Summary Session III:
Halo & Hiro Currents and Forces

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Thanks to the Speakers for their Presentations

- Disruption Detection and Halo Currents in NSTX: S. Gerhardt
- Experimental Results on Halo and Hiro Currents: T. Hender
- Theory of Halo Currents: A. Boozer
- Hiro Currents: L. Zakharov
- Toroidal Rotation and Halo Current Produced by Disruptions: H. Strauss

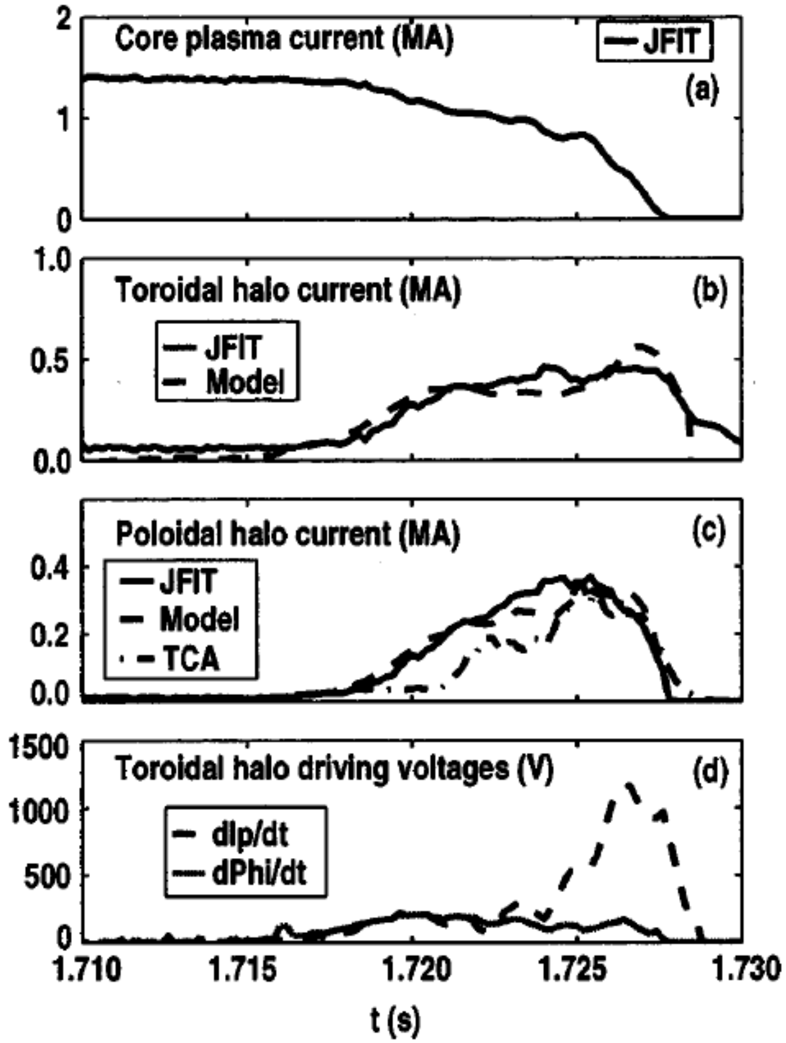
I have also benefitted from the related presentations by:

- Theory of Non-Axisymmetric Vertical Displacement Events : Richard Fitzpatrick
- Simulations of asymmetric VDEs with M3D: model validation and comparison with experimental cases: R. Paccagnella

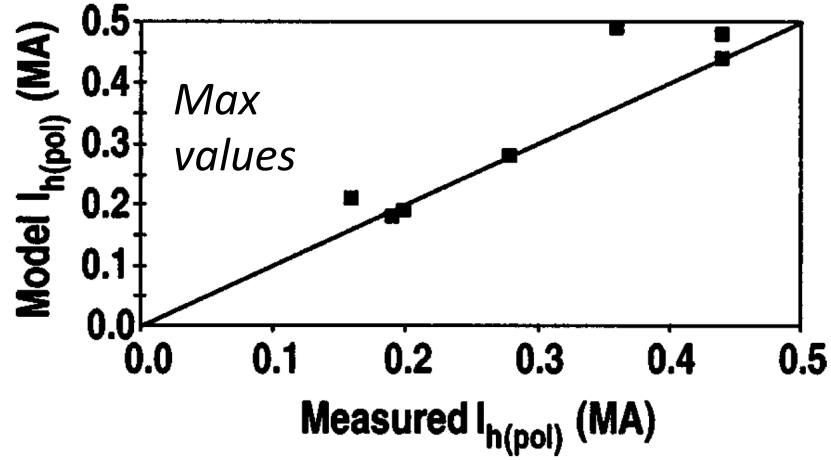
Two Motivations for Understanding the Currents and Forces

- **Important issue for the design of ITER and future power plants**
  - Practical implications associated with the design of all in-vessel components and the vacuum vessel
  - Possibility of a rotating mode coupling with the vacuum vessel and TF coils has potentially significant consequences
  - Approach has to withstand regulatory scrutiny and is setting precedents for the future.
    - ***Experimental results from ITER will have a major impact on the design requirements of future tokamaks; however, we cannot wait.***
- **Challenging and interesting theoretical problem.**
  - How to incorporate the currents in the outer flux surfaces and walls in *engineering*, equilibrium and stability calculations?
  - What determines the magnitude and direction of the currents and rotation of the instability?
  - Need to validate models against experimental data recognizing that despite significant efforts the dataset on any facility is not complete.
    - Variation in results between shots and facilities exists complicating the validation efforts.

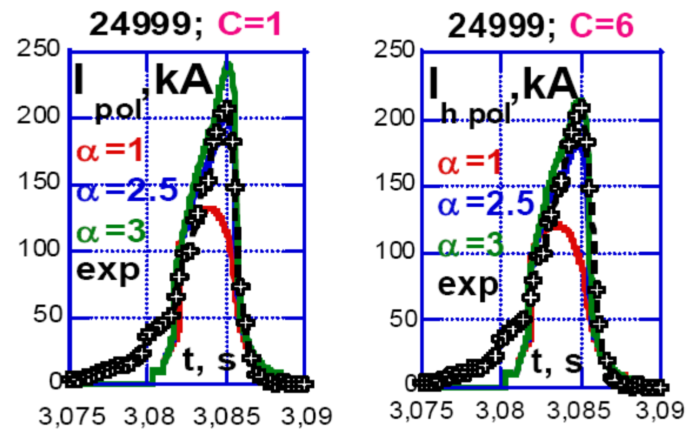
Symmetric Halo Current well understood



D Humphreys et al PoP 1999



- Treats the core and halo current regions as coupled circuits

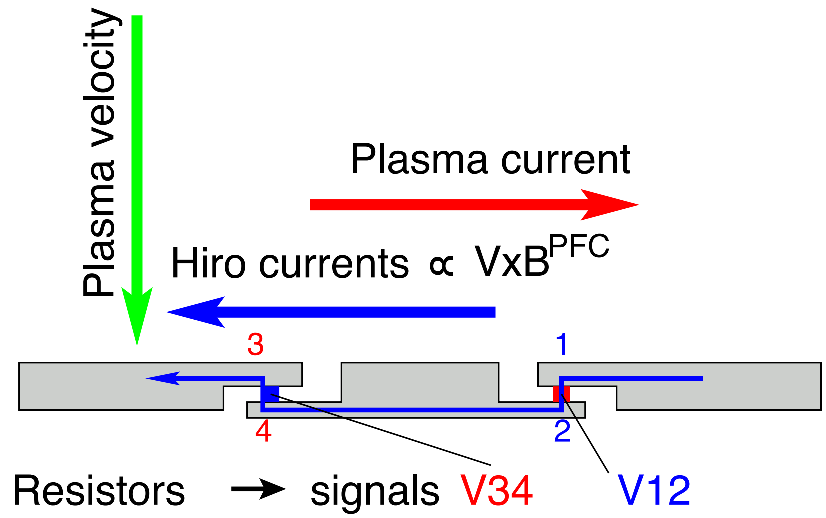


DINA model: *Lukash et al EPS 2010*

- Also halo modelling with TSC

- **Zakharov has challenged this conventional view.**

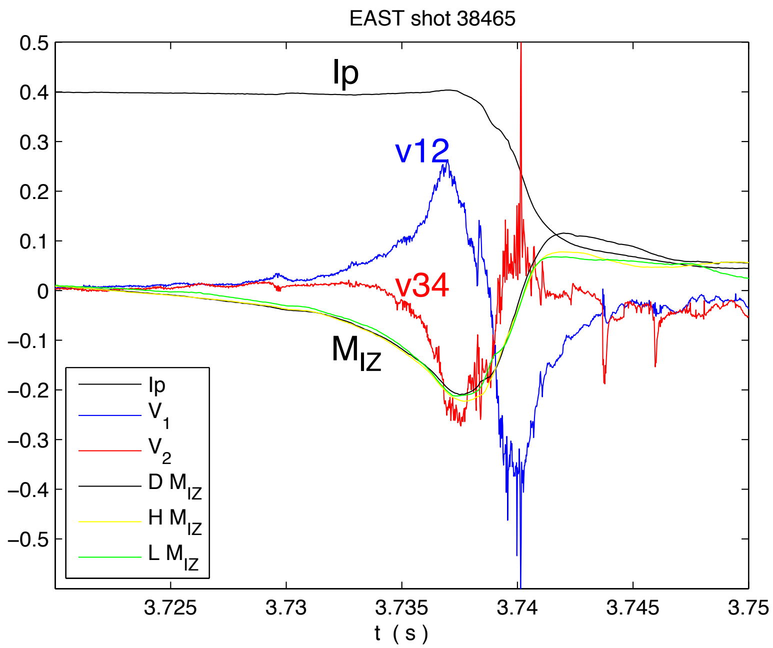
New Data Attempting to Distinguish Hiro from Halo Currents from EAST



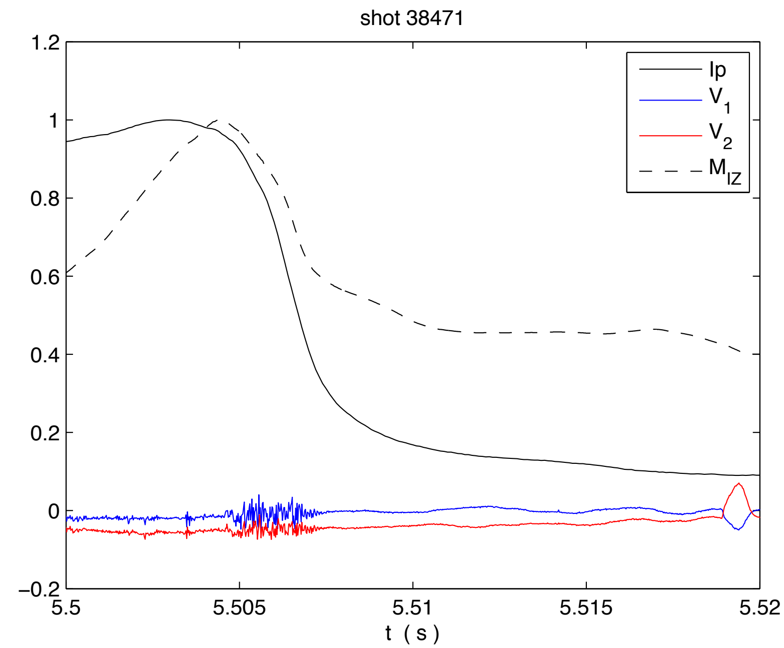
4 types of currents can be distinguished by Xiong tiles.

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)



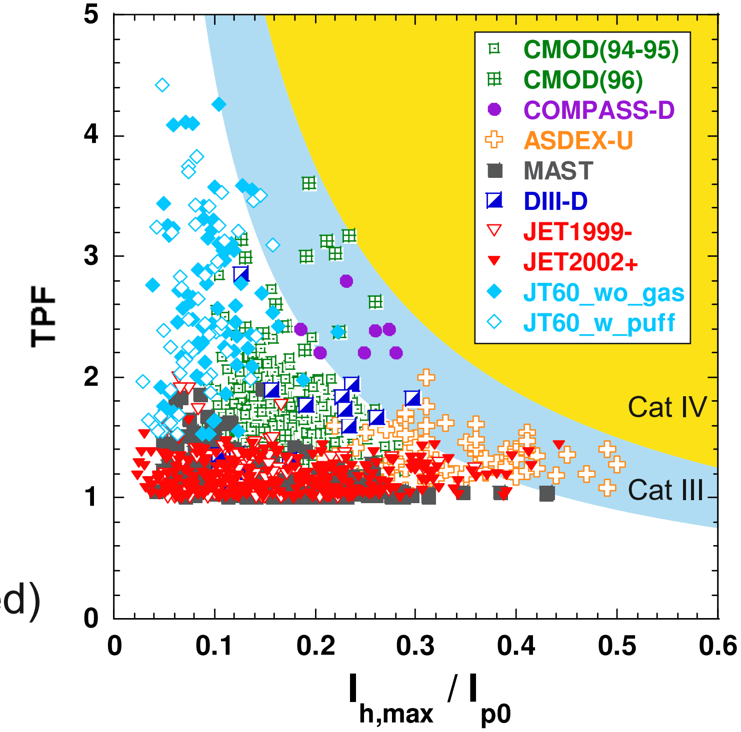
Downward VDE

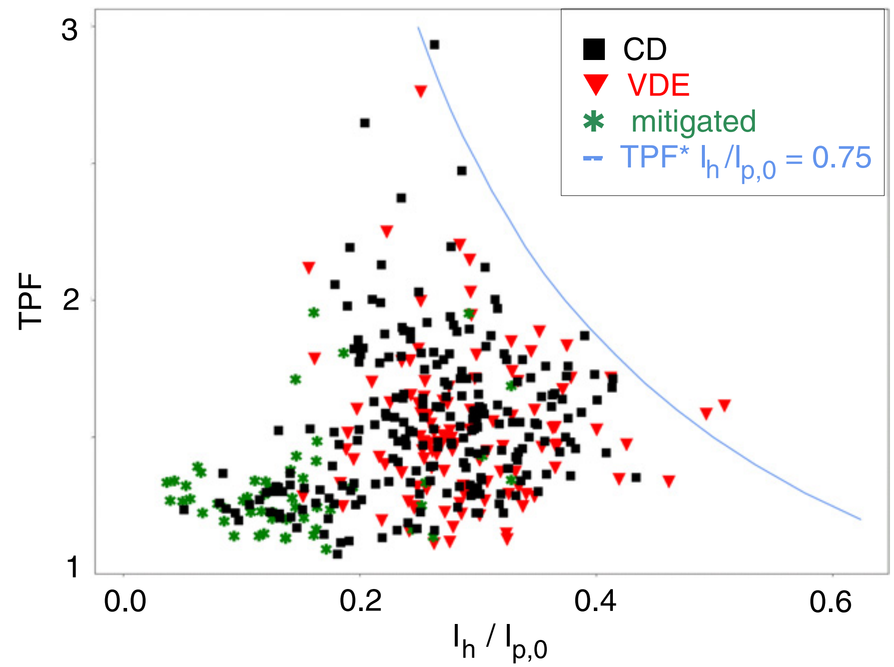


Upward VDE

- Are the Hiro currents in the direction opposite to the plasma current sufficiently large to enable force balance?
  - Can we compare the predicted magnitude of the currents and the footprint.?
- If they are flowing through in-vessel components, can these components withstand the forces?

Significant Variation Between Devices and Types of Disruptions





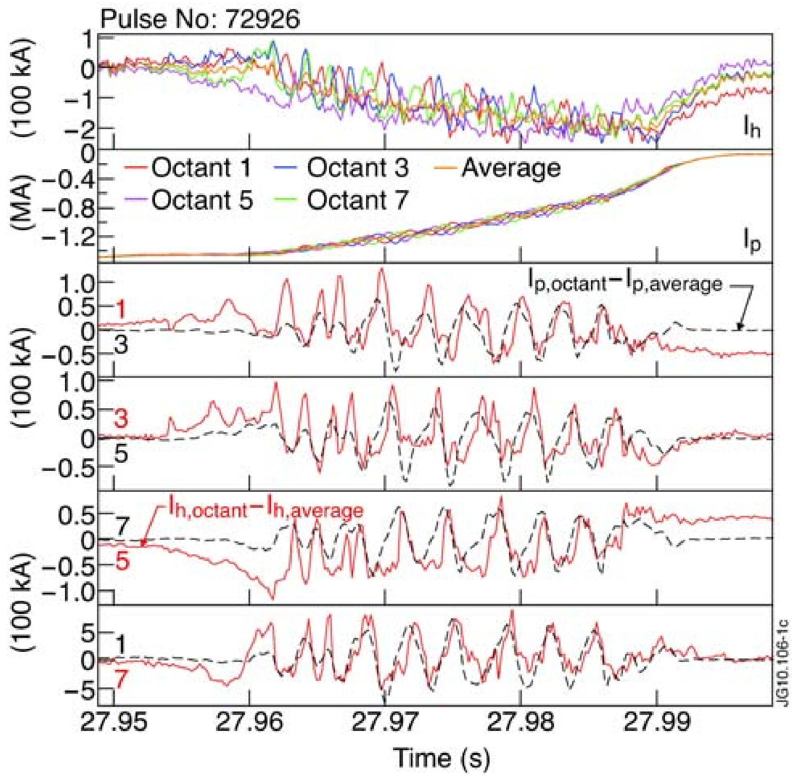
John Wesley has pointed out that the operating boundary is different for different machines. Why? Will ITER be like C-Mod or JET?

Pautasso et al. (AUG) have extensive measurements of the halo currents and observe significant variation associated with the type of disruptions and mitigation.

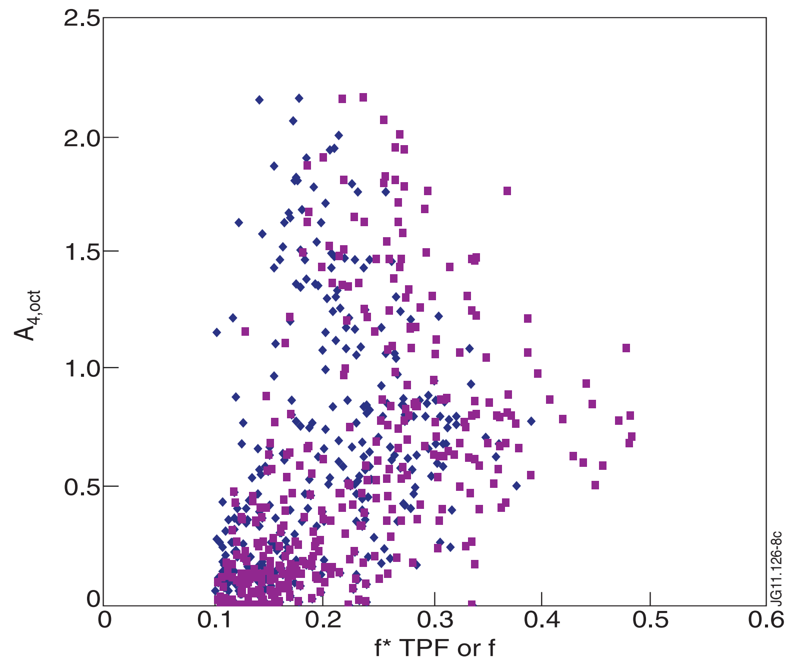
Experimentalists Have Characterized Halo/Hiro Currents

- **Halo current fraction**
  - Sinusoidal behavior though not a pure sine wave
- **Toroidal peaking factor and direct measurements**
  - Indicates that the current is not only due to a n=0 component though in some discharges that is a large component.
  - In general, the **halo current pattern** cannot be described as simply due to n=0 and n=1
- **Onset of halo currents at q~2 in NSTX and AUG but q~1 in JET**
- **Width of halo current**
- **Current Quench duration**
- **Measured current asymmetries in JET**
  - n=1 component responsible for JET sideways force and torque on the vacuum vessel
  - n=1 mode rotation is in the counter direction, few cycles but scaling to ITER is unknown, large variability
- **Are the discrepancies associated with n=1 being a kink mode due to diagnostic interpretation issues?**

JET Observes Relationship in the Toroidal Current Asymmetry and Poloidal Halo Currents

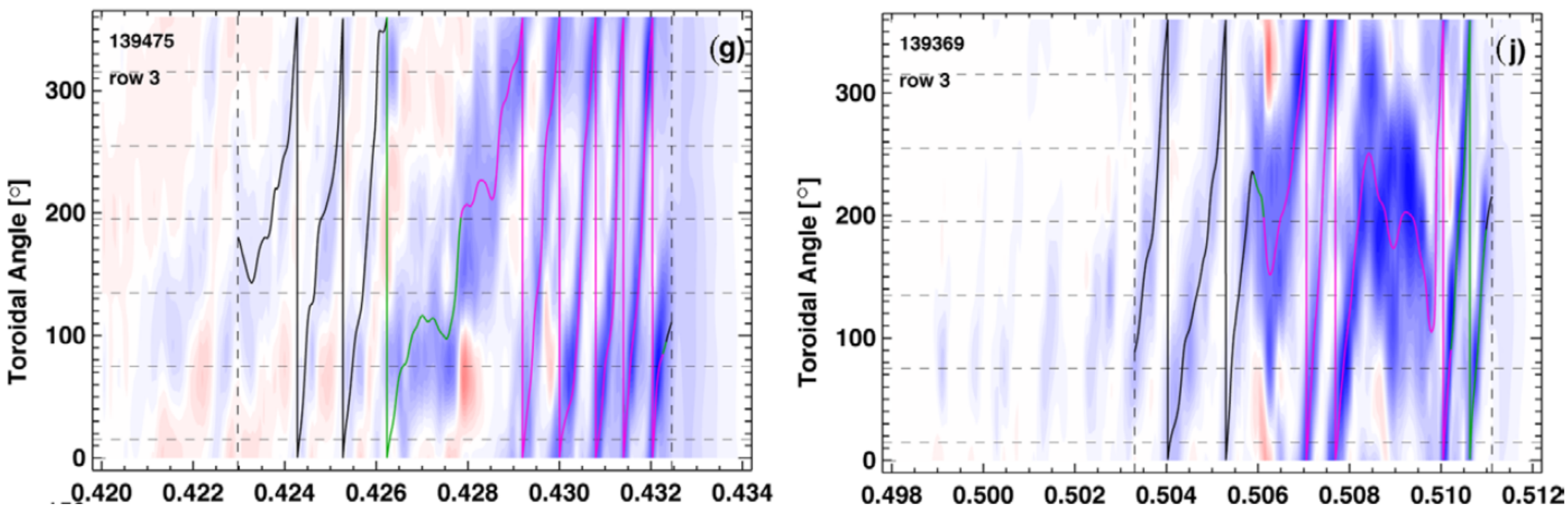


The asymmetric component of the poloidal halo current and the asymmetric component of the toroidal plasma current shifted toroidally by π/2 (Riccardo, 2010)



Time integrated measure of the I_p asymmetry (A_{4oct}), shows the maximum sideways impulse force is not coincident with either maximum spatially averaged halo fraction (f) or with the maximum local halo fraction (f*TPF) (Hender)

NSTX Has a Lot of Variability in Halo Rotation



NSTX: S Gerhardt, NF 2013

⇒ Substantial variability observed in JET as well.

⇒ Modelling halo rotation will be challenging

Need for Further Data and Understanding of Sideways Force

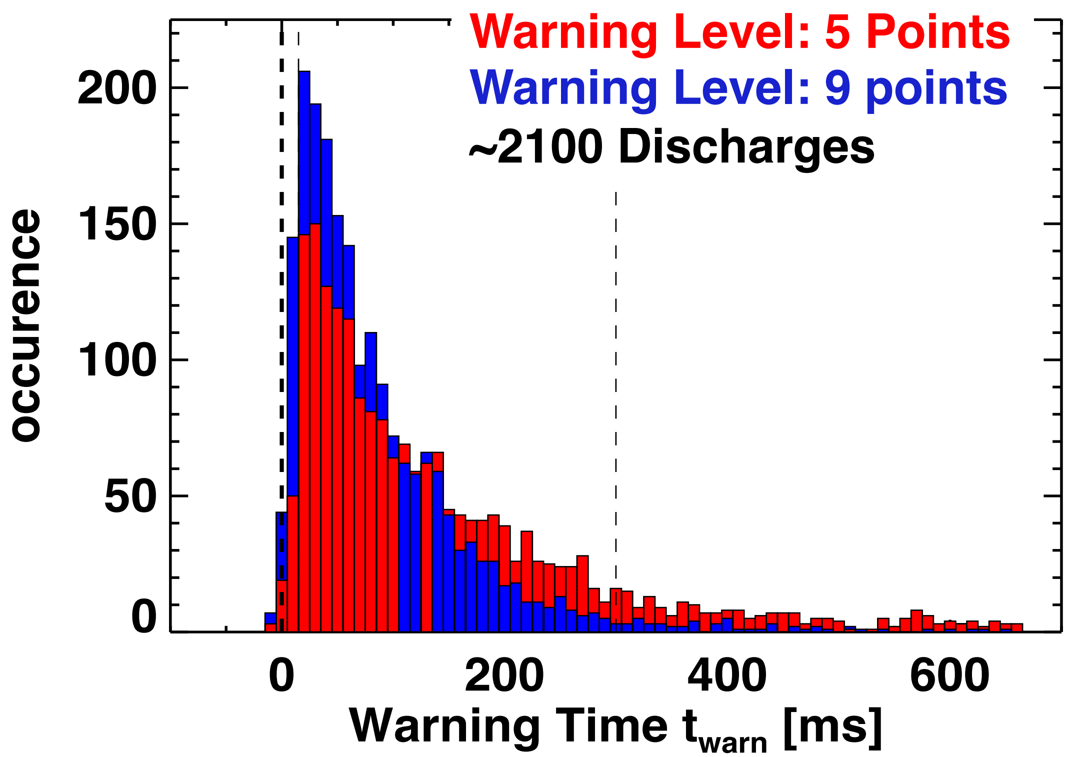
- **Pautasso (2011) provides a detailed discussion of how JET compares with AUG. (Please see her article)**

- **AUG does not observe a large sideways force though they observe significant halo currents and peaking factors.**
  - The interpolation from JET to AUG is off by an order of magnitude.

- ***"the lack of understanding of the differences in the structure and duration of the asymmetries and the absence of a benchmarked physics model make a physics-based prediction of the amplitude of the asymmetric currents (and consequent forces) from AUG to JET and ITER not possible at the moment."***

- **Is the extrapolation to ITER pessimistic or optimistic if we cannot interpolate to AUG?**
  - Is this related to the device construction or measurement limitations?
  - Need more diagnostics and modeling to improve the extrapolation.

Excellent Progress Reported on Disruption Prediction on NSTX and JET



Warning at APT=5 Points

<1% late warning

~15% false positive

Sum: 16%

Warning at APT=9 Points

~2% late warning

~4% false positive

Sum: 6%

(False positive count dominated by near-disruptive MHD events)

Actual algorithm has ~15 rows

NSTX

- **Next step will be demonstrate how to transfer these approaches to another machine.**

How Do the Experimental Timescale Compare with Theory/Simulation?

	NSTX	JET	ITER
τ_A	10^{-6}	10^{-7}	$5\text{x}10^{-8}$-10^{-7}
$\tau_h = \mu_o a\Delta_h/\eta_{hp}$	$0.5\text{x}10^{-3}$		0.03
$\tau_w = \mu_o a\Delta_w/\eta_w$	0.3 (Cu wall) $7\text{x}10^{-3}$ (304SS wall)	$4\text{x}10^{-3}$	0.5
$\tau_p = \mu_o a^2/\eta_p$ (post-disruption)	0.02	0.1	0.3-2.5
S	10^7=>10^5	10^{10}=>10^{6-7}	10^{10-11}=>10^{6-7}
γ_h	0.5-$1\text{x}10^{-3}$	$5\text{x}10^{-3}$	10^{-2}

Crude estimates during the workshop – do not quote

- **Boozer: $\tau_h \ll \tau_w \ll \tau_p$ but can be changed by means of disruption mitigation**
- **M3D values of S may be closer to those on NSTX**
  - τ_w/τ_p is ~ $10^{-(3-5)}$ shorter than in the experiments (Paccagnella)
  - M3D-C1 will enable higher S (Breslau)

Highlights from Boozer's Presentation

- As in a resistive wall mode (RWM), a magnetic perturbation would grow at an Alfvenic rate unless the induced current produces the $\mathbf{B_x}\bullet\mathbf{n}$ distribution for force balance.
  - Halo currents must produce particular $\mathbf{B_x}\bullet\mathbf{n}$ distribution.
  - However, halo currents must flow along **B** in plasma
  - Applies to both n=0 (axisymmetric) and kink instabilities

- **Halo current has a broad toroidal spectrum and is not a direct match to the instability**
  - Halo current enters and leaves the plasma in an elongated elliptical region to satisfy criteria of flow along **B**
    - Constrains the number of toroidal and poloidal transits.
  - Enhances the instability

$$\gamma_h = \frac{4q}{\left\langle D^2 \right\rangle} \frac{\eta_{\|}}{\mu_0 a \Delta_h} s'$$

Highlights from Boozer's Presentation

- **When $\gamma_h \tau_w$ >> 1 path is inductive**
  - Arcing is possible – observed on NSTX
  - Also noted by Zakharov as a manifestation of Hiro currents.

- **Outlined tasks that can be done with current tools (but with additional resources.)**
  - Form of $\mathbf{B_x} \cdot \mathbf{n}$ can be studied using codes like IPEC.
  - Toroidal mode number spectrum of halo currents can be calculated for an assumed Δ_h and compared to experiments.
  - When Δ_κ / a<<1: halo-wall interceptions near $\mathbf{B_x} \cdot \mathbf{n}_w$=0 curve. Axisymmetric displacement simulations can calculate $\mathbf{B_x} \cdot \mathbf{n}_w$ and find strong constraints on halo currents.

- **Optimization of halo current path through structures can be carried out with electromagnetics codes.**

Highlights from Strauss' Presentation

- **Results for asymmetric vertical disruption:**
  - $\tau_{TQ} \sim \gamma^{-1} \sim 10^2 \tau_A$
  - Asymmetric wall force if maximum for $\gamma\tau_w \sim 1$ and $\gamma \sim 0.01\ \tau_A^{-1}$
    - F_x is smaller for $\gamma\tau_w >> 1$, a mitigating effect
    - Predicts lower forces in JET or ITER due to large value of $\gamma\tau_w$
    - Disruption mitigation enabling **reduced** vertical displacement results in decreased sideways force = $c1\xi_{VDE} + c2$
  - Identified need to get more separation of TQ and CQ in simulation
    - Better current controller is expected to achieve this.

- **The TPF varies with S (Paccagnella)**
  - Increasing S stabilized the resistive modes but in a regime of $\gamma\tau_w < 1$
  - Compensated by adjusting the perturbation in the thermal quench.
  - Strength of M3D is ability to model thermal quench but further work is needed for quantitative evaluations.

Highlights from Strauss

- **Calculated MHD induced rotation**
  - Rotation generated by MHD turbulence during thermal quench, requiring vertical asymmetry.
  - In these simulations the thermal quench occurs, can generate rotation and generates the instability responsible for the sideways force.
  - Possible mechanism for intrinsic rotation identified due to MHD events.

- **The relationship between the toroidal asymmetry and the plasma vertical displacement Is consistent with JET data.**

- **Constraint developed on the maximum current asymmetry taking into account 3-D halo current from ∇ j=0:**
  - $\Delta I_\varphi / I_\varphi \leq 1/4 \times TPF \times HF \leq 3/16$

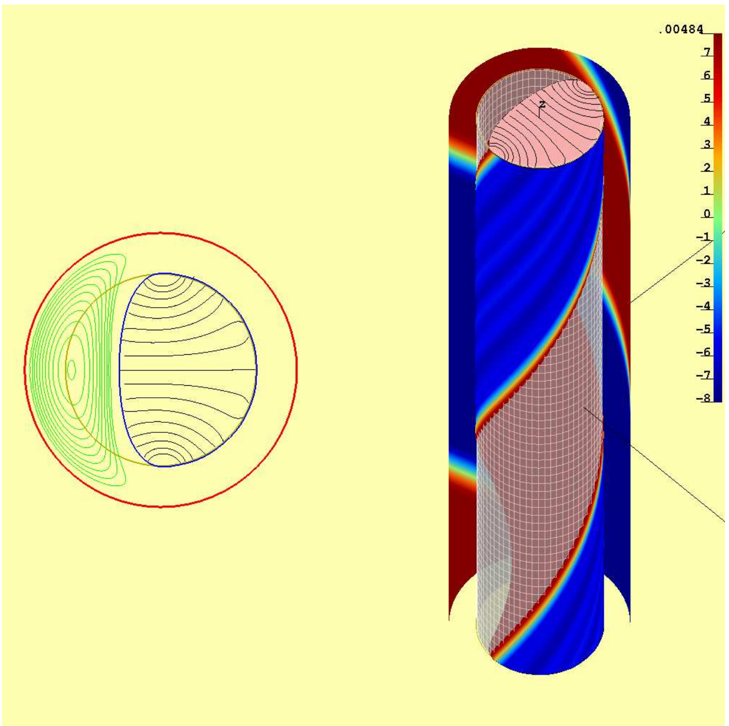
Highlights from Strauss

- **Evaluated the effect of different boundary conditions:**
  - Dirichlet $v_n = 0$ rigid wall
  - Neumann: $\delta v/\delta n = 0$ (absorbing wall)
  - Robbins: $\delta v/\delta n + \alpha\, v_n = 0$ compromise
  - $F_{x\,(}$(Neumann) ~2-3 Fx (Dirichlet) for $\gamma\tau_w >> 1$
  - Plasma is absorbed in about 10nm, much less than the resolution of the MHD codes.
    - Robbins with $\alpha >> 1$ models short wall penetration is approximately Dirichlet
    - Flow has two parts $v_{//}$ and $v_\perp$. If $v_\perp$ were to change on the spatial scale of 10 nm, would create unphysical electric fields in the wall.

Highlights from Zakharov

Hiro, Evans and “halo” currents

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



Transient equilibrium maintained by Hiro currents

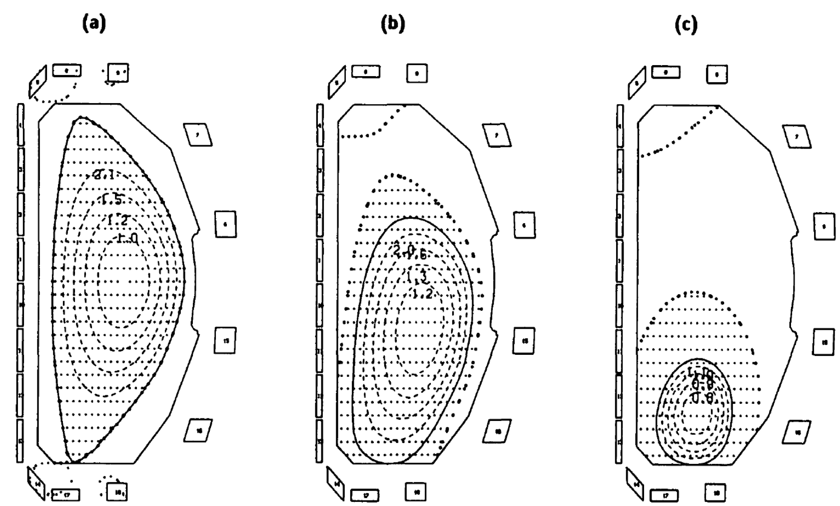


FIG. 3. Equilibrium flux plots from EFIT at three times during the vertical instability: (a) 2660 ms, (b) 2675 ms and (c) 2684 ms. Plasma current was allowed in the hatched region, including part of the SOL.

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 relative role of halo, Hiro and Evans currents remains a hot topic.***

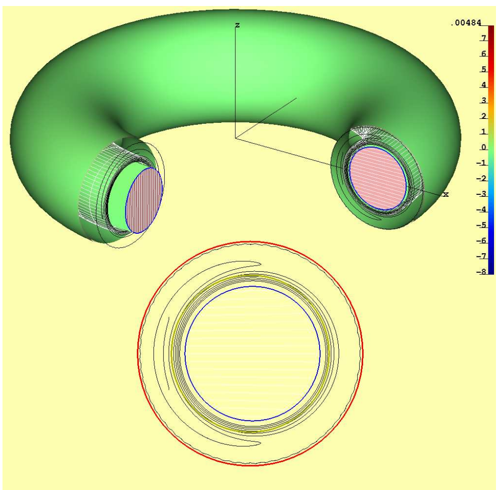
Highlights from Zakharov

- **Developing new suite of codes to address disruption dynamics**
  - *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*
  - *SHL- 3-D shell simulation code*
  - *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.***

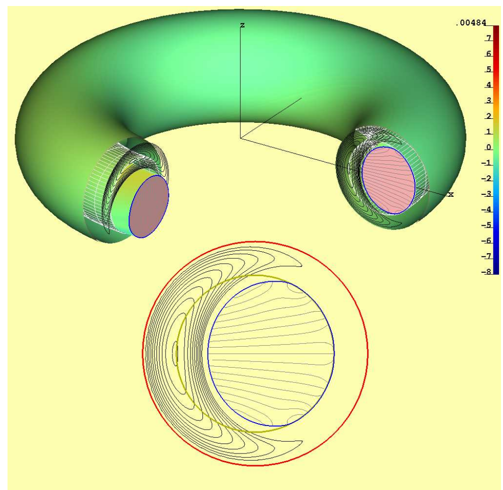
Highlights from Zakharov

Movie 2: Wall touching kink mode. Hiro current excitation

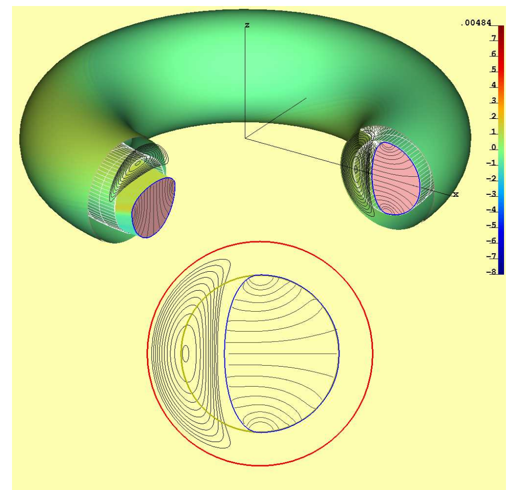
Fast regime of the wall touching kink mode inside the tile surface



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.

Final Comments

- **The role of halo and Hiro currents is important for ITER and beyond.**
  - Need further measurements and one comprehensively diagnosed machine would make a major impact.
  - The variability of experimental data necessitates conservative assumptions for ITER but….

- **Theory and simulations are providing insight into the currents and forces.**

- **Cross-comparisons between codes and analytic models are necessary.**
  - Need to move beyond the debates regarding the boundary conditions.

- **Quantitative comparisons between theory and experiment will (hopefully) establish a firmer basis for ITER operation and design of future devices.**
  - ***This is a very challenging problem!***