Particle Assimilation during Shattered Pellet Injection

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with J-TEXT\textsuperscript{1}, KSTAR\textsuperscript{2}, DIII-D\textsuperscript{3}, and JET\textsuperscript{4} teams

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Particle assimilation is an important metric for SPI performance

- SPI achieves higher assimilation than equivalent MGI
  - Solid fragments penetrate plasma
  - More instantaneous particle delivery

- Injected particle quantities are typically large
  - JET plasma: $n_e \cdot V \sim 8 \times 10^{21}$ electrons
  - 4.5 mm pellet: $4 \times 10^{21}$ Ne atoms
  - 8 mm pellet: $3 \times 10^{22}$ Ne atoms
  - 12.5 mm pellet: $1 \times 10^{23}$ Ne atoms

- But not all of the injected material is assimilated by plasma
Net particle assimilation can be characterized during the disruption CQ

- **CQ density** is a direct indicator of particle assimilation
  - Strong density asymmetry exists early in the disruption, due to localized particle source and finite spreading of pellet ions
  - But relaxes later on (ablation during CQ is much lower)

- When direct measurements of CQ density are unavailable, $I_p$ decay allows comparison under otherwise similar conditions
  - For high-Z injection, higher assimilation accelerates the CQ

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Asymmetric

Symmetric

Commaux, et al. NF 50 (2010) 112001

DIII-D

Faster $I_p$ decay

Higher assimilation
SPI data from multiple machines contribute to assimilation studies

<table>
<thead>
<tr>
<th></th>
<th>Plasma energy</th>
<th></th>
<th>SPI species</th>
<th>Diagnostics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W_{th}$ (MJ)</td>
<td>$W_{mag}$ (MJ)</td>
<td>Ne</td>
<td>D$_2$</td>
</tr>
<tr>
<td>J-TEXT</td>
<td>~ 0.03</td>
<td>0.05</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>KSTAR</td>
<td>0.3 - 0.5</td>
<td>1.2</td>
<td>✓ ✓ *</td>
<td>✓ ✓ *</td>
</tr>
<tr>
<td>DIII-D</td>
<td>0.1 – 2</td>
<td>1 – 3</td>
<td>✓ ✓ *</td>
<td>✓ ✓ *</td>
</tr>
<tr>
<td>JET</td>
<td>0.5 – 7</td>
<td>4 - 23</td>
<td>✓ ✓ *</td>
<td>✓ ✓ *</td>
</tr>
</tbody>
</table>

Including mixtures

* Ar SPI typically for RE dissipation
Outline of talk

• Experimental scalings
• Modeling of SPI assimilation
• Assimilation of multiple SPIs
• Deuterium SPI
Experimental scalings
Experimental scalings for $n_{CQ}$ have been derived from DIII-D database

- Assimilation can depend strongly on plasma parameters

- Ablation/ionization driven by two energy sources

$$W_{th} \sim \langle nT \rangle V$$
$$W_m \sim L I_p^2$$

- Can fit for regression scaling based on remaining parameters:

$$\bar{n}_{CQ} = C \cdot T_e^{\alpha_T} \cdot \bar{n}_e^{\alpha_n} \cdot W_m^{\alpha_m}$$

CQ density Pre-disruption plasma parameters
Scaling reproduces measured CQ densities throughout database

- Global plasma parameters can reasonably predict the densities achieved by SPI
- A small number of outliers suggest that hidden variables may exist

These disruptions do not have REs
Scaling identifies importance of various energy sources throughout disruption

- Dependence on (pre-disruption) temperature/density are constant throughout CQ
  - These affect the early ablation, but the dependences cannot change after the TQ

- Early in the CQ, density is dominantly determined by electron temperature
  - Expected from pellet ablation physics: \( \dot{N} \sim T_e^{5/3} n_e^{1/3} \)

- Early in the CQ, magnetic energy has little influence, but becomes significant by middle of CQ
  - Ohmic dissipation of poloidal magnetic energy becomes important later in sustaining CQ density

\[
\text{Fit: } n_{\text{CQ}} = C T_e^{\alpha_T} n_e^{\alpha_n} W_m^{\alpha_m}
\]
Additional factors such as penetration depth may play a role in determining assimilation

\[ I_p = 160 \text{ kA}, \quad B_t = 1.8 \text{ T}, \quad a \approx 0.25 \text{ m} \]

Pellet size:

\[ D = 5 \text{ mm}, \quad L \approx 5.5 \text{ mm} \]

The time axis of the AXUV and density signal is based on the shot 1058746.

Pellet velocity (Within a certain range)

Impurity assimilation

Small device size allows significant variation of radial penetration

\[ a/v_{pel} \approx 1 \text{ ms} \]
Modeling of SPI assimilation
SPI shutdown can be simulated using energy balance model

- **KPRAD**\(^{1,2}\) simulates volume-averaged (0D) SPI-plasma interaction

- Electron energy:

  \[
  \frac{\partial W_{th,e}}{\partial t} = -n_e V_p \sum_{j=0}^{Z_{inj}} n_j \Delta S_{rad,j}^{inj} - n_e V_p \sum_{j=0}^{Z_{wall}} n_j \Delta S_{rad,j}^{wall} + \frac{1}{n_e} \sum_{j=0}^{Z_{wall}} n_j \Delta S_{rad,j}^{H} + \left( \frac{2\pi R \eta}{A_p} \right) I_p^2 - \frac{\partial W_{pot}}{\partial t} - \frac{3}{2} n_e V_p \nu_e (T_e - T_i)
  \]

  - **Species/charge-dependent radiation**
  - **Ohmic heating**
  - **Ion collisions**
  - **Ionization/ recombination**

- Ion energy:

  \[
  \frac{\partial W_{th,i}}{\partial t} = \frac{3}{2} n_e V_p \nu_i (T_e - T_i)
  \]

- Charge state populations:

  \[
  \frac{\partial n_j}{\partial t} = n_e (n_{j-1} S_{ion,j-1} + n_{j+1} S_{rec,j+1} + n_j S_{ion,j} - n_j S_{rec,j}) + \left( \frac{\partial n_j}{\partial t} \right)_{source}
  \]

- Plasma/wall circuit:

  \[
  \frac{\partial I_p}{\partial t} = \frac{I_p}{\tau_p} + \alpha L \frac{I_w}{\tau_w}, \quad \frac{\partial I_w}{\partial t} = -\frac{\partial I_p}{\partial t} - I_w/\tau_w
  \]

- Pellet ablation\(^{3}\):

  \[
  G = \lambda(X) \left( \frac{T_e}{2000} \right)^{5/3} \left( \frac{r_p}{0.2} \right)^{4/3} n_{e14}^{1/3}
  \]

  \[
  \dot{r}_p = -G / (4\pi r_p^2 \rho_0)
  \]

- **Species/charge-dependent radiation**
- **Neutral source from SPI ablation**
- **Surface recession**

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\(^3\)P.B. Parks, TSDW (2017) Princeton, NJ
KPRAD simulates entire disruption from TQ to CQ

- Ablation of individual pellet fragments are tracked independently
  - Early fragments undergo more ablation

- Ablation process is self-regulated, with radiation causing plasma cooling which limits ablation

- This TQ leads to subsequent CQ including effects of inductive coupling to vessel wall

- Model calculates total assimilation, while simulated densities, $I_p$ decay can be compared to experiment
KPRAD simulations are in good agreement with DIII-D experiments, despite the 0D model

- Density evolution during the CQ is well matched
- Agreement over a wide range of pre-SPI plasma parameters

- Agreement found over entire Ne SPI database
  - With same outliers from the empirical scalings
- Simulated densities are systematically low by ~25%
Simulations match measured CQ rates across multiple machines

- Pellet compositions can be freely varied based on Ne/D$_2$ mixtures
  - Plasma parameters are held constant
- A version of this experiment has been carried out on KSTAR, DIII-D, and JET
KPRAD simulations yield typical assimilation rates

- Pellets with higher neon content have lower assimilation rate
  - Radiative cooling limits ablation

- Total neon assimilation $\sim (\text{Ne }\%) \times \text{(Assimilation fraction)}$
  so higher Ne% still leads to faster CQ

- These assimilation fractions are in agreement with more advanced extended MHD simulations

Range of net assimilation rates: (depending on mixture)

- 3 to 26%
  - KSTAR $W_n = 0.5 \text{ MJ}, I_p = 0.8 \text{ MA}$
    - 7 mm pellet
  - Experiment
  - Simulation

- 5 to 42%
  - DIII-D $W_n = 0.8 \text{ MJ}, I_p = 1.3 \text{ MA}$
    - 7 mm pellet

- 12 to 90%
  - JET $W_n = 4.0 \text{ MJ}, I_p = 2.5 \text{ MA}$
    - 8 mm pellet

$>4$ to 58% assimilation

DIII-D NIMROD Simulations
Assimilation of multiple SPIs
Multiple SPIs will be required for large injection quantities in ITER

- Multiple SPI capabilities currently exist on two devices

**KSTAR:** 180° apart toroidally

**DIII-D:** 120° apart toroidally
Simulations reproduce dual SPI trend observed in DIII-D

- Trend: Presence of second pellet ($\Delta t=0$) reduces Ne assimilation and slows CQ

- Pellet 1: 7 mm with 100% Ne
- Pellet 2: 7 mm with 2.4% Ne

- Pellet mixtures are different, so second SPI lowers the total Ne/D$_2$ ratio
  $\Rightarrow \Delta t=0$ has less Ne assimilation and slower CQ

- Model is successful despite 0D simulation not accounting for SPI locations
  – 3D effects not likely to be important

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**Simulation**

- Assimilated Ne [Pam$^{-1}$]
- Normalized CQ duration [ms/m$^2$]
- Reduction in TQ radiation

**Experiment**

- Measured TQ radiation
- Slowing in CQ duration

Simulations reproduce dual SPI trend observed in KSTAR

- Trend: Presence of second pellet ($\Delta t=0$) accelerates CQ

- Pellet 1: 7 mm with 5% neon
- Pellet 2: 7 mm with 5% neon

- Both pellets are identical, so Ne/D$_2$ ratio does not depend on timing
  $\Rightarrow$ $\Delta t=0$ assimilates more Ne leading to faster CQ

- Model is successful despite 0D simulation not accounting for SPI locations (i.e. 180° apart)
  - 3D effects not likely to be important
Deuterium SPI
KPRAD does not fully capture the physics of D₂ SPI

- DIII-D 16 mm pellet: $N_{SPI}/N_{plasma} = 420$
  - Good estimate of total assimilation
  - CQ rate does not match experiment (i.e. $T_e$ and resulting plasma resistivity)

- DIII-D 7 mm pellet: $N_{SPI}/N_{plasma} = 17$
  - Simulation does not produce disruption
  - In absence of radiative collapse, model has insufficient physics (e.g. MHD)
Some experimental characterization of D$_2$ SPI assimilation is available

- Assimilation studies with 16 mm pellets in DIII-D were carried out

- Measured assimilation fractions were not a strong function of plasma thermal energy

- Densities were determined using VB emission, but are lower bound estimates due to signal saturation

Commaux et al., NF 51 (2011) 103001
Summary

• Empirical scalings successfully match measured CQ densities in large DIII-D database
  – Electron temperature is dominant parameter affecting assimilation, with Ohmic heating becoming important later in CQ for sustaining the density
  – Suggests global energy balance plays a large role in determining assimilation rates

• KPRAD simulations match measurements in KSTAR, DIII-D, and JET
  – Reproduce CQ rates and densities, for a range of plasma parameters, pellet compositions
  – MHD effects are not considered in these simulations, implying lesser importance
  – Typical assimilation rates for moderate pellet sizes (~7 mm) are: ~10% for Ne SPI, or several times higher for mixtures (26 to 90%)

• Dual SPI results on DIII-D and KSTAR can be explained by KPRAD simulations
  – Suggests 3D effects are not as important as total species mixture

• D₂ SPI assimilation is more difficult to model
  – More complete physics model required in absence of radiative collapse
  – (Analysis of MHD signals, consideration of sputtered impurities are ongoing)