Energy Balance During Pellet Assimilation

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Pellet injection is used in tokamaks and stellarators for fuelling, ELM pacing, diagnostics and disruption mitigation. Injection of shattered pellets is a critical part of the envisaged ITER disruption mitigation system. Rapid deposition of a large amount of material is expected to result in a controlled quick cooling of the entire plasma. However, unlike in the case of uniform gas injection, a considerable transfer of thermal energy from the electrons of the background plasma to the ions accompanies a localised material injection. This is the result of the ambipolar expansion along the magnetic field line of the cold and dense plasmoid left behind the ablated pellet. If the cloud is heated at a constant rate, the ions accelerated by the ambipolar electric field acquire half the total energy transferred to the cloud if radiation losses are negligible. If the heating source is depleted and the heating rate drops as the cloud expands, the majority of the energy is eventually transferred to the ions. The present work quantifies this energy transfer for disruption mitigation parameters. It is found that over 90% of the energy may end up in ions for a case of deuterium injection in ITER. The transferred energy is not expected to be lost to the wall within the short electron timescale, which may significantly reduce the expected detrimental effects of a disruption. The role of radiative energy losses in case of high-Z injection is also considered. The initially very dense plasmoid is shown to be opaque to line radiation, which reduces the localised radiative heat loads.

Complete 3D MHD simulations of ITER post-Themal Quench plasmas with realistic Lundquist numbers

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In this work, we explore the 3-Dimensional stability of ITER post-Thermal Quench plasmas that are representative of mitigated disruptions with Massive Material Injection. The low temperatures (~ 20 eV) that are charateristic of these plasmas allow to simulate the full Current Quench phase (here ~50 ms) with realistic Lundquist numbers within the present computational capabilities. We simulate such events including a resistive wall model of the ITER conducting structures with the JOREK-STARWALL code suite. Instead of solving the evolution of the impurity content, we follow a simpler approach here by neglecting the Ohmic heating term in the pressure equation and by assuming that all the internal magnetic energy is lost in the form of radiation.

The computed wall horizontal forces are of the order of 1 MN, and thus, they are about a factor of 40 smaller than the maximum forces obtained with simple extrapolations from JET experiments to ITER. Such a decrease in the wall forces is consistent with theoretical considerations, in which, the wall forces tend to zero when the Current Quench time is much faster than the resistive wall time [1]. The simulations show that tearing modes are present during all the current quench phase and lead to the stochastization of the magnetic field in a large fraction of the plasma volume. An initial particle tracking analysis shows that runaway electrons will be quickly deconfined in the stochastic regions and that such losses would potentially overcome the avalanche generation mechanism. On the other hand, flux surfaces in which runaway electrons could be confined reform in the plasma core during the current quench; a self-consistent RE-MHD simulation is left for future work.

[1] Pustovitov, V. D., Rubinacci, G., & Villone, F. (2017). On the computation of the disruption forces in tokamaks. *Nuclear Fusion*, *57*(12), 126038.

New Observations of Magnetic Island Flux Tunneling, Heteroclinic Bifurcation and Seeding by Non-Linear Three-Wave Coupling

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We report the first experimental observations of the theoretically predicted flux tunneling [1] between magnetic islands, heteroclinic bifurcation [2] and seeding by nonlinear three-wave coupling of magnetic island triplets [3] in DIII-D, with implications for avoidance or ECCD stabilization of tearing modes.

2,1 magnetic island confinement bifurcations due to flux tunneling was observed to be triggered by decoupling of non-overlapping adjacent 5/2 islands. While subject to ECCD, T_e at the 2/1 O-point is flat before but peaks after decoupling. This is shown to be due to a bifurcation from stochastic to nested magnetic topology, caused by the removal of flux tunneling through intersecting manifolds of overlapping heteroclinic tangles. The effectiveness of ECCD stabilization of the 2/1 island is shown to correlate with such coupling events in an ITER baseline scenario plasma, showing the critical impact of flux tunneling on disruption avoidance in tokamaks.

Magnetic island heteroclinic bifurcation was observed in multiple interacting 2,1 islands, each residing at q=2 simultaneously. ORBIT Poincare maps are used to characterize the magnetic structure of the islands whose input parameters are fully constrained by magnetic probe data. In addition, reconstructed local T_e profiles within the islands are used to characterize the island internal structure. When the 4,2 (6,3) relative magnetic amplitude is 100% (80%) compared to the 2,1 amplitude at q=2 ($R_{4,2}$ and $R_{6,3}$, respectively), the simulations show that the 2/1 island is heteroclinic with 3 O-points. At this time, $\triangle T_e$ is split at q = 2, and the split peaks are located at ±π/2 in accord with the O-points in the Poincare maps. The faster 2,1 growth then results in a natural scan of $R_{4,2}$ and $R_{6,3.}$ When $R_{4,2}$ ($R_{6,3}$) decreases below 80% (60%), the heteroclinic 2/1 island bifurcates to a homoclinic 2/1 island as seen from the disappearance of the split $\triangle T_e$ in accord with vacuum island simulations. This phenomenon can be crucial for disruption avoidance via ECCD stabilization of 2/1 islands, as the EC wave energy splits between heteroclinic O-points which may make the stabilization of rotating 2/1 islands harder, while driving current in heteroclinic O-points of locked islands imposes challenges on the EC wave launch geometry which is not accounted for in present tokamaks or in the ITER research plan.

New observations of disruptive 2,1 island seeding by non-linear coupling of 4,3 and 3,2 tearing modes to a central 1,1 sawtooth precursor in ITER baseline scenario discharges will be also presented. The plasmas are robustly stable to classical tearing modes as shown by STRIDE and a number of ELMs and sawtooth crashes occur without seeding. The magnetic energy of the seed island accounts for the drop of the coupling modes' energy and the 2,1 island grows linearly thereafter in accord with neoclassical theory. Therefore, magnetic reconnection at q=2 is not caused by a classical current driven instability, but the 2,1 NTM seed island is formed by frequency matching and nonlinearly interacting NTMs that satisfy the mode number resonance condition. Three-wave interactions between these modes are conclusively identified by bi-spectral analysis, indicating fixed phase relationships in agreement with theory. This new observation of this seeding mechanism has important implications for future reactors that must operate in stable plasma equilibria, free of disruptive 2,1 islands.

[1] L. Bardoczi et al 2021 *Nucl. Fusion* https://doi.org/10.1088/1741-4326/ac0411
[2] L. Bardoczi et al**,** *Phys. Rev. Lett.* **126**, 085003 (2021)
[3] L. Bardoczi et, submitted to *Phys. Rev. Lett.* (2021)

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Difficulty of Plasma Steering and Constraints from the Greenwald Limit

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The primary mechanism for avoiding disruptions and runaway electrons in tokamaks---from ITER to power plants---is considered to be steering to avoid dangerous plasma states. Unfortunately, plasma steering resembles "driving at high speed through a dense fog on an icy road" [1]. The fundamental problem arises from the long time for the coils, which are located outside plasma chamber, to affect the magnetic field inside. The analogy with driving at high speed through a dense fog comes from the short time through which the state of the plasma can be reliably foreseen versus the long time required to take action. The analogy with driving on an icy road comes from the difficulty of regaining axisymmetric position control of the plasma if it is lost. Standard tokamak references are used to make these points, and the fundamental origins of the difficulties are explained.

In order to avoid disruptions, tokamaks must operate with a line-averaged density n that is less than the Greenwald density $n_G = c_G I_p/\pi a^2$ with $c_G = 10^{14}$/A·m a constant, a the minor radius, and I_p the plasma current. The Greenwald limit forces tokamak power plants to operate at T greater than 35 keV to obtain an adequate power density on the wall and requires several times better confinement than if the plasma had a lower temperature. The Greenwald constraint is equivalent [2] to $\beta \equiv 4\mu_0 k_B nT/B^2 < \beta_G$. The Greenwald beta is $\beta_G \equiv 8c_G(\kappa_e/q_{95})(k_B T/BR)$, where the major radius is R, the elongation, height/width of the plasma, is κ_e, and the edge safety factor is q_{95}. At a given magnetic field, the fusion power density is proportional to β^2. The constraint $\beta < \beta_G$ forces the plasma beta to be far below the equilibrium and stability limits and makes the power density unacceptably small at $T = 14$ keV, where the $nT\tau_E$ requirement for ignition is minimized. More importantly, the energy confinement time τ_E in tokamaks and stellarators scales approximately as gyro-Bohm, which means $\tau_E \propto 1/T^{3/2}$. The higher temperature implies far better confinement is required for a fusion burn. The Greenwald limit also complicates disruption avoidance, plasma shutdown, and divertor design. The Greenwald limit is not only reason tokamak power plants require a high temperature; the maintenance of the plasma current is another.

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[2] A. H. Boozer, *Stellarators as a Fast Path to Fusion*, presented at the IAEA Fusion Energy Conference, May 2021; submitted to Nuclear Fusion and is accessible at <https://arxiv.org/pdf/2104.04621.pdf>.

Radiofrequency emission by runaway electrons in FTU

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Emission of radio waves in the lower hybrid and whistler frequency range has been measured on FTU under different plasma regimes, including low-density hot plasmas, pellet-fueled plasmas and post-disruption RE beams. The explored range of the ratio between electron cyclotron and electron plasma frequencies was extended to $\omega_{ce}/\omega_{pe} > 3$, in the ballpark of ITER start-up values. Electromagnetic fluctuations generated by coupling with plasma waves were detected by means of different diagnostic settings, employing a log-periodic antenna, an adjustable dipole antenna, a low noise amplifier, a spectrum analyzer and a PXIe-5186 fast digitizer. The maximum used sampling rate was 6.25 GHz, corresponding to 0.1 s recording duration.

Radio emissions were detected in all examined discharges with significant RE signatures. Both bursting and continuous emissions have been found. An example of bursting emission is shown in Figure 1. Radio bursts appear already in the current ramp-up phase, showing that kinetic instabilities influence RE dynamics already in the formation phase.

Radio emission transiently disappears during disruptions, and subsequently reappears if the post-disruption RE beam lasts long enough, under the action of position-controlled current ramp-down. Sequenced of radio bursts emitted by the RE beam appear correlated with re-heating of the background plasma.

Radio bursts are accompanied in most cases by rapid enhancements of electron cyclotron emission (ECE) and by bursts of the Cherenkov probe signal. Both observations are consistent with occurrence of the so called anomalous Doppler (or fan) instability, which gives rise to rapid pitch-angle scattering of runaway electrons. Unstable waves with frequency falling in the observed spectral range (0.4 − 3.0 GHz) can be either whistlers or magnetized plasma waves. The latter are favored at the high ω_{ce}/ω_{pe} values explored in FTU, for which whistlers can only resonate with RE at high-energies (> 15 MeV typical); however, further studies and multimachine comparisons are required to assess the relative importance of involved wave branches.

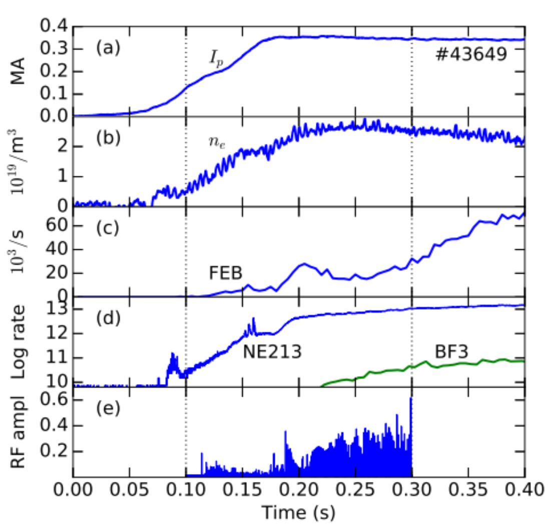

Figure 1. Measurements of plasma waves emitted by runaway electrons. FTU pulse 43649 at 5.3 T. (a) Plasma current. (b) Line-averaged density. (c) HXR count rate from an equatorial channel of the fast electron bremsstrahlung camera. (d) Log10 of HXR and neutron count rate from a liquid organic scintillator (NE213) sensitive to both HXR and neutrons; the neutron contribution from cross-calibrated boron trifluoride (BF3) neutron detectors is shown by the lower line. (e) Radiofrequency emission amplitude from moving RMS, normalized to digitizer saturation. Vertical dotted lines mark the acquisition interval.

Edge-Localized Mode Detection and Correlation with Rotating MHD modes for Disruption Event Characterization and Forecasting*

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Abstract

Edge-Localized Modes (ELMs) are a set of transient instabilities that eject plasma from the edge of a tokamak onto its walls. ELMs pose serious constraints to the successful operation and lifetime of reactor-scale tokamaks. While typically not directly disruptive, ELMs can trigger more detrimental plasma instabilities that can disrupt plasma confinement. ELM identification is hence an important capability to determine the threat ELMs pose to plasma termination. The Disruption Event Characterization and Forecasting (DECAF) code works to resolve, characterize, and forecast event-chains that lead to disruptions – which includes disruptive event "seeds". The newly developed DECAF capability to robustly and reliably identify ELMs using several plasma signals as input is presented. The detection algorithm uses D_α light to find D_α spikes and electron temperature profiles to importantly distinguish edge-localized events from global modes by processing the profile evolution through the mode dynamics. The presented ELM detection capability was validated on a database of ELMing and non-ELMing NSTX and KSTAR plasmas. DECAF event-modules are also being advanced to actively relate relevant DECAF event attributes to other DECAF events, such as active ELMing to the triggering of rotating MHD events, plasma confinement transitions, and others. Further, using the DECAF event chain analysis framework and its existing rotating MHD event module, we apply the novel ELM identification capability to preliminarily study the extent of correlation between ELM-events and rotating MHD-events.

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EXPERIMENTAL RESULTS FROM THE LAST FTU CAMPAIGN ON RUNAWAY ELECTRON MITIGATION

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ABSTRACT

Analyses of experimental data collected in the last FTU campaign provide interesting results on Runaway Electrons (REs) suppression by means of large (wrt FTU plasma volume) deuterium pellets on RE quiescent discharges, mainly inducing bursts of MHD activity that expel the RE seeds. This phenomenon was found to be very reproducible on discharges at 0.5 MA and 5.3 T. Pellets injected during current ramp-ups are also shown to lead to a complete suppression of the RE seed; however, they triggered disruptions as well. These promising results on pellet cleaning effects for different RE quiescent scenarios are discussed. Avalanche multiplication of REs after single pellet injection on 0.36 MA RE quiescent discharges is reported. We provide quantitative indications of RE mitigation effects in terms of increased Connor-Hastie (critical) electrical field due to Anomalous Doppler Instabilities (ADI) for RE quiescent scenarios and post-disruption RE beams. Analysis of large fan-like instabilities on post-disruption RE beams, that seem correlated to the applied negative electrical field and the background density drops, revealed their strong capability to dissipate the RE energy increasing their pitch angle, expelling some of them, and transferring a large fraction of their magnetic energy to the background plasma. Then, ADI can lead to efficient RE energy dissipation (on FTU) as well as full conversion from runaway into thermal electrons (on TCV), indicating a new possible strategy for RE mitigation by controlling the onset of large fan-like instabilities. We also show that short pulses of ECRH, combined with D_2 gas puffing, generate a density increase that gives way to a density decrease, when ECRH is switched off, triggering ADI and opening the path to a possible alternative RE mitigation strategy.

Fig. 1. Shot #43357: on a quiescent 0.5MA/5.3T RE scenario with a consistent RE population (a), the injection of D_2 pellet (b) triggers MHD burst activities that completely expel REs (c) healing the discharge.

GENERATION AND MITIGATION OF RUNAWAY ELECTRONS: SPATIO-TEMPORAL EFFECTS IN DYNAMIC SCENARIOS*

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Abstract

A numerical study of the generation of seed runaway electrons (RE) and the mitigation of fully developed post-disruption RE beams is presented. The main focus is on the role played by the usually neglected, or highly approximated, spatiotemporal effects. The seed generation computations were done using an extended and optimized version of the BMC (Backward Monte Carlo) code that allows to perform accurate and efficient computations of RE generation in fully time dependent dynamic scenarios including radial transport [1,2]. Up to now, most studies on Dreicer generation have either neglected radial transport or limited attention to non-chaotic magnetic fields. However, MHD simulations have revealed the ubiquity of magnetic field stochasticity during the thermal quench. Motivated by this, the paper presents an exploration of the dependence of the seed production on different physics mechanisms in the presence of radial diffusion caused by magnetic field stochasticity. The computations of RE mitigation were done using an extension of the KORC (Kinetic Orbit Runaway electron Code) that includes experimental reconstructed time-sequenced magnetic fields, collisional models for partially ionized impurities, and models of thermal electron and impurity spatiotemporal dynamics fitted to experimental data [3]. It is found that energy dissipation due to collisions with impurities plays a critical role in RE confinement by contributing to the delicate balance determining the relativistic drift orbit effects as the magnetic configuration evolves. Simulations of recent experiments in DIII-D and JET will be presented.

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Advances in Deep-learning-based Prediction & Control of Plasma Instabilities and Disruptions in Tokamaks

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Virtual IAEA-PPPL Workshop, 2021

The successful application of neural networks in the prediction and control of disruptions in tokamaks, especially the demonstration of cross-machine predictive capabilities, provides an essential basis for designing AI-enabled disruption prediction and control system in future toroidal plasma devices such as ITER and SPARC. Here we present recent advances in the development of the deep learning based software suite for the prediction and control of disruptions and associated plasma instabilities. Based on the work introduced in *Nature,* ***568*** *(2019) by J. Kates-Harbeck, A. Svyatkovskiy, W. Tang,* we have further developed the fusion recurrent neural network (FRNN) software suite to include: (1) a fully-convolutional architecture that improves cross-machine predictive capabilities [*G. Dong, et al* , *Journal of Machine Learning for Modeling & Computing,* **2** *1, 2021]*; (2) a real-time sensitivity study scheme to output physics-based interpretation of the disruption alarm [*William Tang, et al., IAEA FEC paper TH-7, Nuclear Fusion (to be published, 2021)]* and to output instability related physical signals in addition to the disruption scores to enable earlier disruption warning and control in future plasma control systems (PCS); (3) the introduction of a deep-learning based framework established to produce surrogate models from the flagship gyrokinetic toroidal code (GTC) in the current SciDAC ISEP Project with the goal of delivering physics-based instability information from first-principles based massively parallel global electromagnetic simulations into the PCS of modern tokamaks. The detailed design, methods, and results of (1), (2) and 3) will be described in this presentation. In future developments, the results of (2) and (3) will be combined to facilitate earlier disruption alarms and the design of realistic reduced models for real-time disruption control algorithms.

Prospects for disruption handling in a commercial tokamak fusion reactor

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Rapid termination of a tokamak discharge due to instability, termed a "disruption", presents one of the greatest challenges to achieving an economically viable fusion reactor. Handling of these damaging transients, including prevention, mitigation, and resilient design, must be incorporated into future burning plasma tokamak designs at the same priority as core performance and steady state heat flux removal if the risk to capital investment due to catastrophic failure is to be reduced to economically acceptable levels. Disruption handling is typically executed along two paths: prevention and mitigation. Prevention requires avoiding unstable regimes, actively stabilizing instabilities if they do appear, or, if those steps should fail, terminating the plasma in a rapid but controlled ramp-down to remove the drivers of instability before it causes a disruption. Mitigation is a last resort that utilizes the injection of massive amounts of impurity to radiate the plasma thermal and magnetic energy as uniformly as possible throughout the vessel to avoid damaging concentrated thermal and mechanical loads. Extremely robust disruption prevention will be of paramount importance in to ensure high duty factor and capital return on the reactor investment. At the same time, successful prevention will face many challenges in a commercial reactor, as actuators will be far more limited, diagnostic access and reliability far less robust, the burning plasmas will be more self-organizing, and the expectation for mean time between failures far longer than in contemporary devices or ITER. Disruption mitigation is a highly undesirable outcome for a reactor, as it can reduce but is unlikely to prevent all damage. Hence, resilient design aims to sustain disruptions without long-term damage in the absence of active intervention. Several possibilities are presented: liquid metal divertors to sustain TQ thermal loads; sacrificial high-field-side limiters to prevent vertically unstable disruptions; and passive 3D conducting structures to prevent the formation of a RE beam.

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Overview of latest runaway electron experiments and analysis at COMPASS

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In the last runaway electron campaigns that were performed in 2020, broad range of experimental results were obtained in several areas of runaway electron physics. Special diagnostic tools and methods were applied including HXR spectrometry, limiter calorimetry, estimates of energy based on runaway electron equilibrium, synchrotron radiation diagnostics (REIS2), matrix SXR detectors and passive and active high frequency antennas. The measurements of RE beam average energy based on the relativistic pressure and equilibrium properties seem to present a fast and efficient method that can be compared well with the methods based on the hard X-ray bremsstralung and synchrotron radiation diagnostics. The comparison of RE beams generated by injections of different gas species and amounts shows that the least dangerous terminations of the RE beam can be achieved via Ne injection or impurity injection followed by a D2 secondary injection. The D2 secondary injection beneficial effects tend to be consistent with DIII-D and JET results. The RMP experiments have also provided many interesting results including significant reduction of HXRs and impact energy of the RE beam with application of RMPs during the RE beam generation. Measurements with high frequency antennas, which will be briefly introduced, also showed presence of wide range of high frequency kinetic instabilities including the whistler-like and various chirping phenomena. Last but not least the room temperature solid state pellet injector has been implemented and used for RE beam generation as well as for enhancing the RE dissipation.

Experimental Measurements of Shattered Pellet Injection Fragment Plume Parameters

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Shattered pellet injection (SPI) has been selected as the baseline disruption mitigation (DM) system for ITER. SPI utilizes cryogenic cooling to desublimate low pressure (<100 mbar) gases onto a cold zone within a pipe gun barrel, forming a cylindrical pellet. Pellets are dislodged from the barrel and accelerated using either a gas driven mechanical punch or high-pressure light-gas delivered by a fast-opening valve. SPI technology is currently deployed and operational on DIII-D, JET, and KSTAR. These SPI systems are currently being used in experiments for physics scaling to ITER thermal mitigation and runaway electron dissipation/avoidance. Once the pellets are dislodged and launched downstream, they impact an angled tube and break into a plume of small fragments. Fragment size distribution, plume duration, and fragment velocity distribution are all important parameters for incorporating a realistic fragment plume into current SPI DM modeling efforts. For relatively small, 4 – 16 mm diameter, pellets the fragment size distribution can be modeled using a statistical fragmentation model for brittle materials. Larger ITER-sized pellets do not follow this model due to a few possible factors, such as a large temperature gradient though the pellet and a size dependence on the fragmentation threshold velocity (currently not assumed to have a size dependence). Plume duration and velocity distribution follow the same general trends independent of pellet size. Experimental measurements of these parameters for a range of pellet materials and sizes are discussed in this presentation with the goal of improving ongoing modeling efforts.

Abstract for IAEA/PPPL Theory and simulation of disruption workshop 2021

Measurements and modeling of pre-thermal quench non-thermal electron formation during pellet injection shutdowns in DIII-D

E.M. Hollmann, I. Bykov, N.W. Eidietis, O. Embreus, J.L. Herfindal, M. Hoppe, A. Lvovskiy, T O'Gorman, P.B. Parks, C. Paz-Soldan, Ž. Popović , D. Shiraki, and I. Svenningsson

Abstract

The formation of non-thermal (hot) electrons during the early (pre-thermal and thermal quench) phases of discharge shutdowns initiated by rapid injection of cryogenic pellets in the DIII-D tokamak is studied. Neon and mixed neon/deuterium shattered pellets are studied, as well as unshattered argon pellets. Non-thermal, hot (multi-keV) electrons are observed to be present at and slightly ahead of the incoming pellets; it is unknown at present if these hot electrons form ahead of the pellets due to impurity ions transport and subsequent radiative temperature collapse or due to fast electron transport. Comparison with ablation rate models indicates that these non-thermal electrons dominate the pellet ablation and are therefore important for understanding the pellet impurity deposition profile. Interpretive Fokker-Planck modeling indicates that the current carried by the non-thermal electrons can be quite significant, thus possibly affecting disruption current profile and MHD evolution. Most of these early-time non-thermal electrons appear to be lost during the large MHD activity during the TQ and start of the CQ, so measurable post-CQ relativistic runaway electrons are not necessarily formed by these early-time non-thermal electrons. This highlights the importance of radial loss in determining post-disruption runaway electron current levels.

Simulations of Neoclassical Tearing Modes Seeded via Transient-Induced-Multimode Interaction

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Nonlinear extended MHD simulations demonstrating seeding of neoclassical tearing modes (NTMs) via MHD-transient-induced multimode interactions are presented. Simulations of NTMs are enabled by two recent NIMROD code developments: the implementation of heuristic neoclassical stresses and the application of transient magnetic perturbations (MPs) at the boundary. NTMs are driven unstable by the inherently kinetic bootstrap current, which arises due to collisional viscosity between passing and trapped electrons. These simulations use heuristic closures that model the neoclassical electron and ion stresses. NTM growth requires a seed island, which is generated by a transiently applied MP in simulations. The capability is demonstrated using kinetic-based reconstructions with flow of a DIII-D ITER Baseline Scenario discharge [R.J. La Haye, et al., Proceedings IAEA FEC 2020]. The applied MP seeds a 2/1 NTM that grows in two phases: a slow growth phase followed by a faster robust growth phase like that observed experimentally. Additionally, an evolving sequence of higher order core modes are first excited. Power transfer analysis shows that nonlinear interactions between the core modes and the 2/1 helps drive the initial slow growth. Once the induced 2/1 magnetic island reaches a critical width, the NTM transitions to faster robust growth which is well described by the nonlinear modified Rutherford

equation. This work highlights the role of nonlinear mode coupling in seeding NTMs in ITER relevant conditions.

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Non-equilibrium impurity treatment for JOREK Disruption Mitigation simulations

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A collisional-radiative non-equilibrium impurity treatment for JOREK simulations has been developed. The impurities are represented by super-particles flowing along the fluid velocity field lines, while ionizing and recombining independently according to ADAS data and local fluid density and temperature. The non-equilibrium impurity contributions are then projected back to the fluid field for self-consistent time evolution. A 2D test case is used to compare the new non-equilibrium impurity model against previous Coronal Equilibrium (CE) impurity treatment, as well as to compare the non-equilibrium impurity behavior between the single and the two temperature model. Further, we conduct benchmark with previously published coronal non-equilibrium results by other 3D nonlinear MHD codes such as M3D-C1 and NIMROD. The new non-equilibrium treatment is shown to successfully capture the early phase cooling by weakly ionized impurities which the CE model missed. The benchmarks with M3D-C1 and NIMROD show general agreement in both the integrated quantities and the 2D profile evolution, despite the difference in the atomic model used. The above comparison and benchmark cases demonstrate the capability of the non-equilibrium impurity model for JOREK, paving the way for more sophisticated 3D non-linear Massive Material Injection (MMI) simulations which have important applications in disruption mitigation studies.

Dispersive shell pellet modeling and comparison with experimental trends

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Nonlinear 3D extended MHD simulations of disruption mitigation by dispersive shell pellet (DSP) injection in DIII-D are performed with the NIMROD code, attempting to reproduce an experimental pellet velocity scan and compare the main observed trends in mitigation parameters. The ablation model for the diamond shell is partly based on theory, but also empirically calibrated to match a single experimental data-point in the scan. Three general trends found in the experiment are reproduced by the simulations: 1) the thermal quench (TQ) mitigation efficiency increases with pellet speed; 2) the amplitude of the plasma current spike decreases with speed; and 3) runaway electron generation is expected only for the fastest pellet speed. The trend in the plasma current spike is found to be associated with the competition between dissipation of poloidal flux at the at the magnetic axis and reconnection at the separatrix x-point as the edge current density profile flattens. The runaway electron observation for the fastest pellet is connected to more central pre-cooling by shell electrons and a more concentrated payload delivery, leading to faster cooling of the core, so that the electric field grows to exceed the critical electric field on a time scale fast enough for hot-tail runaway electron production. Further insight into these observations is gained from the simulations and the results suggest that a predictive model should be possible for shell material quantities that are low enough to avoid triggering pre-TQ MHD instabilities. Such instabilities affect heat transport and make ablation and payload delivery more unpredictable, but non-perturbative shells should be easier to achieve as DSP is scaled up to ITER because of the reduction of the surface-to-volume ratio for larger pellets.

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The ITER Disruption Mitigation System – Design progress and design validation

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The design of the ITER Disruption Mitigation System is progressing and passed a first system design review in June 2021. The system is based on 27 injectors in 3 upper and 3 equatorial ports to provide Shattered Pellet Injection (SPI). The final design review is planned for early 2023, but already now, design decisions are required due to interfaces with other tokamak components. The ITER Disruption Mitigation Task Force (DMTF) provides input on present physics knowledge to support these decisions and coordinates an extensive programme to enhance the physics basis of the design through experiments and modelling and to develop SPI technology compliant with the ITER requirements. The presentation will a) introduce the present design stage together with its risks and challenges, b) summarise the mitigation requirements and their uncertainties, c) give an overview on the DMTF activities.

Alpha particle driven Alfvénic instabilities in ITER post-disruption plasmas

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Abstract.
Fusion-born alpha particles in ITER disruption simulations are investigated as a possible drive of Alfvénic instabilities. The ability of these waves to expel runaway electron (RE) seed particles is explored in the pursuit of a passive, inherent RE mitigation scenario. The spatiotemporal evolution of the alpha particle distribution during the disruption is calculated using the linearized Fokker-Planck solver CODION coupled to a fluid disruption simulation. These simulations are done in the limit of no alpha particle transport during the thermal quench, which can be seen as a most pessimistic situation where there is also no RE seed transport. Under these assumptions, the radial anisotropy of the resulting alpha population provides free energy to drive Alfvénic modes during the quench phase of the disruption. We use the linear gyrokinetic magnetohydrodynamic code LIGKA to calculate the Alfvén spectrum and find that the equilibrium is capable of sustaining a wide range of modes. The self-consistent evolution of the mode amplitudes and the alpha distribution is calculated utilizing the wave-particle interaction tool HAGIS. Intermediate mode number ($n = 7 - 15,\ 22 - 26$) Toroidal Alfvén Eigenmodes (TAEs) are shown to saturate at an amplitude of up to $\delta B/B \approx 0.1\%$ in the spatial regimes crucial for RE seed formation.

The role of impurity transport and temperature in MGI induced runaway dynamics

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Abstract In this contribution, we show how experimental investigations of massive gas injection (MGI) induced disruptions at ASDEX Upgrade (AUG) [1, 2] can be complemented by computational studies using the 1.5D coupled transport codes ASTRA-STRAHL [3–6]. In self-consistent simulations of background plasma evolution, material injection and runaway electron (RE) generation, the temporal evolution of integral plasma parameters (e.g. line-integrated electron density, plasma current) is calculated well in agreement with experimental observations throughout the disruption. Importantly, the rapid increase of the electron density during the thermal quench can be explained only under the assumption of greatly enhanced radial transport of impurity ions inside the $q = 2$ surface during the break-up of magnetic surfaces [5], presumably due to MHD effects. In the absence of such processes, the inward impurity propagation of neutral material at the speed of sound is insufficient to cause a thermal collapse on sub-ms time scales and associated increase of the electron density. For the generation of REs, interactions with partially ionized impurities are demonstrated to be important through application of state-of-the-art reduced-kinetic models [7, 8]. Building on these successful simulations, the post-disruption RE current calculated is shown to increase in AUG MGI scenarios for core temperatures exceeding 10 keV due to an increasing population of hot-tail REs generated during the thermal quench [6]. However experimentally, RE beams are challenging to produce under these conditions, suggesting increased losses of the RE seed.

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Fast wave excited by runaway electrons in disruptive plasma

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Kinetic instabilities in the MHz range have been observed during current quench in DIII-D disruption experiments (A. Lvovskiy et al., PPCF 60, 124003 (2018)). These instabilities are correlated with the RE loss happening at the beginning of disruption. In this work we use a MHD-kinetic code M3D-C1-K to simulate the excitation of this instability. It is found that this mode lies in the fast wave branch, which is similar to the compressional Alfvén eigenmode (CAE) and has large parallel magnetic field component. The mode structure is similar to the fast wave excited by runaway electron in the flattop phase (D.A. Spong et al., PRL 120, 155002 (2018)). The wave can have resonance with high energy trapped runaway electrons, which have precession frequency close to the mode frequency. The excited mode has the potential to increase the diffusion of runaway electron and can play a role in RE mitigation.

Benchmarking Nonlinear, Extended-Magnetohydrodynamic Modeling of Disruption Mitigation

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Future tokamaks will require robust disruption-mitigation systems (DMS) to prevent damage from extreme heat loads, electromagnetic stresses, and runaway electrons. The leading-candidate DMS is shattered-pellet injection (SPI) of impurities, which is being tested experimentally on several tokamaks and will be used on ITER. Sophisticated, verified, predictive models are needed to project the performance of these essential systems on future devices. We present an overview of verification efforts between the M3D-C1 and NIMROD codes for SPI modeling. Both extended magnetohydrodynamic codes have been coupled to a coronal non-equilibrium model for impurity ionization, recombination, and radiation. A 2D, nonlinear benchmark based on a DIII-D equilibrium with core impurity deposition was successfully completed. The two codes showed excellent agreement in the temporal evolution of global plasma quantities (e.g., thermal energy, plasma current, and radiated power), in addition to 2D contours of the temperature and current density through the thermal and current quenches. In addition, a 2D, nonlinear benchmark was performed for an ITER L-mode plasma with a pencil-beam of ablating, mixed-neon-deuterium pellets, also showing good agreement between the codes. Finally, a 3D, nonlinear benchmark for an ablating, injected pellet in a DIII-D plasma is underway. Agreement between the codes has been greatly improved through a number of code enhancements and increased resolution. The codes agree on the peak radiated power as well as time scales for thermal quench, current quench, and onset of macroscopic MHD instability. Results of parametric scans of diffusivity parameters will also be presented. The agreement found between M3D-C1 and NIMROD in these simulations gives confidence in the ability of both codes to perform high-fidelity, predictive modeling of disruption mitigation in ITER and other future devices.

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Progress on SPI ablation and assimilation modeling for ITER DMS using 1.5D INDEX code

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Shattered Pellet Injection (SPI) is the baseline strategy presently envisaged for the ITER Disruption Mitigation System (DMS) [1]. It is presently considered that the ITER DMS offers the capability of injecting up to 24 pellets from the equatorial port plugs at three different toroidal locations. These significant material injection capabilities have been based on the requirements for Runaway Electron (RE) avoidance and mitigation, including redundancy and the possibility to provide pellets with different composition for the different phases of an ITER pulse. Here we report progress on numerical modelling of the SPI assimilation using the 1.5D disruption simulator INDEX and discusses how injection parameters of SPI can be optimized to match the requirements of disruption mitigation and RE avoidance for different target plasma parameters expected in ITER [2]. In order to identify a pre-thermal quench (pre-TQ) SPI scheme that maximises the electron density, a comparison has been made between the injection of pure hydrogen pellets and that of neon mixed hydrogen pellets (composite pellets). Such simplified approaches such as ones based on 1D models can, through extensive and systematic variation of key engineering parameters, provide invaluable data for the design validation and optimization of the ITER DMS. We also present on-going effort to improve the modelling capability of SPI ablation/assimilation with INDEX and the strategies for experimental validation of pellet physics, utilizing not only present tokamaks but also helical devices such as LHD, to strengthen the physics basis for ITER DMS.

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*The work has been performed in collaboration with the ITER Disruption Mitigation Task Force.

MHD Modeling of SPI Injection in JET

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Nonlinear 3D MHD simulations of shattered-pellet injection (SPI) in JET have been performed using the M3D-C1 and NIMROD extended-MHD codes. NIMROD simulations show a radiative thermal quench (TQ) which becomes more rapid as the pellet passes through the safety factor q=3 surface. The results are similar for both a single, monolithic pellet and a pencil-beam model for the SPI plume. A scan in viscosity from 200-2000 m^2/s for 2D MHD simulations shows no significant change to the predicted radiative collapse. The effect of viscosity in 3D NIMROD simulations of JET with significant MHD activity is being assessed. Nonlinear 3D M3D-C1 modeling of JET SPI experiments with a single, monolithic pellet show a prototypical SPI-driven disruption. An initially radiation-driven TQ is accelerated by MHD activity as the pellet crosses the q=2 and q=3/2 surfaces, leading to a radiation spike, global stochasticization of the magnetic field, and a complete TQ. Eventually a current quench (CQ), preceded by a current spike is seen as the ohmic heating balances the radiative cooling. A simulation performed with half the viscosity (500 vs 1000 m^2/s) showed qualitatively similar behavior, but with a slightly higher radiation spike and an earlier CQ without a current spike. These simulations lay the ground work for more-sophisticated validative and predictive modeling of SPI in JET using both M3D-C1 and NIMROD.

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Optimal RF stabilisation of NTMs in large tokamaks

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Neoclassical tearing modes in tokamaks typically rotate while small and then lock at a fixed location when larger. Research on present-day devices has focused almost exclusively on stabilisation of rotating modes, as it has been considered imperative to avoid locked modes in order to prevent loss of confinement and disruptions. However, in larger devices, such as those contemplated for tokamak reactors, the locking occurs at a smaller island size, and the island can be safely stabilised after locking without incurring a disruption. Compared to rotating islands, the stabilisation of these small locked modes can be performed at lower peak and averaged wave power, does not place as strict requirements on the power deposition width and its radial alignment with respect to the island O-point, and is not thwarted by large seeding events. On large devices, it thus becomes surprisingly advantageous to allow the mode to grow and lock naturally before stabilising it.

Calculations indicate that ITER will already be in a regime where that alternative stabilisation strategy becomes preferable. ITER's rotating island stabilisation strategy is seriously challenged by the accelerated locking caused by its blanket modules [1], as well as the large broadening of the electron cyclotron wave due to edge density fluctuations [2]. Locked mode stabilisation should prove more robust to avoid disruptions, as rotating island stabilisation requires detection at small widths, swift stabilisation before locking occurs, narrow and well-aligned RF deposition, and cannot tolerate large seeding events. Locked mode stabilisation has been demonstrated experimentally [3], and its implementation in ITER would be possible with no changes to its design. In particular, the fixed toroidal launching angle, which was optimised for a rotating island stabilisation strategy [4], is shown to be optimal for locked mode stabilisation. Locked mode stabilisation could thus prove crucial to ITER's success, allowing to simultaneously reduce the peak power required for neoclassical tearing mode stabilisation, increase the fusion gain Q, and reduce the disruptivity.

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Early internal detection of MHD by Faraday-effect polarimetry in high-q_{min} DIII-D plasmas and correlation with ideal-wall beta limit

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Faraday-effect polarimetry via the Radial Interferometer Polarimeter (RIP) detects internal magnetic fluctuations in high-q_{min} DIII-D plasmas up to 300 ms before the magnetic sensing coils. The first mode detected by the coils often has $n = 2$ or $n = 1$, but the first mode detected by RIP has $n = 3$, consistent with stability calculations using the DCON code. These plasmas, with $q_{min} >$ 1.4, are designed to achieve high β_N, but β_N is commonly limited by tearing modes, the onset of which is difficult to predict. The RIP diagnostic measures the line integral of magnetic fluctuations across the center of the plasma. The detected $n = 3$ mode appears at the lowest-m/n rational surface available for $n = 3$, with $m = 6$, 7, or 8, depending on q_{min}. The DCON code calculates the ideal-wall kink-mode β_N limits for modes with $n = 1$ - 3, and these limits are used as a proxy for linear tearing mode stability. For these plasmas, the β_N limit for $n = 3$ is generally the lowest. Hence, as β_N increases, DCON predicts the onset of an $n = 3$ mode first, and sampling different shots, RIP detects $n = 3$ instability with $\beta_N \sim 50$ - 75% of the $n = 3$ ideal-wall limit. The 6/3 mode, resonant at the $q = 2$ surface, occurs initially without a 4/2 or 2/1 mode, consistent with the DCON calculation, but the 4/2 and 2/1 modes do appear later in time, and their amplitudes increase as the 6/3 mode amplitude decreases. In other cases, the appearance of an $n = 2$ mode coincides with the disappearance of $n = 3$. The narrow eigenfunctions of higher-n, core-resonant modes render them challenging to detect with sensing coils. With its unique ability to probe the core, RIP has improved understanding of MHD stability and evolution, and its early detection of MHD will allow application of tearing control tools before modes can grow to large amplitude. *Work supported by US DOE under DE-FC02-04ER54698 and DE-SC0019003*.

On Disruption Prediction and the Relative Cost of Disruptions

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Disruption prediction is typically assessed in terms of the True Positive Rate and the False Positive Rate that a given predictor achieves. Here I will demonstrate: (1) that a relationship exists between these prediction performance parameters and the cost of a disruption relative to the cost of an unnecessary discharge termination, (2) that knowing these costs is necessary to determine whether the use of a particular predictor is better than using no predictor at all, and (3) that knowing these costs is necessary to identify the optimal predictor for a particular operating regime. I will show how this cost tradeoff model can be applied to examples from the literature to illustrate that an accounting of disruption costs is essential to making any decision about implementing a disruption predictor.

Access and Extrapolation of Runaway Electron Mitigation via D2 Injection and Large MHD

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D2 injection is found to enable access to a benign termination of mature runaway electron (RE) beams via the excitation of very large and sudden MHD events driving total RE loss [1,2,3]. This presentation will focus on recent experimental developments at DIII-D as well as ongoing modeling work to understand extrapolation of the D2+MHD effect to ITER.

Recent (2021) experiments in DIII-D have explored the effect of several actuations on access to the benign termination. The parameters explored are: 1) the background plasma species (D2, He, Ar, etc); 2) the D2 quantity, 3) the current profile shape, 4) the vertical displacement event (VDE). Access to the benign termination is found to require a collisionless recombined plasma, which sets limits on the required injection, which is found to be necessarily hydrogenic. The current profile, if broadened, is found to promote access to the large-scale MHD at higher safety factor (q) of 3 vs the usual q=2 for DIII-D. The VDE is found to be compatible with the benign termination, but only if the plasma remains recombined. These findings will be compared to results from the JET tokamak where appropriate.

Considering extrapolation to ITER, recent modeling has focused on: 1) the anticipated RE equilibrium evolution during the VDE and access to low q MHD instability, 2) the required wetted area enhancement to disperse the kinetic energy, and 3) the impact of the increased avalanche gain expected in ITER. This work finds that a high current ITER RE beam should robustly access q=3 and 2, where external kink instability is expected, and that the large-scale dispersal of the kinetic energy is still expected. The large avalanche gain expected in ITER is a severe challenge, likely requiring multiple cycles of the benign loss to fully terminate the RE beam.

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**See the author list of ‘Overview of JET results for optimising ITER operation’ by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)

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Resistive Wall Mode stability forecasting in NSTX through Balanced Random Forests and counterfactual explanations

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Recent progress in the Disruption Event Characterization and Forecasting (DECAF) framework [**1**] has shown that Machine Learning (ML) guided by physics theory [**2**] can be easily implemented as a supporting tool for fast computations of ideal stability properties of spherical tokamak plasmas. In order to extend that idea, a customized Random Forest (RF) classifier that takes into account imbalances in the training data is hereby employed to predict Resistive Wall Mode (RWM) stability for a set of high beta discharges from the NSTX spherical tokamak. More specifically, with this approach each tree in the forest is trained on bootstrap samples that are balanced via a user-defined over/under-sampler. The proposed approach has been observed to outperform classical cost-sensitive methods for the problem at hand, in particular when used in conjunction with a random under-sampler, which also results in a threefold reduction in the training time. Additionally, a model-agnostic method to interpret algorithmic predictions based on Diverse Counterfactual Explanations (DiCE) [**3**] has been explored to gain understanding into the model's decisions. In this first attempt, it has been observed that the underlying RF model understands that the presence of hypothetical slowing magnetohydrodinamic (MHD) activity would have prevented the RWM from concurrently going unstable, as expected by prior physics knowledge. Moreover, counterfactuals are used to simulate real-time control by generating rotation and β_N levels that would have kept the RWM stable.

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DISRUPTION PREVENTION VIA INTERPRETABLE DATA-DRIVEN ALGORITHMS ON DIII-D AND EAST

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Abstract

The Disruption Prediction via Random Forest (DPRF) algorithm is currently installed in both DIII-D and EAST PCS, and provides not only predictions of impending disruptions in real-time, but simultaneously identifies the drivers of the disruptivity, i.e. feature contributions – all in about 150 - 250 microseconds. This is the first demonstration that a machine learning-based algorithm can provide interpretable predictions in real-time on multiple devices. Providing indications of the ongoing disruption dynamics to the Plasma Control System (PCS) proves to be essential in actuating the proper response to avoid performance loss and disruptions deleterious consequences. On DIII-D, DPRF was upgraded including real-time calculations of profile-based indicators of temperature, density and radiation. Such peaking factors prove to be relevant metrics in impurity accumulation events leading to disruptions in scenarios close to ITER baseline, providing a warning more than 1s prior to disruption. On EAST, DPRF was trained on high density disruptions. During closed-loop experiments, it has shown to be capable of predicting such cases and triggering the mitigation system with relevant accuracy. Data-driven models will be essential for ITER's and future devices' protection systems, but only if optimal predictive capabilities can be demonstrated and models' predictions are reconciled with the underlying physics dynamics. Current results represent a step forward in data-driven control for scenario optimization and disruption avoidance for ITER and next generation devices. This work establishes the importance of developing tools capable of identifying and informing in real-time the PCS on the dangerous plasma parameters deviations to the disruptive space to enable the proper actuators' response.

Disruption Avoidance via RF Current Condensation in Magnetic Islands Produced by Off-Normal Events

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We are interested in developing a capability to stabilize large islands via RF driven currents to avoid the need for mitigation to the extent possible. Reliance on mitigation alone will increase the exposure of the first wall to high heat fluxes from the radiation flash, and it will involve some increased risk of serious damage to the device. It has been reported that 95% of the disruptions in the JET tokamak with the ITER-like wall are preceded by the growth of large locked islands [1]. The large islands are mostly produced by off-normal events other than neoclassical tearing modes [2]. A statistical analysis of 250 disruptions on JET found a distinct locked mode amplitude at which the plasma disrupted, and further analysis concluded that that locked mode amplitude corresponded to an island width of about 30% of the minor radius [3]. This suggests that the disruptions were being directly triggered by the islands, and further evidence supports that [2]. It will be desirable to use RF driven currents to stabilize such islands in ITER. When the 20 MW of ECCD power available in ITER is used to stabilize large islands, nonlinear effects can arise [4,5]. A nonlinear RF current condensation effect can be used to concentrate the current near the O-point and improve the stabilization efficiency. Failure to properly account for the nonlinear effects in the aiming of the ray trajectories can lead to a shadowing effect that causes the energy in the wave to be prematurely depleted, impairing stabilization.

Islands produced by off-normal events can be Δ' unstable, requiring higher levels of RF driven current for their stabilization than those produced by NTMs. When the islands lock and grow, the plasma will fall out of H-mode, leading to a reduction in temperature and a reduction in the efficiency of the EC current drive. It will not be possible to generate sufficient current to stabilize some of these islands at the fixed toroidal launch angle of 20° planned for the ITER upper EC launchers. It will be desirable to have a capability to increase the toroidal launch angle to increase the current drive efficiency. This will lead to further broadening of the deposition profile beyond the already significant broadening produced by edge density fluctuations. The RF condensation effect can be used to compensate for the broadening, increasing the stabilization efficiency. Nonlinear effects are more pronounced at the larger toroidal launch angles, producing a synergy between the current drive efficiency improvement and the condensation effect.

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Runaway electron beam suppression using impurity flushing and large magnetohydrodynamic instabilities.

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Runaway electrons are considered to be the most challenging consequence of a disruption for future tokamaks like ITER. If runaway generation cannot be avoided, it is mandatory to have a second line of defense to suppress a fully formed runaway beam. Shattered Pellet Injection (SPI) is presently the

baseline disruption and runaway mitigation method for ITER. Experiments using SPI on the JET tokamak showed that high-Z material such as neon or argon injected into a runaway beam with a low-density companion plasma accelerated the decay of the runaway current but did not prevent the final impact on the wall. Beams with high-density companion plasmas were found to be insensitive to SPI as they were with Massive Gas Injection (MGI).Conversely, the injection of a D_2 SPI into a runaway beam led to an increase of the runaway current followed by a complete and abrupt dissipation of runaways. This dissipation did not generate any measurable heat loads on the plasma-facing components and was found to be related to two key ingredients. First, a large MHD instability possibly linked to a hollow current profile led to the loss of runaways on a large area through stochastization. This was supported by JOREK simulations which capture the experimental time scale of the termination event and the broad runaway deposition. The second ingredient was found to be the purity of the companion plasma. The D_2 SPI flushes high-Z material used to trigger the disruption (argon) out of the companion plasma. If the high-Z concentration is low enough when the beam is dissipated by the large MHD burst, no runaway regeneration and therefore no conversion of runaway magnetic and kinetic energy occurs. The “D_2 effect” was also found to be still efficient in conditions where the plasma moved vertically, mimicking the situation foreseen in ITER. The extrapolability of such a promising mitigation scheme for ITER will be discussed.

Offline Torque Balance Analysis of Rotating MHD for Real-Time Application

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Reactor scale tokamak devices require a low disruptivity ceiling for full performance operation. An approach has been developed to automatically establish disruption event chains based on the relevant precursors. An important precursor to disruptions is the presence of rotating neoclassical tearing modes (NTM). Through coupling, NTM's with a saturated island width can slow down the plasma rotation and lock it to the wall reference frame. A balance of the driving torque from the NBI, the perpendicular viscous diffusion drag, the electromagnetic drag of the mode, and its inertia is used to model the rotation dynamics. Threshold rotation frequencies are derived from this model below which the plasma rotation is expected to lead to a mode lock, serving as a forecaster. A zero-crossings analysis of a toroidal array of Mirnov probes is used to calculate the rotation frequency of the mode. From the rotation, the torque components are then calculated based on conditions for the expected drag torque ratios at the mode onset, increases in frequency, and Mirnov signal amplitudes. The approach was validated by comparisons of the viscous diffusion time with energy confinement time, and NBI torque with NBI total power and plasma density. This technique is prepared for real-time analysis of KSTAR plasmas with possible use in engaging active control systems. Results are compared between real-time and offline implementations to establish the feasibility of the forecaster.

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Tokamak Disruption Event Characterization and Forecasting Research and Progress on Expansion to Real-Time Application

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Disruption prediction and avoidance is critical for ITER and reactor-scale tokamaks to maintain steady plasma operation and to avoid damage to device components. The present status and results from the disruption event characterization and forecasting (DECAF) research effort [1] are shown. DECAF is primarily physics-based and determines the relation of events leading to disruption, quantifies their appearance to characterize the most probable chains of events, and forecasts event onset. The code has access to data from multiple tokamaks to best understand and validate models and compare analysis results between them. In the past year, attention has been placed on expanding the scope of DECAF events, their forecasting, and real-time implementation of DECAF on the KSTAR device. Significant new hardware and software for real-time data acquisition and analysis are being designed/written and installed on KSTAR including magnetics, plasma velocity and T_e profiles, pitch angle and magnetic fluctuation profiles, and 2D T_e fluctuations. Real-time magnetics and velocity profile data processed off-line shows excellent agreement with offline data/analysis. Automated analysis of rotating MHD modes allows identification of disruption event chains including coupling, bifurcation, locking, and triggering by other MHD activity. A locked mode forecaster has been developed for off-line and real-time use in DECAF using a torque balance model of the rotating MHD mode. Early warning forecasts of mode locking and subsequent disruption are found on transport timescales potentially allowing active profile control to avoid the mode lock. A new ELM identification event module includes the ability to distinguish localized and global MHD events. Mode stability alteration by ECCD has been examined in experiments studying triggerless and triggered 2/1 NTMs that destabilize in different operational regimes in KSTAR H-mode plasmas. Pre-programmed ECCD reduced the triggerless 2/1 mode amplitude by ~80% and the triggered mode amplitude by 30% when applied to the flux surface region close to the mode rational surface inferred from ECEI data. Resistive stability analysis including calculation of Δ' by DCON is evaluated with comparison to experiment examining sensitivity to localized variations of the kinetic reconstructions of the q profile using MSE data.

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Simulation Study of Pellets and SPI Fragments Ablated by Thermal and Runaway Electrons

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Numerical simulation of pellets and shattered pellet injection (SPI) fragments in tokamaks ablated by thermal and runaway electrons have been performed using the Lagrangian Particle SPI ablation code [R. Samulyak, S. Yuan, N. Naitlho, P.B. Parks, Lagrangian particle model for 3D simulations of pellets and SPI fragments in tokamaks, Nuclear Fusion 61 (4), 046007 (2021)]. The code implements the low magnetic Reynolds number MHD equations, kinetic models for the electronic heating, a pellet surface ablation model, equation of state with multiple ionization support, radiation and a model for grad-B drift of the ablated material across the magnetic field. 3D simulations of single neon and deuterium pellets clarify some aspects of the ablation rate scaling laws in magnetic fields with the resolution of grad-B drift and provide data on pellet ablation using non-uniform plasma parameters at DIII-D conditions (courtesy B. Lyons).

The main focus of this work is the fully resolved simulation of hydrogen SPI into a runaway beam at ITER condition (problem proposed by M. Lehnen and E. Nardon). We consider a large hydrogen pellet, 28.5 mm in diameter and 57 mm in length, shattered into various number of fragments, and injected with the velocity of 500 m/s into a monoenergetic 20 MeV runaway electron beam with the current varying from 1 MA to 10 MA. Simulations study the influence of various processes on the ablated plume dynamics. Some aspects of the problem have been studied using a reduced 1D version of the Lagrangian particle code and good agreement with 3D simulations have been achieved. The parallel heat conduction is shown to be small at relevant time scales, and the thermal ionization is insufficient for MHD effects in the ablation flow. However, the impact ionization of the ablated cloud by runaway electrons (impact ionization rates courtesy N. Garland) leads to the channeling of ablated plumes created by individual fragments along the toroidal magnetic field lines. We study the dependence of the plume structure on the number of fragments and compute the large-scale evolution of the ablated material.

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Findings from a Benchmark Study of 3D Vertical Displacement with JOREK, M3D-C^1, and NIMROD*

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A comprehensive benchmark of the widely used JOREK, M3D-C^1, and NIMROD codes on vertical displacement with 3D dynamics enhances confidence for modeling disruptions and highlights sensitivities in these applications [Artola, *et al.*, Phys. Plasmas **28**, 052511 (2021)]. The simulated case is based on NSTX discharge 139536 (with a simplified resistive-wall geometry) after feedback stabilization was removed. The simulations are constrained to follow axisymmetric evolution until the last closed flux surface (LCSF) contacts the wall. Asymmetric perturbations are then imposed, transport parameters are increased to start the thermal quench (TQ), and 3D computations then follow the development of tearing and external kink dynamics. The asymmetric activity is initially dominated by a (2,1) mode in all three computations, and its growth-rate increases over time as q_{95} decreases together with the self-consistent development of halo current. When q_{95} decreases past 2, other external kink activity grows strongly. Saturation of the asymmetric dynamics leads to the final rapid phase of the TQ. Despite the strong qualitative agreement, there are quantitative differences among the results, such as 70% variation in the duration of the final TQ phase and a factor of 2.7 variation in the peak horizontal force on the resistive wall. We note that there are important differences in the computational models. The JOREK modeling presented here is Ansatz-based reduced-MHD, while M3D-C^1 and NIMROD solve full-MHD equations. JOREK and M3D-C^1 use potential-based representations, while NIMROD evolves magnetic field and fluid moments, directly. There are also differences in the representation of the resistive wall and external vacuum and in the numerical methods. For example, the coupling of JOREK and STARWALL precludes the exchange of conductive electrical current between the JOREK domain and the resistive wall, so technically there is no toroidal variation of the plasma current, unlike the M3D-C^1 and NIMROD computations. In addition, we find that the computations are sensitive to the perturbations that are used to break axisymmetry when the LCFS contacts the wall. Perturbations that excite the (2,1) mode at larger amplitude tend to produce a (2,1)-dominated saturation that leads to an 80% larger horizontal force relative to the result from the same code that shows multi-helicity saturation.

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Thermal quench in ITER locked mode disruptions

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Disruptions in ITER could be much milder in ITER than in JET and present experiments. They might be called disturbances rather than disruptions. In JET, it was found that the thermal quench (TQ) in locked mode disruptions is caused by resistive wall tearing modes (RWTMs) [1]. This result was obtained by comparison of theory and M3D [2] simulations with JET data. The RWTM growth rate is

$$\gamma\tau_A = c_0 S^{-1/3} S_{wall}^{-4/9} \tag{1}$$

where $c_0 = \mathcal{O}(1)$, $\tau_A = R/v_A$ is the Alfvén time, S is the Lindquist number, and $S_{wall} = \tau_{wall}/\tau_A$. The TQ time τ_{TQ} is given by the smaller of $1/\gamma$ or the parallel thermal transport time

$$\tau_{TQ} \approx \left(\frac{1}{\gamma}, \tau_{\|}\right)_{min} \tag{2}$$

where $\tau_{\|} = a^2/(\chi_{\|} b_{n0}^2)$, $\chi_{\|}$ is the parallel thermal diffusivity in the plasma edge region, b_n is the r.m.s. of $\delta B/B$ normal to the plasma boundary. In simulations, $b_n \approx 10^{-3}$.

In ITER, the resistive wall penetration time is 50 times longer than in present experiments. The growth time of the RWTM in ITER could be as large as 100 ms. Thermal loss can also be caused by $\tau_{\|}$, parallel transport along stochastic magnetic field lines. In JET, this process is slower than RWTM advection, because the parallel thermal conduction is relatively low in the plasma edge. In ITER, the edge might be significantly hotter, and the thermal conductivity might be in the collisionless regime. A combined form of $\chi_{\|}$ with both collisionless and collisional limits is

$$\chi_{\|} = \frac{\pi R v_e}{1 + \pi R/(2.1 v_e \tau_e)} \tag{3}$$

Fig.1 shows TQ in ITER for temperature $T \leq 1KeV$. The curve $1/\gamma_{ITER}$ has ITER values $S_{wall} = 3.5\times10^5$, $c_0 = .51$, and $1/\gamma_{JET}$ has the JET value $S_{wall} = 7\times10^3$, $c_0 = 2.2$. The $\tau_{\|}$ curves are $\tau_{\|1}$ with $b_n = 10^{-3}$, and $\tau_{\|2}$ with $b_n = 2\times10^{-3}$. The TQ time given by (2). The value $\tau_{TQ} = 10ms$ is also shown. Simulations indicate that the magnetic fluctuation level will be about the same as in JET, $b_n = 10^{-3}$, similar to estimates from experimental data [3]. The loss time scales would be sufficiently long that runaway electrons and divertor melting should be much less of a problem than anticipated.

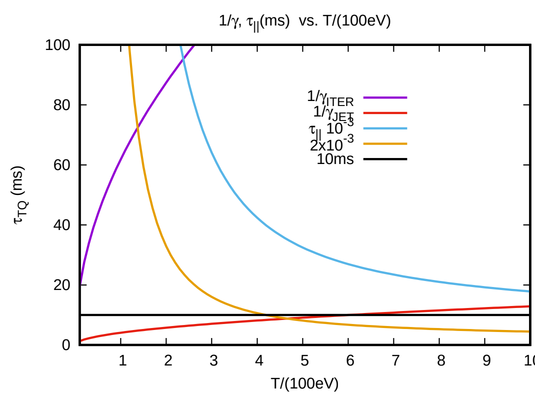

Figure 1: *TQ time from* $1/\gamma$ *and* $\tau_{\|}$*, for JET and ITER.*

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Complete prevention of runaway electron beam formation with a passive 3D coil in SPARC

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In this work, a non-axisymmetric runaway electron mitigation coil (REMC) is passively energized by the disruption current quench (CQ), exciting MHD modes and producing stochastic fields within the plasma, and thereby scatters energetic electrons and prevents potential damage caused by the beam. Such a coil is planned for SPARC, a compact (R_0 = 1.85 m, a = 0.57 m), high-field (B_0 = 12.2 T) and high-current (I_p = 8.7 MA) tokamak capable of reaching Q > 2 in D-T plasmas. With a minimum expected CQ duration of ~3 ms in SPARC, a loop voltage ~5 kV may lead to RE currents up to ~5.2 MA if not mitigated. To calculate the effectiveness of the REMC, the 3D finite element code COMSOL is used to calculate the current coupled to the coil (up to 590 kA) from the plasma current decay and the resulting vacuum magnetic field perturbations. The 3D MHD code NIMROD is then used to model the excitation of plasma MHD with the REMC's external perturbation. The orbit-following code ASCOT5 is used to compute the advection and diffusion coefficients characterizing the transport of electrons in NIMROD's stochastic fields. Finally, the RE modeling framework DREAM is used to evolve RE generation and transport throughout the disruption. Whereas candidate toroidal configurations of n = 2 and 3 show little-to-no mitigation of RE formation, the n = 1 REMC excites a rich spectrum of saturated plasma modes early in the CQ leading to a near fully stochastic magnetic field and complete prevention of RE beam formation.

Simulations of Disruption Mitigation in ITER with Staggered Shattered Pellet Injection

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The currently envisaged method for disruption mitigation in ITER is to use massive material injection. One of the injection schemes considered is a staggered shattered pellet injection, with a pre-disruption diluting deuterium injection followed by a neon injection aiming to radiatively dissipate the plasma energy content [1]. It was recently shown [1] that it will likely be possible to increase the plasma density by at least an order of magnitude, thus strongly reducing the plasma temperature, without unacceptably accelerating the onset of the thermal quench. In this work [2], we perform numerical simulations assessing the performance of such a mitigation scheme in an ITER-like setting, with a particular focus on the generation of runaway electrons.

These studies are performed with the integrated tool DREAM [3, 4], designed to evolve the 1D configuration space and 2D momentum space dynamics during tokamak disruptions. In this work, DREAM has been extended with the ability to simulate shattered pellet injections based on a statistical model for the shattering [5], and the neutral gas shielding model for the ablation [6]. We investigate the degree of pellet shattering resulting in the most efficient use of the injected material for a given pellet size. Using this degree of shattering, we study the subsequent thermal and current quench dynamics and evaluate the disruption mitigation performance over a wide range of pellet sizes in terms of the ratio of conducted energy loss, the current quench timescale, and the maximum runaway current.

Our studies indicate that the diluting deuterium injection can efficiently reduce the runaway generation due to the hot-tail mechanism, by allowing for a moderate temperature equilibration of the superthermal electron population between the injections. The fraction of the initial thermal energy content conducted to the plasma-facing components is also reduced compared to a single-stage injection with the same composition, reducing the localised heat loads. During non-nuclear operation, the maximum runaway current is found to be reduced to acceptable levels with realistic two-stage injection parameters. On the other hand, during nuclear operation, the unavoidable runaway seed from tritium decay and Compton scattering was found to be amplified to several mega-amperes by the avalanche mechanism for all investigated injection parameters. The reason is that the intense cooling from the injected material leads to a high induced electric field and a substantial recombination, resulting in an enhanced avalanche multiplication.

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Collisionless plasma transport mechanisms in open stochastic magnetic field lines associated with thermal quench

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The collisionless plasma transport mechanisms in stochastic magnetic fields open at the wall boundary have been studied for understanding the mechanisms of the thermal quench in tokamak disruption using a global gyrokinetic simulation code GTS. Although the stochastic magnetic field lines are open at the wall, a significant amount of electrons are found to be confined in the system due to trapping by the magnetic mirror force and positive electrostatic potential developed in the stochastic layer. In this study, we present a comprehensive picture of the relation between the dynamics of passing and trapped electrons and the 3-D topology of the stochastic layer, which is essential to understand thermal quench physics. We found that the consistent coupling of electron and ion dynamics through the ambipolar electric fields plays a critical role in determining electron thermal transport. The 3-D ambipolar potential builds up in the stochastic layer to maintain quasi-neutrality in the plasma during the thermal quench. The associated ExB vortices mix particles across the stochastic magnetic field lines, providing a collisionless detrapping of electrons that plays a major role in the loss of high-energy electrons along favorable open field lines. In addition, the ExB mixing enhances the radial electron transport directly contributing to the thermal quench. As a result, the electron temperature decreases steadily in the typical thermal quench time scale of milliseconds.

Simulation of plateau formation during current quench and MHD instabilities with runaway electrons

During a disruption, electrons can runaway and be accelerated to high energies, potentially damaging the first wall. To predict the occurrence and consequences of runaway generation during a disruption, we have developed a runaway electron module for the M3D-C1 code[1]. This fluid runaway electron model is fully coupled to the bulk plasma. It utilizes an implicit time advance with sub-cycling that allows runaway velocities approaching the speed of light, c. Both the Dreicer and avalanche source terms are included, and we have verified their implementation by performing benchmarks with the JOREK code[2].. We have computed the linear stability of a runaway electron discharge and compared with an analytic model for a circular cylindrical discharge and verified that low mode number tearing modes acquire a rotation caused by runaway electron-MHD interaction[3]. Also, the tearing layer is much narrower in a runaway electron discharge[3,4]. Recent emphasis is on modeling runaway electron plateau formation during mitigation experiments on DIII-D, including the intentional shedding of runaways by lowering the edge safety factor, q(a) to 2.0[5].

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Scenario adaptive disruption prediction study for next generation burning plasma tokamaks

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Due to the dangers for serious damage to the devices from unmitigated high current, high power disruptions, developing a reliable disruption predictor for a device's High Performance (HP) operation using its Low Performance (LP) operation data is a key to the success of next generation tokamaks. In this presentation, through explorative data analysis and dedicated numerical experiments on C-Mod, DIII-D and EAST, we demonstrated how the operational regime of existing tokamaks can affect the predictive power of a trained predictor. On one hand, our results suggest limiting the range of a few parameters that are important to tokamak operation but less significant to our predictor can affect the distributions of other parameters related to disruption predictor and change the prediction results. Indeed, our results show that data-driven predictors trained on abundant LP discharges still work poorly on the HP regime of the same tokamaks which confirms signals related to disruption are closely correlated and pushing the limits of less important signals changes the distributions of more significant signals and hence invalidate the trained predictor. On the other hand, we find matching operational parameters among tokamaks strongly improves cross machine accuracy which implies our model learns from the dimensionless physics scaling of these parameters and confirms the validity of these scaling for disruption prediction from the data-driven perspective. Finally, our experiments demonstrate the suitable predictivity on the HP regime of the target machine can be achieved by combining LP data from the target with HP data from other machines. These results provide a possible disruption predictor development strategy for next step tokamaks, like ITER and SPARC, and highlight the importance of developing baseline scenario discharges of future tokamaks on current machines.