Carl Sovinec Panel (A) on Disruptions, Oral talk requested.

Tokamak MHD (TMHD) model of VDE disruptions: theory/simulation aspects

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1 Introduction. Large JET VDE disruption

On August 10 1996, a large disruption ($I_{pl} = 2.7$ MA, shot #38070) in a Vertical Displacement Event (VDE) shook the JET vacuum vessel with a sideways force of $\simeq 2.4$ MN. JET engineers explained it by excitation of the long lasting ($\simeq 30$ ms) $m/n = 1/1$ kink mode, clearly visible on JET diagnostics. They derived a scaling for the sideways force. In 2007, its 40 MN prediction for ITER created an alarming situation in the project requiring a revision of the vacuum vessel design.

This big disruption did not disturb the theory community (with exception of A.Aydemir), which created numerous disruption simulation codes since the mid 1970s, ***all driven by plasma inertia***. In fact, the inertial force in JET VDE is **8 (!!!) orders of magnitude** smaller than the sideways forces.

A brainstorming meeting between JET engineers and me in Dec. 2007 resulted in a theory of the Wall Touching Kink Mode (WTKM) [1, 2]. It has resolved the major plasma physics puzzle of JET VDEs, i.e., the long duration of the $m/n = 1/1$ kink mode, thousands of times longer than expected by classical theory.

This theory, now formalized as Tokamak MHD (TMHD) [4], considers VDE disruptions as fast equilibrium evolution

$$\tau_{MHD} \simeq \frac{R}{V_A} = \underbrace{\frac{R}{2.18\cdot 10^6 B/\sqrt{n}}}_{<1\ \mu s} \quad \ll \quad \underbrace{\tau_{TMHD}}_{\simeq 1\ ms} \quad \ll \quad \underbrace{\tau_{transport}}_{\simeq 0.1\ s} \quad \ll \quad \underbrace{\tau_{resistive}}_{\simeq 1\ s} \qquad (1.1)$$

with conservation of magnetic fluxes.

My theory has confirmed the JET scaling. At the same time, it revealed two mistakes in the engineering interpretation of the kink mode, which fortunately canceled each other in the final scaling.

In addition, this theory has exposed **the contradiction in the direction** of the currents in the wall to the community interpretation of wall currents as halo currents, adopted since 1991. Hesitant to confront physicists, who were promoting the halo current model, the JET engineers, well aware of its inconsistency with data, never exposed explicitly this critical experimental fact and missed the discovery of a new effect. Instead, in 2007 the WTKM theory introduced the Hiro currents which explained the direction of wall currents.

The following sections describe the progress achieved, an understanding of VDE as fast equilibrium evolution, the potential impact and the needs in a special DoE project for implementation of TMHD model into numerical codes.

References

[1] L. E. Zakharov. "The theory of the kink mode during the vertical plasma disruption events in tokamaks". Phys. of Plasmas **15**, 062507 (2008).

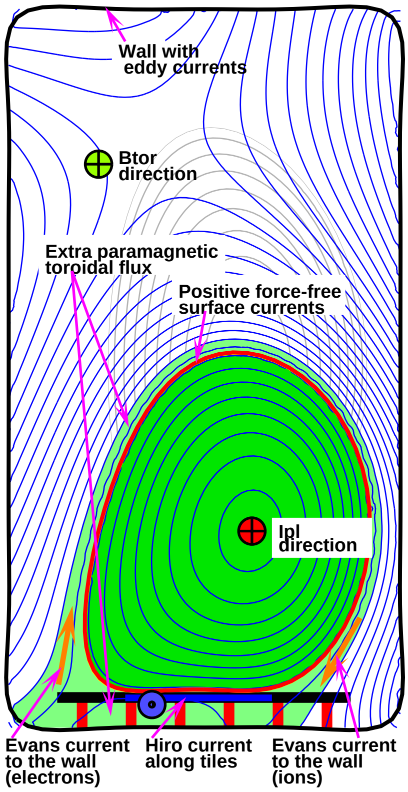
[2] L.E. Zakharov, S.A. Galkin, S.N. Gerasimov and JET-EFDA contributors. "Understanding disruptions in tokamaks". Phys. of Plasmas **19** 055703 (2012)

[3] S.N. Gerasimov, T.C. Hender, J. Morris, V. Riccardo, L.E. Zakharov and JET EFDA Contributors. "Plasma current asymmetries during disruptions in JET". Nucl. Fusion **54** 07309 (2014

[4] L.E. Zakharov, X. Li. "Tokamak Magneto-Hydrodynamics and Reference Magnetic Coordinates for simulations of plasma disruptions". Submitted to Phys. of Plasmas in Oct. 2014.

2 Progress of theory of the Wall Touching Kink Mode (WTKM)

Progress of WTKM theory since 2007 includes:



1. Explanation of toroidal asymmetry of plasma current and diamagnetic signal on JET by Hiro and Evans currents.
2. Amazing consistency of JET waveforms with Hiro currents.
3. Revelation of the negligible amplitude of inertia force relative to MHD forces.
4. Prediction of Hiro currents in axisymmetric VDE (n=0), confirmed by EAST 2012 measurements.
5. Derivation of a rigorous set of TMHD equations consistent with scale separation and having an equation of motion split to an equilibrium and boundary advancing equations.
6. Creation of a 2-D version of the VDE-code for VDE disruption simulations.
7. Discovery of a new plasma-(vacuum magnetic field) reconnection pattern
8. Discovery of 5 regimes of 2-D vertical instability by VDE-code.
10. Introduction of a proper understanding of the halo zone.
11. Prediction of source limitation of halo (Evans) currents.
12. Introduction of two regimes for plasma flow to the wall.
13. Specification of the conceptual design of tile diagnostics for VDE currents on NSTX-U.
14. Derivation of variational energy functionals for all 5 TMHD equations.

The use of energy principles of TMHD can generate stable and efficient numerical schemes with positive symmetric matrix equations and free of Courant limitations on the time step. Adaptive grids, utilizing Reference Magnetic Coordinates for the best alignment with the magnetic field, make the TMHD codes consistent with anisotropy of the high temperature tokamak plasma at any value of Lundquist's number.

3 On a special DoE project on TMHD theory/simulations of VDE

After 7.5 years since 2007, there is no hope of the use or modification of existing 3-D codes for addressing the needs in simulations of VDE disruptions. Inertial dynamics, "extended MHD" plasma core model with equations either irrelevant to MHD or questionable, mixture of all physics length scales, inappropriate substitution of the vacuum region by a fake plasma with Spitzer resistivity at the open field lines, simplistic wall geometry, the "salt-water" boundary condition for the plasma flow to the wall, misalignment of the laboratory numerical grid with the magnetic field, Courant time step and Lundquist number limitations make the existing 3-D code, in the words of W.Pauli, **"not even wrong", they are uncorrectable**.

TMHD has no single deficiency listed for the existing 3-D codes. A 2-D version of VDE-code now is operational and scheduled for calibration with EAST data. With this experience, the development of 3-D version of VDE-code, capable to simulate disruptions on JET and ITER, and to be a research tool for DIII-D, NSTX-U and other tokamaks is straightforward in TMHD approach.

For expeditious addressing the VDE problem, I propose a special DoE project on "Development of Tokamak MHD numerical codes for simulating VDE disruptions" for PPPL. Two PostDoc positions are required: one already is filled this year and another for a well trained person is requested for 2016.

Implementation of MHD and Reference Magnetic Coordinates is critical for assessing the damaging effects of VDE disruptions in ITER as well as for simulations of early non-linear stage and triggering effects of MHD instabilities in general (which are other puzzles in tokamaks).