Review of NSTX-U research milestones R18-6 and R19-4

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on behalf of the ASC TSG

FY2018-19 Research Milestone Review
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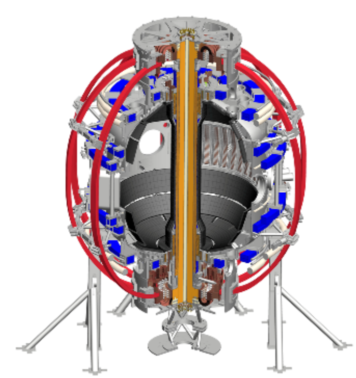
PPPL



Proposed changes to milestones

- R18-6 Simulation framework development for NSTX-U high-performance scenarios
  - Divide original milestone over FY18 and FY19
  - Provide greater detail on tasks in each fiscal year
  - Increased emphasis on connection to MAST-U collaboration
    - Add startup modeling (planned for FY17 summer)

- R19-4 Commission physics and operational tools for obtaining high-performance discharges in NSTX-U
  - Defer to FY20

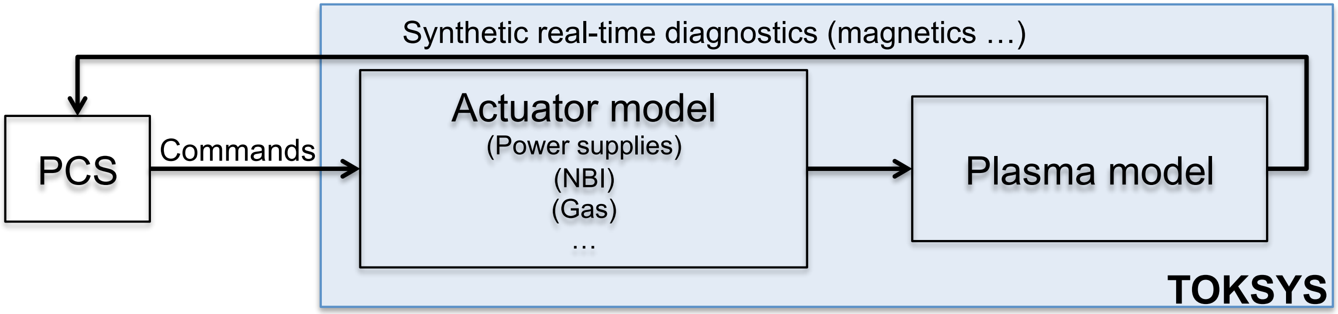
Review of R(17-5): Analysis & modeling of current ramp-up dynamics

- Evaluate elongation limits during ramp-up phase using data and calculations
  - What factors limit the elongation before, during and after diverting?
  - Identify growth rate of vertical instability to predict controllability of high-κ shapes in ramp up
- Establish the dependence of the L-H transition on density, plasma shape, etc. to inform modeling of threshold criteria and scenario targets
- Perform stability analysis of experimental and modeled discharges to identify MHD limits during ramp-up
- Prepare for R18-6: work through technical issues for TOKSYS framework with GA
- Prepare for R18-6: begin TRANSP analysis of ramp-up phase

R(18-6): Develop simulation framework to optimize *breakdown and* ramp-up *in STs*

- Develop TOKSYS framework with free-boundary equilibrium solver in plasma model
  - Reproduce ramp-up cases from NSTX-U with fixed profile evolutions, plasma inductance, resistance, etc.
    - Evaluate if observed shape evolutions are reproduced using PCS algorithms
  - Requires wall, power supply, magnetic diagnostic models (FY17)
    - Implement the same for MAST-U (FY18)

- Apply model to gain insight into shape limits and control
  - Evaluate vertical stability limits during ramp-up in simulation
    - Consider MAST-U and NSTX-U with both pre- and post-recovery designs
  - Use simulation tool to optimize shape control during ramp up
    - Most interested in control around time of diverting (avoid "the bobble")
    - Evaluate trade-off between rtEFIT resolution / constraints and computational time



R(18-6): Develop simulation framework to optimize *breakdown and* ramp-up *in STs*

- Investigate NSTX-U ramp-up dynamics using TRANSP
  - Identify range of NSTX / NSTX-U cases to characterize
    - Use experimental and TRANSP results to evaluate MHD (MS-TSG) and fast ion stability (EP-TSG) in ramp-up
  - Investigate impact of changes in NBI voltage and combos on stability with fixed equilibrium and T, n, Z_{eff} profiles
    - Which beams and shapes are best for startup?

- Develop and evaluate start-up calculations for NSTX-U and MAST-U

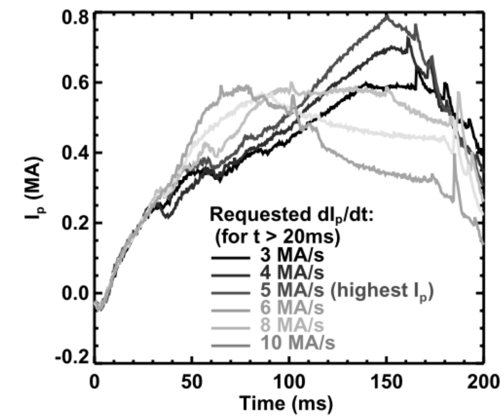
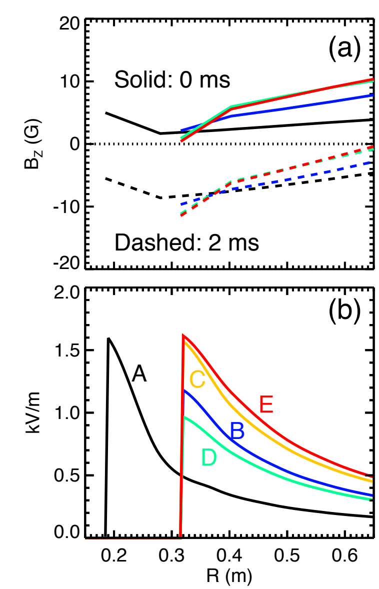


Figure 2. Plasma current traces obtained during a systematic scan of the plasma current ramp rate.

NSTX-U breakdown calculations



R19-?: Optimize ramp-up scenarios and control for spherical tokamaks

- Extend TOKSYS to use reduced models for current and pressure profiles and in L- and H-mode
  - Investigate scenario and control optimization for ramp-up with early heating and examine resiliency to timing of L-H transition
- Extend TRANSP simulation to employ more physics-based models
  - Evolve T_e and T_i based on transport model or neural-net model found to best reproduce experimental data
  - Use neutral fueling feedback in TRANSP to match density request, if available
  - Use free-boundary solver to optimize shape evolution

R19-?: Optimize ramp-up scenarios and control for spherical tokamaks

- Apply available tools to investigate impact of heating mix and timing
  - Experiments will ask for beams at different voltage combinations
- Investigate influence of early density on the ramp-up
- Evaluate the trade-offs in I_p ramp-rate
  - What are the stability limits?
  - What is the impact on shape and stability due to wall currents?
  - Apply MHD and fast-ion stability calculations to characterize stability boundaries in a range of cases
- Perform targeted experiments on MAST-U and NSTX-U

Original FY19 milestone should be deferred to FY20

- Evaluate wall-conditioning boron vs lithium in NSTX-U
  - Evaluate ELM-pacing for impurity control in ELM-free regimes

- Demonstrate optimize ramp-up scenarios for achieving high-elongation and large I_p
  - Assess vertical stability at low-li, identify limiting mechanisms

- Re-optimize EFC and implement in control algorithm
  - Also, start active RWM feedback

- Evaluate stability limits and non-inductive fraction

R(18-6): Simulation framework development for optimizing discharge breakdown and ramp-up in spherical tokamaks

Access to high-performance discharges in spherical tokamaks (STs) requires an optimization of the first phase of the plasma discharge, which includes the initial generation of a plasma discharge (i.e. breakdown) and the increase of the plasma current to the target value (i.e. ramp-up) . Free parameters in the ramp-up phase include the rate of the I_p ramp, the magnitude and timing of neutral gas fueling and neutral beam heating, the evolution of the plasma shape and the timing of the L-H transition. An ideal ramp-up scenario would minimize the internal inductance and flux consumption realized at the start of flattop while exhibiting reasonable resilience to variations in the neutral beam turn-on time and plasma impurity content. This milestone aims to develop and apply computational tools that will accelerate the optimization of the breakdown and ramp-up phase on NSTX-U and MAST-U. The first computational framework that will be developed is a reduced model framework, such as TOKSYS, that links the real-time plasma control algorithms with a time-dependent model including the power supply capabilities, toroidal currents induced in the vessel structures and a free-boundary plasma equilibrium. This model will be used to gain insight into the vertical stability limits during ramp-up and the impact of power supply, wall structures and plasma parameters on the maximum stable elongation in STs. This framework will also be used to develop, test and optimize the real-time control algorithms in the ramp-up phase. For example, the trade-off between the resolution and assumptions used in real-time EFIT versus computational speed can be examined in terms of plasma stability and control tolerances. A second framework approach will use comprehensive transport simulation, such as TRANSP, to investigate the evolution of the kinetic profiles during ramp-up as a function of the free parameters. The initial goal is to optimize the outer gap, density and neutral beam heating in the L- and H-mode phases of the ramp-up that minimize l_i and flux consumption while remaining within MHD and fast-ion stability limits. The results from the first reduced model framework will provide guidance on the target high-elongation shapes, while the second transport model framework will provide guidance on the evolution of equilibrium parameters such as l_i and β_N. This milestone also aims to develop a simulation framework that can be used to optimize the inductive plasma breakdown. The primary goal of this activity is to optimize the null formation and initial increase of the vertical fields on MAST-U and NSTX-U in order to simultaneously conserve volt-seconds and achieve high reliability of breakdown over a range of ohmic solenoid pre-charge and toroidal field currents. The proposed development of simulation frameworks described in this milestone will reduce the experimental studies required to achieve a suitable optimization of the breakdown and ramp-up scenarios for accessing high-performance scenarios on NSTX-U and MAST-U.

R19-?: Optimize ramp-up scenarios and control for spherical tokamaks

This milestone leverages the simulation capabilities developed as part of the 18-6 milestone to realize optimized ramp-up scenarios on NSTX-U and MAST-U. This requires the continued development of the simulation frameworks and dedicated experiments on the two devices. The reduced model framework (TOKSYS) will be extended to include the evolution of the q-profile, temperature, density and fast-ion pressure. The reduced models for the kinetic profiles will be derived from transport models, such as TRANSP, and experimental results. These advances in the model will be leveraged to examine the resiliency of the ramp-up scenarios to expected experimental variations, such as the timing of the L-H transition and the temporary loss or delayed turn-on of a neutral beam. This framework will allow the development of real-time algorithms that can improve the resiliency of the scenarios. For example, experiments on NSTX-U demonstrated that a new control scheme that alters the outer boundary of the plasma shape to achieve a target inner gap distance improved the resiliency of the time of diverting to variations in the neutral beam heating. The transport modeling framework (TRANSP) will be extended to remove assumptions from the initial studies pursued in FY18. For example, the evolution of T_e and T_i would be based on a flux-driven transport model that was benchmarked on a database of ST ramp-up results. This capability would be leveraged to examine the plasma resistivity and current profile relaxation, which are significant drivers of the internal inductance, ohmic flux consumption and MHD stability. Another goal would be to implement a neutral fueling model that would alter the edge fueling to match a target L-mode density, similar to what can be achieved in the experiment. Targeted experiments on NSTX-U and/or MAST-U would be conducted to test the simulation results and provide continued refinement to the assumptions of the models.

Backup

H-mode flattop performance depends on the I_p ramp-up

- **NSTX fiducial** had L-H transition before 150ms
  - l_i ~ 0.5, κ ~ 2.4 with P_{NBI} = 5.8 MW
- NSTX-U: progress in obtaining early L-H transition, higher I_p and κ
  - **202946 → 203679 → 204112**
  - Enabled by increase in P_{NBI}, improvements in shape control, EFC
- Access to higher I_p (> 1.6 MA) and κ (> 2.4) requires further ramp-up development during next run