C – pellet disruption mitigation modeling with M3D-C^1

C F Clauser[1], S C Jardin[1], B C Lyons[2], N M Ferraro[1]

[1] Princeton Plasma Physics Laboratory, Princeton NJ USA

[2] General Atomics, San Diego CA USA

* Work supported by the US DOE Contract DE-AC02-09CH11466 and the SciDAC CTTS

Acknowledgement: R. Raman

IAEA – Technical Meeting on Plasma Disruptions and their Mitigation
07/20-23/2020

C – pellet disruption mitigation modeling with M3D-C^1

Outline:

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

Motivation

- **Electromagnetic Pellet Injector (EPI) is a good candidate for a DMS [1]**
- **EPI would offer advantages for ITER**
  - Very fast response time (2-3 ms)
  - Speeds up to 1 km/s
- **The NSTX-U Team is interested in testing this concept**

In support of this interest

- **We have started single C-pellet injection simulations using M3D-C^1**
  - 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

[1] R. Raman et al., Nucl. Fusion **59** (2019) 016021

See R. Raman presentation at this meeting

Modelling pellets in M3D-C^1

The ablation rate is provided

The ablated material is weighted by a spatial distribution

- The **size of the ablated cloud has to be specified**. Limitations arise due to mesh size and number of toroidal planes
- **Smaller cloud sizes require more toroidal planes and smaller time steps**

Plasma evolves self-consistently in time

- Single fluid equations (same velocity, $\mathbf{v}$, for all species (e, i, Z^j))
- Continuity equation for each ion species
    - Electron density is defined to satisfy quasi-neutrality
- Radiation is calculated using the KPRAD module (ionization, recombination, etc)
- Two temperature equations ($\sum$ions and e^-) coupled with the radiation losses calculated by KPRAD

[4] B. Lyons et al., Plasma Phys. and Contr. Fusion **61** 064001 (2019)
[5] N.M. Ferraro et al., Nucl. Fusion **59** 016001 (2019)

C ablation model

Based on a Neutral Gas Shielding Model (NGS) [2-3]

- 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

The ablation rate $\dot{N}$ combines expressions for both strong and weak shielding limits

- **Strong shielding: $\boldsymbol{\delta \to 0}$** (i.e. Hydrogen pellets)

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

- **Weak shielding: $\boldsymbol{\delta \to 1}$** (i.e. Refractory pellets)

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

C pellets can have an intermediate shielding

- There is no analytical model for this regime
- A standard interpolation was proposed [3]:

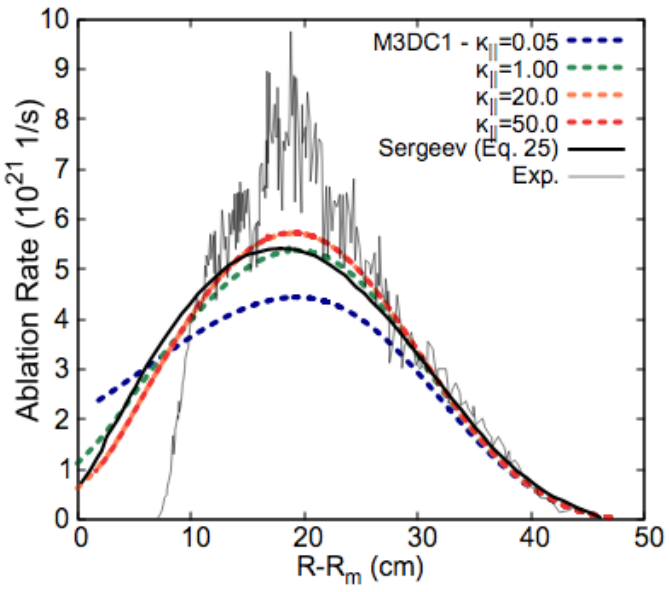
$$\dot{N} = \frac{\dot{N}_0\,\dot{N}_1}{\dot{N}_0 + \dot{N}_1}$$

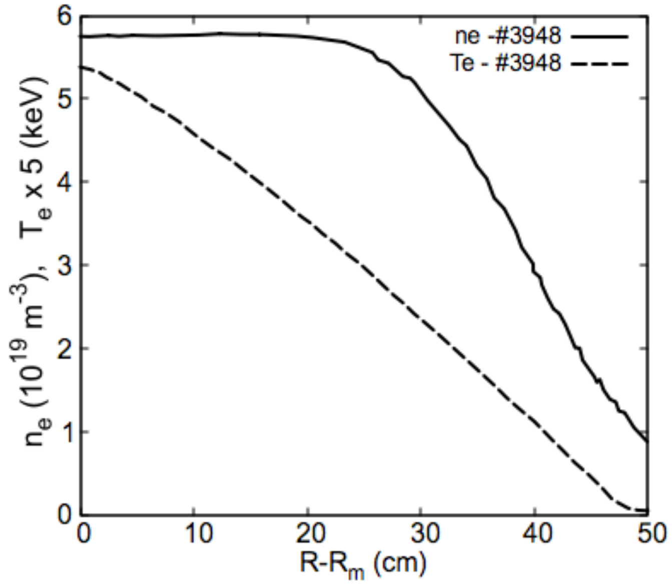
Expression we have implemented in M3D-C^1

[2] Kuteev et al., Sov. J. Plasma Phys. 10 (1984) 675
[3] Sergeev et al., Plasma Phys. Rep. 32 (2006) 363

M3D-C1 implementation tested in AUG

We tested the implementation in an AUG-#3948-like plasma (no G-EQDSK available) in which data existed [3]





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
$\kappa_\perp$	$3 \cdot 10^{-6}$

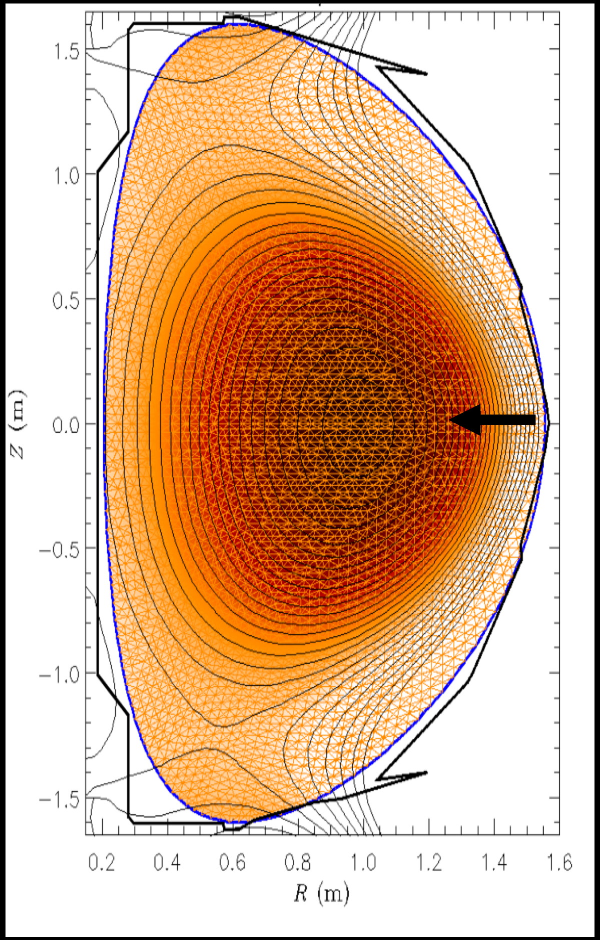
- **Agreement is very good**
- **Large $\kappa_\|$ increases the ablation rate**

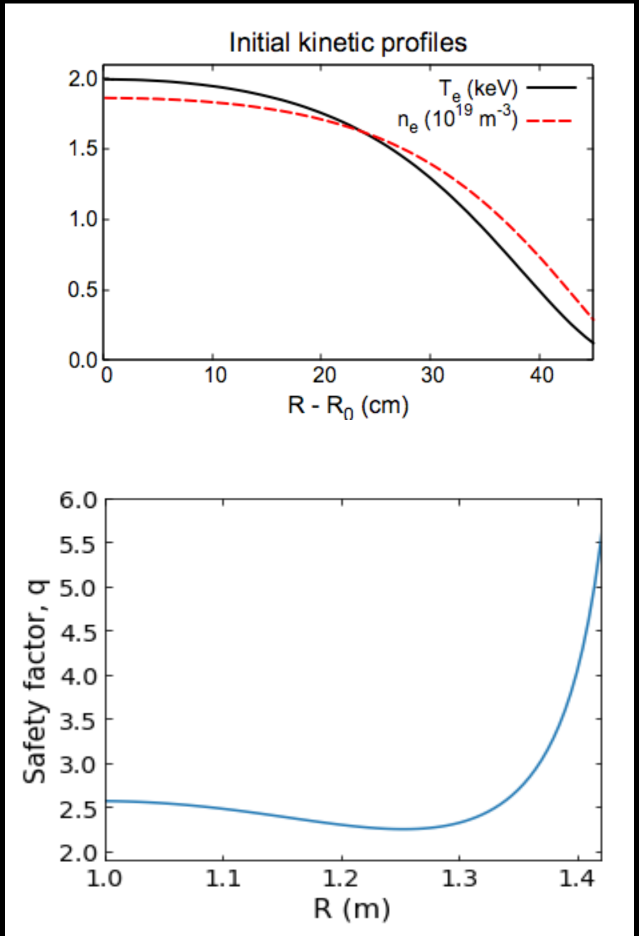
[3] Sergeev et al., Plasma Phys. Rep. 32 (2006) 363

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

- **2D Preliminary studies**
- **3D – Pellet injection studies (1 mm C pellet): Scan over different parameters**
  - **Modelling**
    - Pellet cloud size
    - Parallel Transport
  - **Pellet parameters**
    - Pellet radial velocity, v_p
  - Other parameters were also scanned (density diffusion, viscosity, etc)

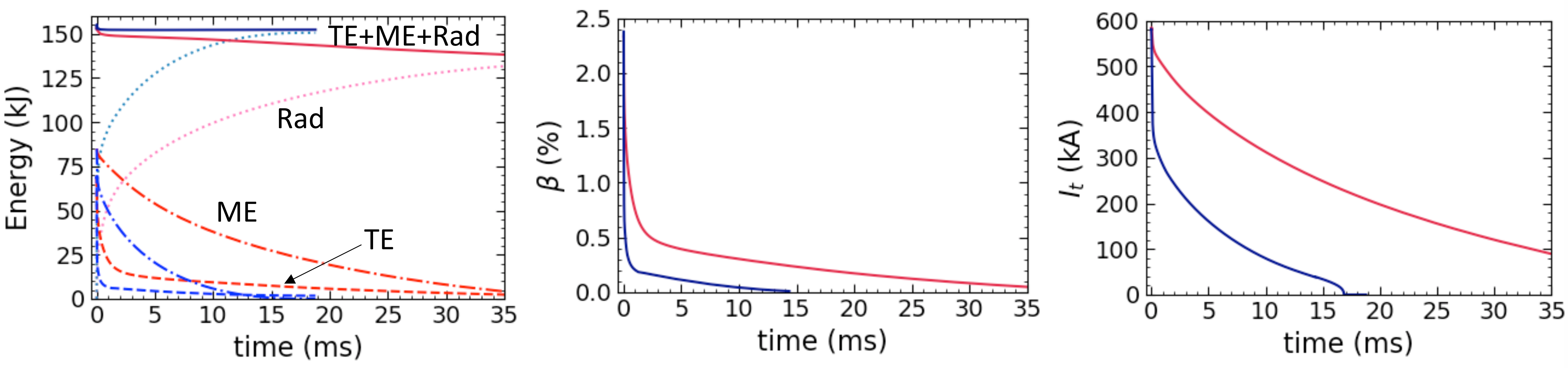
We want to evaluate the role of different parameters on the thermal quench

NSTX-U: 2D preliminary study (no pellet)

Comparing different initial distributed Carbon content

We performed 2D simulations with initially distributed Carbon density to evaluate the amount of Carbon needed to mitigate the plasma

Initial condition	#C atoms	Reference
$n_C = n_e$	2×10^{20}	1 mm C-pellet $= 3.2\times10^{20}$
$n_C = 2n_e$	4×10^{20}	

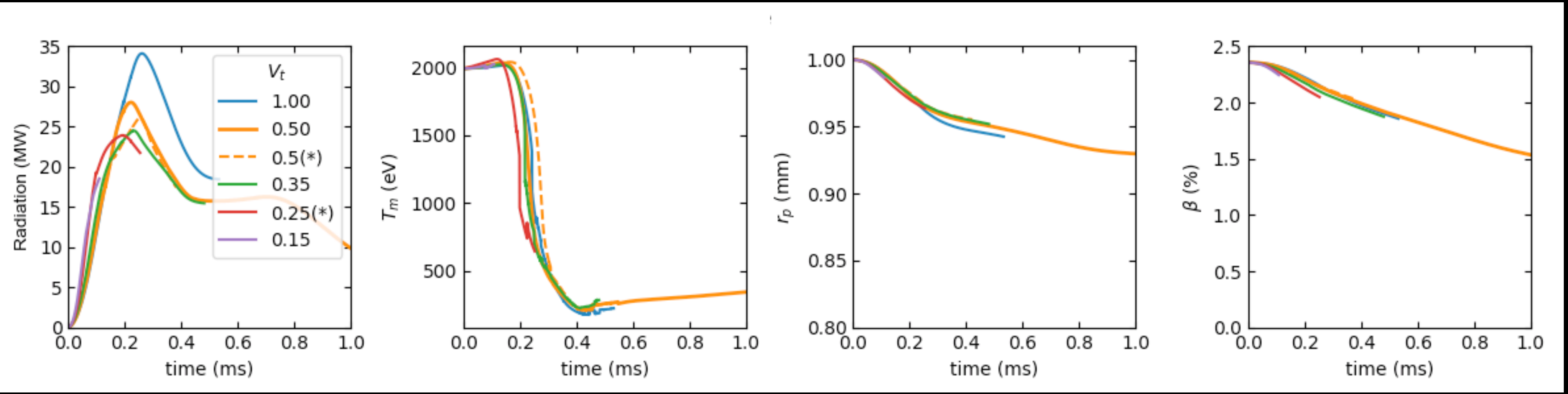


Results suggest that the amount of Carbon in 1 mm pellet would be enough to mitigate the plasma *if it were entirely ablated*

NSTX-U: 3D – Pellet injection studies

Effect of pellet ablated cloud size

We ran several cases varying the ablated cloud size to determine its sensitivity on global quantities
$v_p = 1000$ m/s



- **Smaller cloud size are much more computationally expensive**
  - much smaller time steps
  - more spatial resolution (finer mesh and more toroidal planes)
- **The reference case is taken to be $V_t = 0.50$ m (16 planes) and $V_p = 50r_p$.**

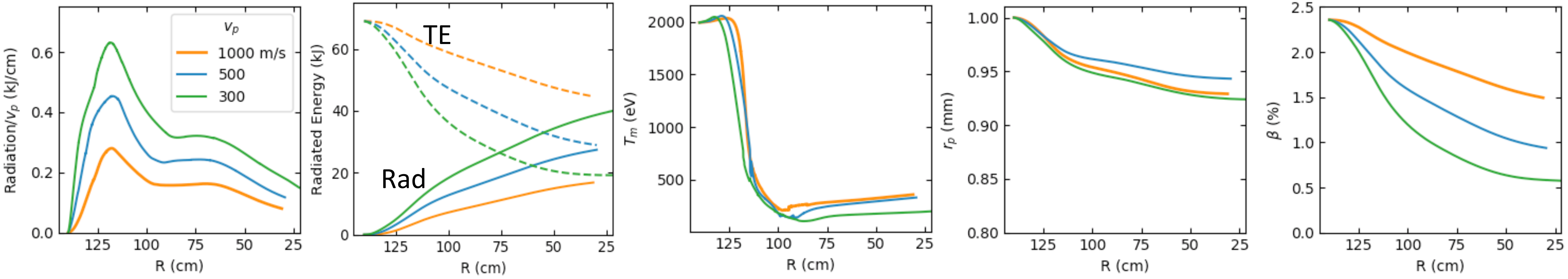
All cases show both incomplete ablation and TQ

Case	# planes	Smallest dt
1.0	12	0.20
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

NSTX-U: 3D – Pellet injection studies

Effect of different pellet velocities

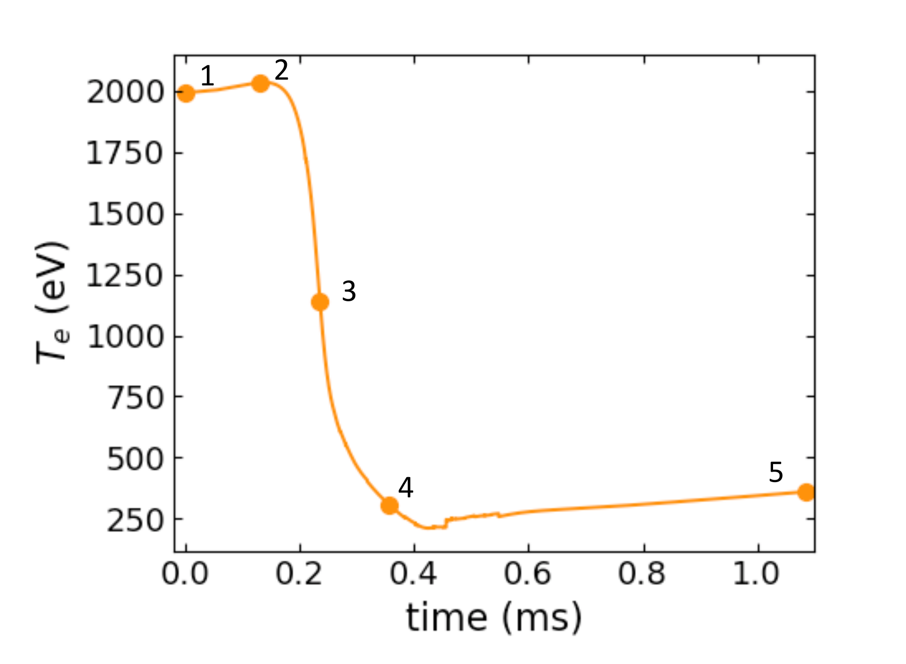
- $v_p = 1000$ **m/s is does not produce a complete TQ**
- We ran a cases with pellet velocities of 500 m/s and 300 m/s.
- Figures are shown as a function of the pellet radial position (not time as previous cases).



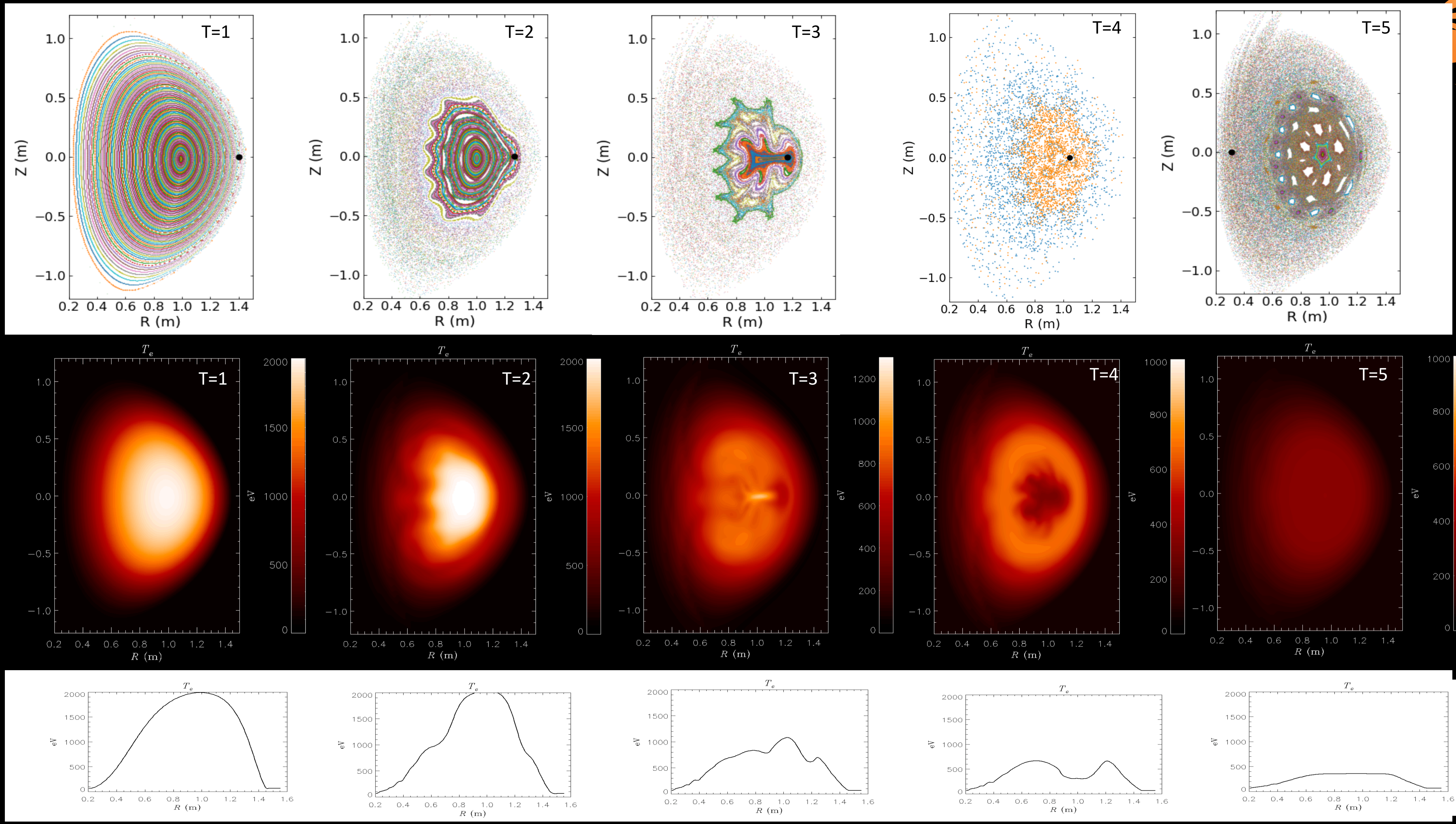
- **Thermal energy drop is sensitive to the pellet velocity, but**
- **Even though the central temperature fall is significant, all the cases still show an incomplete thermal quench**

NSTX-U: Understanding the central T_e fall

Central temperature as a function of time



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



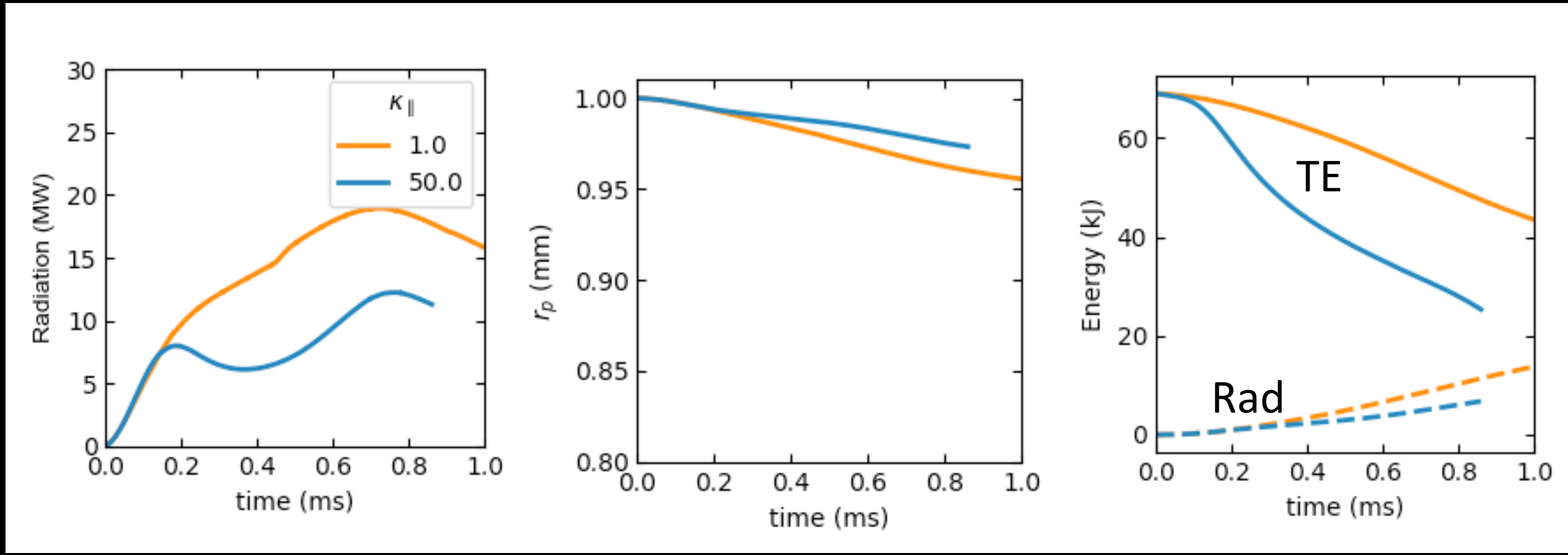
T=1
T=2
T=3
T=4
T=5
Z (m)
R (m)
T_e
eV

NSTX-U: 3D – Pellet injection studies

Effect of parallel heat flux, $\kappa_{\|}$

We showed in the AUG-U test that larger parallel heat flux usually led to larger ablation rates

For bigger pellets, stochastization of the field lines can link the temperature around the pellet position with the boundary temperature.



- This can lead to a reduction of the ablation rate and radiation (Rad) when travelling in the outer region if $\kappa_{\|}$ is large enough
- Heat flux loss also increases and becomes more important leading to a stronger reduction of the thermal energy (TE)

NSTX-U: Summary

Carbon pellet disruption mitigation simulations is being conducted for a NSTX-U geometry

- We incorporated a C-ablation model in M3D-C1. Tested in an AUG discharge
- We are completing a convergence study for an NSTX-U geometry
  - We evaluated the sensitivity of different parameters
  - Parallel heat flux and pellet velocity are very important to the TQ
- **Single C-pellet injection have shown to produce an incomplete TQ**

Moving forward (*)

- Injecting array of C-pellets
- Injecting at a toroidal angle
- Coated pellet. Reduce initial ablation
- Explore other pellet materials
- Simulate an ITER pellet injection

(*) R. Raman, private communication

Extra Slides…

Modelling pellets in M3D-C1

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

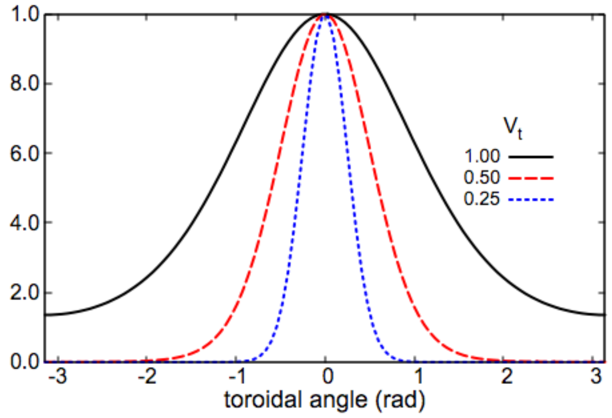
Spatial distribution for the ablated material is prescribed:

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

- 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



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.

Case v_p=300 m/s