Using GTS for simulation of thermal quench and runaways in tokamak disruptions

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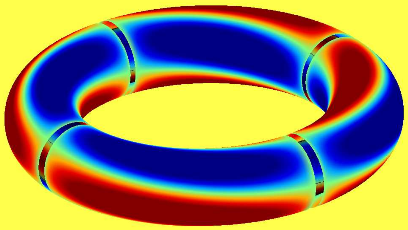
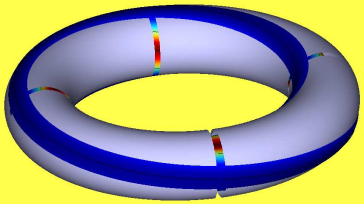
Recently, the positive current spike during tokamak disruptions (the puzzle since 1963) has been explained using a rigorous MHD consideration

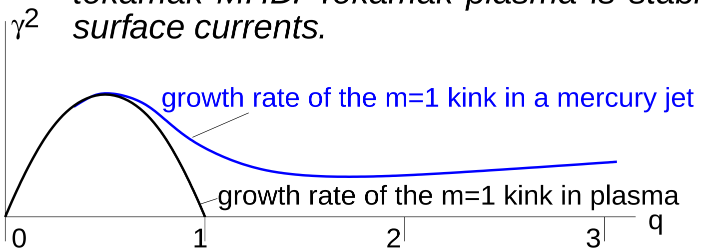


Eddy currents, m/n=2/1

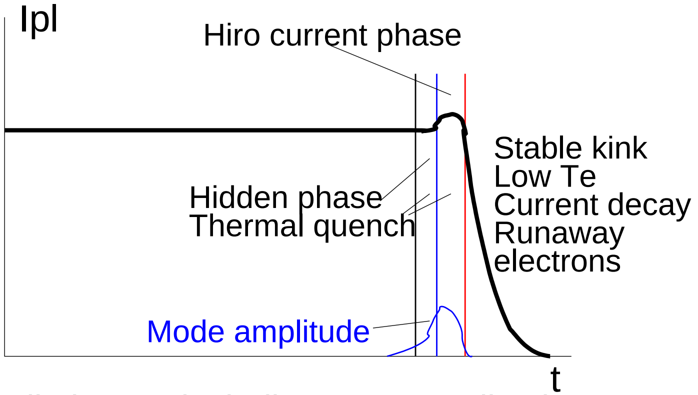


Hiro currents, m/n=2/1

1. *Surface currents at the plasma edge are the most fundamental effect of tokamak MHD. Tokamak plasma is stable exclusively due to excitation of surface currents.*



2. *Hiro currents are the same surface currents going to the wall when plasma makes an electric contact with the wall. They explain the current spike.*
3. *Hiro currents are not the loop-like eddy currents (which are much smaller) or halo currents (which are opposite in direction).*



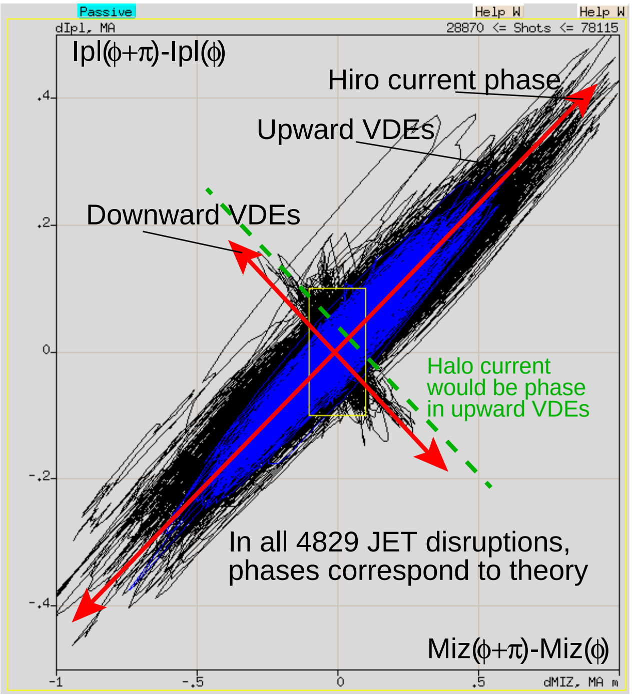
All phases, including current spike, have now theory understanding

MHD, being necessary, is insufficient for simulation of abnormal events during disruptions, such as the thermal quench, runaway electrons in magnetically perturbed configurations

$$\lambda_{\parallel,\ m} = 120\frac{T_{keV}^2}{n_{20}} \simeq 10\ km \quad for \quad T \simeq 10\ keV$$

Kinetic codes, like GTS, should be involved in self-consistent simulations of particle and energy losses. The goal is disruption mitigation schemes.

Now, we have sufficient understanding of time sequence of events during disruptions in order to set up the perturbed magnetic configurations for kinetic codes by gradually approaching a realistic situation:



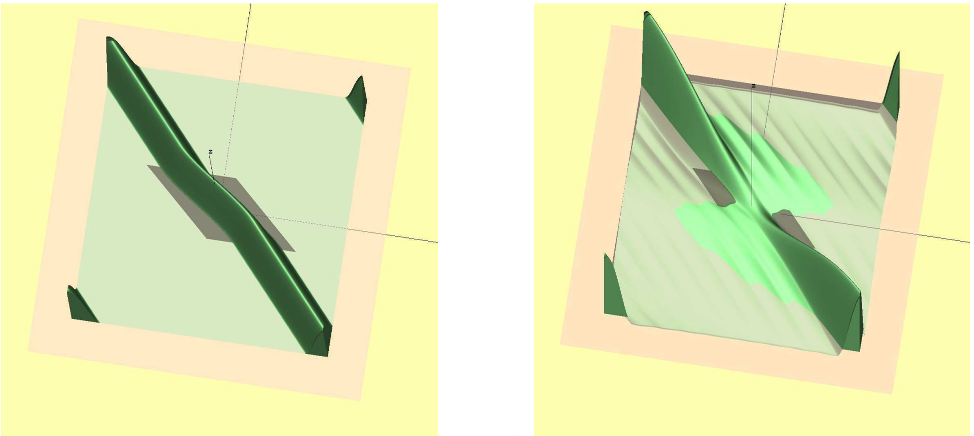
In all 4829 JET disruptions, phases correspond to theory

Toroidal asymmetry of plasma current measurements vs asymmetry in plasma vertical displacement

Without single exception, Hiro currents are consistent with more than 1800 JET VDEs available for processing.

The 15 year long community "understanding", based on halo current, is totally irrelevant to experiments

1. *Use of linear perturbations, based on the simple long wave limit for circular plasma*



3-D plot of current flow function $I(\omega,\varphi)$ *and surface perturbation* $\xi(\omega,\varphi)$ *for a m=1 wall touching kink mode*

2. *TEARING16 code (C.V.Atanasiu) - full linear toroidal code for general cross-section with* $p = 0$
3. *Modification of matching condition in DCON code (A.Glasser) for treating perturbed equilibria (what A.H.Booser and J-K Park failed to do)*
4. *NIMROD and M3H are missing the crucial for disruptions effect of tokamak MHD and are not useful at the moment. Potentially (?) in the future.*

GTS has already the operational interface with ASTRA-ESC, including the particle driving routine. The interface will be extended to the perturbed magnetic configurations

Proposed gyrokinetic simulations focus on two issues

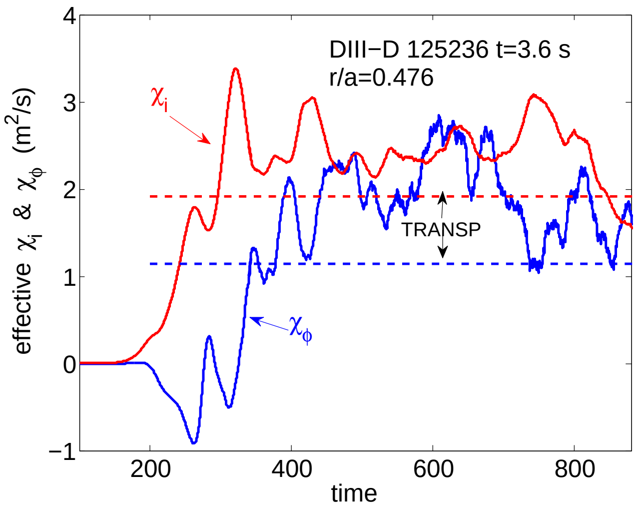
- Qualitatively and quantitatively physics picture of plasma thermal energy and particle loss to wall during thermal quench

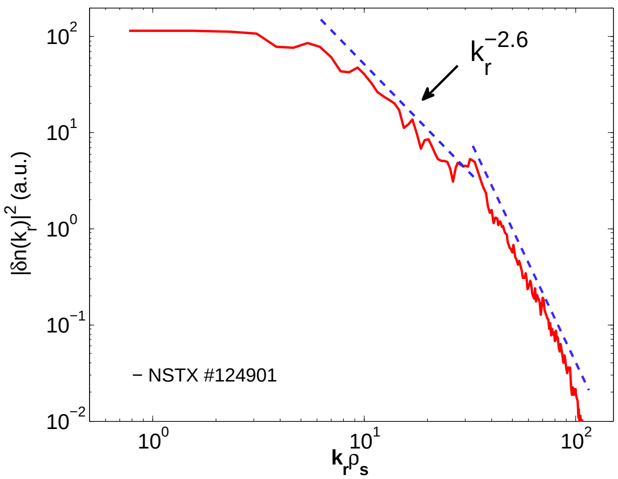
- Sensitivity of runaway electron generation on magnetic perturbations
  $\Longrightarrow$ to develop mitigation scheme for RE suppression

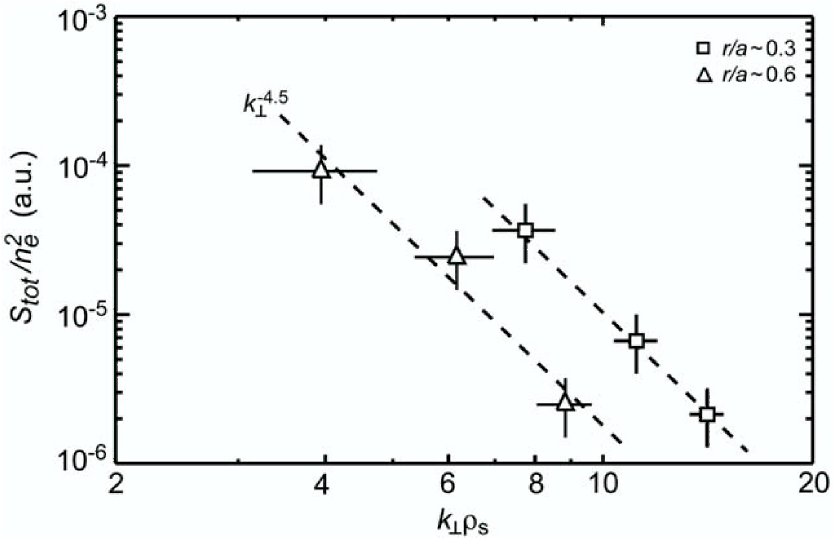
Gyrokinetic Tokamak Simulation (GTS) code: a full geometry GK PIC simulation

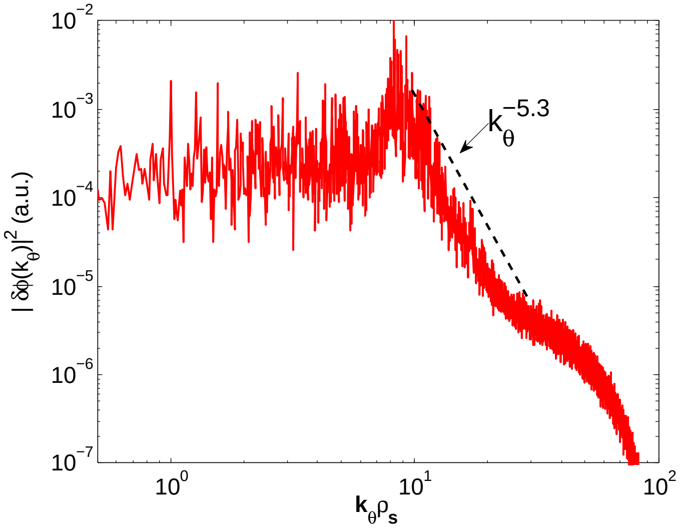
- Based on use of realistic magnetic configurations (Wang et al,. PoP'06)
- δf approach
- Fully kinetic electrons: drift kinetic for ITG, TEM; gyrokinetic for ETG
- Coulomb collisions conserving particles, momentum and energy
- $\{\langle n(r,\theta)\rangle$, $T(r)$, $\Phi_0(r)$, and $\omega_t(r)\}$ $\Longrightarrow$ turbulence & transport
  (energy, particle and momentum flux)
- Interfaced with MHD equilibrium codes and experimental data base (via ESC-I and TRANSP)
- Interfaced with NC via GTC-NEO (Wang et al,. CPC'04)
- Massively parallelized to run on hundreds of thousands of processors

GTS has been extensively used to investigate ITG, TEM and ETG turbulence for NSTX and DIII-D plasmas









Experiment (Mazzucato et al., NF'09)

GTS simulation

Kinetic simulation approach of thermal quench

- Kinetic treatment is required for perturbed configurations

$$\lambda_{\parallel,m} \approx 120\frac{T_{\mathrm{keV}}^2}{n_{20}} \sim 12\ \mathrm{km}\ \text{for 10 keV}$$

- Neglect change in magnetic field during thermal quench $\Longrightarrow$ electrostatic
- $k_\perp \rho_i \ll 1$, $\omega/\Omega_i \ll 1 \Longrightarrow$ drift kinetic for ions and electrons (micro-turbulence is a minor player)
- Thermodynamic equilibrium is absent

  $\Longrightarrow$ full-f (mild modification for GTS and partially done)
- Perturbed magnetic field prescribed in terms of kink instabilities etc.
- Calculate self-consistent electric field and distribution functions due to particle dynamics in 3D geometry
- Follow plasma from initially hot quasi-equilibrium to cooling down state

Runaway generation in perturbed magnetic field

- Simulation basically similar to thermal quench
- In addition:
  - Source model for runaways required
  - modification of collision operator (close collisions)
  - relativistic equation for electron parallel motion

A few key technique issues

- 3D electric field (expected in large spatial scale) is calculated from gyrokinetic Poisson equation in $\rho_i \to 0$ limit
- Lagrangian equations calculates particle drift motion $\mathbf{x} = (r, \theta, \varphi, \rho_\parallel)$ (flexible in choosing coordinates)

  $$\frac{d}{dt}\left(\frac{\partial}{\partial \dot{x}_i} L\right) - \frac{\partial}{\partial x_i} L = 0, \qquad L(\mathbf{x}, \dot{\mathbf{x}}; t) = (\mathbf{A} + \rho_\parallel \mathbf{B}) \cdot \mathbf{v} - H \text{ (Littlejohn)}$$
- Nonlinear Monte Carlo binary collision model with exact conservations simulates Fokker-Plank collisions (Wang et al., JCP'96)
- Boundary conditions, particularly for electric field, needs special attention

  Debye sheath region may be excluded from simulation

  i) full recycling of electrons from walls

  ii) choose Debye sheath height in terms of $\Gamma_{i,\parallel} = \Gamma_{e,\parallel}$