Validation of 3D nonlinear visco-resistive MHD codes for predictive modeling of transients in fusion plasmas

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Summary of proposed research: We recommend a diverse validation strategy for 3D nonlinear visco-resistive MHD models, using codes such as NIMROD, which are being applied to model tokamak disruptions and ELMs. This entails experimental measurements and computational modeling over as broad a parameter space as possible, and we provide an example of such work based on MST RFP plasmas. These RFP plasmas share multiple traits with tokamak transients, particularly disruptions, including impulsive magnetic reconnection, magnetic stochasticity, and strong nonlinearity. That RFP plasmas are similar to but also distinct from tokamak plasmas, given the RFP's small applied Bt and $q < 1$ everywhere in the plasma, is an advantage for robust validation that extends beyond targeted tokamak operating regimes. But we also describe below possible validation effort that may be possible based on newly-realized tokamak plasmas in MST. Including work done on MST and elsewhere, near-term goals of this validation effort include gauging the viability of these MHD codes in modeling tokamak transients and improving the understanding of these transients. An important longer-term goal is predictive capability.

Background: 3D nonlinear MHD modeling is an important tool in understanding tokamak transient events like disruptions and ELMs. Such modeling has been conducted with codes such as NIMROD (see, for example, Refs. 1-6), but the physics of these transients in present devices is not yet firmly established, nor is our ability to predict how these transients will behave in ITER and beyond. Validation of the codes utilized in this modeling is critical to addressing these issues. In a limited sense, validation of MHD codes has been occurring for decades with numerous, but often qualitative, comparisons of MHD code results to various experimental data. But rigorous validation requires metrics defined to quantitatively characterize a code's ability or inability to model experimental data. This also requires one to stretch the experimental-modeled parameter space as far as one can. Only thus can one attempt to determine the predictive capability of a given code in a parameter space occupied only by future devices. In the remainder of this white paper, we describe initial work contributing to the validation of the NIMROD and DEBS MHD codes with RFP plasmas produced in MST. We also describe work that may be possible with MST tokamak plasmas.

Validation of NIMROD and DEBS with MST RFP plasmas: NIMROD has been applied to many magnetic configurations, including the tokamak and the RFP. It can model a two-fluid plasma in toroidal geometry. An older code, DEBS, has primarily been applied to the RFP, and it can model a single-fluid plasma in cylindrical geometry. The MST plasmas to which these codes are being applied are host to a large number of m = 1 current-gradient-driven tearing modes, which gives rise to

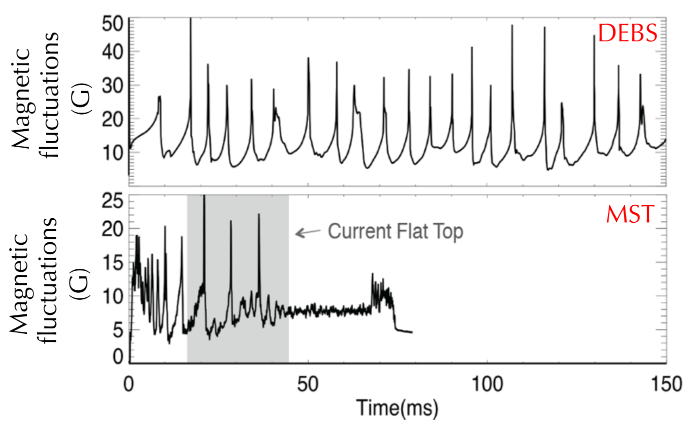

Fig. 1. Temporal evolution of magnetic fluctuations, summed over dominant tearing modes, from DEBS simulation and from an MST plasma. Courtesy of J. Reusch.

overlapping magnetic islands and magnetic stochasticity. And as shown in Fig. 1, these plasmas exhibit periodic global transients (magnetic reconnection events), characterized by strong nonlinear mode coupling, a sudden increase in all mode amplitudes, and an intensification of stochasticity. Hence, there is strong overlap in the physics of these plasmas and, e.g., a disrupting tokamak plasma. The highly nonlinear RFP plasma is qualitatively well described by visco-resistive MHD, as illustrated by the comparison in Fig. 1. This plus MST's advanced diagnostic capability (e.g., multi-chord interferometry-polarimetry and high-rep-rate multi-point Thomson scattering) makes MST an ideal setting for validation of resistive MHD codes.

The present goal of MST's RFP validation work is the diagnosis and modeling of RFP plasmas over a wide range of Lundquist number, $S \sim I_p T_e^{3/2}/Z$, an important dimensionless parameter in resistive MHD. The initial target for validation is the temporal evolution of the tearing mode amplitudes, including the global transients. The data in Fig. 1, at a single value of S, shows that while the single-fluid MHD model DEBS roughly captures the timing of the global transients, there is a discrepancy in the mode amplitudes. Recent two-fluid modeling with NIMROD appears to resolve some of these discrepancies. Validation metrics have been developed that capture the level of agreement/disagreement in quantities like mode amplitudes and the time between global transients, and as shown in Fig. 1, these quantities can vary substantially from transient to transient, much like disruptions and ELMs.

Possible validation work based on MST tokamak plasmas: As described in the Community Input Workshop, MST now produces tokamak plasmas and has recently contributed to an ITPA study on runaway electrons, Fig. 2. We are now exploring what can be done in the realm of MHD code validation, possibly including MST tokamak disruptions. From a validation perspective, studying both RFP and tokamak plasmas in the same device with the same diagnostics would be advantageous.

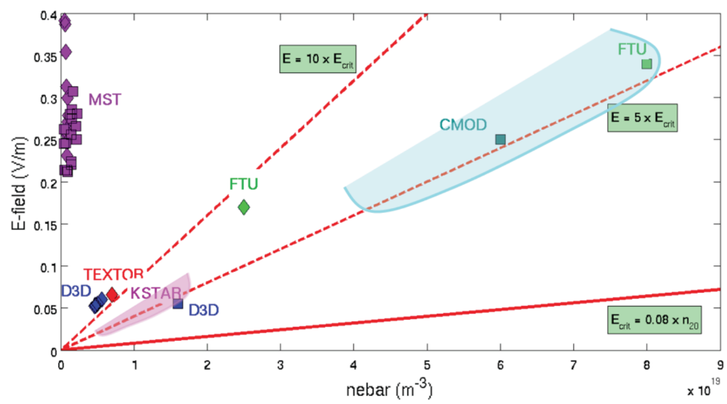

Fig. 2. Onset and suppression thresholds for runaway electrons (IAEA 2014). Courtesy of R. Granetz.

The challenge of validation: Validation of nonlinear MHD codes is experimentally and computationally demanding. Measurement uncertainties must be characterized carefully, and model-critical data is sometimes simply unavailable and must be estimated. Compounding this is the fact that the sensitivity of the model to variations in the input parameters is not always well known in advance, necessitating multiple code runs with suitable variations of input parameters. Particularly for a two-fluid code like NIMROD, even a single run with experimentally relevant parameters requires substantial CPU time. Hence, a serious validation effort requires serious resources.

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