Disruption Modelling with M3D-C1

C. F. Clauser, S. C. Jardin, N. M. Ferraro

Princeton Plasma Physics Laboratory

PPPL

Outline

- **2D – VDE studies in an ITER plasma: A Summary**
  Vertical Forces and the role of halo currents

- **3D – VDE studies in an ITER plasma: progress status**
  Sideways forces (underway)

- **Modelling C pellets in NSTX-U**

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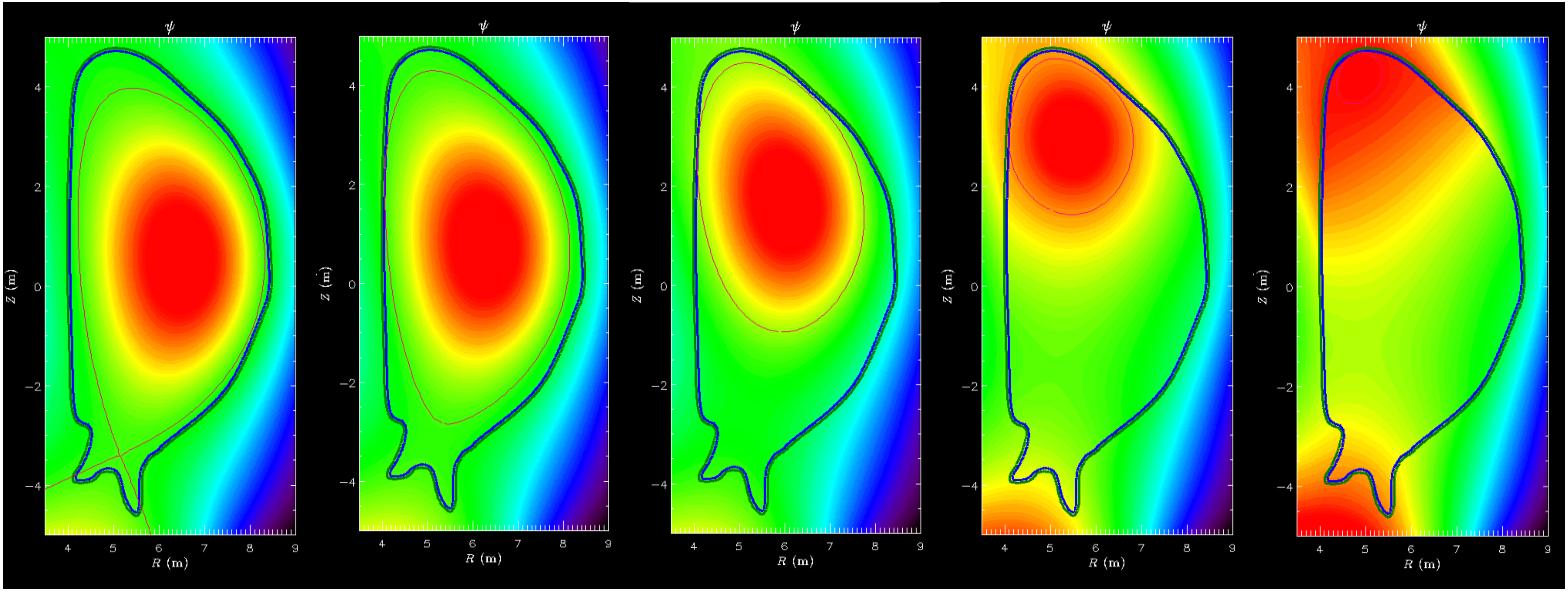
2D – VDE in ITER. A summary

Initial equilibrium	375 ms Wall Contact	635 ms Thermal Quench	678 ms Max Vert Force	700 ms LCFS disappears

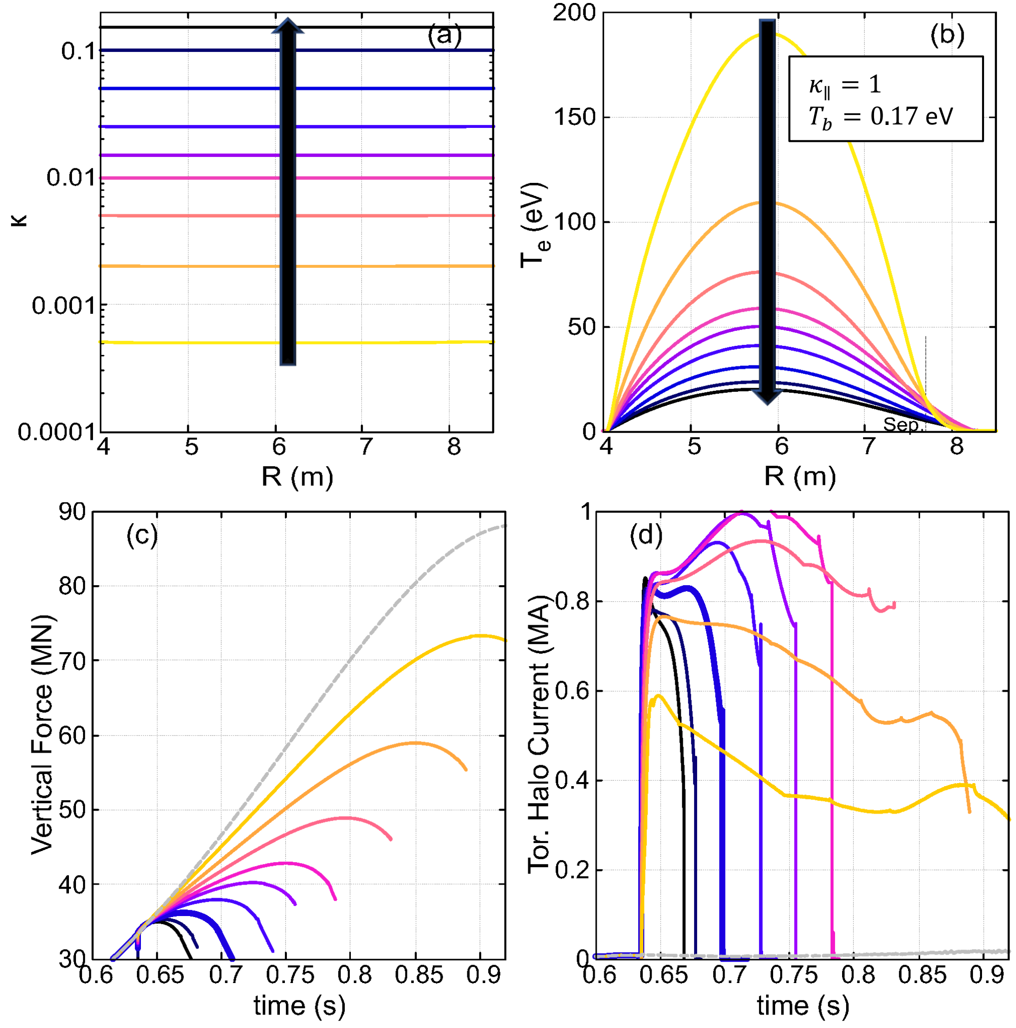


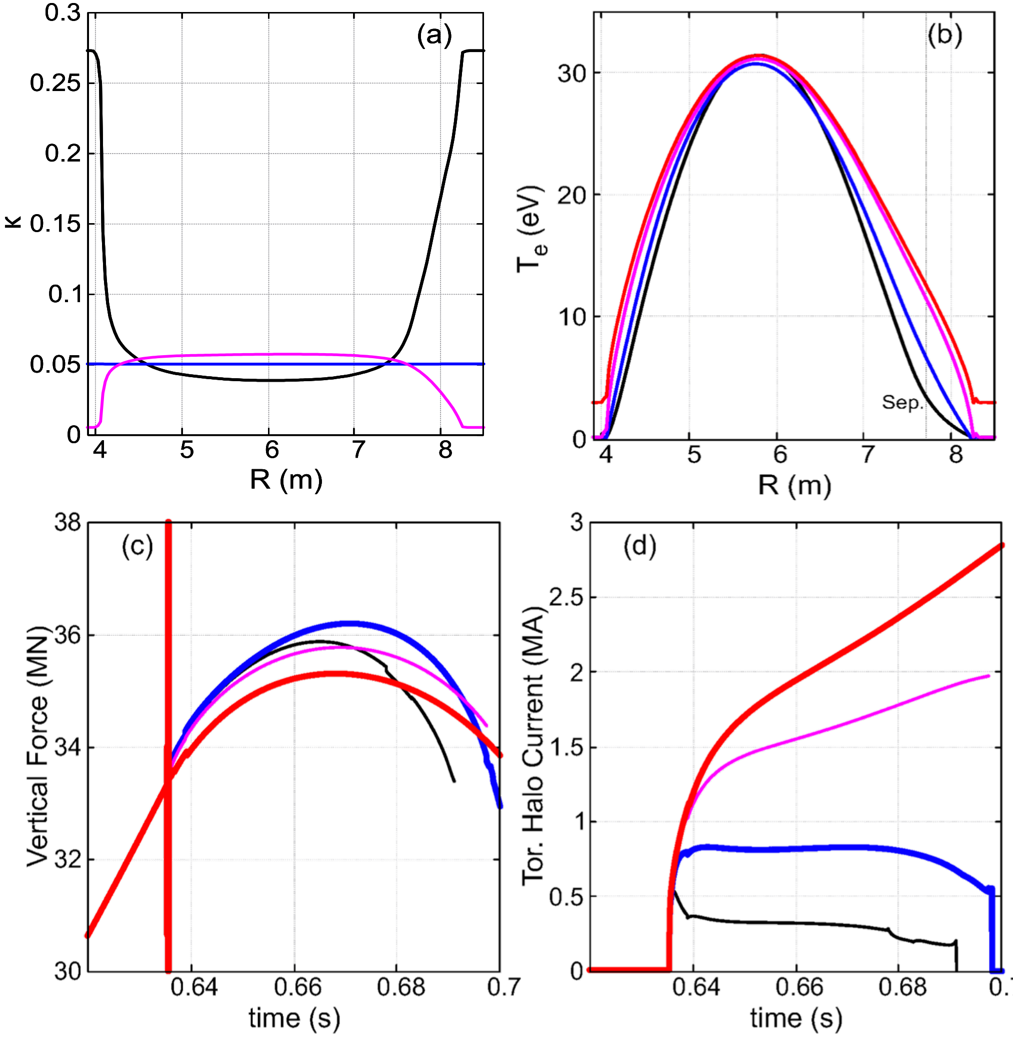
APS Poster session: Wed 23rd Morning. PP10.00072

C. F. Clauser, S. C. Jardin and N. M. Ferraro, Nucl. Fusion 59 126037 (2019).

2D – VDE in ITER. A summary

We have scanned different post-TQ conditions by varying the post-TQ $\kappa_\perp$





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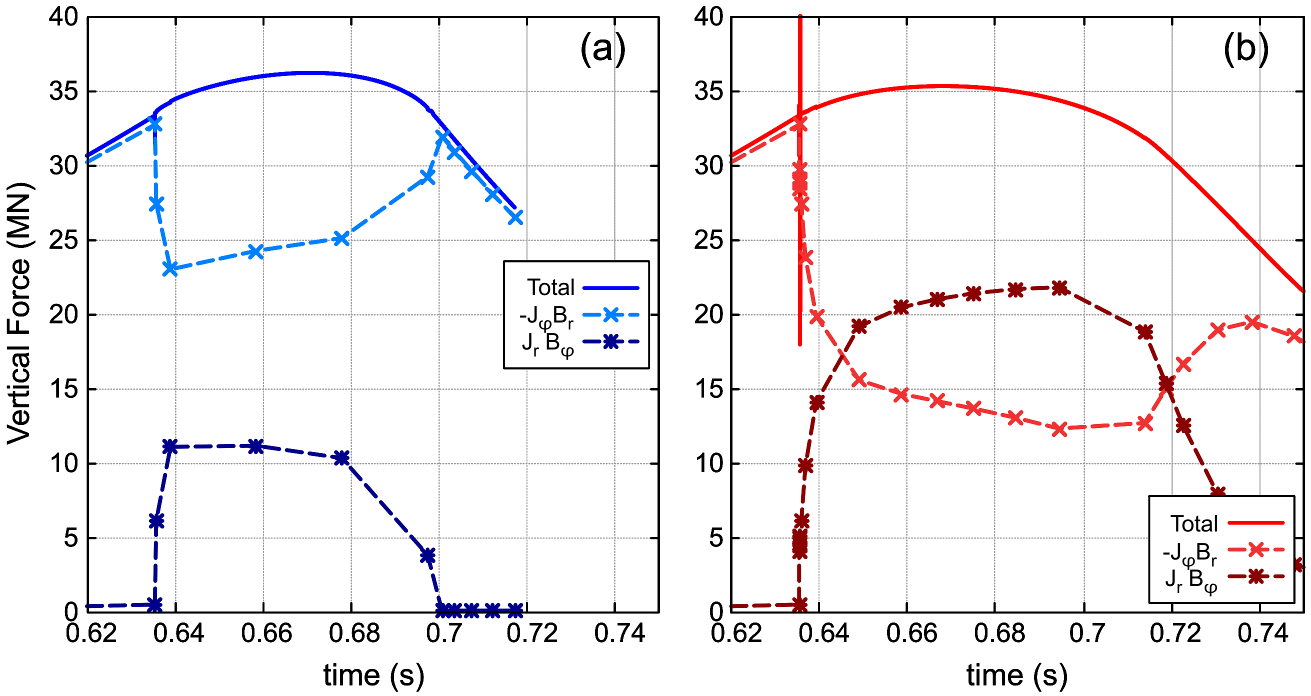
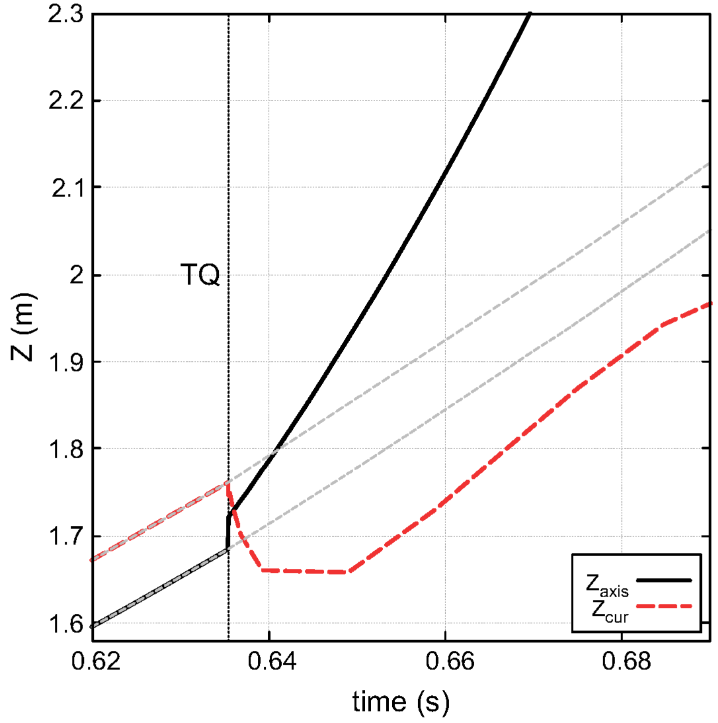
2D – VDE in ITER. A summary

Constant κ, .17 eV T_e BC **Decreasing κ, 3 eV T_e BC**





- Larger halo current had larger $J_r B_\varphi$ term, as expected,
- but, it is offset by a stronger reduction in the $J_\varphi B_r$ contribution.
- **Total vertical force is almost unaffected by magnitude of halo current.**

The halo region formation produces a current density centroid displacement

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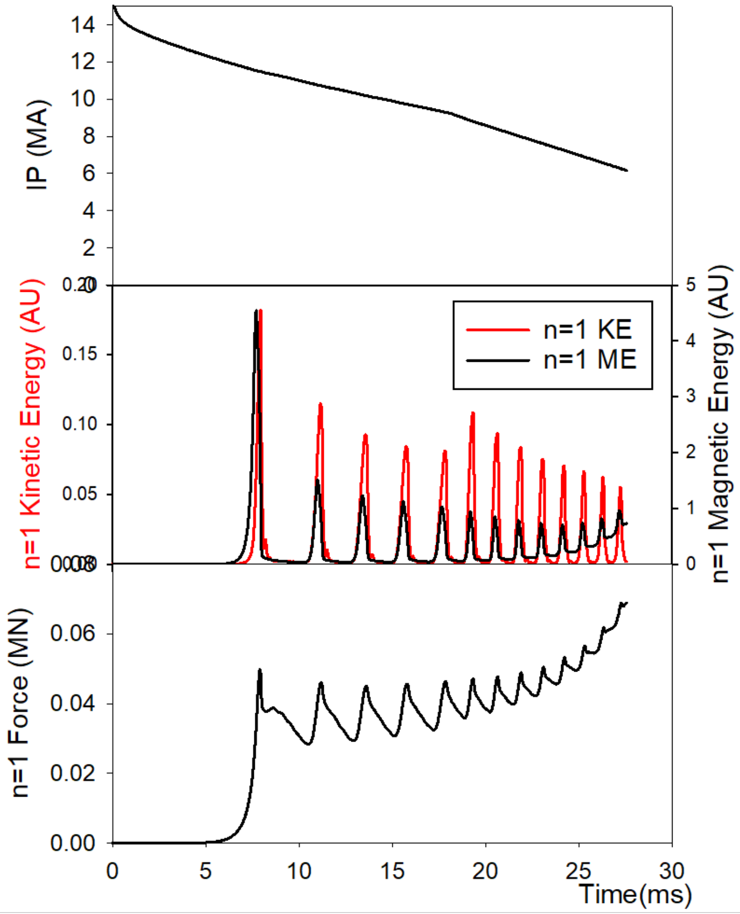
3D – VDE Studies (TQ also initiated by $\kappa_\perp$)

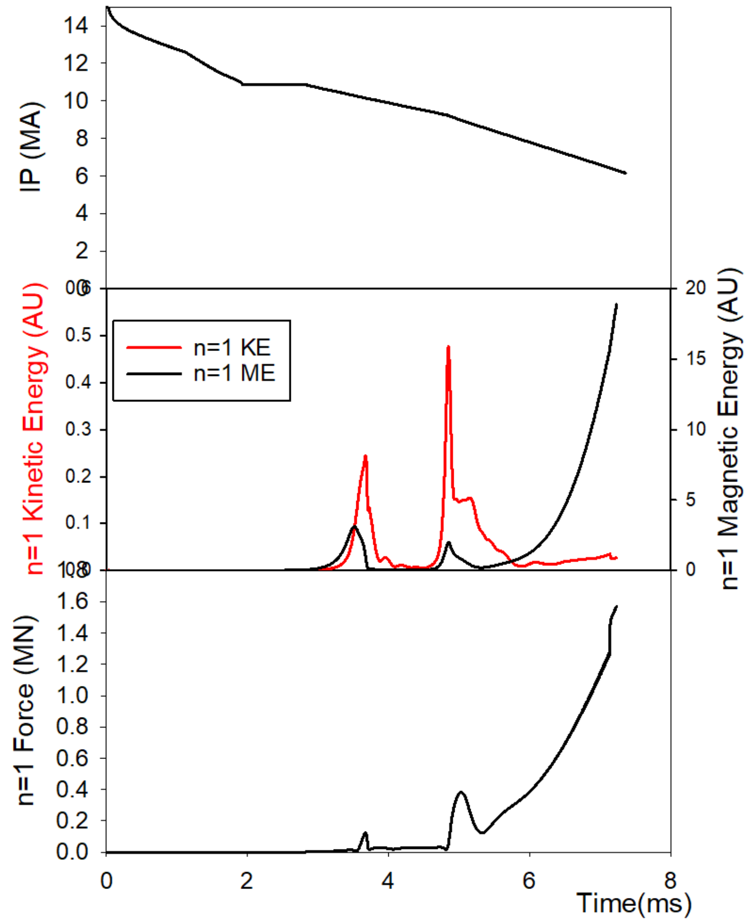
Using actual vessel time

$\tau_w \approx 235$ ms



Wall resistivity increased by 1000

$\tau_w \approx 0.235$ ms

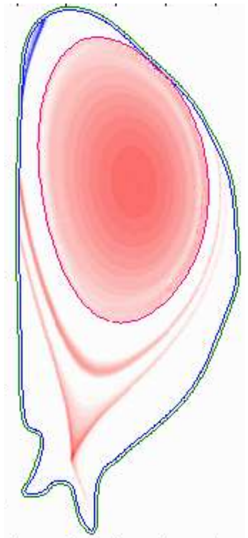


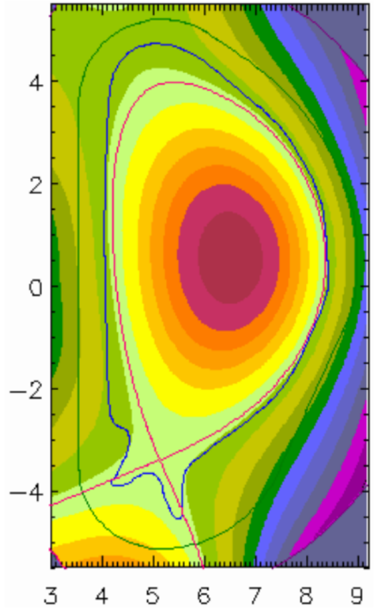
3D – VDE Studies (TQ also initiated by $\kappa_{\perp}$)

- Comparison of two simulations with $\tau_w = 235$ ms and $\tau_w = 0.235$ ms shows that small sideways force is due to $\gamma\,\tau_w$>>1 for n=1 mode with ITER vessel

- Large halo current case in progress

- Now in discussions with F. Villone about using CARRIDI to generate a more detailed wall model that can be incorporated into M3D-C1
    - Need to separate "first wall" and vessel
    - Need more detailed model of vessel structure





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Modelling C pellets in M3D-C1

- **We are starting a systematic study of C pellet injection in a NSTX-U-like configuration**
- **This is motivated by the EM pellet injector that is being proposed for NSTX-U**
  - Very fast response time (2-3 ms)
  - Speeds up to 1 km/s

C ablation model based on…

- 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

Neutral Gas Shielding Model (NGS)

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

- Hydrogen pellets
  - Low sublimation energy ε
  - $\delta \ll 1$: Most of the plasma heat flux is absorbed by the neutral pellet cloud

- Refractory pellets
  - High sublimation energy
  - $\delta \geq 0.8$: Most of the plasma heat flux reaches the pellet surface
  - Delayed time at which evaporation begins

The model does not include

- Suprathermal particle contribution
- Electrostatic shielding does not work well

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- 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

For both limits an analytical expression for the reaction rate $\dot{N}$ is derived

Strong shielding ($\delta \to 0$)

Based on scaling laws

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

Weak shielding ($\delta \to 1$)

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

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

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

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

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

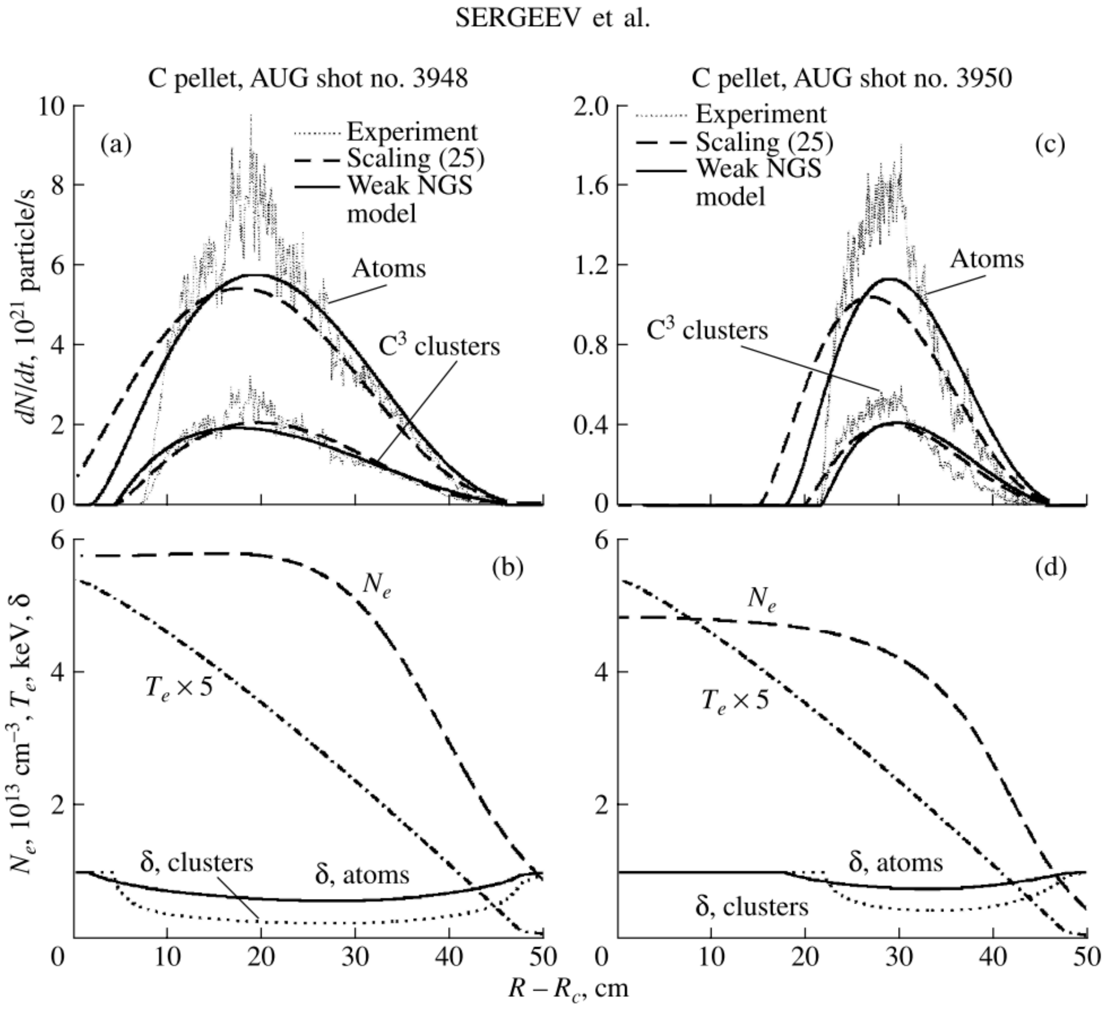
$$\dot{N} = \frac{\dot{N}_0\ \dot{N}_1}{\dot{N}_0 + \dot{N}_1}$$

Ablation models agree well with experimental data

They have been tested on a series of AUG shots

Parameter	3948	3950
r_p	0.25 mm	0.16 mm
v_p	485 m/s	265 m/s

Parameter	C atom	C^3 cluster
ε [eV]	8.8	11.6
γ	5/3	8/6
Z_p	6	18



Modelling C pellet in M3D-C1

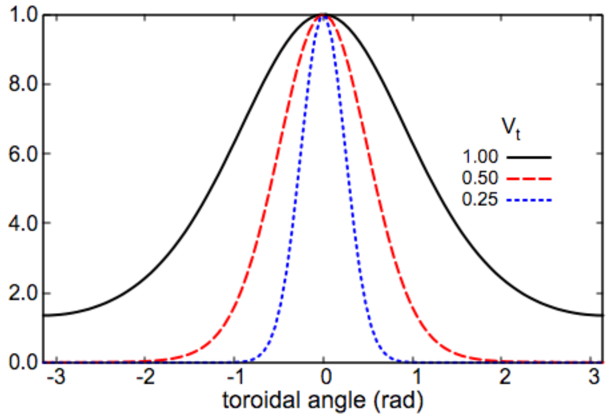
We have incorporated these ablation models in M3D-C1

However, the spatial distribution for the neutral cloud is prescribed:

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

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

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

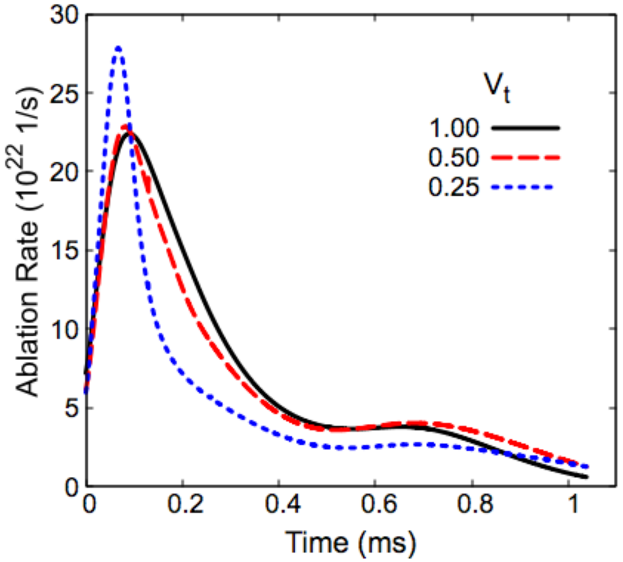


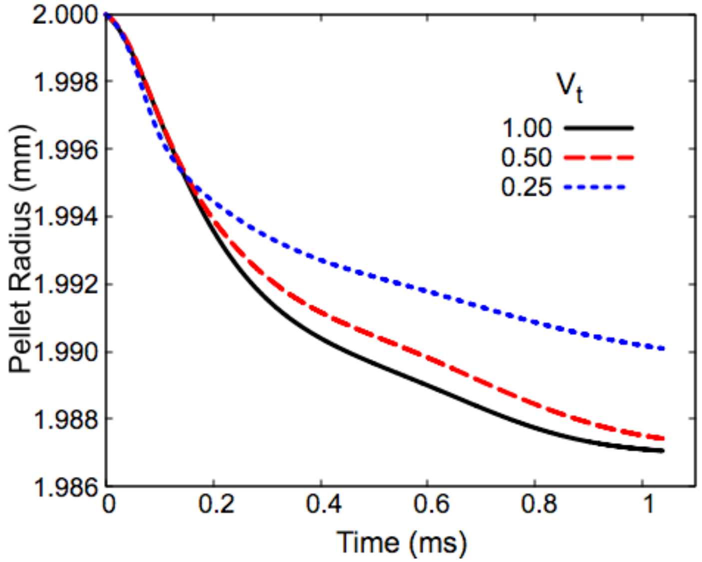
* Using spatially uniform toroidal planes. Now the code has the capability to increase the number of toroidal planes in a localized region.

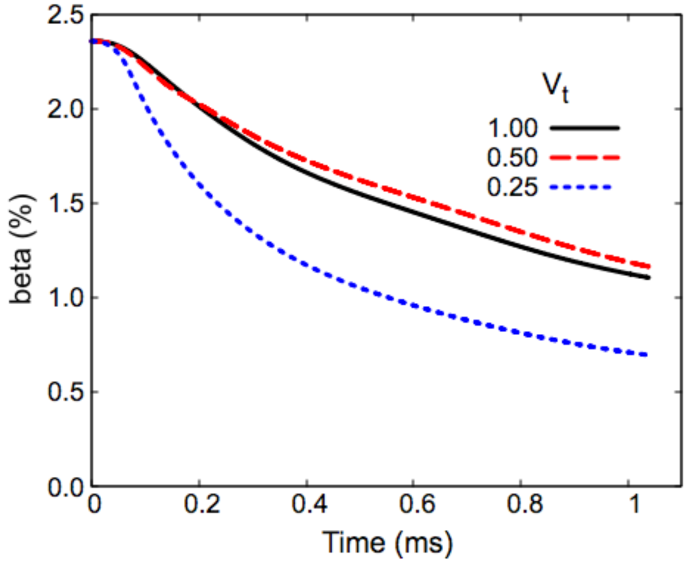
Preliminary Studies

We have carried out preliminary simulations to evaluate how sensitive are the toroidal neutral cloud size

Parameter	Initial value
Pellet radius	2 mm
Pellet velocity	1000 m/s
Poloidal size V_p	10 cm







Next steps…

- **We have requested the previous AUG shots with C pellets injection in order to Validate/calibrate our implementation.**
  - This will be important to determine how large can be the neutral cloud

Assuming that ablated particles follow an adiabatic expansion:

$T_s \approx 5000\ \mathrm{K} \quad \rightarrow \quad V_s \approx 2.4\times10^5\ \mathrm{cm/s}$ (Carbon atoms)

$\nu_{ion} \gtrsim 10^6\ \mathrm{s}^{-1}$ ($\mathrm{C}^0 \rightarrow \mathrm{C}^1$ with kprad)

Thus, the mean-free path $\lambda \lesssim 0.2\ \mathrm{cm}$

This is a very small size for 3D modelling.

Next steps…

- **Evaluate whether or not adding the initial pellet heating**
  - “The interaction of refractory pellet with plasmas differs substantially from that of Hydrogen pellets in that there is a noticeable delay between the time the pellet enters the plasma and the time at which evaporation begins” [Kuteev84]

Thus, for pellet with high enough sublimation energy – like C pellets – there is a non-zero time in which the pellet is heated before ablation.

This could be important for very fast pellet injection

$$C_P \frac{\mathrm{d}T}{\mathrm{d}t} = Q \longrightarrow T(t) = T_0 + \frac{1}{(4/3)\pi r_p^3 c_p} \int_0^t Q(t')\mathrm{d}t$$

Next steps…

- **Carry out a series of simulations in NSTX-U scanning different parameters**
  - **Toroidal neutral cloud size**
  - **Using non-uniform toroidal plane distribution: increasing the spatial resolution around the pellet injection position**
  - **Different pellet velocities**
  - **Different ratio between the ablation to $\mathbf{C}$ and $\mathbf{C^3}$**

- **We are also interested in Be and W pellet injections into an ITER-like plasma**

Extras…

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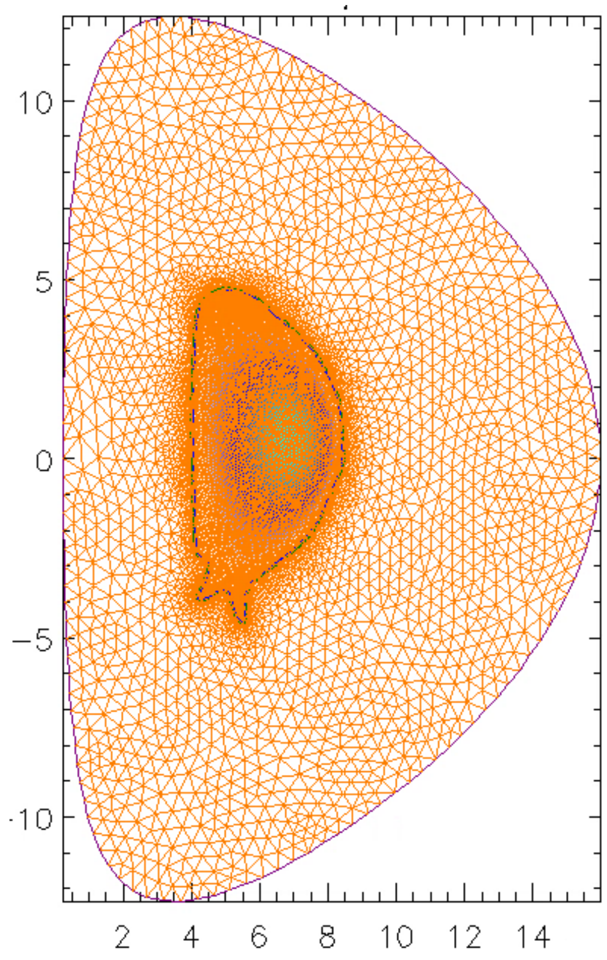
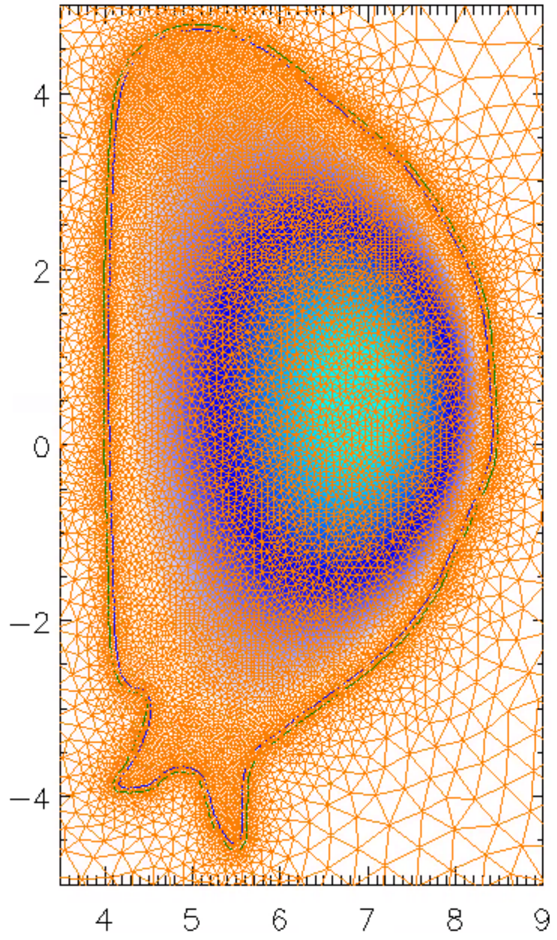
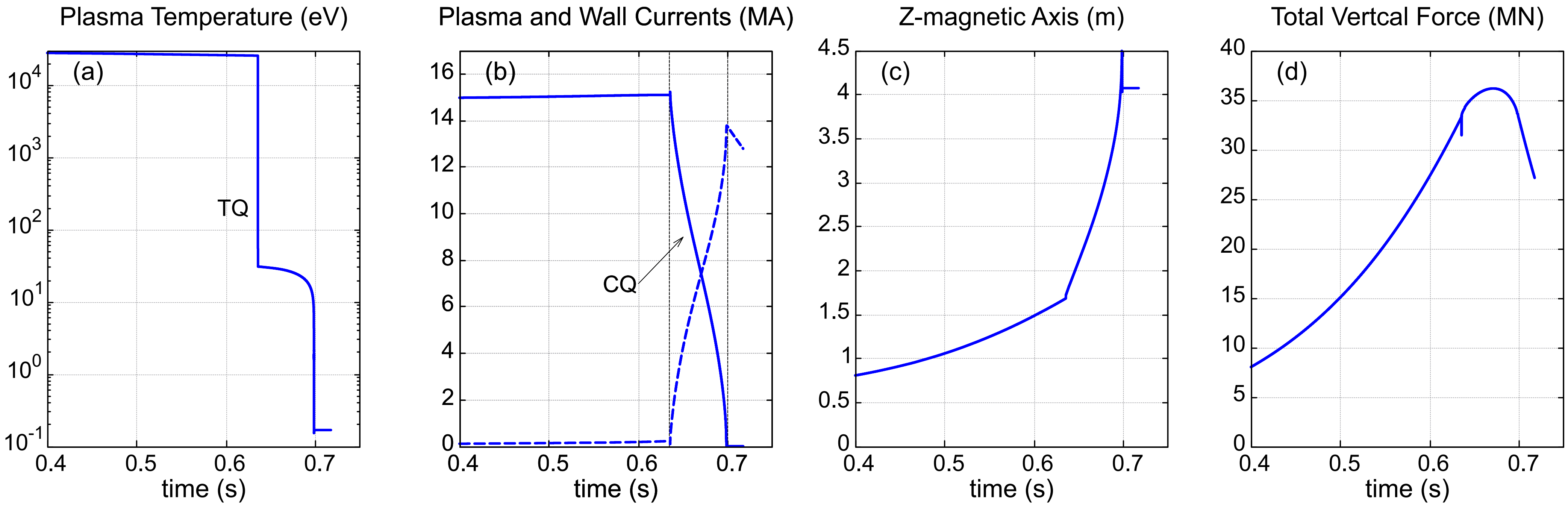




Extras…



When we initiate the **Thermal Quench**, TQ, the plasma temperature falls down very sharply. This increases the plasma resistivity.

Because of the resistivity increasement at TQ, the plasma current starts decaying (**Current Quench**). This induces a total current in the wall.

The CQ increases the force imbalance and the plasma speeds up its vertical drift.

The currents flowing in the wall produce a total vertical force via $\mathbf{J}\times\mathbf{B}$

Extras…

Maximum vertical wall force for all the cases presented