NSTX-U

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NSTX-U 5 Year Plan for Macroscopic Stability

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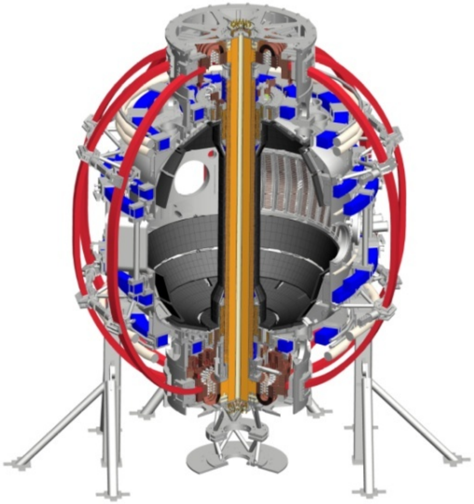

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Overall objective: establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

- Overview of 2014-2018 NSTX-U Five Year Plan
  - Thrust 1, Stability:

    Understand and advance passive and active feedback control to sustain macroscopic stability at low collisionality
  - Thrust 2, 3D Fields:

    Understand 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields
  - Thrust 3, Disruptions:

    Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas
- MS TSG milestone, FY15 (with ASC):
  - Develop physics and operational tools for high-performance discharges
- The proposed research is directly coupled to ITER through the ITPA
  - Through the experimental outage, the group maintains contributions to five joint experiments and two working groups (see backup slide)

Overall objective: establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

- Overview of 2014-2018 NSTX-U Five Year Plan
  - Thrust 1, Stability:

    Understand and advance passive and active feedback control to sustain macroscopic stability at low collisionality
    - Resistive wall mode (RWM) active control
    - New NCC coils and enhanced magnetics
    - MHD mode stability physics
  - Thrust 2, 3D Fields:

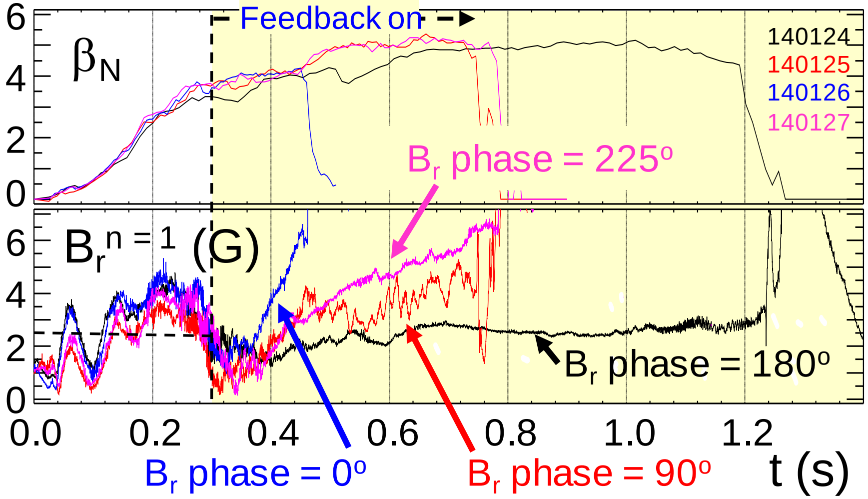
    Understand 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields
  - Thrust 3, Disruptions:

    Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas

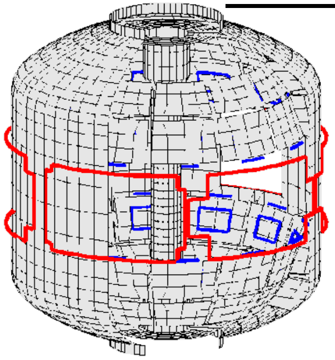
Dual-component PID (B_r + B_p) and model-based RWM state-space (RWMSC) active control will enable long pulse, high β operation

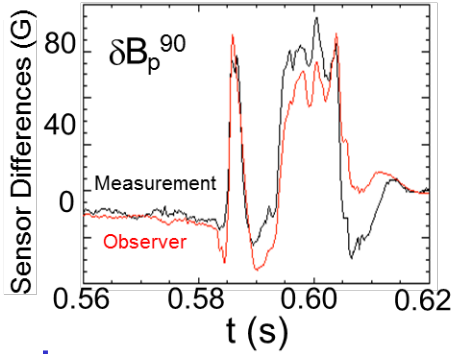
- Year 1 of 5 year plan (FY14):
  - Expand/analyze RWMSC for 6 coil control and n>1 physics
- Years 2 & 3:
  - Establish B_r + B_p active control capability in new operational regime, use with snowflake divertor, compare to theory
  - Examine RWMSC with:
    - independent actuation of six control coils
    - multi-mode control with n up to 3
    - rotational stabilization in the controller model
- Years 4 & 5:
  - Utilize model-based active control with the new NCC to demonstrate improved global MHD mode stability and very low plasma disruptivity, producing highest-performance, longest-pulse plasmas

Active n = 1 B_p + B_R feedback control



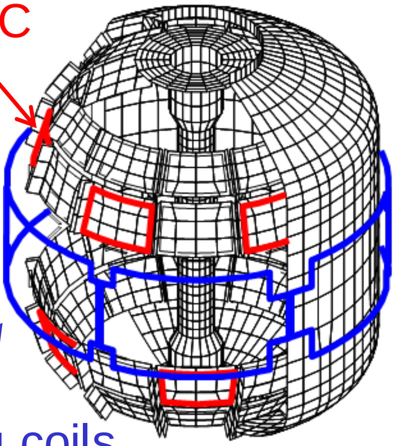
RWMSC





NCC will greatly enhance physics studies and control; Enhanced magnetics near divertor will measure multi-modes

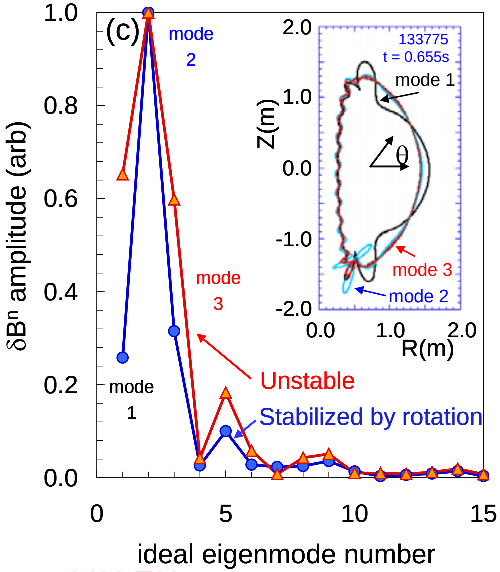
- Years 4 & 5:
  - Implement improvements to active feedback of n =1-3 modes via RWMSC control allowed by the partial NCC
  - Utilize rotation profile control capabilities allowed by the partial NCC to demonstrate reduced disruptivity by actively avoiding global instability boundaries


Partial NCC

Existing coils

(Next talk by Park will concentrate on NCC)

Multi-mode n = 1 ideal eigenfunction for fiducial plasma



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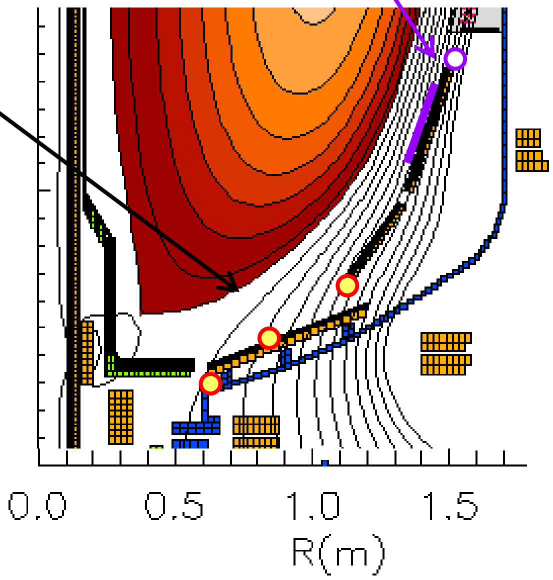
Proposed new sensor locations

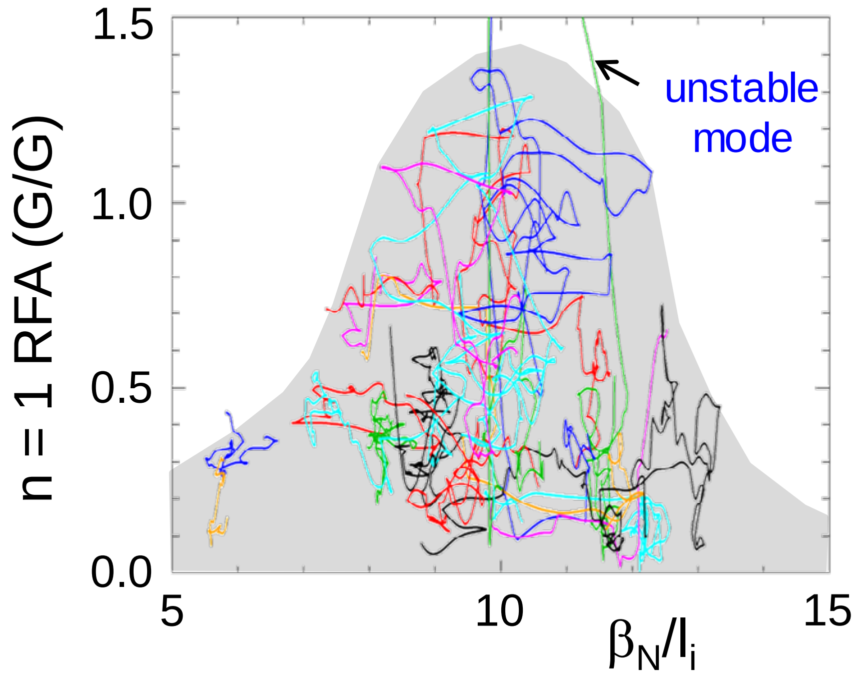
- Mode diagnosis:
  - Measure increased amplitude near divertor
  - Similar results in ITER simulations
- 3D analysis shows:
  - >2x field increase over present sensors
  - Reversal in sign of field perturbation
- Significant toroidal phase change would be measured
  - Constrain RWMSC, test observer physics

Present sensor locations



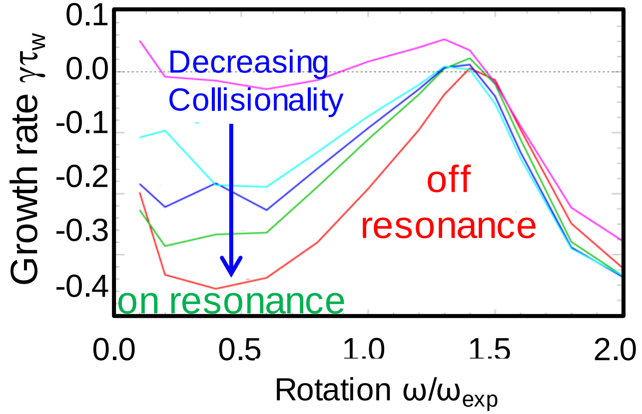
MHD spectroscopy shows improved stability at high β_N/l_i, and kinetic RWM stability may be enhanced at low ν

Resonant Field Amplification (RFA) vs. β_N/l_i



- Mode stability directly measured in experiment using MHD spectroscopy
    - Decreases up to β_N/l_i = 10
    - Increases at higher β_N/l_i
    - Supports kinetic RWM stability theory
    - Decreases with ν “on resonance”
    - Independent of ν “off resonance”

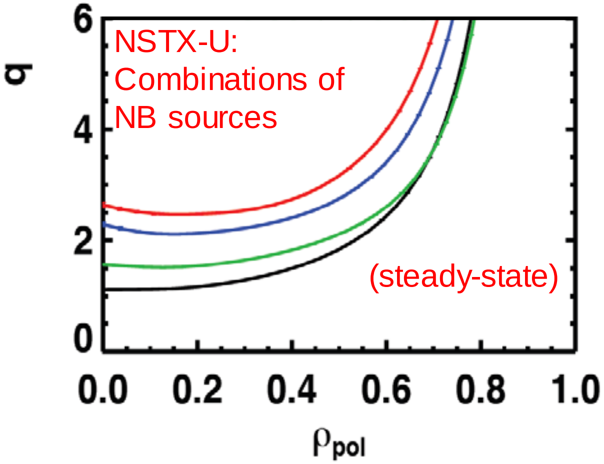
Theory: RWM γ vs. ν and ω_ϕ



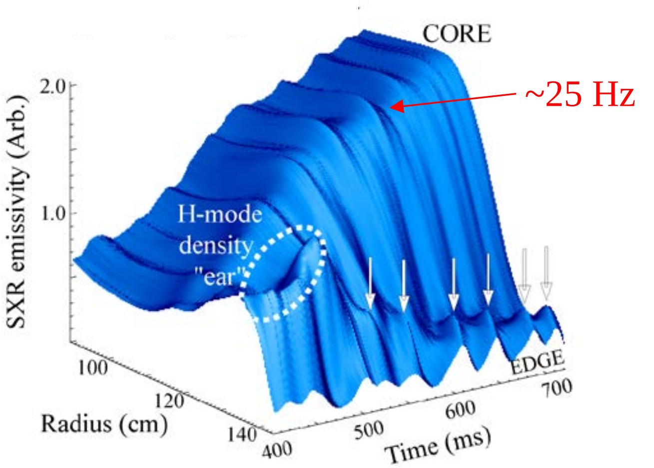
- Years 2 & 3:
    - Investigate the dependence of stability on reduced ν through MHD spectroscopy; compare to kinetic stabilization theory
- Years 4 & 5:
    - Utilize rotation control, NCC, and cryo-pump (for reduced ν) to change proximity to kinetic resonances for RWM control

Realizing NSTX-U long-pulse scenarios will require stability of internal MHD modes

Coupled m/n = 1/1+2/1 modes grow when q_{min} -> 1



Low frequency mode activity measured with multi-energy soft X-ray



- Years 2 & 3:
  - Use new neutral beam and q_{min} control to determine increment of q_{min} above rational values to avoid internal modes
  - Measure internal modes non-magnetically with RWMSC and ME-SXR
- Years 4 & 5:
  - Examine time-evolution of global mode internalization using newly-installed, additional toroidally-displaced ME-SXR diagnostic
  - Combine rotation, q, and β_N control to demonstrate improved RWM/internal MHD mode stability

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  - Thrust 2, 3D Fields:

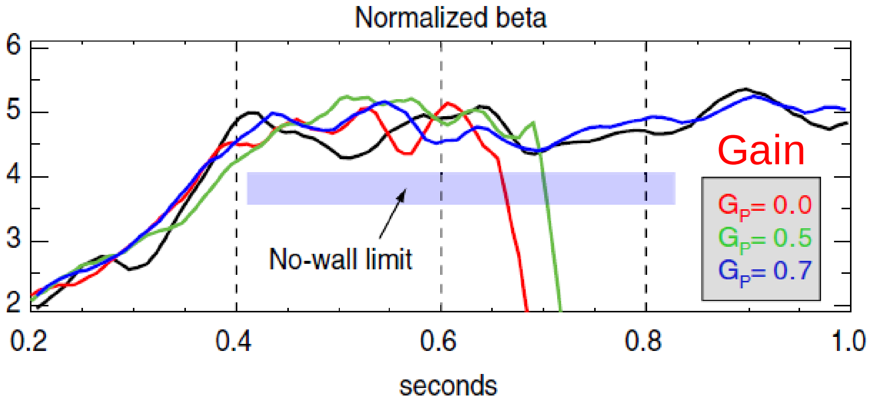
    Understand 3D field effects and provide physics basis for optimizing stability through equilibrium profile control by 3D fields
    - Error field (EF) correction
    - Locking and tearing modes with resonant and non-resonant EFs
    - Neoclassical toroidal viscosity
  - Thrust 3, Disruptions:

    Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas

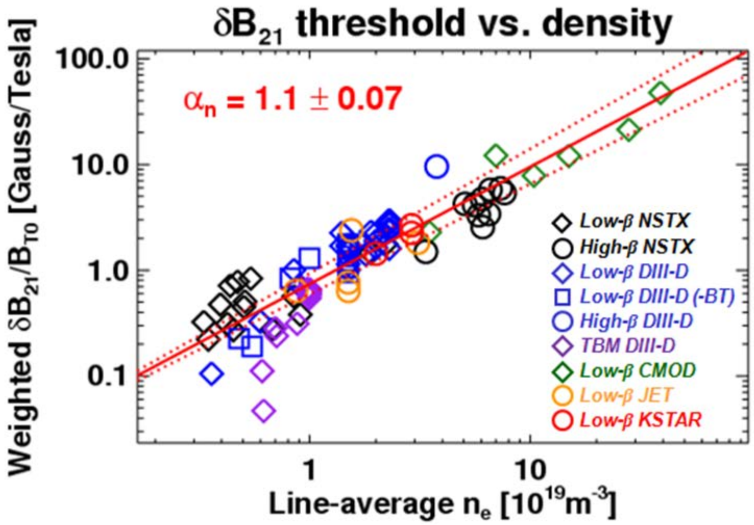
Correction of intrinsic error fields (EFs) is critical for performance; Resonant and non-resonant EFs affect locking and tearing stability

- Year 1:
  - Use IPEC to model EFs
- Years 2 & 3:
  - Assess intrinsic EFs in new machine
  - Optimize dynamic EF correction, including n>1 and using 6 SPAs and RWMSC
  - Investigate resonant EF effects on tearing mode onset
- Years 4 & 5:
  - Utilize NCC to understand locking and tearing modes in the presence of resonant and non-resonant EFs
    - develop predictability for ITER

Dynamic error field correction in NSTX



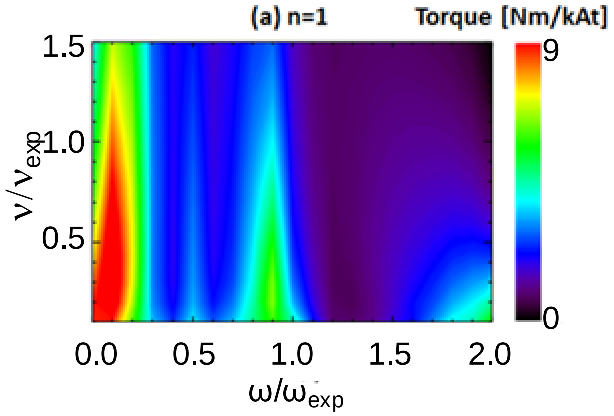
Error field threshold vs. locking density (IPEC) for five devices



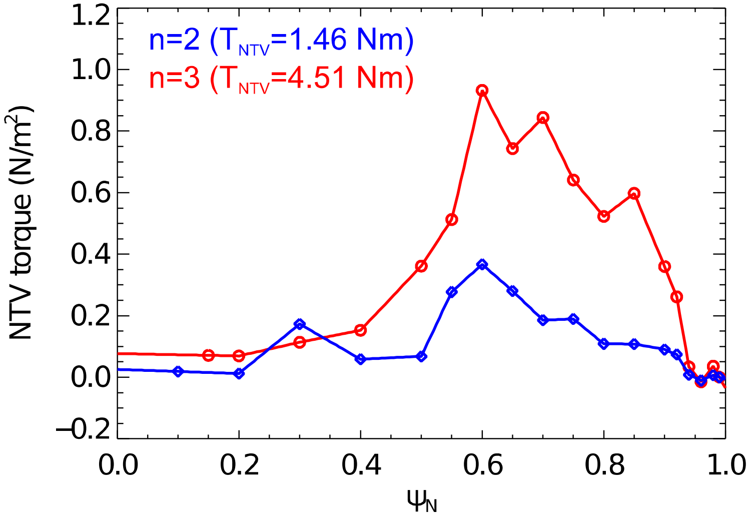
NSTX-U will investigate neoclassical toroidal viscosity (NTV) at reduced ν, which is important for rotation control and ITER

- Year 1:
  - Analyze existing NSTX NTV data on ν dependence and offset rotation
  - Develop/benchmark leading theory/codes
    - NTVTOK, IPEC, POCA, FORTEC-3D
- Years 2 & 3:
  - Assess NTV profile and strength at reduced collisionality, and examine the NTV offset rotation at long pulse
  - Prepare an initial real-time model of NTV profile for use in initial tests of the plasma rotation control system
- Years 4 & 5:
  - Utilize NCC, demonstrate low rotation profile operation (ITER-like) in steady-state with closed-loop rotation control

Analytic NTV calculations for n=1 magnetic braking in NSTX



POCA NTV calculations for n=2 and n=3 magnetic braking in NSTX



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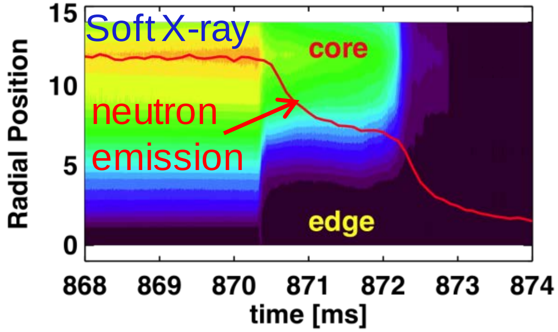
    Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas
    - Thermal quench, heat loads, and halo currents
    - Prediction and avoidance
    - Mitigation with MGI

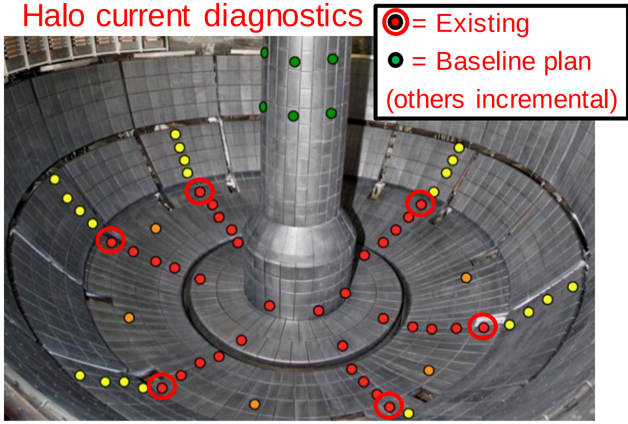
NSTX-U will provide projections of thermal quench physics, transient heat loads, and halo currents for ITER and FNSF

- Year 1:
  - Examine thermal loading projections for ITER, including assumptions of axisymmetry
- Years 2 & 3:
  - Investigate halo current toroidal asymmetry and loading on the center column, using newly installed center column shunt tiles
  - Upgrade shunt tile diagnostics for complete coverage of divertor
  - Study spatial extent and timing of the heat deposition during VDEs
- Years 4 & 5:
  - Assess halo current scalings using the full field and current capabilities
  - Study 3D and non-axisymmetric effects on the divertor heat loading

Rapid thermal quench

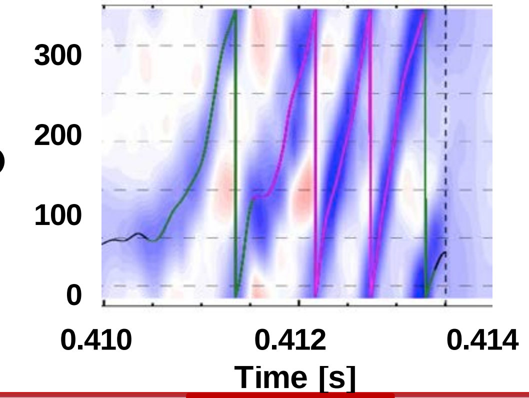


Halo current diagnostics

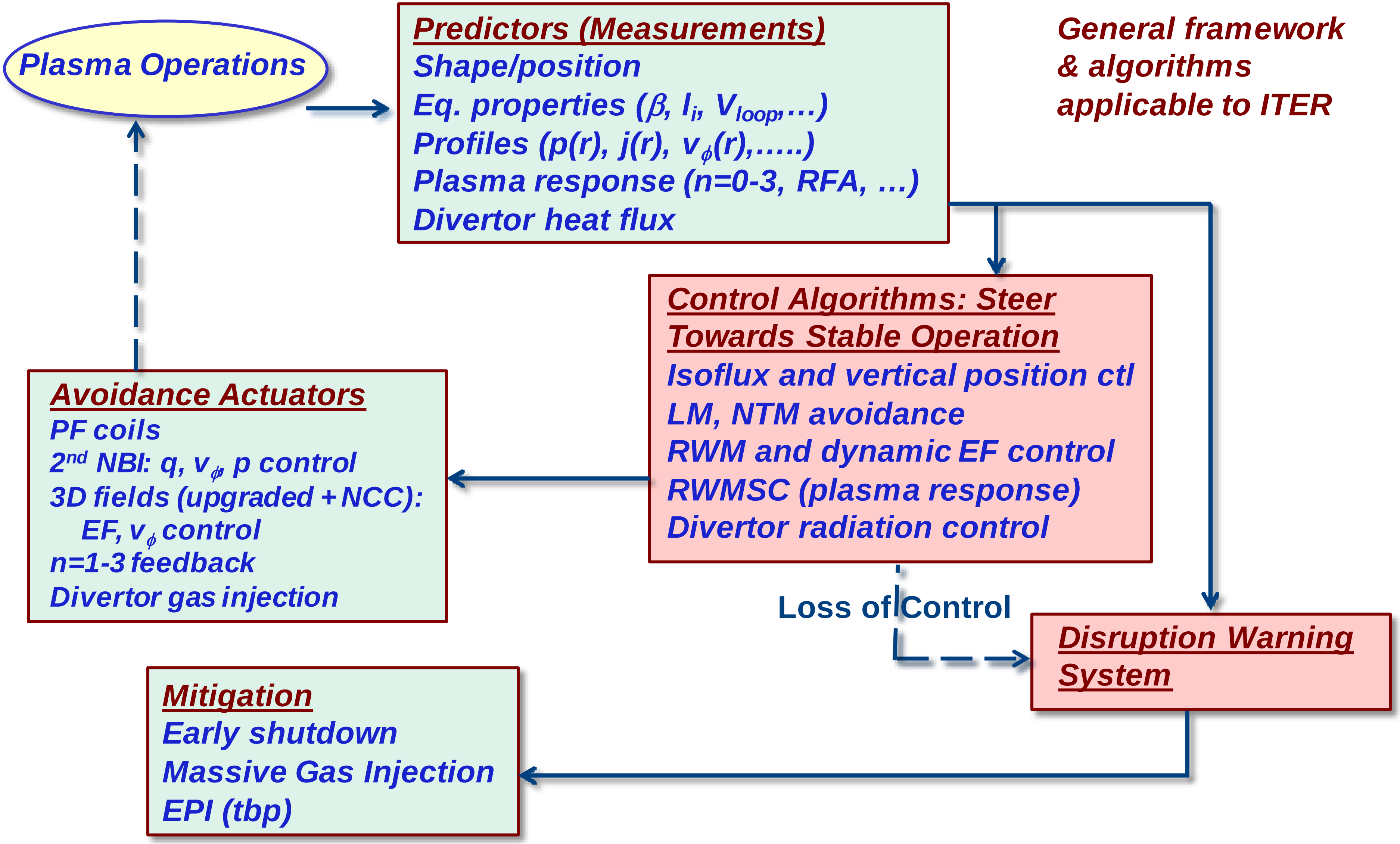


Halo current rotation

Halo currents: ITER high priority item



Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI (1)



General framework & algorithms applicable to ITER

Plasma Operations

Predictors (Measurements)

Shape/position

Eq. properties (β, l_i, V_{loop},…)

Profiles ($p(r)$, $j(r)$, $v_\phi(r)$,…..)

Plasma response (n=0-3, RFA, …)

Divertor heat flux

Control Algorithms: Steer Towards Stable Operation

Isoflux and vertical position ctl

LM, NTM avoidance

RWM and dynamic EF control

RWMSC (plasma response)

Divertor radiation control

Avoidance Actuators

PF coils

2nd NBI: q, v_ϕ, p control

3D fields (upgraded + NCC):

EF, v_ϕ control

n=1-3 feedback

Divertor gas injection

Loss of Control

Disruption Warning System

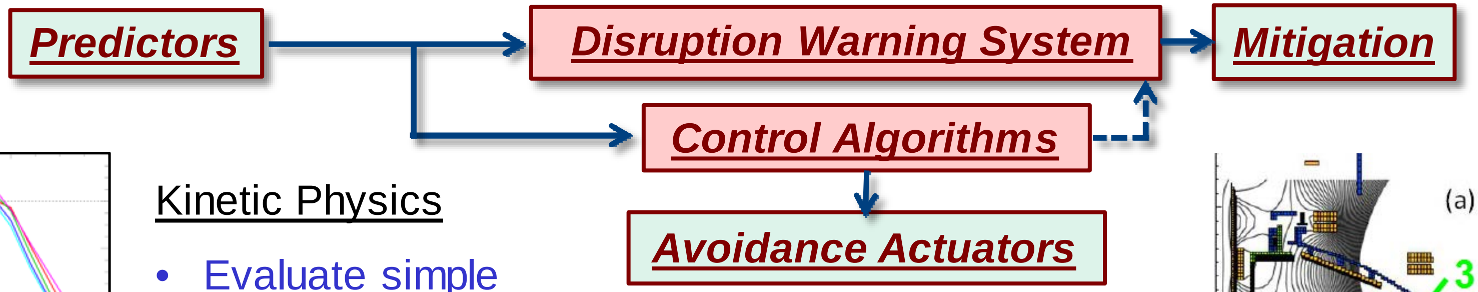
Mitigation

Early shutdown

Massive Gas Injection

EPI (tbp)

Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI (2)



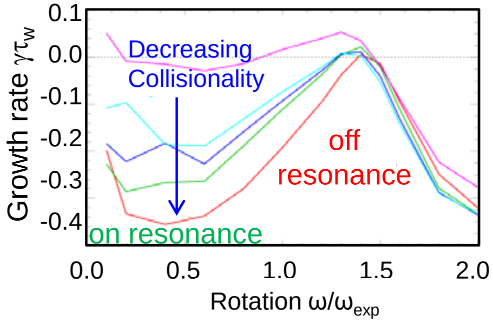
Predictors

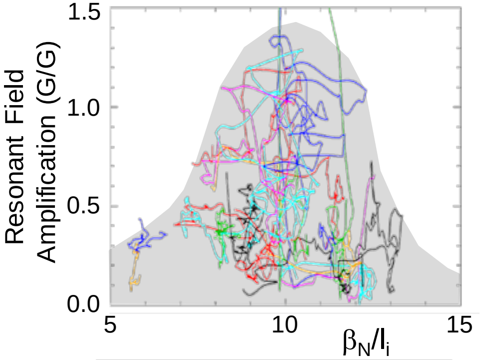
Disruption Warning System

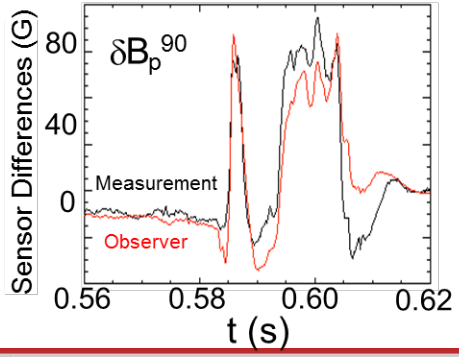
Mitigation

Control Algorithms

Avoidance Actuators







Kinetic Physics

- Evaluate simple physics criteria for global mode marginal stability in real-time

MHD Spectroscopy

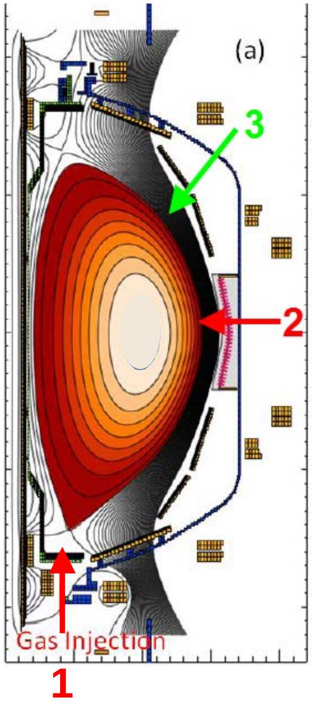
- Use real-time MHD spectroscopy while varying rotation, q_{min}, and β_N to predict disruptions

q, v_ϕ, β_N control

RWMSC observer

- Compare mismatch between the RWMSC observer and sensor measurements, and disruption occurence

3D fields, feedback



ITER gas-loading :

Injection into private flux region with higher assimilation efficiency?

Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI (3)

Predictors

- Year 1:
  - Evaluate initial simple physics model for marginal stability based on kinetic stability physics
- Years 2 & 3:
  - Measure plasma stability using MHD spectroscopy vs. key variables and compare to theory
  - Compare the mismatch between the RWMSC observer model and sensor measurements, and disruption occurrence
- Years 4 & 5:
  - Implement real-time evaluations of: kinetic stability model, MHD spectroscopy, and RWMSC observer disruption prediction for input to profile control algorithms

Mitigation

- Year 1:
  - Model neutral gas penetration of SOL
- Years 2 & 3:
  - Commission MGI system
  - Characterize density assimilation vs. poloidal location
- Years 4 & 5:
  - Trigger the MGI system based on warning of an impending disruption

Summary of NTSX-U 5 year plan for Macroscopic Stability

- MS research is establishing the physics understanding and control capabilities needed for sustained stability of high performance ST plasmas
  - In unexplored ST operational regime: low ν, high β, low l_i, long pulse
- NSTX-U will make critical contributions in the areas of:
  - Advancement of stability physics and control to sustain macroscopic stability at low collisionality
  - Understanding 3D field effects and providing the physics basis for profile control by 3D fields
  - Understanding disruption dynamics and developing techniques for disruption prediction, avoidance, and mitigation
- MS research in NSTX-U will be greatly enriched, and have significantly greater impact on ITER, by having the NCC coils

Backup

NSTX-U macroscopic stability research is directly coupled to ITER through the ITPA

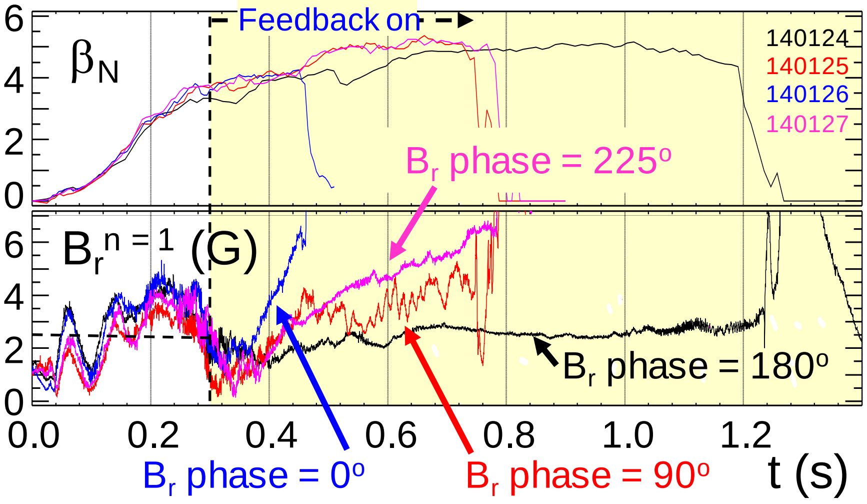
- Through the experimental outage, our group:
  - Maintains contributions to five joint experiments and two working groups
    - leads the MDC-2 joint experiment / analysis on RWM physics
    - co-leads the Working Group 7 effort on aspects of active mode control

	MHD		
MDC-2	Joint experiments on resistive wall mode physics	MDC-17	Active disruption avoidance
MDC-8	Current drive prevention/stabilization of NTMs	MDC-18	Evaluation of axisymmetric control aspects
MDC-15	Disruption database development		

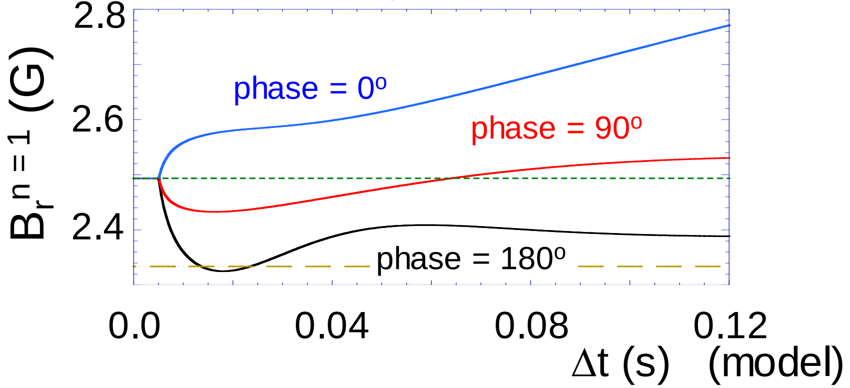
  - Communicated NSTX research bi-annually at each ITPA MHD Stability group meeting for many years
  - Led two elements of the recent ITPA Integrated Plasma Control Working Group study, led by Dr. Joseph Snipes of ITER
    - also contributed with direct calculations for ITER on RWM and error field control associated with this effort.
- NSTX-U stability research plans expand this effort in the coming five year period.

Dual component (B_R, B_p) PID and state space control

Active n = 1 B_p + B_R feedback control

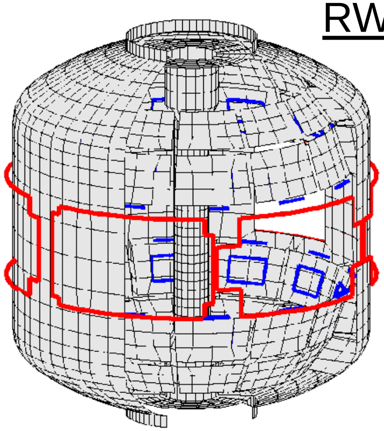


Calculation of B_r + B_p control (VALEN)

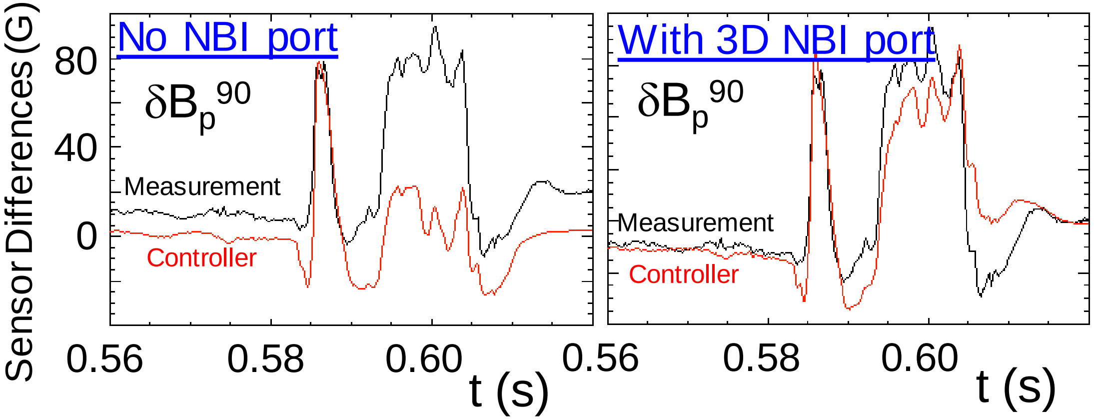


Model validation and predictive capability:
VALEN code feedback predictions

RWM State Space Controller



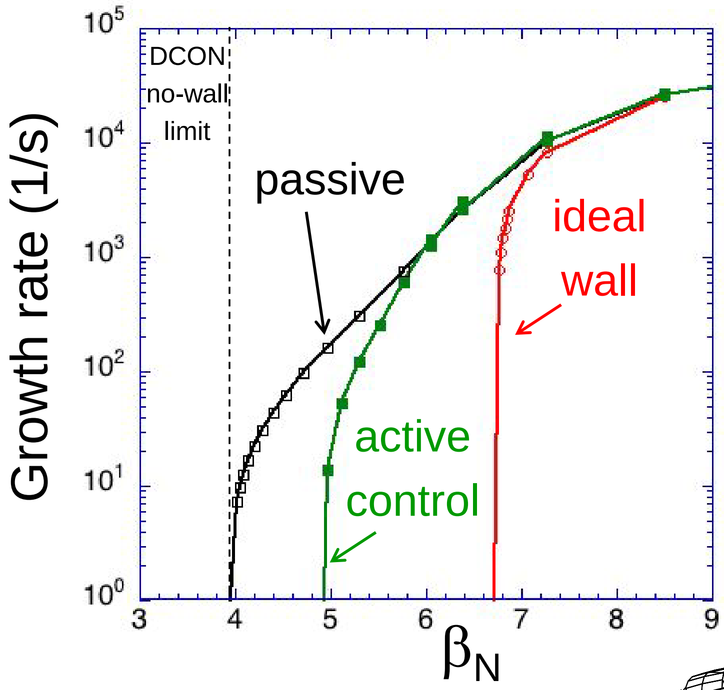
3D wall, ports, mode currents



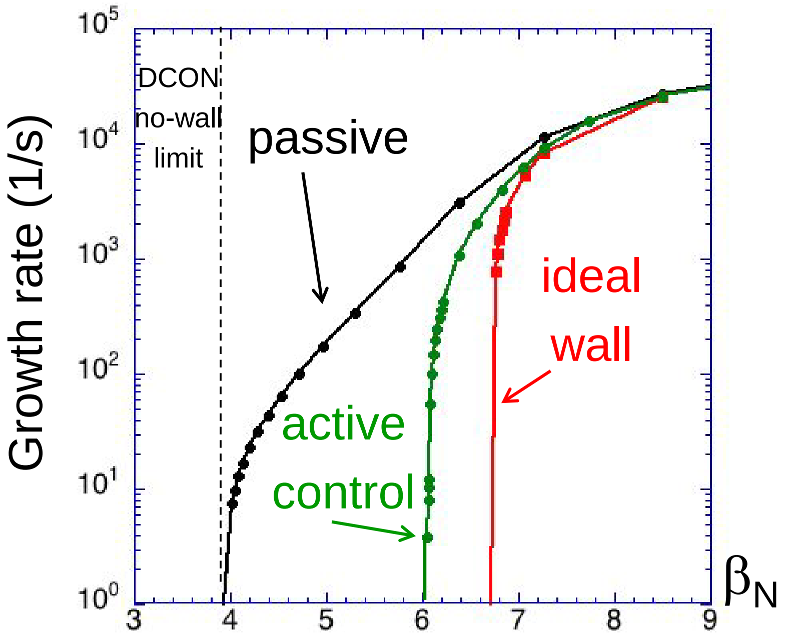
- Inclusion of 3D mode and wall detail improves control

RWM active control capability increases as partial NCC coils are added

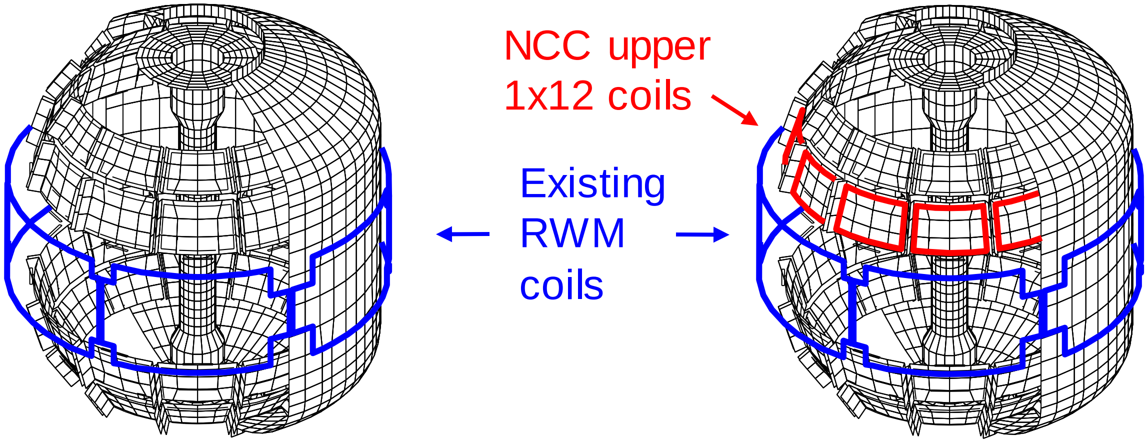
Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors

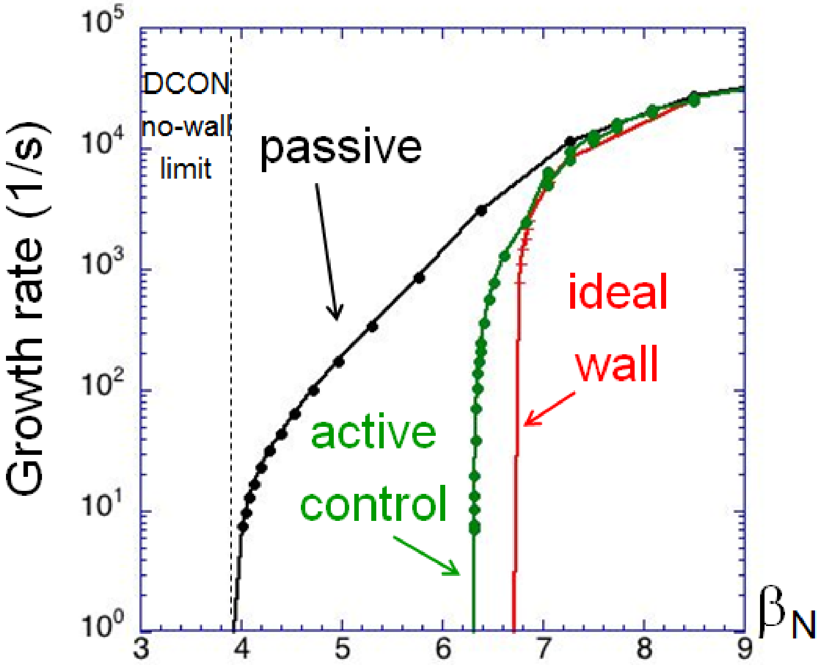


- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.54$

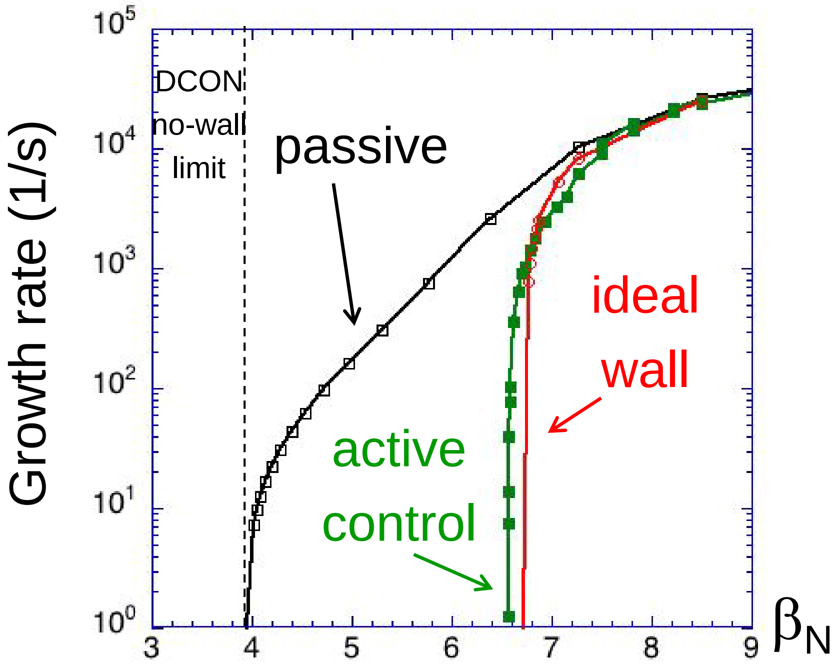


RWM active control capability increases further with full NCC

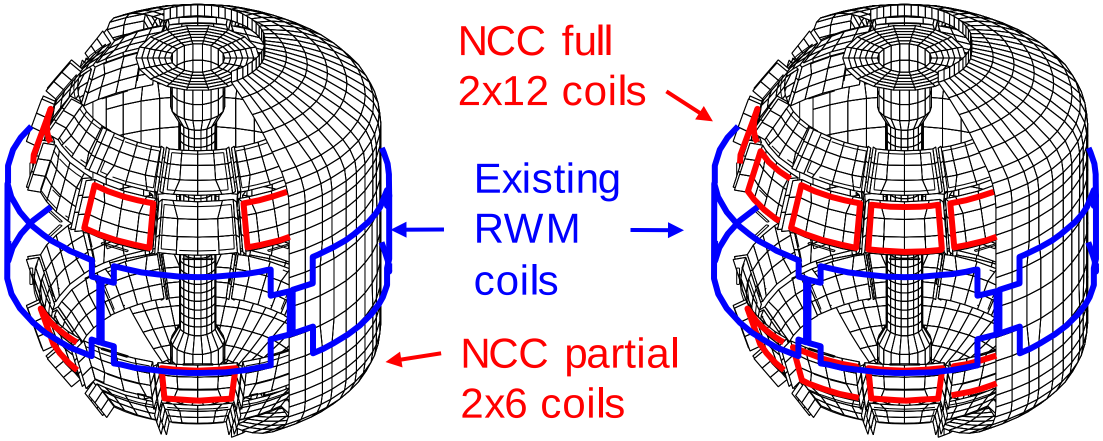
NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain

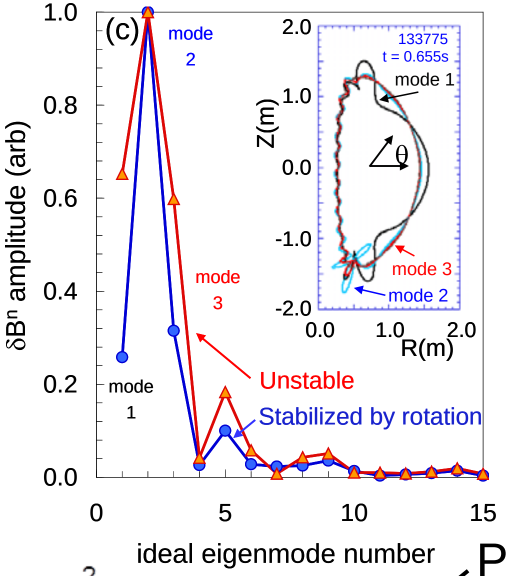


- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.61$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.70$



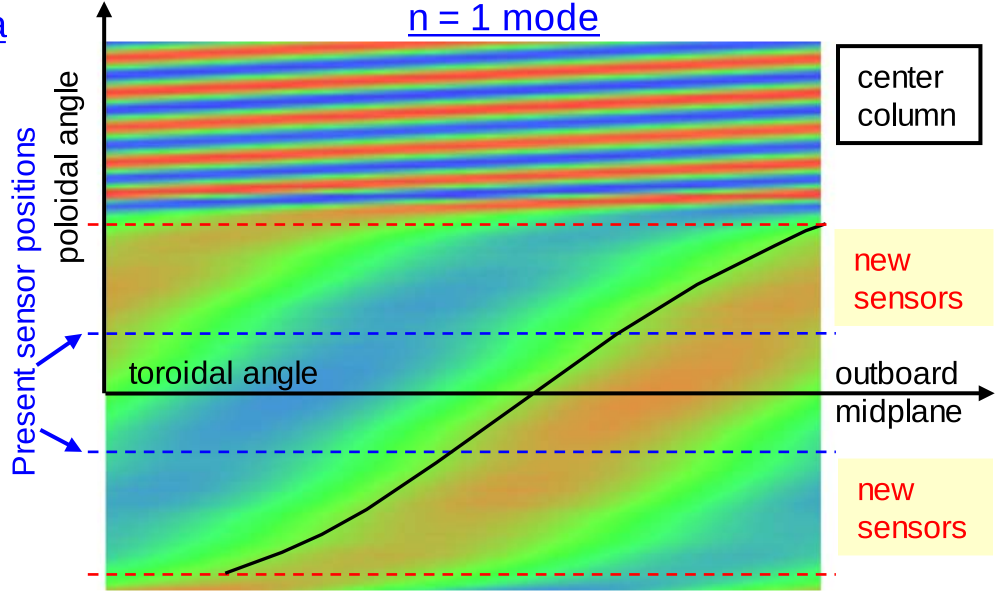
Multi-mode theory shows high amplitude near divertor, enhanced magnetics proposed

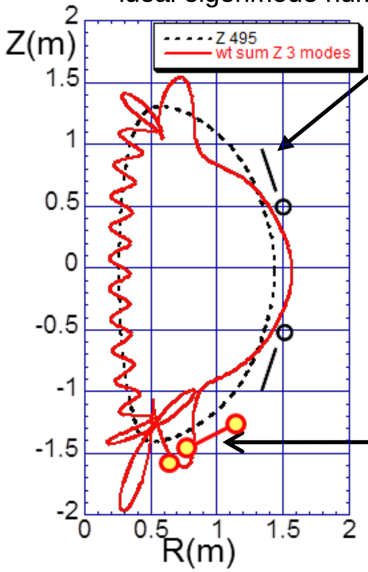
Multi-mode n = 1 ideal eigenfunction for fiducial plasma



Multi-mode physics

- Implement in RWMSC
- Validate theory predictions with measurements
- Found similar results in ITER simulations



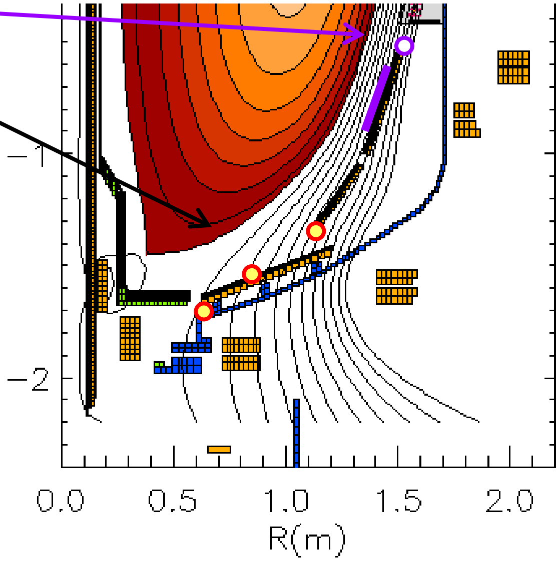


mmVALEN code

Present sensor locations

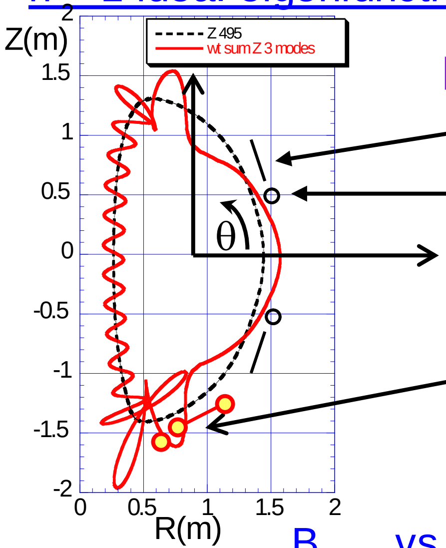
Proposed new sensor locations

- Global mode diagnosis: measure theoretically increased amplitude in the divertor at high β_N
- 3D analysis of candidate sensor positions show >2x increase in signal over present sensors
- Significant toroidal phase change would be measured
  - Constrain RWM state space controller



3D analysis of extended MHD sensors show significant mode amplitude off-midplane, approaching divertor region

n = 1 ideal eigenfunction for high beta plasma

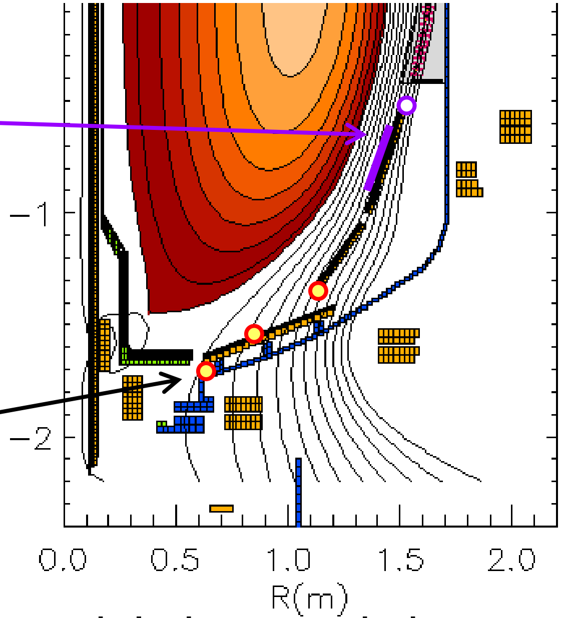


Present sensor locations

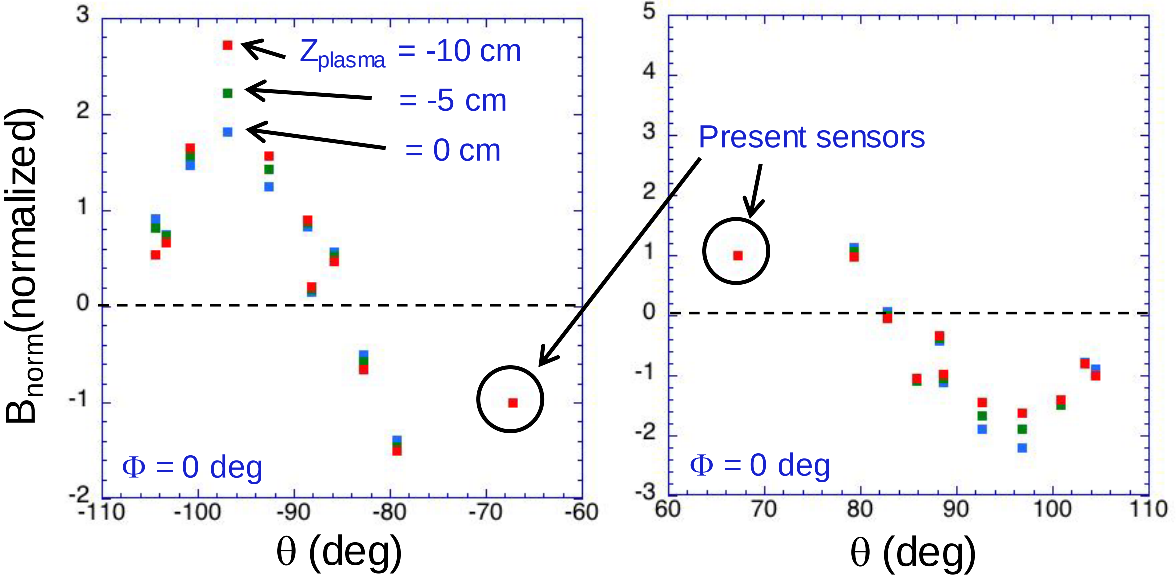
B_R sensors (nominally normal, B_{norm})

B_p sensors (nominally tangential, B_{tan})

New sensor locations (includes one new location above midplane)

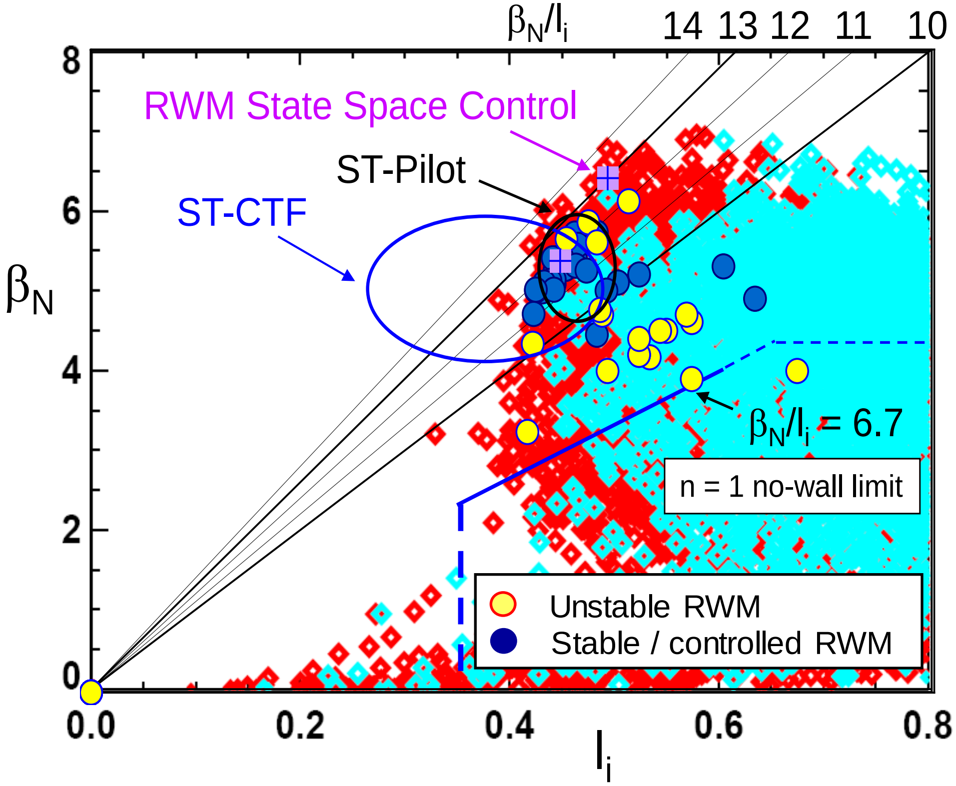


B_{norm} vs. theta (normalized to present Br sensors)



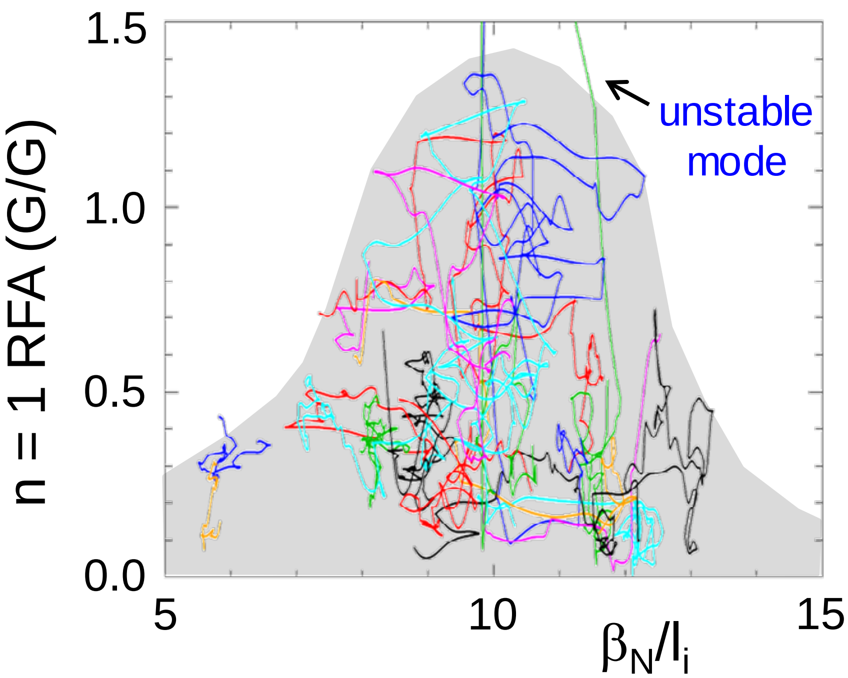
- Model characteristics
  - New 3D model of divertor plate
  - 3D sensors with finite toroidal extent; n*A of existing sensors
- Results summary
  - Field amplitude increases >2x with new sensors
  - Perturbed field reversals observed with new sensors
  - Signals sufficient with plasma shifted off-midplane

Stability control improvements significantly reduce unstable RWMs at low l_i and high β_N; improved stability at high β_N/l_i



- Disruption probability reduced by a factor of 3 on controlled experiments
  - Reached 2 times computed n = 1 no-wall limit of $\beta_N/l_i = 6.7$
- Lower probability of unstable RWMs at high β_N/l_i

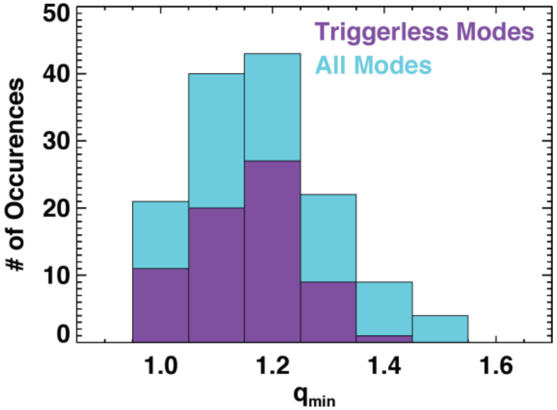
Resonant Field Amplification (RFA) vs. β_N/l_i

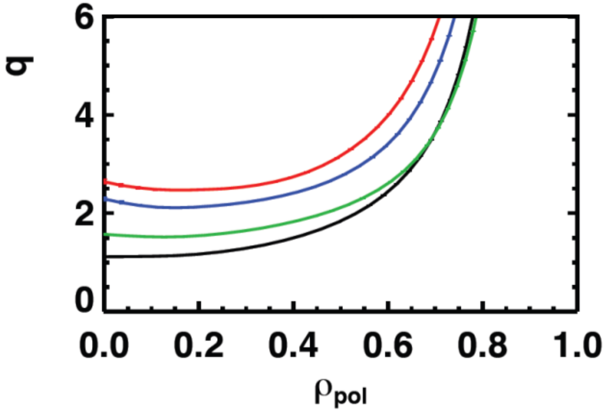


- Mode stability directly measured in experiments using MHD spectroscopy
  - Stability decreases up to $\beta_N/l_i = 10$
  - Stability increases at higher β_N/l_i
  - Presently analysis indicates consistency with kinetic resonance stabilization

Internal modes may limit long-pulse scenarios; kinetic RWM stability may be enhanced at low ν

- Coupled m/n = 1/1+2/1 modes grow when q_{min} approaches 1
  - EPM or ELM triggers cause modes to onset at larger q_{min}.
  - "triggerless" internal kinks as q_{min} -> 1



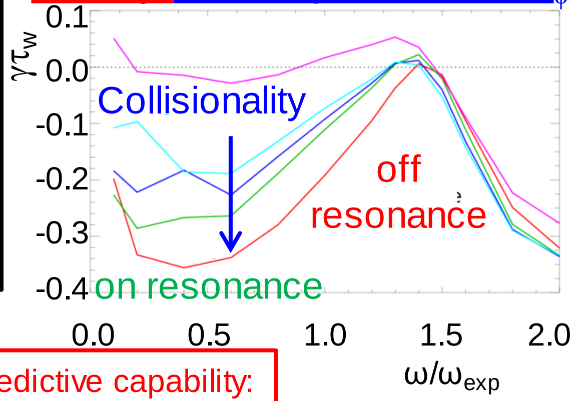


Various combinations of neutral beam sources

- NBCD can determine the required increment of q_{min} above rational values to avoid internal modes

Experiments measuring global stability vs. ν support kinetic RWM stability theory

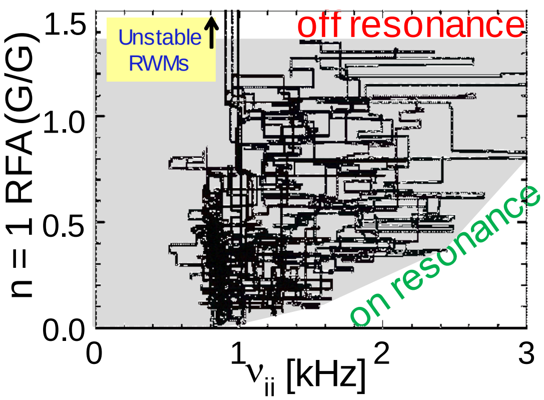
Theory: RWM γ vs. ν and ω_ϕ



Model validation and predictive capability: MISK code RWM stability calculations

- Expectations at lower ν:
  - More stability on resonance almost no effect off-resonance

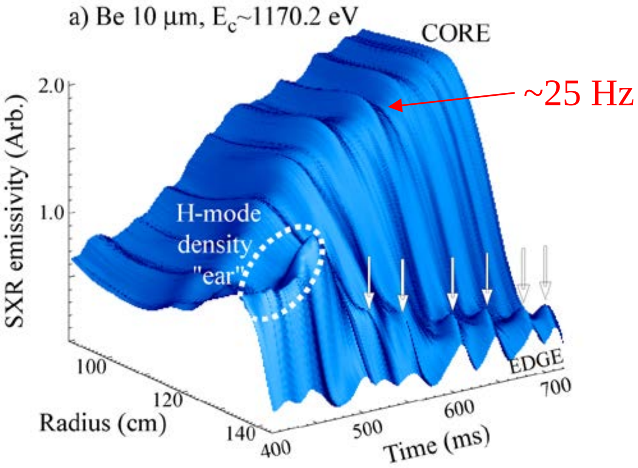
Experiment: RFA vs ν

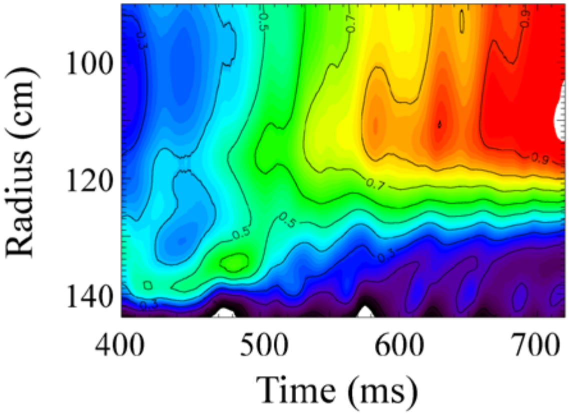


- Mode stability directly measured in experiment using MHD spectroscopy
  - Decreases with ν "on resonance"
  - Independent of ν "off resonance"

Internal kink/ballooning modes must be measured via non-magnetic means

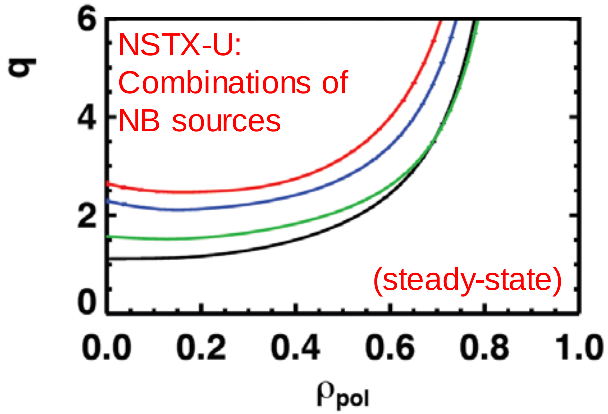
- Non-magnetic measurement is also important for mode control systems to be used in future devices with high neutron fluence
- The RWMSC can determine how incorrect the observer is in reproducing the measured magnetic flux
  - Can be used as a criterion as input to a disruption warning system.
- Multi-energy soft X-ray can measure low frequency mode activity
  - used to determine mode amplitude and in conjunction with the external magnetic sensors to determine the degree to which the mode is internal





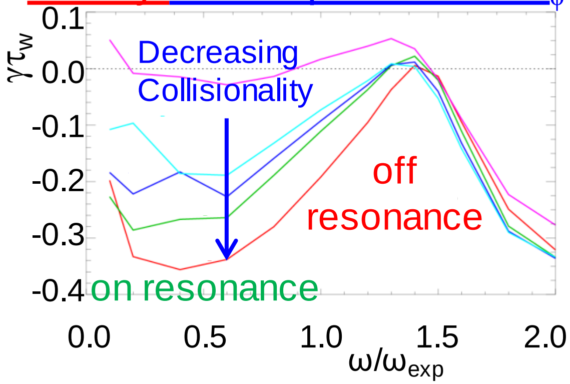
Realizing NSTX-U long-pulse scenarios will require stability of internal and external MHD modes

Coupled m/n = 1/1+2/1 modes grow when q_{min} -> 1



Experiments measuring global stability vs. ν support kinetic RWM stability theory

Theory: RWM γ vs. ν and ω_ϕ



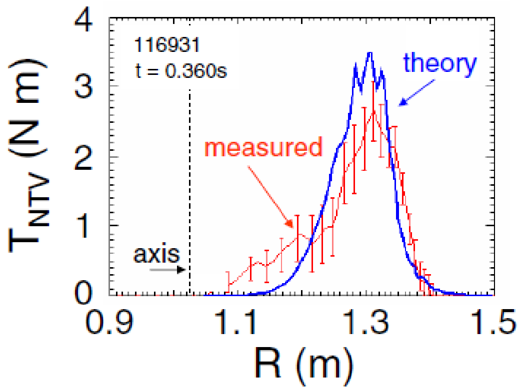
- Years 2 & 3:
  - Use new neutral beam and q_{min} control to determine increment of q_{min} above rational values to avoid internal modes
- Years 2 & 3:
  - Investigate the dependence of stability on reduced ν through MHD spectroscopy; compare to kinetic stabilization theory.
- Years 4 & 5:
  - Utilize rotation control, NCC, and cryo-pump (for reduced ν) to change proximity to kinetic resonances for RWM control.
  - Combine rotation, q, and β_N control, and use ME-SXR (non-magnetic) to demonstrate improved RWM/internal MHD mode stability.

Understanding neoclassical toroidal viscosity (NTV) is crucial for rotation control

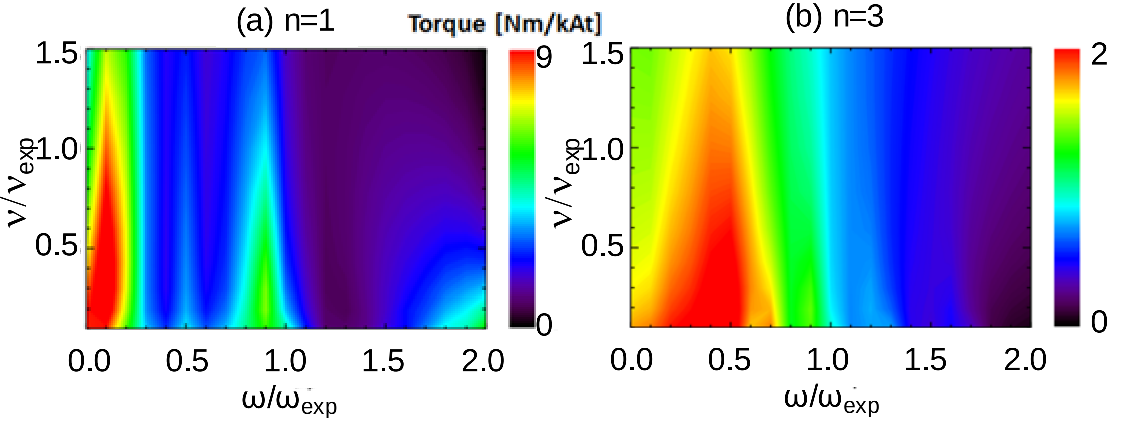
R(12-1) “Investigate magnetic braking physics to develop toroidal rotation control at low ν”

Model validation and predictive capability: NTV calculations with multiple codes, comparison to experiments

- NTVTOK code:
  - Shaing theory NTV computation including ion and electron effects
  - Comparison to experiment of NTV in all collisionality regimes

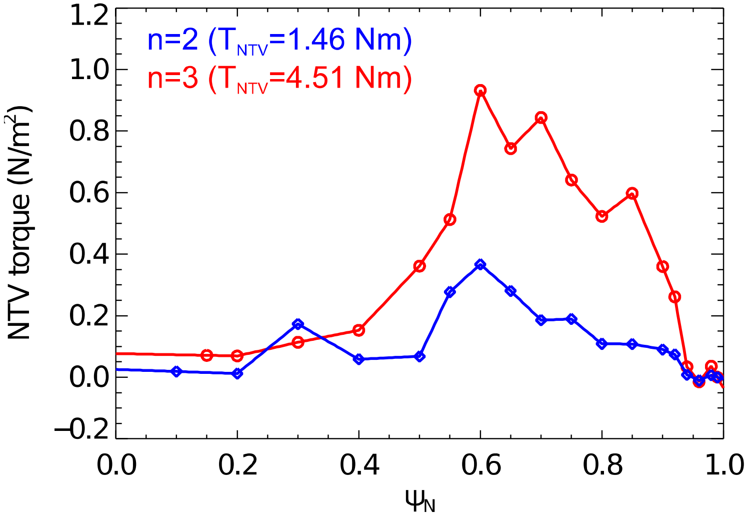


Analytic NTV calculations for (a) n=1 and (b) n=3 magnetic braking in NSTX, as a function of collisionality and rotation



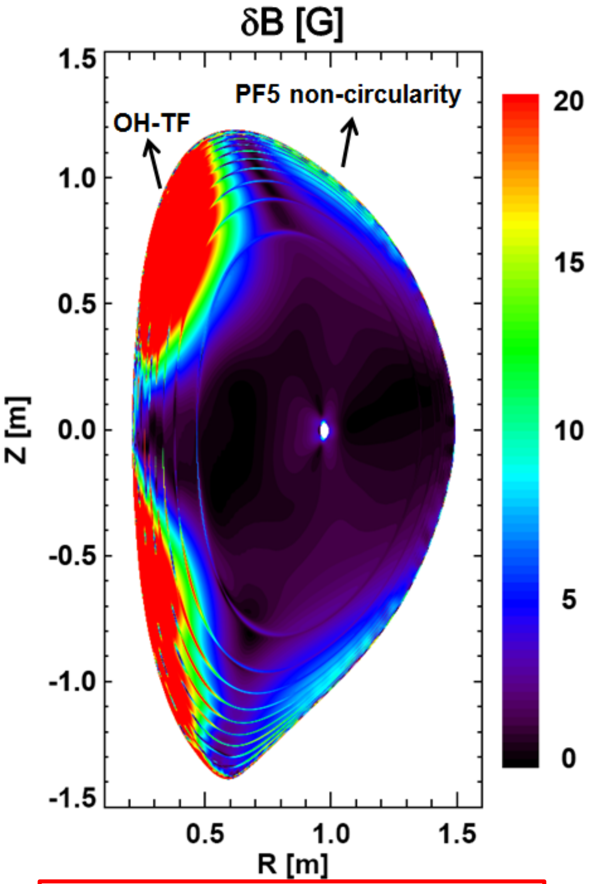
- A new δf guiding-center particle code, POCA, was developed to investigate neoclassical transport in perturbed tokamaks.
  - solves the Fokker-Planck equation with non-axisymmetric magnetic field perturbations

POCA NTV calculations for n=2 and n=3 magnetic braking in NSTX



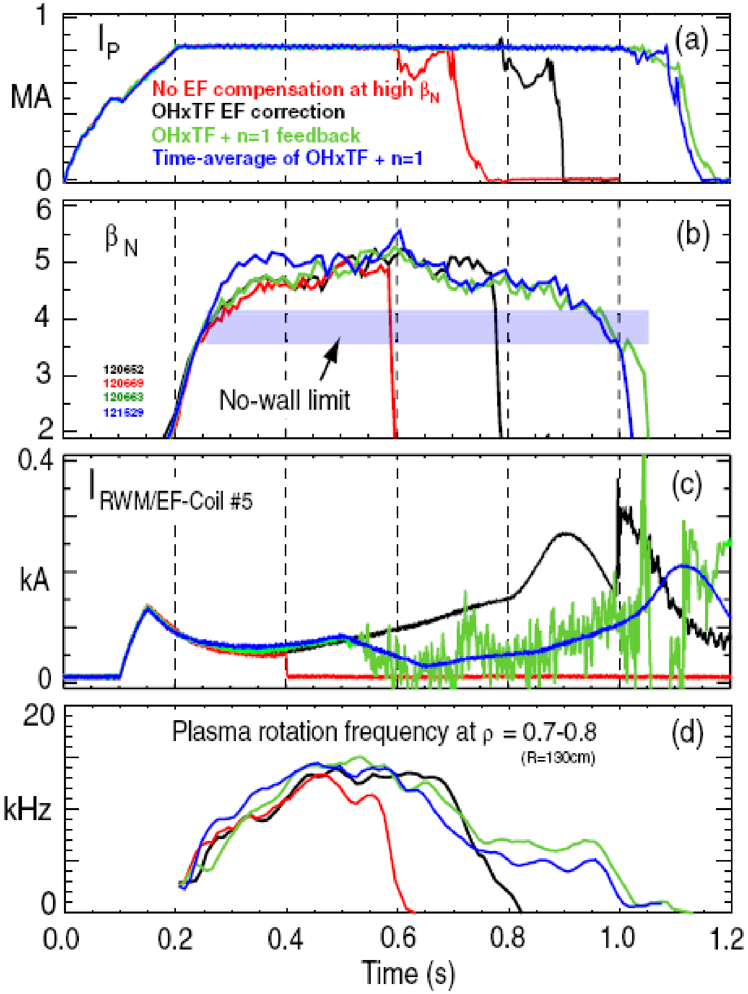
Correction of intrinsic error fields is critical for studies of 3D field physics and for performance

The perturbed n=1 field (IPEC) from intrinsic error fields in NSTX



Predictive capability:
IPEC model of error fields

Various successful error field correction schemes in NSTX

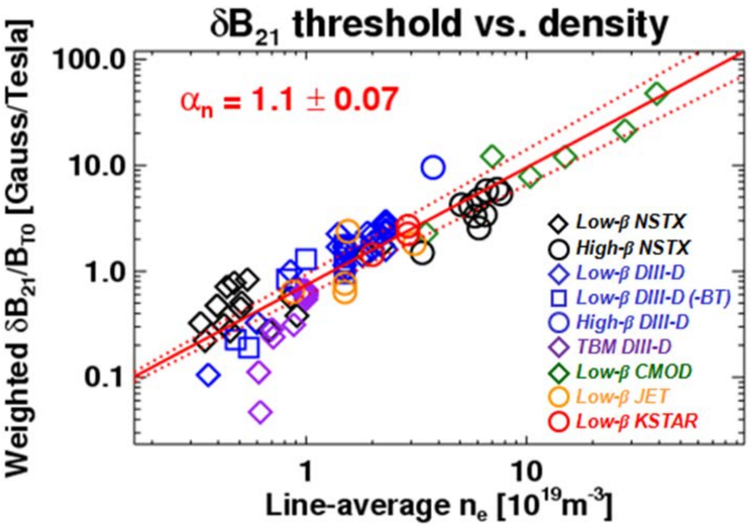


- Dynamic error field correction (green)
  - sustains β_N above the no-wall limit
  - sustains substantial toroidal rotation
- NSTX-U will have a different error field
  - Identification of error field in first year of operation
  - measure vacuum fields; revise models
  - Perform n=1,2 compass scans with 6 independent SPAs.
  - RWMSC for dynamic error field correction

Resonant and non-resonant error fields affect locking and tearing stability

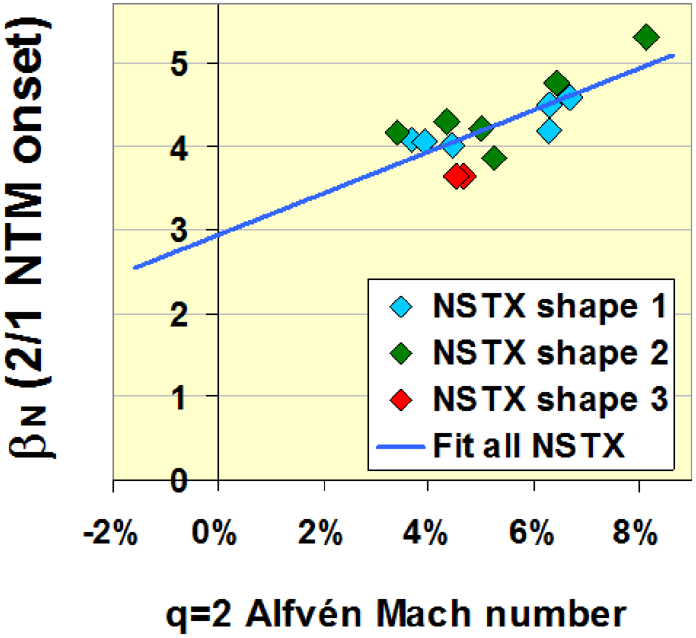
Goal: Understand locking and tearing modes in the presence of resonant and non-resonant error fields, and develop predictability for FNSF and ITER

Error field threshold vs. locking density (IPEC) for five devices



- Studies of intrinsic error fields focus on compensation of the resonant component to avoid locking
  - Error field threshold at locking will be used to predict the tolerance of error fields in ITER

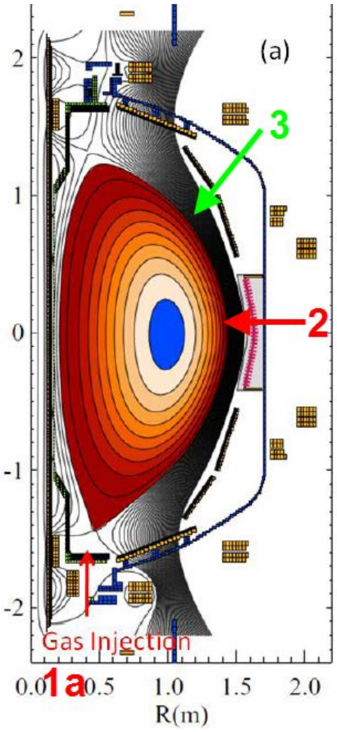
Change of the β_N threshold of the NTM with rotation

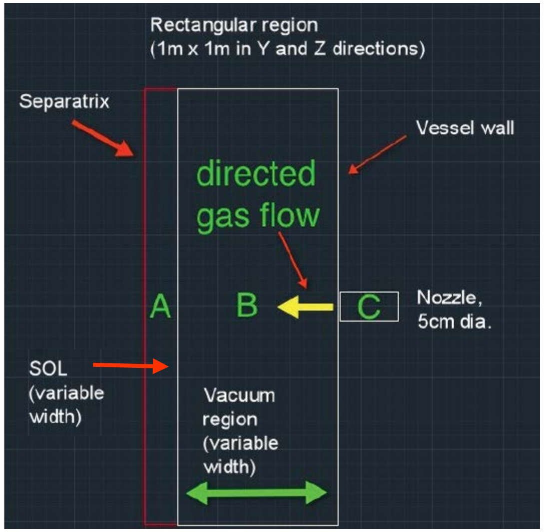


- Tearing mode onset modified by both resonant and non-resonant error fields
  - β_N threshold will be decreased by non-resonant error field magnetic braking

Disruption mitigation technologies that will benefit the ITER design are being prepared

MGI research will assess gas penetration efficiency by injection at different poloidal locations

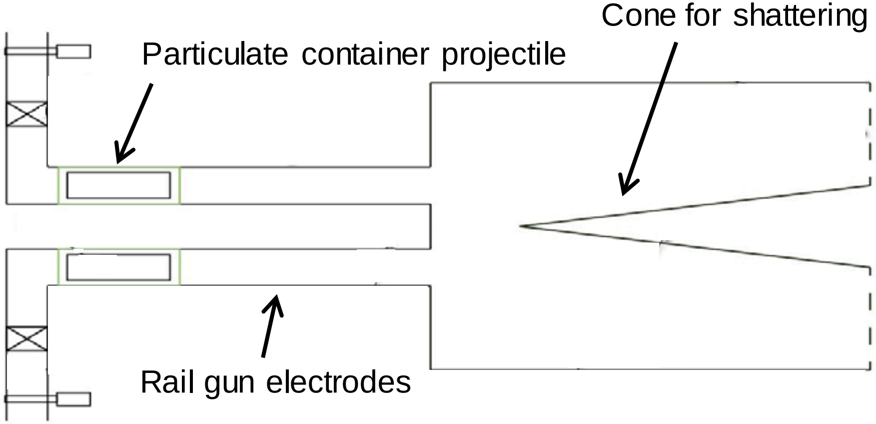




Predictive capability: Modeling using DEGAS-2 is quantifying the gas penetration past the SOL for NSTX-U

- NSTX-U can offer new insight by
  - Reducing the amount of gas
  - Injecting gas into the private flux and lower x-point regions of divertor to determine if these are more desirable locations for MGI.

A novel mitigation technology, an electromagnetic particle injector (EPI), will be used to terminate plasmas

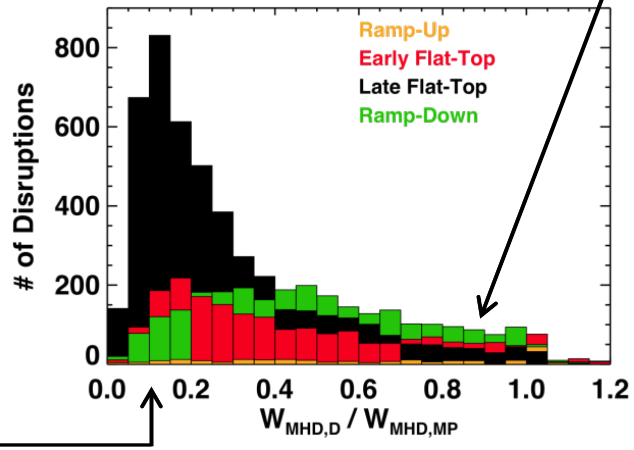


- The EPI is capable of delivering:
  - A large particle inventory
  - All particles at nearly the same time
  - Particles tailored to contain multiple elements in different fractions and sizes
  - Tailored particles fully ionized only in higher current discharges (to control current quench rates)
- Well suited for long stand-by mode operation

Understanding of thermal quench physics and transient heat loads is critical for projections

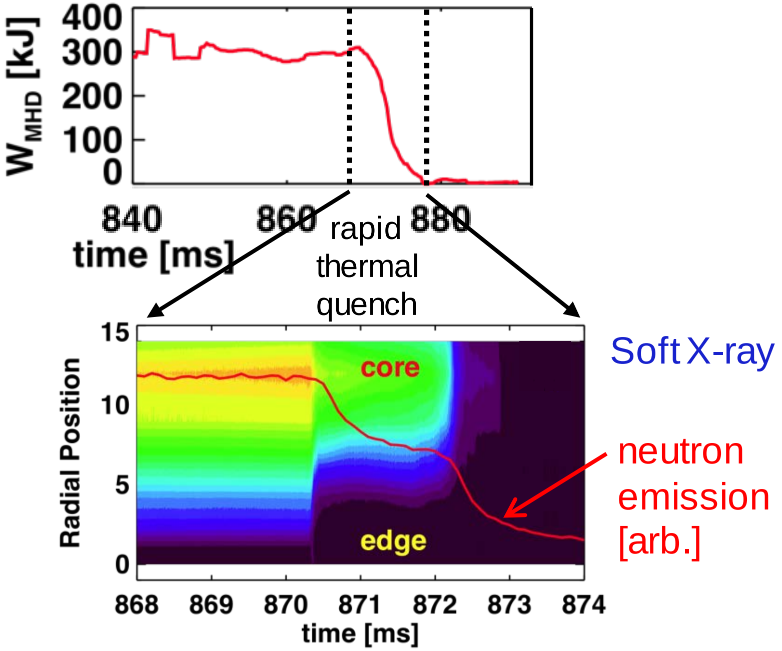
	NSTX-U	ITER	ST-Pilot	Power Reactor
Thermal Loading [MJ m^2 $s^{-1/2}$]	15	540	768	2061

- Examining assumptions:
  - How much stored energy?

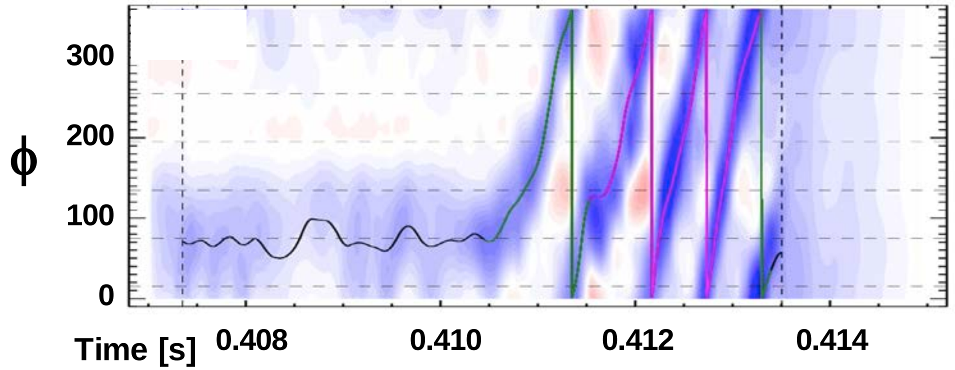


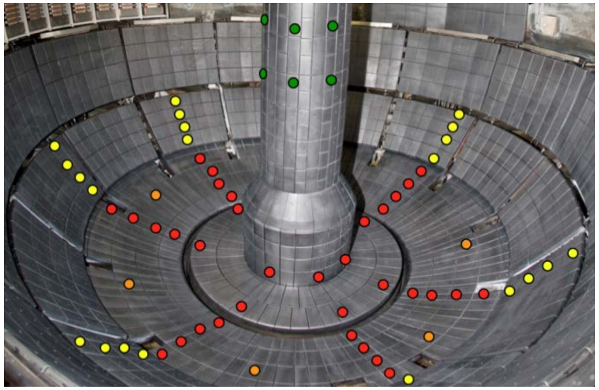
Typically only 15-20% of the stored energy remains in a late flat top disruption in NSTX

Example of rapid disruption with high stored energy



  - Halo currents are non-axisymmetric, but are heat fluxes?

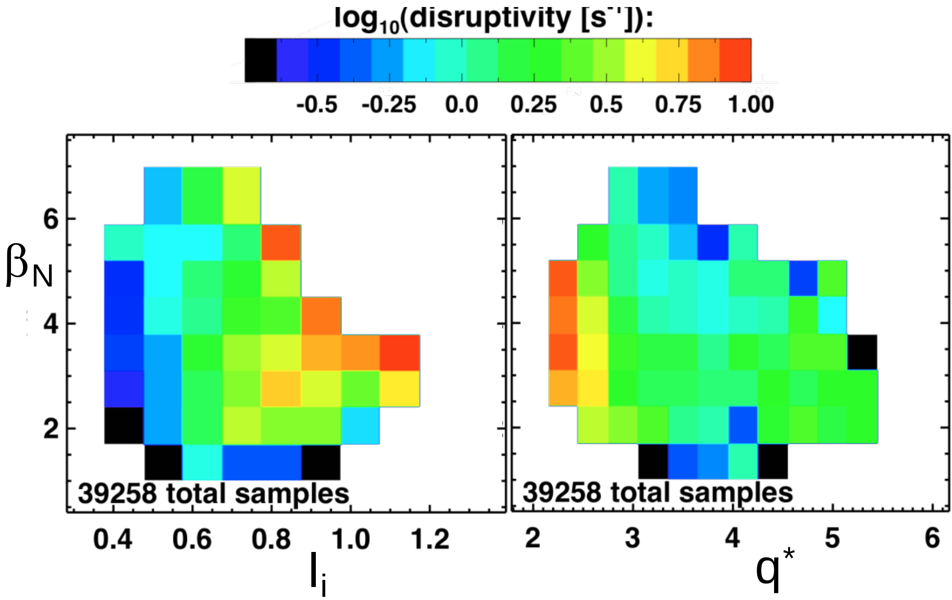




Proposed expansion of the NSTX-U shunt tile diagnostic set

Disruptivity studies and warning analysis of NSTX database are being conducted for disruption avoidance in NSTX-U

Disruptivity

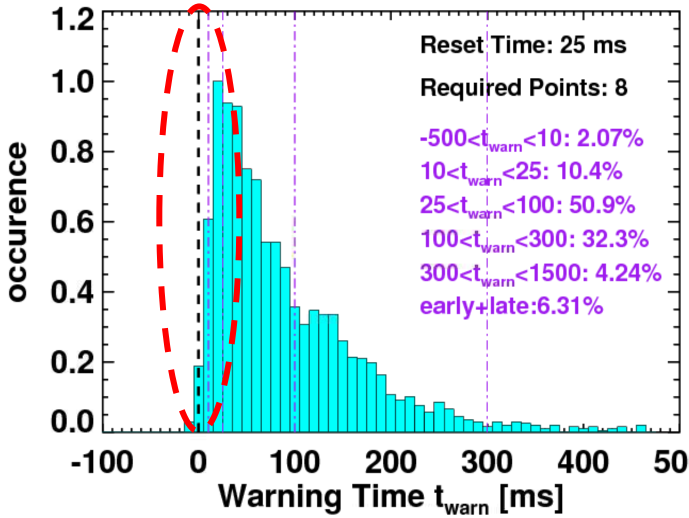


All discharges since 2006

- Physics results
  - Low disruptivity at relatively high $\beta_N \sim 6$; $\beta_N / \beta_N^{\text{no-wall}(n=1)} \sim 1.3\text{-}1.5$
    - Consistent with specific disruption control experiments, RFA analysis
  - Strong disruptivity increase for $q^* < 2.5$
  - Strong disruptivity increase for very low rotation

Warning Algorithms

- Disruption warning algorithm shows high probability of success
  - Based on combinations of single threshold based tests

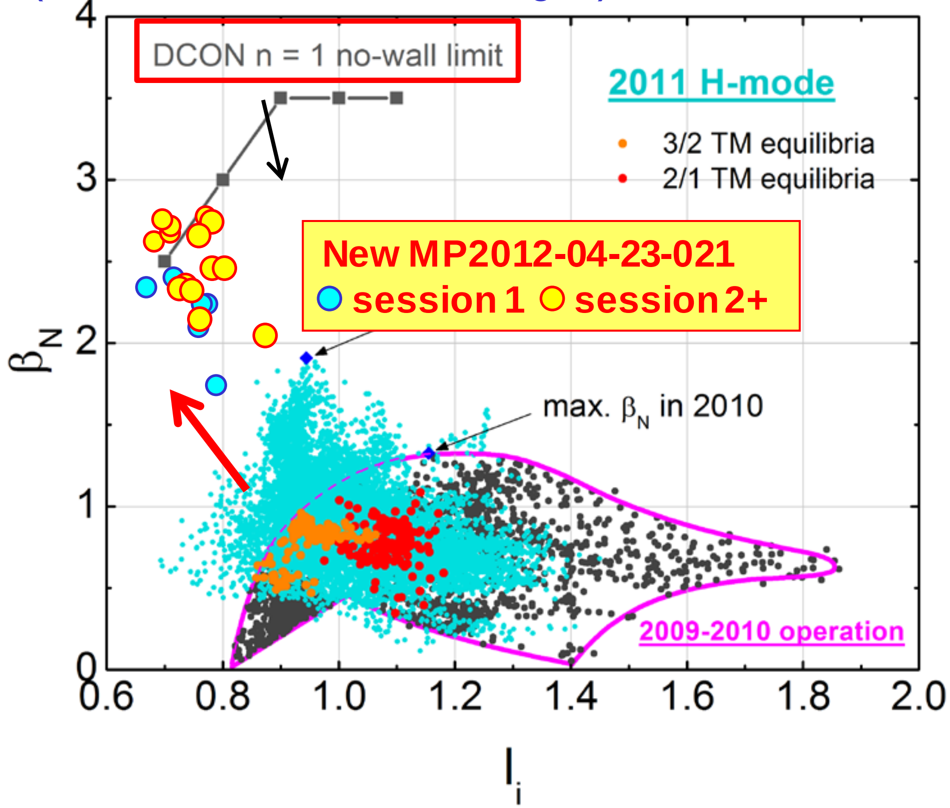


- Results
  - ~ 98% disruptions flagged with at least 10ms warning, ~ 6% false positives
  - False positive count dominated by near-disruptive events

MS group continues strong collaborations with other devices such as KSTAR, DIII-D, and ITER team

KSTAR: equilibrium operating space 2009 –11

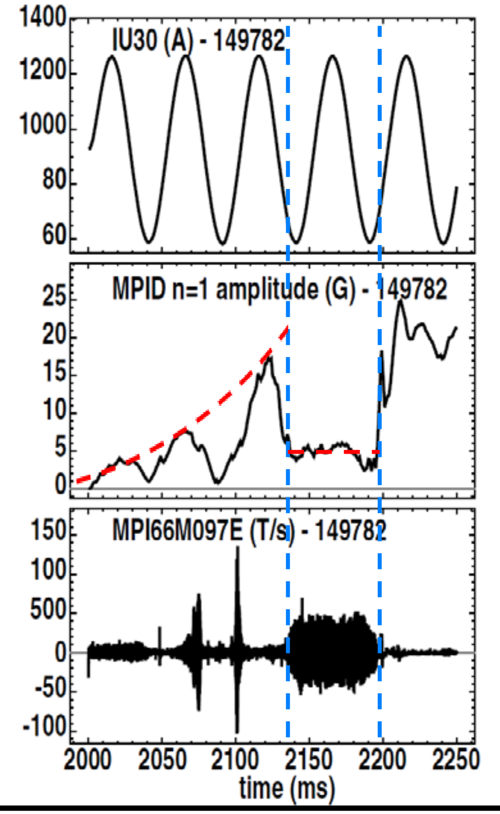
(evolution of > 130 discharges) + new results



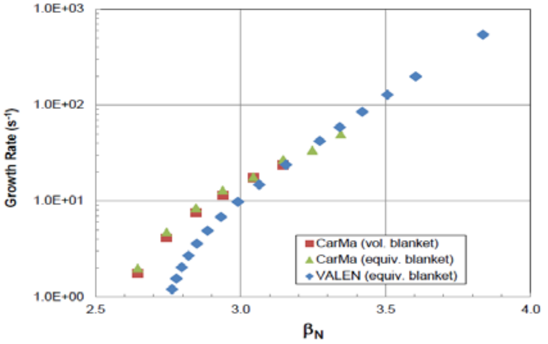
New MP2012-04-23-021
○ **session 1** ○ **session 2+**

- Plasmas have passed the predicted "closest approach" to the n = 1 ideal no-wall stability limit: $l_i = 0.7$, $\beta_N = 2.5$

- **DIII-D**: RFA of ~ 20Hz n = 1 increase to very high levels while β_N increases and rotation decreases
- Rapidly rotating n = 1 appears (TM?), clamps RFA amplitude



ITER: RWM passive growth rates by CarMa and VALEN

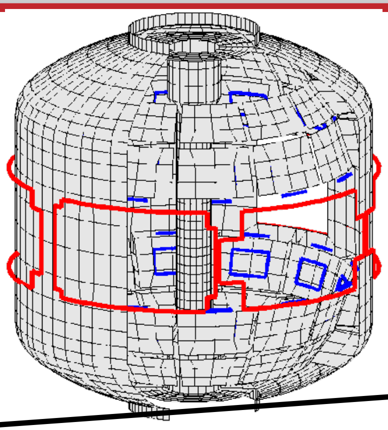


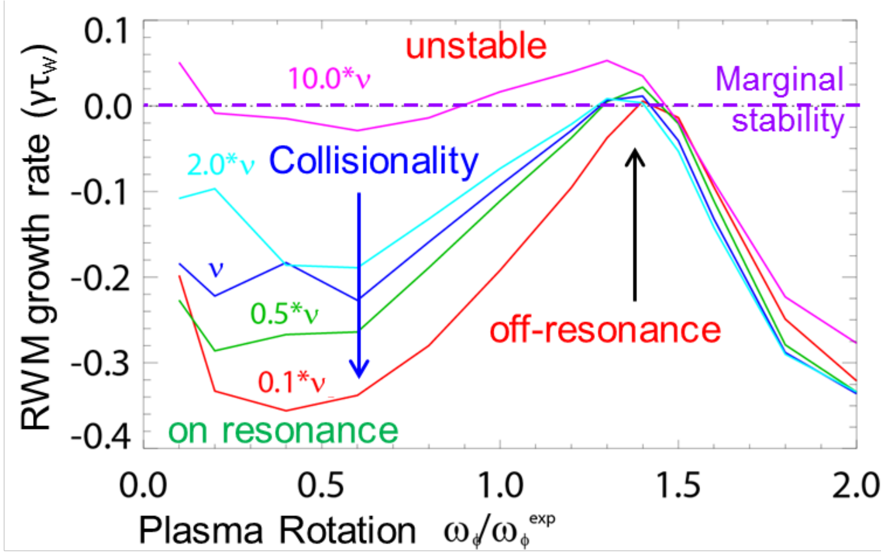
Many important computational codes are used for theory-experiment comparison on NSTX-U

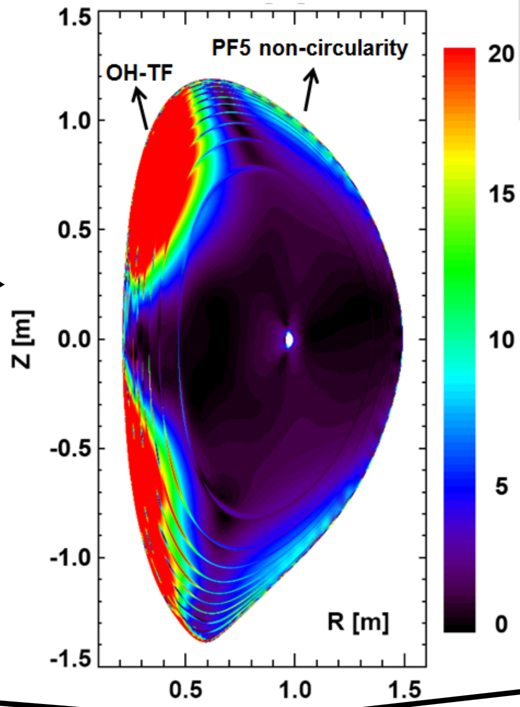
Code	Description	Scope	Improvements
VALEN	Models currents in structures with thin shell finite elements	RWM active feedback simulation, growth rate prediction with 3D walls	Multi-mode effects, study extra time delay in plasma model
RWMSC	Resistive wall mode state-space controller computations	Generate control matrices for real-time controller, and offline physics studies	Generalization for partial actuator availability, n > 1 and multi-mode spectrum
NTVTOK	Shaing theory NTV computation including ion and electron effects	Calculation for comparison to experiment of NTV in all collisionality regimes	Continued implementation of NTV models, guided by experiment
DCON	Ideal MHD stability code	Ideal Kink stability analysis with and without the wall up to n=6	Resistive layer physics across rational surfaces (Resistive DCON)
MISK	Modifications to ideal stability by kinetic effects	Calculation of resistive wall mode stability	Improved model of energetic particle, anisotropy effects
DEGAS-2	Monte Carlo code to compute transport of neutral atoms	Calculation of neutral gas penetration through SOL	Include multiple gas species Use exact NSTX-U SOL conditions from UEDGE
EFIT	Equilibrium reconstruction code	Between-shots equilibriumreconstruction	Higher resolution, auto best level, new diagnostics
IPEC/GPEC	Ideal and general perturbed equilibrium with 3D fields	Plasma response, locking, and NTV studies with 3D fields	General force balance equation including general jump conditions
MARS-K	Self-consistent kinetic stability calculation	Calculation of RWM stability and plasma response to perturbation	Inclusion of energy dependent collisionality for NTV calculation
M3D-C[1]	Implicit resistive and 2-fluid MHD code	Linear and nonlinear MHD stability	Neoclassical terms, resistive wall being added
FORTEC-3D			
POCA	δf guiding-center orbit code	Calculation of neoclassical transport, perturbed pressures and NTV	Improved numerical scheme to enhance computation speed

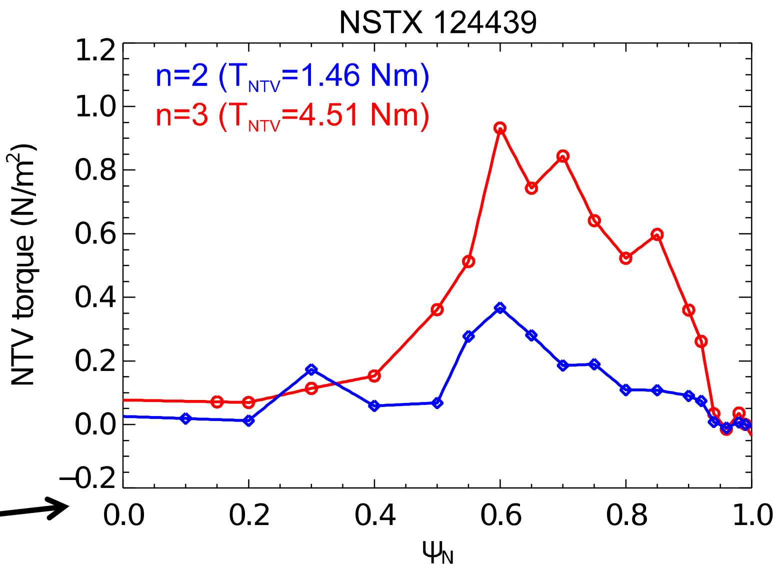
Many important computational codes are used for theory-experiment comparison on NSTX-U

Code
VALEN
RWMSC
NTVTOK
DCON
MISK
DEGAS-2
EFIT
IPEC/GPEC
MARS-K
M3D-C^1
FORTEC-3D
POCA

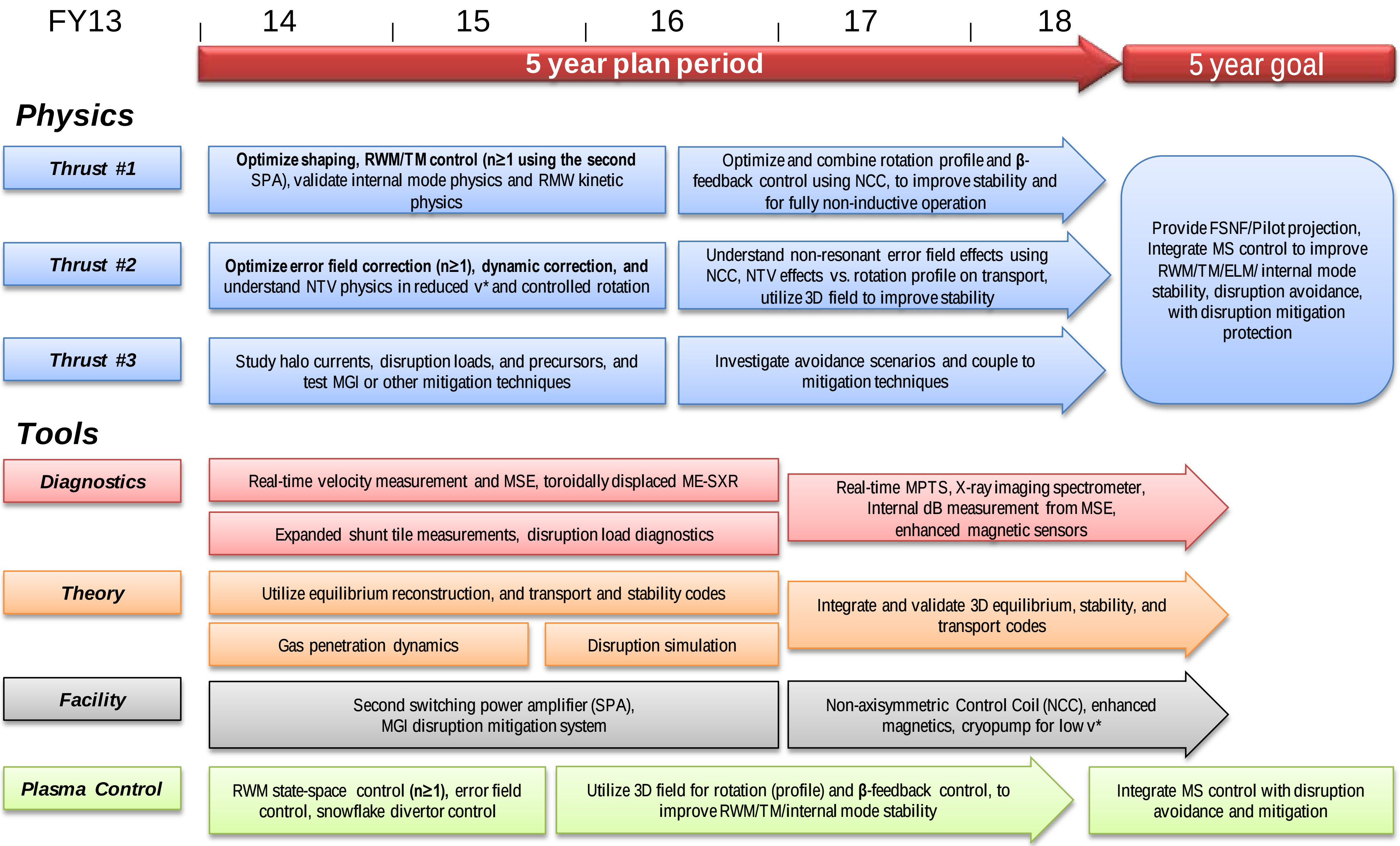








2014-18 Macroscopic Stability Research Timeline



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 v* 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

Real-time velocity measurement and MSE, toroidally displaced ME-SXR

Expanded shunt tile measurements, disruption load diagnostics

Real-time MPTS, X-ray imaging spectrometer, Internal dB measurement from MSE, enhanced magnetic sensors

Theory

Utilize equilibrium reconstruction, and transport and stability codes

Gas penetration dynamics

Disruption simulation

Integrate and validate 3D equilibrium, stability, and transport codes

Facility

Second switching power amplifier (SPA), MGI disruption mitigation system

Non-axisymmetric Control Coil (NCC), enhanced magnetics, cryopump for low v*

Plasma Control

RWM state-space control (**n≥1**), error field control, snowflake divertor 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

Thrust MS-1: Understand and advance passive and active feedback control to sustain macroscopic stability

- Vary q (via B_T and 2nd NBI), plasma rotation (via 2nd NBI and NTV), beta, collisionality (via Li and cryo) to investigate passive stability thresholds for locked modes, RWM, NTM

- Quantify disruption frequency reduction using active mode control (RWM state-space controller) + profile control
  - In particular, investigate interplay/compatibility between fast (~ms) mode growth (RWM) and feedback control and slower (~0.05-1s) equilibrium profile evolution and control (rotation, q, beta)

- Optimize passive stability and state-space control to minimize control power needs for ITER, next-steps

Thrust MS-2: Understand 3D field effects to provide basis for optimizing stability thru rotation profile control by 3D fields

- Study 3D field effects on rotation as a function of:
  - Plasma collisionality as density/collisionality control is improved
  - Torque deposition profile using 2nd NBI
  - Relative strength of resonant vs. non-resonant rotation damping
    - Enabled by off-midplane non-axisymmetric control coils (NCC) to vary poloidal spectrum to vary resonant/non-resonant at fixed n-number
- Utilize independent control of n=1,2,3 fields from midplane coils - enabled by 2nd switching power amplifier (SPA)
  - Study non-resonant field effects on resonant error field correction
  - Develop the physics basis for control of toroidal rotation through magnetic braking while also controlling error fields and RWM
- Use combination of 2nd NBI + 2nd SPA + partial-NCC + collisionality to vary, understand, control toroidal rotation

Thrust MS-3: Understand disruption dynamics, develop disruption detection, avoidance, and mitigation

- Explored low-f, n=1 resonant field amplification (RFA) as a means to detect approach to global stability limit
  - If effective, real-time RFA detection will be implemented and coupled to control of β_N + rotation + q to keep plasma in stable regime
- Measure dynamics of NSTX-U disruptions and develop models to improve understanding of:
  - Heat loading from disruptions, dynamics of the thermal quench, and the generation of halo currents
- Develop and explore disruption mitigation:
  - Examine poloidal angle dependence of Massive Gas Injection (MGI) mitigation efficiency/assimilation
    - Model/interpret SOL gas penetration with DEGAS-2
  - Explore novel electromagnetic particle injector (EPI) (rail-gun)
    - Potential to rapidly deliver large quantities of material to the plasma

Global mode stability at lower collisionality

- Years 2 & 3:
  - Assess β_N and q stability limits at the increased aspect ratio of NSTX-U, with new shaping control and off-axis NBI.
  - Utilize off-axis NBI to produce initial investigation determining the effect of pressure, q, and v_ϕ profile variations on RWM and NTM stability
  - Investigate the dependence of stability on reduced ν through MHD spectroscopy, and compare to kinetic stabilization theory.
- Years 4 & 5:
  - Utilize rotation control and NCC to alter rotation shear for improved NTM control and change proximity to kinetic resonances for RWM control.
  - Combine rotation, q, and β_N control to demonstrate improved RWM/TM/internal MHD mode stability in 100% non-inductive plasmas.

Dual-field component active RWM control and improved mode discrimination at high normalized beta

- Years 2 & 3:
  - Establish dual field component n = 1 active control capability in new NSTX-U operational regime with 6 independent SPAs and more standard use of the snowflake divertor.
  - Attempt initial control of internal MHD modes that appear at low density during current ramp-up.
- Years 4 & 5:
  - Characterize n = 1 – 3 global mode activity using enhanced RWM sensor set, and compare to multi-mode spectrum.
  - Employ superior multi-mode settings for n = 1 and 2 active control with the partial NCC to demonstrate improved global MHD mode stability in 100% non-inductive plasmas.

Model-based RWM state-space controller for active RWM control

- Year 1:
  - Expand RWMSC real-time control software to allow independent actuation of 6 RWM control coils, and a general sensor input scheme.
- Years 2 & 3:
  - Examine effectiveness of RWM model-based state space control with:
    - independent actuation of six control coils
    - multi-mode control with n up to 3
    - plasma rotation-induced stabilization in the controller
- Years 4 & 5:
  - Examine superior RWMSC settings and multi-mode active control with n up to 3, enhanced magnetics, and the partial NCC to demonstrate improved global MHD mode stability in 100% non-inductive plasmas.

Internal kink/ballooning mode control scoping study

- Years 2 & 3:
  - Determine the degree of global mode internalization by comparing diagnosis by magnetic and SXR means as a function of proximity to the mode marginal stability point.
- Years 4 & 5:
  - Examine mode internalization with new toroidally-displaced ME-SXR diagnostic

Use of NCC for mode control and integration of stability control elements

- Years 4 & 5:
  - Determine improvements to kinetic RWM and NTM stability possible by utilizing expanded capability for non-resonant rotation control by the enhanced 3D field spectrum afforded by the partial NCC
  - Implement improvements to active feedback of n > 0 modes via PID and RWMSC control allowed by the partial NCC.
  - Utilize rotation profile control capabilities allowed by the partial NCC to demonstrate reduced disruptivity by actively avoiding global instabilities.

Error field and island dynamics

- Years 2 & 3:
  - Optimize and combine dynamic error field correction with intrinsic error field correction, including n>1 and using 6 SPAs.
  - Investigate resonant error field effects on tearing mode onset
- Years 4 & 5:
  - Utilize NCC to understand locking and tearing modes in the presence of resonant and non-resonant error fields, and develop the predictability for FNSF, ST-Pilot, ITER.

Neoclassical toroidal viscosity at reduced collisionality and applicability to an ST-FNSF and ITER

- Year 1:
  - Analyize existing NSTX data from experiments investigating NTV
  - Update all NTV analysis tools for NSTX-U capabilities
- Years 2 & 3:
  - Assess NTV profile and strength as a function of plasma collisionality, and examine the NTV offset rotation.
  - Prepare an initial real-time model of NTV profile for use in initial tests of the plasma rotation control system
- Years 4 & 5:
  - Demonstrate low rotation profile operation in steady-state with closed-loop rotation control, producing plasma rotation most applicable to ITER and utilizing the partial NCC.

Understanding neoclassical toroidal viscosity (NTV) physics to control rotation braking

- Years 2 & 3:
  - Investigate NTV physics with enhanced 3D field spectra and NBI torque profile at increased pulse lengths, and NTV behavior at reduced ν* regime.
- Years 4 & 5:
  - Study NTV physics in the lowest ν* regimes.
  - Optimize v_ϕ feedback control in regimes of high non-inductive fraction to improve RWM/TM stability.
  - Fully explore the rotation control system to maintain the optimized $v\phi$ and its profiles for microscopic and macroscopic instabilities.

Stability physics for disruption prediction

- Year 1:
  - Evaluate simple physics criteria for the approach to global mode marginal stability based on kinetic stability physics
- Years 2 & 3:
  - Construct an MHD spectroscopy database to determine the measured variation of global mode stability as a function of key parameters.
  - Compare the mismatch between the RWMSC observer model and sensor measurements, and the occurrence of plasma disruptions
- Years 4 & 5:
  - Implement a real-time evaluation of a simple global mode marginal stability model including important parameters available in real-time
  - Examine real-time MHD spectroscopy in determining global mode stability boundaries for input to stability profile control systems
  - Improve disruption prediction using the RWMSC observer by the addition of the newly-installed expanded RWM sensor set.

Stability control for disruption avoidance

- Years 2 & 3:
  - Perform experiments using open-loop plasma rotation, current profile, and energetic particle control to demonstrate the ability to avoid stability boundaries based on kinetic RWM stabilization models.
  - Implement and test initial disruption avoidance using the RWMSC observer model in real-time.
- Years 4 & 5:
  - Implement simple global mode marginal stability model, single mode RFA amplitude and RWMSC observer model as input to profile control systems and disruption warning system.
  - Combine disruption avoidance control with simultaneous use of n > 0 active feedback and the partial NCC, determining physics implications of this combination and potential control conflicts.

Rapid shutdown techniques via mass injection for disruption avoidance

- Years 2 & 3:
  - Commission MGI system and diagnostics, test EPI capsule injection
  - Investigate high-Z gas fractions, gas transit times, the amount of gas required, and symmetry of the radiated power profile
- Years 4 & 5:
  - Assess reduction in divertor heat loads and reduction in divertor halo currents for variations in the gas injection location.
  - Trigger the MGI or EPI systems based on sensor provided data on an impending disruption.

Disruption physics

- Years 2 & 3:
  - Investigate halo current loading on the center column, using newly installed center column shunt tiles.
  - Upgrade shunt tile diagnostics for complete coverage of divertor.
  - Assess total halo current fraction, toroidal structure, and poloidal width.
  - Study spatial extend and timing of the heat deposition during VDEs
- Years 4 & 5:
  - Assess halo current scalings using the full field and current capabilities
  - Assess disruption power balance for the different disruption types
  - Utilize upgraded 3D magnetics for comparison of helical distortions and local halo currents.
  - Study 3D and non-axisymmetric effects on the divertor heat loading.