Development of tools for understanding, predicting and controlling fast ion driven instabilities in fusion plasmas

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The performance of burning plasmas (e.g. in ITER and FNSF) will largely depend on the dynamics of energetic ions which originate from fusion reactions (alpha particles), Neutral Beam (NB) injection and RF wave heating. Energetic particles (EP) play a critical role in heating, current drive, and momentum input, yet are subject to transport or loss by a variety of instabilities and toroidal symmetry-breaking fields. Of particular concern are instabilities driven by the energetic particles themselves, such as Alfvén eigenmodes (AEs), fishbones, and energetic particle modes (EPMs). In the presence of AEs or other EP-driven instabilities, energetic particle transport is enhanced, resulting in (presently) unpredictable variations in the NB driven current profile, loss of macroscopic stability and - ultimately - degraded performance. Progress has been made in recent years to understand the coupled and predominantly non-linear dynamics of fast ions and fast ion related instabilities. The challenge for the next decade is to build on that foundational knowledge to develop validated integrated tools and techniques for reliable prediction and real-time control of the EP population and associated instabilities, with the goals of both minimizing risk and maximizing fusion energy output in fusion reactors.

I. OVERVIEW OF THE PROPOSED INITIATIVE

To fully address the challenges presented by future burning plasmas dominated by self-heating, strong programs in both experimental as well as computational Energetic Particle (EP) physics are a necessity. Computationally, efficient/fast algorithms for mode stability and EP transport analysis and prediction will be required. Experimentally, tools for the improved diagnosis of instabilities and energetic particle dynamics will be necessary with a focus on reactor relevant technologies. Future experiments must employ improved diagnostics that facilitate high fidelity measurements of instabilities and EP transport levels while considering the possibility of application in reactor relevant scenarios.

No control tools have been demonstrated yet for the mitigation or suppression of EP driven instabilities, unlike for other phenomena such as edge-localized modes (ELMs), resistive wall modes (RWMs) and neoclassical tearing modes (NTMs). For instance, recent experiments have indicated the potential of applied 3D fields, RF injection and electron cyclotron heating (ECH) to exert some desirable influence over EP driven instabilities including AEs. However, dedicated effort is still required to advance this research from the stage of semi-empirical observation to one of actuator development. The development - and experimental demonstration - of the reliability of both predictors of mode stability and actuators for mode control is therefore a high priority. With a modest increase in their overall budget, the major US fusion facilities and computational centers will be well positioned to address these issues in the next 5 years (FY15-20).

In addition, the JET D-T campaign presently scheduled for FY17-18 would provide a unique test bed for predictions and control schemes of EP-driven instabilities, informing on specific needs for conditions closer to those expected in ITER, FNSF and future burning plasmas. Results from the first 5-year period will then be projected to ITER and FNSF in the following 5-year time frame (FY20-25). Contribution from Universities and basic plasma physics research must also be strengthened during the next 10 years to advance fundamental science of EP and associated instabilities in well-controlled experiments and train a new generation of EP scientists.

Success of the proposed research enables the US Fusion Program to maintain and even strengthen its forefront position in the international EP research community. A comprehensive understanding of energetic particle physics coupled with the operational ability to manipulate EP transport will prove indispensable as we approach the ITER era and start planning for next-step devices. These goals are well aligned with the priorities in the US Fusion Program summarized in the final report of the 2009 Research Needs Workshop (ReNeW [1]) planning activity of the Office of Fusion Energy Sciences. In particular, three ReNeW Themes are addressed:

- Theme #1, *Burning plasmas in ITER*: develop improved methods for controlling key aspects of burning plasmas [...] incorporating validated theories for alpha particle behavior into integrated simulation tools.

- Theme #2, *Predictable, high-performance, steady-state plasmas*: integrate development of [systems] needed to maintain plasma state seeking to maximize performance; understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas.
- Theme #5, *Optimizing the magnetic configuration*: develop the Spherical Torus to advance fusion nuclear science [for FNSF]; power handling, controlled stability and sustainment issues would be studied.

The next Sections provide a more detailed description of the proposed initiative for understanding, predicting and controlling EP-driven modes. Section II briefly summarizes the present status on real-time mode detection, prediction of mode stability and effects on the EP population. Examples of potential tools to affect the mode properties by means of external tools are also illustrated. A timeline for the initiative, including budget elements for the estimated resources required during the next ten years, is discussed in Sec. III. Section IV concludes the paper.

II. PRESENT STATUS: MODE DETECTION, PREDICTION AND CONTROL

Integration of three main elements is required to implement successful techniques for the control of EP-driven instabilities in burning plasmas:

- *Real-time mode detection*, based on available diagnostics which can monitor mode properties (such as amplitude, frequency, spatial localization) and their temporal evolution.
- *Prediction of mode stability and of mode effects on the EP distribution function*, to project present information to future plasma states and inform on optimum strategies to optimize the discharge (e.g., by suppressing or mitigating potentially harmful unstable modes).
- *Development of actuators for mode control*, to react on the plasma based on both detected and predicted behavior of modes and EP distribution function.

The present status of each of these tasks is shortly summarized below. A more complete summary is provided by a companion White Paper by Fredrickson *et al.*, cf. Ref. [2].

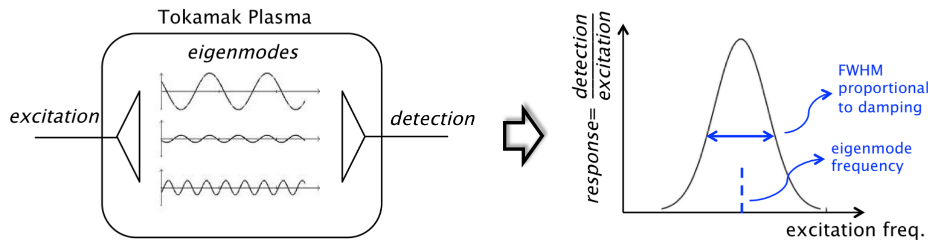

FIG. 1: Schematic of active spectroscopy for characterization of plasma eigenmode stability (e.g. toroidal AEs) from the plasma response to an external stimulus.

A. Real-time mode detection

Present plasma devices are well equipped with diagnostics that provide information on the main properties of plasma instabilities. Data are typically acquired during operations and stored in a database for *a posteriori* analysis, with the exception of signals used by the Plasma Control System (PCS) to feed back on parameters such as plasma position, magnetic configuration, density/pressure. More advanced feedback control schemes take into account stability of specific classes of modes to optimize the plasma discharge, for instance to prevent disruptions. Examples include control of RWM and NTM through either magnetic perturbations excited at the plasma edge or modulated injection of electron cyclotron waves [3][4][5][6].

Although well established schemes exist for real-time detection of low frequency MHD instabilities such as RWM and NTM, few examples exist of similar schemes for routine detection of higher frequency, EP-driven instabilities during a plasma discharge. As of today, no such capability is implemented on any of the US facilities.

Arguably, the most notable example of real-time detection of EP-driven modes has been implemented in the past years on the JET tokamak [7][8] for the characterization of toroidal and elliptical Alfvén eigenmodes (TAEs and EAEs). The principles of the JET *AE antenna* are illustrated in Fig. 1. Similarly to schemes for detection of RWMs through *resonant field amplification*, the plasma is probed by small perturbations over the range of frequency of the targeted modes the plasma response is characterizeded, e.g. by magnetic sensors at the vessel wall or by measuring the (complex) antenna impedance vs. frequency. Analysis of the plasma response provides information on the mode stability (i.e. damping rate, in the absence of mode drive), for instance from the broadening of the frequency response.

B. Prediction of mode stability and EP response

The present status of theory and modeling effort on stability of EP-driven modes is summarized in Refs. [2][9]. For the purpose of this initiative, it should be noted that theories

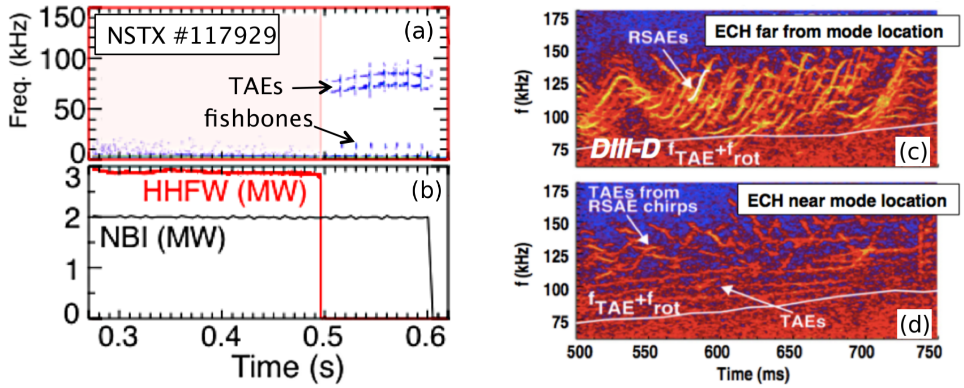

FIG. 2: Left column: Example of TAE and fishbone modes stabilized during injection of 3 MW of High-Harmonic Fast Wave (HHFW) power on NSTX. (a) Spectrogram from Mirnov coils. (b) NB and HHFW waveforms. Right column: Example of reversed-shear AE (RSAE) mitigation by ECH on DIII-D. Shown are spectrograms from interferometer with ECH injected (a) on axis and (b) near the mode location, respectively.

and numerical codes that compute mode evolution and effects on the EP distribution do exist, but they are not optimized for inclusion into a real-time control scheme. Future work will focus on the development of such tools. The proposed approach is to complement existing measurements (cf. Sec. II A) with *reduced* models, whose development and validation are enabled by first-principles codes, theories and experimental results. Although effort has been put in recent years to develop such models [10][11][12], their use for real-time control is still out of scope for present projects.

A very important element for successful model development and validation is the range of parameters over which models are tested. In this regard, present US facilities - including University-based devices - provide an excellent test bed for the models, with scenarios ranging from low- to high-aspect-ratio, and magnetic configuration spanning from linear to tokamak and reversed-field pinch. Further progress can be indeed achieved by strengthening US collaborations with other international institutions, as proposed in this initiative (see Sec. III).

C. Potential for mode control techniques

Mode control schemes based on real-time characterization of AE stability (cf. Sec. II A) were discussed for JET [13], but never actually implemented or tested. Since then, additional evidence has been collected from various devices on means (or *actuators*) to affect both energetic particle population and EP-driven instabilities. The latter can be considered as a first step towards the actual implementation of closed-loop control schemes.

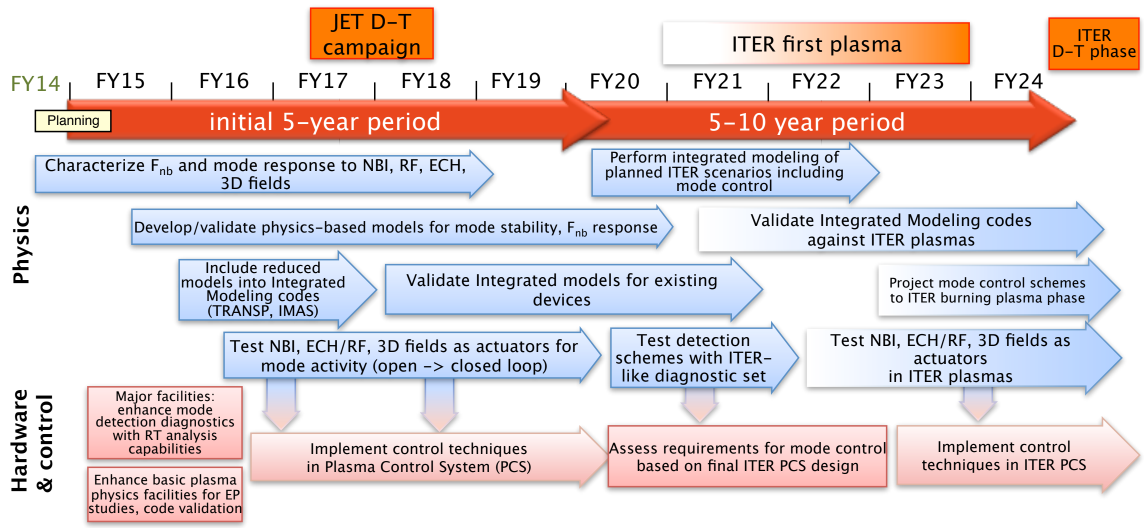

FIG. 3: Timeline for the proposed initiative.

Mode stability can be altered in multiple ways by affecting the mode's drive and damping properties. For example, modifications of the EP distribution through injection of RF and electron-cyclotron waves, or by applying external 3D perturbations have resulted in suppression and mitigation of Alfvénic instabilities [14][15][16], see Fig. 2. In addition, induced variations of the background plasma, e.g. through heating via EC/RF injection or via shape changes (as proposed in Ref. [13]) may affect the mode damping. In some cases, nonlinear coupling between modes have also proven to be effective in modifying mode dynamics [17][18].

The previous examples demonstrate that it is indeed possible to affect the mode dynamics, leading to mode mitigation or even suppression. However, many of those observations still lack of a well-established understanding, which is required to implement control tools and for quantitative projection to future devices such as ITER and FNSF.

III. TIMELINE OF PROPOSED INITIATIVE

The proposed initiative spans over 10 years, from FY15 to FY24. A timeline with the main elements of the initiative is shown in Fig. 3. Two sub-periods are identified, covering the initial and final 5 years. The latter period includes the beginning of ITER operations in the so-called *non-nuclear* phase.

A. Proposal for FY15 through FY19

The focus during the initial 5 years (FY15 through FY19) is on two parallel activities, namely (i) implementation and demonstration of closed-loop mode control schemes and (ii) development and validation of control algorithms. Algorithms include reduced models to complement measurements in determining the mode and EP distribution evolution during a discharge and to predict the response to different actuators (cf. Sec. II B).

Development of reduced models which can be integrated in real-time control schemes is a necessary step towards closed loop control. Validation of the models is conducted by comparison with both first-principles models and directly against experiments. Experiments will target a detailed characterization of the fast ion distribution response to potential actuators such as NBI, RF/ECH and 3D fields. This will also provide initial results on the open-loop response of fast ions and instabilities to those actuators. Characterization of EP response to actuators will proceed in parallel with ongoing research to assess the fast ion response to instabilities such as Alfvénic modes and other Energetic Particle driven modes.

Once validated, the reduced models will be integrated into existing tools for integrated simulations of tokamak discharges, including TRANSP [19] and the ITER Integrated Modeling and Analysis Suite (IMAS) [20]. Integrated modeling will guide the optimization and development of closed loop control schemes, which will then be implemented in the Plasma Control System of existing devices for further tests by the end of the first 5-year period.

During the first time period covered by this initiative, a D-T campaign is planned on the JET tokamak [21]. This is the first set of D-T experiments since the TFTR and JET experiments in the 1990's, and represents the only opportunity for experiments in D-T for the next decade or more. For this reason, it is also proposed to strengthen the US collaboration with JET (and, through JET, with other partner institutions) on EP research, with the goal of testing mode control schemes in conditions closer to those expected in ITER and FNSF. A specific outcome will be to validate models for mode stability in a "burning plasma" environment with simultaneous presence of energetic particles from fusion, NB injection and (possibly) ICRF.

B. Proposal for FY20 through FY24

The second time period (FY20 through FY24) builds on the achievements from early years to project EP-driven mode control schemes to future reactors. ITER operations are expected to begin during this time frame with the so-called *non-nuclear* phase, in which He, H and D plasmas are planned. Validation of the proposed mode control schemes during this period is crucial, before moving into the *nuclear* phase in later years. Firstly, integrated modeling including EP dynamics is planned for ITER scenarios achievable in the non-nuclear phase.

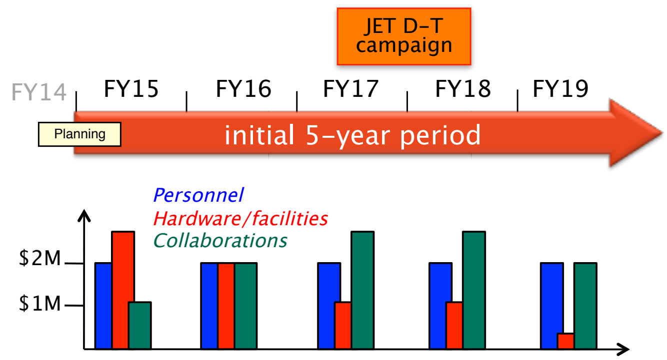

FIG. 4: Budget timeline for the proposed research. Emphasis is on hardware and facilities upgrade in the early years, then shifting to collaborations to support the JET D-T campaign. Increment in personnel involved with EP research for mode control is steady over the years.

This will inform on the requirements for PCS algorithms and integration with available actuators. Beginning of ITER operations will provide the required data for model validation, with emphasis on predictions of mode stability and EP response to instabilities. Secondly, the response of instabilities and EP population to the planned control schemes will be assessed in open-loop. The final step once a set of validated tools is available is the final integration in the ITER closed-loop PCS, which will then enable projections for the future ITER D-T phase (post-FY24).

Finalization of a FNSF design is also expected by the end of the next decade. As the design evolves, requirements for EP-driven mode control on FNSF will be assessed. For instance, the choice between a compact FNSF based on the Spherical Torus concept (see Ref. [22]) as opposed to a conventional aspect ratio design will influence the availability of actuators (e.g., ECH is likely to be unavailable in a lower field, overdense ST-FNSF).

C. Budget and resources

Incremental resources for EP studies, estimated to be of the order of $\$4-6$M/year for the next decade, are required to meet the goals of the proposed initiative, see chart in Fig. 4. Additional personnel is needed on both major facilities and University-based programs for coordinated research activities which specifically target the development of mode control techniques. This implies to strengthen collaborations both between US institutions and with institutions abroad, such as JET. Besides the advancements in physics, an important outcome will be the education of new generations of plasma physicists which will constitute the back-bone team for US contributions to the ITER program on energetic particle research.

On the shortest term, present facilities must be upgraded with enhanced diagnostics (e.g. for real-time mode detection and characterization) and control tools (detectors and algorithms development). The required budget for hardware and facilities upgrades is expected to peak at the beginning of the 10-year period, then stabilize after FY18 once the tools are implemented. Additional resources for national and international collaborations (including diagnostics support, e.g. on JET) are also required, with a budget peaking during the JET D-T campaign and at the beginning of ITER operations.

Although not discussed in detail herein, it should be noted that support of theory/modeling effort is of paramount importance for the successful achievement of the required predictive capability, as discussed in Refs. [2][9].

IV. SUMMARY AND CONCLUSIONS

An initiative is proposed to develop an integrated set of tools for understanding, predicting and - ultimately - control energetic particle driven instabilities in burning plasmas. The initiative leverages on existing facilities (both in the US and abroad) for a coordinated effort in EP physics. The estimated budget increment is $\$4-6$M/year for the next decade. Although the main focus of the initiative is on experimental physics, its success depends on the close connection with enhanced theory and simulation programs.

Success of the proposed research enables the US Fusion Program to maintain and even strengthen its forefront position in the international EP research community.

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