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1. Overview of the NSTX Upgrade Research Plan for 2014-2018

- 1.1. Introduction
- 1.2. Mission elements of the NSTX-U research program (Menard)
    - 1.2.1. Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
    - 1.2.2. Develop solutions for plasma-material interface
    - 1.2.3. Advance toroidal confinement physics predictive capability for ITER and beyond
    - 1.2.4. Develop ST as fusion energy system
- 1.3. Unique Parameter Regimes Accessed by NSTX and NSTX-U (Menard + TSGs)
    - 1.3.1. Macroscopic Stability (Park)
    - 1.3.2. Transport and Turbulence (Ren)
    - 1.3.3. Boundary Physics
        - 1.3.3.1. H-mode ped. formation (LH), transport, stability (Kaye, Diallo, Maingi)
        - 1.3.3.2. SOL physics (Zweben)
        - 1.3.3.3. Divertor physics (Soukhanovskii)
        - 1.3.3.4. Particle control
    - 1.3.4. Plasma Material Interactions and Plasma Facing Components
        - 1.3.4.1. Lithium-based plasma facing component R&D (Jaworski, Skinner)
        - 1.3.4.2. High-Z PFC R&D (Jaworski, Maingi, Soukhanovskii)
    - 1.3.5. Energetic Particles (**Podestà, Fredrickson, Gorelenkov**)
        - 1.3.5.1. *AE instability drive
        - 1.3.5.2. Fast ion response to *AE
        - 1.3.5.3. Importance of *AE to NBI and combined NBI/HHFW
    - 1.3.6. Wave heating and current drive (Taylor, Phillips)
        - 1.3.6.1. High-harmonic fast wave
        - 1.3.6.2. ECH/EBW
    - 1.3.7. Plasma formation and current ramp-up (Raman, Mueller)
    - 1.3.8. Plasma sustainment, advance scenarios and Control (Gerhardt)
- 1.4. Contributions to tokamak physics and ITER (Kaye)
    - 1.4.1. ITPA – physics basis for ITER
    - 1.4.2. Contributions to ITER Design and Operation
- 1.5. Fusion Energy Science Applications of the ST (Menard, Ono)
    - 1.5.1. Development and prototyping of advanced divertor and first-wall solutions
    - 1.5.2. ST-based Fusion Nuclear Science Facility / Component Test Facility
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- 1.6. Gaps Between Present and Future STs (Menard)
- 1.7. Summary of Research Goals and Opportunities in NSTX-U (Menard + TSGs)
    - 1.7.1. Overview
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    - 1.7.6. Energetic Particles
    - 1.7.7. Wave heating and current drive
    - 1.7.8. Plasma formation and current ramp-up
    - 1.7.9. Plasma sustainment, advanced scenarios and control
- 1.8. NSTX-U Long-term Goals (Years 5-10) (Menard, Ono, Kaye)
- 1.9. NSTX-U Scientific Organizational Structure (Menard, Kaye)

6. Research Goals and Plans for Energetic Particles

6.1. Overview of goals and plans **[Podestà, Gorelenkov]**

- 6.1.1. Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER

- 6.1.2. Assess requirements for fast-ion phase-space engineering techniques through selective excitation/suppression of *AE modes
  - 6.1.2.1. Investigate *AE dynamics and associated fast ion transport mechanisms
    - 6.1.2.1.1. Compare experimental results with theory & numerical codes
  - 6.1.2.2. Develop physics-based models for *AE-induced fast ion transport, e.g.:
    - 6.1.2.2.1. Stochastic transport models
    - 6.1.2.2.2. Quasi-linear models
  - 6.1.2.3. Assess modifications of *AE dynamics using NB, HHFW and active *AE antenna as actuators

6.2. Research Plans

- 6.2.1. **Year 1:**
  - 6.2.1.1. Compare (classical) TRANSP predictions with FIDA for 2nd NB line
  - 6.2.1.2. Measure fast-ion transport with tangential FIDA
  - 6.2.1.3. Measure *AE eigenfunctions with BES and reflectometers **[Crocker]**
  - 6.2.1.4. Compare eigenfunctions to predictions performed in FY12-14 **[Crocker]**
  - 6.2.1.5. Test prototype *AE antenna **[Fredrickson]**

- 6.2.2. **Year 2:**
  - 6.2.2.1. Characterize *AE activity driven by more tangential 2nd NBI
  - 6.2.2.2. Compare to existing (more perpendicular) NBI
  - 6.2.2.3. Use tangential+perpendicular FIDA, NPA/ssNPA to characterize distribution function modifications induced by *AE modes
  - 6.2.2.4. Improve NPA analysis tools in TRANSP to include ‘halo’ density
  - 6.2.2.5. Extend simulations to operations with full 1T magnetic field
  - 6.2.2.6. Compare measured *AE damping rates with models & theory **[Fredrickson]**
  - 6.2.2.7. Characterize scenarios with combined NBI+HHFW (see Wave Heating and CD plans, Sec. 6.2.1.1) **[Taylor, Podestà, Heidbrink]**

- 6.2.3. **Year 3:**
  - 6.2.3.1. Extend study of *AE activity driven by different NBI configurations to full 1T, 2MA scenarios
    - 6.2.3.1.1. Extend to non-linear physics and multi-mode physics (coupling between different classes of MHD modes: TAE+kinks, CAE/GAE+TAE, CAE/GAE+kinks)
  - 6.2.3.2. Compare numerical and theoretical simulations to data on mode dynamics, mode-induced fast ion transport
  - 6.2.3.3. Optimize *AE antenna design for efficient coupling to *AE modes **[Fredrickson]**

6.2.3.4. Consider replacing 2 HHFW antenna straps with optimized *AE antenna (with Heating and CD group) **[Taylor, Fredrickson, Podestà]**
6.2.3.5. Extend simulations of *AE-induced fast ion transport to FNSF/Pilot

6.2.4. **Year 4:**
6.2.4.1. Utilize *AE predictive capability to optimize/minimize *AE activity during non-inductive current ramp-up with 2nd NBI
6.2.4.2. Compare simulations to experimental results
6.2.4.3. Assess performance of upgraded *AE antenna **[Fredrickson]**
6.2.4.4. Measure stability of high-*f* *AEs; assess capability of mode excitation **[Fredrickson]**

6.2.5. **Year 5:**
6.2.5.1. Assess requirements for "fast-ion phase-space engineering" techniques through selective excitation of *AE modes **[Podestà, Gorelenkov, Fredrickson]**
6.2.5.2. Actuators: NBs, HHFW, active *AE antenna
6.2.5.3. Extend simulations of *AE-induced fast ion transport to FNSF/Pilot current ramp-up phase
6.2.5.4. Assess implications for FNSF/Pilot design (eg: optimum NBI geometry), expected NB-CD

6.3. Summary timeline for tool development to achieve research goals

6.3.1. Theory and simulation capabilities

6.3.1.1. ORBIT - gyro-center particle following **[Podestà, White]**
6.3.1.1.1. Stochastic transport by TAEs

6.3.1.2. SPIRAL - full-orbit particle following **[Kramer]**
6.3.1.2.1. Fnb response to kinks, CAE/GAE, TAE modes
6.3.1.2.2. Compare with gyro-center simulations w/ ORBIT

6.3.1.3. NOVA, PEST – ideal MHD **[Gorelenkov]**
6.3.1.3.1. (Ideal) mode eigenfunctions
6.3.1.3.2. Linear stability/damping rates

6.3.1.4. HYM – non-linear, hybrid/MHD **[Belova]**

6.3.1.4.1. Research goals:
6.3.1.4.1.1. Study excitation of GAE and CAE modes, and their effects on particle confinement **[Belova]**
6.3.1.4.1.2. Detailed comparison with experimental results **[Kramer, Fredrickson, Crocker, Medley]**

6.3.1.4.2. Plans:
6.3.1.4.2.1. Study the effects of the sub-cyclotron modes on fast ion distribution function in NSTX/NSTX-U **[Belova]**

6.3.1.4.2.2. Study the effects of finite frequency (Hall term) on the stability properties of the NBI-driven sub-cyclotron frequency modes **[Belova]**
6.3.1.4.2.3. Effects of GAE modes on the electron transport **[Gorelenkov, Belova]**
6.3.1.4.2.4. Add sources and sinks in the HYM numerical model **[Belova]**
6.3.1.4.2.5. Perform long time scale nonlinear numerical simulations to study the nonlinear evolution of unstable modes **[Belova]**

6.3.1.5. M3D-K – non-linear, self-consistent **[Fu]**
  6.3.1.5.1. Add realistic model of Fnb (from NUBEAM/TRANSP)
  6.3.1.5.2. Full mode dynamics, fast ion transport

6.3.1.6. Quasi-linear models **[Gorelenkov]**
  6.3.1.6.1. Fnb response to given set of modes; testing on DIII-D, then NSTX-U

6.3.1.7. Reduced models to be included in NUBEAM/TRANSP **[Podestà, White]**
  6.3.1.7.1. Fnb response to given set of modes; testing with NSTX data, then explore possibility of using the model in ‘predictive’ mode with *AEs from NOVA-K

6.3.1.8. FIDASIM + Fnb evolving codes (long term: NUBEAM) **[Heidbrink]**
  6.3.1.8.1. Infer Fnb from set of data (FIDA, NPA, neutrons, …)

6.3.2. Diagnostics

6.3.2.1. Diagnostics under development during NSTX-U Outage period:
  6.3.2.1.1. Tangential FIDA – complement existing systems
  6.3.2.1.2. Fusion source profile via charged D-D fusion products – test on MAST in FY13 **[Darrow]**
  6.3.2.1.3. Fixed sightline E//B NPA – must be re-located **[Medley]**
  6.3.2.1.4. Upgraded ssNPA **[Liu, Heidbrink]**
  6.3.2.1.5. *AE antenna for stability measurements, excitation of *AE mdoes **[Fredrickson]**

6.3.2.2. New/upgraded diagnostics **[Podestà with input from diagnosticians]**
  6.3.2.2.1. BES expansion & increased resolution
  6.3.2.2.2. Neutron collimator
  6.3.2.2.3. Profile reflectometry with increased frequency range
  6.3.2.2.4. FIDA & BES Imaging
  6.3.2.2.5. Radial polarimetry, currently testing on DIII-D
  6.3.2.2.6. Toroidally-displaced in-vessel multi-energy DXR arrays
  6.3.2.2.7. Dual-energy, ultra-fast SXR arrays
  6.3.2.2.8. VB imaging of *AE modes
  6.3.2.2.9. BES passive FIDA view

- 6.3.3. Other facility capabilities including plasma control
  - 6.3.3.1. 2nd more tangential NBI to modify fast-ion distribution function
  - 6.3.3.2. *AE antenna to study stability of (possibly drive) high-f CAE/GAEs, TAE
    - 6.3.3.2.1. Goal: direct measurements of damping rate of stable *AE modes
    - 6.3.3.2.2. Target high-f modes
      - 6.3.3.2.2.1. NSTX-U will have unique capabilities for CAE/GAE studies
      - 6.3.3.2.2.2. Complement JET, MAST data for TAEs
    - 6.3.3.2.3. With upgrades, assess requirements for “phase space engineering” – e.g.: assess capability of driving modes, compare to other actuators such as NBI, HHFW