Particle Assimilation during Shattered Pellet Injection

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[1] Author list: https://conferences.iaea.org/event/214/contributions/17452/
[2] Author list: https://conferences.iaea.org/event/214/contributions/17095/
[3] Author list: https://conferences.iaea.org/event/214/contributions/17094/
[4] Author list: https://conferences.iaea.org/event/214/contributions/17092/

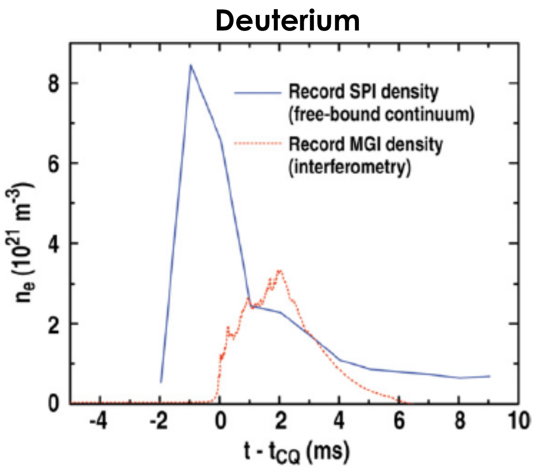
Particle assimilation is an important metric for SPI performance

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

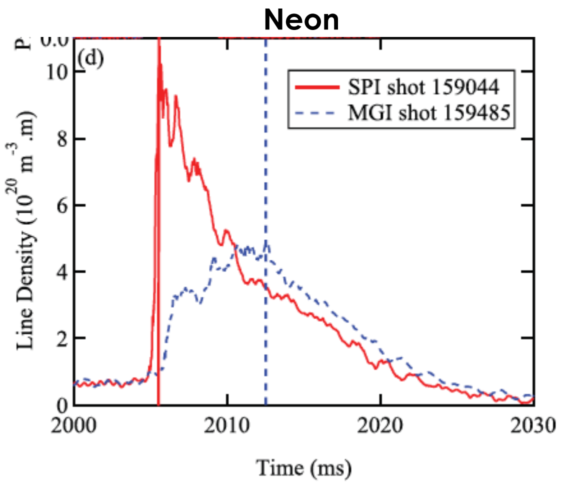
- Injected particle quantities are typically large
  - JET plasma: $n_e \bullet V$ ~ 8×10^{21} electrons

4.5 mm pellet:	4×10^{21} Ne atoms
8 mm pellet:	3×10^{22} Ne atoms
12.5 mm pellet:	1×10^{23} Ne atoms

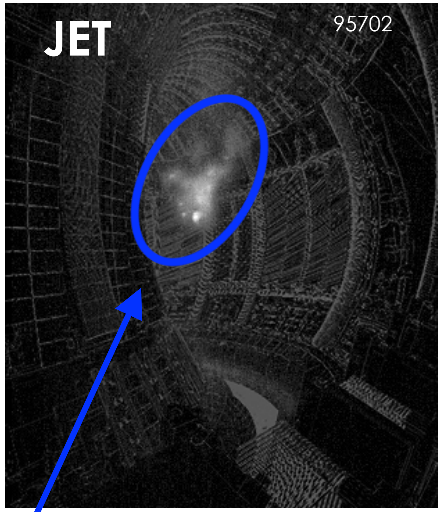
- But not all of the injected material is assimilated by plasma



Commaux, et al. NF 50 (2010) 112001



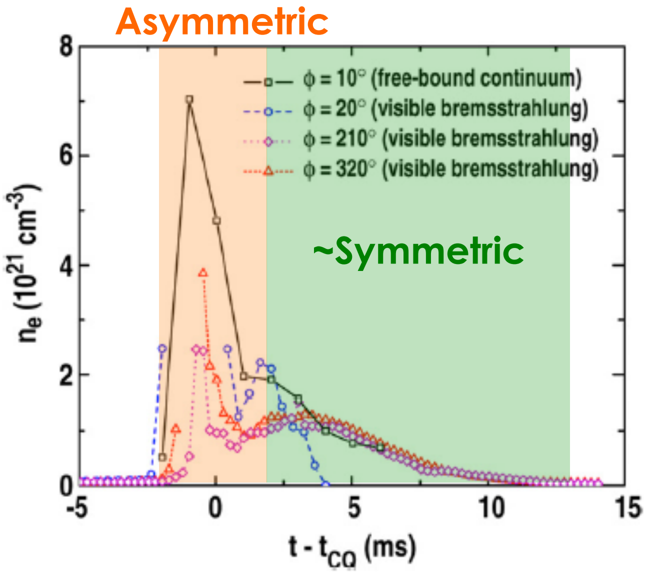
Commaux, et al. NF 56 (2016) 046007



Unassimilated fragments (traveling ballistically through plasma)

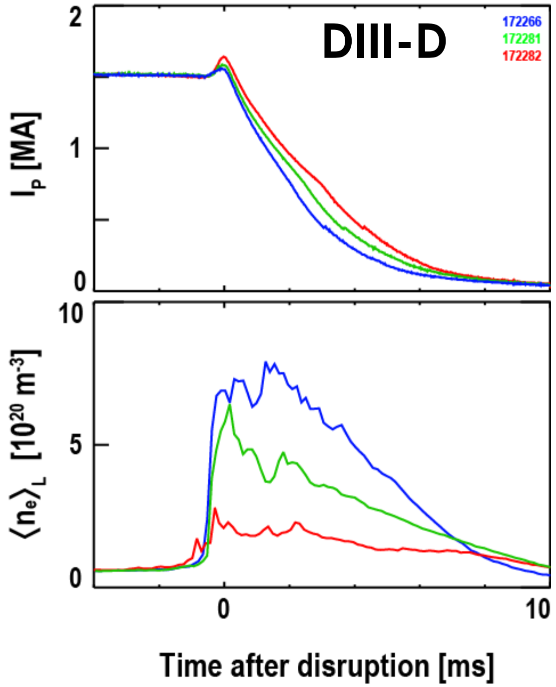
Net particle assimilation can be characterized during the disruption CQ

- **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)



Commaux, et al. NF 50 (2010) 112001

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



Faster I_p decay

=

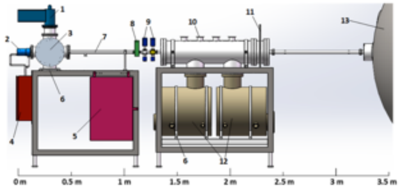
Higher assimilation

SPI data from multiple machines contribute to assimilation studies

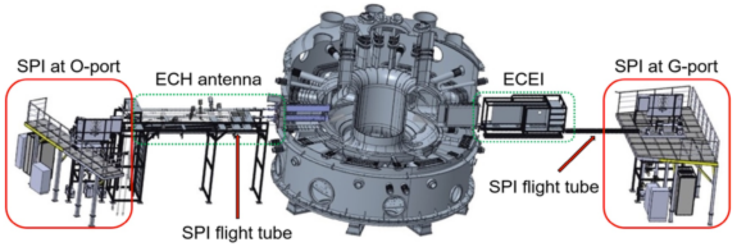
	Plasma energy		SPI species			Diagnostics	
	W_{th} (MJ)	W_{mag} (MJ)	Ne	D_2	Ar	CQ n_e	CQ I_p
J-TEXT	~ 0.03	0.05			✓	✓	✓
KSTAR	0.3 - 0.5	1.2	✓	✓	*	✓	✓
DIII-D	0.1 – 2	1 – 3	✓	✓	*	✓	✓
JET	0.5 – 7	4 - 23	✓	✓	*		✓

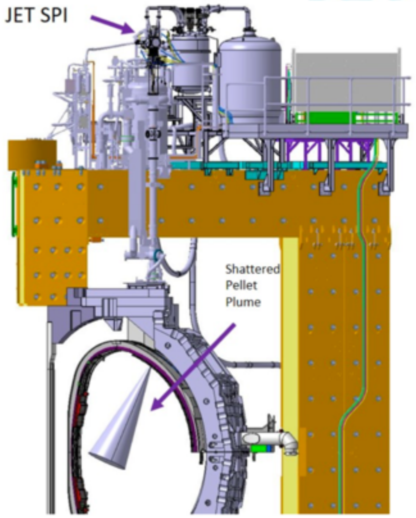
Including mixtures

* Ar SPI typically for RE dissipation



J-TEXT





Outline of talk

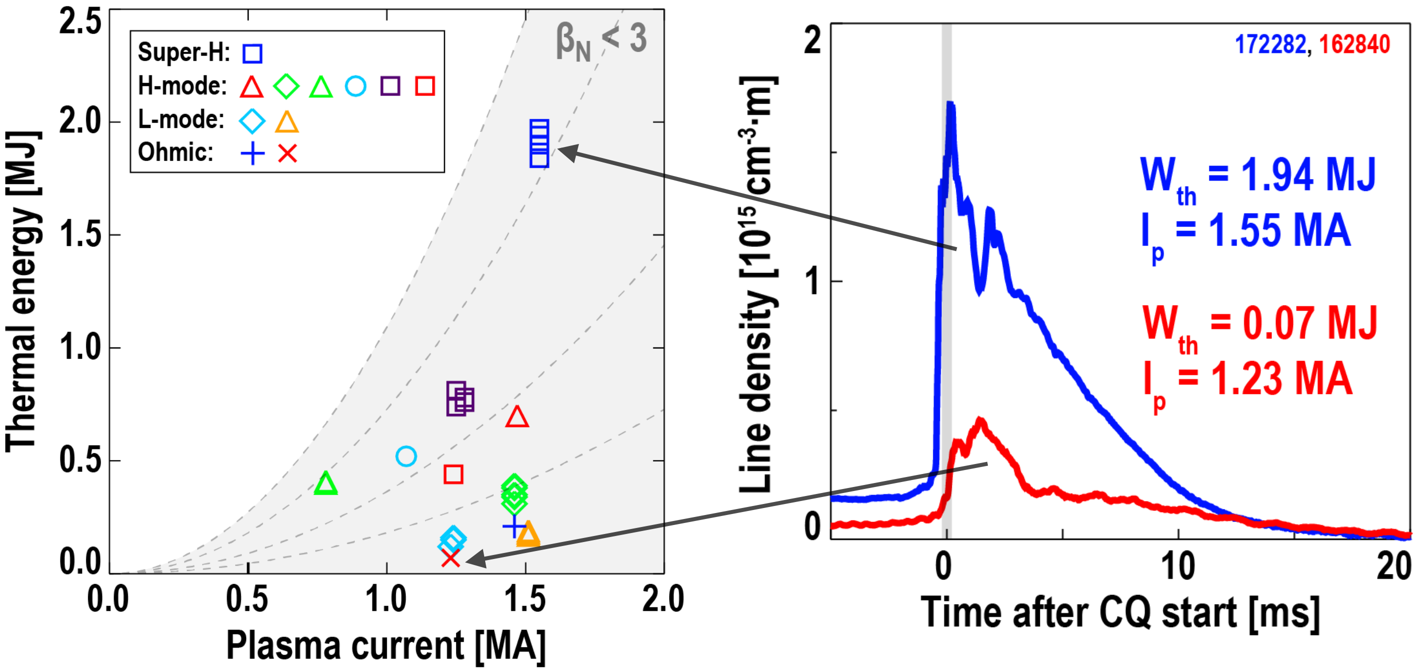
- Experimental scalings
- Modeling of SPI assimilation
- Assimilation of multiple SPIs
- Deuterium SPI

Experimental scalings

Experimental scalings for n_{CQ} have been derived from DIII-D database

- Assimilation can depend strongly on plasma parameters

7 mm Ne SPI database



- Ablation/ionization driven by two energy sources

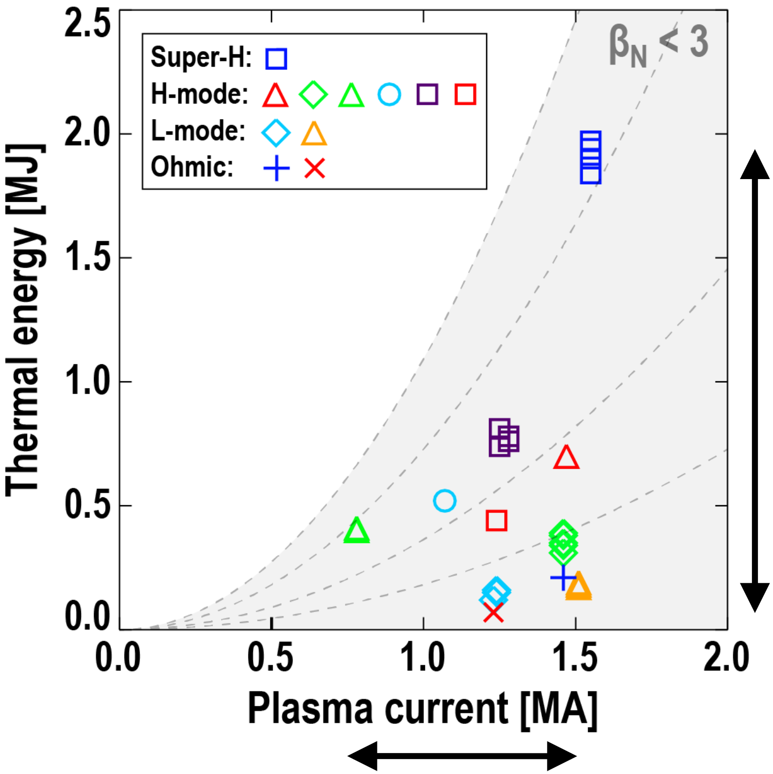
$$\left.\begin{aligned} W_{\mathrm{th}} &\sim \langle nT\rangle V \\ W_{\mathrm{m}} &\sim L I_{\mathrm{p}}^2 \end{aligned}\right\}$$

Constant geometric factors (Ignorable)

- Can fit for regression scaling based on remaining parameters:

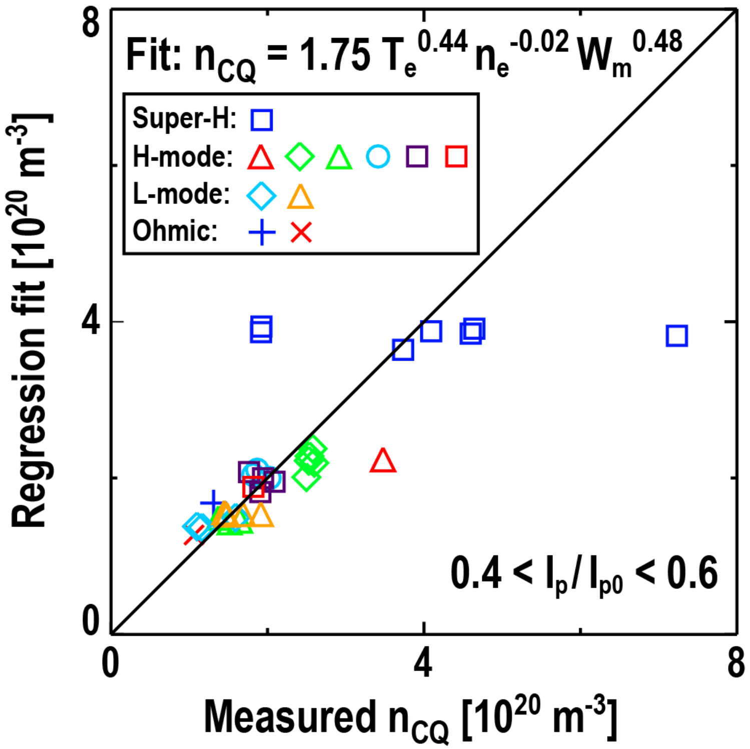
$$\underbrace{\bar{n}_{\mathrm{CQ}}}_{\textbf{CQ density}} = C \cdot \underbrace{T_{\mathrm{e}}^{\alpha_T} \cdot \bar{n}_{\mathrm{e}}^{\alpha_n} \cdot W_{\mathrm{m}}^{\alpha_{\mathrm{m}}}}_{\textbf{Pre-disruption plasma parameters}}$$

Scaling reproduces measured CQ densities throughout database



×20 change in thermal energy

×4 change in magnetic energy

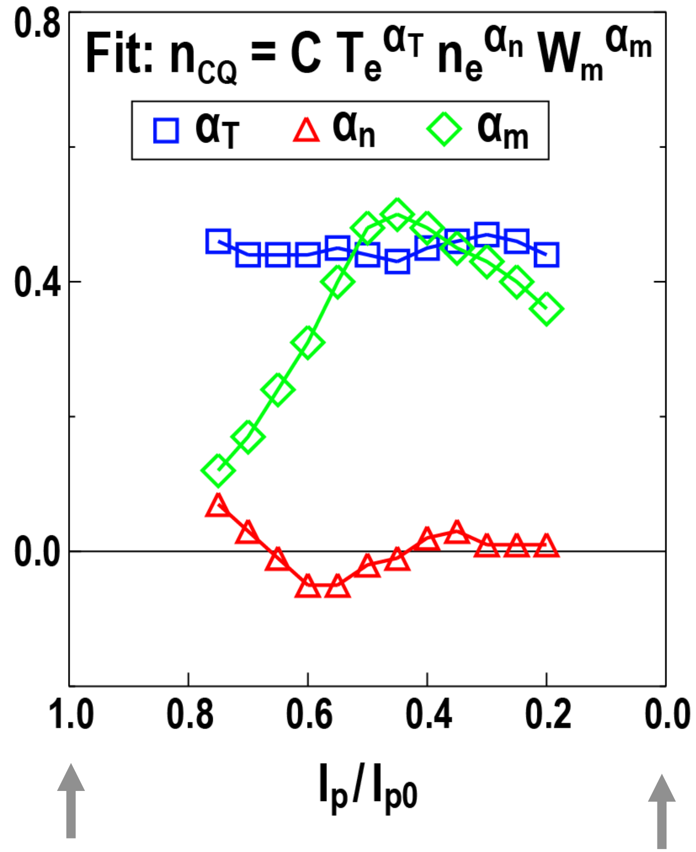


These disruptions do not have REs

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

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



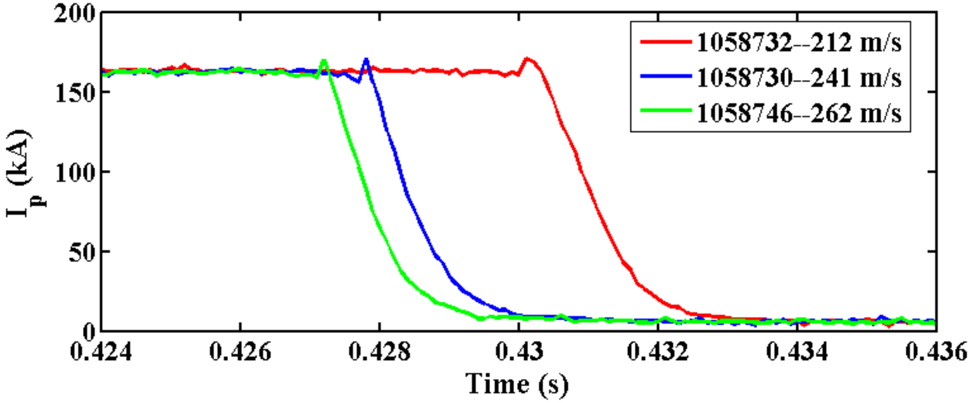
Beginning of CQ

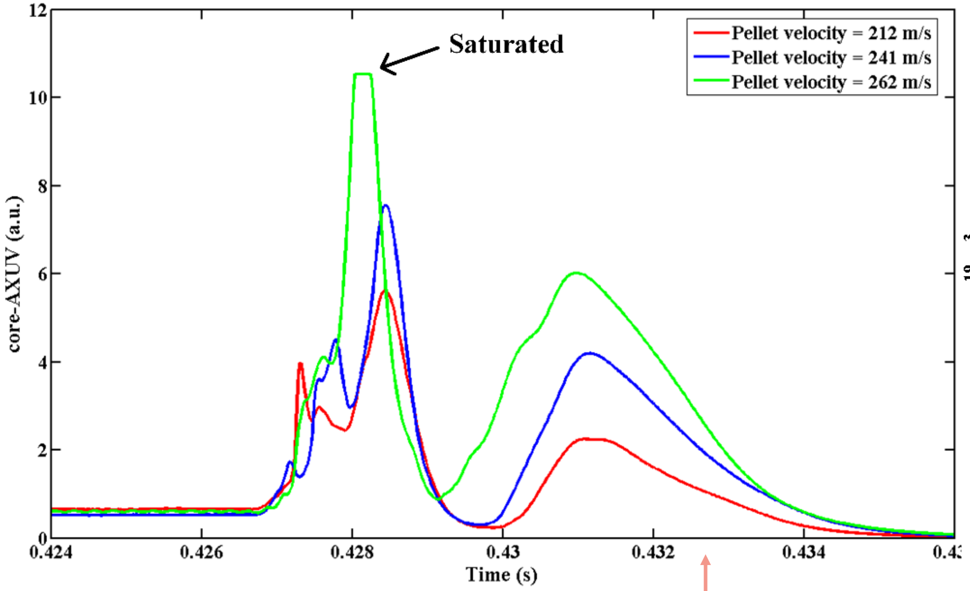
End of CQ

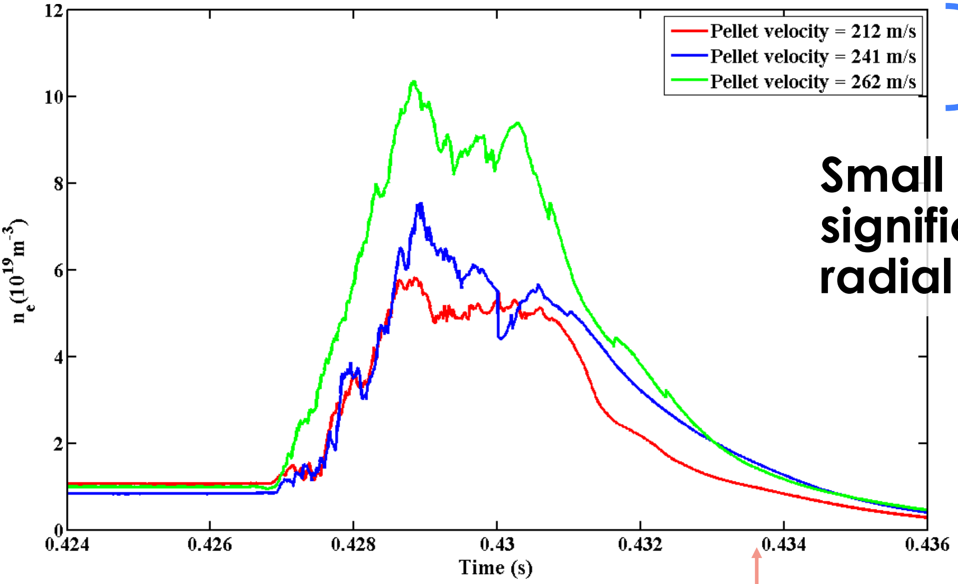
Additional factors such as penetration depth may play a role in determining assimilation

I_p=160 kA, B_t=1.8 T, a ~ 0.25 m
Pellet size：
D= 5 mm, L =~5.5 mm

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







a/v_{pel} ~ 1 ms

Small device size allows significant variation of radial penetration

Pellet velocity
(Within a certain range)

Impurity assimilation

J-TEXT

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:

$$\frac{\partial W_{th,e}}{\partial t} = \underbrace{-n_e V_p \sum_{j=0}^{Z_{inj}} n_j^{inj} S_{rad,j}^{inj} - n_e V_p \sum_{j=0}^{Z_{wall}} n_j^{wall} S_{rad,j}^{wall} - n_e V_p \sum_{j=0}^{1} n_j^{H} S_{rad,j}^{H}}_{\textbf{Species/charge-dependent radiation}} + \overbrace{\left(\frac{2\pi R\eta}{A_p}\right) I_p^2}^{\textbf{Ohmic heating}} - \underbrace{\frac{\partial W_{pot}}{\partial t}}_{\substack{\textbf{Ionization/}\\ \textbf{recombination}}} - \overbrace{\frac{3}{2} n_e V_p \bar{\nu}_{ei} \left(T_e - T_i\right)}^{\textbf{Ion collisions}}$$

- Ion energy: $\frac{\partial W_{th,i}}{\partial t} = \frac{3}{2} n_e V_p \bar{\nu}_{ei} \left(T_e - T_i\right)$

Ionization **Recombination** **Neutral source from SPI ablation**

- Charge state populations: $\frac{\partial n_j}{\partial t} = n_e \left(n_{j-1} S_{ion,j-1} + n_{j+1} S_{rec,j+1} - n_j S_{ion,j} - n_j S_{rec,j}\right) + \left(\frac{\partial n_j}{\partial t}\right)_{source}$

- Plasma/wall circuit: $\frac{\partial I_p}{\partial t} = -\frac{I_p}{\tau_p} + \alpha_L \frac{I_w}{\tau_w} \quad , \quad \frac{\partial I_w}{\partial t} = -\frac{\partial I_p}{\partial t} - \frac{I_w}{\tau_w}$

- Pellet ablation[3]: $\underbrace{G = \lambda(X)\left(\frac{T_e}{2000}\right)^{5/3}\left(\frac{r_p}{0.2}\right)^{4/3} n_{e14}^{1/3}}_{\textbf{Species-dependent ablation}} \qquad \underbrace{\dot{r}_p = -G/(4\pi r_p^2 \rho_0)}_{\textbf{Surface recession}}$

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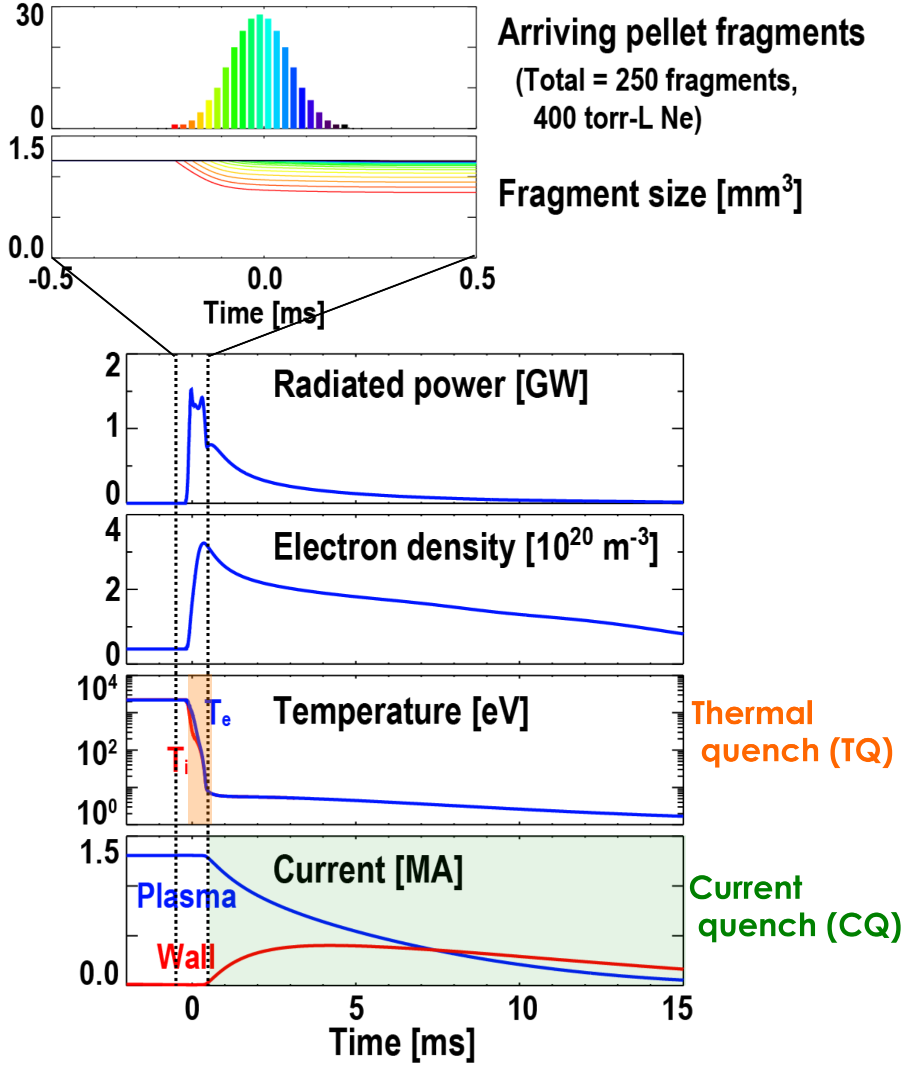
[1] D.G. Whyte et al. J. Nucl. Mater. **313** (2003) 1239
[2] E.M. Hollmann et al. Contrib. Plasma Phys. **48** (2008) 260
[3] P.B. Parks, TSDW (2017) Princeton, NJ

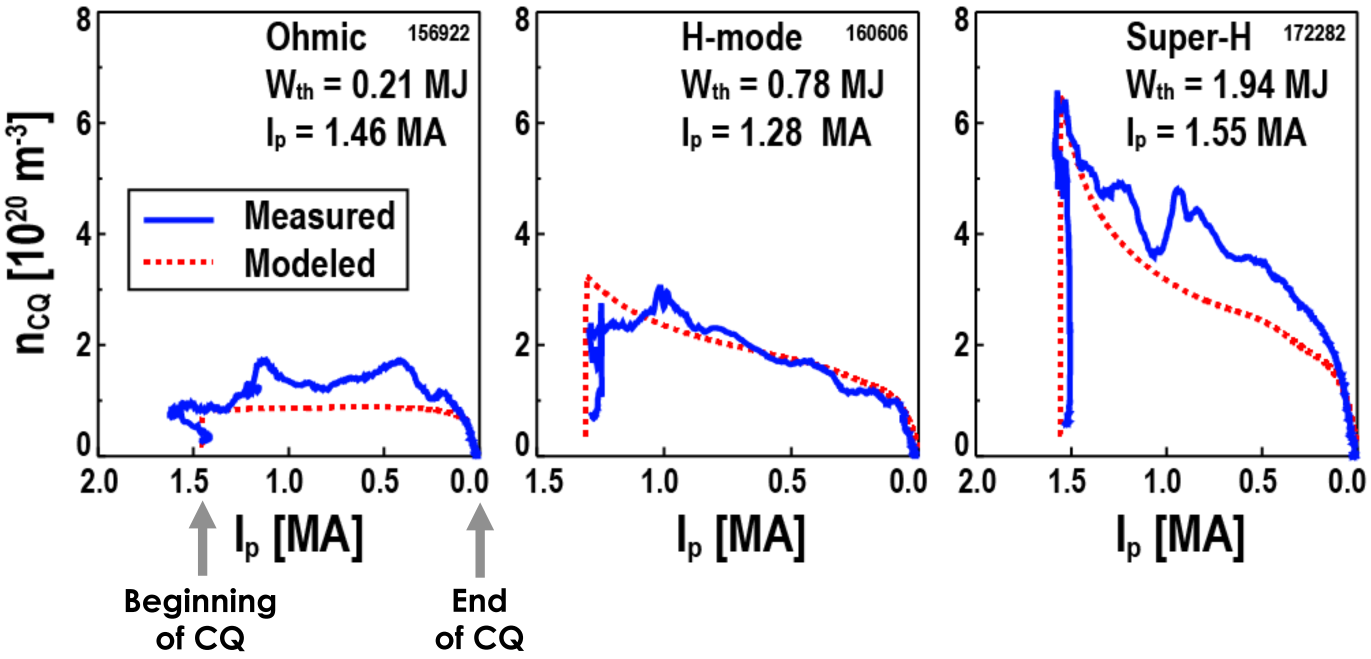
KPRAD simulates entire disruption from TQ to CQ

- 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

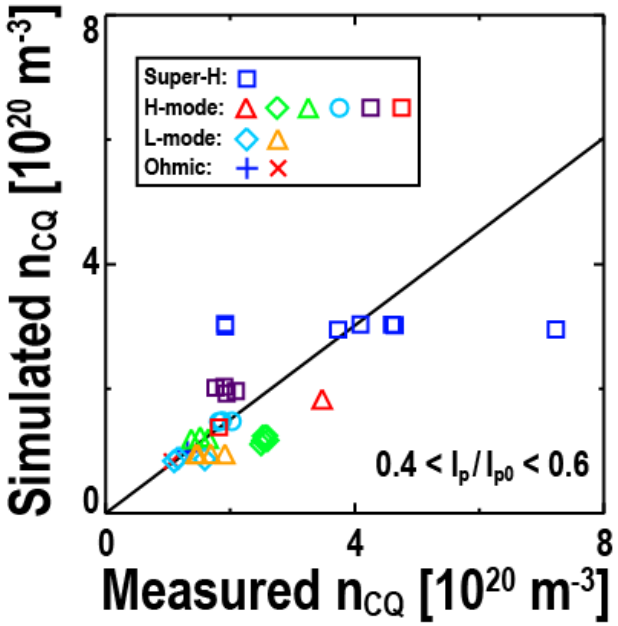
Example: 7 mm Ne SPI in DIII-D H-mode plasma



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

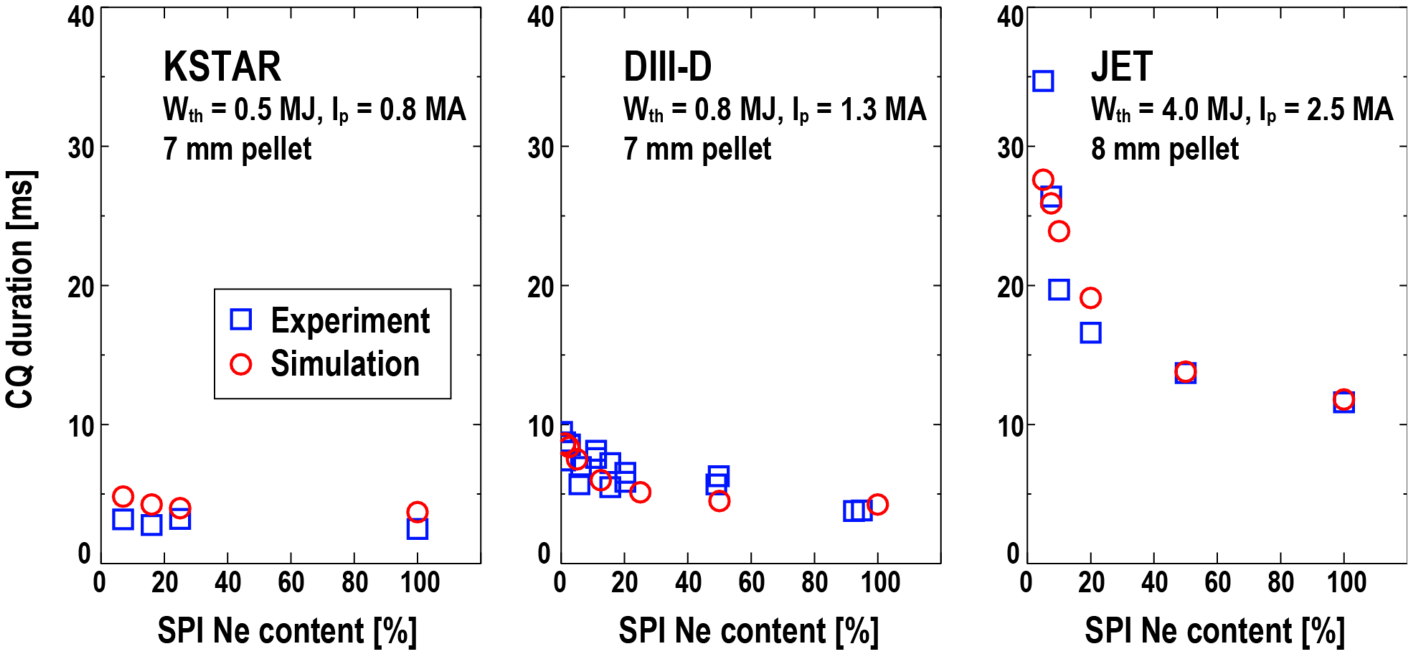


- Agreement found over entire Ne SPI database
  - With same outliers from the empirical scalings
- Simulated densities are systematically low by ~25%

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

Range of net assimilation rates:
(depending on mixture)

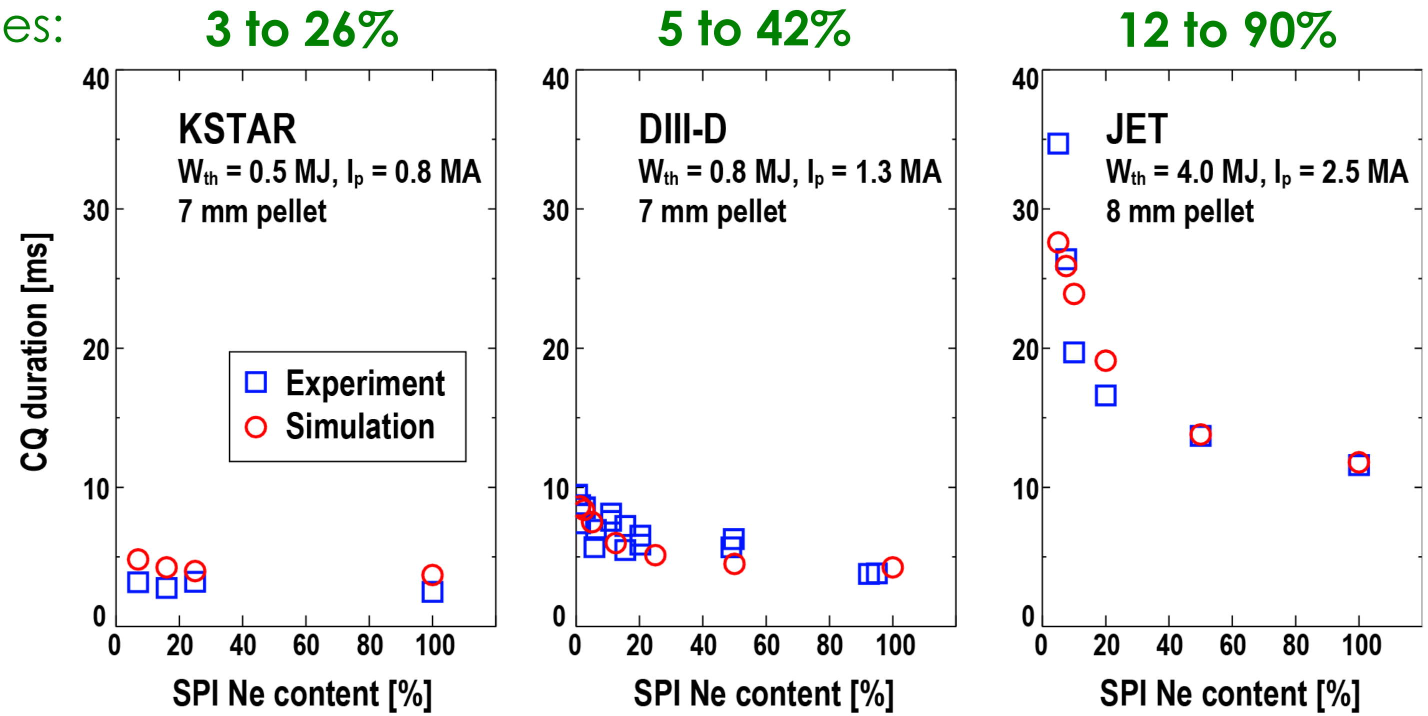
- Pellets with higher neon content have lower assimilation rate
  - Radiative cooling limits ablation

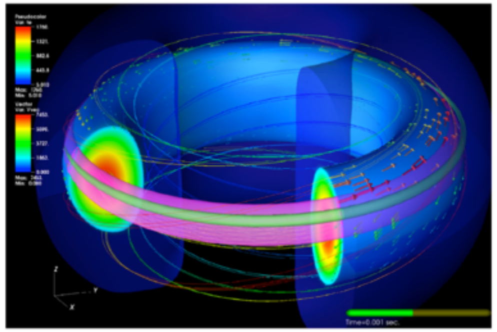
- Total neon assimilation ~

  (Ne %) × (Assimilation fraction)

  so higher Ne% still leads to faster CQ

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





C. Kim et al., PoP 26 (2019) 042510

>4 to 58% assimilation

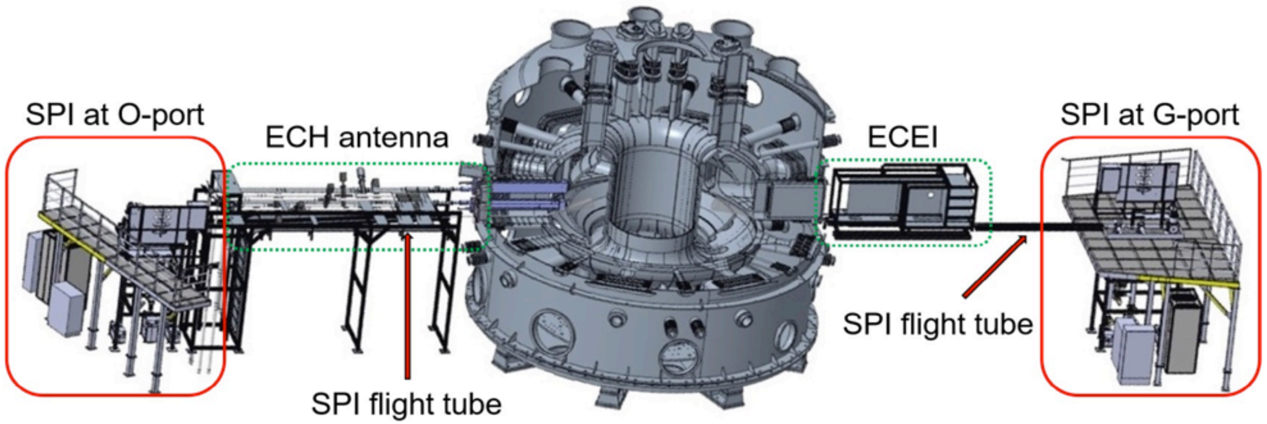
DIII-D NIMROD
Simulations

Assimilation of multiple SPIs

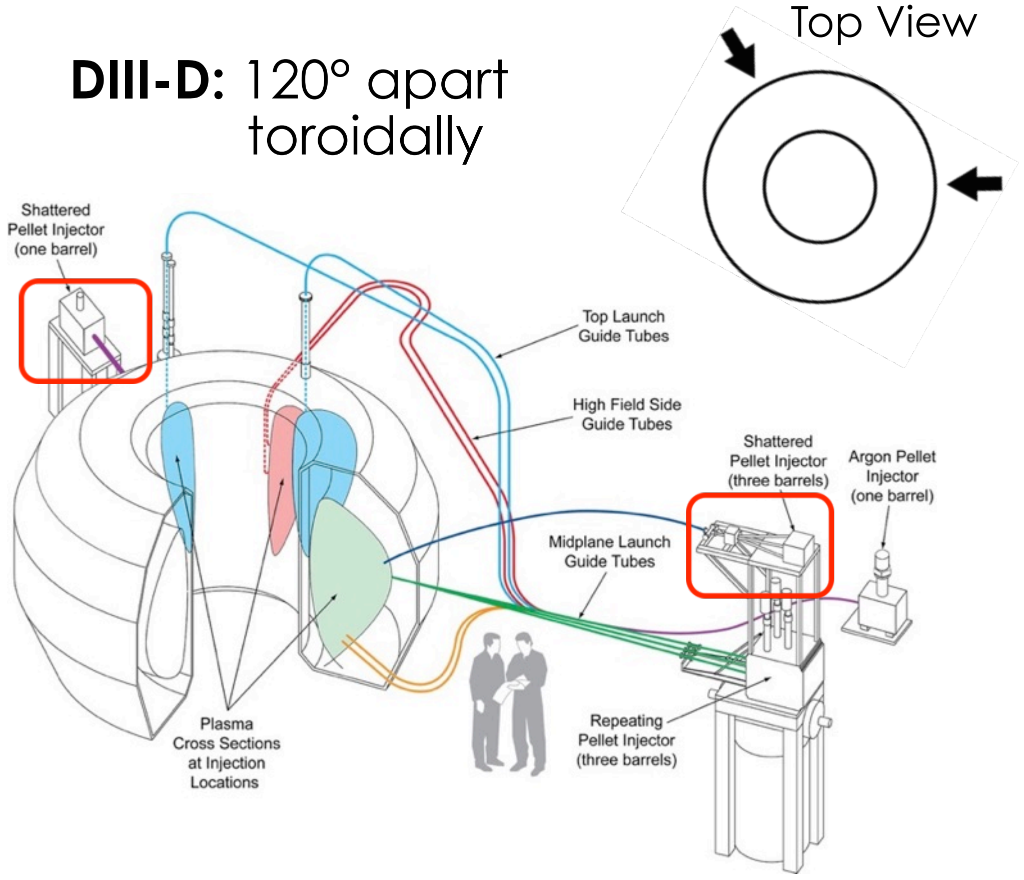
Multiple SPIs will be required for large injection quantities in ITER

- Multiple SPI capabilities currently exist on two devices

KSTAR: 180° apart toroidally

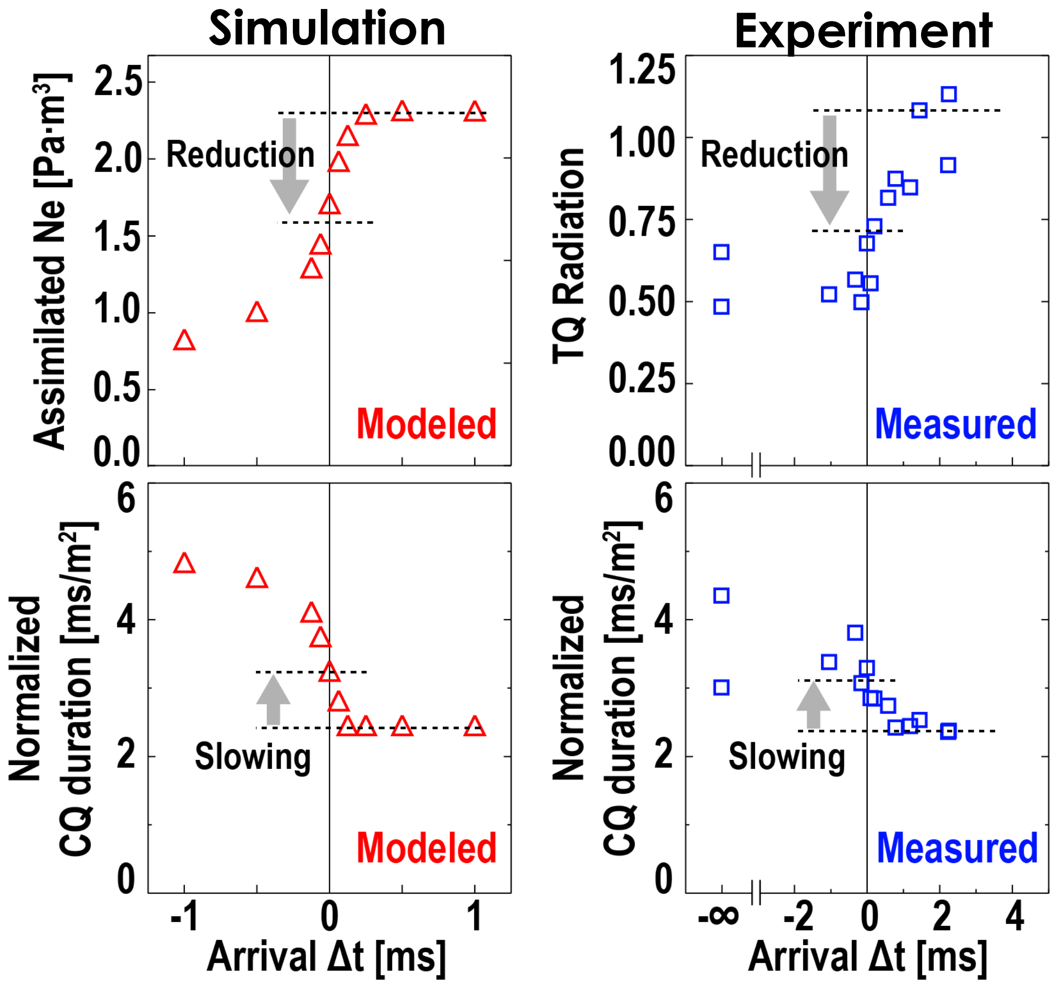


DIII-D: 120° apart toroidally



Simulations reproduce dual SPI trend observed in DIII-D

- Trend: Presence of second pellet (Δt=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
  → Δt=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



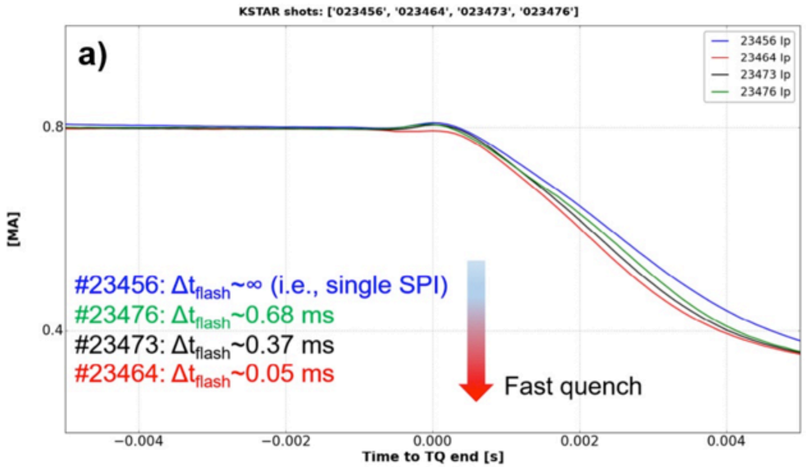
Simulations reproduce dual SPI trend observed in KSTAR

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

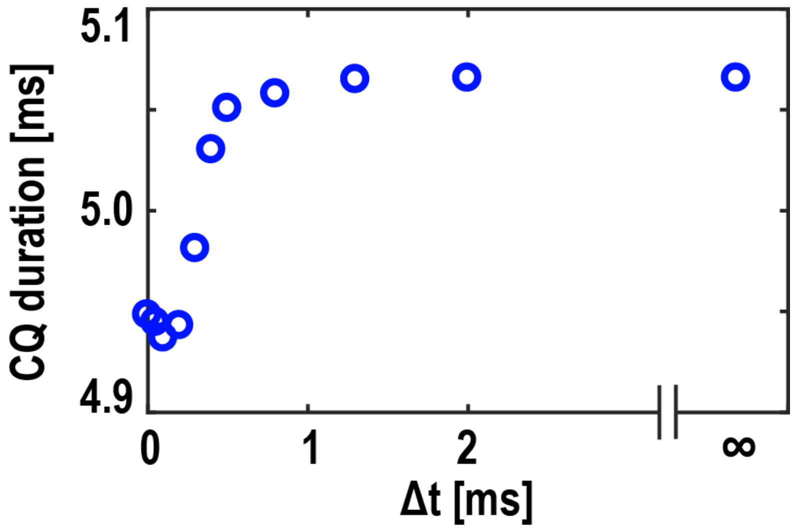
- Pellet 1: 7 mm with 5% neon
- Pellet 2: 7 mm with 5% neon

- Both pellets are identical, so Ne/D_2 ratio does not depend on timing
  → $\Delta t=0$ 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



Experiment

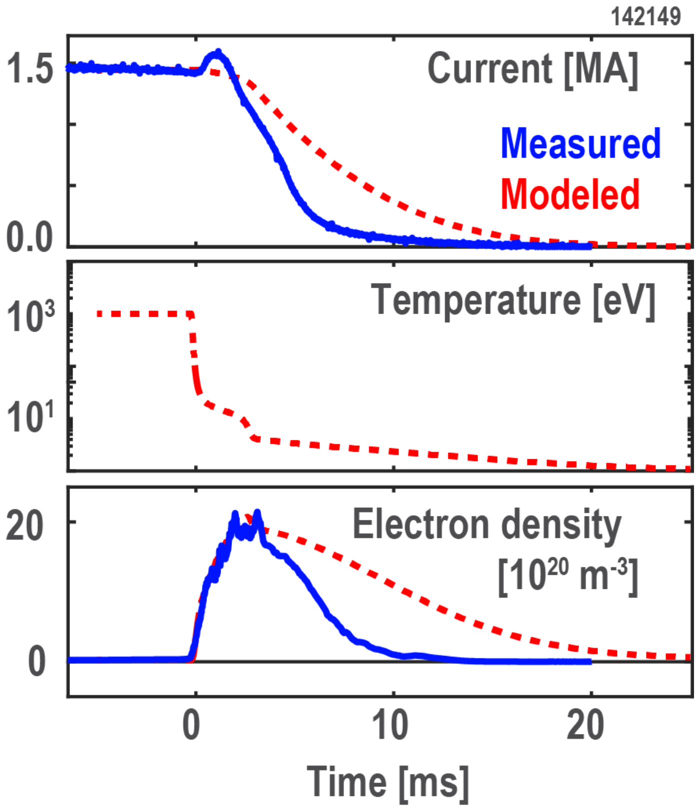


Simulation

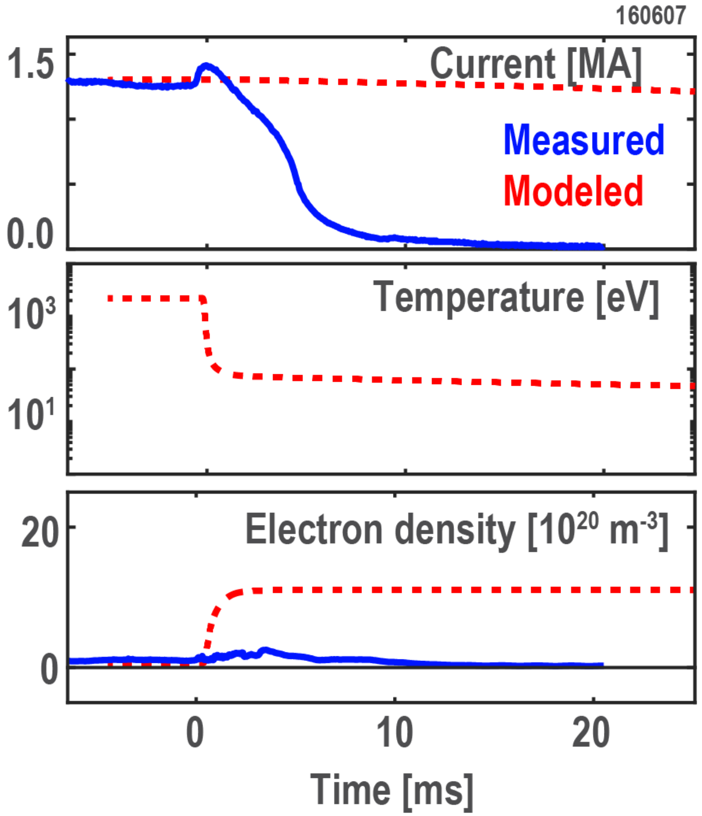
Deuterium SPI

KPRAD does not fully capture the physics of D_2 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)

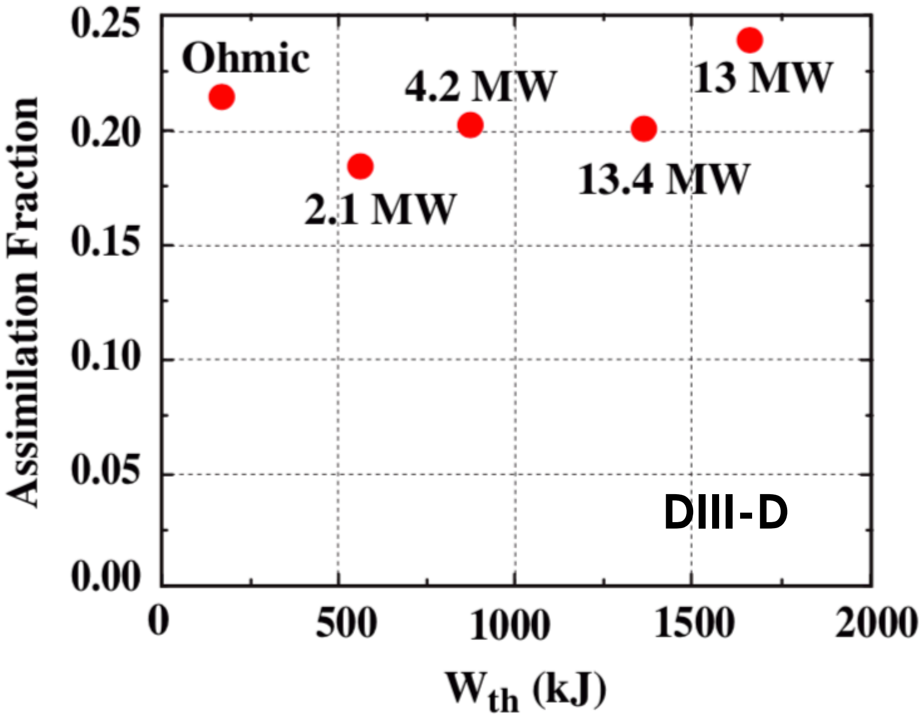


- DIII-D 7 mm pellet: N_{SPI}/N_{plasma} = 17
  - Simulation does not produce disruption
  - **In absence of radiative collapse, model has insufficient physics** (e.g. MHD)



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
- D_2 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)