Vessel Forces From a Vertical Displacement Event in ITER

Invited Talk ID #124

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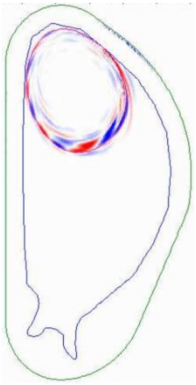
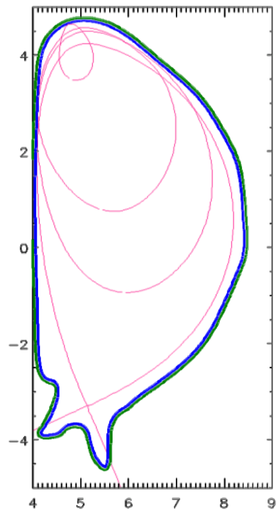
Motivation

- Vertical Displacement Events (VDEs) are major disruption events in tokamaks
- They occur when the vertical stability control is lost, and the entire plasma column moves up/down, hitting the wall and disrupting
- These events produce large current densities in the wall
  - Due to induction from plasma motion and current quench
  - Due to “halo currents” shared by the plasma and the wall
- The J x B forces due to these currents will produce large forces that potentially can damage the vessel
- A good understanding of these forces is required for several reasons
  - To gain confidence/approvals during initial operation to increase plasma current and toroidal field to full design values
  - To evaluate and employ effective mitigation techniques to minimize stresses on the components



2D (Axisymmetric) Analysis

- Extensive modeling has been done with 2D DINA/TSC/CarMa0NL
  - Maximum vertical force on VV 80-85 MN[1]
  - This could increase another 10-20 MN in worst case vertical stability system malfunction[2]
- Similar results have been obtained with the 3D MHD codes run in 2D[3]
  - Focus of these more recent studies has been on the effect of different assumptions regarding the current quench time and the halo current on the vessel force[3]
    - Conclusion: Slower current quenches lead to larger vertical forces
    - Conclusion: The net vertical force is almost independent of the strength of the halo current



[1]Sugihara, et al, Nuclear Fusion, 2007
[2]Miyamoto, et al, Fus. Eng. Des., 2012
[3]Clauser, et al, Nuclear Fusion, 2019

Importance of 3D effects

When the plasma undergoes 3D distortions, it will produce asymmetric currents in the wall through induction and conduction which will interact with the toroidal field producing a sideways force[1]

- The vessel asymmetric currents are due to the toroidal variation of plasma vertical position and current:

$$Z_p = Z_{p0} + \delta Z_p \cos\varphi$$

$$I_p = I_{p0} + \delta I_p \cos\varphi$$

- Largest effect will come from (m,n) = (1,1) mode: $\sim \cos(\theta - \varphi)$
  if the boundary safety factor drops below one: $q(a) < 1$

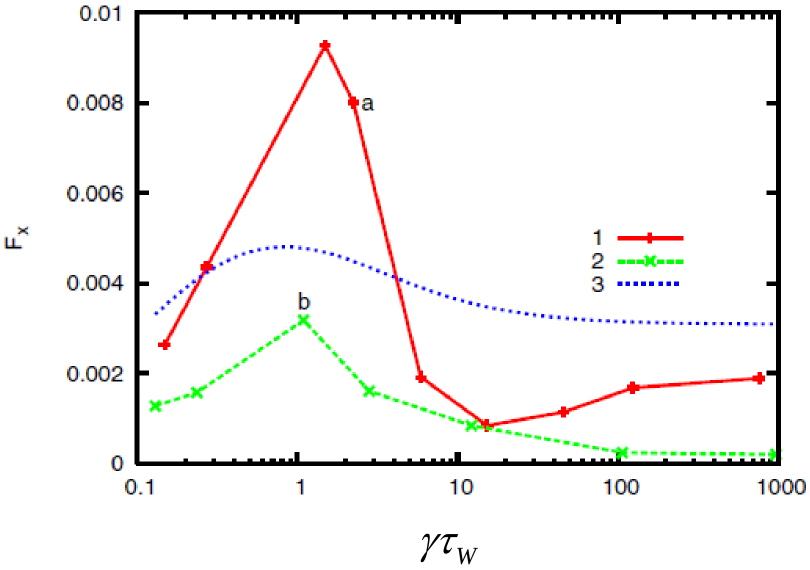
- For analysis of these modes, the plasma motion and vessel currents must be constrained by the fact that the plasma remain force-free

[1]V. Riccardo *et al* 2000 Nucl. Fusion **40** 1805

Unresolved issue #1

$$\gamma \, \tau_W \sim 1$$

Dependence of Force on the vessel time constant-1



- Strauss has a series of papers using the M3D code (not M3D-C1) to simulate VDEs
- Because of the time-step limitations of that code, he uses very large wall resistivity, and scales the results to the wall time
- The simulations are typically run for several hundred Alfven times …$T_{max} = \sim 300\ \tau_A$
- He finds that the wall force peaks at $\gamma\tau_W \sim 1$ where γ is the mode growth rate, τ_w is wall L/R time.
- These scalings are not rigorous, but suggest the wall force will be maximum at intermediate $\gamma\tau_W$

Strauss, *et al*, Nuclear Fusion **53** 073018 (2013)
Strauss, *et al*, Phys. Plasmas **17** 082505 (2010)

Dependence of Force on the vessel time constant-2

Using only Maxwell Equations and the fact that the electromagnetic force on the plasma must be negligible, Pustovitov showed that the net force on the vessel can be obtained by an integral over the *exterior* of the vessel:

$$\mathbf{u}\bullet\mathbf{F}_W = \mathbf{u}\bullet\int_{wall} \mathbf{j}x\mathbf{B}dV = \oint_{wall+}\left[(\mathbf{u}\bullet\mathbf{B})\mathbf{B} - \frac{B^2}{2}\mathbf{u}\right]\bullet d\mathbf{S}$$

- Here **u** is any constant vector (such as $\mathbf{e}_x$)
- Implies force vanishes at $\gamma\tau_W \rightarrow \infty$ (ideal wall) and at $\gamma\tau_W \rightarrow 0$ (no current)
- Qualitatively in agreement with Strauss result that the wall force is maximum at an intermediate value of $\gamma\tau_W$

Pustovitov, Nucl. Fusion 55 113032 (2015)

Unresolved issue #1

$$\gamma\,\tau_W \sim 1$$

- Will the sideways force be much smaller in ITER, compared to that obtained by scaling JET data, because γ is similar but τ_W is over 10 times larger?
- Or, is the relevant γ that of the resistive wall mode, such that $\gamma_{RWM} \sim 1/\tau_W$, so that $\gamma\tau_W$ will be unchanged from the JET value?

Unresolved issue #2

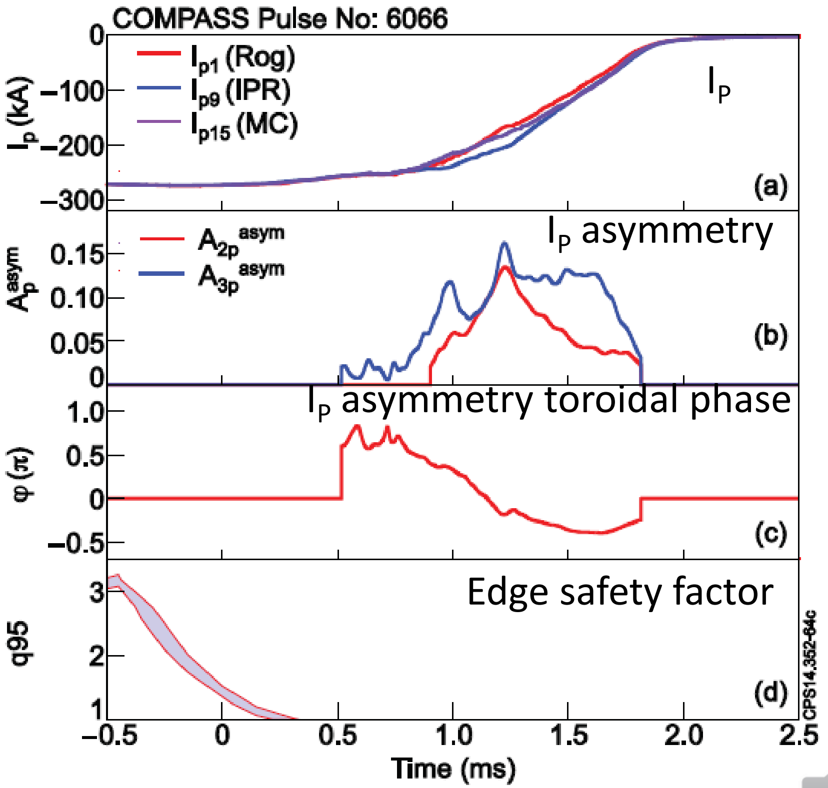
Will $q(a) < 1$ occur during a VDE disruption in ITER?

Experimental evidence that q(a) < 1 for most severe disruptions

Existence of strong (1,1) activity implies q(a) < 1

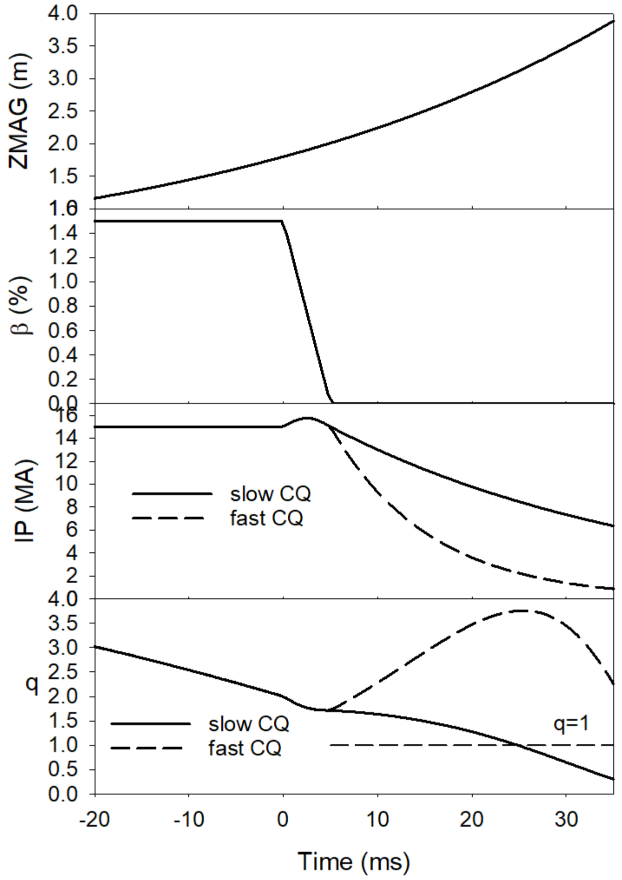
JET: "These asymmetries have a dominantly *n*=1 structure **and probably arise from a *m*=1 *n* =1 kink mode**, though a full comparison with an appropriate simulation is needed to unambiguously establish this[1]"

COMPASS: "drop of q95 sometimes down to unity[2]" (EFIT analysis)



[1]Gerasimov, *et al*, Nucl. Fusion **54** 073009 (2014)
[2]Gerasimov, *et al*, Nucl. Fusion **55** 113006 (2015)

Ratio of VDE time to current quench time matters

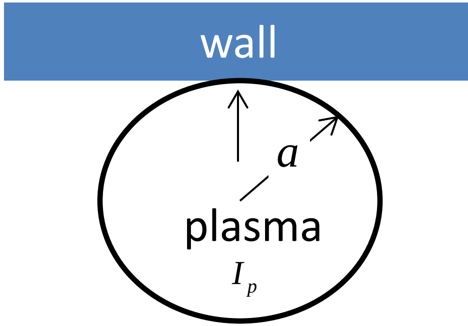


$$q(a) \cong 2\pi \frac{B_T a^2}{R\mu_0 I_p}$$

$$a = a_0 e^{-\gamma_{VDE} t}$$

$$I_p = I_{p0} e^{-\gamma_{CQ} t}$$

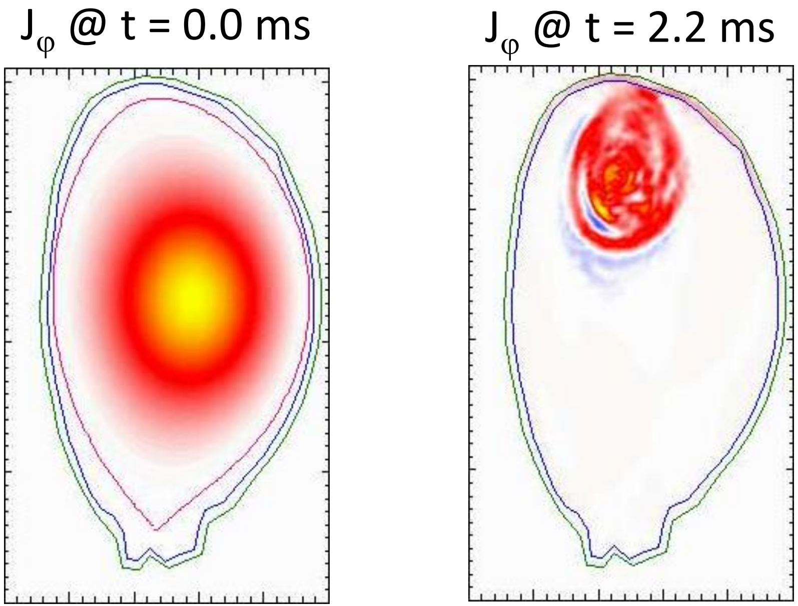
$$\frac{\dot{q}}{q} = \left[-2\gamma_{VDE} + \gamma_{CQ}\right]$$

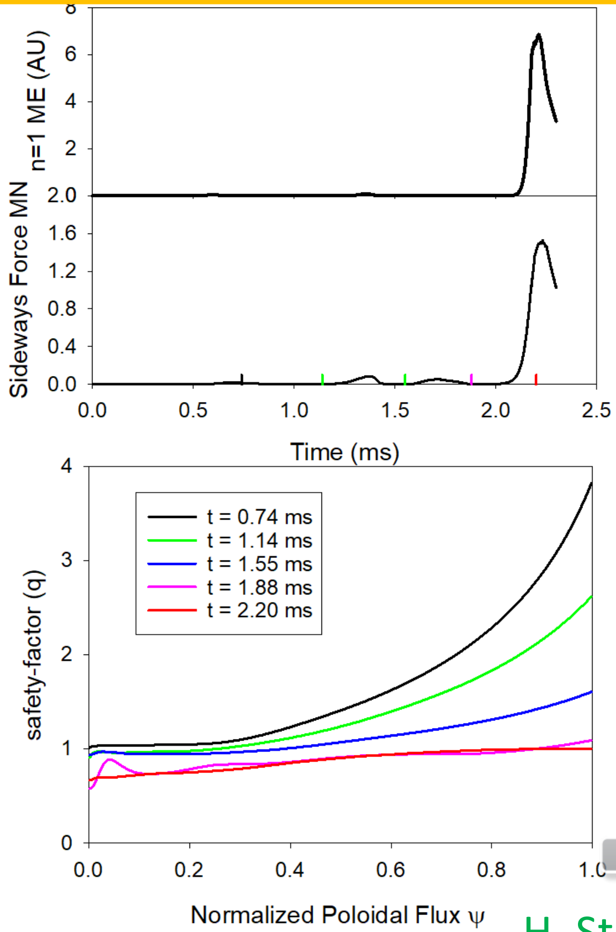


If current decays too slowly so that $\gamma_{CQ} < 2 \times \gamma_{VDE}$ q(a) will decrease during the current quench, leading to q(a) < 1 ➔ large (1,1) mode and sideways force. Seen in JET and in modeling [1,2]

[1]Strauss, *et al*, Phys. Plasmas **25** 020702 (2018)
[2]Strauss, *et al*. Phys. Plasmas **27** 022508 (2020)

M3D-C1 Simulation of a JET disruption shows q(a) → 1





- Plasma drifts upward and scrapes off
- q(a) at final time (t=2.2 ms) has dropped to 1
- Large (1,1) mode develops causing large sideways force

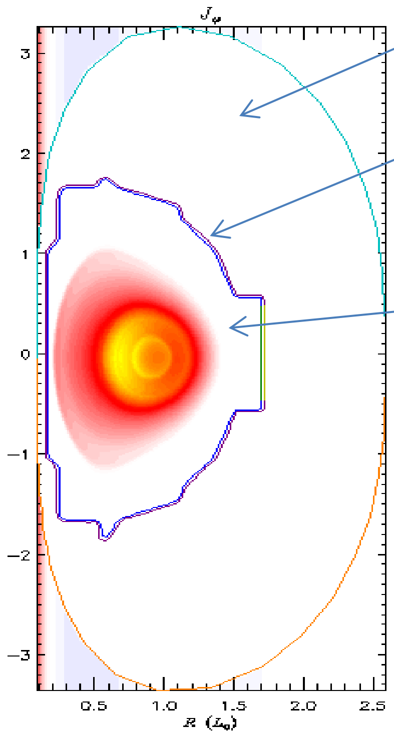
H. Strauss

Unresolved issue #2

Will q(a) < 1 occur during a disruption in ITER?

- A disrupting VDE unstable ITER plasma should not have q(a) < 1 unless the current-quench time is very long: $\tau_{CQ} > \sim 200$ms
- In the absence of q(a) < 1, the (1,1) mode should be small and the sideways force should be small compared to scaling JET data

3D Physics of VDE described by 3 region MHD code[1]



Vacuum: $\nabla \times \mathbf{B} = 0$

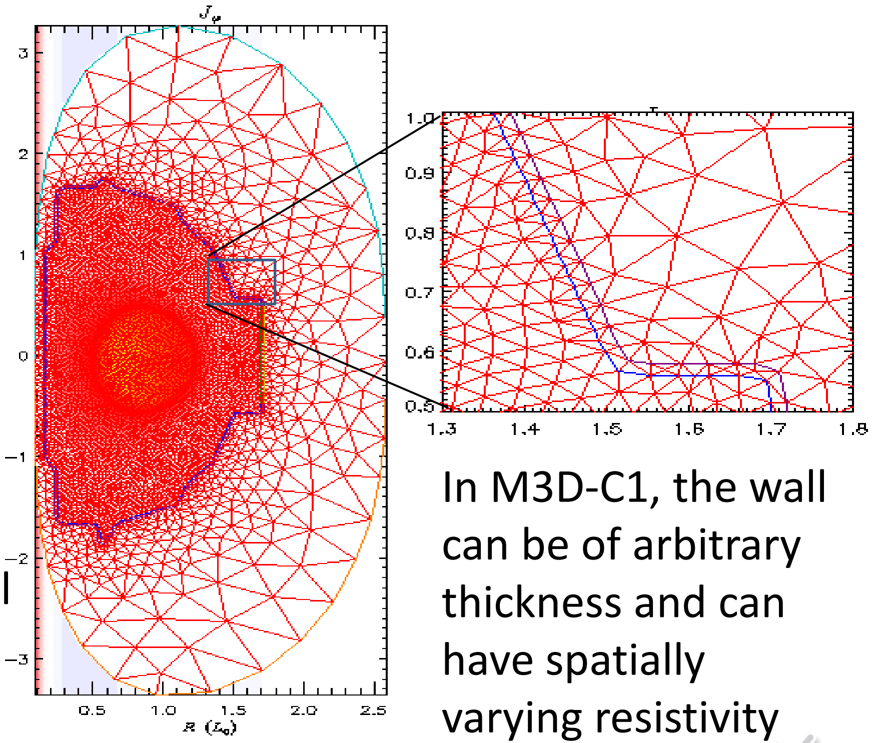
RW: $\mathbf{E} = \eta_W \mathbf{J}$

$\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E}$

Plasma (X-MHD)

BC:

- **v**, p, n set at inner wall
- **B** set at outer (ideal) wall
- No boundary conditions on **B** or **J** at the resistive wall
- Current can flow into and out of the wall from the plasma region (halo current)



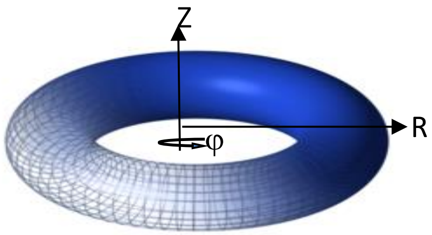
In M3D-C1, the wall can be of arbitrary thickness and can have spatially varying resistivity

[1]M3D-C1: Ferraro, *et al.* ,Phys Plasma**23** 056114 (2015)

M3D-C[1] form of 3D Extended MHD Equations

$$\frac{\partial n}{\partial t} + \nabla \bullet (n\mathbf{V}) = \nabla \bullet D_n \nabla n + S_n$$

$$\frac{\partial \mathbf{A}}{\partial t} = -\mathbf{E} - \nabla\Phi, \quad \mathbf{B} = \nabla \times \mathbf{A}, \quad \mathbf{J} = \nabla \times \mathbf{B}, \quad \nabla_\perp \bullet \frac{1}{R^2}\nabla\Phi = -\nabla_\perp \bullet \frac{1}{R^2}\mathbf{E}$$



$$nM_i\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \bullet \nabla\mathbf{V}\right) + \nabla p = \mathbf{J} \times \mathbf{B} - \nabla \bullet \mathbf{\Pi}_i + \mathbf{S}_m$$

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{ne}\left(\mathbf{R}_c + \mathbf{J} \times \mathbf{B} - \nabla p_e - \nabla \bullet \mathbf{\Pi}_e\right) - \frac{m_e}{e}\left(\frac{\partial \mathbf{V}_e}{\partial t} + \mathbf{V}_e \bullet \nabla \mathbf{V}_e\right) + \mathbf{S}_{CD}$$

$$\frac{3}{2}\left[\frac{\partial p_e}{\partial t} + \nabla \bullet \left(p_e \mathbf{V}\right)\right] = -p_e \nabla \bullet \mathbf{V} + \frac{\mathbf{J}}{ne} \bullet \left[\frac{3}{2}\nabla p_e - \frac{5}{2}\frac{p_e}{n}\nabla n + \mathbf{R}_c\right] + \nabla\left(\frac{\mathbf{J}}{ne}\right) : \mathbf{\Pi}_e - \nabla \bullet \mathbf{q}_e + Q_\Delta + S_{eE}$$

$$\frac{3}{2}\left[\frac{\partial p_i}{\partial t} + \nabla \bullet \left(p_i \mathbf{V}\right)\right] = -p_i \nabla \bullet \mathbf{V} - \mathbf{\Pi}_i : \nabla\mathbf{V} - \nabla \bullet \mathbf{q}_i - Q_\Delta + S_{iE}$$

$$\mathbf{V}_e = \mathbf{V}_i - \mathbf{J} / ne$$

$$\mathbf{R}_c = \eta ne\mathbf{J}, \qquad \mathbf{\Pi}_i = -\mu\left[\nabla\mathbf{V} + \nabla\mathbf{V}^\dagger\right] - 2(\mu_c - \mu)(\nabla \bullet \mathbf{V})\mathbf{I} + \mathbf{\Pi}_i^{GV}$$

$$\mathbf{q}_{e,i} = -\kappa_{e,i}\nabla T_{e,i} - \kappa_\parallel \nabla_\parallel T_{e,i}$$

$$\mathbf{\Pi}_e = (\mathbf{B} / B^2)\nabla \bullet \left[\lambda_h \nabla\left(\mathbf{J} \bullet \mathbf{B} / B^2\right)\right], \qquad Q_\Delta = 3m_e(p_i - p_e) / (M_i \tau_e)$$

Blue terms are 2-fluid terms. Equations are solved in (R,ϕ,Z) coordinates so there are no coordinate singularities at the magnetic axis or separatrix

M3D-C^1 uses unique 3D high-order finite elements

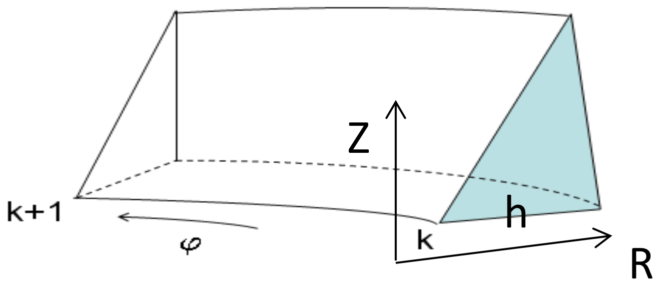
- M3D-C^1 uses high-order curved triangular prism elements

- Within each triangular prism, there is a polynomial in (R,φ,Z) with 72 coefficients

- The solution *and 1st derivatives* are constrained to be continuous from one element to the next.

- Thus, there is much more resolution than for the same number of linear elements

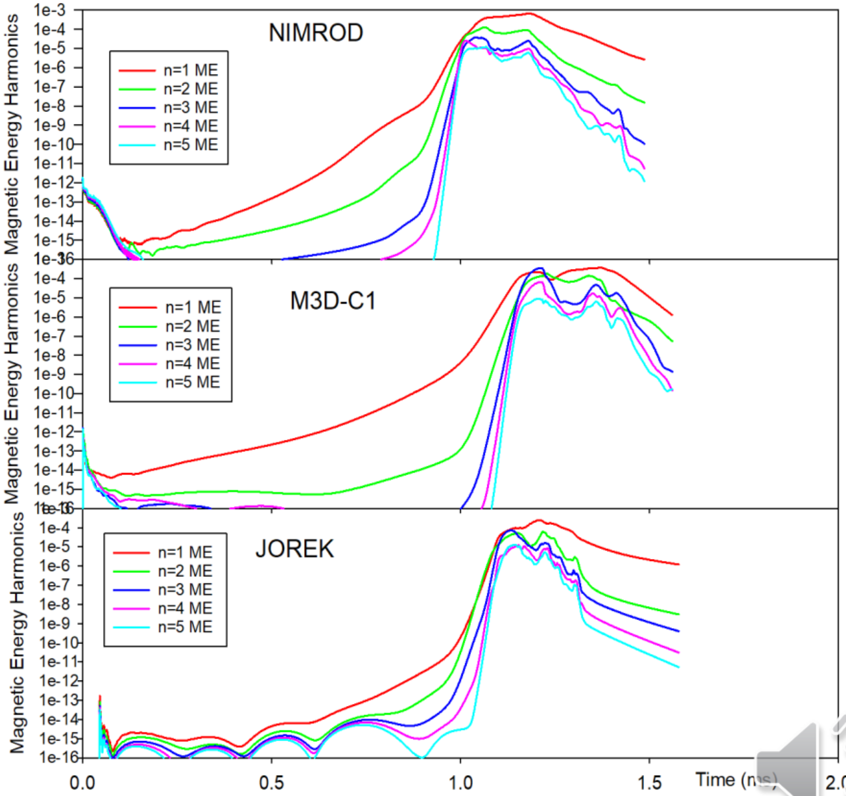
- Error ~ h^5



Also, implicit time-stepping allows for very long time simulations

Code Verification in 2D and 3D

- NIMROD, M3D-C1, JOREK have capability of modeling 3D VDEs
- We recently set up benchmark problems, first in 2D and then in 3D
- Excellent agreement in 2D, now published[1]
- Shown at right are magnetic energy in diff-erent toroidal harmonics for the 3 codes for the final, 3D phase of the VDE
- Not exact agreement in 3D because of differences in initial conditions, but wall forces agree to within 3% to 5%

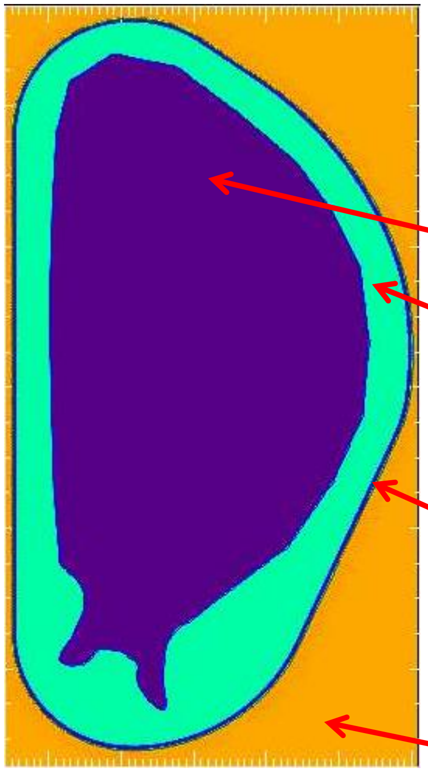


[1]I. Krebs, *et al*. Phys Plasmas **27** 022505 (2020)

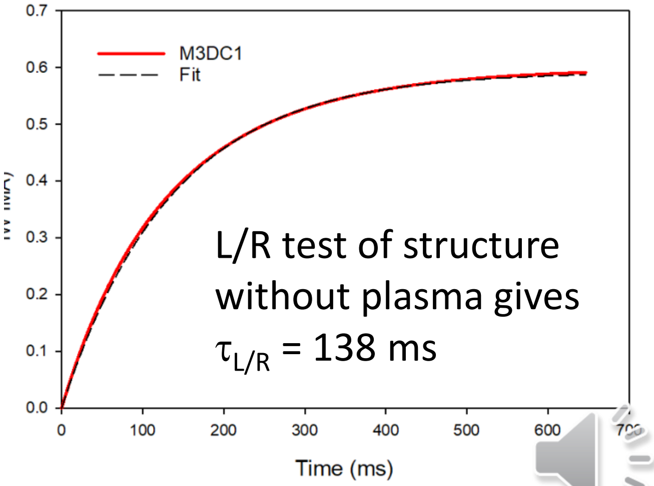
Difficulties in Modeling the Forces in ITER

- Very long vessel time constant
  - $\tau_W > 10^5\ \tau_A$
- Complicated vessel geometry with blanket modules, etc.
  - Working with CARIDDI group to define structure

We presently have a 2-region ITER structure model with anisotropic resistivity to approximate actual ITER vessel

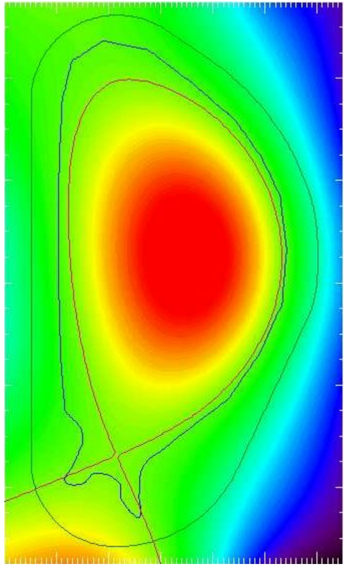


- Plasma region (MHD Eqns.)
- Conductor with high toroidal resistivity but low poloidal resistivity
- 6-cm steel wall with low poloidal and toroidal resistivity
- Vacuum region

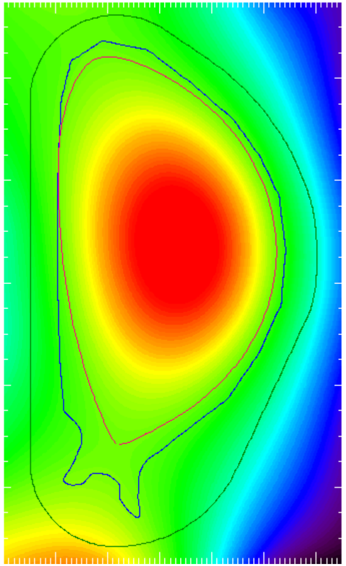


Status of ITER M3D-C1 VDE Simulation

Ψ@ t = 0
diverted

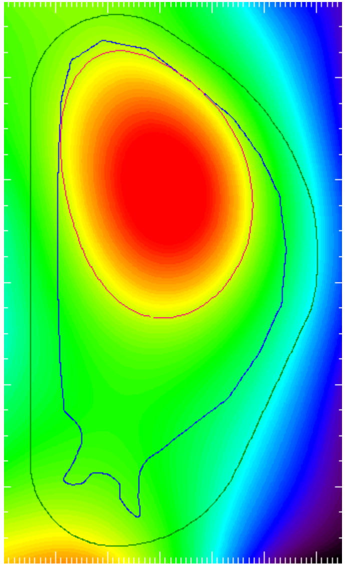


Ψ@ t = 64 ms
q(a) = 5



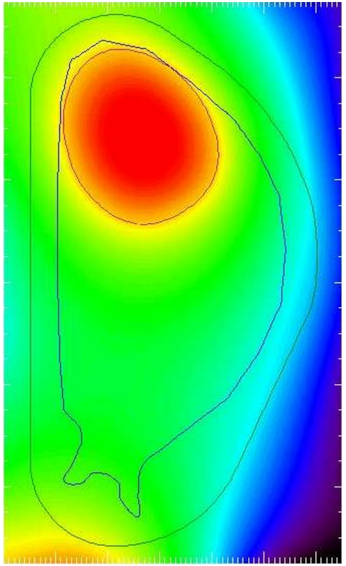
First becomes limited

Ψ@ t = 155 ms
q(a) = 2



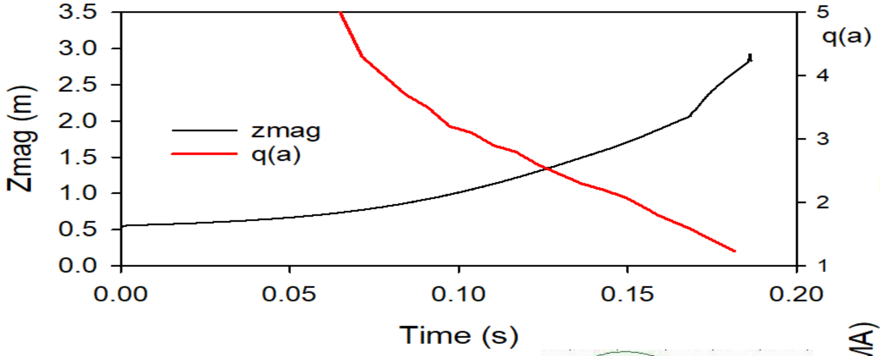
Start of Thermal Quench

Ψ@ t = 186 ms
q(a) = 1.14

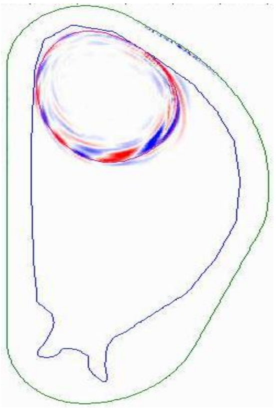


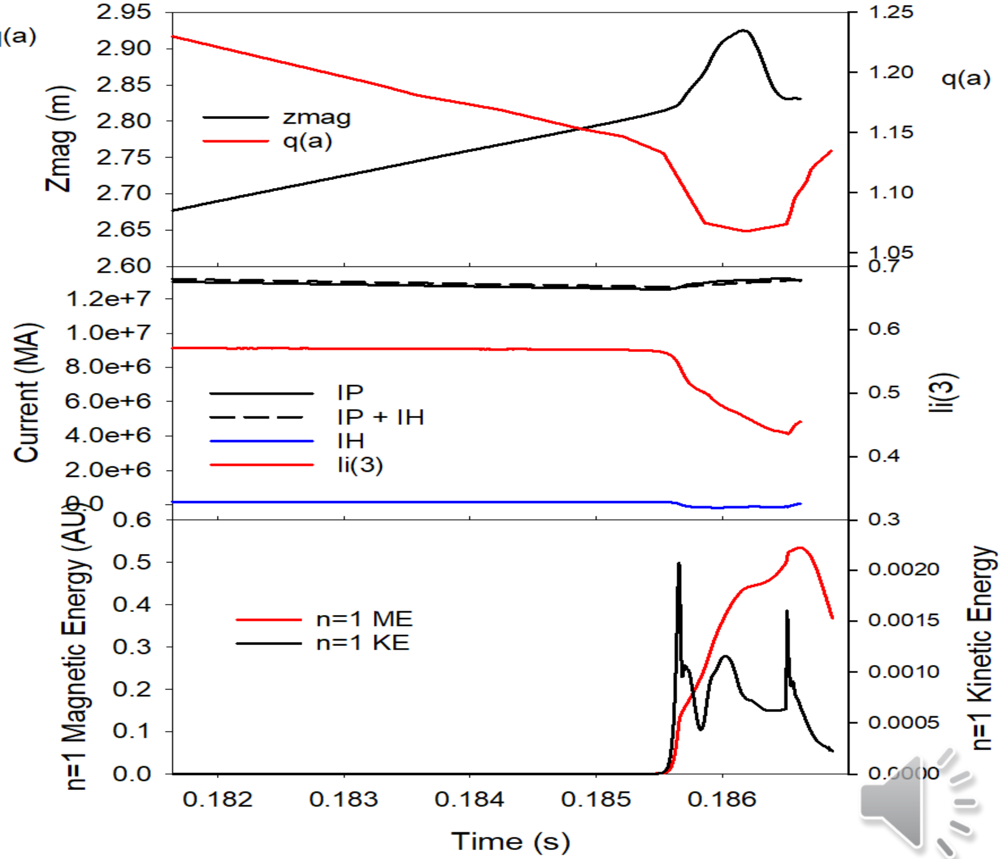
End of Calculation

More on ITER VDE Simulation

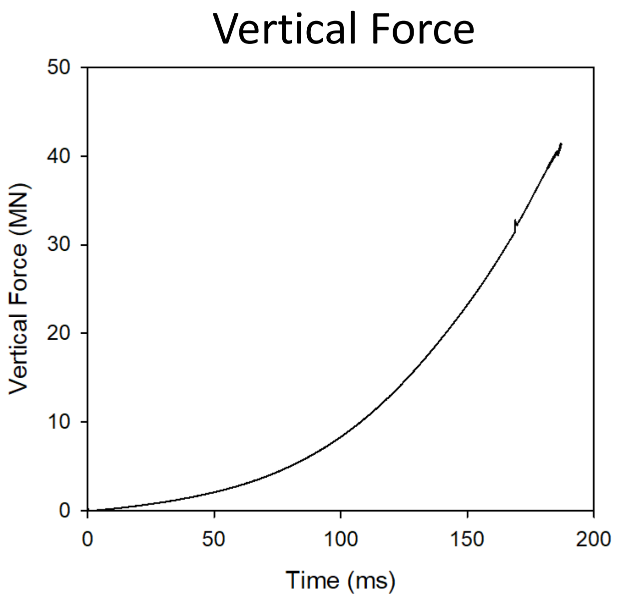


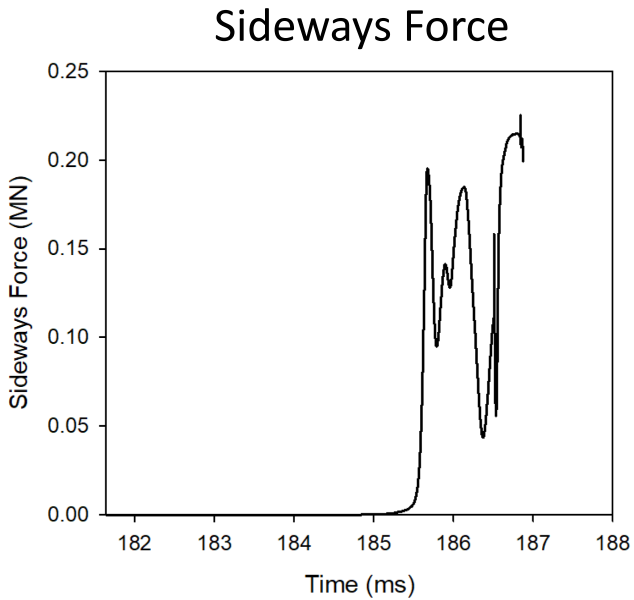
- Started 3D run at t=181ms when q(a) = 1.22
- q(a) does not go below 1 in 3D as li(3) drops!
- n=1 MHD activity develops but saturates at low value
- Need to go to longer times!





Forces from ITER simulations to date are small





- Maximum vertical force (40 MN) still increasing during current quench
- Maximum sideways force small (0.2 MN). May increase if q(a) < 1

Other Results for Sideways Force

- Strauss, et al, Phys. Plasmas 17 082505 (2010)
    - F_x = 70 MN in ITER, max. force for $\gamma\tau_{wall} \sim 1$, scaled simulation for 50 τ_A, $\tau_W = 10\tau_A$
- Zakharov, Galkin, Gerasimov, Phys. Plasmas **19** 055703 (2012)
    - Sideways force in ITER is 40-60 MN, based on a scaling of JET results
- Mironov and Pustovitov, Phys. Plasmas **22** 052502 (2015)
    - Sideways force in ITER 40-80 MN, maximum force at $\gamma\tau_{wall} \to \infty$ (analytic)
- Mironov and Pustovitov, Phys. Plasmas **24** 092508 (2017)
    - F_x in ITER 3.2 MN (max. at $\gamma\tau_{wall} \sim 1$): analytic, uses “force on plasma must be zero”
- Strauss, *et al*, Phys. Plasmas **27** 022508 (2020)
    - In ITER, $F_x < 5$ MN if $\tau_{CQ} / \tau_{wall} < 1$ (simulation and scaled JET data)
- Martynov and Medvedev, Phys. Plasmas **27** 012508 (2020)
    - F_x in ITER = 3.2 MN ($q(a) < 1$), 0.3 MN ($q(a) > 1$); max for $\gamma\tau_{wall} \sim 2$ (analytical + KINKX)

Summary

- Vertical force on ITER VV of 80-100 MN predicted by several codes, both 2D and 3D
  - Net vertical force almost independent of size of halo current
  - However, local stresses will depend on current paths and hence halo current
  - Slower current quenches lead to larger net forces
- Asymmetrical (sideways) forces arise from n=1 mode and associated halo currents
  - Mounting evidence that the m=1,n=1 mode is present in worst case disruptions
- Several 3D MHD codes are now modeling 3D VDEs
  - Requires MHD region, conducting structure, vacuum region
  - 3 Codes have performed VDE verification benchmark exercises
- Code results and analysis shows max force at intermediate value of $\gamma\tau_W$
- JET modeling shows large forces only if q(a) $\rightarrow$ 1 during disruption
  - Larger sideways forces for slower current quenches
- Simulations of ITER with realistic structure have yet to show large sideways force
  - ITER unlikely to have q(a) < 1 and large sideways force during VDE unless Current Quench time is very long: > 200 ms

Future Directions

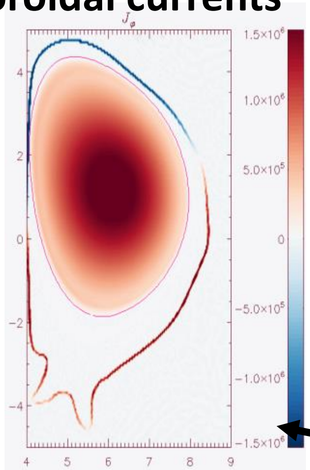
- 3D MHD codes with resistive walls need improved algorithms/computing capability to allow 3D calculations of ITER VDE and current quench with realistic parameters

- Need to better couple 3D MHD code to engineering code with more realistic description of conducting structures. Coupling of M3D-C1 to CARIDDI is underway

Extra Slides

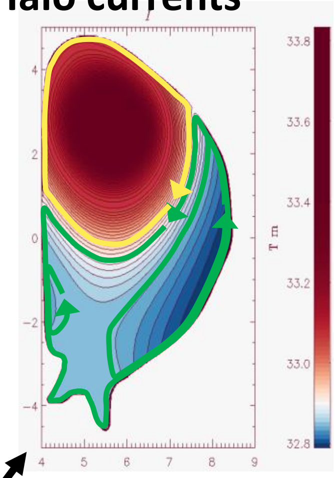
Current patterns during a VDE and vertical force

Toroidal currents



Toroidal currents are **induced** by the plasma movement + current quench.

Halo currents



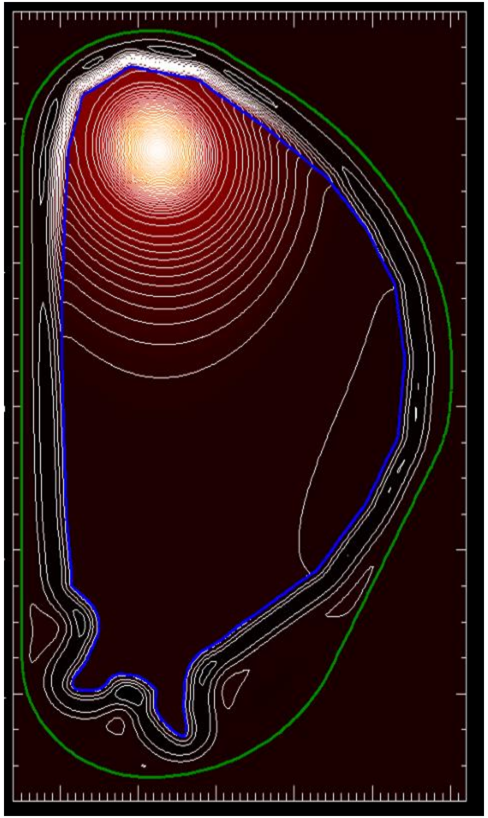
Poloidal halo currents build up and **flow** after the TQ. They are shared by the plasma and the vessel.

Vertical Force:

$$\hat{z} \cdot \mathbf{F}_V = \hat{z} \cdot \int_{vessel} \mathbf{J} \times \mathbf{B} \, \mathrm{d}V = \int_{vessel} \left(-J_\varphi B_R + J_R B_\varphi\right) \mathrm{d}V$$

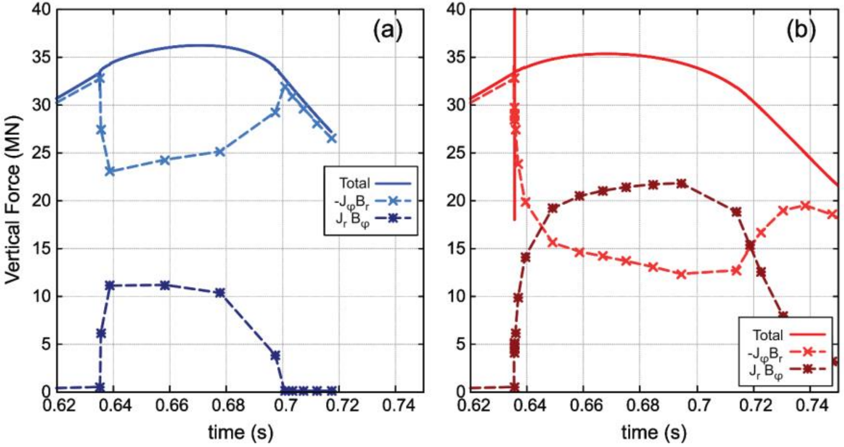
Forces come from both toroidal and poloidal currents in the vessel, but they tend to compensate for one another as shown in the next slide

Comparison of forces with small and large halo currents



Smaller halo current

Larger halo current



- Shown are 2 simulations, with similar current quench times and other parameters, but with different halo currents.
- Case (b) with the larger halo current has larger $J_R B_\varphi$ term, as expected,
- But, it is offset by a stronger reduction in the $J_\varphi B_R$ (toroidal) contribution. Total force almost identical in the two cases

[3]Clauser, et al, Nuclear Fusion, 2019

Total Vessel Force obtainable from toroidal currents only

Net force on Vessel + Coils+ Plasma must vanish

$$\mathbf{F}_{\mathbf{v}} + \mathbf{F}_c + \mathbf{F}_p = 0$$

In an axisymmetric system, all the poloidal currents within the vessel close on themselves and do not exert a net force on the TF, so we can include PF coils only.

Net force on the plasma must be zero: $\mathbf{F}_p = 0$

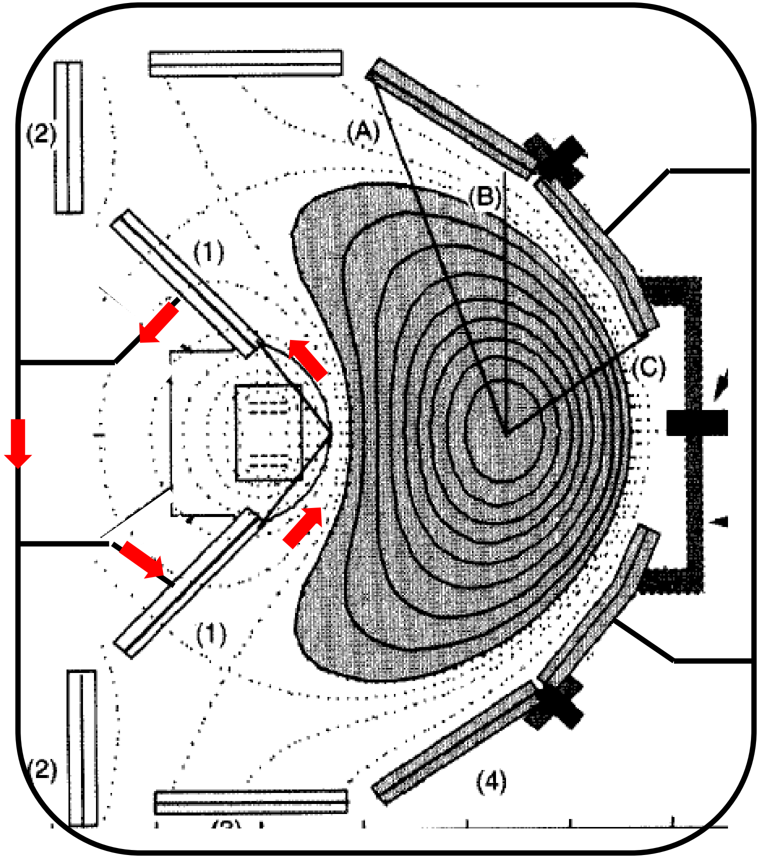
It follows that the net force on the vessel must be opposite the net force on the PF coils, which is due to the fields produced by the toroidal plasma and vessel currents

$$\mathbf{F}_{\mathbf{v}} = \mathbf{F}_v^{eddy} + \mathbf{F}_v^{halo} = -\mathbf{F}_c = -\mathbf{F}_{c,p} - \mathbf{F}_{c,v}$$

It follows that halo currents *by themselves* do not lead to larger forces in 2D.

Miyamoto, *et al*, Fusion. Eng. and Design **87** (2012)

Lesson From PBX-M (1996)



- PBX-M was a modification of the PDX experiment at Princeton which included passive conductors mounted to the vacuum vessel
- During a violent disruption, the plasma completed the path for a large poloidal halo current that damaged the machine
- Aside from the net force on the vessel, the halo current can drive currents along new paths, potentially causing damage.