Progress on Disruption Modeling

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for

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CTTS- Physics Team

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CTTS-Physics Topics

Based on development and application of NIMROD and M3D-C1 codes

1.0 Ideal MHD Driven Disruptions
- 1.1 Prediction and Avoidance of Disruptions
- 1.2 3D Modeling of the Thermal Quench
- 1.3 3D Modeling of the Current Quench

2.0 VDEs and RWMs
- 2.1 Vertical Displacement Events
- 2.2 Resistive Wall Modes

3.0 NTMs and Mode Locking
- 3.1 Kinetic-MHD Stability of NTMs
- 3.2 Locking of NTMs in the presence of resistive walls and error fields
- 3.3 Growth of Locked Modes and how they cause disruptions

4.0 Disruption Mitigation
- 4.1 SPI Plume Model Development
- 4.2 SPI Simulations and Modeling

Emphasize code benchmarking in new regimes

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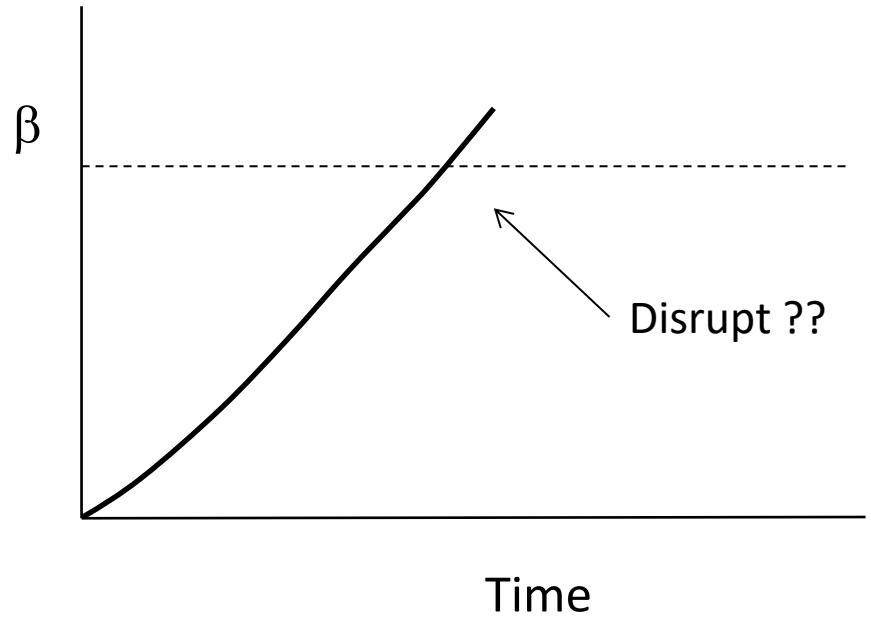
1.1 Prediction and Avoidance of Disruptions

- When does crossing a linear instability boundary lead to a disruption (hard limit)?
- When does it merely lead to increased transport which limits the β (soft limit)?



- To explore this, we have performed some long-time simulations of NSTX discharges that reach or exceed the linear ideal-MHD β-limit.
- To separate the physical mechanisms we perform identical calculations in 2D and in 3D to isolate the 3D effects

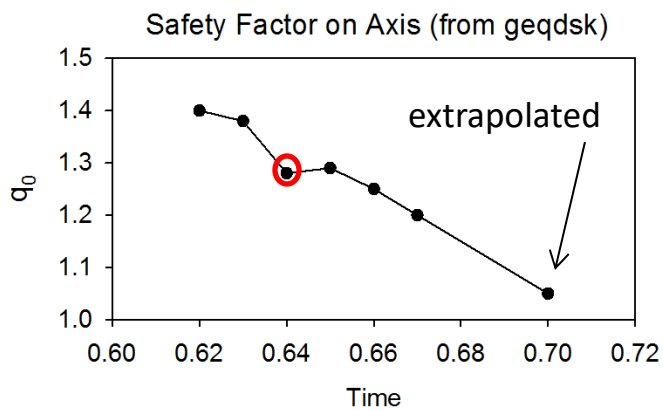
Possible mechanism for soft beta limit

Shot 124379

Time .640

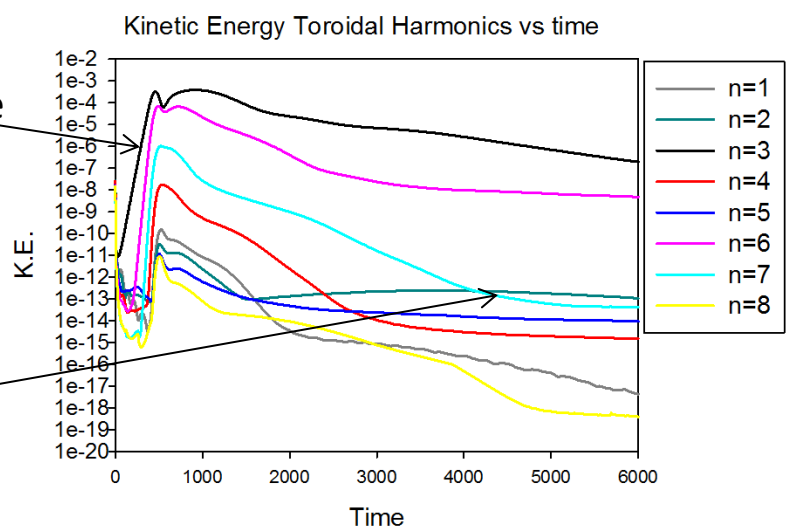
$q_0 = 1.28$

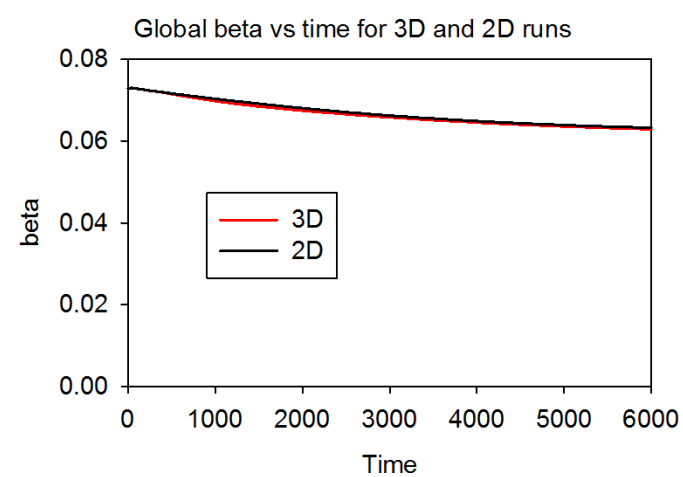
No toroidal rotation



Initially, only n=3 is unstable

All modes saturate with K.E. decreasing with time





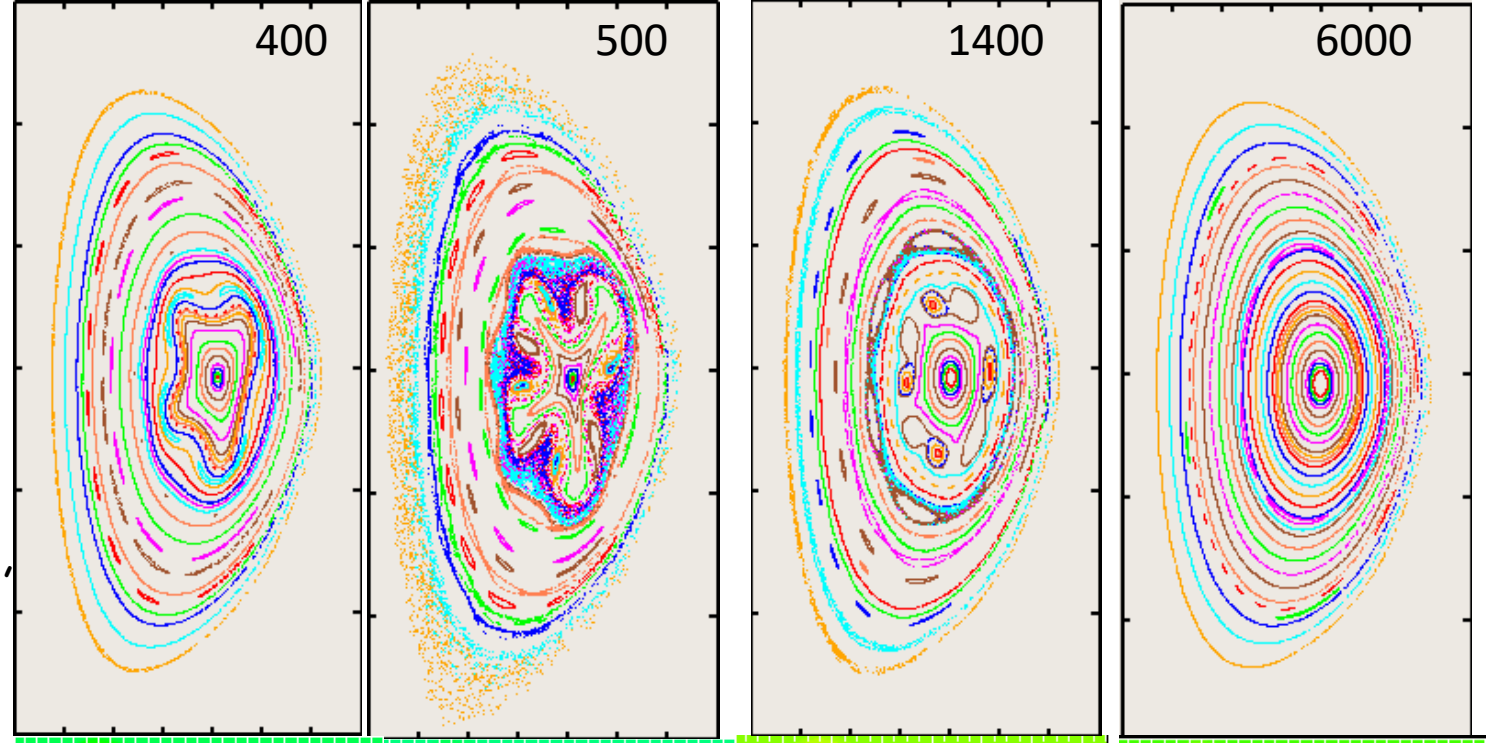
β decreases slightly in time, but no more than in an 2D run with same transport model

Soft beta limit

$q_0 = 1.28$

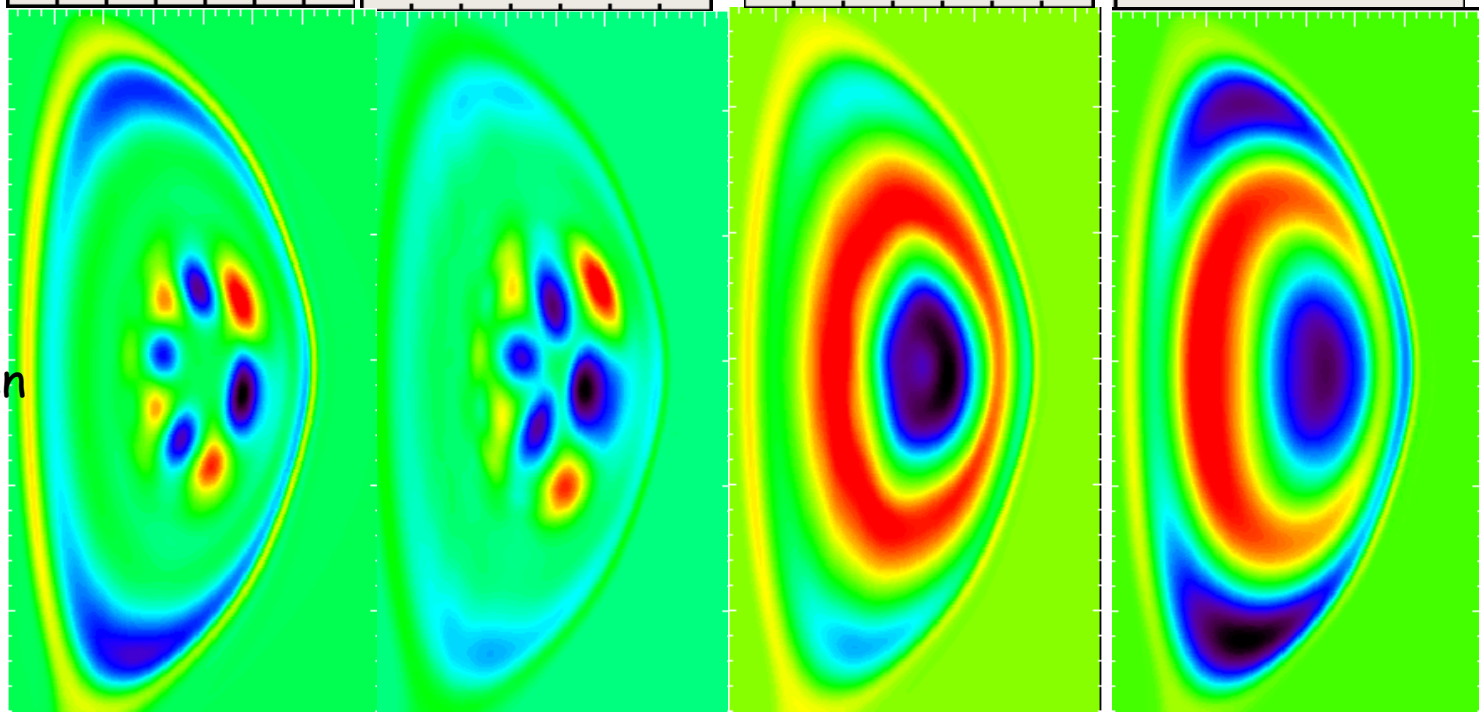
Poincare plots →

Surfaces deform, become stochastic, & completely heal.



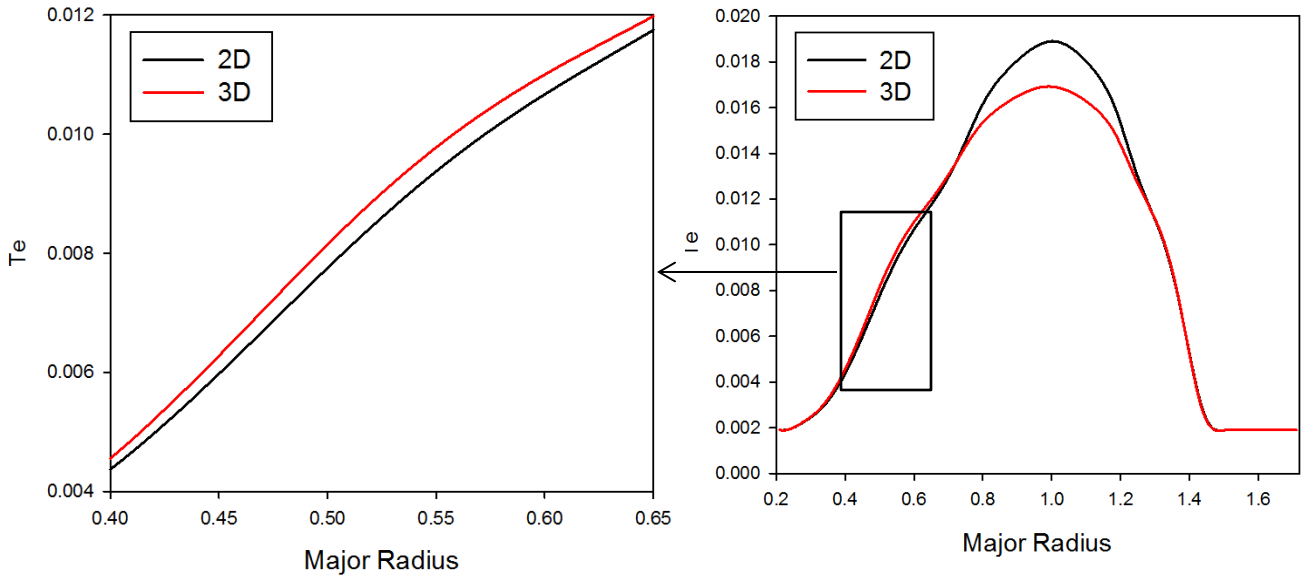
ΔTe →

First pure n=3, then nonlinear, finally axisymmetric annulus



Job33

soft beta limit -- continued



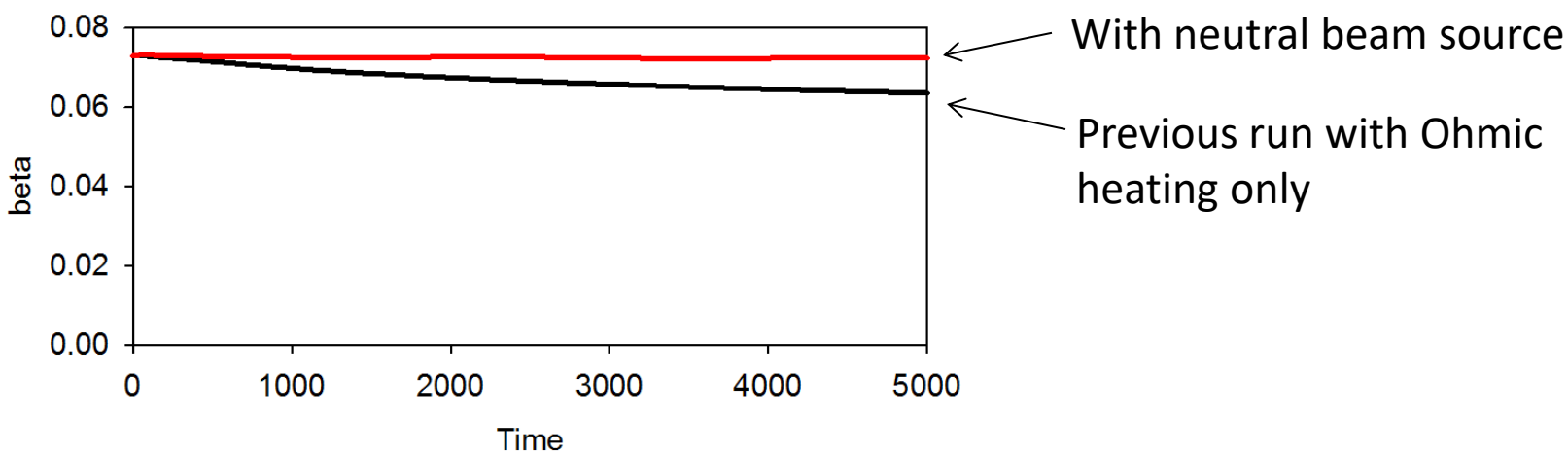
- Comparison of 3D run at t=6000 with 2D run with identical transport coeffs. shows thermal energy has been redistributed.

- Central Te differs by 10%, beta differs by only 0.6 %

dependence on heating source

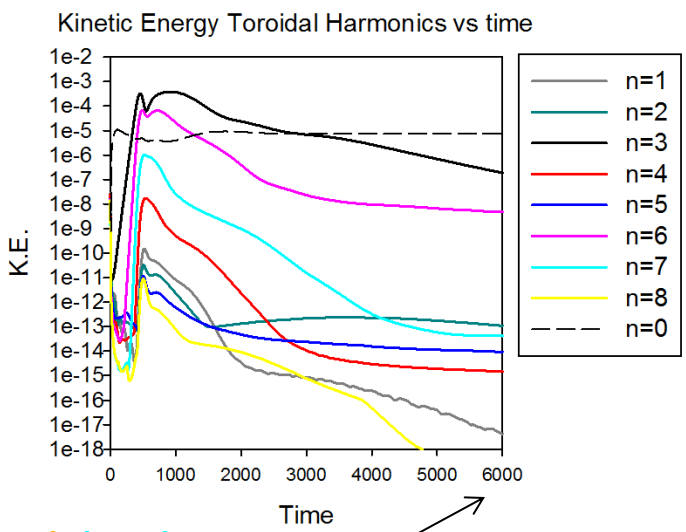
- Previous run had beta decreasing in time, even in 2D case, because there was no heating source (except Ohmic).

- Now add *neutral beam source* to keep beta constant and to drive sheared toroidal rotation

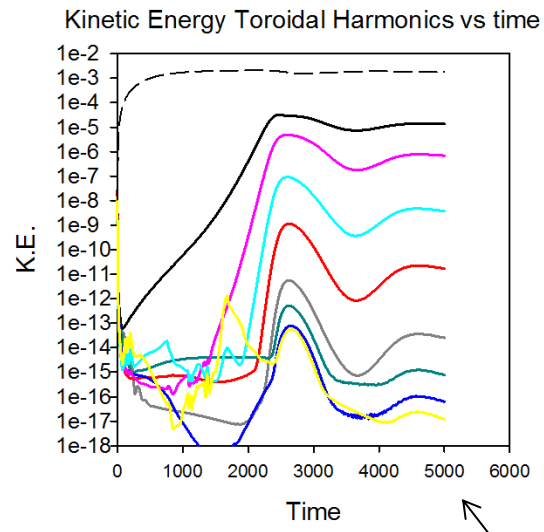


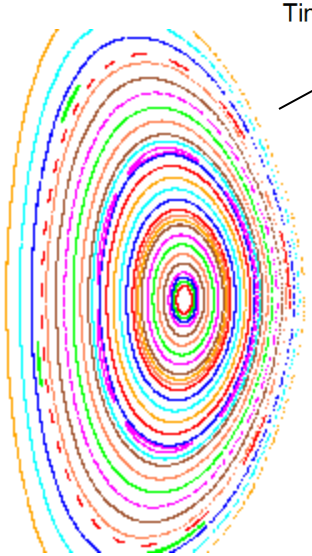
dependence on heating source-cont.

Ohmic heating only



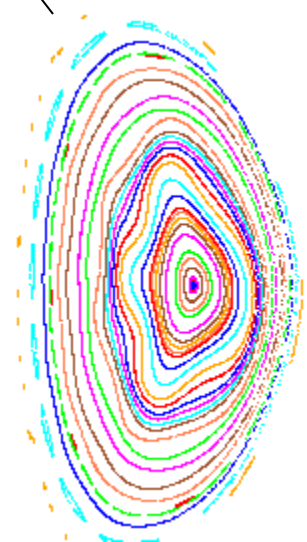
With neutral beam source



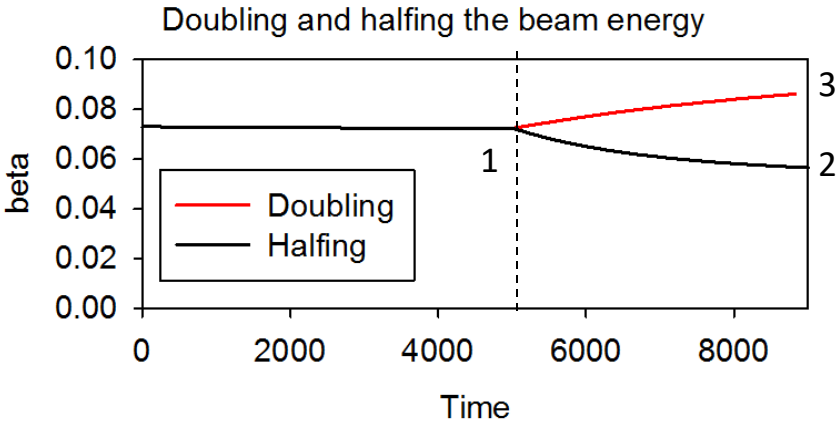


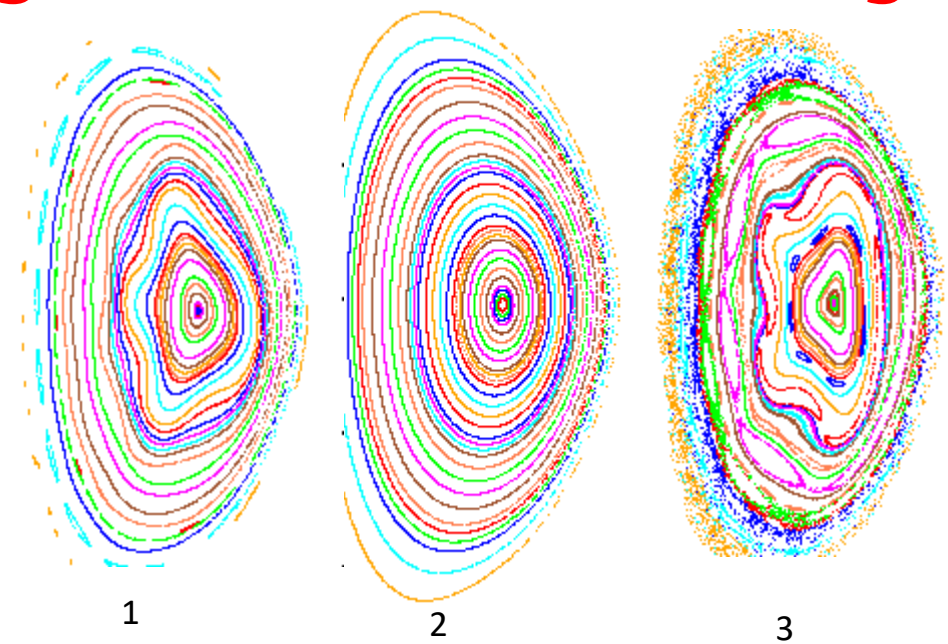
With heating and momentum source:
(constant beta and sheared rotation)

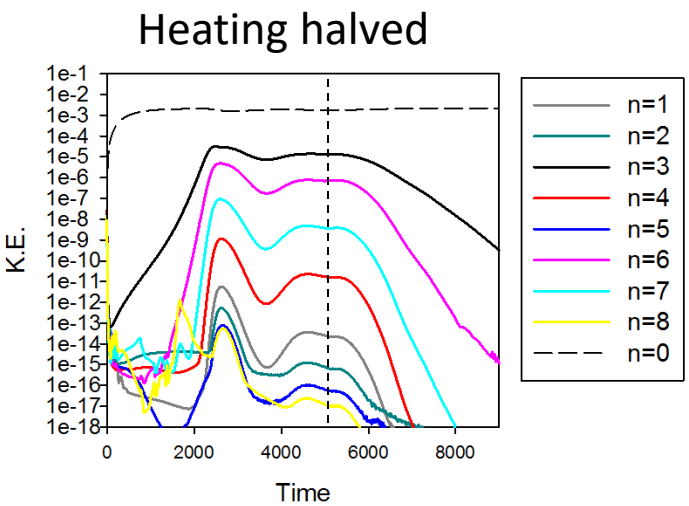
- Initial linear growth of n=3 mode much slower
- n=3 and higher harmonics do not decay away: surfaces distort

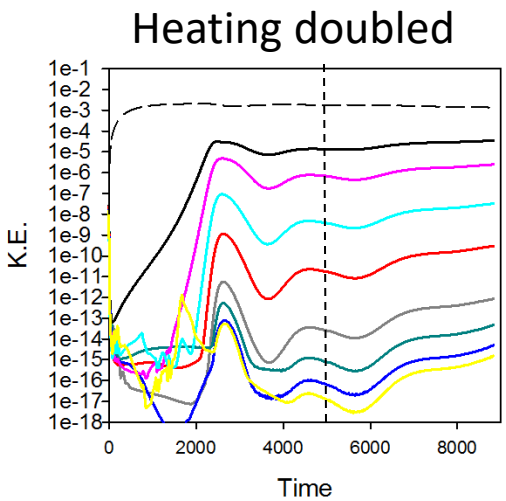


effect of increasing (decreasing) heating



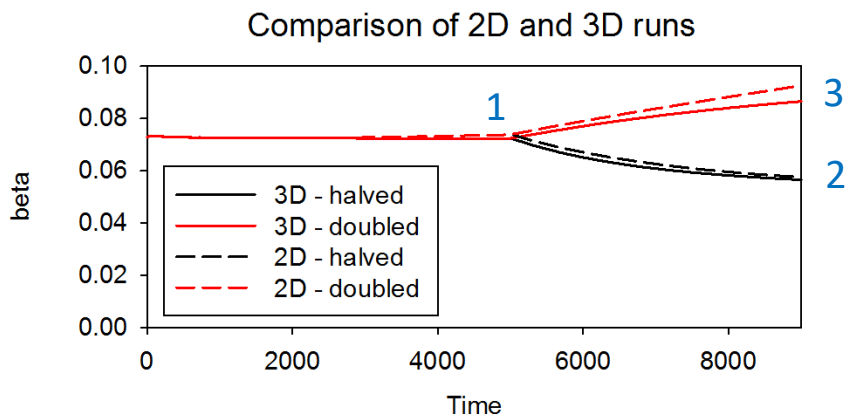




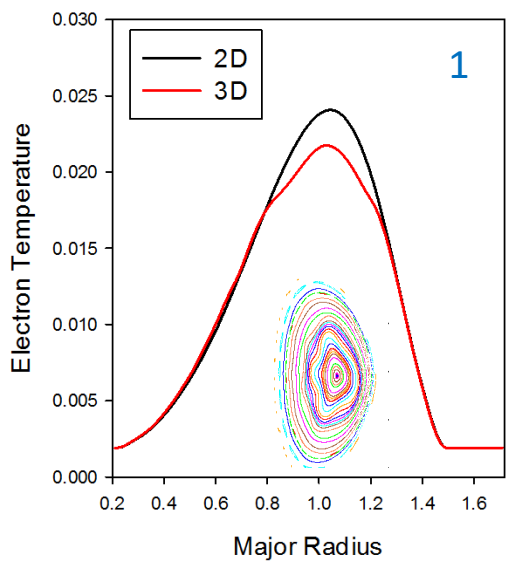


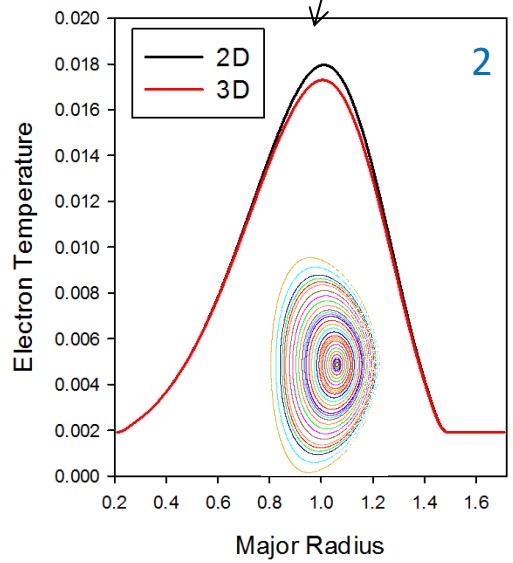
- With heating *reduced*, plasma returns to an axi-symmetric state (2)
- With heating *increased*, surfaces become more distorted, but still exhibits confinement (3)

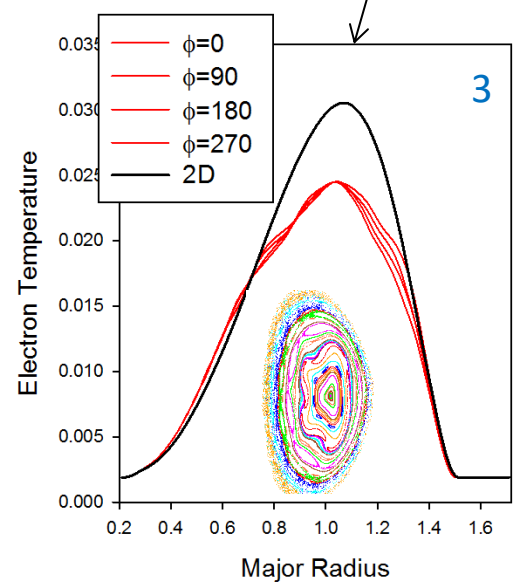
effect of increasing (decreasing) heating



- at low heating power, Te profiles from 2D and 3D agree
- at higher heating powers, they differ considerably



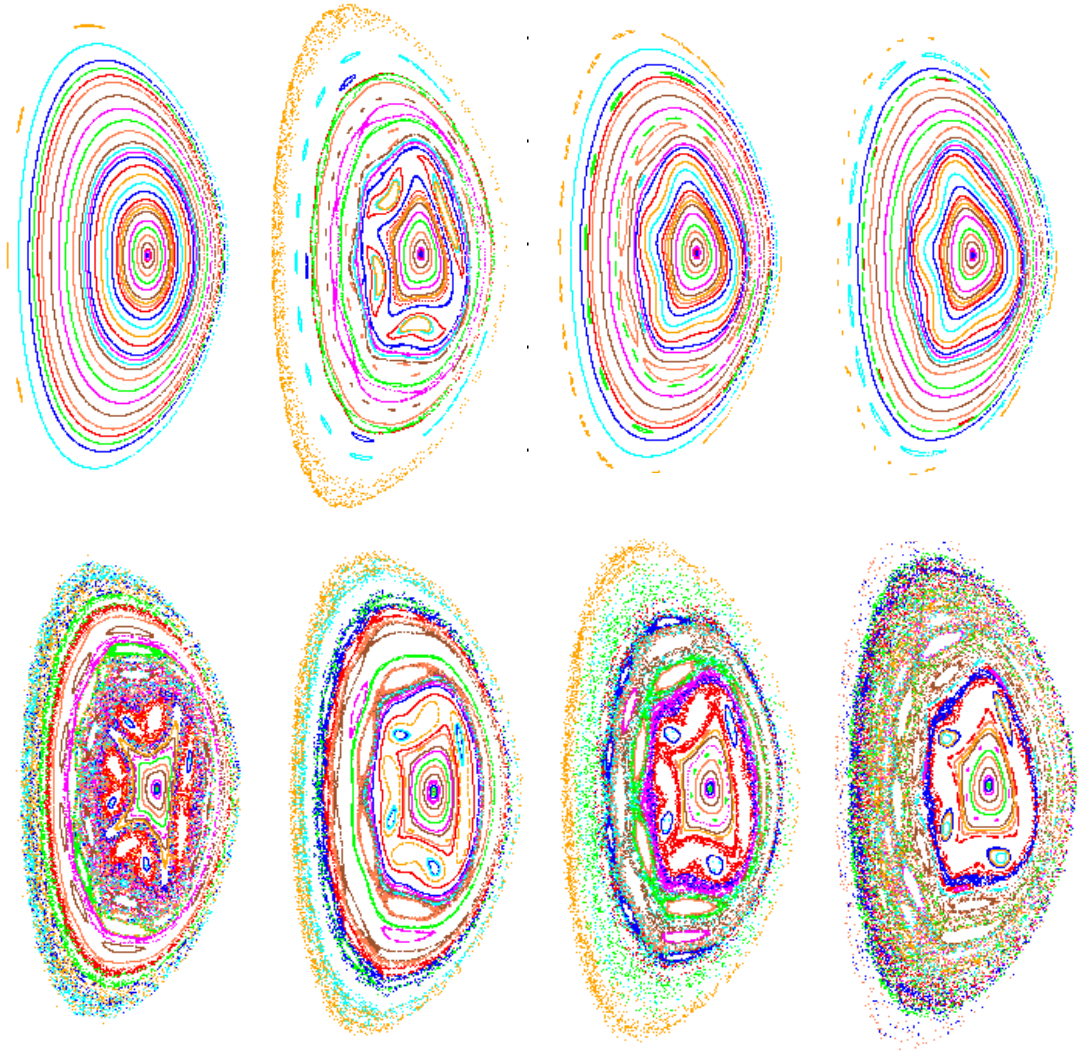




importance of sheared rotation

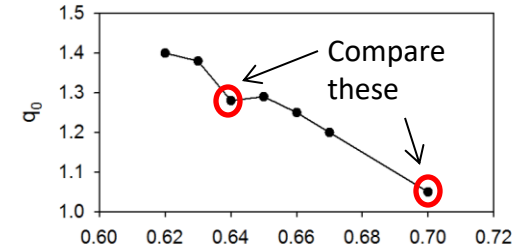
With heating and momentum input (sheared rotation)

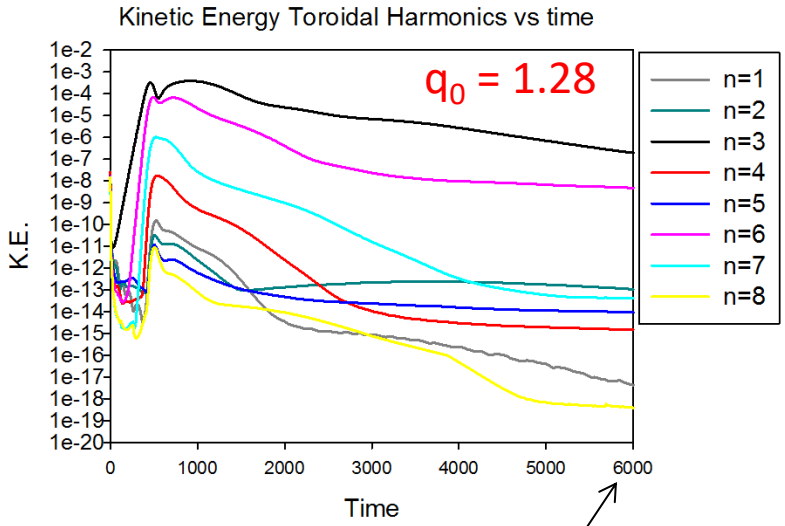
With heating only (no rotation)

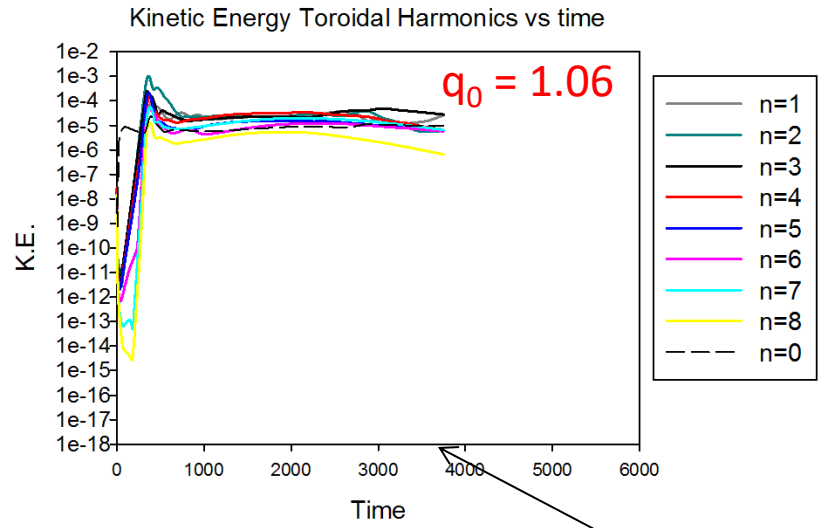


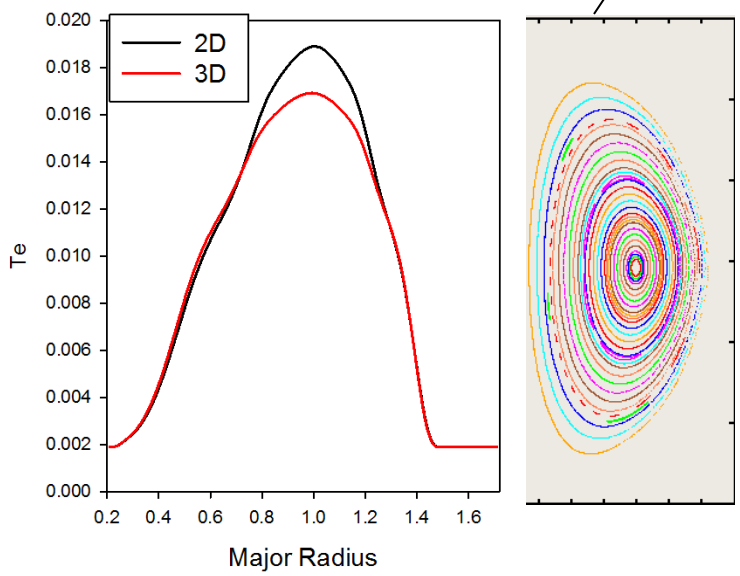
t=2000 t=3000 t=4000 t=5000

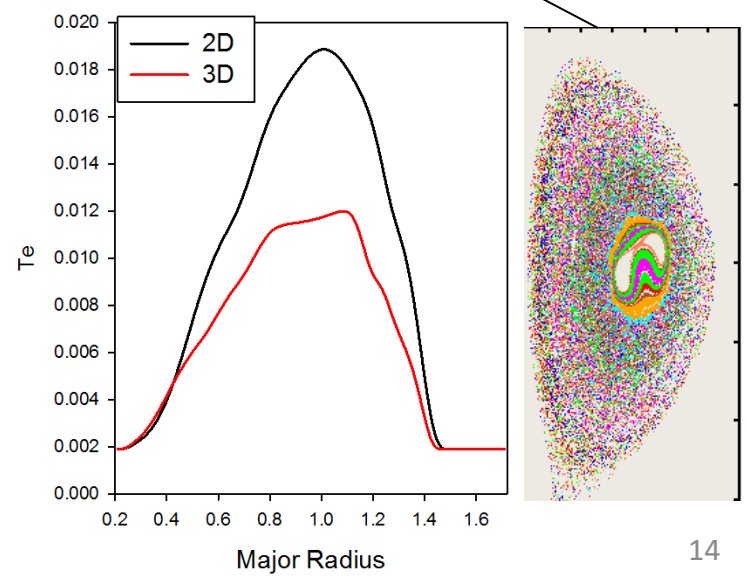
equilibrium with lower q_0 shows thermal collapse





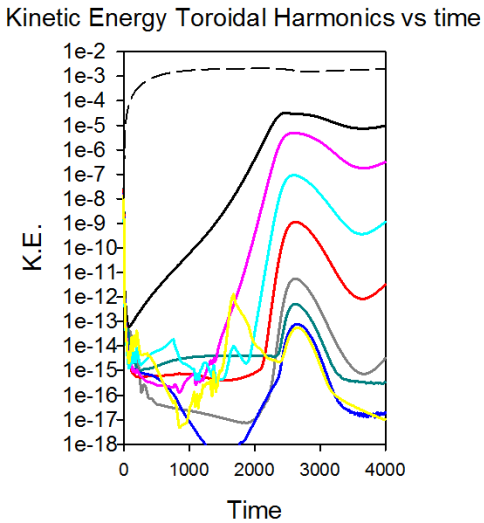


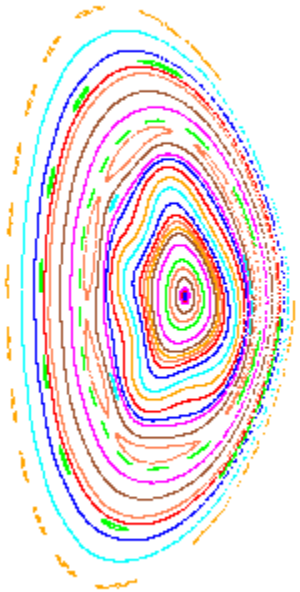




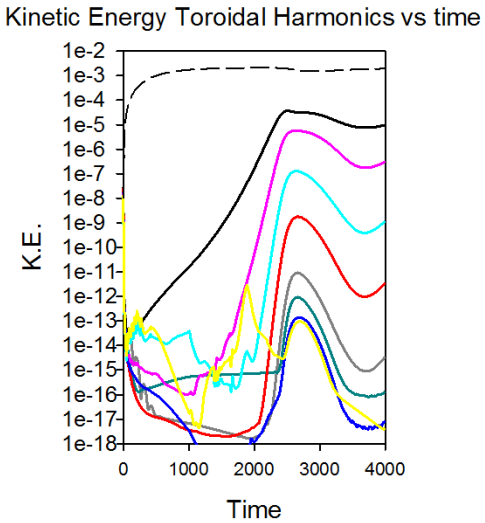
numerical convergence study

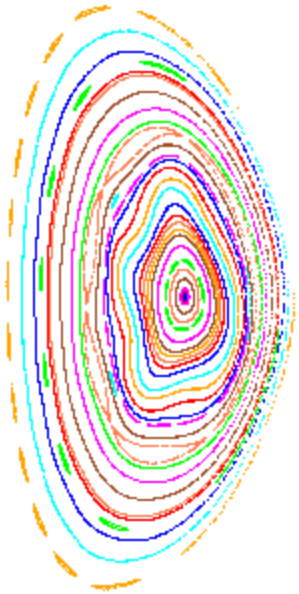
Original constant β run





With double the poloidal zones





Summary of NSTX β-limit studies

- We found some cases with q_0 ~ 1.28 where a soft limit exists
- Similar cases with q_0 ~ 1.08 seem to show a hard limit
- Much more study is needed

CTTS-Physics Topics

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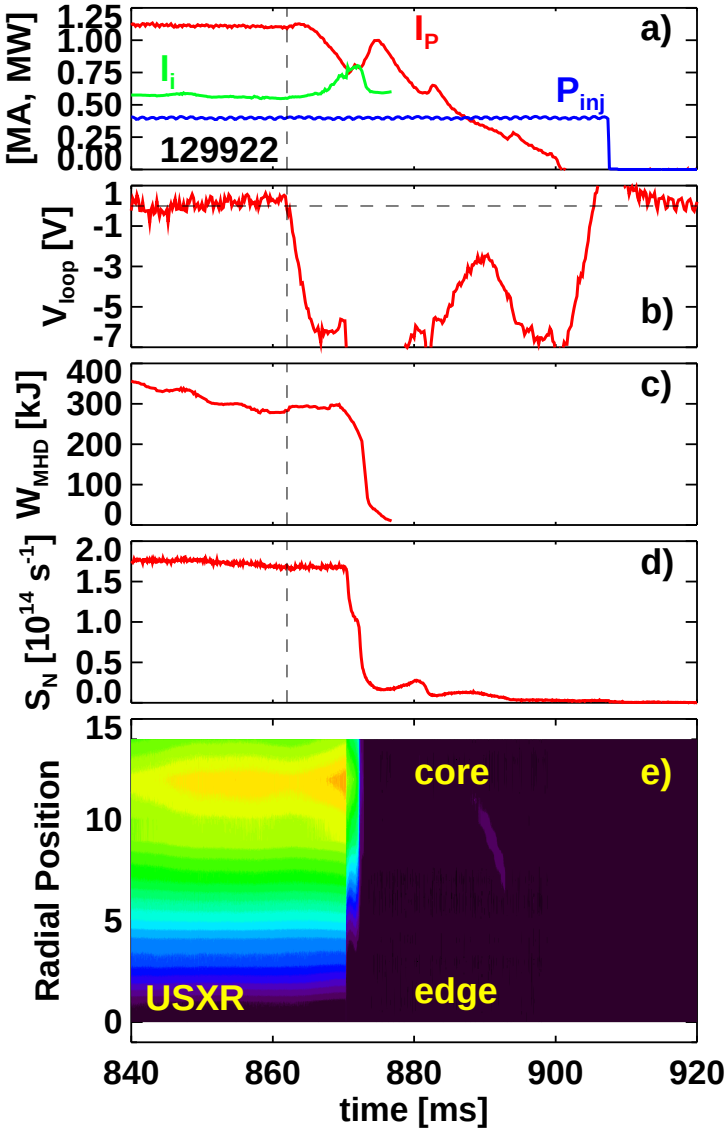
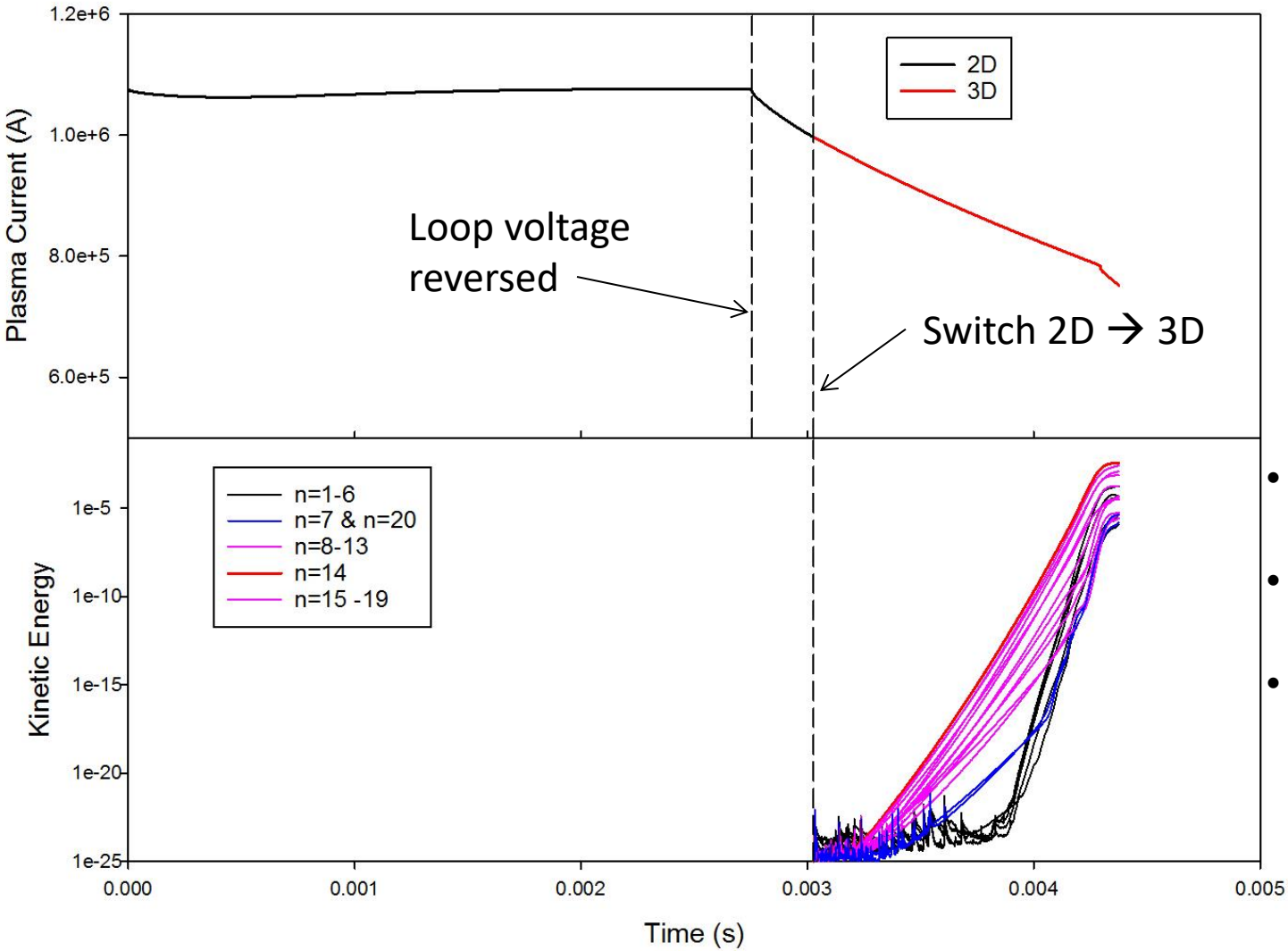
Unique Class of Major Disruptions Identified in NSTX

- Recipe:
  - Generate a stable low(er) q95 discharge.
  - Run it to the current limit of the OH coil.
  - Ramp the OH coil back to zero, applying a negative loop voltage, while leaving the heating on.
  - Watch l_i increase, then disruption occurs.
- Mechanism responsible for 21 for the 22 highest W_{MHD} disruptions in NSTX.
- Specific example in the general area of how unstable current profiles lead to catastrophic instability



[S. Gerhardt, Nov. 2013]

Current and Harmonics Plots for typical calculation



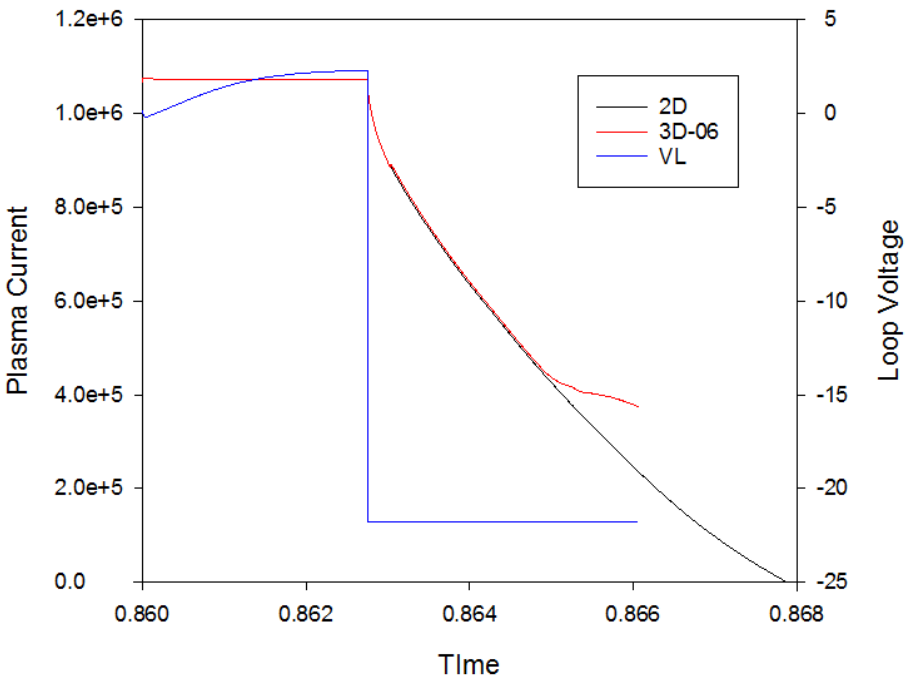
- All modes stable at start of 3D
- $7 \leq n \leq 20$ become linearly unstable
- Lower and higher modes driven non-linearly

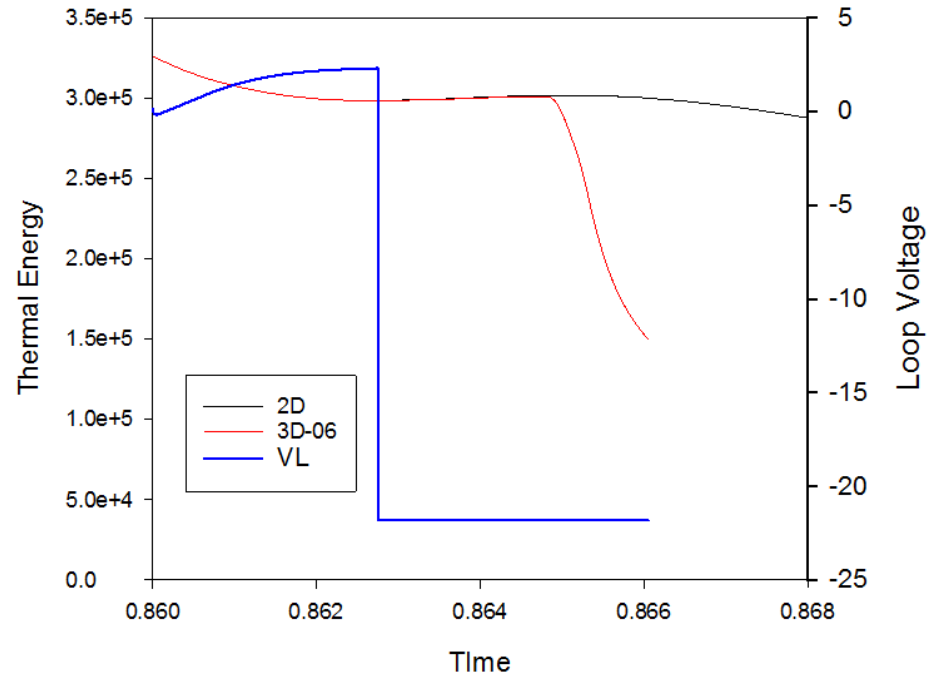
Run07

Time traces of Plasma Current, Thermal Energy, and Loop Voltage

Compare:

- 2D (axisymmetric) run (black)
- 2D -> 3D run (red)





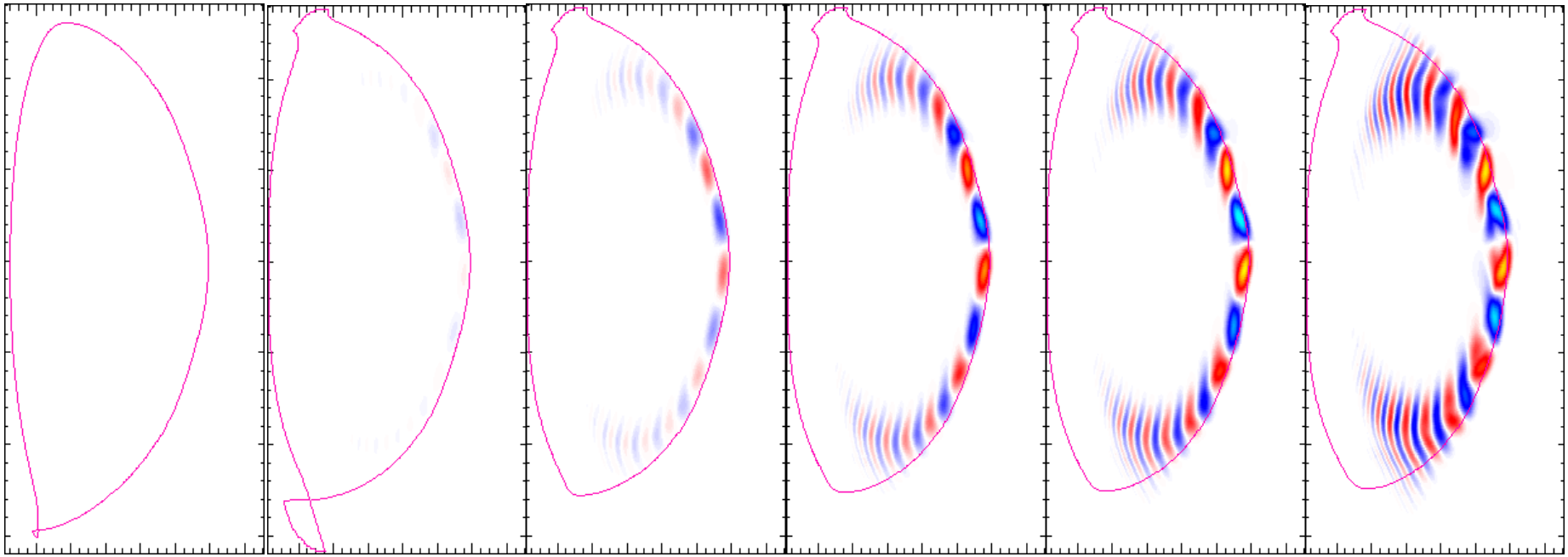
- Both runs have identical I.C. and boundary conditions (V_L)
- 3D run has slower current decay near end of calculation
- 3D run shows thermal energy loss, 2D run does not

Run06b

Run05

Toroidal derivative of pressure at several time slices

1.28 ms 3.90 ms 4.10 ms 4.28 ms 4.40 ms 4.62 ms



Same color scale in all frames: strongly ballooning:

First becomes unstable at very edge, then instability moves inward. Retains linear structure.

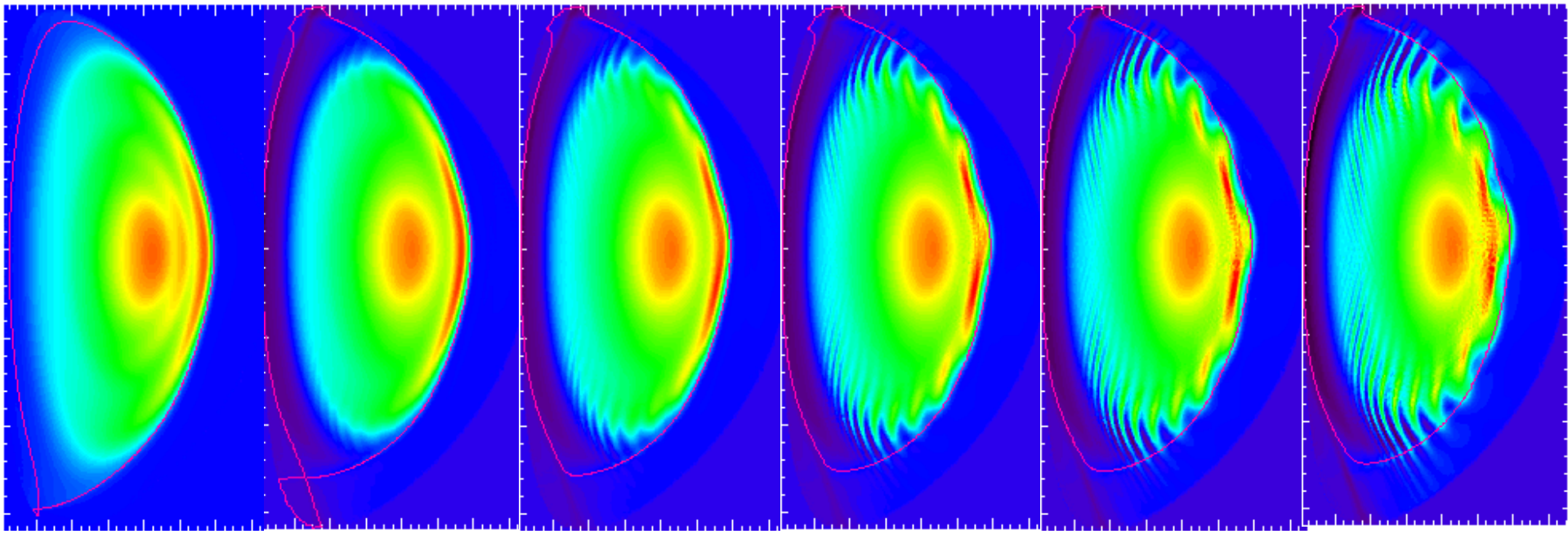
Voltage reversed at 1.28 ms

Becomes limited shortly after ramp-down starts. Impurity generation??

Run05

Plasma current density at several time slices

1.28 ms 3.90 ms 4.10 ms 4.28 ms 4.40 ms 4.62 ms



Same color scale in all frames

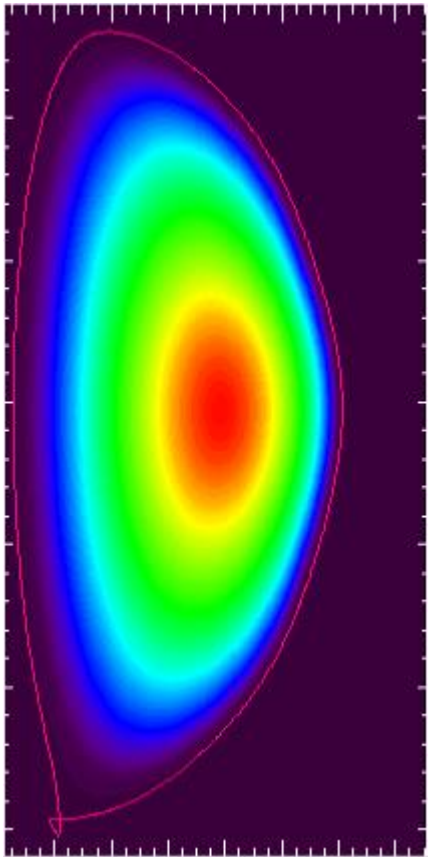
Current forms filaments all around, with shorter poloidal wave lengths on HFS

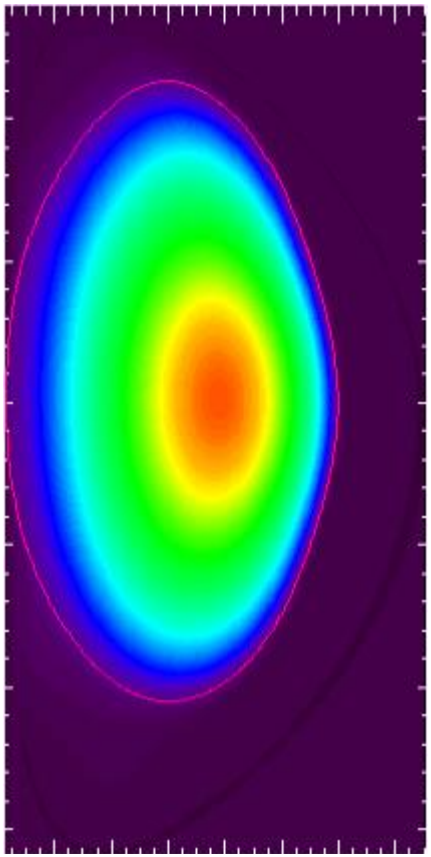
Initial Equilibrium

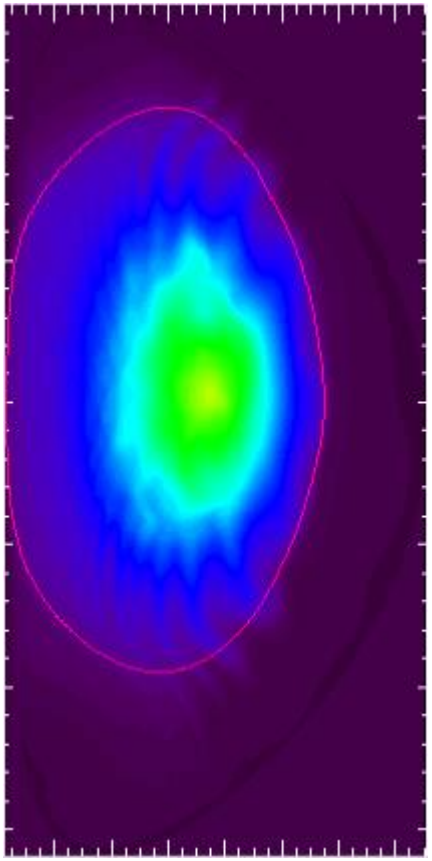
P

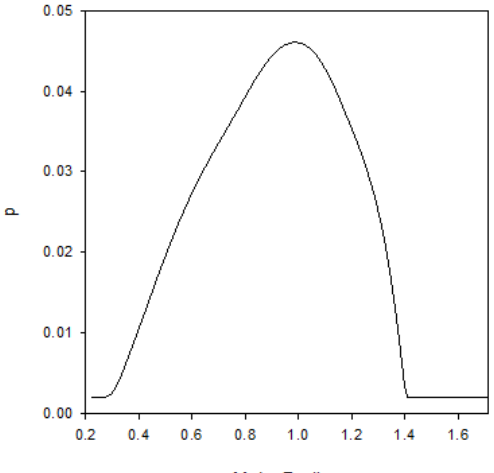
2D – t = 6.0 ms

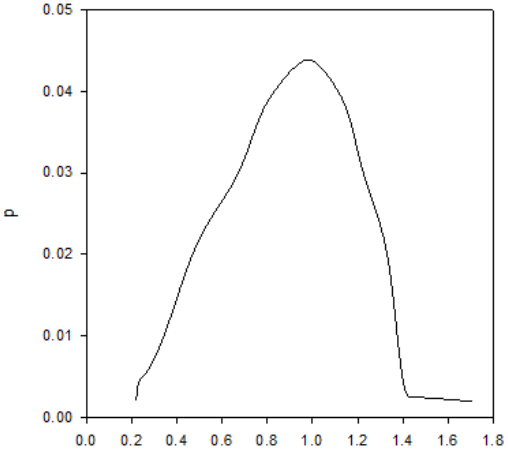
3D – t = 6.0 ms

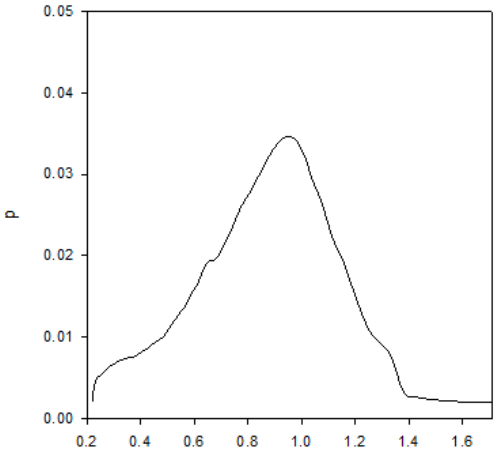












3D pressure is smaller and more peaked than 2D

Run06b

Comparison with Experimental Data:

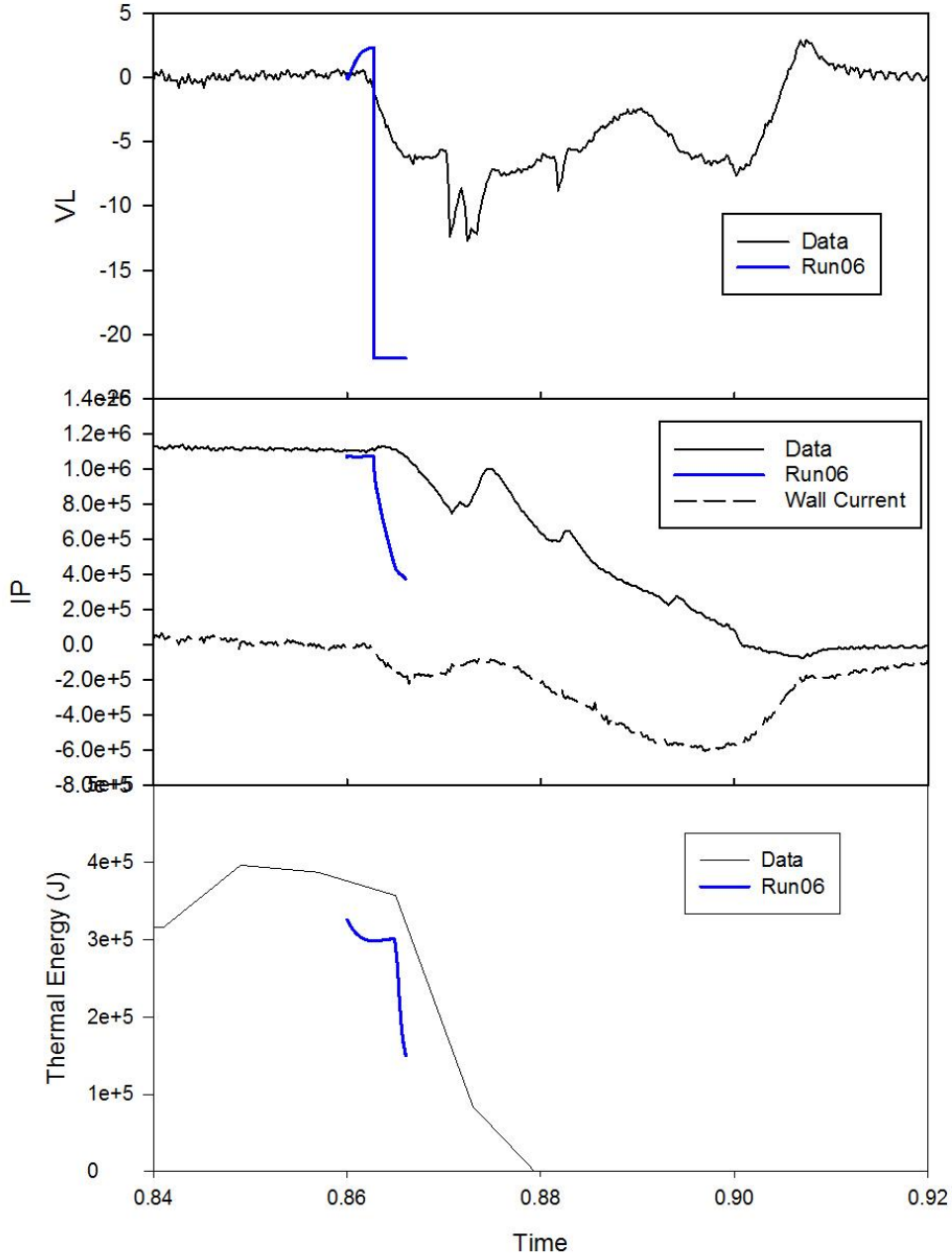
Run06: VL = -20 V

Current Quench

- Initial decay rate reasonable
- Can we see the current spike?

Thermal Quench

- Initial drop reasonable
- Need impurity radiation to get full drop?



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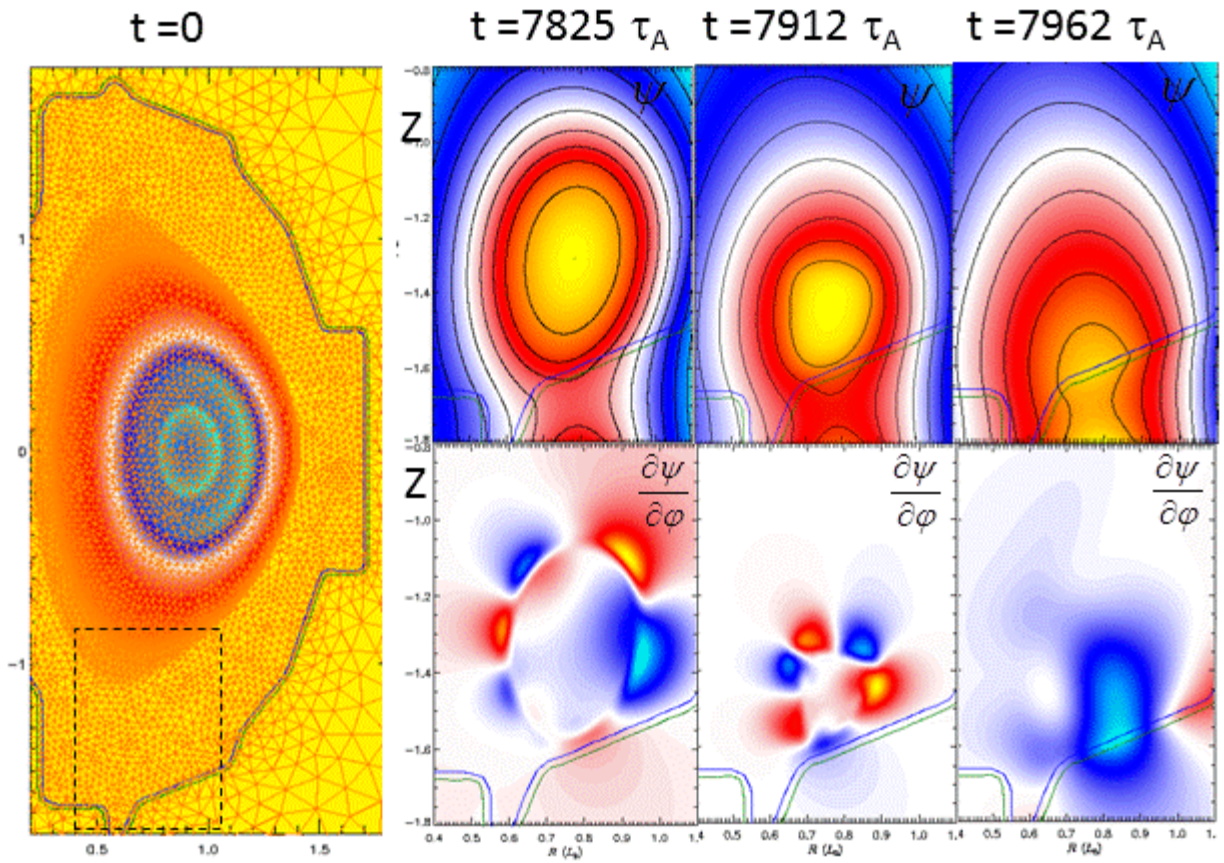
2.1 Vertical Displacement Events

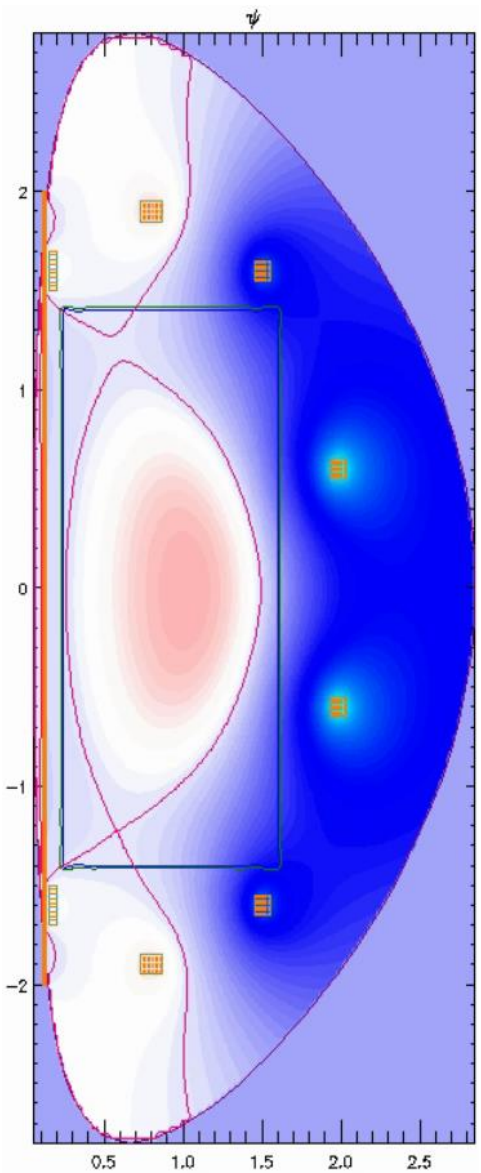
- Both NIMROD and M3D-C1 can now simulate VDEs with a resistive wall in both 2D and 3D and calculate wall forces
- Our initial emphasis is to perform benchmark calculations in both 2D and 3D , primarily for code validation … also with JOREK, DINA, TSC as time allows
- We are also validating results as much as possible with DIII-D data
- Instead of Halo Width and Temperature, we are specifying the *ratios of the parallel to perpendicular thermal conductivities*

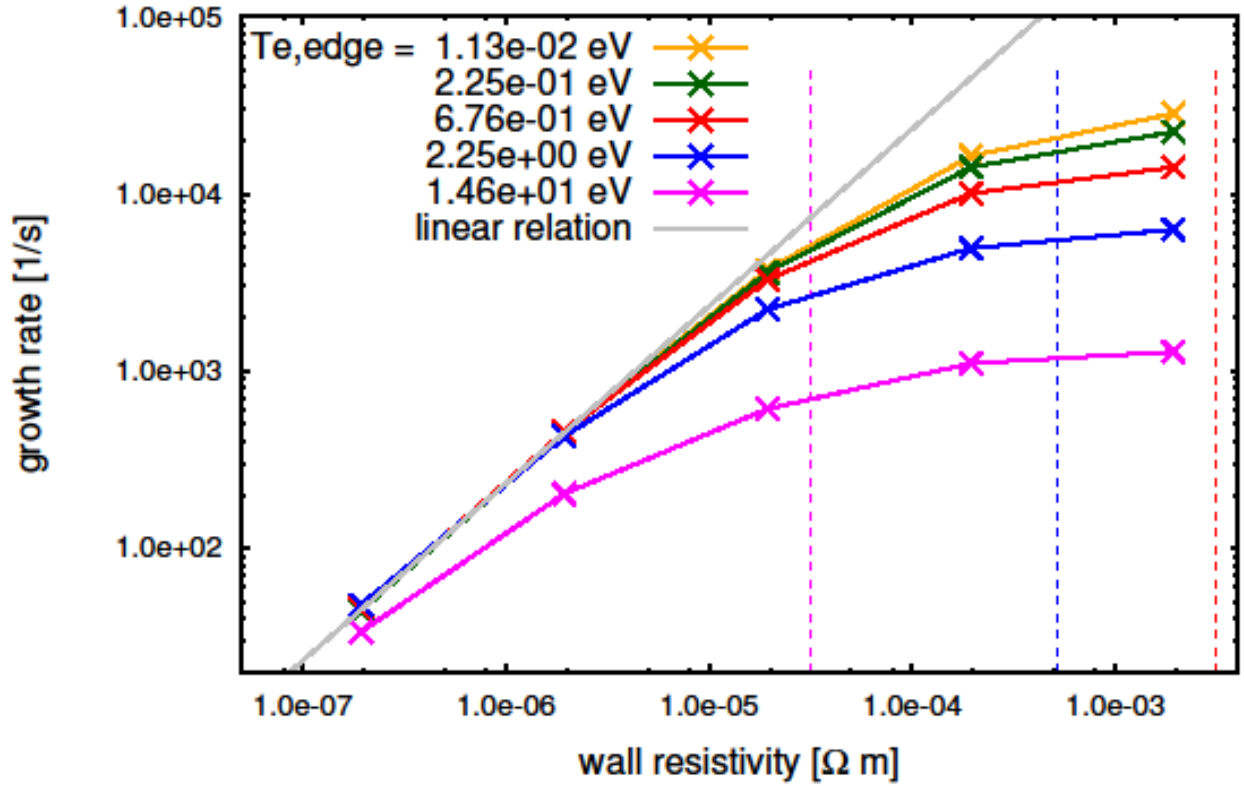
Typical result for a M3D-C1 3D VDE Simulation of NSTX



- We presently don't have any 3D benchmarks because no 2 codes have modeled the same case

Linear VDE growth benchmark: NSTX plasma in model vessel



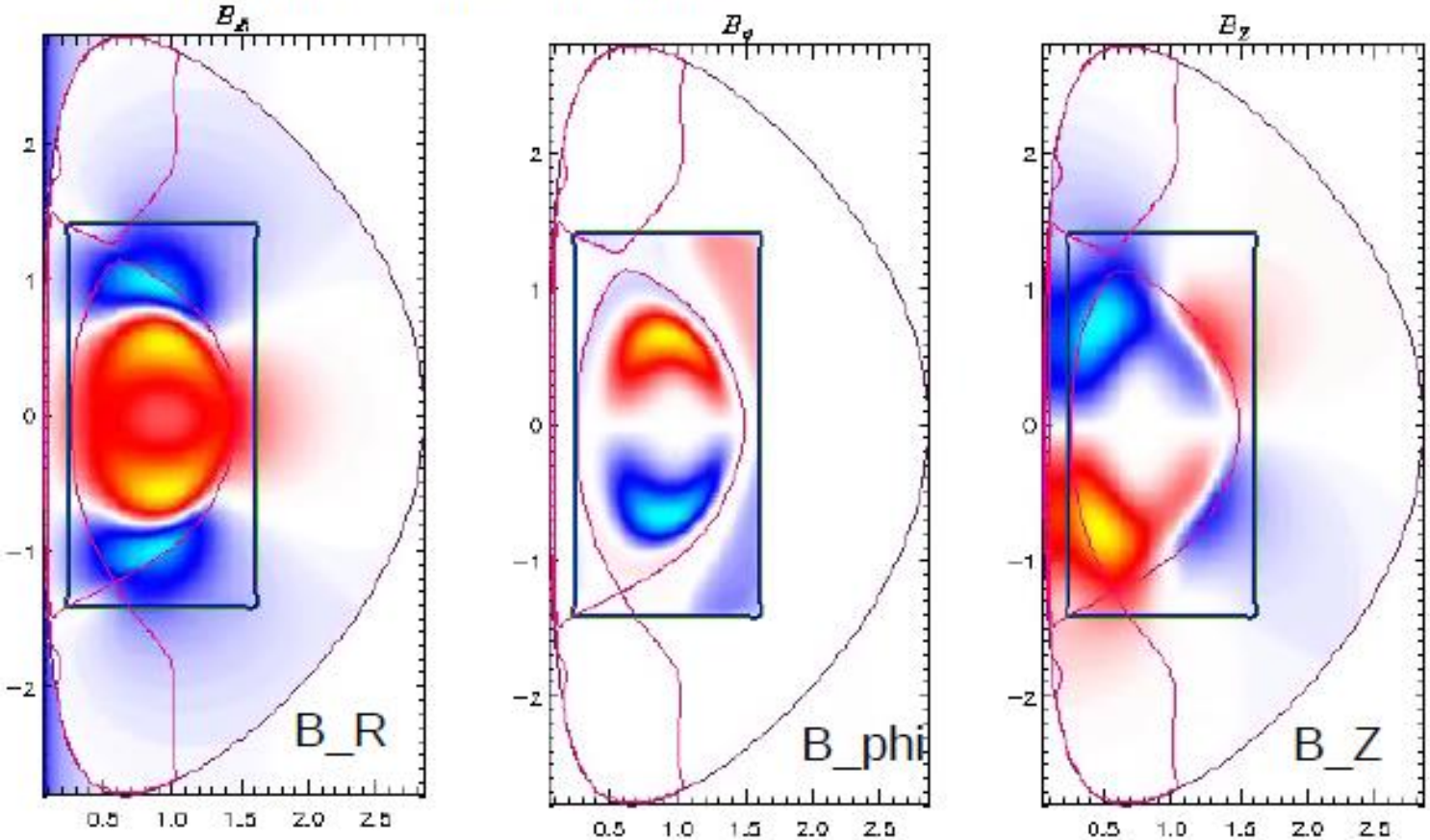


- equilibrium based on NSTX VDE discharge
- growth rate ~ wall resistivity for $\eta_{wall} < \eta_{edge}$
- edge currents dominate evolution for $\eta_{wall} > \eta_{edge}$

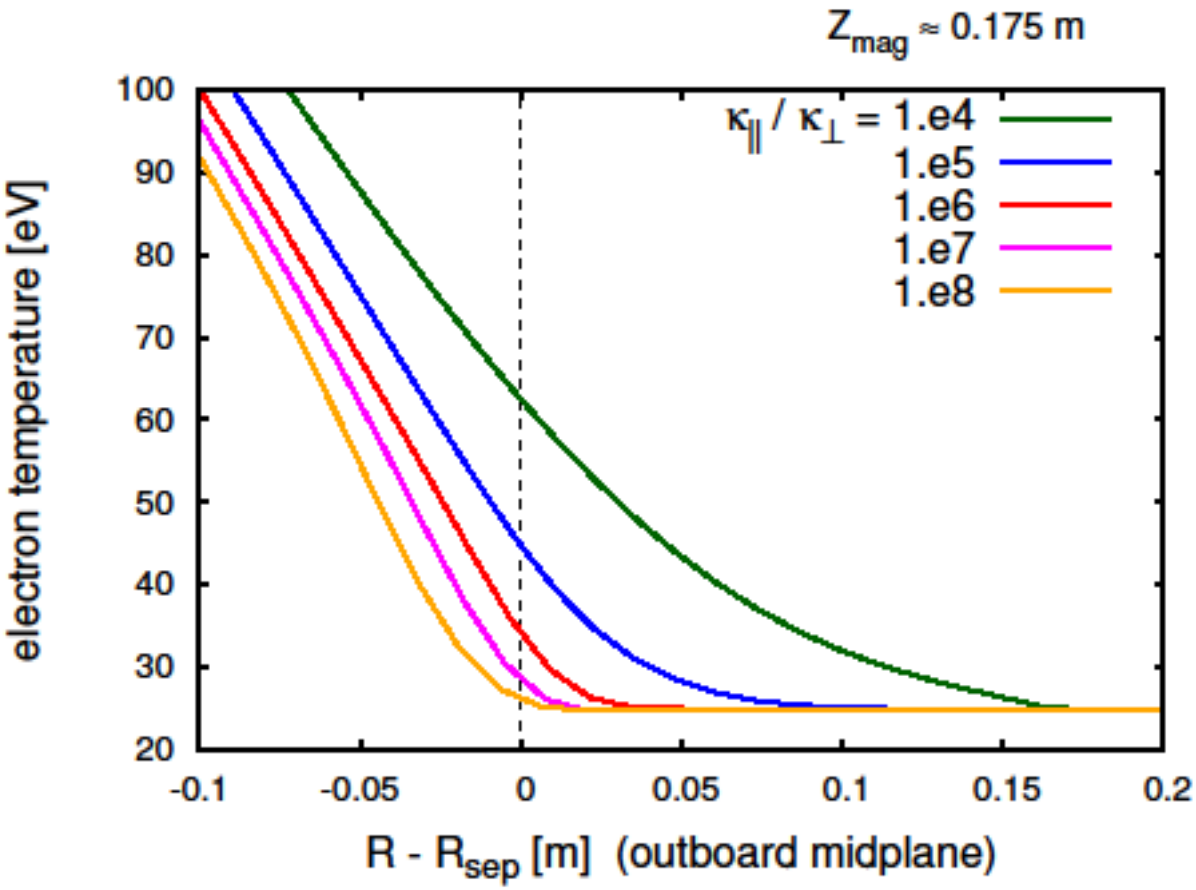
Linear VDE Eigenfunctions

wall resistivity = 1.938e-4 Ohm m
Te,edge = 1.46e1 eV

red = positive blue = negative



Heat diffusion anisotropy determines halo width



- equilibrium based on DIII-D VDE discharge
- 2D axisymmetric simulations

CTTS-Physics Topics

Based on development and application of NIMROD and M3D-C1 codes

1.0 Ideal MHD Driven Disruptions
- 1.1 Prediction and Avoidance of Disruptions
- 1.2 3D Modeling of the Thermal Quench
- 1.3 3D Modeling of the Current Quench

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- 3.1 Kinetic-MHD Stability of NTMs
- 3.2 Locking of NTMs in the presence of resistive walls and error fields
- 3.3 Growth of Locked Modes and how they cause disruptions

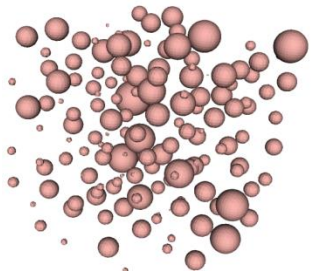
4.0 Disruption Mitigation
- 4.1 SPI Plume Model Development
- 4.2 SPI Simulations and Modeling

4.1 Plume Model Development

We are pursuing 2 approaches and are benchmarking and comparing them:

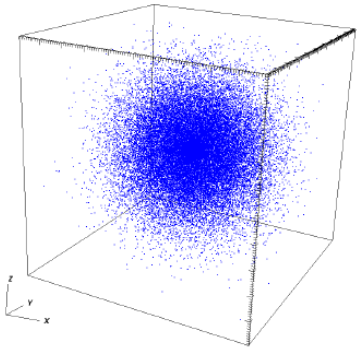
FronTier[1]

- Tracks interfaces (ablation pellet surface)
- Does not have AMR capabilities
- Must solve equations everywhere



Lagrangian Particle Method[2]

- Continuous additivity to density changes
- Solves equations only for the ablated material
- Interfaces of arbitrary complexity

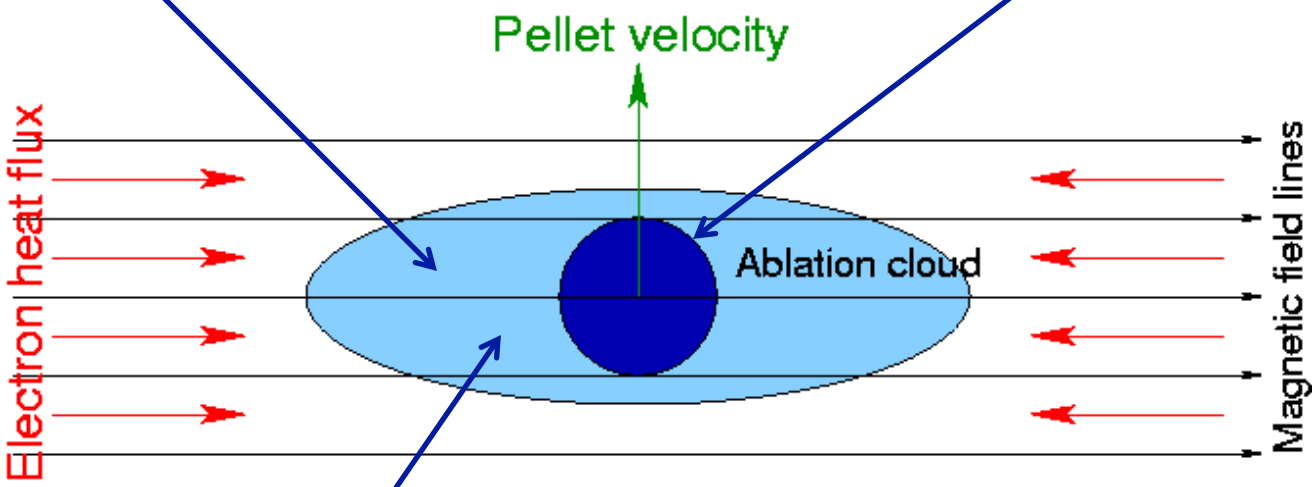


[1]Samulyak R., et al, "A numerical algorithm for MHD of free surface flows at low magnetic Reynolds numbers", J. Comp. Phys. 226, 1532 (2007)
[2]Samulyak, R. ,et al, "Lagrangian Particle Method for Compressible Fluid Dynamics", JCP, https://doi.org/10.1016/j.jcp.2018.02.004 (2018)

Physics Models for Pellet Simulations

- Kinetic model for the interaction of hot electrons with ablated gas

- Explicitly tracked pellet surface
- Phase transition (ablation model)



- Low Magnetic Re MHD equations
- Equation of state with atomic processes
- Radiation model
- Conductivity models
- Pellet cloud charging models

Ne pellet baseline case, no atomic processes, previous results

$$\gamma = 5/3,\ r_p = 2\ \text{mm},\ T_{e\infty} = 2\ \text{keV},\ n_{e\infty} = 10^{14}\ \text{cm}^{-3}$$

Case	G (g/s)	T_* (eV)	r_* (mm)	P_{sur}/p_*
Semi-analytic	109.05	29.4167	5.858	6.478
FronTier	112.8	30.11	6.025	6.44

Ar pellet baseline case, no atomic processes

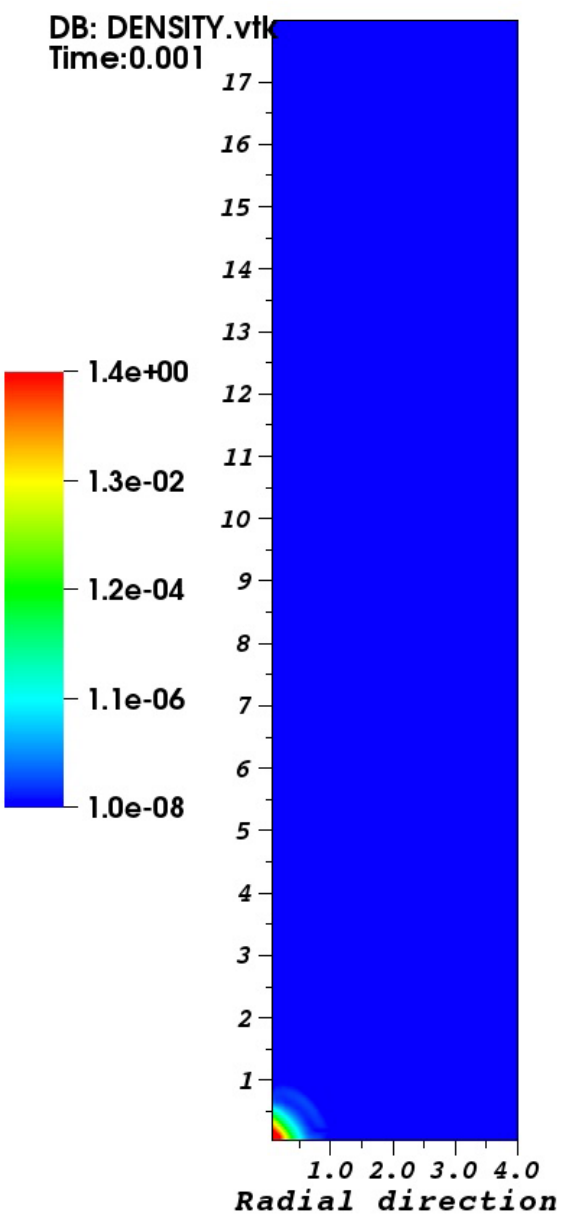
Case	G (g/s)	T_* (eV)	r_* (mm)	P_{sur}/p_*
Semi-analytic	103.1	61.59	5.858	6.47796
FronTier	103.8	61.81	5.877	6.3046

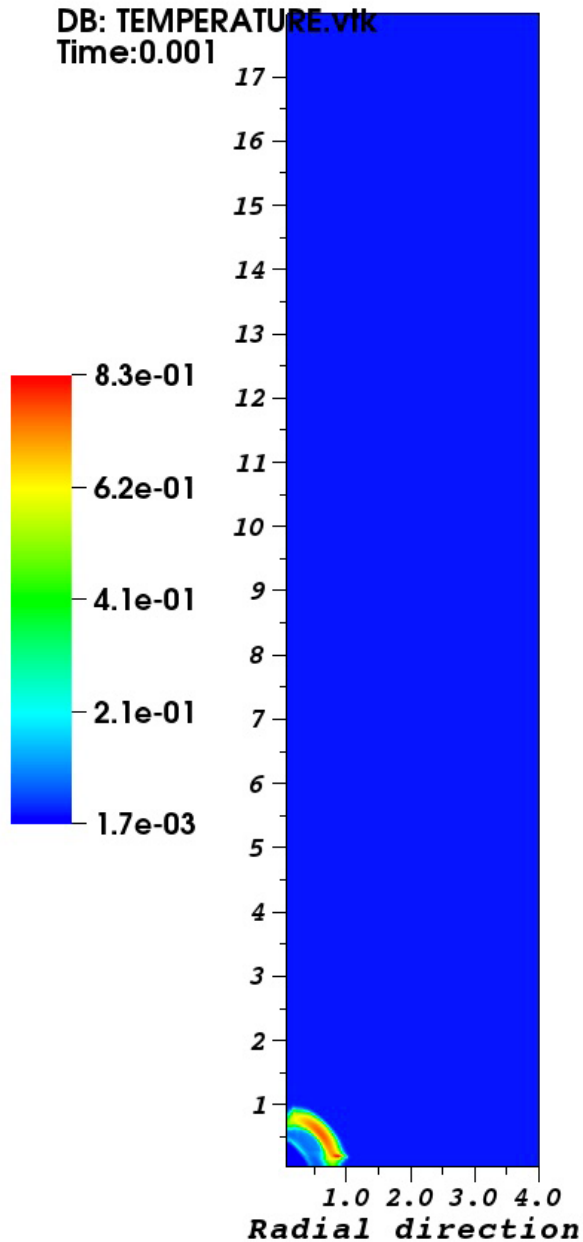
Cylindrically symmetric MHD simulations

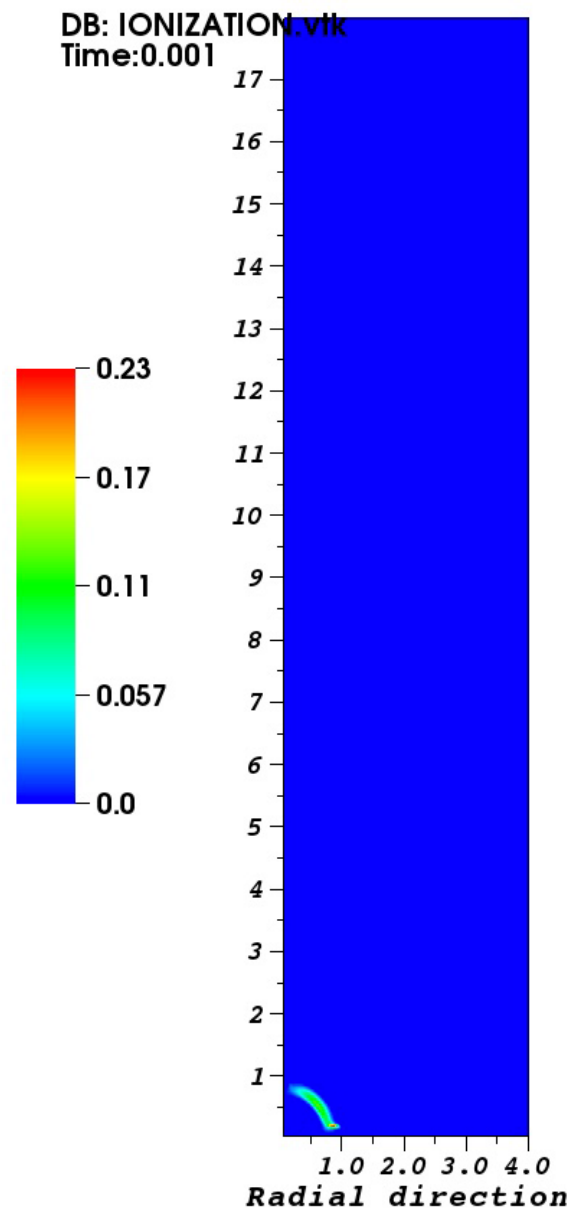
Simulation Parameters:

- Background electron density: 1.e14 1/cc – electrostatic shielding
- Electron Temperature: 2 keV
- Pellet radius: 2 mm
- “Warm-up time” (time during which the pellet crosses the pedestal: 10 microseconds
- Magnetic field: 6T
- MHD in low magnetic Reynolds number approximation
- No artificial “channel length”, which was imposed in our earlier DT simulations

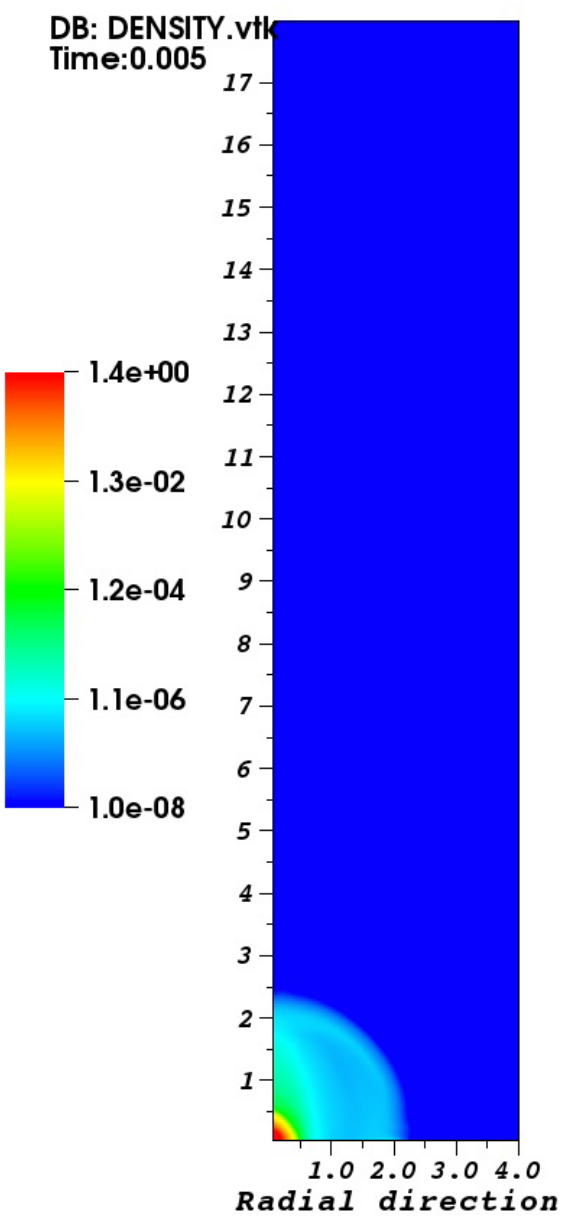
Density, Temperature, Average Ionization at 1 microsecond

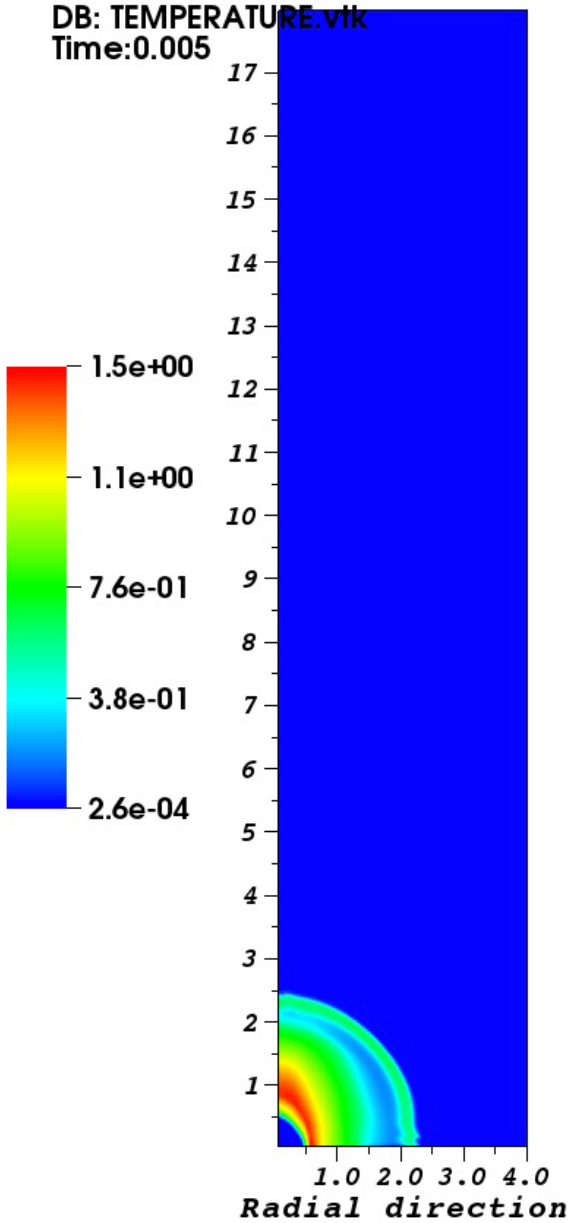


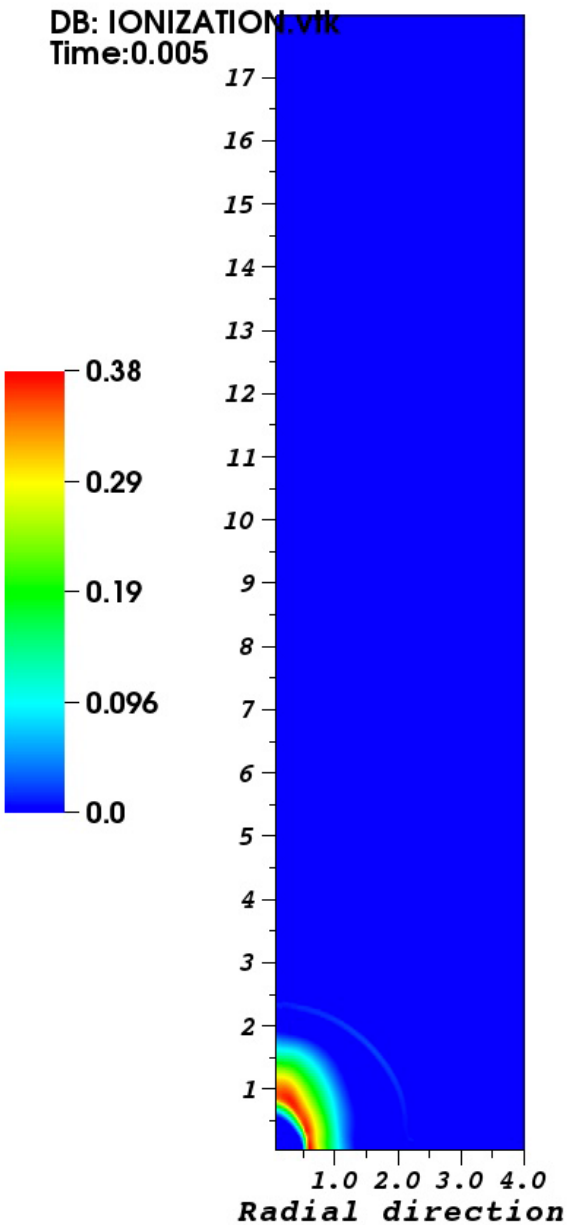




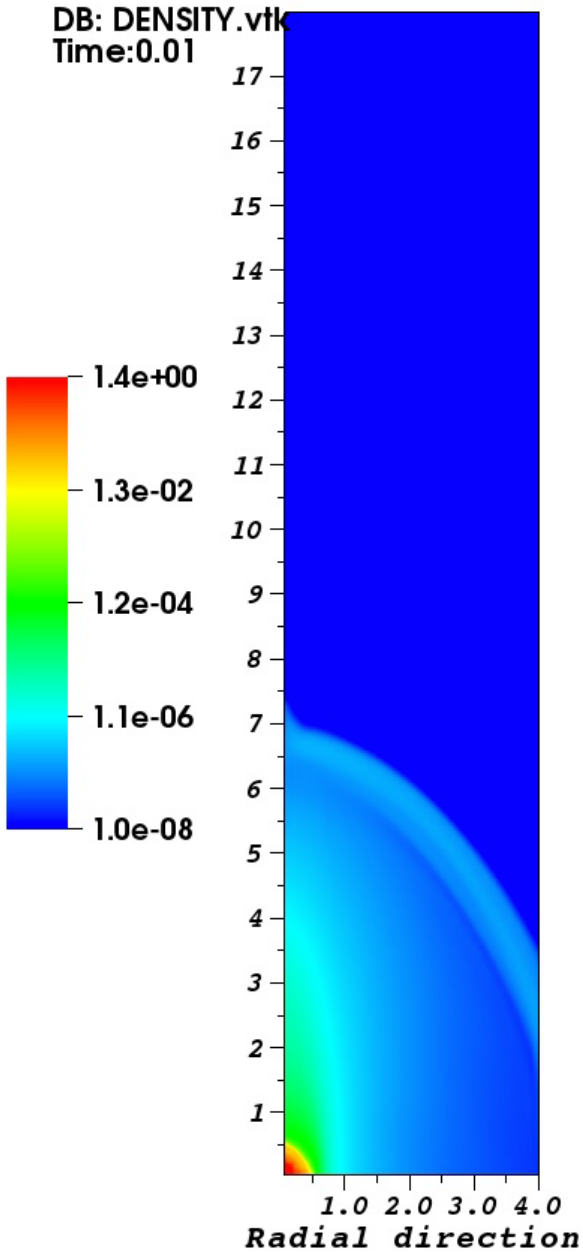
Density, Temperature, Average Ionization at 5 microsecond

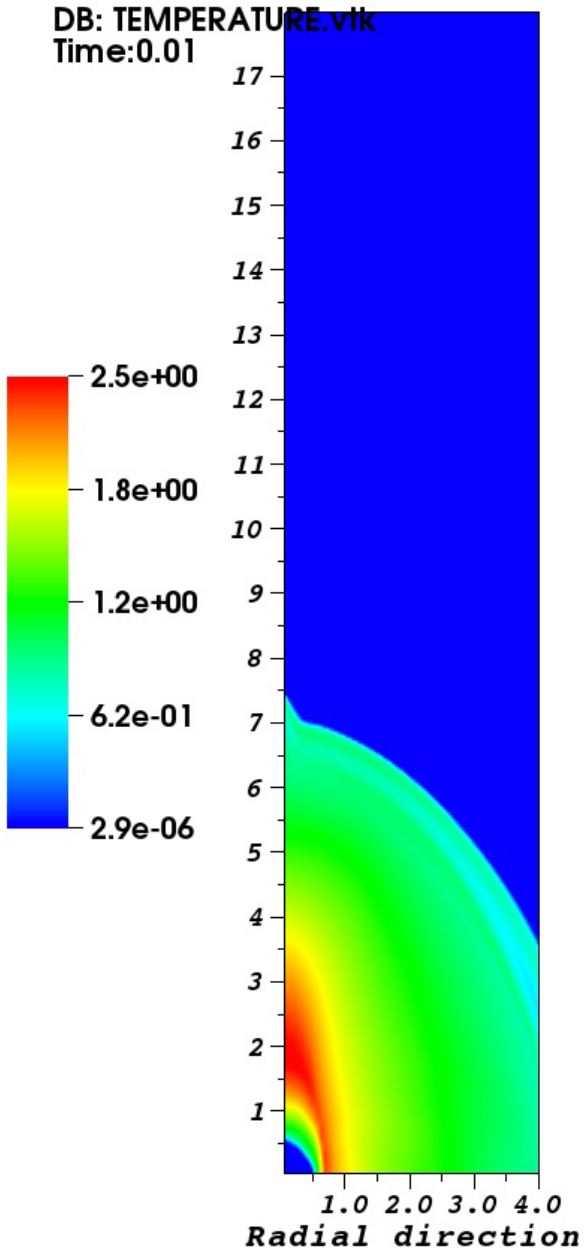


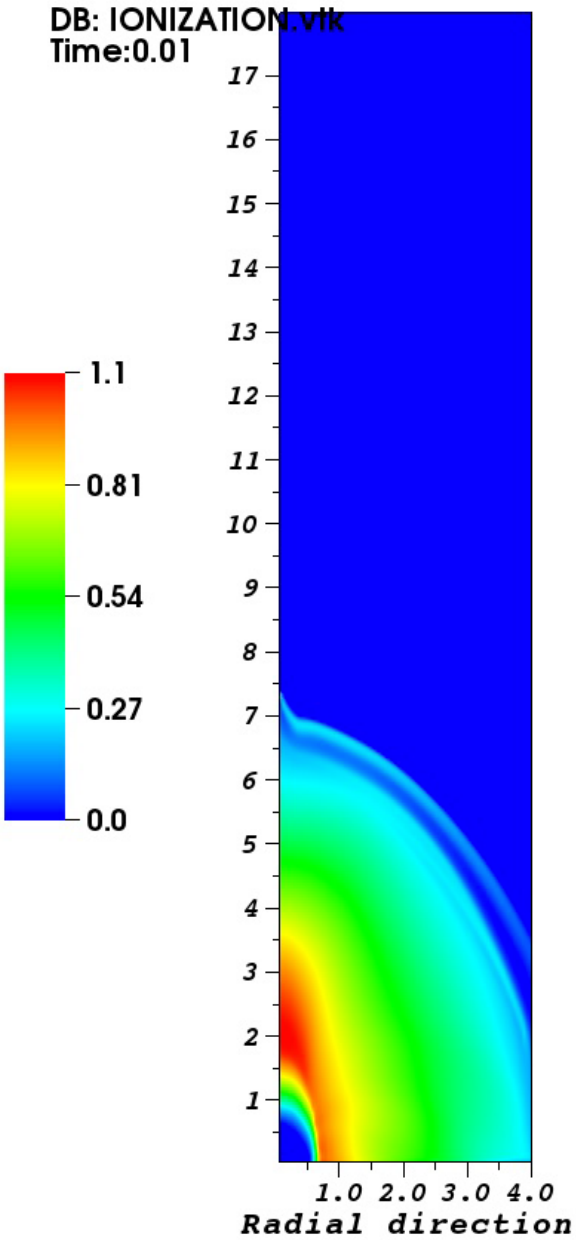




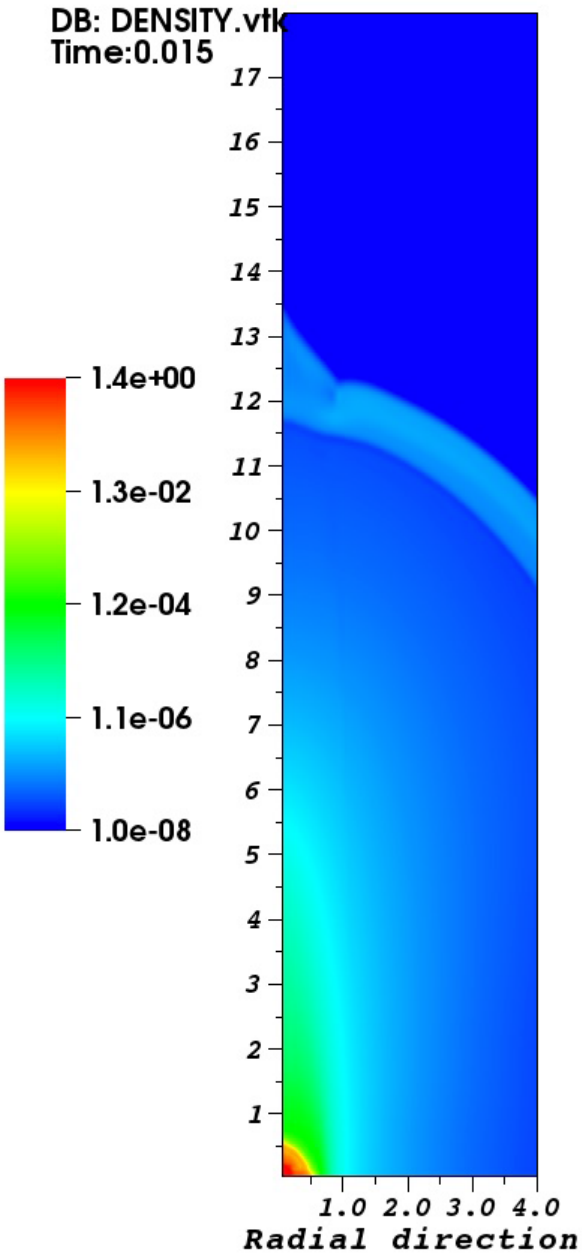
Density, Temperature, Average Ionization at 10 microsecond

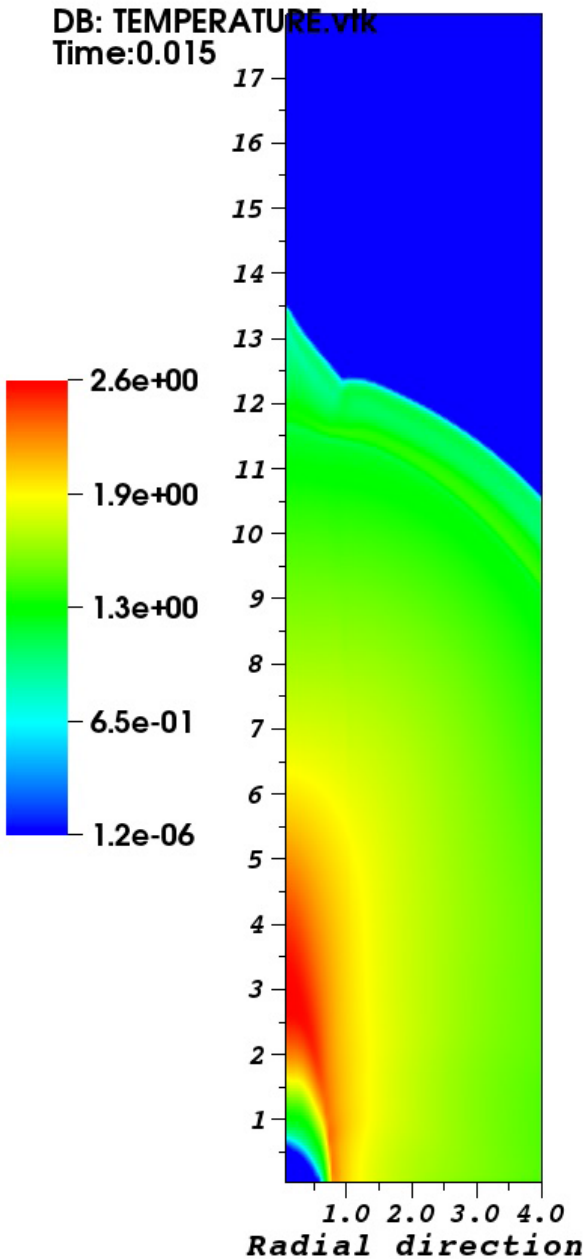


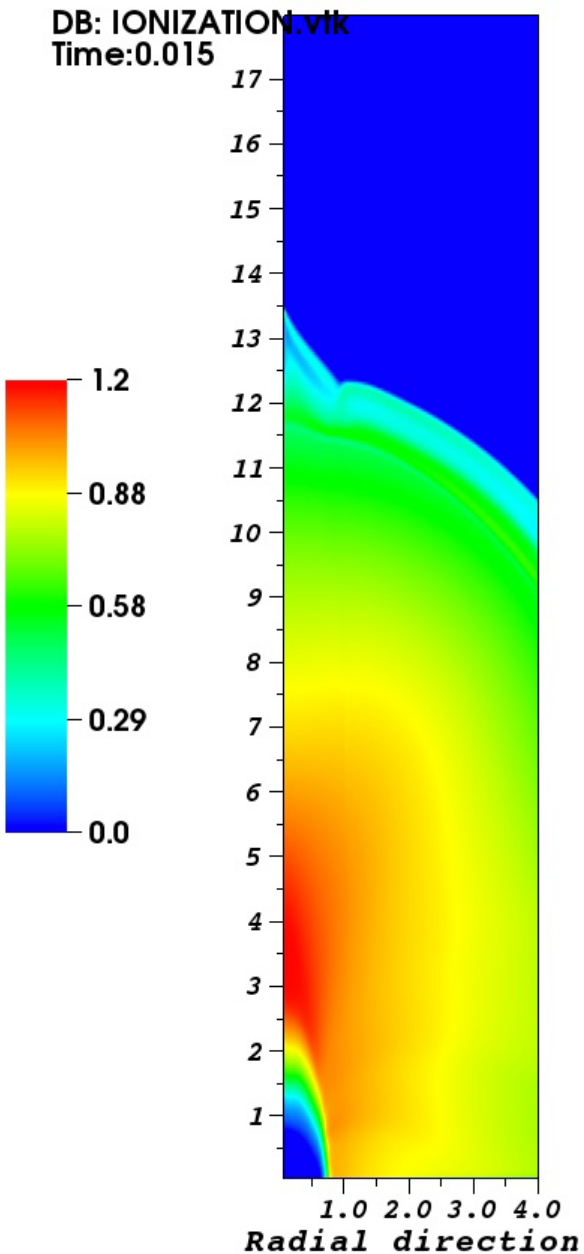




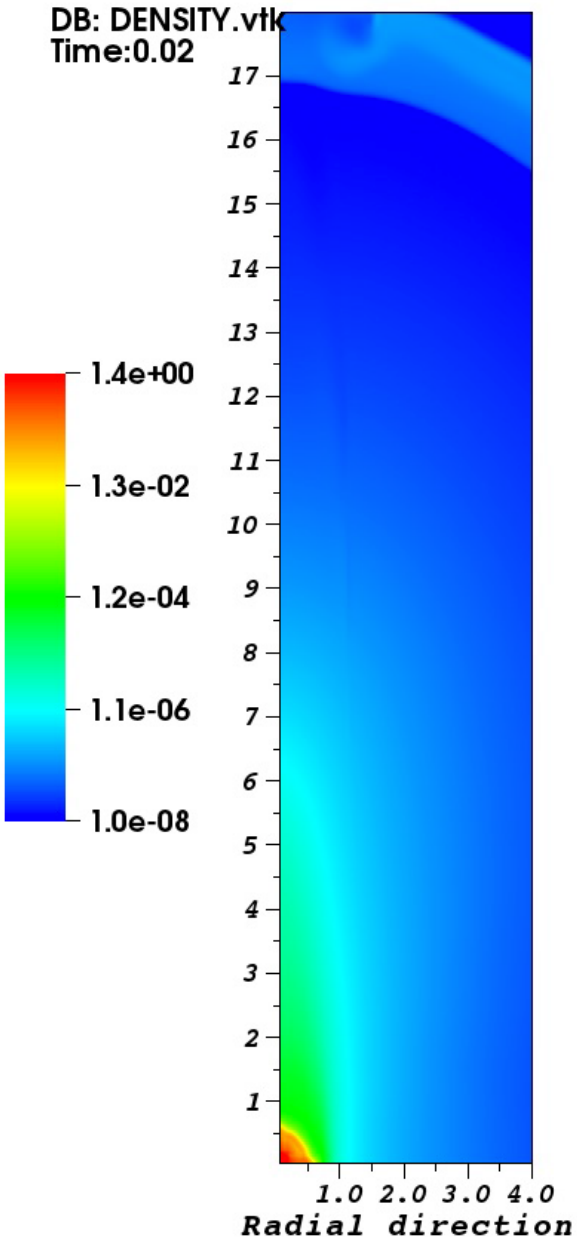
Density, Temperature, Average Ionization at 15 microsecond

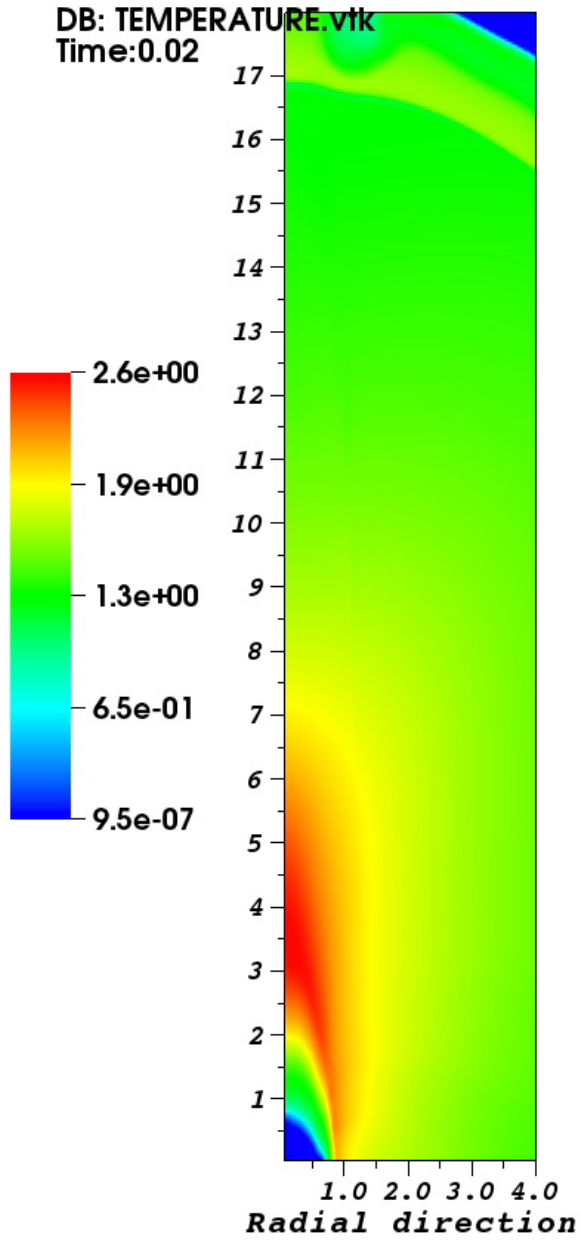


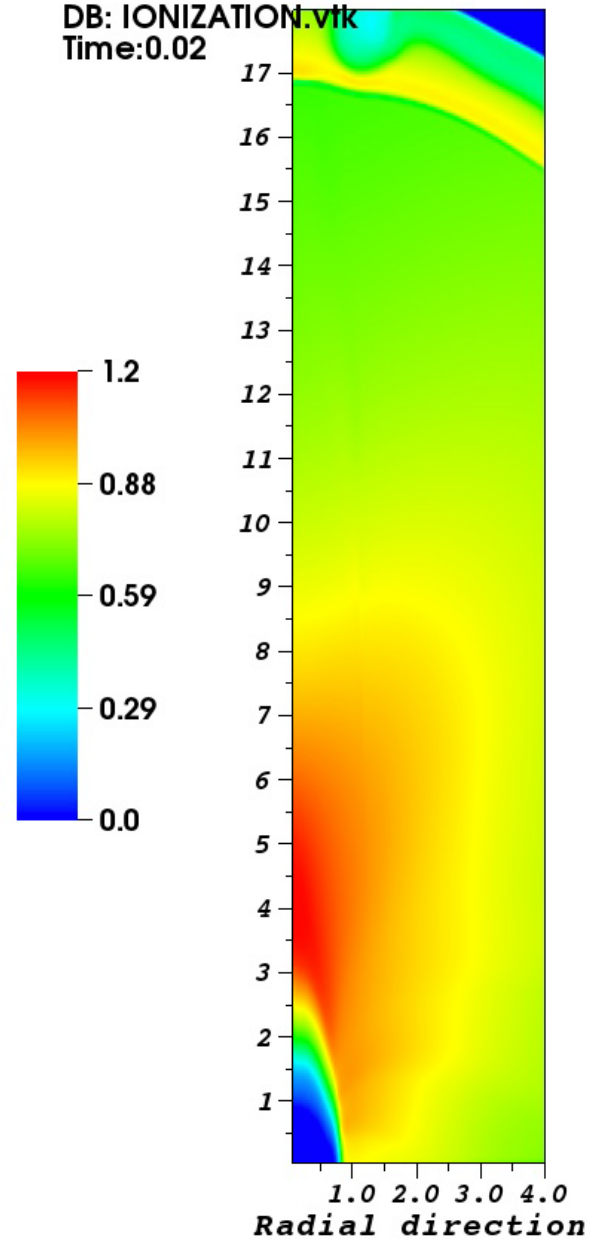




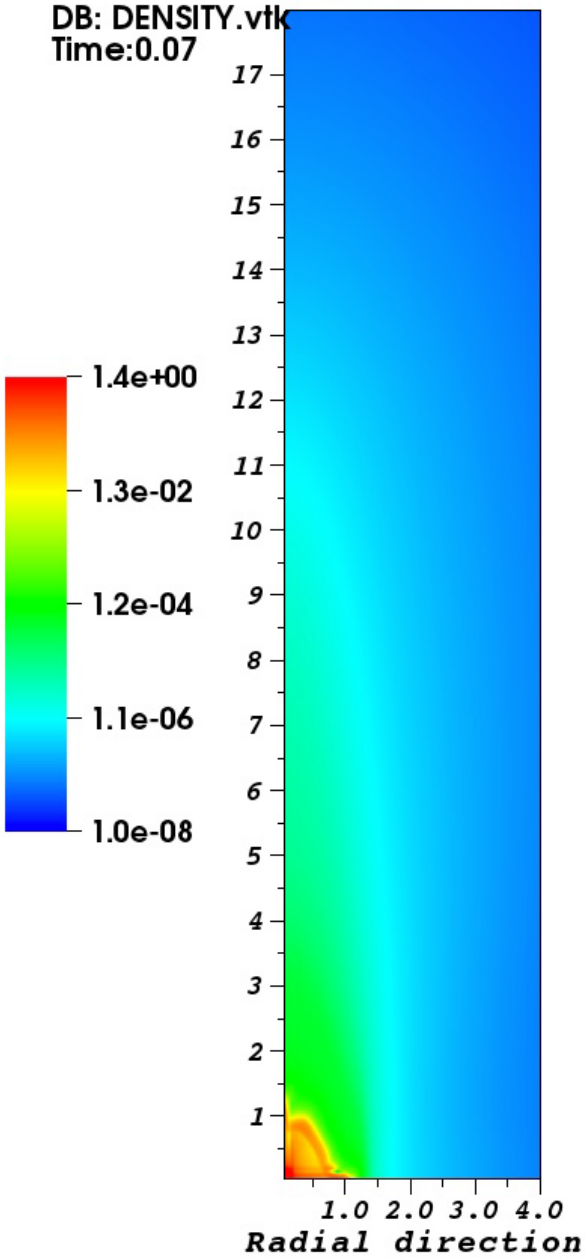
Density, Temperature, Average Ionization at 20 microsecond

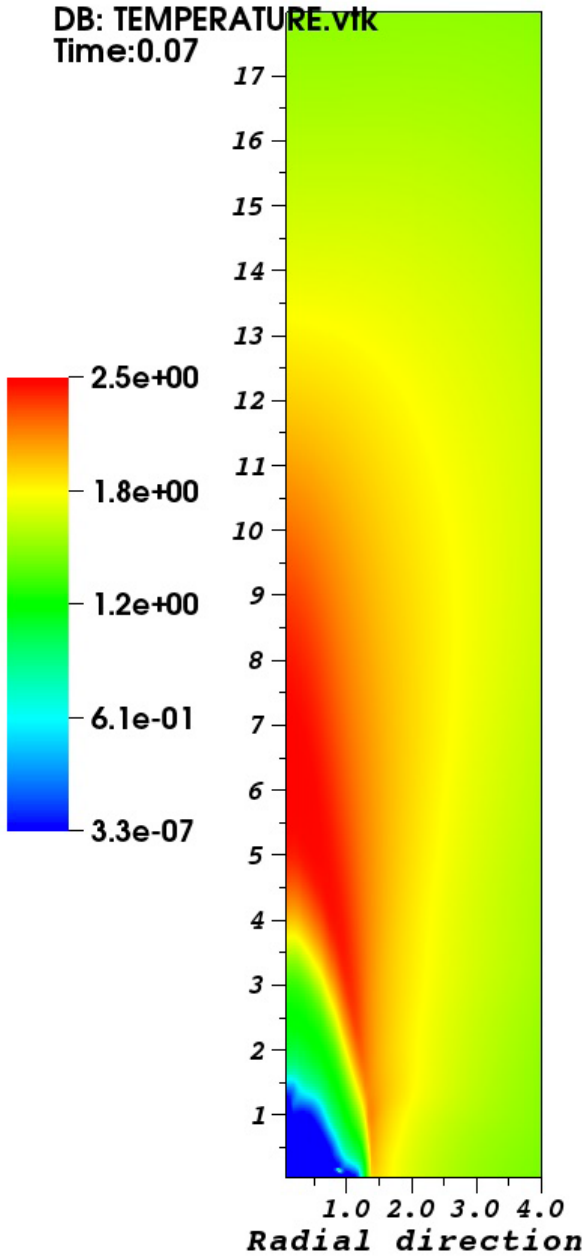


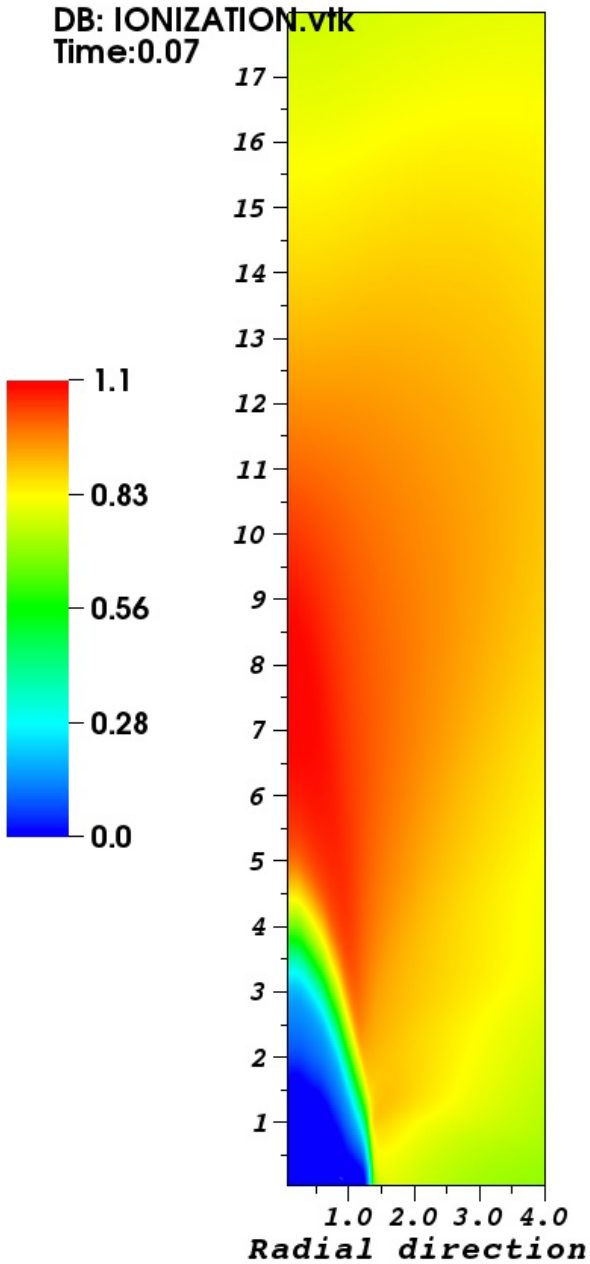




Density, Temperature, Average Ionization at 70 microsecond







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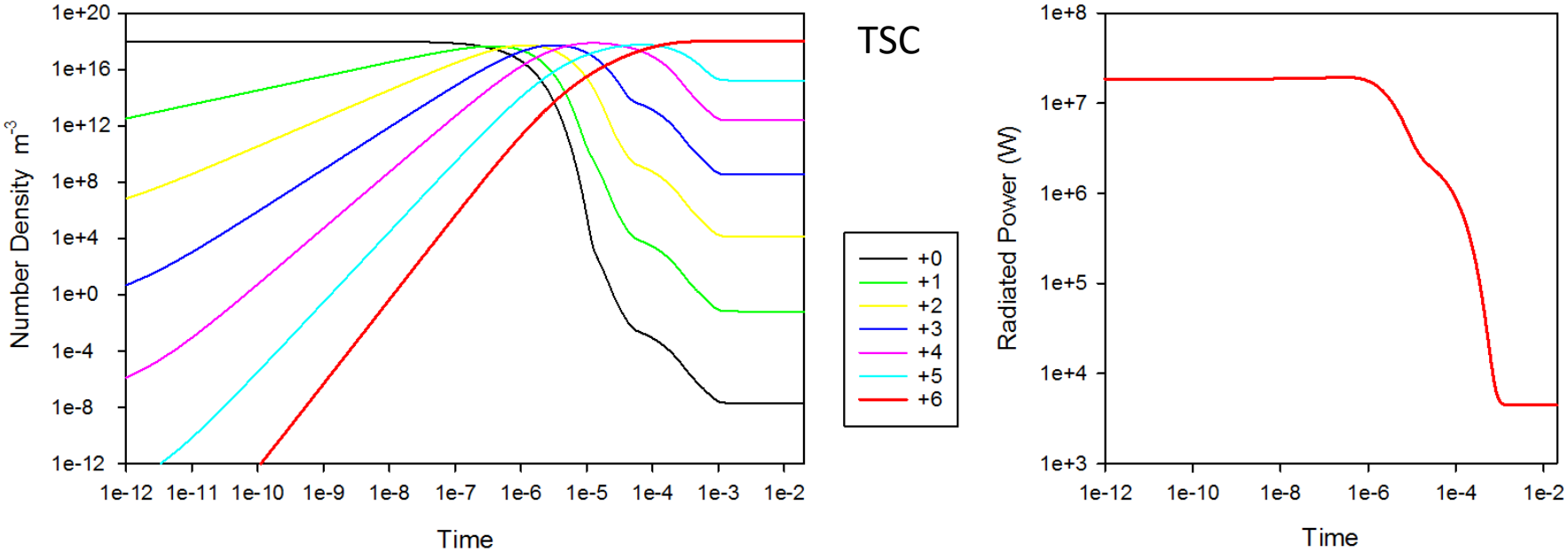
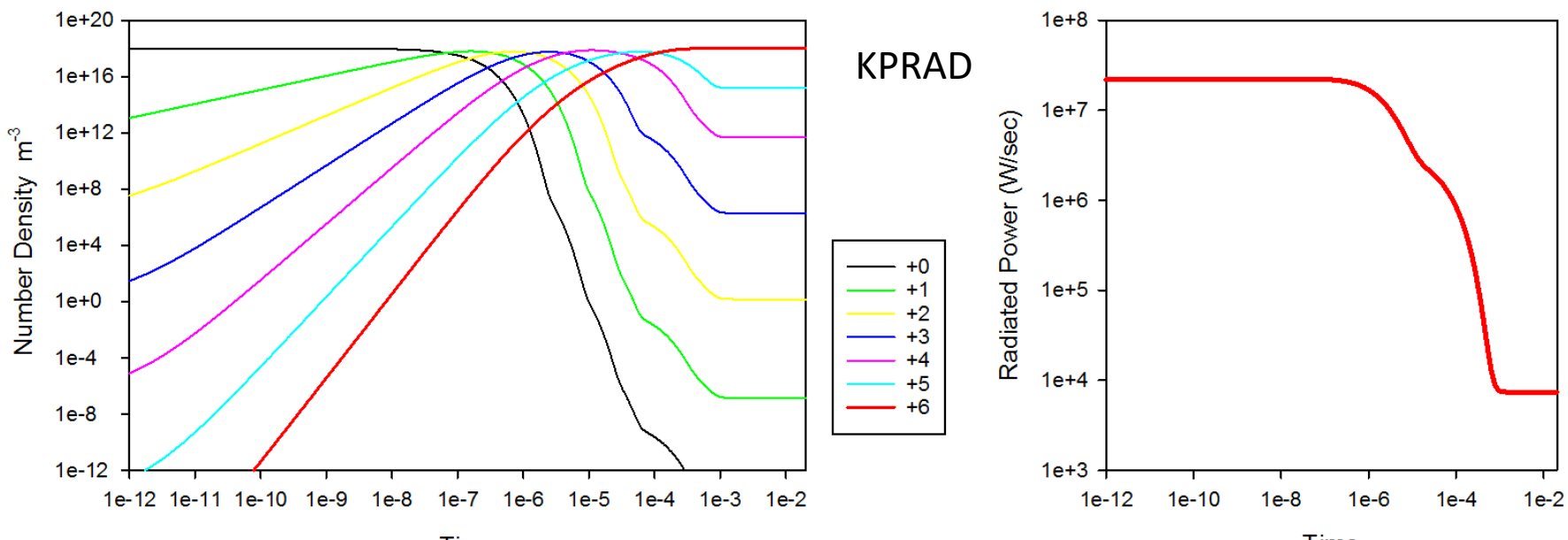
4.2 SPI Simulation and Modeling

- We have benchmarked the KPRAD radiation model used in NIMROD with the TSC radiation model (taken from MIST)
- The KPRAD radiation model and full impurity transport has been put into M3D-C1 and is being tested
- NIMROD has now modelled a full killer-pellet disruption WITH A MOVING PELLET and simple ablation model
- Next step is to benchmark M3D-C1 and NIMROD on same DIII-D mitigation shot
- Later stage will incorporate SGI model (from Frontier or LPM) into both NIMROD and M3D-C1

ne = 10^{20} m^{-3} 1keV 1 m^3 volume

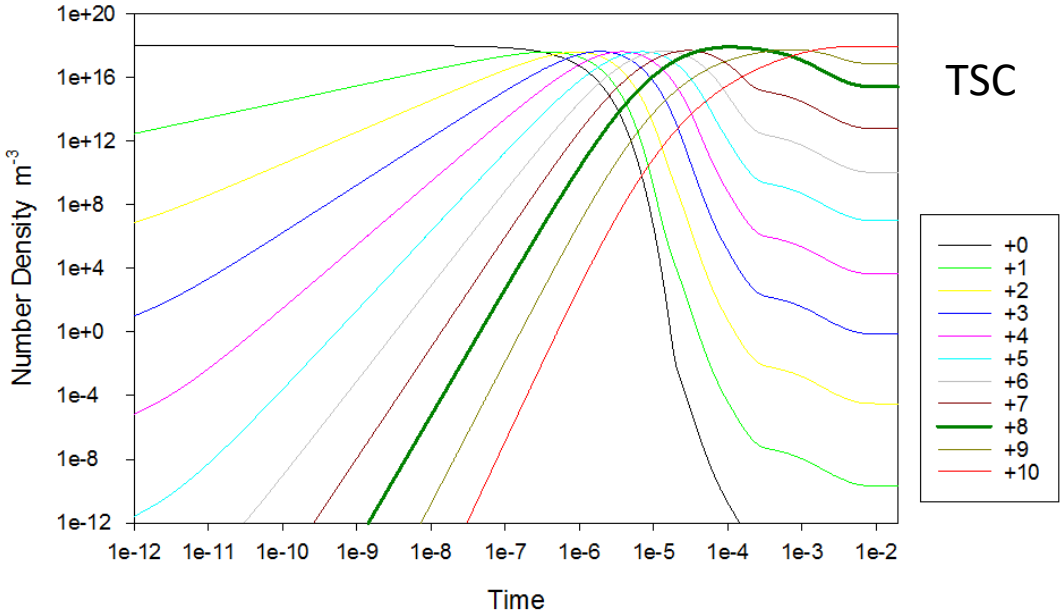
1% Carbon (initially neutral)

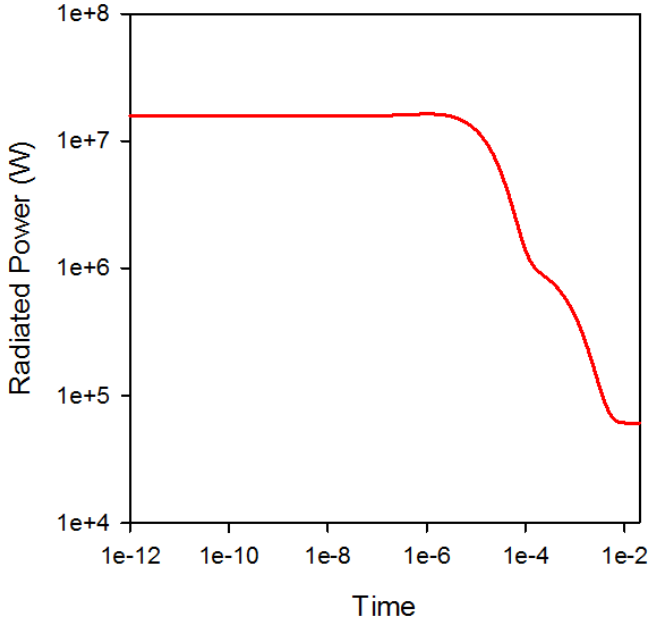


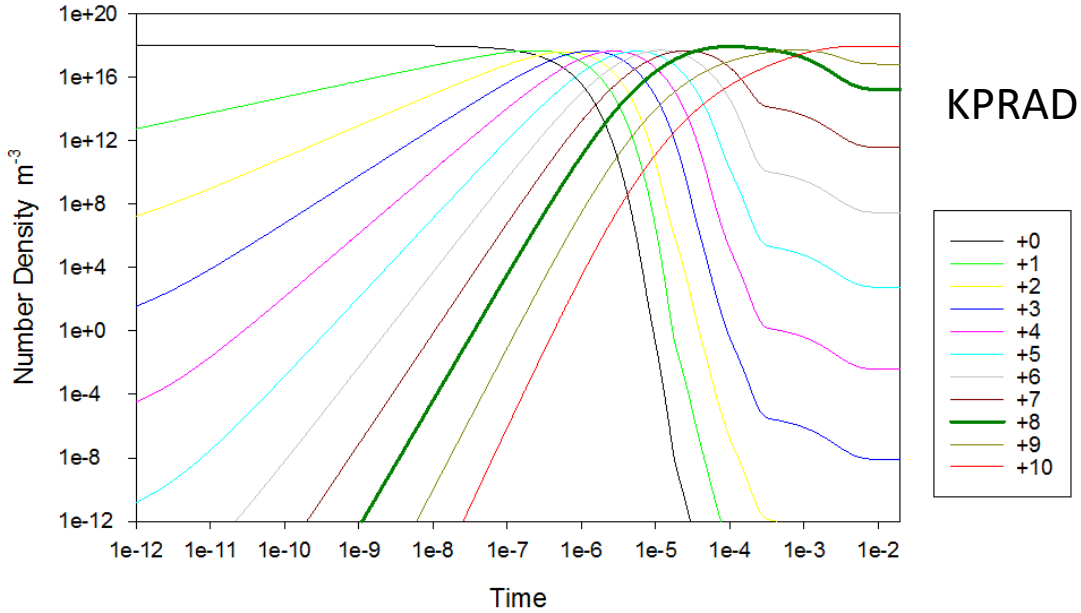


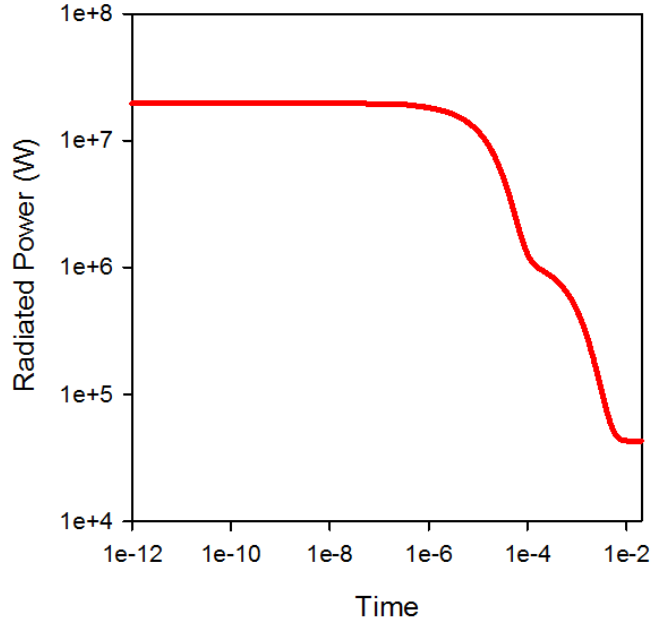
ne = 10^{20} m^{-3} 1keV 1 m^3 volume

1% Neon (initially neutral)



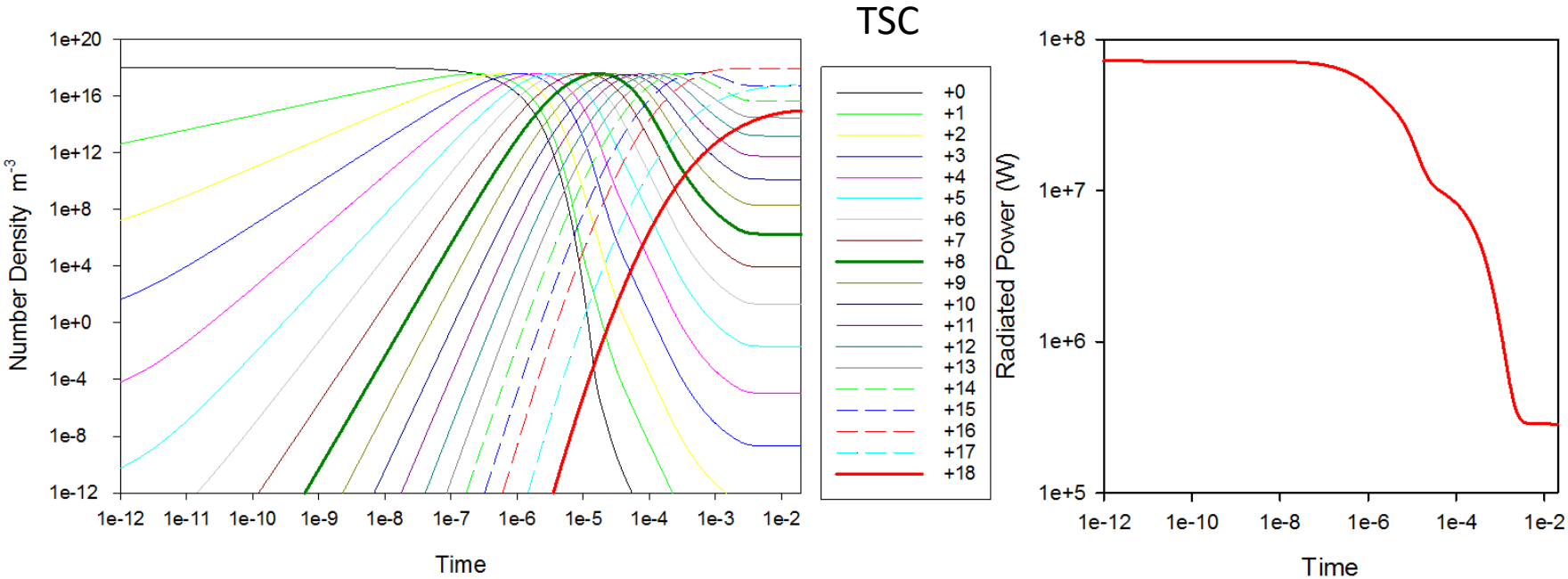


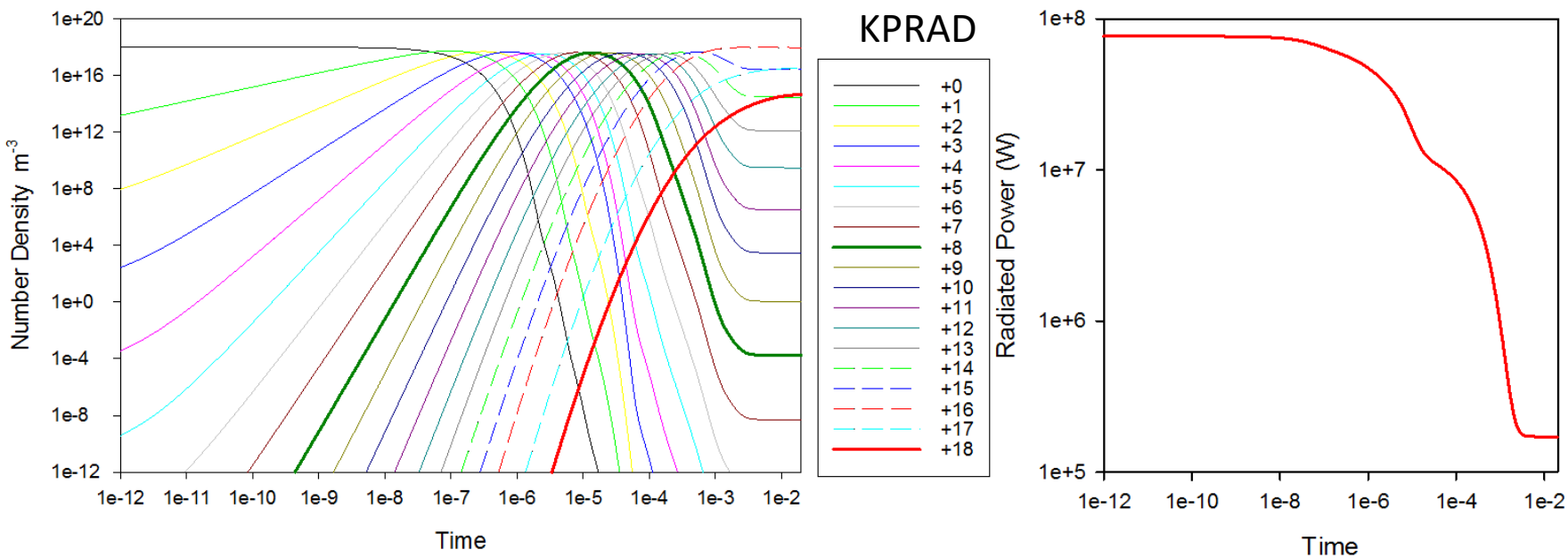




ne = 10^{20} m^{-3} 1keV 1 m^3 volume

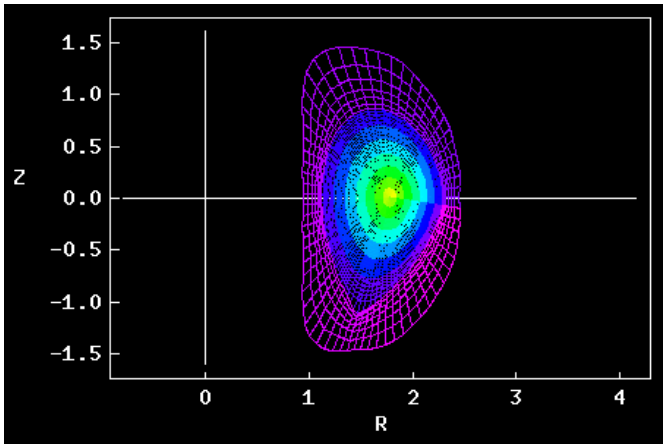
1% Argon (initially neutral)



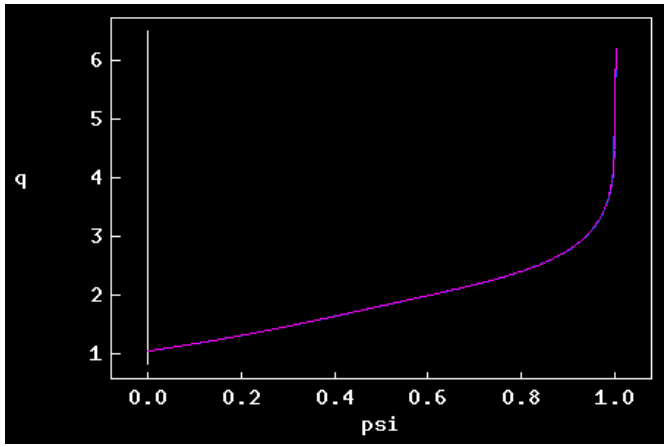


D3D, shot#137611 t=1950ms - 1MJ, 1.5MA

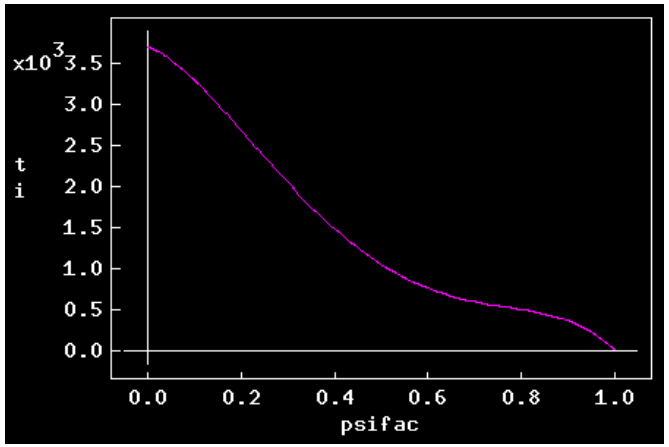
NIMROD grid



q vs ψ_n



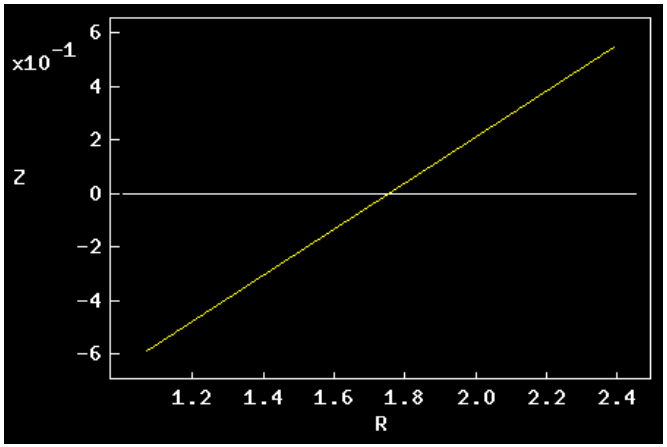
T vs ψ_n



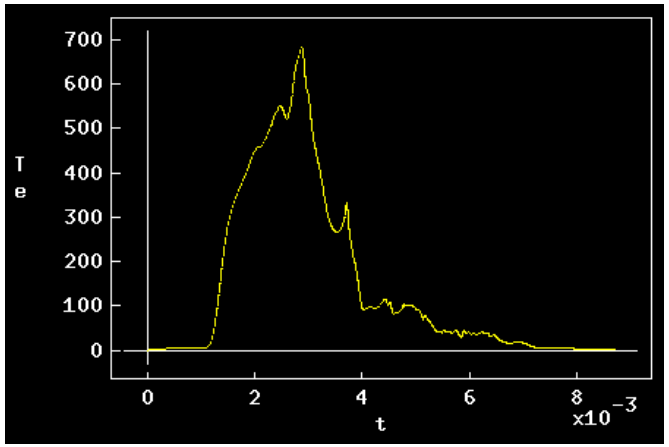
- H-mode, q>1, peak T 3.6keV
- single fluid rMHD
- temperature dependent resistivity and thermal conduction
- one temperature for all species : ions, electrons, all impurities
- instant thermalization
- 0-D coronal equilibrium radiation/impurity model
- advance densities of each charge state with single fluid velocity

Fragment Diagnostics Details Ablation and TQ

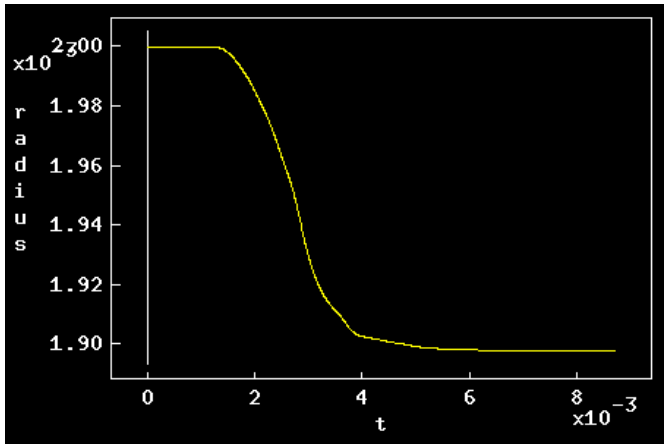
fragment trajectory



fragment temperature vs time



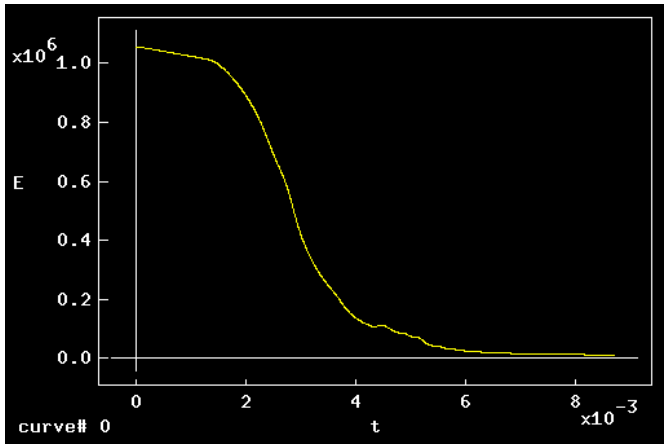
fragment radius vs time



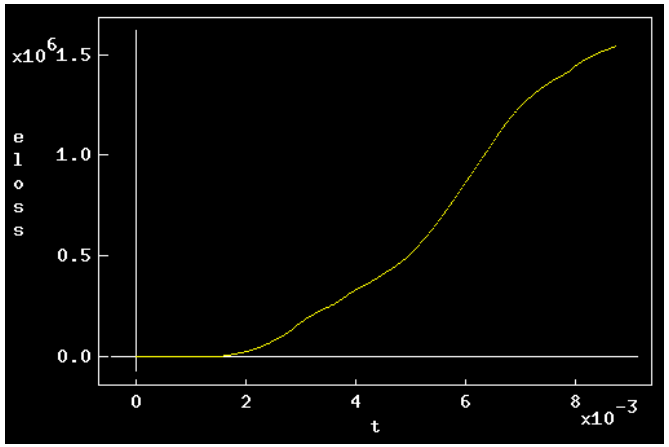
- PIC model to deposit moving source of neutral impurities through grid
- SPI - single fragment, r_{frag}=2.0mm, 200torr·L, v=200m/s
- simple straight line trajectory for now ($\mathbf{F}_{frag} = 0$)
- PIC evaluates local temperature and density to compute ablation
- PIC fragment ablates and reduces in size
- ablation rate a function of density, temperature, and size
- temperature collapses before fragment reaches axis

SPI Power Diagnostics

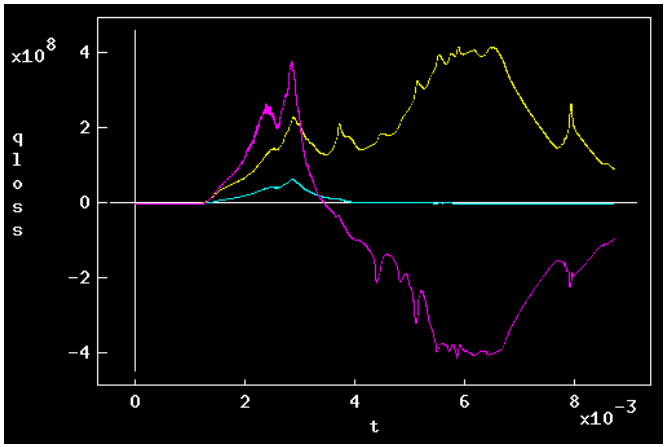
Thermal Energy(J)



Radiated Energy(J)



Power(W) vs time

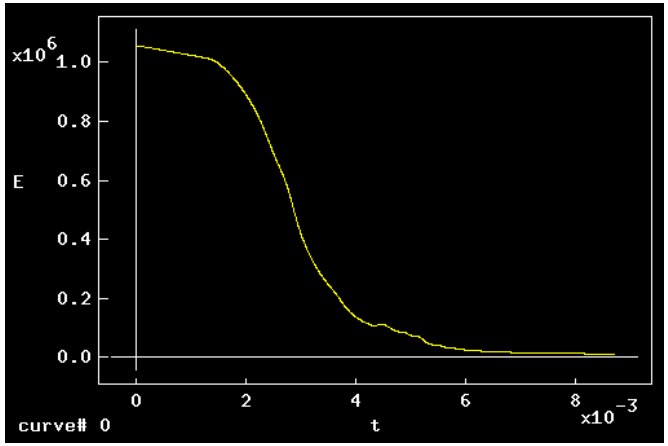


radiation,ionization,dilution

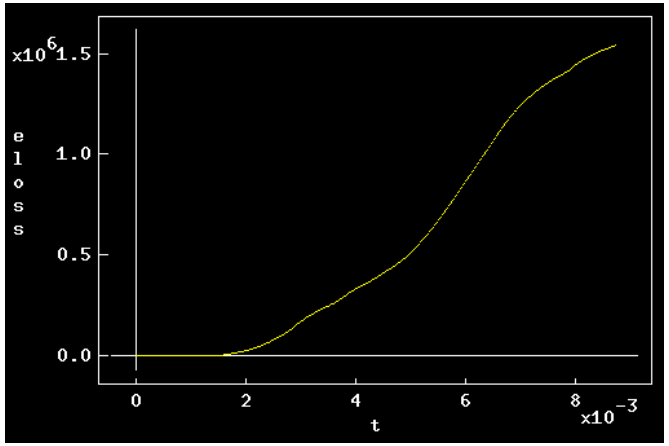
- t=0-2ms, fragment crossing vacuum
- active ablation from t=2-4ms, 90% T.E. lost but only 30% radiated
- tail of TQ from t=5-6ms shows radiation peak
- **note** symmetry in radiation and dilution(+Ohmic) heating after 4ms
  - negative dilution is actually increase in Ohmic heating
  - late time Ohmic heating drives increase in radiation
- increasing Ohmic heating has two components
  - increase in resistivity with decreasing temperature
  - currents generated as pressure collapses

Thermal Quench and Current Quench Overlap

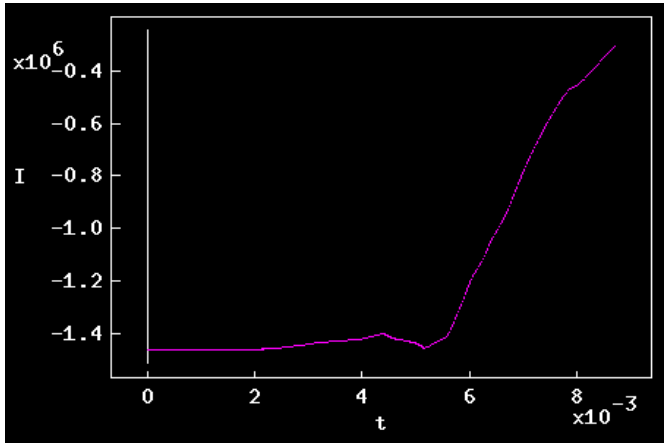
Thermal Energy(J)



Radiated Energy(J)

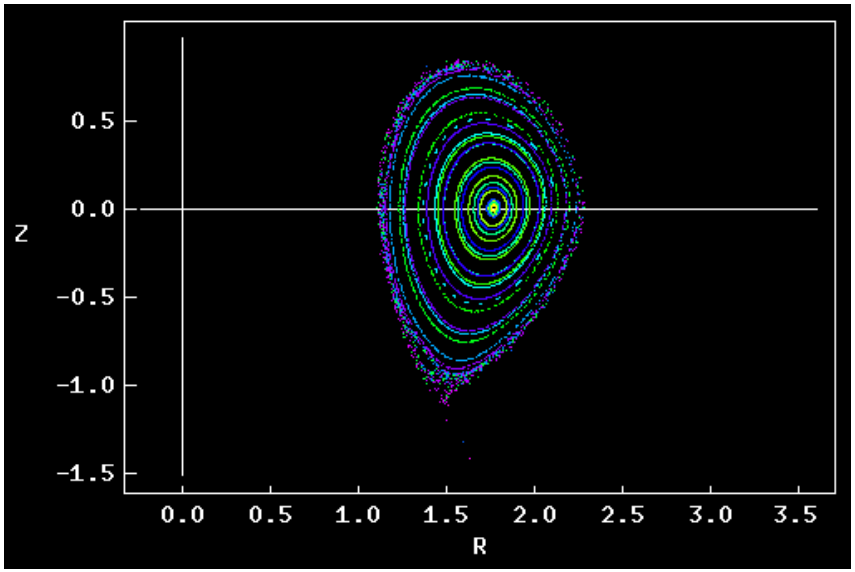


Plasma Current(A) vs time

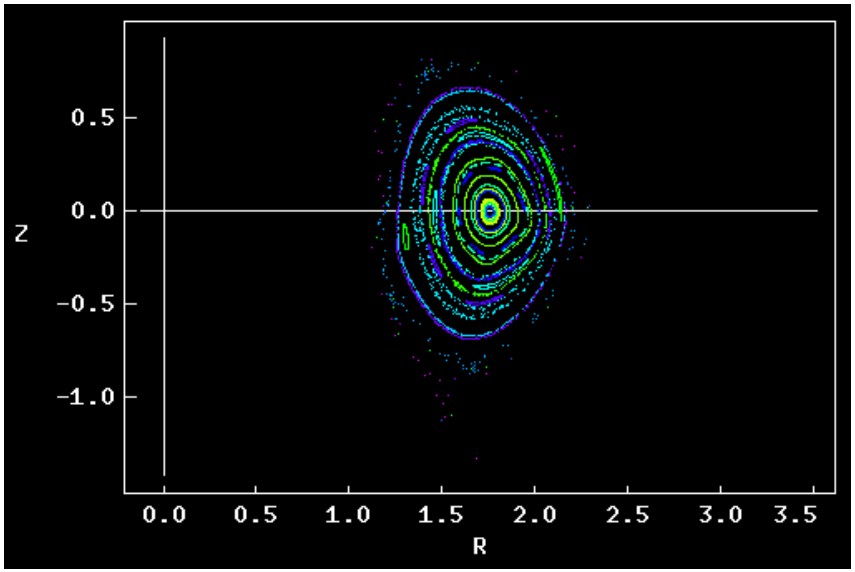


- not much ablation after t=4ms
- radiated energy exceeds thermal energy at t>6.5ms
- at t=6.5ms, current has decayed appreciably
- current quench begins at t=5ms, overlap with tail of TQ
- peak in radiation / steeper slope in radiated energy at t$\simeq$[5-7]ms
- overlap may be sensitive to diffusion parameters
- note the modest change in current throughout TQ

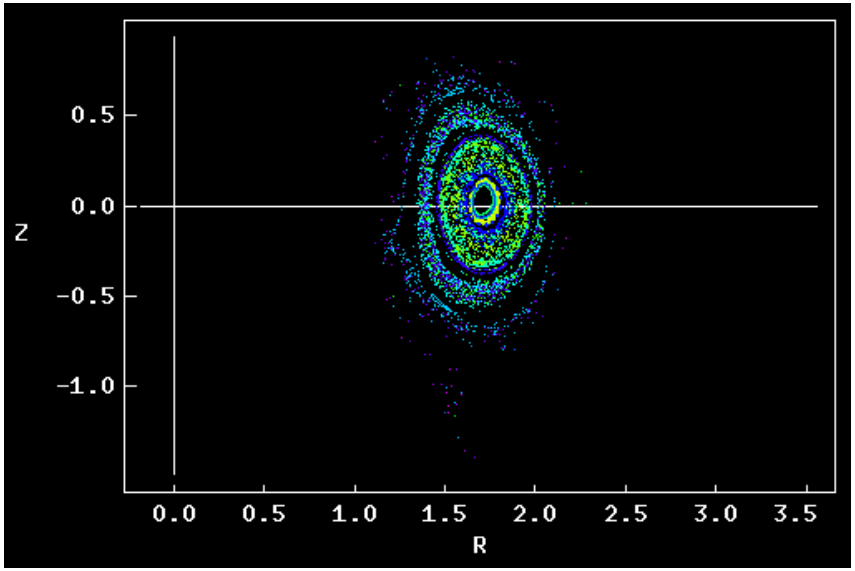
Poincare Show Islands and Flux Surface Breakup



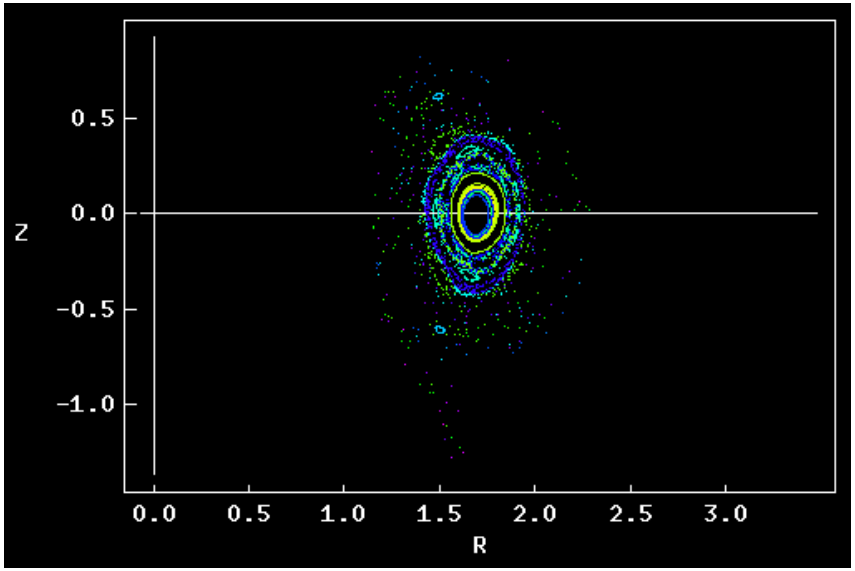
t=2.0ms



t=2.50ms



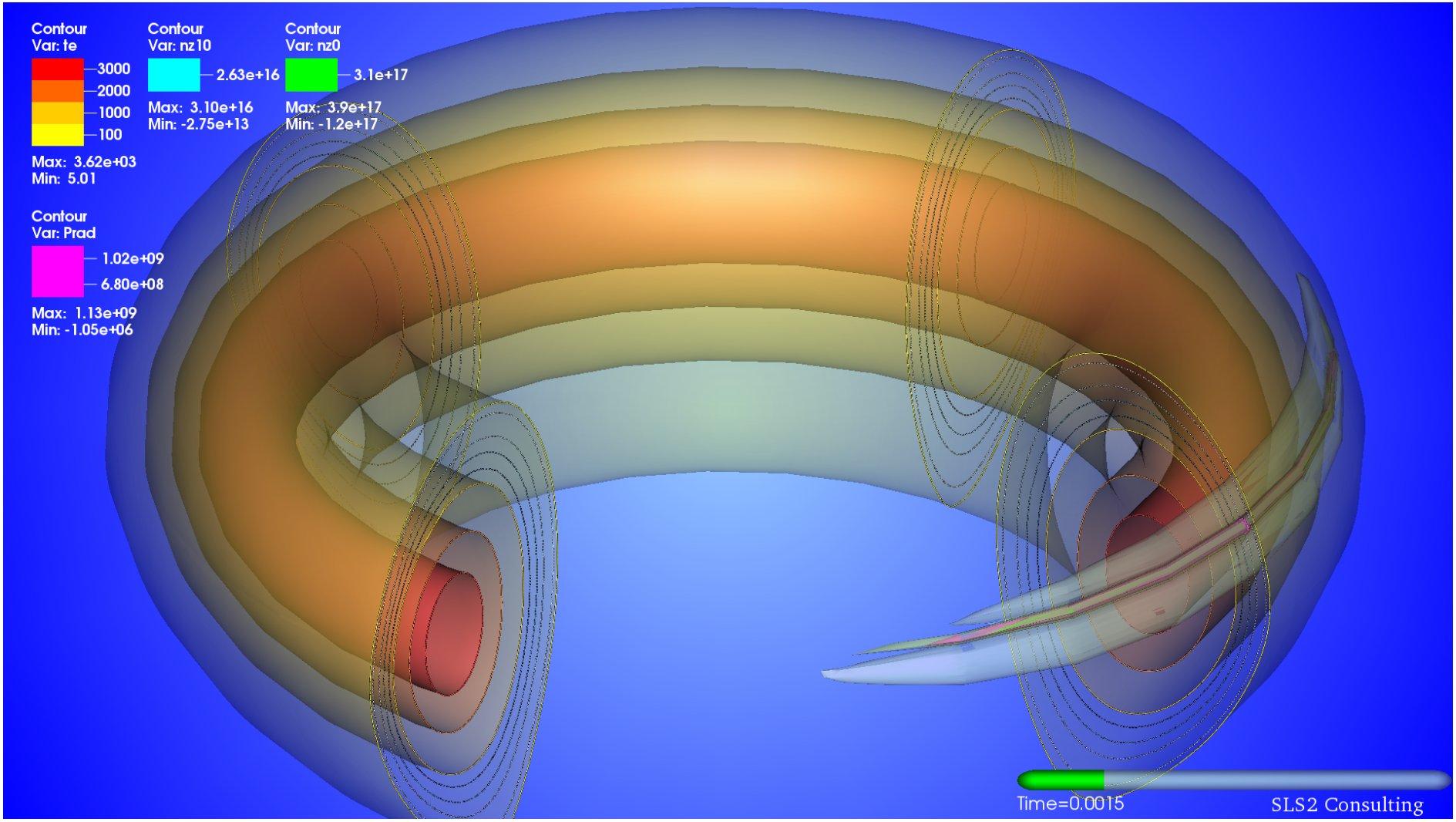
t=3.0ms



t=3.50ms

D3D H-mode, shot#137611 t=1950ms, 1MJ, 1.5MA

https://youtu.be/DHuQzeQKzEM



animation shows thermal quench mediated by (1,1)

NIMROD SPI Simulations Progressing

- D3D SPI simulations going well
- single fragment SPI shows complete thermal quench
- modest radiation during main thermal collapse
- strong radiation seen with Ohmic collapse of plasma
- ongoing studies to examine dependence on diffusion parameters
  - core dynamics requires low resistivity
  - low ceiling on resistivity to prevent Ohmic dominance
  - thermal conduction parameters are probably important too
- tricky to correctly resolve range of temperature dependent dynamics
  - can't ignore the low temperature stuff
- gets worse with ITER
- L-mode simulations are numerically less challenging

THANK YOU!