http://w3.pppl.gov/~zakharov/LEZ-130422.pdf

Hiro currents: physics and a bit of politics*

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Theory and Simulation of Disruptions Workshop

July 17-19, 2013, 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

Hiro currents in the wall surface are generated when the unstable plasma during disruptions touches the conducting structures. In contrast to eddy currents in the wall, which are generated by perturbations of the magnetic field between the plasma and the wall, Hiro currents are generated by the plasma motion into the wall surface VxB.

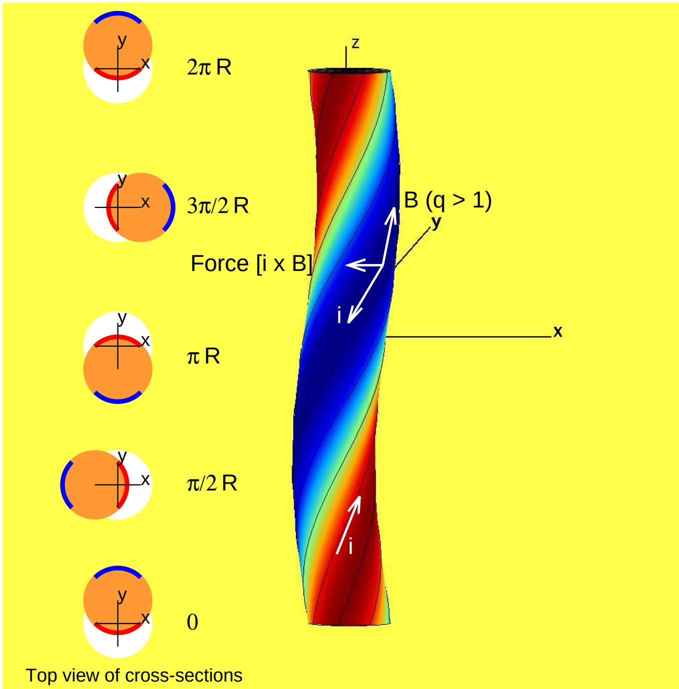
Hiro currents due to m/n=1/1 Wall Touching Kink Mode, well identified in JET VDEs, are missed in 3-D simulations due to inappropriate boundary condition on the plasma velocity. After May 2012 and direct measurements on EAST of axisymmetrical Hiro currents during VDE, it became clear that this effects was missed also in interpretations and 2-D simulations of VDEs.

New numerical schemes, based on adaptive coordinates, aligned with the magnetic field, should be used to reproduce tge Hiro currents. Here we present the steps for development of the VDE simulation code system, which includes the interfacing of the core equilibrium code ESC, plasma edge equilibrium code EEC, and conducting shell simulation code SHL. ESC calculates the core plasma up to a virtual internal boundary using Fourier representation of flux coordinates, EEC uses Hermite finite elements between virtual and the real plasma boundary, while the SHL code calculates vacuum magnetic field and the currents (both eddy and Hiro) in a realistic 3-D shell of a tokamak.

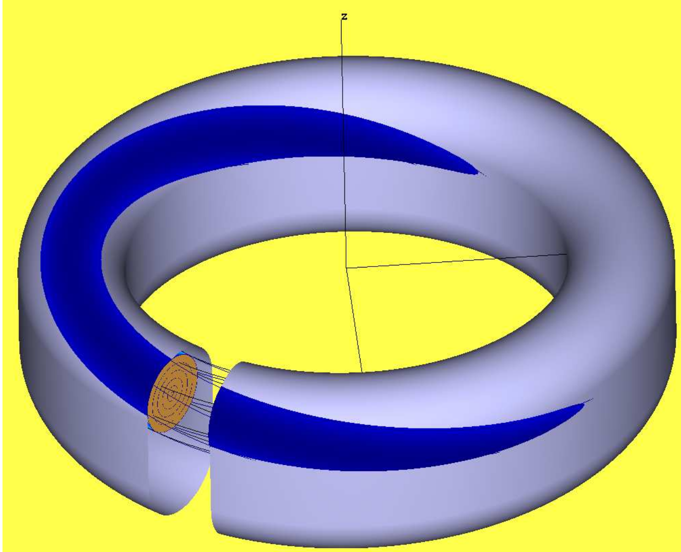
Contents

1 Hiro currents and Wall Touching Kink Mode (WTKM)

Introduced in 2007 as a key element of disruptions



Hiro currents*



****named in the honor of Hironori Takahashi***

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

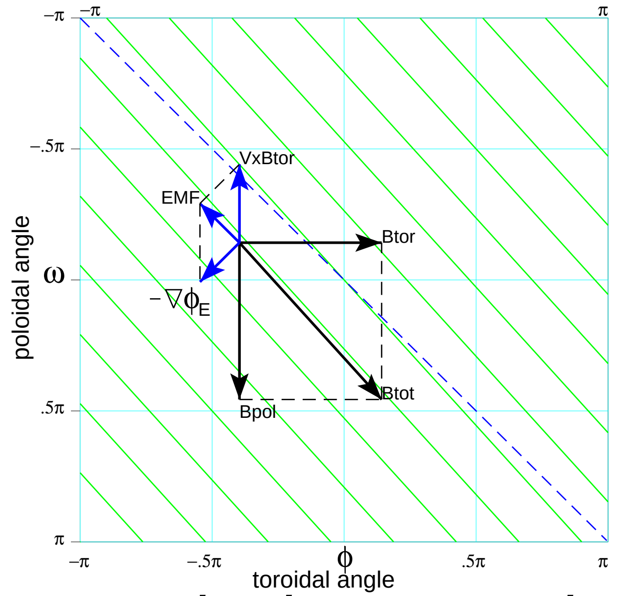
The m/n=1/1 WTKM in VDE always leads to asymmetry in plasma current measurements.

Hiro currents are predicted by theory of perturbed equilibrium

In contrast to ideal or resistive MHD models, equilibrium describes a real plasma.

This makes the Hiro currents prediction unshakable.

Electro Motive Force driving surface currents



Rectangular plane representing the plasma surface

The Faraday (Ohm's) law at the plasma edge

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

$$-\frac{\partial \vec{A}^{i,surf}}{\partial t} \quad \underbrace{-\frac{\partial \vec{A}^{pl,core}}{\partial t} + V B_\omega \vec{e}_\varphi}_{vanishes\ \ for\ \ m=1} - \underbrace{V B_\varphi \vec{e}_\omega}_{driving\ \ EMF} - \nabla \phi_E^{surf} = \frac{\vec{\jmath}}{\sigma} \qquad (1.1)$$

Surface currents are driven by the plasma motion VB_φ in the toroidal magnetic field B_φ (for all m=1 and m > 1 modes)

- ***The amplitude of the surface current DOES NOT contain the resonant factor $(1-q)$***

$$\mu_0 \vec{\imath}_{11} = -2\xi_{11} \frac{B_\varphi}{R} \left(\vec{e}_\varphi + \frac{a}{R} \vec{e}_\omega \right) \cos(\omega - \varphi) \qquad (1.2)$$

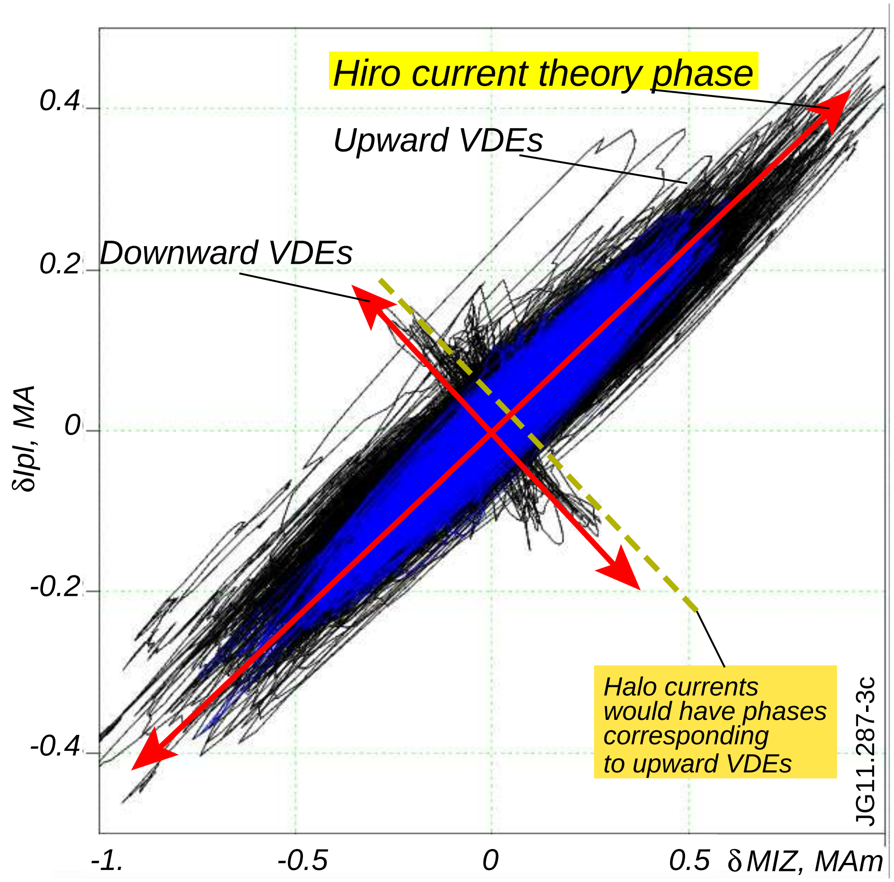
- ***The value of the current is determined solely by plasma deformation.***

Instability acts as a current (rather than voltage) generator.

Hiro currents explain toroidal asymmetry in Ipl

100 % success in explanation of the sign of toroidal asymmetry on wall currents on JET

(in contrast to 100 % failure of "halo current"interpretations)



Phase diagram for all 4457 (August 2011), 4693 (July 2012) disruption shots based on all dB data from octants

7,3 ($\varphi_7 = 270^o,\ \varphi_3 = 90^o$), black color and 5,1 ($\varphi_5 = 150^o,\ \varphi_1 = \ 0^o$), blue color

Vertical axis: $I_{pl}(\varphi + \pi, t) - I_{pl}(\varphi, t),$

Horizontal axis: $M_{IZ}(\varphi + \pi, t) - M_{IZ}(\varphi, t),$

$(M_{IZ} \simeq I_{pl}\delta z$ ***- measured signal***$)$

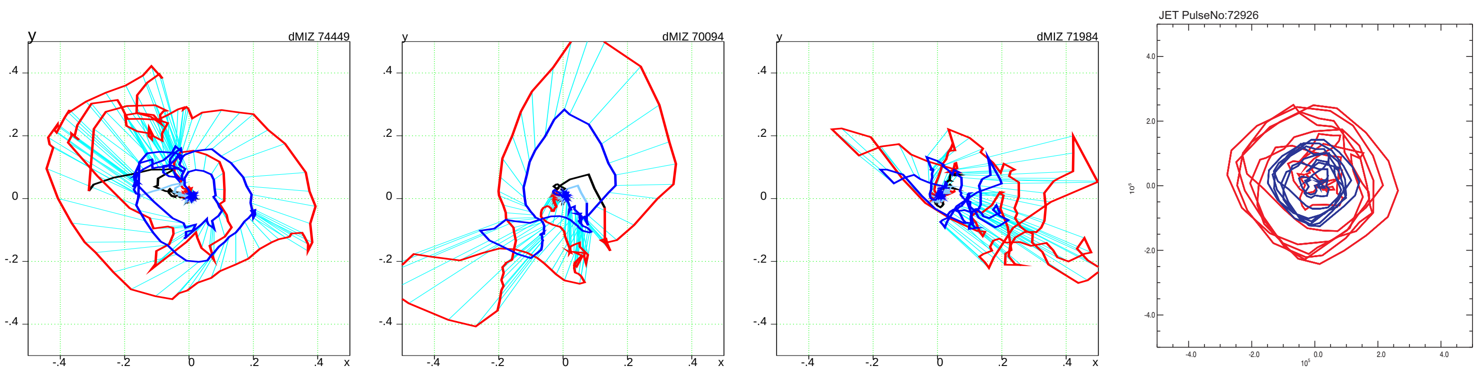
Recent data on ILW confirm the same pattern

Important properties of Hiro currents

- ***Absolutely necessary for slowing down plasma dynamics from μs-time scales to observable $1-10ms$ equilibrium evolution;***
- ***Plasma act as Hiro current, rather than voltage generator;***
- ***Can confuse interpretations of magnetic measurement regarding plasma displacement, values of a, q_a;***
- ***Can shorten the gaps between tiles and create large electric circuits along the PFC surface (in contrast to broken by gaps eddy currents);***
- ***Can significantly affect plasma azimuthal motion and rotation.***

Theory confirmed the early (2007) assessment of Fx forces in ITER by JET engineers, thus, making the issue addressed.

Understanding of the disruption physics is impossible without understanding effects associated with Hiro currents. Mode rotation is an important challenge.



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

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

2 "Halo" currents on JET

So far, there is no indications of Halo currents on JET and never was !

In disruption analysis, JET people use measured (!) currents from direct measurements of plasma current asymmetry.

The sign of these measured currents is opposit to "halo" currents as the rest of the community interpret them them.

What JET calls "halo" currents is, in fact, the Hiro currents.

In 1996 unique, excellent magnetic diagnostics, designed for JET by Peter Noll, provided the discovery of named-now-Hiro currents and their unusual direction.7

I (LZ) am not responsible for the fact, that JET engineers did not properly claim the discovery and named it. I also never challenged priority of these engineers.

Why did they decide to be undistinguishable from the community ? Dominance of physicists ?

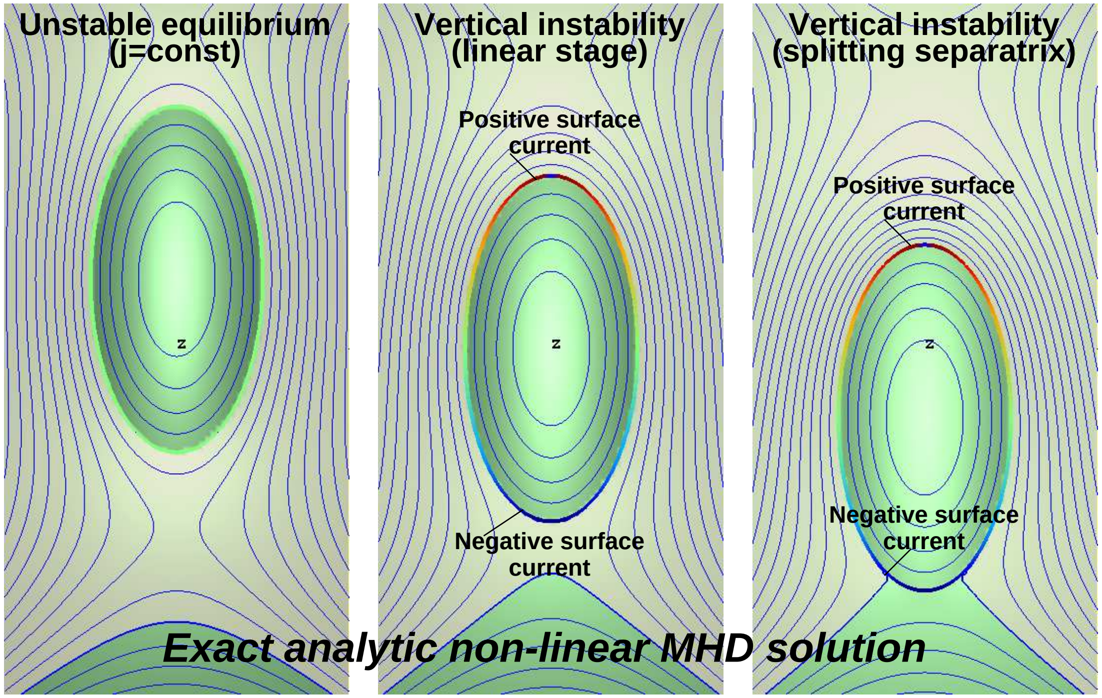
The use of confusing names would be not so important if people still understand what is behind the names. Unfortunately, misuse of names is not so benign. E.g.,

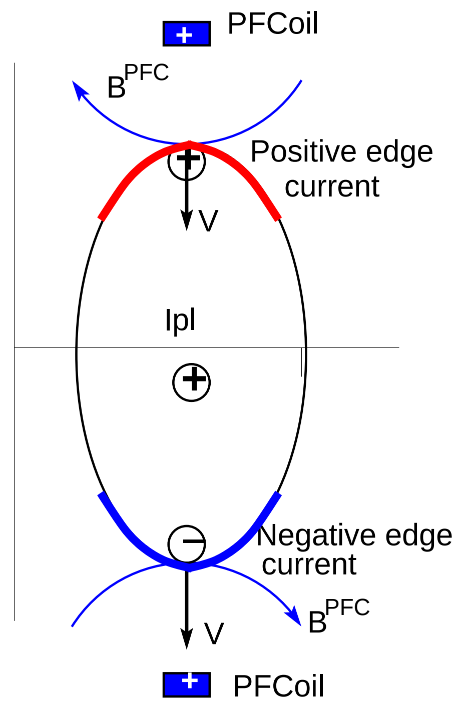
1. ***N.Pomphrey's paper with fake physics and wrong sign of currents to the wall, is adopted as a model of TPF.***
2. ***Any way to a refining physics of disruption is blocked.***
3. ***Theory, numerical simulations and code development are misguided (see, e.g., the yesterday non-sense with a halo blanket VDE)***

New names of new physics effects are the expression of progress.

Intentional (often encouraged) ignorance of new effects blocks further progress.

3 Axisymmetrical Wall Touching Vertical Mode (WTVM)





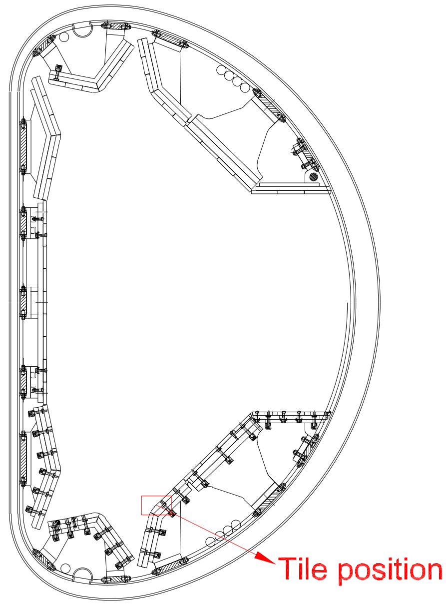
$$-\frac{\partial \vec{A}^{i,surf}}{\partial t} \underbrace{-\frac{\partial \vec{A}^{pl,core}}{\partial t} + V B_{pl}\vec{e}_{\varphi}}_{vanishes\ for\ m/n=1/0} + \underbrace{\vec{V} \times \vec{B}^{PFC}}_{Driving\ EMF} - \nabla \phi_E^{surf} = \frac{\vec{j}}{\sigma} \tag{3.1}$$

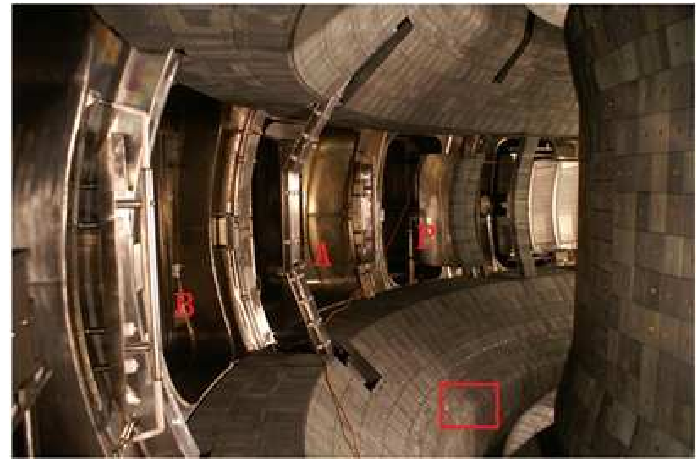
Hiro currents in WTVM:

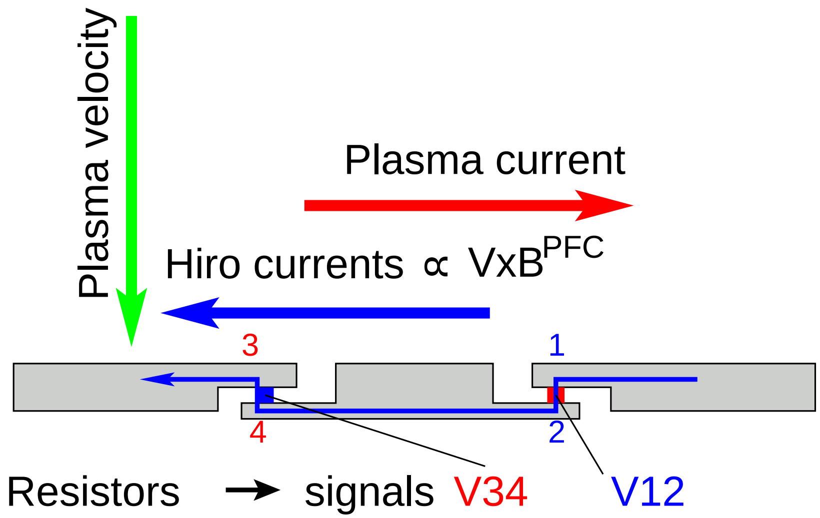
- ***Are generated by the same plasma motion to the wall/tile surface;***
- ***Are axisymmetrical;***
- ***Are not shared with the plasma (in contrast to the kink modes).***

Hiro currents in WTVM cannot be confused with "halo" currents.

Xiong tiles on EAST - New diagnostics for VDE



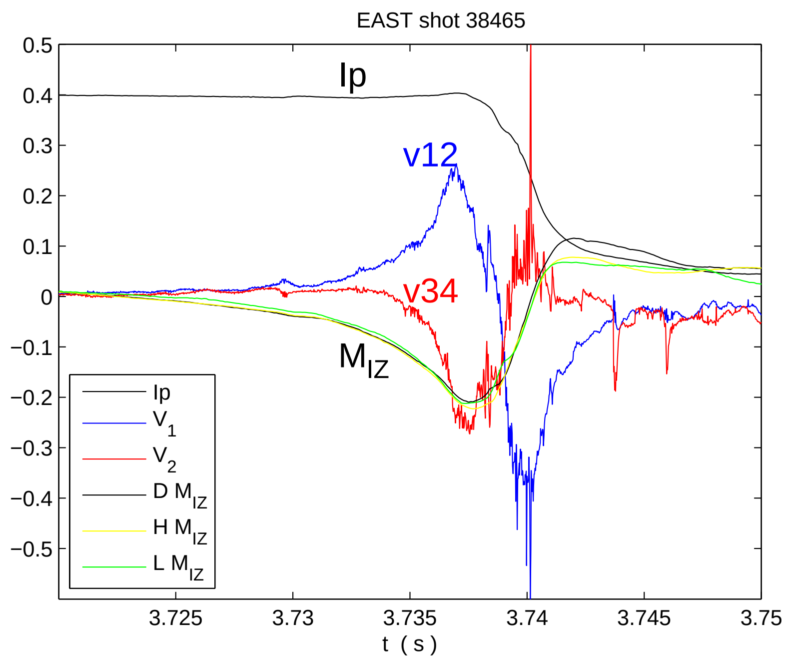




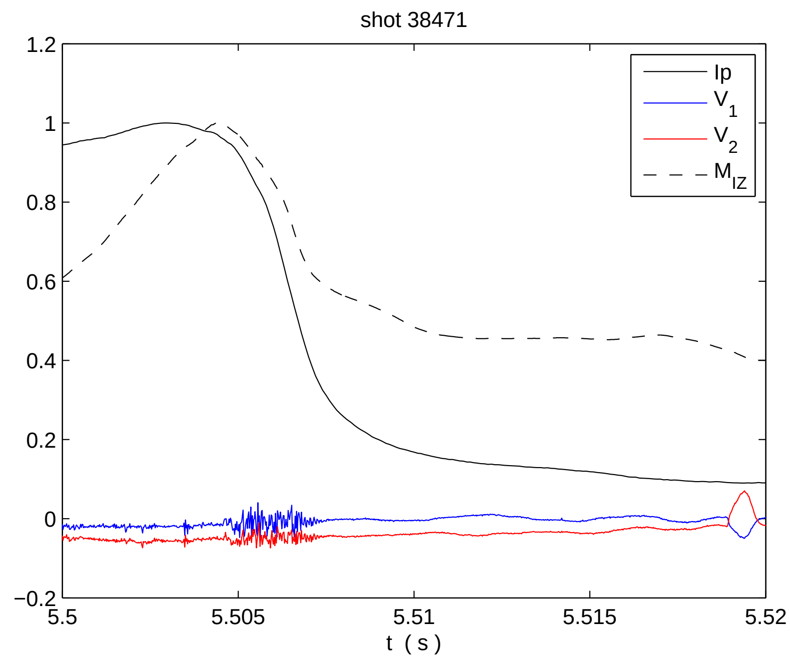
4 types of currents can be distinguished by Xiong tiles.

First measurements of Hiro currents in VDE

Toroidal currents, opposite to the plasma current, predicted by theory (L.Zakharov) and for 2 decades being overlooked in interpretations and simulations of Vertical Disruptions, were measured on EAST in May 2012 (H.Xiong)



Downward VDE



Upward VDE

No toroidal asymmetry.

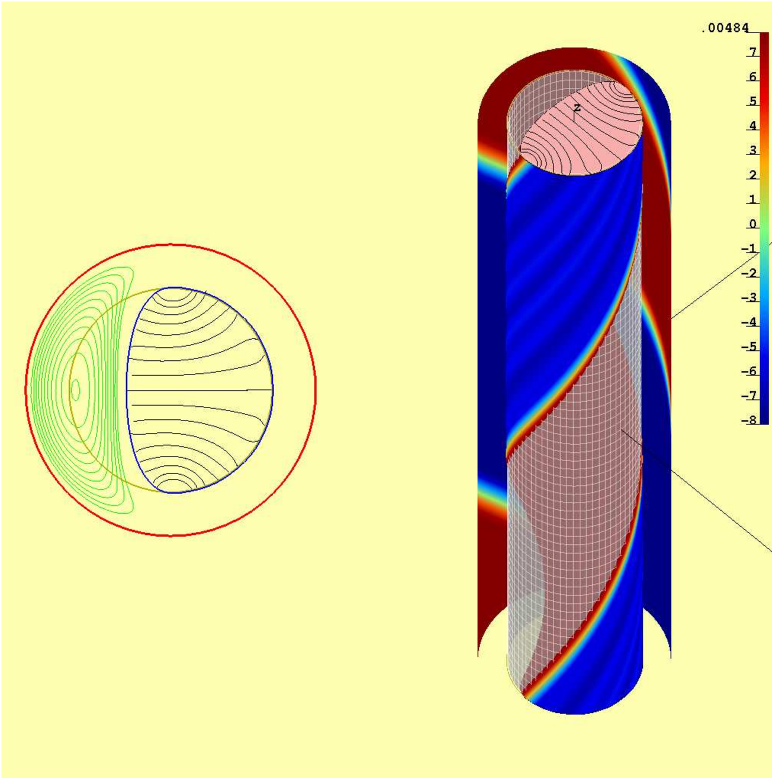
Hiro currents in VDE are NOT SHARED between plasma and the tiles.

Only certified MHD experts can confused the measured Hiro currents in VDE with the “halo” currents.

Failed first on JET, the fiction of “halo” currents failed now on EAST.

Hiro, Evans and “halo” currents

During instability fast plasma motion is stopped by the Hiro currents in tiles



Transient equilibrium maintained by Hiro currents

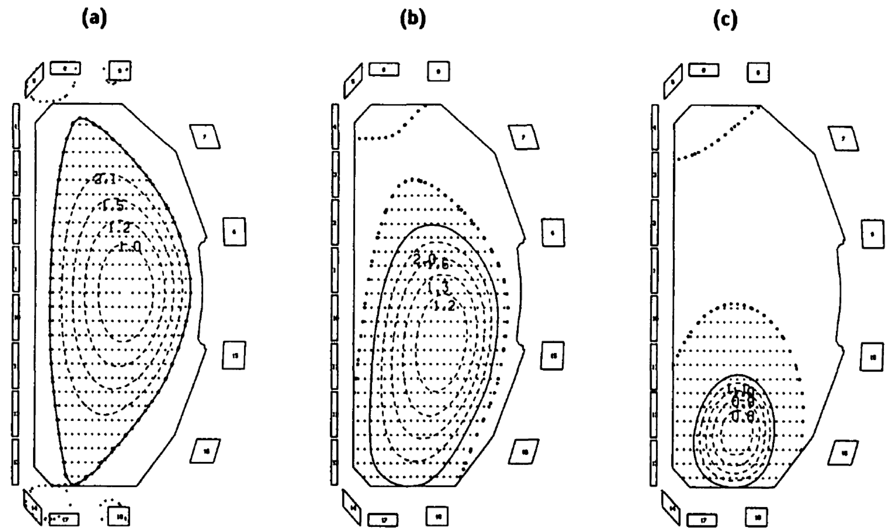


FIG. 3. Equilibrium flux plots from EFIT at three times during the vertical instability: (a) 2660 ms, (b) 2675 ms and (c) 2684 ms. Plasma current was allowed in the hatched region, including part of the SOL.

VDE tile currents suggest totally different interpretation.

- ***Negative Hiro currents are flowing along the tile surface***
- ***Positive (force free) surface currents from the plasma edge may go to the tile surface as “Evans” currents. They are measured, but misinterpreted as the halo currents.***

The physics of Hiro and Evans currents is different from the physics of halo currents and summarized in the Table.

	Hiro currents	Evans currents:	Halo currents:
1	*Both result from magnetic flux conservation.*		*Derived from questionable use of equilibrium reconstruction. No strong reason for existence.*
2	*Driven by instability acting as current generator.*	*Driven by instability acting as voltage generator.*	*Assumed to be driven by a residual voltage outside the last closed magnetic surface.*
3	*Highly concentrated at the plasma edge.*		*Diffused in space with open field lines.*
4	*Big in amplitude, proportional to plasma deformation.*		*Limited by the ion saturation current.*
5	*Absolutely necessary to slow down the instability.*	*Force-free, little, if any, effect on stabilization.*	*Secondary, if any, effect on stabilization.*
6	*Opposite to I_{pl}.*	*Same direction as I_{pl}.*	*Same direction as I_{pl}.*
7	*Consistent with toroidal asymmetry in JET VDEs.*		*Ruled out as a reason of toroidal asymmetry.*
8	*The real plasma physics objects*		*Most probably the result of misinterpretation*
		May 2012	
9	*Consistent with EAST VDE measurements.*	*No indication of presence*	*No indication of presence*

LLD-10 most probably was damaged by the Hiro currents

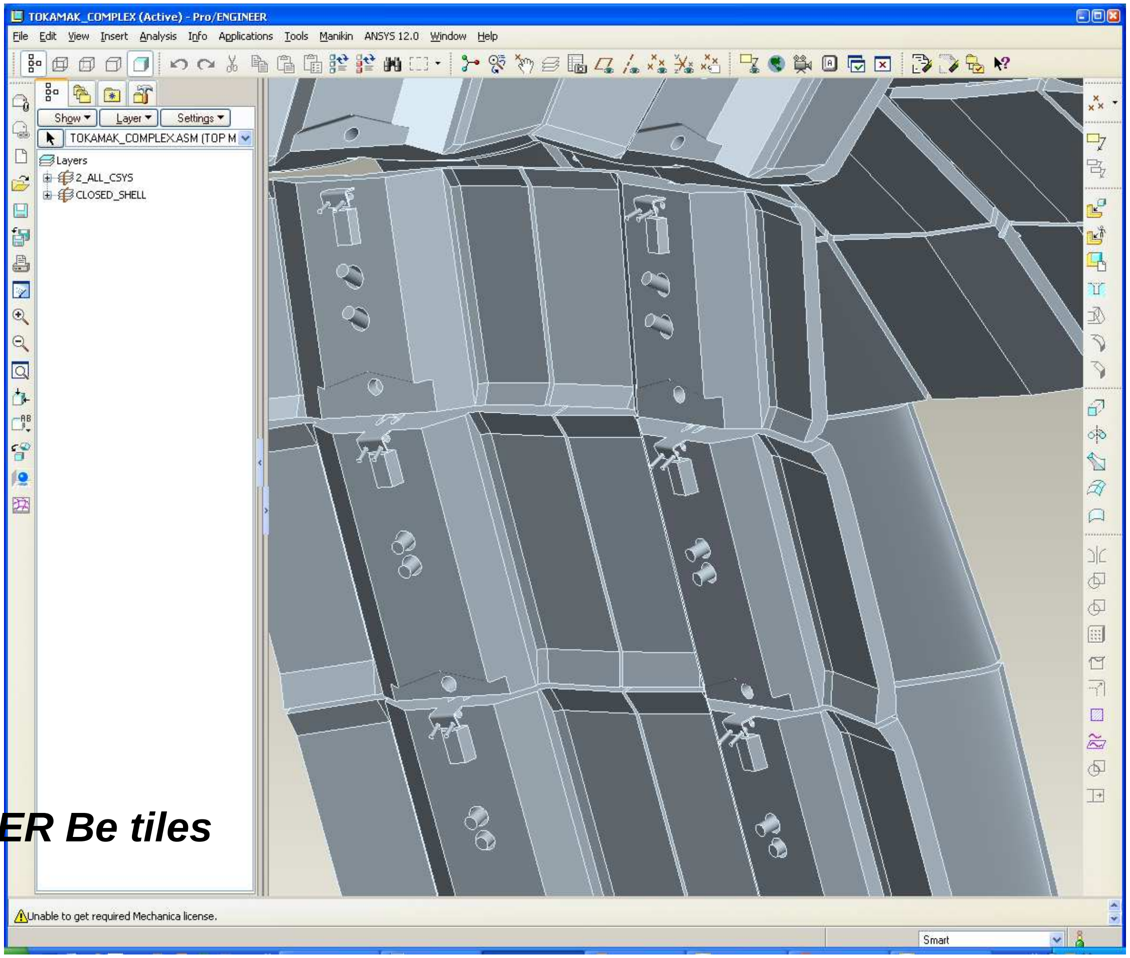
Liquid lithium divertor target system commissioned

Utilized in four LLD experimental proposals in three campaigns

LLD plate covered with lithium
Significant over-flow evident consistent with evaporating 2 x fill capacity

- **Plasma surface heating raised the LLD surface temperature to ~ 200 - 250 °C.**
- **No significant moly surface damage or moly influx observed.**
- **Damage discovered after operations. Plasma disruptions caused mechanical support and arcing damages. Explains why electrical heaters failed. Air heater has worked well but the heating tubes were arc damaged.**
- **LLD plates being reinstalled with improvements in the mechanical support structure and grounding. No active heaters but will utilize plasma heating.**

Hiro current may damage ITER Be tiles



ITER Be tiles

If disruptions and Hiro currents are responsible for the damage of LLD on NSTX, the effect on Be tiles in ITER could be devastating.

We propose to make the LLD installation design consistent with the following guidance.

1. ***Make several ground points for each LLD sector.***
2. ***Arrange the value of the resistance of grounding at a minimal level (TBD) tolerable for the OH solenoid performance and PF-Coil control of equilibrium.***

Implementation of these guidance's in FY11 campaign and then confirmation of our guess about the reason of LLD damage will allow to make specific recommendations for designing Be tiles in ITER, thus, giving NSTX an opportunity to make a unique contribution to the ITER project.

4 2-D version of DSC simulates 3 regimes of kink modes

The Wall Touching Kink Mode (WTKM), associated with the Hiro currents, is a new kind of MHD modes. It is well distinguishable from the Free Boundary Kink Modes (FBKM).

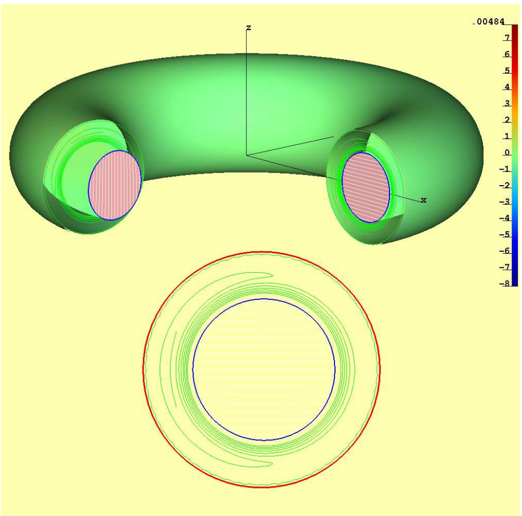
WTKM is a natural candidate for triggering the thermal quench.

New codes, based on adaptive grids are necessary for simulation of WTKM.

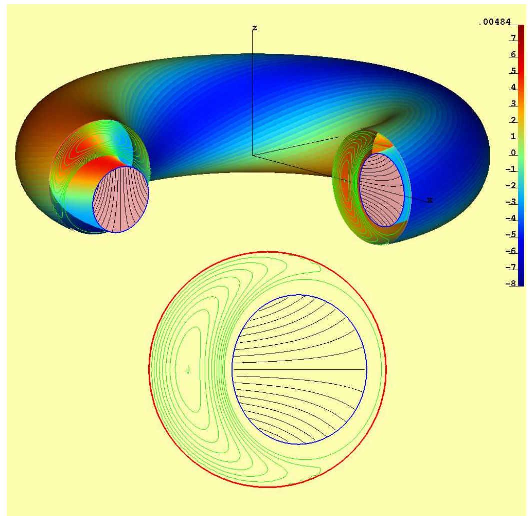
So far, Kadomsev-Pogutse reduced MHD model was implemented.

Movie 1: Free boundary kink mode inside a shell

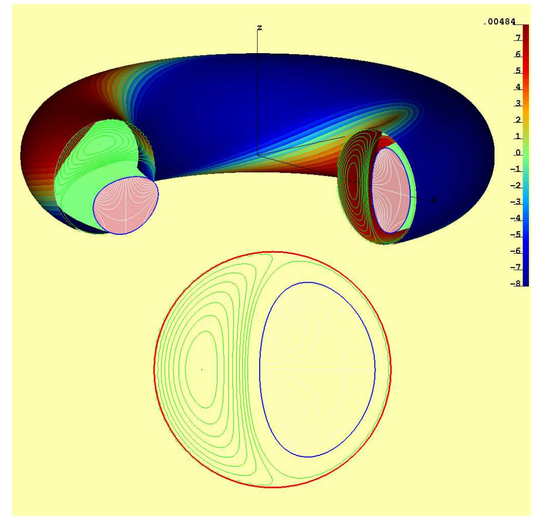
Fast regime of the kink mode inside the ideal wall (idealized theoretical model)



Initial perturbed plasma



Fast phase of instability



Saturation of the mode

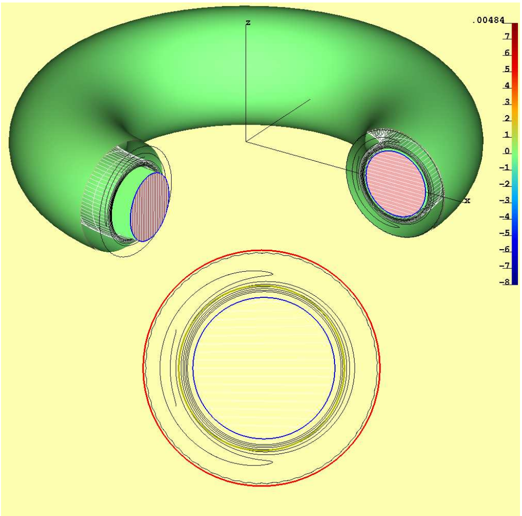
After saturation, plasma is maintained in equilibrium by the eddy currents in the ideal wall.

6in

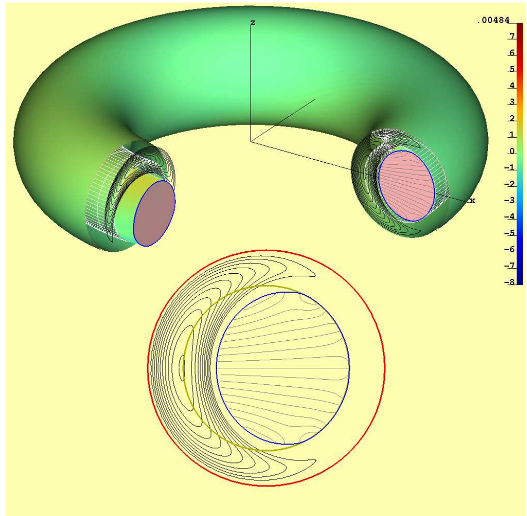
NIMROD can simulate this regime

Movie 2: Wall touching kink mode. Hiro current excitation

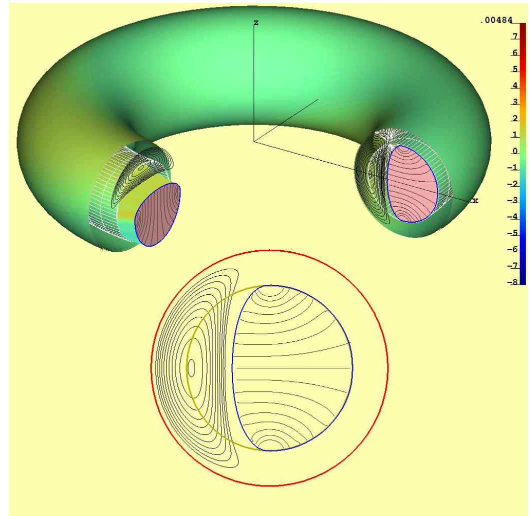
Fast regime of the wall touching kink mode inside the tile surface



Initial perturbed plasma



Fast phase of instability, excitation of Hiro currents



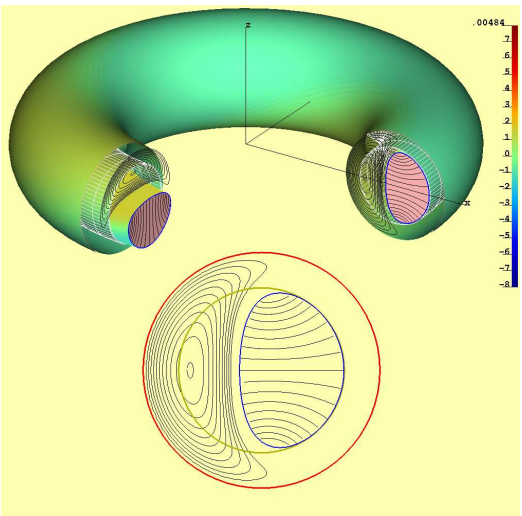
Saturation of the mode due to Hiro currents

Plasma motion slows down due to excitation of the Hiro currents along the tile surface.

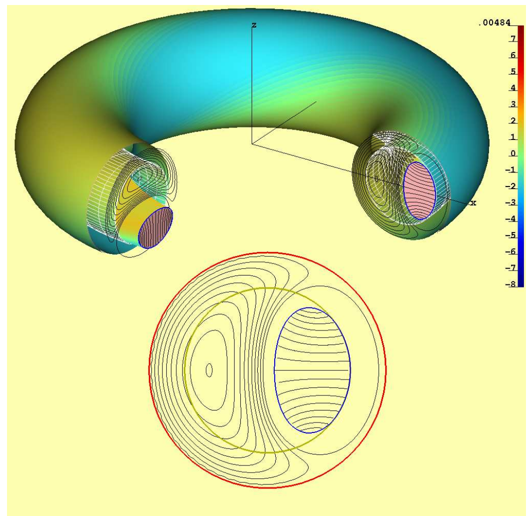
Movie 3: Plasma decay and termination

Self-consistent plasma/(Hiro currents) decay with plasma moving into the wall.

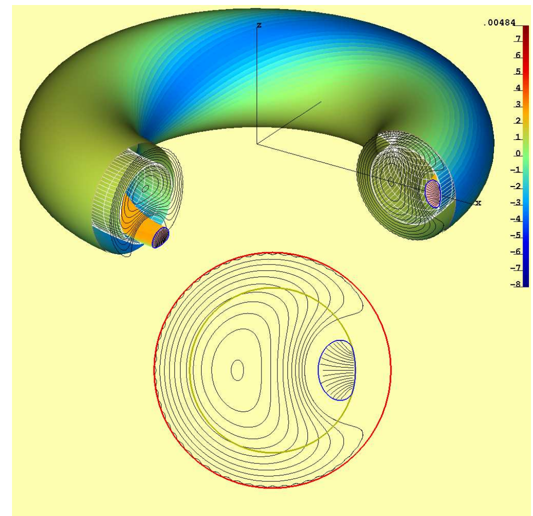
This is the most important new regime for MHD simulations.



Initial phase of decay



Intermediate phase of decay



Final phase of plasma termination

Two regimes: (a) generation of the Hiro currents, and (b) plasma decay cannot be reproduced by existing 3-D numerical codes

"Salt water" boundary condition $V_{normal} = 0$, remaining uncorrected for 5.5 years, makes M3D, NIMROD and other 3-D codes irrelevant to disruption simulations

5 Politics against the science

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.

Everything is upside down in the last paragraph.

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

6 ESC-EEC-EPC-ASTRA-STB-SHL-DSC ⟹ RTF,DSC

Moving forward with tokamak simulations

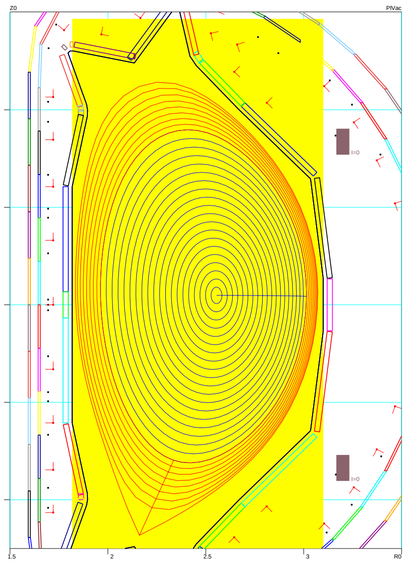
- ***ESC*** - ***Equilibrium and Stability Code***
- ***EEC*** - ***Edge Equilibrium Code***
- ***EPC*** - ***Edge Particle Code***
- ***ASTRA*** - ***Automatic System for Transport Analysis***
- ***STB*** - ***linear stability and perturbed equilibrium code (reduced MHD version of STB was supplied to ITER in 2012)***
- ***SHL*** - ***3-D Shell simulation code***
- ***DSC*** - ***Disruption Simulation Code (2-D version is functional)***
- ***ESI*** - ***Equilibrium Spline Interface as a basis for communications***
- ***Cb*** - ***CodeBuilder as a tool for implementation of code-talking and control***

- ***RTF*** - ***Real Time Forecast of tokamak discharges***

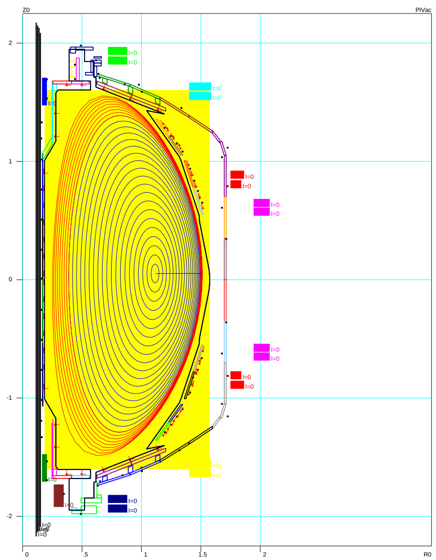
All these components (or their versions) are necessary for addressing disruption problem.

Speed, flexibility in modifications, compactness, integration with formalized documentation and On-Line help are required.

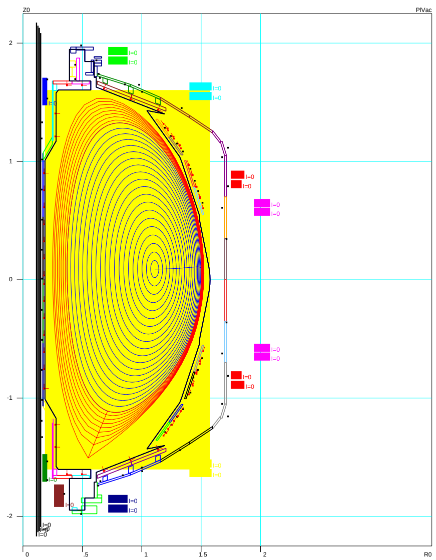
ESC-EEC fixed-free boundary code with flux coordinates



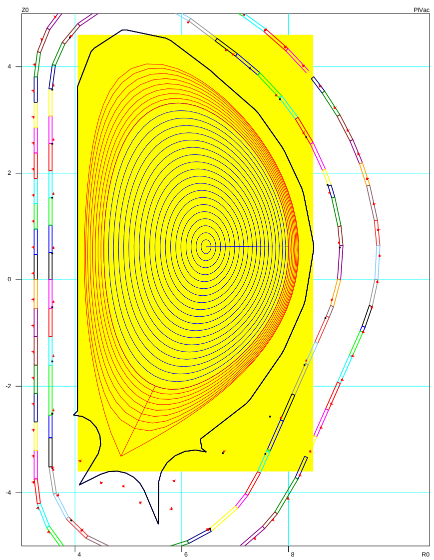
EAST $R/a = 2.0/0.5$, $\beta = 3\%$



NSTX $R/a = 0.88/0.65$, $\beta = 35\%$



NSTX $R/a = 0.88/0.65$, $\beta = 33\%$



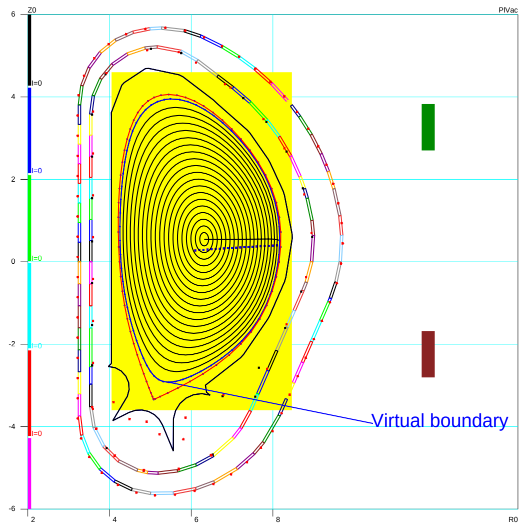
ITER $\beta = 5\%$

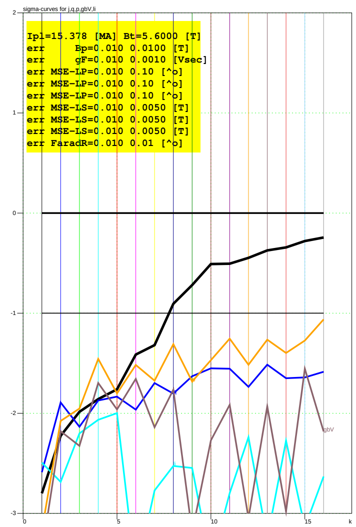
The resulting ESC-EEC code system acquired unmatched ability

1. ***in fast free and fixed boundary equilibrium calculations for arbitrary plasma shapes,***
2. ***in using both $r-z$ and different flux coordinates,***
3. ***in choosing different combinations of input profiles,***
4. ***in performing equilibrium reconstruction together with variances analysis, and***
5. ***in assessing the diagnostics used for equilibrium reconstruction.***

Reliable equilibrium reconstruction

Preventions of disruptions needs the best possible equilibrium reconstruction

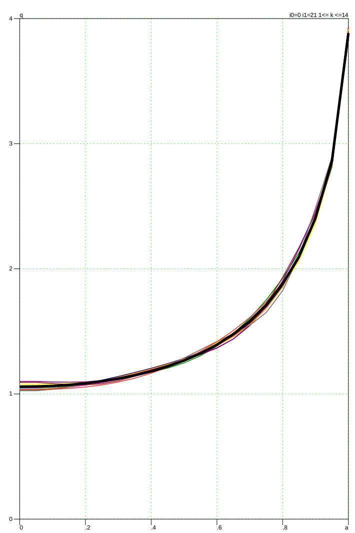


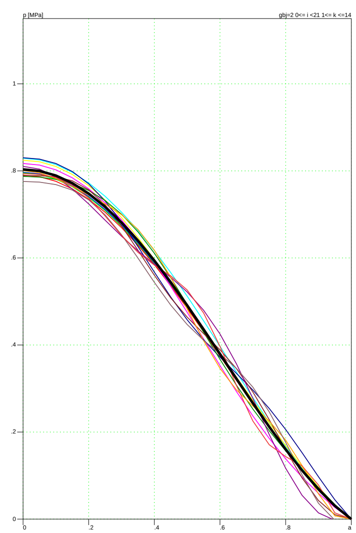


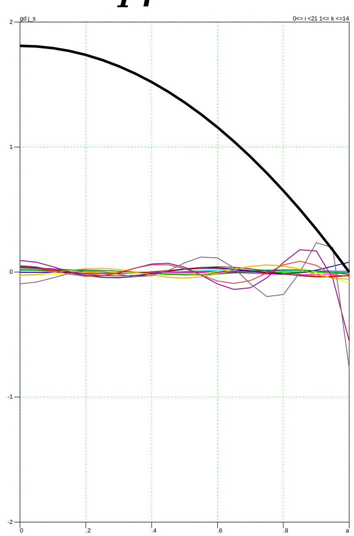
Unique capabilities of ESC in reconstruction

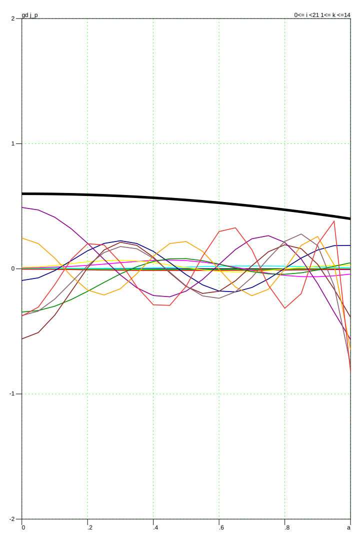
Variances in equilibrium reconstruction of ITER core using MSE-LP, MSE-LS, Faraday rotation and magnetic diagnostics

ITER ***σ-curves*** ***q-profile***





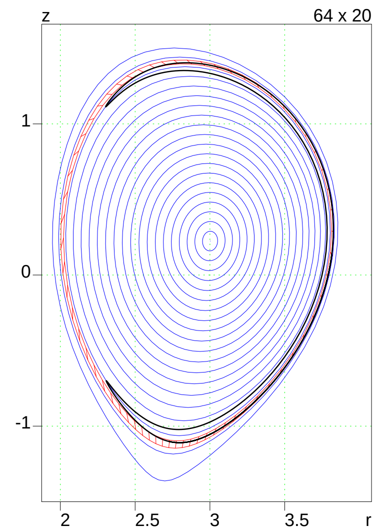


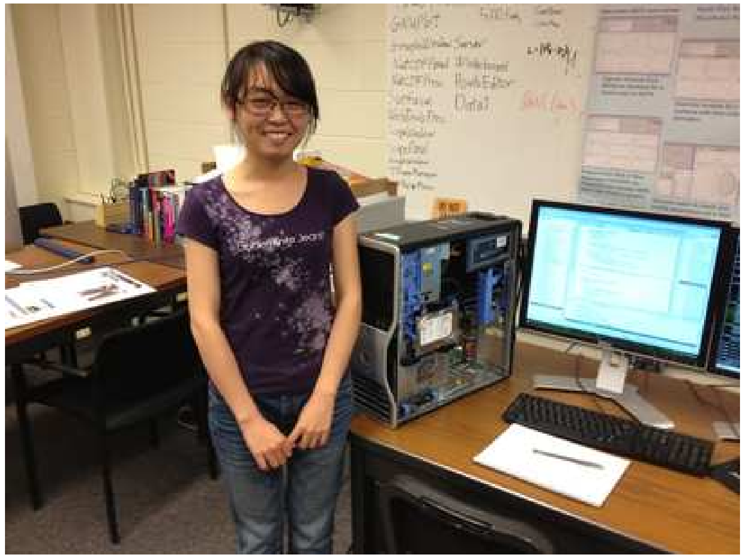


p-profile ***j_s-profile*** ***j_p-profile***

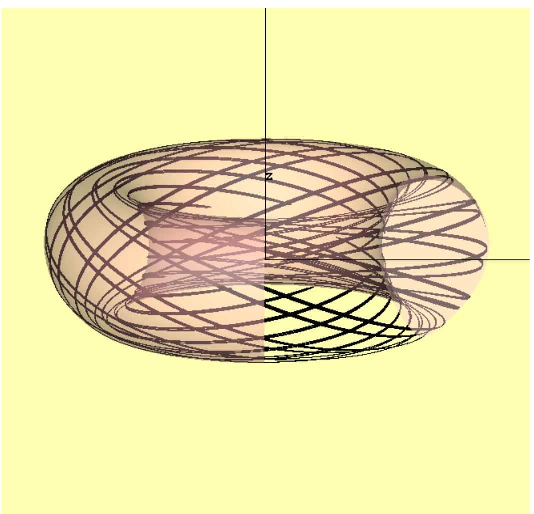
Edge Particle Code (EPC) driven by GPU

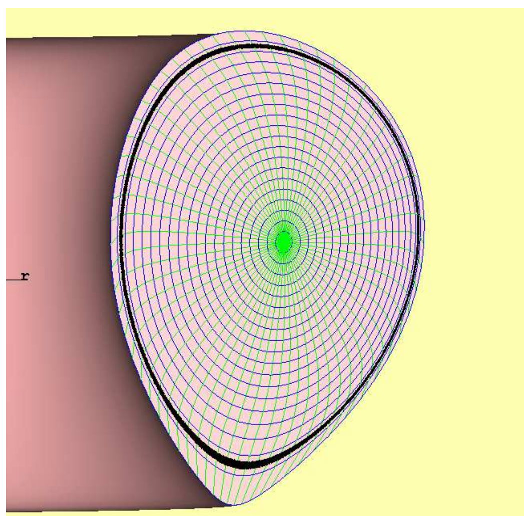
Particle losses due to collisions at the plasma edge (testing an idea on L-H transition)

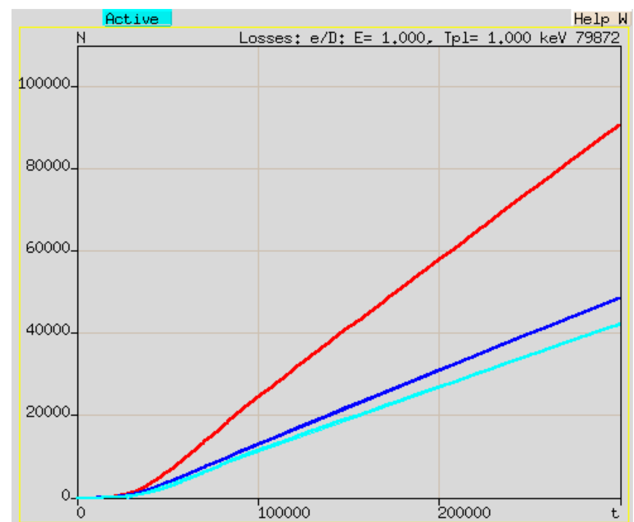




1. ***GC motion routine confines collision-less particles indefinitely.***
2. ***Collisions are included as a pitch angle diffusion.***
3. ***GPU inside a tiny PC provides an astonishing speed of calculations: 300,000 time steps for 80,000 particles one minute.***







Speed of GPU simulations makes RTF realistic not only for ITER but for existing tokamaks as well.