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2. Research Goals and Plans for Macroscopic Stability

2.1. Overview of goals and plans (Park)

2.1.1. Establish predictive capability for the sustained stability of high performance FNSF, ST Pilot, and ITER plasmas

2.1.2. Thrusts and goals by topical area

2.1.2.1. Understand and advance passive and active feedback control to sustain macroscopic stability

2.1.2.2. Understand 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields

2.1.2.3. Understand disruption dynamics and develop techniques on disruption detection, mitigation, and avoidance, in high-performance ST plasmas

2.2. Research Plans

2.2.1. **Thrust 1 – Understand and advance passive and active feedback control to sustain macroscopic stability (Berkery, Sabbagh, Park)**

2.2.1.1. Year 1 of NSTX-U operation

2.2.1.1.1. Recover and explore NSTX MS control capabilities on stability

2.2.1.1.2. Assess the β or q limit with new shaping control and off-axis NBCD

2.2.1.1.3. Recover and test upgraded RWM multi-component sensor and model-based state space control with independent actuator coils, including n>1 and multi-mode control

2.2.1.1.4. Study and attempt initial control of internal MHD modes during current ramp-up (Gerhardt)

2.2.1.2. Year 2 of NSTX-U operation

2.2.1.2.1. Validate RWM physics at reduced ν^* and varied fast ion populations

2.2.1.2.2. Utilize off-axis NBCD to vary V_ϕ and q-profile and investigate RWM/TM stability

2.2.1.2.3. Understand and control internal MHD mode physics for long pulse, high performance scenarios (Gerhardt)

2.2.1.3. Year 3 of NSTX-U operation

2.2.1.3.1. Utilize the rotation control to improve RWM/TM stability

2.2.1.3.2. Explore the lowest ν^* regimes and test RWM/TM stability

2.2.1.3.3. Assess and optimize tradeoffs between V_ϕ, q-profile, β to improve RWM/TM/internal MHD mode stability

2.2.1.4. Year 4 of NSTX-U operation

2.2.1.4.1. Utilize non-axisymmetric control coil (NCC) to control V_ϕ-profile and improve RWM/TM stability

2.2.1.4.2. Investigate the combination of V_ϕ-profile, β-feedback, and active mode control to improve RWM/TM/internal MHD mode stability and to sustain high performance plasmas
2.2.1.4.3. Extend the study of RWM multi-mode control with various NCC coil combinations
2.2.1.4.4. Provide FNSF/Pilot projection on macroscopic stability

2.2.2. Thrust 2 – Understand 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields (Park, Sabbagh, Berkery)

2.2.2.1. Year 1 of NSTX-U operation
2.2.2.1.1. Identify n > 1 intrinsic error fields and optimize correction using independent actuator coils
2.2.2.1.2. Explore upgraded 3D capabilities of active mode control and dynamic error field correction
2.2.2.1.3. Initiate NTV physics investigation with enhanced 3D field spectra and NBI torque profile

2.2.2.2. Year 2 of NSTX-U operation
2.2.2.2.1. Optimize and combine dynamic error field correction with intrinsic error field correction
2.2.2.2.2. Investigate NTV physics at increased pulse lengths and behavior at reduced ν^* regime
2.2.2.2.3. Investigate NTV physics vs. V_ϕ and q-profile with new NBIs and independent actuator coils

2.2.2.3. Year 3 of NSTX-U operation
2.2.2.3.1. Initiate the investigation of non-resonant vs. resonant error field effects
2.2.2.3.2. Study NTV physics in the lowest ν^* regimes
2.2.2.3.3. Optimize V_ϕ feedback control in regimes of high non-inductive fraction to improve RWM/TM stability
2.2.2.3.4. Utilize 3D field to assess and optimize tradeoffs between V_ϕ, q-profile, β to improve RWM/TM/internal MHD mode stability

2.2.2.4. Year 4 of NSTX-U operation
2.2.2.4.1. Utilize NCC and understand non-resonant and resonant error field effects vs. V_ϕ
2.2.2.4.2. Optimize 3D field with NCC in combined V_ϕ-profile, β-feedback, and active mode control to maximize performance
2.2.2.4.3. Examine FNSF/Pilot projections on 3D field physics understanding

2.2.3. Thrust 3 – Understand disruption dynamics and develop techniques on disruption detection, mitigation, and avoidance in high-performance ST

plasmas (Gerhardt, Raman, Park)

2.2.3.1. Year 1 of NSTX-U operation
- 2.2.3.1.1. Examine halo current loading on center column, and heat loading on divertor in disruption
- 2.2.3.1.2. Assess improved MHD spectroscopy and examine model-based observer for disruption detection and avoidance (Sabbagh)
- 2.2.3.1.3. Install MGI and conduct initial tests (Raman)
- 2.2.3.1.4. Study the feasibility of EPI and CT injector system (Raman)

2.2.3.2. Year 2 of NSTX-U operation
- 2.2.3.2.1. Expand shunt tile measurements of halo currents in divertor
- 2.2.3.2.2. Utilize model-based and also non-magnetic mode observers for disruption detection and avoidance (Sabbagh)
- 2.2.3.2.3. Identify disruption characteristics in various scenarios obtained by off-axis NBCD
- 2.2.3.2.4. Conduct MGI tests by varying positions and actuators (Raman)
- 2.2.3.2.5. Test EPI and CT injection system if installed (Raman)

2.2.3.3. Year 3 of NSTX-U operation
- 2.2.3.3.1. Investigate thermal loading during VDEs and major disruptions using fast IR cameras and fast TCs
- 2.2.3.3.2. Investigate disruption precursors and study avoidance scenarios with various MHD origins
- 2.2.3.3.3. Explore MGI triggering and other mitigation techniques for real-time actuation (Raman)

2.2.3.4. Year 4 of NSTX-U operation
- 2.2.3.4.1. Utilize disruption precursors and test avoidance scenarios
- 2.2.3.4.2. Couple real-time mitigation techniques to other MHD sensors (Raman)
- 2.2.3.4.3. Provide FNSF/Pilot projection on disruption physics understanding

2.2.4. **Year 5 of NSTX-U operation (Park, Berkery)**

2.2.4.1. Integrate MS control to avoid RWM/TM/ELM/internal MHD instability, disruption, with disruption mitigation protection

2.2.4.2. Provide FNSF/Pilot projection for integrated control

2.2.4.3. Validate integrated modeling of macroscopic stability

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. EFIT (Sabbagh)

2.3.1.2. DCON (Park)
2.3.1.3. IPEC / GPEC (Park)
2.3.1.4. MISK (Berkery)
2.3.1.5. POCA (Kim)
2.3.1.6. VALEN (Bialek)
2.3.1.7. MARS-K (Menard)
2.3.1.8. M3D-C1 (Jardin)
2.3.1.9. DEGAS (Raman)

2.3.2. Diagnostics (Park)

2.3.2.1. Magnetic sensors including B_P and B_R sensors will be refurbished and upgraded (Sabbagh)
2.3.2.2. Real-Time Velocity measurement for successful implementation of rotation control, and disruption detection (Podesta)
2.3.2.3. Toroidally displaced multi-energy SXR to study 3D physics including island dynamics, and RWM eigenfunctions (Tritz)
2.3.2.4. Core X-ray imaging spectrometer to study rotation effects on error field and early MHD without NBIs (Delgado)
2.3.2.5. Internal magnetic fluctuation measurement for island structures (Howard)
2.3.2.6. Real time MSE and MPTS for fast and precise kinetic equilibrium reconstruction (Howard, Le Blanc)

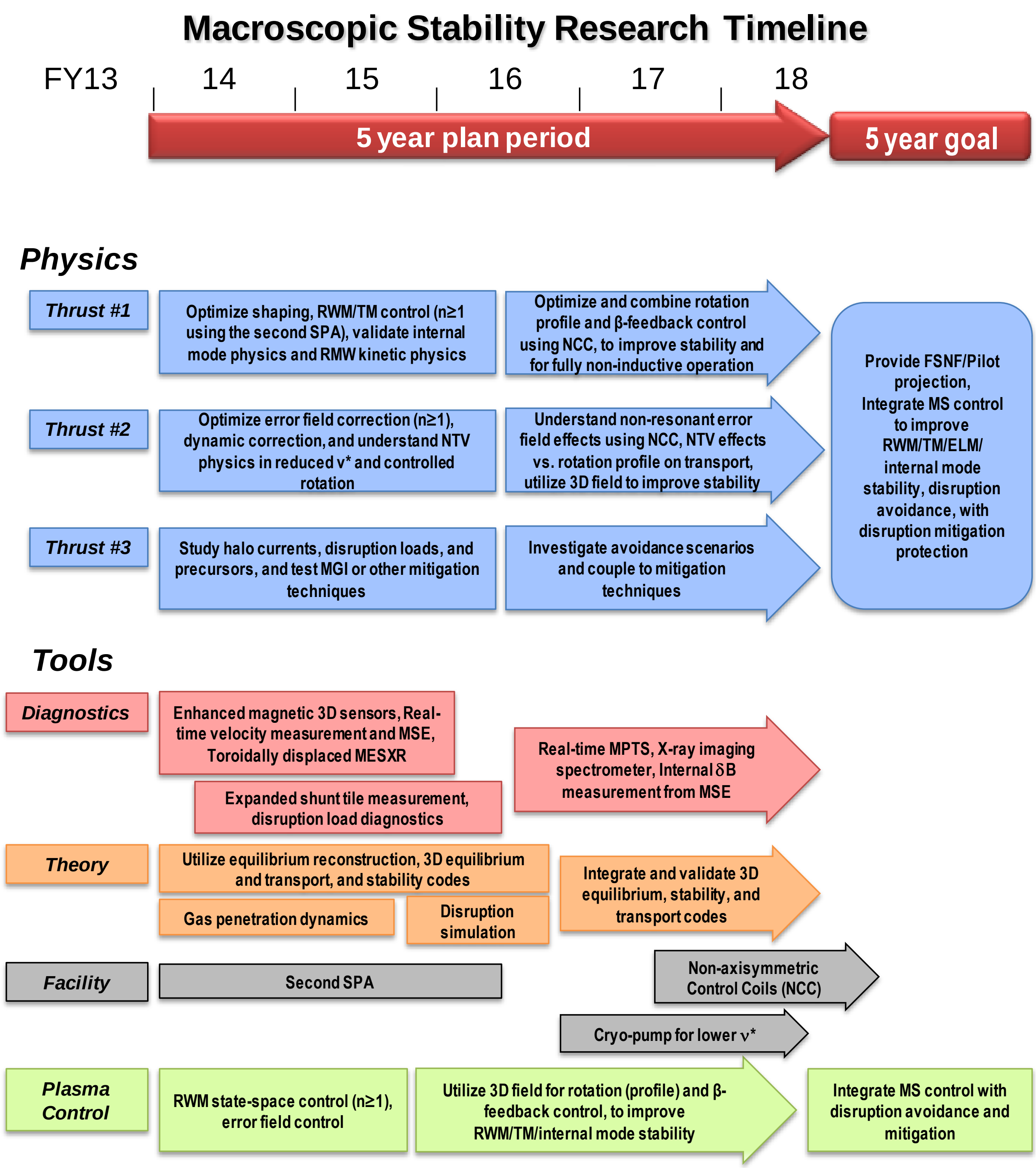
2.3.3. Other facility capabilities including plasma control

2.3.3.1. Non-axisymmetric Control Coil (NCC) (Park, Berkery, Sabbagh)

2.3.3.1.1. Motivation and design

2.3.3.1.2. Summary of physics studies

2.3.3.1.2.1. RWM active control for significant multi-mode spectrum (Bialek)
2.3.3.1.2.2. Rotation control by NTV braking
2.3.3.1.2.3. Error field correction and tearing mode stabilization
2.3.3.1.2.4. RWM kinetic stabilization (Berkery)
2.3.3.1.2.5. ELM control and stabilization (Evans, Maingi)
2.3.3.1.2.6. Simultaneous control for rotation, error field, RWM, TM, ELM
2.3.3.1.2.7. Prediction for ITER 3D coil capabilities


Macroscopic Stability Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Thrust #1
Optimize shaping, RWM/TM control (n≥1 using the second SPA), validate internal mode physics and RMW kinetic physics
Optimize and combine rotation profile and β-feedback control using NCC, to improve stability and for fully non-inductive operation
Thrust #2
Optimize error field correction (n≥1), dynamic correction, and understand NTV physics in reduced ν* and controlled rotation
Understand non-resonant error field effects using NCC, NTV effects vs. rotation profile on transport, utilize 3D field to improve stability
Thrust #3
Study halo currents, disruption loads, and precursors, and test MGI or other mitigation techniques
Investigate avoidance scenarios and couple to mitigation techniques
Provide FSNF/Pilot projection, Integrate MS control to improve RWM/TM/ELM/ internal mode stability, disruption avoidance, with disruption mitigation protection
Tools
Diagnostics
Enhanced magnetic 3D sensors, Real-time velocity measurement and MSE, Toroidally displaced MESXR
Expanded shunt tile measurement, disruption load diagnostics
Real-time MPTS, X-ray imaging spectrometer, Internal δB measurement from MSE
Theory
Utilize equilibrium reconstruction, 3D equilibrium and transport, and stability codes
Gas penetration dynamics
Disruption simulation
Integrate and validate 3D equilibrium, stability, and transport codes
Facility
Second SPA
Non-axisymmetric Control Coils (NCC)
Cryo-pump for lower ν*
Plasma Control
RWM state-space control (n≥1), error field control
Utilize 3D field for rotation (profile) and β-feedback control, to improve RWM/TM/internal mode stability
Integrate MS control with disruption avoidance and mitigation

3. Research Goals and Plans for Transport and Turbulence

3.1. Overview of goals and plans

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

3.1.1.1. Identify most relevant scenario (H-mode, fully and partially non-inductive; advanced scenario, e.g. ITB plasmas regime)

3.1.1.2. Identify most relevant transport issues: mechanism behind anomalous transport and reduced transport models validated for a wide parametric regime by varying engineering parameter and using different scenarios (L, H-mode, ITB plasmas, NBI/RF plasmas)

3.1.2. Thrust 1: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U (Ren)

3.1.2.1. Motivations: Observed neoclassical ion thermal transport, but anomalous electron thermal, momentum, and particle/impurity transport in STs

3.1.2.2. Prioritize goals: 1. electron thermal 2. Momentum; 3. Particle/impurity

3.1.2.3. Relevant turbulence to different transport channels

Low-k turbulence (ITG/KBM, TEM, microtearing): thermal, momentum and particle/impurity

High-k turbulence (ETG): electron thermal

Alfvenic eigenmodes (with EP TSG): electron thermal

3.1.2.4. Identify regimes of validity for instabilities

Diagnostics, experimental tools (flow, current profile control by 2nd NBI and 3D coils) and simulations to distinguish turbulence through parametric dependence

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

3.1.3.1. Existing 0D confinement scalings (ST scaling, ITER scaling), their projection to NSTX-U and remaining issues

3.1.3.2. Existing 1D models (neoclassical model, TGLF, etc.), their validation and applicability to NSTX, NSTX-U and beyond, issues for applicability, and the needs of further development of 1D reduced models for different parametric regimes/radial regions

3.2. Research Plans

3.2.1. **Thrust 1: Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U** (Ren)

3.2.1.1. Thermal transport

3.2.1.1.1. Electron:

Near term plans (Year 1-2):

3.2.1.1.1.1. Measure low-k turbulence with BES, reflectometry and polarimetry in a variety of regimes (guided by GK simulations): ITG/TEM dominant and microtearing-dominant regimes, and correlate measurement with electron thermal transport trends by varying engineering parameters and active q and flow profile variations through 2^{nd} NBI and 3D coils

3.2.1.1.1.2. Take preliminary high-k measurements in ETG-dominant regime (guided by GK simulations)

3.2.1.1.1.3. Measure *AE mode structure using calibrated BES/reflectometry with a range of B_T, I_p, ν^* and NB power and correlate with electron thermal transport

Long-term plans (Year 3-5):

3.2.1.1.1.4. Identify ETG and microtearing modes and their operational regimes using a high-k_θ scattering system, BES, reflectometry and polarimetry measurements with improved NSTX-U parameters, variations of plasma parameters/profiles (2^{nd} NBI and 3D coils) and steady-state/ perturbative (cold pulses from laser blow-off) transport measurements, coupled with interpretative and predictive GK/reduced model simulations and synthetic diagnostics

3.2.1.1.1.5. Investigate electron thermal dependence with PFC/divertor conditions

3.2.1.1.1.6. Determine the role of *AE mode in electron thermal transport with BES measurements and transport analysis and its range of applicability and compare with available reduced models for *AE driven χ_e (w/ EP)

3.2.1.1.2. Ion :

Near term plans (Year 1-2):

3.2.1.1.2.1. Determine if Â$_i$ is still near neo-classical level in lower º* H-mode plasmas with higher Bt and Ip; compare with neoclassical calculation, NCLASS/GTC-NEO

3.2.1.1.2.2. Use 2^{nd} NBI and 3D coils to vary q and flow profiles, determine the change in ion thermal diffusivity and correlate with low-k turbulence measurements from BES, reflectormetry and polarimetry in L and H-mode plasmas, and compare with gyrokinetic simulations with both transport and measured turbulence through synthetic diagnostics

Long-term plans (Year 3-5):

3.2.1.1.2.3. Determine χ_i in full range of Bt, Ip and ν^* in H-mode plasmas and compare with neoclassical calculations, NCLASS/GTC-NEO

3.2.1.1.2.4. Identify relevant low-k turbulence (ITG/TEM, KBM) and determine its operational regime when $\chi_{i,}$ is anomalous through low-k turbulence measurement coupled with gyrokinetic simulations and the full range of Bt, Ip and ν* and active q and flow profile variations through 2nd NBI and 3D coils

3.2.1.2. Momentum transport

Near term plans (Year 1-2):

3.2.1.2.1. Measure low-k turbulence with BES, reflectometry in a variety of regimes (guided by GK simulations): ITG/TEM dominant, microtearing-dominant and correlate measurement with perturbative momentum transport measurement (NBI/3D coil pulses)

Long term plans (Year 3-5):

3.2.1.2.2. Identify low-k turbulence responsible for anomalous momentum transport and its operational regime with turbulence measurement (BES, reflectometry, etc.) and perturbative momentum transport measurement (NBI/3D coil pulses) in a wide range of plasma parameters

3.2.1.2.3. Investigate intrinsic rotation (passive CHERS, MSE-LIF) coupled with low-k turbulence measurements (BES, reflectometry, etc.)

3.2.1.3. Particle/impurity transport

Near term plans (Year 1-2):

3.2.1.3.1. Measure impurity diffusivity with perturbative methods (gas puff with SXR measurements) and low-k turbulence with BES, reflectometry in reflectometry in a variety of regimes (guided by GK simulations): ITG/TEM dominant, microtearing-dominant with improved NSTX-U parameters and profile variation capabilities from 2nd NBI and 3D coil; compare with neoclassical calculations and GK simulations via synthetic diagnostics.

Long term plans (Year 3-5):

3.2.1.3.2. Identify low-k turbulence responsible for anomalous particle/impurity transport and its operational regime with turbulence measurement (BES, reflectometry, etc.) and perturbative particle/impurity transport measurement (gas puff/laser blow-off) in the full range of plasma parameters of NSTX-U and profile variation capability from 2nd NBI and 3D coil; Compare with neoclassical calculations and GK simulations via synthetic diagnostics.

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

3.2.2.1. Confinement and transport scaling measurements

Year 1-2

3.2.2.1.1. Establish 0D confinement scaling at higher B_T, I_p, lower ν_*

Year 2-3

3.2.2.1.2. Extend 0D confinement scaling to full range of B_T, I_p, ν_* (available with short pulse), distinguishing W_{core}, W_{ped}

3.2.2.1.3. Establish profile database of relevant scenarios for 1D analysis and model validation (I_p, B_T, ν_*, … scans)

3.2.2.1.4. Project 0D performance to FNSF/Pilot with full range I_p, B_T, ν_*

Year 4-5

3.2.2.1.5. Extend 0D confinement scaling for long pulse (t >> τ_{CR}) and high non-inductive fraction scenarios (relevant to ASC/FNSF goals)

3.2.2.1.6. Refine 0D projections to FNSF/Pilot with data from full range I_p, B_T, ν_* , long pulse, and variation in PFC conditions (e.g. following Li trends)

3.2.2.1.7. Investigate ρ_* scaling with improved density control ($n \sim \rho_*^{-2}$)

3.2.2.2. **Model development and validation**

Years 1-2

3.2.2.2.1. Predict Ti at reduced nu and over expanded operational regimes, confirm if ion thermal transport remains NC

3.2.2.2.2. Compare TGLF with linear/nonlinear simulations for range of NSTX-U plasmas (initial focus on electron thermal transport)

3.2.2.2.3. Predictions using reduced modes (TGLF)

3.2.2.2.3.1. Compare 0D predictions with expanded Ip, Bt, n* scaling

3.2.2.2.3.2. Predict Te,Ti profiles (single time slice) starting with idealized scenarios (e.g. isolated mechanisms); use measured pedestal properties as boundary condition, test sensitivity to BCs

3.2.2.2.4. Identify where thermal model fails, e.g. due to inaccuracy or missing EP/*AE model

3.2.2.2.5. Explore alternative reduced model development specifically for Te predictions, e.g. semi-empirical/"Multi-Mode" (MT+ETG+*AE, etc…), based on available simulations and experimental observations

Years 2-3

3.2.2.2.6. Perform ORBIT simulations for electron orbits using measured *AE structure **[w/ Tritz, Gorolenkov]**

3.2.2.2.7. Validate TGLF particle/impurity transport with linear/nonlinear simulations (sensitivity to Te/Ti gradients)

3.2.2.2.8. Predict ne profiles for scenarios with good understanding of particle sources, test sensitivity to uncertainty in part/imp sources

3.2.2.2.9. Test TGLF flow profile predictions

3.2.2.2.10. Validate TGLF predictions of χ_φ, Pr, RV_φ/χ_φ with non-linear simulations

3.2.2.2.11. Revise TGLF as required (general equilibrium; basis functions; QL transport model)

Years 3-5

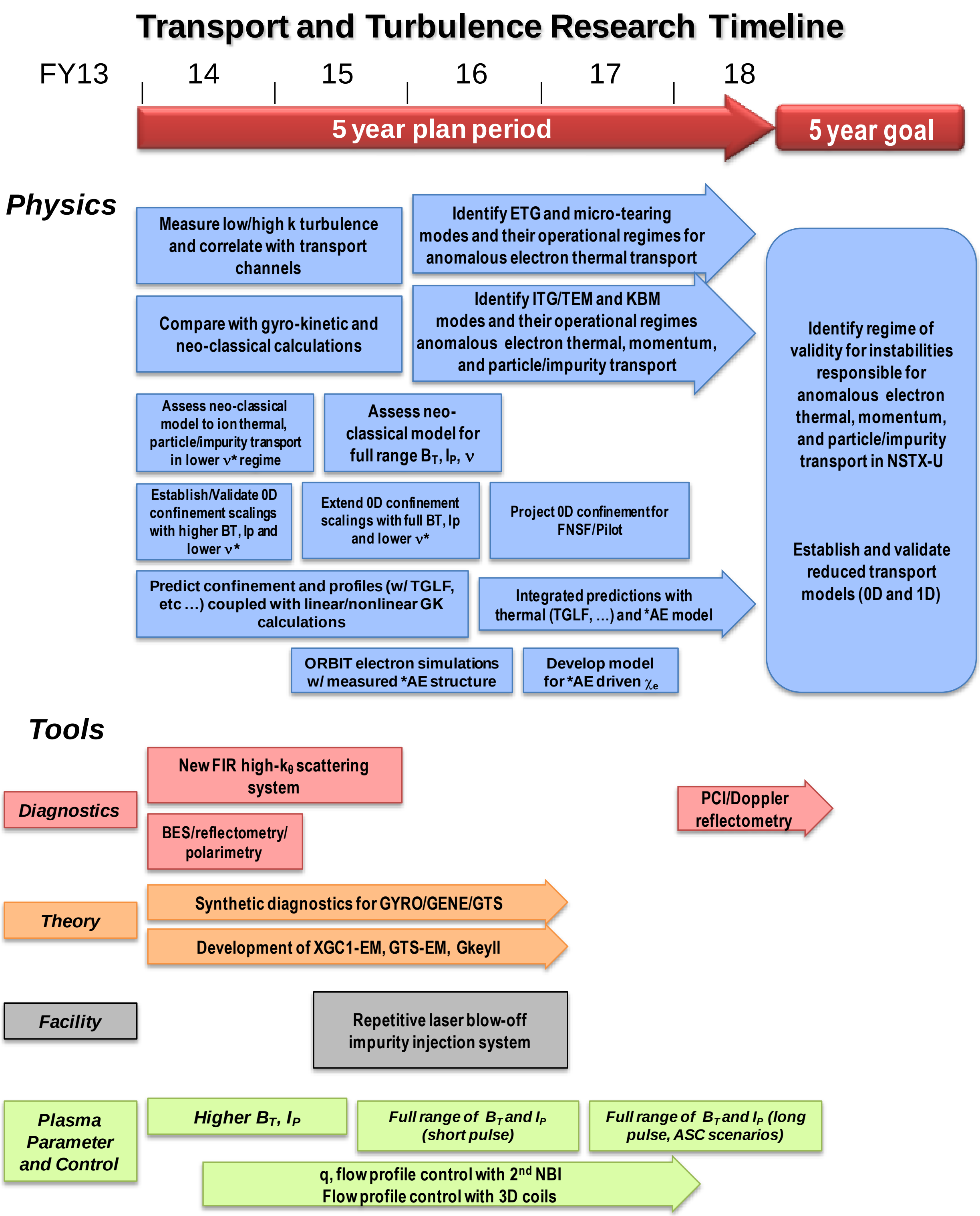
3.2.2.2.12. Develop semi-empirical model for χ_e driven by *AE based on ORBIT simulations, stochastic model, and observations **[w/ Tritz, Gorolenkov]**
3.2.2.2.13. Incorporate semi-empirical/theory-based *AE model into integrated predictions
3.2.2.2.14. Incorporate empirical pedestal scaling or theory-based models into integrated predictions for both 0D and 1D, primary focus on electron energy confinement **[w/ Diallo]**
3.2.2.2.15. Perform predictions for ASC/long pulse scenarios (pTRANSP, etc…), testing sensitivity of current evolution to profile predictions **[w/ Gerhardt]**
3.2.2.2.16. Perform 0D and 1D predictions for FNSF/Pilot scenarios

3.3. Summary timeline for tool development to achieve research goals

3.3.1. Theory and simulation capabilities (Guttenfelder)
3.3.1.1. Local codes (GYRO, GS2, GENE, GKW) – scaling studies with comprehensive physics
3.3.1.2. Global/full-F codes (GYRO, GENE, GTS, XGC-1, Gkeyll) – clarify limits of local and delta-f assumptions, esp. core/pedestal transition
3.3.1.3. Synthetic diagnostics (BES, high-k, pol., refl., etc…)
3.3.1.4. Neoclassical theory (NCLASS, NEO, GTC-NEO, XGC0)
3.3.1.5. Transport models (TLGF; *AE; EPED; …)
3.3.1.6. Transport solvers (PTRANSP, TYGRO, TRINITY, XPTOR)

3.3.2. Diagnostics (Ren, Smith, Tritz, UCLA(TBD))
3.3.2.1. New FIR high-k_θ scattering system
3.3.2.2. Polarimetry system
3.3.2.3. Additional BES channels
3.3.2.4. In-vessel multi-energy SXR (ME-SXR) arrays
3.3.2.5. Further diagnostic development: PCI and Doppler reflectometry

3.3.3. Other facility capabilities including plasma control (Ren)
3.3.3.1. 2^{nd} NB for q and flow profile control
3.3.3.2. Repetitive laser blow-off impurity injection system
3.3.3.3. NCC for 3D field rotation profile control
3.3.3.4. MSE-LIF for q profile, more XP flexibility (intrinsic rotation)
3.3.3.5. Divertor/PFC/cyro for density control, ρ_* scaling


Transport and Turbulence Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Measure low/high k turbulence and correlate with transport channels
Identify ETG and micro-tearing modes and their operational regimes for anomalous electron thermal transport
Compare with gyro-kinetic and neo-classical calculations
Identify ITG/TEM and KBM modes and their operational regimes anomalous electron thermal, momentum, and particle/impurity transport
Assess neo-classical model to ion thermal, particle/impurity transport in lower ν* regime
Assess neo-classical model for full range B_T, I_P, ν
Establish/Validate 0D confinement scalings with higher BT, Ip and lower ν*
Extend 0D confinement scalings with full BT, Ip and lower ν*
Project 0D confinement for FNSF/Pilot
Predict confinement and profiles (w/ TGLF, etc …) coupled with linear/nonlinear GK calculations
Integrated predictions with thermal (TGLF, …) and *AE model
ORBIT electron simulations w/ measured *AE structure
Develop model for *AE driven χ_e
Identify regime of validity for instabilities responsible for anomalous electron thermal, momentum, and particle/impurity transport in NSTX-U
Establish and validate reduced transport models (0D and 1D)
Tools
Diagnostics
New FIR high-k_θ scattering system
BES/reflectometry/ polarimetry
PCI/Doppler reflectometry
Theory
Synthetic diagnostics for GYRO/GENE/GTS
Development of XGC1-EM, GTS-EM, Gkeyll
Facility
Repetitive laser blow-off impurity injection system
Plasma Parameter and Control
Higher B_T, I_P
Full range of B_T and I_P (short pulse)
Full range of B_T and I_P (long pulse, ASC scenarios)
q, flow profile control with 2nd NBI
Flow profile control with 3D coils

4. Research Goals and Plans for Boundary Physics

4.1. Overview of goals and plans [**Soukhanovskii**, Diallo, Maingi]

4.1.1. Goals
- 4.1.1.1. Develop understanding of the physical properties of pedestal structure and stability for ITER and FNSF
- 4.1.1.2. Develop and validate divertor heat and particle control to support projections of divertor scenarios to ST-FNSF.

4.1.2. Thrusts in boundary research
- 4.1.2.1. Thrust #1: Assess, optimize, and control of the pedestal structure, edge transport and stability
- 4.1.2.2. Thrust #2: Assess and control divertor heat and particle fluxes

4.2. Research Plans

4.2.1. H-mode pedestal formation, transport, and stability [Diallo, Maingi]

4.2.1.1. LH transition physics **[Battaglia, Chang, Maingi, Kaye (?)]**
- 4.2.1.1.1. Re-establish reliable H-mode access and operation
- 4.2.1.1.2. Threshold studies and pedestal formation

4.2.1.2. Pedestal transport and stability (complete assessment of confinement, threshold trends wrt NSTX) **[Diallo, Maingi]**

4.2.1.2.1. Research Plan

- 4.2.1.2.2. Years 1-2: Dependence on Bt, Ip, shaping
- 4.2.1.2.3. Years 3-5: Perform experiments, develop models enabling projections to FNSF
- 4.2.1.2.4. Years 3-5: Assess and optimize pedestal structure and SOL parameters for advanced ST operation

4.2.2. Pedestal control [Canik, Park, Maingi, Rob]

4.2.2.1. Operational scenarios and tools to be explored:
- 4.2.2.1.1. EPH mode
- 4.2.2.1.2. I-mode
- 4.2.2.1.3. 3D fields (midplane and NCC)
- 4.2.2.1.4. Li granule injector
- 4.2.2.1.5. EHO antenna

4.2.2.2. Research plan

4.2.2.2.1. Years 1-2: Response to 3D magnetic field perturbations
4.2.2.2.2. Years 1-2: ELM studies, ELM control development, pedestal transport
4.2.2.2.3. Years 1-2: EPH-mode, I-mode development
4.2.2.2.4. Years 3-5: Utilize 3D fields to optimize pedestal transport and stability
4.2.2.2.5. Years 3-5: Perform experiments, develop models enabling projections to FNSF
4.2.2.2.6. Years 3-5: Assess and optimize pedestal structure and SOL parameters for advanced ST operation

4.2.3. Edge/SOL physics [Zweben]

4.2.3.1. Motivation and Goals
4.2.3.1.1. understand physics of SOL in NSTX-U
4.2.3.1.2. learn how to better control SOL in NSTX-U
4.2.3.1.3. predict and control SOL in ITER and beyond

4.2.3.2. Understand 3-D structure edge/SOL turbulence
4.2.3.2.1. Years 1-2: Compare existing outer midplane edge/SOL turbulence measurements
4.2.3.2.2. Years 2-4: Develop edge/SOL turbulence diagnostics at other poloidal angles
4.2.3.2.3. Years 3-5: Compare results with 3D turbulence codes, e.g. XGC-1

4.2.3.3. Zonal (poloidal) flow of SOL/edge turbulence
4.2.3.3.1. Years 1-2: Compare existing measurements of zonal flow at outer midplane
4.2.3.3.2. Years 2-4: Develop edge/SOL zonal flow diagnostics at other poloidal angle
4.2.3.3.3. Years 3-5: Compare results with 3D turbulence codes, e.g. XGC-1

4.2.3.4. Cross-field and parallel transport in edge/SOL
4.2.3.4.1. Years 1-2: Compare various existing measurements of edge/SOL transport
4.2.3.4.2. Years 2-4: Measure edge/SOL transport, e.g. with trace gases
4.2.3.4.3. Years 3-5: Compare results with 3D turbulence codes, e.g. XGC-1

4.2.3.5. Develop and test new methods for active control of SOL/edge profiles
4.2.3.5.1. Years 1-2: Evaluate effect of added neutrals/impurities on edge/SOL turbulence
4.2.3.5.2. Years 2-4: Evaluate effect of perturbed magnetic fields on edge/SOL turbulence
4.2.3.5.3. Years 3-5: Evaluate effect of applied SOL currents on edge/SOL turbulence

4.2.4. Divertor physics **[Soukhanovskii, Ahn]**

4.2.4.1. Years 1-2: Heat flux width scaling, connection to SOL models
4.2.4.2. Years 1-2: Snowflake divertor studies and control development
4.2.4.3. Years 1-2: Radiative divertor
with D2, Ne, Ar seeding
High radiation fraction: mantle + lithium radiator
4.2.4.4. Years 1-2: Impurity erosion and SOL transport studies
4.2.4.5. Years 1-2: Experiments to support validation of cryo-pump designs
4.2.4.6. Years 3-5: Develop and validate divertor heat and particle control
4.2.4.7. Years 3-5: Support projections of heat flux width and divertor scenarios to ST-FNSF
4.2.4.8. Years 3-5: Utilize magnetic control for long-pulse snowflakes with reduced heat flux
4.2.4.9. Years 3-5: Implement radiative divertor control
4.2.4.10. Years 3-5: Assess Mo divertor PFCs
4.2.4.10.1. High-Z impact on scenarios and H-mode confinement
4.2.4.10.2. Core Mo density and transport in baseline scenarios
4.2.4.10.3. Assess effect of lithium coatings on molybdenum PFCs (synergistic study with EAST)
4.2.4.10.4. Divertor Mo influx in baseline and impurity-seeded radiative divertor scenarios

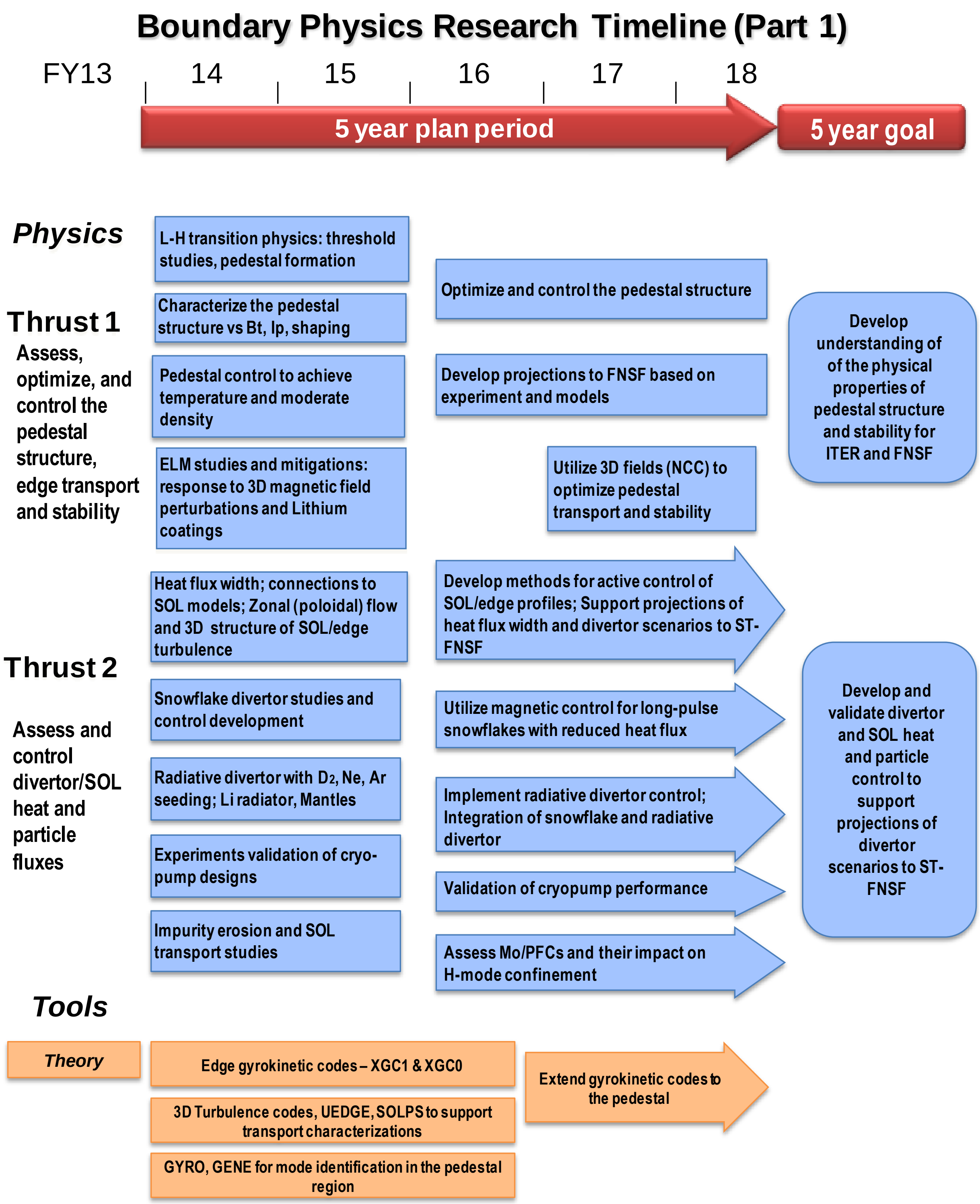
4.2.5. Particle Control **[Soukhanovskii, Canik, Raman]**

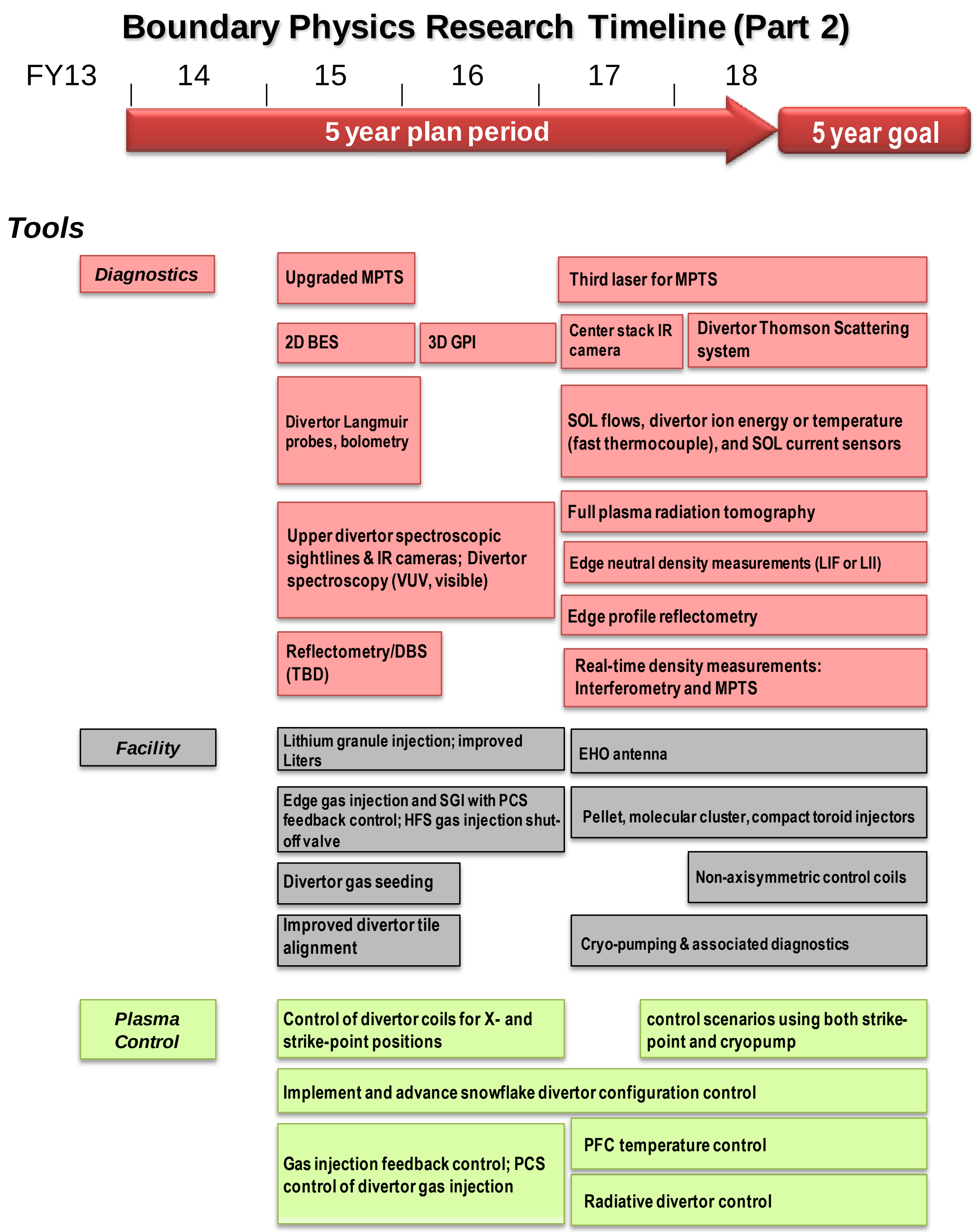
4.2.5.1. Motivation
4.2.5.1.1. Control ramp-up density evolution to avoid MHD
4.2.5.1.2. Maintain/control flat-top density/collisionality

4.2.5.2. Real-time density measurement
4.2.5.2.1. Interferometry **[Kaita]**
4.2.5.2.2. MPTS **[Diallo, LeBlanc]**

4.2.5.3. Edge and core fueling
4.2.5.3.1. LFS/HFS conventional **[Kaita]**
4.2.5.3.2. SGI **[Soukhanovskii]**
4.2.5.3.3. SMBI **[Soukhanovskii, Majeski]**
4.2.5.3.4. CT injection **[Raman]**
4.2.5.3.5. Pellets**[Gray]**

4.2.5.4. Cryo-pumping **[Canik]**


Boundary Physics Research Timeline (Part 1)
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Thrust 1
Assess, optimize, and control the pedestal structure, edge transport and stability
L-H transition physics: threshold studies, pedestal formation
Characterize the pedestal structure vs Bt, Ip, shaping
Pedestal control to achieve temperature and moderate density
ELM studies and mitigations: response to 3D magnetic field perturbations and Lithium coatings
Optimize and control the pedestal structure
Develop projections to FNSF based on experiment and models
Utilize 3D fields (NCC) to optimize pedestal transport and stability
Develop understanding of of the physical properties of pedestal structure and stability for ITER and FNSF
Thrust 2
Assess and control divertor/SOL heat and particle fluxes
Heat flux width; connections to SOL models; Zonal (poloidal) flow and 3D structure of SOL/edge turbulence
Snowflake divertor studies and control development
Radiative divertor with D2, Ne, Ar seeding; Li radiator, Mantles
Experiments validation of cryo-pump designs
Impurity erosion and SOL transport studies
Develop methods for active control of SOL/edge profiles; Support projections of heat flux width and divertor scenarios to ST-FNSF
Utilize magnetic control for long-pulse snowflakes with reduced heat flux
Implement radiative divertor control; Integration of snowflake and radiative divertor
Validation of cryopump performance
Assess Mo/PFCs and their impact on H-mode confinement
Develop and validate divertor and SOL heat and particle control to support projections of divertor scenarios to ST-FNSF
Tools
Theory
Edge gyrokinetic codes – XGC1 & XGC0
3D Turbulence codes, UEDGE, SOLPS to support transport characterizations
GYRO, GENE for mode identification in the pedestal region
Extend gyrokinetic codes to the pedestal


Boundary Physics Research Timeline (Part 2)
FY13
14
15
16
17
18
5 year plan period
5 year goal
Tools
Diagnostics
Upgraded MPTS
Third laser for MPTS
2D BES
3D GPI
Center stack IR camera
Divertor Thomson Scattering system
Divertor Langmuir probes, bolometry
SOL flows, divertor ion energy or temperature (fast thermocouple), and SOL current sensors
Full plasma radiation tomography
Upper divertor spectroscopic sightlines & IR cameras; Divertor spectroscopy (VUV, visible)
Edge neutral density measurements (LIF or LII)
Edge profile reflectometry
Reflectometry/DBS (TBD)
Real-time density measurements: Interferometry and MPTS
Facility
Lithium granule injection; improved Liters
EHO antenna
Edge gas injection and SGI with PCS feedback control; HFS gas injection shut-off valve
Pellet, molecular cluster, compact toroid injectors
Non-axisymmetric control coils
Divertor gas seeding
Improved divertor tile alignment
Cryo-pumping & associated diagnostics
Plasma Control
Control of divertor coils for X- and strike-point positions
control scenarios using both strike-point and cryopump
Implement and advance snowflake divertor configuration control
Gas injection feedback control; PCS control of divertor gas injection
PFC temperature control
Radiative divertor control

5. Research Goals and Plans for Materials and Plasma-Facing Components

5.1. Overview of goals and plans

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

5.1.2. Physics thrusts and goals by topical area (Jaworski, Skinner)
- 5.1.2.1. Lithium surface-science for long-pulse PMI and PFCs
- 5.1.2.2. The physics of tokamak-induced material migration and evolution
- 5.1.2.3. The physics of continuous vapor shielding

5.1.3. Enabling technologies and tools (Jaworski, Skinner)
- 5.1.3.1. Surface science to establish atoms-to-PFCs understanding
- 5.1.3.2. Upgrade path to an all-metal NSTX-U
- 5.1.3.3. Laboratory R&D on liquid metal systems and PFCs

5.2. Research Plans

5.2.1. Lithium surface-science for long-pulse PMI and PFCs (Skinner, Koel, Allain, Maingi, Jaworski)

5.2.1.1. Motivation: FNSF needs high H-factor, lithium wall conditioning has demonstrated ability to achieve relevant H-factors in NSTX – overview of NSTX confinement gains

5.2.1.2. Machine performance studies with lithium coatings
- 5.2.1.2.1. NSTX-U studies on ATJ (w, w/o Li)
- 5.2.1.2.2. NSTX-U studies on high-Z substrate (w, w/o Li)

5.2.1.3. Critical parameters affecting lithium-based PFC performance
- 5.2.1.3.1. Surface chemistry (e.g. deuterium uptake, recycling, impurity gettering, desorption, as functions of temperature, contamination, Li replenishment, etc). Role of oxygen in D uptake.
- 5.2.1.3.2. Li wetting of substrate (e.g. ATJ vs. TZM vs. ODS steel)
- 5.2.1.3.3. Recovery of clean Li surface after vents.
- 5.2.1.3.4. Connections between laboratory studies, in-situ material analysis (MAPP probe) and plasma performance.
- 5.2.1.3.5. Beyond lithium: surface science of high-Z liquid metals Ga and Sn

5.2.1.4. Flowing liquid metal PFC design to extend lithium supply to long-pulse.

5.2.2. The physics of tokamak-induced material migration and evolution (Jaworski, Skinner, Koel, Soukhanovskii, Stotler)

5.2.2.1. Motivation: wall erosion estimated to result in tons of material circulating the next step long pulse machines and may not be sustainable for a solid PFC

5.2.2.2. Assessing divertor and wall erosion and migration
- 5.2.2.2.1. Background-plasma diagnosis of divertor and SOL and reconstruction for material transport studies
- 5.2.2.2.2. Optical spectroscopy for gross erosion
- 5.2.2.2.3. QMB methods for net erosion/deposition
- 5.2.2.2.4. Marker tiles, ion beam analysis methods
- 5.2.2.2.5. Isotope experiments in lithium machines (Li-6/7 campaign)
- 5.2.2.2.6. MAPP probe for in-vacuo characterization

5.2.2.3. Assessing the composition and morphology of eroded/redeposited material
- 5.2.2.3.1. Surface science analysis of eroded and redeposited material composition, morphology
- 5.2.2.3.2. Dust production from eroded material
- 5.2.2.3.3. Codeposits: low-Z and high-Z materials and their remediation

5.2.2.4. Integrated design of liquid metal PFCs for supply and collection of liquid metal

5.2.3. Establish the science of continuous vapor shielding (Jaworski, Gray, Goldston, Soukhanovskii, Kaganovich, Chang, Stotler)

5.2.3.1. Motivation: fusion heat-fluxes on advanced PFCs expected to result in elevated temperatures and strong eroded fluxes from evaporation and sputtering. SOL may no longer be in a minority-impurity plasma but vapor-shielded regime

5.2.3.2. Lithium transport and SOL response in the vapor-shielded regime
- 5.2.3.2.1. Background plasma diagnosis of the divertor and SOL and reconstruction (e.g. with interpretative such as OEDGE and/or predictive codes such as UEDGE/SOLPS)
- 5.2.3.2.2. Optical methods of diagnosing lithium behavior near the PFC and in the SOL
- 5.2.3.2.3. Infrared thermography and other techniques for quantifying power balance
- 5.2.3.2.4. Fluid and kinetic descriptions of energy and particle transport of systems with vapor-shielded PFCs

5.2.3.3. Liquid metal PFC design for long-pulse removal of heat and supply of lithium including gaseous active cooling

5.2.4. Enabling technologies and other supporting R&D

5.2.4.1. Surface-science laboratories and tools for establishing an understanding from atoms-to-PFCs (Skinner, Koel, Allain)

5.2.4.2. Summary of T260, C123 facilities

5.2.4.3. Liquid metal loop development in support of liquid metal PFCs (Jaworski)

5.2.4.4. Integrated liquid metal PFC and thermal-hydraulic design and testing (Jaworski)

5.2.4.4.1. Lithium laboratory work and testing for technological readiness

5.2.4.4.2. Technical demonstrations of candidate PFCs on linear test-stands (e.g. Magnum-PSI)

5.2.4.5. An all-metal NSTX-U (Jaworski, Kaita)

5.2.4.5.1. Upgrade from ATJ to Molybdenum in the divertor

5.2.4.5.2. Qualification of Molybdenum coatings on graphite tiles and/or full Molybdenum tiles for wall armor

5.2.4.6. Additional and alternative lithium delivery systems (Jaworski, Mansfield?, Skinner, Andruczyk)

5.2.4.6.1. LITER

5.2.4.6.2. LITER-Upward and LITER-FAST

5.2.4.6.3. Metered lithium evaporator

5.2.4.6.4. Diffusive evaporation

5.2.4.6.5. Gravity-assisted powder injection

5.2.4.6.6. Granule injection

5.2.4.6.7. Electrostatic spray

5.2.5. Plan: Years 1 & 2 (Jaworski, Skinner, Stotler, Kaita)

5.2.5.1. Surface Science Thrusts

5.2.5.1.1. Lithium performance metrics from Surface Science studies

5.2.5.1.1.1. Continuing research on theoxidation of single crystal Mo

5.2.5.1.1.2. Continuing research on D uptake on Li coated TZM and single crystal Mo vs. temperature (solid/liquid Li) using new ECR plasma source.

5.2.5.1.1.3. Continuing research comparing D uptake on C-coated Li-coated TZM and single crystal Mo.

5.2.5.1.1.4. Role of oxygen in D uptake.

5.2.5.1.1.5. Year 1 Analysis of MAPP samples (SAM, ALISS…)

5.2.5.1.1.6. Year 1 Li wetting studies vs. substrate temperature, surface preparation…using SAM

5.2.5.1.2. Impact of lithium conditioning and coverage on machine performance

5.2.5.1.2.1. Comparison to initial boronized plasmas

5.2.5.1.2.2. Effect of increased lithium coverage (via LITER-Upward or diffusive evaporation)

5.2.5.2. Material Migration Thrusts
- 5.2.5.2.1. Lithium conditioning lifetime and erosion studies
- 5.2.5.2.2. Whole-machine material migration studies of applied lithium and PFC substrate material (graphite)

5.2.5.3. Continuous Vapor Shielding Thrusts
- 5.2.5.3.1. Heavy lithium evaporation experiments once Molybdenum tiles installed

5.2.6. Plan: Years 3-5 (Jaworski, Skinner, Stotler, Kaita)

5.2.6.1. Surface Science Thrusts
- 5.2.6.1.1. Liquid-metal surface-science experiments – relation of metrics to surface coating experiments
  - 5.2.6.1.1.1. Surface analysis and Li wetting of liquid Li PFC prototype materials
  - 5.2.6.1.1.2. Extension to Ga and Sn.
- 5.2.6.1.2. Impact of vapor shielding on machine performance

5.2.6.2. Material Migration Thrusts
- 5.2.6.2.1. Near-PFC plasma characterization during continuous vapor-shielding
- 5.2.6.2.2. Physics of material migration with vapor-shielded PFCs

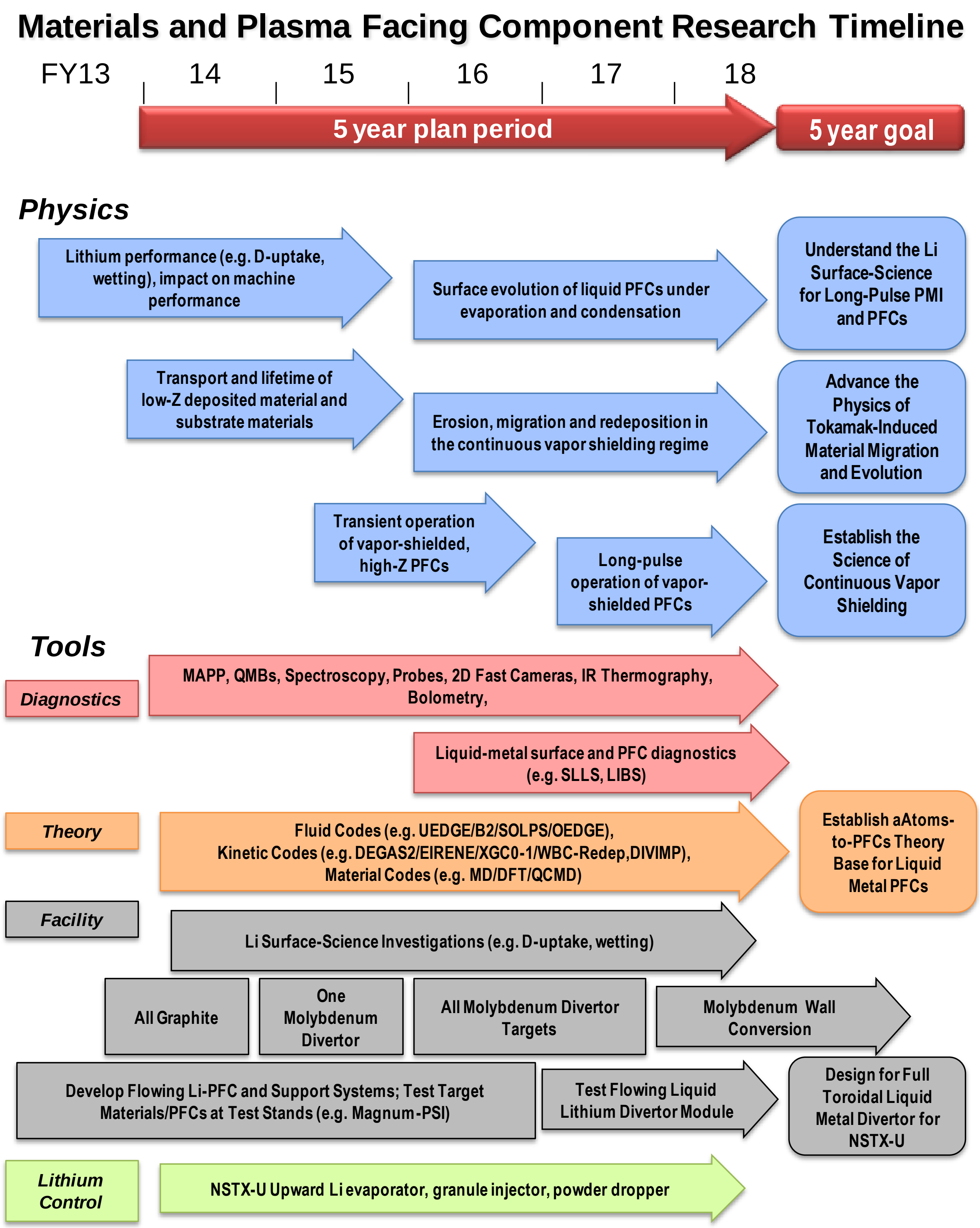
5.2.6.3. Continuous Vapor Shielding Thrusts
- 5.2.6.3.1. Long-pulse vapor-shielding experiments
- 5.2.6.3.2. Particle and power balance with vapor-shielded PFCs

5.2.7. Plan: Years 5-10 (Jaworski, Skinner, Stotler, Kaita)

5.2.7.1. Surface Science Thrusts
- 5.2.7.1.1. Material science of liquid metal PFCs under very high heat flux and long pulse conditions.

5.2.7.2. Material Migration Thrusts
- 5.2.7.2.1. Demonstration of lithium-cycle closure

5.2.7.3. Continuous Vapor Shielding Thrusts
- 5.2.7.3.1. Demonstration of full toroidal coverage of flowing liquid metal divertor


Materials and Plasma Facing Component Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Lithium performance (e.g. D-uptake, wetting), impact on machine performance
Surface evolution of liquid PFCs under evaporation and condensation
Understand the Li Surface-Science for Long-Pulse PMI and PFCs
Transport and lifetime of low-Z deposited material and substrate materials
Erosion, migration and redeposition in the continuous vapor shielding regime
Advance the Physics of Tokamak-Induced Material Migration and Evolution
Transient operation of vapor-shielded, high-Z PFCs
Long-pulse operation of vapor-shielded PFCs
Establish the Science of Continuous Vapor Shielding
Tools
Diagnostics
MAPP, QMBs, Spectroscopy, Probes, 2D Fast Cameras, IR Thermography, Bolometry,
Liquid-metal surface and PFC diagnostics (e.g. SLLS, LIBS)
Theory
Fluid Codes (e.g. UEDGE/B2/SOLPS/OEDGE), Kinetic Codes (e.g. DEGAS2/EIRENE/XGC0-1/WBC-Redep,DIVIMP), Material Codes (e.g. MD/DFT/QCMD)
Establish aAtoms-to-PFCs Theory Base for Liquid Metal PFCs
Facility
Li Surface-Science Investigations (e.g. D-uptake, wetting)
All Graphite
One Molybdenum Divertor
All Molybdenum Divertor Targets
Molybdenum Wall Conversion
Develop Flowing Li-PFC and Support Systems; Test Target Materials/PFCs at Test Stands (e.g. Magnum-PSI)
Test Flowing Liquid Lithium Divertor Module
Design for Full Toroidal Liquid Metal Divertor for NSTX-U
Lithium Control
NSTX-U Upward Li evaporator, granule injector, powder dropper

6. Research Goals and Plans for Energetic Particles

*(Contributors for each section in green, lead co-author in **bold**)*

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

6.1.1. Research Thrusts:

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

6.1.1.2. Assess requirements for "fast-ion phase-space engineering" techniques through selective excitation/suppression of *AE modes

6.1.2. Research needed to enable these Thrusts:

6.1.2.1. Investigate *AE dynamics (drive, damping mechanisms; include linear and non-linear dynamics) and associated fast ion transport mechanisms

6.1.2.2. Compare experimental results with theory & numerical codes
- Theory & code development needs, e.g. HYM, M3D-K, TRANSP/NUBEAM

6.1.2.3. Develop physics-based models for *AE-induced fast ion transport, e.g. resonant/stochastic transport model, quasi-linear model

6.1.2.4. Assess modifications of *AE dynamics using NB, HHFW and active *AE antenna as actuators

6.2. Research Plans

6.2.1. Thrust 1

Year 1-2:

- Compare (classical) TRANSP predictions with FIDA, NPA/ssNPA for 2nd NB line
- Measure *AE eigenfunctions with Reflectometers and BES; compare eigenfunctions to predictions performed in FY12-14 [**Crocker**]
- Characterize *AE activity driven by more tangential 2nd NBI; compare to existing (more perpendicular) NBI
- Use tangential+perpendicular FIDA, NPA/ssNPA to characterize distribution function modifications induced by *AE modes [**Podestà**, Heidbrink, Liu, Medley]
- Improve NPA analysis tools in TRANSP to include 3D 'halo neutrals' model **[Medley]**
- Extend *AE simulations to operations with full 1T magnetic field

Year 3-5:

- Extend study of *AE activity driven by different NBI configurations to full 1T, 2MA scenarios
- Extend studies to non-linear physics and multi-mode physics (e.g. coupling between different classes of MHD modes: TAE+kinks, avalanching CAE/GAE+TAE, CAE/GAE+kinks)
- Compare numerical and theoretical simulations to data on mode dynamics, mode-induced fast ion transport
- Extend simulations of *AE-induced fast ion transport to FNSF/Pilot; steady-state first, then extend to current ramp-up phase
- Assess implications of simulations and theory/experiment comparison for FNSF/Pilot design (eg: optimum NBI geometry), expected NB-CD

6.2.2. Thrust 2

Year 1-2:
- Test prototype *AE antenna [**Fredrickson**]
- Compare measured *AE damping rates with models & theory [**Fredrickson**]
- Characterize scenarios with combined NBI+HHFW (w/ Wave Heating and CD group); characterize *AE activity, fast ion distribution vs. NBI, HHFW parameters [**Taylor, Podestà**, Heidbrink]

Year 3-5:
- Optimize *AE antenna design for efficient coupling to *AE modes; consider replacing 2 HHFW antenna straps with optimized *AE antenna (with Wave Heating and CD group) [**Taylor, Fredrickson**, Podestà]
- Assess performance of upgraded *AE antenna [**Fredrickson**]
- Measure stability of high-*f* *AEs; assess capability of & requirements for mode excitation [**Fredrickson**]
- Study effects of GAE/CAE on thermal plasma: stochastic ion heating, thermal electron transport (w/ Turbulence & Transport group)
- Assess requirements for "fast-ion phase-space engineering" techniques through selective excitation of *AE modes (actuators: NBs, HHFW, active *AE antenna) [**Podestà**, Gorelenkov, Fredrickson]

6.3. Summary timeline for tool development to achieve research goals

6.3.1. Theory and simulation capabilities – Summary Table

6.3.1.1. ORBIT - gyro-center particle following; simulate resonant/stochastic fast ion transport by TAEs [**Podestà**, White]

6.3.1.2. SPIRAL - full-orbit particle following [**Kramer**]
- Fnb response to kinks, CAE/GAE, TAE modes
- Study interaction between NB ions and HHFW

- Compare with gyro-center simulations w/ ORBIT

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

6.3.1.4. HYM – non-linear, hybrid/MHD [**Belova**, Kramer, Fredrickson, Crocker, Gorelenkov, Medley]
- Study excitation of GAE and CAE modes, and their effects on particle confinement; perform detailed comparison with experiments
- Study the effects of the sub-cyclotron modes on fast ion distribution function in NSTX/NSTX-U
- Study the effects of finite frequency (Hall term) on the stability properties of the NBI-driven sub-cyclotron frequency modes
- Effects of GAE modes on the electron transport
- Add sources and sinks in the HYM numerical model
- Perform long time scale nonlinear numerical simulations to study the nonlinear evolution of unstable modes

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

6.3.1.6. Quasi-linear model **[Gorelenkov]**
- Fnb response to given set of modes
- Testing on DIII-D, then apply to NSTX/NSTX-U scenarios

6.3.1.7. Reduced model to be included in NUBEAM/TRANSP **[Podestà,** White**]**
- Provide time-dependent Fnb response to given set of modes
- Need help/assistance from TRANSP/NUBEAM developers
- Test/validate with NSTX data, then explore possibility of using the model in ‘predictive’ mode with *AEs from NOVA-K, M3D-K

6.3.1.8. FIDASIM + Fnb evolving codes (long term: NUBEAM) **[Heidbrink]**
- Infer Fnb from set of data (FIDA, NPA, neutrons, …)
- Lead by UCI, collaboration w/ NSTX, DIII-D, AUG, MAST

6.3.2. Diagnostics – Summary Table

6.3.2.1. Diagnostics under development during NSTX-U Outage period:
- Tangential FIDA to complement existing systems; upgraded ssNPA **[Liu,** Heidbrink**]**
- Fusion source profile via charged D-D fusion products – test on MAST in FY13 **[Darrow]**

- Fixed sightline E//B NPA – must be re-located **[Medley]**
- *AE antenna for stability measurements, excitation of *AE modes **[Fredrickson]**

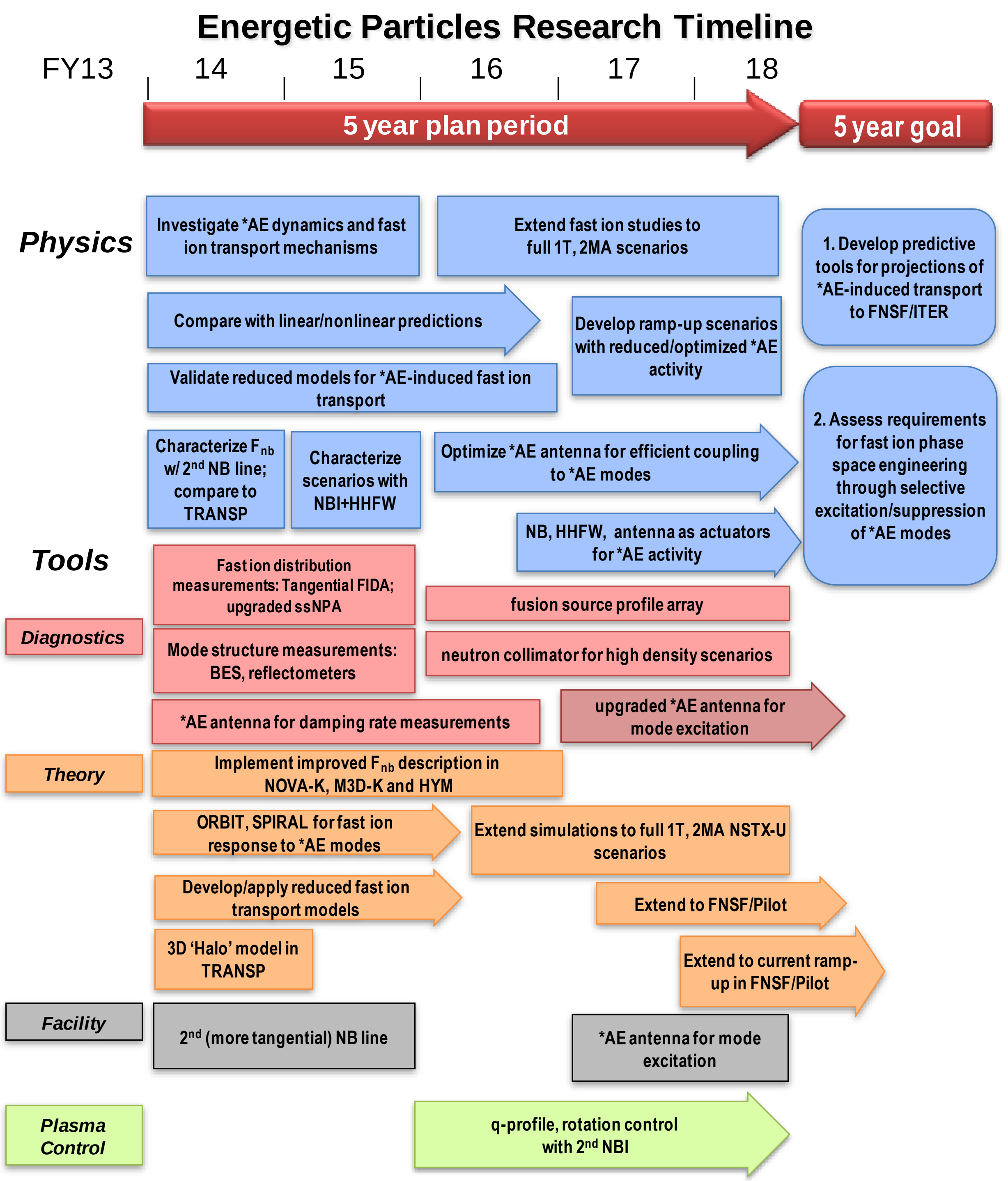
6.3.2.2. New/upgraded diagnostics: **[Podestà** with input from diagnosticians**]**

- BES expansion & increased resolution
- Neutron collimator
- Profile reflectometry with increased frequency range
- FIDA & BES Imaging
- Radial polarimetry, currently testing on DIII-D
- Toroidally-displaced in-vessel multi-energy DXR arrays
- Dual-energy, ultra-fast SXR arrays
- VB imaging of *AE modes
- BES passive FIDA view

6.3.3. Other facility capabilities, including plasma control – to be included in Sec. 6.2

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

- *AE antenna to study stability of (possibly drive) high-f CAE/GAEs, TAE **[Fredrickson]**
  - Goal: direct measurements of damping rate of stable *AE modes
  - Target high-f modes: NSTX-U will have unique capabilities for CAE/GAE studies
  - Will complement JET, MAST data for TAEs
  - With upgrades, assess requirements for “phase space engineering” – e.g.: assess capability of driving modes, compare to other ‘actuators’ such as NBI, HHFW, profile control


Energetic Particles Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
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
Validate reduced models for *AE-induced fast ion transport
2. Assess requirements for fast ion phase space engineering through selective excitation/suppression of *AE modes
Characterize F_{nb} w/ 2nd NB line; compare to TRANSP
Characterize scenarios with NBI+HHFW
Optimize *AE antenna for efficient coupling to *AE modes
NB, HHFW, antenna as actuators for *AE activity
Tools
Diagnostics
Fast ion distribution measurements: Tangential 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 for mode excitation
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
Extend to current ramp-up in FNSF/Pilot
Facility
2nd (more tangential) NB line
*AE antenna for mode excitation
Plasma Control
q-profile, rotation control with 2nd NBI

Chapter 7: Research Goals and Plans for Wave Heating and Current Drive

[Section coauthors in green, **with lead coauthor in bold**]

7.1 Overview of Goals and Plans [Taylor]

7.1.1 Research Thrusts:

Thrust #1: Develop HHFW and EC/EBW heating and current drive for fully non-inductive plasma start-up and H-mode sustainment

Thrust #2: Optimize HHFW current drive in HHFW and HHFW+NBI H-mode plasmas

Thrust #3: Determine the validity of advanced RF codes for NSTX-U RF-heated plasmas and use these codes to predict RF performance in FNSF and ITER

7.1.2 Research Needed to Enable these Thrusts:

7.1.2.1 Assess HHFW interaction with neutral beam fast-ions, and develop capability to heat high-power NBI H-modes with HHFW
7.1.2.2 Mitigate HHFW power losses in scrape off layer of H-mode plasmas
7.1.2.3 Model and implement ECH/EBWH to support plasma startup and local heating and current drive in NBI H-mode
7.1.2.4 Develop advanced RF codes that include SOL, realistic antenna geometry and accurately model interaction between the wave fields and NBI fast-ions

7.2 Research Plans:

7.2.1 HHFW Research Supporting Thrusts 1-3:

Year 1-2:

- Assess performance of 12-strap, double-feed antenna and compatibility with NBI H-modes [**Hosea**, Perkins, Wilson]
- Evaluate, study and mitigate RF power flows in the SOL and to the divertors in the H-mode regime [**Hosea**, Perkins, Wilson]
- Study and minimize HHFW interaction with NBI fast-ions [**Taylor,** Podestà, LeBlanc]

Year 3-5:

- Simulate/mockup reduced-strap HHFW antenna [**Hosea**, Perkins, Wilson]

7.2.2 Thrust 1:

Year 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: [**Taylor**, Raman]

Year 3-5:

- Assess impact of HHFW electron heating on NBI current ramp-up [**Taylor**, Raman]
- Utilize HHFW to assist start-up plasma formation and compare to ECH [**Taylor**, Raman]
- Test high-power ECH system for conditions under which ECH power absorption can be maximized in a CHI plasma [**Taylor**, Raman]
- Test ECH with CHI plasma conditions that extrapolate to FNSF [**Taylor**, Raman]
- Non-inductive start-up with EBW [**Taylor,** Raman]
- EBW heating and current drive in NBI H-mode plasmas [**Taylor**]

7.2.3 Thrust 2:

Year 1-3:

- Maximize core current drive in H-mode plasmas using 12-strap HHFW antenna [**Hosea**, Taylor, Perkins]

Year 4-5:

- Maximize core current drive in H-mode plasmas using reduced-strap HHFW antenna [**Hosea**, Taylor, Perkins]

7.2.4 Thrust 3:

Year 1-3:

- Determine validity of advanced RF codes that include SOL, realistic antenna geometry, accurate modeling of fast-ion interaction and effect of edge fluctuations [**Taylor**, Phillips]

Year 4-5:

- Use advanced RF codes to predict RF performance in FNSF and ITER [**Taylor**, Phillips]

7.3 Summary Timeline for Tool Development Needed to Achieve Research Goals

7.3.1 Theory and Simulation Capabilities: **[Phillips]**

7.3.1.1 HHFW only (support for experiments on start-up; on understanding RFinteractions outside of the LCFS on understanding RF heating and CD at mid-harmonics in the higher B_T of NSTX-U)

- AORSA-3D full-wave code for HHFW modeling, including SOL and realistic antenna model [**Green**]
- TORIC full wave code, with SOL model – also available in TRANSP for time-dependent modeling [**Phillips**, Valeo, Bertelli, Bonoli, Wright]
- GENRAY ray tracing modeling with SOL model and edge fluctuations for HHFW [**Bertelli**, Harvey, Bonoli, Phillips]

7.3.1.2 HHFW+NBI (support for start-up and long pulse high performance plasmas with co-resonant NBI; also for support of interpretations of FIDA measurements of fast ion profiles)

- Full finite orbit width CQL3D Fokker-Planck code for HHFW modeling of NBI plasmas, for use with AORSA and TORIC [**Harvey**, Petrov]
- Use of DC (Diffusion Coefficient code) for NSTX-U [**Harvey**]
- AORSA/ORBIT-RF full-wave/Monte-Carlo code for HHFW modeling of NBI plasmas [**Choi**]
- SPIRAL code for HHFW + NBI modeling, using fields from TORIC [**Kramer**, Valeo, Bertelli, Phillips]
- Upgrade of NUBEAM with RF operator for HHFW modeling of NBI plasmas – important TRANSP upgrade for time dependent modeling [**Green**]

7.3.1.3 EBW/ECH (Supporting start-up and sustainment of long pulse high performance plasmas)

- GENRAY ray tracing and TORBEAM beam tracing for ECH modeling [**Harvey**, Bertelli]
- CQL3D for EBW heating and current drive modeling [**Harvey**]
- 1-D full-wave study of O-X-B mode conversion efficiencies with density fluctuations [**Green**]
- GENRAY ray tracing modeling with SOL model and edge fluctuations for EBW/ECH [**Bertelli**, Harvey, Bonoli, Phillips]

7.3.2 Diagnostics:

7.3.2.1 Fast IR camera for SOL power losses [**Hosea**, Perkins, Wilson]

7.3.2.2 Measurements of SOL E-fields during edge power loss [**Hosea**, Perkins, Wilson]

7.3.2.3 Magnetic and Langmuir probes in protective tiles above and below antenna to document RF power flow to divertor for comparison to advanced RF codes [**Hosea**, Perkins, Wilson]

7.3.2.4 Diagnostic enhancements to measure fast-ion distribution from HHFW acceleration [**Podesta**]

7.3.2.5 10-40 GHz reflectometer for edge and SOL density measurements [**Taylor**, Ryan]

7.3.2.6 Synthetic aperture imaging for EBW coupling efficiency and edge fluctuation measurements [**Taylor**]

7.3.2.7 Diagnostics for HHFW and EBW power deposition and current drive [**Taylor**]

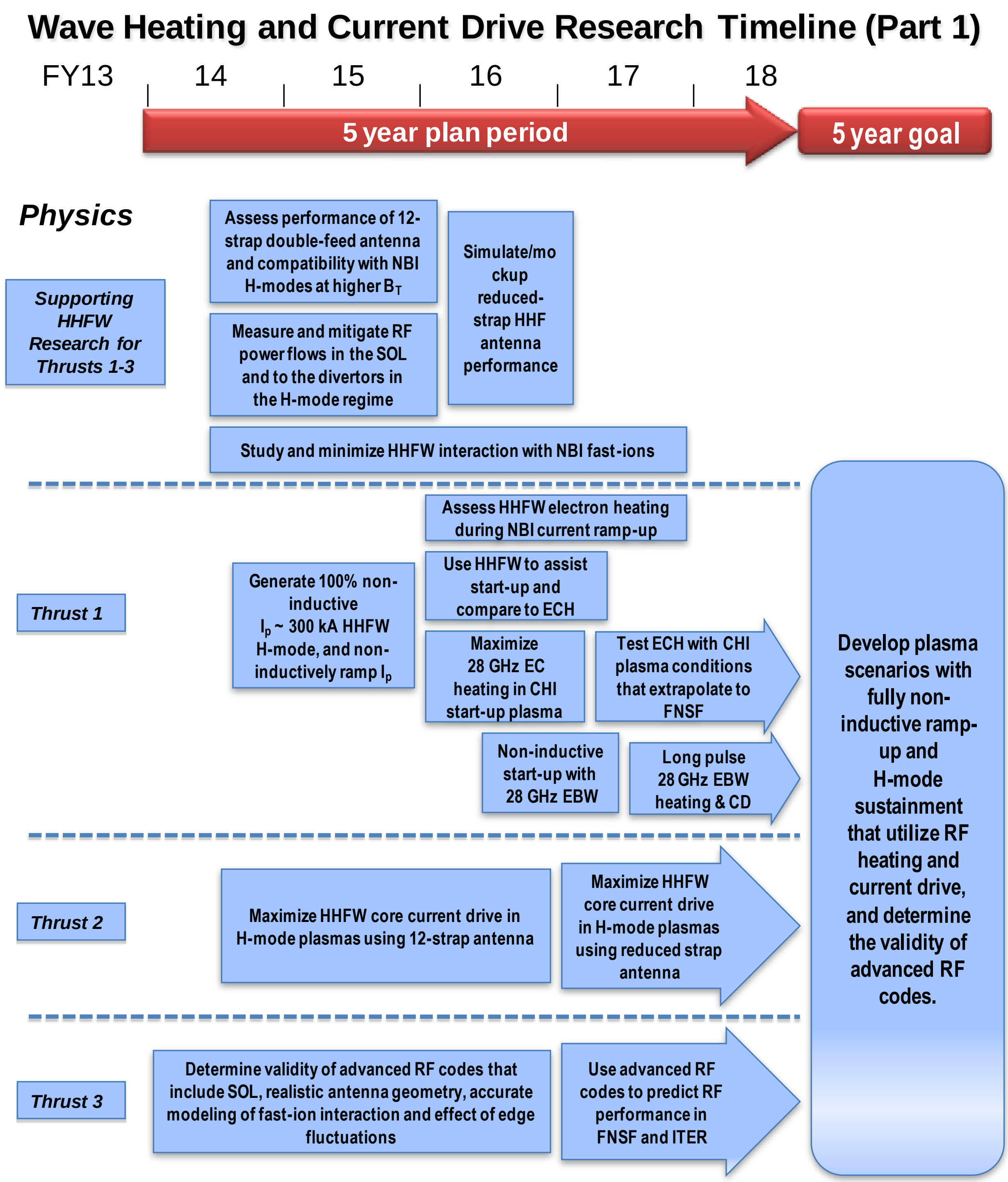
7.3.3 Other Facility Capabilities:

7.3.3.1 Implement compliant attachments between antenna current straps and RF feedthroughs to withstand 4x increase in disruption loads [**Hosea**, Ryan, Perkins, Wilson]

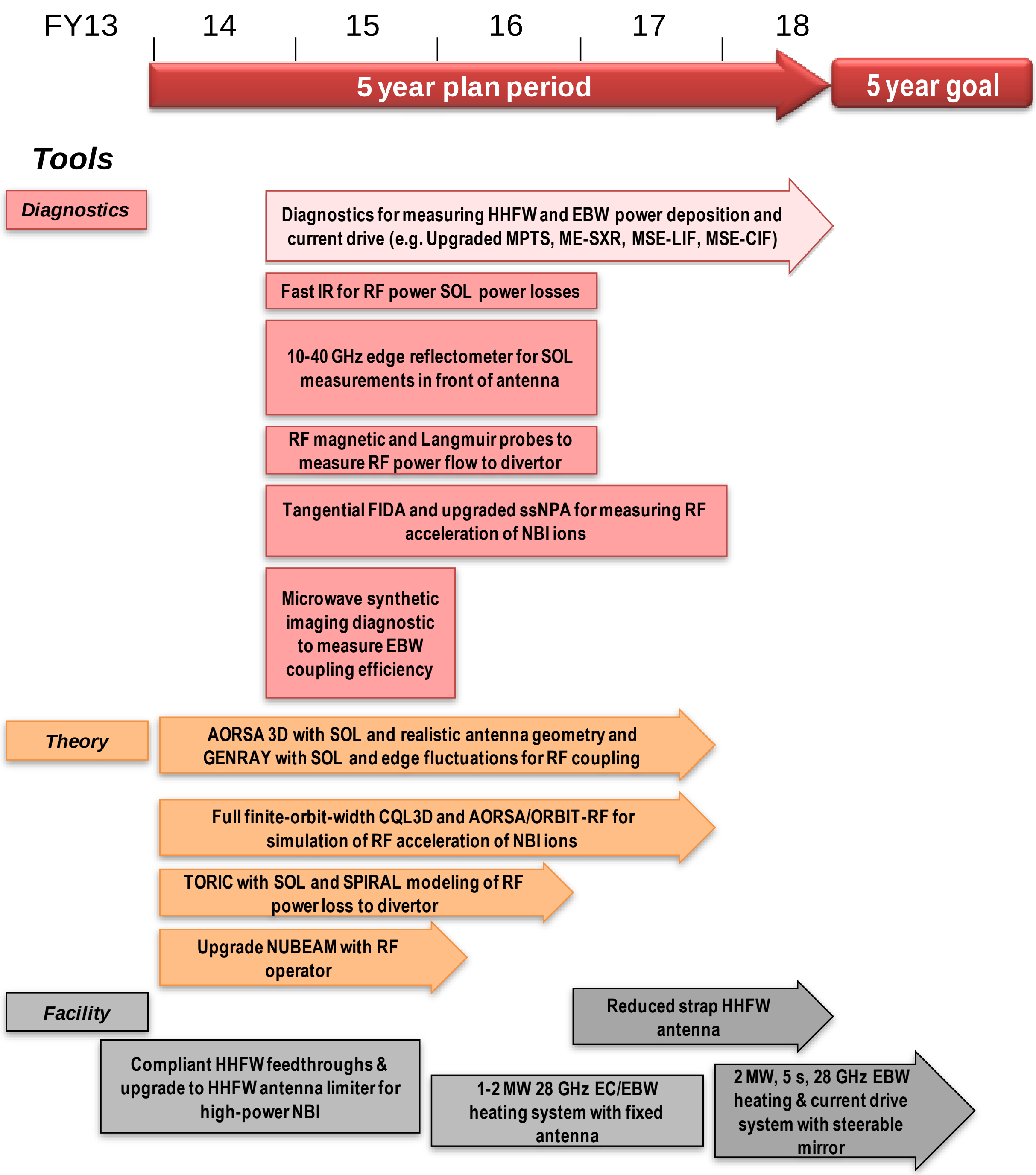
7.3.3.2 Modifications to NBI armor/limiter to allow HHFW operation with high NBI power [**Hosea**, Ryan, Perkins, Wilson]

7.3.3.3 Implement EHO and/or *AE antenna [**Hosea**, Fredrickson, Goldston]

7.3.3.4 Modify HHFW antenna to have reduced number of straps [**Hosea**, Ryan, Perkins, Wilson]
7.3.3.5 Implement 28 GHz (1-2 MW, 1-5s) EC/EBW heating system with fixed horn [**Taylor**, Ellis]
7.3.3.6 Upgrade 28 GHz EBW antenna to metal steerable mirror for EBW heating and current drive studies [**Taylor**, Ellis]


Wave Heating and Current Drive Research Timeline (Part 1)
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Supporting HHFW Research for Thrusts 1-3
Assess performance of 12-strap double-feed antenna and compatibility with NBI H-modes at higher B_T
Measure and mitigate RF power flows in the SOL and to the divertors in the H-mode regime
Simulate/mockup reduced-strap HHF antenna performance
Study and minimize HHFW interaction with NBI fast-ions
Thrust 1
Assess HHFW electron heating during NBI current ramp-up
Use HHFW to assist start-up and compare to ECH
Generate 100% non-inductive I_p ~ 300 kA HHFW H-mode, and non-inductively ramp I_p
Maximize 28 GHz EC heating in CHI start-up plasma
Test ECH with CHI plasma conditions that extrapolate to FNSF
Non-inductive start-up with 28 GHz EBW
Long pulse 28 GHz EBW heating & CD
Thrust 2
Maximize HHFW core current drive in H-mode plasmas using 12-strap antenna
Maximize HHFW core current drive in H-mode plasmas using reduced strap antenna
Thrust 3
Determine validity of advanced RF codes that include SOL, realistic antenna geometry, accurate modeling of fast-ion interaction and effect of edge fluctuations
Use advanced RF codes to predict RF performance in FNSF and ITER
Develop plasma scenarios with fully non-inductive ramp-up and H-mode sustainment that utilize RF heating and current drive, and determine the validity of advanced RF codes.

Wave Heating and Current Drive Research Timeline (Part 2)



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

Lead writer, supporting writers

Raman, Mueller, Nelson, Gerhardt, Kessel, Poli, Jarboe, Jardin – CHI
Redd, Raman, Mueller – Gun plasma start-up
Taylor, Raman, Mueller - ECH (closely coupled to Wave Particles TSG)

Raman and Mueller will write sections that do not have identifying authors

8.1 Overview of goals and plans

- 8.1.1 Establish predictive capability for the performance of FNSF

- 8.1.2 Thrusts and goals
  - 8.1.2.1 Demonstrate and understand solenoid-free current start-up
  - 8.1.2.2 Use CHI and point helicity injection as initial current seed for subsequent non-inductive current ramp-up

8.2 Research Plans

- 8.2.1 **Years 1-2:**
  - 8.2.1.1 Establish initial transient CHI discharges
  - 8.2.1.2 Use graphite divertor plates
  - 8.2.1.3 Use full Li coverage to reduce low-Z impurities
  - 8.2.1.4 Test benefits of (partial) upper metal divertor and Lithium during absorber arcs
  - 8.2.1.5 Initially couple to induction, then assess coupling to NBI
  - 8.2.1.6 Assess ramp-up of a 400kA inductive target with NBI (Raman, Kessel, Gerhardt)
  - 8.2.1.7 Establish plasma gun start-up in NSTX-U (Redd, Raman, Mueller)

- 8.2.2 **Years 3-5:**

  - 8.2.2.1 Establish CHI discharges using metal divertor plate electrodes
  - 8.2.2.2 Assess benefits and compare to QUEST results (if available)
  - 8.2.2.3 Assess benefits of cryo pumping in the absorber region
  - 8.2.2.4 Maximize current start-up

  - 8.2.2.5 Ramp a 400 kA inductive target using NBI (Raman,Kessel,Gerhardt)
  - 8.2.2.6 Ramp CHI target using 1 MW ECH, then HHFW for coupling to NBI (Raman, Kessel, Gerhardt)
  - 8.2.2.7 Couple plasma gun started plasma to induction and NBI (Redd, Raman,Mueller)

8.3 Summary timeline for tool development to achieve research goals

8.3.1 Theory and simulation capabilities

8.3.1.1 2D resistive MHD simulations – TSC (Raman, Kessel, Poli)
8.3.1.2 3D Resistive MHD simulations – NIMROD, M3D
8.3.1.3 GENRAY for ECH/EBW (Taylor)
8.3.1.4 PTRANSP for NBI coupling to low-Ip CHI plasma (Raman, Kaye, Gerhardt)

8.3.2 Diagnostics

8.3.2.1 New additional fast voltage monitors for upper divertor
8.3.2.2 Additional dedicated current monitors near injector
8.3.2.3 Special set of EMI shielded inner vessel magnetics (Raman, Gerhardt)
8.3.2.4 Additional flux loops and Mirnov coils on lower and upper divertor (Raman, Gerhardt)
8.3.2.5 Langmuir probe array on lower divertor (Raman, Jaworski)
8.3.2.6 Multipoint Thomson scattering, Filter scopes, multi chord bolometers and SXR arrays (Raman, Ahmed, Vlad, Tritz)

8.3.3 Other facility capabilities including plasma control

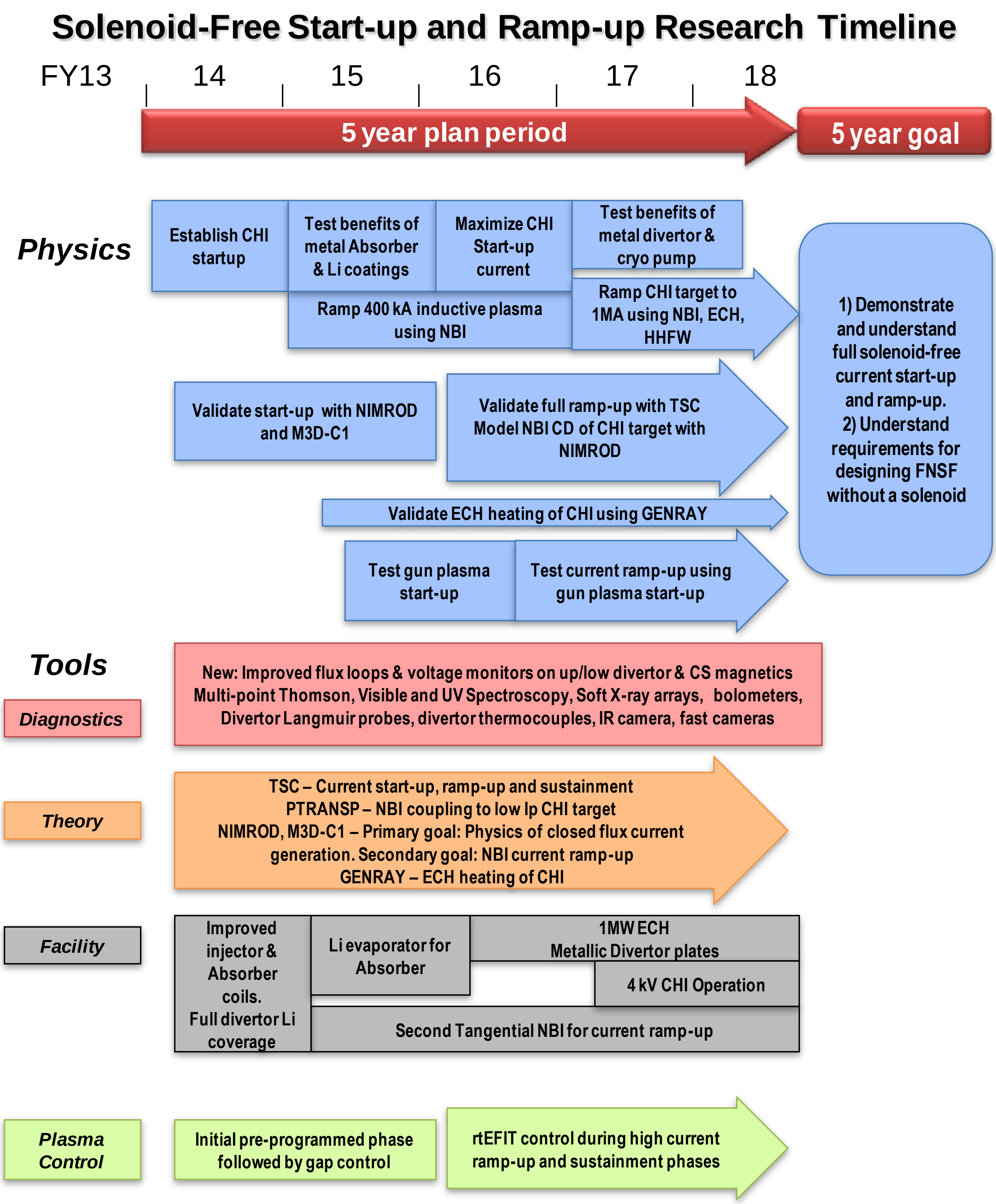
8.3.3.1 2nd NBI for coupling to low-Ip CHI plasma

8.3.3.2 Baseline capacitor bank power supply
8.3.3.2.1 Voltage increased to ~2 kV & improve voltage snubbing systems
8.3.3.2.2 NSTX-U to support 4kV Ops including transients
8.3.3.2.3 Design study of next generation power supply system

8.3.3.3 Upgraded capacitor bank power supply
8.3.3.3.1 Voltage increased to ~3 kV, bank energy increased to 200 kJ
8.3.3.3.2 Additional modules for improved voltage control

8.3.3.4 1MW → 2MW ECH for heating low-Ip CHI plasma

8.3.3.5 Point helicity sources/plasma guns


Solenoid-Free Start-up and Ramp-up Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Physics
Establish CHI startup
Test benefits of metal Absorber & Li coatings
Maximize CHI Start-up current
Test benefits of metal divertor & cryo pump
Ramp 400 kA inductive plasma using NBI
Ramp CHI target to 1MA using NBI, ECH, HHFW
1) Demonstrate and understand full solenoid-free current start-up and ramp-up.
2) Understand requirements for designing FNSF without a solenoid
Validate start-up with NIMROD and M3D-C1
Validate full ramp-up with TSC Model NBI CD of CHI target with NIMROD
Validate ECH heating of CHI using GENRAY
Test gun plasma start-up
Test current ramp-up using gun plasma start-up
Tools
Diagnostics
New: Improved flux loops & voltage monitors on up/low divertor & CS magnetics
Multi-point Thomson, Visible and UV Spectroscopy, Soft X-ray arrays, bolometers,
Divertor Langmuir probes, divertor thermocouples, IR camera, fast cameras
Theory
TSC – Current start-up, ramp-up and sustainment
PTRANSP – NBI coupling to low Ip CHI target
NIMROD, M3D-C1 – Primary goal: Physics of closed flux current generation. Secondary goal: NBI current ramp-up
GENRAY – ECH heating of CHI
Facility
Improved injector & Absorber coils. Full divertor Li coverage
Li evaporator for Absorber
1MW ECH
Metallic Divertor plates
4 kV CHI Operation
Second Tangential NBI for current ramp-up
Plasma Control
Initial pre-programmed phase followed by gap control
rtEFIT control during high current ramp-up and sustainment phases

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

9.1. Overview of goals and plans (Gerhardt)

9.1.1. Develop the basis for steady state operations and axisymmetric plasma control for next step STs while helping resolve key scenario and control issues for ITER.

9.1.2. Thrusts and goals by topical area

9.1.2.1. Scenario development
9.1.2.2. Axisymmetric control development
9.1.2.3. Event handling
9.1.2.4. Scenario optimization for next step devices

9.2. Research Plans

9.2.1. **Thrust 1 – Scenario Development (Mostly Gerhardt, some Raman & Taylor)**

9.2.1.1. Pursue 100% Non-Inductive Current at high β and progressively Higher I_P and B_T
- 9.2.1.1.1. Year 1: 0.75T, 600-800kA, few tau-E
- 9.2.1.1.2. Year 2: 0.75-1T, 600-800kA, few tau-R
- 9.2.1.1.3. Years 3-5: 1T, 800-1300kA, up to 4-5s
- 9.2.1.1.4. Utilize cryo-pump for density control in these scenarios
- 9.2.1.1.5. Assess impact of metal PFC on scenarios

9.2.1.2. Develop Long-Pulse Partial Inductive Operation Up to 2 MA, High Power
- 9.2.1.2.1. Two types of partial inductive operation:
  - 9.2.1.2.1.1. High-I_P operation supports collisionality scaling and divertor heat flux studies
  - 9.2.1.2.1.2. Long pulse operation for particle retention and disruptivity reduction studies
- 9.2.1.2.2. Years 1 & 2: Re-optimize startup for reduced fuelling at IP=1200-1500 kA
  - 9.2.1.2.2.1. Goal: Enhance utility of Li pumping by reducing the early gas load
- 9.2.1.2.3. Years 3-5: Performance Extension
  - 9.2.1.2.3.1. Discharges up to 2 MA for 5 seconds
  - 9.2.1.2.3.2. Long pulse at ~1 MA for up to 10 seconds
  - 9.2.1.2.3.3. Utilize cryo-pump for density control in these scenarios
  - 9.2.1.2.3.4. Assess impact of metal PFCs on scenarios
  - 9.2.1.2.3.5. High-I_P development is connected to progress on heat flux mitigation

9.2.1.3. RF Heating for improved NSTX-U scenarios (Gerhardt, Taylor)
- 9.2.1.3.1. Assess HHFW heating for increasing T_e and the non-inductive fraction in high-performance plasmas

9.2.1.3.2. Assess EBW H&CD for optimization of current and pressure profiles in steady state.
9.2.1.4. Coupling to non-inductive ramp-up (w/SFSU) (Gerhardt, Raman)

9.2.2. **Thrust 2 – Axisymmetric Control Development**
9.2.2.1. n=0 Boundary and VDE control (Kolemen, Gerhardt)
9.2.2.1.1. Assess and improve n=0 vertical stability
9.2.2.1.2. Incorporate bipolar PF-2 coils into shape and n=0 control loop
9.2.2.1.3. Develop MIMO shape control for improved inner and bottom gap regulations
9.2.2.2. Axisymmetric Divertor Control
9.2.2.2.1. Years 1 & 2: (Kolemen, Soukhanovskii, Gerhardt)
9.2.2.2.1.1. Develop upper/lower snowflake control at higher current
9.2.2.2.1.2. Assess schemes for dual X-point control w/ new divertor coils
9.2.2.2.1.3. Assess magnetic balance control in the presence of 4 X-points
9.2.2.2.1.4. Document heat flux reductions compared to standard DN
9.2.2.2.2. Years 3-5: (Gerhardt, Soukhanovskii)
9.2.2.2.2.1. Utilize cryopump and divertor upgrades to control density in long pulse scenarios
9.2.2.2.2.2. Years 3-5: Pending progress in BP TSG, begin implementation of closed loop radiative divertor control
9.2.2.3. Current and Rotation Profile Control (Gerhardt, Park, Kolemen, Yuh, Sabbagh, Podesta)
9.2.2.3.1. Years 1 & 2: realtime diagnostics and testing
9.2.2.3.1.1. Feed-forward test ability of different beam combinations to modify the q-profile. (Gerhardt)
9.2.2.3.1.2. Install and commission rtMSE and implement as constraint in rtEFIT. (Yuh, Kolemen)
9.2.2.3.2. Years 2-4: Current and rotation profile control tests (Kolemen, Gerhardt)
9.2.2.3.2.1. Complete controllers for $\beta_N + q_{min}$, $\beta_N + F_{T,0}$ control
9.2.2.3.2.2. Develop first β_N + F profile control
9.2.2.3.3. Years 4-5
9.2.2.3.3.1. Utilize NCC coil for better NTV control (Sabbagh, Park, Sabbagh)
9.2.2.3.3.2. Assess feasibility of combined control (for instance, $\beta_N+q_{min}+F_{T,0}$ profile control) (Kolemen, Gerhardt)

9.2.3. Thrust 3 - Disruption Avoidance and Off-Normal Event Handling
9.2.3.1. Years 1 & 2: (Gerhardt)
9.2.3.1.1. Implement basic detector in PCS, and design architecture of control response
9.2.3.1.2. Incorporate data from new “Digital Coil Protection System”
9.2.3.1.3. Assess accuracy of predictor for NSTX-U disruptions, and refine as necessary

9.2.3.1.4. Do initial tests of automated rampdowns

9.2.3.2. Years 3-5 (Gerhardt)

9.2.3.2.1. Add additional realtime diagnostics for improved detection fidelity

9.2.3.2.2. Optimize rampdowns for different types of alarms

9.2.3.2.3. Incorporate closed loop MGI if it appears promising

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

9.2.4.1. Study optimal profiles for high confinement and good stability (Gerhardt)

9.2.4.1.1. Years 3-5: Simultaneous optimization of the current and rotation profile for best confinement and global stability

9.2.4.1.2. Years 3-5: Explore alternative optimal scenarios - EPH or w/ ITBs

9.2.4.2. Study the conditions for classical beam current drive (Gerhardt)

9.2.4.2.1. Years 1-2: Study what parameters determine when *AE modes lead to anomalies in the fast ion diffusion and NBCD

9.2.4.2.2. Years 3-5: Determine if anomalous diffusion be used for scenario optimization.

9.2.4.3. Pedestal control tools (Gerhardt, Soukhanovskii,…)

9.2.4.3.1. ELM pacing with Li pellets.

9.2.4.3.2. Pedestal control w/ 3D fields.

9.2.4.4. Explore & validate integrated models for projections to FNSF (Gerhardt, Guttenfelder)

9.2.4.4.1. Years 1-2: Compare NBCD & q-profile predictions from integrated codes to NSTX-U

9.2.4.4.2. Years 3-4: Test reduced transport models against profiles from most attractive scenario targets.

9.2.4.4.3. Years 3-5: Use knowledge to project scenarios to ST FNSF devices

9.3. Summary timeline for tool development to achieve research goals

9.3.1. Theory and simulation capabilities (Gerhardt, Guttenfelder, Kaye)

9.3.1.1. TRANSP/pTRANSP/NCLASS

9.3.1.2. GTS

9.3.1.3. GTC-Neo

9.3.1.4. FIDASIM

9.3.1.5. Reduced thermal transport model?

9.3.1.6. Reduced fast-ion redistribution model?

9.3.2. Diagnostics (Gerhardt)

9.3.2.1. Real-time rotation

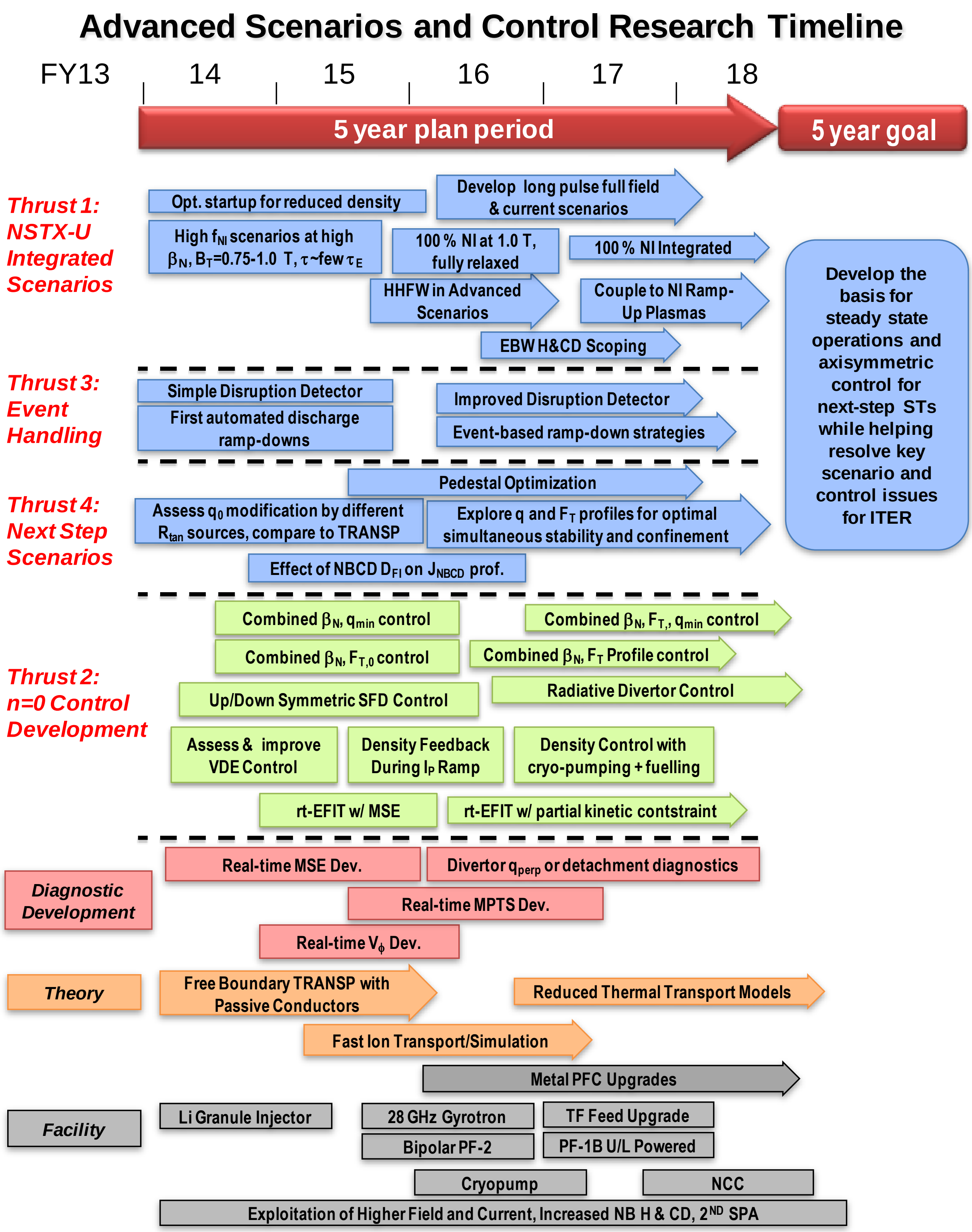
9.3.2.2. Real-time MSE

9.3.2.3. Real-time Thomson Scattering

9.3.2.4. Real-time neutron rate

9.3.3. Other facility capabilities including plasma control

9.3.3.1. 2nd NBI for current and rotation profile actuator (Gerhardt)
9.3.3.2. 2nd SPA for NTV rotation braking control (Gerhardt)
9.3.3.3. Divertor cryopumps for density control (Gerhardt, Canik)
9.3.3.4. NCC for NTV rotation braking control (Park, Sabbagh, Gerhardt)
9.3.3.5. EBW heating and current drive for J-profile control in advanced scenarios (Taylor, Gerhardt)


Advanced Scenarios and Control Research Timeline
FY13
14
15
16
17
18
5 year plan period
5 year goal
Thrust 1: NSTX-U Integrated Scenarios
Opt. startup for reduced density
Develop long pulse full field & current scenarios
High f_{NI} scenarios at high β_N, B_T=0.75-1.0 T, τ~few τ_E
100 % NI at 1.0 T, fully relaxed
100 % NI Integrated
HHFW in Advanced Scenarios
Couple to NI Ramp-Up Plasmas
EBW H&CD Scoping
Develop the basis for steady state operations and axisymmetric control for next-step STs while helping resolve key scenario and control issues for ITER
Thrust 3: Event Handling
Simple Disruption Detector
First automated discharge ramp-downs
Improved Disruption Detector
Event-based ramp-down strategies
Thrust 4: Next Step Scenarios
Pedestal Optimization
Assess q_0 modification by different R_{tan} sources, compare to TRANSP
Explore q and F_T profiles for optimal simultaneous stability and confinement
Effect of NBCD D_{FI} on J_{NBCD} prof.
Thrust 2: n=0 Control Development
Combined β_N, q_{min} control
Combined β_N, $F_{T,}$, q_{min} control
Combined β_N, $F_{T,0}$ control
Combined β_N, F_T Profile control
Up/Down Symmetric SFD Control
Radiative Divertor Control
Assess & improve VDE Control
Density Feedback During I_P Ramp
Density Control with cryo-pumping + fuelling
rt-EFIT w/ MSE
rt-EFIT w/ partial kinetic contstraint
Diagnostic Development
Real-time MSE Dev.
Divertor q_{perp} or detachment diagnostics
Real-time MPTS Dev.
Real-time V_ϕ Dev.
Theory
Free Boundary TRANSP with Passive Conductors
Reduced Thermal Transport Models
Fast Ion Transport/Simulation
Facility
Metal PFC Upgrades
Li Granule Injector
28 GHz Gyrotron
TF Feed Upgrade
Bipolar PF-2
PF-1B U/L Powered
Cryopump
NCC
Exploitation of Higher Field and Current, Increased NB H & CD, 2ND SPA

10. NSTX-U Facility Status and Proposed Upgrades

10.1. Abstract
10.2. Facility Overview

10.2.1. Facility Status and Plan
- 10.2.1.1. New Center Stack Upgrade
- 10.2.1.2. Second Neutral Beam Injection System Upgrade
- 10.2.1.3. NSTX-U Facility Subsystems
  - 10.2.1.3.1. Other Heating and Current Drive Systems
    - 10.2.1.3.1.1. HHFW and upgrades Upgrades
    - 10.2.1.3.1.2. 1/2MW 28GHz ECH/EBW system
  - 10.2.1.3.2. Macro-stability Tools
    - 10.2.1.3.2.1. 2nd SPA
    - 10.2.1.3.2.2. NCC
  - 10.2.1.3.3. Boundary Physics Tools
    - 10.2.1.3.3.1. Divertor Cryo-pump
    - 10.2.1.3.3.2. EHO antenna
    - 10.2.1.3.3.3. Fueling tools, real-time density diagnostics
  - 10.2.1.3.4. Advanced Plasma Facing Components
    - 10.2.1.3.4.1. Upgraded lithium coating systems
    - 10.2.1.3.4.2. High-Z metallic divertor
    - 10.2.1.3.4.3. High-Z outer and inner wall PFCs
    - 10.2.1.3.4.4. Flowing liquid lithium divertor/module
  - 10.2.1.3.5. Start-up and Ramp-up
    - 10.2.1.3.5.1. CHI upgrades
    - 10.2.1.3.5.2. Plasma guns

10.2.2. NSTX-U Diagnostic System Status and Plans
- 10.2.2.1. Profile Diagnostics
- 10.2.2.2. Turbulence Diagnostics
- 10.2.2.3. MHD Diagnostics
- 10.2.2.4. Boundary Physics Diagnostics
- 10.2.2.5. Energetic Particle Diagnostics
- 10.2.2.6. Wave Diagnostics
- 10.2.2.7. Start-up, ramp-up, and sustainment diagnostics

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

10.3. NSTX-U Facility Utilization

11. NSTX-U Collaboration Research Plans