Tokamak magneto-hydrodynamics (TMHD) as a model for macroscopic plasma dynamics in tokamaks

(In memory of Vitaly D. Shafranov)

***Leonid E. Zakharov*[1]*, Xujing Li*[2]*, Sergei Galkin*[3]**

[1] *Princeton Plasma Physics Laboratory, MS-27 P.O. Box 451, Princeton NJ 08543-0451*
[2] *Institute of Computational Mathematics and Scientific/Engineering Computing, Academy of Mathematics and Systems Science,Chinese Academy of Sciences, P.O. Box 2719, Beijing 100190, China*
[3] *FAR-TECH, Inc. 10350 Science Center Dr. Bld 14, St 150, San Diego, CA 92121, USA*

Theory and Simulation of Disruptions Workshop

July 09-11, 2014, PPPL, Princeton NJ

*This work is partially supported by US DoE contract No. DE-AC02-09-CH11466, and by the National Magnetic Confinement Fusion Science Program 2011GB105003

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Shafranov's contribution to magnetic fusion:

- *1952 (at 22) - stability criterion $q > 1$ gave birth to tokamak configurations with $B_{tor} \gg B_{pol}$*
  (Sakharov in USSR invented toroidal confinement, non tokamaks)
- *1955 - equilibrium theory as a practical tool for plasma control in tokamaks*
- *1970 - tokamaks with non-circular cross-section for enhanced confinement, beta and divertors*

Everything was simple, fundamental and significant for progress in fusion.

This talk introduces and explains the notion of Tokamak Magneto-Hydrodynamics (TMHD), which explicitly reflects the anisotropy of a high temperature tokamak plasma. The set of TMHD equations is formulated for simulation of macroscopic plasma dynamics and disruptions in tokamaks.

Free from the Courant restriction on the time step, this set of equations is adequate to plasma dynamics with realistic parameters of high performance plasmas and does not require any extension of the MHD plasma model.

At the same time, TMHD requires the use of magnetic field aligned numerical grids. Examples of their use in 2-dimensional cases of tokamak equilibria and dynamics of the wall touching kink mode are presented.

The model was used for creation of theory of the Wall Touching Kink and Vertical Modes (WTKM and WTVM), prediction of Hiro and Evans currents, design of an innovative diagnostics for Hiro current measurements, installed on EAST device.

While Hiro currents have explained the toroidal asymmetry in the plasma current measurements in JET disruptions, the recently developed Vertical Disruption Code (VDE) have confirmed also the generation of Evans currents, which explain the tile current measurements in tokamaks.

In particular, the TMHD model gives a clean understanding of Hiro currents as a source of forces on the vacuum vessel (both vertical and sideways), while the force-free Evans as an explanation of the currents to the tiles in tokamaks.

Numerical simulations of WTVM, based on TMHD, have challenged the 24 years long misinterpretation by the entire fusion community of the tile currents in tokamaks as "halo" currents, which were a product of misuse of equilibrium reconstruction for interpretation of experimental measurements in vertical displacement events.

Contents

1 Macroscopic Tokamak MHD (TMHD)

The TMHD model utilizes the following properties of disruptions

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

1. ***During disruptions plasma conserves magnetic fluxes. As a result, singular currents are generated at the plasma boundary and at the resonant surfaces (for $n \neq 0$)***
2. ***The macroscopic tokamak plasma dynamics is driven by a small imbalance of large forces, which are much bigger than the plasma inertia. Plasma inertia is negligible (except along the resonant layers).***

- ***TMHD considers the disruption dynamics as a fast equilibrium evolution with conservation of magnetic fluxes and with singular currents.***
- ***At the same time TMHD provides the scale separation, suitable for interfacing with the non-MHD physics of singular layers and plasma edge.***

1.1 TMHD and plasma inertia

All existing MHD numerical codes represent a hydro-dynamic model, modified by the $\vec{j} \times \vec{B}$ force. Accordingly, their "salt water MHD" is driven by the inertia term

$$\rho \frac{d\vec{V}}{dt} = -\nabla p + (\vec{j} \times \vec{B}), \qquad (1.2)$$

Not reflecting the reality of tokamak physics, the inertia term represents an obstacle for simulations of tokamaks: fast magneto-sonic waves, which play no role in tokamaks, still require a very small time step.

In contrast TMHD is, in fact, a fast equilibrium evolution with excitation of sheet currents or islands at the resonant surfaces and surface currents at the plasma boundary due to magnetic flux conservation ($\tau_{TMHD} \ll \tau_{resistive}$)

In TMHD, following Kadomtsev and Pogutse (1973), the plasma inertia is replaced by a displacement term, which is equivalent to a friction force $\propto -\vec{V}$:

$$\lambda\vec{\xi} = -\nabla p + (\vec{j} \times \vec{B}), \quad \lambda\vec{\xi} \equiv \gamma\vec{V}. \qquad (1.3)$$

This replacement provides an iteration algorithm for driving the system (even far away from equilibrium).

By eliminating plasma oscillations it removes the 4-decade (!!!) old problem with Courant limitations on the time step in MHD simulations.

1.2 Plasma anisotropy and adaptive grids

High plasma anisotropy is the critical property of tokamaks plasma, which distinguish it from liquid metals or salt water.

TMHD expresses the anisotropy in a very simple manner, consistent with the high temperature plasma

$$(\vec{B}\cdot\nabla T_e)\simeq 0 \quad \rightarrow (\vec{B}\cdot\nabla\sigma)=0, \tag{1.4}$$

$\sigma=\sigma(T_e)$ ***is the electric conductivity.***

High plasma anisotropy makes the REAL plasma behaving as ideally conducting. I fact, tokamaks are microscopically stable exclusively because of high plasma anisotropy

The hydro-dynamic numerical codes cannot implement Eq. (1.4): the problem of large 'S'. They hide the problem into the mess of "Extended MHD", which adds a train of irrelevant to dynamics terms, starting from heat conduction.

In contrast, TMHD requires adaptive grids, aligned with magnetic field:

1. ***The separation of physics scales is automatic.***
2. ***The interface with the non-MHD physics of resonant layers is easy.***
3. ***In particular, any 'S' parameter of existing or future devices can be simulated: the higher is 'S' the better is the accuracy of TMHD***

1.3 Basic TMHD equations

1. ***Equation of motion***

$$\lambda\delta\vec{r} = -\nabla p + (\vec{\jmath}\times\vec{B}) \qquad (1.5)$$

No inertia, no velocity, no time, no Courant limitation on the time step

2. ***Toroidal flux conservation instead of equation of state***

$$(\nabla\times(\delta\vec{r}\times\vec{B}_\varphi)) = 0. \qquad (1.6)$$

3. ***The resistive part of TMHD***

   (a) ***Faraday's (Ohm's) law***

$$-\frac{\partial\vec{A}}{\partial t} - \nabla\varphi_E + (\vec{V}\times\vec{B}) = \frac{\vec{\jmath}^{pl}}{\sigma^{pl}}. \qquad (1.7)$$

   $\vec{\jmath}$ is determined by force balance, the Faraday law determines $\vec{V}$.

   (b) ***Plasma anisotropy***

$$(\vec{B}\cdot\nabla\sigma) = 0. \qquad (1.8)$$

   Plasma anisotropy, $(\vec{B}\cdot\nabla T_e)\simeq 0$ is explicitly reproduced by adaptive grids

4. ***Electro-magnetic boundary condition at a wall***

$$\vec{E}^{pl}_{\|} = \vec{E}^{wall}_{\|} = \frac{\vec{\jmath}^{pl}}{\sigma^{pl}} - (\vec{V}\times\vec{B}) = \frac{\vec{\jmath}^{wall}}{\sigma^{wall}}. \qquad (1.9)$$

No extra boundary condition for V is required !

1.4 Numerical scheme of TMHD

TMHD is not only consistent with the physics of the high temperature plasma. It also leads to the extremely efficient numerical schemes

The equilibrium equations can be derived from a variational principle

(V.D. Shafranov (Voprosy Teorii Plasmy, GosAtomIsdat, v .2, 1963, (Reviews of Plasma Physics, Vol. 2, 1966, p. 103)))

$$W_{TMHD} = \frac{1}{\mu_0}\int\left\{\lambda\mu_0\frac{\vec{\xi}^2}{2} + \frac{\mathrm{B}^2}{2} - \bar{p}\right\}dv, \quad \bar{p} \equiv \mu_0 p, \tag{1.10}$$

$$\delta\mathrm{B} = (\nabla \times (\vec{\xi} \times \mathrm{B})), \quad \delta\bar{p} = -(\vec{\xi}\cdot\nabla\bar{p})$$

with $\vec{\xi}$ as a variation.

Numerically, approximated by finite elements, the minimization of this functional leads to symmetric matrix equations.

As a result, the TMHD equations can be solved using Cholesky decomposition!!!

It is well suitable for GPU !

The applications of Cholesky decomposition is given below for 2-D equilibria.

Recently with Xujing Li we understood the use of GPU and created a collisional particle orbit routine which for 80,000 orbits is 40 times faster than the 32 processor CPU.

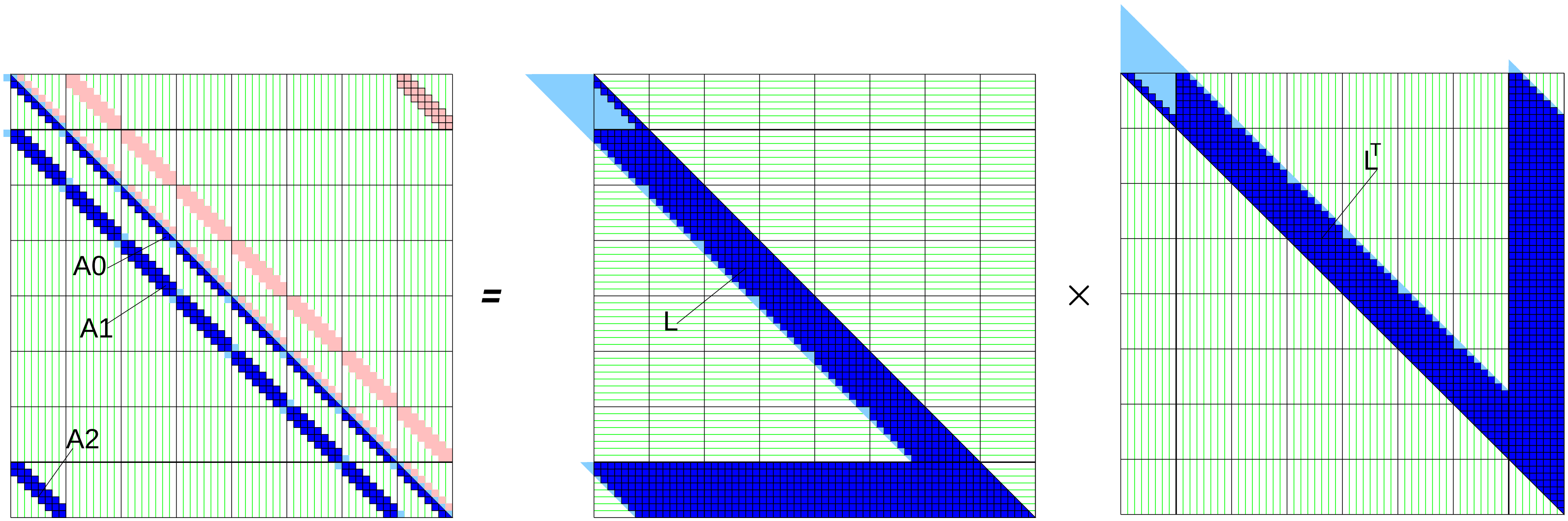
Numerical scheme of EEC

By appropriate enumeration, for both 2- and 3-D cases, the resulting matrix can represented as a block-tri-diagonal cycle matrix

This structure can be utilized for developing an efficient direct solver

- ***First, a block-tri-diagonal algorithm was implemented as a first solver of matrix equation***
- ***Second, faster Cholesky decomposition scheme was developed to utilize advantages of matrix structure***

$$\mathsf{A} = \mathsf{L}\mathsf{L}^T. \tag{1.11}$$



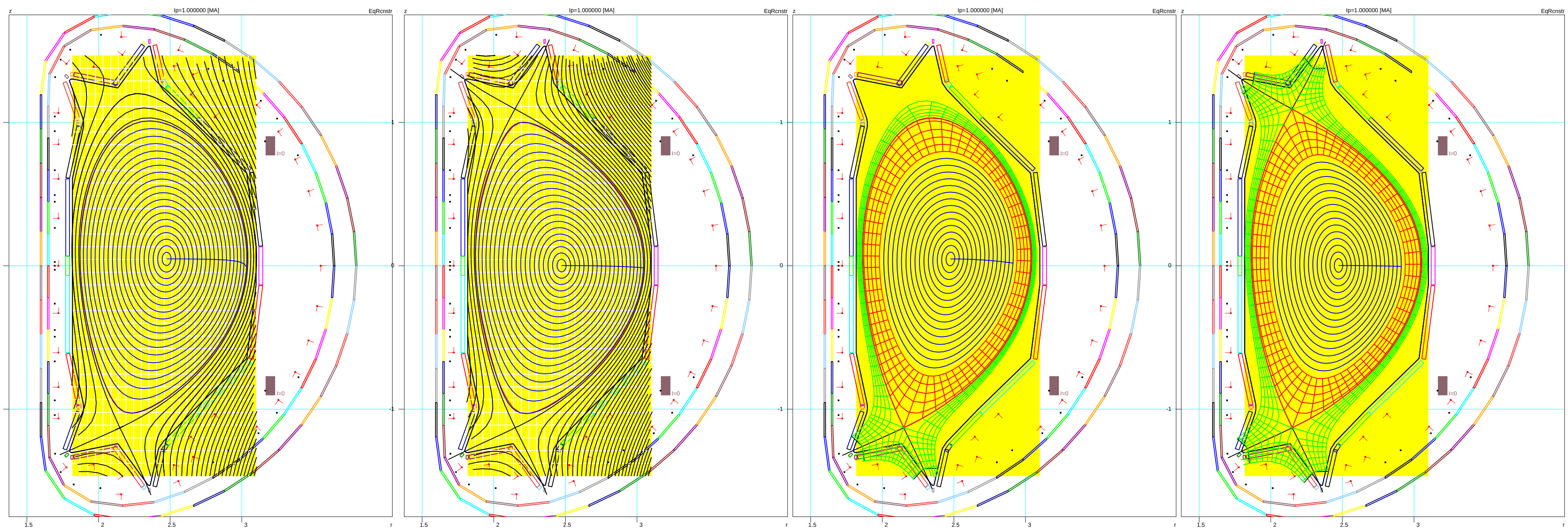
Original matrix ***L factor*** ***L^T factor***

EEC uses the same ESC algorithm, $\xi\bar{\Psi}'_0 = -\psi$, for grid advancing

1.5 Free-boundary equilibria with ESC-EEC

ESC-EEC can calculate free-boundary equilibria in both $r - z$ and flux coordinates

The Equilibrium Spline Interface (ESI) is developed for equilibrium codes instead of present mess in interfacing



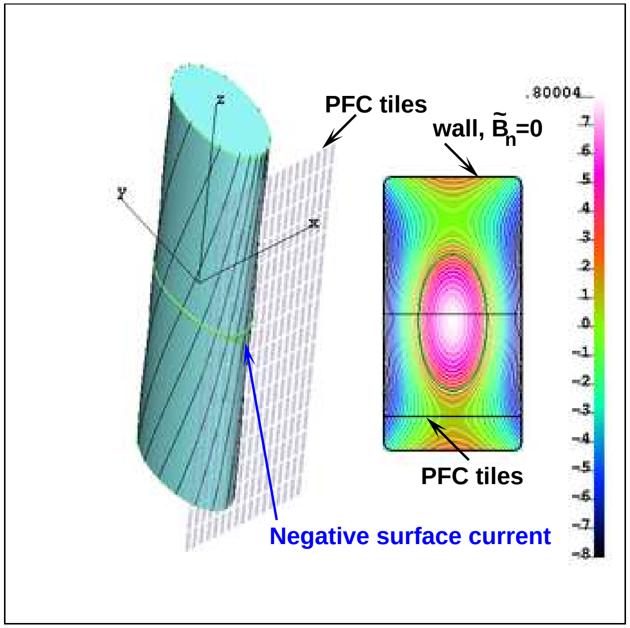
(a) ID=00,1,00,00,00 (b) ID=00,01,00,00,00 (c) ID=00,40,00,00,23 (d) ID=00,40,00,00,23

Examples of EAST free boundary equilibrium configurations with (a,c) single and (b,d) double null separatrixes calculated by ESC-EEC.
a),b) Interface IDs for equilibria with $r - z$ coordinate data;
(c),d) ESI IDs for equilibria with the core, edge and vacuum flux coordinate data

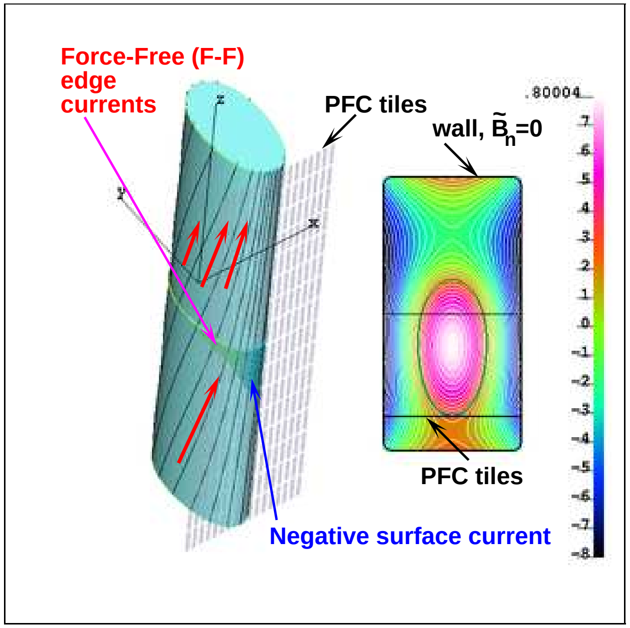
1.6 VDE with tiles and a wall

In tokamaks, the plasma is always "separated" from the wall based on $\Psi_{pl}, \Psi_X, \Psi_{Wall}$.

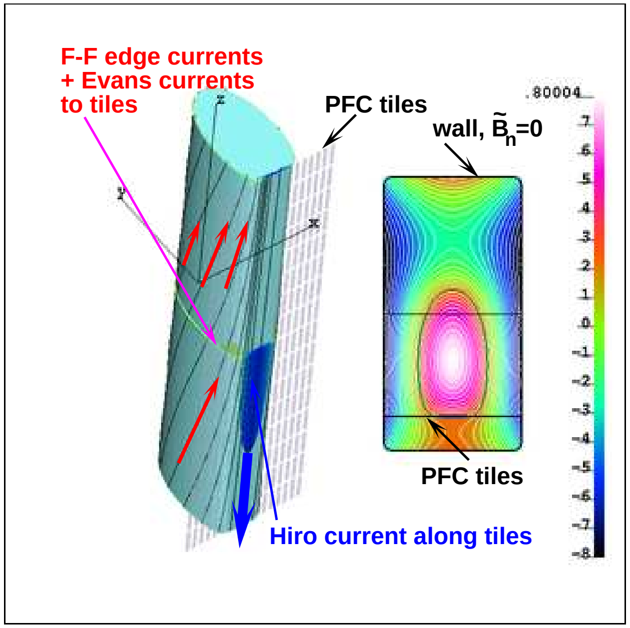
The presence of the wall does not affect VDE significantly



Initial plasma displacement



Negative surface current at the leading edge

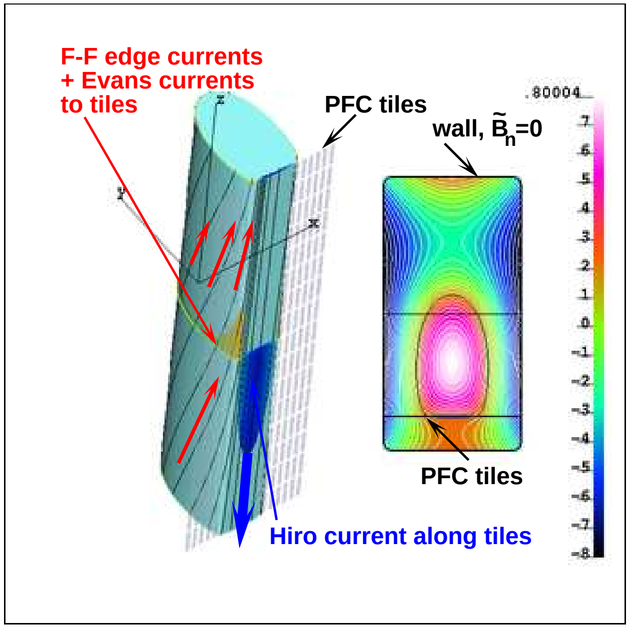


Hiro, Evans currents, formation of two Y-points

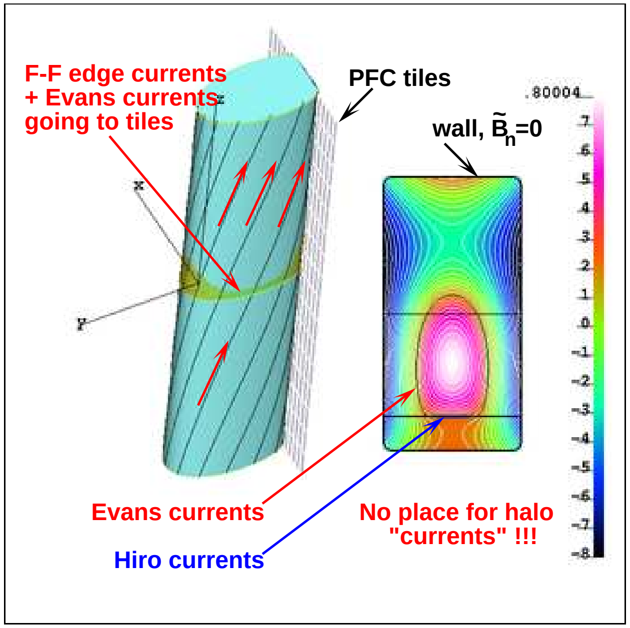
Due to stabilizing wall action, Y-points are less separated than in the absence of the wall

Otherwise, the plasma motion in both cases is similar.

Case 3: Intermediate equilibrium (wall and tiles)



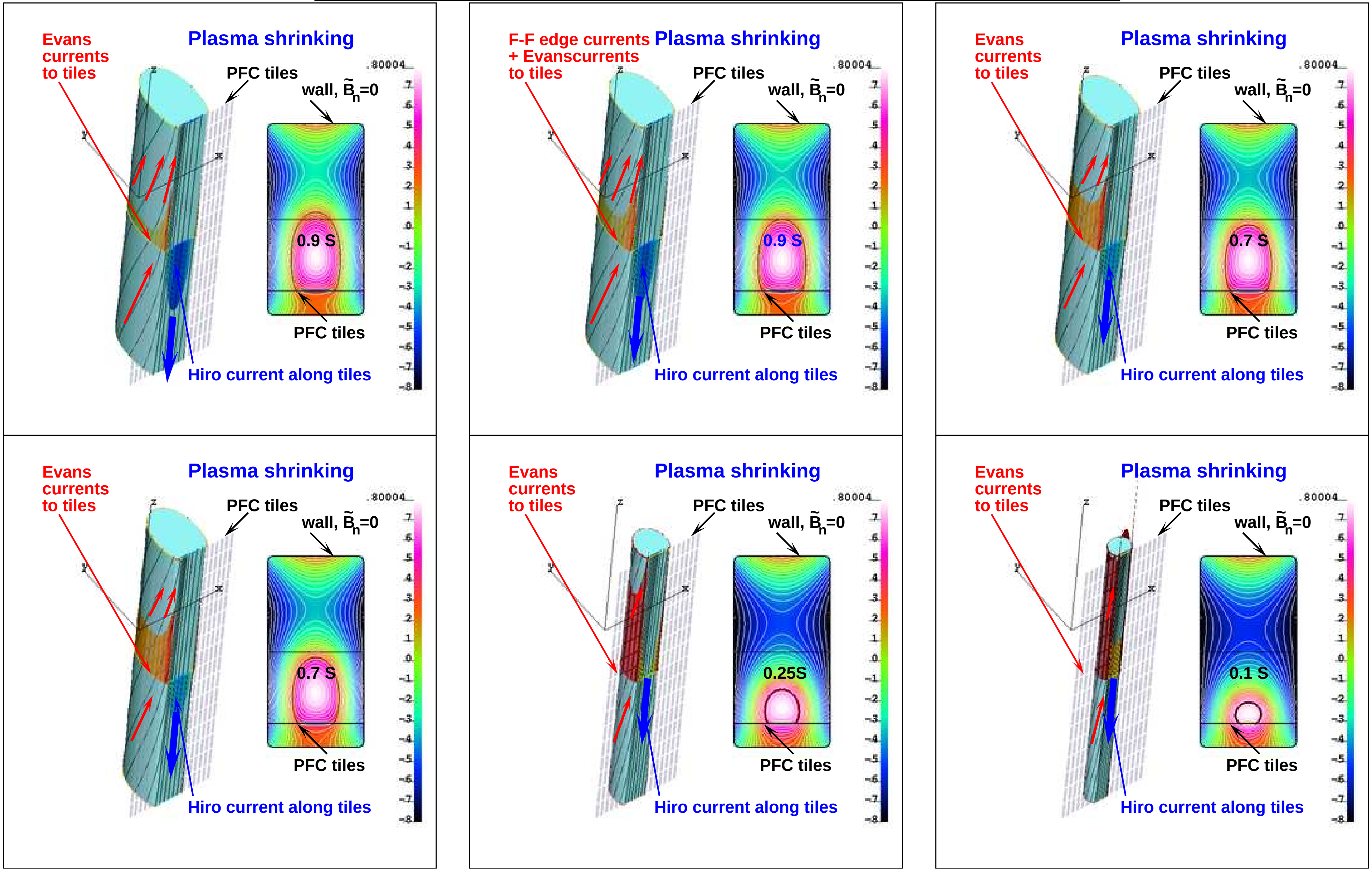
Hiro currents apply the force to tiles



Evans currents. No place for fake "halo" currents

Case 3: Plasma shrinking (wall and tiles)

Plasma shrinking due to decay of Hiro currents



TMHD challenges the community regarding tile currents

The physics of VDE was significantly confused in 1991 (Strait et al, Nucl. Fus. 1991) where currents to the tiles were discovered.

The misuse of EFIT reconstruction code led to misinterpretation of these electric currents as "halo" currents.

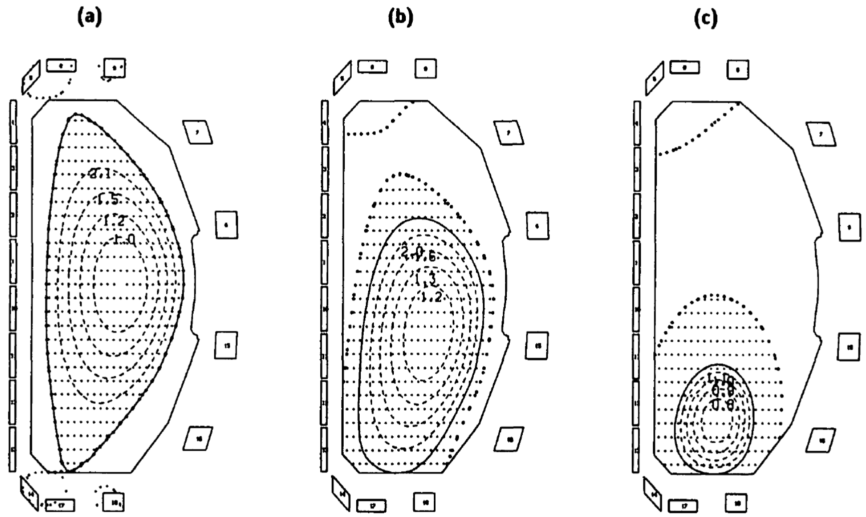


FIG. 3. Equilibrium flux plots from EFIT at three times during the vertical instability: (a) 2660 ms, (b) 2675 ms and (c) 2684 ms. Plasma current was allowed in the hatched region, including part of the SOL.

Figure 1: EFIT reconstruction of plasma configuration in VDE

Despite of wide acceptance by fusion community, the physics picture supporting the halo-current interpretation was never established.

In fact, the model is in strong contradiction witth every direct measurement (JET, EAST).

In fact, VDE is described by TMHD, which includes fast plasma evolution and generation of surface currents, which explain the original measurements.

TMHD does not need any special condition for V_{normal}: the continuity of $\vec{E}_{\parallel}$ is sufficient

On the plasma side, the Faraday law

$$-\frac{\partial \vec{A}^{pl}}{\partial t} - \nabla\varphi^{pl} + (\vec{V} \times \vec{B}) = \eta^{pl}\vec{\jmath}^{pl} \tag{2.1}$$

gives

$$\vec{E}_{\parallel}^{pl} \equiv -\frac{\partial \vec{A}_{\parallel}^{pl}}{\partial t} - \nabla_{\parallel}\varphi^{pl} = \eta^{pl}\vec{\jmath}^{pl} - (\vec{V} \times \vec{B}) \tag{2.2}$$

At the wall side

$$\vec{E}_{\parallel}^{wall} = \eta^{wall}\vec{\jmath}^{wall}. \tag{2.3}$$

These two Eqs. determine V_{normal} uniquely.

The BIG question is

"Why all these salt-water hydroqdynamic codes, like M3D, need a separate boundary condition for V_{normal} ?"

In fact, there is no reason for this. Not only these codes use the wrong boundary condition and are inconsistent with implementation of force balance, plasma anisotropy,

they are also SELF CONTRADICTORY

Another question is

What is behind the claims on M3D ability of disruption modeling ?

1. ***H. R. Strauss, R. Paccagnella, J. Breslau. "Wall forces produced during ITER disruptions" PHYSICS OF PLASMAS 17, 082505 (2010)***

   "In the following, M3D is used to calculate a disruption. The initial state is an ITER reference equilibrium, FEAT15MA, written to a file in EQDSK Ref. 19 format. This was read into M3D and used to generate a mesh and initialize a nonlinear simulation."

   For this case the only driving mode is a benign $m/n = 1/1$ internal kink mode.

   The trick of M3D team is simple: to convert the internal kink mode to a disruptive one by enhancing ITER I_{pl} from 15 to 24 MA and make M3D looking relevant.

2. ***Same PoP 2010. How this trick was without raising questions ? In a very simple manner by hiding the manipulation inside a big paragraph:***

   . . . VDE and then adding a kink perturbation as the plasma ap- proached the wall. Figure 1 shows the nonlinear kink and VDE at time t = 34.07 A after adding the kink perturbation. The wall resistivity for this example had w 1 and the current enhancement was I/I0 = 1.6. The poloidal magnetic flux is shown in Fig. 1 a and the toroidal current density C = -RJ in Fig. 1 b . A current sheet is visible on the side of the current next to the wall. The toroidal flux RB , which gives the major contribution to the poloidal current, includ- ing the halo current 19 , is shown in Fig. 1 c . The contours. . .

   so nobody (e.g., referees, ITER people, reviewers, . . .), except Leonid, would be able to notice the substitution.

3. ***Same PoP 2010. The "corellations" of M3D version of superITER and JET asymmetry are established very easily, by ignoring the electro-dynamics behind***

$$I = \int (\vec{B} \cdot d\vec{l}) \tag{3.1}$$

In JET,[5,21] the quantity $dI_\phi/d\phi$ was measured, where I_ϕ is the toroidal plasma current as a function of toroidal angle and was compared to the ϕ derivative of the vertical plasma displacement $d\xi_Z/d\phi$. The current was measured in disruptions in which there was usually an upward VDE, and occasionally a downward VDE. This implies that the perturbations are shifted by the VDE displacement

$$J_\phi = J_{\phi 0}(r - \xi_{\rm VDE} \sin\theta) + J_{\phi 1}(r - \xi_{\rm VDE}\sin\theta)\cos(\theta+\phi), \quad (50)$$

where $\xi_{\rm VDE} > 0$ for an upward displacement. The vertical VDE displacement $\xi_{\rm VDE}$ interacts with the helical kink. Effectively, the $\xi_{\rm VDE}$ displacement gives a $\sin\theta$ weighting of the current. The total toroidally varying plasma current is

$$I_{\phi 1} = -\int drrd\theta \frac{dJ_{\phi 1}}{dr}\xi_{\rm VDE}\sin\theta\cos(\theta+\phi) = -\pi\xi_{\rm VDE}\int drJ_{\phi 1}\sin\phi, \quad (51)$$

where $J_{\phi 1}$ was first Taylor expanded and then integrated by parts. The quantity M_{IZ} is also measured in experiments. It is the vertical moment of the plasma current

$$M_{IZ} = \int d\theta drr^2 \sin\theta J_{\phi 1}\cos(\theta+\phi) = -\pi\int drr^2 J_{\phi 1}\sin\phi. \quad (52)$$

Using Eqs. (29) $J_{\phi 1} = K_a\delta(r-a)$ yields

$$\frac{dI_\phi}{d\phi} = \frac{\xi_{\rm VDE}}{a^2}\frac{dM_{IZ}}{d\phi}. \quad (53)$$

In JET experiments,[21] $dI_\phi/d\phi$ and $dM_{IZ}/d\phi$ were found to be positively correlated for an upward VDE and negatively correlated for a downward VDE, as in Eq. (53). The net toroidal variation of I_ϕ is here not caused by Hiro current flowing into the wall,[5] but by the vertical asymmetry produced by the VDE displacement.

On the left, highlighted by red, is a statement from the Strauss, Paccagnella, and Breslau paper, Phys. Plasmas 17, 082505 (2010), p.082505-6:

The net toroidal variation of I_ϕ is here not caused by Hiro current owing into the wall,5 but by the vertical asymmetry produced by the VDE displacement.
In fact, all equations (50,51,53), "supporting" this claim, are erroneous.
If there is a toroidal current $J_{\phi 1}(r)\cos(\theta+\phi)$, induced by a kink mode 1/1

$$J_{\phi 1}(r)\cos(\theta+\phi) = J_{\phi 1}(\sqrt{x^2+y^2})\frac{x\cos\phi - y\sin\phi}{\sqrt{x^2+y^2}}, \quad (3.2)$$

then the vertical displacement ξ_{VDE} redistributes it simply as

$$J_{\phi 1}(x,y) \rightarrow= J_{\phi 1}(x, y-\xi_{VDE}, \phi), \quad (3.3)$$

what obviously does not contribute to the total mode induced current $I_{\varphi 1} = \int J_{\phi 1}dxdy$.

The mistake, made by Strauss is evident from the following real expression of the shifted $J_{\phi 1}$ in Strauss's polar coordinates r,θ

$$J_{\phi 1}(r,\theta) = J_{\phi 1}(\sqrt{x^2+(y-\xi_{VDE})^2})\frac{x\cos\phi - (y-\xi_{VDE})\sin\phi}{\sqrt{x^2+(y-\xi_{VDE})^2}}. \quad (3.4)$$

He has missed ξ_{VDE} in the second factor in this expression by using it the same as in Eq. (3.2).

M3D discovery of JET irrelevance to ITER

4. ***H. Strauss, R. Paccagnella, J. Breslau, L. Sugiyama and S. Jardin. "Sideways wall force produced during tokamak disruptions" Nucl. Fusion 53 (2013) 073018***

   "Simulations are carried out of two kinds of disruptions. The first kind is caused by VDEs which scrape off magnetic flux at the wall, destabilizing an (m, n) = (2, 1) mode. The sideways force is found to be maximum when wall 1, where is the growth rate of the n = 1 mode, and wall is the growth rate of the VDE. We found that the value of wall at which the peak force occurs depends on the initial conditions. The second type. . . "

In fact, JET has no evidence of sideways forces caused by $m/n = 2/1$ mode.

What is the conclusion of M3D leader from the yesterday talk ? Very simple: Not only Hiro currents, but even JET are not relevant to ITER, unlike M3D.

5. ***H. R. Strauss. "Velocity boundary conditions at a tokamak resistive wall". PHYSICS OF PLASMAS 21, 032506 (2014)***

The only question is how a paper with not single correct formula (except of textbook level) was published in the central plasma physics journal.

How can it happen that such a faulty code as M3D, contradicting the basic physics, full of manipulations, inconsistent with reality makes all kinds of far reaching statements ?

M3D is well backed up by the "Extended M3D" from PPPL

In 2011-12, two Theory Dept. reports (one by Boozer's, and another by M.Bell's committees) have been fabricated to prase M3D and TSC as disruption simulation codes. Intentionally biased, both approved the faulty approach of M3D and TSC, while complementing each mentioning of Hiro current theory exclusively by negative comments.

The spirit of reports was expressed by S.Jardin (ITPA-MHD Meeting, Padova, Oct. 4-7, 2011)

In 2010, a single scientist in the U.S. fusion community was repeatedly making the following claim (and being quite vocal about it)

"...the present numerical codes (M3D, NIMROD) are not applicable of simulating disruptions because of their "salt-water" boundary condition Vnorm = 0, irrelevant to tokamak plasma. For almost 4 years this boundary condition was not corrected. In fact, it represents a fundamental flaw of numerical scheme, making it not suitable for plasma dynamics in tokamaks."

This claim was not backed-up by any mathematical, physical, numerical, or experimental analysis, but arose primarily because the code's results did not support that scientist's theory of disruptions.

Wow, so great !

In fact, while comprehensive JET data analysis, physics of Hiro currents, their explicit mathematical expressions and DSC simulations

revealed the GIGO nature of M3D,

the EAST Hiro current measurements

have proved the GIGO nature of 2-D TSC as well

- **“This claim was not backed-up by any mathematical”** ***is an explicit lie. In fact***

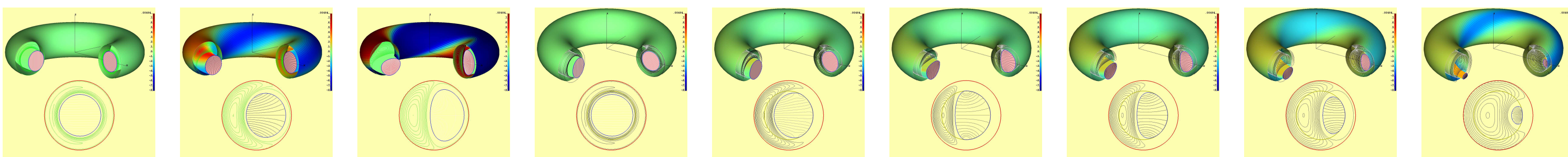
$$\mu_0 \vec{i}_{11} = -2\xi_{11}\frac{B_\varphi}{R}\left(\vec{e}_\varphi + \frac{a}{R}\vec{e}_\omega\right)\cos(\omega-\varphi) \tag{3.5}$$

- **“physical”** ***is an explicit lie. In fact***

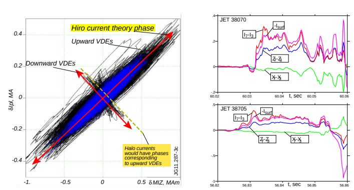
$$-\frac{\partial \vec{A}^{i,surf}}{\partial t} \quad \underbrace{-\frac{\partial \vec{A}^{pl,core}}{\partial t} + VB_\omega \vec{e}_\varphi}_{vanishes\ for\ m=1} - \underbrace{VB_\varphi \vec{e}_\omega}_{driving\ EMF} - \nabla\phi_E^{surf} = \frac{\vec{j}}{\sigma} \tag{3.6}$$

This Faraday law provides the physics of excitation of Hiro currents

- **“numerical”** ***is an explicit lie. In fact the kink mode simulations are complemented by VDE code***



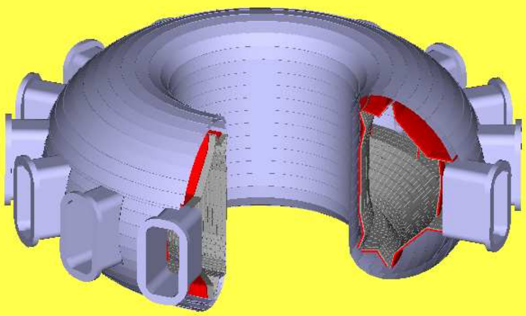
- **“or experimental analysis”** ***is a explicit lie. In fact, the consistency with experiment is outstanding.***



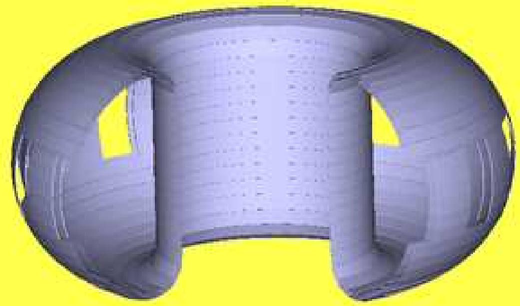
- **“but arose primarily because the code’s results did not support that scientist’s theory of disruptions”** ***is lie. In fact, it is evident that M3D and TSC are exactly the GIGO codes, which blocked the progress in the field.***

TMHD moves forward, motivating new research

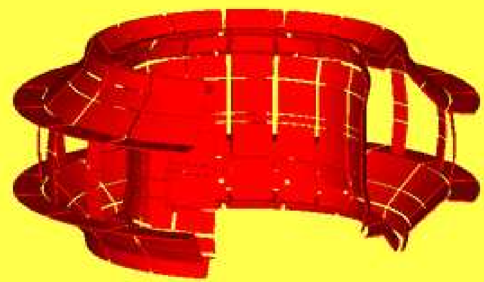
Real EAST in-vessel geometry is used for VDE simulations.



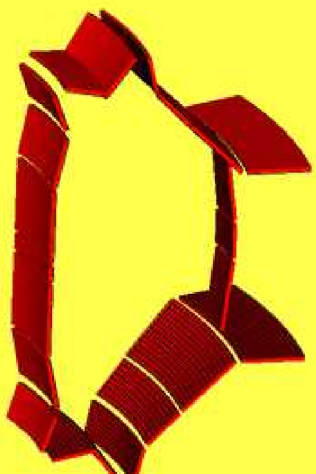
Vacuum Chamber



Double layer vacuum vessel



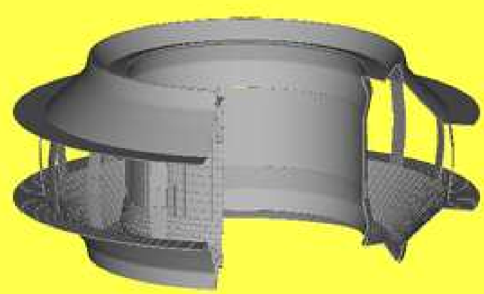
Stabilizer elements (16 toroidal sections)



One toroidal sector of copper stabilizers (8728 triangles)

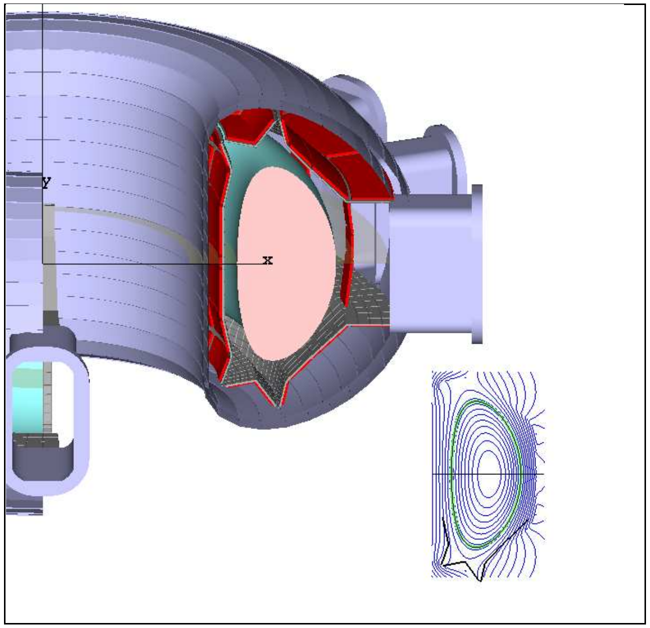
Numerical model of EAST passive structures (as of 2008)

2014 update is available, but not yet implemented

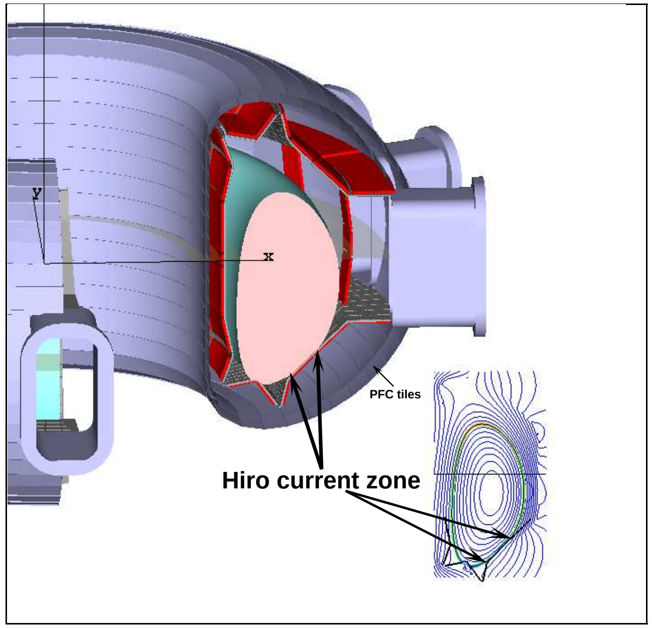


Carbon plasma facing tiles

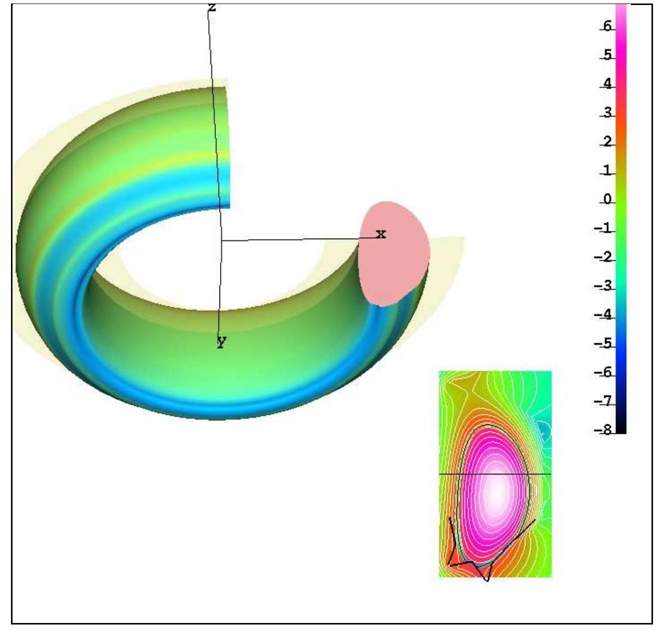
Real EAST in-vessel geometry is used for VDE simulations.



Initial unstable plasma



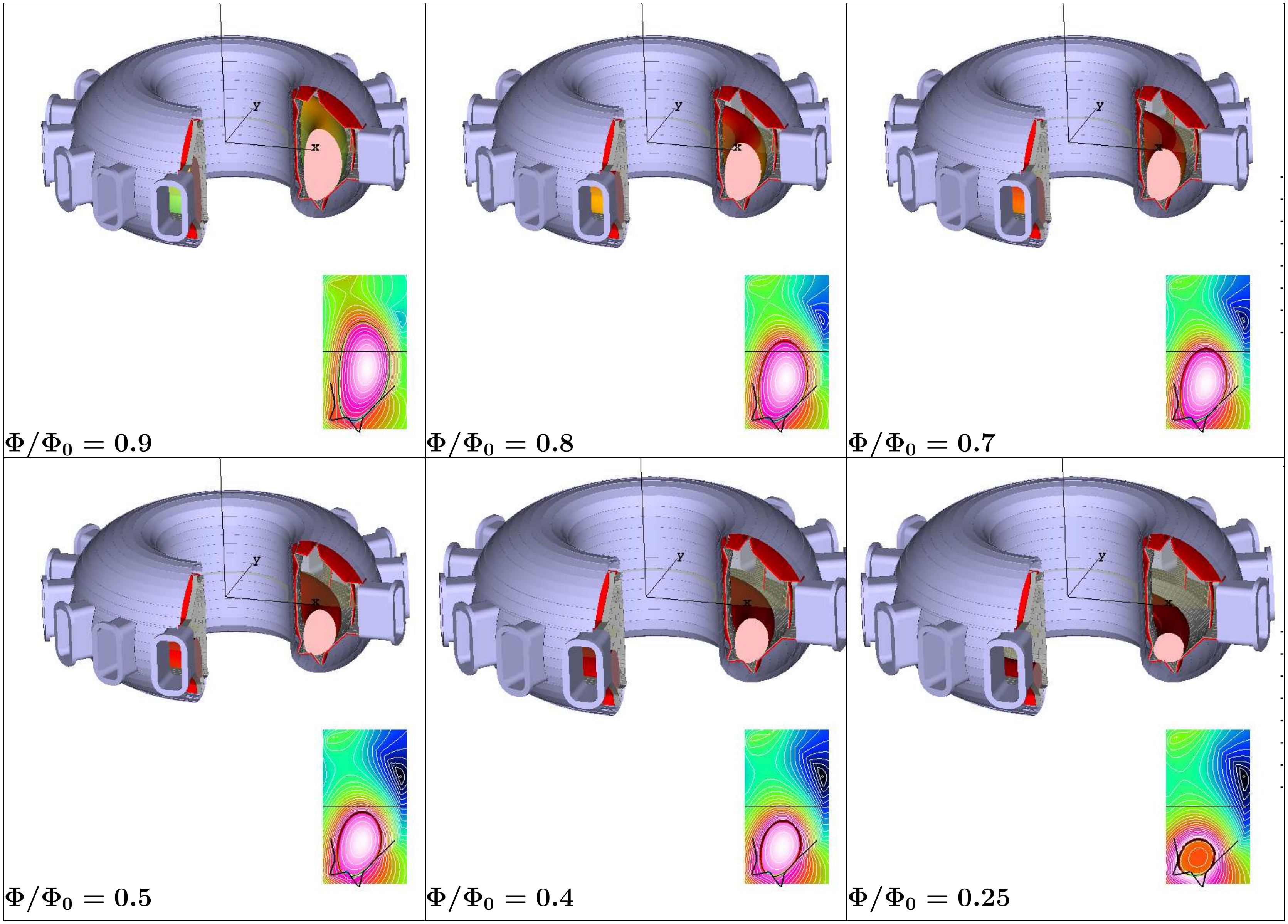
Plasma touches the divertor plate and generate Hiro currents, $\Phi/\Phi_0 = 1$



Negative Hiro currents (blue), shown in the contact area of plasma

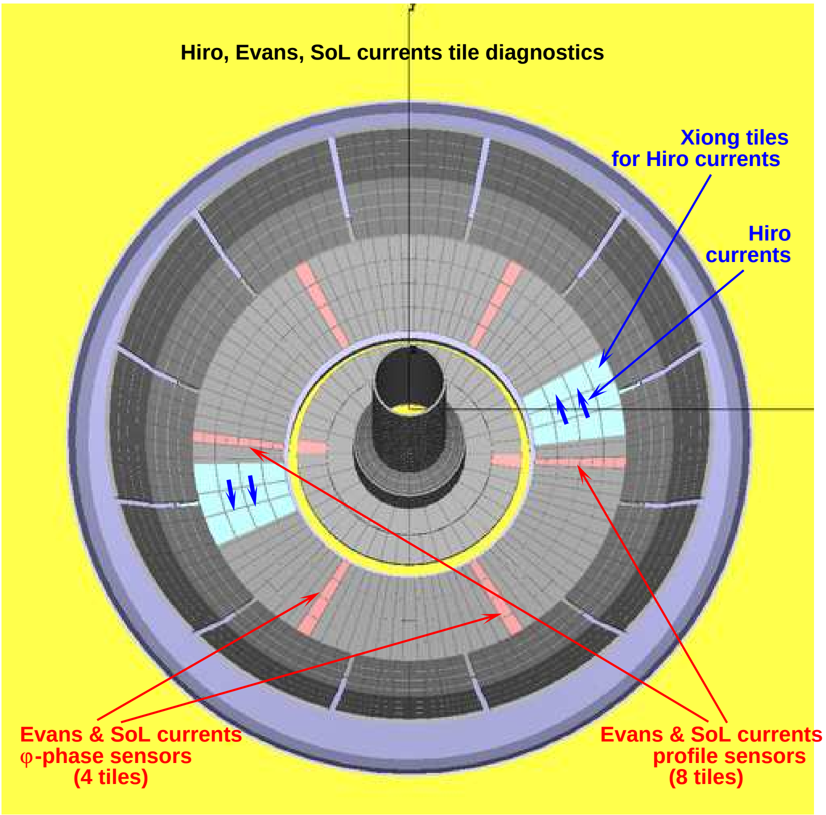
!!! Our VDE code shows the contact zone right at the position of Xiong tiles !!!

Plasma VDE in EAST geometry



VDE simulations motivate innovative diagnostics

We suggested a comprehensive set of innovative tile diagnostics for Hiro, Evans and SoL current measurements on NSTX-U



Tile sensors for measuring Hiro, Evans, and SoL currents and different kinds of diagnostics including

1. ***Hiro current diagnostics***
2. ***Evans current profile diagnostics with enhanced radial resolution***
3. ***Evans current φ-phase diagnostics***
4. ***SoL current measurements***

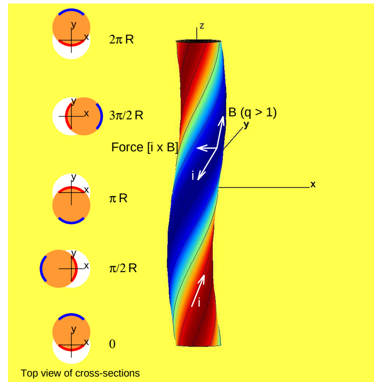
Evans currents carry important information on plasma-PFC interactions, never touched

4 Summary

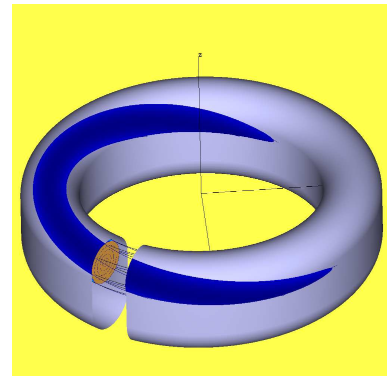
TMHD model finally addresses the long term overdue problem of developing numerical MD codes for the high temperature tokamak plasma: 2D ESC-EEC, VDE, DSC are operational

Basics TMHD was understood in 2007:

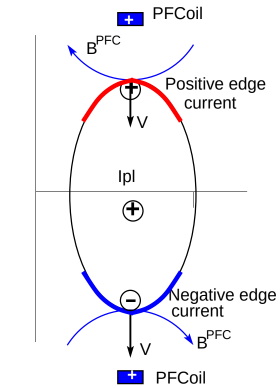
- ***Any plasma deformation excites the surface currents at the plasma***
- ***Plasma goes to a slowdown evolution when negative surface currents are converted into as Hiro currents at the wall***
- ***Wall Touching Kink and Vertical Modes are introduced into theory***



m/n=1/1 surface currents



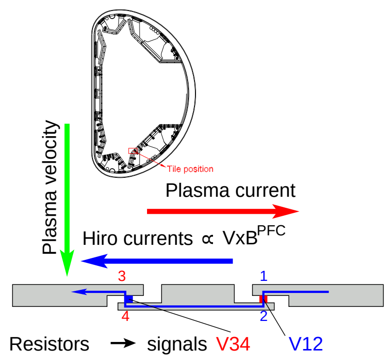
Wall Touching Kink Mode (JET)



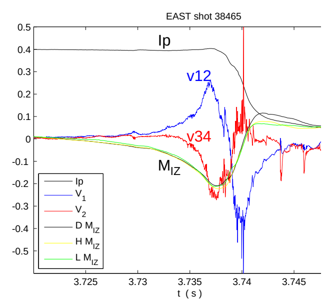
Surface currents in VDE

Successes of theory of Hiro currents:

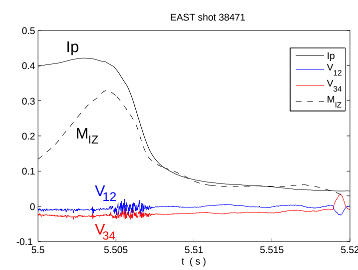
- ***100 % success in explanation of the sign of toroidal asymmetry δI_{pl} in plasma current in JET VDE***
- ***Prediction of Hiro currents in axisymmetric Vertical Disruption Event (VDE)***
- ***Design of first measurements of Hiro currents in VDE on EAST***
- ***Design and installation of special tiles by B.Xiong (ASIPP) on EAST***



4 types of currents can be distinguished on EAST



Downward VDE generates Hiro currents



Upward VDE does not produce a signal

The EAST measurements have confirmed the critical prediction of TMHD:

Plasma motion to the plates is necessary for excitation of Hiro currents