# Multiphysics disruption modeling with M3D-C1

by

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with

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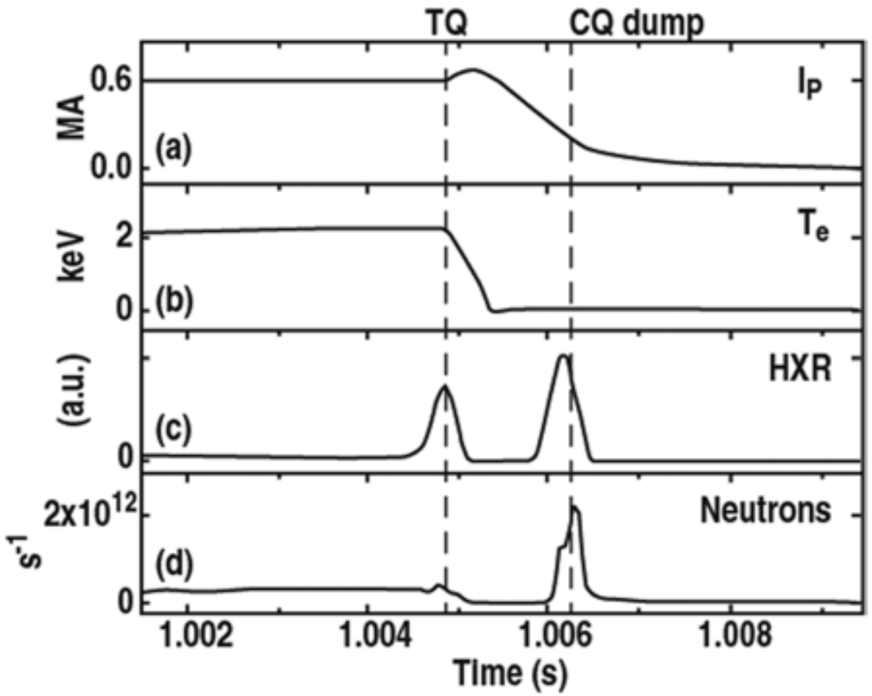
# Future tokamaks will require disruption mitigation

- **Disruptions result in rapid loss of stored plasma energy**
  - Thermal quench can melt of plasma-facing components
  - Current quench
    - Can induce damaging wall forces
    - Can produce dangerous runaway electrons
- **Impurity injection can mitigate disruptions by radiating stored energy**
- **Two techniques under experimental and theoretical investigation**
  - Massive gas injection (MGI)
  - Pellet injection



MGI-triggered disruption in C-Mod
(a) Current quench
(b) Thermal quench
Runaway electrons detected by hard X-ray (c) and photo-neutron measurements(d)

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# Modeling of disruption dynamics and mitigation requires a multiphysics model

- **Simulations, validated against mitigation experiments, are required to project techniques to future devices**
- **Integrated model is required to capture all relevant physics**
  - Magnetohydrodynamics (MHD) for macroscopic evolution of disruption dynamics
  - Atomic physics for ionization and radiation from injected impurities
  - Drift-kinetics for phase-space evolution of runaway electron population
- **Here we present testing and benchmarking of coupled MHD-atomic physics simulations**
  - Coupling KPRAD to M3D-C1
  - Axisymmetric test of different coupling methods
  - Benchmark with NIMROD

# M3D-C1 [1] is an extended-MHD solver

- **Three-dimensional**
- **Includes resistivity, density diffusivity, viscosity, & thermal conductivity**
- **Two-fluid effects (optional)**
- **Linear and nonlinear modes**
- **High-order, $C^1$ continuous finite element representation**
- **Mesh adapted to input equilibrium**

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \vec{v}) = 0$$

$$m_i n_i \left[ \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right] = \vec{J} \times \vec{B} - \nabla p - \nabla \cdot \Pi_i$$

$$\frac{\partial \vec{B}^p}{\partial t} = -\nabla \times \vec{E}$$

$$\vec{E} = \eta \vec{J} - \vec{v} \times \vec{B} + \frac{1}{n_e e} \left( \vec{J} \times \vec{B} - \nabla p_e \right)$$

$$\Pi = -\mu (\nabla \vec{v} + \nabla \vec{v}^t) + \Pi_i^{\parallel} + \Pi_i^{\wedge}$$

$$\begin{aligned} \frac{\partial p}{\partial t} + \vec{v} \cdot \nabla p + \Gamma p \nabla \cdot \vec{v} &= (\Gamma - 1) \big( \eta J^2 - \nabla \cdot \vec{q} - \Pi_i : \vec{v} \big) \\ &\quad + \frac{1}{n_e e} \vec{J} \cdot \left( \nabla p_e - \Gamma \frac{\nabla n_i}{n_i} p_e \right) \end{aligned}$$

$$\begin{aligned} \frac{\partial p_e}{\partial t} + \vec{v} \cdot \nabla p_e + \Gamma p_e \nabla \cdot \vec{v} &= (\Gamma - 1) \big( \eta J^2 - \nabla \cdot \vec{q}_e \big) \\ &\quad + \frac{1}{n_e e} \vec{J} \cdot \left( \nabla p_e - \Gamma \frac{\nabla n_i}{n_i} p_e \right) \end{aligned}$$

$$\vec{q}_{e,i} = -\kappa \nabla T_e - \kappa_{\parallel} \frac{\vec{B}\vec{B}}{B^2} \cdot \nabla T_e \qquad \vec{q} = -\kappa \nabla (T_e + T_i)$$

[2]

[1] S. C. Jardin, et al., Comput. Sci. Discovery 5, 014002 (2012).
[2] N.M. Ferraro et al., Phys. Plasmas 23, 056114 (2016)

# KPRAD provides need atomic physics information

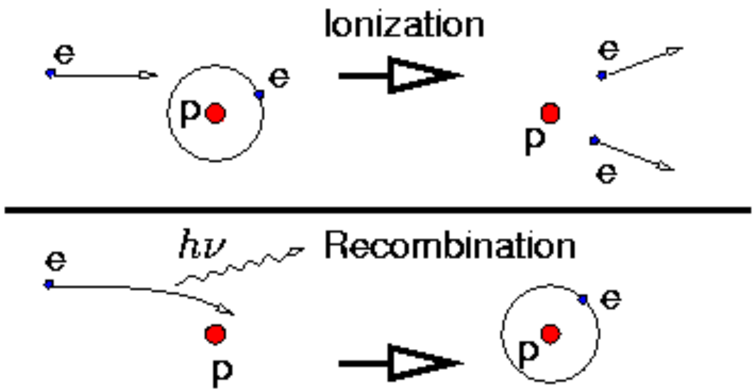
- **KPRAD [1] solves for impurity-plasma interaction in low-density, coronal equilibrium model**
  - Based on ADPAK rate coefficients
  - Impurity charge states and electron density evolve according to ionization and recombination
  - Thermal energy lost from plasma due to
    - Ionization
    - Line radiation
    - Bremsstrahlung radiation
    - Recombination radiation
- **Can be subcycled much faster than typical MHD time steps**

[1] D.G. Whyte, et al., Proc. of the 24th Euro. Conf. on Controlled Fusion and Plasma Physics, Berchtesgaden, Germany, 1997, Vol. 21A, p. 1137.

# Most recombination radiation comes from ionization/potential energy, not thermal/kinetic

- **Ionization process**
  - Thermal energy converted to potential energy
  - Electrons equilibrate causing dilution cooling
- **Recombination process**
  - Thermal electron trapped by ion
  - Thermal (kinetic) and potential energy released as radiation
  - Potential (~$10^1$-$10^3$ eV) greatly exceeds kinetic in cold plasma (~$10^0$ eV)
  - Only kinetic part of recombination radiation should be subtracted from plasma thermal energy
- **We have updated KPRAD to split kinetic and potential recombination energy**

Kinetic energy to potential energy



Kinetic & potential to radiation

Figure from Ahmadi & Ahmadi,
MSE Vol.119,159 - 166 (2016)

# KPRAD couples to the M3D-C1 pressure equation(s)

- **Total and electron pressure equations**
  - Electrons lose energy to ionization, line radiation, bremsstrahlung, and kinetic part of recombination radiation
  - Main ions lose energy only through cooling on electrons

$$\frac{\partial p}{\partial t} + \mathbf{v}\cdot\nabla p + \Gamma p \nabla\cdot\mathbf{v} = (\Gamma - 1)\left(\eta J^2 - \nabla\cdot\mathbf{q} - \mathbf{\Pi} : \mathbf{v} - \mathcal{P}_{rad}\right)$$

$$\frac{\partial p_e}{\partial t} + \mathbf{v}\cdot\nabla p_e + \Gamma p_e \nabla\cdot\mathbf{v} = (\Gamma - 1)\left(\eta J^2 - \nabla\cdot\mathbf{q_e} + Q_{ei} - \mathcal{P}_{rad}\right)$$

- **Single pressure equation**
  - Evolve only total pressure equation (above)
  - $p_e/p$ constant throughout time, implicitly assuming
    - No thermal equilibration
    - Losses split between ions and electrons by same fraction

# KPRAD couples to the M3D-C1 temperature equation(s)

- **Electron and all-ions temperature equations**
  - Ions and electrons experience dilution cooling
  - Electrons lose energy to ionization and radiation
  - Main ions cool on electrons

$$n_e\left[\frac{\partial T_e}{\partial t}+\mathbf{v}\cdot\nabla T_e+\Gamma T_e\nabla\cdot\mathbf{v}\right]=(\Gamma-1)\left(\eta J^2-\nabla\cdot\mathbf{q}_e+Q_{ei}-\mathcal{P}_{rad}\right)-T_e\left(\frac{\partial n_e}{\partial t}+\mathbf{v}\cdot\nabla n_e\right)$$

$$n_{ti}\left[\frac{\partial T_i}{\partial t}+\mathbf{v}\cdot\nabla T_i+\Gamma T_i\nabla\cdot\mathbf{v}\right]=(\Gamma-1)\left(-\nabla\cdot\mathbf{q}_i-Q_{ei}-\mathbf{\Pi}:\mathbf{v}\right)-T_i\left(\frac{\partial n_{ti}}{\partial t}+\mathbf{v}\cdot\nabla n_{ti}\right)$$

- **Single temperature equation**

$$n_{ti}=\sum_{s=i,z}n_s$$

  - Evolves sum over all species
  - $T_e/T_i$ constant throughout time, implicitly assuming
    - Instantaneous thermal equilibration
    - Split of losses between species evolves as pressure ratio changes

$$n_{tot}\left[\frac{\partial T}{\partial t}+\mathbf{v}\cdot\nabla T+\Gamma T\nabla\cdot\mathbf{v}\right]=(\Gamma-1)\left(\eta J^2-\nabla\cdot\mathbf{q}-\mathbf{\Pi}:\mathbf{v}-\mathcal{P}_{rad}\right)-T\left(\frac{\partial n_{tot}}{\partial t}+\mathbf{v}\cdot\nabla n_{tot}\right)$$

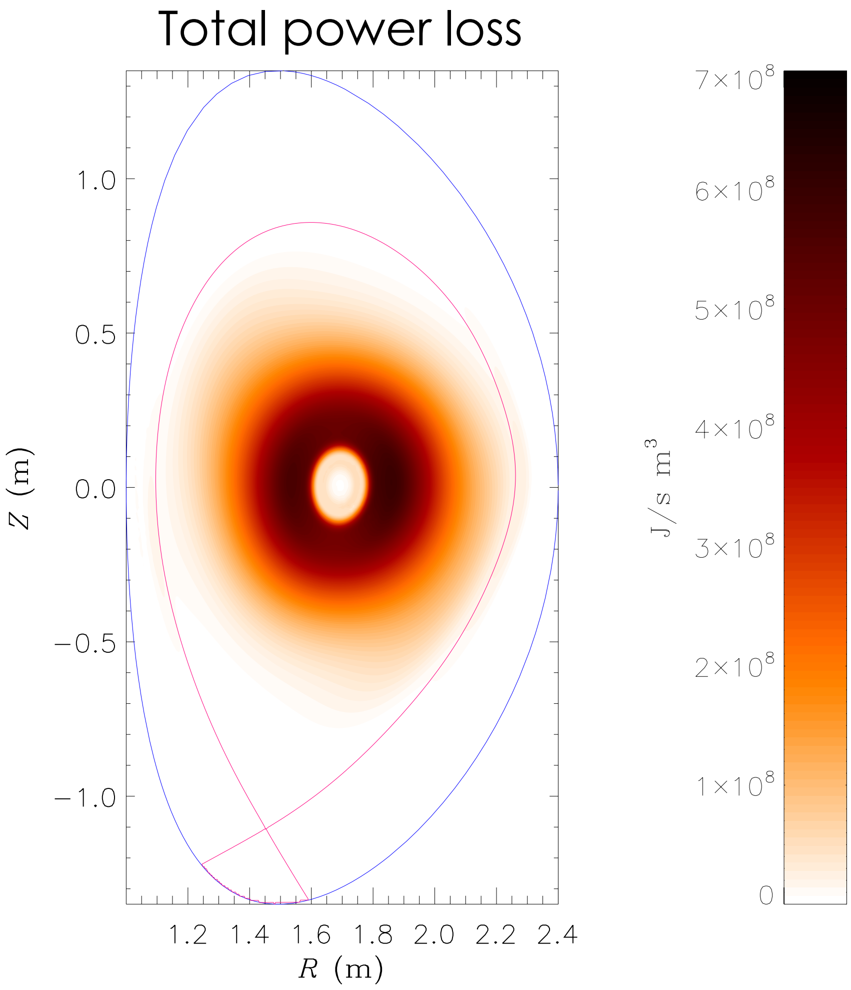
$$n_{tot}=\sum_{s=e,i,z}n_s$$

# Fast argon injection in DIII-D core used as test case

- **DIII-D shot 137611 @ 1950 ms**
- **2D, nonlinear, single-fluid**
- **Neutral argon impurity deposition**
  - No impurities to start
  - Gaussian source

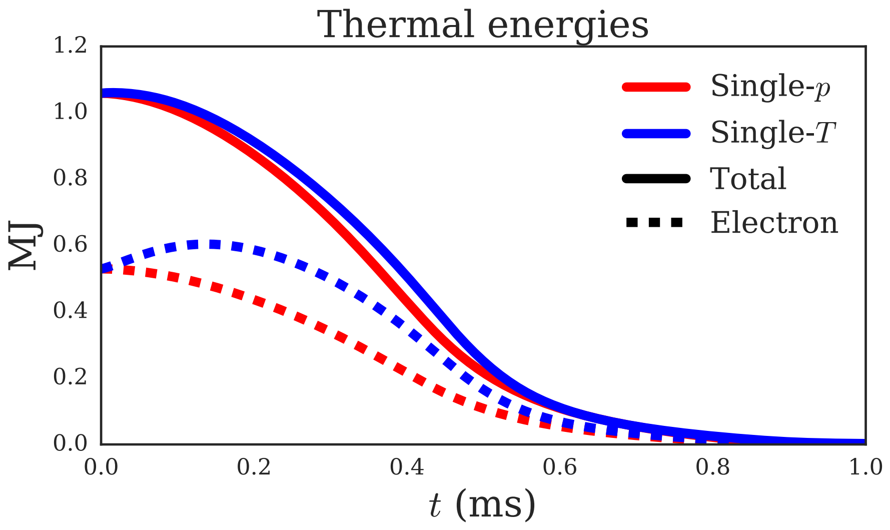
$$\frac{dn_z}{dt} = \nu \frac{R_0}{R} \exp\left[-\frac{(R-R_0)^2 + (Z-Z_0)^2}{2\delta^2}\right]$$

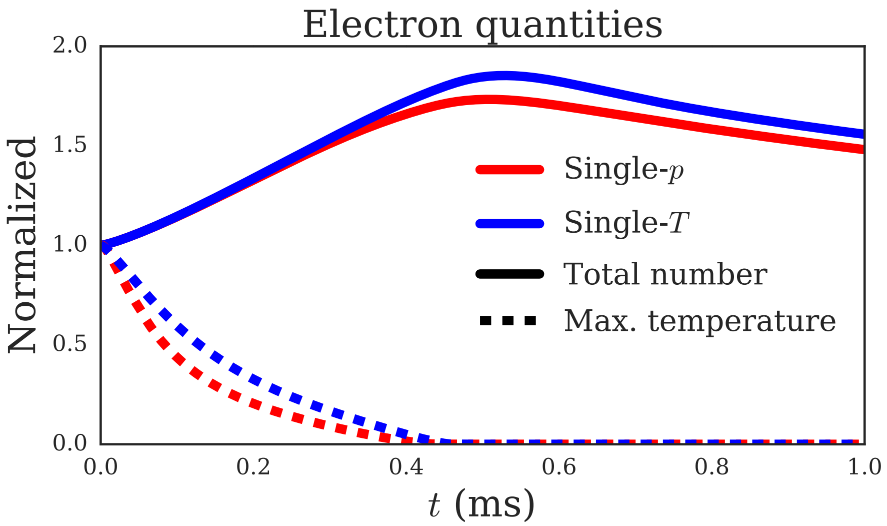
  - $\delta$ = 0.25 m & $\nu$ = $10^{23}$ $m^{-3}$ $s^{-1}$
- **Ohmic heating artificially turned off**
- **Constant main ion density: $10^{20}$ $m^{-3}$**
- **Constant diffusivities**
  - Isotropic density, momentum, and thermal diffusivities: 10 $m^2/s$
  - Parallel thermal diffusivity: $10^6$ $m^2/s$
  - Resistivity: $10^{-5}$ Ohm*m, 7.96 $m^2/s$



# Single pressure vs. temperature equation results: Qualitatively similar thermal quenches

- **Thermal quench times of about ~0.5 ms**
- **Dilution cools plasma at early times without changing total thermal energy**
- **Electron thermal energy rises for single-T due to electron density increasing faster than ion**





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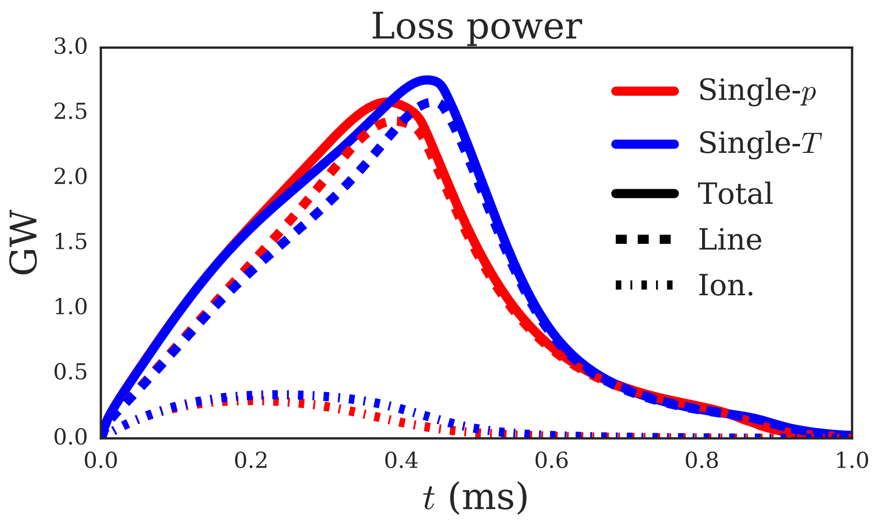
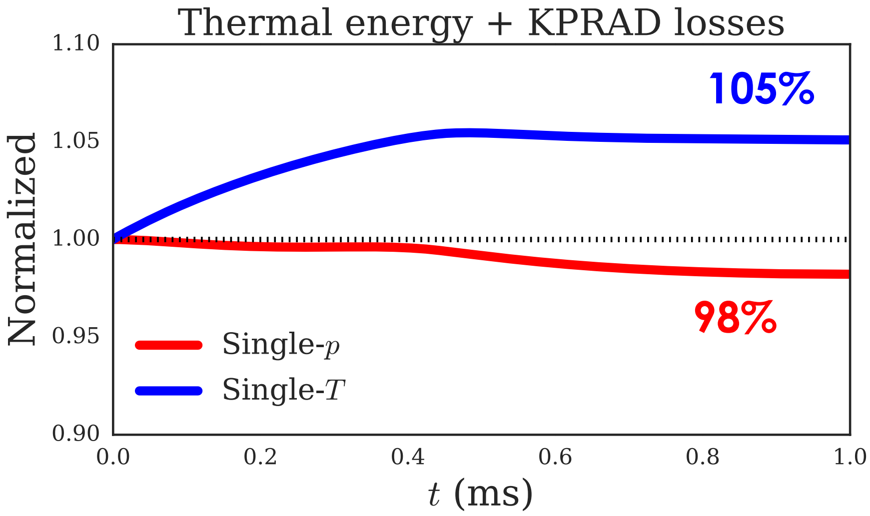
# Single pressure vs. temperature equation results: Radiation/ionization is dominant thermal energy sink

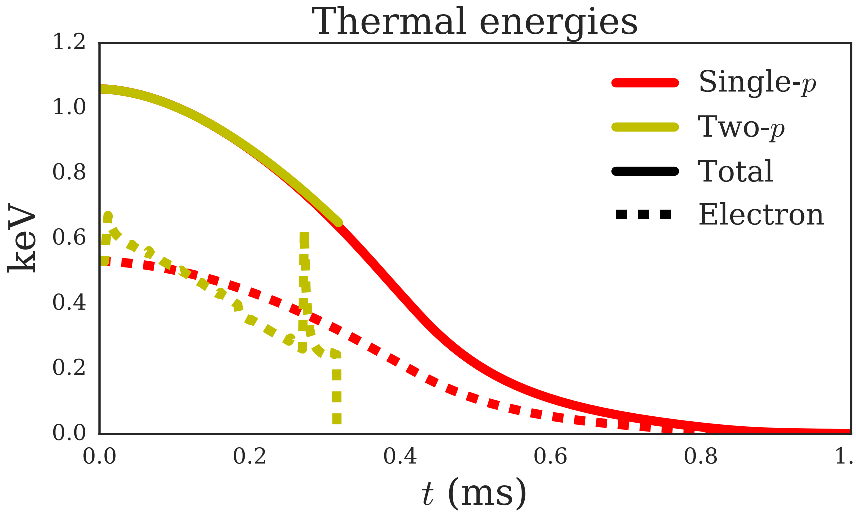
- **KPRAD loss power mostly from line radiation and ionization**
- **KPRAD energy loss accounts for most of thermal energy change**
  - Single-p
    - 2% less radiation than thermal energy (conduction?)
  - Single-T
    - 5% more radiation than thermal energy (dilution not conservative?)
- **More careful energy accounting underway**

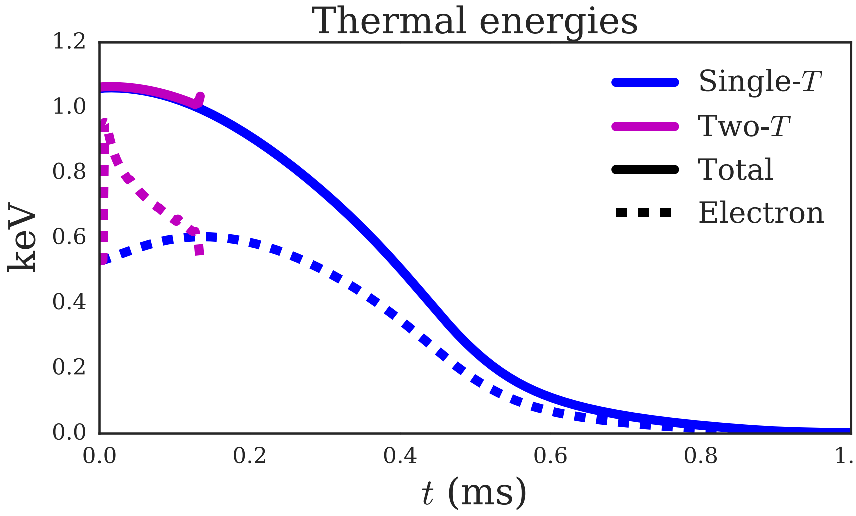


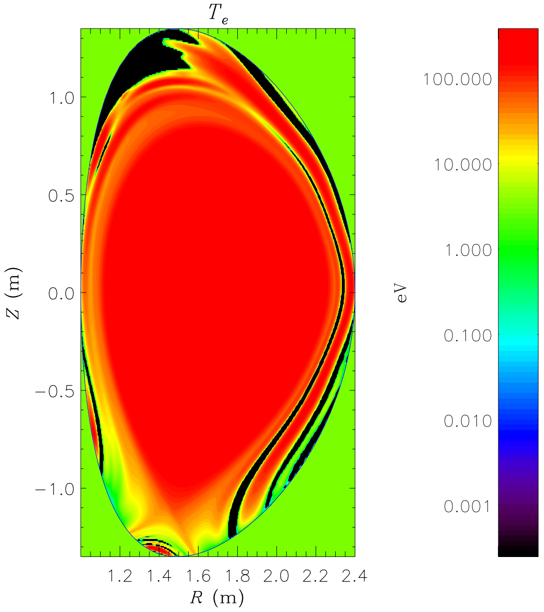


# Two pressure/temperatures still under-development

- **Similar evolution of total thermal energies**
- **Electron thermal energies**
  - Exhibit strange behavior
  - Negative temperatures seen in open-field-line region
  - Numerical instability?
- **Work will continue to fix issue**





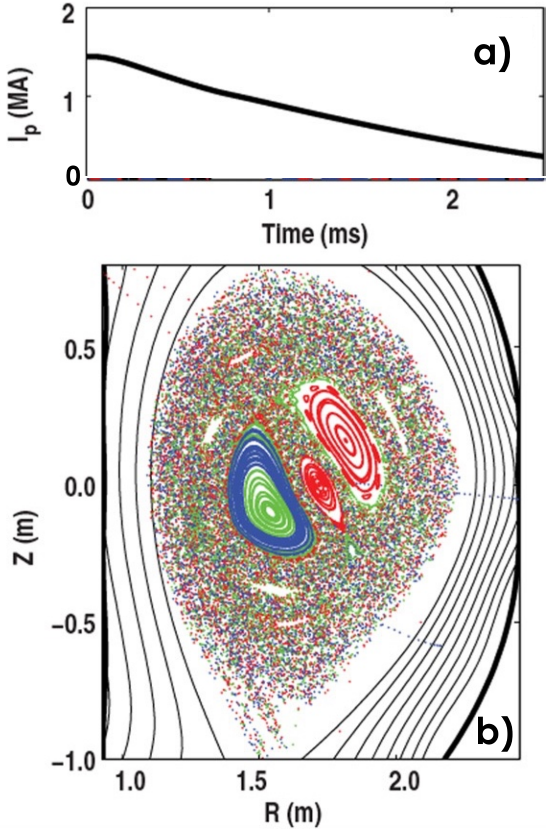


# Coupled NIMROD-KPRAD simulations used for MGI and pellet-mitigation simulations

- **Solves extended-MHD equations with different methods from M3D-C1**
- **Current state of KPRAD coupling**
  - Single temperature equation for electrons

$$\frac{n_\alpha}{\Gamma-1}\left(\frac{\partial T_\alpha}{\partial t}+\mathbf{V}_\alpha\cdot\nabla T_\alpha\right)=-p_\alpha\nabla\cdot\mathbf{V}_\alpha-\nabla\cdot q_\alpha+Q_\alpha-\Pi_\alpha:\nabla\mathbf{V}_\alpha$$

  - All particles are equal radiators, so $Q_\alpha$ scaled by pefrac
  - Dilution is largest and most troublesome source term:
    - Densities directly updated by KPRAD, no explicit source for density
    - Possible mismatch in accounting under investigation
- **Used in past MGI simulations and current pellet mitigation studies**



NIMROD MGI simulation showing (a)current quench and (b)induced core MHD

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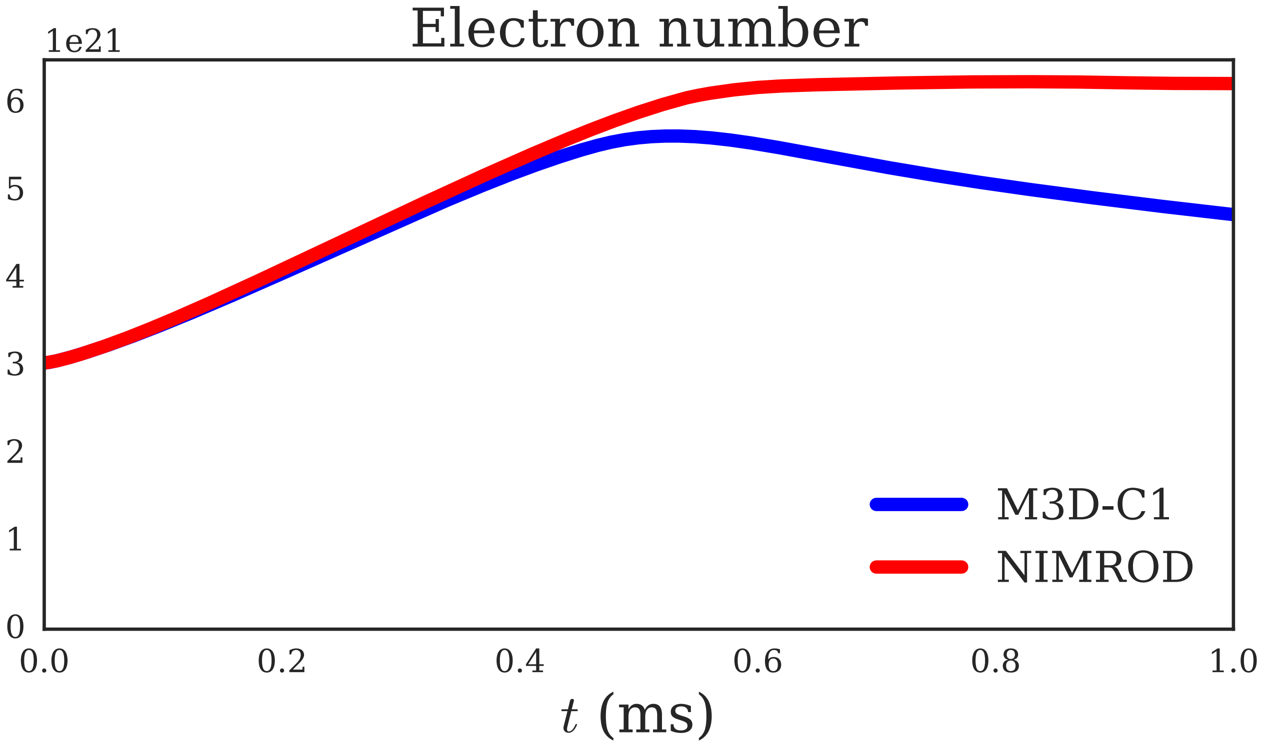
# NIMROD also modeled fast-argon-injection test case

- **Nearly identical setup to M3D-C1, but some differences**
  - Fixed boundary placed separatrix, so no open-field-line region
  - Potential part of recombination radiation also subtracted from thermal energy
  - Turning off KPRAD coupling at low-$T_e$ avoids any problems
- **Initial benchmarking with M3D-C1 helped identify source of shortfall in radiated energy**
  - Due to double counting of source
  - Trhs source term is missing pefrac=ne/ntot, ntot=ne+ni+nz+neutrals
- **Similar fast-injection simulations also performed with neon**

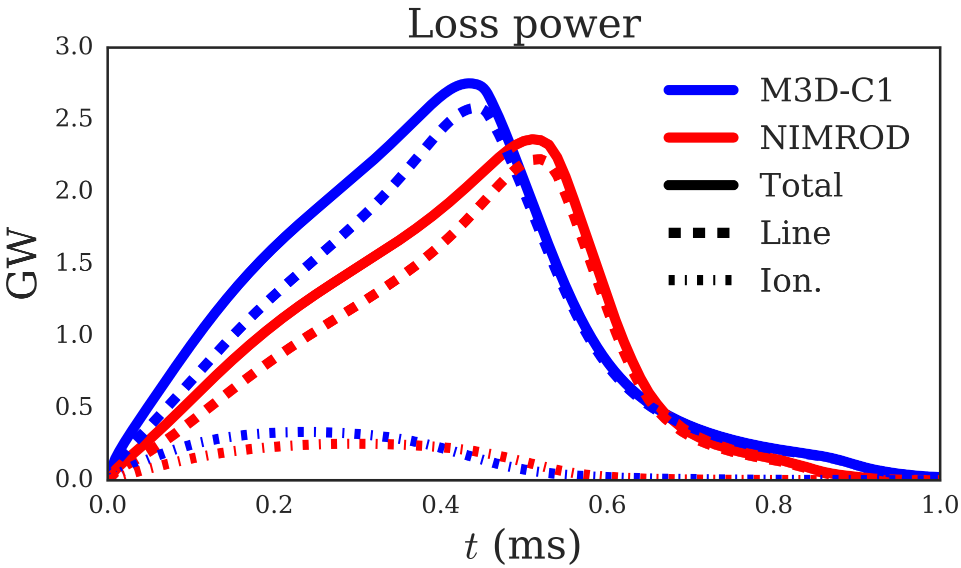
# Codes see similar rate of electron production

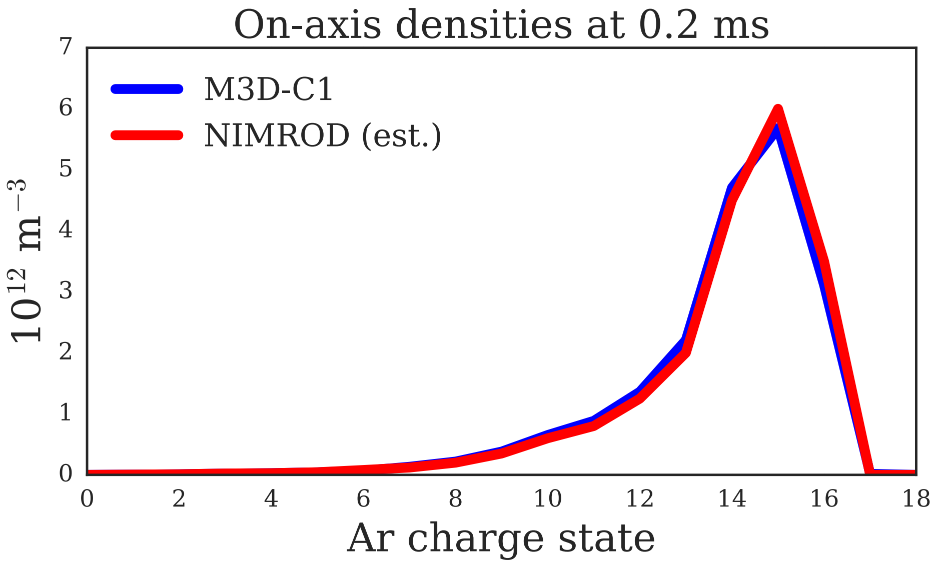
- Total electron number nearly identical at early times, indicating similar ionization rates
- Difference over long time likely due to KPRAD turning off at low temperatures in NIMROD (no recombination)

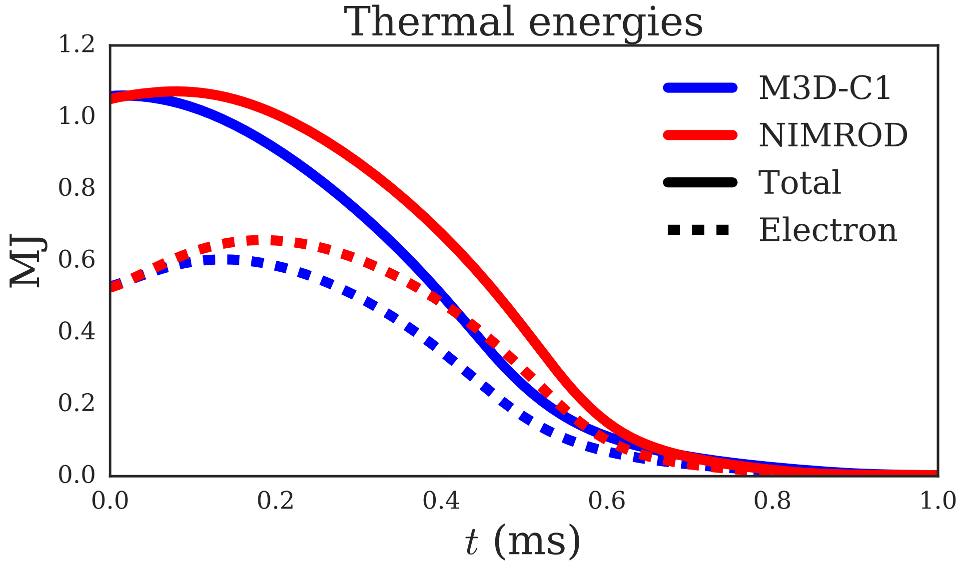


# Codes see qualitatively similar quenches, but quantitative differences

- **NIMROD sees**
  - Less loss power despite similar charge states
  - Slight increase in thermal energy early in time
  - May indicate issue with dilution
- **Detailed comparison of each source term underway**

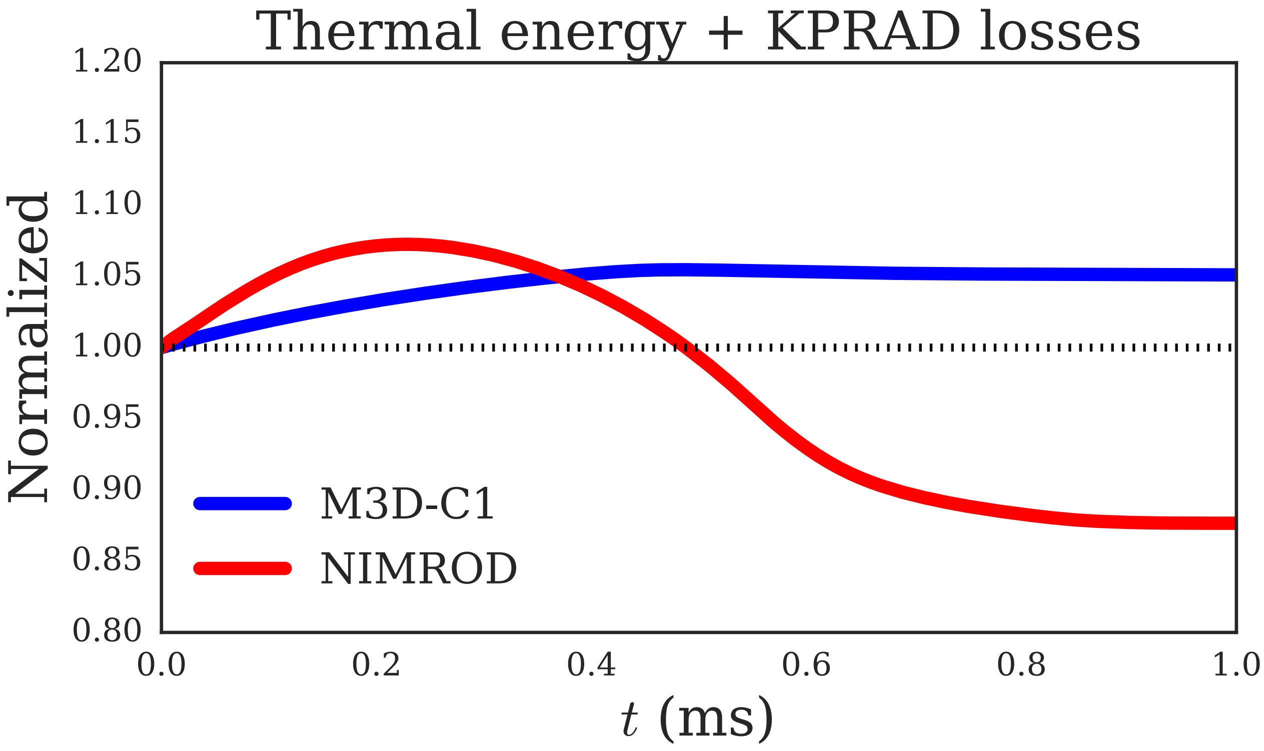

Loss power


On-axis densities at 0.2 ms


Thermal energies

# Thermal & radiated energy balance evolves more in NIMROD simulations

- **M3D-C1: thermal energy lost > radiated energy at all times**
- **NIMROD: balance changes sign with time**
- **Implementation of dilution may affect these too**



# Conclusions

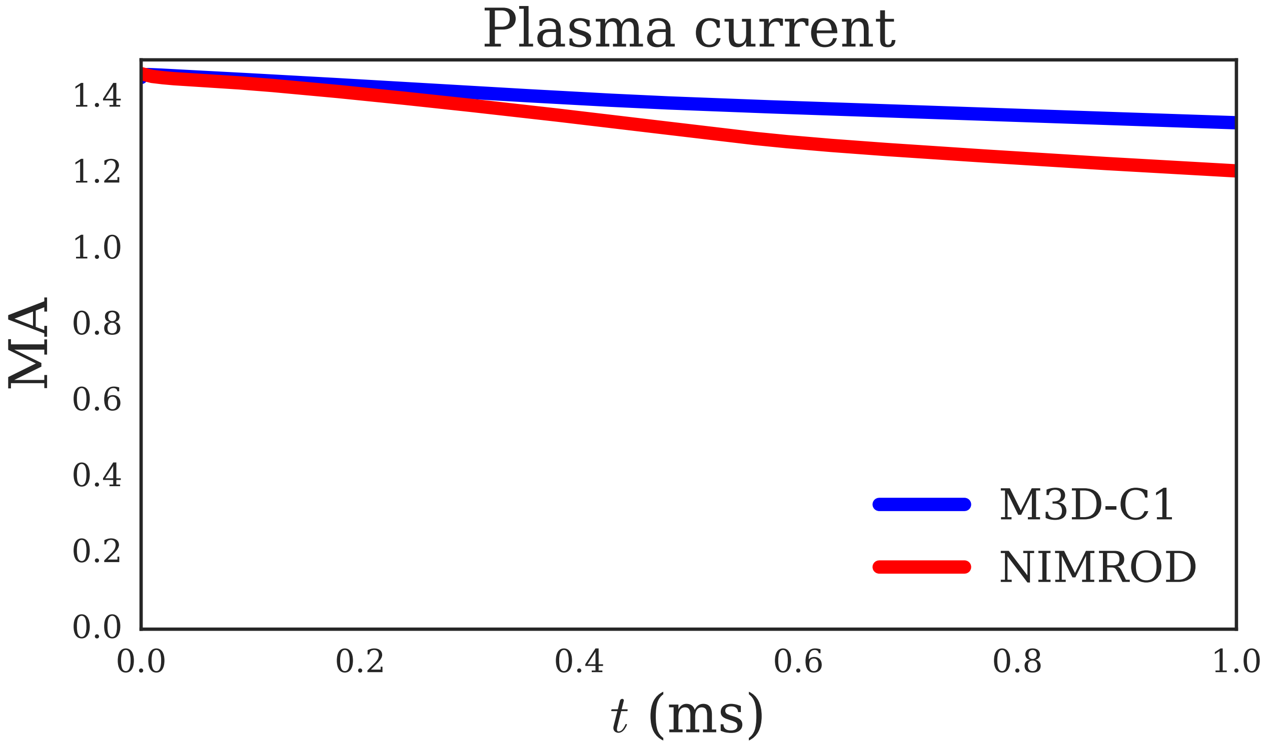
- **KPRAD has been coupled to M3D-C1, providing ionization and radiation loss model**
- **Axisymmetric argon injection test**
  - Promising initial results showing thermal quench
  - Fruitful benchmark with NIMROD ongoing
- **Future work**
  - Continue 2D benchmark and track down source of discrepancies
  - Perform benchmark with other impurity species (e.g., neon)
  - Perform 3D nonlinear benchmark, allowing for MHD instabilities
  - Implement pellet ablation model within M3D-C1
  - Validate coupled KPRAD/M3D-C1 to DIII-D pellet-mitigation experiments
  - Perform predictive simulations for ITER pellet mitigation

# Other CTTS work at GA

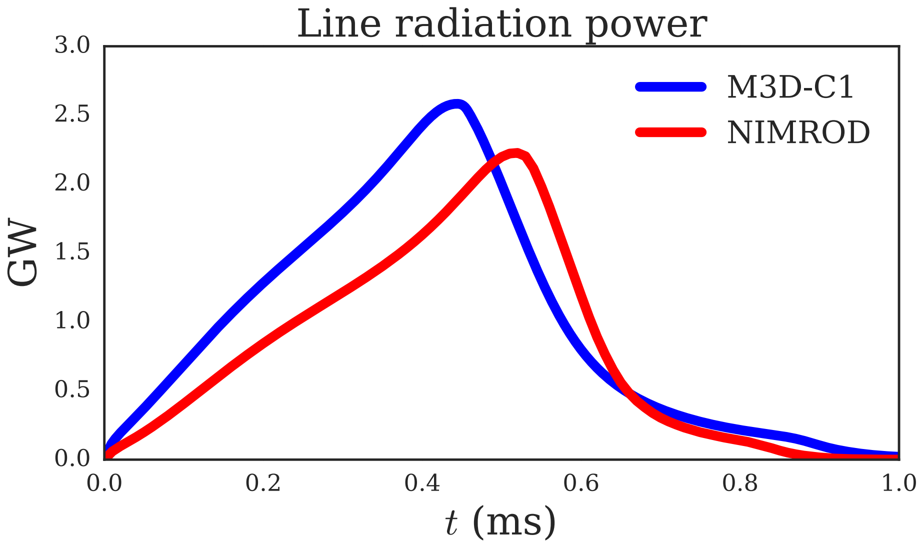
- **Charlson C. Kim**
  - Continuing SPI simulations of D3D and ITER
  - Developing runaway electron capabilities in NIMROD (as part of SCREAM effort)
- **Paul B. Parks**
  - Working with Roman on FRONTIER (later presentation)
  - Preparing key paper for PoP submission: “The ablation rate of some low-Z pellets in fusion plasmas using a kinetic electron energy flux treatment”
- **Yueqiang Liu**
  - Performing systematic scans of MGI with NIMROD
  - Runs with radiation correction from benchmark are currently underway

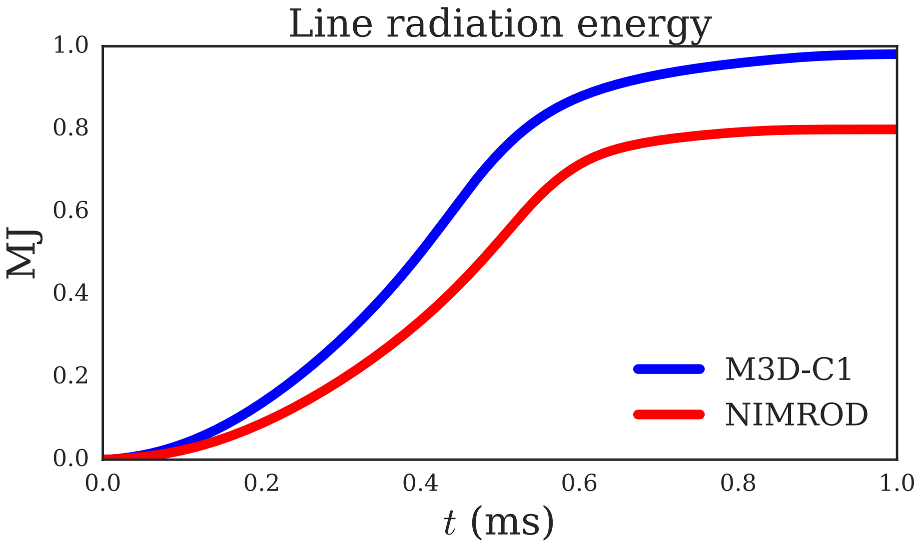
# Additional slides

# Plasma current

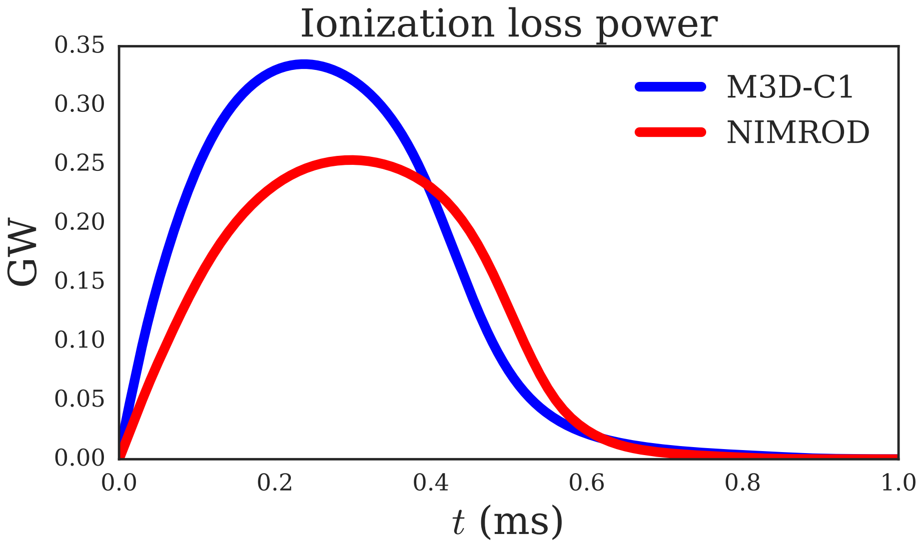


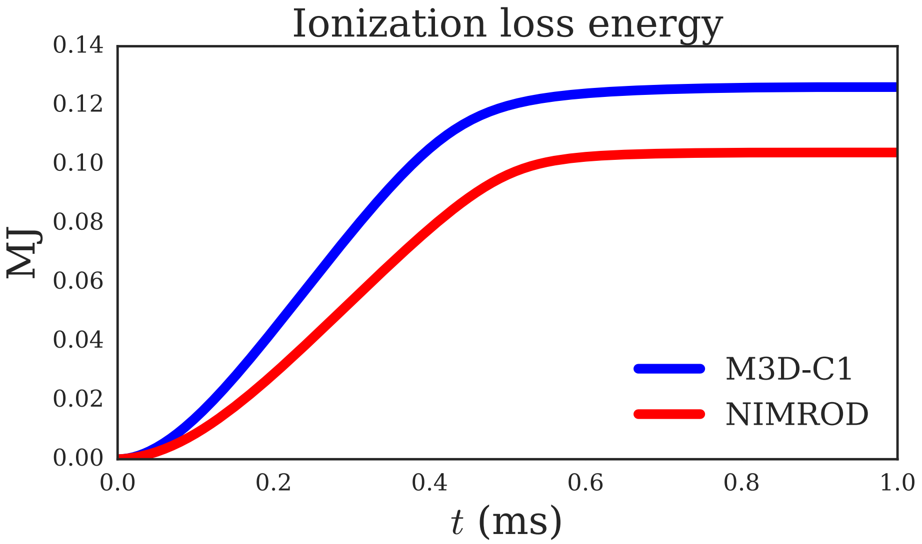
# Line radiation



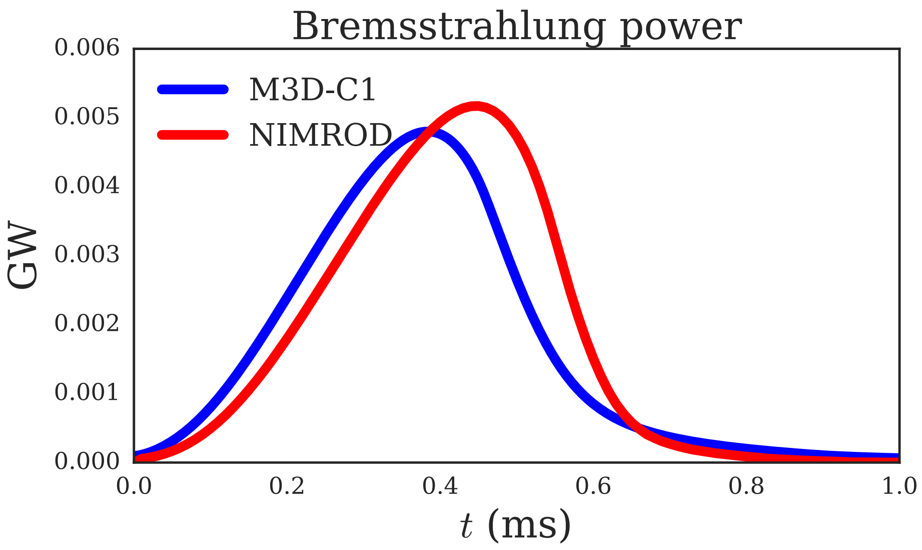


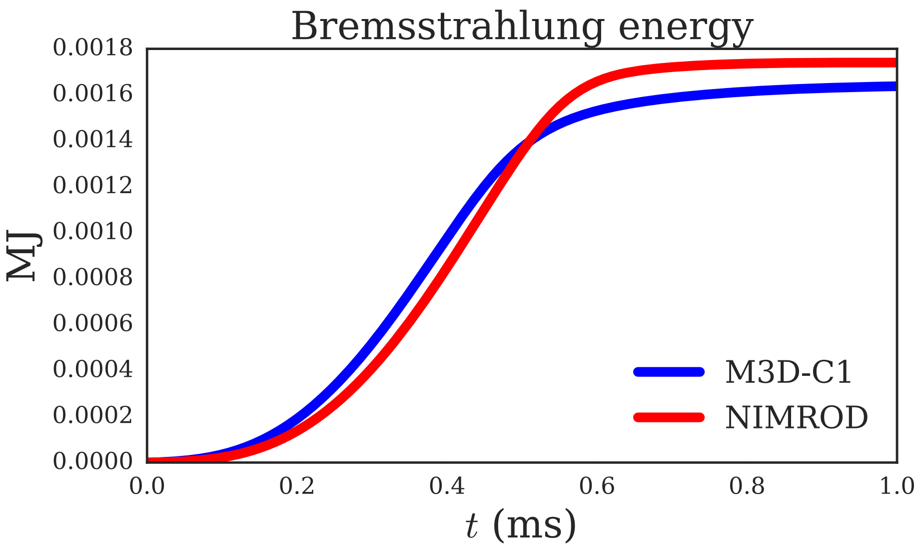
# Ionization loss



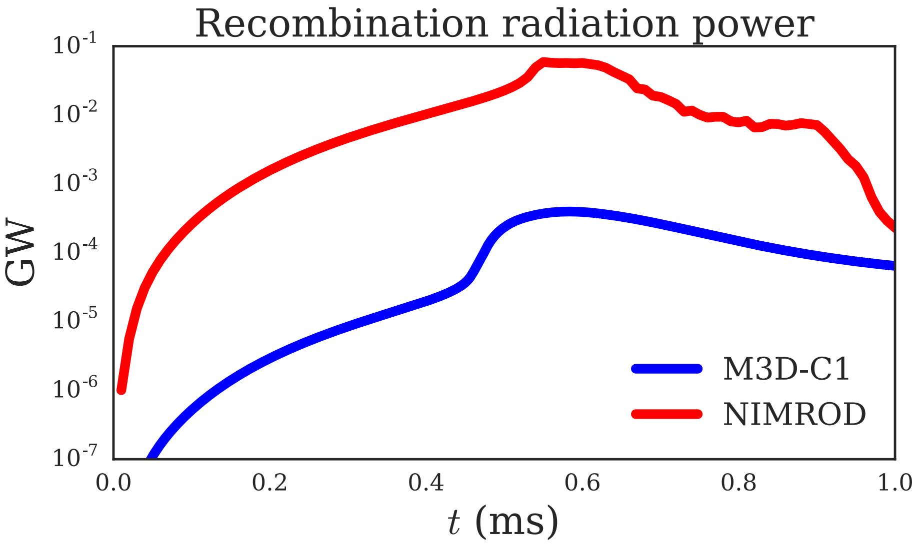


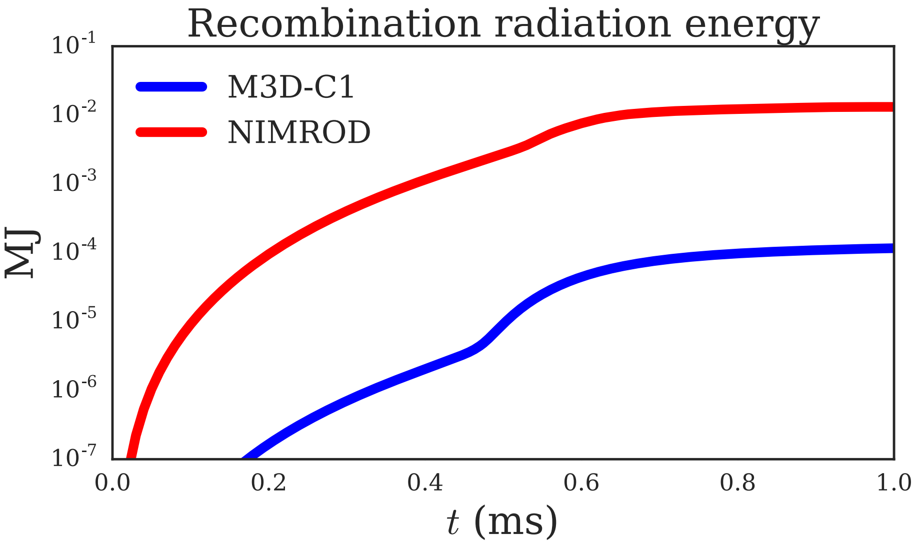
# Bremsstrahlung radiation


Bremsstrahlung power


Bremsstrahlung energy

# Recombination radiation


Recombination radiation power


Recombination radiation energy