C – pellet disruption mitigation modeling with M3D-C1

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CTTS Talk Series

PPPL

C – pellet disruption mitigation modeling with M3D-C1

Outline:

- Motivation
- C ablation model
- Validation/comparison (ASDEX-U)
- Modelling pellets in M3D-C1
- NSTX simulations
  - Convergence study
- Summary and future work

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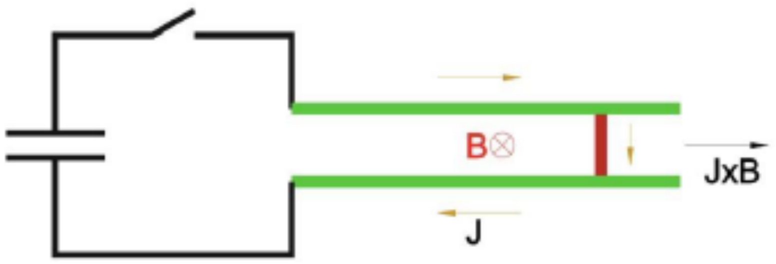
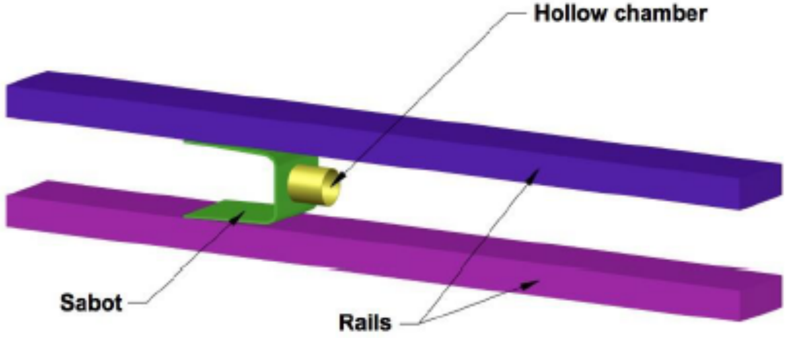
Motivation

- **An Electromagnetic Pellet Injector (EPI) has been developed ***
- **EPI would offer advantages for ITER**
  - Very fast response time (2-3 ms)
  - Speeds up to 1 km/s
- **Proposal to test on NSTX-U.**





- **We have started single C-pellets injection simulations using M3D-C1**
  - C-ablation model has been incorporated.
  - Simulations on NSTX-U are being conducted:
    - Convergence study
    - TQ quench sensitivity on modelling parameters
    - Understanding the physics involved

*R. Raman, Nucl. Fusion **59** (2019) 016021

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C ablation model

- Sergeev et al., Plasma Phys. Rep. 32 (2006) 363
- Sergeev et al., ECA 18B (1994) 1364
- Kuteev et al., Sov. J. Plasma Phys. 10 (1984) 675

Based on a Neutral Gas Shielding Model (NGS)

- Key quantity is $\delta = q_p/q_0$ → shielding factor

q_p →heat flux reaching the pellet surface
q_0 →heat flux from the surrounding plasma

- Hydrogen pellets (strong shielding)
  - Low sublimation energy ε
  - $\delta \ll 1$: Most of the plasma heat flux is absorbed by the neutral pellet cloud
- Refractory pellets (weak shielding)
  - High sublimation energy
  - $\delta \geq 0.8$: Most of the plasma heat flux reaches the pellet surface
  - Delayed time at which evaporation begins

C ablation model

For both limits ($\delta \to 0$ and $\delta \to 1$) analytical expressions for the ablation rate $\dot{N}$ is derived

Strong shielding ($\delta \to 0$)

Based on scaling laws

$$\dot{N}_0 \left[\frac{\text{Atom}}{\text{s}}\right] \cong 1.94\times10^{14}\, n_e^{0.45}[\text{cm}^{-3}] \times T_e^{1.72}[\text{eV}]\, r_p^{1.44}[\text{cm}]\varepsilon^{-0.16}[\text{eV}] \times A_p^{-0.28}[\text{amu}]\, Z_p^{-0.56}(\gamma-1)^{0.28}$$

Tabulated for various materials

Weak shielding ($\delta \to 1$)

$$\dot{N}_\delta \left[\frac{\text{Atom}}{\text{s}}\right] \cong \frac{\delta}{\varepsilon} r_p^2 n_e \sqrt{\frac{8\pi T_e^3}{m_e}}$$

$$\delta^{-1} = 1 + \frac{1.725\sqrt{\pi}(\pi-2)Z_p e^4 r_p n_e E_1(I_{eff}/T_e)}{\varepsilon\, V_s \sqrt{2\, m_e\, T_e}}$$

$$V_s = \sqrt{\gamma T_s/m_p} \qquad T_s \approx 5000\text{ K}$$

Also applicable to Li, Be, B

However, C pellet can have an **intermediate shielding**

- There is no analytical model for this regime
- They propose a standard interpolation:

$$\dot{N} = \frac{\dot{N}_0\, \dot{N}_1}{\dot{N}_0 + \dot{N}_1}$$

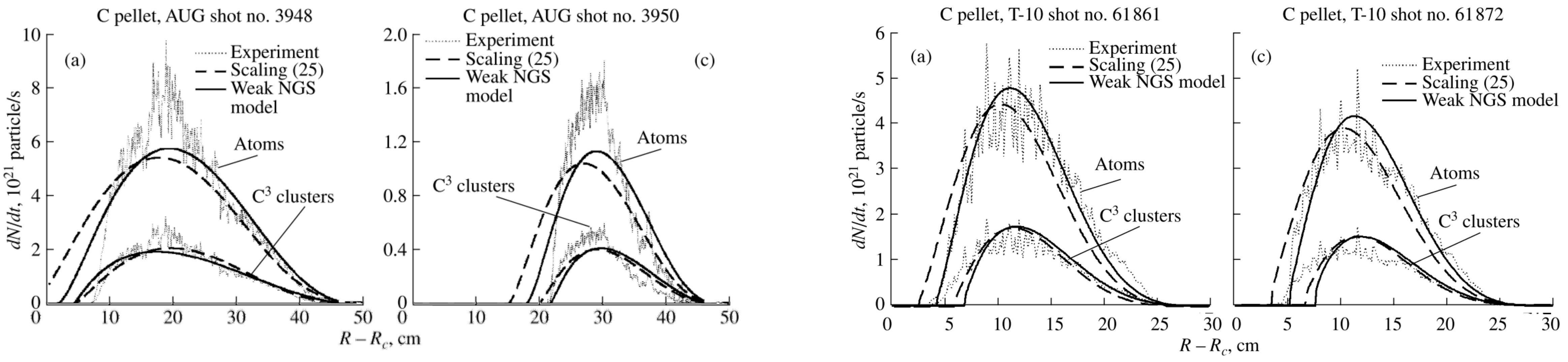
Expression we have implemented in M3D-C^1

Sergeev et al., Plasma Phys. Rep. 32 (2006) 363

Model were tested with experimental data

Ablation rate model was tested in several discharges obtaining good agreement

- **No MHD evolution**



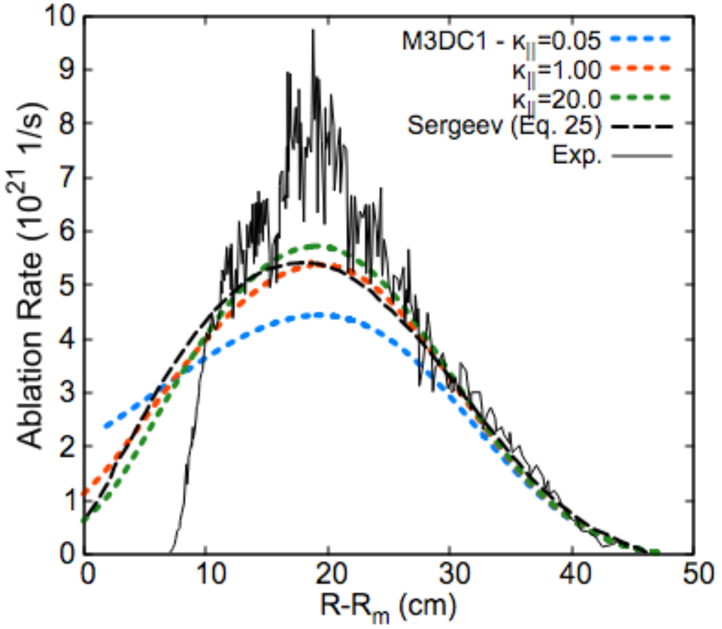
AUG #3948 AUG #3950 T-10 #61861 T-10 #61872

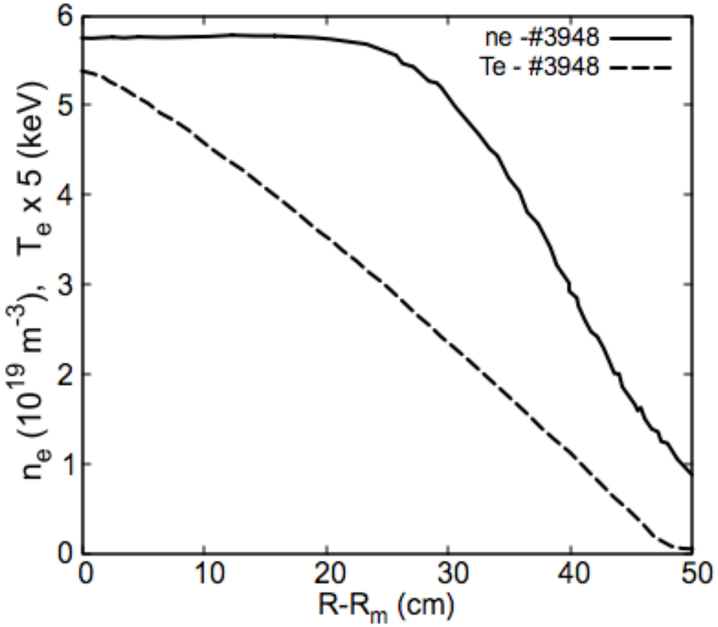
It was also tested for different pellet materials

Sergeev et al., Plasma Phys. Rep. 32 (2006) 363

M3D-C1 implementation also tested

We tested our implementation in an AUG-#3948-like plasma (no G-EQDSK available)





Parameter	#3948
r_p	0.25 mm
v_p	485 m/s
B_0	1.96 T
I_p	0.8 MA
R_0	1.7 m
Enlong.	1.6
$\kappa_\perp$	$3 \cdot 10^{-6}$

Agreement is very good.

Main modeling features in M3D-C1:

- Pellet neutral cloud is prescribed
- Plasma evolves self-consistently in time

Modelling pellets in M3D-C1

The ablated material (given by $\dot{N}$) is weighted by the neutral cloud distribution

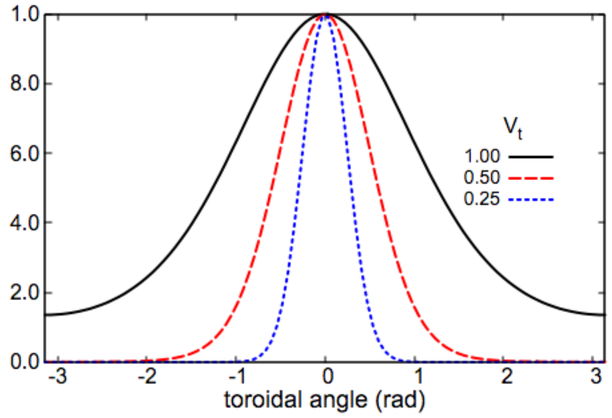
Spatial distribution for the neutral cloud is prescribed:

$$S = \frac{1}{(2\pi)^{3/2} V_p^2 \, V_t} \exp\left[-\frac{\left(R - R_p\right)^2 + \left(Z - Z_p\right)^2}{2 \, V_p^2} - \frac{R R_p\left(1 - \cos\left(\varphi - \varphi_p\right)\right)}{V_t^2} \right]$$

- Thus, The **size of the neutral cloud has to be specified (Vp, Vt)**. Limitations arise due to mesh size and number of toroidal planes.
- **Smaller cloud sizes require more toroidal planes and smaller time steps.**

Example: In NSTX-U $R_{out} \sim$ 1.4 m. Thus, the minimum toroidal neutral cloud size scales roughly as

# tor. Planes	V_t
8	$\lesssim$ 1.00 m
16	$\lesssim$ 0.50 m
32	$\lesssim$ 0.25 m



Modelling pellets in M3D-C1

Plasma evolves self-consistently in time

- B. Lyons, C. Kim, Y. Liu, N. Ferraro, S. Jardin, J. McClenaghan, P. Parks, L. Lao, Plasma Phys. and Contr. Fusion **61** 064001 (2019)
- N.M. Ferraro, B. C. Lyons, C.C. Kim, Y.Q. Liu, and S.C. Jardin, Nucl. Fusion **59** 016001 (2019)

- Single fluid equations (same velocity, $\mathbf{v}$, for all species (e, i, Z^j))
- Continuity equation for each ion species
  - $\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}) = D\nabla^2 n_i + \sigma_i$ (same for n_Z^j)
  - Electron density is defined to satisfy quasi-neutrality
- σ_Z^j is calculated using KPRAD module (ionization, recombination)
- All ionized impurities (Z^j) have the same temperature as the main ion species, T_i
- Two temperature equations (∑ions and e^-) also include the radiation losses calculated by KPRAD

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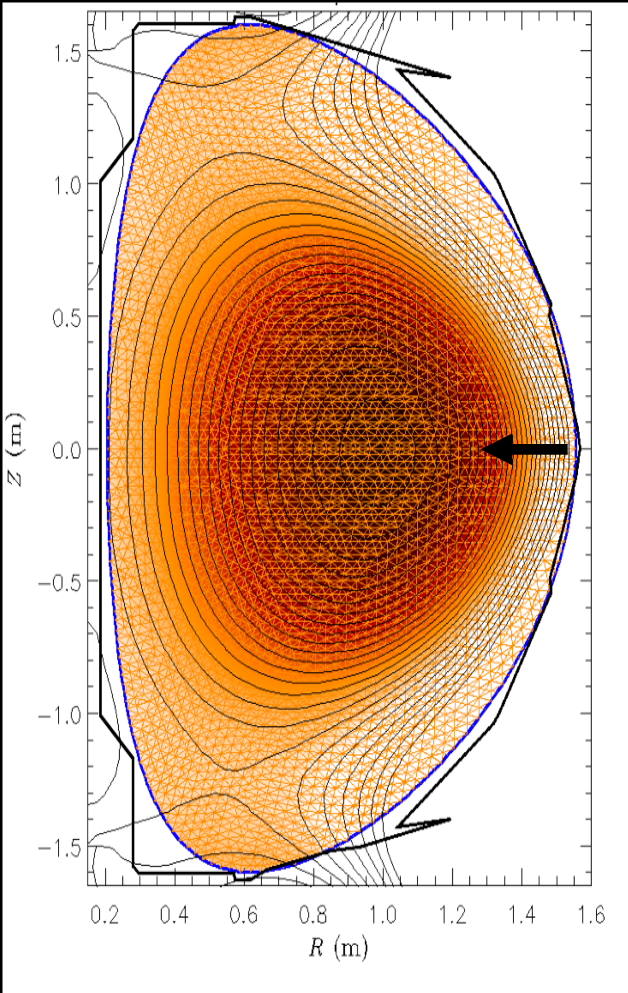
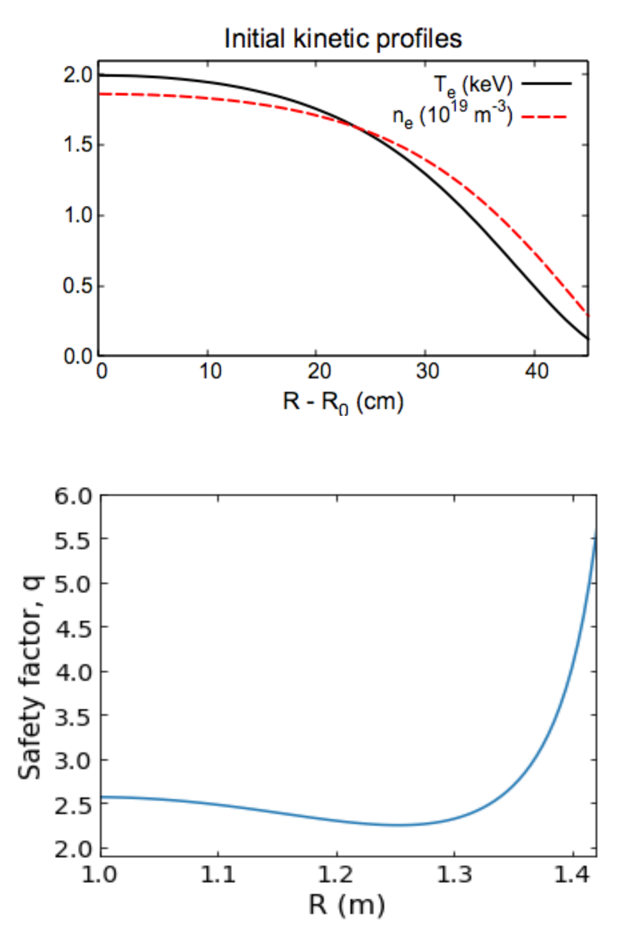
NSTX-U C-pellet Disruption Mitigation Study

We studied single C-pellet injection in NSTX-U (#139536) to support EPI proposal

We started from equilibrium (g-eqdsk provided) and injected a C-pellet radially at the midplane





Parameter	#139536
T_{e0}	2 keV
n_{e0}	$\sim 2\times10^{19}\ m^{-3}$
B_0	0.44 T
I_p	0.58 MA
R_0	0.99 m
β	2.25 %

NSTX-U C-pellet Disruption Mitigation Study

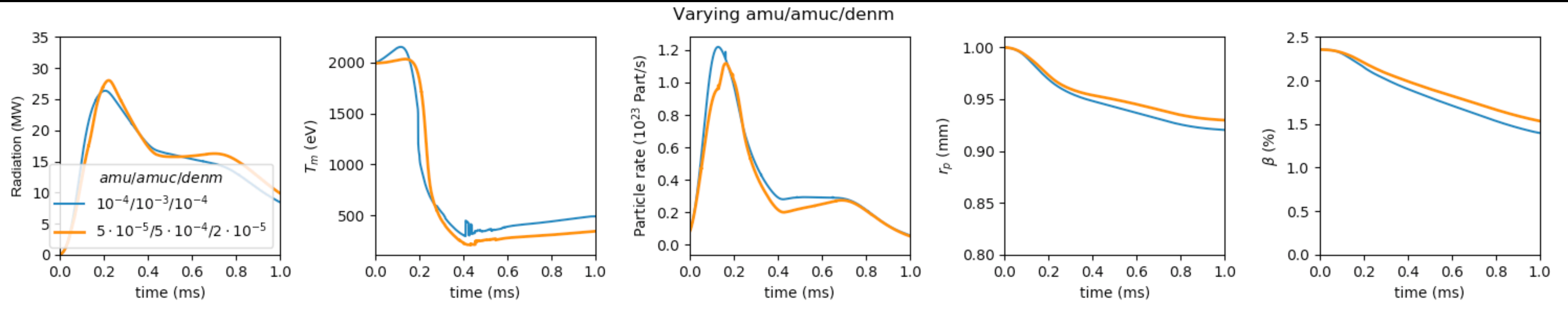
- **We carried out a scan over different parameters**
  - **Modelling & other parameters**
    - Transport and other parameters (density diffusion, viscosity)
    - Pellet neutral cloud size (V_p & V_t)
  - **Pellet parameters**
    - Pellet radial velocity, v_r
    - Pellet mass density, ρ_Z
    - Pellet radius, r_p (experimental limit for NSTX-U would be 1 mm. We fixed at this value)

We need first a clear picture on modelling parameters before moving to scan pellet parameters

In addition, scanning on different parameters can help clarifying the physics behind this process

NSTX-U: Scanning over modelling parameters

Effect of viscosity (μ, μ_c) and density diffusion (denm)

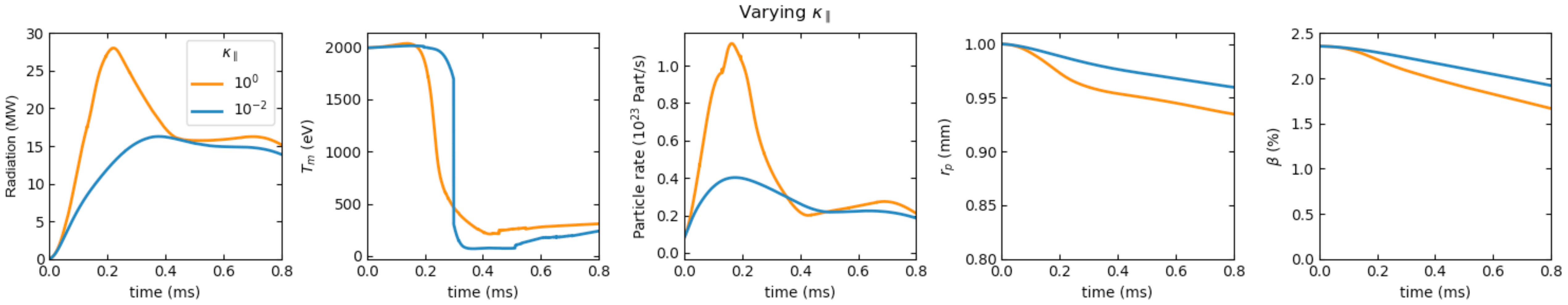


The orange case will be our reference case

- Having larger diffusion coefficients allow bigger time steps (0.5 blue and 0.2-0.25 orange)
- Central temperature can show some differences, but global quantities are similar.
- We can show that reducing even more this quantities does not produce further differences (in progress)

NSTX-U: Scanning over modelling parameters

Effect parallel thermal conductivity



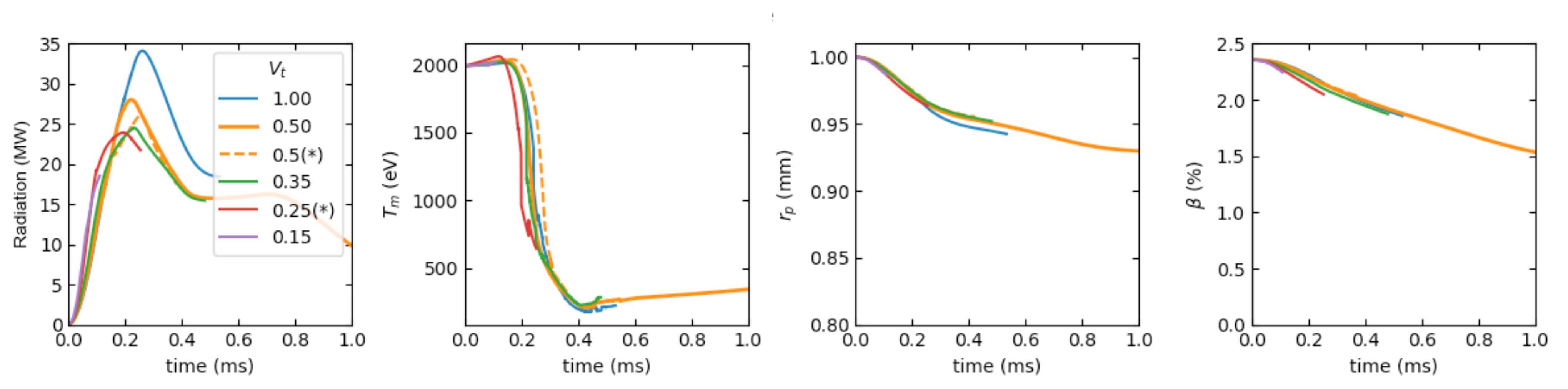
Parameter	value
v_p	1000 m/s
V_p	$50r_p$ (~ 5 cm)
$\kappa_{\perp}$	$2 \cdot 10^{-6}$
μ/μ_c	$5 \cdot 10^{-5}/5 \cdot 10^{-4}$

- **$\boldsymbol{\kappa_{\parallel}}$ has a strong role on pellet related quantities**
- From the comparison with the AUG discharge, $\kappa_{\parallel} = 1$ seems to be a fear value
- Larger $\kappa_{\parallel}$ also requires smaller time steps
- In addition, very large $\kappa_{\parallel}$ values can lead to anomalous perpendicular heat flux (if the mesh is not fine enough) *
- In progress: explore larger $\kappa_{\parallel}$

* S.C. Jardin., J. Comp. Phys. **200** (2004) 133

NSTX-U: Scanning over modelling parameters

Effect of pellet neutral cloud size



Parameter	value	Obs
v_p	1000 m/s	
V_p	$50r_p$ (~ 5 cm)	Case 0.5(*) has $25r_p$
$\kappa_\parallel/\kappa_\perp$	$\sim 10^6$	

Case	# planes	Smallest dt needed
1.0	12	0.15
0.50	16	0.20
0.5(*)	16	0.15
0.35	16	0.05
0.25(*)	32	< 0.1
0.15	32	< 0.02

- Case 0.25(*) has a bit larger viscosity.
- **Almost everything looks similar, except the radiation for $V_t = 1.00$** (a bit larger).
- **Thus, the reference case is taken to be $V_t = 0.50$ (16 planes) and $V_p = 50r_p$.**

All the previous cases show an incomplete TQ

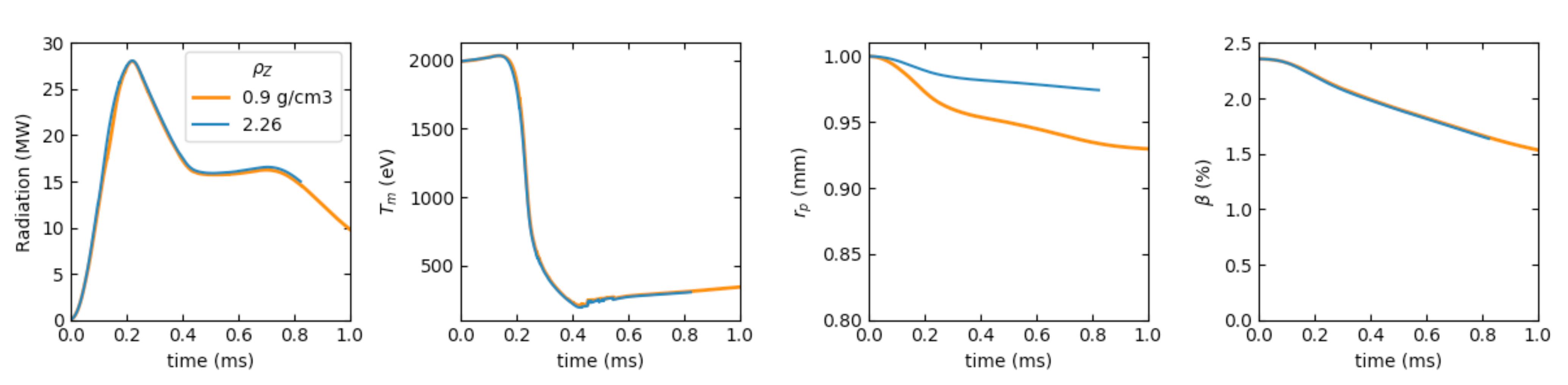
NSTX-U: Scanning over pellet parameters

Covering different pellet densities

There are different C materials: Candidate is vitreous carbon

We covered both ends

material	ρ_Z (g/cm³)
Graphite	2.267
Vitreous	1.51
Sergeev*	0.9



Parameter	value
v_p	1000 m/s
V_t/V_p	0.5 / $50r_p$
$\kappa_{\parallel}/\kappa_{\perp}$	$\sim 10^6$

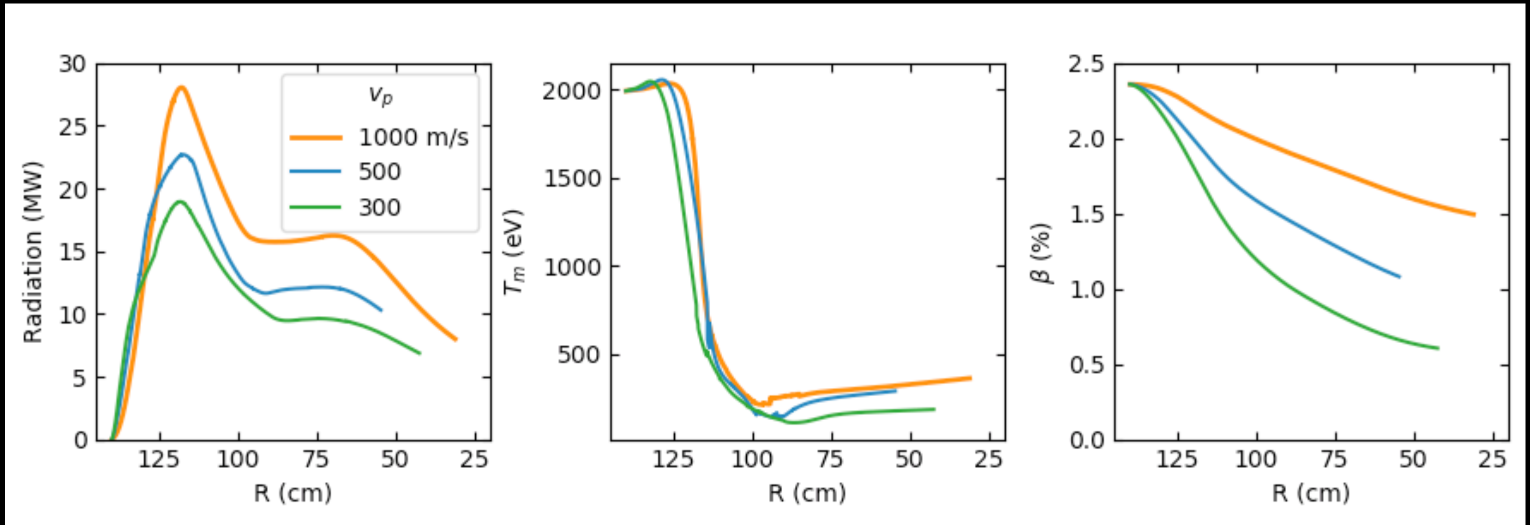
Results are almost identical
Pellet radius is different because of the different pellet densities but the same ablation rate.

* 0.9 is the reported density in their job

NSTX-U: Scanning over pellet parameters

Effect of different pellet velocities

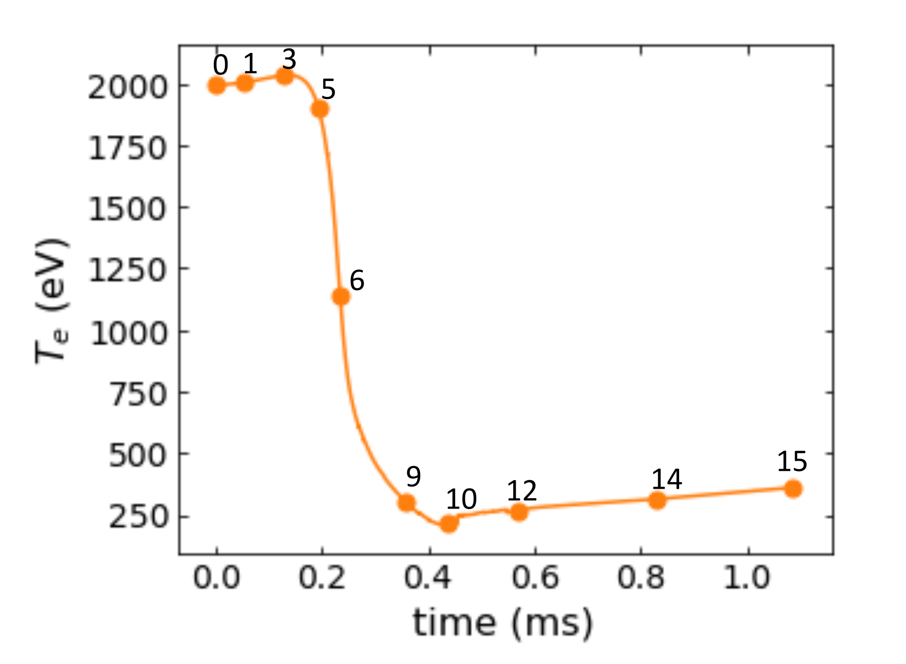
- **The reference case (orange curve) is not enough to produce a complete TQ since β dropped from 2.5% to 1.5%**
- We ran a cases with pellet velocities of 500 m/s and 300 m/s.
- In this case figures are shown as a function of the radial position (not time as previous cases).



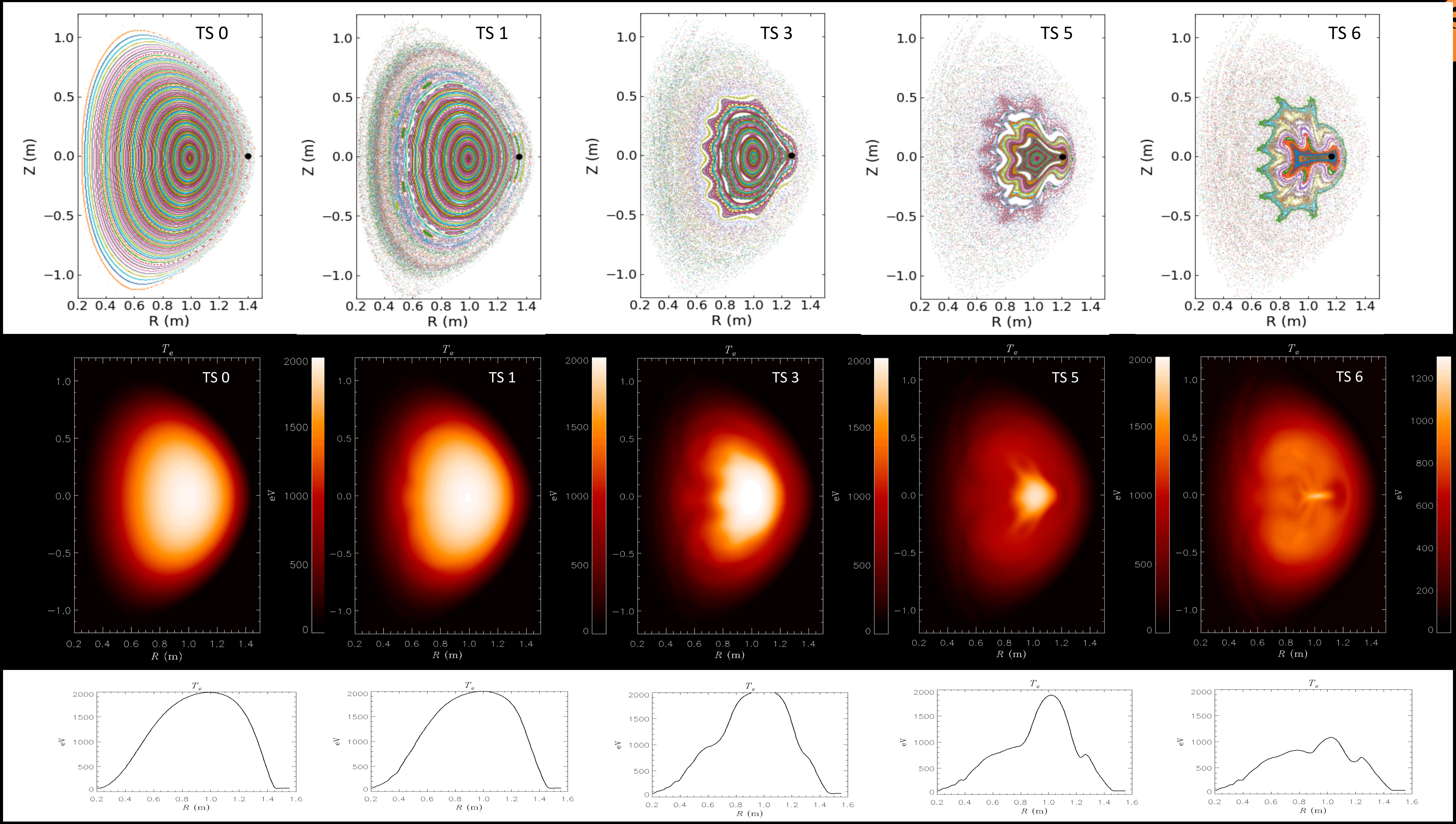
- **β drop is very sensitive to the pellet velocity**

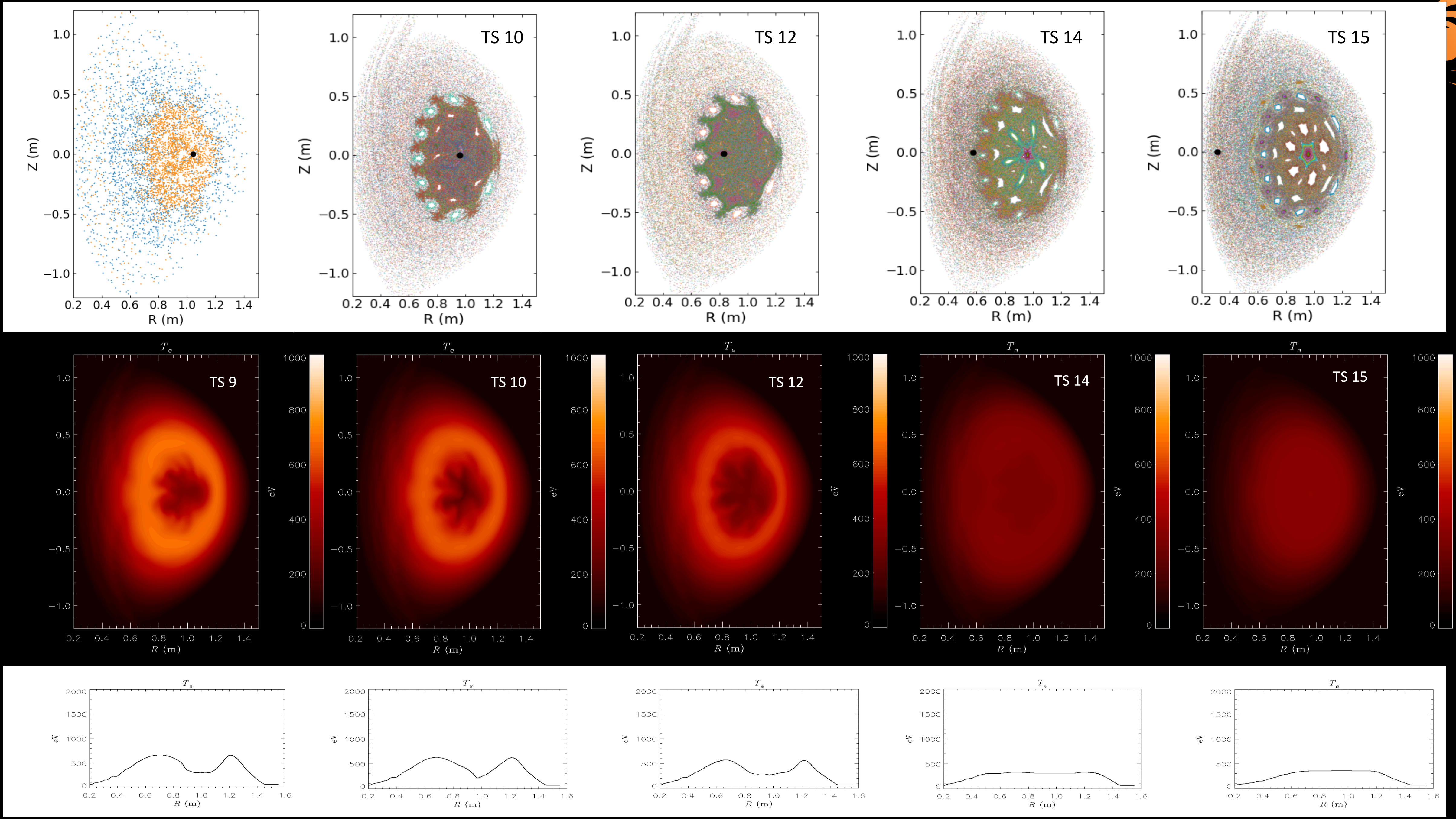
NSTX-U: Understanding the TQ

Central temperature as a function of time



- In the next slides we will show Poincare plots and temperature distribution at all these timeslices.


TS 0
TS 1
TS 3
TS 5
TS 6
Z (m)
R (m)
T_e
eV



TS 10
TS 12
TS 14
TS 15
Z (m)
R (m)
T_e
TS 9
TS 10
TS 12
TS 14
TS 15
eV
R (m)
T_e
eV
R (m)

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NSTX-U: Summary

- We incorporated a C-ablation model in M3D-C1
  - The model was tested in an AUG discharge in which data exists getting a very good agreement
- We have carried out a convergence study for an NSTX-U discharge
  - We evaluated the sensitivity of different parameters
  - Parallel heat flux and pellet velocity are the most important parameters to produce a TQ
  - We showed that central temperature cools down before the pellet reaches it

Still in progress

- Larger $\kappa_{\parallel}$ (to the mesh limit)
- Explain the central cooling mechanism
  - We are analyzing each term in the temperature equation separately
- Compute the Current Quench for selected case(s)

Moving forward (*)

- Shell pellet. Start ablating inside the q=2
  - Our equilibrium has $q \gtrsim 2$ at the core
  - Search for a new equilibrium with $q < 2$
- Explore other pellet materials: B, Boron Nitride, Be, W.
- Simulate an ITER pellet injection

(*) R. Raman, private communication

KPRAD Coupling in M3D-C1

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}) = D\nabla^2 n_i + \sigma_i \quad \text{(idem } n_Z^{(j)}\text{)}$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi - \bar{\omega}\mathbf{v}$$

$$\rho = m_i n_i + \sum_{j=1}^{Z} m_Z n_Z^{(j)} \qquad \bar{\omega} = m_i \sigma_i + \sum_{j=1}^{Z} m_Z \sigma_Z^{(j)}$$

$$\mathbf{E} = \eta\mathbf{J} - \mathbf{v}\times\mathbf{B}$$

$$n_e\left[\frac{\partial T_e}{\partial t} + \mathbf{v}\cdot\nabla T_e + (\Gamma-1)T_e\nabla\cdot\mathbf{v}\right] + T_e(D\nabla^2 n_e + \sigma_e) = (\Gamma-1)[\eta\mathbf{J}^2 - \nabla\cdot\mathbf{q}_e + Q_e + Q_\Delta - \Pi_e:\nabla\mathbf{v}]$$

$$n_*\left[\frac{\partial T_i}{\partial t} + \mathbf{v}\cdot\nabla T_i + (\Gamma-1)T_i\nabla\cdot\mathbf{v}\right] + T_i(D\nabla^2 n_* + \sigma_*) = (\Gamma-1)\left[-\nabla\cdot\mathbf{q}_* + Q_* - Q_\Delta - \Pi_*:\nabla\mathbf{v} + \frac{1}{2}\bar{\omega}v^2\right]$$

$Q_{e,*}$ is the radiation source. It includes line radiation, Bremsstrahlung, recombination.

Large density diffusion can increase the central temperature at the beginning

At the **beginning** and at the **center, w**e have

- $\sigma_e = 0$ (no sources)
- V=0 (no rotation)
- heat flux is small (equil) and radiation should be small: q=0, Q=0
- Ohmic heating should be small: \eta J = 0

So, initially at the plasma center the equations reduces to

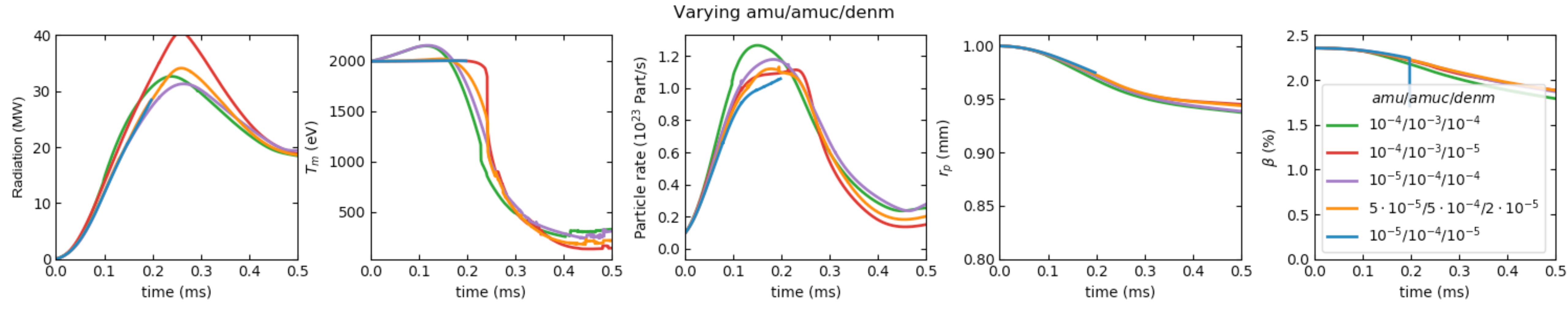
$$\frac{\partial n_e}{\partial t} = D\nabla^2 n_e$$

$$n_e \left[\frac{\partial T_e}{\partial t}\right] + T_e(D\nabla^2 n_e) = 0$$

$\nabla^2 n_e$ is basically negative: that is why the density decreases, but that is also why the temperature increases

NSTX-U: Scanning over modelling & other parameters

Effect of viscosity (μ, μ_c) and density diffusion (denm)



- Large density diffusion increases the central temperature
- Having higher diffusion coefficients allow larger time steps
- But also the central temperature can differ about 150 eV after the temperature fall

Orange case will be our reference case.

μ/μ_c/denm	$5 \cdot 10^{-5}/5 \cdot 10^{-4}/2 \cdot 10^{-4}$

Case	Smallest dt needed
green	1.00
red	0.20
violet	0.30
orange	0.10
blue	0.02

Case v_p=300 m/s