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EXPLORATION OF THE EQUILIBRIUM AND STABILITY PROPERTIES OF SPHERICAL TOKAMAKS AND PROJECTION FOR MAST-U

J.W. BERKERY, S.A. SABBAGH, J. BIALEK, Y. JIANG
Department of Applied Physics, Columbia University,
New York, NY, USA
Email: jberkery@pppl.gov

C. HAM, L. KOGAN, D. RYAN, A. THORNTON, G. XIA
Culham Centre for Fusion Energy, UKAEA
Abingdon, UK

D. BATTAGLIA, Z. WANG
Princeton Plasma Physics Laboratory
Princeton, NJ, USA

A. PICCIONE, Y. ANDREOPOULOS
Dept. of Electronic & Electrical Eng., University College London
London, UK

L. GUAZZOTTO
Auburn University
Auburn, AL, USA

S. GIBSON
Centre for Advanced Instrumentation, Durham University,
Durham, UK

Y.Q. LIU
General Atomics
San Diego, CA, USA

Abstract

In preparation for high fusion plasma performance operation of the newly operating spherical tokamak MAST-U, the equilibrium and stability properties of plasmas in the MAST database, as well as projections for MAST-U, are explored. The disruption event characterization and forecasting (DECAF) code is utilized to map disruptions in MAST, particularly with regard to vertical displacement events. Loss of vertical stability control was not found to be common in MAST, providing reassurance for MAST-U operation. MAST equilibria were reconstructed with magnetic diagnostics, adding kinetic diagnostics, or finally also adding magnetic pitch angle data. The reconstructions work well for MAST and the procedures are set up for MAST-U, including determination of the plasma current in the first MAST-U discharges. A 3D wall model of MAST-U has been constructed in the VALEN code, indicating that significant toroidal currents may be induced in the conducting structure. Rotation measurements may also be included in the reconstructions, and a test with the FLOW code of a rotating MAST plasma indicates a modest shift of the pressure contours off of the magnetic flux surfaces may be expected. Unstable resistive wall modes (RWMs) may constrain the performance of high pressure MAST-U plasmas. A machine learning (ML) assisted algorithm for stability calculation developed for the NSTX spherical tokamak has been applied to MAST plasmas. Improvements and expansion of the ML techniques continue, including semi-supervised learning techniques and a detection algorithm for unstable RWMs. Finally, projections of MAST-U plasma stability have been performed, indicating that a region of high pressure operational space exists in which the new passive stabilization plates act to stabilize ideal kink modes and RWMs may be stabilized by kinetic effects or active control.

1. INTRODUCTION

Spherical tokamak fusion plasma confinement devices utilizing magnetic fields to contain high pressure plasmas create a component of their own confining magnetic field by carrying a large toroidal current. If the current is disrupted, a loss of plasma confinement results, which can lead to large heat deposition and electromagnetic forces on the surrounding structures. These so-called disruptions have varying causes and must be avoided for the safe operation of future devices. The present paper outlines the determination of the equilibrium states, physics of stability, and the characterization of causes and forecasting of disruptions in the MAST and MAST-U spherical tokamaks. The MAST-U experiment, an upgrade of the previous MAST device [1], recently began plasma operations and is currently entering its first physics campaign [2]. In preparation for MAST-U high β_N (normalized ratio of plasma pressure to magnetic pressure) operation, research was performed on the existing database of MAST discharges on the topics listed above. Two recent publications [3,4], as well as presentations at recent conferences [5,6,7,8] outline the progress made in equilibrium and stability analyses for MAST-U. This paper summarizes that work as well as presents new steps and details.

2. DISRUPTION EVENT CHARACTERIZATION AND FORECASTING FOR MAST

It is important for stable tokamak operation to identify chains of events that lead to disruptions and the specific physics elements that comprise those chains. If these events can be forecast, cues can be provided to an avoidance system to attempt to break the chain, or if avoidance is deemed untenable, a prediction of the impending disruption can be provided to a mitigation system to significantly reduce disruption ramifications. The ultimate goal of the physics model-based Disruption Event Characterization and Forecasting (DECAF) code [9,10,11] is to provide forecasts which integrate with a disruption avoidance system and are used in real-time during a device's operation.

The DECAF code's many separate physical event modules provide warnings and declare occurrences of certain events leading to disruption. A routine in the DECAF code that automatically detects the time of disruption of a tokamak plasma has been applied to the MAST database [5,10]. The code can generate diagrams showing the probability of a DECAF event occurring within a given parameter space of tokamak operation. Each colored square in parameter space is only plotted if at least 10 equilibrium points from the database exist within that space. Most commonly the time of disruption, or DIS event, is used, resulting in a familiar disruptivity plot. Disruptivity diagrams for MAST have been previously generated to examine Greenwald density limits [5] and compared to other devices in β_N vs. l_i (internal inductance) space [10]. In the present paper, an analysis of vertical displacement events (VDE) and disruptions for MAST will be shown.

Analysis of a database of discharges in the NSTX spherical tokamak has shown that plasmas were prone to a loss of vertical control at higher levels of elongation, κ, for a given plasma internal inductance and that the intolerable level of κ decreased with increasing l_i. The region of κ, l_i parameter space where the loss of vertical stability control, VDE, event was detected in DECAF was quite different from where plasmas end up at the DIS event. For the DECAF code to declare that a VDE event had occurred, there are three tests performed: comparison of axis position ($|Z|$), axis velocity ($|dZ/dt|$), and $Z\ dZ/dt$ vs. threshold levels set by the user. These three tests are then combined and when the total warning points exceed a user-defined total level for VDE, the VDE event is declared.

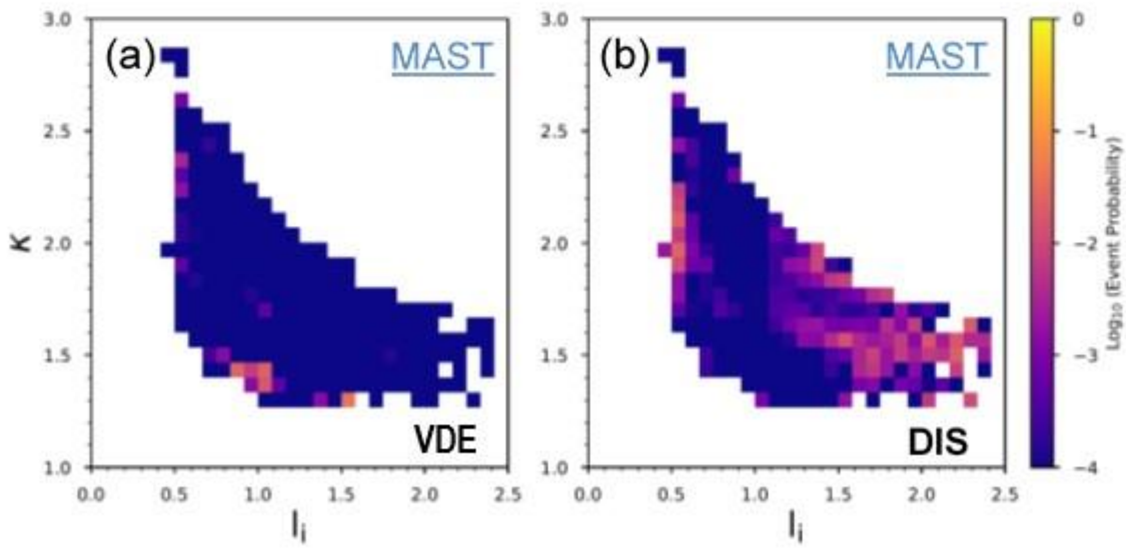


FIG 1: Event probability diagrams of a) VDE and b) DIS in a database of MAST discharges in the κ vs. l_i parameter space, with the colors showing the probability of each event within a segment of that space.

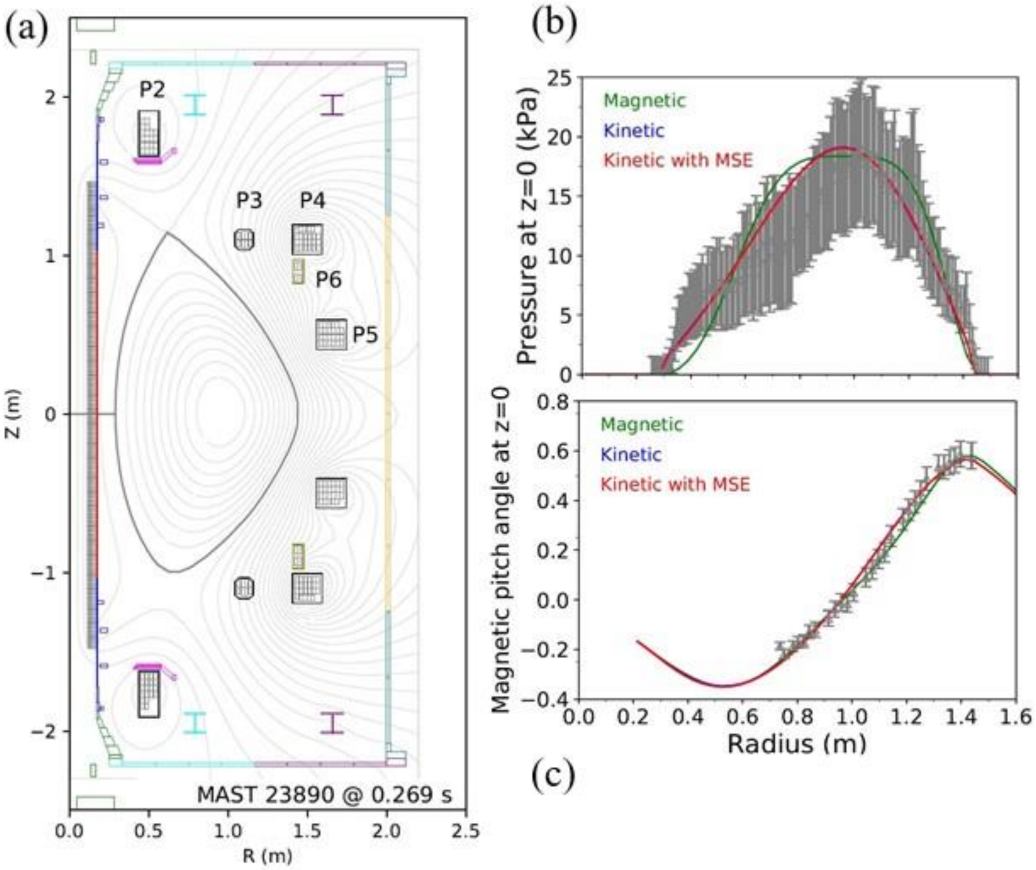


FIG 2: (a) Diagram of MAST poloidal field coils (grey), their cases (black), and all toroidally continuous conducting vessel structures (colors), as well as the flux surfaces of an example plasma equilibrium reconstruction; (b) Pressure and (c) magnetic pitch angle (in radians) profiles vs. radius at z = 0 for MAST discharge 23890 at 0.269 s. Three levels of equilibrium reconstruction are compared to the measured profiles (the pressure profile being partially measured and partially modelled). From Ref. [4].

When applied to the MAST database, loss of vertical stability control was not found to be a common occurrence in MAST. Figure 1a shows the probability of the VDE event being detected by DECAF in the parameter space of κ vs. l_i, while Fig. 1b shows where in the same parameter space the disruption events occur. It should be noted that this analysis does not include current ramp-up periods, where there were known to be some occurrences of vertical displacement events in MAST. While MAST did not often access high elongations ($\kappa > 2.2$), it seems that when it did vertical stability was not a major issue. Note that the vertical control capability planned for MAST-U is designed to control plasmas up to $\kappa = 2.5$ at $l_i = 0.9$. One possible explanation for the relative lack of VDE events is that MAST had (and MAST-U has) close fitting internal coils that were used for active vertical control.

3. EQUILIBRIUM RECONSTRUCTION

Accurate equilibrium reconstruction is crucial for the operation of MAST-U, as well as for stability analyses and disruption event characterization and forecasting. An instantiation of the EFIT code has been used for this purpose for NSTX(/-U), KSTAR, and now MAST(/-U). Once the sources of current from both applied current in coils and estimated induced current in vessel structures are included, various levels of diagnostic data can be input. Three different levels of equilibrium reconstruction have been tested for MAST plasmas, first with magnetics data only. For this level, the available diagnostics were up to 16 raw loop voltage signals, 10 hardware-integrated flux loops on the center column and 36 spaced around the vessel poloidally, 40 center column pickup coils measuring vertical field, and 19 pickup coils on the outboard side measuring vertical field and 19 measuring radial field. The second level, called “kinetic”, also includes partial pressure profile constraints from electron pressure from 130 channels of Thomson scattering measurement and ion temperature from 64 channels of charge exchange recombination spectroscopy. Finally, 35 channels of polarization angle from the motional Stark effect diagnostic (MSE) is added to the kinetic reconstruction. A solution to fit the diagnostic data is iterated until a low convergence error is obtained. All three levels of equilibrium reconstruction are working well for plasmas in the MAST database [4].

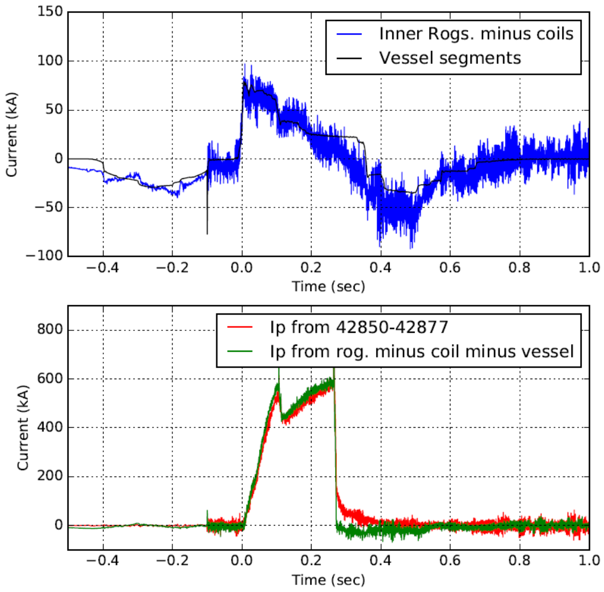


FIG 3. (top) Comparison of modelled vessel segment currents to measured inner Rogowski minus coil current for MAST-U vacuum shot 42877, and (bottom) plasma current for MAST-U shot 42850 determined from comparing the vacuum and plasma shot inner Rogowski measurement, vs. the plasma inner Rogowski measurement minus measured coil and modeled vessel currents.

Figure 2 shows reconstructed flux surfaces for an example case of MAST discharge 23890 at 0.269 s, and a comparison of the reconstructed pressure and magnetic pitch angle profiles at the midplane from the three levels of reconstruction. One can see differences in the profiles between the three levels of analysis. The change in pressure profile shape allowed by the higher level of polynomial order for the kinetic fits is clear. Note that in this particular case the kinetic (blue) and kinetic plus MSE (red) are so similar they nearly identically overlay in the figure.

The equilibrium reconstructions also include fitting of field shaping coil currents, and for equilibrium analyses of spherical tori it is important to include currents in the conducting structure of the tokamak modeled, as they can comprise a significant component of the total toroidal currents well into the plasma current, I_p, flat-top. To create the best 2D model of the effective resistances of the wall segments for equilibrium reconstruction, we have created 3D models of the MAST and MAST-U walls (including 3D features such as NBI ports and other large vessel penetrations, coil casings with 3D flanges, etc.) using the VALEN code [13] and have generated a set of 2D effective resistances of wall segments from the full 3D model [4]. VALEN predictions for the coil case currents match Rogowski coil measurements from operations quite well, giving confidence in the VALEN analysis. This technique is then used to determine effective resistances and estimated currents in vessel segments which are not measured. This model set-up and testing is complete for analysis of the first MAST-U plasmas [4].

3.1. Determination of the plasma current Rogowski measurement

Additionally, plasma current is one of the most critical measurements to determine and constrain equilibrium reconstructions. MAST-U is equipped with two sets of Rogowski coils for measuring the plasma current, an inner and outer set. The Rogowski coil sets actually measure all the current which is enclosed by them, so in order to determine the plasma current, certain known currents must be subtracted from the Rogowski measurements. These include the currents in the poloidal field coils, plus induced currents in their cases, which are also measured by their own Rogowskis, and induced currents in metal vessel segments enclosed by the sets. Since the inner set encloses less currents, we will focus on it here. The inner Rogowski set runs under the center stack tiles, the divertor tiles, and along the outer wall. The carbon tiles it encloses could possibly carry some lower level of induced toroidal current, but for now we will ignore that material to focus on the metal that is enclosed which includes the P4, P5, P6, DP, D5, and D6 coils and their cases, as well as the gas baffle, passive stabilization plates, and a triangular piece of metal on the upper and lower center stack. After the measured coil plus case currents are subtracted from the Rogowski measurements, the final piece, the induced currents in the vessel segments, is now determined by the method previously described of using a nearby loop voltage measurement and dividing by the effective resistances of those segments. A comparison of the measured and modeled final pieces of the enclosed currents are shown in Fig. 3 for the MAST-U vacuum shot 42877.

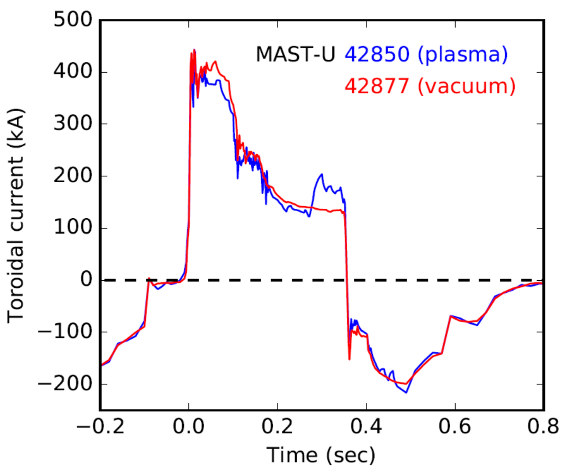


FIG 4. Total induced toroidal current MAST-U conducting structure with (blue) and without (red) plasma current, as calculated by VALEN.

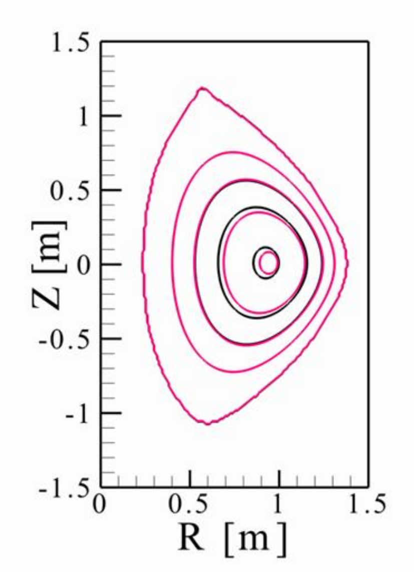
In order to assess the reliability of this method, a pair of pulses was compared – one with plasma (42850) and one without, the only difference between the two being gas puffing and plasma breakdown on one vs. vacuum conditions in the other. In one case, the plasma discharge's inner Rogowski measurement minus the vacuum discharge's determined the plasma current, while in the other, the plasma discharge's inner Rogowski measurement minus the coil, case, and induced currents (as described above) determined the plasma current. The comparison is shown in Fig. 3, showing a close, though not perfect, match. Knowledge of the difference is useful for setting an error bar on the plasma current determined in this way, for input into equilibrium reconstruction codes.

3.2. Comparison of induced vessel currents with and without plasma in MAST-U

Time-domain calculations were performed with VALEN to examine the difference in the modeled induced current between the vacuum and plasma shots 42877 and 42850. As an approximation, the plasma current was uniformly distributed in a circular cross section at the experimental major and minor radius. Figure 4 shows this comparison, plotting the net toroidal currents in the conducting structure of MAST-U. The toroidal current is induced by the changing poloidal field coil currents, especially the swing in the P1 Ohmic solenoid in the center case. By comparison, the flat-top plasma current in discharge 42850 was ~600 kA, so the induced current is quite large. As expected, the toroidal current in the conducting structure is reduced when plasma current is present [4]. Additionally, the figure indicates that the decay of 600kA of plasma current (at ~0.3s) can induce ~60kA of additional current in the vessel.

3.3. Inclusion of rotation in the kinetic reconstructions

The effect of plasma rotation on equilibrium reconstruction might be significant in STs like MAST-U due to the low aspect ratio of the plasma and the generally high levels of toroidal rotation with neutral beam injection providing torque. While the EFIT code is capable of including rotation [14] and the measurement capabilities make this level of analysis possible, for the initial assessment of rotation's impact the FLOW code [15] was utilized. FLOW is not a reconstruction code, but rather it calculates an updated equilibrium from a provided reconstruction (here from EFIT), and provided measured velocity and density profiles. With zero poloidal velocity, the Bernoulli equation has an analytic solution, the effect of which is a shift between the pressure and flux surfaces, which increases as device aspect ratio decreases. We tested the impact of this effect on MAST discharge 24306 at 0.261s, which had a toroidal rotation profile that peaked at about 190 km/s. Figure 5 shows that this moderate level of rotation causes a small shift of the pressure profiles off of the magnetic flux surfaces. A smaller, but numerically resolvable, outward shift of the magnetic axis is also observed, largest at the plasma center. The causes and extent of these shifts will be analyzed in more detail in future work.



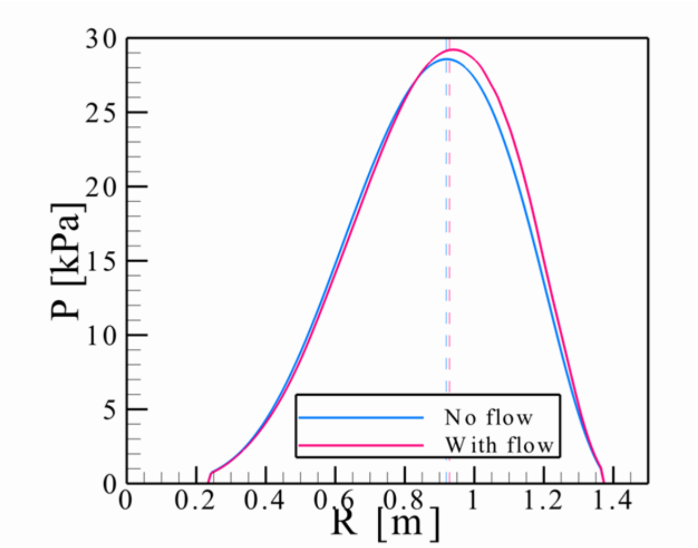


FIG 5: FLOW code calculations for MAST discharge 24306 at 0.261s, of (left) equilibrium flux surfaces in black and pressure surfaces in magenta, and (right) of the pressure profile with (magenta) and without (blue) toroidal rotation.

4. STABILITY ANALYSIS

The resistive wall mode (RWM) is a global mode of instability of high pressure tokamak fusion plasmas which can lead to disruption of the plasma current and termination of the discharge. Therefore a method of detection and forecasting of RWM stability is desired. In past human post-discharge analysis of discharges, an exponential rise in an n = 1 toroidal mode number poloidal magnetic field measurement (known as the RWM sensor) on the time scale of magnetic flux penetration through conducting surfaces surrounding the plasma, τ_w, was used as the primary indicator of RWM instability. This signal is insufficient alone, however, so other considerations, such as the β_N level and the lack of indication of a locked tearing mode were also examined. A tearing mode is another mode of instability of tokamak plasmas that is localized to rational magnetic surfaces rather than the global RWM. The presence of low frequency rotating magnetohydrodynamic (MHD) activity, which can lead to a locked tearing mode, has been seen to almost always preclude an RWM from going unstable at the same time.

Analysis of the physics of RWM instabilities identified other important signals such as plasma rotation and collisionality, however the dependencies were too complex for typical human identification efforts. For example, a physicist could not simply look at a plasma rotation profile and use it as an indication of RWM stability or instability; what mattered were resonances between those rotation profiles and certain particle motions. Complex physics codes which analyzed these kinetic resonances, such as MISK [16,17] and MARS-K were developed and benchmarked. However, it was apparent that while these codes were useful to understand the physics of RWM stability, they were too complex to be run in real-time to predict instabilities so they could be avoided. An alternative approach was then developed where the physics of RWM instability uncovered by these codes was distilled into a reduced model which maintained the major physics but in a more tractable form that could potentially be calculated in real-time [3]. This reduced kinetic model was included in the DECAF code. The reduced kinetic model was tested on post-discharge analysis of plasmas from the National Spherical Torus Experiment (NSTX) and performed well on a limited number of discharges [3].

Stability analysis conducted on plasmas in the MAST database in preparation for operation of high beta MAST-U plasmas was the following. First, attempts have been made to identify cases of unstable RWMs in MAST [18], which were quite rare. Second, machine learning assisted stability calculations made for NSTX have been applied in a cross-device study on MAST. Additionally, improvements to the machine learning techniques, including a detection algorithm for unstable RWMs and causal graph structures with Bayesian techniques, continue. Finally, projections of ideal stability for MAST-U plasmas have been performed.

4.1. Machine learning assisted stability calculations

Recently, machine learning (ML) algorithms are being explored as a numerical tool for disruption prediction and avoidance. In a physics-guided machine learning approach, physics knowledge of the problem is used to pre-process input data and also to interpret the output. Machine learning techniques have now been used for one piece of the kinetic RWM stability problem - determining the ideal stability, including in the physics-guided framework [11], and this piece has been incorporated into DECAF. The resulting techniques have been applied in a cross-machine manner (trained on NSTX data and applied to MAST discharges) in two ways. First, the no-wall β_N limit for MAST determined with the NSTX-trained ML algorithm was seen to perform well, compared to other methods of determination of the limit [11]. Secondly, the output of the DCON ideal stability code for the change in potential energy, δW, has been emulated with ML and when first used for MAST discharges these also provided encouraging results [11].

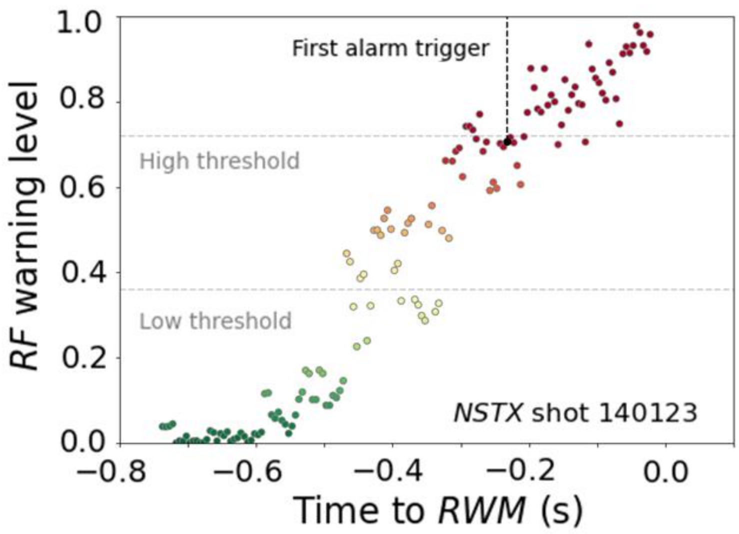


FIG 6. Random forest warning level for NSTX discharge 140123 vs. the time leading to the human-defined time of resistive wall mode instability.

Presently this work is being extended to use ML to predict when the RWM will go unstable. Specifically, a Random Forest (RF) based algorithm is tested on discharges where human analysis has determined the time of RWM instability, or lack thereof. Inputs to the algorithm include the previous physics-guided neural network (PGNN) determinations of the ideal no-wall and with-wall β_N limits [11], the measured β_N, two measured quantities related to the rotation and collisionality inspired by the full kinetic and reduced kinetic models, and finally a signal indicating the presence of a tearing mode. The latter signal is used in the ML scheme to reduce false positives and is also used in DECAF as part of a MHD / locked tearing mode warning module. In DECAF the absence of an MHD warning will be used in conjunction with a simple threshold test on the RWM sensor signal to indicate the possible presence of a growing RWM. Figure 6 shows an example of the RF calculated warning level for an NSTX discharge that had an unstable RWM (at time 0 on the x-axis). A high threshold is set to trigger the warning as long as the level does not fall below a low threshold level in a certain amount of time. In this case, over 200ms of warning time would have been provided to a control system to steer the plasma to a more stable operating space.

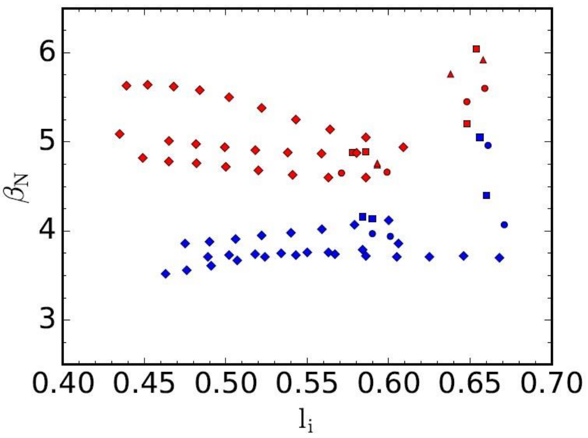


FIG 7. Calculated no-wall (blue) and with-wall (red) stability limits in various projected MAST-U equilibria.

The method presented here proposes a different approach than the reduced kinetic model for RWM stability forecasting, utilizing ML tools while still retaining physics-guidance. A future direction of this work is to go further into combining machine learning and physics knowledge by employing causal graph structures with Bayesian networks underlying them. Defining the most physics-based graph and imposing reasonable priors is key to use this approach. Then the so-called "do-intervention" can be performed (ie. exploring what if something had or had not happened and how this affects the outcome).

4.2. Projected global stability of high beta MAST-U spherical tokamak plasmas

Prior to operation of MAST-U in high beta, an assessment was desired of the limits of stability. To this end, projected equilibria were used, and scanned in pressure and current profiles to find the ideal MHD stability limits. Theoretically, above the no-wall beta limit, RWM instabilities should be expected (if no other stabilizing effects are present), and the with-wall limit is the highest achievable performance point. The DCON, MARS-F, and VALEN codes were used to find these limits in Ref. [3]. For a collection of equilibria with different plasma boundary shapes and profile shapes, and with the different code calculations, generally, the no-wall beta limit increased as internal inductance increased. For the with-wall limit, different wall models were used, both 2D and 3D, but they found similar levels for the β_N limit. A collection of calculated no-wall and with-wall β_N limits from Ref. [3] is illustrated in Fig 7. The spread in the calculated points is mostly due to the various plasma shapes and profiles, as is to be expected, and also somewhat to the different codes used. The operating space in between these limits is a potential region of high beta operation, if kinetic effects or active control can stabilize the RWM, which is opened up by the effect of eddy currents in the structures surrounding the plasma. This region of operation was projected to be larger in MAST-U than for MAST because of the newly installed stainless steel passive stabilization plates in MAST-U divertor region.

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