JET AVDE disruption and runaway electron simulations

H. Strauss,HRS Fusion

E. Joffrin, IRFM, CEA centre de Cadarache ,

V. Riccardo, EURATOM/UKAEA Fusion Association

J. Breslau, Princeton Plasma Physics Laboratory

Guyong Fu, Princeton Plasma Physics Laboratory

CEMM meeting, APS, 2016

JET AVDE disruption simulations

- MHD asymmetric vertical displacement event (AVDE) disruption simulations using the M3D code were carried out, initialized with EFIT equilibrium reconstruction of JET disruption shot 71985 at $t = 67.3128s$, $B = 2T$

Gerasimov *et al.* Nucl. Fusion **55**, 113006 (2015), Riccardo *et al.* Plasma Phys. Contr. Fusion, **52**, (2010)

- Simulation parameters: $S = \tau_R/\tau_A = 10^6$, $S_{wall} = \tau_{wall}/\tau_A = 250 - 1300$.

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

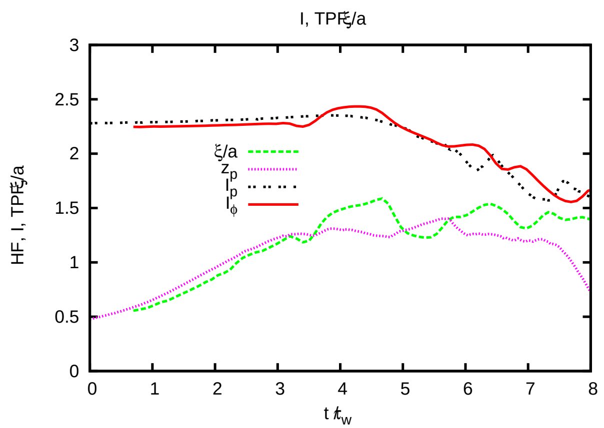
- In recent shot 71985 simulations, the CQ was included, using experimental data $I_\phi(t)$.

quantities to compare in simulation and experiment

Several variables were compared in simulation and experiment and are in reasonable agreement.

- time history of VDE and current
- Amplitude and time history of toroidal variations
  - halo current
  - toroidal current
  - toroidal flux
  - toroidal rotation
  - Noll relation

Time history of simulation of shot 71985 with VDE and CQ

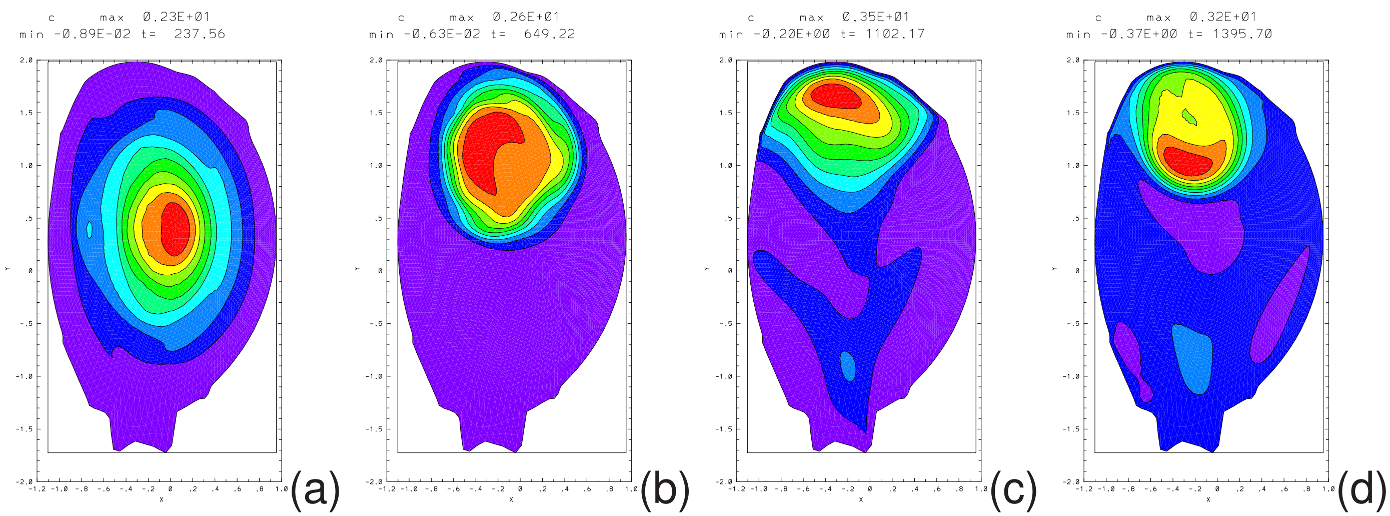


Time history plots for $S_{wall} = 250$. Time in units of wall time τ_{wall}. The current is ramped down using rescaled experimental time history data, where time in seconds is divided by $t_w = 0.005s$ to give wall time units. The simulation current is driven by normalized experimental current in wall time units.

Shown are simulation total current I and vertical displacement ξ/a, and the rescaled experimental measurements of I_p and $z_p = \xi$. It is noteworthy that ξ agrees well with z_p during the growth phase.

Toroidal current in modeled shot 71985 during CQ

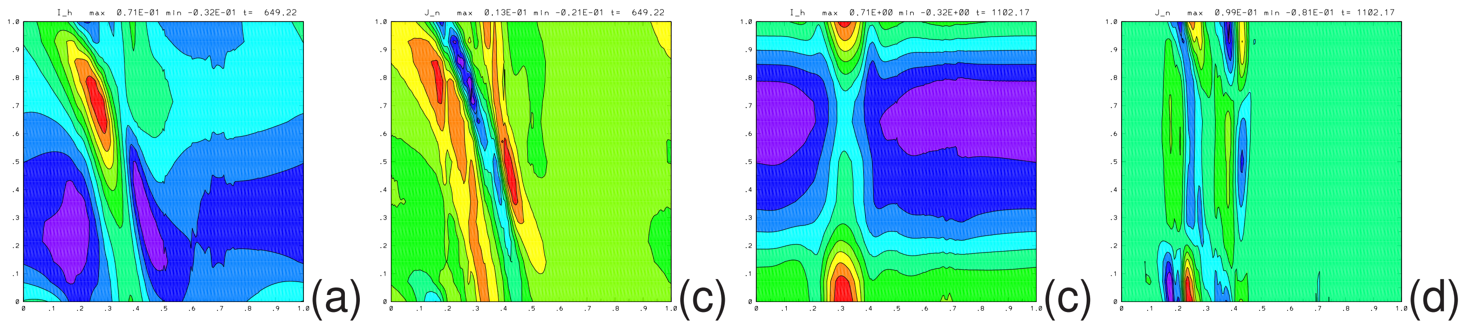
During the CQ, the VDE saturates. Some current flows along the separatrix.



Contour plots of toroidal current with $S_{wall} = 250$, (a) $t = 0.95\tau_{wall}$, with $(1,1)$ and $(2,1)$ modes (b) $t = 2.63\tau_{wall}$, (c) $t = 4.41\tau_{wall}$, (d) $t = 5.58\tau_{wall}$. There is some toroidal current flow along the magnetic separatrix. It can be assumed that the current (a) is nearly parallel to B, so current outside closed contours is proportional to poloidal halo current.

It can be seen that a large $(1,1)$ mode is present during the VDE, but it is an internal rather than external kink.

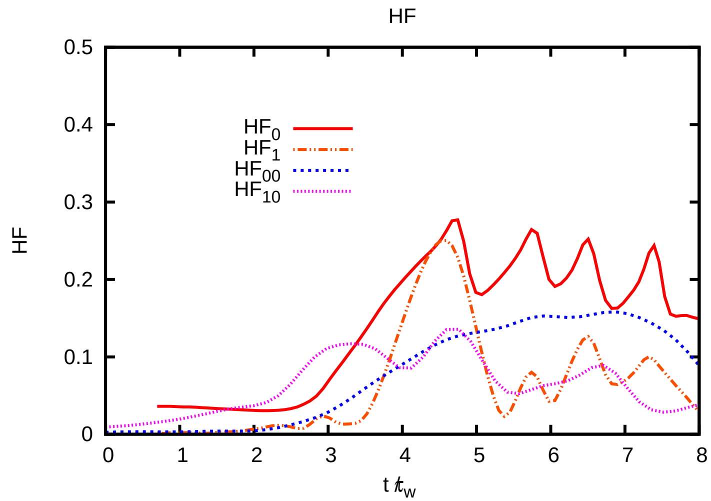
Halo current in modeled JET shot 71985



(a) perturbed toroidal flux $R(B_\phi(t) - B_\phi(0))$ at $t = 2.63\tau_{wall}$. It is the difference between the flux at $t = 2.63\tau_{wall}$ and $t = 0$. Both $n = 0$ and $n \geq 1$ perturbations are included. (b) halo current density RJ_n at the same time. The vertical coordinate is the toroidal angle $\phi/(2\pi)$, and the horizontal coordinate is a poloidal angle $\theta/2\pi$. (c) toroidal flux $R(B_\phi - B_\phi(0))$ at $t = 4.4\tau_{wall}$. (d) halo current density RJ_n at the same time.

The JET halo current detectors measure toroidal flux $R(B_\phi - B_\phi(0))$ at $\theta \approx 0.3$ are positioned to detect the halo current, at the top of the wall. This measures the largest flux perturbations. There is a substantial difference between the perturbed flux and the halo current density.

Time history of halo current in shot 71985



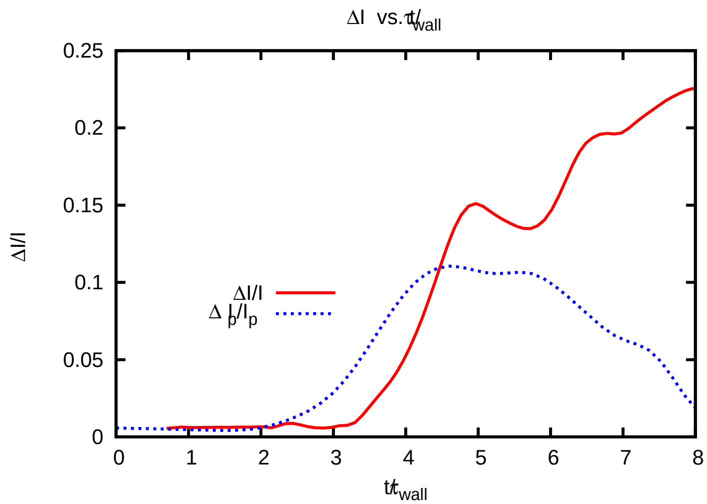
The toroidally varying halo current in JET is measured as

$$\delta H_{fJ} = 2\pi R \frac{\delta B_\phi}{I_\phi},$$

where $\delta B_\phi = B_\phi(\theta_0, \phi, t) - B_\phi(\theta_0, \phi, 0)$ the time change of toroidal magnetic field at observation angle $\theta_1 \approx 2\pi/3$, at the top of the JET wall, near the typical VDE strike point; measured at toroidal angles $\phi \approx (k-1)\pi/2$, with $k = 1, \ldots 4$. HF_0 is the $n = 0$ part of δHF_J and HF_1 is the $n = 1$ part, in simulational time history. HF_{00} and $HF10$ are the $n = 0$ and $n = 1$ part of δHF_J from JET data.

δH_{fJ} is not really the halo fraction but it is related to it. The simulation values have large fluctuations compared to experiment, but the order of magnitude agreement is reasonable.

Toroidal current variation in shot 71985



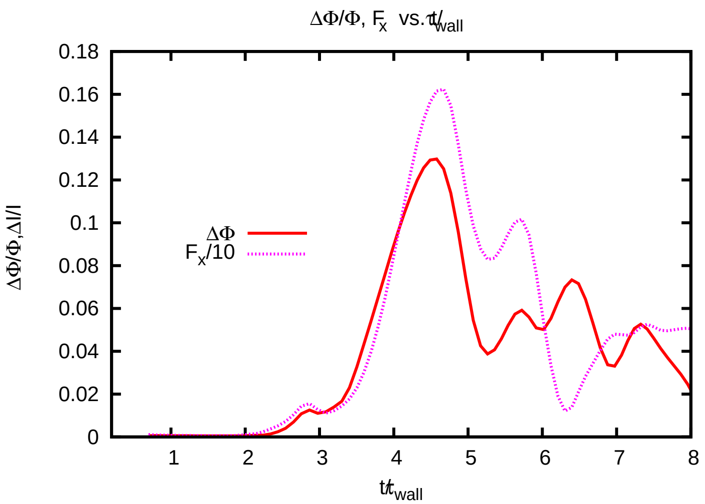
Toroidal $n = 1$ variation of toroidal current was observed in JET [Gerasimov, 2014,2015]. Time history plot shows magnitude of toroidal current variation comparing JET and simulation.

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

$$\partial I/\partial\phi = -\oint J_n R dl = -\tilde{I}_{halo}.$$

The right side is the 3D varying part of the halo current.

Toroidal variation of toroidal flux in modeled shot 71985



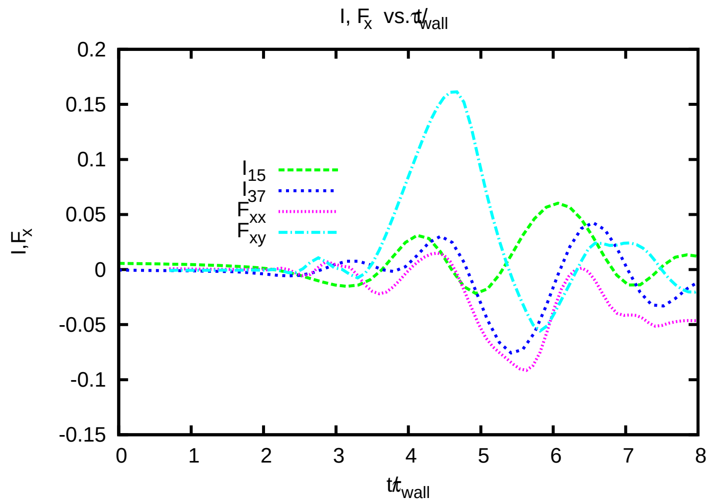
Toroidal $n = 1$ variation of toroidal flux was also observed in JET [Gerasimov, 2015]. Time history plot shows magnitude of toroidal current variation and toroidal flux variation. It is shown here to be an MHD effect.
Here $\tilde{\Phi} = \int \tilde{B}_\phi d^2x$.

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

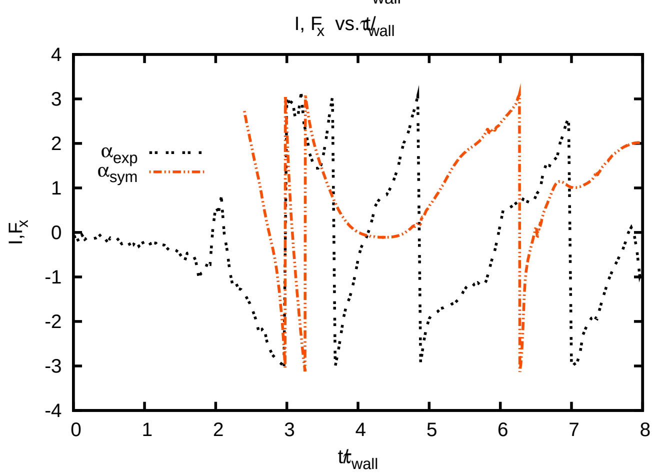
The toroidal flux is well correlated with F_x. This is because the normal wall force is given by [Strauss *et al.*, Phys. Plas. (2010)] $F_n = \frac{1}{2}(\mathbf{B}_p^2 - \mathbf{B}_v^2)$ where $\mathbf{B}_p$ is the magnetic field on the inside, the plasma side, of the wall and $\mathbf{B}_v$ is the field on vacuum side.

$$\frac{\partial B_n}{\partial t} = \frac{\eta_{wall}}{\delta_{wall}} \hat{\mathbf{n}} \times (\mathbf{B}_v - \mathbf{B}_p) \times \hat{\mathbf{n}} \qquad \frac{\partial^2 \Phi}{\partial \phi dt} \propto (B_\phi^v - B_\phi^p) \propto F_n$$

Rotation in shot 71985



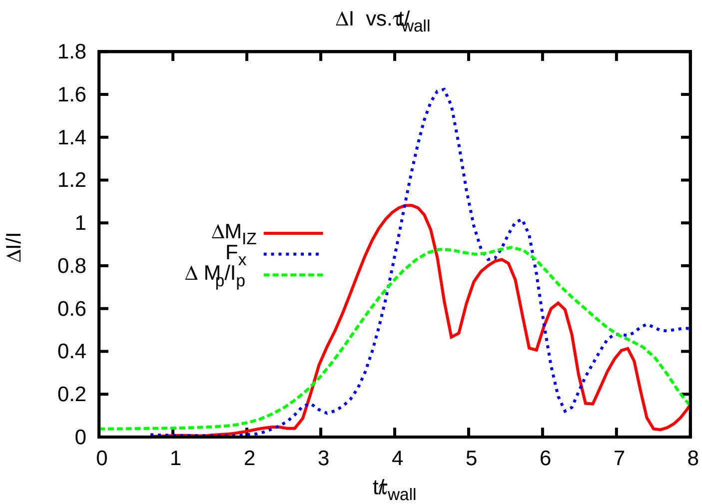
(a)



(b)

Asymmetric force rotation is of concern in ITER. Rotation is observed in both experiment and simulations. The experimental rotation is measured by comparing the toroidal variation of the toroidal current in octants separated by π. Here $I_{15} = I(0) - I(\pi)$, $I_{37} = I(\pi/2) - I(3\pi/2)$. This diagnostic was not implemented in this simulation, but in instead the asymmetric wall force is compared in the $\hat{\mathbf{x}}$ and $\hat{\mathbf{y}}$ directions, $F_{xx} = \mathbf{F} \cdot \hat{\mathbf{x}}$, and $F_{xy} = \mathbf{F} \cdot \hat{\mathbf{y}}$ [Strauss *et al.* NF 2014, PoP 2015]. It can be seen that there is about one rotation. The period seems to be about $2\tau_{wall}$. (a) data and simulation (b) $\alpha_{exp} = \tan^{-1}(I_{15}/I_{37})$ and $\alpha_{sim} = \tan^{-1}(F_{xy}/F_{xx})$.

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



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

$$F_x = \pi B_\phi M_{IZ}$$

with

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

The simulated asymmetric wall force is consistent with the Noll formula [Strauss, Phys. Plasmas 2015].

Runaway electrons

- MGI shutdown of ITER shots may cause REs
- previous simulations have used test particles to see if REs are confined
  - Izzo *et al.* [Nucl. Fusion(2011]
  - Nardon, JOREK simulations, EPS 2016
- nonlinear self consistent fluid method
  - Helander *et al.* , [Phys. Plasmas (2007)]
    - ∗ resistive modes can be more unstable
  - Cai and Fu [Nucl. Fusion (2015)]
    - ∗ added RE equation to M3D
    - ∗ studied effect on n = 1 resistive internal kink

Runaway electron equations

Runaways move along the magnetic field at speed c. Source is S_{re}.

$$\frac{\partial j_{re}}{\partial t} = -c\nabla_{\|} j_{re} + S_{re}$$

Runaways are not affected by resistivity

$$E = \eta(j - j_{re})$$

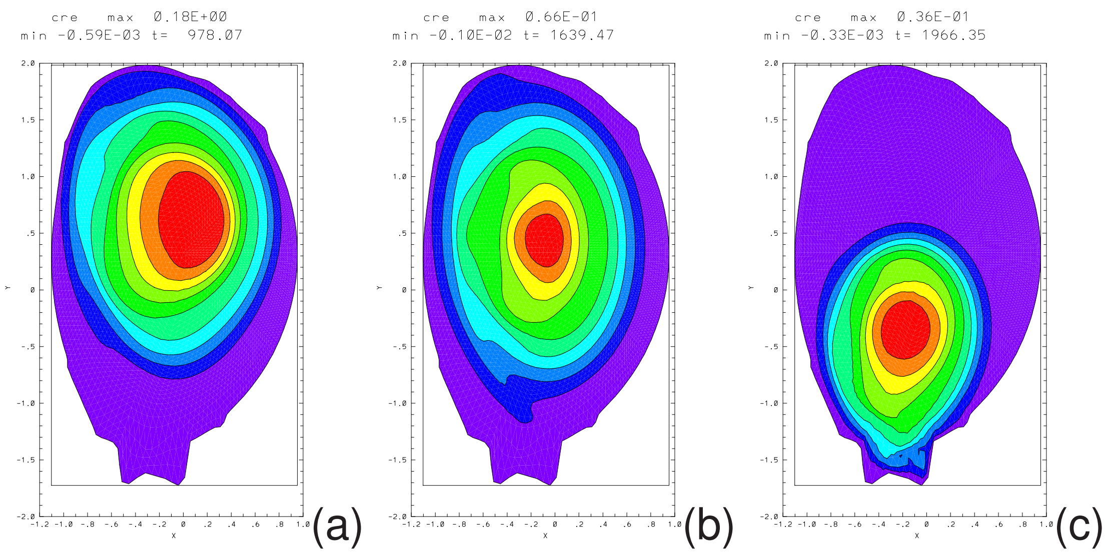
Numerical implementation

- subcycling
- parallel smoothing

$$\begin{aligned} \frac{\partial j_{re}}{\partial t} &= -c\nabla_{\|}(j_{re} + dt\frac{\partial j_{re}}{\partial t}) \\ &= -c\nabla_{\|}(j_{re} - cdt\nabla_{\|} j_{re}) + \ldots \end{aligned}$$

Runaway electron simulation

runaway electron current contours



Nonlinear, preliminary simulation starting from disruption shown previously. Half the current is replaced by runaway current at time $t = 3.9\tau_{wall}$. (b) $t = 6.56\tau_{wall}$. (c) downward VDE at $t = 7.9\tau_{wall}$.

Experimentally runaways are stable, except perhaps late in discharge.

Summary

- Reasonable agreement between simulation and experiment
  - VDE and toroidal current
  - halo current
  - toroidal current asymmetry
  - toroidal flux asymmetry
  - toroidal rotation frequency
  - Noll relation
- need better parameter agreement with experiment
  - have run with $S_{wall} = 1000$, experimentally $S_{wall} = 7000$.
- simulations are beginning of runaway electrons
  - fluid model
  - possible RE driven MHD instabilities
  - source model to be included later