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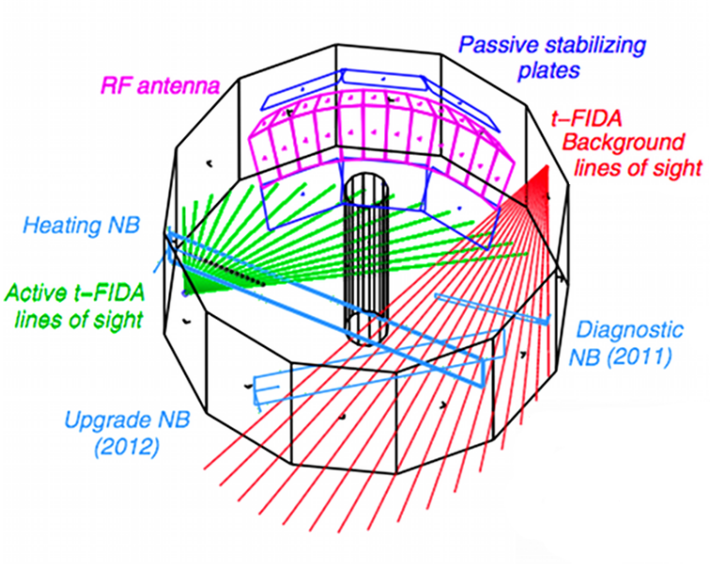
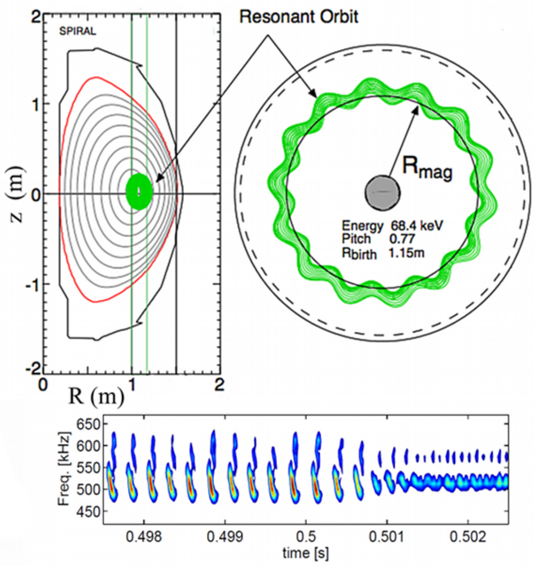
Chapter 6





Research goals and plans for Energetic Particle Research

6.1 Introduction

The fundamental scientific goal of ITER is to generate plasmas dominated by self-heating and to understand the dynamics of the thermal and energetic plasma particles under such conditions. The relatively large population of energetic ions originates in fusion devices from fusion reactions (alpha particles), Neutral Beam (NB) injection and injected rf waves [1]. The resulting fast ion pressure can destabilize Alfvén Eigenmodes (AEs) and other fast ion driven instabilities (e.g. fishbones) that, in turn, affect the fast ion distribution through enhanced transport in space and energy [2][3]. This may cause unpredictable variations in the NB-driven current profile [4], loss of macroscopic stability [5] and degraded performance.

Of particular concern are fast ion related 'explosive' phenomena that occur on fast time scales, since no fast control tools are available (or envisioned) for their mitigation or suppression. Energetic Particle (EP) research is of paramount importance to understand the coupled and predominantly non-linear dynamics of fast ions and fast ion related instabilities, and eliminate or minimize their potential harm to a reliable exploitation of fusion energy. The challenge for present tokamaks is to provide the required physical basis to enable the development, verification and validation of predictive theoretical and numerical tools. NSTX-U will encompass an even broader parameter space than NSTX [6]. For instance, relevant NSTX-U parameter regimes for Energetic Particle research will more closely approach those expected for future devices such as ITER and a ST-FNSF, as shown in Fig. 6.1.1. The capability of spanning a much broader range of parameters for EP physics than conventional tokamaks represents an important advancement for extrapolations from today's experiments to burning plasma regimes, with significant contributions to the development of 100% non-inductive, steady-state scenarios and of NBI current ramp up schemes.

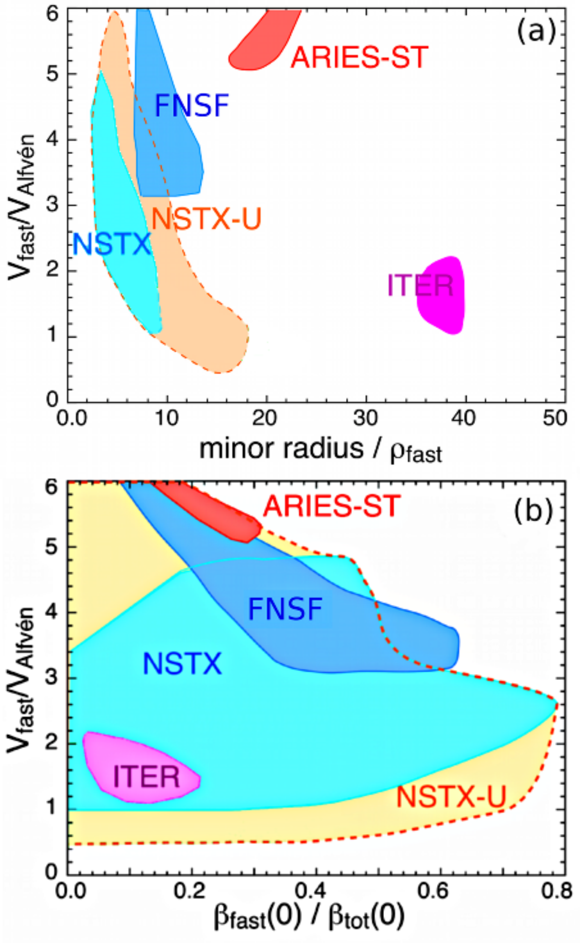


Figure 6.1.1: Representative parameters for Energetic Particles research for NSTX and NSTX-U in comparison with values for a ST-based FNSF and for ITER. (a) Ratio of fast ion to Alfvén velocity vs. inverse of the normalized fast ion Larmor radius. (b) Ratio of fast ion to Alfvén velocity vs. ratio of fast ion to total pressure. Fast ion parameters v_{fast} and ρ_{fast} are calculated at the NB injection energy.

EP research in the initial 5 years of NSTX-U operations will focus on two high-level goals that will directly contribute to developing predictive capability for FNSF, ITER and future devices. Firstly, experiments in the upgraded machine will aim at extensive validation of both linear and non-linear numerical codes and models, taking advantage of the upgraded NSTX-U diagnostic tools for stringent theory/experiment comparisons. This will enable projections of fast ion transport and AE dynamics from present experiments to scenarios relevant for FNSF, ITER and a ST-based Pilot device and provide guidance for further improvements in the design of future reactors.

Secondly, tools and techniques to affect AE and fast ion dynamics through selective excitation/suppression of fast ion-driven instabilities will be assessed. This requires a detailed knowledge of AE drive and damping mechanisms and of the fast ion response to different instabilities. Upgraded diagnostics (e.g. reflectometer arrays [7], beam-emission spectroscopy [8], fast-ion D-alpha spectrometers [9][10], neutral particle analyzers [11][12], and fusion product profile arrays [13]) are being developed to provide detailed measurements of the mode dynamics and of the properties of confined fast ions. The possibility of exploiting instabilities to optimize the NB-driven current profile or enhance the energy transfer from NB ions to thermal ions in a controlled way [14] will be explored. Development of schemes to regulate the electron thermal transport through high-frequency modes [15] will be also pursued. Neutral beam and rf injection are the primary actuators, possibly complemented by coils to induced magnetic perturbations at the plasma edge. For a more refined mode control, a dedicated *AE antenna system will be developed. The latter will be utilized to characterize the *AE stability properties and, pending upgrades of the driving amplifier to >10 kW power levels, to attempt excitation/stabilization of specific modes.

In the past years, NSTX experiments have considerably broadened and enriched the fusion science with respect to EP physics. Research on NSTX-U will further expand the knowledge acquired on NSTX of phenomena that are potentially harmful to ITER and burning plasmas, building upon a unique combination of broad and flexible parameter regime, excellent fast ion diagnostic suite and strong theoretical involvement.

The relatively low field and high current on NSTX, coupled with NB injection at energies up to 90 keV, implies a ratio of beam ion to Alfvén velocity in excess of 2, which is directly relevant for the regimes expected in ITER and FNSF, see Fig. 6.1.1. This, along with the large ratio of fast ion to total pressure, resulted in a broad spectrum of beam-driven instabilities (kinks, fishbones, Energetic Particle Modes and AEs in the sub-ion-cyclotron range of frequency). Therefore, virtually all NB-heated discharges in NSTX provided useful data on the modes' stability and non-linear physics (such as saturation amplitude and mode coupling). As an example, Toroidal Alfvén Eigenmodes (TAE) were found to develop non-linearly [16], as characterized by frequent, rapid bursts (*avalanches*) that resulted in redistribution and loss of fast ions [17][18][15]. There is compelling experimental evidence that TAE avalanches also cause a prompt redistribution of NB-driven current [4], see Fig. 6.1.2. Simulations with TRANSP using a *ad-hoc* time-dependent fast ion diffusivity to simulate enhanced redistribution at TAE bursts were able to reproduce the experimental neutron rate and current profile evolution. However, more recent simulations of fast ion redistribution using a combination of the NOVA/ORBIT codes indicate that the effect of TAEs on fast ions is more complicated than a simple enhancement of radial diffusion. In the presence of multiple modes characterized by different helicity, fast ions can be redistributed in energy as well as space, resulting in more complex effects on NB-driven current. Research on NSTX-U, facilitated by the enhanced flexibility in NB injection geometries, will serve as guidance to incorporate our improved understanding of fast ion distribution modifications by TAEs into the TRANSP code for improved simulations of beam heating and current drive in the presence of AE instabilities. Moreover, this topic is of great relevance to address Thrusts ASC-1, ASC-2 and SFSU-2 of the FY14-18 NSTX-U 5-year plan on non-inductive scenario development and non-inductive current ramp up (cf. Secs. 9.1.2.1, 9.1.2.4 and 8.3.2).

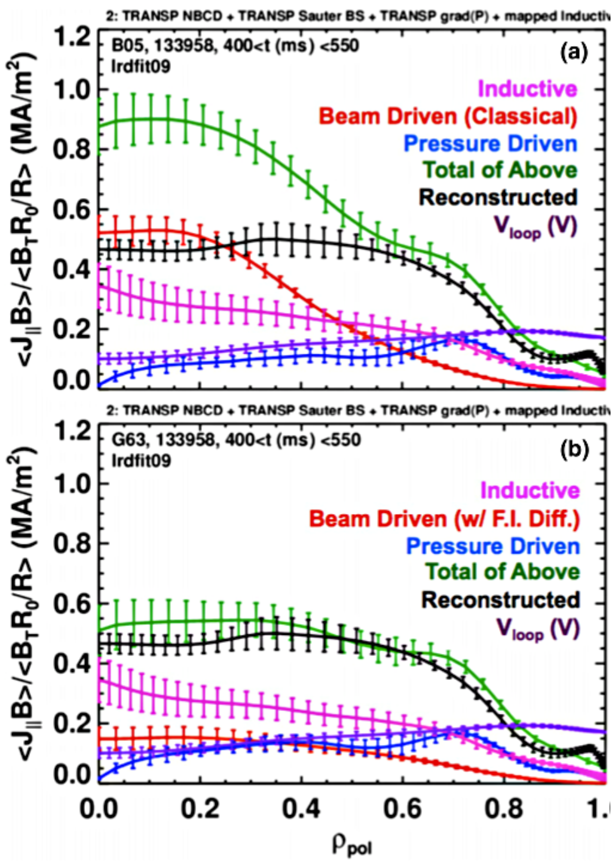


Figure 6.1.2: TRANSP calculations of the different terms contributing to the total plasma current on NSTX in the presence of TAE avalanches. Reconstructions are performed assuming (a) classical and (b) anomalous fast ion diffusion. (From Ref. [4]).

Besides the characterization of known instabilities such as the Toroidal Alfvén Eigenmode [19][20][21], the investigation of new instabilities and new aspects of AE physics [22][23][24][25][26], as well as associated fast ion transport will be extended to the new regimes achievable in NSTX-U. For example, a broad spectrum of Global and Compressional Alfvén eigenmodes (GAE/CAE) was typically observed in NSTX at frequencies comparable to the ion-cyclotron frequency. Experimental evidence suggests that these modes redistributed fast ions and, possibly, affected electron thermal transport [23]. Progress has been made in simulating and understanding the complicated Doppler-shifted cyclotron resonance drive for counter-propagating CAE and GAE modes [25]. It seems plausible that the relatively low ratio of the cyclotron frequency to the transit frequency in NSTX facilitates this type of resonance drive. The higher field of NSTX-U will enable a thorough assessment of this hypothesis.

Another important area of research in NSTX-U will be the exploration of the possible coupling between different AE instabilities, which can further complicate the non-linear mode dynamic and its effect on the fast ion population. Transient destabilization of otherwise (linearly) stable modes through non-linear coupling [16] has been observed on NSTX. The non-linear saturation level of Alfvénic instabilities can also be affected by non-linear coupling. More generally, experiments on NSTX have indicated [19][21][25] non-linear coupling among TAEs, GAE/CAEs and low-frequency MHD activity (kinks or tearing modes). The broad spectrum of Alfvénic activity on NSTX can potentially lead to direct interactions, through wave-wave coupling, as well as through indirect ones mediated by modifications of the fast ion distribution. In turn, the latter affects stability and saturation of energetic particle driven modes.

Section 6.2 presents an overview of the two major research thrusts on Energetic Particle research, including a summary of the research needed to support these thrusts. The research plans are described in detail in Section 6.3. Plans are divided into two periods, namely years 1-2 and years 3-5 of the 5-year plan. Summary timelines for each period are provided at the end of each Section. The planned theory/modeling capabilities and NSTX-U facility upgrades are described in Sections 6.4 and 6.5. A description of the main diagnostics that are relevant for EP studies is provided in Chapter 10 (see Section 10.6). Section 6.6 provides a summary timeline for the research goals and tools that are required for the Energetic Particles 5-year program on NSTX-U.

6.2 Overview of goals and plans

6.2.1 Research Thrust EP-1: Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER

Heating and some non-inductive current drive methods for next step magnetic fusion devices utilize non-thermalized (*e.g.* fast) ion populations whether as rf-tail ions, energetic neutral beam ions or fusion alphas. Instabilities driven by these fast ions, in particular Toroidal Alfvén Eigenmodes, can modify the expected heating and current drive profiles. Projecting which operational regimes will minimize these instabilities, or if necessary, predicting the effect of these modes on the fast ion population, is valuable for designing new devices and planning their operation (see also Chapter 9, Sec. 9.2.4). These predictions are made through the extrapolation of results obtained in present research devices to larger scale, fusion-grade reactors. The development and benchmarking of numerical codes based on experimental observations from existing experiments is therefore one of the most critical issues in fusion research.

A primary goal for the next 5 years of Energetic Particle research on NSTX-U is to develop capabilities that enable reliable and *quantitative* predictions on properties of, and fast ion response to, unstable modes in future devices such as ITER and FNSF. Good progress has been made in recent years in developing and validating tools to compute fast ion transport caused by a given set of instabilities. However, self-consistent and reliable predictions of the modes' properties and of the modes' regime at saturation (e.g. stationary vs. bursting dynamics) still require extensive work from both experimentalists and theory/codes developers. Based on results from NSTX and other devices, modes that can induce substantial redistribution and loss of fast ions will be targeted first. These include TAEs, Reverse-Shear AEs (RSAEs) and Energetic-Particle modes (EPMs), as well as higher frequency *AEs (GAE/CAEs) that are responsible for deviations of the F_{nb} evolution from classical behavior.

This first thrust will be approached from two complementary directions, i.e. (i) study of the modes' properties (radial structure, frequency and wavenumber spectrum, stability) and (ii) characterization of the fast ion transport associated with specific classes of *AEs. In parallel with the experimental research on NSTX-U, the development of numerical and theoretical tools is required to lay the basis for predictive capability. Experimental results will be utilized for extensive code verification and validation, based on the detailed characterization of instabilities and fast ion distribution available on NSTX-U from the upgraded set of fast ion diagnostics.

6.2.2 Research Thrust EP-2: Assess requirements for *fast-ion phase-space engineering* techniques

So-called Phase-Space Engineering (PSE) consists in controlled, externally-induced modifications of the fast ion distribution in order to achieve specific goals such as performance improvement or enhanced stability. PSE is being discussed over several years (including its application to NSTX scenarios) as a potential technique for *AE control, stochastic ion heating [27], alpha-channeling [28][29][14] and stabilization/regulation of sawtooth [30] and other MHD modes (e.g. NTMs), among other possibilities. More specifically, the longer-term PSE objective that requires dedicated research on NSTX-U is the development of schemes for direct *AE control. Experiments will aim at developing tools to *control* AE activity in NSTX-U and *exploit* instabilities as an additional actuator to modify, in a controlled way, the evolution of fast ion radial profile and energy spectrum. A parallel line of research is the regulation of electron thermal transport through high-frequency AEs.

The development of PSE methods on NSTX-U is foreseen to assess these issues. The proposed PSE plan takes advantage of a unique combination of tools that can alter the fast ion distribution (hence the *AE stability), such as NB sources with different tangency radii, the High-Harmonic Fast Wave (HHFW) rf heating system and additional coils to induced controlled magnetic perturbations. The latter include a set of Magnetic Perturbations (MP) coils, a new set of non-axisymmetric control coils (NCC) proposed for the FY14-18 period and a newly developed *AE antenna system operating at higher frequency (*f*>>1 kHz). Pending incremental resources and based on the capability of the *AE antenna to detect modes, further progress in exploring *AE control schemes will be achieved through an upgrade of the *AE detection system. The upgrade would enable the real-time detection of marginally stable (via excitation from the *AE antenna) and unstable modes, thus providing the required information to the Plasma Control System (PCS) to implement active control schemes during a discharge, for instance by utilizing different NB injection parameters, MP/NCC coils, rf injection or the *AE antenna itself.

If successful, PSE will help NSTX-U (and PPPL) to maintain a leadership position in the EP physics within the fusion community, both nationally and internationally. It will also help to control the TAE and other Alfvénic instabilities in a reactor by bypassing the thresholds imposed by thermonuclear instabilities, which is an important (and often under-estimated) issue for devices such as ITER, FNSF and future Pilot plants.

Detailed knowledge of the stability properties of AEs, including damping and drive mechanisms, is of paramount importance for PSE research (and EP studies, in general) in order to assess which modes can be more effectively affected by external means. Although theoretical understanding has made good progress in the past years to understand and model specific damping mechanisms for AEs in conventional aspect ratio devices, the applicability of those models to STs is still debated and requires more detailed comparison between theory and experiments. Active spectroscopy experiments planned for NSTX-U, similar to those previously carried out on JET, C-Mod and (more recently) MAST, will provide direct information of linear *AE damping rates for further benchmarking of stability codes at low aspect ratio. This would also help to validate ITER/FNSF projections by challenging our fundamental understanding of the physics underlying the drive and stability mechanisms of AE modes.

In the lower portion of the *AE frequency range, TAE linear damping rates have been measured on the C-Mod and JET tokamak experiments [31] with the goal of benchmarking codes used to project TAE stability to ITER relevant regimes. Linear damping rates are inferred by exciting stable modes with an antenna and by computing the resonance width from the complex impedance modeling the driven plasma response [32]. Next step Spherical Tokamaks will operate in a different fast ion parameter regime, which also implies different properties of potentially unstable modes such as their radial structure. It is therefore necessary to extend the previous benchmarking activity to encompass a broader range of scenarios and different classes of *AE instabilities. For example, the much stronger magnetic shear at the plasma edge (found to be stabilizing in triangularity scans on JET) and the relatively stronger rotational shear, resulting in enhanced continuum interactions, are predicted to affect TAE stability in STs.

Looking beyond the lower frequency TAE modes, higher frequency Alfvénic instabilities are routinely observed in START [33], MAST [34][35] and NSTX [25][36][37] NB-heated plasmas.

These instabilities clearly have the potential to affect the fast ion distribution, although direct experimental evidence of the extent of the perturbations is weak at present. Reliance on fast ions to destabilize the natural eigenmodes of Compressional and Global Alfvén waves (CAE and GAE) reveals only a limited subset of the eigenmode spectrum. Extending the bandwidth of external antennae to study these modes will provide valuable information in the development of our theoretical understanding of these instabilities. Ultimately, the higher frequency of GAE/CAE modes, together with the possibility of cyclotron resonances, may provide an attractive route towards controlled modifications of the non-thermal ion distribution function and its dynamic [28]. The latter scheme would enable a more efficient transfer (or *channeling*) of fast ion energy to the thermal ions. Because the transfer is mediated by instabilities, it happens on time-scales much faster than the typical slowing-down time, thus lowering the overall fast ion pressure. At constant total pressure (e.g. limited by macroscopic stability considerations), this implies that a reactor could achieve a larger thermal ion pressure via an increase of the ion temperature, which is indeed beneficial to enhance the thermonuclear fusion reactivity.

The outcome from PSE research on NSTX-U will be evaluated, possibly in conjunction with results from other devices such as DIII-D, MAST and JET, to assess the feasibility and potential of PSE schemes on future devices. The assessment will be done in terms of efficiency of the different systems (e.g. NB vs. rf or other coils/antenna types), required power and - for rf/*AE antennae and MP/NCC coils - excited spectrum, temporal response, time-scales for diagnostics and control. Extrapolations to future devices, such as a ST-based FNSF/Pilot and ITER, will provide information on achievable performance improvement, for instance through the implementation of alpha-channeling schemes.

6.2.3 Research needed to enable EP Research Thrusts

6.2.3.1 Investigate *AE dynamics and associated fast ion transport mechanisms

Although many aspects of the dynamics of Alfvénic instabilities are known from today's experiments, extrapolations to future burning plasma scenarios require an even deeper understanding of instability drive and damping mechanisms. Even assuming that present stability codes can predict the spectrum of unstable modes for a given set of experimental parameters, the complex mode dynamics observed in the experiments is still hardly recovered. For example, the mechanisms that cause the development of a TAE bursting/chirping regime are still debated, and so are the exact causes of TAE avalanches. In particular, non-linear effects need to be understood to predict mode saturation level and the effects of disparate classes of modes, including their possible coupling, on fast ion redistribution and transport.

Validation of linear theories on mode stability is required before approaching the non-linear physics aspects. This is especially true for spherical tori such as NSTX-U, for which the large plasma beta, the large rotation, the small aspect ratio and the large gradients in the equilibrium profiles (including the magnetic field and the safety factor profile) clearly pose a challenge for theories and numerical codes. Development of MHD spectroscopy tools, such as a dedicated *AE antenna system, is planned to measure the damping rate of *AEs and provide the data required for a detailed theory/experiment comparison.

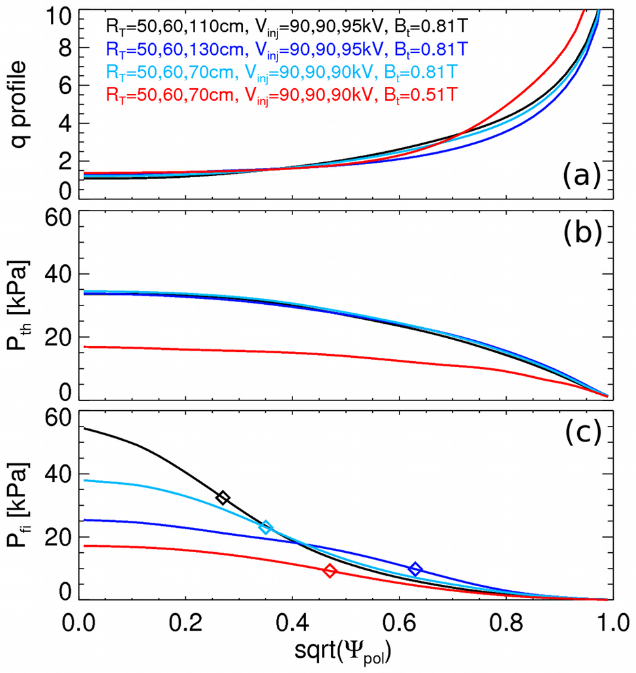


*Figure 6.2.1: Examples of profiles corresponding to different NB injection schemes utilizing sources with different tangency radius. The reference profiles, corresponding to a NSTX H-mode discharge with B_t=0.5 T, are shown in red for comparison. Shown are (a) q-profile, (b) thermal plasma pressure and (c) fast ion pressure. Diamonds indicate the radius of steepest fast ion pressure gradient, where *AE drive is expected to be stronger. Profiles are calculated by TRANSP.*

Ultimately, non-linear mode dynamics will dominate EP physics in burning plasmas, because of its role in affecting mode saturation amplitudes and the mode regime (e.g. stationary vs. bursting mode activity). Saturation mechanisms and non-linear physics (e.g. mode-mode coupling, coupling and interactions between different classes of MHD instabilities) will be investigated in NSTX-U as a function of plasma and NB/rf heating parameters. The latter have large influence on the fast ion distribution function. Future reactors will operate with distribution functions that are considerably different than in today's devices, for instance because of the additional presence of alpha particles from fusion reactions. Therefore, the dependence of stability and saturation of *AEs on the fast ion distribution function will be studied in detail, and the results compared with code predictions to validate our understanding of the drive mechanisms for various distributions. Because of its relevance and broad scope, it is anticipated that this line of research will encompass multiple Topical Science Groups, including Energetic Particle, Macroscopic Stability and Advanced Scenarios & Control groups.

The enhanced flexibility of NSTX-U in terms of NB injection geometry provides a powerful tool to vary F_{nb} in a systematic way, as shown in Fig. 6.2.1. NB injection energy and power scans are also possible, in order to vary the ratio of fast ion to Alfvén velocity and of relative fast ion beta. The dependence of resonant drive for the different *AEs on those parameters will be investigated, along with the effects of the q-profile on the mode's location and stability. The higher toroidal field of NSTX-U is another important parameter to understand the scaling of unstable spectrum and mode stability toward high-field devices such as a ST-based FNSF and ITER.

Existing (or upgraded) and new diagnostics will be utilized to gather the required information for a meaningful and accurate comparison. The new "tangential" FIDA and fusion product profile systems, along with an upgraded ssNPA and the existing NPA and neutron rate counters, will provide complementary measurements of different phase space portions of the fast ion distribution. Upgraded reflectometer and BES arrays will be available to measure the mode structure. Mirnov coils will provide mode frequency evolution and mode number information.

6.2.3.2 Compare experimental results with theory & numerical codes

Verification & Validation of numerical codes are fundamental steps to enable predictive capabilities. Theory-experiment comparisons on EP-related topics are planned in order of complexity for NSTX-U scenarios. Initial comparison with predictions from numerical codes will be performed in terms of radial structure and frequency of the observed (unstable) modes. Then, the comparison will be extended to the mode dynamics, including saturation level and quasi-stationary vs. bursting regime. The final step will be the full simulation of non-linear *AE mode physics, including for example multi-mode scenarios and mode-mode coupling phenomena. The ultimate goal is to develop and validate self-consistent (non-linear) models to predict how *AEs affect the fast ion population for the complex F_{nb} in a fusion plasma and, in turn, how the modified fast ion distribution affect the *AE dynamics. This is a critical R&D issue for ITER, which can be addressed on NSTX-U based on the great flexibility in NB injection parameters, complemented by rf injection, to explore a broad range of fast ion distributions.

A detailed knowledge of the fast ion distribution function is required for accurate theory-experiment comparison. Good progress has been made in experiments to cover extended regions of phase space, for instance by using different viewing geometries for the same spatial region or comparing results from diagnostics with complementary phase space selectivity. Similarly, a realistic model for F_{nb} is needed in simulation codes to capture the *nuances* of wave-particle interaction in phase space. In fact, whereas a simple slowing-down distribution may be suitable to represent the distribution of fusion-born alphas, it appears as an over-simplification for fast ions originating from NB injection with specific values of pitch and energy. The picture is further complicated by the fact that the injected energy spectrum for a specific NB system typically includes at least three energy components, whose relative fraction depends (among other parameters defining the NB working point) on the injection energy. Codes that are designed to predict the full, non-linear mode dynamics (e.g. M3D-K and HYM) will therefore be upgraded to include a realistic description for F_{nb}, such as the one computed by the NUBEAM [38] module in TRANSP [39].

Another important feature for numerical codes that aim at modeling the non-linear aspects of F_{nb} evolution is the inclusion of source and sink terms. Linear stability can be studied by following the initial mode's growth for a short time, typically of the order of a few milliseconds or less, over which classical mechanisms (scattering, slowing-down) have little effect on the fast ion distribution. As the modes grow in amplitude and, possibly, saturate in a non-linear phase, the mutual interaction between instabilities and fast ions becomes important. Mode-induced fast ion transport (in both configuration and phase space) competes then with restoring sources (NBI injection) and other transport mechanisms (radial diffusion, scattering and slowing-down), which makes the details of source and sink terms relevant to reproduce the experimental observations.

A number of numerical codes are already being used to simulate NSTX scenarios and their use will be naturally extended to NSTX-U discharges. In particular, a summary of the main capabilities and planned improvements for the numerical tools directly developed (or under development) by NSTX-U researchers and collaborators is provided in Section 6.4 and summarized in Table 6.4.1 at the end of this Chapter. Besides NB injection, HHFW injection is also known to induce modifications of the fast ion distribution [40][41]. Plans and numerical tools that will be available for HHFW research on NSTX-U are described in detail in Chapter 7.

In addition to the codes directly available at PPPL, NSTX-U results will be available for comparison with simulations performed by other groups, both nationally and internationally. For example, initial comparisons between NSTX data on chirping TAE modes and predictions from the gyrokinetic code GTC have started and will be further pursued once NSTX-U begins operations. Other gyrokinetic codes (e.g. GYRO and GEM) will also be considered for Verification & Validation, based on the unique *AE regimes attainable on NSTX-U and STs in general.

6.2.3.3 Develop reduced physics-based models for *AE-induced fast ion transport

Dedicated ("first-principles") codes for comprehensive simulations of MHD instabilities and fast ion dynamics are indispensable tools for EP research. However, their use is somewhat limited in terms of potential users and routine application to a large number of discharges. Energetic Particle research in the next 5 years is required to fill in the gap between dedicated codes and general, multi-purpose transport simulation codes such as TRANSP [39]. This will make available more detailed information on modifications of F_{nb} by MHD that, in turn, can be used to infer MHD effects on background plasma and fast particles. For instance, more accurate and reliable calculations of NB-driven current would be possible, as required for scenario development and predictions in devices with large NB current drive and central fast ion pressure (cf. Chapter 9, Secs. 9.1.2.1 and 9.1.2.4). Extended comparison of TRANSP analysis and simulations with experimental results will be also enabled by the combination of improved F_{nb} measurements and simulations for a broad range of experimental conditions. To accomplish this goal, knowledge of the transport mechanisms must be translated into *reduced* models that are suitable for inclusion in TRANSP but - at the same time - retain the essential physics of fast ion transport.

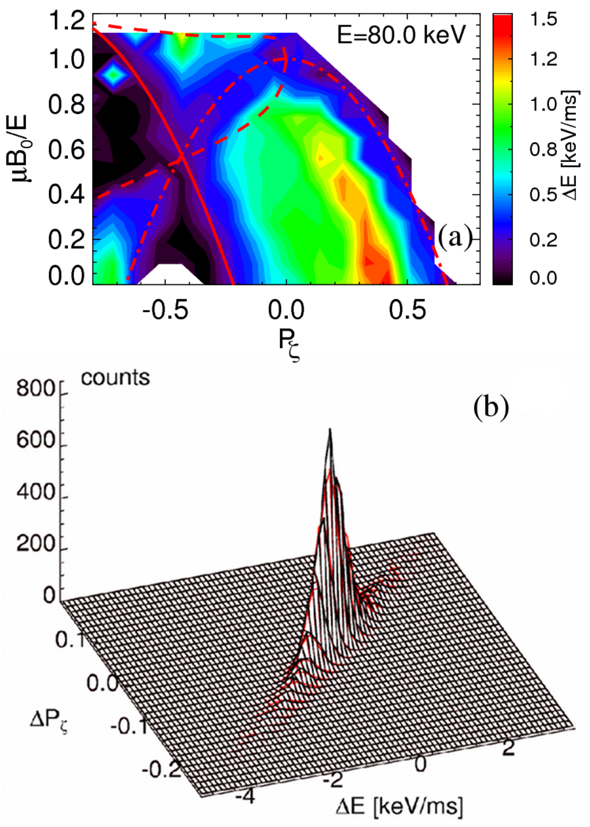


Figure 6.2.2: (a) ORBIT calculations of the average energy step caused by 4 TAE modes after 1 ms for fast ions with initial energy of 80 keV. Red lines show the different domains in phase space. (b) Example of probability distribution for correlated steps in energy and canonical toroidal momentum for E=80 keV, P_ζ*~0.5 and pitch ~0.2.*

Several fast ion transport models are already implemented in the NUBEAM module of TRANSP. However - as of today - a main limitation is the over-simplified description of *resonant* and *stochastic* transport mechanisms that affect fast ion dynamics primarily in phase space, as opposed to configuration space. New models are therefore required to complement the diffusive/convective radial transport models that are already available. To understand the importance of phase space dynamics in regulating macroscopic fast ion transport and redistribution, it suffices to observe that *AE modes with comparable spatial localization and amplitude, but different frequency and/or polarization, can have very different effects on fast ions. Whereas high-frequency CAE/GAE modes can induce energy and pitch variations with relatively small radial transport, lower frequency TAEs (and EPMs) are much more effective in causing radial redistribution and, eventually, loss from the main plasma. These differences are not correctly captured by standard radial diffusion, as they mostly arise from the details of resonant wave-particle interactions in phase space. Moreover, the same type of interaction set constraints between phase space variables like energy and canonical angular momentum that are lost in the radial diffusive models.

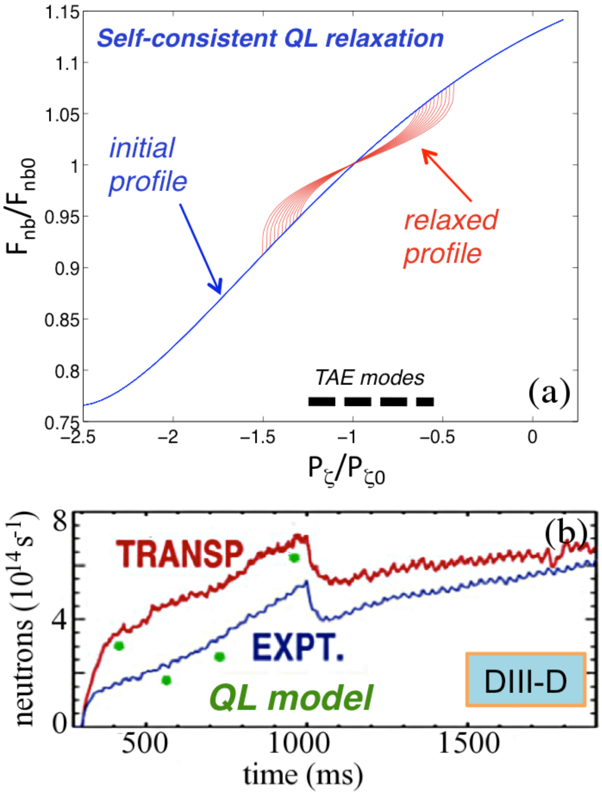


Figure 6.2.3: (a) Schematic of quasi-linear relaxation process showing partial flattening of Fnb in the presence of TAE modes. (b) Initial comparison of neutron rate from the QL model with DIII-D data and TRANSP predictions. (Adapted from Ref. [42]).

Two approaches to develop reduced fast ion transport models are currently being pursued by NSTX-U researchers, cf. Secs. 6.4.7 and 6.4.8. A first approach is based on results from combined modeling of fast ion response to a given set of *AE modes or other low frequency MHD modes (kinks, NTMs) through the NOVA-K and ORBIT codes [24]. The initial development is focusing on TAEs and TAE avalanches, but the model is general enough to treat various classes of instabilities. From ORBIT simulations, a probability distribution function, $p(\Delta E, \Delta P_\zeta, \Delta\mu)$, is derived for the expected "kicks" in phase space variables over a certain time as a function of mode amplitude, see example in Fig. 6.2.2. (Variables are energy E, canonical angular momentum P_ζ and pitch μ). This information will be used in NUBEAM/TRANSP to advance the fast ion distribution at each simulation step. (Note that other codes, for example SPIRAL, can also be used to generate $p(\Delta E, \Delta P_\zeta, \Delta\mu)$). In its initial formulation, the model will be suitable for simulations of real discharges, for which information on mode properties (frequency, radial structure, amplitude evolution) is available. More work is required to *predict* the F_{nb} evolution for future devices. Research on NSTX-U will permit to consolidate our understanding of *AE behavior under different plasma conditions, especially at higher magnetic field and with different NB injection geometries.

A second approach is based on recent improvements of the so-called "quasi-linear" (QL) model to incorporate the effects of resonance line broadening and multi-mode scenarios [42]. The QL theory models the effect of TAE modes on the fast ion distribution by retaining second order perturbations in Vlasov's equation to compute the relaxed F_{nb} radial profile. The model is self-consistent, in that the mode amplitude evolves at the instantaneous linear rate derived from the distribution function itself (Fig. 6.2.3). The model is presently being tested on DIII-D scenarios and extended to ITER predictions. After the validation phase, it will be tested against NSTX scenarios with TAE-induced fast ion transport and then to predicted NSTX-U scenarios. Its implementation in NUBEAM/TRANSP is foreseen for general use.

6.2.3.4 Assess modifications of *AE dynamics using externally-controllable *actuators*

Future reactors will operate with a mix of additional heating schemes, including NB and rf injection, whose effects combine with those from fusion reactions (i.e. the generation of alpha particles) to define the actual F_{nb}. Our present understanding of the relationship between the expected F_{nb} and possibly deleterious *AE instabilities must progress by including the new scenarios that will be achievable on NSTX-U. Moreover, EP research needs to develop schemes to affect the instabilities and reduce their impact on the successful exploitation of fusion reactors. This long-term goal requires accurate measurements of plasma profiles, of the evolution of F_{nb} and of the instabilities, along with improved theories and modeling of their mutual interactions.

Establishing the link between plasma equilibrium profiles (e.g. q-profile), NB injection parameters (geometry, injection energy) and *AE activity is the first priority and will already provide indications on possible NB injection schemes that minimize (or suppress) *AE activity. An example of NSTX-U profiles predicted by TRANSP for different choice of NB injection geometry is illustrated in Fig. 6.2.1(c), showing the broad range of variations in fast ion pressure for comparable NSTX-U thermal pressure profiles that will be achievable for a similar q-profile.

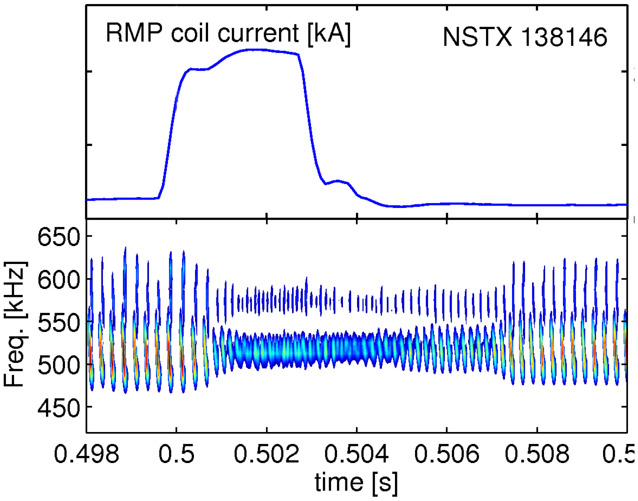


Figure 6.2.4: Modification of GAE dynamic on NSTX through pulses of Magnetic Perturbations with n=3. (Adapted from Ref. [44]).

Scenarios with combined NB and rf injection will then be studied. Based on NSTX experiments, F_{nb} modifications by HHFW injection include both direct acceleration of fast ions and more subtle redistribution in phase space. For example, early NSTX experiments have shown some evidence of modified behavior of “Angelfish” modes (i.e. high-frequency *AEs in the CAE/GAE range of frequency) during HHFW injection [43]. A few examples of HHFW affecting TAE/RSAE stability in NB-heated plasmas have been occasionally collected from NSTX experiments [21]. The new scenarios of NSTX-U require new experiments in the next 5-year period for further studies of the instability's response to combined NB and HHFW injection, as described in Sec. 6.3.3.4 and Chapter 7, Sec. 7.1.3.1.

A third tool that will be available on NSTX-U is represented by the set of external mid-plane error-field correction and resistive wall mode coils that can be used to apply magnetic perturbations (MP) with a range of toroidal mode numbers (see Chapter 2 for more details). Modification of the behavior of GAE modes from bursting to more stationary has been observed on NSTX during short (2-6 ms), static MP pulses with $n=3$ configuration [44], see Fig. 6.2.4. Initial analysis indicates that the modification in mode activity is caused by a perturbation of the fast ion orbits that resonate with GAEs. Research on NSTX-U will explore this avenue in more detail, exploiting the enhanced flexibility of the MP power supplies control to vary the spectrum and the amplitude of the excited perturbation. The installation after FY16 of *internal and off-midplane* Non-axisymmetric Control Coils (NCC) represents a further, important improvement to study *AE response to applied 3D fields.

Besides the exploitation of NB/rf injection and of MP coils, the development of more refined PSE techniques is envisioned. Two main tasks are foreseen in the 5-year time period FY14-18. The first task is the development, optimization and installation of the required hardware (e.g. an *AE antenna system with frequency and wave-number scanning capabilities). A system comprising up to 4 modules, whose design is based on the prototype antenna that was installed in-vessel for the FY12 Run, will be tested during the first year of NSTX-U operations. Because of the low-power amplifier (~1-5 kW) initially available to drive the antenna, only small perturbations with $\delta B/B \leq 10^{-5}$ will be excited at the plasma edge. Therefore, this prototype system will mainly be used for *AE stability measurements and to provide damping rate data to challenge present theories on *AE damping mechanisms in STs.

Based on the available resources, upgrades/improvements will be implemented in the following years. Improvements of the *AE antenna modules design will be considered to optimize the coupling to *AEs with specific polarization. The diagnostics associated with the antenna system will be upgraded to enable real-time detection of the modes driven by the antenna, and using that information to implement a closed-loop control of the antenna frequency during a discharge. Finally, a high-power amplifier capable of delivering up to 100 kW of power will be used as driver for the *AE antenna modules. Pending the completion of these upgrades, the second task is the experimental assessment of *AE control schemes, that include single-mode entrainment and regulation, multi-mode synchronization/control via three-wave coupling mediated by the external perturbation, and mock-up of so-called *alpha-channeling* processes with fast ions from neutral beam injection (NBI).

6.3 Research Plans

6.3.1 Research Plans for Thrust EP-1: Year 1-2

6.3.1.1 Compare classical TRANSP predictions to experiments for $1^{st}+2^{nd}$ NB line

One of the major new features on NSTX-U is the addition of a second NB line with more tangential injection than the line already available on NSTX. The first task for EP-related research is to compare experimental results to standard numerical tools that model NBI, namely the NUBEAM module in TRANSP, which is a pre-requisite for all subsequent studies of fast ion confinement in the presence of MHD and other instabilities. Conditions with quiescent MHD activity during NB injection will be explored to assess the consistency of (classical) calculations of fast ion confinement and slowing down processes obtained through NUBEAM with measurements. The comparison will be conducted in terms of direct measurements (e.g. of fast ion distribution function, neutron rate and prompt fast ion losses) as well as derived quantities such as NB-driven current profile. Different NB injection geometries, from more perpendicular to more tangential, will be investigated. Similar to earlier experiments on NSTX that confirmed the validity of classical predictions for beam ion confinement and slowing-down models [45] for "diluted" fast ion populations, scans of plasma current and toroidal field will be performed. For this study, conditions for which MHD activity is minimized or absent will be initially used. For instance, well-established techniques based on the neutron rate evolution following short pulses (*blips*) of NB power [45][46] are envisioned (see example in Fig. 6.3.1).

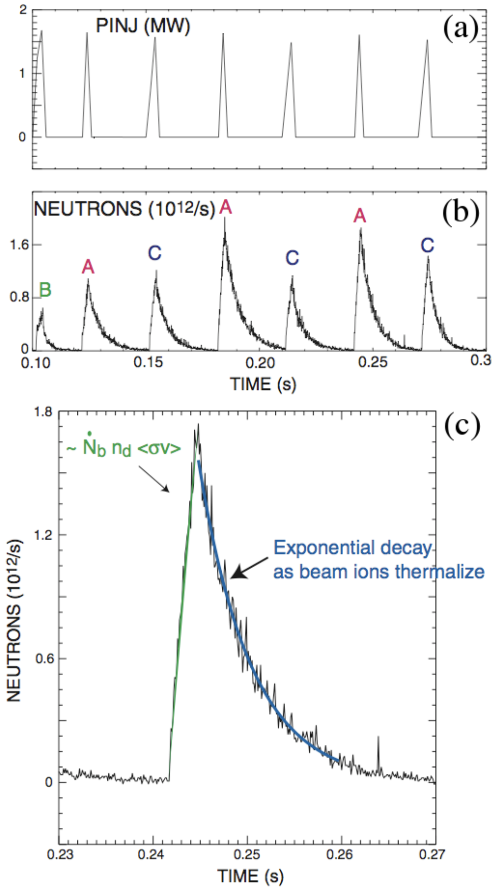


Figure 6.3.1: Example of fast ion confinement study utilizing (a) short NB blips and (b) neutron rate measurements. (c) Data on characteristic rise/decay times are then compared with TRANSP predictions to assess the validity of classical fast ion confinement. (From Ref. [45]).

In addition to EP-related research, the characterization of fast ion properties from NB injection has a broader scope in the NSTX-U research program. In particular, it is also crucial for research on non-inductive scenarios and current ramp-up, cf. Chapters 8 and 9.

In collaboration with the ASC group, the assessment of conditions for classical vs. anomalous fast ion behavior and NB current drive will be extended to high-performance H-mode discharges that are relevant for scenario development and projections to future STs (Thrusts ASC-1 and ASC-4). Scans of plasma current (0.6-1.5MA) and NB power (up to ~12MW) are planned for discharges near the full 1T toroidal field after Year 2 of NSTX-U operation. NB injection voltage will be varied from its maximum value of 100 kV, required to maximize the NB-driven current level, to the 80 kV level required for long pulse duration >5 s. Finally, the possibility of exploiting anomalous fast ion diffusion for scenario optimization, for example to sustain an elevated q_{min} (see details in Sec. 9.2.4), will be explored in later years (Year 3-4).

The EP group will also contribute to the development of non-inductive current ramp-up schemes (Thrust SFSU-2) led by the Solenoid-Free Plasma Start-Up (SFSU) and the WH&CD groups. The goal is to ramp up a 300-400 kA plasma with zero loop voltage up to the 1 MA current level by using a combination of NB-driven and bootstrap current (Sec. 8.6.4). The EP group will focus on the study of fast ion behavior during the ramp up process and on the comparison with TRANSP/NUBEAM predictions. Experiments will indicate the minimum required current that can be ramped up by NB-CD for B_t=0.8-1 T, as well as the optimum NB injection geometry and the requirements on fast ion confinement, for example as a function of toroidal field.

In addition to supporting EP research, scenario development and non-inductive current ramp-up studies, this study will also provide information on more specific issues that are relevant for modeling and interpretation of experimental data. For instance, conservation of magnetic moment of fast ions is debated in spherical tokamaks [47][48] because of the large fast ion gyro-radius compared to the typical scale-length of the background magnetic field. The flexibility of NSTX-U to operate with toroidal field in the range 0.35-1 T provides an excellent opportunity to explore a broad range of conditions in terms of ratio between gyro-radius and gradient scale-length. Conservation of magnetic moment can thus be assessed and quantified through comparison with predictions from the ORBIT and SPIRAL codes, and the most suited codes identified for future studies.

Measurements will exploit the upgraded suite of fast ion diagnostics that will be available on NSTX-U, a summary of which is given in Chapter 10, Section 10.6. Two Fast-ion D-alpha (FIDA, see Fig. 6.3.2) systems [49][50] and an upgraded solid-state Neutral Particle Analyzer (ssNPA) array [51] will provide fast ion radial profile and its temporal evolution with 5 cm, 10 ms spatial and temporal resolution. After the first year of NSTX-U operation, spectral

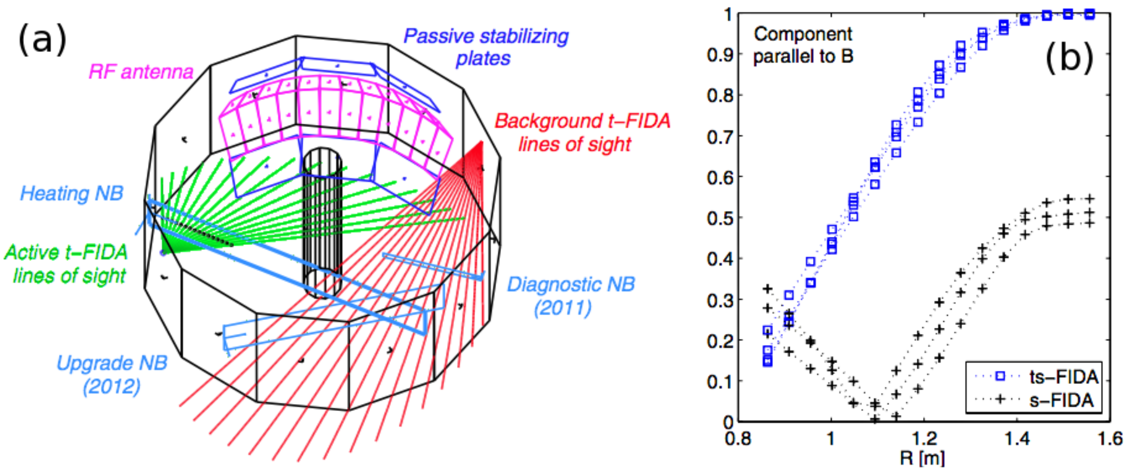


Figure 6.3.2: (a) Layout of the new tangential FIDA system. (b) Expected component parallel to the magnetic field for the tangential (ts-FIDA) and vertical (s-FIDA) FIDA systems. A value of 1 (0) on the y axis corresponds to a parallel (perpendicular) view. (From Ref. [50]).

information from the FIDA systems will be complemented by more accurate energy spectra at one fixed location from the re-located E||B Neutral Particle Analyzer (NPA) [52].

A novel charged fusion products array [53] will complement FIDA and ssNPA data after Year 2 (FY15) by providing space-resolved information, in addition to the volume-integrated data from neutron counters. Pending incremental funding, the latter will eventually be complemented by a set of 2-4 collimated neutron detectors in Years 4-5. It should be noted that fusion products and neutron diagnostics do not rely on charge-exchange, as is the case for FIDA and neutral particle analyzers. Therefore, they maintain good performance even at the high densities ($>10^{20}$ m^{-3}) characterizing some of the projected NSTX-U regimes.

Internal measurements from the diagnostics mentioned above will be compared to energy and pitch resolved measurements from a scintillator-based Fast Loss Ion Probe (sFLIP) that measures fast ions lost to the outer vessel wall at mid-plane [54]. The combination of data from both confined and lost fast ions will give a detailed picture of fast ion dynamics as a function of NB injection parameters and plasma discharge conditions. This information can then be compared with predictions from numerical simulation codes to assess the consistency of measurements with models based on classical fast ion dynamics.

6.3.1.2 Characterize *AE activity driven by more tangential 2nd NBI and associated fast ion transport

Starting from the characterization of reference scenarios with quiescent MHD activity, previous research on *AE physics will resume by investigating *AE activity for the broader operating space of NSTX-U. A nearly twofold increase in toroidal field, from 0.4-0.45 T for typical NSTX plasmas up to ~0.8 T, is anticipated for the first year of NSTX-U operations. Based on the maximization of wave-particle interaction for values $k_\perp \rho_{fi} \sim 1$ ($k_\perp \sim nq/a$ is the poloidal wave vector, $\rho_{fi} \sim v_f/\omega_{ci}$ the fast ion gyro-radius, *a* the minor radius and v_f the fast ion velocity), an up-shift of the wave-number spectrum roughly proportional to B_t is expected [55]. However, other considerations about improved confinement of both thermal and fast ion species, along with F_{nb} modifications caused by the 2nd NB line, may affect drive and damping of *AEs in more subtle ways. A detailed characterization of *AE modes over their entire spectral range (from 10's of kHz up to the ion cyclotron frequency) is therefore required, see Sec. 6.3.1.3.

Characterization of *AE and other MHD instabilities will proceed in parallel with the study of their effects on fast ion transport. Fast ion profile diagnostics (FIDA, ssNPA and fusion product array) are used to infer macroscopic modifications of the radial fast ion profile caused by the modes. Broadening and flattening of the profile will be correlated with change in the NB-driven current profile. The resulting change in macroscopic stability for low-frequency MHD modes (kinks, NTMs) is also investigated, in collaboration with the Macro-Stability Topical Science Group.

The possibly different effects on fast ions with different energy and pitch (e.g. passing vs. trapped particles) are inferred from diagnostics with complementary sensitivity in phase space, such as the perpendicular and tangential FIDA systems (Fig. 6.3.2). More precise information on energy and pitch evolution is available from the E//B NPA diagnostic, whose excellent energy resolution is required to investigate subtle changes in F_{nb} induced by instabilities.

6.3.1.3 Compare measured *AE properties to predictions performed in FY12-14

In order to develop a predictive capability for the effects of fast ion driven modes on the plasma, validation of theory is critical. A key ingredient of this is the measurement of mode structure and amplitude. NSTX-U will feature multiple diagnostics with complementary capabilities for measuring the structure and amplitude of fast ion driven modes. For instance, UW Madison's multi-channel Beam Emission Spectroscopy (BES) system [8] will feature 48 channels in the FY14/FY15 time-frame and then later be expanded to 56 channels, which is a significant improvement over the 16 channels that were available on NSTX. The BES system will be capable of density fluctuation measurements over a vertically ($\Delta Z > \sim 20$ cm) and radially ($r/a > 0.1$) distributed matrix of locations. In addition to density fluctuations, it will permit time-delay estimation of poloidal flow velocity fluctuations from poloidally-distributed measurements of the density fluctuations.

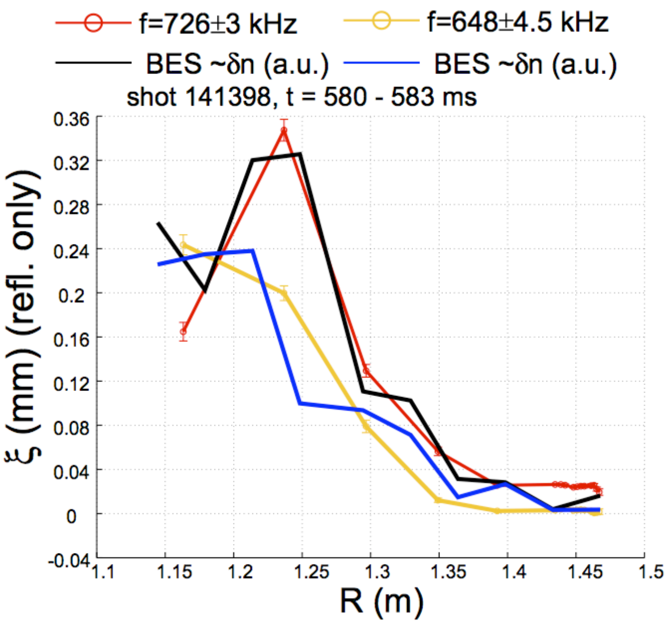


Figure 6.3.3: Comparison of BES and reflectometer measurements of high frequency Alfvén eigenmode structure. (Figure courtesy of K. Tritz, Johns Hopkins University, see Ref. [56]).

NSTX-U will also feature UCLA's 16 channel array of fixed-frequency reflectometers [7] and a radial chord polarimeter, both of which will be operational by FY15. The reflectometer array, with operating frequencies spread over 30–75 GHz, will probe density fluctuations at cutoff locations corresponding to equilibrium densities in the range 1.1–6.9x10^{19} m^{-3}. The polarimeter will provide internal measurements of magnetic fluctuation amplitude. Each of these diagnostics will individually prove valuable in pursuit of validation of theory. However, the greatest value will be derived through integration of the diagnostics to obtain a much more comprehensive picture of mode structure. One benefit is the greater spatial coverage and higher spatial sampling enabled by differences in measurement localization of the various systems. Another important benefit is that the different measured quantities (e.g. density, poloidal flow and magnetic fluctuations) offer substantially independent and complementary measurements of the mode's property, which significantly strengthen the comparison with theory when simultaneously available. For instance, density fluctuations associated with shear AEs (i.e. TAEs or GAEs) are primarily a product of displacement of the equilibrium density gradient by radial ExB flow fluctuations (neglecting compressional terms). Thus, combination of density with poloidal flow fluctuation measurements would allow full determination of the perpendicular electric field fluctuation, in the approximation of negligible compressional contribution to density fluctuations. Integration of measurements from multiple diagnostics is a central goal for the next 5-year period.

Existing reflectometry and BES data from NSTX in 2010 offer the opportunity to begin this effort in preparation for *AE modes investigation in NSTX-U plasma. Figure 6.3.3 illustrates an example of high frequency Compressional Alfvén eigenmode measured simultaneously using BES and the reflectometer array [56]. These measurements were obtained in a high power, beam-heated H-mode plasma similar to those in which high frequency AE activity is observed to correlate with enhanced core electron thermal transport [23].

Mode structure measurements in NSTX via the reflectometer array have produced a variety of results that motivate follow-up in NSTX-U using the full, integrated capabilities of BES, reflectometry and polarimetry. One such result is the measurement of TAE radial structure, including both amplitude and phase (Fig. 6.3.4). The measurements show a radial phase variation that is not consistent with expectation from ideal MHD, a theory that has been notably successful in predicting TAE structure in other cases [57][58]. Preliminary comparison with M3D-K simulations, however, has yielded reasonable agreement between the measured and predicted radial profile of mode amplitude and phase [58]. A key element of the M3D-K simulation that is missing from ideal MHD theory is the kinetic treatment of the fast ion population. One important question arising from these results is what are the limits of ideal MHD theory in predicting the TAE structure. A goal in the development of a predictive capability is the construction of reduced models for prediction of fast-ion transport. An ideal MHD code such as NOVA-K, which is less computationally intensive than M3D-K, would prove a valuable component of such a model if its limits were well understood. NSTX-U will offer the opportunity, even in its first years of operation, to validate codes such as NOVA-K and M3D-K in a new parameter regime, while retaining the ability to connect to NSTX results.

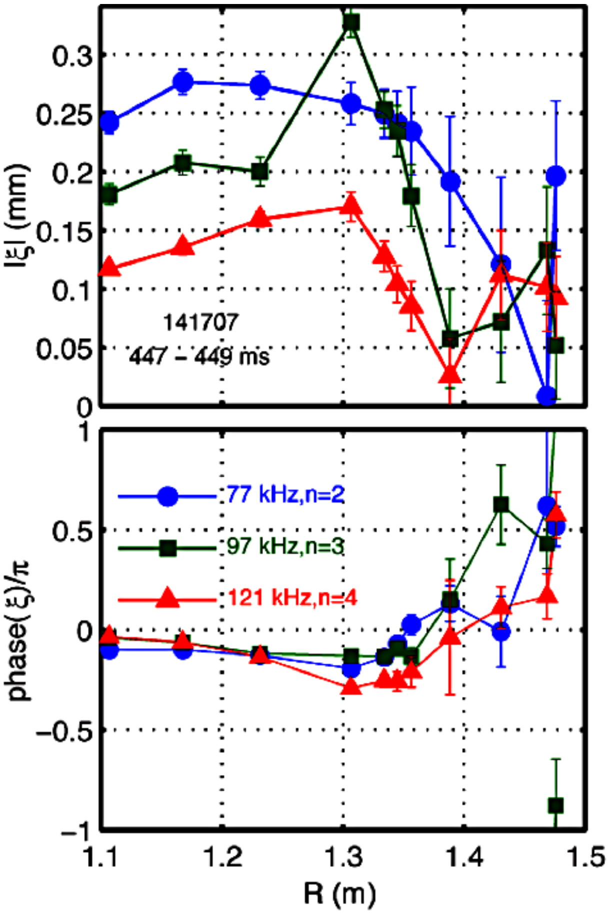


Figure 6.3.4: (a) Amplitude and (b) phase of effective displacement of toroidicity-induced Alfvén eigenmodes measured via the UCLA reflectometer array (cf. Ref. [7]).

6.3.1.4 Study effects of GAE/CAE modes on thermal plasma

The study initiated on NSTX of the effect of GAE/CAE modes on the thermal plasma via the modification of the electron thermal heat conductivity is an important topic to continue on NSTX-U. The study will be carried on in collaboration with the Turbulence and Transport Topical Science Group, see Sec. 3.3.3.1 in Chapter 3.

Two mutually exclusive mechanisms have been proposed to explain the GAE/CAE-induced electron transport. The first mechanism invokes GAE mode conversion to local kinetic Alfvén waves (KAWs) in the region near the edge [59], whereas the second mechanism is based on the magnetic field line stochastization due to multiple GAE instabilities [60]. The two proposed mechanisms were the subject of experimental studies on NSTX and have to be verified with the wealth of diagnostics that are available on NSTX-U.

Detailed analysis of the measured Alfvén wave spectrum is foreseen to exclude one of the proposed physical mechanisms in favor of the other. In recent years, an improved characterization of GAEs and CAEs became available [7]. Along with measurements of the modes' polarization, analysis of data from Mirnov coils and reflectometers, coupled to measurements of plasma profile evolution, are used to differentiate between the two classes of modes. These improvements motivate a dedicated effort on NSTX-U to separate the effects of CAEs from those of GAE modes. As the initial studies on electron thermal transport were based primarily on GAE modes [23], it is important to improve the analysis to account for the Compressional modes as well. One particular change required to use the ORBIT code as it was done for GAEs [60] is the incorporation of the perpendicular component ($A_\perp$) of the vector potential of the perturbation. This is an immediate problem to solve in the near term.

6.3.1.5 Extend *AE simulations to full NSTX-U parameter space

By the end of the initial 2 years of NSTX-U operation, numerical simulations of *AE instabilities and *AE-induced transport will be extended to scenarios with full 1 T toroidal field and 2 MA current that will be achievable in Year 3-5. Predictions will be made for the expected spectrum of unstable *AEs and for their effects on the fast ion distribution. This will provide a reference to guide further experimental studies, as well as an opportunity to assess the maturity of the codes.

For a more direct comparison between experiments and codes, an interface to import F_{nb} data directly from the NUBEAM code will be developed. The goal is to retain all the main features of the beam ion distribution function as calculated by NUBEAM, without introducing further assumptions on the fast ion relaxation and slowing down processes. This interface will first be tested with the M3D-K code. In the present version of the code, an analytic equilibrium distribution function is used with a slowing-down distribution in velocity and an anisotropic distribution in pitch. However, this simple analytic distribution cannot usually describe the full details of a realistic distribution from NUBEAM, which has a complicated 3D structure in phase space. Thus, we plan to use a numerical distribution obtained from the NUBEAM distribution after removal of the inherent MonteCarlo noise. This is necessary to accurately model the excitation and nonlinear evolution of fast ion driven AEs in NSTX and NSTX-U. The implementation of the same interface in other codes (for instance, NOVA-K and HYM) will be then considered for a more consistent treatment of F_{nb} among different numerical codes.

M3D-K will be applied to investigate the nonlinear evolution of multiple beam-driven Alfvén modes and fast ion transport. We also plan to investigate fast ion effects on global MHD modes such as non-resonant kink modes and the Resistive Wall Mode. The ultimate goal is to predict fast ion transport and effects of fast ion instabilities on the plasma confinement.

The present implementation of the HYM free-boundary equilibrium solver will be improved by adding fixed-plasma-shape capability for equilibrium fits that can better reproduce the experimental profiles. Options for including a more realistic fast ion distribution function, as discussed above for the M3D-K code, will also be developed. Based on the previous work, the study of the excitation mechanisms of GAE and CAE modes will be extended to NSTX-U regimes with higher B_t. This requires the development of numerical diagnostics to identify and characterize the location of resonant particles in phase-space. The upgraded HYM code will be then used to study the self-consistent effects of the sub-cyclotron modes on fast ion distribution function in NSTX-U. Comparisons will be done in terms of the experimentally observable mode properties (such as frequency, mode number, radial structure) and of the variation of mode stability measured under different conditions. The latter include scans of NB tangency radius and injection energy to vary the pitch and energy distribution of F_{nb} in a systematic way.

6.3.2 Research Plans for Thrust EP-1: Year 3-5

6.3.2.1 Extend *AE studies to non-linear and multi-mode physics

Although improving our understanding of linear stability of *AEs (with particular attention to ST configurations) is a necessary first step, investigations of the full non-linear mode dynamics is nevertheless the most important goal. Experiments in Year 3-5 will be aimed at unraveling the mechanisms that determine the coupling between multiple modes, either of the same type (e.g. multi-mode TAE avalanches) or of different types (e.g. TAE coupling to low-frequency MHD modes).

Once the coupling mechanisms are identified, their effect on the saturation level of *AE instabilities will be investigated. In fact, non-linear physics is known to alter linear predictions for the mode saturation level, which may become independent of the linear growth rate [61].

6.3.2.2 Compare numerical and theoretical simulations to data on mode dynamics, mode-induced fast ion transport

As the focus is shifted from linear to non-linear aspects of *AE dynamics, the range of applicability of different models will be established. Predictions of mode stability obtained from the M3D-K and HYM codes will be compared to experimental data and to predictions from linear codes such as NOVA-K to assess the accuracy and the limits of applicability of simple theories as opposed to more self-consistent, non-linear models. The code Verification & Validation effort will also include comparisons with the measured amount of fast ion transport, with emphasis in Year 3-5 on the higher B_t and I_p scenarios.

Further improvements of the HYM code are planned for Year 3-5 to include the effects of finite equilibrium electric field due to bulk plasma rotation and Hall term in the equilibrium model. In order to fully exploit the capability of the code to simulate non-linear phenomena on long time-scales (several growth-rate periods), particle sources and sinks will be added. Numerical diagnostics will finally be included to investigate the effects of GAE and CAE modes on the electron thermal transport

Agreement between codes and experiments will be quantified on the basis of mode dynamics and fast ion response at different levels, based on the level of accuracy that the simulation tools are required to provide. Whereas simpler theories are – at most – expected to provide information on the expected *AE spectrum and qualitative radial structure, more complete numerical tools should also yield the saturation level of the instabilities and any possible mode-mode coupling and other non-linear phenomena. The latter typically involve fast ion redistribution in energy and pitch even in the absence of macroscopic radial transport or loss. The suite of fast ion diagnostics available on NSTX-U can indeed provide the experimental data required for a thorough comparison between theory and experiment.

6.3.2.3 Extend simulations of *AE-induced fast ion transport to FNSF/Pilot

The ultimate goal of *AE stability studies and Verification and Validation of numerical tools is the ability to predict if (and what) *AEs will be potentially unstable in future reactors. If incremental funding is available during the 5 year period considered herein, typical scenarios for FNSF will be identified by Year 5 and *AE stability investigated. Based on the expected unstable spectrum, predictions of fast ion redistribution and loss will be then performed. Simulations will start from steady-state regimes (i.e. during the current flat-top phase) for which background plasma parameters are rather constant in time, thus simplifying the task. Once a reliable predictive capability is demonstrated, e.g. on the basis of previous agreement between the outcome from the codes and real experiments, simulations will be extended to the even more challenging transient phase of current ramp-up on FNSF. During this phase, the large variations of q-profile and ratio between thermal and fast ion pressure are expected to cause transitions between regimes dominated by different instabilities. The inherently transient mode behavior needs to be characterized, so that specific control schemes can be developed to limit or suppress the appearance of deleterious *AEs.

Predictions for FNSF scenarios performed in Year 5 will also serve as a guide for the optimization of its design. For instance, simulations may suggest an *optimum* NBI configuration that would ensure flexibility in *AE control while providing the required NB-driven current and additional heating. Moreover, design of rf systems may also benefit from EP-related simulations once a deeper understanding of the synergy between NB ions and injected rf waves is achieved. Finally, additional tools may be envisaged (or required) for *AE control in fusion reactors, that is the main focus of Thrust #2 detailed in the next Sections.

6.3.2.4 Summary of research plans by year for Thrust EP-1

Assume a Baseline Funding scenario (*Baseline+10% Incremental scenario in italics*).

Year 1 (2014):

- Improve CX analysis tools in TRANSP for better accuracy in the interpretation of data based on charge-exchange processes (e.g. NPA/ssNPA, FIDA).
- Develop and assess reduced models for *AE-induced fast ion transport. Include reduced models in TRANSP/NUBEAM for improved modeling of NB-heated plasmas, for example to include anomalous fast ion transport driven by resonant *AEs and its effects on NB-driven current profile.
- Improve F_{nb}, rotation description in numerical codes.

Year 2:

- Compare classical TRANSP/NUBEAM predictions with experiments for 1st + 2nd NB line in collaboration with WH&CD, ASC and SFSU groups to establish a baseline for future EP, scenario development and current ramp-up studies.
- Characterize *AE activity driven by more tangential 2nd NB line. Study response of *AE stability to different NB injection geometries for discharge optimization.
- Perform theory/experiment comparison on TAE properties for Verification & Validation of improved codes for *AE stability and associated fast ion transport.

- Extend predictions to full NSTX-U parameter space in preparation for the full 1 T, 2 MA operations in Years 3-5.

Year 3:

- Characterize TAE-induced F_{nb} modifications. Characterize *AE regimes leading to fast ion redistribution (in both space and energy/velocity) or loss.
- Extend TAE studies to non-linear, multi-mode physics for the higher toroidal field and current of NSTX-U.
- Perform theory/experiment comparison on GAE/CAE modes properties.
- Study GAE/CAE effects on electron thermal transport.

Year 4/5:

- Extend characterization of *AE-induced F_{nb} modifications to higher-frequency *AEs to assess the role of high-frequency *AEs in fast ion redistribution.
- Assess theory/experiment comparison on mode dynamics.
- Extend multi-mode *AE studies to higher-frequency *AEs. Study coupling between different classes of instabilities through modifications of F_{nb}.
- Extend *AE simulations to FNSF/Pilot (steady-state); assess implications of *AE and fast ion studies for FNSF/Pilot optimization.
- *Extend *AE simulations to FNSF/Pilot (ramp-up phase). Assess implications of *AEs for current ramp-up with NB in future STs.*

6.3.3 Research Plans for Thrust EP-2: Year 1-2

6.3.3.1 Assess requirements for *fast ion phase-space engineering*

The results on *AE stability and fast ion response achieved during the next 5-year period form the basis for the development of active tools to affect F_{nb} through selective excitation or suppression of specific classes of *AE modes. Experiments will be conducted to assess whether an efficient control of F_{nb} and fast ion driven instabilities can be achieved through the combination of (and synergy between) several techniques.

Neutral beam injection is the primary tool to vary the q-profile, that is one of the most important parameters affecting the stability of *AEs. For instance, maintaining a reversed-shear configuration during current ramp-up phase may favor strong RSAE activity that can redistribute fast ions radially, thus enhancing NB-driven current diffusion to achieve a broader current profile (and improved MHD stability) at early times in the discharge. Similarly, off-axis NB injection during the flat-top phase may be required to sustain the central value of q well above $q_0=1$ and suppress or reduce the occurrence of low-frequency MHD (kinks and fishbones). Another important parameter is the NB injection voltage, which sets the ratio of fast ion to Alfvén velocity. The latter value is expected to play an important role in the particular saturation regime of instabilities such as TAEs, for instance to reduce the avalanching behavior of the modes and to minimize fast ion losses. The efficacy of different NB injection schemes to affect *AE stability and fast ion profile will be assessed as a function of toroidal field, plasma current, confinement mode (L- vs. H-mode).

Besides NB injection, the use of HHFW injection to control *AEs and affect F_{nb} will be investigated. Experiments will be performed to separate the direct effect of rf waves that modify fast ion phase space from indirect effects on *AE stability through variations of the background (thermal) plasma parameters. This requires accurate measurements of F_{nb}, coupled to advanced numerical codes to unfold the effects of HHFW injection on various drive and damping mechanisms. Scans of the HHFW phasing are planned to vary the amount of power coupled to thermal electrons and to fast ions. Similarly, scenarios with different NB injection voltage will be explored to map regions of fast ion phase space that are mostly affected by HHFW.

Existing Magnetic Perturbations external coils, with improved control over the excited spectrum through an additional set of Switching Power Amplifiers (SPAs), will also be used to affect the dynamics of high-frequency *AEs. Further enhancements are expected from a (partial) set of Non-axisymmetric Control Coils (NCC) after FY16. Initial analysis from NSTX data indicates that pulses of static MP perturbations can indeed modify the drive for GAEs by altering the fast ion distribution, as shown in Fig. 6.2.4. Research on NSTX-U will proceed by investigating the dependence of F_{nb} modifications, and the resulting mode dynamics, on amplitude and spectrum of the magnetic perturbation induced by the 3D field coils. Experimental data on variation of the fast ion profile caused by the applied fields will be compared to results from the SPIRAL code with perturbed magnetic field calculated through the IPEC code.

A more sophisticated control of *AE modes can be achieved by dedicated antenna systems. The first goal for Years 1-2 is to design a *AE antenna system such that the coupling with modes peaking in the core plasma is maximized. A broad range of frequency, spanning from the TAE range (10-200 kHz) up to the GAE/CAE range (~2 MHz), is required to cover the entire range of interest for *AE studies. The antenna design proposed for NSTX-U will have a specific polarization, which would allow the propagation of the power throughout the plasma. For example, one possibility is to excite the Compressional AEs via the excitation of such oscillations near the edge of the plasma. It seems reasonable to expect that the most helpful tools for design and optimization of the system are codes used in the ICRH studies. These capabilities will be developed in the planning and development phases of PSE techniques.

Depending on the availability of incremental funding, the *AE antenna system will be upgraded throughout Years 3-5 to improve the selectivity in the injected frequency and mode number spectrum. The antenna control system will also be improved from the initial pre-programmed mode of operation to a closed-loop control that can track specific modes during the discharge, for example based on measurements from Mirnov coils. The ultimate goal of this research is to assess the requirements for efficient coupling to *AEs over the entire frequency range from TAEs to high-frequency GAE/CAEs. Coupling efficiency will be evaluated in terms of tangible effects on the mode's characteristics (e.g. reduced amplitude/suppression or variations of induced fast ion redistribution and loss). The main figure of merit is the required purity of injected spectrum and amount of coupled power to induce measurable effects.

Based on these experiments, projections to future devices will be performed to assess whether the *AE control techniques developed on NSTX-U are a viable and promising tool that should be further pursued.

6.3.3.2 Test *AE antenna system

A prototype *AE antenna was installed on NSTX in 2011, but never operated. It consists of a single 5-turn coil obtained from a polyamide-insulated 10 AWG copper wire (see Fig. 6.3.6). The 10 AWG copper conductor is stiff enough to be self-supporting. No significant heating is expected at the projected current levels in the low power phase of the experiments.

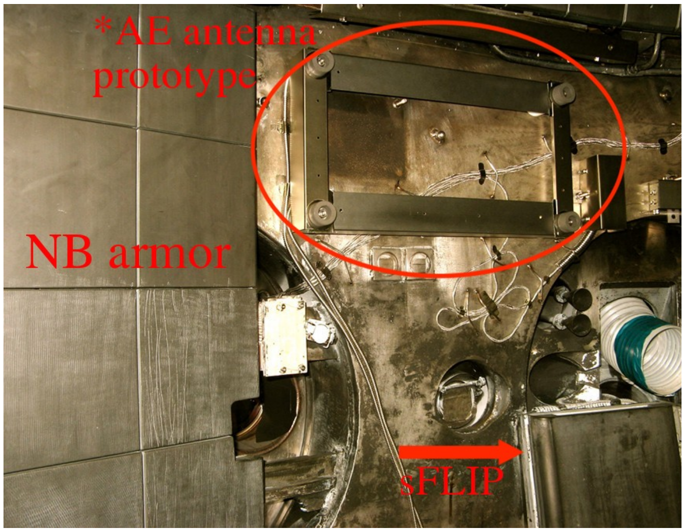


*Figure 6.3.6: Prototype *AE antenna as installed in-vessel prior to the FY-12 Run. The antenna consisted of a 5-turn coil installed above the mid-plane, next to the NB armor (left) and above the sFLIP diagnostic (bottom right).*

The prototype module was intended as the first step to test the efficiency of coupling to different classes of *AEs. However, being a single element, it cannot provide selectivity and flexibility in terms of excited spectrum of toroidal mode numbers. The main limitation for a practical utilization of a single *AE antenna as an *active* tool for MHD spectroscopy is that the rf power is diluted over the entire mode number spectrum, thus increasing considerably the power requirements for damping rate measurements of single modes. To overcome this limitation and proceed more aggressively with the active *AE spectroscopy project, a set of 4 modules, based on the original prototype design, is being developed for NSTX-U. Suitable locations have been identified at bays F-G. The four modules will be installed in pairs, both above and below the midplane, in regions not occupied by (or potentially useful for) other diagnostics. The small toroidal separation of the modules will enable a greatly improved control of the excited spectrum over the single-module prototype for mode numbers up to $n=9\text{-}10$, as required for CAE studies.

For the initial operation, the antenna modules will be driven through a broad bandwidth linear amplifier built by Amplifier Research Corp. The amplifier bandwidth extends from 10 kHz up to 100's of MHz. Nominal output power is 1kW CW into a 50 Ohm resistive load. Operations of the amplifier at up to 5 kW are possible in pulsed mode, with a pulse length effectively comparable to the NSTX-U discharge duration. The output power of 1 kW into 50 ohms translates into ≈220V, 4.5A rms. This is a linear amplifier, so a programmable function generator will be used as the source driver for pre-programmed frequency sweeps, with the possibility of implementing more advanced feedback control schemes in later years. The 1-5 kW power level is comparable to what has been used in other MHD spectroscopy experiments. Upgrades to higher power RF systems will be considered after Year 2, based on the available resources (see below).

Improvements to the antenna design will be considered during Years 2-5 to optimize the coupling to TAE and CAE modes. In parallel, the coupling network and control hardware and software will be developed. There are several potential avenues by which to improve the antenna performance. The addition of more modules in the antenna array will improve both coupling to the modes and selectivity in the excited (toroidal) mode number spectrum. If the heat loading of the existing antenna design by thermal plasma and beam ions appears modest, moving the antenna closer to the plasma surface will likely improve coupling. Finally, a sub-set of coils oriented in the poloidal/toroidal direction might be preferable to the present radial, picture-frame coils. The extent of the antenna will, of course, be constrained by requirements of other internal diagnostics and hardware.

Along with the *AE antenna improvements, an upgrade of the existing set of magnetic pick-up coils will be considered. Pending incremental resources and the success of the *AE antenna, the upgraded coil system will enable real-time detection of unstable (or potentially unstable) *AEs during a discharge. The resulting information on *AE stability and dynamics can then be used to implement a feed-back loop on the *AE antenna to track modes in real time. In addition, it would enable the implementation of *AE control schemes through the Plasma Control System (PCS) by using NBI, MP/NCC coils or rf injection in response to the *AE mode activity for discharge optimization.

6.3.3.3 Compare measured *AE damping rates with models & theory

In the course of the initial *AE antenna operations, it will be natural to exploit any data acquired on *AE damping rate to develop the needed analysis codes, and to identify the necessary experimental conditions. It is envisioned that the initial years of experimentation will be at relatively low power, of the order of ~1 kW, similar to the power level used in experiments on the C-Mod and MAST devices.

Emphasis in Year 3 will be on designing experiments to measure *linear* TAE damping rates under as broad a range of conditions as possible, in order to establish a connection with previous work on C-Mod and JET. It is anticipated that these studies will be complicated in NB-heated NSTX-U plasmas by the fairly ubiquitous presence of unstable *AEs. Thus, initial physics studies will probably concentrate on Ohmic and HHFW-heated plasmas. This will be followed by measurements in beam-heated plasmas using low voltage beams and high plasma density to reduce the fast ion beta. Linear stability can then be measured as a function of NB power to separate fast ion drive from linear damping. Comparison between the measured rates and the outcome of numerical codes is planned. For the lower frequency TAE modes, damping rates will be computed via the NOVA-K and M3D-K codes. Comparison between the predictions from both linear and non-linear codes with experimental values will provide a further cross-validation between codes. The HYM code will be used for the analysis of high-frequency GAE/CAE modes and comparison with experimental results.

While the highest priority in Years 2-3 will be to develop the capability to study stability properties of TAE modes, experimental time will be devoted to assess the antenna and coupling network performance at frequencies up to 2 MHz, as will eventually be needed for Global and Compressional Alfvén Eigenmode studies. Most likely, this will require modifications of the matching network between the amplifier and the antenna.

6.3.3.4 Characterize scenarios with combined NBI+HHFW

HHFW heating accelerates NBI fast-ions [62][63], altering the fast ion distribution, the spectrum of *AE activity, the fast-ion transport and consequently the NB-driven current profile. While the dominant fast-wave heating mechanisms in NSTX were found to be Transit Time Magnetic Pumping damping on electrons and fast ion damping at high cyclotron harmonics, at the mid-harmonic range expected at the highest toroidal fields in NSTX-U the power partitioning may change.

Initial simulations with advanced rf codes (AORSA, TORIC, METS, GENRAY and CQL3D) indicate that significantly more thermal deuterium damping, in addition to increased NBI fast ion damping, may occur in NSTX-U (see Chapter 7 and references therein). Experiments during the first two years of NSTX-U operation will employ the existing 12-strap HHFW antenna to study the effect of fast-wave heating on F_{nb}, the spectrum of *AE activity and fast-ion transport. Results from these experiments, conducted in collaboration with the Wave Heating and CD group (cf. Chapter 7, Sec. 7.1.3.1), will be used to validate the predictions of rf and energetic particle simulations.

6.3.4 Research plans for Thrust EP-2: Year 3-5

6.3.4.1 Optimize *AE antenna for efficient coupling to *AE modes

After the initial two years of NSTX-U operations, several straps of the HHFW antenna may be disconnected from the 30 MHz rf sources to allow for the installation of an upgraded *AE antenna (see Chapter 7, Section 7.2.1.4 for more details). If removal of (up to) four HHFW antenna straps is found to be acceptable, experiments during Years 4-5 will employ the reduced-strap HHFW antenna for fast-wave heating and an upgraded *AE antenna system for EP studies.

The availability of more in-vessel space would provide more flexibility for the optimization of the layout of the antenna modules to achieve optimum coupling efficiency to modes with a specific toroidal mode number.

Based on the available NSTX-U budget for Year 5, upgrades of the rf amplifier driving the antenna and of the mode detection/antenna control systems will be considered. Higher power operations (>10 kW) would be possible by utilizing rf oscillators instead of the linear amplifier envisaged for Years 1-2, at the expenses of flexibility in the range of excited frequencies. A 100-kW system is available at PPPL, although development work is required to tune the frequency range down to the 1-2 MHz frequencies at which CAE/GAE modes are expected. Such higher-power system would be especially important for assessing the ability to drive modes at sufficiently large amplitudes, so that they can induce measurable effects on the fast ion distribution and, possibly, on the thermal plasma (electrons), see next Section. A coherent detection system is also foreseen to detect and track the mode frequency in real time during a discharge. This implies improvements to the existing Mirnov coils set to reduce the direct coupling to the antenna and improve the signal-to-noise for the detection of *AE modes that are coherent with the antenna excitation. The ability to track modes in real time would enable the implementation of a feedback loop in the antenna driver, in order to maintain good coupling with a specific mode. (*A priori*, that is clearly not guaranteed by operating the system with open loop, i.e. pre-programmed, frequency settings).

6.3.4.2 Measure stability of high-*f* *AEs; assess capability of & requirements for mode excitation

In Years 4-5 there will be increased focus on the higher frequency Alfvén instabilities. The initial goal will be to map the spectrum of natural CAE/GAE eigenmodes. Then, the linear damping rates of the stable modes will be measured with different combinations of neutral beams, including scans of NB injection energy and tangency radius to alter the fast ion distribution. Extensive comparison with numerical codes such as HYM is foreseen.

Low power (≈1 kW) *AE antenna experiments will provide important information on antenna coupling and natural damping rate for each of the eigenmodes. This information will be used to determine the potential benefits of higher power experiments aimed at driving the modes to substantial amplitude. Multiple antenna modules are required to improve the antenna selectivity and focus the rf power over a narrow range of the toroidal mode number spectrum, especially for *AEs with intermediate to high mode numbers, $n>5$. An upgraded *AE antenna system is therefore needed, making this area of research subject to the available budget for Years 3-5.

Stability properties of high-frequency *AEs are also very important in the area of *AE effects on thermal plasma. If the natural eigenmode damping rates are small, there is the possibility of driving them to amplitudes where stochastic heating of thermal ions occurs [27]. This gives an attractive option to spherical tokamaks of direct rf wave heating of the thermal ion population. Conversely, for strongly damped eigenmodes, the rf wave heating will be partitioned between thermal electrons and thermal ions and may still be of interest, if adequate coupling can be obtained through antennae of reasonably compact size.

6.3.4.3 Summary of research plans by year for Thrust EP-2

Assume a Baseline Funding scenario (*Baseline+10% Incremental scenario in italics*).

Year 2 (2015):

- Assess requirements for phase-space engineering using NBI as actuator.
- Test prototype *AE antenna system. Assess antenna performance in terms of coupling to lower frequency *AEs (TAEs, RSAEs).
- Investigate scenarios with combined NBI+HHFW to characterize rf-induced modifications of F_{nb} and implications for efficient rf heating during NB injection.

Year 3:

- Compare TAE damping rates measured via *AE antenna with theory to validate models for *AE damping in ST geometry.
- Based on the results from Years 1-2, assess requirements for phase-space engineering using NBI, HHFW and magnetic coils as actuators. Explore the possibility of controlling *AE modes and resulting F_{nb} modifications to affect NB-driven current and q-profile.

Year 4/5:

- Extend *AE damping rate measurements through *AE antenna to higher-frequency *AEs to validate CAE/GAE stability models and numerical codes.
- Optimize AE antenna for efficient coupling to *AEs. Improve spectrum selectivity to couple to specific modes.
- Assess capability of, and requirements for, mode excitation. Determine power level and spectral requirements to excite *AEs to sufficient amplitude for detectable variations of F_{nb}.
- *Implement and test high-power *AE excitation system.*

6.4 Summary of Theory and Simulation capabilities

Code	*Description*	*Scope*	*Improvements*
ORBIT	Gyro-center particle following code.	Infer fast ion response to given set of modes.	Improved methods for resonance identification.
SPIRAL	Full-orbit particle following code.	Infer fast ion response to given set of modes.	
NOVA-K	Ideal MHD; linear.	Compute eigenfunctions, stability for *AEs.	Improved F_{nb} model. Improved treatment of finite plasma rotation.
M3D-K	Hybrid model; self-consistent, non-linear.	Infer mode dynamics (low-f *AEs, kinks) and fast ion response.	Improved F_{nb} model.
HYM	Hybrid model; self-consistent, non-linear.	Infer mode dynamics (high-f *AEs) and fast ion response.	Improved F_{nb} model. Include sources and sinks.
F_{nb} inversion code	Package for analysis of experimental data.	Infer F_{nb} from a set of measurements.	Under development. Adapt to NSTX-U.
QL model	Reduced model for quasi-linear relaxation of $F_{nb.}$	Compute relaxed $F_{nb}(r)$ in the presence of *AE modes.	Under test. To be included in TRANSP/NUBEAM and validated against NSTX/NSTX-U data.
Resonant fast ion transport model	Reduced model for resonant/stochastic AE-induced fast ion transport.	Advance F_{nb} in NUBEAM under the effects of resonant *AE modes.	Under development. To be included in TRANSP/NUBEAM and validated against NSTX/NSTX-U data.

Table 6.4.1: Summary table of the codes directly developed (or under development) by NSTX-U researchers and collaborators for Energetic Particles related theory-experiment comparison on NSTX-U.

6.4.1 ORBIT

ORBIT [64] is a particle-following code based on the Hamiltonian formulation for the particle guiding center motion in the presence of axisymmetric perturbations. The code has been widely used to simulate the fast ion response to MHD instabilities [65][66] (mostly RSAEs and TAEs) in various magnetic configurations, from tokamaks (including NSTX) to reverse-field pinches. A novel, efficient technique has being developed to identify stochastic regions based on the relative phase between pairs of particles with nearby orbits in phase space coordinates. This technique will be used to identify resonances and characterize magnetic field stochastic regions for *AE modes observed on NSTX-U. More generally, ORBIT provides a consolidated framework to investigate fast ion loss and redistribution in the presence of TAEs, including the transport scaling as a function of mode amplitude, mode structure and frequency.

The ORBIT code is also used to investigate thermal electron response to high-frequency GAE/CAE modes [60]. Future improvements are mainly based on the accuracy of the mode structure and amplitude used in the simulations. Previous works utilized theoretical mode structures and amplitudes consistent with measurements of magnetic and density fluctuations from Mirnov coils and interferometers. Based on the improved measurements achieved through reflectometry [7], the experimental mode structure can be used [67] to improve the overall mode description in ORBIT for CAE and GAE instabilities. Future work also includes comparisons between thermal electron transport predictions from the ORBIT and HYM codes.

6.4.2 SPIRAL

The SPIRAL code [68] is a full particle-orbit following code recently developed at PPPL for the interpretation and simulation of fast ion dynamics in toroidal plasmas. All gyro-orbit effects are retained, so that the code can also be used to study fast ion interaction with instabilities and externally launched waves with frequency near or above the ion cyclotron frequency. Effects of finite gyro-radius may be particularly important in devices such as NSTX and NSTX-U, in which the combination of small aspect ratio and relatively low toroidal field results in large fast ion orbits compared to the typical scale-lengths of variation of plasma profiles and magnetic field.

The fast ion motion in the presence of general electromagnetic fields is inferred by solving the Lorentz equation. Slowing down and pitch angle scattering are also included. The initial fast ion distribution can be either imported from other codes (e.g. TRANSP/NUBEAM) or defined internally. Initial benchmark and applications of the SPIRAL code are summarized in Ref. [68].

6.4.3 NOVA-K and PEST

The family of NOVA codes [69] has been successfully used and validated in recent years and is now able to comprehensively compute the stability of TAE-like modes in tokamaks. It is capable of using input plasma parameters in the post-processor fashion from TRANSP simulations. The code has been successfully applied to different tokamaks, such as NSTX, DIII-D, C-MOD and ITER for TAE stability predictions. Typically, the kinetic post-processor NOVA-K can compute the mode stability for experiments with relatively small rotation. Rotation enters in the dispersion relation and stability calculation as a Doppler shift term, and it can therefore modify both the TAE mode structure and its stability (including damping and drive terms).

For low aspect ratio plasmas with large NB input torque such as NSTX and NSTX-U, Doppler shift corrections are of the order of, or larger than, the typical mode frequencies in the plasma frame. (This applies to TAE mode calculations as well as for the internal kink modes). Under these conditions, rotation cannot be considered a small correction and it must be treated more consistently. Improvements of the NOVA code are planned to include a more consistent model for plasma rotation at all levels, from eigenmode structure calculations to damping/drive calculations. Doppler shift corrections based on rotation profiles that are already included in the ideal MHD part (NOVA) will be extended and incorporated in the kinetic part (NOVA-K). A more self-consistent approach is presently implemented in the NOVA-KN code, which already is in working conditions in the MHD approximation. The NOVA-K EP has rotation included for the growth rate calculations, but need better interface with TRANSP profiles.

A separate activity on NOVA-K improvement, which is important for the growth rate calculations, includes the generalization of the model for the distribution function. This becomes especially important for the NSTX-U, which will have a second NBI line and a large variety of possible injection geometries. Improvements will allow the user to import realistic distributions, for example obtained through TRANSP. The more accurate treatment of F_{nb} developed for NOVA-K will then be implemented in the newly developed code NOVA-KN.

In addition to the NOVA code, the ideal MHD code PEST is also available. Possible improvements include a better interface with other codes, e.g. to import profiles from TRANSP, similarly to what is now available for NOVA. One advantage of this improvement would be to allow the user to use the same equilibrium for the different codes. This work was started but did not progress well enough to become available for common use and production runs.

6.4.4 M3D-K

M3D-K is a global nonlinear kinetic-MHD hybrid code [70][71]. In the model, the thermal plasma is treated as single fluid and the energetic particles are described using the drift-kinetic or gyrokinetic equation. The kinetic effects of energetic particles are coupled to the MHD equations via the stress tensor term in the momentum equation. The model is non-perturbative so can be also used to treat strongly driven modes, such as Energetic Particle Modes (EPMs). The code uses numerical tokamak equilibria as initial conditions with capability of treating strong shape and small aspect ratio together with finite plasma rotation. The code has been used successfully to simulate energetic particle stabilization of internal kink mode and excitation and saturation of fishbone [71], the nonlinear saturation of fast ion-driven TAE with source and sink [72][73], the fast ion stabilization of tearing modes [74], the beam ion excitation of TAE modes in NSTX plasmas [58], the beam-driven Alfven eigenmodes in DIII-D [75], and the fast ion transport due to the non-resonant kink mode in NSTX [76].

6.4.5 HYM

The Hybrid and MHD simulation code HYM is a 3D, non-linear global stability code that includes fully kinetic ion description. It employs a *delta-f* particle simulation method to reduce numerical noise and a full-ion-orbit description of supra-thermal ions in toroidal geometry, as required to study wave-particle interaction in the presence of instabilities in the ion-cyclotron frequency range.

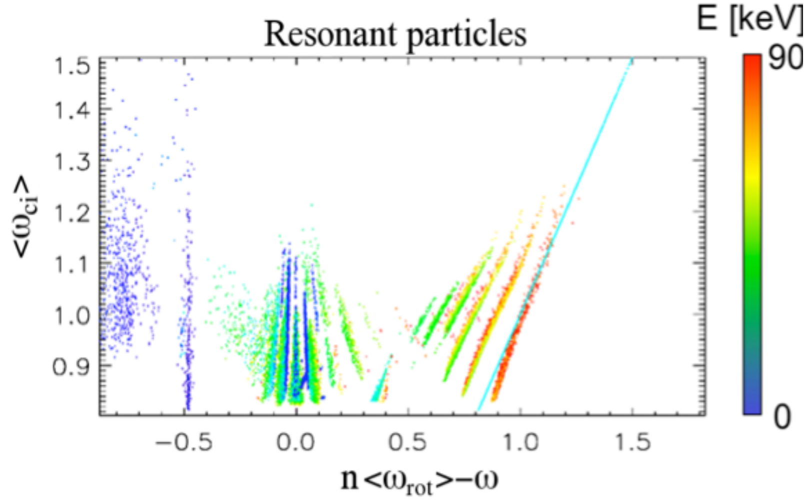


Figure 6.4.1: Resonant particles shown with orbit-averaged cyclotron and toroidal rotation frequencies, normalized to the ion cyclotron frequency at the axis, ω_{ci0} (f_{ci}=2.48 MHz). Results from HYM simulations of the n=8 co-rotating CAE mode (NSTX shot #141398), with $\omega=0.48\omega_{ci0}$, $\gamma=0.004\omega_{ci0}$. Particle color corresponds to different energies from E=0 (purple) to E=90 keV (red), see color bar.

HYM is utilized to study the excitation of GAE modes and co- and counter-rotating CAE modes on NSTX [77][78]. For example, a specific H-mode NSTX discharge, featuring all the high frequency mode activity commonly observed on NSTX, has been analyzed in detail (Figure 6.4.1). In agreement with experimental observations, co- and counter rotating CAE modes are found unstable for low toroidal mode numbers (n=4), whereas lower-frequency counter-rotating GAEs are unstable for intermediate toroidal mode numbers (n=5-7), and co-rotating CAEs are unstable for even higher toroidal mode numbers (n=8,9). The presence of two separate groups of resonant particles, corresponding to regular and Doppler-shifted cyclotron resonances, has been discovered for high-n co-rotating CAEs (cf. Fig. 6.4.1).

In addition to studying F_{nb} modifications caused by sub-ω_{ci} modes, a drift-kinetic description of the thermal electrons has been implemented in HYM to investigate the effect of those modes on thermal electron transport. Evidence of enhanced thermal transport has been already reported from NSTX, and it will be the subject of future experiments on NSTX-U as a candidate mechanism for the regulation of electron temperature profile.

6.4.6 F_{nb} inversion code for interpretation of fast ion data

The fast-ion distribution function F_{nb} is a complicated function of velocity, space, and time. A common choice of independent variables to describe F_{nb} is the energy E and pitch $v_{\|}/v$ in velocity space and the major radius R and elevation z in configuration space. Typically, the distribution function has a non-trivial dependence on all four variables. Because the functional dependencies are complicated, no single diagnostic provides enough information to determine F_{nb} accurately. The sensitivity of a particular fast-ion diagnostic to these variables is described by a *weight function* [79], W (see Fig. 6.4.2). The signal S measured by a diagnostic is the product of W with the distribution function F_{nb}, i.e. $S=\int W*F_{nb}$, where the integral is over all phase-space variables. (In statistical terms, this integral is a kind of "marginalization"; in instrumentation language, the weight function is a type of instrument function.)

Presently, forward-modeling codes exist that predict diagnostic signals S for a given F_{nb}. For example, TRANSP uses the distribution function calculated by NUBEAM to predict the neutron rate. TRANSP also has a module that predicts NPA data. The FIDASIM code [80] predicts FIDA, NPA, and beam emission signals. The code can accept as input distribution functions produced by NUBEAM, CQL3D, SPIRAL and ORBIT. Presently, the production version of FIDASIM is written in IDL. However, in collaboration with ASDEX-Upgrade (AUG), a much faster FORTRAN version has been written and is currently being tested.

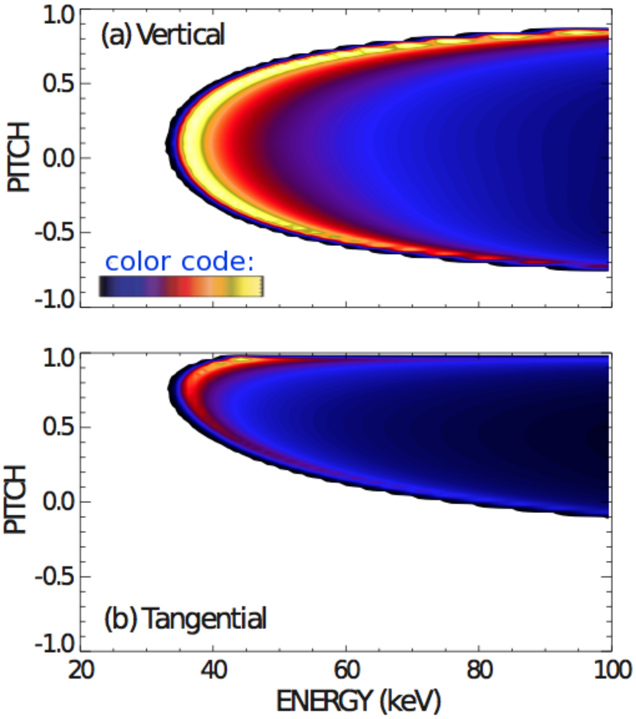


Figure 6.4.2: Example of calculated response function for (a) the vertical and (b) the new tangential FIDA systems for R=1.2 m and at measured energy E_l=35 keV. The color scale, shown in panel (a), is normalized to the maximum value. (From Ref. [10]).

Although forward modeling is useful, it has limitations. In particular, cases exist when *all* available theoretical predictions disagree with the data. For these cases, it is highly desirable to infer the distribution function directly from the data to provide guidance to theory. Another urgent need is better quantification of errors in the comparison between theory and experiment.

Recent progress in understanding the nature of weight functions [81], together with advances in computer power and the development of extensive sets of fast-ion diagnostics, have made it feasible to develop techniques to infer F_{nb} directly from the data [82]. The planned approach is based on Bayesian techniques. An international team involving scientists from NSTX-U, Danish Technical University, DIII-D, ASDEX-Upgrade, and MAST is involved. In Bayesian terminology, the *likelihood functions* for the various diagnostics utilize diagnostic weight functions. Diagnostics with markedly different sensitivities in phase space are essential for a well-constrained inversion. The combination of complementary fusion product, FIDA, and NPA diagnostics provide the needed data. Initially, these new techniques will be developed and applied to facilities with extensive fast-ion measurements (probably DIII-D and AUG). As fast-ion data become available, the analysis framework will be extended to NSTX-U. During subsequent NSTX-U operation, the inversion capability will be refined and extended as new instruments become reliable.

It is anticipated that the Bayesian inversion code will provide the most accurate and detailed analysis of the data. However, for control-room guidance and data mining, reduced models that sacrifice some accuracy for computational efficiency are needed. Tools of this sort will also be developed by our international development team and adapted for use at NSTX-U.

6.4.7 Quasi-linear model of AE-induced fast ion profile relaxation

The Quasi-Linear (QL) model has been recently validated on DIII-D tokamak plasmas [83]. Several other AE- unstable tokamak scenarios were analyzed using this model [84][85]. The QL model is ready to be used in the regimes of planned NSTX-U operation. In fact, the predicted NSTX-U scenarios are closer than NSTX plasmas to the required conditions for the QL model to be applicable.

The QL procedure can be readily utilized in TRANSP simulations as its integral part. There are two ways the model can be applied. The first case is when the growth and damping rate of the unstable modes can be computed using analytic expressions. This version seems to be more applicable for the burning plasma conditions. Its employment in the integrated codes could be corrected by scaling parameters, similarly to the H-factor parameter in confinement studies. The second case is more suitable for machines with smaller size. A hybrid version is used, in which the NOVA code is first utilized for an initial calculation of the mode drive and damping rate terms, followed by a calculation of the relaxed fast ion profile that leads to a vanishing net growth rate. This method predicts the value of the critical gradient of fast ions. In this case, the initial NOVA analysis requires additional effort and is more time consuming. However, this procedure is especially important for validation purposes and to develop the required database for the “H-factor like” corrections that are then used for the analytic computation of growth rates.

Figure 6.4.3 illustrates an example of QL model applied to ITER scenarios. Here not only the thresholds are predicted for TAEs to be excited but the losses also follow from this model. (It should be noted that additional corrections for the H-like factor might cause a shift of the instability boundary, depending on its value).

Although the full distribution function is not evolved self-consistently by the QL model, the relaxation of the EP profiles could be implemented in codes like TRANSP to change particles' weighting in the calculations. It makes sense to introduce the H-factor like parameter for the QL model to be used in the comparison with experiments.

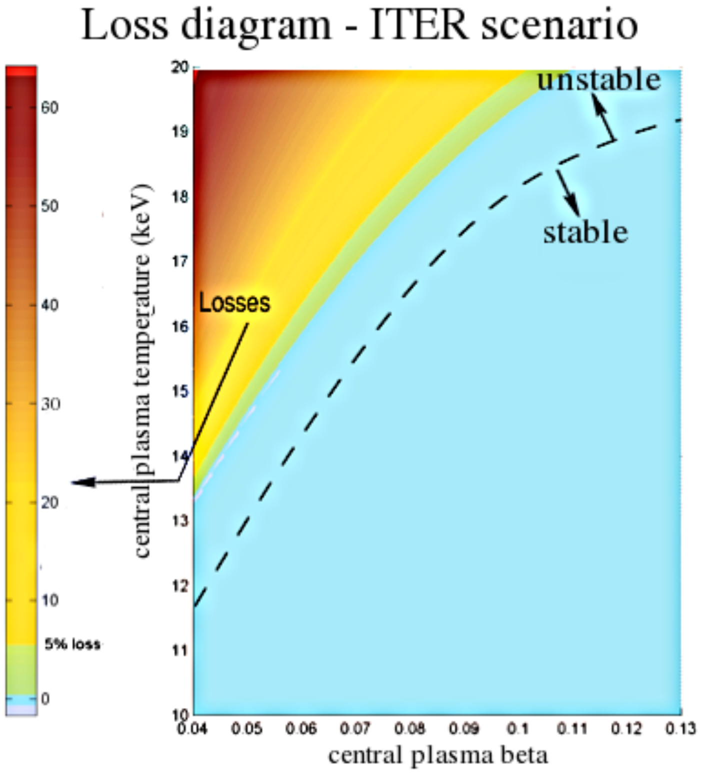


Figure 6.4.3: Example of quasi-linear model predictions of TAE stability for nominal ITER scenarios. On the abscissa is the central value of the plasma beta and on the ordinate is the central plasma temperature. TAE stability regions are indicated, along with the amount of losses expected in the presence of unstable modes.

6.4.8 Resonant fast ion transport model for TRANSP

The NUBEAM module implemented in TRANSP already contains different implementations for specifying anomalous fast ion transport coefficients. However, those models do not contain explicitly any details on the resonant interaction (and resulting transport in phase space) between instabilities and fast ions. In fact, the resonance condition implies that only narrow regions in phase space are strongly affected by the modes, whereas adjacent regions are possibly not affected.

The following features will be included in a new fast ion transport model to mimic the resonant interaction between fast ions and instabilities:

- Characterize particles based on their orbit topology, e.g. in terms of magnetic moment μ, energy E and canonical toroidal angular momentum P_ζ, instead of real-space coordinates such as radius, poloidal/toroidal angles.
- Model transport as steps (or kicks) in phase space, e.g. kicks in energy associated with the resonant interaction. Make no *a priori* assumption on the resulting radial transport, which should naturally follow from the particle dynamics in phase space (namely, from variations of the toroidal angular momentum P_ζ).
- Calculate variations of E and P_ζ consistently. Based on the guiding center Hamiltonian formulation of the particle's motion in the presence of a mode with toroidal mode number n and frequency $\omega = 2\pi f$, one obtains the relationship $\omega P_\zeta - nE = constant$. This implies that, for a single mode, variations in E and P_ζ for particles satisfying are related through $\Delta P_\zeta / \Delta E = n/\omega$, which sets a constraint for the allowed trajectories in the (P_ζ, E, μ) space. In reality, and if more than one mode is present, ΔE and ΔP_ζ can depart from the ideal linear relation between ΔP_ζ and ΔE.
- Derive transport coefficients from consistent simulations or theory, plus comparison with experimental data (whenever possible).
- The model must be suitable for inclusion in the NUBEAM module. In this regard, a Monte Carlo framework is the best approach.

In the proposed approach, the problem is split into two parts: (i) derive a set of transport coefficients in some given form, and (ii) use those coefficients in NUBEAM for the actual computation of fast ion evolution. By doing so, the NUBEAM part of the problem can be developed independently of the different models (or theories) used to infer the transport coefficients. To specify the transport coefficients, the new model introduces the probability distribution function $p(\Delta E, \Delta P_\zeta, \Delta\mu)$ that a particle, whose orbit is characterized by the tern of constant of motions (P_ζ, E, μ), experiences a change over a time δt in energy and canonical toroidal angular momentum of magnitude ΔE and ΔP_ζ (and, possibly, of magnetic moment: $\Delta\mu$) in the presence of a mode with a given amplitude.

In the present plans, the model will first be used to analyze cases for which information on mode structure and amplitude is available, e.g. from reflectometer and Mirnov coils data. To use the model for predictions for future scenarios, some assumptions for the mode behavior have to be made. One possibility is to identify a set of candidate (unstable) modes, for instance through linear stability analysis with NOVA-K. Then, a series of runs with different assumptions on the mode amplitude (e.g. low-amplitude saturation with quasi-stationary modes, weakly busting modes, strong avalanches) may then provide indications on the possible effects on fast ion transport, NB-driven current redistribution and plasma rotation.

6.4.9 Improved 3D 'halo neutrals' model in TRANSP

Existing analysis tools will be improved to extract the required information from the experimental data and enable more reliable projections to future scenarios. For example, the TRANSP code contains a NPA/ssNPA simulation package that has been applied to model charge-exchange neutral particle flux measurements. However, the contribution of 'halo neutrals', surrounding the NB footprint, to the charge exchange flux is not included in the simulation. The existing TRANSP code does not yet treat halo neutrals properly. The effect of halos would be to nearly double the simulated charge exchange flux, thus enabling extension of projected measurements to higher plasma density. An upgrade of TRANSP to provide correct treatment of halo neutrals is nearing completion and will be available for the beginning of NSTX-U operations.

As an example of the present TRANSP capabilities to simulate CX-based diagnostics, discharge scenarios from NSTX-U performance studies [4] are used to assess the viability of NPA measurements for the high-density regimes ($n>10^{20}$ m^{-3}) expected on NSTX-U. NPA simulations were performed for scenarios with 6 NB sources at E_b=90 and 110 keV for low and high n_e cases. An example is shown in Figure 6.3.5 for E_b=90 keV, chosen because this energy enables the simulation to be normalized to existing NPA data from NSTX. The result from this comparison is that quality NPA measurements can be envisioned for NSTX-U, since the calculated flux is above the NPA measurement threshold (shown by the shaded bar). The capability of E||B NPA measurements for even higher performance NSTX-U scenarios with I_p=2 MA, B_T=1 T, E_b=110 keV, P_b=17.4 MW, $n_{e,0}$=2.2x10^{20} m^{-3} (e.g. NSTX-U TRANSP run 142301K54) cannot be adequately addressed until the upgraded halo neutral model is available.

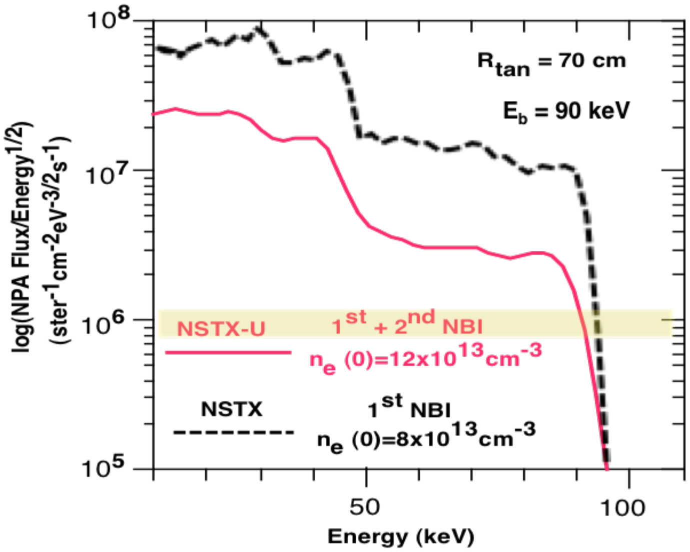


Figure 6.3.5: Comparison of E||B NPA flux calculated by TRANSP for a NSTX discharge with 3 NB sources (black curve: I_p = 1 MA, B_T = 0.5 T, P_b = 6 MW) with a "baseline-142301D48" NSTX-U scenario with all 6 NB sources (red curve: I_p = 1 MA, B_T = 1 T, P_b = 12 MW). The shaded bar depicts the flux threshold for quality NPA measurements above the background noise.

6.5 Summary of other facility capabilities, including plasma control

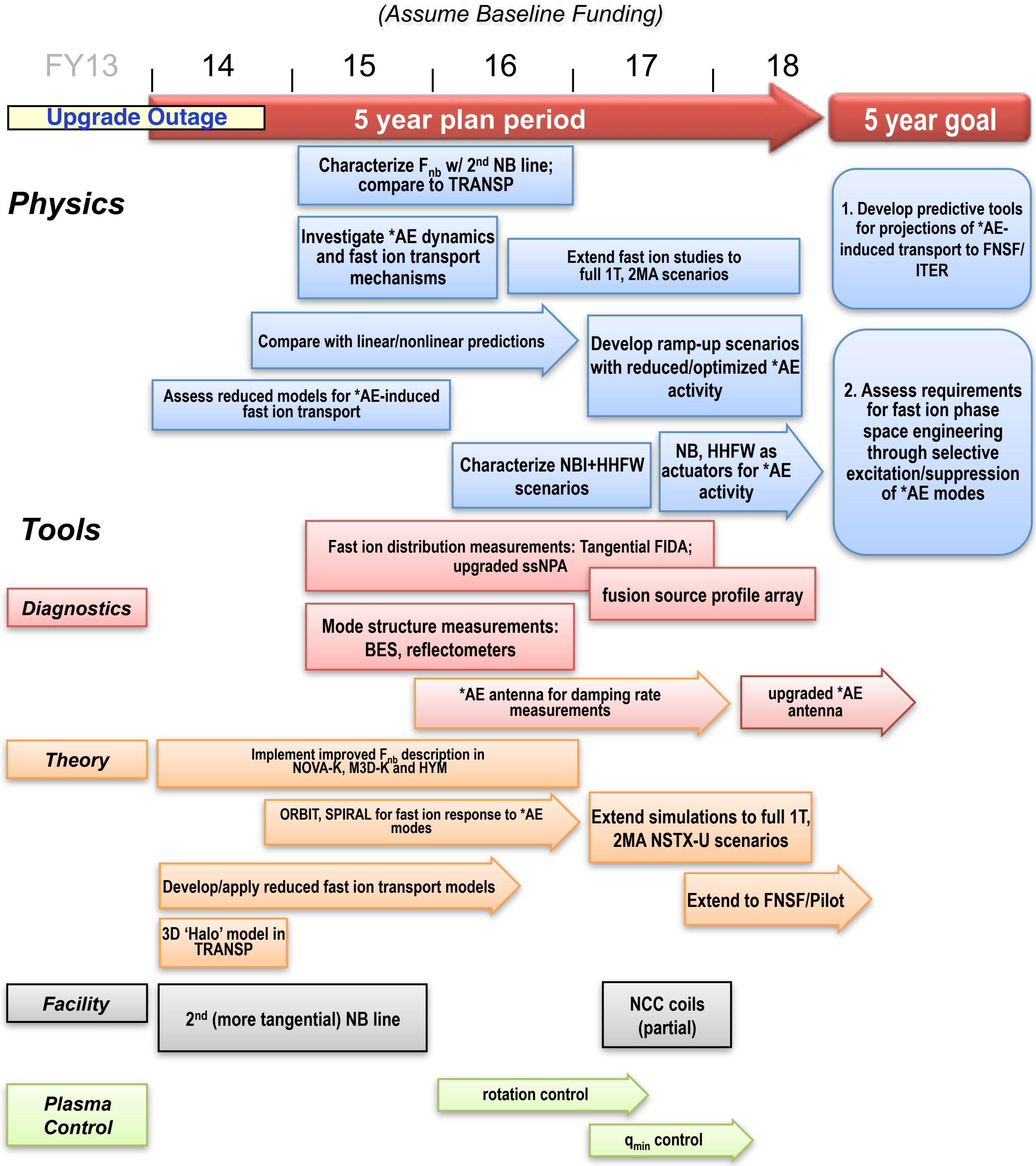
The Energetic Particle Research plans on NSTX-U will greatly benefit from the improved device capabilities enabled by the second NB line and by the new center-stack. The expanded range of some of the EP-relevant plasma parameters with respect to NSTX has already been discussed in the Introduction of this Chapter, cf. Fig. 6.1.1. In addition, the second NB line will provide enhanced flexibility in terms of NB injection parameters. Although injection energy and flux of the accelerated neutrals from each source will be essentially the same as on NSTX, the different tangency radii of the new sources will translate in an improved capability of manipulating the fast ion distribution and investigate its effects on *AE stability and associated fast ion transport.

The enhancements of both external and internal coils to induced magnetic perturbation will enable studies of fast ion and *AE response to 3D fields, which is an active area of research for ITER and future devices.

The planned improvements to the NSTX-U Plasma Control System also represent an opportunity to target specific issues of *AE physics. For instance, rotation and rotation profile control is essential for an extensive study of rotation effects on the structure of the Alfvén gaps and the resulting *AE stability. Similarly, a better control of the evolution of the safety factor and of the density (keeping other plasma parameters constant) will translate in detailed single-parameter scans that enable (and simplify) the thorough comparison between experiment and theory.

The importance of a dedicated *AE antenna system for EP research on NSTX-U has been already discussed in detail in the previous Sections and is not further discussed here.

6.6 Energetic Particle Research Timeline



(Assume Baseline Funding)

FY13 | 14 | 15 | 16 | 17 | 18

Upgrade Outage

5 year plan period

5 year goal

Physics

Characterize F_{nb} w/ 2nd NB line; compare to TRANSP

Investigate *AE dynamics and fast ion transport mechanisms

Extend fast ion studies to full 1T, 2MA scenarios

Compare with linear/nonlinear predictions

Develop ramp-up scenarios with reduced/optimized *AE activity

Assess reduced models for *AE-induced fast ion transport

Characterize NBI+HHFW scenarios

NB, HHFW as actuators for *AE activity

1. Develop predictive tools for projections of *AE-induced transport to FNSF/ ITER

2. Assess requirements for fast ion phase space engineering through selective excitation/suppression of *AE modes

Tools

Diagnostics

Fast ion distribution measurements: Tangential FIDA; upgraded ssNPA

fusion source profile array

Mode structure measurements: BES, reflectometers

*AE antenna for damping rate measurements

upgraded *AE antenna

Theory

Implement improved F_{nb} description in NOVA-K, M3D-K and HYM

ORBIT, SPIRAL for fast ion response to *AE modes

Extend simulations to full 1T, 2MA NSTX-U scenarios

Develop/apply reduced fast ion transport models

Extend to FNSF/Pilot

3D 'Halo' model in TRANSP

Facility

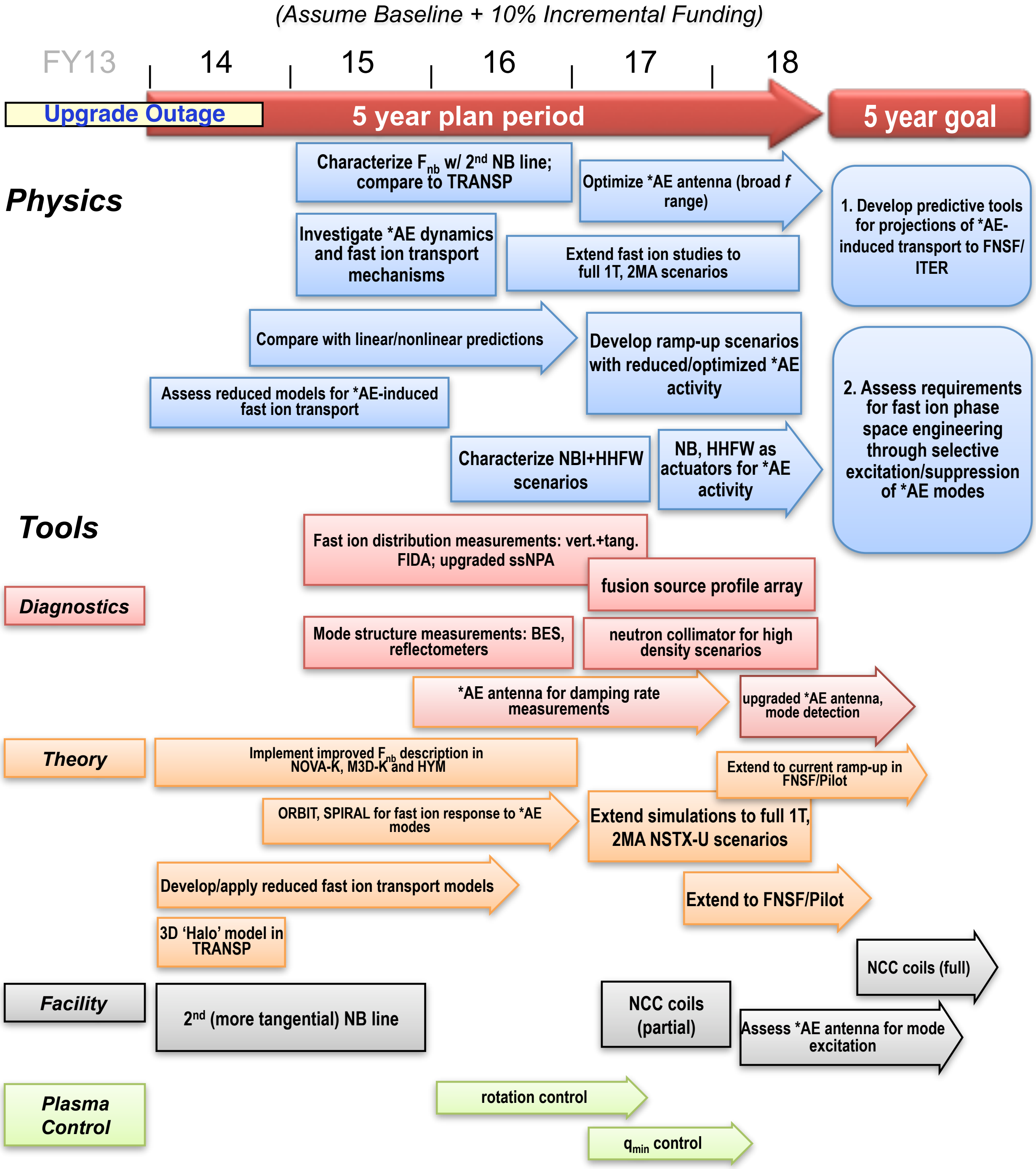
2nd (more tangential) NB line

NCC coils (partial)

Plasma Control

rotation control

q_{min} control



(Assume Baseline + 10% Incremental Funding)

FY13 14 15 16 17 18

Upgrade Outage

5 year plan period

5 year goal

Physics

Characterize F_{nb} w/ 2nd NB line; compare to TRANSP

Optimize *AE antenna (broad *f* range)

Investigate *AE dynamics and fast ion transport mechanisms

Extend fast ion studies to full 1T, 2MA scenarios

1. Develop predictive tools for projections of *AE-induced transport to FNSF/ ITER

Compare with linear/nonlinear predictions

Develop ramp-up scenarios with reduced/optimized *AE activity

Assess reduced models for *AE-induced fast ion transport

Characterize NBI+HHFW scenarios

NB, HHFW as actuators for *AE activity

2. Assess requirements for fast ion phase space engineering through selective excitation/suppression of *AE modes

Tools

Diagnostics

Fast ion distribution measurements: vert.+tang. FIDA; upgraded ssNPA

fusion source profile array

Mode structure measurements: BES, reflectometers

neutron collimator for high density scenarios

*AE antenna for damping rate measurements

upgraded *AE antenna, mode detection

Theory

Implement improved F_{nb} description in NOVA-K, M3D-K and HYM

Extend to current ramp-up in FNSF/Pilot

ORBIT, SPIRAL for fast ion response to *AE modes

Extend simulations to full 1T, 2MA NSTX-U scenarios

Develop/apply reduced fast ion transport models

Extend to FNSF/Pilot

3D 'Halo' model in TRANSP

Facility

2nd (more tangential) NB line

NCC coils (partial)

NCC coils (full)

Assess *AE antenna for mode excitation

Plasma Control

rotation control

q_{min} control

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