIII-D MGI simulations

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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:

- \( N_{\text{shell}} \): total number of atoms in the shell
- \( N_{\text{payload}} \): total number of atoms in the payload
- \( f_{\text{ablate}} \): location at which shell breaks open (fraction of \( r/a \))
- \( f_{\text{disperse}} \): location at which payload dispersal is complete (fraction of \( r/a \))
- \( v_{\text{pellet}} \): 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 \((1/s) = \frac{N_{\text{shell}}v_{\text{pellet}}}{a f_{\text{ablale}}})\)

Payload delivery rate \((1/s) = \frac{N_{\text{payload}}v_{\text{pellet}}}{a(f_{\text{disperse}} - f_{\text{ablale}})})\)

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 $3.01 \times 10^{20}$ atoms and $1.17 \times 10^{21}$ 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 $\chi_\parallel = \text{const.}$ (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 \(\rightarrow\) purely outside-in flux surface destruction

<table>
<thead>
<tr>
<th>Case</th>
<th>Ablated shell material</th>
<th>Payload delivery location (r/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>100 %</td>
<td>r/a = 0.4</td>
</tr>
<tr>
<td>Case 2</td>
<td>100 %</td>
<td>r/a = 0.2</td>
</tr>
<tr>
<td>Case 3</td>
<td>25 %</td>
<td>r/a = 0.2</td>
</tr>
</tbody>
</table>
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

**Case 2:** 100% of experimental shell material ablated before payload delivery at $r/a=0.2$ → some mid-range flux surfaces retained
Pre-TQ: ideal-like flux surface retention shell quantities in ballpark of experimental quantities

**Case 2:** 100% of experimental shell material ablated before payload delivery at r/a=0.2 → some mid-range flux surfaces retained

**Case 3:** 25% of experimental shell material ablated by payload delivery r/a=0.2 → purely inside-out flux surface destruction
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.
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 Ip spikes)

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

Mini-Ip 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 $T_e$ 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


