Highlights from the Theory and Simulation of Disruptions Workshop.

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A workshop addressing the theory and modeling of tokamak disruptions was held at PPPL during June 17-19, 2013. This workshop included talks by both theorists and experimentalists assessing all aspects of disruption physics. Participants came from multiple US and European institutions, including two representatives from the ITER organization (IO). The meeting was divided into 6 sessions, highlights from which are presented below.

The detailed agenda for the meeting can be found at https://ext-sweb.pppl.gov/tsd/schedule.html, and individuals looking for additional information are encouraged to directly contact the speakers.

Session I: ITER Needs

The first session focused on ITER needs and JET results with the ITER-like-wall (ILW); this latter is a modification of the JET plasma facing components (PFCs) from all carbon to having a beryllium first wall and tungsten divertor. The first talk of the session, by M. Lehnen (IO), identified three critical areas for disruption physics research which were repeatedly discussed in the meeting: halo current loads, thermal loads to the plasma facing components (PFCs) during the thermal quench (TQ), and runaway electron (RE) generation and dynamics.

Halo currents are those currents during a disruption whose path is partly in the edge plasma and party in the vessel and PFCs. While toroidally asymmetric halo currents are a long-known issue, much recent attention has been paid to so-called asymmetric vertical displacement events (AVDEs), where a significant tilt of the plasma column, asymmetric halo currents, and very large sideways vessel forces are observed. Furthermore, if this asymmetry rotates toroidally at the resonant frequency of the ITER vacuum chamber (1-20 Hz), then significant resonant amplification can arise. Key questions in this area include understanding the physics that determines the rotation frequency of the halo current asymmetry and how to extrapolate sideways force data from ASDEX-Upgrade and JET to ITER.

REs can cause severe damage to first wall components, and may become a safety issue if they cause internal water leaks. This problem is expected to be more severe in ITER than present large tokamaks as the avalanche gain, which scales as $e^{2.5I_P}$, will be a factor of ~e^{27} larger in ITER (I_P=15MA) than in JET (I_P=4 MA). A key issue is better understanding of the energy deposition process during RE termination, including the question of how much RE current magnetic energy is converted to RE kinetic energy during termination, as opposed to conversion to wall and thermal

Ohmic plasma currents. Furthermore, improved understanding of RE generation and dissipation processes are critical.

The talk also discussed disruption mitigation needs for ITER. Here mitigation refers to generating a comparatively benign triggered disruption in advance of an intrinsic, uncontrolled disruption. All of the mitigation techniques are based on the premise of injecting sufficient mass into the plasma to radiate the plasma thermal energy and control the current quench rate. Mitigation technologies under consideration for ITER include massive gas injection (MGI), shattered pellet injection (SPI), and potentially beryllium pellet injection. Of particular interest is an apparent conflict: the material injection amounts required for mitigation of thermal loads may very well result in a very fast current quench (CQ). These fast current quenches would then result in unacceptable electromagnetic loads on the blanket shield modules. These mitigation techniques also appear likely to assist in the production of large RE currents, emphasizing the need for RE control or dissipation strategies following the initial material injection. Finally, toroidally localized radiation at the location of gas jet or shattered pellet entry may locally melt the Be wall, and care must be taken to minimize these asymmetries.

The second talk of the session, by Peter de Vries (JET, EFDA) addressed how the ILW has changed disruption dynamics in JET. With the ILW, the fraction of energy radiated during the TQ has dropped substantially, resulting in higher post-TQ temperatures. This in turn leads to larger conducted energy to the PFCs and longer CQ durations. The larger conducted energy has led to some observed melting of Be PFCs, while the slower current quenches lead to longer halo current durations and larger impulses to the vessel. Hence, on-line disruption mitigation by MGI was required for all operation with I_P>2.5 MA.

The disruption rate in the first campaign with the ILW increased compared to previous operation with carbon walls, though this rate is expected to decrease as operations experience is gained. It was also found than nearly half of all disruptions with the ILW were due to excessive core tungsten radiation. Finally, the lack of a current quench immediately following some thermal quenches with the ILW makes assessment of disruption statistics more challenging.

Session II: Disruption Dynamics

The session on disruption dynamics began with a talk by Dylan Brennan (Princeton Univ.) on the physics of the onset of disruptive instabilities. This talk reviewed theory and simulations of the onset of disruptions as the system parameters are driven through a stability limit. The point was made that a significant effort is needed in understanding the evolution to disruption, in part to support avoidance, in addition to studies focused on the consequences and mitigation of disruptions. It then described NIMROD simulations showing that most of the essential capabilities exist in extended MHD codes to address this problem. The talk concluded by summarizing the physics that has been implemented as well as that which is needed to simulate nonlinear disruptive instabilities in experimentally relevant regimes.

Richard Fitzpatrick (IFS, Univ. Texas) provided an interlude between talks on nonlinear initial value simulations by describing a semi-analytic model of VDEs that takes into account halo currents. This model is based on a sharp-boundary plasma equilibrium evolving quasi-statically under the influence of wall and halo resistivity. A key feature is the determination of the effect of the wall on the halo currents by evaluating the resistance and effective emf of the available current paths and using these in a circuit equation. The circuit equation then yields the growth rate. The model yields TPF a little under two and vertical and horizontal forces of 31 and 12 MN, respectively, for ITER. It also reproduces the experimentally observed inverse relation between the toroidal peaking factor (TPF) and the poloidal halo current fraction.

Roberto Paccagnella (Consorzio RFX) presented the results of M3D simulations of asymmetric VDEs. This talk offered a candid assessment of how the difficulty of achieving the correct proportions between time scales characterizing the VDE, the current and temperature evolution, and the evolution of the resistive modes underlies the computational challenge of performing disruption simulations. One consequence is that for large Lundquist numbers, non-axisymmetry must be seeded through the initial conditions. The resulting simulations can reproduce some, but not all of the experimental observations. In particular, the thermal quench is well before the current quench unless the perpendicular transport is enhanced, but doing so leads to unrealistic peaking factors. The asymmetric evolution is dominated by the 2/1 mode. An important conclusion of the studies was the importance of reproducing the right conditions after the thermal quench, as these determine the subsequent evolution.

Ben Tobias (PPPL) concluded the session with a talk on 3D equilibria with internal island and external perturbation currents. The theme of this talk was the analogy between the resonant response of a plasma and that of a tuning fork. Experimental observations show that the radial eigenfunction of 3/2 modes have two T_e phase-inversion layers, as measured by ECE. The Mirnov signals are well correlated to the amplitude of the response diagnosed in the core, and uncorrelated to the narrow island width, showing that the MHD response is dominated by the kink component. The properties of the kink can be determined from its response to ELM. The line width yields Q=60 as the quality factor of the oscillator. Comparisons of the response of the plasma to internally and externally excited modes showed that the responses were similar, and that the poloidal mode number m significantly exceeded nq. In this respect the experimental observations differ from predictions of linear ideal MHD codes.

Session III: Halo/Hiro Currents and Forces

The third session of the meeting dealt with the topic of halo/Hiro currents and the resulting vessel forces. S. Gerhardt (PPPL) and T. Hender (CCFE) presented experimental results from NSTX, DIII-D, JET, and ASDEX-Upgrade. The observed halo current asymmetries tend to rotate in the counter-I_P direction in JET and NSTX, and to typically not rotate in DIII-D and ASDEX-Upgrade. Typical rotation frequencies are ~500-1000 Hz in DIII-D and NSTX, and 100 Hz in JET. However, the rotation can be erratic, even changing sign during a single disruption. Evidence was shown of cases with halo currents flowing in arcs between various places on the NSTX vessel. It was noted that while many machines have some set of halo current diagnostics, no machine can form a complete picture by itself. The talk by S. Gerhardt also presented results on disruption prediction in NSTX. A simple, physics based algorithm can predict ~94% of all disruptions in NSTX, with ~4% false positive rate and 2% late warning rate.

A number of theory related talks followed, largely focusing on the generation of and effects from non-axisymmetric halo currents. The talk by A. Boozer (Columbia University) emphasized that these current must form a particular $\mathbf{B}\cdot\mathbf{n}$ distribution ($\mathbf{n}$ is the unit vector pointing out of the wall), while also remaining parallel to $\mathbf{B}$ in the zero-pressure halo region. These results imply that the halo current asymmetry will have a broad toroidal spectrum. The idea of modifying the internal conducting structure in ITER to protect against halo currents ("lightening rods") was discussed.

The talk by L. Zakharov (PPPL) discussed the physics mechanisms behind these halo currents and emphasized the role of "Hiro currents". This mechanism occurs when surface currents, generated by a kink instability and flowing counter to I_P at the location of wall contact, are transferred to the vessel or PFCs. Data from EAST was shown providing evidence of toroidal currents flowing in tiles in the plasma edge in a direction opposite to the plasma current. The talk also expressed concern that the v_N=0 boundary condition (no flow to the wall) in extended MHD codes is not appropriate.

Finally H. Strauss (NYU) discussed disruption simulations for ITER with the M3D code. He presented analytic calculations and simulations of asymmetric VDEs, indicating that the sideways force is highest with $\gamma\tau_w$=1, where γ is the growth rate of the m/n=2/1 growing mode and τ_w is the resistive wall time. The talk also showed how these M3D simulations can produce both a TQ and a CQ. The direction of the asymmetric currents are in the same direction as the vertical displacement, as in the model by Zakharov. Strauss indicated confidence that the v_N=0 boundary condition is indeed acceptable.

Session IV: Runaway Electrons and Thermal Loads

This session focused on critical issues of TQ thermal loads and runaway electron generation, confinement, and loss. The talk by N. Eidietis (GA) provided data from DIII-D for cases where argon pellets are used to trigger disruptions and RE formation, and emphasized areas of potential theory collaboration. The RE issues were broken into formation, anatomy, dissipation, and final loss of the RE beam. It was found that RE formation in DIII-D is very sensitive to details of the target plasma and disruption initiating pellet. The RE beam tends to dissipate more rapidly than expected from electron-electron collisions, indicating some anomalous dissipation. Finally, it was found that for short RE termination times, there tends to be a large conversion of RE magnetic energy to wall and Ohmic plasma currents.

This was followed by a talk by Valerie Izzo (UCSD) discussing modeling of the TQ and RE mitigation, using the coupled NIMROD+KPRAD codes. These simulations showed that even for toroidally symmetric low-field side Neon injection, toroidally asymmetric mixing due to n≥0 MHD modes can result in toroidal peaking of the radiation on the FW. For asymmetric neon injection, the peaking can be even stronger, and it is important to resolve the toroidal phase of the MHD modes with respect to the gas jets. Simulations of RE loss due to surface breakup during the TQ indicate better RE confinement in larger devices. This indicates that while this mechanism may impede the formation of REs in C-MOD and result in sensitivity to equilibrium and pellet parameters in DIII-D, it is unlikely to translate to ITER.

The termination of RE currents, and their re-conversion to Ohmic currents during the termination process, was the focus of a talk by J.R. Martin-Solis (Universidad Carlos III de Madrid). A key conclusion was that the fundamental parameter determining the fraction of a RE beam that is converted to Ohmic current during the loss phase is $\tau_{res}/\Delta t_{hxr}$, where τ_{res} is the decay time of the Ohmic current and Δt_{hxr} is the RE conversion time, as defined by hard X-ray measurements. This implies that substantial conversion of magnetic energy into runaway kinetic energy is likely occurring for the slowest terminations.

Session V: Disruption Mitigation

Disruption mitigation was the topic of the fifth session. The talk by R. Granetz (MIT) using C-MOD data showed that during the pre-thermal quench phase, the P_{rad} asymmetry can be controlled by varying the timing of the two gas jets, and that there was a strong correlation between the P_{rad} asymmetry, the n=1 MHD growth rate, and the relative timing of multiple jets. However, during the thermal quench, the P_{rad} asymmetry is not well controlled with two gas jets, with the P_{rad} asymmetry correlated with the rotation of peaked P_{rad} feature.

This was followed by a talk by J. Wesley (GA), which emphasized the need to use moderate amounts of gas in present MGI experiments, so as to achieve normalized current quench rates that would be safe for ITER. The talk also emphasized the potential role of MHD mixing in determining the relationship between the injected gas amount and the mitigation results.

The session ended with a talk by M. Okabayashi (PPPL) that demonstrated avoidance of NTM-locking induced disruptions based on feedback driven mode control in DIII-D. Key elements of the control included a forced toroidal shift between the detected mode and feedback field and built in dynamic error field correction.

Session VI: Integrated simulation of disruptions

The final session of the meeting highlighted integrated simulations. The talk by S. Jardin (PPPL) emphasized the use of the advanced extended MHD code M3D-C^1 for the simulation of disruptive instabilities. An NSTX example was shown, where MHD instabilities provide a soft β-limit, but no disruption, and convergence studies were presented. Regimes with thermal and current quenches will be addressed in future simulations.

S. Kruger (Tech-X) gave the following talk, focusing on whole device modeling (WDM) issues for disruption avoidance. WDM codes evaluate the full discharge evolution, including transport and current drive models, and can thus predict the future state of the plasma. A scheme was presented where “clouds” of equilibria centered on the present discharge state would be evaluated for stability, after which the actuators would attempt to drive the plasma towards a more stable configuration. Tools from the applied math community, for instance, uncertainty quantification (UQ), can be useful for this effort.

Following these technical talks, some summary comments were provided. Chuck Greenfield (GA), speaking as head of the USBPO, emphasized the need for coordination between experiments, and between experiments and theory, in order to solve the problems described above. The USBPO task group on disruptions, led by John Wesley (GA) and Bob Granetz (MIT) is a mechanism to provide some of the required coordination. Amitava Bhattacharjee (PPPL) then announced that a follow-up meeting would be held next summer in order to continue this critical dialog between experiments and theory.