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Hiro currents and boundary conditions in MHD codes[1]

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Contents

1 Needs in disruption simulations

The following objectives are urgent for ITER:

1. *Refining assessments of forces acting on the vacuum vessel during vertical disruptions (VDE). (gone, no urgency already)*
2. *Determining duration of the kink mode $m/n = 1/1$ during VDE, and its rotation (m, n here are the dominant poloidal and toroidal wave numbers). (highly important, but the critical time is over)*
3. *Assessing the possibilities of suppression of runaway electrons during the current quench phase. (highest priority and demand)*

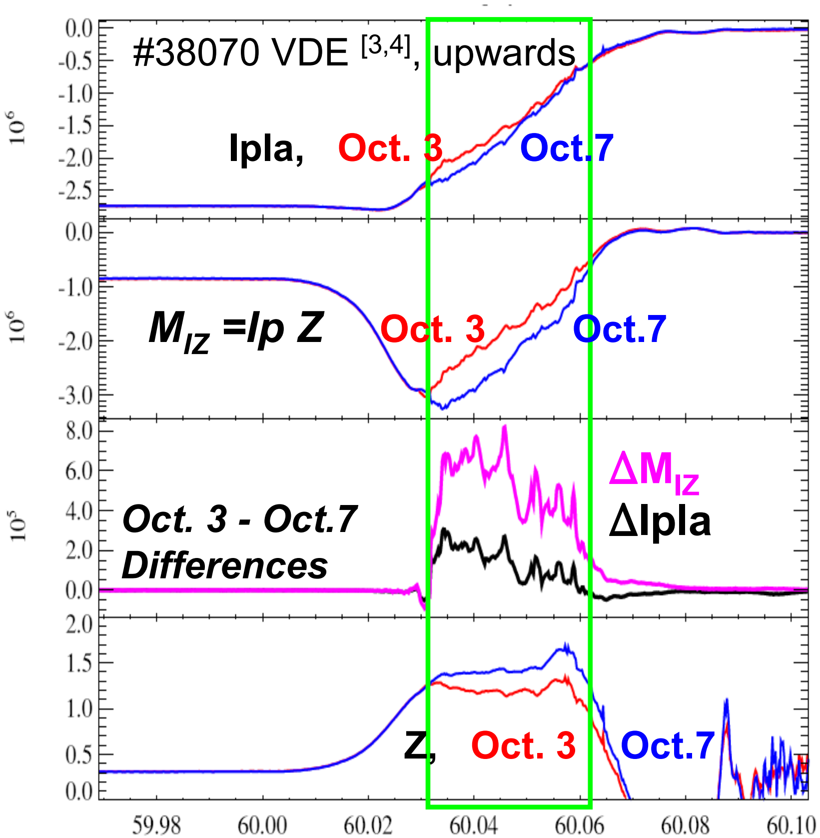
Special Disruption Simulation Code System is necessary for addressing disruption modeling for ITER and large machines

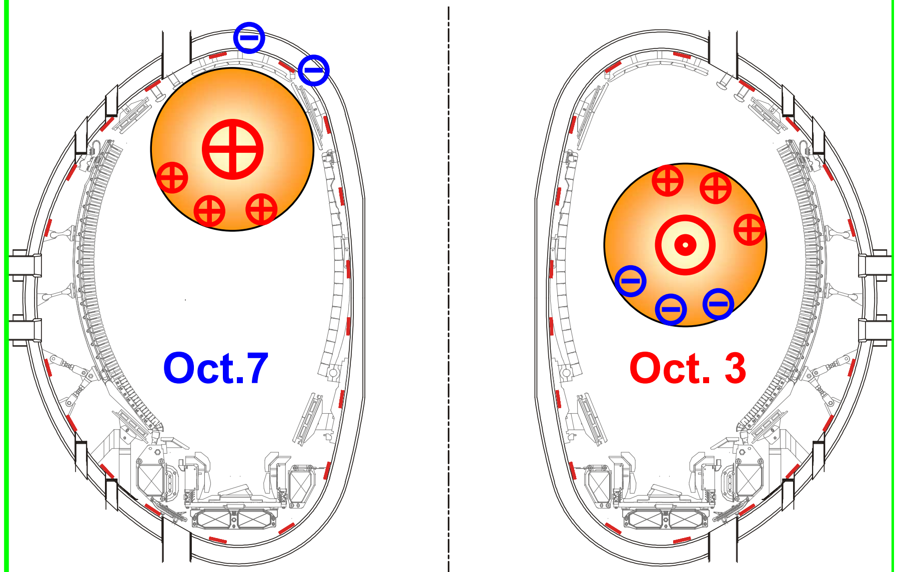
Less urgent, but by no means less important, issues are related to plasma stability control, prediction and prevention of disruptions.

They are not part of DSCS.

2 VDE and kink mode 1/1

Vessel current during VDE, #38070





- In octant 7 the plasma is closer to top of the vessel than in octant 3.
- **The current from plasma flows on vessel in octant 7.**

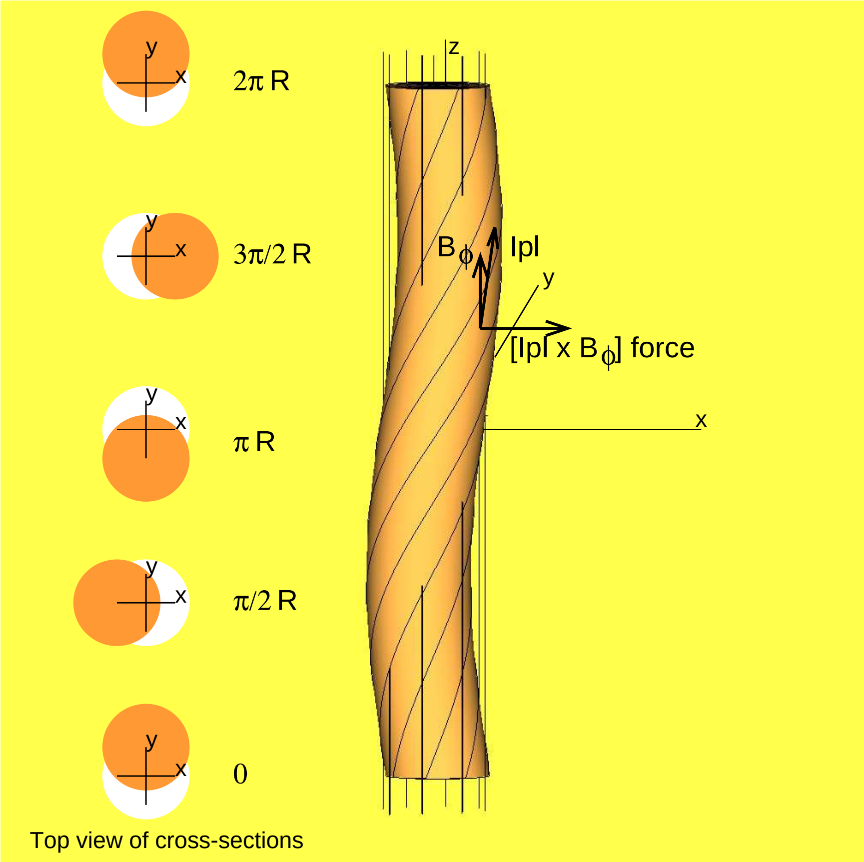
The measured Ipla in octant 7 is higher then in octant 3 ➔ the missing vessel current in octant 7 is OPPOSITE to Ipla!

The “halo” current based interpretation predicts the opposite sign of asymmetry in the current measurement and contradicts JET Ipla’s.

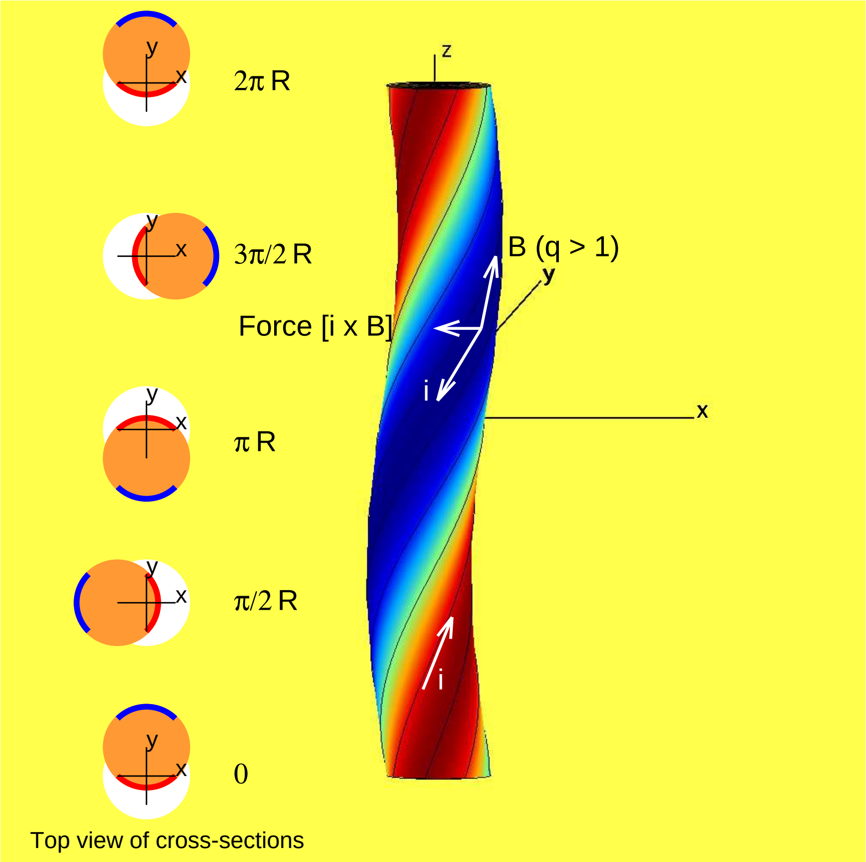
S N Gerasimov et al, Scaling JET Disruption Data to ITER. W70 7/10/09 8/24

3 Kink modes and surface currents

Surface currents $\vec{\imath}_{11} = i_{11}\cos(\omega-\varphi)(\vec{e}_\omega + \frac{a}{R}\vec{e}_\varphi)$ are excited in order to eliminate the normal component of magnetic field.



Toroidal magnetic field lines punch the plasma surface

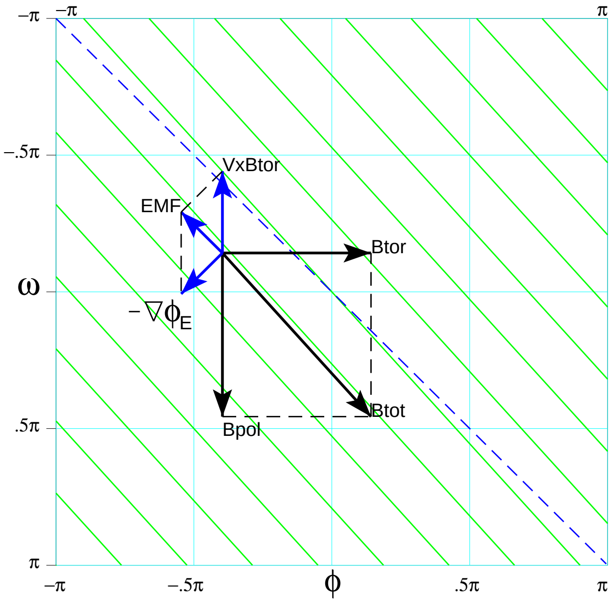


surface currents: blue ones are opposite to plasma current, reds are in the same direction

Magnetic field of the surface currents provides equilibrium in the core.
Surface currents stabilize the mode at $q > 1$

Electro Motive Force

Surface currents are driven by plasma motion $VB_\varphi na/(mR)$ in the toroidal magnetic field B_φ (for m=1 and m > 1)



The Ohm's law in the plasma

$$-\frac{\partial \vec{A}}{\partial t} + \vec{V} \times \vec{B} - \nabla \phi_E = \frac{\vec{j}}{\sigma},$$

$$-\frac{\partial \vec{A}^{i,surf}}{\partial t} \underbrace{-\frac{\partial \vec{A}^{pl,core}}{\partial t} + VB_\omega \vec{e}_\varphi}_{vanishes\ \ for\ \ m=1} \qquad (3.1)$$

$$-VB_\varphi \vec{e}_\omega - \nabla \phi_E^{surf} = \frac{\vec{j}}{\sigma}$$

Projection of EMF on the helical path of the current

$$-VB_\varphi \vec{e}_\omega \cdot \left(\vec{e}_\varphi + \frac{a}{R}\vec{e}_\omega\right)\cos(\omega - \varphi) = -VB_\varphi \frac{a}{R}\cos(\omega - \varphi) \qquad (3.2)$$

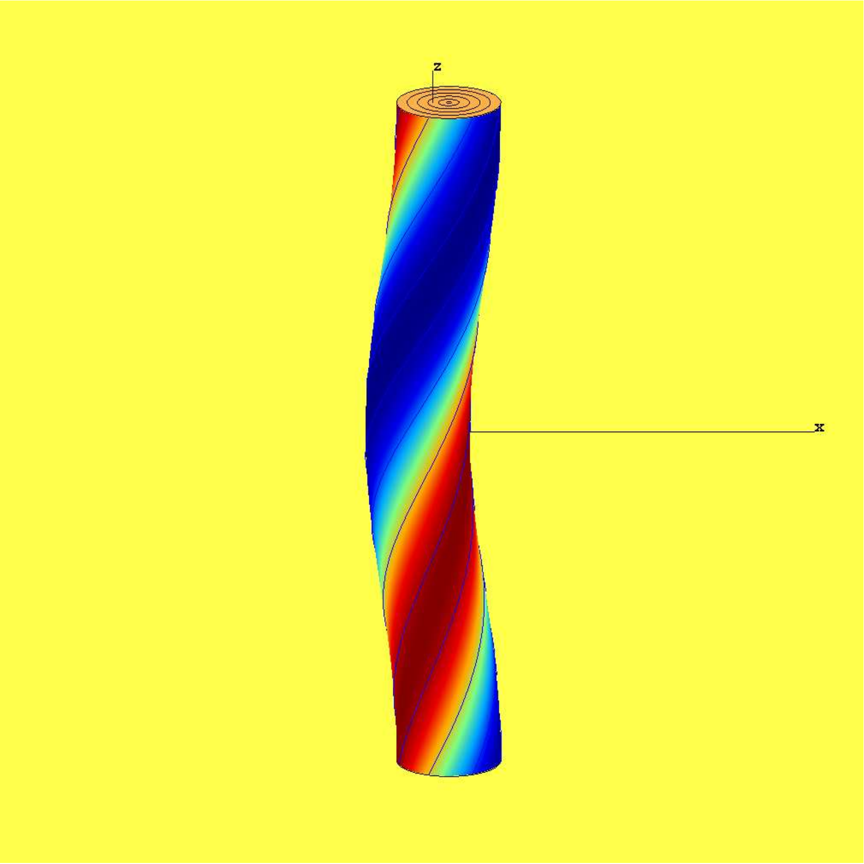
drives the surface current

$$\mu_0 \vec{i}_{11} = \mu_0 i_{11}\left(\vec{e}_\varphi + \frac{a}{R}\vec{e}_\omega\right)\cos(\omega - \varphi) = -2\xi_{11}\frac{B_\varphi}{R}\left(\vec{e}_\varphi + \frac{a}{R}\vec{e}_\omega\right)\cos(\omega - \varphi) \qquad (3.3)$$

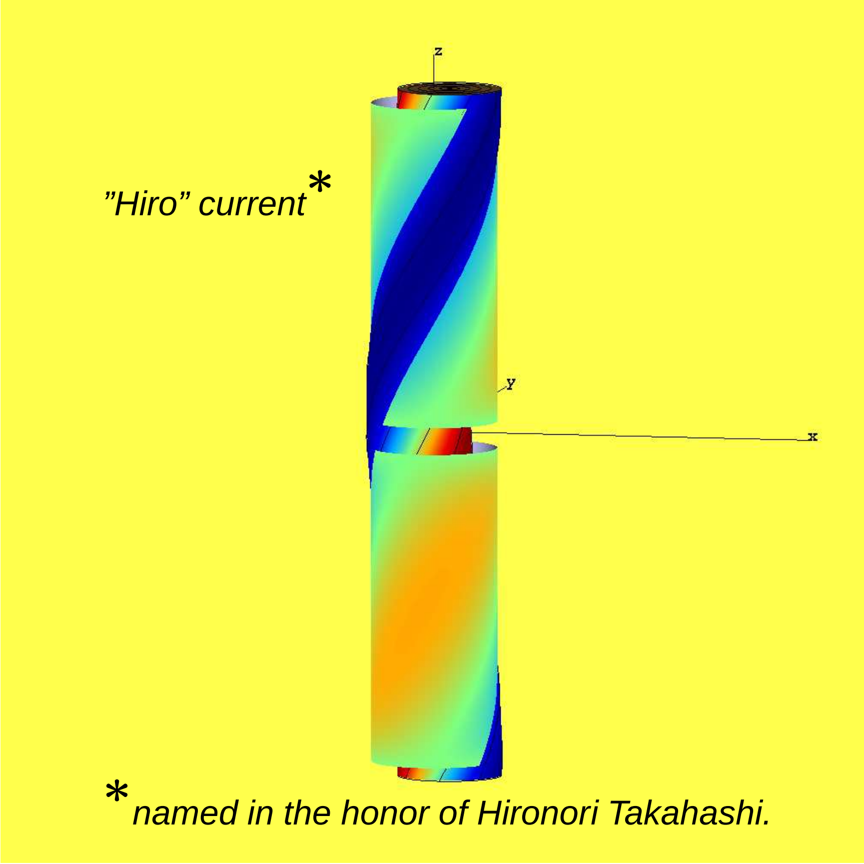
at the plasma boundary. Driving EMF is the same for m>1 modes.

Electric contact and Hiro currents

During disruption plasma touches the wall, and surface current $i(\omega,\varphi)$ may be shared between wall and the plasma.



At the plasma side, which is close to the wall, the surface current $i(\omega,\varphi)$ is always negative.



*"Hiro" current**

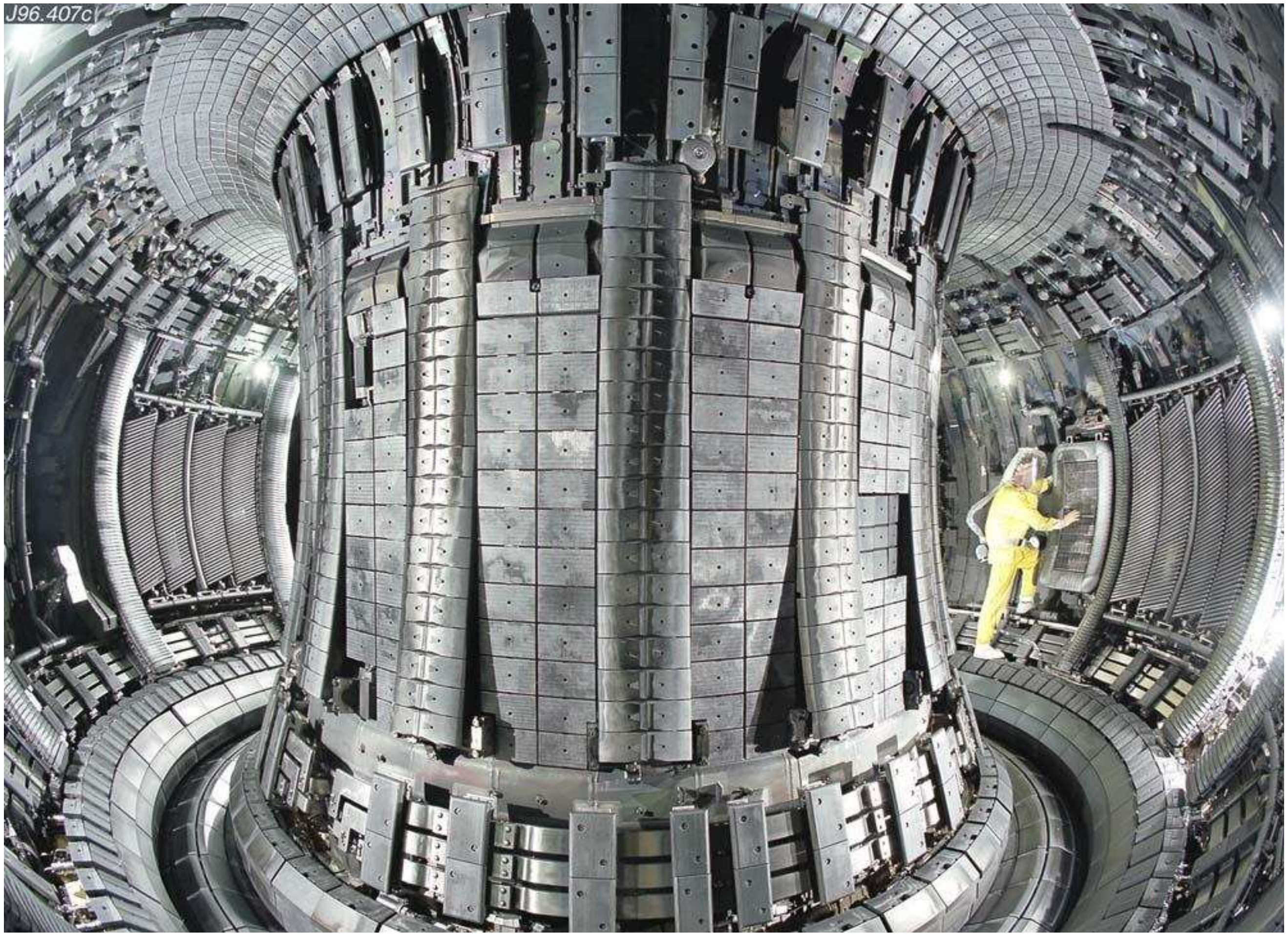
**named in the honor of Hironori Takahashi.*

Only negative part of $i(\omega,\varphi)$ can be shared between plasma and the wall. These are the "Hiro" currents.

Hiro currents are driven by the plasma motion TO the wall.

In-vessel components of JET

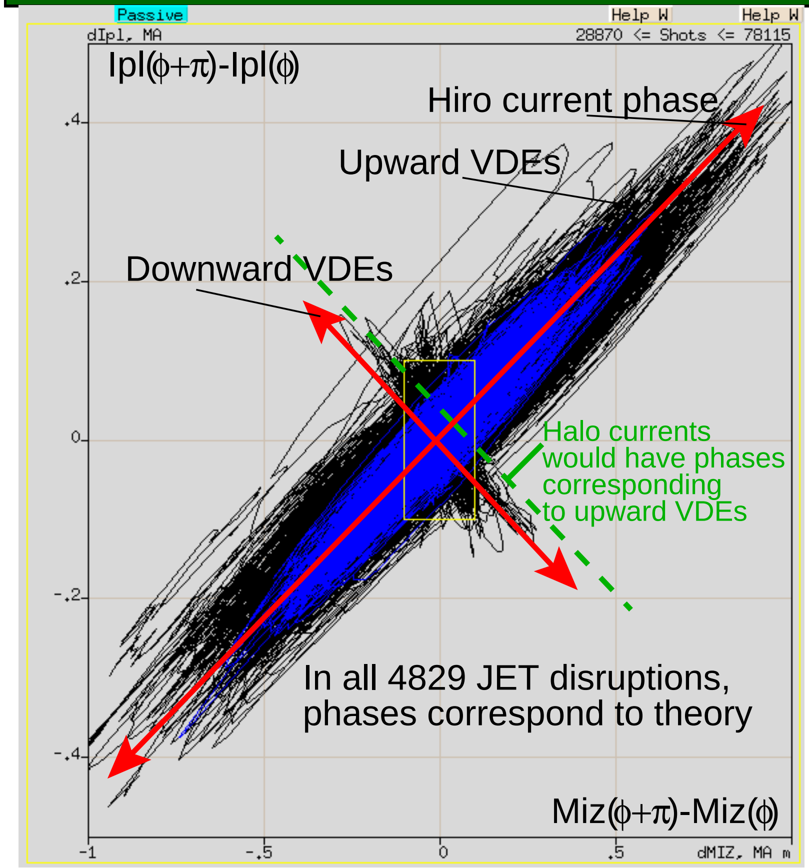
In a real device the structure of the conducting in-vessel components has little in common with typical theory models



Galvanic electric contact of plasma and the wall can be easily established

Hiro currents explain asymmetry in JET VDEs

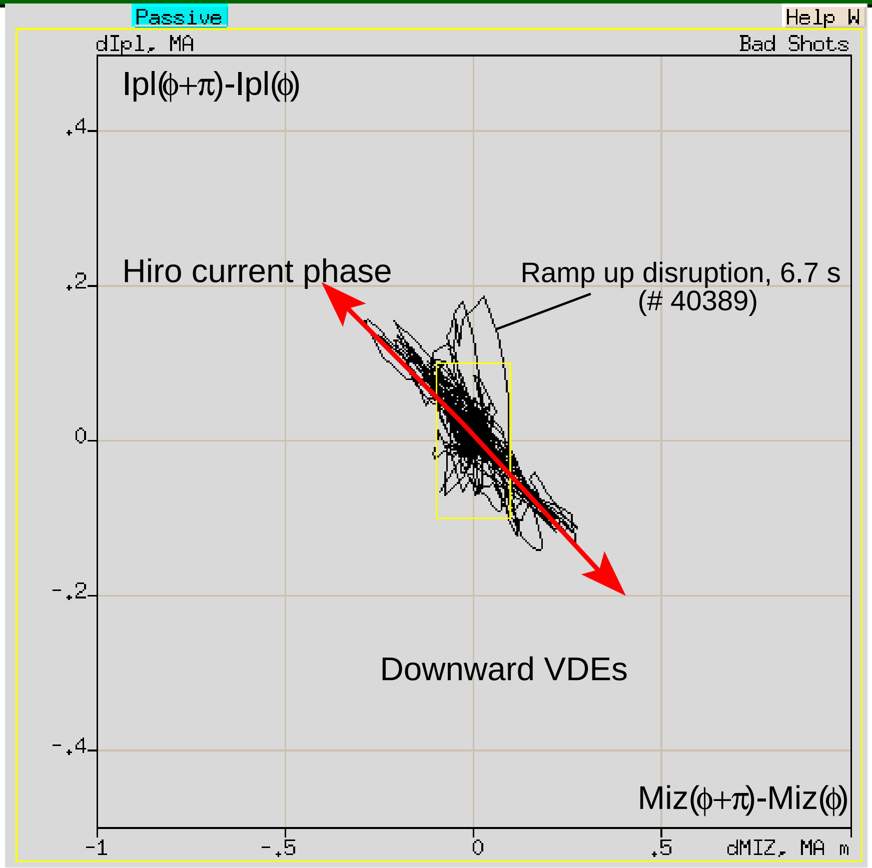
Phase diagram of asymmetry in the $I_{pl,7} - I_{pl,3}$ vs asymmetry of $M_{IZ,7} - I_{IZ,3}$ in opposite cross-sections of JET



Halo currents would have phases corresponding to upward VDEs

In all 4829 JET disruptions, phases correspond to theory

Black: $I_{pl,7}(t) - I_{pl,3}(t)$ vs $M_{IZ,7}(t) - I_{IZ,3}(t)$
Blue: $I_{pl,5}(t) - I_{pl,1}(t)$ vs $M_{IZ,5}(t) - I_{IZ,1}(t)$
(All 4829 disruption shots, 1814 upward+20 downward VDEs)

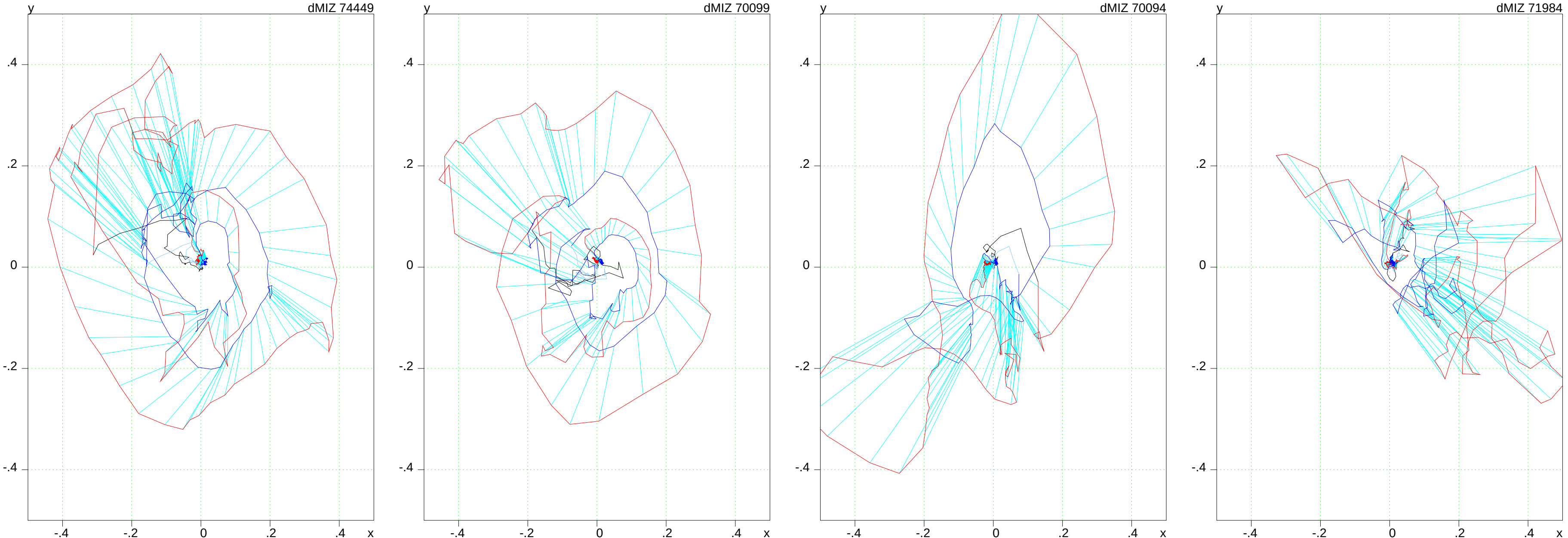


Black: $I_{pl,7}(t) - I_{pl,3}(t)$ vs $M_{IZ,7}(t) - I_{IZ,3}(t)$
(20 downward disruption shots)

Unambiguously, (with no single exception) JET disruption data rules out the "halo" currents as the source of asymmetry

Mode rotation

Mode rotation (based on 4 JET cross-sections) is sporadic, no regular pattern.



Trajectories of the tip of vectors of asymmetries in $\delta\vec{M}_{iz}$ ***and*** $\delta\vec{I}_{pl}$, *the top view on JET.*

Red line: $\delta\vec{M}_{iz}(t) = \delta M_{iz,5-1}(t)\overrightarrow{\mathrm{e}}_x + \delta M_{iz,7-3}(t)\overrightarrow{\mathrm{e}}_y$

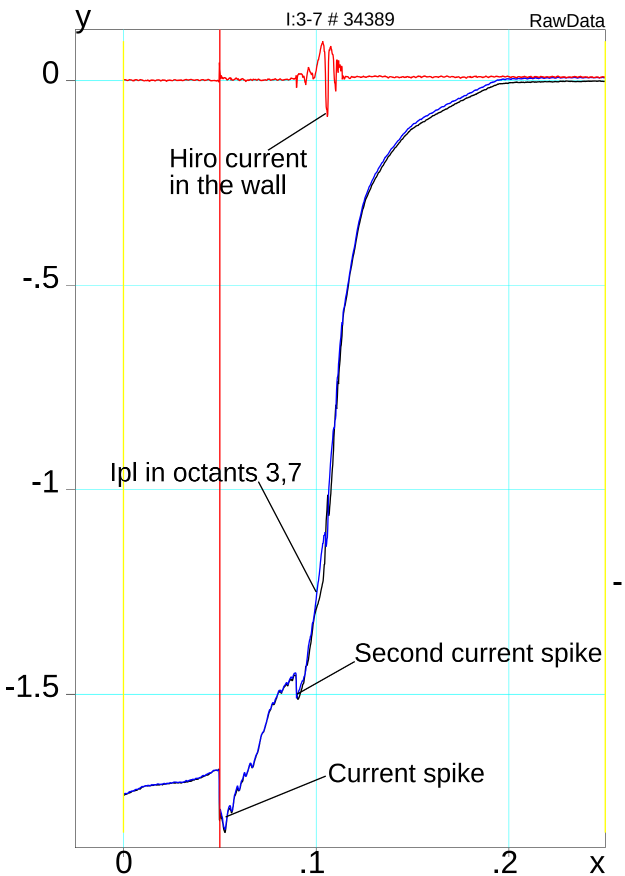
Blue line: $\delta\vec{I}_{pl}(t) = \delta I_{pl,5-1}(t)\overrightarrow{\mathrm{e}}_x + \delta I_{pl,7-3}(t)\overrightarrow{\mathrm{e}}_y$

Possible resonance of plasma rotation with mechanical eigen-frequencies of the vessel can significantly amplify the vessel displacement.

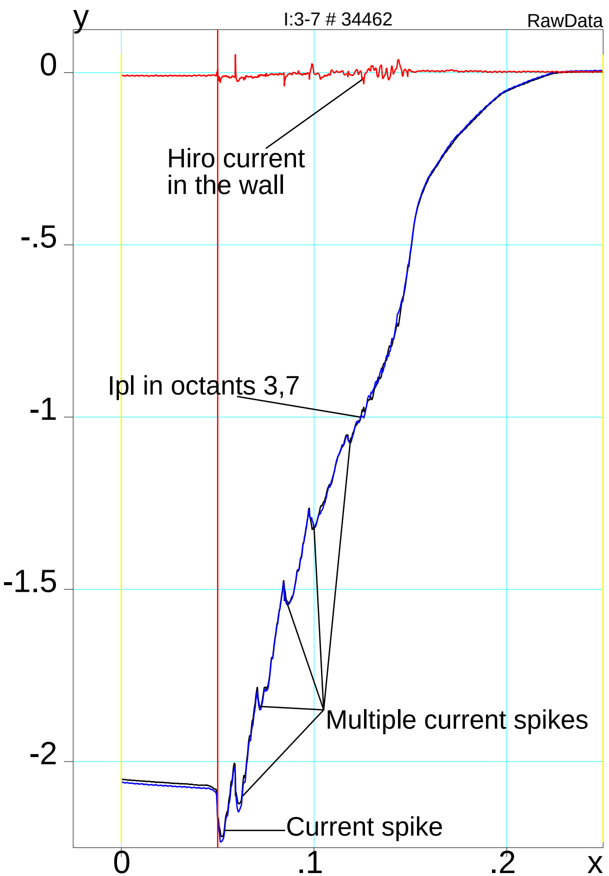
Unlike in the case of forces, there is no reasonable scaling of mode rotation from JET to ITER. The information should come exclusively from theory and numerical simulations. Boundary physics is crucial.

4 m > 2 (non-vertical) disruptions

Current spike during disruptive plasma termination was a puzzle since 1963



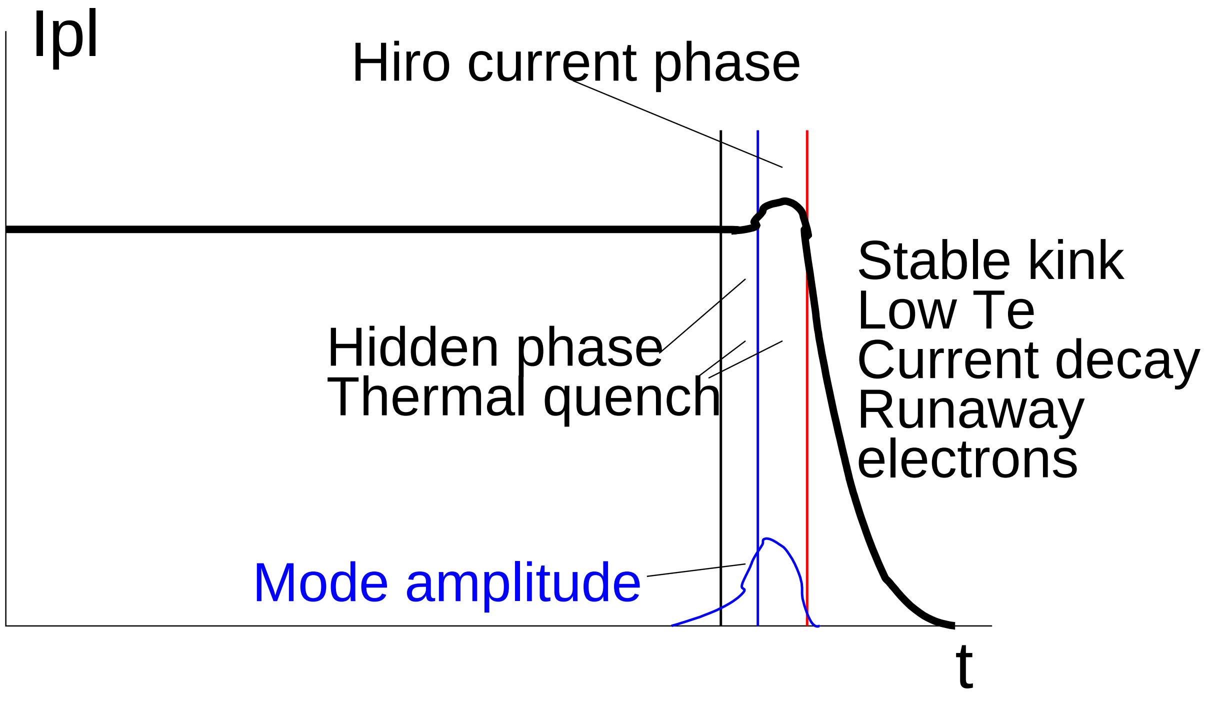
Disruption with a double current spike



Multiple current spikes in a disruption

Hiro currents explain the current spike. Uderstanding of multiple current spikes can be crucial for prevention of generation of Runaway Electrons.

Different stages of disruptions



***Crossing* $q = m$ *Crossing* $q = m$**

$\longrightarrow$ hidden external kink

$\longrightarrow$ touching the wall and exciting the Hiro currents (current spike)

$\longrightarrow$ current quench:

- ***$\longrightarrow$ stabilization of the mode***
- ***$\longrightarrow$ generation of runaway electrons***

Plasma touches the wall very early

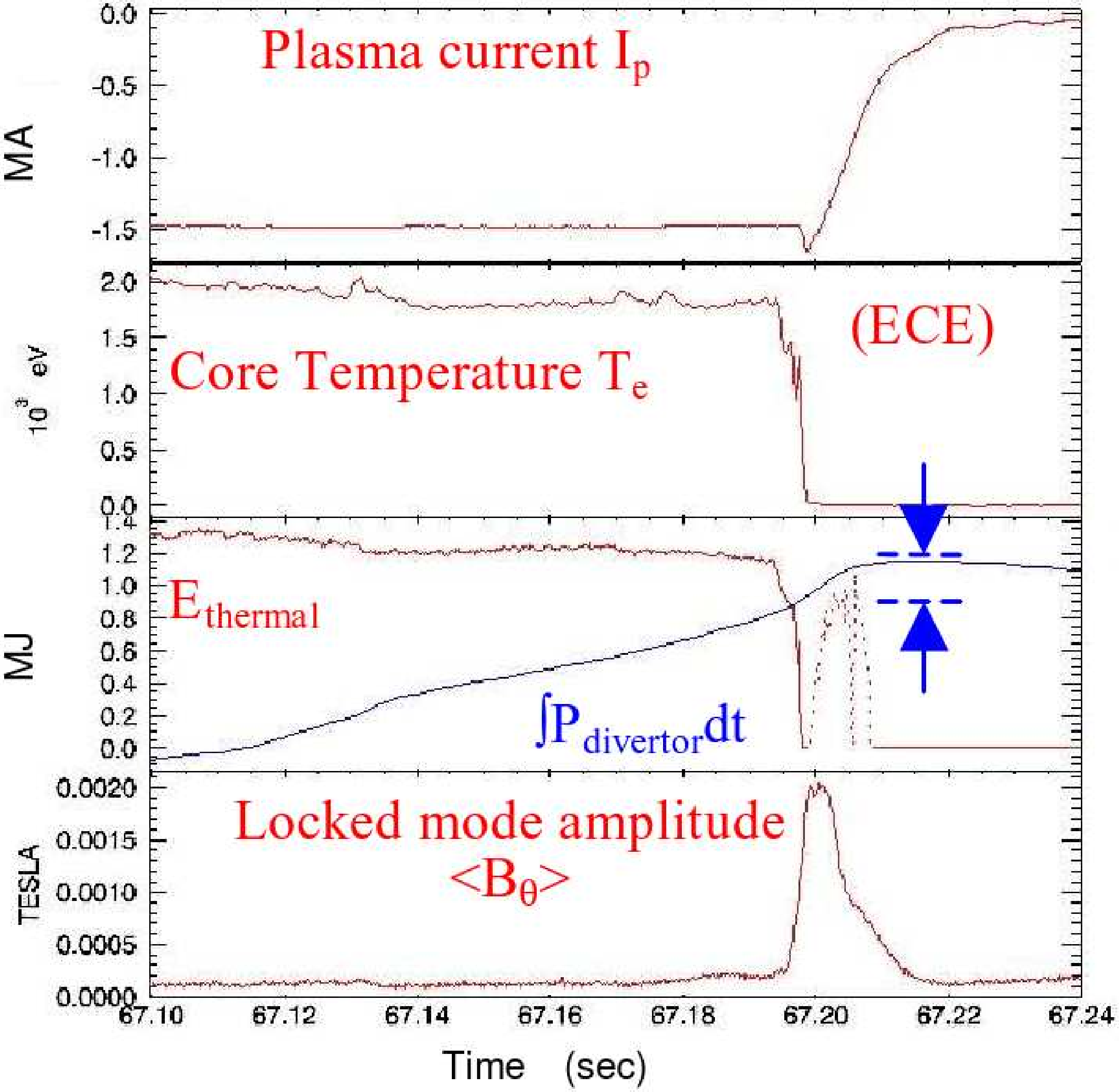
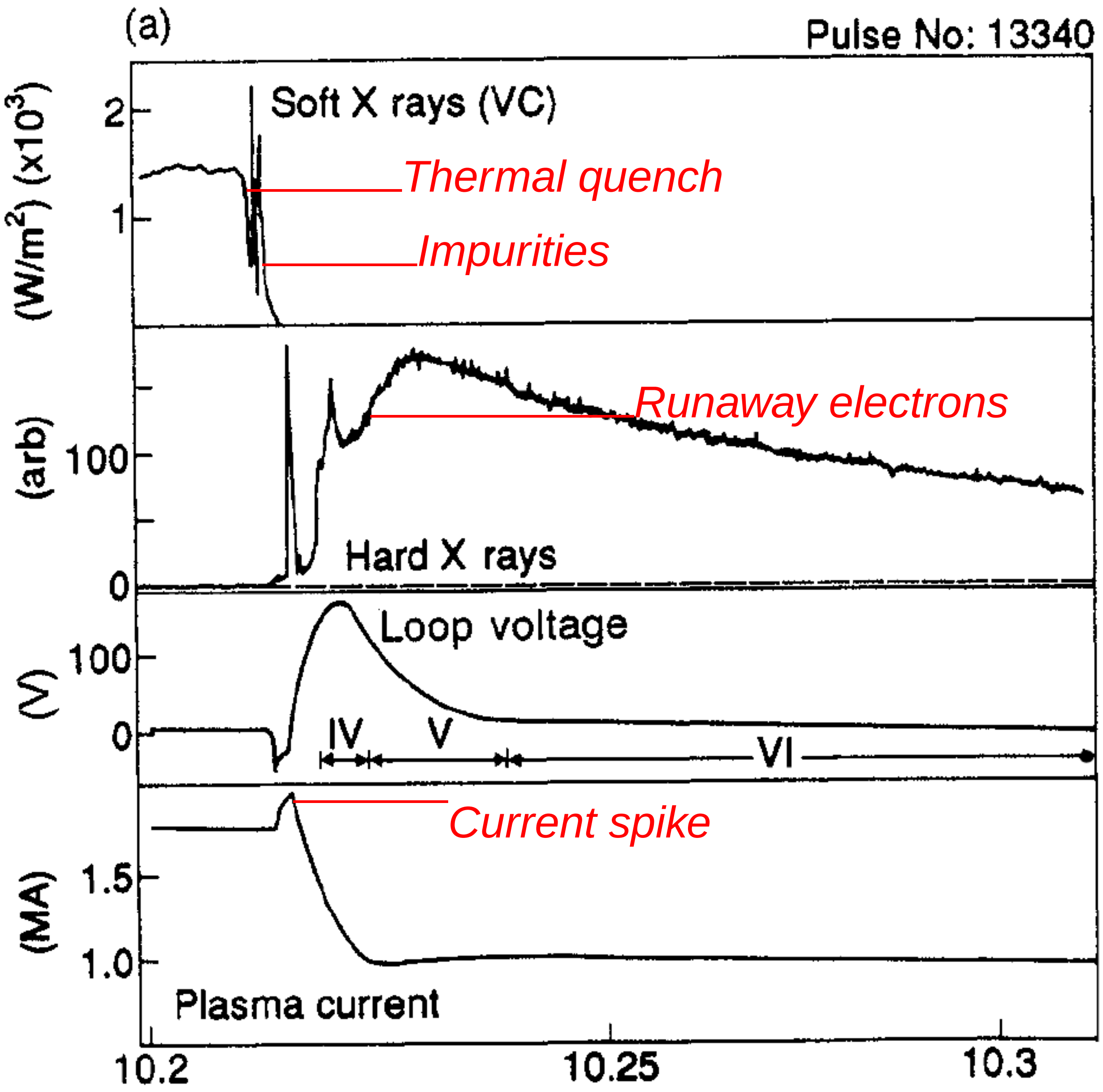


Fig.1. from P.Andrew, W.Fundamenski et al. 30th EPS Conf. on Contr. Fusion and Plasma Phys., Vol.27A, p.1-108 (2003)

Disruptions in JET



Thermal quench

Impurities

Runaway electrons

Current spike

Fig.2. from R.D.Gill. Nucl. Fusion, Vol.33, p. 1613 (1993)

Disruptions in JET

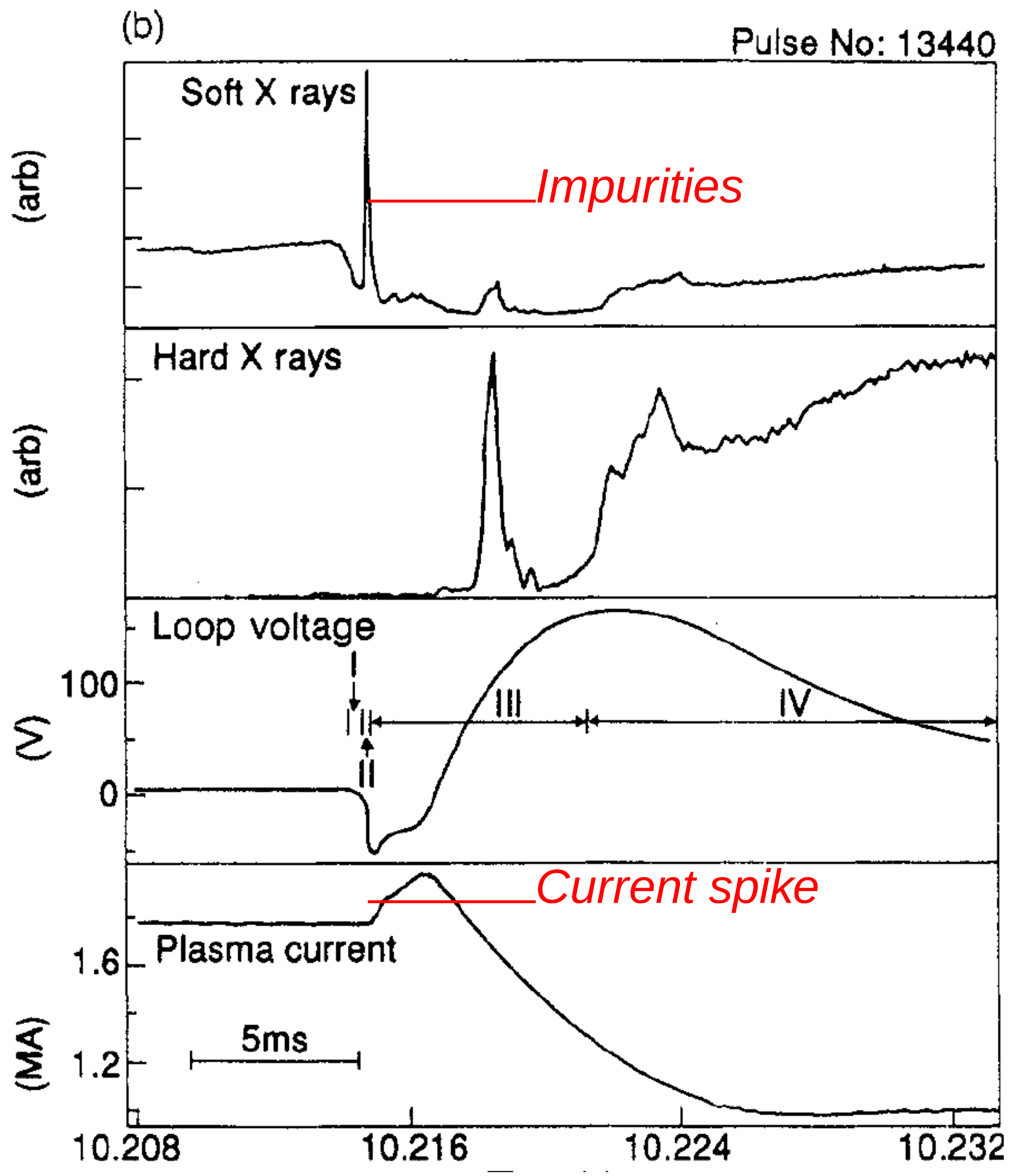


Fig.2. from R.D.Gill. Nucl. Fusion, Vol.33, p. 1613 (1993)

We have now basic theory of disruptions

It already has explained:

1. *The importance of the electric contact of plasma with the wall in disruptions.*
2. *Hiro currents in the wall.*
3. *Quasi-stationary (20 ms in JET) m=1 kink mode.*
4. *Toroidal asymmetry in plasma current measurements.*
5. *The scaling of sideways forces from JET to ITER.*
6. *Difference in amplitude of measured plasma displacements δz and δr.*
7. *The current spike in non-VDE disruptions.*
8. ***A practical RE suppression scheme (RTMD) has been proposed to IO (Nov. 2009)***

The kink mode theory now gives the basic understanding of disruptions, sufficient for guiding their simulations.

5 DSCS

The following plasma physics elements are crucial for disruption simulations:

1. **Plasma motion to the wall surface (driving EMF for Hiro currents)**
2. **Electric contact of plasma edge with the wall (contact resistivity, emission)**
3. **Realistic in-vessel structure description (ribs, gaps, ports)**
4. **Plasma edge (localization of Hiro currents, localized plasma drift motion, electric resistivity to Hiro currents)**
5. **Plasma-wall interaction (localized heat loads, sheath potential, mode rotation, thermal quench, RE losses)**
6. **Self-consistent particle kinetics for thermal quench and RE**
7. **Plasma edge interaction with localized high pressure gas injection (prevention of RE formation)**

In disruption simulations MHD, taken to the necessary level of complication, is the most straightforward part. The major part of the theory models does not exist and require development.

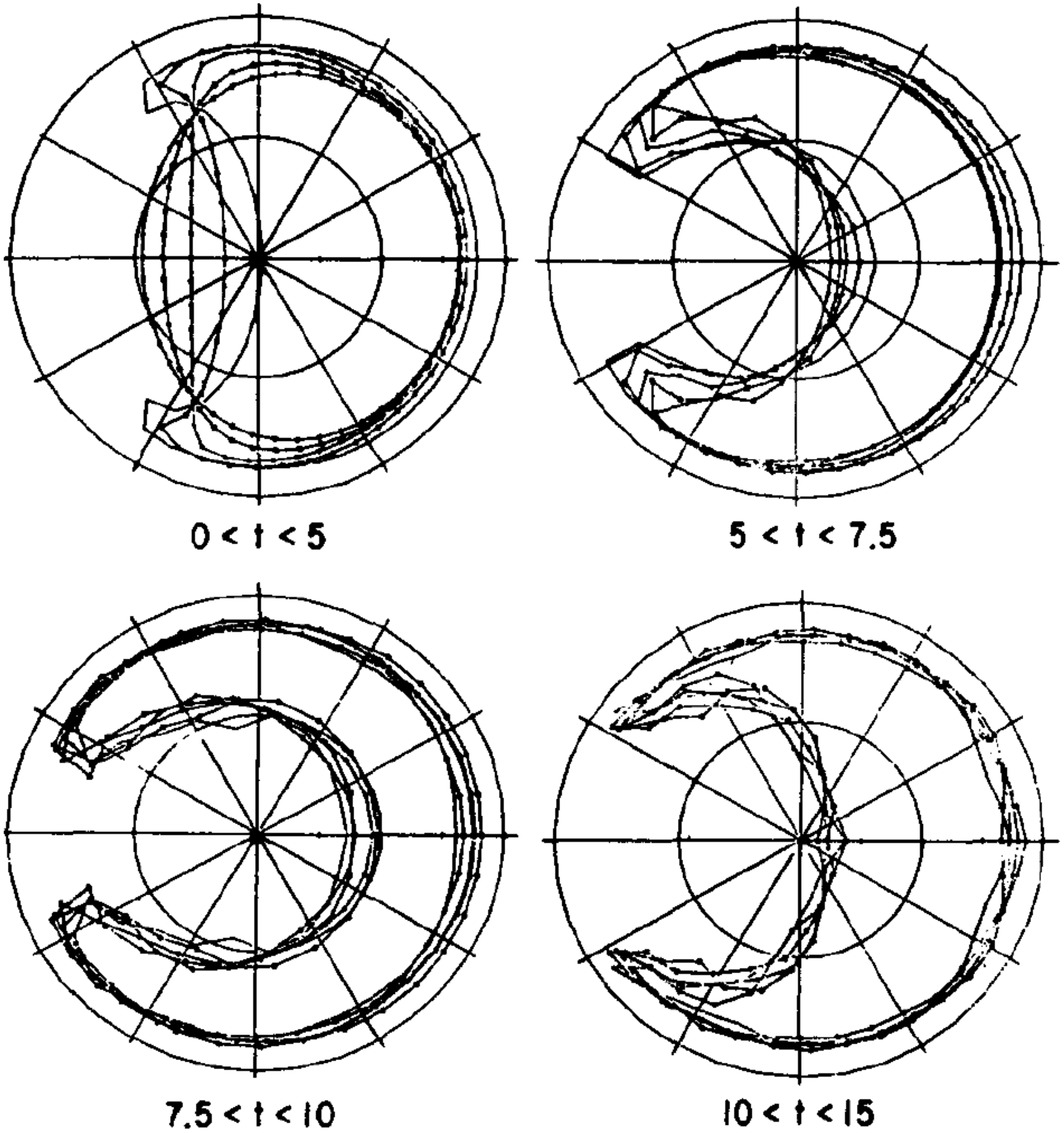
Close interaction with parallel theory development is absolutely crucial

Numerical aspects of DSCS

Accordingly, the numerical approach should:

1. Describe the MHD motion of free boundary plasma (adaptive mesh is crucial)
2. Be unlimited in resolution of the boundary layer. It is not determined simply by resistivity. Again adaptive grid with ability of local refinement.
3. Implement for core simulations the Reference Magnetic Coordinates (RMC) with the best possible alignment with magnetic field.
4. Use Greens functions for electro-magnetic interaction with conducting structures of realistic complexity.
5. Rely on particle kinetic codes for thermal quench and RE simulations (with magnetic geometry from the MHD part).

6 What we have


$0 < t < 5$

$5 < t < 7.5$

$7.5 < t < 10$

$10 < t < 15$

Fig.4. from M.Rosenbluth. . . R.White. Phys. Fluids, Vol.1, p. 1987 (1976)

In free boundary simulations in 1973-74 the plasma boundary was reproduced by an adaptive grid

Free boundary simulations

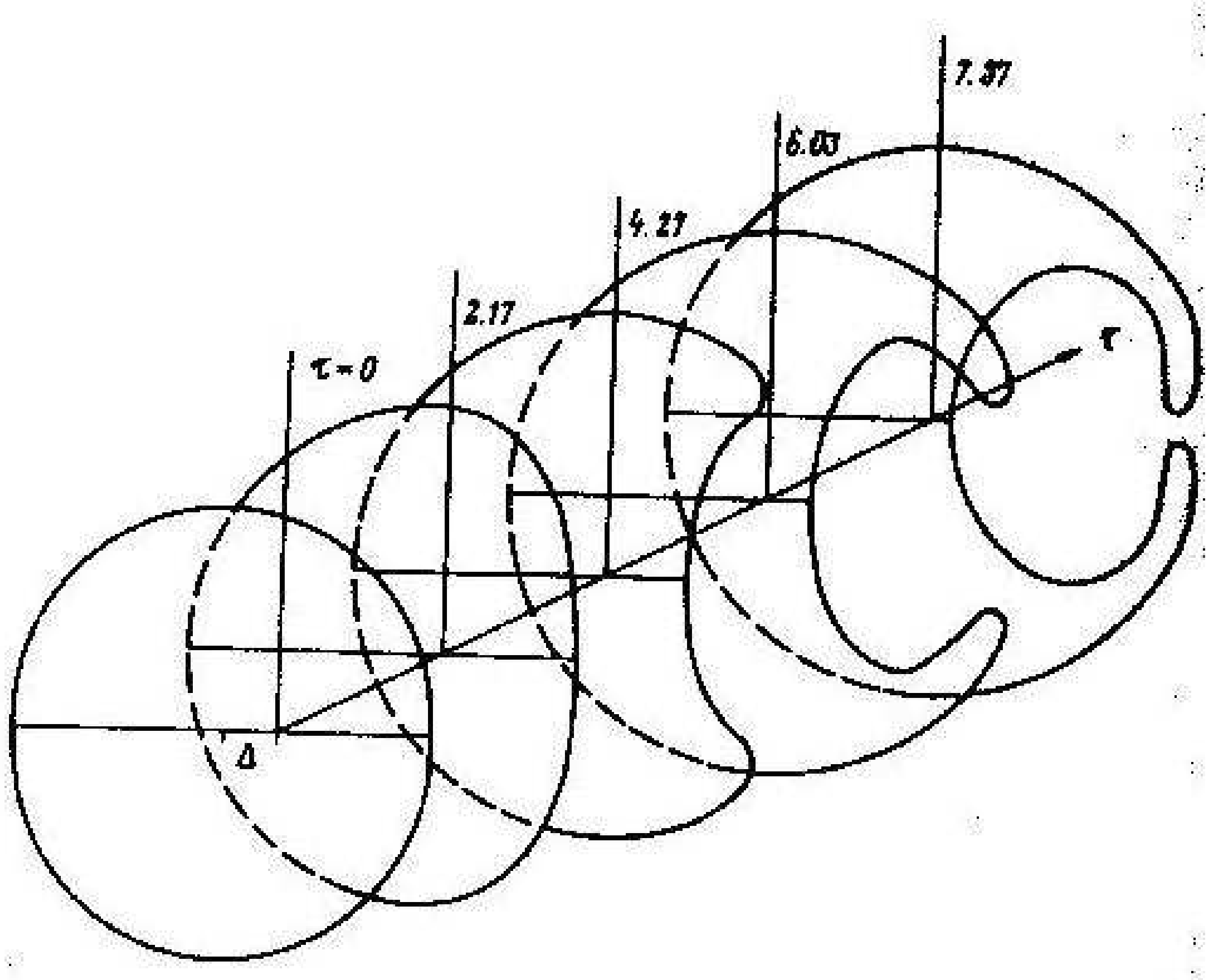


Fig. 1

Two weeks after Dubna workshop (1973) were sufficient to perform calculations

Fig.1. from Yu.N.Dnestrovskii, L.E.Zakharov et al. Pis'ma Zh.Tekh.Fiz., Vol.1, p. 45 (1975)

Free boundary simulations

IAEA-CN-33/A13-3 501

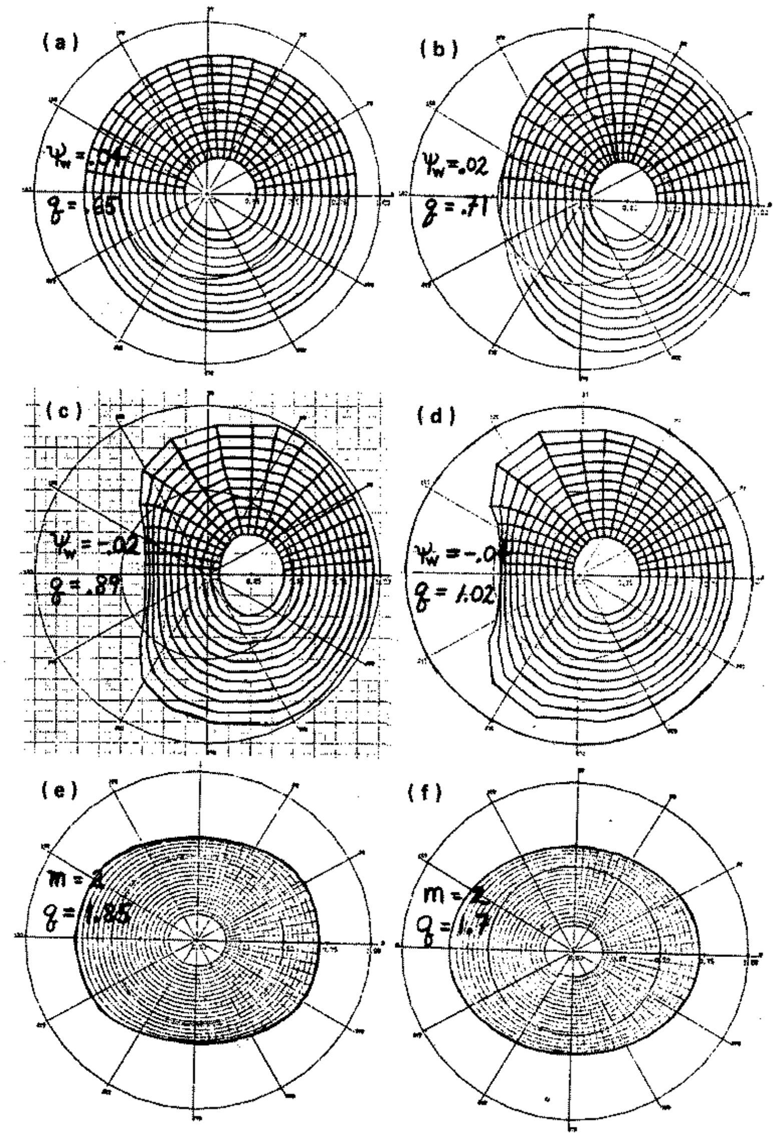


FIG.4. Final plasma configurations for m = 1 for a parabolic current profile and a = 0.8. (a) $\psi_W = 0.04$,

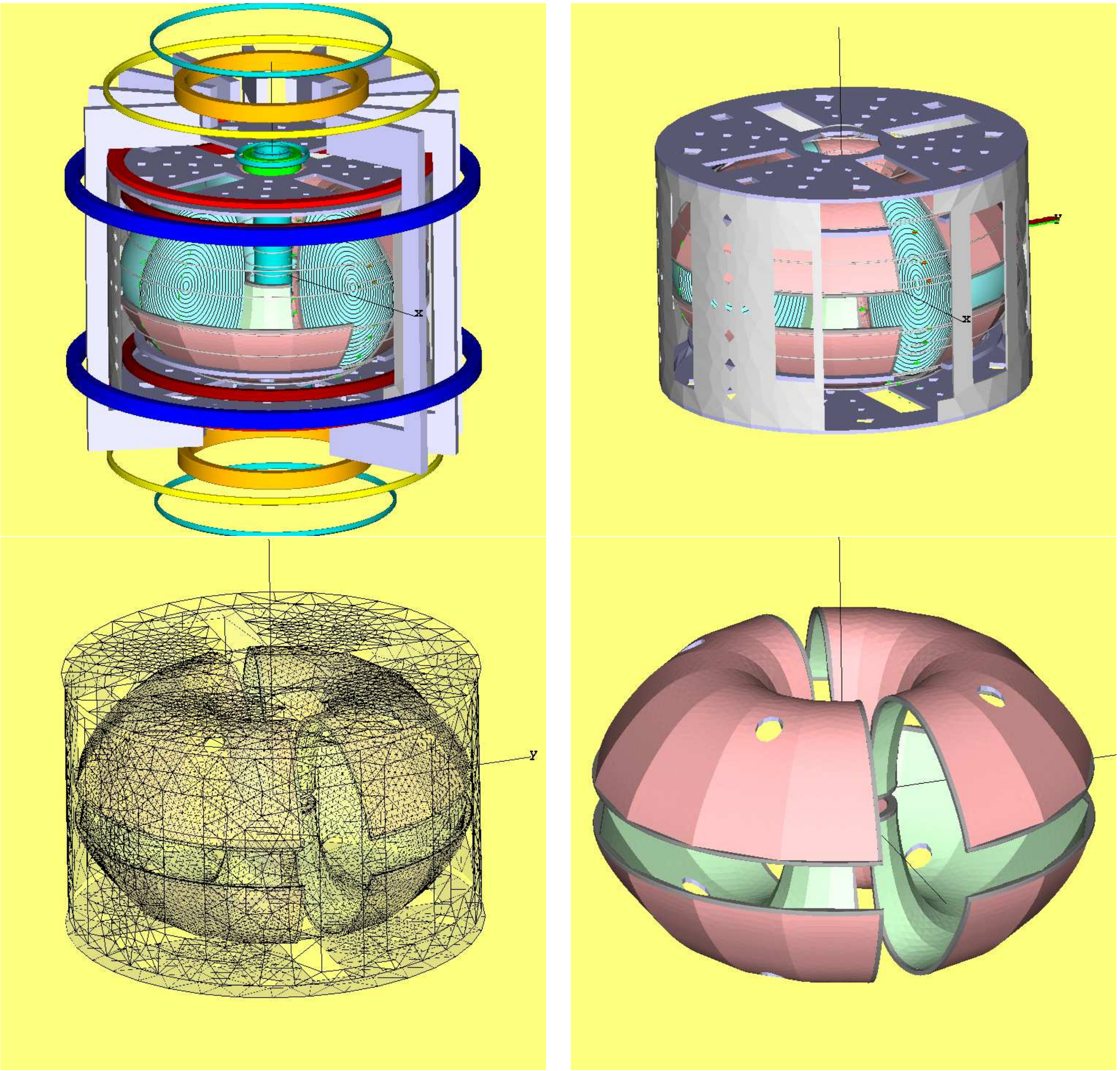
The free boundary numerical code was developed from the scratch for less than 1 year

The MHD part was adequate as a step for disruption simulations.

Electric contact, realistic walls and associated physics was absent

Fig.11. from M.Rosenbluth. . . R.White. IAEA-74, Vol.1, p. 492 (1974)

LTX shell model



Is crucial for developing a numerical model of ITER disruptions. It is the first step in building DSCS.

Double shell plasma environment make numerical model of passive structure absolutely necessary for interpretation of magnetic signals.

LTX gives an excellent opportunity for tuning up the electromagnetic shell model.

LTX shell model

Greens functions have been calculated a year ago for $\simeq$ 14838 triangles representing the LTX conducting structures

Circuit equations for the shell ***(for both equilibrium reconstruction and disruptions)*** *need computer power.*

$$\sum_j \vec{L}_{ij}\frac{dI_j}{dt} + \vec{R}_i I_i - \nabla\phi_i = -\frac{\partial \vec{A}_i^{pl+PFC}}{\partial t} \qquad (6.1)$$

```
Shell0222> wc -c Wrk/*.bo
1063761532 total
Shell0222> ls Wrk/*.bo
Wrk/ee00x00.bo Wrk/ee03x03.bo Wrk/ee05x03.bo Wrk/ee06x06.bo Wrk/sig01.bo
Wrk/ee01x00.bo Wrk/ee04x00.bo Wrk/ee05x04.bo Wrk/LijPFC00.bo Wrk/sig02.bo
Wrk/ee01x01.bo Wrk/ee04x01.bo Wrk/ee05x05.bo Wrk/LijPFC01.bo Wrk/sig03.bo
Wrk/ee02x00.bo Wrk/ee04x02.bo Wrk/ee06x00.bo Wrk/LijPFC02.bo Wrk/sig04.bo
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Wrk/ee03x02.bo Wrk/ee05x02.bo Wrk/ee06x05.bo Wrk/sig00.bo
```

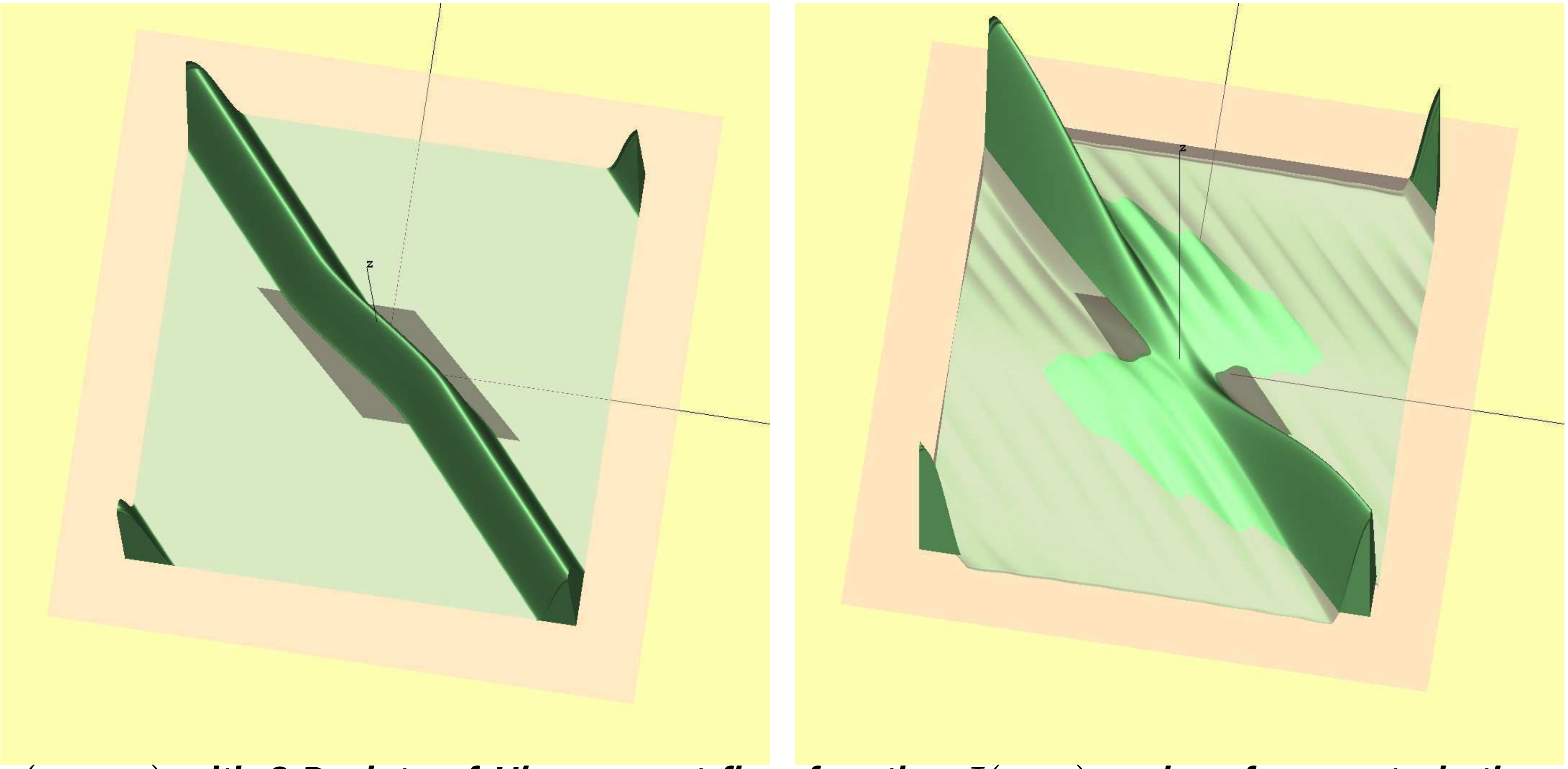
The triangle shell model will be tested against LTX calibration shots.

In additions now we have:

1. *Understanding of disruptions MHD physics and needs in its other aspects.*
2. *Experience with free boundary simulations. aspects.*
3. *Linear stability codes, (like DCON, TEARING16) modifiable for quasi-linear destruction of magnetic configuration.*
4. *GTS code for particle kinetics (after introduction of relativistic electrons, near collisions and boundary conditions at the wall)*

Linear 2-D MHD codes for 3-D disruptive plasma

Example of conversion of Hiro currents into plasma boundary displacement.



$(\varphi-\omega)$ with 3-D plots of Hiro current flow function $I(\omega,\varphi)$ and surface perturbation $\xi(\omega,\varphi)$ for a m=1 wall touching kink mode. All m,n are present in $\xi(\omega,\varphi)$.

Unlike R.White case, the Wall Touching Kink Mode consists of many m,n and can destroy the code confinement. Existing linear MHD codes are already useful.

Numerical codes and plasma physics

The speed of creation of numerical codes depends strongly on understanding the physical problem, rather than on speed of programming

Numerical codes (NIMROD, M3D)

Variables: $\mathrm{B}, \vec{V}, n, T_{e,i}$

PDE System: The fluid-based plasma model is related to MHD, but the Hall effect and other two-fluid terms decouple the magnetic field from ion motion at short wavelength.

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \left(\eta \mathbf{J} - \mathbf{V} \times \mathbf{B} + \frac{1}{ne} \mathbf{J} \times \mathbf{B} - \frac{T}{ne} \nabla n - \frac{1}{ne} \nabla \cdot \Pi_e \right) + \kappa_{divb} \nabla \nabla \cdot \mathbf{B}$$

Faraday's / Ohm's law

$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$

low-ω Ampere's law

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = \mathbf{J} \times \mathbf{B} - \nabla p - \nabla \cdot \Pi_i(\mathbf{V})$$

flow evolution

$$\frac{\partial n}{\partial t} + \nabla \cdot (n \mathbf{V}) = \nabla \cdot D \nabla n$$

particle continuity
with artificial diffusivity

$$\frac{n}{\gamma - 1} \left(\frac{\partial T_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla T_\alpha \right) = -p_\alpha \nabla \cdot \mathbf{V}_\alpha - \nabla \cdot \mathbf{q}_\alpha + Q_\alpha$$

temperature evolution

- The magnetic divergence term and particle diffusion term are used for numerical purposes.
- The implementation of electron stress is under development and will represent the effects of rapid momentum equilibration along magnetic field-lines.

C.Sovinec (UW Plasma Seminar October 29, 2007)

Numerical codes (NIMROD, M3D)

“The boundary conditions considered here for Eqs. (4a)-(4f) are Dirichlet conditions for the normal component of B*, for* T*, and* ***for all components of*** V ***along the bounding surface.***

C.Sovinec at all Journal of Comput. Physics, v. 195, p. 335 (2004)

Both codes need “fake” plasma in the vacuum region. The Dirichlet boundary condition

$$\mathbf{n}\cdot\mathbf{V}=0, \qquad (6.2)$$

for velocity of the“fake” plasma (necessary exclusively for the specific numerical scheme) prevents the real plasma from contacting the wall.

Hiro currents are missing. The entire dynamics is questionable. There is no realistic plasma-wall interaction.

In tokamaks there is no fake plasma. Plasma is not water. For plasmas

$$\mathbf{n}\cdot\mathbf{V}\neq 0 \qquad (6.3)$$

Together with absence of two other crucial elements of DSCS (high resolution of plasma edge, and Greens functions for wall simulations) V=0 makes both codes irrelevant to disruptions.

NIMROD and M3D

With working coordinates in both codes misaligned with the magnetic field, the high order finite elements or a super-high S-parameter does not affect the fundamental deficiency of the numerical scheme even beyond the disruptions simulations.

7 Summary

DSCS is going to be a this year SciDAC proposal.

The present situation when ITER urgent needs cannot be addressed should be changed ASAP.

Three options have sense and are possible

1. ***DSCS is going forward as independent proposal, competing with both M3D and NIMROD.***
2. ***DSCS and M3D are going together against NIMROD***
3. ***DSCS will be an independent part (covering the disruption issues) of joint proposal with M3D and NIMROD (covering all other aspects of MHD).***

The third options, relying on collaboration, rather on confrontation, is certainly preferable.