C – pellet disruption mitigation modeling with M3D-C

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C – pellet disruption mitigation modeling with M3D-C¹

Outline:

• Motivation
• Modelling pellets in M3D-C1
• C ablation model
• Validation/comparison (ASDEX-U)
• NSTX-U simulations
• Summary and future work
Motivation

- Electromagnetic Pellet Injector (EPI) is a good candidate for a DMS [1]
- EPI would offer advantages for ITER
  - Very fast response time (2-3 ms)
  - Speeds up to 1 km/s
- The NSTX-U Team is interested in testing this concept

In support of this interest
- We have started single C-pellet injection simulations using M3D-$C^1$
  - C-ablation model has been incorporated
  - Simulations on NSTX-U are being conducted
    - Convergence study
    - TQ quench sensitivity on modelling parameters
    - Understanding the physics involved

See R. Raman presentation at this meeting
Modelling pellets in M3D-C$^1$

The ablation rate is provided

The ablated material is weighted by a spatial distribution

- The size of the ablated cloud has to be specified. Limitations arise due to mesh size and number of toroidal planes
- Smaller cloud sizes require more toroidal planes and smaller time steps

Plasma evolves self-consistently in time

- Single fluid equations (same velocity, $v$, for all species ($e, i, Z^j$))
- Continuity equation for each ion species
  - Electron density is defined to satisfy quasi-neutrality
- Radiation is calculated using the KPRAD module (ionization, recombination, etc)
- Two temperature equations ($\Sigma$ions and $e^-$) coupled with the radiation losses calculated by KPRAD

References:
Based on a Neutral Gas Shielding Model (NGS) [2-3]

- Key quantity is $\delta = q_p/q_0$ → shielding factor
  - $q_p$ → heat flux reaching the pellet surface
  - $q_0$ → heat flux from the surrounding plasma

The ablation rate $\dot{N}$ combines expressions for both strong and weak shielding limits

- **Strong shielding:** $\delta \rightarrow 0$ (i.e. Hydrogen pellets)
  \[
  \dot{N}_0 \left[\frac{\text{Atom}}{s}\right] \approx 1.94 \times 10^{14} n_e^{0.45} [\text{cm}^{-3}] \times T_e^{-1.72} [\text{eV}] r_p^{1.44} [\text{cm}] \epsilon^{-0.16} [\text{eV}] \times A_p^{-0.28} [\text{amu}] Z_p^{-0.56} (\gamma - 1)^{0.28}
  \]

- **Weak shielding:** $\delta \rightarrow 1$ (i.e. Refractory pellets)
  \[
  \dot{N}_\delta \left[\frac{\text{Atom}}{s}\right] \approx \frac{\delta}{\epsilon} r_p^2 n_e \sqrt{\frac{8\pi T_e^3}{m_e}}
  \]

**C pellets can have an intermediate shielding**

- There is no analytical model for this regime
- A standard interpolation was proposed [3]:

\[
\dot{N} = \frac{\dot{N}_0 \dot{N}_1}{\dot{N}_0 + \dot{N}_1}
\]


Expression we have implemented in M3D-C$^1$
M3D-C1 implementation tested in AUG

We tested the implementation in an AUG-#3948-like plasma (no G-EQDSK available) in which data existed [3].

- Agreement is very good
- Large $\kappa_\parallel$ increases the ablation rate

<table>
<thead>
<tr>
<th>Parameter</th>
<th>#3948</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_p$</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>$v_p$</td>
<td>485 m/s</td>
</tr>
<tr>
<td>$B_0$</td>
<td>1.96 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>0.8 MA</td>
</tr>
<tr>
<td>$R_0$</td>
<td>1.7 m</td>
</tr>
<tr>
<td>Enlong.</td>
<td>1.6</td>
</tr>
<tr>
<td>$\kappa_\perp$</td>
<td>$3 \cdot 10^{-6}$</td>
</tr>
</tbody>
</table>

We studied single C-pellet injection in NSTX-U (#139536) to support EPI proposal. We started from equilibrium (g-eqdsks provided) and injected a C-pellet radially at the midplane.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>#139536</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{e0}$</td>
<td>2 keV</td>
</tr>
<tr>
<td>$n_{e0}$</td>
<td>$\sim 2 \times 10^{19} \text{ m}^{-3}$</td>
</tr>
<tr>
<td>$B_0$</td>
<td>0.44 T</td>
</tr>
<tr>
<td>$I_p$</td>
<td>0.58 MA</td>
</tr>
<tr>
<td>$R_0$</td>
<td>0.99 m</td>
</tr>
<tr>
<td>$\beta$</td>
<td>2.25 %</td>
</tr>
</tbody>
</table>
NSTX-U C-pellet Disruption Mitigation Study

- 2D Preliminary studies
- 3D – Pellet injection studies (1 mm C pellet):
  Scan over different parameters
  - Modelling
    - Pellet cloud size
    - Parallel Transport
  - Pellet parameters
    - Pellet radial velocity, \( v_p \)
  - Other parameters were also scanned (density diffusion, viscosity, etc)

We want to evaluate the role of different parameters on the thermal quench
Comparing different initial distributed Carbon content

We performed 2D simulations with initially distributed Carbon density to evaluate the amount of Carbon needed to mitigate the plasma.

<table>
<thead>
<tr>
<th>Initial condition</th>
<th>#C atoms</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_c = n_e )</td>
<td>( 2 \times 10^{20} )</td>
<td>1 mm C-pellet</td>
</tr>
<tr>
<td>( n_c = 2n_e )</td>
<td>( 4 \times 10^{20} )</td>
<td>( = 3.2 \times 10^{20} )</td>
</tr>
</tbody>
</table>

Results suggest that the amount of Carbon in 1 mm pellet would be enough to mitigate the plasma if it were entirely ablated.
Effect of pellet ablated cloud size

We ran several cases varying the ablated cloud size to determine its sensitivity on global quantities $v_p = 1000$ m/s

- Smaller cloud size are much more computationally expensive
  - much smaller time steps
  - more spatial resolution (finer mesh and more toroidal planes)
- The reference case is taken to be $V_t = 0.50$ m (16 planes) and $V_p = 50r_p$.

All cases show both incomplete ablation and TQ

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<table>
<thead>
<tr>
<th>Case</th>
<th># planes</th>
<th>Smallest dt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>12</td>
<td>0.20</td>
</tr>
<tr>
<td>0.50</td>
<td>16</td>
<td>0.20</td>
</tr>
<tr>
<td>0.5(*)</td>
<td>16</td>
<td>0.15</td>
</tr>
<tr>
<td>0.35</td>
<td>16</td>
<td>0.05</td>
</tr>
<tr>
<td>0.25(*)</td>
<td>32</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>0.15</td>
<td>32</td>
<td>&lt; 0.02</td>
</tr>
</tbody>
</table>
Effect of different pellet velocities

- $v_p = 1000$ m/s is does not produce a complete TQ
- We ran a cases with pellet velocities of 500 m/s and 300 m/s.
- Figures are shown as a function of the pellet radial position (not time as previous cases).

- Thermal energy drop is sensitive to the pellet velocity, but
- Even though the central temperature fall is significant, all the cases still show an incomplete thermal quench
NSTX-U: Understanding the central $T_e$ fall

Central temperature as a function of time

- In the next slides we will show Poincare plots and temperature distribution at all these timeslices.
Effect of parallel heat flux, $\kappa_\parallel$

We showed in the AUG-U test that larger parallel heat flux usually led to larger ablation rates.

For bigger pellets, stochastization of the field lines can link the temperature around the pellet position with the boundary temperature.

- This can lead to a reduction of the ablation rate and radiation (Rad) when travelling in the outer region if $\kappa_\parallel$ is large enough.
- Heat flux loss also increases and becomes more important leading to a stronger reduction of the thermal energy (TE).
Carbon pellet disruption mitigation simulations is being conducted for a NSTX-U geometry

- We incorporated a C-ablation model in M3D-C1. Tested in an AUG discharge
- We are completing a convergence study for an NSTX-U geometry
  - We evaluated the sensitivity of different parameters
  - Parallel heat flux and pellet velocity are very important to the TQ
- Single C-pellet injection have shown to produce an incomplete TQ

Moving forward (*)
- Injecting array of C-pellets
- Injecting at a toroidal angle
- Coated pellet. Reduce initial ablation
- Explore other pellet materials
- Simulate an ITER pellet injection

(*) R. Raman, private communication
Modelling pellets in M3D-C1

The ablated material (given by $\dot{N}$) is weighted by the ablated cloud distribution. Spatial distribution for the ablated material is prescribed:

$$S = \frac{1}{(2\pi)^{3/2}V_p^2 V_t} \exp \left[ -\frac{(R - R_p)^2 + (Z - Z_p)^2}{2 V_p^2} - \frac{R R_p (1 - \cos(\varphi - \varphi_p))}{V_t^2} \right]$$

- Thus, the size of the neutral cloud has to be specified ($V_p, V_t$). Limitations arise due to mesh size and number of toroidal planes.
- Smaller cloud sizes require more toroidal planes and smaller time steps.

Example: In NSTX-U $R_{\text{out}} \sim 1.4$ m. Thus, the minimum toroidal neutral cloud size scales roughly as

<table>
<thead>
<tr>
<th># tor. Planes</th>
<th>$V_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$\leq 1.00$ m</td>
</tr>
<tr>
<td>16</td>
<td>$\leq 0.50$ m</td>
</tr>
<tr>
<td>32</td>
<td>$\leq 0.25$ m</td>
</tr>
</tbody>
</table>
KPRAD Coupling in M3D-C1

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}) = D \nabla^2 n_i + \sigma_i \quad \text{(idem } n_Z^{(j)}) \]

\[ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi - \bar{\omega} \mathbf{v} \]

\[ \mathbf{E} = \eta \mathbf{J} - \mathbf{v} \times \mathbf{B} \]

\[ n_e \left[ \frac{\partial T_e}{\partial t} + \mathbf{v} \cdot \nabla T_e + (\Gamma - 1) T_e \nabla \cdot \mathbf{v} \right] + T_e (D \nabla^2 n_e + \sigma_e) = (\Gamma - 1)[\eta]^2 - \nabla \cdot \mathbf{q}_e + Q_e + Q_{\Delta} - \Pi_e \cdot \nabla \mathbf{v} \]

\[ n_* \left[ \frac{\partial T_i}{\partial t} + \mathbf{v} \cdot \nabla T_i + (\Gamma - 1) T_i \nabla \cdot \mathbf{v} \right] + T_i (D \nabla^2 n_* + \sigma_*) = (\Gamma - 1) \left[ -\nabla \cdot \mathbf{q}_* + Q_* - Q_{\Delta} - \Pi_* \cdot \nabla \mathbf{v} + \frac{1}{2} \bar{\omega} \mathbf{v} \right] \]

\( Q_{e,*} \) is the radiation source. It includes line radiation, Bremsstrahlung, recombination.
Case $v_p=300$ m/s