M3D-C1 modeling of DIII-D disruption with runaway current and pellet injection

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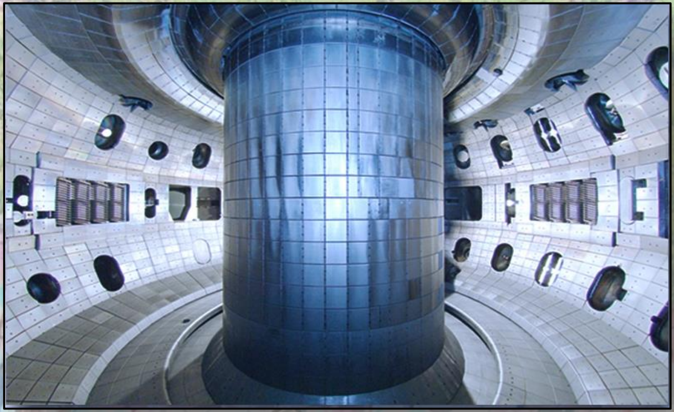

Oct 2022

outline

- Introduction of M3D-C1
- DIII-D 177053 shot disruption with pellet injection and runaways
  - Thermal quench (TQ) dynamics
  - Current quench (CQ) dynamics
- Summary

3D Extended MHD Equations in M3D-C[1]

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = \nabla \bullet D_n \nabla n + S_n$$

Density equation

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B}, \quad \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi = -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E}$$

Field equation

$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla\mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_i + \mathbf{S}_m$$

Momentum equation

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R}_c + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \bullet \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \bullet \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \bullet \mathbf{V} + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla\mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE}$$

Pressure equations

$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla\mathbf{V} + \nabla\mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \bullet \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV} \qquad \mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B}/B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B}/B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e)/\left(M_i \tau_e\right)$$

Blue terms are 2-fluid(thermal electron) terms. Also, now have impurity, pellet, runaway electron, high energy particle models (both CPU & GPU version) for disruption mitigation. **NOT reduced MHD.**

Fluid Runaway Electron Model

$$\frac{\partial n_{RE}}{\partial t} + \nabla \bullet \left(n_{RE} c \frac{\mathbf{B}}{B} \right) = \nabla \bullet \left(\mathbf{B} \frac{D_{RE}}{B^2} \mathbf{B} \bullet \nabla n_{RE} \right) + S_{RE}$$

RE density equation

$$\mathbf{J}_{RE} = -e n_{RE} \left(c \frac{\mathbf{B}}{B} + \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right)$$

RE current assumption

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne} \left(\mathbf{R}_c - \mathbf{R}_{RE} - \nabla \bullet \Pi_e \right) + \mathbf{S}_{CD}$$

Single fluid Ohm's law with RE

Red terms are additional runaway electron terms.

D_{RE} is the diffusion term of runaways, $\mathbf{R}_{RE} = \eta n e \mathbf{J}_{RE}$.

- In our model, the parallel runaway electron velocity is the speed of light c (~150 Alfven speed).
- We keep the E cross B drift and ignore the magnetic drift since the runaway electron current induced by magnetic drift is much smaller than that induced EXB drift.
- We have advection and diffusion with RE source terms in 3D runaway electron density continuity equation.
- Runaway electron current are coupled to background plasmas through the Ohm's law equation.

Runaway Electron source terms

$$S_{RE} = S_D + S_A$$

$$S_D = n_e \nu_{ee} \boldsymbol{\epsilon}_D^{-\frac{3}{16}} \exp\left[-\frac{1}{4}\boldsymbol{\epsilon}_D^{-1} + \left(1 + Z_{eff}\right)^{\frac{1}{2}} + \boldsymbol{\epsilon}_D^{-\frac{1}{2}}\right]$$

Dreicer term

$$\boldsymbol{\epsilon}_D = \frac{E_{||}}{E_D}, E_D = \frac{n_e e^3 ln\Lambda}{4\pi\varepsilon_0^2 T_e}, \nu_{ee} = \frac{n_e e^4 ln\Lambda}{4\pi\varepsilon_0^2 m_e^{1/2} T_e^{3/2}}$$

$$S_A = n_{re}\nu_c \frac{\boldsymbol{\epsilon}_c - 1}{ln\Lambda}\sqrt{\frac{\pi\zeta}{3\left(5 + Z_{eff}\right)}} \exp\left[1 - \boldsymbol{\epsilon}_c^{-1} + \frac{4\pi\left(1 + Z_{eff}\right)}{3\zeta\left(5 + Z_{eff}\right)\left(\boldsymbol{\epsilon}_c^2 + 4\zeta^{-2} - 1\right)}\right]$$

Avalanche term

$$\boldsymbol{\epsilon}_c = \frac{E_{||}}{E_c}, E_c = \frac{n_e e^3 ln\Lambda}{4\pi\varepsilon_0^2 m_e c^2} = \frac{T_e}{m_e c^2} E_D, \nu_c = \frac{n_e e^4 ln\Lambda}{4\pi\varepsilon_0^2 m_e^2 c^3} = \frac{T_e^{3/2}}{m_e^{3/2} c^3}\nu_{ee}$$

- The runaway source includes both the Drecier term and the Rosenbluth – Putvinski avalanche term.
- The Drecier term will be induced by the larger electric field generated during thermal quench.
- The avalanche term will dominate the runaway electron generation after thermal quench when there are enough runaway electrons generated by the Drecier term.

Pellet model in M3D-C1

Impurity pellet source equation

$$S = G_{2D}\frac{R}{\sqrt{2\pi}V_t}\left\{(1-f_c)\exp\left[-\frac{RR_p(1-\cos(\phi-\phi_p))}{V_t^2}\right] + f_c\frac{\cosh\left(\frac{V_t}{\sqrt{RR_p}}\right)-\cos\phi}{\cosh\left(\frac{V_t}{\sqrt{RR_p}}\right)-\cos(\phi-\phi_p)}\right\}$$

$$G_{2D} = \frac{1}{2\pi RV_p^2}\exp\left[-\frac{(R-R_p)^2+(Z-Z_p)^2}{2V_p^2}\right]$$

Momentum equation with runaway electron and pellet

$$nm\frac{d\boldsymbol{V}}{dt} = (\boldsymbol{J}-\boldsymbol{J}_{\boldsymbol{RE}})\times\boldsymbol{B} - \nabla p - \nabla\cdot\boldsymbol{\Pi} + \varpi\boldsymbol{V}$$

Temperature equation with runaway electron and pellet

$$\frac{n}{(\gamma-1)}\left[\frac{\partial T}{\partial t} + \nabla\cdot(T\boldsymbol{V})\right] + ST_s = -\mathrm{n}T\nabla\cdot\boldsymbol{V} - \nabla\cdot\boldsymbol{q} - \eta(\boldsymbol{J}-\boldsymbol{J}_{\boldsymbol{RE}})^2 + \frac{1}{2}\varpi V^2$$

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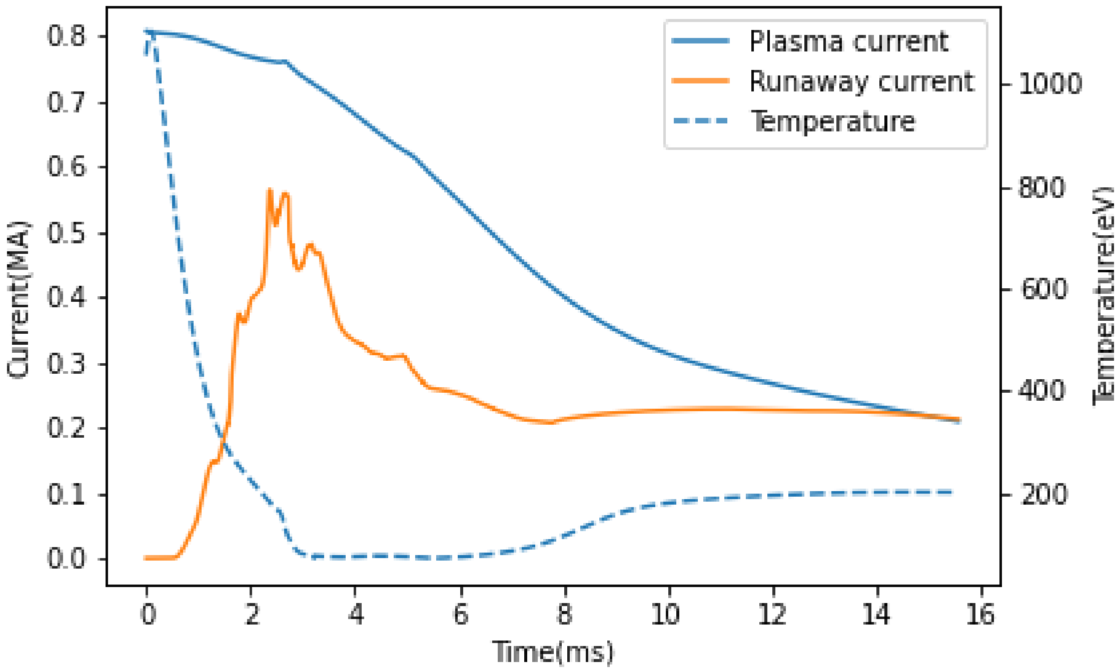
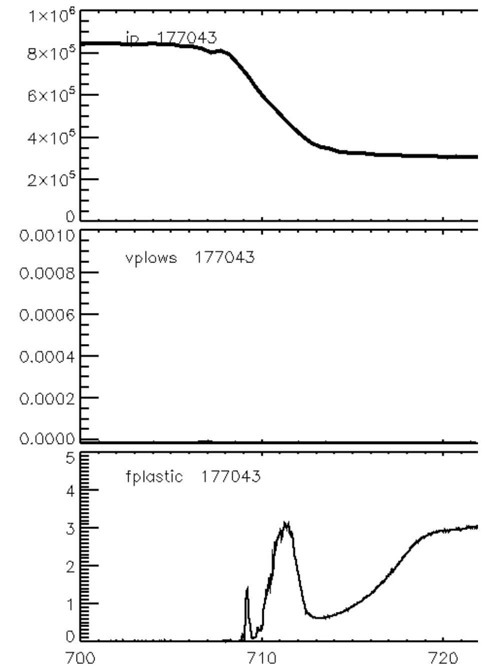
GENERAL ATOMICS

M3DC1 results match the experiment

M3D-C1 results vs DIII-D shot 177053





At the end of current quench, the runaway current plateau forms and the final value of current matches with the experiment.

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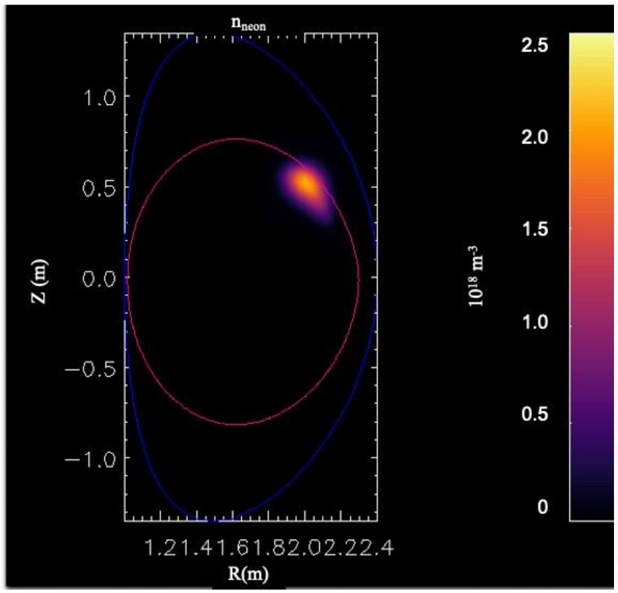
GENERAL ATOMICS

Thermal Quench

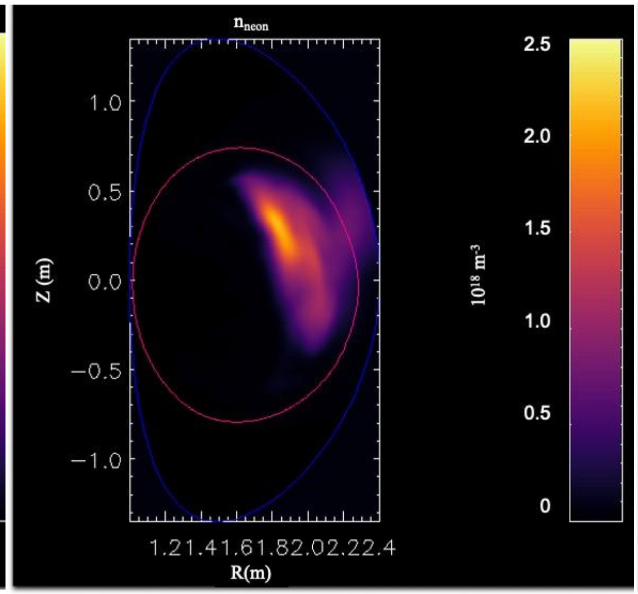
Neon pellet ablates and the impurities spread during TQ

t=0.2ms



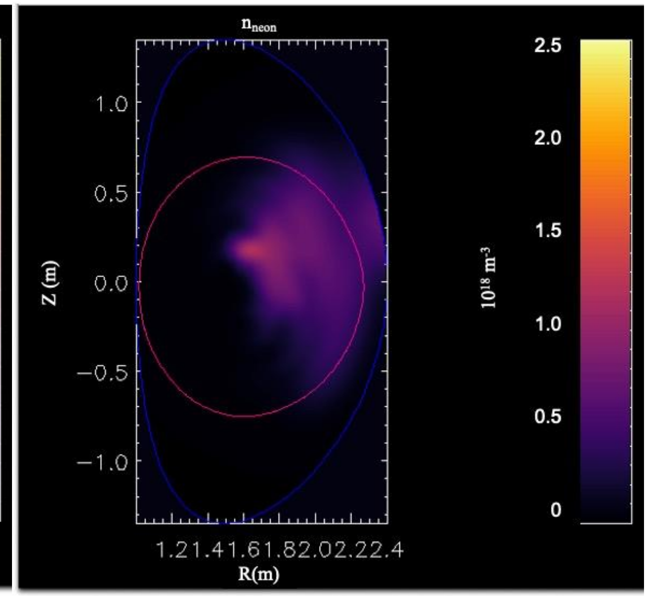
The neon pellet touches the plasma region.

t=1.2ms



The neon pellet goes in and spreading.

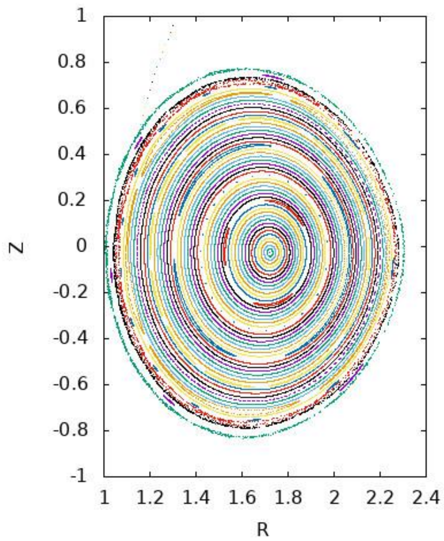
t=2.4ms



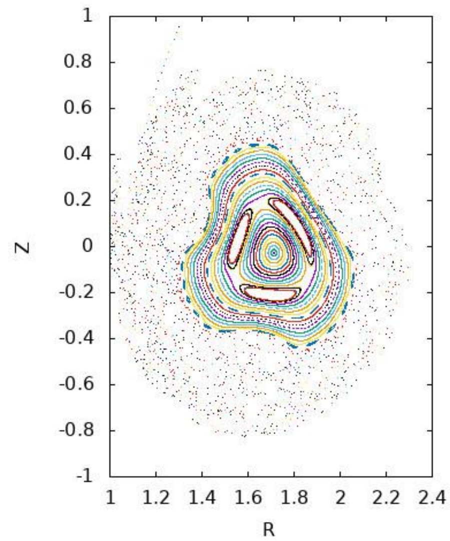
The neon pellet reaches the plasma core.

The TQ process causes a 3/1 mode and finally stochastic field lines

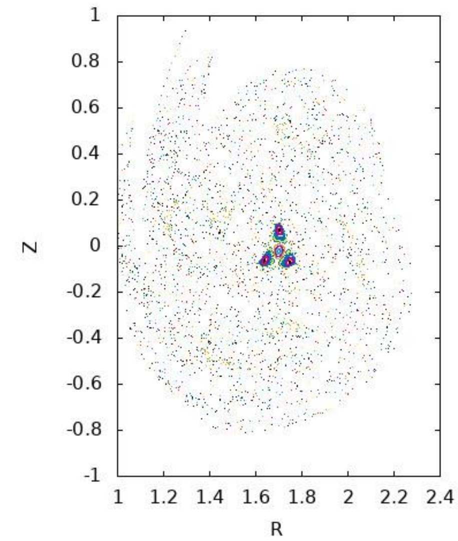
t=0.2m



t=1.2ms



t=2.4ms



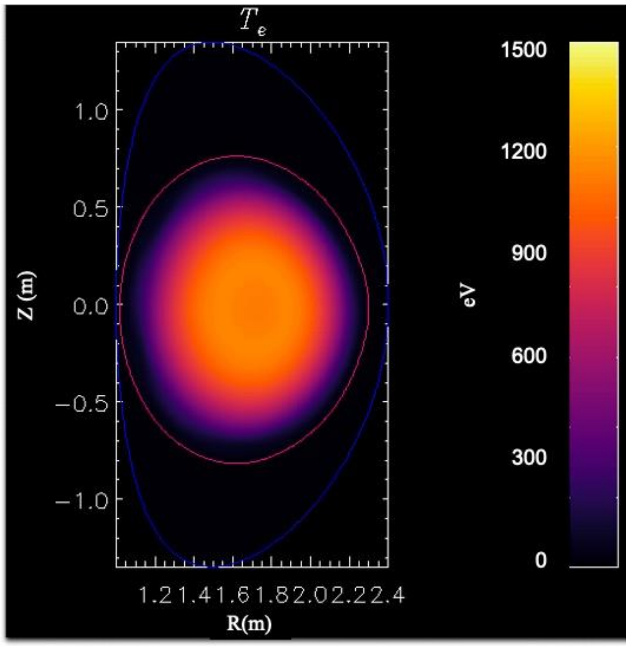
Magnetic field line does not change very much when the neon pellet first touch the plasma region.

Outside-in TQ causes a 3/1 mode.

At the end of TQ, the magnetic field line becomes stochastic.

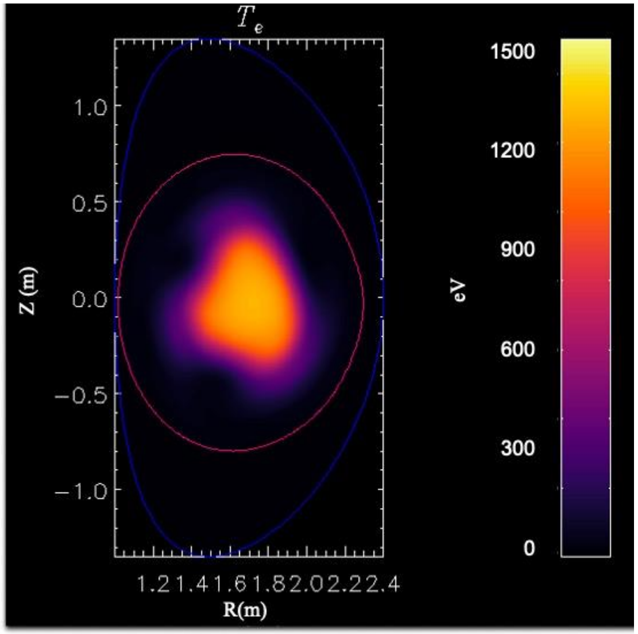
Temperature drops down due to the neon dilution, ionization and radiation

t=0.2ms



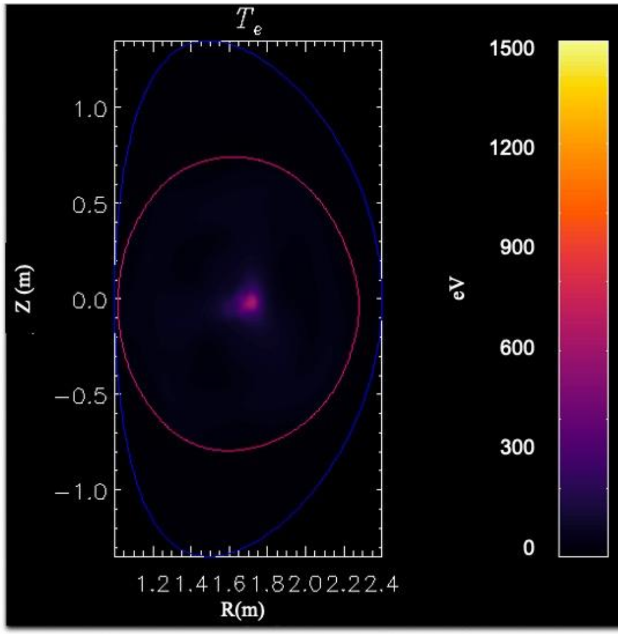
The temperature near the separatrix drops down when the neon pellet touches the plasma region.

t=1.2ms



The edge temperature keeps decreasing while the neon spreading.

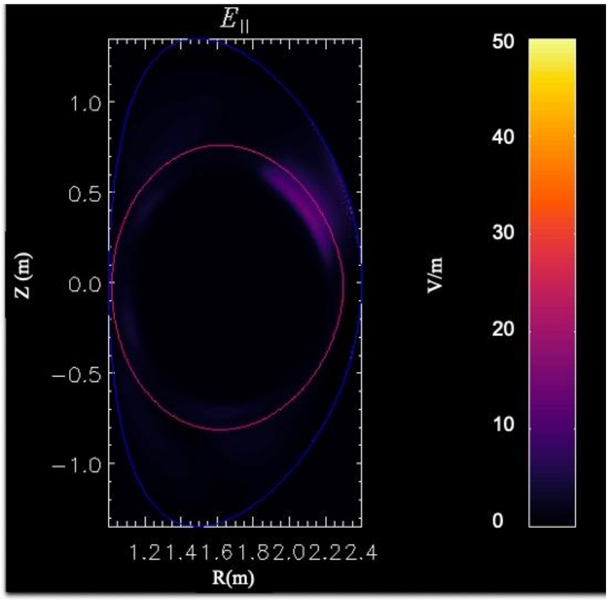
t=2.4ms



When the neon pellet reaches the core, the core temperature significantly drops down.

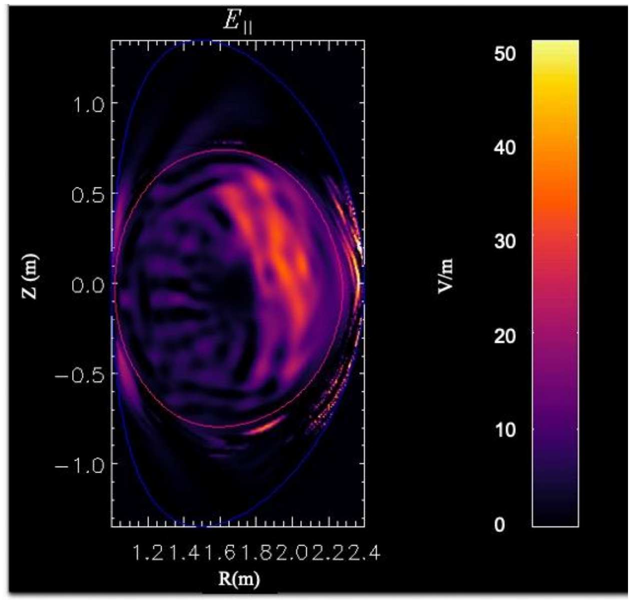
Reduced temperature and increased resistivity induces the parallel E-field

t=0.2ms



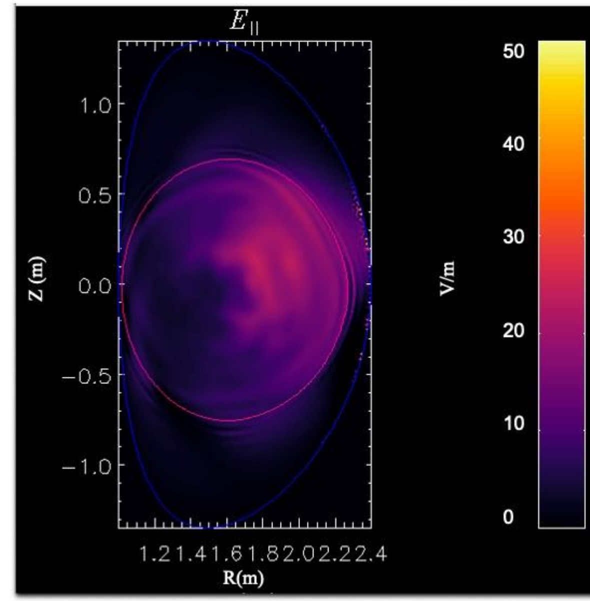
E field first grows near the neon pellet region.

t=1.2ms



Large E-field perturbations are induced when the neon pellet nearly reach the core.

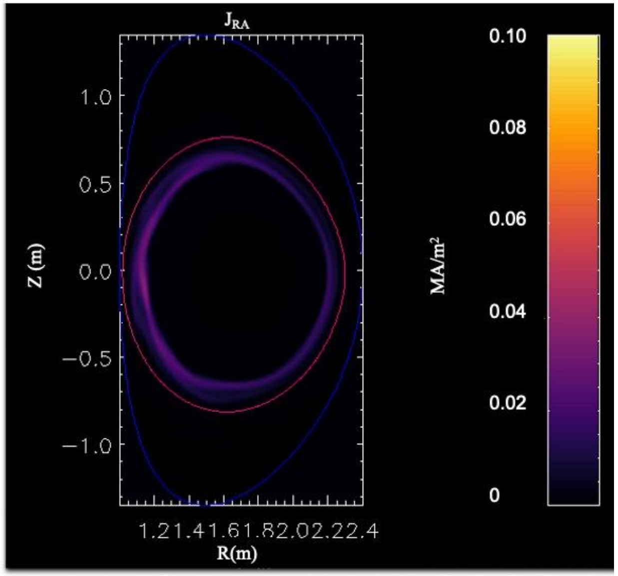
t=2.4ms



Electric field trend to be uniform after the neon pellet reaches the core.

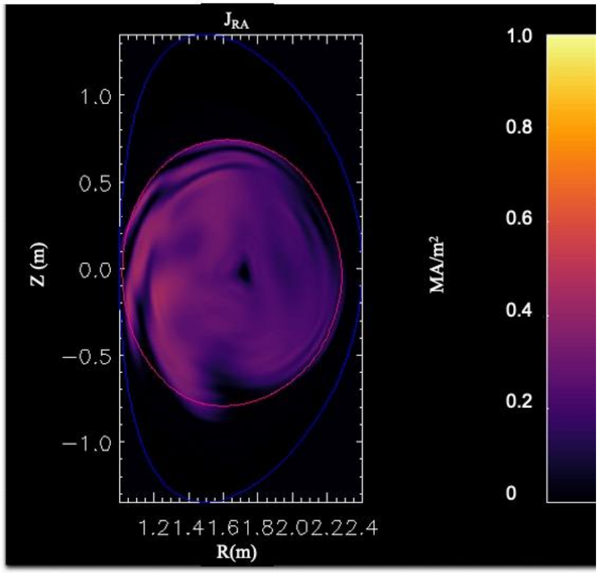
Runaway current is generated due to the large parallel E-field induced during TQ

t=0.2ms



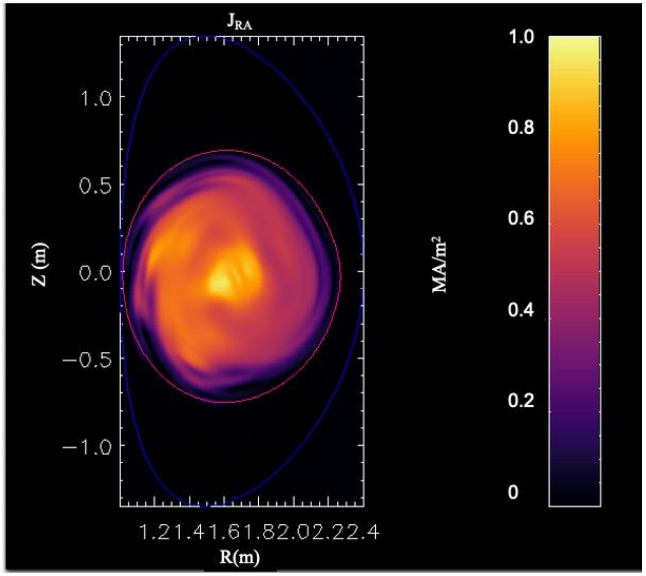
Runaways are generated near the pellet and the move to the whole surface.

t=1.2ms



Runaways spreading while the pellet goes close to the core.

t=2.4ms



The runaways current covers the whole plasma region because of the runaway avalanche.

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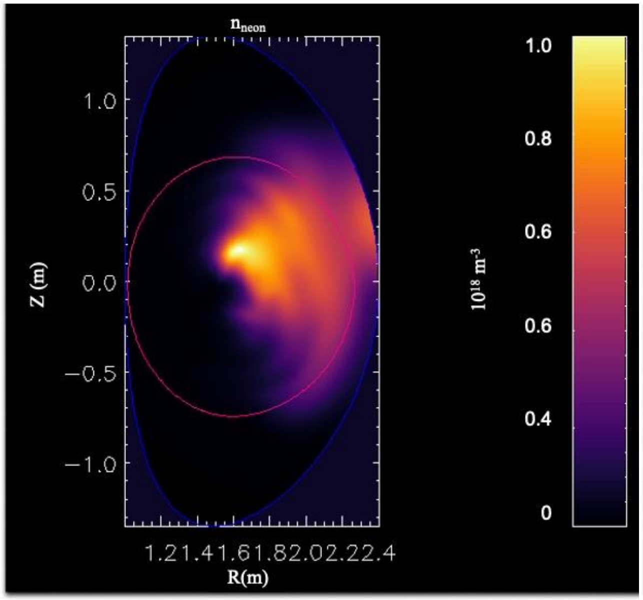
GENERAL ATOMICS

Current Quench

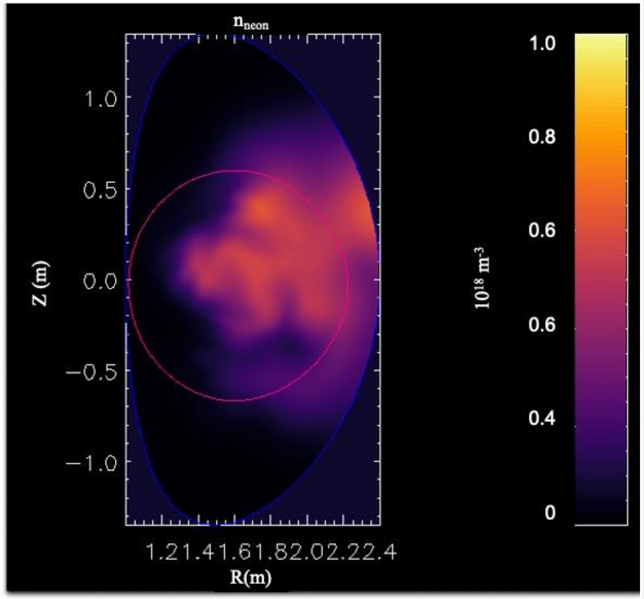
Neon spreads to the whole plasma region during CQ

t=3.0ms



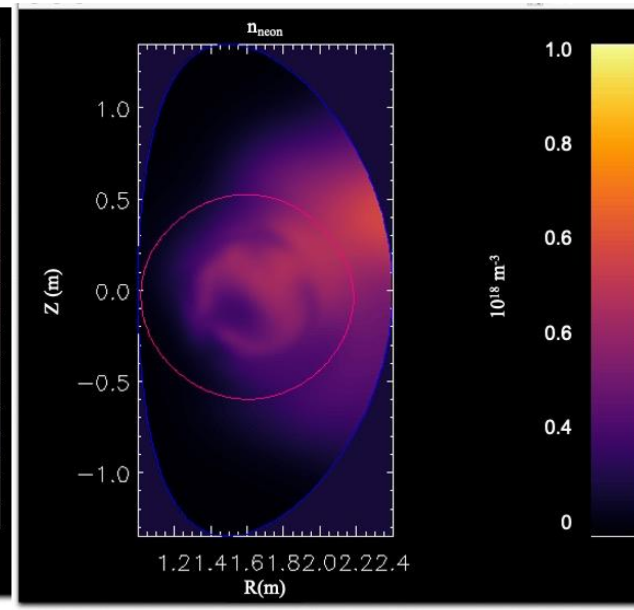
The neon pellet passed the core region and the neon spreading faster in the stochastic field.

t=7.0ms



The neon pellet spreads during the CQ.

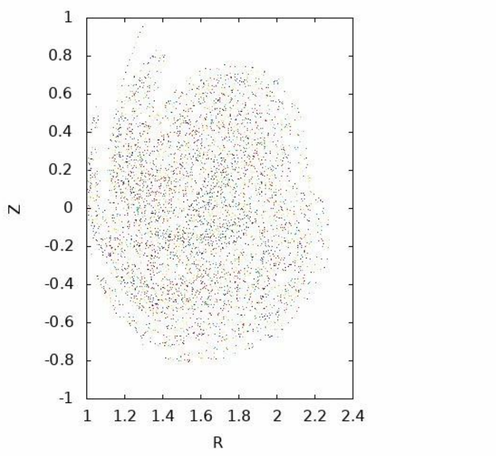
t=11.0ms



At the time of the end of CQ, the neon almost spreads to the whole plasm region.

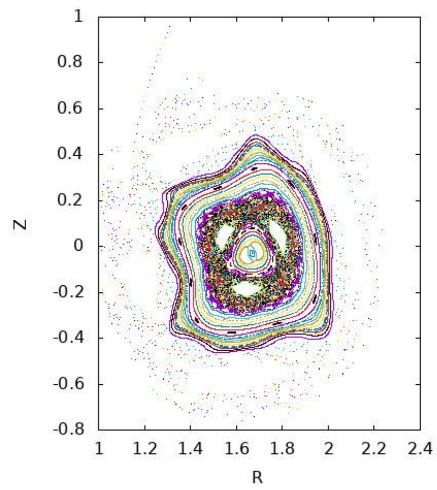
The stochastic magnetic field line has been restored during the CQ

t=3.0ms



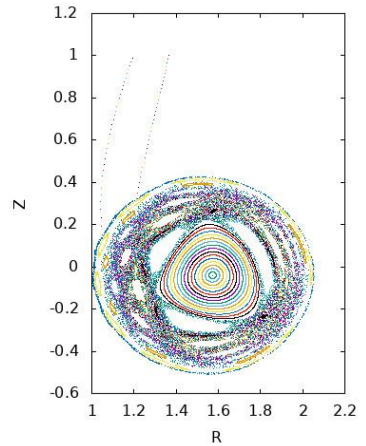
The magnetic field line is stochastic at the start of the CQ.

t=7.0ms



The 3/1 mode is induced and the magnetic field line starts to restore.

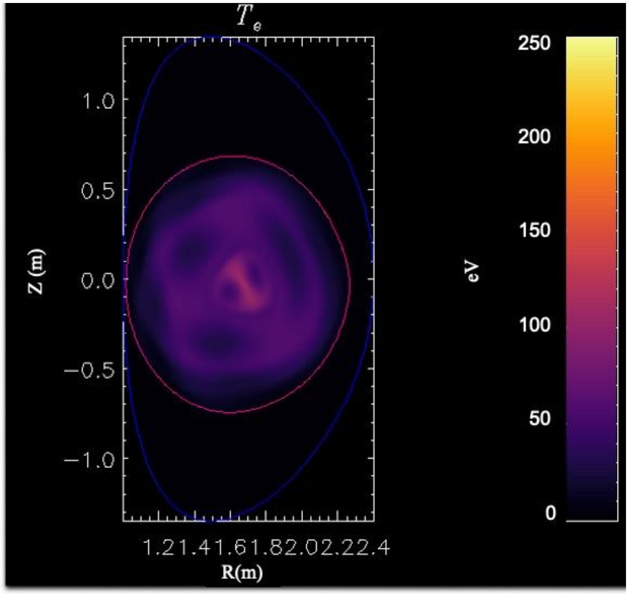
t=11.0ms



The 3/1 mode finally restores the whole core region magnetic field line at the end of CQ.

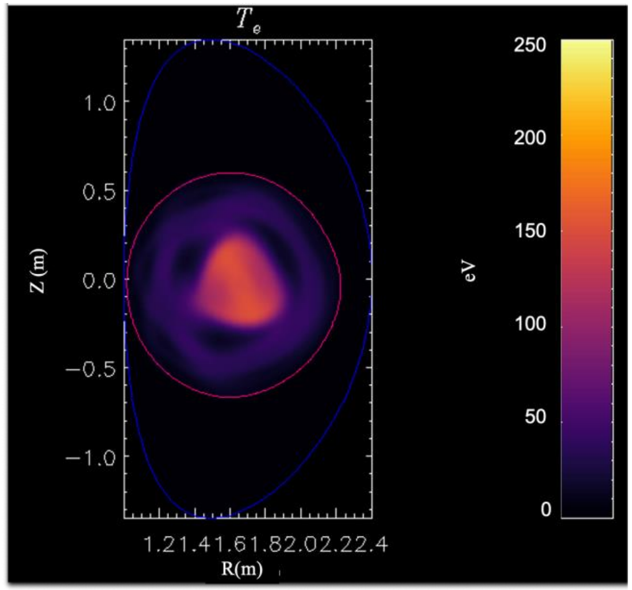
3/1 mode appears in temperature profile and the closed field line helps the core reheating

t=3.0ms



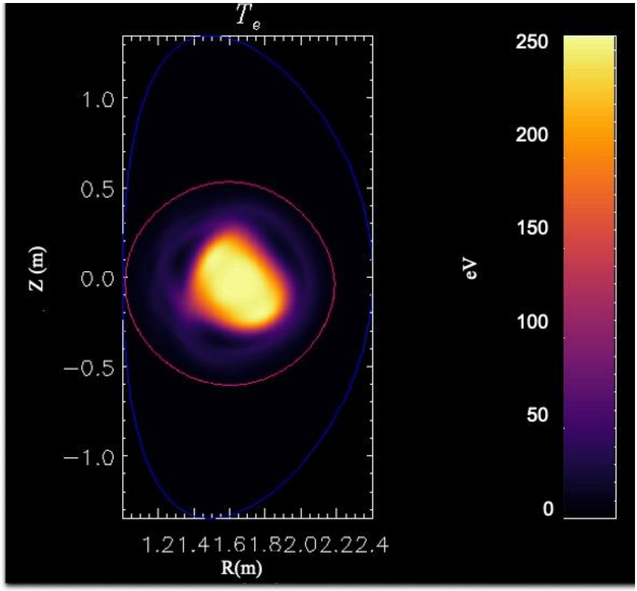
3/1 mode in the temperature profile.

t=7.0ms



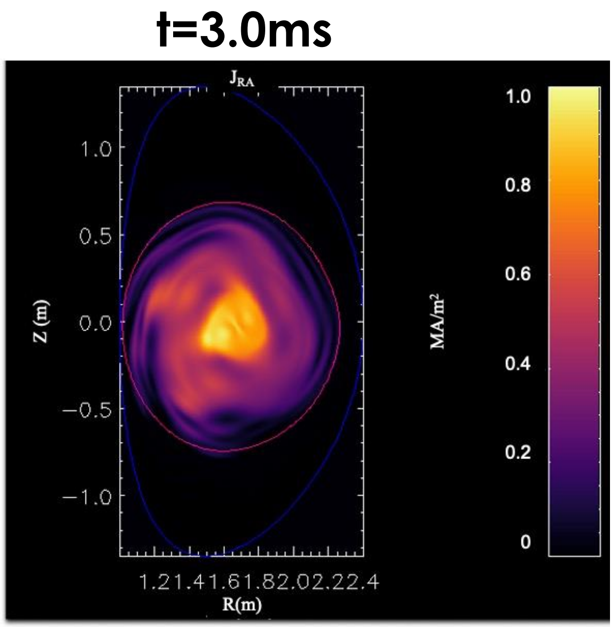
The core plasma is reheating during CQ.

t=11.0ms

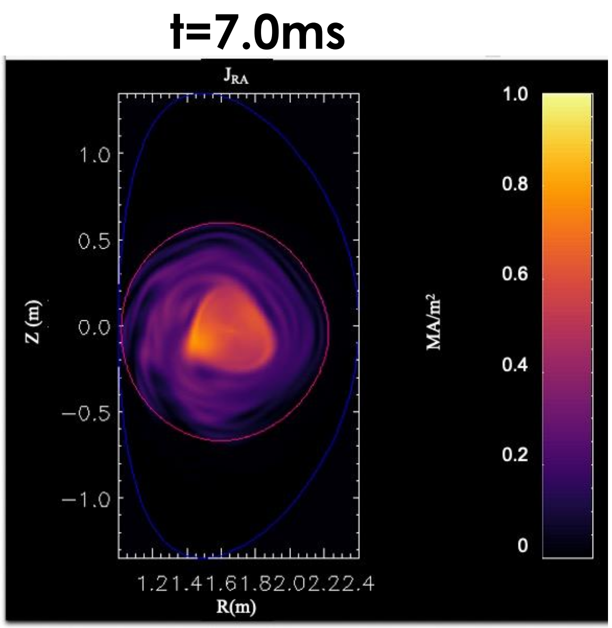


The 3/1 mode exist the during the CQ and the core plasma is reheated.

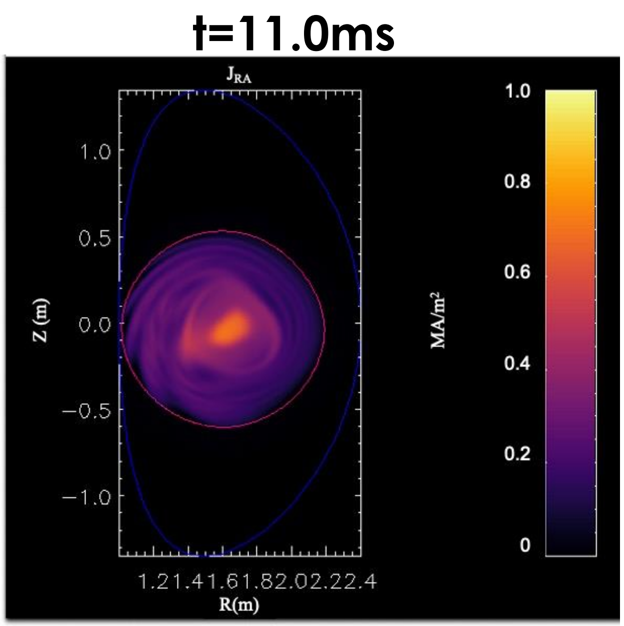
3/1 mode appears in runaway current profile and the closed field maintains the runaways at core



3/1 mode in the runaway current profile similar to what appears in temperature profile.



The runaway current drops down but the 3/1 mode still there.



The closed field line helps keeping the core runaway current not loss.

Summary

- We have the full disruption simulation in M3D-C1 includes thermal quench and current quench.
- There are complicated interactions between impurities, runaways and MHD mode during thermal quench, which induce larger E-field fluctuations, stochastic magnetic field lines and large runaway current loss.
- 3/1 modes induced during current quench restore magnetic surfaces, reducing runaway loss and maintaining the runaway electron plateau.
- Future work will continue to examine these dynamics in more detail