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Disruption Prediction and Avoidance at High Beta in NSTX-U – Spherical Tokamak Science and Real-Time Application - Deliverables

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Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 1

- **Element 1: Fundamental physics analysis with direct support for disruption prediction**
  - 1) (no budgeted manpower for physics analysis of Element 1 in FY21)
  - ADDITION: Expanded equilibrium reconstruction analysis as requested by NSTX-U management and team members
  - Status: started implementing NSTX-U device conducting structure alteration (w/Stefano, Devon), increasing equilibrium resolution, etc.
- **Element 2: Physics-based disruption prediction validation and expanded development**
  - 1) (no budgeted manpower for physics analysis of Element 2 in FY21)
- **Element 3: Real-time disruption avoidance analysis and control**
  - 1) Update NSTX-U VALEN 3D models to allow VALEN analysis
  - 2) Update the VALEN 3D model for the RWM state-space controller and equilibrium reconstruction support

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 2

- **Element 1: Fundamental physics analysis with direct support for disruption prediction**
  - 1) Update between-shot run workflow for kinetic equilibrium reconstructions of NSTX-U plasmas, distributed to the NSTX-U Team
  - 2) Implement and test a plasma torque balance model including resonant braking by magnetic island formation in the DECAF code to predict loss of torque balance and bifurcation leading to mode locking
  - 3) Update and interface software to compute low frequency MHD spectroscopy for NSTX-U
- **Element 2: Physics-based disruption prediction validation and expanded development**
  - 1) Prepare interface of offline disruption forecasting analysis to the NSTX-U off-normal event handler (preparation for real-time interface)
  - 2) Expand the initial plasma torque balance model in DECAF to include the evolution of the island size in predicting loss of torque balance and bifurcation of the island rotation frequency leading to mode locking
- **Element 3: Real-time disruption avoidance analysis and control**
  - 1) Interface to magnetic pick-up loops for input to real-time MHD computer

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 3 (I)

- **Element 1: Fundamental physics analysis with direct support for disruption prediction**
  - 1) Generate kinetic equilibrium reconstructions with the self-consistent inclusion of toroidal rotation and separation of pressure and magnetic flux surfaces
  - 2) Conduct assessment of stability limits on normalized β and plasma rotation, V_ϕ, at the increased aspect ratio of NSTX-U
  - 3) Conduct experiments and analysis to examine passive RWM stabilization at initial values of lower collisionality
  - 4) Determine behavior of passive RWM stabilization as a function of plasma rotation at further reduced collisionality
  - 5) Test theory/model developments in long-pulse NSTX-U plasmas especially the expected dependence of NTV strength at lower collisionality with dominant non-resonant n = 1, 2, and 3 applied fields.
  - 6) Compare the results of low frequency MHD spectroscopy as a measure of the proximity of mode marginal stability to corresponding theoretical stability analysis and to disruption forecasting based on DECAF analysis. Analyze resonant field amplification (RFA) for future real-time (r/t) disruption avoidance
  - 7) Demonstrate outer rotation profile control based on the Generalized Neoclassical Toroidal Rotation Profile effect (requires high harmonic fast wave, HHFW

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 3 (II)

- **Element 2: Physics-based disruption prediction validation and expanded development**
  - 1) Generate non-existing databases that are required to validate preferred high-performance operational regimes for disruption prediction (e.g. 100% non-inductive current scenarios)
  - 2) Analyze resonant field amplification (RFA) for use in disruption prediction
  - 3) Analyze RWM state space control observer for use in disruption prediction
  - 4) Conduct offline validation of magnetic pick-up loops for disruption forecasting
- **Element 3: Real-time disruption avoidance analysis and control**
  - 1) Complete testing of RWM state space controller w/2nd SPA, n > 1, etc.; establish dual field component Br + Bp PID control for NSTX-U
  - 2) Use of r/t RWM state-space controller observer for disruption forecast
  - 3) Quantitatively evaluate real-time disruption forecasting analysis output sent to the NSTX-U off-normal event handler
  - 4) Perform RWM PID and state-space control for disruption avoidance and related physics studies (e.g. partial coil coverage, non-optimal sensor set)
  - 5) Interface to real-time V_ϕ for input to disruption forecasting
  - 6) Implement and use real-time NBI control for disruption avoidance from r/t physics-based analysis

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 4 (I)

- **Element 1: Fundamental physics analysis with direct support for disruption prediction**
  - 1) Conduct experiments and analysis to examine passive RWM stabilization at further reduced values of collisionality
  - 2) Determine behavior of passive RWM stabilization as a function of plasma rotation at further reduced collisionality
  - 3) Conduct experiments and analysis of pre-programmed rotation (and possible equilibrium profile) control for RWM stabilization in NSTX-U
  - 4) Test unified global MHD stabilization physics theory in NSTX-U plasmas
  - 5) Perform NTM analysis for NSTX-U plasmas including the pressure gradient and magnetic field curvature terms in the modified Rutherford equation. Compare results to classical tearing mode stability analysis; determine the impact of low aspect ratio on resistive stability analysis, including the curvature effect for steady-state plasma profiles in NSTX-U and KSTAR

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 4 (II)

- **Element 2: Physics-based disruption prediction validation and expanded development**
  - 1) Generate databases that are high performance but also low disruptivity based on offline disruption prediction analysis (continues into later years)
  - 2) Perform offline validation of V□ control for input to disruption forecasting
  - 3) Prepare an initial simplified real-time model of NTV profile as a function of applied field and available plasma parameters for use in initial plasma rotation control system
  - 4) Conduct offline validation of the effectiveness of using real-time pitch angle measurement by MSE for disruption forecasting
  - 5) Utilize initial NSTX-U ME-SXR and poloidal USXR diagnostics to characterize the RWM eigenfunction by non-magnetic means
- **Element 3: Real-time disruption avoidance analysis and control**
  - 1) Interface to real-time Thomson for input to disruption forecasting
  - 2) Interface to real-time pitch angle data from MSE for input to disruption forecasting
  - 3) Implement and use real-time RFA-based control for disruption avoidance, interfaced to r/t physics-based analysis
  - 4) Determine physics implications of scenarios that overload 3D field and NBI actuators for simultaneous use in meeting open-loop requests for plasma profile targets for rotation, q, β_N, and other key parameters for disruption avoidance; determine actuator prioritization
  - 5) Real-time plasma shape control for disruption avoidance from r/t physics-based analysis
  - 6) Examine multi-mode RWM in stability/control, partial sensor and actuator coil coverage

Columbia U. Disruption Prediction and Avoidance - NSTX-U deliverables – Summary for Year 5

- **Element 1: Fundamental physics analysis with direct support for disruption prediction**
  - 1) Analyze the disruption event chains in NSTX-U through DECAF analysis as a function of plasma non-inductive fraction
  - 2) Extend the reduced model of resistive MHD stability for DECAF utilizing the proposed resistive stability analyses, and to determine the accuracy of the analysis to allow reliable disruption forecasting warnings when compared to experimental MHD mode detection
- **Element 2: Physics-based disruption prediction validation and expanded development**
  - 1) Generate a comprehensive, quantitative, validated physics-based disruption forecasting analysis covering all major causes of both minor and major disruptions (e.g. stability, transport (power balance, momentum balance), technical issues, etc.)
  - 2) Conduct offline validation of the effectiveness of using real-time delta-B profile measurement by MSE for disruption forecasting
- **Element 3: Real-time disruption avoidance analysis and control**
  - 1) Interface to real-time delta-B measurement by MSE for input to disruption forecasting
  - 2) Apply developments of NTV model to model used for r/t V_ϕ control
  - 3) Implement and use real-time V_ϕ control for disruption avoidance from r/t physics-based analysis using both NBI and NTV as actuators, interfaced to r/t physics-based analysis