M3D Simulation of JET disruptions and Runaway Electrons

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with contributors

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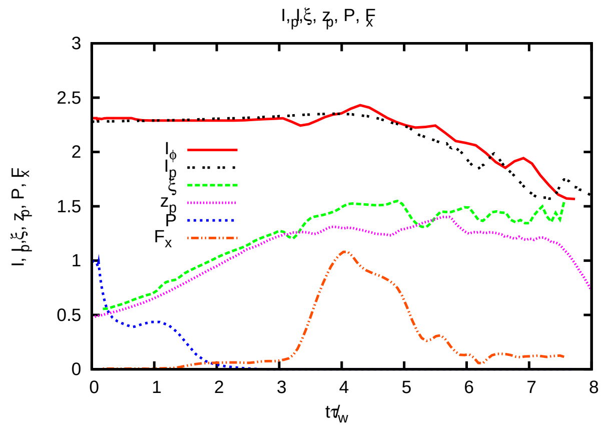
JET AVDE disruption simulations

- M3D asymmetric vertical displacement event (AVDE) disruption simulations were carried out, initialized with EFIT equilibrium reconstruction of JET disruption shot 71985 at $t = 67.3128s$, $B = 2T$
  - Several variables were compared in simulation and experiment including • vertical displacement ξ, • halo fraction HF, • toroidal variation of toroidal current, • asymmetric wall force and Noll relation $\Delta F_x = \pi B \Delta M_{IZ}$, • toroidal rotation N_{rot}.

- JET simulations with $\tau_{wall} \sim \tau_{CQ}$ changed artificially
  - wall force can be much less than $\tau_{wall} \ll \tau_{CQ}$
  - ITER relevant regime

- Runaway electrons
  - JET RE data
  - RE MHD equations
  - preliminary simulations

Time history of simulation of shot 71985 with VDE and CQ



Time history plots for $S_{wall} = 1000$. Time in units of wall time τ_{wall}. The current was driven using experimental time history data for shot 71985, in wall time units.

$$I_\phi(t/\tau_{wall}) \approx I_p(t/\tau_{wall}^{JET}) \tag{1}$$

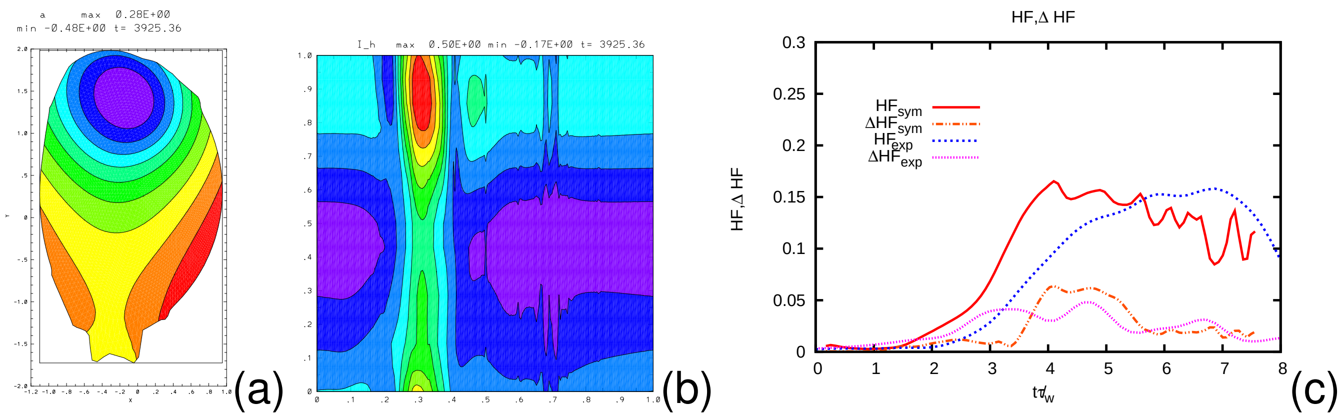
Shown are simulation total current I and vertical displacement ξ, and the measurements of I_p and z_p. Note that ξ agrees well with z_p during the growth and saturation phases.

The normalized pressure P shows the TQ. Also shown is asymmetric wall force F_x, in MN.

- Simulation parameters: $S = \tau_R/\tau_A = 10^6$, $S_{wall} = \tau_{wall}/\tau_A = 250, 500, 1000$.

- Experimental parameters: $S = 10^9$ (pre TQ), $S \approx 10^5$ (post TQ), $S_{wall}^{JET} = 7 \times 10^3$, $\tau_{wall}^{JET} = 0.005s$.

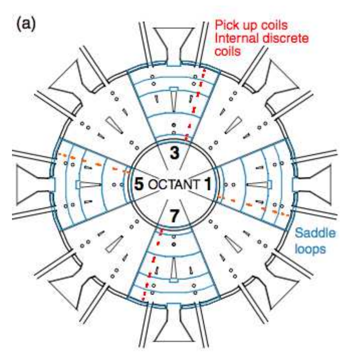
Halo current evolution in shot 71985



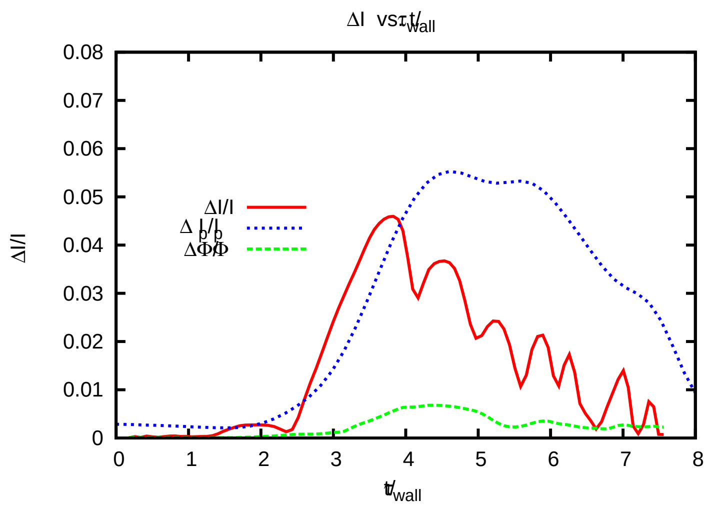
(a) Contour plot of poloidal magnetic flux ψ at time $t = 4\tau_{wall}$ in the (R, Z) plane with $\phi = 0$, $S_{wall} = 1000$, when ξ displacement has saturated. (b) Perturbed toroidal flux on the wall $R\delta B_\phi$, at the same time, where $\delta B_\phi = B_\phi(t) - B_\phi(t = 0)$. Vertical coordinate is toroidal angle $\phi/(2\pi)$, horizontal coordinate is a poloidal angle $\theta/2\pi$. (c) Time history of toroidally averaged halo current HF, and toroidally varying halo current ΔHF, at $\theta = 2\pi/3$.

$$HF = 2\pi R \delta B_\phi / I_0.$$

$$\Delta HF = (R/I_0)\left[\oint (\delta B_\phi - \delta \overline{B}_\phi)^2 d\phi\right]^{1/2}$$



Toroidal current and toroidal flux toroidal variation



Toroidal $n = 1$ variation of toroidal current was observed in JET [Gerasimov, 2014,2015]. Time history plot shows magnitude of toroidal current variation ΔI, comparing JET and simulation. Also shown is the toroidally varying toroidal magnetic flux $\Delta\Phi/\Phi$, where $\Phi = \int B_\phi dRdZ$. The amplitude of $\Delta I/I$ decays more rapidly in time than the experimental data.

The toroidal variation of toroidal current follows from $\nabla \cdot \mathbf{J} = 0$, which has the integral form

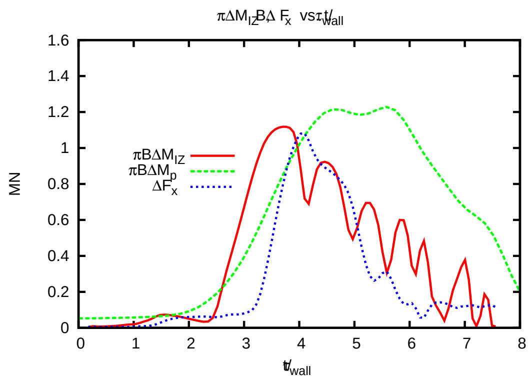
$$\frac{\partial I}{\partial \phi} = -\oint J_n R dl = -\tilde{I}_{halo} \qquad \frac{\Delta I}{I} \approx \Delta HF. \tag{2}$$

The toroidal variation of toroidal flux follows from $\nabla \cdot \mathbf{B} = 0$, $\partial\Phi/\partial\phi = -\oint RB_n dl$.

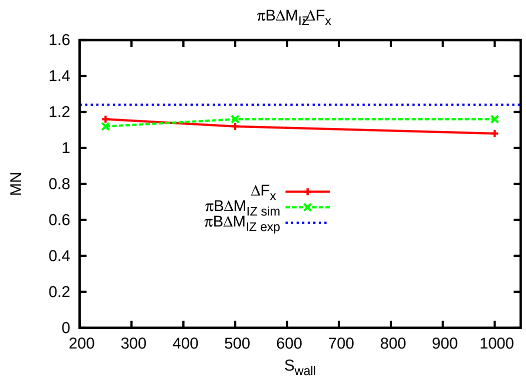
Take $J_n \approx B_n/a$, where a is the minor radius. Then $\Delta I \approx \Delta\Phi/a$. With $J_\phi \approx B_\phi/(qR)$, then

$$\frac{\Delta\Phi}{\Phi} \approx \frac{a}{qR}\frac{\Delta I}{I}$$

Noll relation of F_x and M_{IZ} in JET shot 71985



(a)



(b)

The wall force is

$$\mathbf{F}_{wall} = \delta_{wall} \oint \oint d\phi dl R \mathbf{J}_{wall} \times \mathbf{B}_{wall} \qquad (3)$$

where δ_{wall} is the wall thickness. The magnitude of the asymmetric horizontal force is defined as

$$\Delta F_x = [(\tilde{\mathbf{F}} \cdot \hat{\mathbf{x}})^2 + \tilde{\mathbf{F}} \cdot \hat{\mathbf{y}}^2)]^{1/2}.$$

The Noll relation is used in JET to estimate the asymmetric wall force,

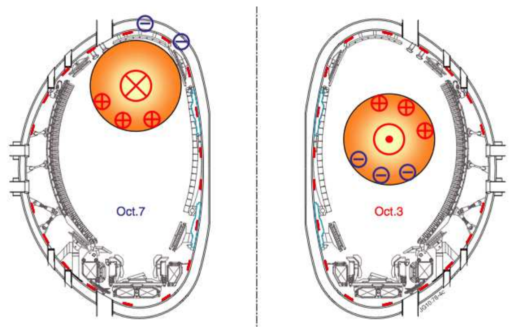
$$\Delta F_x = \pi B_\phi \Delta M_{IZ} \qquad (4)$$

with

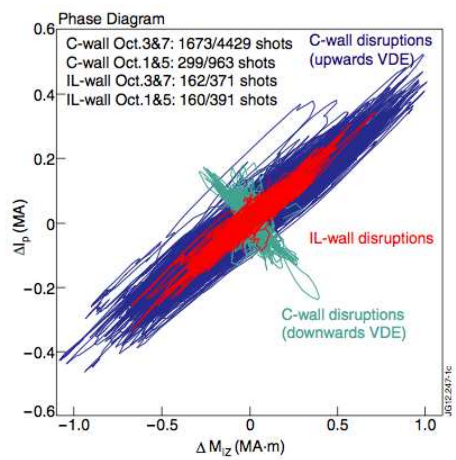
$$M_{IZ} = \int Z J_\phi d^2 x.$$

The units are in MN. The scaled asymmetric force amplitude is $\Delta F_x = 1.1MN$. The experimental Noll formula predicts a force of $1.3MN$, while the simulated formula predicts $1.2MN$. (b) shows simulations with different values of S_{wall}. The agreement is essentially independent of S_{wall}.

Correlation of toroidal current and vertical displacement asymmetry

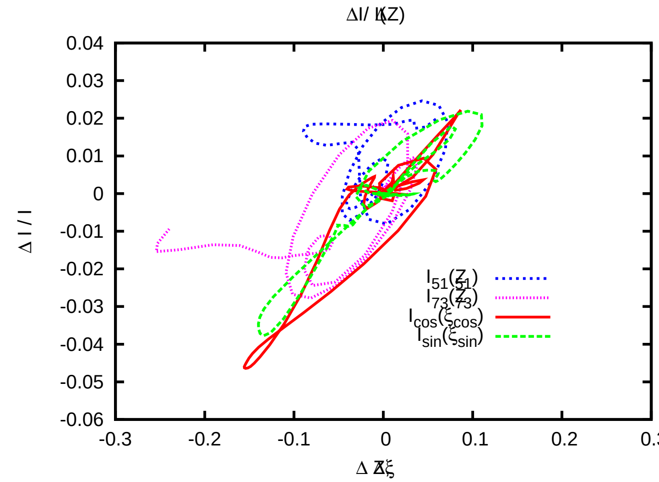


(a)



(b)

(a) variation of vertical displacement
(b) correlation of current and displacement [Gerasimov NF 2014]



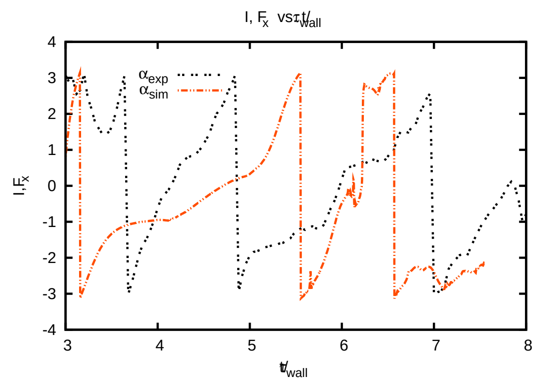
(c)

The toroidal variation of the current ΔI and the vertical displacement $\Delta\xi$ are positively correlated, indicating that the toroidal plasma current is higher at toroidal locations where the plasma position is closer to the wall [Gerasimov 2014, Strauss 2015].

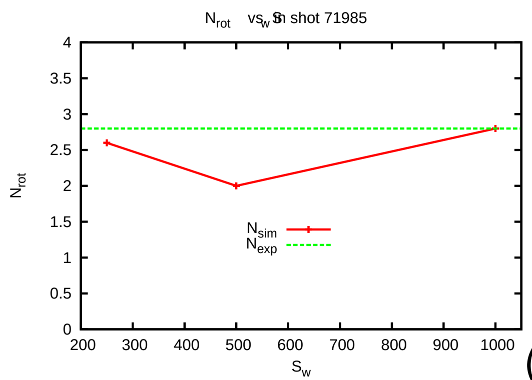
(c) experimental time histories of toroidal current difference $(I_5 - I_1)/I$ vs. $(Z_5 - Z_1)$, $(I_7 - I_3)/I$ vs. $(Z_7 - Z_3)$. Also shown are simulation toroidal harmonics I_{cos}/I vs. ξ_{cos}, and I_{sin}/I vs. ξ_{sin}.

The correlation does not require skin current flowing from the plasma to the wall.

Toroidal Rotation



(a)



(b)

(a) wall force angle in wall time units. The rotation angle calculated from the experimental data is

$$\alpha_{exp} = \tan^{-1}\left(\frac{I_5 - I_1}{I_7 - I_3}\right)$$

The simulated rotation angle of the current was rather noisy, so the force angle was used, with $S_{wall} = 10^3$,

$$\alpha_{sim} = \tan^{-1}(\frac{\tilde{F}\cdot\hat{\mathbf{y}}}{\tilde{F}\cdot\hat{\mathbf{x}}})$$

(b) Rotation number during the time of large halo current

$$2\pi N_{rot} = \alpha(t = 8\tau_{wall}) - \alpha(t = 3\tau_{wall})$$

as a function of S_{wall}. Also shown is the experimental value of N_{rot} from (a). This implies the rotation frequency is

$$f_{rot} = N_{rot}/\tau_{CQ} \approx (2S_{wall})^{-1},$$

It suggests the rotation is involved with the resistive wall interaction.

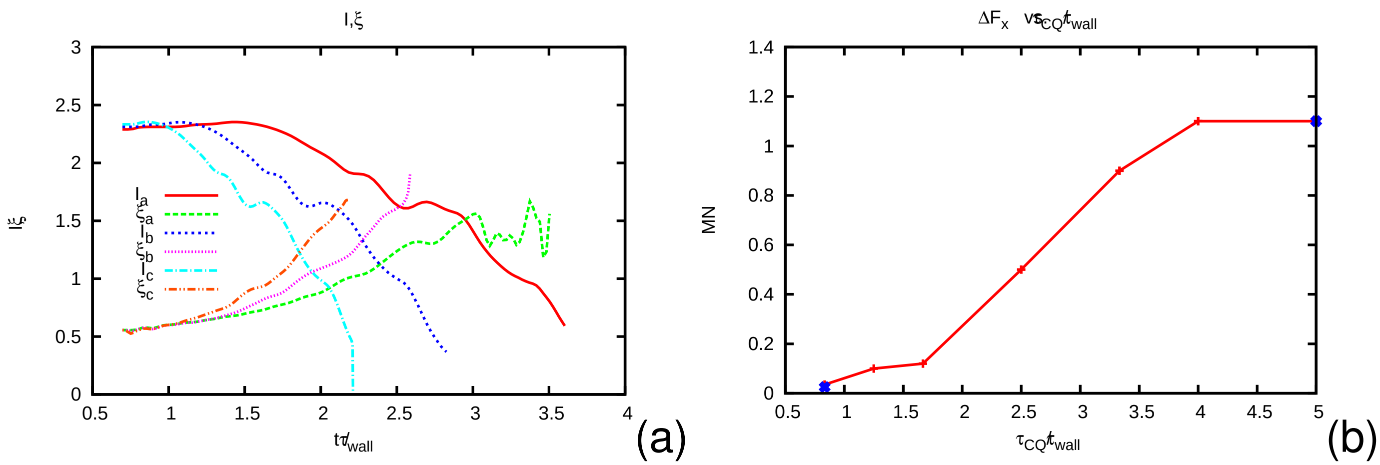
JET and ITER comparison of τ_{wall}

- JET is in the short τ_{wall} regime, $\tau_{wall} \ll \tau_{CQ}$.
  - JET resistive wall penetration time $\tau_{wall}^{JET} = 5ms$.
  - JET with carbon wall, $\tau_{CQ} \approx 25ms$. with ILW, $125ms$.

- JET simulations were done to artificially increase τ_{wall} keeping τ_{CQ} fixed. In the long τ_{wall} regime, the asymmetric wall force is an order smaller.

- ITER is in the long τ_{wall} regime, $\tau_{wall} \gtrsim \tau_{CQ}$.
  - ITER walls [Gribov 2002] have thickness $\delta = 6cm$, resistivity $\eta = 0.825\mu\Omega m$, and radius $a_w = 2.7m$.
  - ITER wall time $\tau_{wall}^{ITER} = \mu_0 a_w \delta/\eta = 0.26s$.
  - ITER CQ time $0.05s \leq \tau_{CQ}^{ITER} \leq 0.3s$ [Lehnen, TSDW 2016], [Kiramov, EPS 2016] [Hollman, 2015].

JET long τ_{wall} simulations

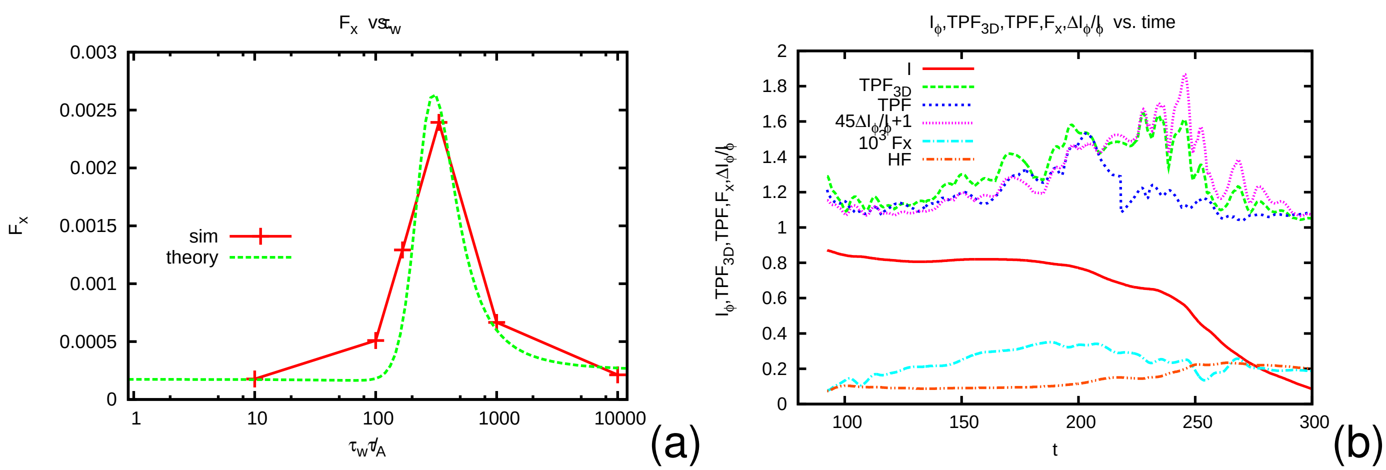


(a) Time history including $\Delta F_x(MN)$, of JET simulation with $S_{wall} = 250$, with current scaled to a longer wall times. Subscipts denote values of $\tau_{CQ}/\tau_{wall} =$ (a) 1.67, (b) 1.25, (c) 0.83. In case (a) ξ saturates in a steady state, while in (b) , (c) ξ does not saturate.

(b) Peak ΔF_x as a function of τ_{CQ}/τ_{wall}. In the ITER regime $\tau_{CQ}/\tau_{wall} \lesssim 1.5$, the VDE does not saturate, and the asymmetric wall force is small. In the JET regime $\tau_{CQ}/\tau_{wall} \gtrsim 4$, the VDE saturates, and the asymmetric wall force is large. There is also an intermediate regime in which the VDE saturates. Blue dots: $S_{wall} = 10^3$.

In ITER the force might be comparable to JET: $25 \times 0.04 = 1$.

previous ITER simulations have wide range of F_x



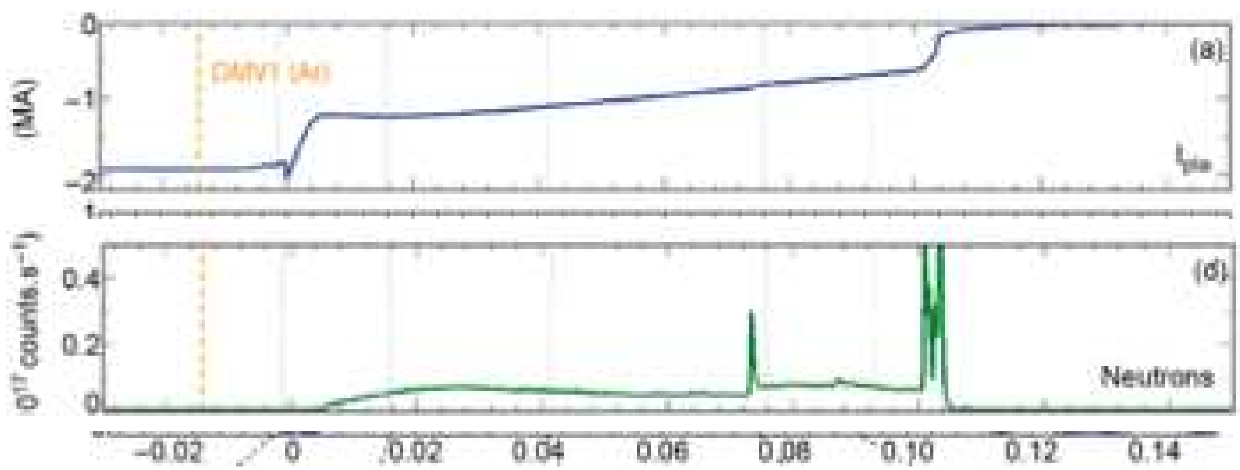
From [Strauss *et al.* , NF 2013]

(a) "hot" ITER simulations, peak with $\gamma\tau_{wall} = \mathcal{O}(1)$, γ is growth rate of predominantly $(2,1)$ mode.

(b) Time history including $\Delta F_x(MN)$, of ITER MGI model simulation with $S_{wall} = 10^4$, $\tau_{CQ} \approx 250$. Peak $F_x \lesssim 10\%$ the peak value in (a).

In these simulations, τ_{CQ} was not controlled. Further simulations similar to JET needed to verify relation of F_x to τ_{wall}/τ_{CQ} in ITER.

Runaway Electrons



RE measurements in JET shot 87940 [Reux *et al.* 2015].

(a) total current I_p as a function of time. It drops by half in time $0.01s$ after the TQ, in a VDE time: $\tau_{vde} = 3\tau_{wall} = 0.015s$. The current persists for $\tau_{re} = 20\tau_{wall}$. (b) neutron count, a measure of high energy REs. Spikes near $t = 0.11s$ before current terminates might indicate MHD activity which terminates the current.

Fluid model of REs

Runaway fluid equations are [Helander 2007],[Cai and Fu 2015]

$$\frac{1}{c}\frac{\partial \psi}{\partial t} = \nabla_{\|}\Phi - \eta(J_{\|} - J_{r\|}) \tag{5}$$

and $J_{r\|}$ is the RE current.

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

$$\frac{\partial J_{r\|}}{\partial t} \approx -c\mathbf{B}\cdot\nabla\left(\frac{J_{r\|}}{B}\right) + S_r \tag{6}$$

where S_r is a source term.

The perpendicular momentum equation is

$$\nabla\cdot(m_i n_i \frac{d\mathbf{v}_i}{dt}) = 2\kappa\times\nabla p_{tot}\cdot\frac{\mathbf{B}}{B^2} - \mathbf{B}\cdot\nabla\frac{J_{\|}}{B} \tag{7}$$

where $\kappa = \mathbf{b}\cdot\mathbf{b}$ and the effective total pressure p_{tot} is

$$p_{tot} = p + \frac{1}{2}\mathcal{E}_r n_r, \qquad \mathcal{E}_r = m_e c^2 \gamma_r \tag{8}$$

The RE energy increases with time

$$\frac{\partial \mathcal{E}_r}{\partial t} = S_{\mathcal{E}} \tag{9}$$

In the presence of REs, the total pressure p_{tot} survives the TQ the current survives the CQ. It is possible to have a second disruption caused by REs.

If the current is carried by REs, then $en_r = B/(4\pi q)$ and

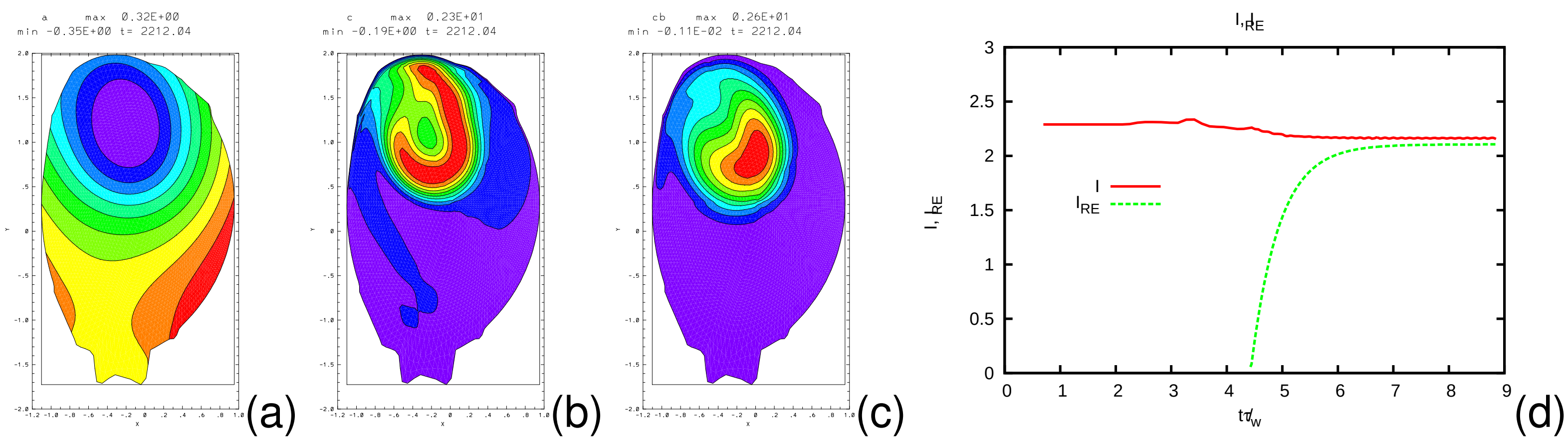
$$\frac{n_r \mathcal{E}_r}{n_e T} = \frac{v_A}{c}\frac{\delta_i}{qR}\frac{\mathcal{E}_r}{T} \tag{10}$$

where δ_i is the ion skin depth and v_A is the Alfvén velocity, which implies that the RE fraction must be small, $n_r/n_e \approx 4 \times 10^{-4}$. If $\mathcal{E}_r \geq 12$ MeV , and $T = 5$ KeV , $\mathcal{E}_r n_r/p \geq 1$.

Possible MHD instabilities include tearing modes, RWMs, ELMs.

RE evolution in JET

Simulations were continued of JET shot 71985, replacing current with RE current.



(a) Contours of magnetic flux $\psi(R, Z, 0)$ at $t = 8.8\tau_{wall}$.

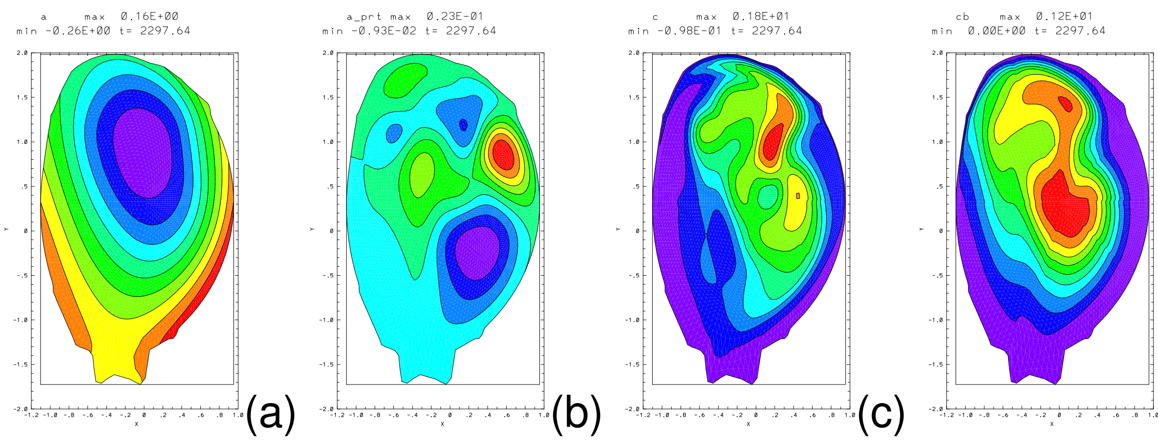
(b) Contours of toroidal current I at the same time

(c) Contours of RE current I_{RE} at the same time.

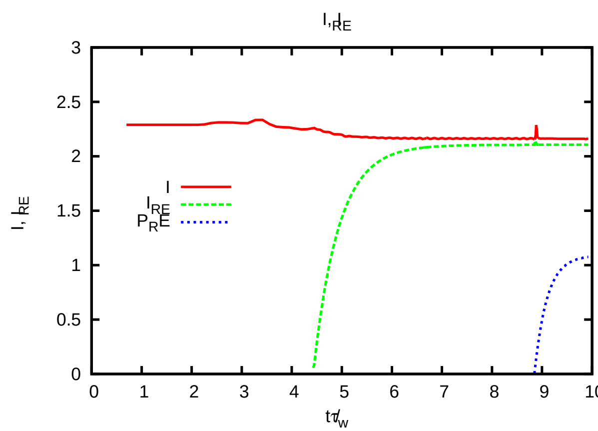
(d) time history of I and I_{RE} (d) time history of current I , RE current I_{RE}, and runaway pressure P_{RE}.

RE evolution in JET with P_{RE}

Simulations were continued of JET shot 71985, adding RE pressure.



(a) (b) (c) (d)

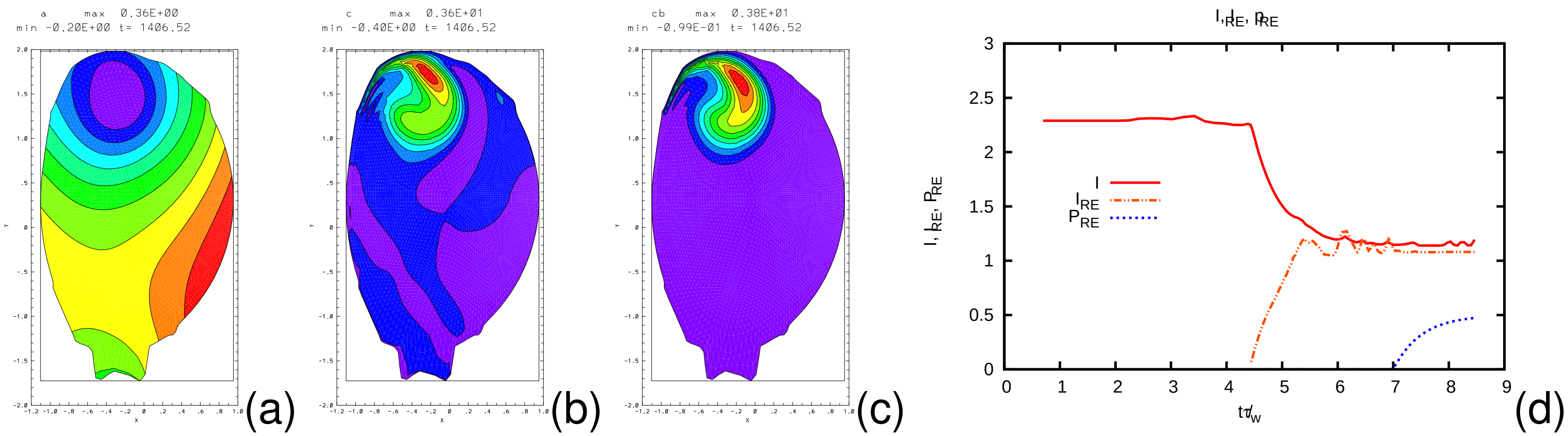


(d)

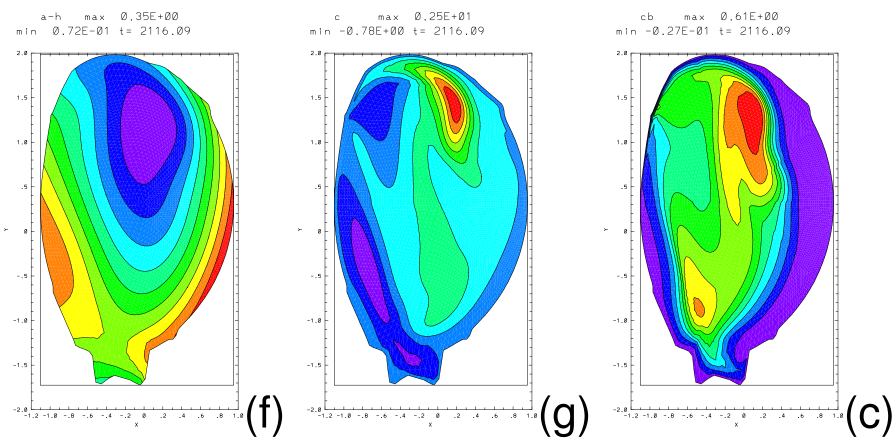
(a) Contours of $\psi(R, Z, 0)$ at $t = 9.2\tau_{wall}$,
(b) Contours of $\tilde{\psi}(R, Z, 0)$ at the same time.
(c)current I at the same time,
(d) RE current I_{RE}.
(e) time history of current I , RE current I_{RE}, and runaway pressure P_{RE}. RE pressure appears to cause instability.

RE evolution in JET with $I/2$

Simulations were continued of JET shot 71985, replacing current with RE current.



Contour plots of poloidal magnetic flux ψ at times (a)$t = 5.5\tau_{wall}$ (e) $8.5\tau_{wall}$ in the (R, Z) plane with $\phi = 0$.



(b),(f) Contours of toroidal current at the same times (c), (g) Contours of RE current at the same times. (d) time history of current I , RE current I_{RE}, and runaway pressure P_{RE}.

Summary

- Several measured quantities are in reasonable agreement between simulation and experiment
  - VDE displacement, • halo current, • toroidal variation of toroidal current, • Noll relation, • correlation of current and vertical displacement variation, • Toroidal rotation

- JET simulation has fast and slow τ_{wall} regimes.
  - fast τ_{wall} regime: asymmetric wall force F_x is large; JET experiment.
  - slow τ_{wall} regime, F_x is much smaller; regime relevant to ITER.

- Runaway electrons
  - Fluid equations
  - similar to MHD behavior without REs
  - REs could produce secondary disruption to terminate discharge