Final Technical Report
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Executive Summary

Disruptions are a critical issue for ITER. Only a few disruptions are tolerable [21], as compared to present experiments: in JET 5% - 10% of shots end in disruptions [22]. The wall force produced in a disruption can be shown [14] to scale as the square of the total current. Hence the wall force in ITER could be about 25 times larger than typical in JET, about 60MN. It is important to use MHD codes to calculate the wall force to be expected in ITER during various disruption scenarios, as well as forces produced in existing tokamaks. These calculations could be compared to experimental data, providing a way to validate the simulations.

Disruptions can be caused by several mechanisms which lead to MHD instability. Pressure increase due to heating, including α particle heating, can destabilize resistive wall modes. Failure of vertical stabilization can lead to VDEs. These carry the plasma near the wall, where the the plasma edge is cooled or scraped off. This shrinks the current channel. The rise of current density causes the safety factor q to drop, causing an $(m, n) = (2, 1)$ tearing mode and /or a $(1, 1)$ kink instability. A density increase can cause increased radiation and partial thermal collapse, again shrinking the current channel and leading to MHD instability.

The perturbed plasma current produced by the MHD instabilities induces eddy current in the walls. The eddy current, multiplied by the magnetic field, produces the wall force. Poloidal plasma current (halo current) can also flow directly into the wall, contributing to the wall force. A proposed mechanism, Hiro current [18], is controversial and may require more study.

The simulation of the wall boundary is obviously important. Disruption simulations so far have used an ideal wall [26] or a thin resistive wall [23, 15, 14]. The magnetic field perturbations outside the wall are calculated with Green's functions [24, 25]. The jump in the magnetic field across the thin wall gives the wall force. It may be necessary to allow for 3D wall structure. This may involve coupling to a 3D vacuum magnetic field solver, such as codes used in stellarator research.

Another important disruption issue is the heat load on the walls. Even the heat load produced by type I ELMs may be problematic for ITER; how much more so would be the heat dumped on the wall during a disruption.

Because disruptions are such a big problem for ITER, avoidance and mitigation are critical issues. Avoidance is linked to understanding the causes of disruptions and the diagnostic signatures of disruption precursors. For example, do VDEs always indicate a disruption will follow? Are these the worst disruptions?

Mitigation is the subject of intense study. Will killer pellets or gas injection quench the plasma current in time to avoid a disruption? Physics models to study these effects need to be improved and should be integrated with MHD disruption simulations. A new topic is the possible role of static edge magnetic fields (RMP) in smoothing the wall interaction.

Tasks

• improve thin wall model to include a double wall, to simulate the ITER double wall, or to include the limiter in JET modeling. The magnetic field in the space between the wall could either be solved with Green's functions or by solving on a mesh. The first stage will be 2D walls. Later, a 3D wall model could be developed, perhaps using an existing 3D vacuum field solver that has been used in stellarator research. The effects of the JET 3D limiter structure may be important for the wall interaction.

• Add models of impurity radiation and bremstrallung to MHD codes to give plasma edge cooling, which will shrink the plasma current channel and destabilize large scale MHD modes. Add models of pellet ablation and cooling.

• Perform large scale simulations of ITER, JET and NSTX. Compare results of JET and NSTX computations with experimental data. The data could include wall forces, variation of plasma current with toroidal angle and correlation with variation of vertical displacement with toroidal angle, heat deposition during disruptions, behavior of pressure and current quench, and many other possibilities.

• study types of disruptions. The combination of a VDE and kink seems to be the worst case for producing sideways force. Pressure driven modes destabilized by α heating are important for thermal wall load. It is important to understand the MHD modes produced by the $q = 2$ and density limits.

• study the thermal and current quench in detail. Where is thermal energy deposited? Does current flow out along stochastic field, or is Ohmic dissipation more important?

• include dynamical effects of runaway electrons in disruptions.

Progress Report 2011- 2012

During the past year, we continued work in simulating tokamak disruptions with the M3D code [20]. The goal is to simulate the sideways electromagnetic force produced in ITER disruptions.

The following results were reported at the IAEA FEC meeting, San Diego, Oct. 8 - 12, 2012, and at the APS meeting, Providence RI, Oct. 29 - Nov. 2, 2012. The Appendix is the paper submitted to the IAEA proceedings, which contains more information.

Work is in progress calculating the sideways force at higher $S = 10^6$ than in previous simulations [14, 15]. We investigated the destabilization of kink / tearing modes as magnetic flux is scraped off by a Vertical Displacement Event (VDE). This causes the value of q on the last closed flux surface to drops to $q \approx 2$, exciting an $n = 1$ mode. This is discussed in Section I and the Appendix.

We also clarified the relationship between the wall force and wall penetration time. The wall force depends strongly on $\gamma\tau_{wall}$, where γ is the mode growth rate and τ_{wall} is the wall resistive penetration time. A model was developed which shows how the wall force depends on the amplitudes of $(2, 1)$ and $(1, 1)$ modes, as well as the amplitude of the $(1, 0)$ VDE, where (m, n) refers to poloidal and toroidal mode numbers respectively This is discussed in Section II and the Appendix.

In the past year we clarified the relation of halo current to the toroidal variation of the toroidal current, introducing what we call the 3D halo current. It was shown in simulations that the 3D halo current is about half of the halo current, and that the toroidally varying part of the toroidal current is about 10 % of the total toroidal current. This is described in Section III and in the Appendix.

The next phase of the project will require a more elaborate wall model. The first wall and vacuum walls will be treated as thin resistive walls using the GRIN [24] Green's function code. The GRIN code is being extended by the code author, A. Pletzer, in order deal with a more complicated resistive wall boundary condition.

I. Destabilization of kink modes by VDE

We are investigating the destabilization of kink / tearing modes by a VDE. When the original separatrix poloidal flux contour passes through the wall, the last closed flux surface has $q \approx 2$. At this point the plasma is unstable to an $(m, n) = (2, 1)$ external kink or resistive wall mode. This mode causes an $n = 1$ halo current to flow to the wall, producing the sideways force. As the VDE scrapes of magnetic flux, an $n = 1$ mode is destabilized. Work is in progress on further linear and nonlinear simulations of the instability.

More information is given in the Appendix.

II. Wall force as a function of wall penetration time

A robust finding in our simulations is that the wall force F_x is a function of $\gamma\tau_{wall}$. The force peaks at a value of $\gamma\tau_{wall} = \mathcal{O}(1)$. An analytic model, which is good agreement with simulations, shows that the sideways force is proportional to the product of displacements of a $(2, 1)$ kink and the VDE vertical displacement. It is also linearly proportional to the displacement of a $(1, 1)$ kink, as was shown previously [14]. The force arises partly from a competition between $(2, 1)$ and $(1, 0)$ modes. In this model, the VDE amplitude grows and decays as the plasma is pushed into the wall. Similarly, the $(2, 1)$ kink amplitude grows and decays when it becomes nonlinear and produces magnetic stochasticity. The maximum force is produced when the two modes reach their maximum amplitude at the same time.

More information is given in the Appendix.

III. 3D halo current and toroidal variation of toroidal current

We have clarified the relation between toroidally varying halo current and toroidally varying toroidal current during disruptions.

It was found in JET that during disruptions, the toroidal current varied with toroidal angle [18, 19]. Specifically, the toroidal current was measured several equally spaced poloidal cross sections. A sinusoidal variation of the toroidal current was observed, with toroidal mode number $n = 1$. This toroidal variation was correlated with the vertical moment of the moment of the current, defined below, which also varied with toroidal angle. These observations inspired a theory of "hiro" current [18]. According to this theory, the plasma, which was undergoing a vertical displacement event (VDE), became unstable to a kink mode with poloidal and toroidal mode numbers $(m, n) = (1, 1)$. The kink mode produces a helical surface current at the plasma edge. The VDE brings the plasma into contact with the wall. The "wall touching kink mode" "wets" the wall, and transfers toroidal plasma surface current to the wall. The surface current which flows in the wall is called "hiro current."

Unlike the hiro current theory, our formulation rests on a firm mathematical foundation, and is more general than hiro current. The toroidal variation of toroidal current comes from what we will call the three dimensional halo current, The three dimensional halo current is the net halo current, defined by

$$I_{halo3D} = \oint J_n R dl. \tag{1}$$

In two dimensions it vanishes, but in three dimensions it does not vanish. In three dimensions there can be a net outflow or inflow of current to the plasma as a function of toroidal angle ϕ. Using $\nabla \cdot J = 0$, and integrating over a poloidal cross section, yields the relation between I_{halo3D} and toroidal current I_ϕ:

$$\frac{dI_\phi}{d\phi} = -I_{halo3D} \tag{2}$$

where the toroidal current is

$$I_\phi = \int J_\phi dRdZ \tag{3}$$

and J_ϕ is the toroidal current density. This is the fundamental relation between halo current and toroidal current.

More detail is provided in the Appendix.

Progress Report 2013-2014

During the past year, we continued work in simulating tokamak disruptions with the M3D code.

Four papers [6, 11, 12, 13] were published on our recent results.

Results were also reported at the

CEMM meeting March 23, 2014 and Sherwood Theory Meeting, San Diego, CA, March 24 - 26;

PPPL disruption theory workshop, Princeton, July 9 - 11, 2014;

IAEA FEC meeting, St. Petersburg, Russia Oct. 13 - 17, 2014;

CEMM meeting Oct. 26, and APS meeting, New Orleans LA, Oct. 27 - 31, 2014.

I. Tokamak Toroidal Rotation

We recently discovered [6] that disruptions could produce toroidal rotation. The rotation is of concern for ITER. It is possible that there may be a resonance between rotating toroidal perturbations and the resonant frequencies of the vacuum vessel, causing enhanced damage. It was shown both computationally and analytically, that toroidal rotation can be produced by MHD effects during disruptions and ELMs. The sign of the rotation changes in different plasma layers, resembling a zonal flow. The peak value of the toroidal velocity is substantially larger than average value. Rotation can be generated in the presence of a vertical asymmetry, such as produced by a VDE, as well as a spectrum of 3D MHD perturbations with at least two mode numbers $(m, n), (m + 1, n)$. ELMs also produce rotation. It is possible that ELM activity may contribute to intrinsic toroidal rotation.

II. Velocity boundary conditions

Velocity boundary conditions appropriate for magnetohydrodynamic (MHD) simulations have been controversial recently. A comparison of numerical simulations of sideways wall force in disruptions is presented for Dirichlet, Neumann, Robin, and DEBS boundary conditions. It was shown [11] that all the boundary conditions give qualitatively similar results. It was also shown that Dirichlet boundary conditions are valid in the small Larmor radius limit of electromagnetic sheath boundary conditions. A reply to a Comment in Phys. Plasmas was also published [12].

The result of this work is that the standard velocity boundary conditions used by standard MHD codes such as M3D-C0, M3D-C1, and NIMROD are valid, despite claims to the contrary.

III. Toroidal current asymmetry

It was discovered on JET that disruptions were accompanied by toroidal asymmetry of the toroidal plasma current I_ϕ. It was found that the toroidal current asymmetry $\tilde{I}_\phi(\phi) = \int \tilde{J}_\phi dRdZ$ was proportional to the vertical current moment asymmetry $\tilde{M}_{IZ}(\phi) = \int Z\tilde{J}_\phi dRdZ$ with positive sign for an upward vertical displacement event (VDE) and negative sign for a downward VDE. It was observed that greater displacement leads to greater measured I_ϕ asymmetry. Here it is shown that this is essentially a kinematic effect produced by a vertical displacement event (VDE) interacting with three dimensional MHD perturbations. The relation of toroidal current asymmetry and vertical current moment was calculated analytically and was verified by numerical simulations [13]. The relation of toroidal plasma current and vertical current moment inspired a theory of "Hiro" current. Here is was shown that the relationship is essentially kinimatic, and could be obtained in numerical simulations in which there was no Hiro current. The toroidal variation of the toroidal plasma current is accompanied by an equal and opposite variation of the toroidal current flowing in a thin wall surrounding the plasma. These currents are connected by 3D halo current, which is $\pi/2$ radians out of phase with the toroidal current variations.

IV. Scaling of Toroidal Rotation

In [6], a scaling of the toroidal rotation with measurable quantities $\delta B/B, \beta_N$, and vertical displacement ξ was derived. In [13] a set of VDE states with both upward and downward displacements ξ was obtained. The toroidal rotation velocity v_ϕ and the asymmetric wall force F_x were also measured. This data can be used to obtain scaling of v_ϕ and F_x with $\delta B/B, \beta_N$, and ξ. These results were presented at the 2014 FEC and APS meetings. They will be further developed in the coming year and submitted for publication.

Annual Progress Report 2015 - 2016

Four papers [6, 11, 12, 13] were published in 2014. A paper on "Asymmetric Wall Force and Toroidal Rotation in Tokamak Disruptions" was submitted in 2015.

Results were also reported at the

IAEA FEC meeting, St. Petersburg, Russia Oct. 13 - 17, 2014;

CEMM meeting Oct. 26, and APS meeting, New Orleans LA, Oct. 27 - 31, 2014.

Sherwood meeting, March 16-18, NYC, 2015.

PPPL disruption theory workshop, Princeton, July 13 - 15, 2015;

Asymmetric Wall Force and Toroidal Rotation in Tokamak Disruptions

In [6], a scaling of the toroidal rotation with measurable quantities $\delta B/B, \beta_N$, and vertical displacement ξ was derived. In [13] a set of vertical displacement event (VDE) states with both upward and downward displacements ξ was obtained. The toroidal rotation velocity v_ϕ, the asymmetric wall force F_x, the vertical current moment M_{IZ}, and the magnetic field on the wall were measured. This data was be used to obtain scaling of v_ϕ, F_x,and M_{IZ}, with $\delta B/B, \beta_N$, and ξ. It was shown numerically and analytically that the asymmetric force and vertical current moment satisfy a relation

$$F_x = \pi B(1 - 1/q) M_{IZ}$$

which similar to a well known relation used to analyze wall force in JET. As such it provides a validation of the simulations. The wall force and vertical current moment are produced by a mode with amplitude δB, having poloidal and toroidal mode numbers $(m, n) = (2, 1)$, along with a VDE displacement ξ with $(m, n) = (1, 0)$. These perturbations interact to give $F_x, M_{IZ} \propto \xi\delta B$. An implication is that for $(2, 1)$ modes with small ξ, there is a self mitigation of the wall force. This is related to the self mitigation of the wall force produced by $(2, 1)$ modes and a VDE, when $\gamma\tau_{wall} >> 1$, where γ is the mode growth rate and τ_{wall} is the wall resistive penetration time [5]. The scaling of the toroidal rotation was improved by identifying a new term independent of β_N which drives the rotation. The scaling in this case is simple,

$$\frac{V_\phi}{v_A} = \frac{\xi}{4a\gamma\tau_A q}\left(\frac{\delta B}{B}\right)^2$$

where a is the average wall radius. This was checked in simulations.

Appendix: accomplishments 2010 - 2015

My research in 2010 - 2015 was mostly concerned with asymmetric vertical displacement event (AVDE) disruptions, which are the worst case scenario for producing a large asymmetric wall force. In these simulations, an axially symmetric vertical displacement event (VDE) pushes magnetic flux into the wall, causing it to be scraped off from the plasma. This causes q at the last closed flux surface to drop to $q = 2$, which sets off an MHD instability [2, 3, 5]. The dominant instability had $(m, n) = (2, 1)$. The force F_x was maximum when $\gamma\tau_{wall} \sim 1$. The force was found to be proportional to $\xi\delta B$. Evidently the force is maximum when both factors reach maximum amplitude at the same time. It was also found that disruptions generate toroidal rotation [6], which might be important in ITER if the rotating wall force resonates with external conducting structures. In JET AVDEs, there was found to be a correlation between toroidal variation of toroidal current and vertical current moment, $\delta I \propto M_{IZ}$. The sign of proportionality was positive for upward VDEs, and negative for downward VDEs. This was simulated, and explained theoretically [13]. In fact $\delta I \propto \xi M_{IZ}$, which accounts for the sign of the VDE. There were also developments in MHD modeling. An improved formulation of the Green's function method for vacuum magnetic field [4] was obtained, and a version of the GRIN Green's function code for multiple vacuum walls was developed. There was a dispute of the correct MHD velocity boundary conditions [11, 12]. It was shown that the generally accepted boundary condition $v_n = 0$ is consistent with sheath boundary conditions, and that in any case, the magnetic boundary condition is more important than the velocity boundary condition.

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