JET disruptions using M3DC1

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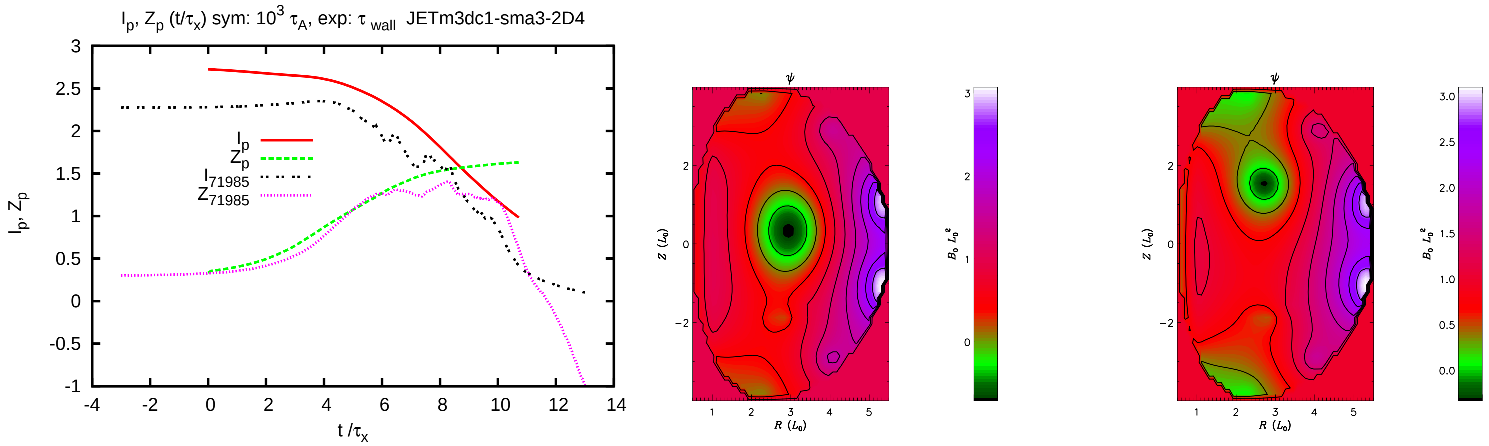
CTTS @Sherwood Meeting 2018

Outline

- 2D VDEs
  - 2D VDEs with M3DC1
  - VDE growth time
- 3D VDEs
  - comparison of JET with M3D
  - force reduction in simulation and JET MGI experiments
  - preliminary M3DC1 JET simulations
- TQ and precursor
  - M3DC1 linear simulations
  - M3D nonlinear simulations
- Runaway electron fluid MHD

M3DC1 Simulations of JET shot 71985

M3D simulations: [Strauss, *et al.* Phys. Plas. **24** (2017)]



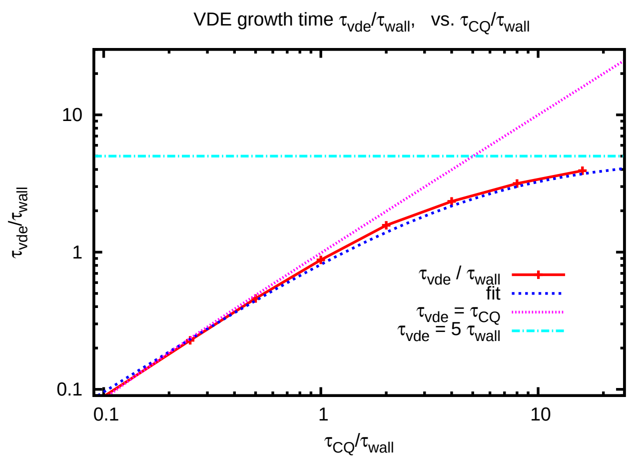
Time history plot of toroidal current I_p, and vertical displacement Z_p as function of t/τ_x. Simulation time units $\tau_x = 10^3\tau_A$, experimental time units $\tau_x = \tau_{wall}$. ψ at $t = 0$ and $t \approx 8\tau_x$.

In simulations, evidently $\tau_{wall} \approx 10^3\tau_A$.

$$\frac{\tau_{wall}}{\tau_R} = \frac{\delta_{wall}}{a_{wall}}\frac{\eta}{\eta_{wall}} \approx 0.06$$

with $\delta_{wall}/a_{wall} = 0.06$, $a_{wall} = 1$, τ_R is resistive decay time. The decay of I_p and saturation of Z_p agrees qualitatively with experimental data.

scaling of VDE growth time in ITER simulations



The growth time of the VDE is well fit by

$$\tau_{vde} = \frac{\tau_{CQ}}{1 + \tau_{CQ}/(5\tau_{wall})}$$

where $\tau_{vde} = t(\xi = 4m) - t_1$.

There are two limits of the VDE.

Small τ_{CQ}/τ_{wall}, $\tau_{vde} = \tau_{CQ}$. VDE is driven by CQ. ITER 2D simulations are in this limit [Miyamoto, 2014].

Large τ_{CQ}/τ_{wall}, $\tau_{vde} = 5\tau_{wall}$. VDE is an $n = 0$ RWM. This is the JET limit.

3D M3D simulation and JET shot 71985 data

Validation of M3D compared maximum values in time history of several variables

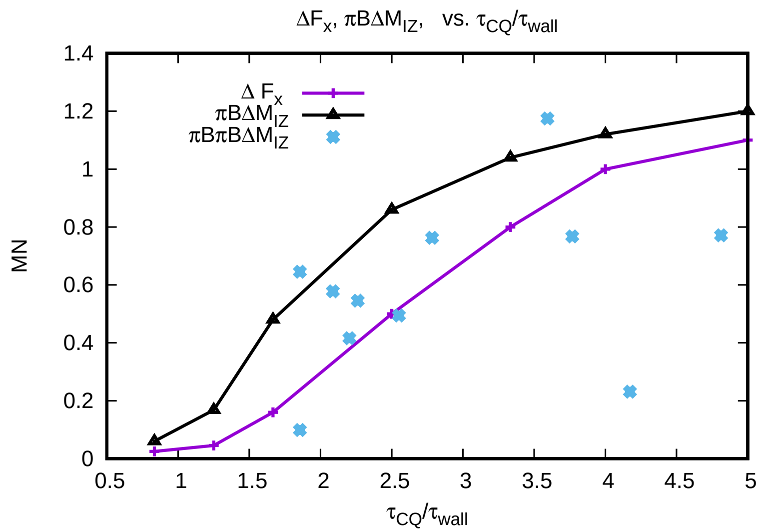
variable	M3D	JET 71985
Z_{max}	1.5m	1.4m
HF	0.16	0.16
ΔHF	0.07	0.05
$\pi B \Delta M_{IZ}$	1.2 MN	1.3 MN
ΔF_x	1.1 MN	
$N_{rotation}(a)$	2.8	2.8
$\Delta I/I$	0.045	0.055

Z_{max} - maximum vertical displacement
Δ - amplitude of toroidal variation
HF - halo fraction
$M_{IZ} = Z_p I_p$ - vertical current moment
ΔF_x - sideways or asymmetric wall force
$N_{rotation}$ - number of toroidal rotation periods
ΔI - amplitude of toroidally varying part of toroidal current

Comparison with M3DC1 is in progress.

Reduction of asymmetric wall force

Asymmetric wall force depends on τ_{CQ}/τ_{wall}.



Solid curves: M3D simulations of shot 71985 where τ_{CQ}/τ_{wall} was artificially varied. Plots of asymmetric wall force ΔF_x and Noll formula $\Delta F_x \approx \pi B \Delta M_{IZ}$.

dots: ΔM_{IZ} and τ_{CQ} calculated for all JET shots "VDE+MGI" with ILW, 2011-2016, superimposed on simulation results.

Effect of MGI on τ_{CQ} might be modelled with M3DC1.

JET locked mode TQ precursor

It may be possible to predict TQ by monitoring precursor of locked mode [DeVries, 2017]

If the mode produces a (2,1) island width $\approx 0.3a$ there will be a TQ

In JET, the mode has to be measured on the outside of the vacuum vessel, rather far from the plasma. It was assumed that the mode amplitude falls off as $(a/r)^2$.

Is this correct? (S. Gerasimov)

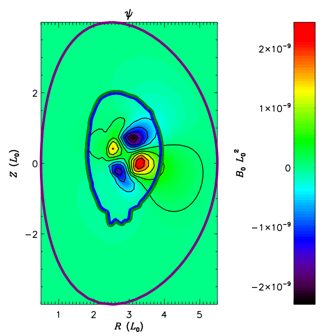
Jet shot 81540 linear mode was calculated with M3DC1 and its structure and growth rate were calculated.

(The shot was also unstable to a (1,1) mode. The equilibrium toroidal field was rescaled - Bateman scaling - to eliminate the q = 1 surface)

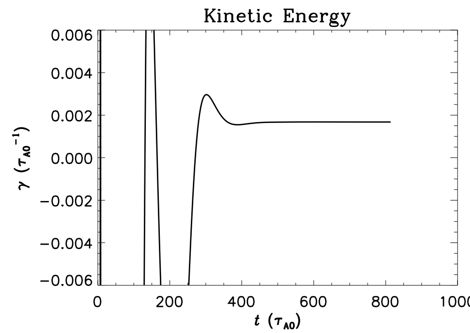
JET locked mode TQ precursor with M3DC1

Linear M3DC1 simulations of JET shot 81540.

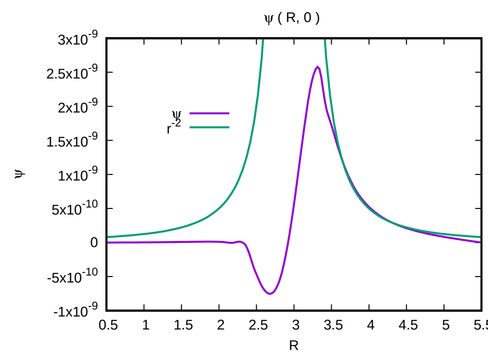
The purpose was to find the ratio of magnetic perturbations measured outside the plasma, at the saddle coils on vacuum chamber wall, at $R = 4.5$ to the perturbation in the plasma. From Fig. 1 (c) it seems the ratio is 0.1, between the maximum at $R = 3.3$ and $R = 4.5$. The figure has a curve $\propto 1/(R - R_0)^2 = 1/r^2$, indicating that ψ is well fit by this function in the midplane.



(a)



(b)



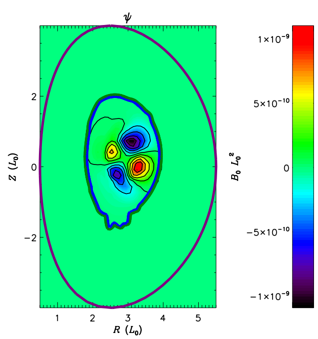
(c)

(a) linear $\psi(R, Z, 0), \eta_w = 10^{-3}$ (b) $\gamma(t)$ (c) $\psi(R, 0, 0)$

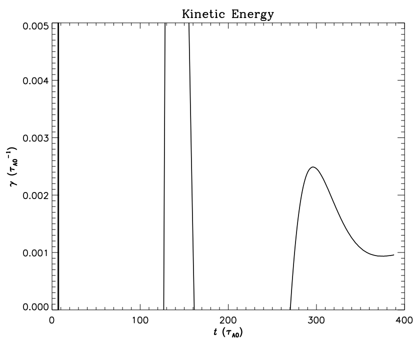
JET locked mode - effect of τ_{wall}

It was shown that τ_{CQ}/τ_{wall} has a substantial effect on wall force. There might be a similar effect on thermal wall load in a TQ.

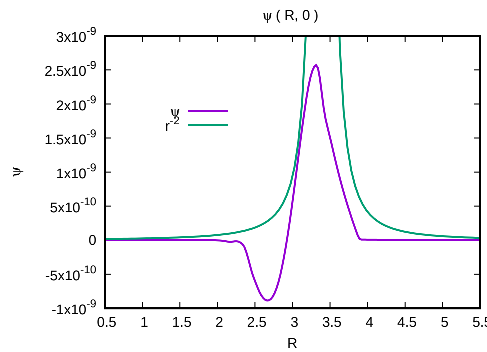
When $\gamma\tau_{wall} > 1$, the mode grows faster than flux perturbation can penetrate the wall. The wall acts like an ideal wall.



(a)



(b)

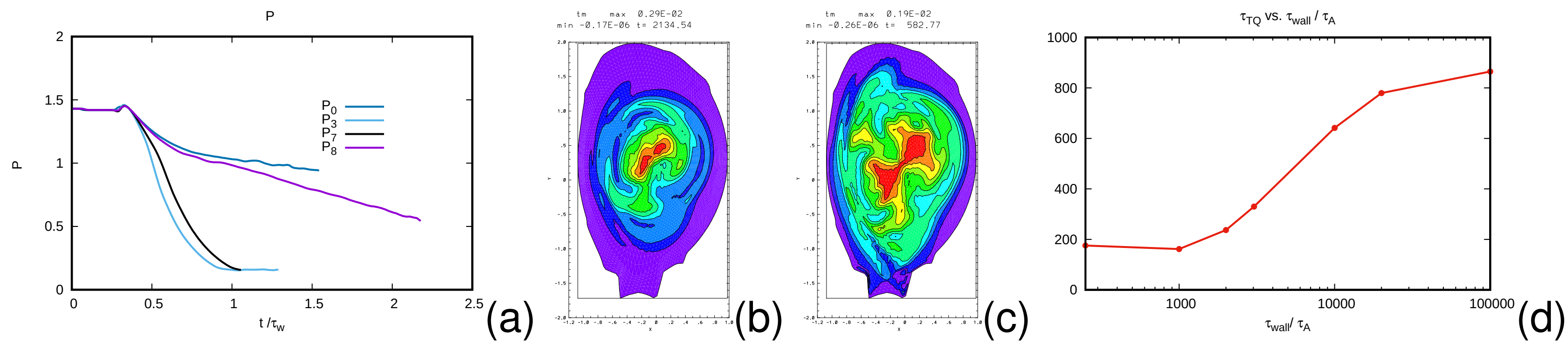


(c)

(a) linear $\psi(R, Z, 0), \eta_w = 10^{-6}$ (b) $\gamma(t)$ (c) $\psi(R, 0, 0)$

This has to be checked nonlinearly.

M3D nonlinear simulations of JET shot 81540



(a) time history of total pressure for cases with different τ_{wall} : $P_0 = 0$, $P_8 = 5 \times 10^4 \tau_A$, $P_7 = 2 \times 10^3$, $P_8 = 10^3$. For cases P_0, P_3 the pressure decays slowly, while for P_7, P_8 it decays rapidly. (b) pressure at time $t = 2134\tau_A$, case P_8. The pressure is confined, (c) pressure at time $t = 583\tau_A$, case P_7. The pressure is less confined. (d) Temperature quench time τ_{TQ} vs. τ_{wall}.

JET is in a regime $\gamma\tau_{wall} < 1$, with fast TQ.

ITER is likely to be in regime $\gamma\tau_{wall} > 1$, with slow TQ.

This might be relevant to ITER, because the long ITER wall time might mitigate the TQ wall loading.

Runaway Electrons - Fluid model

MHD simulations were extended by added RE fluid. Runaway fluid equations are [Helander 2007],[Cai and Fu 2015]

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\parallel}\Phi - \eta(J_{\parallel} - J_{\parallel RE}) \tag{1}$$

and $J_{\parallel RE}$ is the RE current density.

The RE continuity equation can be expressed in terms of the RE current assuming the REs have speed c

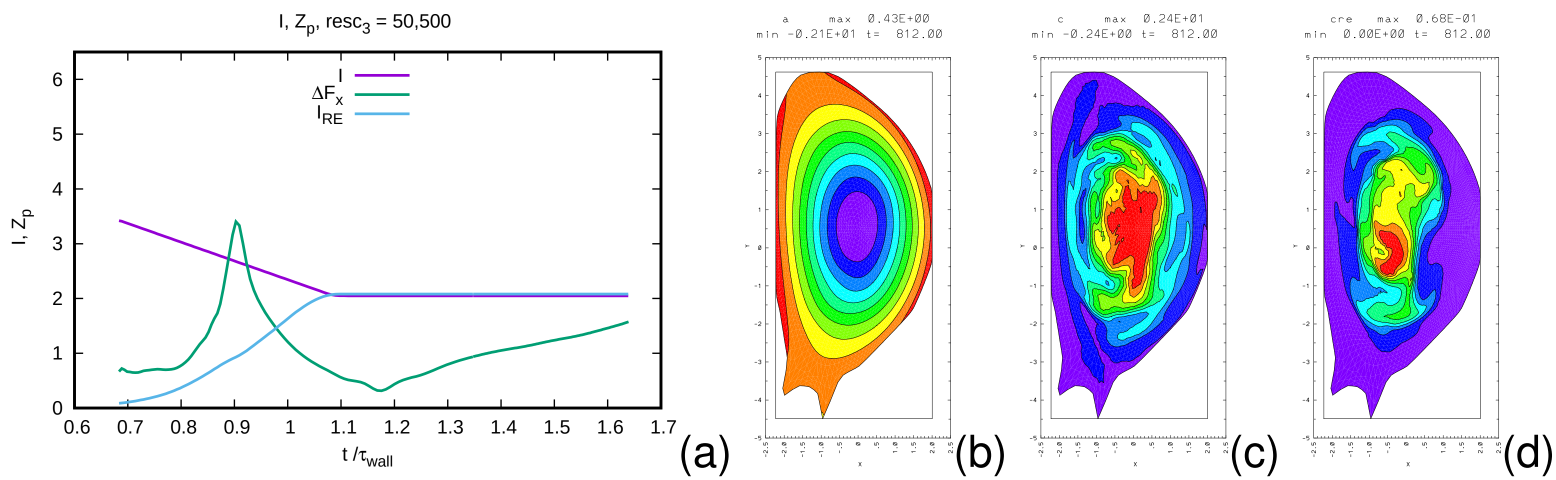
$$\frac{\partial J_{\parallel RE}}{\partial t} \approx -c\mathbf{B}\cdot\nabla\left(\frac{J_{\parallel RE}}{B}\right) + S_{RE} \tag{2}$$

where S_{RE} in the following is a model avalanche source term

$$S_{RE} = c_1\eta(J - J_{RE})J_{RE}$$

Runaway Electron simulation

Runaway electrons quench slowly, REs might change the regime to $\tau_{CQ}/\tau_{wall} > 1$



(a)Time history of RE simulation with total current I, runaway current I_{RE}, and wall force ΔF_x. (b) ψ at $t = 0.8\tau_{wall}$. (c) J_ϕ (d) J_{RE} at same time.

Summary

- Goal is to compare M3DC1 and M3D simulations of JET
- M3DC1 2D VDE saturates and is consistent with JET shot 71985
- 3D AVDE
  - M3DC1 in progress: several asymmetric variables are measured in JET
  - M3D: agreement with JET
  - decreasing the CQ time lowers the asymmetric wall force
- JET locked mode TQ precursor
  - linear M3DC1 gives mode amplitude
  - nonlinear M3D shows TQ mitigation
- Runaway Electrons fluid model simulations