NIMROD Modeling of Disruption Mitigation on EAST and CFETR

Debabrata Banerjee[1]

with

Ping Zhu[1,2], Yanmin Duan[3], Songtao Mao[3], Charlson C. Kim[4], Vincent Chan[1,5], the CFETR team and the NIMROD team

[1]University of Science and Technology of China
[2]University of Wisconsin-Madison
[3]Institute of Plasma Physics, Chinese Academy of Sciences
[4]SLS2 Consulting
[5]General Atomics

CTTS Meeting , April 22, 2018
Auburn University, Auburn AL
(presentation via zoom)

Model in NIMROD for MGI disruption mitigation

Continuity equations:

$$\frac{dn_i}{dt} + n_i\left(\vec{\nabla}\cdot\vec{V}\right) = \vec{\nabla}\cdot D\vec{\nabla}n_i + S_{ion/rec}$$

$$\frac{dn_Z}{dt} + n_Z\left(\vec{\nabla}\cdot\vec{V}\right) = \vec{\nabla}\cdot D\vec{\nabla}n_Z + S_{ion/rec}$$

KPRAD calculates ionization and recombination rates for all impurity charge states and deuterium.

Quasi-neutrality condition: $n_e = n_i + \sum n_Z Z$; z = all charge states of impurity gas

Momentum equation of combined single –fluid: $\rho\frac{d\vec{V}}{dt} = -\vec{\nabla}p + \vec{J}\times\vec{B} + \vec{\nabla}\cdot\overleftrightarrow{\Pi}$

MHD pressure: $p = p_i + p_e + p_Z$

MHD density: $\rho = \rho_e + \rho_i + \rho_Z$

Impurity contributed to MHD density and pressure

V. A. Izzo et. al. Physics Plasmas, 15, 056109 (2008).

Continued …

Faraday's law coupled with Ohm's law:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{V} \times \vec{B}\right) - \vec{\nabla} \times \left(\eta \vec{J}\right)$$

Spitzer resistivity with impurity contribution:

$$\eta\left(T_i, Z_{eff}\right) = \eta_o Z_{eff} \left(\frac{T_{io}}{T_i}\right)^{3/2}$$

Pressure evolution equation:

$$\frac{3}{2} n_i \frac{dT_i}{dt} = -nT_i \vec{\nabla} \cdot \vec{V} - \vec{\nabla} \cdot \vec{q}_i - Q_{loss} + Q_{Ohm}$$

$$Q_{loss} = Q_{line\ \ radiation} + Q_{bremsstrahlung} + Q_{ionization} + Q_{recombination} + Q_{dilution}$$

Anisotropic Heat conductive tensor:

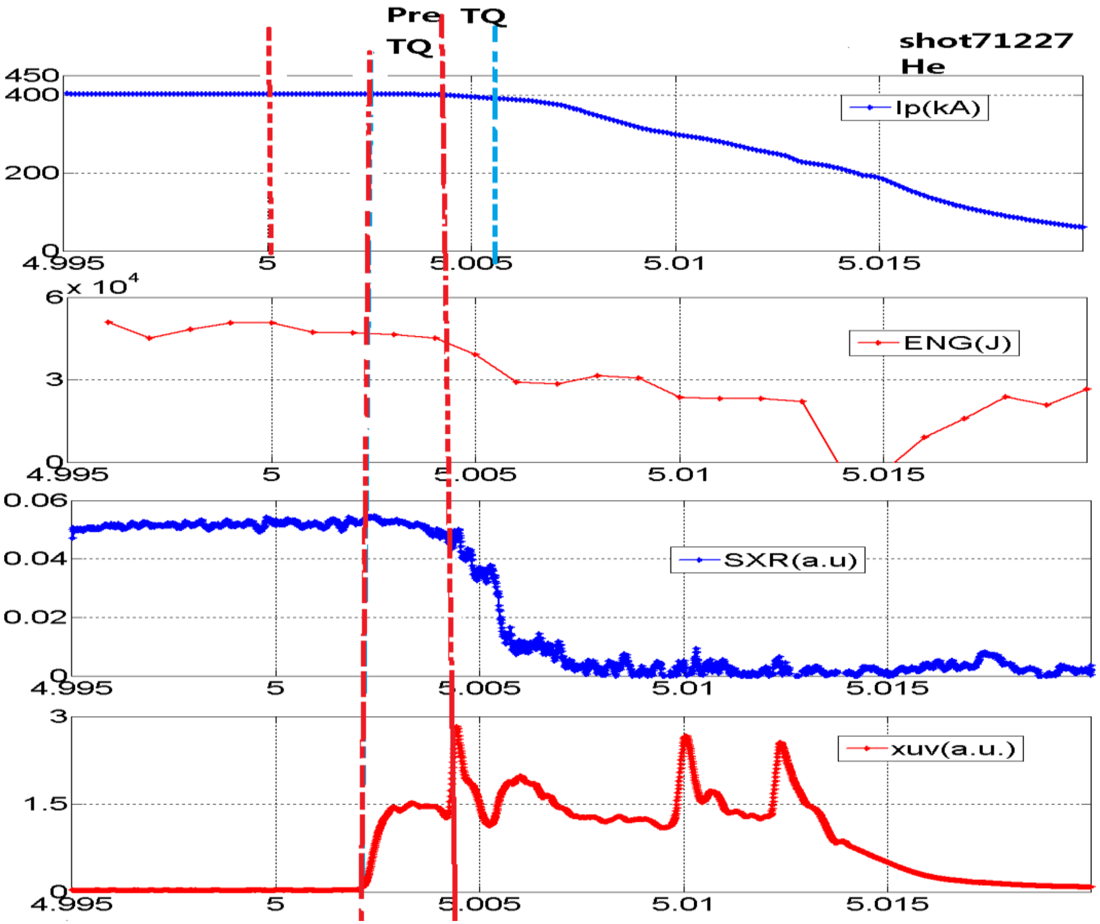
$$q_i = -n\left[\chi_{\|}\hat{b}\hat{b} + \chi_{\perp}\left(1 - \hat{b}\hat{b}\right)\right] \cdot \vec{\nabla} T_i$$

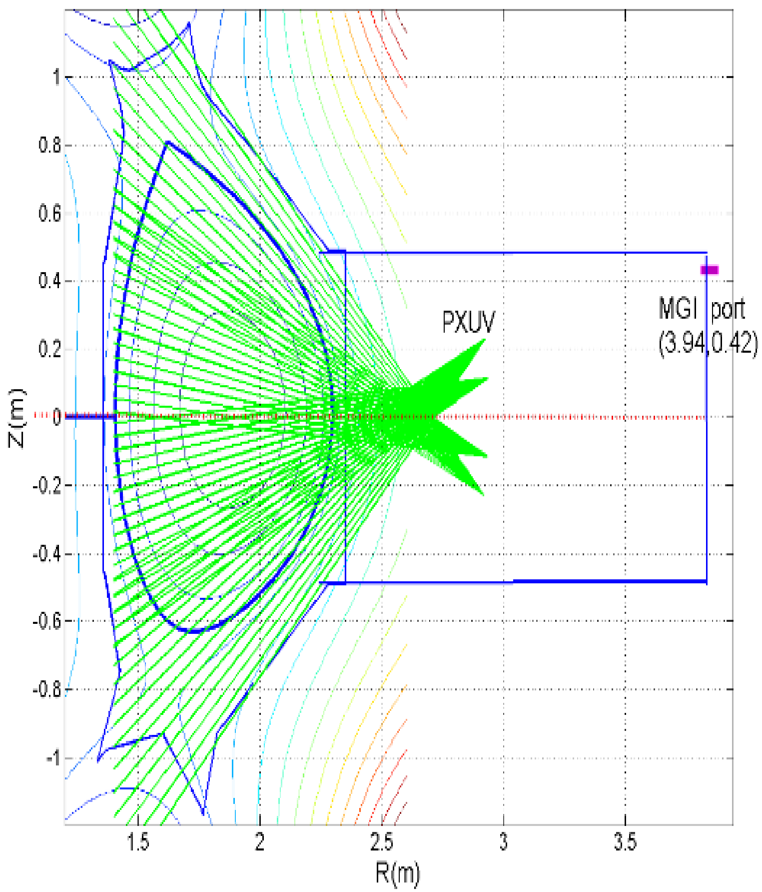
$$\chi_{\perp} = 1.0 \mathrm{m}^2 s^{-1} \quad , \quad \chi_{\|} = 10^{10}\ \mathrm{m}^2 s^{-1}$$

V. A. Izzo et. al. Physics Plasmas, 15, 056109 (2008).

Part-I: Simulation of Helium MGI on EAST equilibrium

Experiment: He MGI triggered on EAST #71227 shot

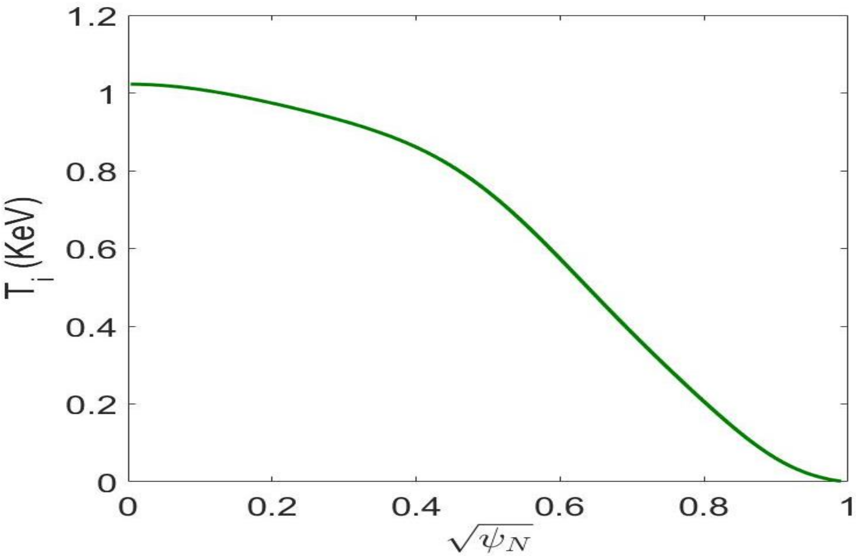


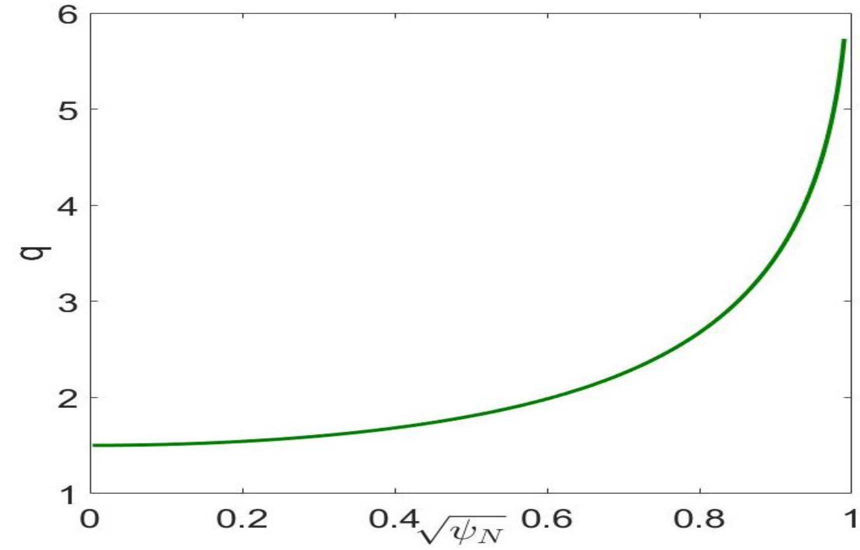


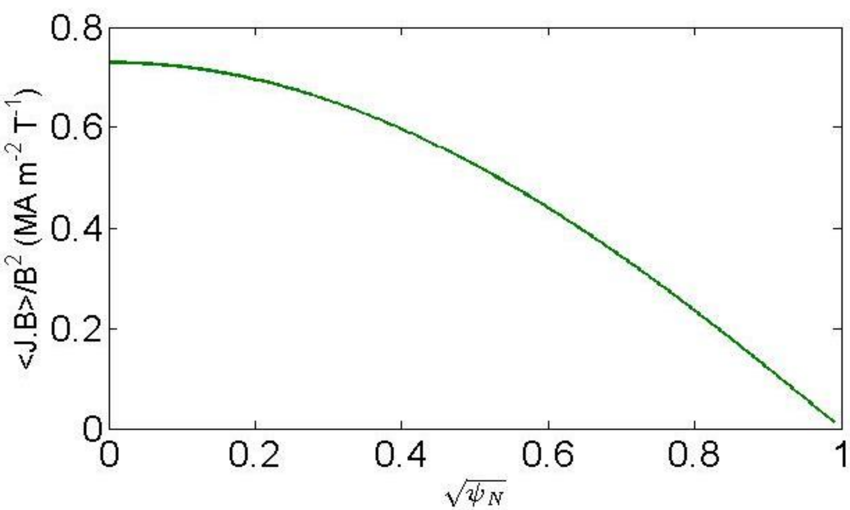
Thermal energy drops in two steps.
Radiation level remains high in CQ phase, with several peaks of MHD activity.

Songtao Mao et. al., under preparation (2018).

NIMROD: EAST G-file at 4.8 s -- initial equilibrium







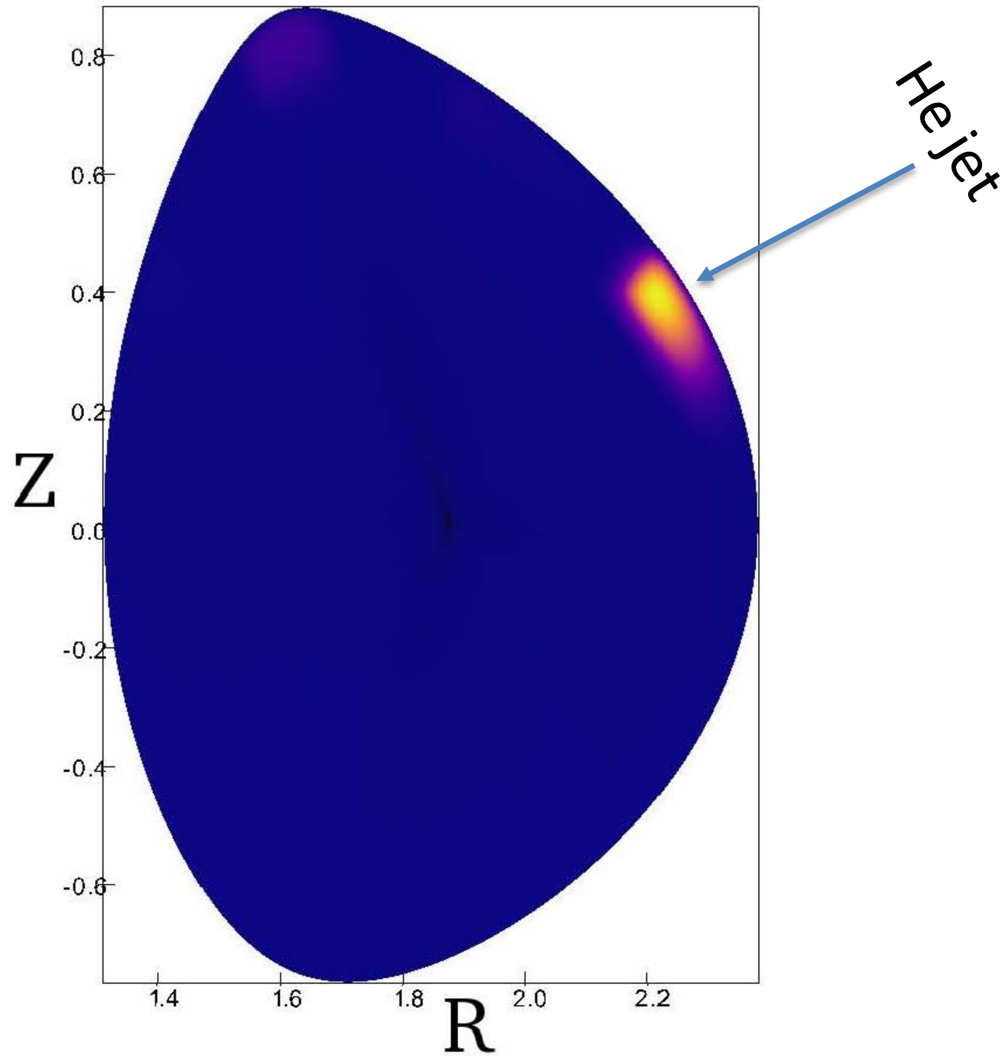
Uniform plasma density: n_0 = 3.5e19 /m^3

T_{i0} = 1.0 KeV .

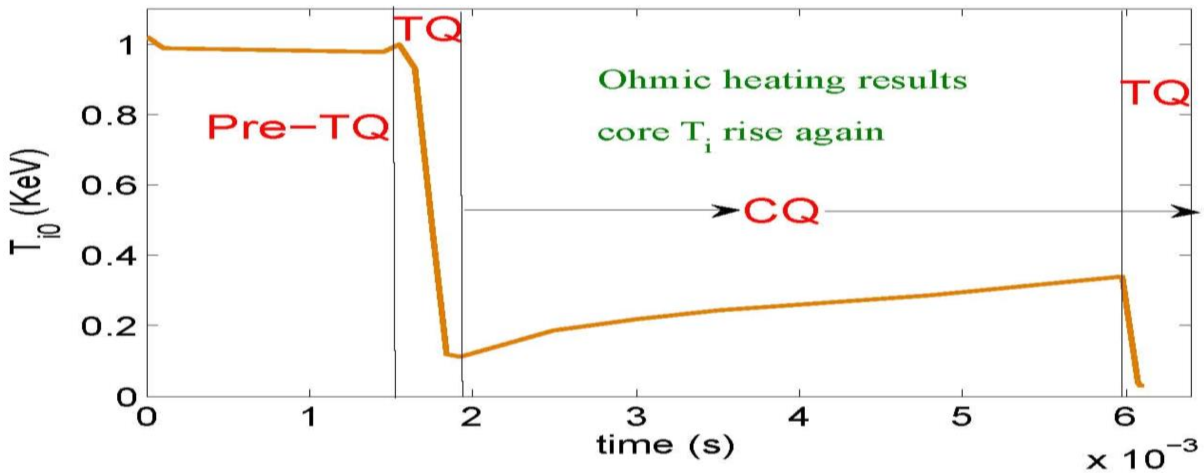
W_{th} = 40 KJ.

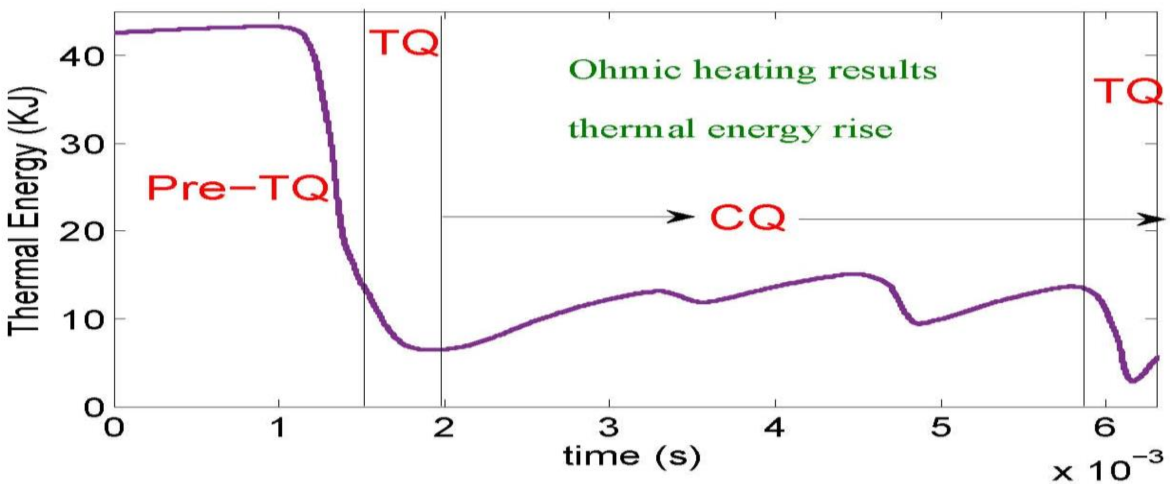
Ip = 380 kA ,   B = 1.8 T

NIMROD: He gas is deposited as localized function at constant rate



NIMROD: TQ appears twice, before and at middle of CQ





Pre-TQ time scale:

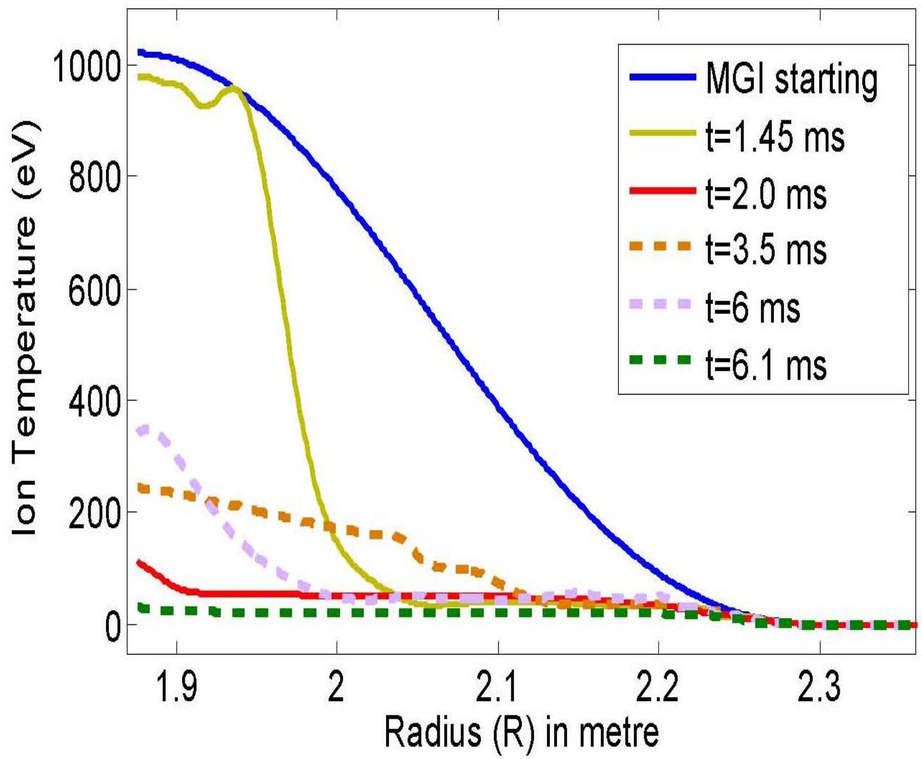
NIMROD ~ 1.5 ms
EAST ~ 2.5 ms

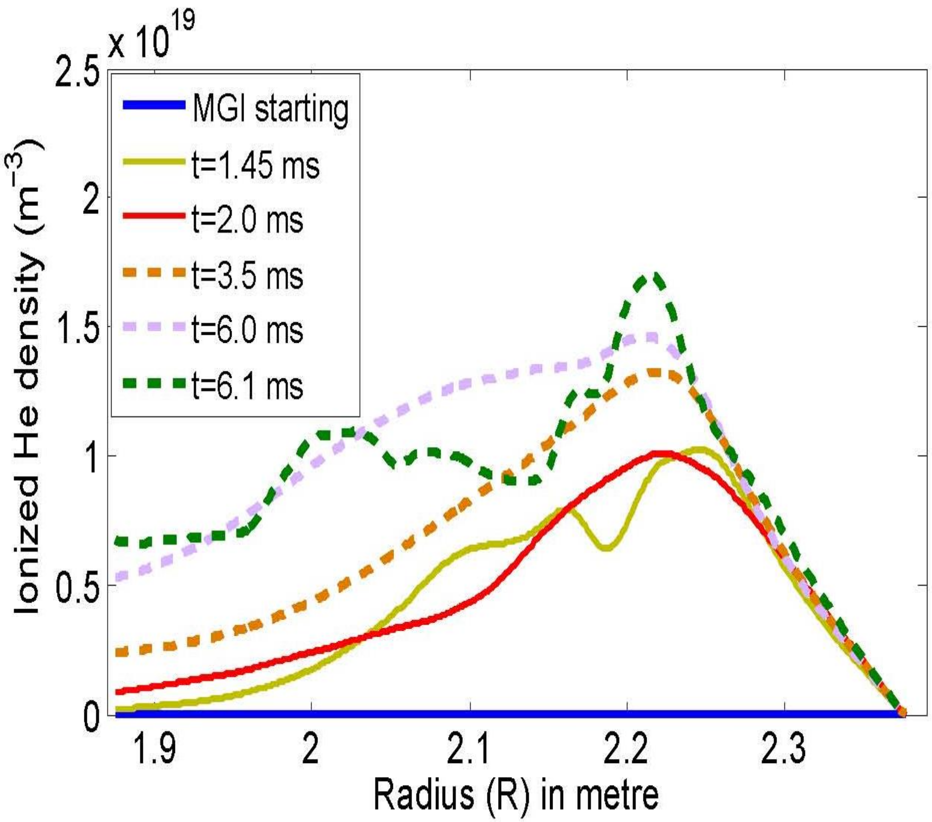
TQ time scale:

NIMROD ~ 0.55 ms
EAST ~ 1.1 ms

NIMROD observes pre-TQ and TQ happened earlier than experiment.

NIMROD: T_i profiles clearly depict occurrence of 2nd TQ

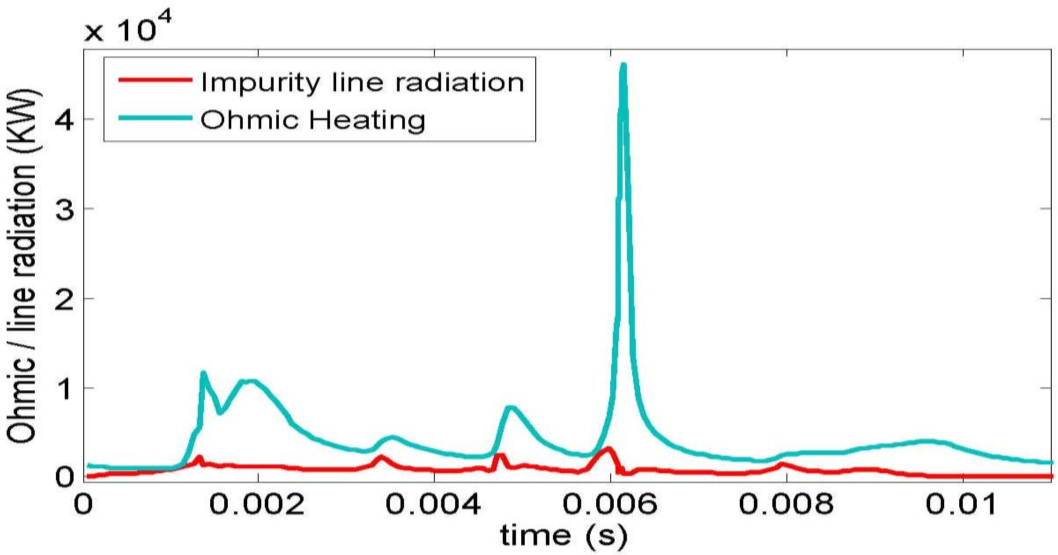




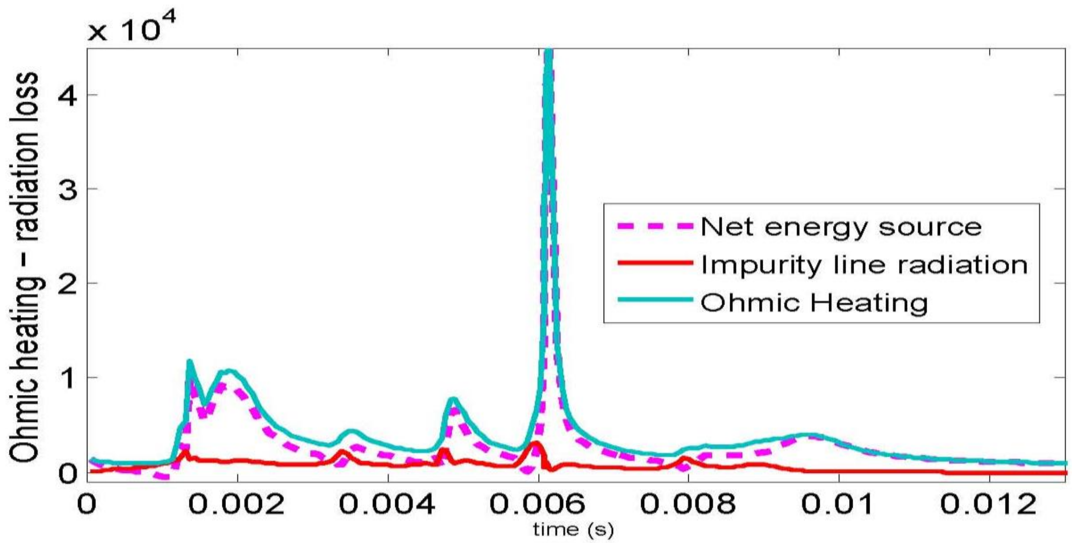
1st TQ = 1.45 ms – 2 ms (solid lines).
2nd TQ = 3.5 ms – 6.1 ms (dashed lines).

During 2nd TQ, ambient amount of ionized He transports to core region.

NIMROD: Ohmic heating dominates over radiation losses

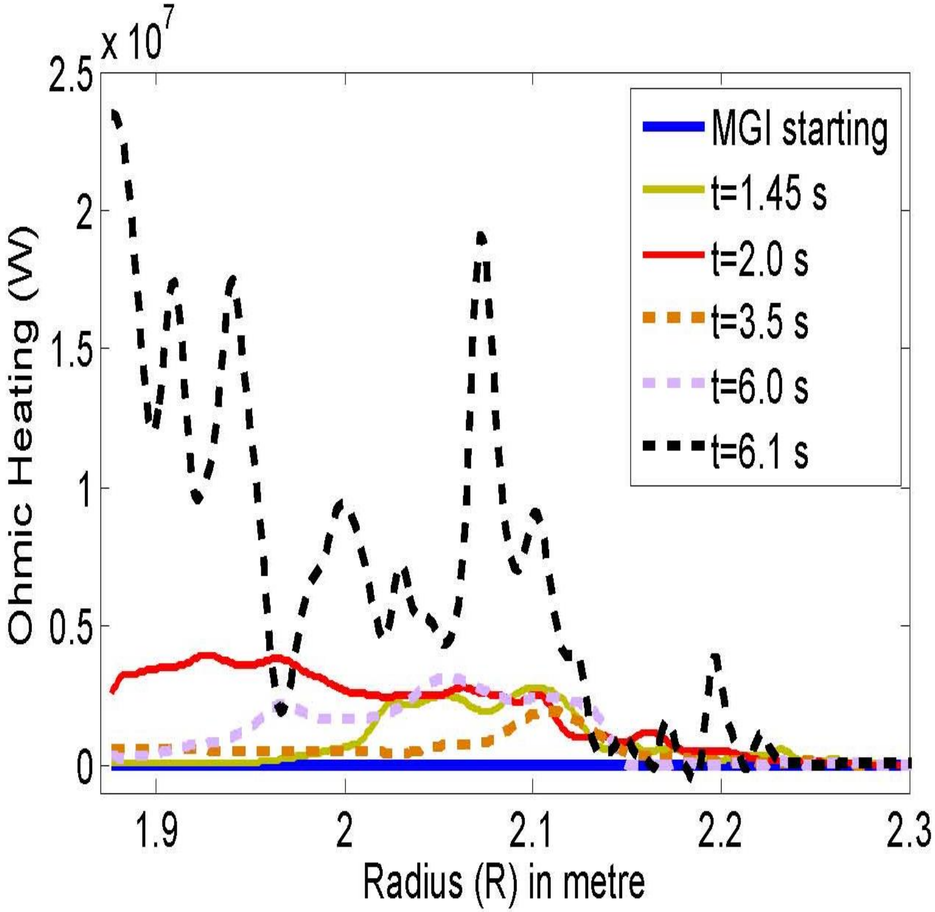


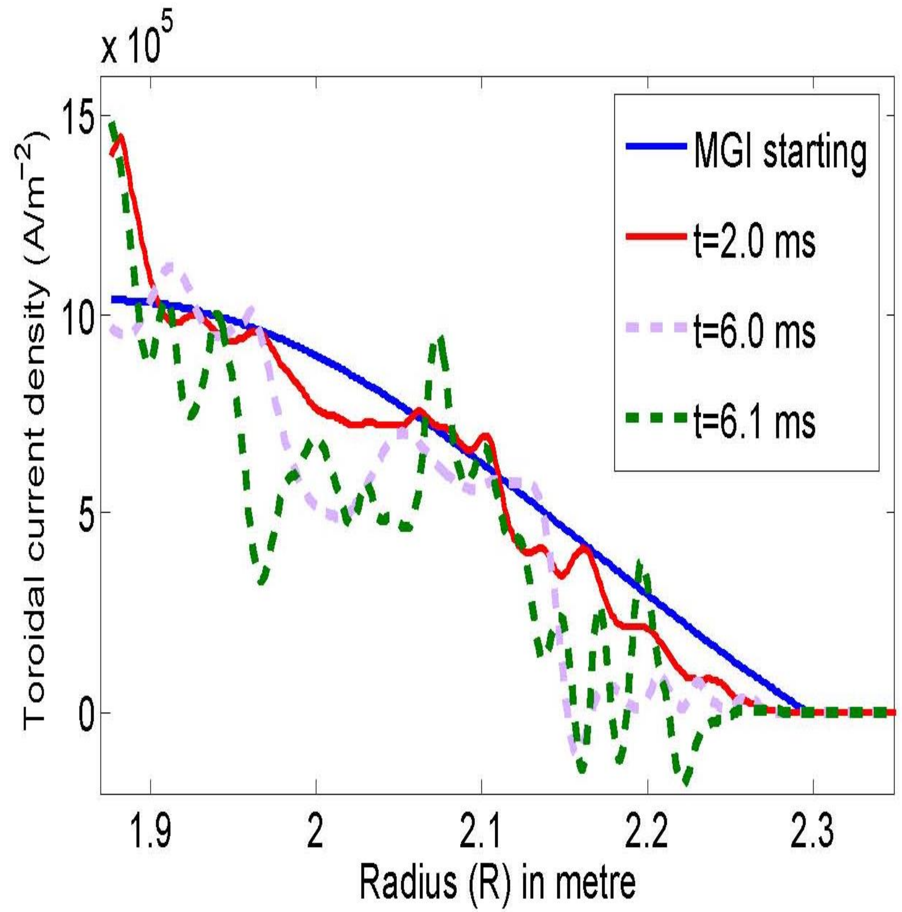
Ohmic heating jumps at every mode excitation, so does impurity line radiation. (dominating radiation process)



He is less efficient radiator, but contributes to Zeff and hence Ohmic heating.

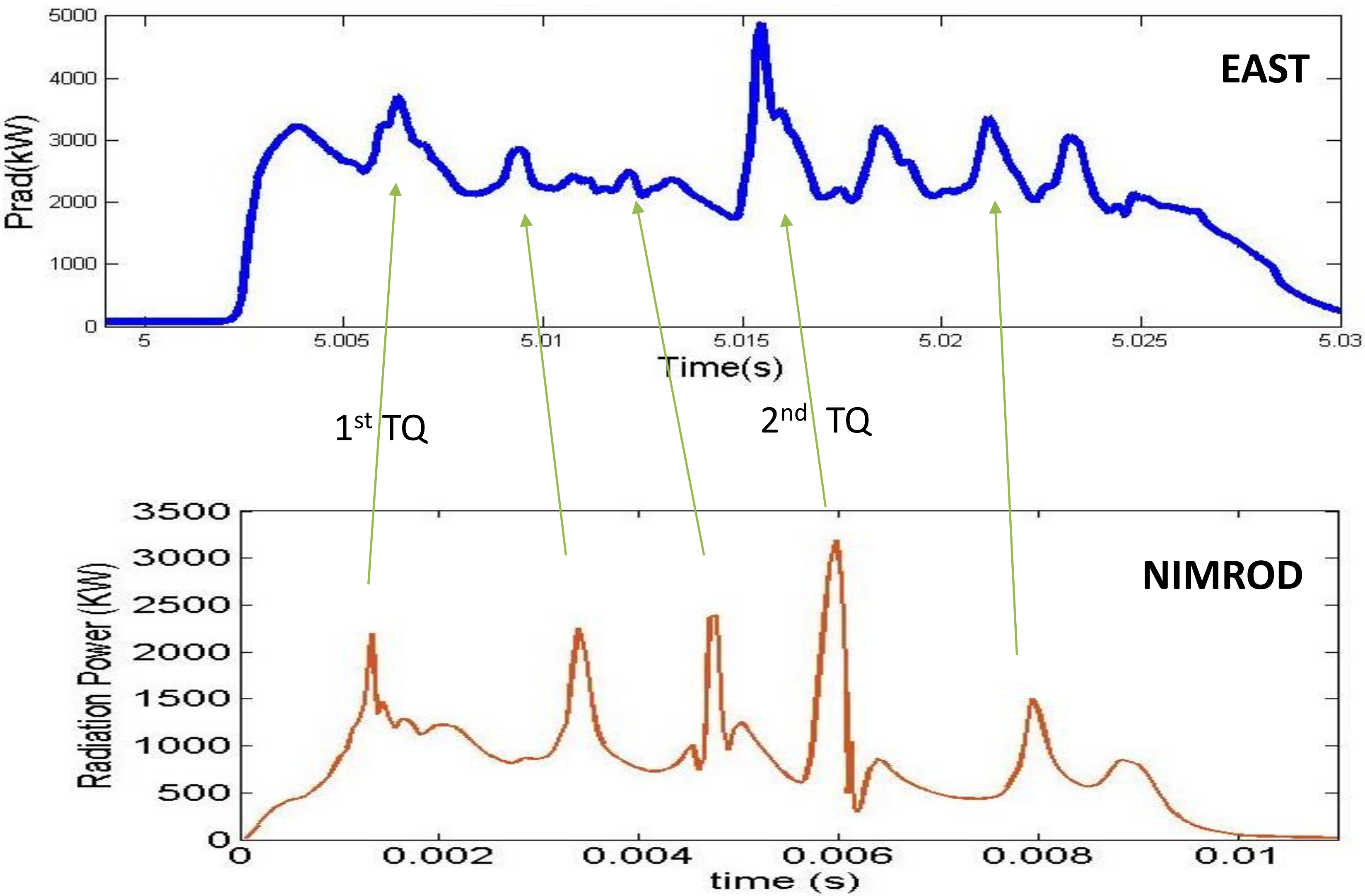
NIMROD: Current peaks at axis, Ohmic heating increases at core





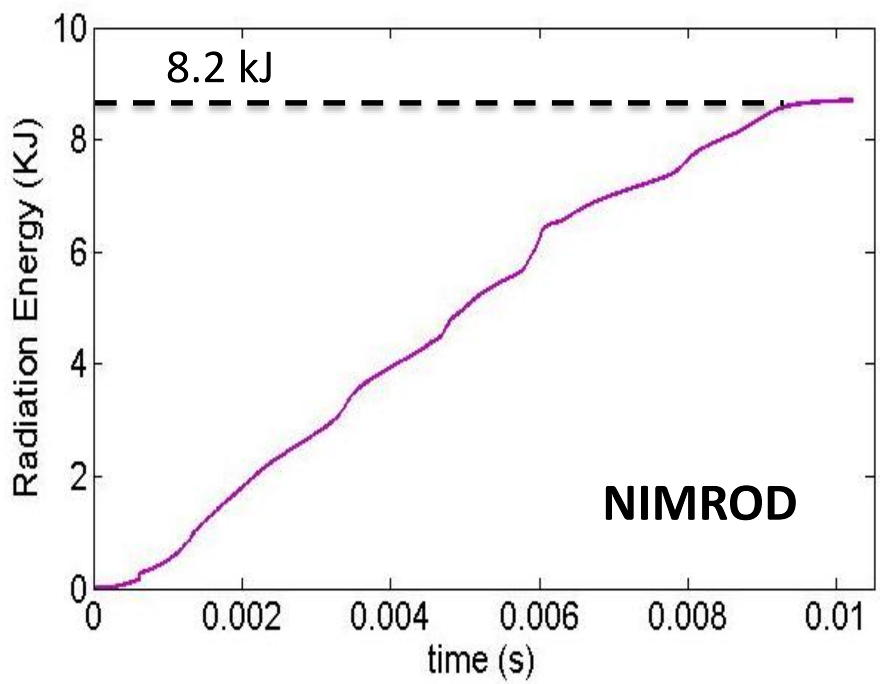
Comparison between NIMROD simulation and EAST experiment

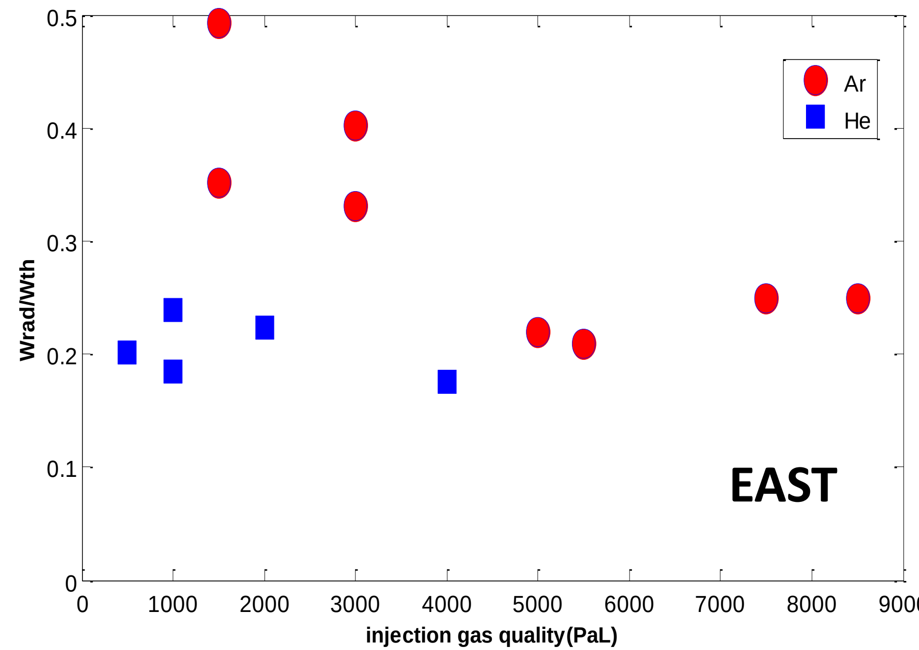
1. Total Radiation: similarity with experiment in values and peaks, Time scale falls shorter than experiment.



Experimental graph from Songtao Mao et. al., under preparation (2018).

2. W_{rad}/W_{th}: quantitatively well agreed with experiment





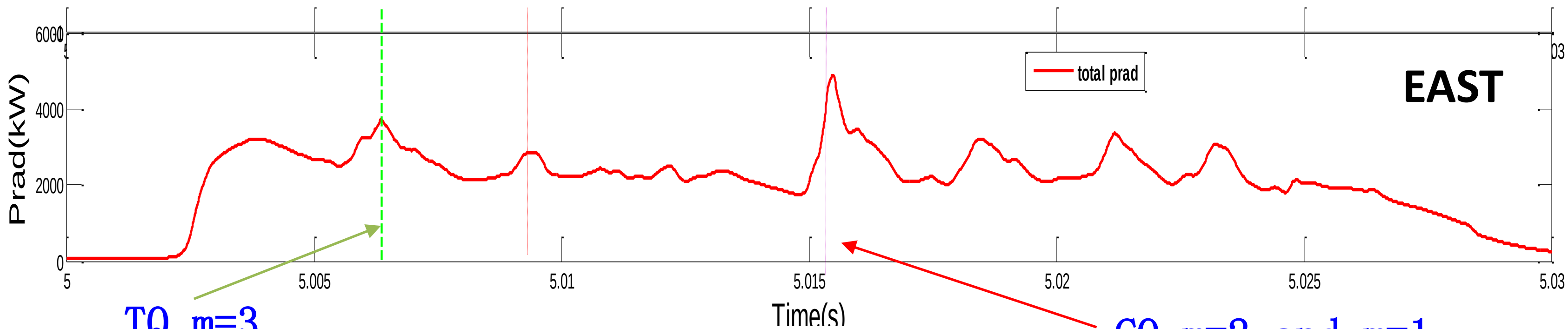
Total thermal energy at starting phase – 40 kJ

Total radiation energy at CQ saturated phase – 8.2 kJ

W_{rad}/W_{th} – 0.2 nearly equal to experimental value.

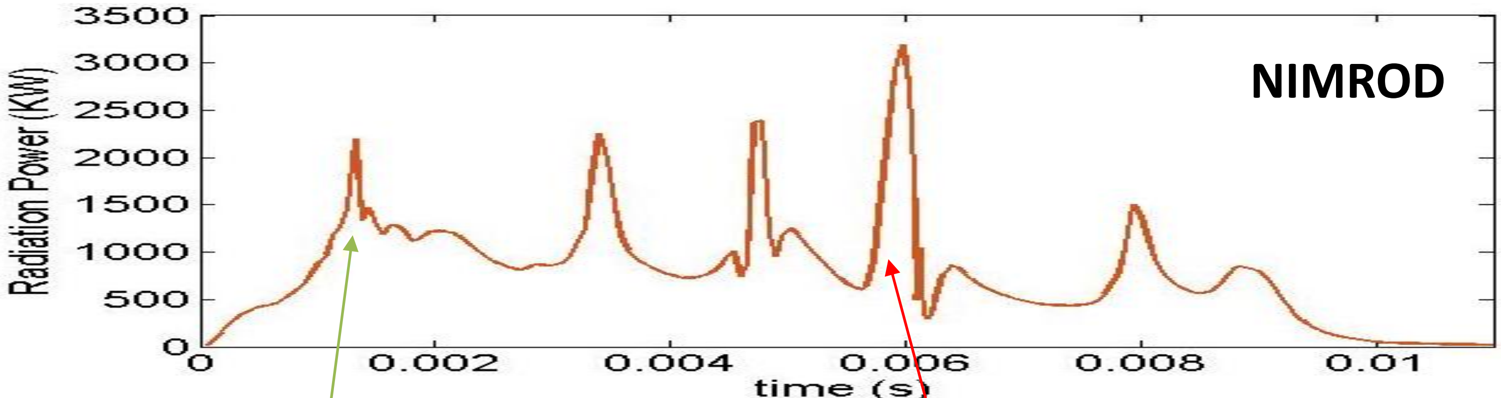
Experimental graph from Songtao Mao et. al., under preparation (2018).

3. n=1 mode: poloidal harmonics are same with experiment



TQ, m=3

CQ, m=2 and m=1,



TQ, m=3,2

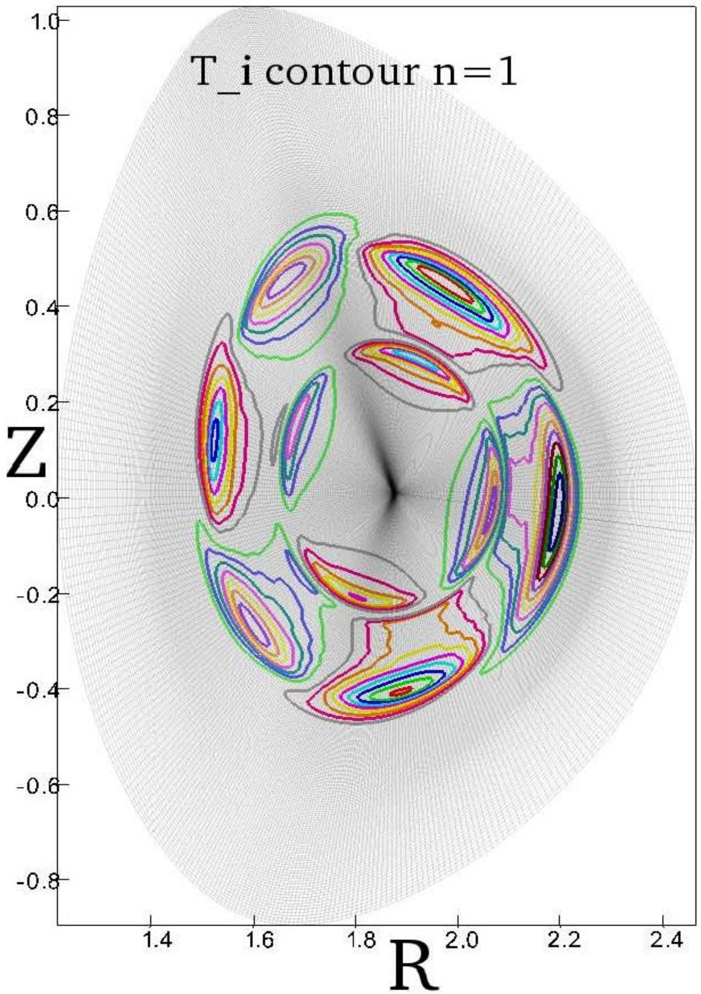
CQ, m=2 and m=1

Mode structures are shown in next slides.

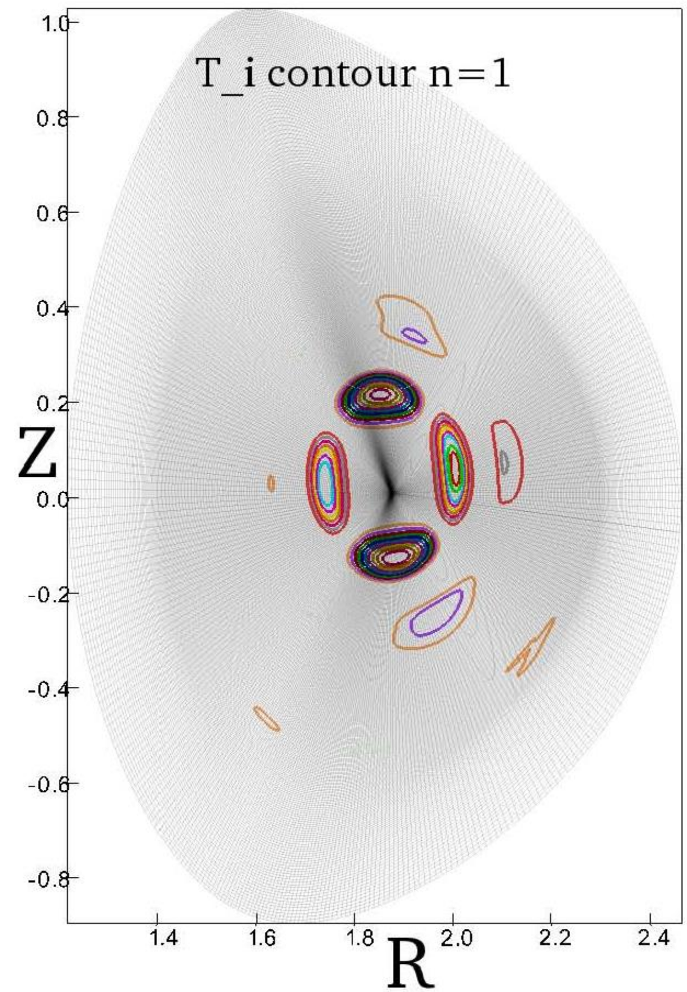
Experimental graph from Songtao Mao et. al., under preparation (2018).

NIMROD: n=1 mode structure

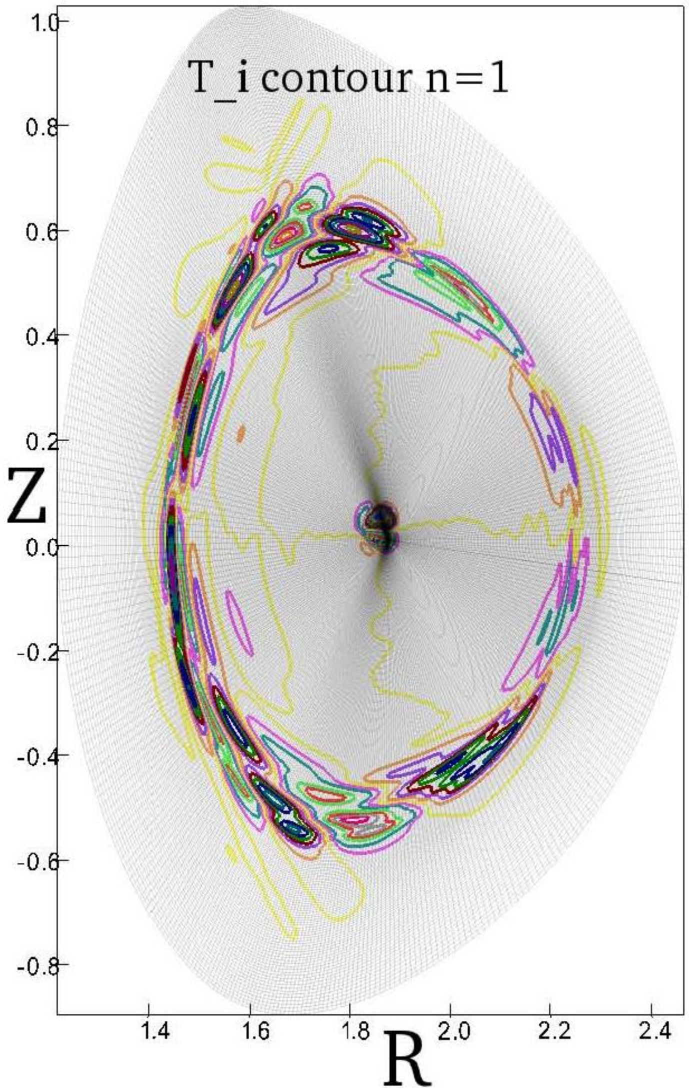
TQ phase: n=1/m=2,3

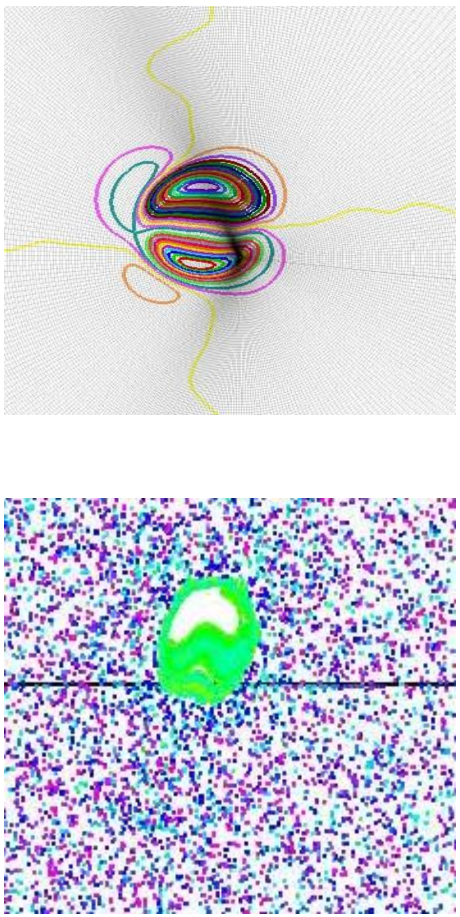


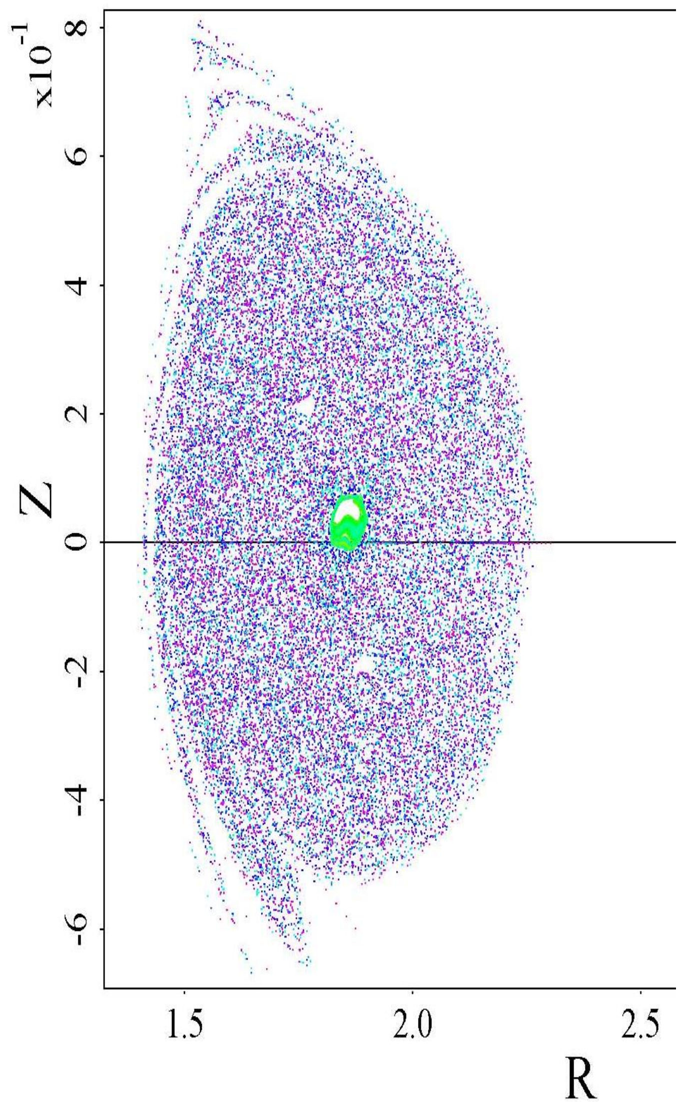
CQ phase: n=1/m=2



CQ phase: n=1,m=1 in contour/Poincare plot from simulation







Summary: Good agreement between NIMROD simulation and EAST experiment on He MGI process

1. Pre-TQ/TQ/CQ time scales: simulation and experiment match qualitatively.
2. Radiation level and peaks: Radiation level is in the same order and no. of peaks are equal.
3. Thermal Energy drop: Thermal energy dropped in two steps similarly as observed in experiment. Ohmic heating delays the process.
4. Wrad/Wth: Exactly equal to experimental value.
5. MHD mode activity: Same harmonics m=3,2,1 of n=1 appeared in NIMROD and EAST MGI.

Part-II: Neon MGI study on CFETR phase-I scenario

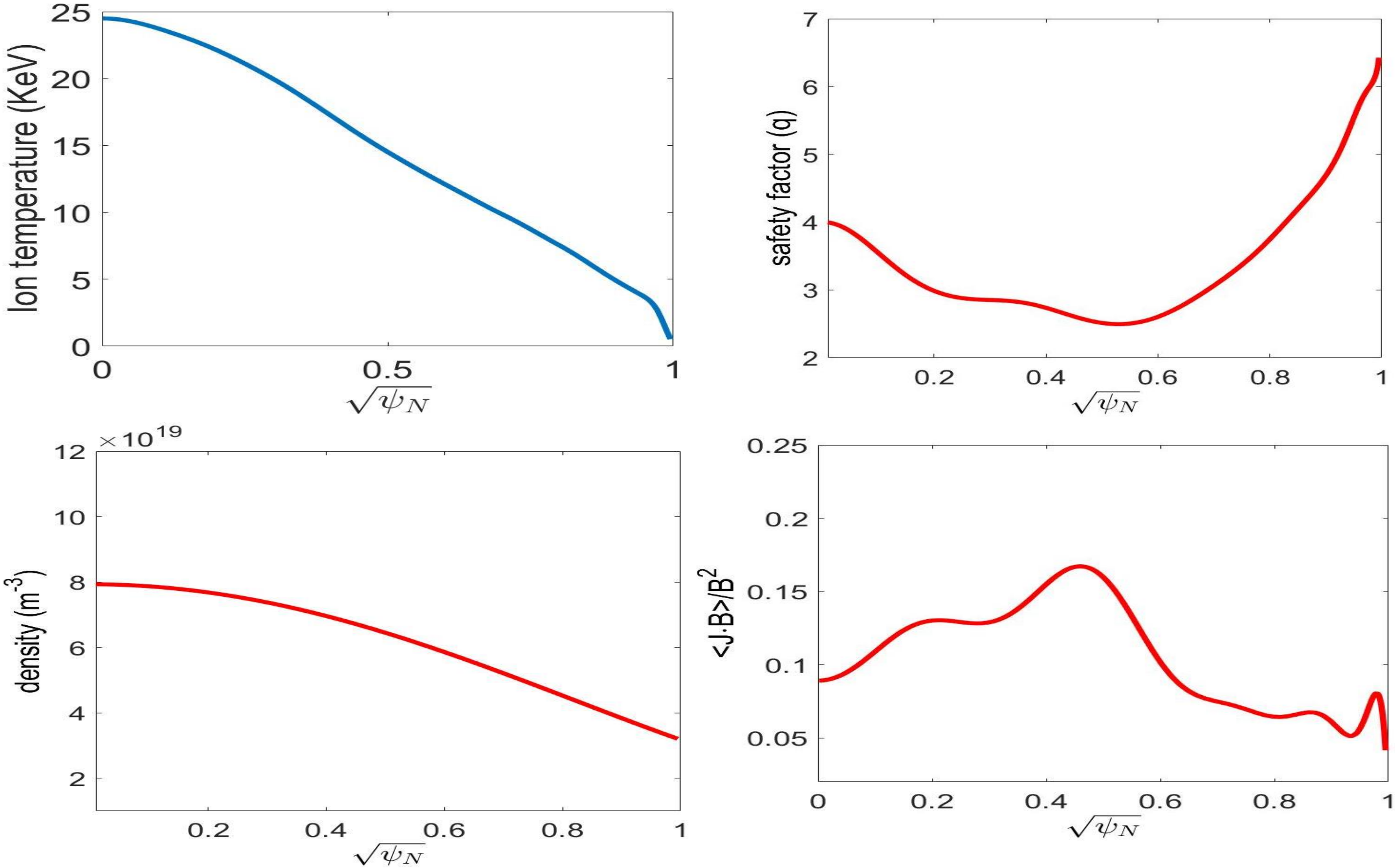
CFETR: China Fusion Engineering Test Reactor

China Magnetic fusion program roadmap

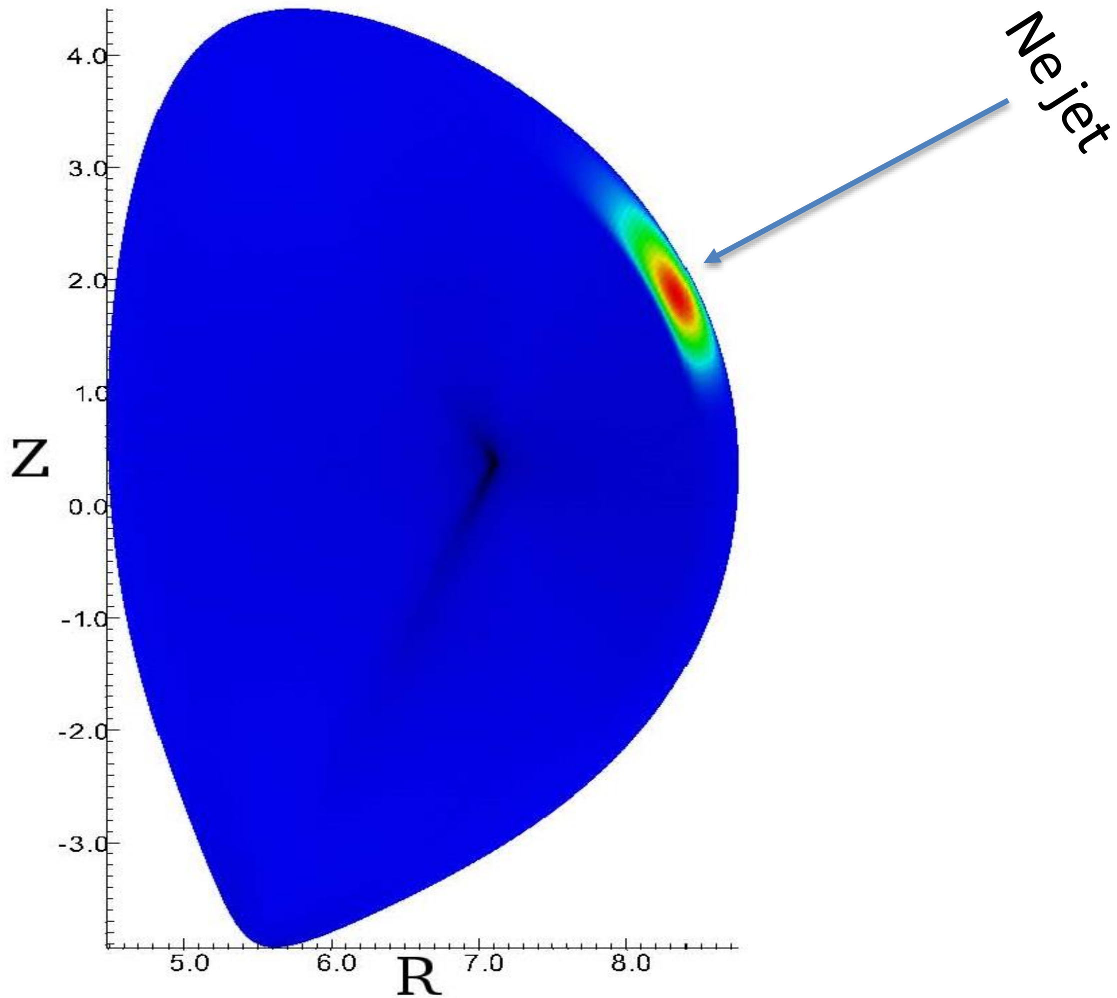
Parameter	Phase - I
Major Axis Radius (m)	6.6
Minor Axis Radius (m)	1.79
Aspect Ratio	3.688
Fusion power (MW)	200
Beta Normal	1.890
Plasma Current (MA)	7.65
Magnetic field (T)	5.99
Elongation	2.02
Stored Thermal energy(MJ)	189
Q plasma	1.5
Paux (MW)	131.8
Bootstrap fraction	0.5

Yuanxi Wan et al 2017 Nucl. Fusion 57 102009

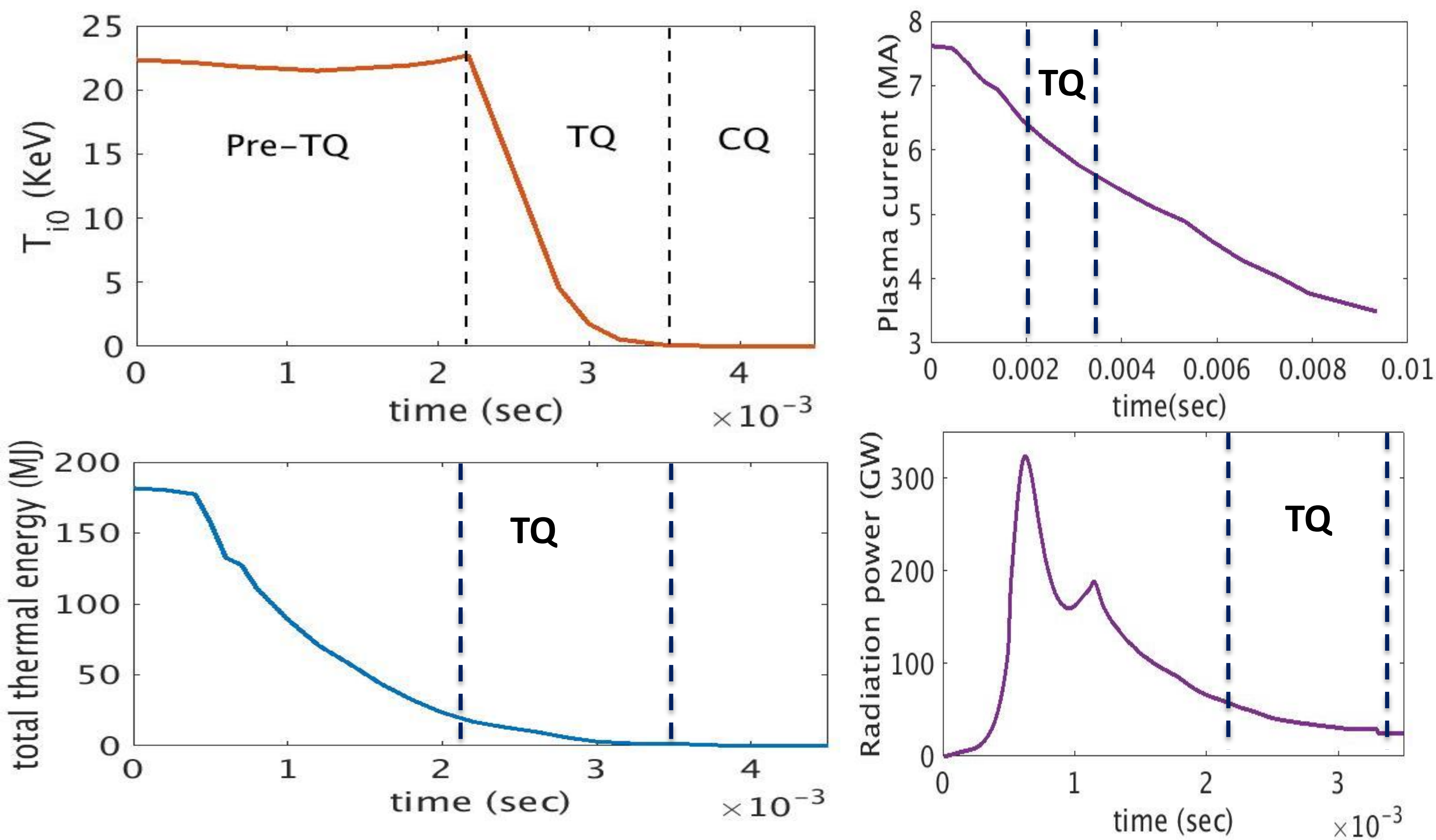
CFETR Phase-I: 6 T, 7.65 MA, W_{th} = 189 MJ



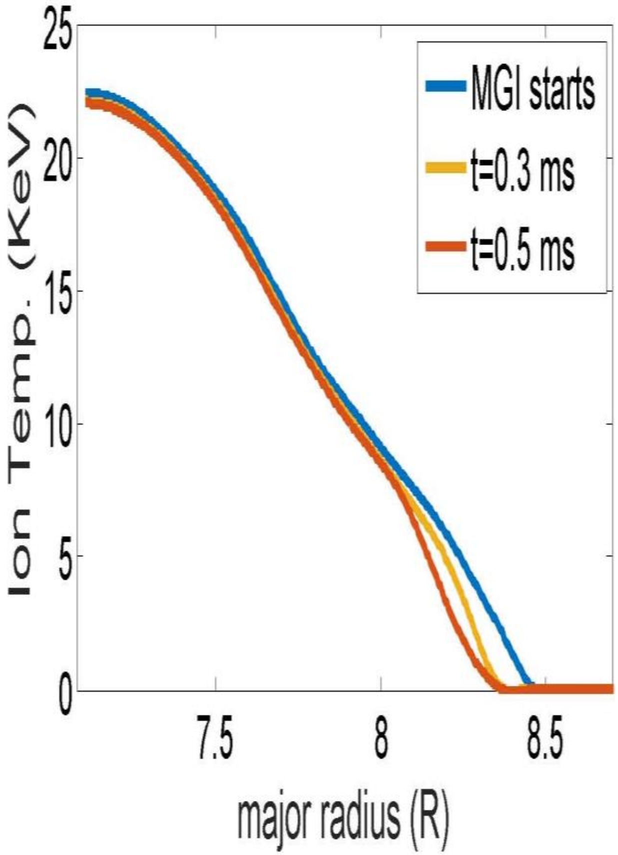
Ne gas is deposited as localized function at constant rate



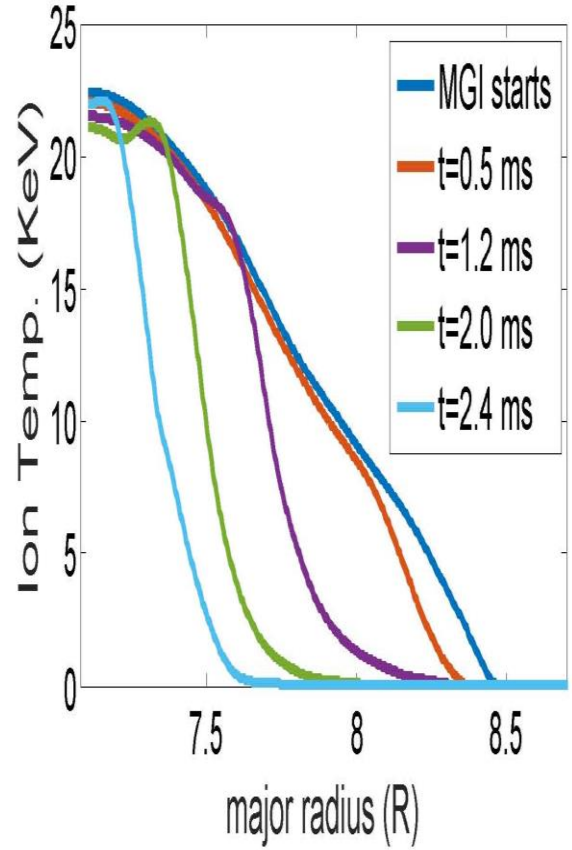
Time history: TQ ~1.2 ms, Pre-TQ has 87% energy loss



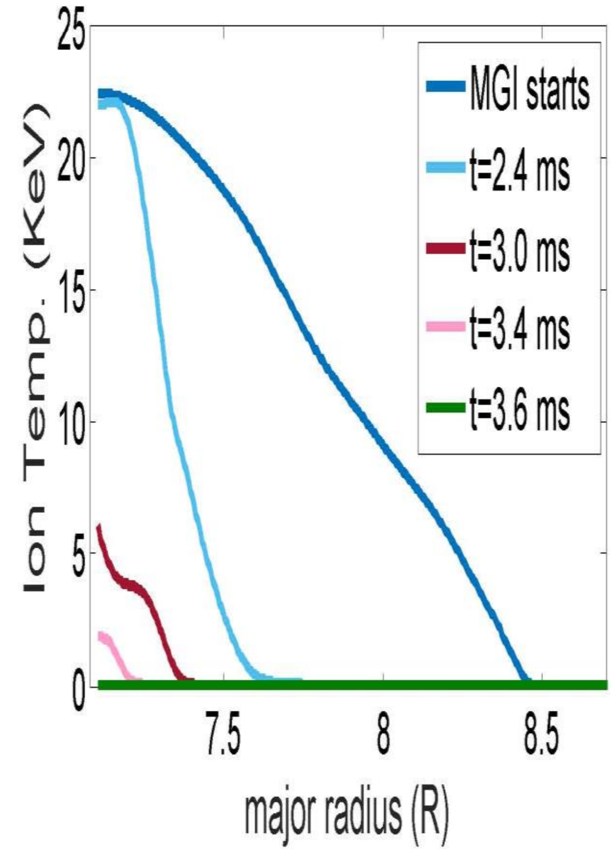
Sequence of Ion temperature dropping down (~3.5 ms)



Edge T_i drops~ 0.5 ms

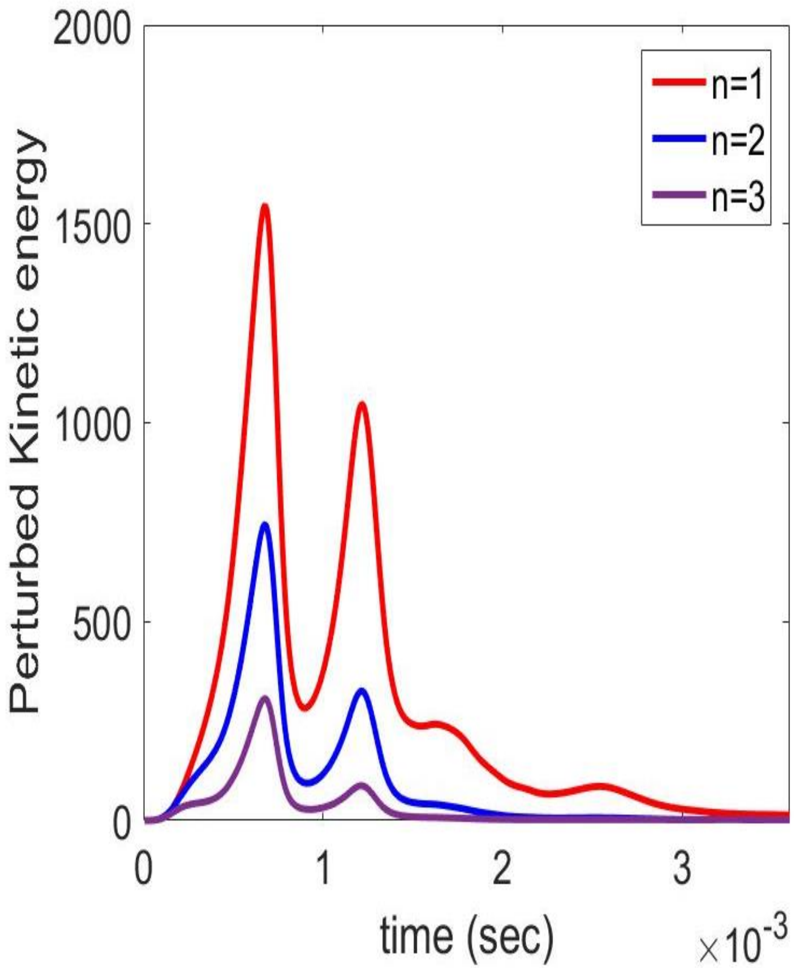


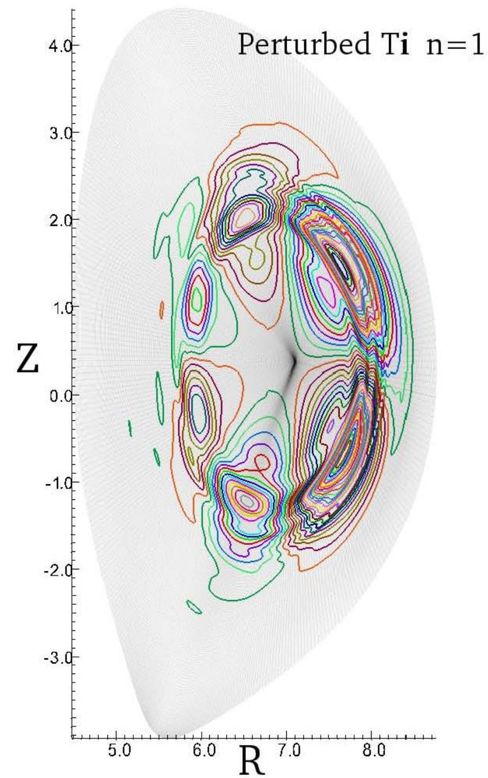
Middle T_i drops ~ 1.9 ms



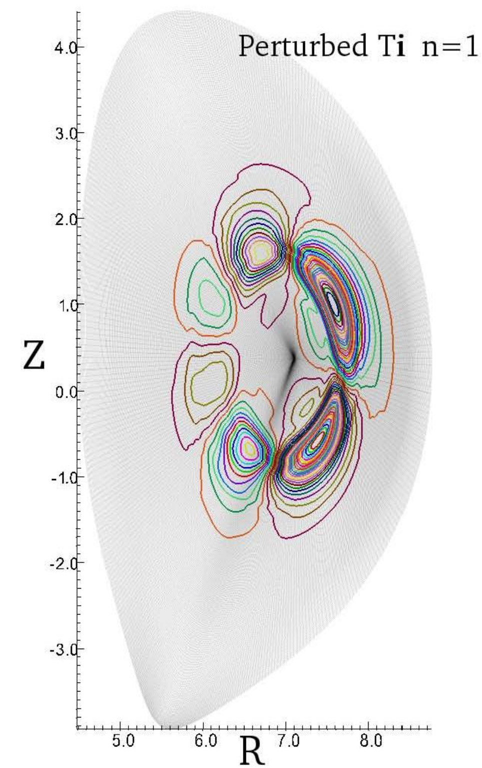
core T_i drops ~ 1.2 ms

MHD mode – n=1 dominates (total n=6)



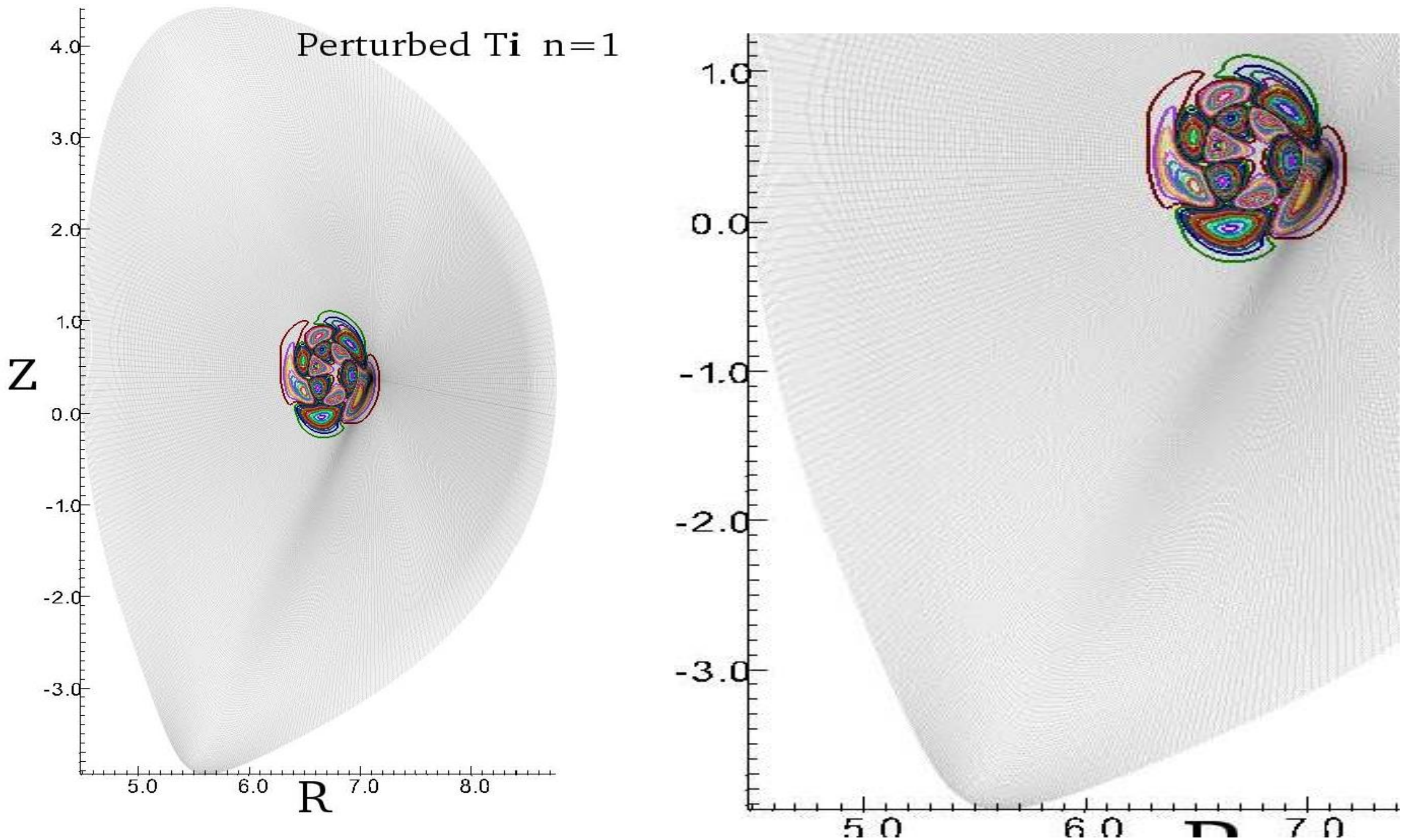


At 1st peak
of K.E.

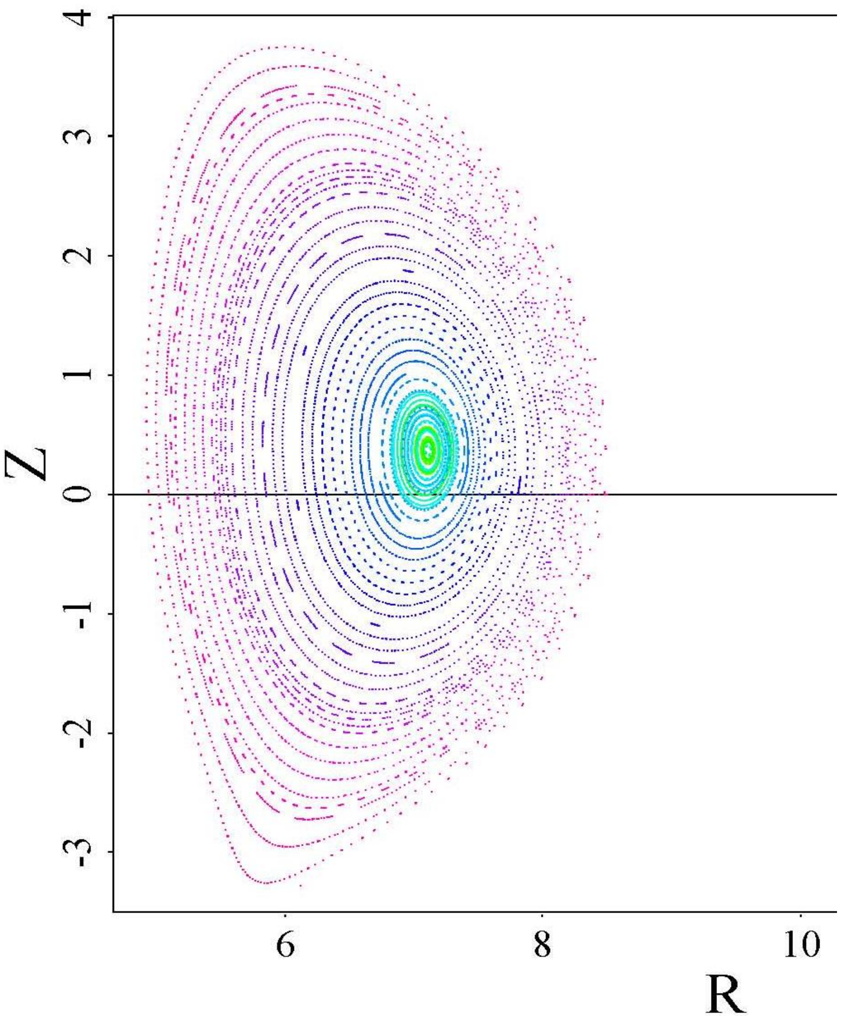


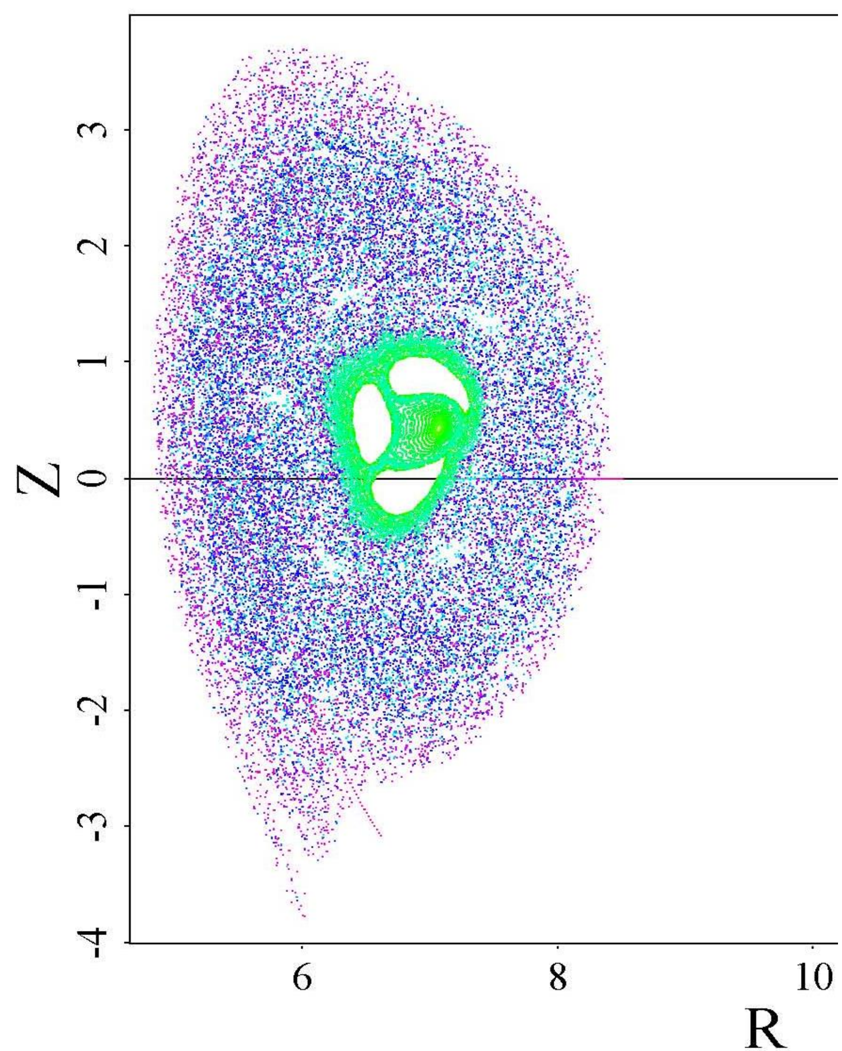
At 2nd peak
of K.E.

n=1 / m=3 is active in TQ phase

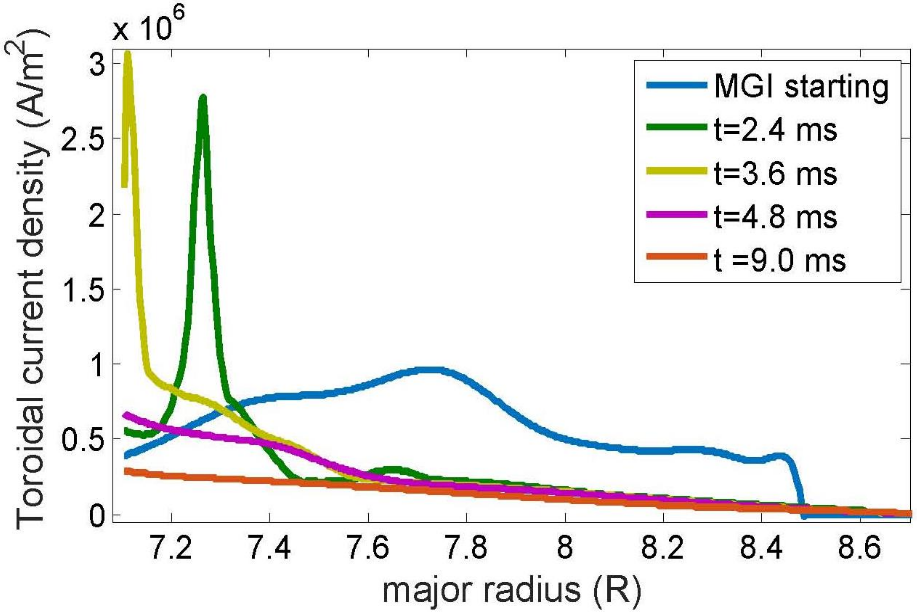


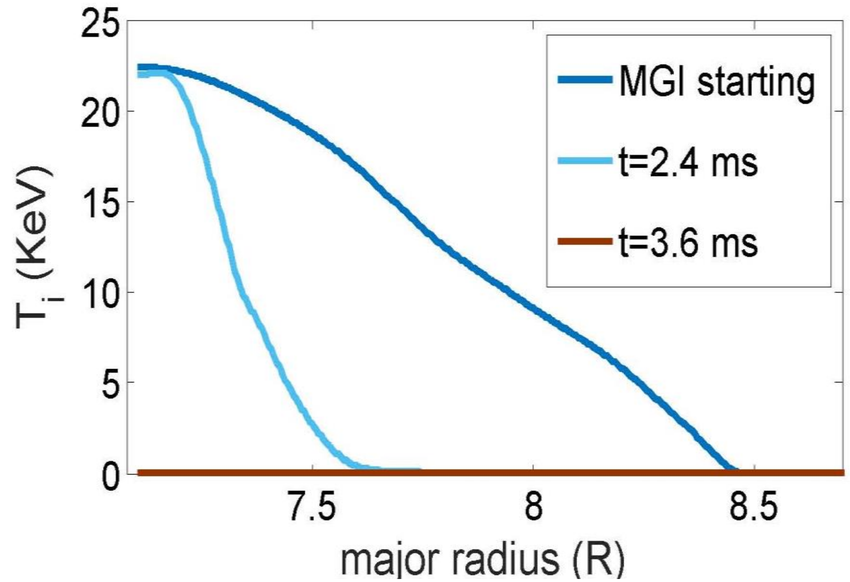
Puncture of good flux surfaces at TQ

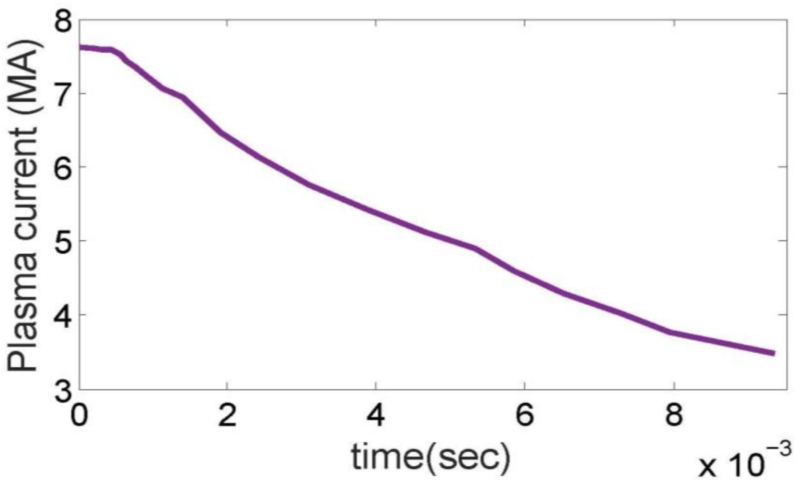




Toroidal current density shrinks towards axis during TQ

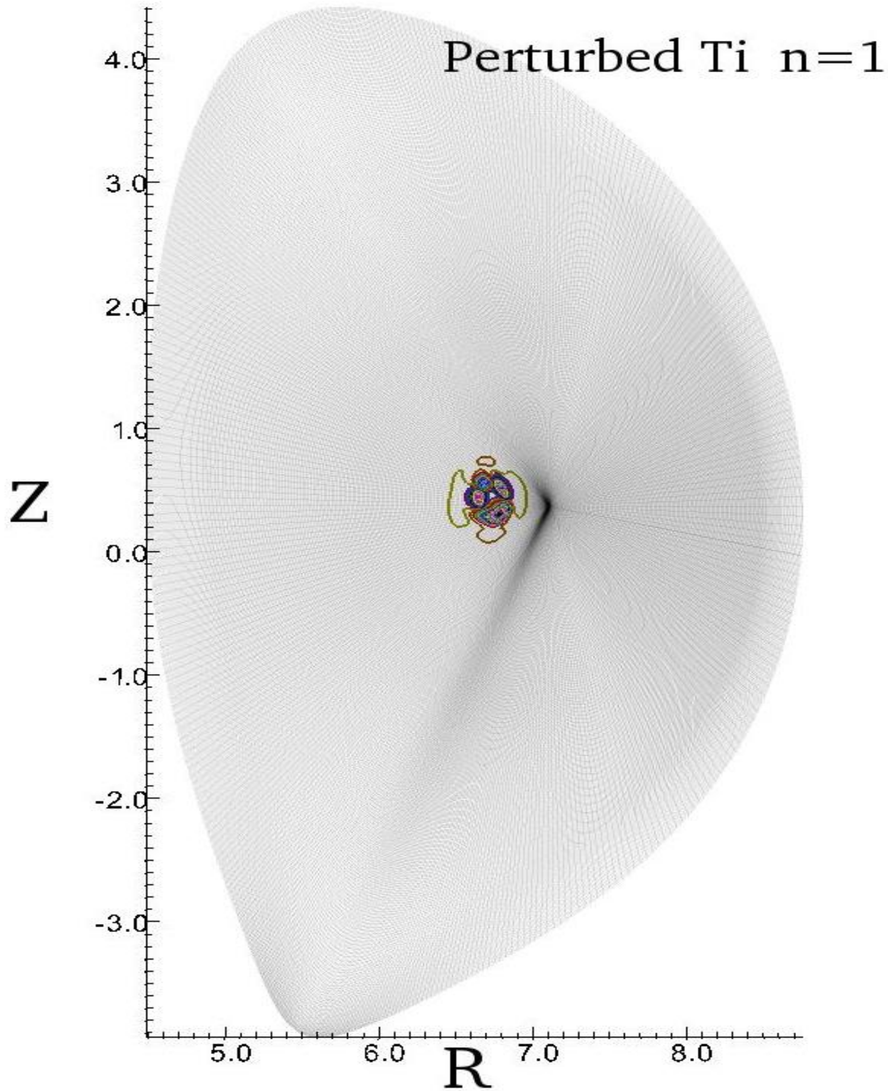


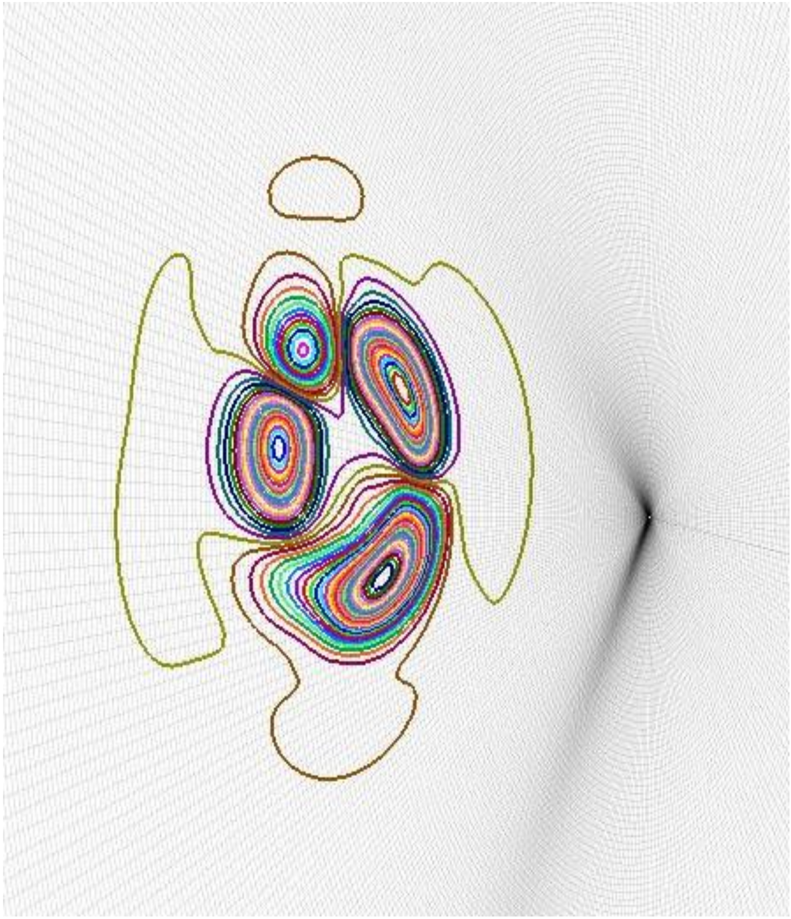




Current quench (CQ) kicks off at later phase of TQ

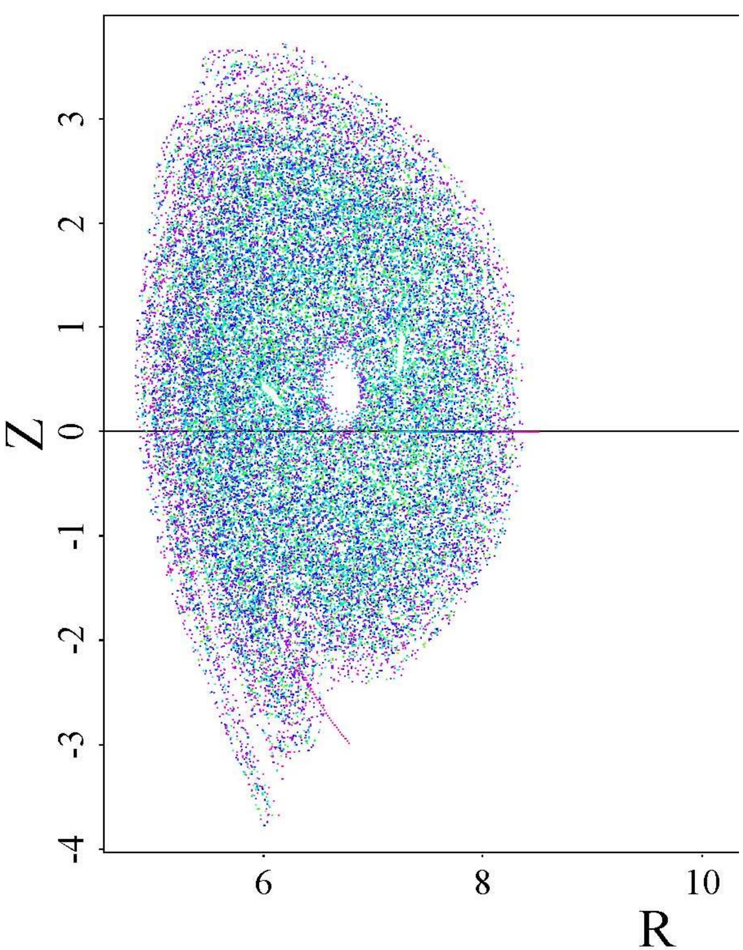
n=1 / m=2 excites during CQ phase



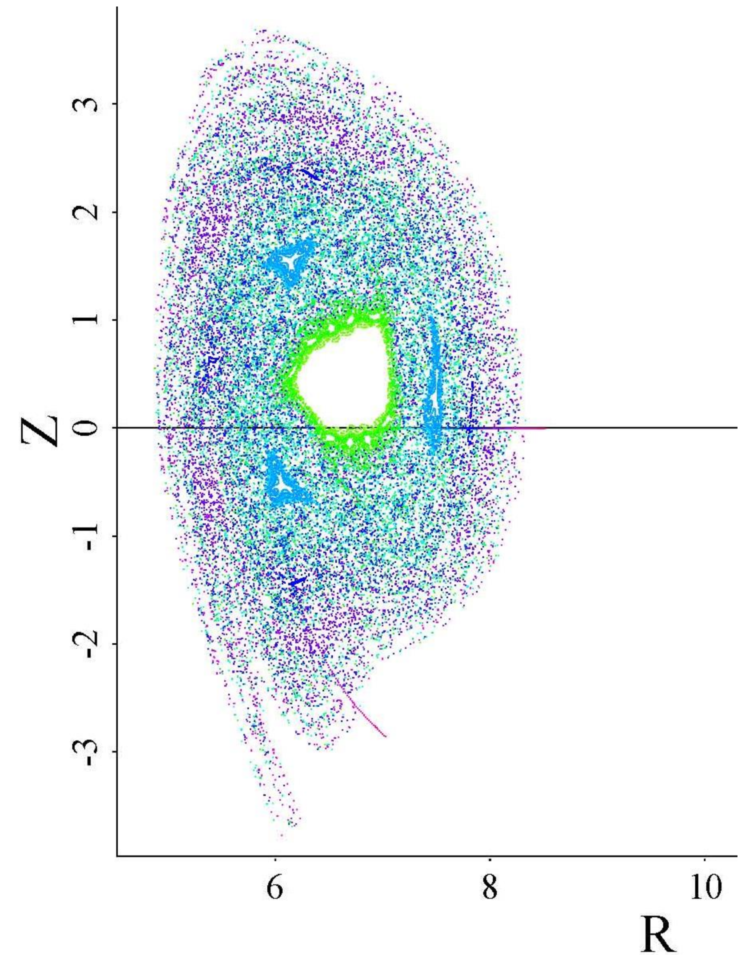


Puncture of good flux surfaces at CQ phase (no flux surface reconstruction)

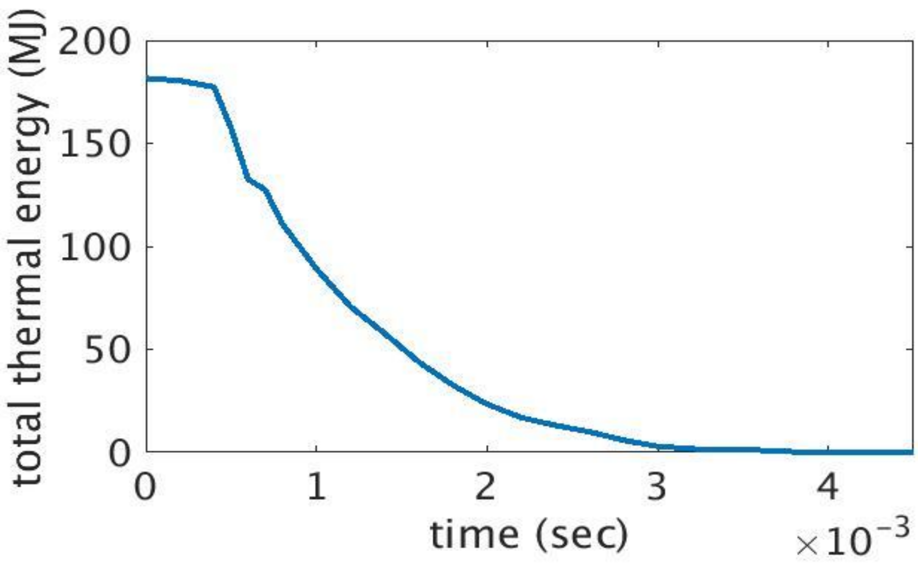
Time – 4.8 ms

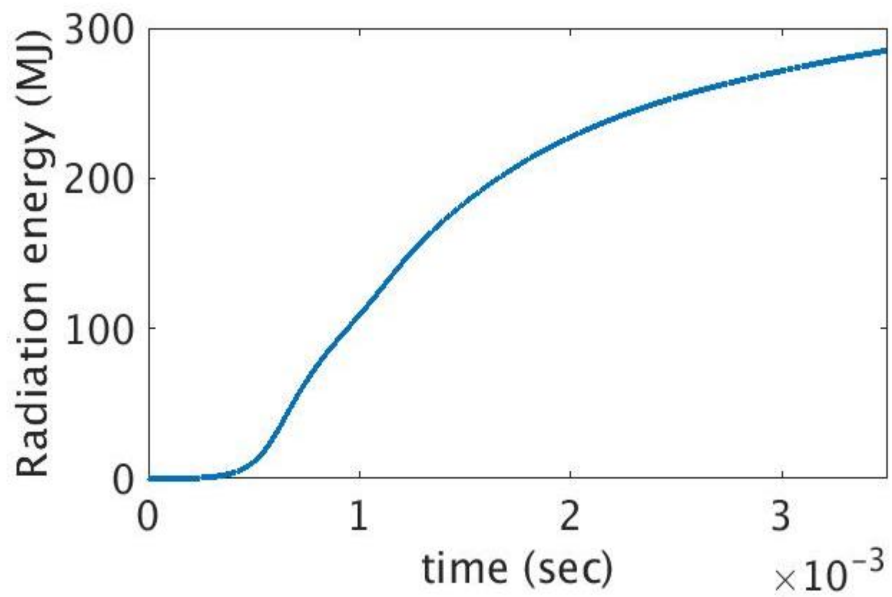


Time – 10.0 ms



A large amount of energy being radiated





99.8% of total thermal energy has been lost before CQ phase kicks off.

Total stored energy loss ~ 280 MJ

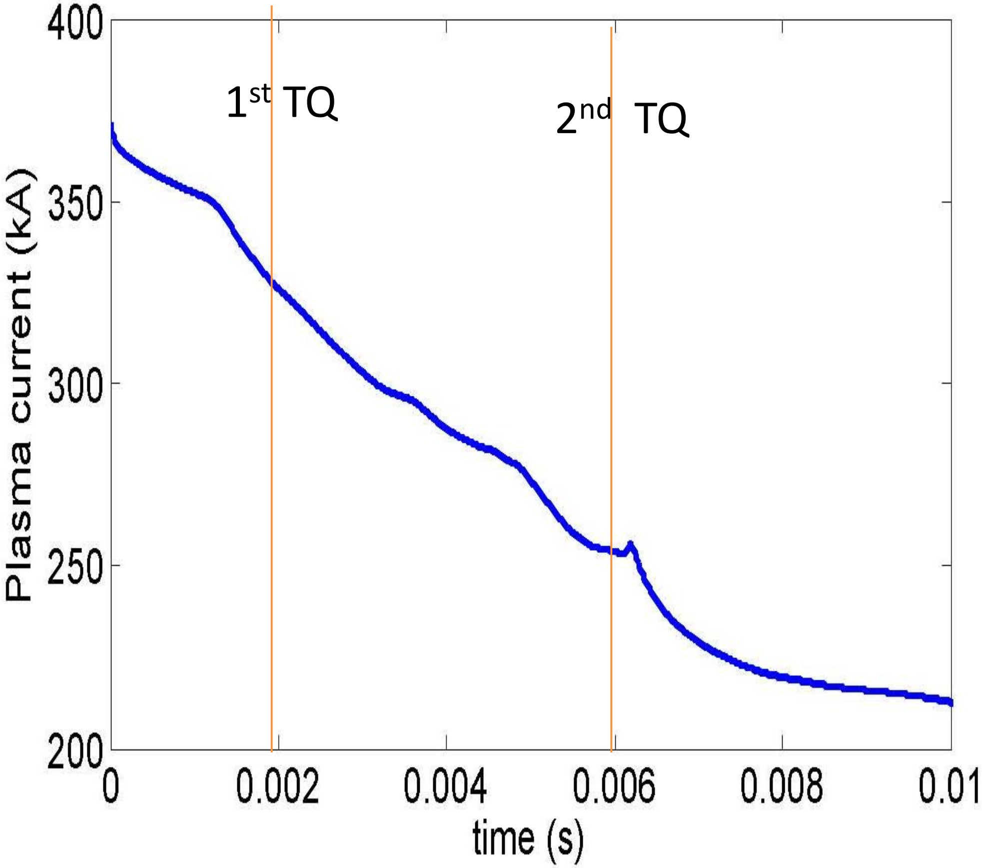
Total energy radiated ~ 260 MJ

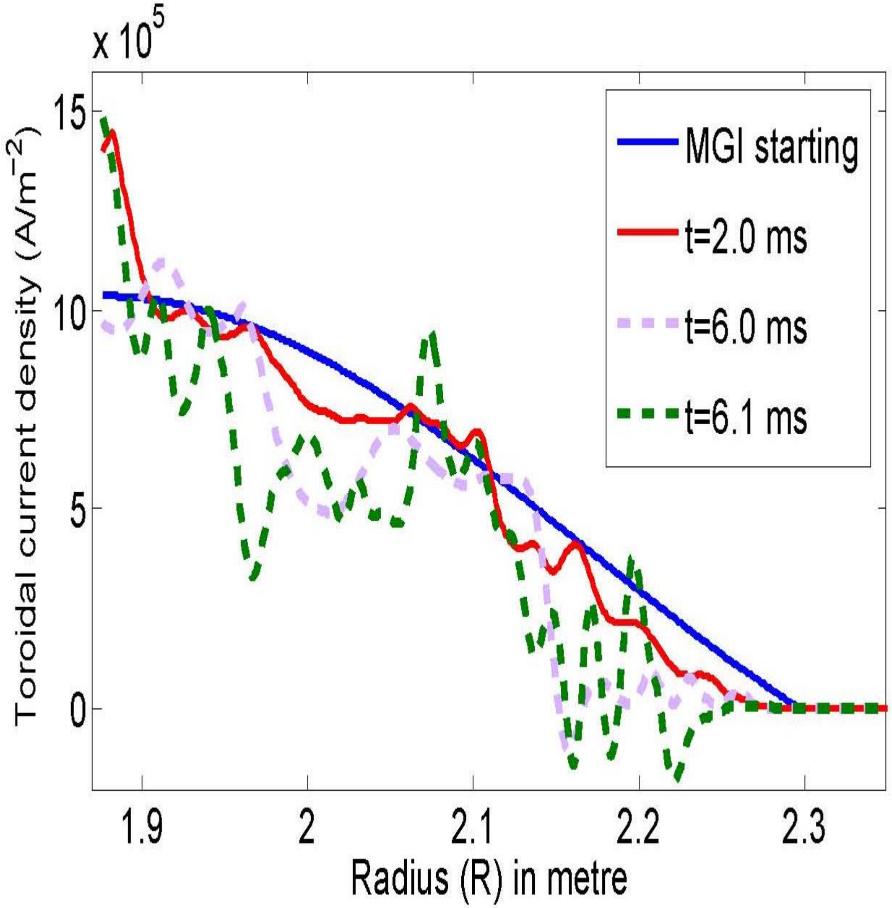
Summary on CFETR MGI

- Complete TQ phase has been represented with 98.5% loss of stored thermal energy within ~ 3.5 ms.
- Core T_i drops within 1.2 ms. m/n=3/1 mode was present during TQ phase.
- Case will be compared with MGI applied on ITER baseline scenario.
- Ar gas is to be considered next to compare with Ne results.

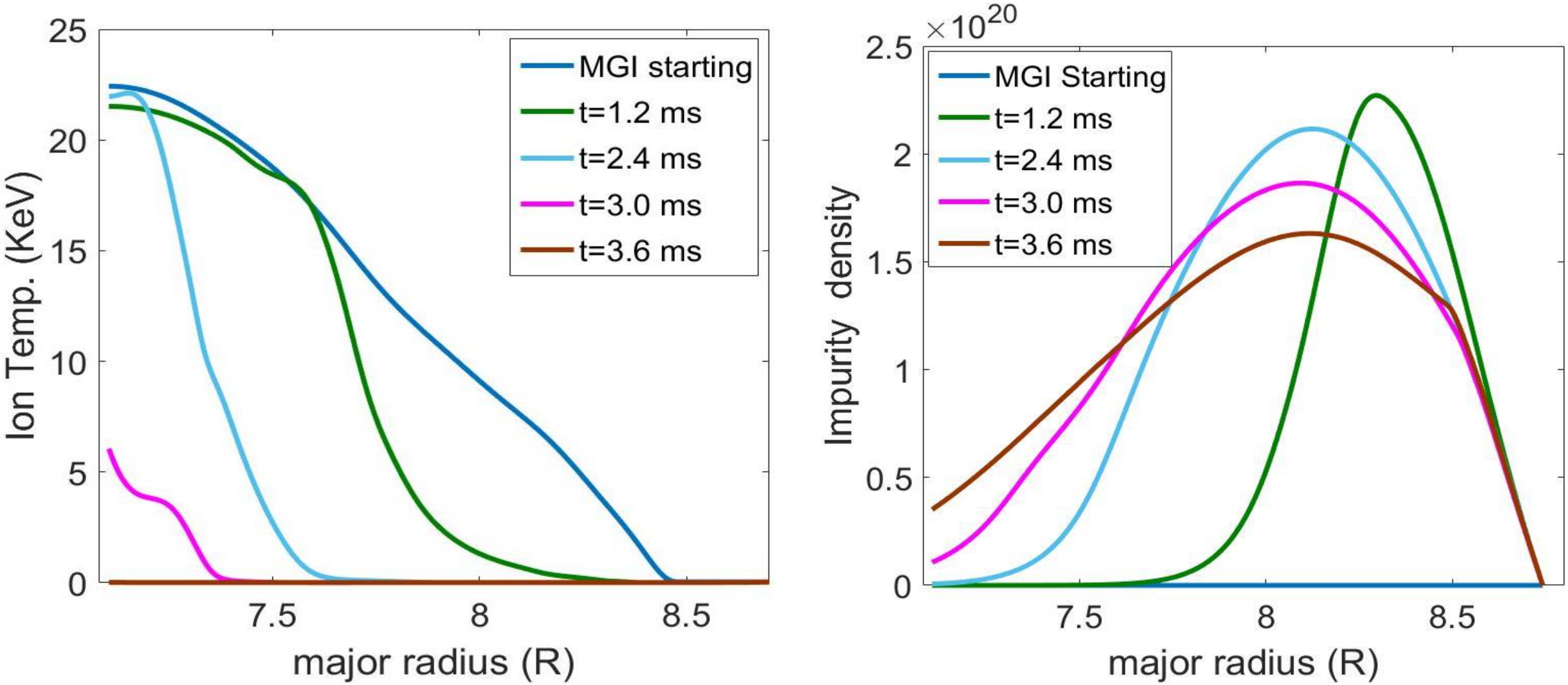
Thank you so much

NIMROD: Current peaking around axis happens at both TQ phases





Ti drops with increasing Core impurity density



Wish you happy ‘Sherwood Conference’