Extended-MHD simulations of disruption mitigation in SPARC using massive gas injection*

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*Work supported by Commonwealth Fusion Systems and by the US Department of Energy under contract DE-AC0204CH11466. This work was funded under the INFUSE program - a DOE SC FES private-public partnership.

Outline

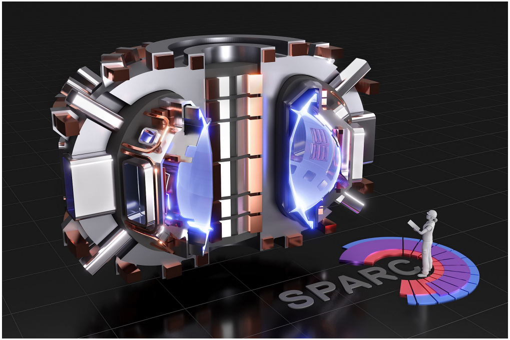
1. Motivation & Goals
2. Physical model & simulation setup
3. Preliminary Results
4. Summary & Outlook

SPARC is a compact high-field tokamak projected to reach $Q > 1$

- SPARC follows high field path to fusion energy using HTS magnets
- D-T fusion
- First plasma planned for 2025

Some device parameters:

$$
\begin{aligned}
B_T &= 12.2\,\mathrm{T} \\
I_p &= 8.7\,\mathrm{MA} \\
R_0 &= 1.85\,\mathrm{m} \\
a &= 0.57\,\mathrm{m}
\end{aligned}
$$



[T. Henderson, CFS/MIT-PSFC]

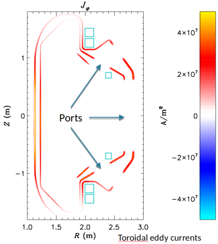
Inform SPARC MGI layout about ideal injector configuration for disruption mitigation

- SPARC will use massive gas injection (MGI) for disruption mitigation
- Injection of impurities can mitigate disruptions by radiating parts of the stored energy
- How do MGI parameters (injection rate, location & number of injectors) affect heat loads, thermal quench (TQ) time, toroidal peaking factor, wall forces, etc.?

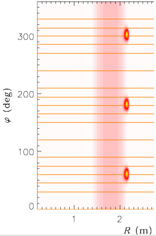
Outline

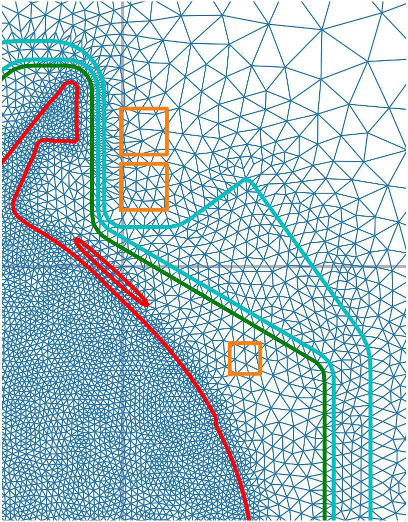
Modeling massive gas injection in SPARC with M3D-C1

- M3D-C1 uses integrated model
  - **Extended-MHD** for mascroscopic evolution of disruption dynamics
  - **KPRAD** [Whyte et al. (1997)] models ionization, recombination and radiation
- **Spatially resolved conducting elements** inside wall modeled with realistic resistivities
  Note: *Passive plates were removed from SPARC design*
- **Anisotropic resistivity** to represent ports
- **Fully 3D** with mesh toroidally packed around injectors



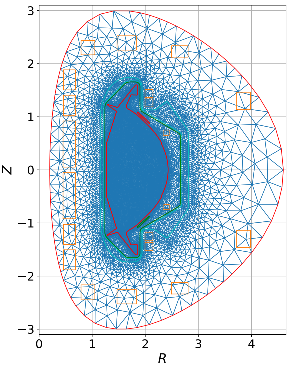
Toroidal eddy currents





M3D-C1 extended-MHD model

- Non-linear extended-MHD initial value stability code
  [Jardin et al., Comput. Sci. Discov. **5** 014002, 2012]
  [Ferraro et al., Phys. Plasmas **23** 056114, 2016]
- C^1 (quintic) finite element mesh
- Extended-MHD region beyond LCFS, resistive wall, vacuum region
- Single-fluid model, Spitzer resistivity ($S \sim 10^9$)



$$\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) = \Sigma \qquad \text{with } \Sigma := \sigma + D\nabla^2 n$$

$$nm_i\left(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u}\right) = \vec{J}\times\vec{B} - \nabla p - \nabla\cdot\Pi + \vec{F} - m\vec{v}\Sigma$$

$$\frac{\partial p}{\partial t} + \vec{u}\cdot\nabla p + \Gamma p\nabla\cdot\vec{u} = (\Gamma - 1)\left[Q - \nabla\cdot\vec{q} + \eta J^2 - \vec{u}\cdot\vec{F} - \Pi : \nabla u - \frac{1}{2}mv^2\Sigma\right]$$

$$\vec{E} = -\vec{u}\times\vec{B} + \eta\vec{J} \quad , \quad \vec{J} = \frac{1}{\mu_0}\nabla\times\vec{B} \quad , \quad \frac{\partial\vec{B}}{\partial t} = -\nabla\times\vec{E}$$

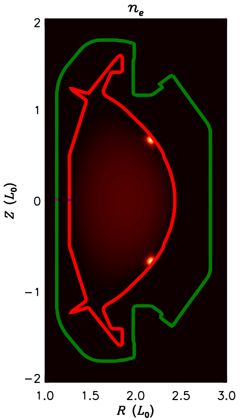
KPRAD provides model for atomic physics

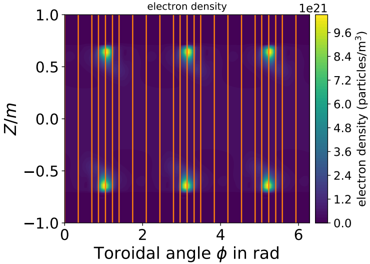
- Coronal equilibrium not assumed
- Ionization and recombination determine impurity charge state evolution
- Radiation rates L_k taken from ADPAK database ($P_{rad,k} = n_k n_e L_k$)
- Impurity (Ne) is injected at zero temperature and brought to T_i upon ionization
- Loss of thermal energy due to ionization, line radiation, bremsstrahlung, recombination radiation
- Subcycling much faster than MHD time step

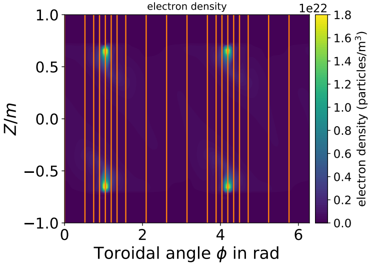
[Whyte et al., Proc. of 24th European Conference on Controlled Fusion and Plasma Physics, vol. **21A**, p. 1137, 1997]
[Ferraro et al, Nucl. Fusion **59** 016001, 2019]

SPARC MGI simulation setup

- Up to 6 different injectors
  - Up-down symmetric: 6, 4, 2
  - Asymmetric: 5, 1
- Injected gas is mixture of **neutral Ne and ionized D** (1:10 ratio) with Gaussian shape and toroidally localized
- Total injection rate: 7.5×10^{23} Ne/s for 6 injectors
  - Rate per injector is held constant
  - Number of injected particles scales with number of injectors



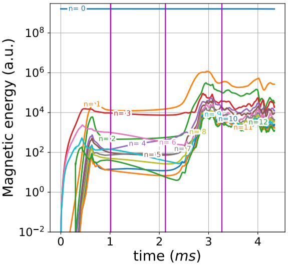




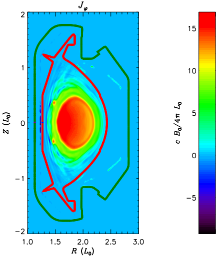
Outline

Shown here: 6 injector case

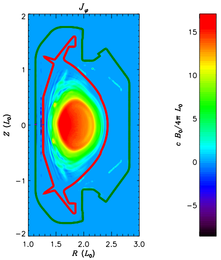
- MGI triggers low-n edge modes
- SPARC baseline case exhibits sawtooth, but no core radiation in early phase
- This is followed by stochastization of core



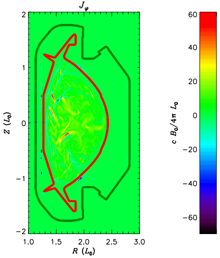
Pre-TQ



Early TQ

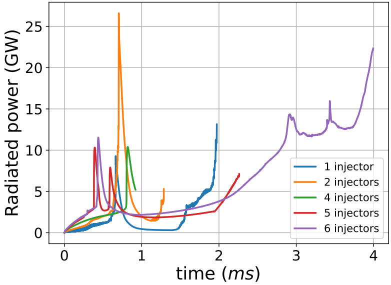


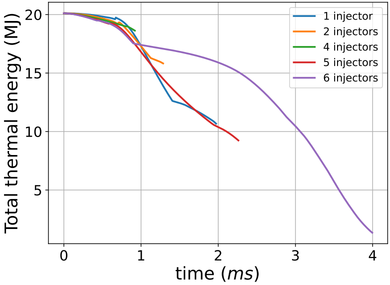
Late TQ



Evolution of radiated power and thermal energy

- Impurity is injected at $t = 0$

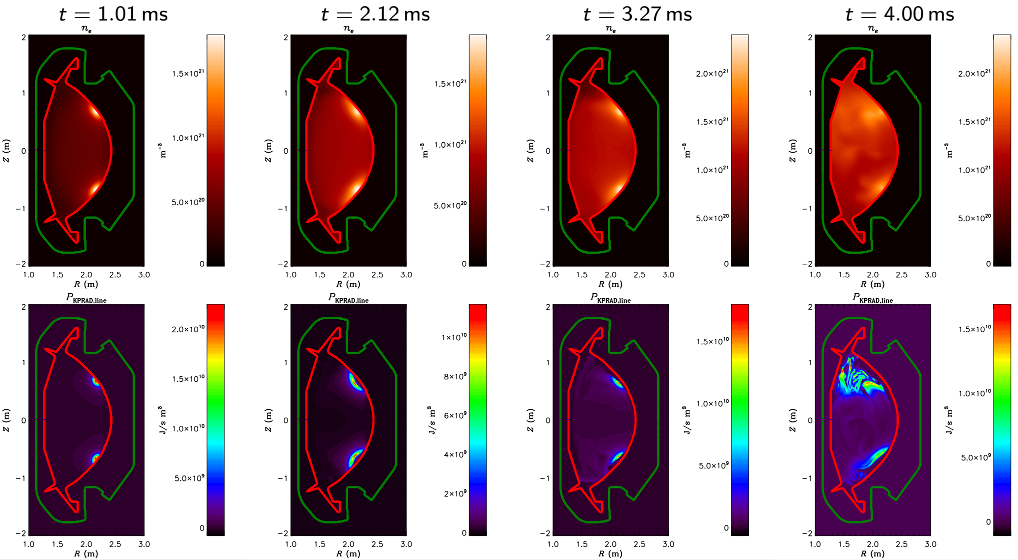




- Thermal energy W_{th} decreases due to radiation and conduction (sensitive to κ and D)
- In pre-TQ Loss of W_{th} scales with number of injectors
- With 1 injector TQ happens earlier than in 6 injector case
- Spikes of radiation occur in all cases during pre-TQ phase
- Simulations still in progress

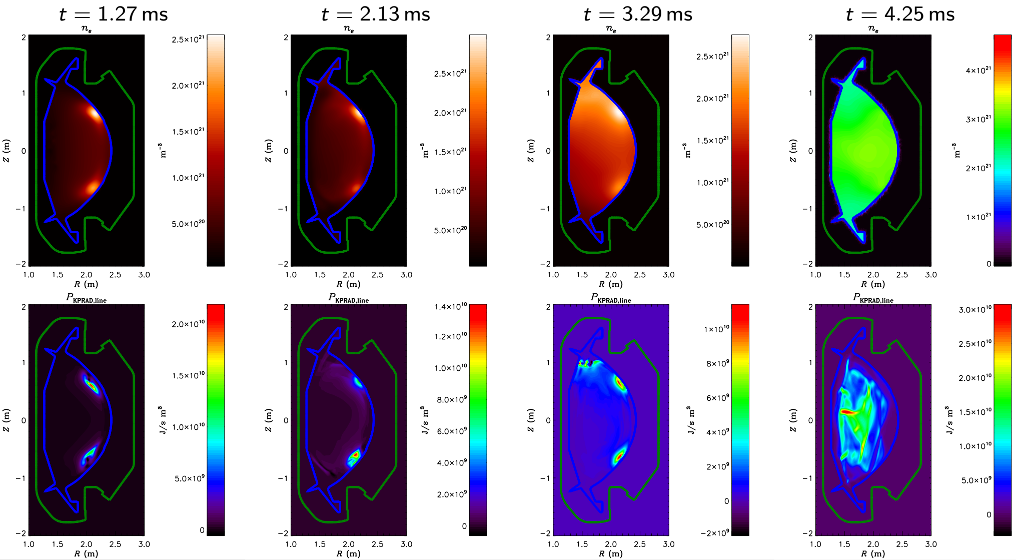
Radiation remains mostly localized near edge and injector sites

Shown here: **6 injector case**



Radiation remains mostly localized near edge and injector sites

Shown here: **2 injector case**



Radiation peaking factors scale with size of gas plume

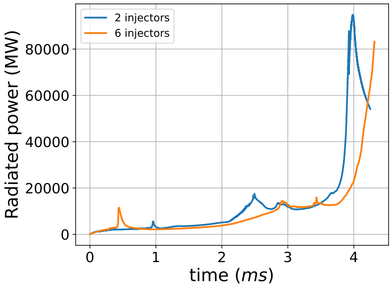
- Simulations use different widths for impurity Gaussian

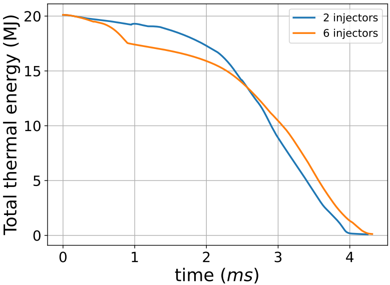
# Injectors	Injector width	Total rate of injection	TPF max
1	0.08	1.25×10^{23}	12.6
2	0.08	2.50×10^{23}	14.2
4	0.08	5.00×10^{23}	≈ 8
5	0.24	6.25×10^{23}	4.9
6	0.24	7.50×10^{23}	≈ 3
2	0.8	7.50×10^{23}	5.5

- Width of gas plumes directly affects TPF as a result of localized impurities
- TPF is not correlated with low-n MHD activity
- Distributing injector sites toroidally reduces TPF

Evolution of radiation and W_{th} at same total injection rate

- Simulations use different widths for impurity Gaussian
- Total injection rate: 7.5×10^{23} Ne/s

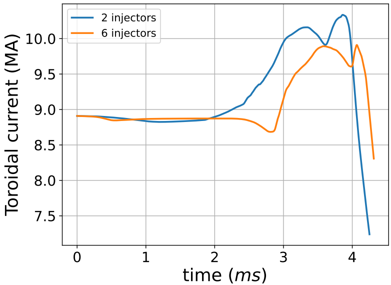


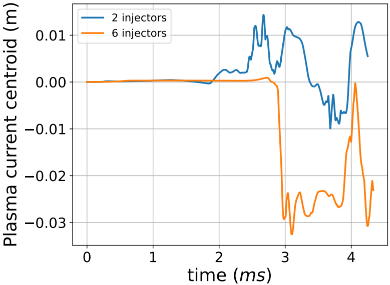


- TQ is slightly delayed in 6 injector case
- End of TQ: Energy from Ohmic heating converted to radiation

Current and vertical displacement at same total injection rate

- Simulations use different widths for impurity Gaussian
- Total injection rate: 7.5×10^{23} Ne/s





- 6 injectors result in slightly lower current peak
- No significant vertical displacement until at least early CQ

Outline

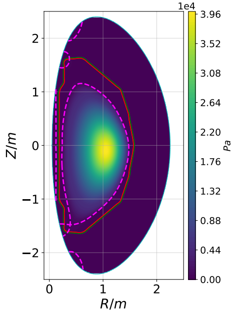
Summary & Outlook

- Recent improvements to the M3D-C1 model allow higher-fidelity disruption simulations
- Early onset of sawtooth and edge instabilities
- Thermal quench happens earlier with fewer injectors
- Radiation stays localized in pre-TQ phase and during TQ
- Decrease of thermal energy due to thermal conduction and radiated power
- TPF does not correlate well with low-n MHD activity
    - Spreading gas injectors toroidally, i.e. using 6 injectors helps decrease radiation PF
- Impurities are advected by bulk plasma flow only (no local increase in pressure or equilibrium flow)
    - Localization of impurities / radiation could be reduced by adding toroidal flows and with multi-fluid model

Bonus slides

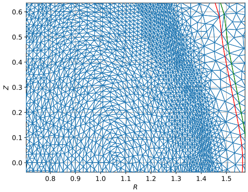
Full two-fluid M3D-C1 extended-MHD model

- Non-linear extended-MHD initial value stability code
  [Jardin et al., Comput. Sci. Discov. **5** 014002, 2012]

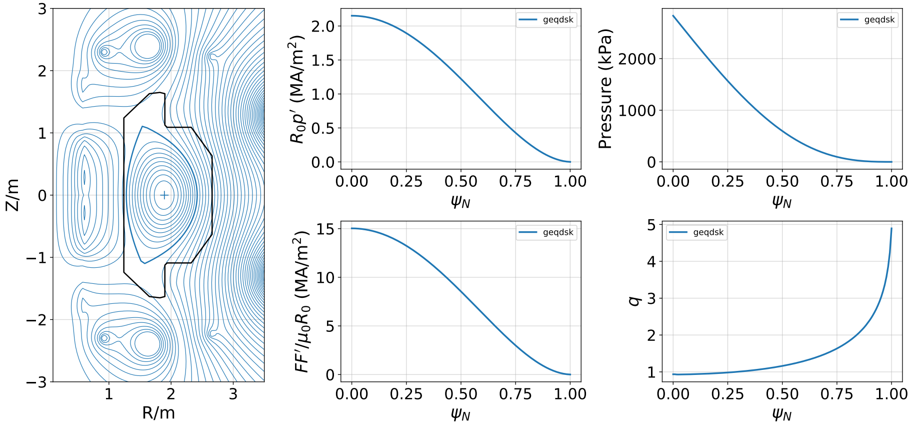


$$
\begin{aligned}
\frac{\partial n}{\partial t} + \nabla \cdot (n\vec{u}) &= 0 \\
nm_i \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \nabla \vec{u} \right) &= \vec{J} \times \vec{B} - \nabla p - \nabla \cdot \Pi + \vec{F} \\
\frac{\partial p}{\partial t} + \vec{u} \cdot \nabla p + \Gamma p \nabla \cdot \vec{u} &= (\Gamma - 1) \left[Q - \nabla \cdot \vec{q} + \eta J^2 - \vec{u} \cdot \vec{F} - \Pi : \nabla u \right] \\
&\quad + \frac{1}{ne} \vec{J} \cdot \left(\frac{\nabla n}{n} p_e - \nabla p_e \right) + (\Gamma - 1) \Pi_e : \nabla \left(\frac{1}{ne} \vec{J} \right) \\
\frac{\partial p_e}{\partial t} + \vec{u} \cdot \nabla p_e + \Gamma p_e \nabla \cdot \vec{u} &= (\Gamma - 1) \left[Q_e - \vec{q}_e + \eta J^2 - \vec{u} \cdot \vec{F}_e - \Pi_e : \nabla u \right] \\
&\quad + \frac{1}{ne} \vec{J} \cdot \left(\frac{\nabla n}{n} p_e - \nabla p_e \right) + (\Gamma - 1) \left[\Pi_e : \nabla \left(\frac{1}{ne} \vec{J} \right) + \frac{1}{ne} \vec{J} \cdot \vec{F}_e \right] \\
\vec{E} &= -\vec{u} \times \vec{B} + \eta \vec{J} + \frac{1}{ne} \left(\vec{J} \times \vec{B} - \nabla p_e - \nabla \cdot \Pi_e + \vec{F}_e \right)
\end{aligned}
$$

$$
\vec{J} = \frac{1}{\mu_0} \nabla \times \vec{B} \qquad , \qquad \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}
$$

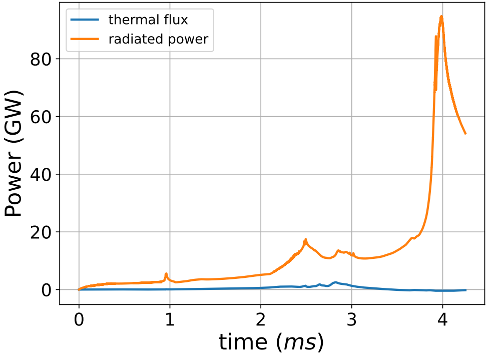


SPARC baseline case



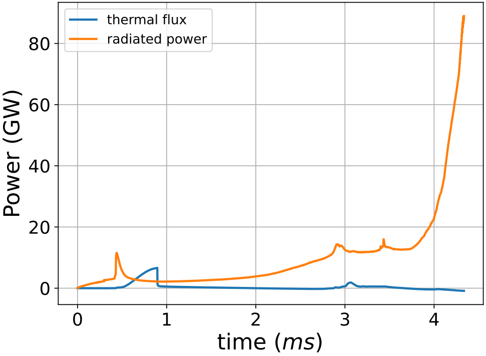
Radiated and conducted power

2 injectors



$$W_{cond} = 1.8\,\text{MJ}$$
$$W_{rad} = 56\,\text{MJ}$$

6 injectors



$$W_{cond} = 2.1\,\text{MJ}$$
$$W_{rad} = 44\,\text{MJ}$$