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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. Transport and Turbulence (Ren)
  - 1.3.2. Macroscopic Stability (Park)
  - 1.3.3. Boundary Physics
    - 1.3.3.1. Pedestal Physics (Diallo, Maingi)
    - 1.3.3.2. SOL physics (Zweben)
    - 1.3.3.3. Divertor physics (Soukhanovskii)
    - 1.3.3.4. High-Z PFC R&D (Maingi, Soukhanovskii)
    - 1.3.3.5. Lithium-based plasma facing component R&D (Jaworski, Skinner)
  - 1.3.4. Energetic Particles (Podesta, Fredrickson, Gorelenkov)
    - 1.3.4.1. *AE instability drive
    - 1.3.4.2. Importance of *AE to NBI
  - 1.3.5. Wave heating and current drive (Taylor, Phillips)
    - 1.3.5.1. High-harmonic fast wave
    - 1.3.5.2. ECH/EBW
  - 1.3.6. Plasma formation and current ramp-up (Raman, Mueller)
  - 1.3.7. 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
  - 1.5.3. ST-based Pilot Plant
- 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
  - 1.7.2. Transport and Turbulence
  - 1.7.3. Macroscopic Stability
  - 1.7.4. Boundary Physics
  - 1.7.5. Energetic Particles
  - 1.7.6. Wave heating and current drive
  - 1.7.7. Plasma formation and current ramp-up
  - 1.7.8. 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)

2. Research Goals and Plans for Transport and Turbulence

2.1. Overview of goals and plans

2.1.1. Establish predictive capability for the performance of FNSF and ITER

2.1.2. Thrust 1: Identify instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport

2.1.2.1. Low-k turbulence : ITG/KBM, TEM, microtearing
2.1.2.2. High-k turbulence: ETG
2.1.2.3. Alfvenic eigenmodes

2.1.3. Thrust 2: Establish and validate reduced transport models (0D and 1D)

2.2. Research plans

2.2.1. Measure instabilities responsible for anomalous electron thermal, momentum and particle/impurity transport (Thrust 1)

Near-Term Research Goals: Years 1-2 of NSTX-U operation

2.2.1.1. Focus on low-k and take preliminary high-k measurements (BES, high-k scattering, polarimetry and reflectometry)
2.2.1.2. Differentiate/control turbulence (higher B_T and I_p, 2nd NB and 3D coils)
2.2.1.3. Determine if chi_i is still near neo-classical level in lower n* H-mode plasmas
2.2.1.4. Correlate transport channels with low/high k turbulence
2.2.1.5. Compare with gyro-kinetic/neo-classical calculations
2.2.1.6. Calibrate BES/reflectometry for *AE mode structure with a range of B_T, I_p, ν^* and NB power
2.2.1.7. Measure same in L-mode (ITG/TEM dominant) and ITB plasmas

Long-Term Research Goals: Years 3-5 of NSTX-U operation

2.2.1.8. Identify responsible k ranges for different transport channels in H-mode plasmas by correlating measured local transport trends (against n_e, I_p, B_T, γ_E, s, q, …) with low/high-k and *AE measurements and theoretical predictions
2.2.1.9. Identify key local transport dependences on plasma parameters to identify/develop the most appropriate transport models for NSTX-U
2.2.1.10. Identify ETG and microtearing modes and their operational regimes using the high-k_θ scattering system, BES and polarimetry measurements
2.2.1.11. Identify instabilities responsible for particle/impurity, momentum transport
2.2.1.12. Use steady state transport analysis and perturbative techniques

2.2.2. Establish & validate 0D scaling and start 1D modeling (Thrust 2)

Near-Term Research Goals: Years 1-2 of NSTX-U operation

2.2.2.1. Establish/Validate 0D confinement scalings with higher B_T, I_p and lower ν^* and project 0D performance of FNSF/Pilot
2.2.2.2. Start applying existing reduced transport models (TGLF, GLF23, etc) to NSTX-U parameters, coupled with linear/nonlinear gyrokinetic calculations

Long-Term Research Goals: Years 3-5 of NSTX-U operation

2.2.2.3. Validate 0D confinement scalings with full range of Bt, Ip and n* and use it to project 0D performance of FNSF/Pilot
2.2.2.4. Reduced transport models for micro-turbulence/*AE against first-principle models in improved NSTX-U parameter regimes
2.2.2.5. Apply predictive transport simulations for NSTX/NSTX-U/MAST

2.3. Summary timeline for tool development to achieve research goals

2.3.1. Theory and simulation capabilities (both existing capabilities to be utilized and new capabilities to be developed)
2.3.1.1. GYRO
2.3.1.2. GS2
2.3.1.3. NCLASS
2.3.1.4. Etc

2.3.2. Diagnostics
2.3.2.1. New FIR high-k_θ scattering system
2.3.2.2. Polarimetry system
2.3.2.3. Additional BES channels
2.3.2.4. PCI?
2.3.2.5. In-vessel multi-energy SXR (ME-SXR) arrays

2.3.3. Other facility capabilities including plasma control
2.3.3.1. 2nd NB for q and flow profile control
2.3.3.2. Repetitive laser blow-off impurity injection system
2.3.3.3. NCC for 3D field rotation profile control

3. Research Goals and Plans for Macroscopic Stability

3.1. Overview of goals and plans

3.1.1. Establish predictive capability for the performance of FNSF and ITER

3.1.2. Thrusts and goals by topical area (need more definitive thrusts…)

- 3.1.2.1. Beta and profile control support, expected impact on stability
- 3.1.2.2. Error field identification and control
- 3.1.2.3. RWM – passive stability and active control
- 3.1.2.4. NTV: 3D field effects on equilibrium, transport, turbulence, etc
- 3.1.2.5. Disruption physics, detection, and mitigation

3.2. Research Plans (**perhaps the plans should be organized by topic as in 3.1.2 above?**)

Year 1 of NSTX-U operation
3.2.1. Recover and explore NSTX MS control capabilities
3.2.2. Identify n=1,2,3 error fields and optimize corrections with new SPAs
3.2.3. Assess the βN or q limit with new shaping control and off-axis NBCD
3.2.4. Recover and upgrade RWM BP+Br and state space control with SPAs, including n>1 and multi-mode control
3.2.5. Revisit disruptivity and study halo current dynamics and heat loads on divertor
3.2.6. Apply MGI mitigation and explore dependency on injection locations*

Year 2 of NSTX-U operation
3.2.7. Explore NTV physics with new NBIs and SPAs
3.2.8. Begin implementation of rotation control with new NBIs and SPAs
3.2.9. Validate RWM physics in reduced ν* and varied fast ion populations
3.2.10. Utilize off-axis NBCD to vary q-profile and applies to RWMs and tearing modes
3.2.11. Identify disruption characteristics in various scenarios obtained by off-axis NBCD
3.2.12. Test and optimize MGI techniques by varying positions and actuators

Year 3 NSTX-U operation:
3.2.13. Optimize rotation feedback control for improving RWM and TM stability
3.2.14. Assess and optimize tradeoffs between q, rotation, β to improve stability
3.2.15. Explore the lowest ν* regimes and optimize RWM and TM stability
3.2.16. Explore disruption precursors and avoidance scenarios with various MHD origins
3.2.17. Explore MGI triggering for real-time actuation for disruption mitigation

Year 4 NSTX-U operation:
3.2.18. Combine rotation and β feedback control to maximize performance
3.2.19. Provide FNSF/Pilot projection on RWM and TM stability and disruption
3.2.20. Couple MGI triggering techniques to mitigate disruptions

Year 5 NSTX-U operation:

- 3.2.21. First use of NCC (if resources permitting)
- 3.2.22. Integrate MS control to avoid RWM, TM, ELM instability, disruption, with disruption mitigation protection
- 3.2.23. Integrate validation of models for FSNF/Pilot

3.3. Summary timeline for tool development to achieve research goals

- 3.3.1. Theory and simulation capabilities (both existing capabilities to be utilized and new capabilities to be developed)
  - 3.3.1.1. VALEN
  - 3.3.1.2. IPEC
  - 3.3.1.3. Etc, etc…
- 3.3.2. Diagnostics
  - 3.3.2.1. Real-Time Velocity measurement for successful implementation of rotation control, and disruption detection
  - 3.3.2.2. Toroidally displaced multi-energy SXR to study 3D physics including island dynamics, and RWM eigenfunctions
  - 3.3.2.3. Core X-ray imaging spectrometer to study rotation effects on error field and early MHD without NBIs
  - 3.3.2.4. Internal magnetic fluctuation measurement for island structures
  - 3.3.2.5. Real time MSE and MPTS for fast and precise kinetic equilibrium reconstruction
  - 3.3.2.6. Magnetic sensors including BP and BR sensors will be refurbished and upgraded
- 3.3.3. Other facility capabilities including plasma control
  - 3.3.3.1. Non-axisymmetric Control Coil (NCC) to achieve:
    - 3.3.3.1.1. Rotation control, and thereby RWM kinetic stabilization, error field correction, tearing mode stabilization
    - 3.3.3.1.2. RWM active control for significant multi-mode spectrum
    - 3.3.3.1.3. ELM control and stabilization
    - 3.3.3.1.4. Prediction for ITER 3D coil capabilities
    - 3.3.3.1.5. Simultaneous control for rotation, RWM, error field, TM, ELM
    - 3.3.3.1.6. IPEC, NTV, VALEN-3D, RWMSC codes will be actively used for 3D physics studies with NCCs

4. Research Goals and Plans for Boundary Physics

4.1. Overview of goals and plans

4.1.1. Establish predictive capability for the performance of FNSF and ITER

4.1.2. Thrusts and goals by topical area

4.1.2.1. Pedestal Physics
4.1.2.2. Edge and SOL physics
4.1.2.3. Divertor research
4.1.2.4. Liquid Metal PFC

4.2. Research Plans

4.2.1. Pedestal Transport and Stability

4.2.1.1. Re-establish reliable H-mode operation
4.2.1.2. Complete assessment of confinement, threshold trends wrt NSTX
4.2.1.3. Pedestal structure

Years 1-2
4.2.1.3.1. Dependence on Bt, Ip, shaping
4.2.1.3.2. Response to 3D magnetic field perturbations
4.2.1.3.3. ELM studies, ELM control development, pedestal transport
4.2.1.3.4. EPH-mode, I-mode development

Years 3-5
4.2.1.3.5. Utilize 3D fields to optimize pedestal transport and stability
4.2.1.3.6. Perform experiments, develop models enabling projections to FNSF
4.2.1.3.7. Assess and optimize pedestal structure and SOL parameters for advanced ST operation

4.2.2. Edge and SOL physics

4.2.2.1. Midplane and divertor turbulence
4.2.2.2. Zonal flows
4.2.2.3. L-H transition

4.2.3. Divertor research

Years 1-2
4.2.3.1. Heat flux width scaling, connection to SOL models
4.2.3.2. Snowflake divertor studies and control development
4.2.3.3. Radiative divertor with D2, Ne, Ar seeding
4.2.3.4. Impurity erosion and SOL transport studies
4.2.3.5. Experiments to support validation of cryo-pump designs

Years 3-5
4.2.3.6. Develop and validate divertor heat and particle control
4.2.3.7. Support projections of heat flux width and divertor scenarios to ST-FNSF
4.2.3.8. Utilize magnetic control for long-pulse snowflakes with reduced heat flux
4.2.3.9. Implement radiative divertor control
4.2.3.10. Assess Mo divertor PFCs and their impact on H-mode confinement

  4.2.3.10.1. Core Mo density and transport in baseline scenarios
  4.2.3.10.2. Assess effect of lithium coatings on molybdenum PFCs (synergistic study with EAST)
  4.2.3.10.3. Divertor Mo influx in baseline and impurity-seeded radiative divertor scenarios

4.2.4. Lithium-based plasma facing component R&D

4.2.4.1. Motivation: Liquid flow over tungsten/steel substrate may be unique way to eliminate net erosion and flaking to help protect substrate, etc

4.2.4.2. Liquid Metal PFC Research Strategy
  4.2.4.2.1. Demonstrate stability of the liquid metal (LM) surface (ie LLD)
    4.2.4.2.1.1. Design against ejection events and substrate exposure
    4.2.4.2.1.2. Near-term strategy: Emphasize capillary-restrained schemes

  4.2.4.2.2. Establish control over the in-vessel inventory of liquid metal
    4.2.4.2.2.1. Control evaporation and condensing surface locations and material collection
    4.2.4.2.2.2. Near-term strategy: Leverage existing active cooling technologies for thermal control while developing next-step schemes

  4.2.4.2.3. Develop adequate means of maintaining the liquid metal
    4.2.4.2.3.1. Perform efficient purification and establish robust operation and maintenance
    4.2.4.2.3.2. Near-term strategy: Learn from IFMIF EVEDA and develop robust, maintainable systems from day 1

  4.2.4.2.4. Understand plasma response and physics of LM-PFC
    4.2.4.2.4.1. Develop descriptive and prescriptive models for the SOL/PMI of LM-PFCs
    4.2.4.2.4.2. Near-term strategy: Validate fluid and kinetic codes and databases against available linear-machine data as well as tokamak database

Plan: Years 1-2:
4.2.4.3. Test Li evaporation for pumping longer pulse duration NSTX-U plasmas

- 4.2.4.4. Test Li evaporation to upper vessel by evaporator/injector, He diffusion, electrostatic sprayer
- 4.2.4.5. Assess impact of full wall Li coverage on pumping, confinement
- 4.2.4.6. Test ELM control by midplane Li granule injector
- 4.2.4.7. Test Li-PFC prototypes on Magnum PSI and possibly LTX or EAST
- 4.2.4.8. Down select to best flowing Li-PFC concepts
- 4.2.4.9. Test on Magnum PSI and LTX or EAST
  - 4.2.4.9.1. Li coating lifetime
  - 4.2.4.9.2. Hydrogenic recycling/retention as a function of exposure time & temperature
  - 4.2.4.9.3. Erosion, migration, impurity production with and without lithium
- 4.2.4.10. Surface analysis experiments using MAPP
- 4.2.4.11. Modeling support - Neoclassical Li-physics simulation with XGC0 + DEGAS2
  - 4.2.4.11.1. Self-consistent "kinetic" plasma modeling capability (successor to fluid plasma codes B2-EIRENE, UEDGE-DEGAS2, etc)
  - 4.2.4.11.2. Non-equilibrium Li radiation, non-Maxwellian electrons
  - 4.2.4.11.3. Include effect of Mo impurities, compared to C
  - 4.2.4.11.4. Effect of Li influx on pedestal and plasma behavior

Plan: Years 3-5:

- 4.2.4.12. Test flowing Li-PFC on at least one toroidal sector of NSTX-U, possibly full toroidal coverage system, pending lab-based tests and modeling

- 4.2.4.13. Modeling support - Neoclassical-turbulence Li simulation in XGC1 + DEGAS2
  - 4.2.4.13.1. Add self-consistent turbulence to the above
  - 4.2.4.13.2. Adapt the code geometry to Magnum-PSI for Li radiation simulation validation
  - 4.2.4.13.3. Study Li issues under 3D RMPs

4.3. Summary timeline for tool development to achieve research goals

4.3.1. Theory and simulation capabilities

- 4.3.1.1. SOLPS
- 4.3.1.2. UEDGE
- 4.3.1.3. XGC0, XGC1
- 4.3.1.4. DEGAS
- 4.3.1.5. NCLASS, MIST, STRAHL
- 4.3.1.6. ELITE, EPED
- 4.3.1.7. Atomistic MD modeling

4.3.2. Diagnostics

4.3.2.1. Re-establish NSTX existing pedestal and SOL/divertor diagnostics

4.3.2.2. High priority improvements for initial NSTX-U operation:
4.3.2.2.1. Pedestal and SOL fluctuation diagnostics (2D BES, 3D GPI)
4.3.2.2.2. Divertor Langmuir probes
4.3.2.2.3. Divertor bolometry
4.3.2.2.4. Upper divertor IR and visible cameras and spectroscopy
4.3.2.2.5. Inner divertor (lower and upper) IR and visible cameras and spectroscopy
4.3.2.2.6. MAPP probe
4.3.2.2.6.1. XPS, AES, TPD, SAM…

4.3.2.3. Longer term NSTX-U boundary diagnostics:
4.3.2.3.1. Molybdenum core, edge, divertor spectroscopy (VUV, visible)
4.3.2.3.2. Edge profile reflectometry
4.3.2.3.3. Full plasma radiation tomography
4.3.2.3.4. Edge neutral density measurements (LIF or LII)
4.3.2.3.5. Divertor Thomson Scattering system
4.3.2.3.6. SOL flow measurements
4.3.2.3.7. SOL and divertor ion energy or temperature
4.3.2.3.8. SOL current sensors

4.3.3. Other facility capabilities including plasma control

4.3.3.1. Wall condition/material, PMI control
4.3.3.1.1. Transition to full metal coverage for FNSF-relevant PMI development
4.3.3.1.2. Wall conditioning: GDC, Li and / or boron coatings
4.3.3.1.3. PFC bake-out at 300-350C
4.3.3.1.4. PCS control of divertor coils for X and strike-point control

4.3.3.2. Non-axisymmetric control coils

4.3.3.3. Fueling tools
4.3.3.3.1. Near-term: NBI and edge gas injection (including SGI) with PCS feedback control
4.3.3.3.2. Divertor impurity gas seeding
4.3.3.3.3. Longer term: pellet, molecular cluster, compact toroid injectors

4.3.3.4. Lithium PFC supporting technology
4.3.3.4.1. Possible upgrades of existing Lithium evaporator (LiTER)
4.3.3.4.2. Midplane Li granule injector for ELM control, Li delivery
4.3.3.4.3. Upward Li evaporator
4.3.3.4.4. Mo upper and lower divertor tiles
4.3.3.4.5. Lab-based R&D

4.3.3.4.5.1. Laboratory studies of D uptake as a function of Li dose, C/Mo substrate, surface oxidation, wetting…
4.3.3.4.5.2. Tests of prototype of scalable flowing liquid lithium system (FliLi) at PPPL and on HT7 and/or EAST
4.3.3.4.5.3. Basic liquid lithium flow loop on textured surfaces
4.3.3.4.5.4. Analysis and design of actively-cooled PFCs with Li flows due to capillary action and thermoelectric MHD
4.3.3.4.5.5. Magnum-PSI tests and supporting hardware

5. Research Goals and Plans for Energetic Particles

5.1. Overview of goals and plans

5.1.1. Establish predictive capability for the performance of FNSF and ITER

5.1.2. Thrusts and goals by topical area

5.1.2.1. Investigate fast ion transport mechanisms, compare experimental results with theory & numerical codes

5.1.2.2. Develop physics-based fast ion transport models, eg:
  - 5.1.2.2.1. Stochastic transport models
  - 5.1.2.2.2. Quasi-linear models
  - 5.1.2.2.3. Develop models for *AE mode-induced fast-ion transport
  - 5.1.2.2.4. Assess requirements for fast-ion phase-space engineering techniques through selective excitation of *AE modes

5.2. Research Plans

5.2.1. **Year 1:**

- 5.2.1.1. Compare (classical) TRANSP predictions with FIDA for 2nd NB line
- 5.2.1.2. Measure fast-ion transport with tangential FIDA
- 5.2.1.3. Measure *AE eigenfunctions with BES and reflectometers
- 5.2.1.4. Compare eigenfunctions to predictions performed in FY12-14
- 5.2.1.5. Test prototype *AE antenna

5.2.2. **Year 2:**

- 5.2.2.1. Use tangential+perpendicular FIDA, NPA/ssNPA to characterize distribution function modifications induced by *AE modes
- 5.2.2.2. Characterize *AE activity driven by more tangential 2nd NBI
- 5.2.2.3. Compare to existing (more perpendicular) NBI
- 5.2.2.4. Extend simulations to operations with full 1T magnetic field
- 5.2.2.5. Compare measured *AE damping rates with models & theory

5.2.3. **Year 3:**

- 5.2.3.1. Extend study of *AE activity driven by different NBI configurations to full 1T scenarios
- 5.2.3.2. Compare numerical and theoretical simulations to data on mode dynamics, transport
- 5.2.3.3. Characterize scenarios with combined NBI+HHFW
- 5.2.3.4. Optimize *AE antenna design for efficient coupling to *AE modes
- 5.2.3.5. May consider replacing 2 HHFW antenna straps with *AE antenna (w/ HHFW group)
- 5.2.3.6. Extend simulations of *AE avalanches to FNSF/Pilot

5.2.4. **Year 4:**
- 5.2.4.1. Utilize *AE predictive capability to optimize/minimize *AE activity during non-inductive current ramp-up with 2nd NBI
- 5.2.4.2. Compare simulations to experimental results
- 5.2.4.3. Assess performance of upgraded AE antenna
- 5.2.4.4. Measure stability of high-*f* *AEs; assess capability of mode excitation

5.2.5. **Year 5:**
- 5.2.5.1. Assess requirements for "fast-ion phase-space engineering" techniques through selective excitation of *AE modes
- 5.2.5.2. Actuators: NBs, HHFW, active *AE antenna
- 5.2.5.3. Extend simulations of *AE avalanches to FNSF/Pilot current ramp-up phase
- 5.2.5.4. Assess implications for FNSF/Pilot design (eg: optimum NBI geometry), expected NB-CD

5.3. Summary timeline for tool development to achieve research goals

5.3.1. Theory and simulation capabilities

5.3.1.1. ORBIT - gyro-center particle following
- 5.3.1.1.1. Stochastic transport by TAEs

5.3.1.2. SPIRAL - full-orbit particle following
- 5.3.1.2.1. Fnb response to kinks, CAE/GAE modes
- 5.3.1.2.2. Starting w/ TAEs

5.3.1.3. NOVA, PEST – ideal MHD
- 5.3.1.3.1. (Ideal) mode eigenfunctions
- 5.3.1.3.2. Linear stability/damping rates

5.3.1.4. HYM – non-linear, hybrid/MHD

- 5.3.1.4.1. Research goals:
  - 5.3.1.4.1.1. Study excitation of GAE and CAE modes, and their effects on particle confinement
  - 5.3.1.4.1.2. Detailed comparison with experimental results

- 5.3.1.4.2. Plans:
  - 5.3.1.4.2.1. Study the effects of the sub-cyclotron modes on fast ion distribution function in NSTX
  - 5.3.1.4.2.2. Study the effects of finite frequency (Hall term) on the stability properties of the NBI-driven sub-cyclotron frequency modes
  - 5.3.1.4.2.3. Effects of GAE modes on the electron transport
  - 5.3.1.4.2.4. Add sources and sinks in the HYM numerical model

            - 5.3.1.4.2.5. Perform long time scale nonlinear numerical simulations to study the nonlinear evolution of unstable modes

    - 5.3.1.5. M3D-K – non-linear, self-consistent
        - 5.3.1.5.1. Full mode dynamics, transport

    - 5.3.1.6. Quasi-linear models
        - 5.3.1.6.1. Fnb response to given set of modes; testing on DIII-D, then NSTX-U

    - 5.3.1.7. FIDASIM + Fnb evolving codes (long term: NUBEAM)
        - 5.3.1.7.1. Infer Fnb from set of data (FIDA, NPA, neutrons, …)

- 5.3.2. Diagnostics

    - 5.3.2.1. Diagnostics under development during NSTX-U Outage period:
        - 5.3.2.1.1. Tangential FIDA – complement existing systems
        - 5.3.2.1.2. Fusion source profile via charged D-D fusion products – test on MAST
        - 5.3.2.1.3. Fixed sightline E//B NPA – must be re-located
        - 5.3.2.1.4. Upgraded ssNPA
        - 5.3.2.1.5. *AE antenna for stability measurements, excitation of *AE mdoes

    - 5.3.2.2. New/upgraded diagnostics
        - 5.3.2.2.1. BES expansion & increased resolution
        - 5.3.2.2.2. Neutron collimator
        - 5.3.2.2.3. Profile reflectometry with increased Df
        - 5.3.2.2.4. FIDA & BES Imaging
        - 5.3.2.2.5. Radial polarimetry
        - 5.3.2.2.6. Toroidally-displaced in-vessel multi-energy DXR arrays
        - 5.3.2.2.7. Dual-energy, ultra-fast SXR arrays
        - 5.3.2.2.8. VB imaging of AE* modes
        - 5.3.2.2.9. BES passive FIDA view

- 5.3.3. Other facility capabilities including plasma control

    - 5.3.3.1. 2nd more tangential NBI to modify fast-ion distribution function

    - 5.3.3.2. *AE antenna to study stability of (possibly drive) high-f CAE/GAEs, TAE
        - 5.3.3.2.1. Goal: direct measurements of damping rate of stable *AE modes
        - 5.3.3.2.2. Target high-f modes
            - 5.3.3.2.2.1. NSTX-U will have unique capabilities for CAE/GAE studies
            - 5.3.3.2.2.2. Complement JET, MAST data for TAEs
        - 5.3.3.2.3. With upgrades, assess requirements for “phase space engineering”

6. Research Goals and Plans for Wave heating and Current Drive

6.1. Overview of goals and plans

6.1.1. Establish predictive capability for the performance of FNSF and ITER

6.1.2. Thrusts and goals by topical area

- 6.1.2.1. Optimize HHFW current drive in HHFW and HHFW+NBI H-mode plasmas
  - 6.1.2.1.1. Mitigate HHFW power losses in scrape off layer (SOL) of H-mode plasmas
  - 6.1.2.1.2. Assess HHFW interaction with neutral beam fast-ions, and develop capability to heat NBI H-modes with HHFW
- 6.1.2.2. Develop HHFW heating for fully non-inductive plasma start-up and H-mode sustainment
- 6.1.2.3. Develop ECH/EBW heating for fully non-inductive plasma start-up
  - 6.1.2.3.1. Model ECH/EBWH for NSTX-U plasma scenarios
  - 6.1.2.3.2. Implement ECH/EBW system

6.2. Research Plans

6.2.1. **Years 1-2:**

- 6.2.1.1. Assess performance of 12-strap, double-feed antenna and compatibility with NBI H-modes:
  - 6.2.1.1.1. Use boronization & minimum lithium conditioning needed to control edge density, and reduce surface wave excitation and other edge power losses
  - 6.2.1.1.2. Will be conducted before significant lithium conditioning starts
  - 6.2.1.1.3. Compare coupling and heating efficiency to single-feed operation in 2008
  - 6.2.1.1.4. Assess HHFW coupling to high-NBI power H-modes at higher magnetic field and higher plasma density

- 6.2.1.2. Heat I_p ~ 300 kA plasma with HHFW power to achieve sustained 100% non-inductive (NI) H-mode, and non-inductively ramp I_p with HHFW power:
  - 6.2.1.2.1. 100% NI results important for supporting FNSF design → can be obtained one year earlier with incremental funding
  - 6.2.1.2.2. Use NBI blips for MSE q profile measurements, C density pump out
  - 6.2.1.2.3. Use MSE-LIF to measure q profile without needing heating NBI blips
  - 6.2.1.2.4. Similar 100% NI experiments are possible on EAST and DIII-D

- 6.2.1.3. RF group support of design of new antenna systems (*AE and/or EHO)

- 6.2.1.4. Support solenoid-free start-up by implementing 1MW 28 GHz ECH system
    - 6.2.1.4.1. Gyrotron originally developed in Japan for GAMMA 10; capable of 1-5 s pulses
    - 6.2.1.4.2. Fixed horn antenna & low-loss HE11 corrugated circular waveguide
    - 6.2.1.4.3. Locate gyrotron + associated equipment in former TFTR test cell
    - 6.2.1.4.4. Analysis for NSTX CHI start-up plasma predicts 25-30% single-pass absorption for 28 GHz 2nd harmonic X-mode → reflections will enhance absorption

6.2.2. **Years 3-5:**

- 6.2.2.1. Test high-power ECH system for plasma start-up - assess impact on closed-flux current achieved, discharge pulse-length, and non-inductive fraction
- 6.2.2.2. Utilize HHFW to assist start-up plasma formation and compare to ECH
- 6.2.2.3. Assess impact of HHFW electron heating on NBI current ramp-up
- 6.2.2.4. Simulate/mock-up HHFW antenna performance using a reduced # of straps
- 6.2.2.5. Implement EHO and/or *AE antenna
- 6.2.2.6. Modify HHFW antenna to have reduced number of straps
- 6.2.2.7. Test reduced-strap HHFW system and optimize plasma start-up, ramp-up, and sustainment during NBI H-mode
- 6.2.2.8. Test EHO antenna for impact on density/particle control
- 6.2.2.9. Test upgraded 28GHz system for EBW heating and current drive studies (1-2 MW, 1-5s)
- 6.2.2.10. Upgrade ECH system to O-X-B oblique launch EBWH system to metal steerable mirror, 5 s, 2 MW, located near midplane, outside vacuum vessel
- 6.2.2.11. Pending successful EBW heating results project EBW CD performance to a FNSF/CTF

6.3. Summary timeline for tool development to achieve research goals

6.3.1. Theory and simulation capabilities

- 6.3.1.1. AORSA-3D
- 6.3.1.2. AORSA/ORBIT-RF
- 6.3.1.3. TORIC
- 6.3.1.4. FOW CQL-3D
- 6.3.1.5. GENRAY for ECH/EBW
- 6.3.1.6. IPEC
- 6.3.1.7. PTRANSP

6.3.2. Diagnostics

- 6.3.2.1. Fast (2-color?) IR for SOL power losses
- 6.3.2.2. Measurements of SOL E-fields during edge power loss?
- 6.3.2.3. Anything for fast-ion distribution from HHFW FI acceleration?

- 6.3.3. Other facility capabilities including plasma control
  - 6.3.3.1. Implement compliant attachments between antenna current straps and RF feedthroughs to withstand 4x increase in disruption loads
  - 6.3.3.2. Allocate space for ECH/EBW and/or *AE or EHO antennas
    - 6.3.3.2.1. Consider using only 8 straps to free up space for other antenna(s)
    - 6.3.3.2.2. Tests of two elements on test stand
    - 6.3.3.2.3. Optimize voltage standoff in vacuum with aid of antenna modeling
  - 6.3.3.3. For compatibility with high NBI power, modify edge tiles of the NBI armor to extend into to R = 157 m to serve as the limiter for the HHFW antenna
  - 6.3.3.4. Add RF probes in protective tiles above and below antenna to document RF power flow to divertor for comparison to advanced RF codes
  - 6.3.3.5. Implement 1MW 28 GHz ECH system, later upgrade to 2MW
  - 6.3.3.6. Metal steerable mirror for 5s, 2 MW, near midplane, outside vessel

7. Research Goals and Plans for Plasma Formation and Current Ramp-up

7.1. Overview of goals and plans

7.1.1. Establish predictive capability for the performance of FNSF

7.1.2. Thrusts and goals by topical area

7.1.2.1. Demonstrate and understand solenoid-free current start-up

7.1.2.2. Use CHI and point helicity injection as initial current seed for subsequent non-inductive current ramp-up

7.2. Research Plans

7.2.1. **Years 1-2:**

7.2.1.1. Re-establish initial transient CHI discharges

7.2.1.2. Use graphite divertor plates

7.2.1.3. Use full Li coverage to reduce low-Z impurities

7.2.1.4. Test benefits of upper metal divertor and Lithium during absorber arcs

7.2.1.5. Initially couple to induction, then assess coupling to NBI

7.2.1.6. 1 MW ECH coupling to NBI during Year 2

7.2.2. **Years 3-5:**

7.2.2.1. Establish discharges using metal divertor plate electrodes

7.2.2.2. Assess benefits and compare to QUEST results (if available)

7.2.2.3. Assess benefits of cryo pumping in the absorber region

7.2.2.4. Maximize current start-up

7.2.2.5. 1 MW ECH, then HHFW to increase Te to ~ 1keV for coupling to NBI

7.2.2.6. Test plasma gun start-up on NSTX-U

7.2.2.6.1. Collaboration with PEGASUS on point helicity injection

7.3. Summary timeline for tool development to achieve research goals

7.3.1. Theory and simulation capabilities

7.3.1.1. 2D resistive MHD simulations – TSC

7.3.1.2. 3D Resistive MHD simulations – NIMROD, M3D

7.3.1.3. GENRAY for ECH/EBW

7.3.1.4. PTRANSP for NBI coupling to low-Ip CHI plasma

7.3.2. Diagnostics

7.3.2.1. New additional fast voltage monitors for upper divertor

7.3.2.2. Additional dedicated current monitors near injector

7.3.2.3. Special set of EMI shielded inner vessel magnetics

7.3.2.4. Additional flux loops and Mirnov coils on lower and upper divertor

7.3.2.5. Langmuir probe array on lower divertor

7.3.2.6. Multipoint Thomson scattering, Filter scopes, multi chord bolometers and SXR arrays

7.3.3. Other facility capabilities including plasma control

7.3.3.1. 2^{nd} NBI for coupling to low-Ip CHI plasma

7.3.3.2. Baseline capacitor bank power supply
  7.3.3.2.1. Voltage increased to ~2 kV & improve voltage snubbing systems
  7.3.3.2.2. NSTX-U to support 4kV Ops including transients

7.3.3.3. Upgraded capacitor bank power supply
  7.3.3.3.1. Voltage increased to ~3 kV, bank energy increased to 200 kJ
  7.3.3.3.2. Additional modules for improved voltage control

7.3.3.4. 1MW → 2MW ECH for heating low-Ip CHI plasma

7.3.3.5. Point helicity sources/plasma guns

8. Research Goals and Plans for Plasma sustainment: Advanced Scenarios and Control

8.1. Overview of goals and plans

8.1.1. Establish predictive capability for the performance of FNSF and ITER

8.1.2. Thrusts and goals by topical area

- 8.1.2.1. Scenario development
- 8.1.2.2. Axisymmetric control development
- 8.1.2.3. Event handling
- 8.1.2.4. Scenario optimization for next step devices

8.2. Research Plans

8.2.1. **Thrust 1 – Scenario Development**

- 8.2.1.1. Pursue 100% Non-Inductive Current at Progressively Higher I_P and B_T
  - 8.2.1.1.1. Year 1: 075T, 600-800kA, few tau-E
  - 8.2.1.1.2. Year 2: 075-1T, 600-800kA, few tau-R
  - 8.2.1.1.3. Years 3-5: 1T, 800-1300kA, up to 4-5s
- 8.2.1.2. Develop Long-Pulse Partial Inductive Operation Up to 2 MA, High Power
  - 8.2.1.2.1. Two types of partial inductive operation:
    - 8.2.1.2.1.1. High-IP operation supports collisionality scaling and divertor heat flux studies
    - 8.2.1.2.1.2. Long pulse operation for particle retention and disruptivity reduction studies
  - 8.2.1.2.2. Years 1 & 2: Re-optimize startup for reduced fuelling at IP=1200-1500 kA
    - 8.2.1.2.2.1. Goal: Enhance utility of Li pumping by reducing the early gas load
  - 8.2.1.2.3. Years 3-5: Performance Extension
    - 8.2.1.2.3.1. Discharges up to 2 MA for 5 seconds
    - 8.2.1.2.3.2. Long pulse at ~1 MA for up to 10 seconds
  - 8.2.1.2.4. High-IP development is connected to progress on heat flux mitigation

8.2.2. **Thrust 2 – Axisymmetric Control Development**

- 8.2.2.1. Axisymmetric Divertor Control
  - 8.2.2.1.1. Years 1 & 2:
    - 8.2.2.1.1.1. Develop upper/lower snowflake control at higher current
    - 8.2.2.1.1.2. Assess schemes for dual X-point control w/ new divertor coils
    - 8.2.2.1.1.3. Assess magnetic balance control in the presence of 4 X-points
    - 8.2.2.1.1.4. Document heat flux reductions compared to standard DN
    - 8.2.2.1.1.5. Assess impact of limited Mo coverage on scenarios
  - 8.2.2.1.2. Years 3-5:

- 8.2.2.1.2.1. Utilize cryopump and divertor upgrades to control density in long pulse scenarios
- 8.2.2.1.2.2. Years 3-5: Pending progress in BP TSG, begin implementation of closed loop radiative divertor control

- 8.2.2.2. Current and Rotation Profile Control
  - 8.2.2.2.1. Years 1 & 2
    - 8.2.2.2.1.1. Test rotation control using NB 3D field torque
    - 8.2.2.2.1.2. Feed forward test ability of different beam combinations to modify the q-profile
    - 8.2.2.2.1.3. Install and commission rtMSE and implement as constraint in rtEFIT
  - 8.2.2.2.2. Years 2-4: Test current profile control
  - 8.2.2.2.3. Years 4-5:
    - 8.2.2.2.3.1. Utilize NCC coil for better NTV control
    - 8.2.2.2.3.2. Study feasibility of combined control

8.2.3. Thrust 3 - Disruption Avoidance and Off-Normal Event Handling

- 8.2.3.1. Years 1 & 2:
  - 8.2.3.1.1. Implement basic detector in PCS, and design architecture of control response
  - 8.2.3.1.2. Incorporate data from new “Digital Coil Protection System”
  - 8.2.3.1.3. Assess accuracy of predictor for NSTX-U disruptions, and refine as necessary
  - 8.2.3.1.4. Do initial tests of automated rampdowns
- 8.2.3.2. Years 3-5
  - 8.2.3.2.1. Add additional realtime diagnostics for improved detection fidelity
  - 8.2.3.2.2. Optimize rampdowns for different types of alarms
  - 8.2.3.2.3. Incorporate closed loop MGI if it appears promising

8.2.4. Thrust 4 - Explore Optimal Scenarios for Next Step STs

- 8.2.4.1. Study optimal profiles for high confinement and good stability
  - 8.2.4.1.1. Years 3-4: Optimization of the current profile for best confinement and core n=1 stability
  - 8.2.4.1.2. Years 3-5: Explore alternative optimal scenarios - EPH or w/ ITBs

- 8.2.4.2. Study the conditions for classical beam current drive
  - 8.2.4.2.1. Years 1-2: Study what parameters determine when *AE modes lead to anomalies in the fast ion diffusion and NBCD
  - 8.2.4.2.2. Years 3-5: Determine if anomalous diffusion be used for scenario optimization

- 8.2.4.3. Explore & validate integrated models for projections to FNSF
  - 8.2.4.3.1. Years 1-2: Compare NBCD & q-profile predictions from integrated codes to NSTX-U
  - 8.2.4.3.2. Years 3-5: Use knowledge to project scenarios to ST FNSF devices

8.3. Summary timeline for tool development to achieve research goals

8.3.1. Theory and simulation capabilities

- 8.3.1.1. TRANSP/pTRANSP/NCLASS
- 8.3.1.2. GTS
- 8.3.1.3. GTC-Neo
- 8.3.1.4. FIDASIM
- 8.3.1.5. Reduced thermal transport model?
- 8.3.1.6. Reduced fast-ion redistribution model?

8.3.2. Diagnostics

- 8.3.2.1. Real-time rotation
- 8.3.2.2. Real-time MSE
- 8.3.2.3. Real-time Thomson Scattering
- 8.3.2.4. Real-time neutron rate

8.3.3. Other facility capabilities including plasma control

- 8.3.3.1. 2nd NBI for current and rotation profile actuator
- 8.3.3.2. 2nd SPA for NTV rotation braking control
- 8.3.3.3. Divertor cryopumps for density control
- 8.3.3.4. NCC for NTV rotation braking control
- 8.3.3.5. EBW heating and current drive for J-profile control in advanced scenarios

9. NSTX-U Facility Status and Proposed Upgrades

- 9.1. Abstract
- 9.2. Facility Overview

    - 9.2.1. Facility Status and Plan
        - 9.2.1.1. New Center Stack Upgrade
        - 9.2.1.2. Second Neutral Beam Injection System Upgrade
        - 9.2.1.3. NSTX-U Facility Subsystems
            - 9.2.1.3.1. Other Heating and Current Drive Systems
                - 9.2.1.3.1.1. HHFW and upgrades Upgrades
                - 9.2.1.3.1.2. 1/2MW 28GHz ECH/EBW system
            - 9.2.1.3.2. Macro-stability Tools
                - 9.2.1.3.2.1. 2nd SPA
                - 9.2.1.3.2.2. NCC
            - 9.2.1.3.3. Boundary Physics Tools
                - 9.2.1.3.3.1. Divertor Cryo-pump
                - 9.2.1.3.3.2. High-Z metallic divertor
                - 9.2.1.3.3.3. High-Z outer and inner wall PFCs
                - 9.2.1.3.3.4. Upgraded lithium coating systems
                - 9.2.1.3.3.5. Flowing liquid lithium divertor/module
            - 9.2.1.3.4. Start-up and Ramp-up
                - 9.2.1.3.4.1. CHI upgrades
                - 9.2.1.3.4.2. Plasma guns

    - 9.2.2. NSTX-U Diagnostic System Status and Plans
        - 9.2.2.1. Profile Diagnostics
        - 9.2.2.2. Turbulence Diagnostics
        - 9.2.2.3. MHD Diagnostics
        - 9.2.2.4. Boundary Physics Diagnostics
        - 9.2.2.5. Energetic Particle Diagnostics
        - 9.2.2.6. Wave Diagnostics
        - 9.2.2.7. Start-up, ramp-up, and sustainment diagnostics

    - 9.2.3. Plasma Control System Upgrade Plans
        - *9.2.3.1. To be completed by Stefan, Egemen, Dave, Dennis based on requirements from other chapters + team prioritization*

- 9.3. NSTX-U Facility Utilization

10. NSTX-U Collaboration Research Plans