NSTX-U 5 Year Plan for Macroscopic Stability

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NSTX-U 5 Year Plan Review
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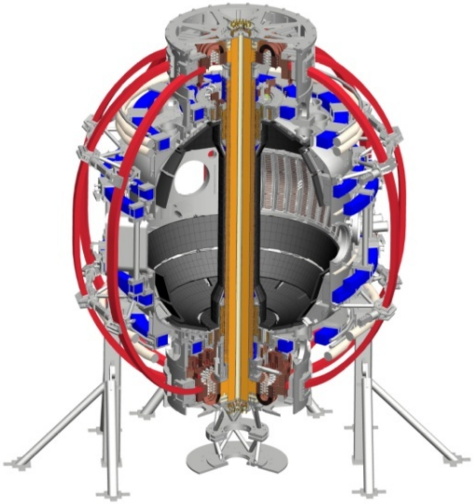

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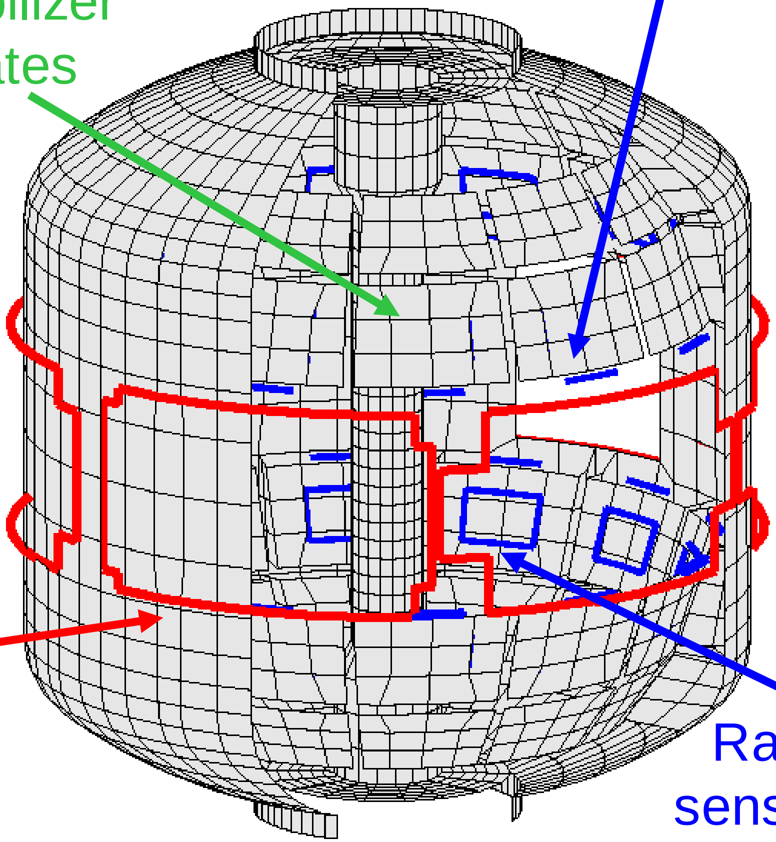
Macroscopic stability group will provide the physics basis for long-pulse sustainment

- Uniqueness of NSTX/NSTX-U:
  - high β above no-wall limit, high rotation with strong NTV braking
- Accomplishments in NSTX:
  - EF correction; RWM active control
  - Comparison of kinetic RWM stabilization theory to experiments
  - NTV physics for magnetic braking
  - Disruption prediction algorithm and halo current measurements
- Midplane control coils
  - n = 1 – 3 error field correction
  - Magnetic braking of ω_φ by NTV
  - n = 1 active RWM control with: combined B_r and B_p PID control or model-based RWM state-space (RWMSC) active control



Poloidal sensors (B_p)

Stabilizer plates

Radial sensors (B_r)

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

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF

2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

- 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

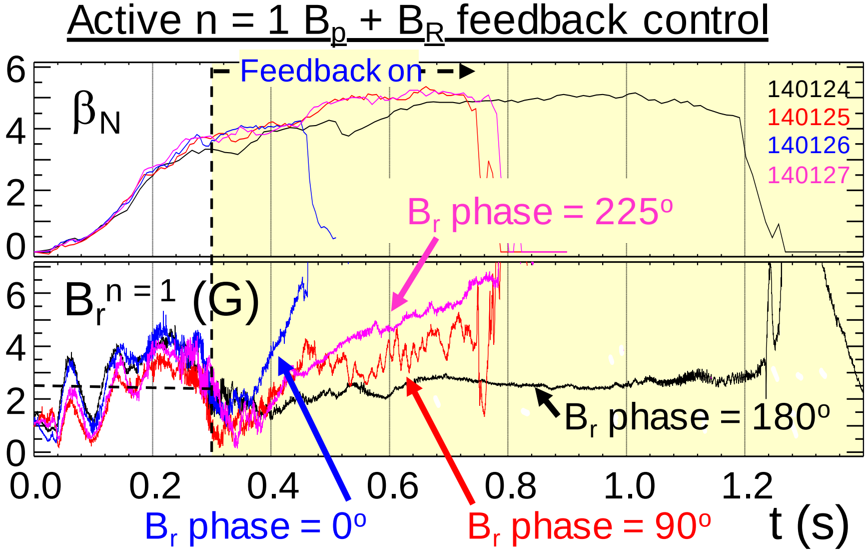
Overall objective: establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

- 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 non-axisymmetric control coils (NCC) and enhanced magnetic sensors
    - 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 (2014):
  - Expand/analyze RWMSC for 6 coil control and n>1 physics

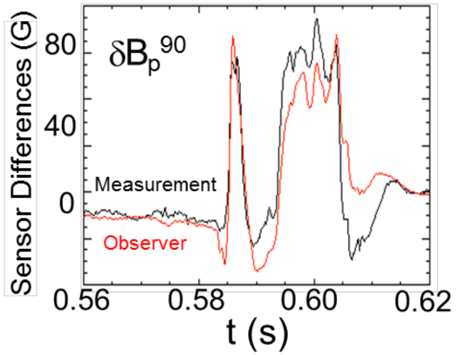
- Years 2 & 3:
  - Establish $B_r + B_p$ active control capability in new machine, use with snowflake divertor
  - Examine RWMSC with:
    - independent actuation of six coils
    - multi-mode control with n up to 3
    - rotational stabilization in the model


Active n = 1 $B_p + B_R$ feedback control

RWMSC

Advantages:

potential for use of external coils with less power

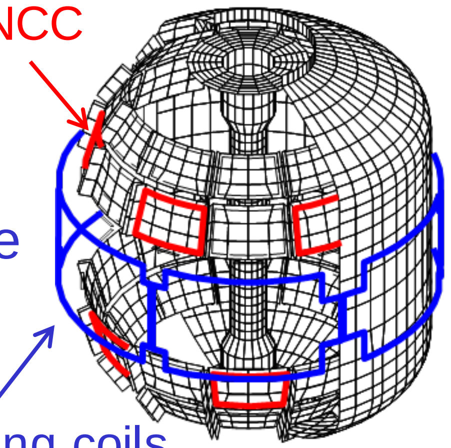


- Years 4 & 5:
  - Utilize model-based active control with the new NCC to demonstrate improved global MHD mode stability and very low plasma disruptivity, producing highest-performance, longest-pulse plasmas

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

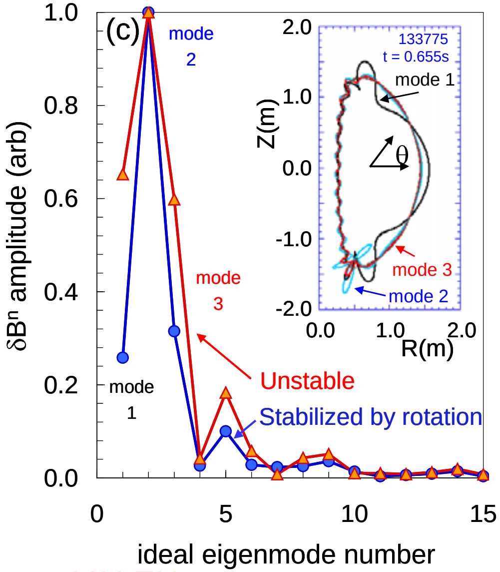
(Next talk by Park will concentrate on NCC)



Partial NCC

Existing coils

Multi-mode n = 1 ideal eigenfunction for fiducial plasma

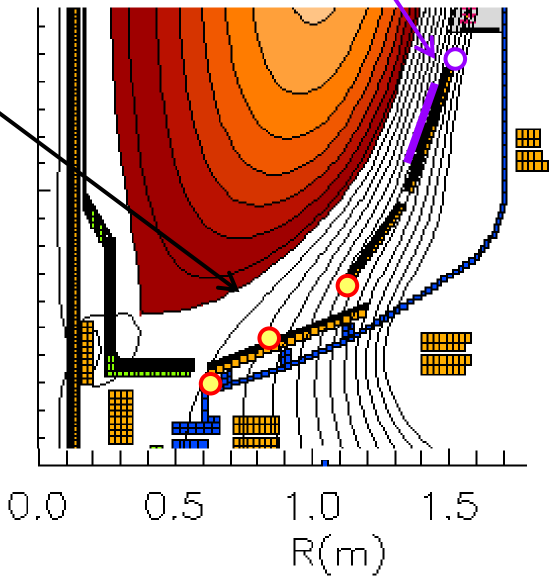


mmVALEN

Proposed new sensor locations

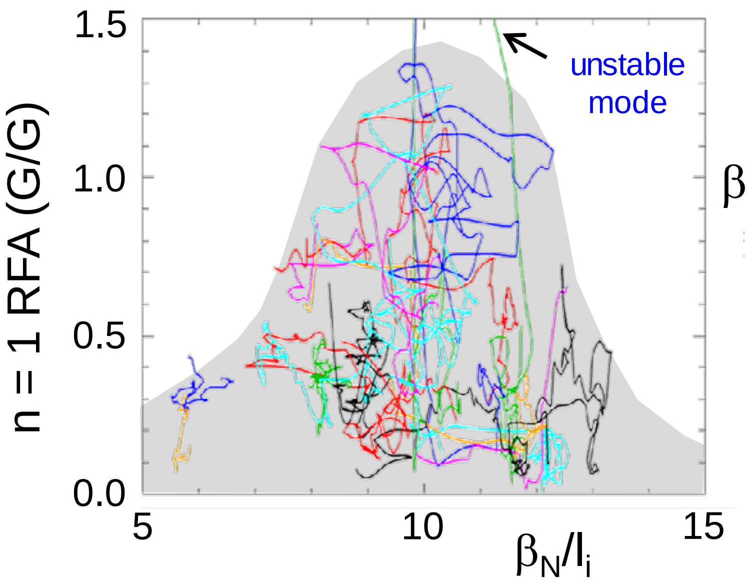
- Mode diagnosis:
  - If two modes are near marginal, need to be able to distinguish
  - Measure increased amplitude near divertor (3D analysis shows >2x increase over present sensors)
  - Similar results in ITER simulations
- Significant toroidal phase change would be measured
  - Can help constrain the RWMSC

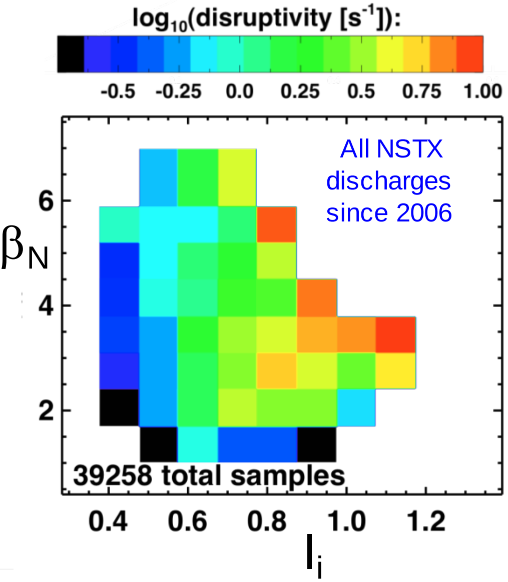
Present sensor locations



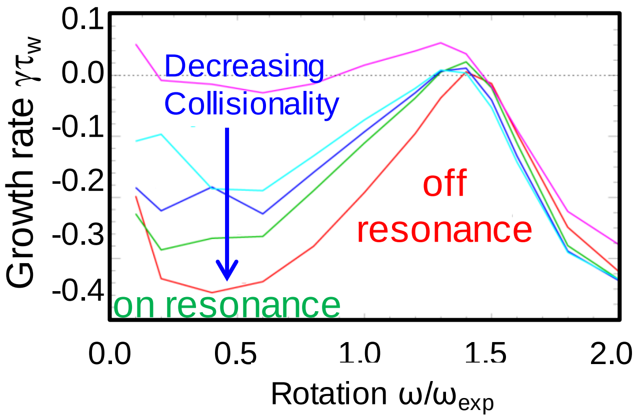
MHD spectroscopy shows improved stability at high β_N/l_i; kinetic RWM stability may be enhanced at low ν

Resonant Field Amplification (RFA) vs. β_N/l_i





Theory: RWM γ vs. ν and ω_ϕ

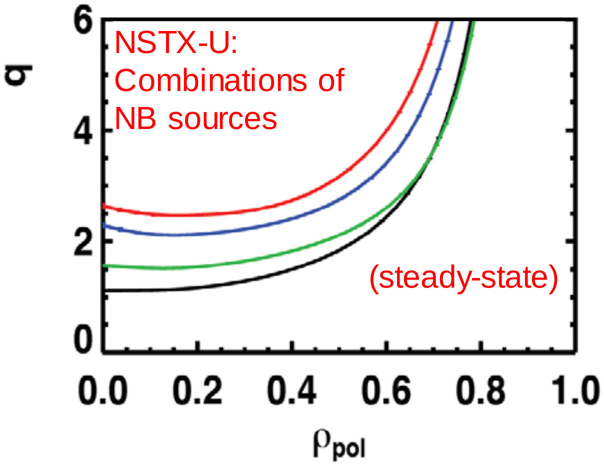


- Mode stability directly measured in experiment using MHD spectroscopy
  - Decreases up to $\beta_N/l_i = 10$ then increases at higher β_N/l_i
  - Agrees with larger NSTX disruption database

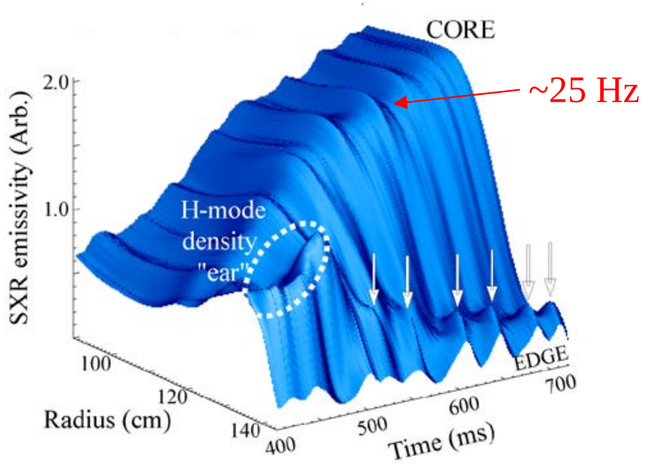
- Years 1 - 3:
  - Investigate the dependence of stability on reduced ν through MHD spectroscopy; compare to kinetic stabilization theory
- Years 4 & 5:
  - Utilize rotation control, NCC, and cryo-pump (for reduced ν) to change proximity to kinetic resonances for RWM control

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

Coupled saturated 1/1 kink and 2/1 tearing 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
  - Detect internal modes with RWMSC and non-magnetically with 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

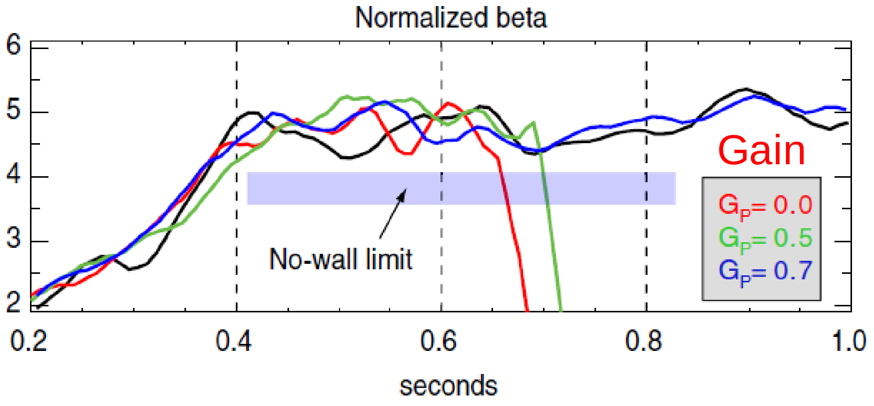
Overall objective: establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

- 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
    - Error field (EF) correction
    - Locking and tearing modes with resonant and non-resonant Efs
    - Tearing mode physics vs. rotation and rotation shear
    - Neoclassical toroidal viscosity
- Thrust 3, Disruptions:
  - Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas

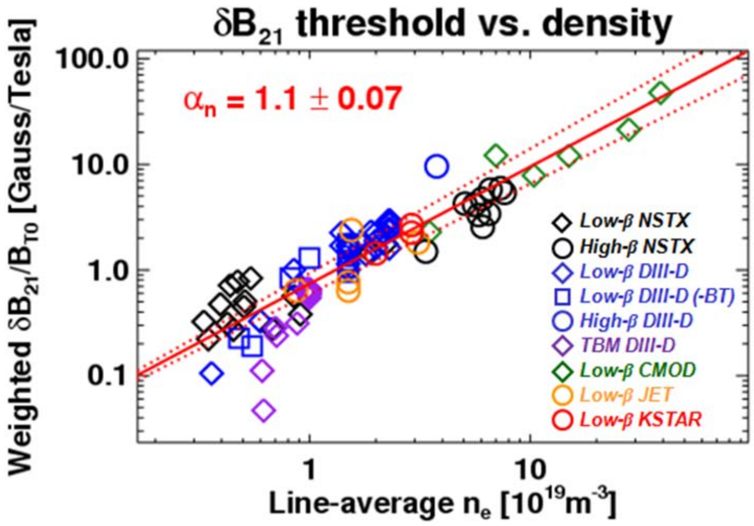
Correction of intrinsic error fields (EFs) is critical for performance; Resonant and non-resonant EFs affect locking and tearing stability

- 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



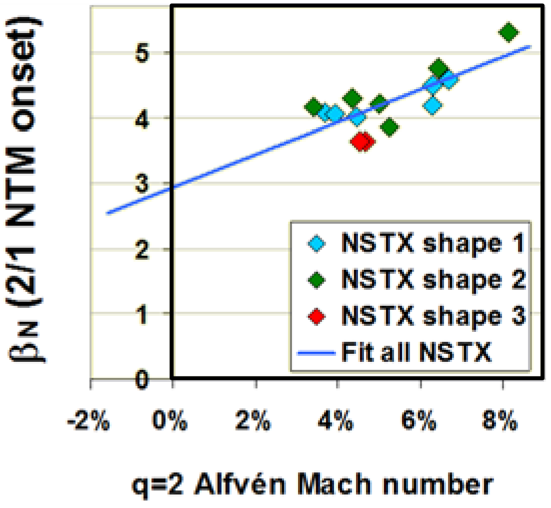
Resonant error field threshold vs. locking density (IPEC) for five devices



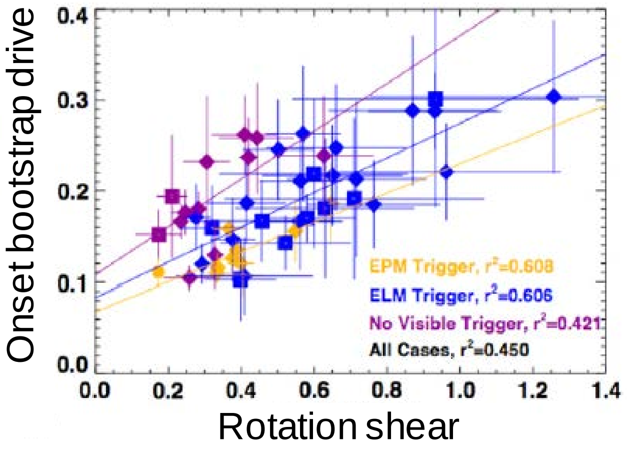
NSTX-U will investigate tearing mode physics vs. rotation and rotation shear

- Year 1:
  - Analyze NSTX TM/NTMs, project to NSTX-U with resistive DCON, MARS-K, M3D-C1
- Years 2 & 3:
  - Investigate the rotation and rotational shear vs. TM/NTM in NSTX-U, compared with NSTX
  - Investigate the β limit for TM/NTM onsets with varied rotation and rotation-shear
- Years 4 & 5:
  - Use the partial NCC and the 2nd NBI beam to study TM/NTM dynamics as a function of (β_N,v_ϕ)
    - develop predictability for ITER

Low rotation is bad for the NTM threshold



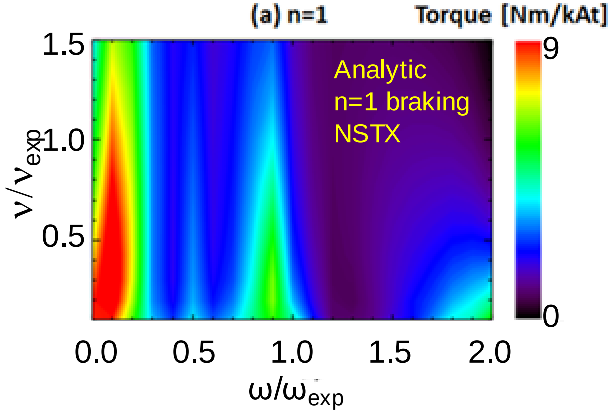
Rotation shear may be an even more important parameter



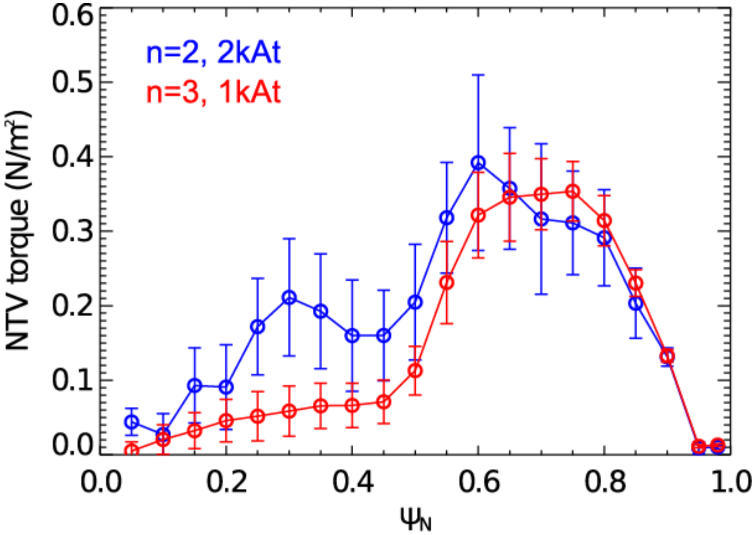
NSTX-U will investigate neoclassical toroidal viscosity (NTV) at reduced ν, which is important for rotation control and ITER

- 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

Theoretically, torque can be a strong function of rotation and ν



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



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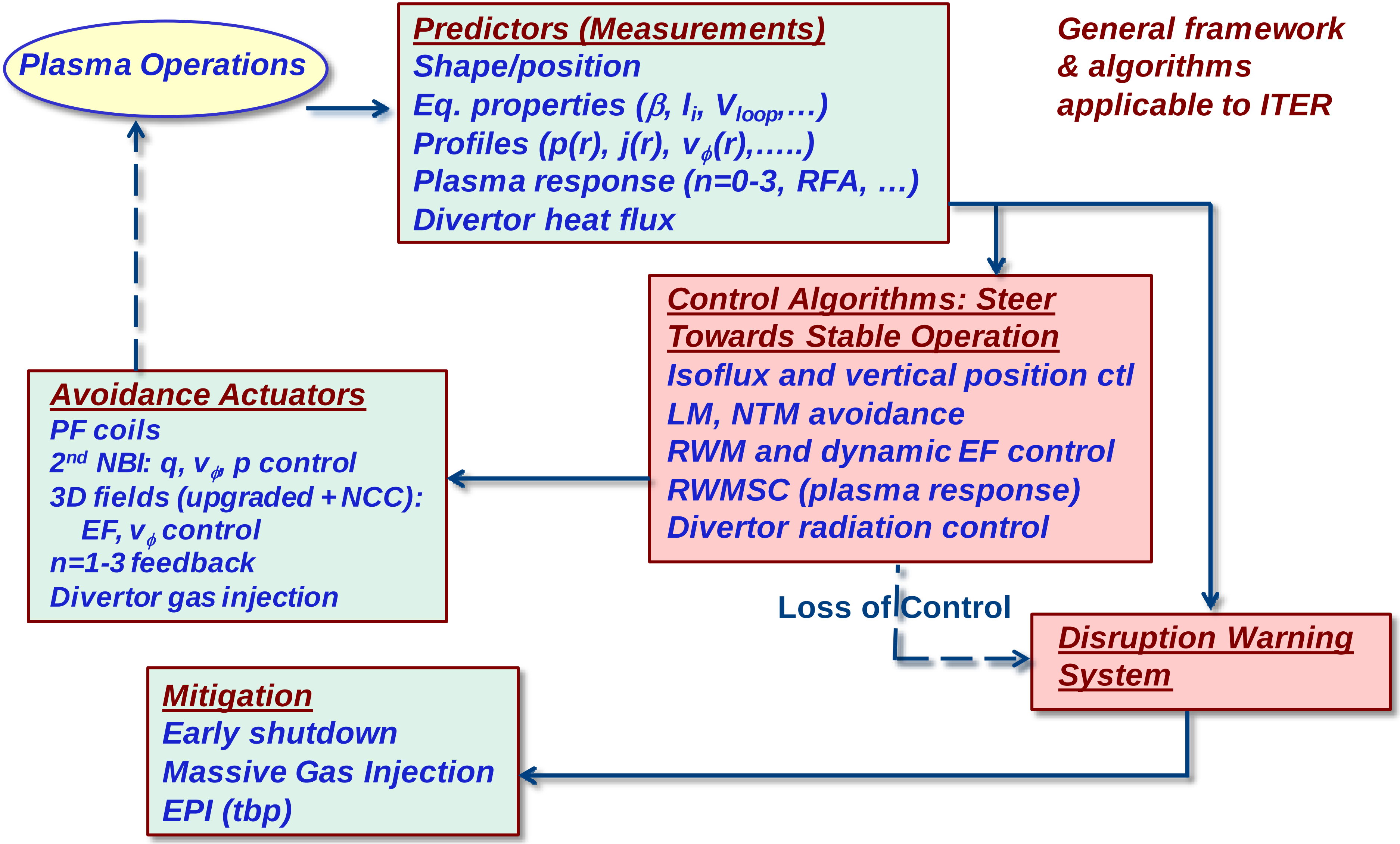
- Thrust 3, Disruptions:
  - Understand disruption dynamics and develop techniques for disruption prediction, avoidance, and mitigation in high-performance ST plasmas
    - Prediction and avoidance
    - Mitigation with MGI
    - Transient heat loads and halo currents

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



Plasma Operations

Predictors (Measurements)
Shape/position
Eq. properties (β, l_i, V_{loop},…)
Profiles (p(r), j(r), v_ϕ(r),…..)
Plasma response (n=0-3, RFA, …)
Divertor heat flux

General framework & algorithms applicable to ITER

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

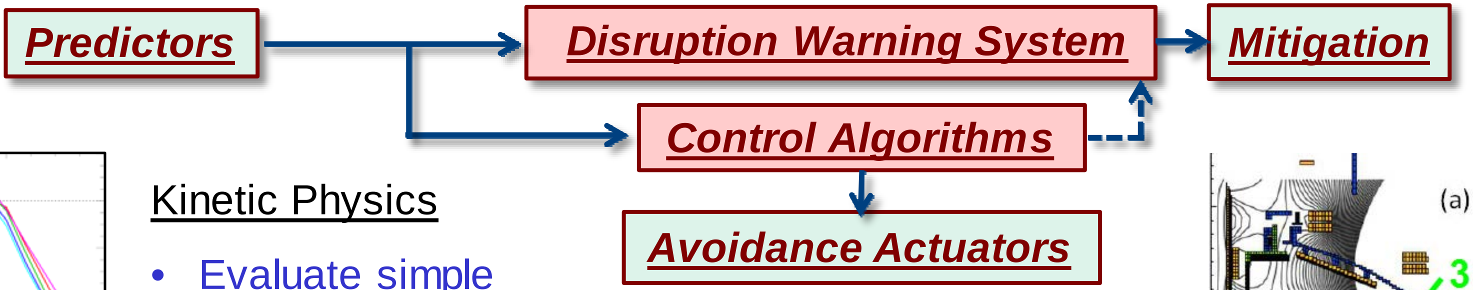
Avoidance Actuators
PF coils
2nd NBI: q, v_ϕ, p control
3D fields (upgraded + NCC):
EF, v_ϕ control
n=1-3 feedback
Divertor gas injection

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)



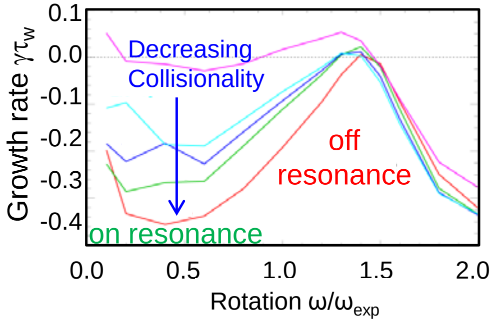
Predictors

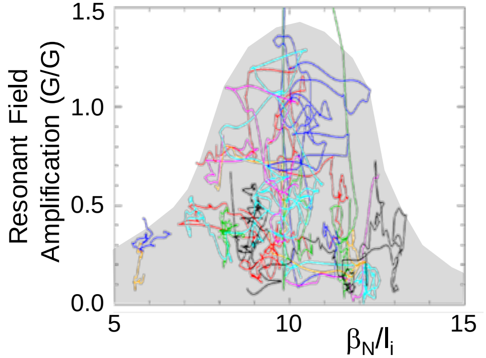
Disruption Warning System

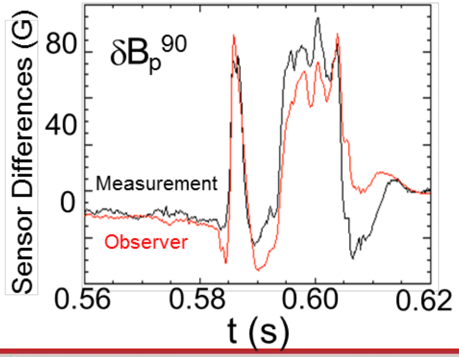
Mitigation

Control Algorithms

Avoidance Actuators







Kinetic Physics

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

MHD Spectroscopy

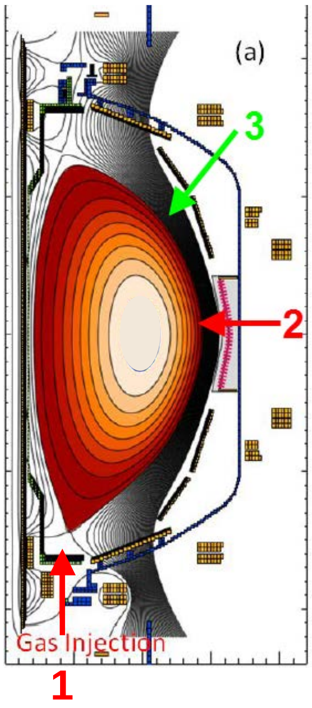
- Use real-time MHD spectroscopy while varying rotation, q_{min}, and β_N to predict disruptions

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

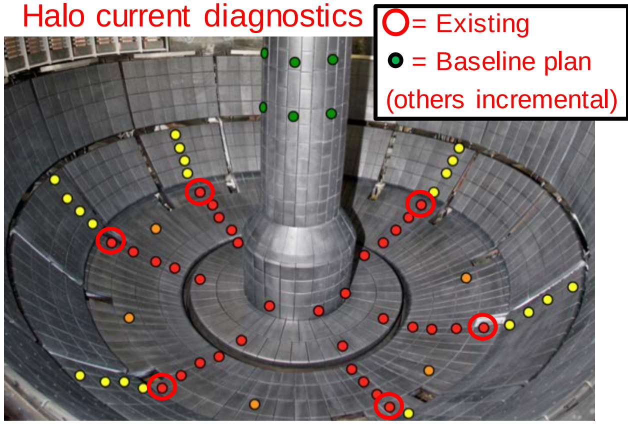
- Year 1:
  - Model neutral gas penetration of SOL
- Years 2 & 3:
  - Commission MGI system
  - Characterize density assimilation vs. poloidal location
- Years 4 & 5:
  - Utilize EPI system
  - Trigger the MGI system based on warning of an impending disruption

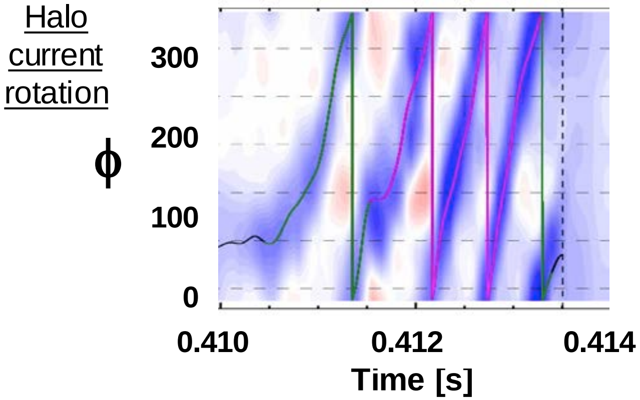
NSTX-U will provide projections of transient heat loads and halo currents for ITER and FNSF

- 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

New diagnostic: high-speed IR thermography (ORNL)

Halo current diagnostics





ITER high priority item: ITER has vessel resonances at frequencies of rotating halo currents

Summary of NSTX-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

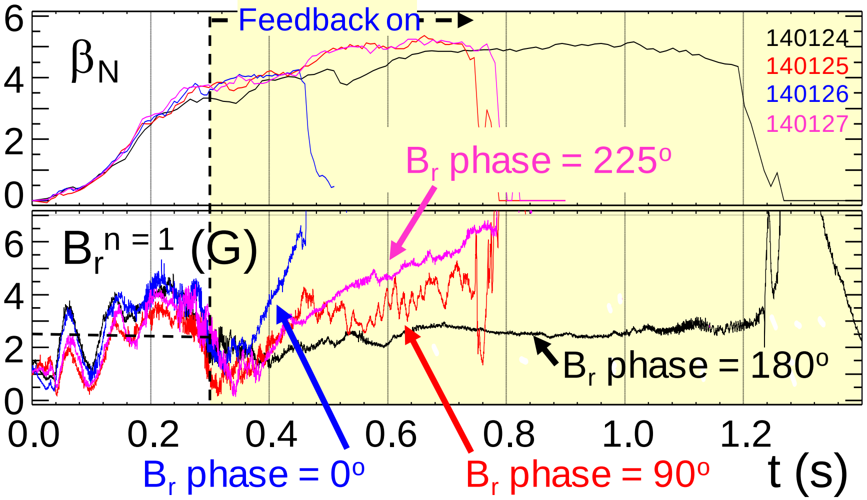
- Through the experimental outage, our group:
  - – Maintains contributions to five joint experiments and two working groups
    - leads the MDC-2 joint experiment / analysis on RWM physics
    - co-leads the Working Group 7 effort on aspects of active mode control

	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	MDC-21	Global mode stabilization for disruption prediction and avoidance (proposed)

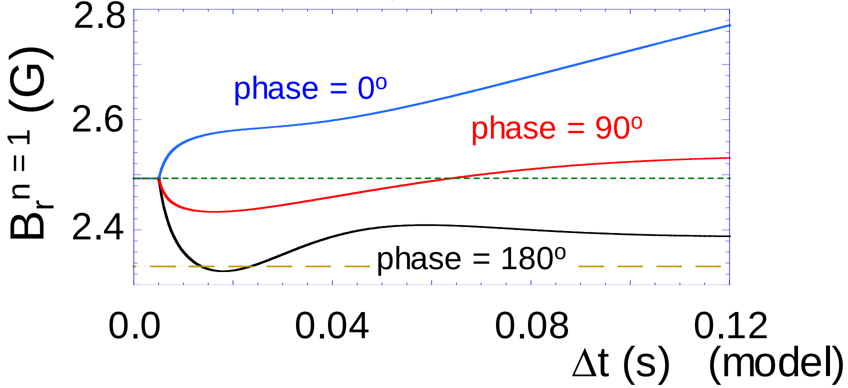
  - – Communicated NSTX research bi-annually at each ITPA MHD Stability group meeting for many years
  - – Led two elements of the recent ITPA Integrated Plasma Control Working Group study, led by Dr. Joseph Snipes of ITER
    - also contributed with direct calculations for ITER on RWM and error field 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

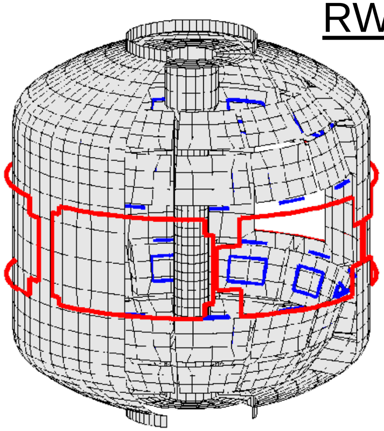


Calculation of B_r + B_p control (VALEN)

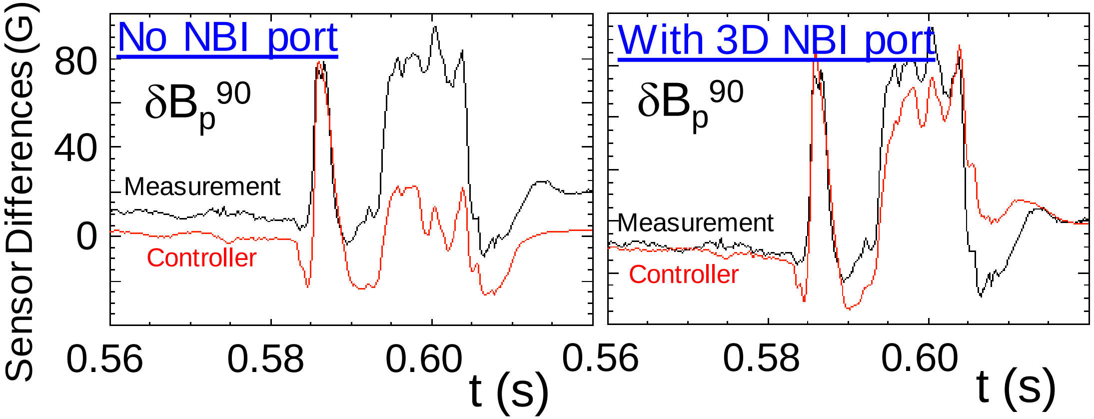


Model validation and predictive capability:
VALEN code feedback predictions

RWM State Space Controller



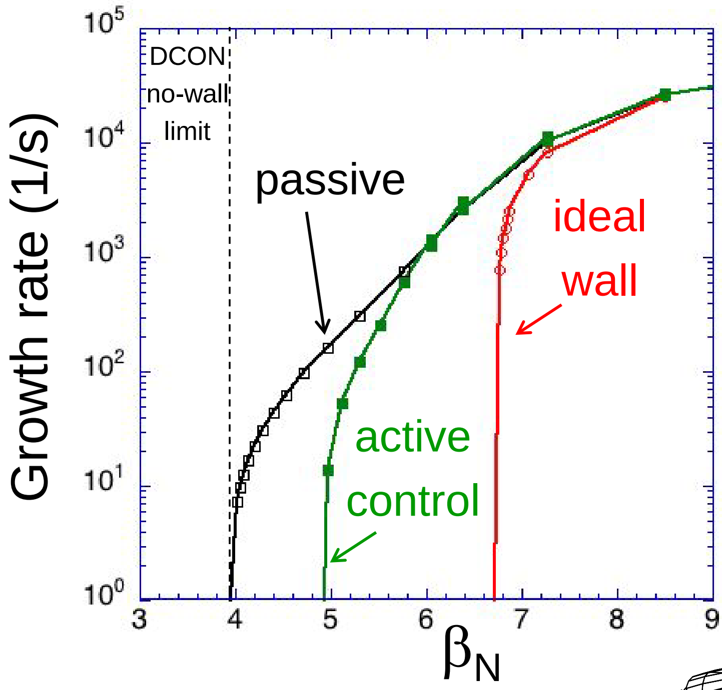
3D wall,
ports,
mode
currents



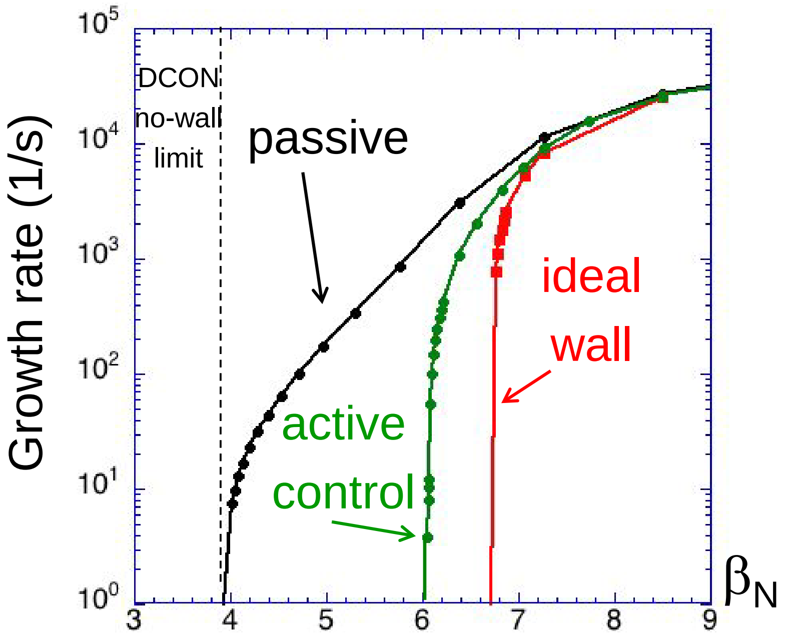
- Inclusion of 3D mode and wall detail improves control

RWM active control capability increases as partial NCC coils are added

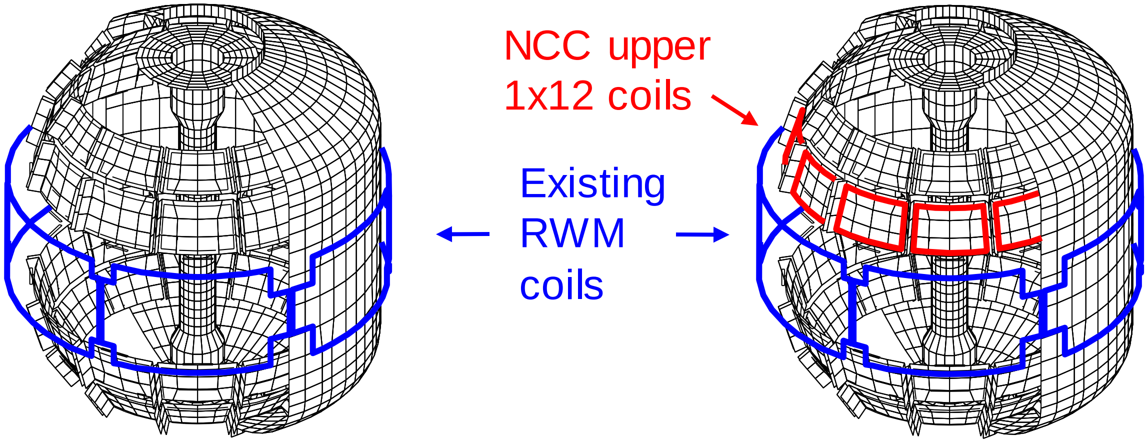
Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors

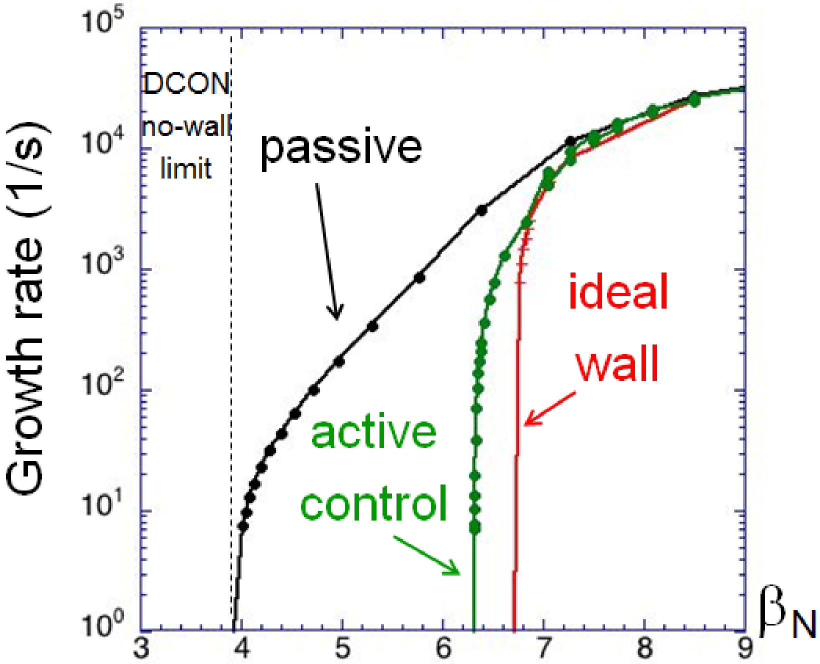


- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.54$

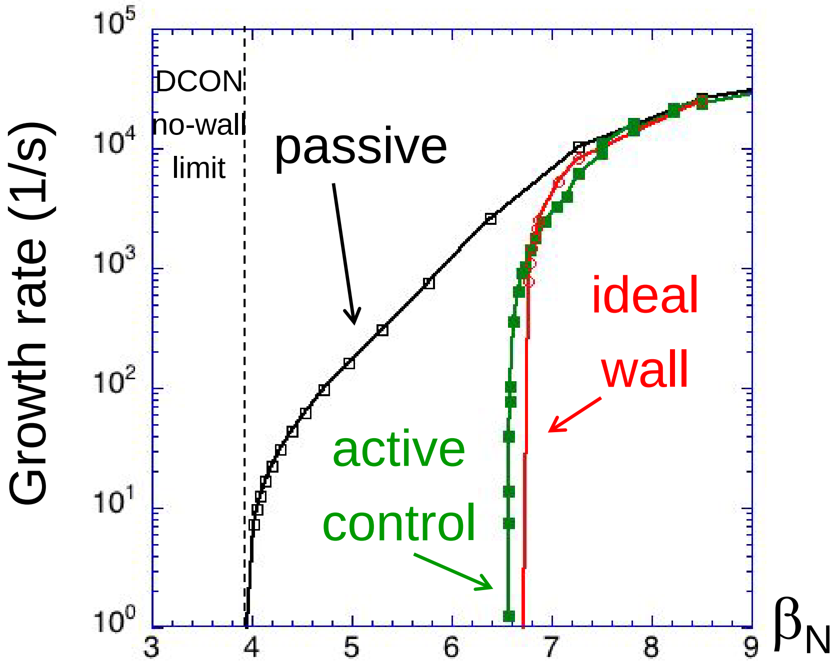


RWM active control capability increases further with full NCC

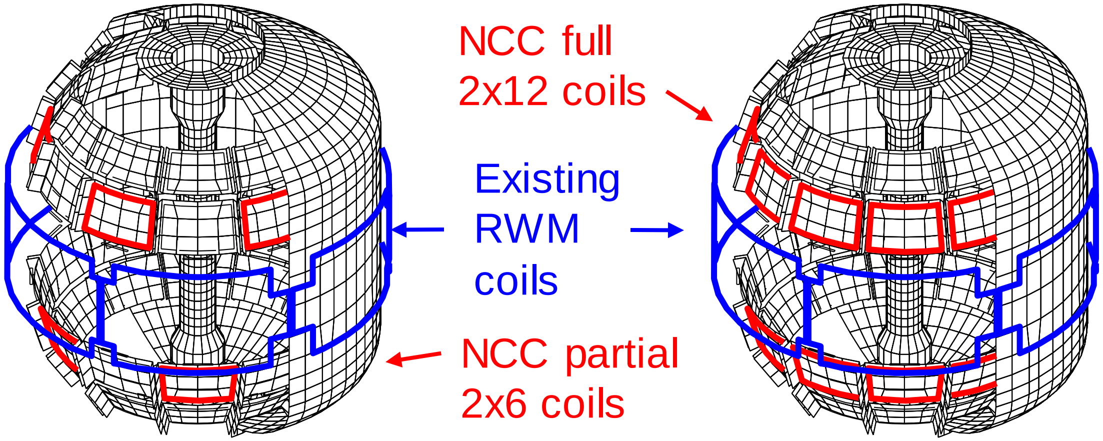
NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain

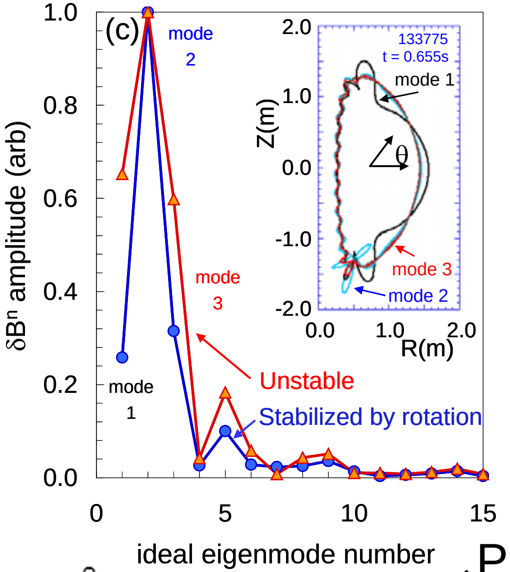


- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.61$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.70$



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

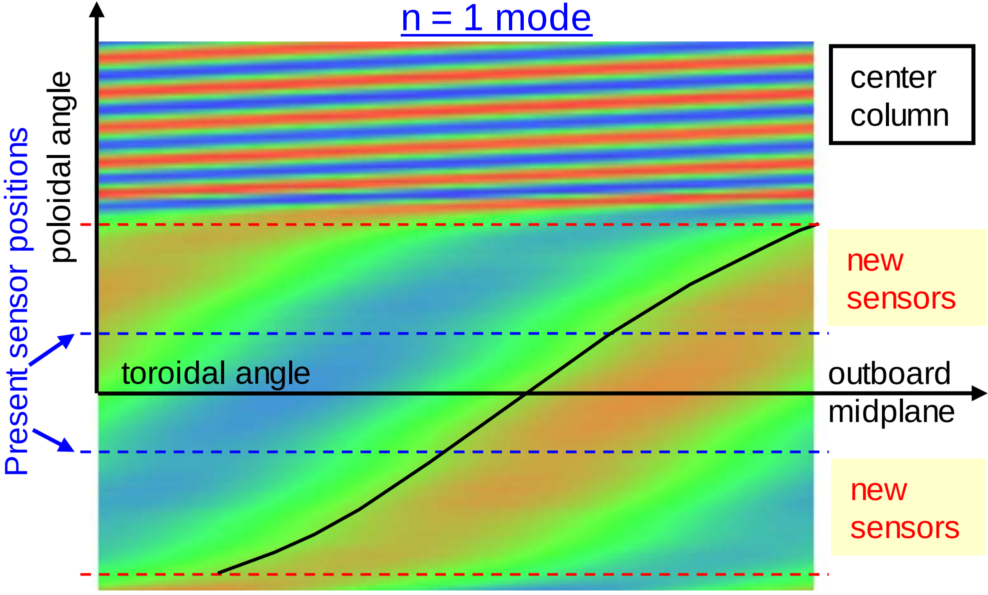
Multi-mode n = 1 ideal eigenfunction for fiducial plasma



Multi-mode physics

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

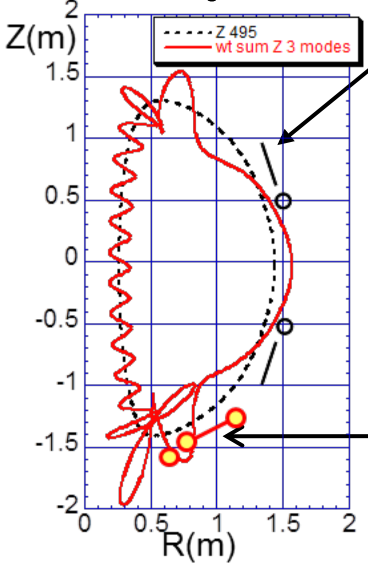
n = 1 mode



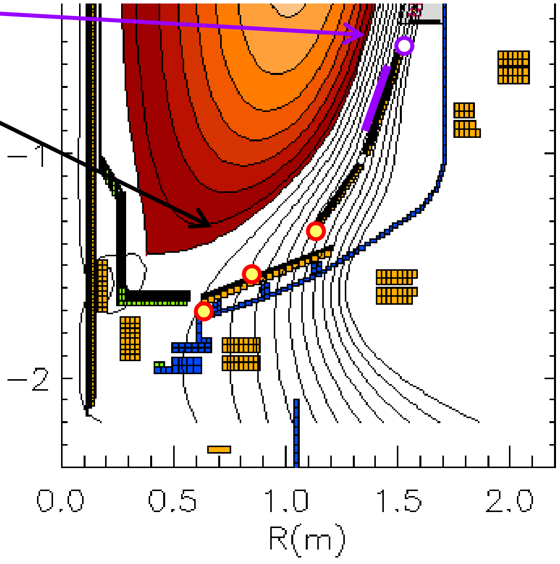
Present sensor locations

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

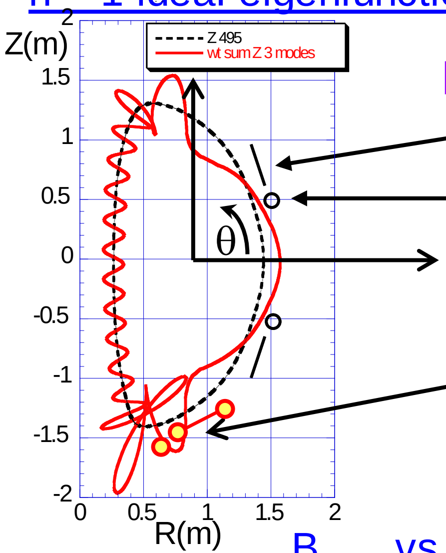


mmVALEN code



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

n = 1 ideal eigenfunction for high beta plasma

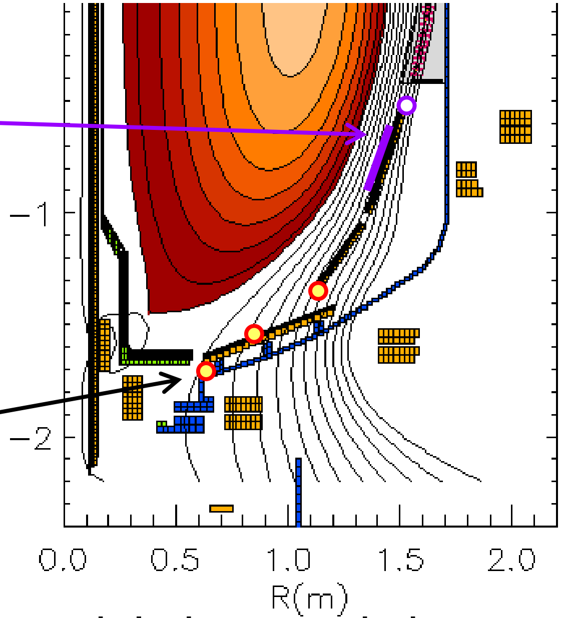


Present sensor locations

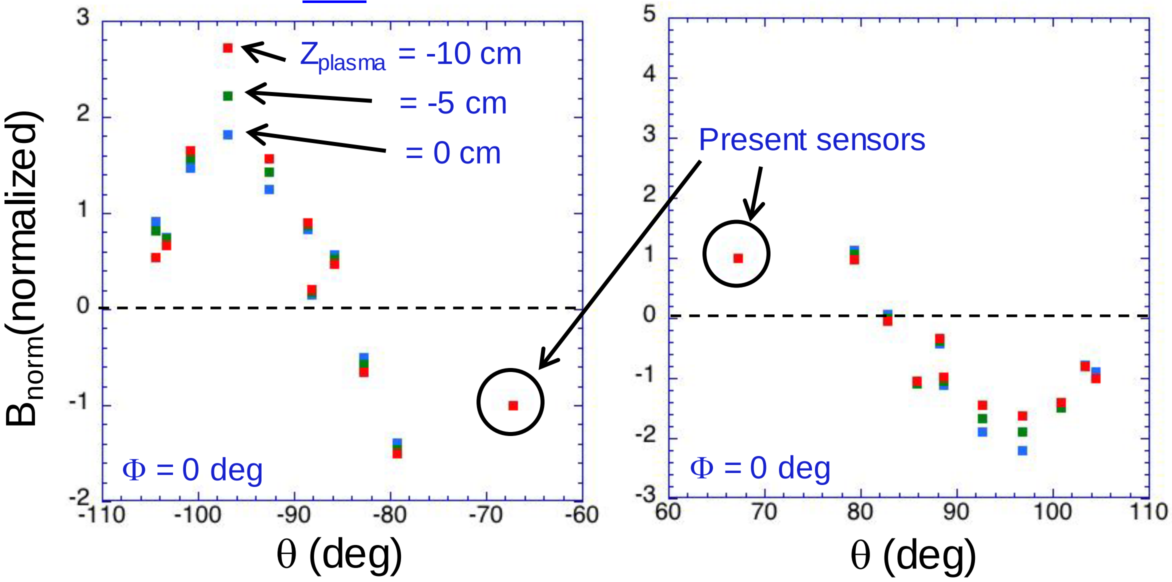
B_R sensors (nominally normal, B_{norm})

B_p sensors (nominally tangential, B_{tan})

New sensor locations (includes one new location above midplane)

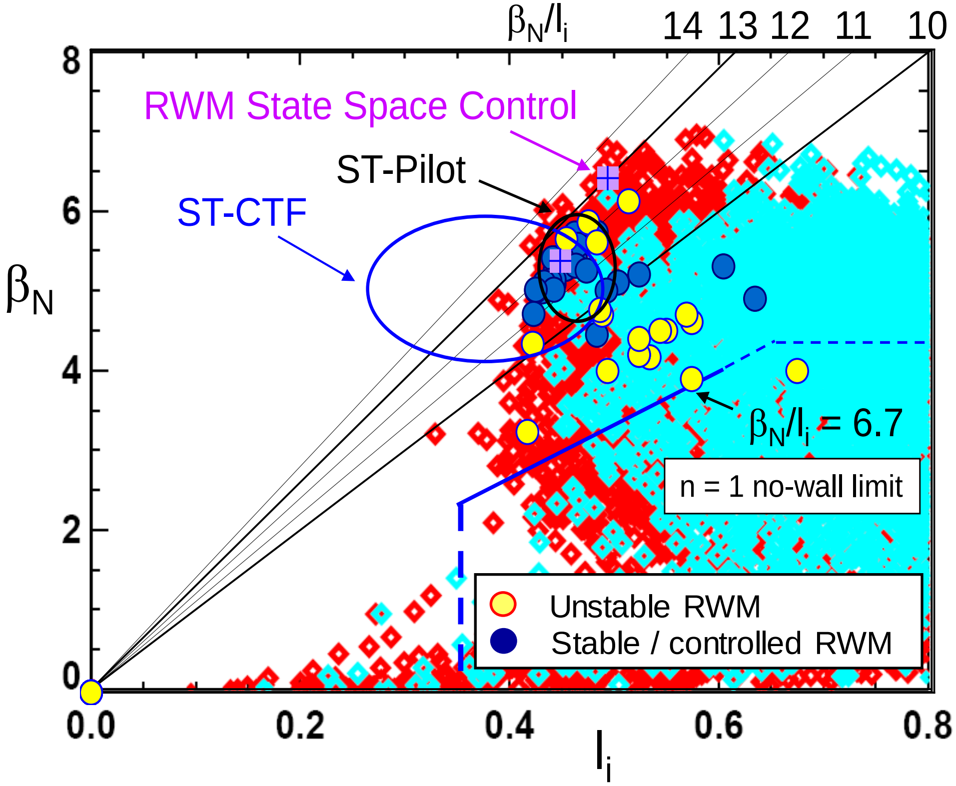


B_{norm} vs. theta (normalized to present Br sensors)



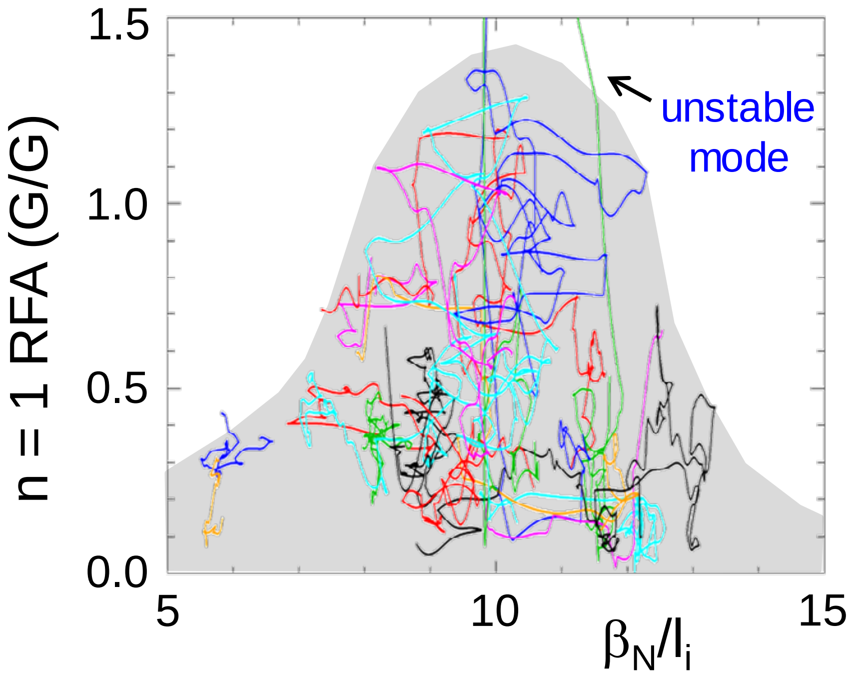
- Model characteristics
  - New 3D model of divertor plate
  - 3D sensors with finite toroidal extent; n*A of existing sensors
- Results summary
  - Field amplitude increases >2x with new sensors
  - Perturbed field reversals observed with new sensors
  - Signals sufficient with plasma shifted off-midplane

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

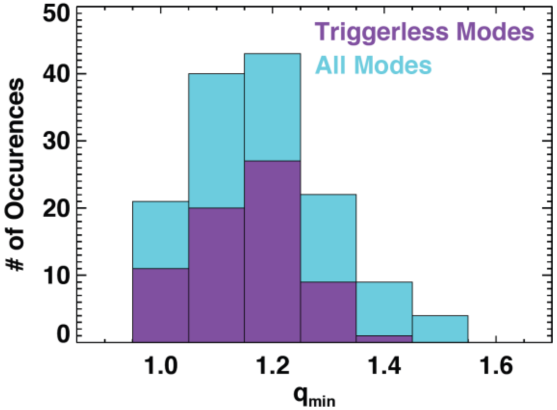
Resonant Field Amplification (RFA) vs. β_N/l_i

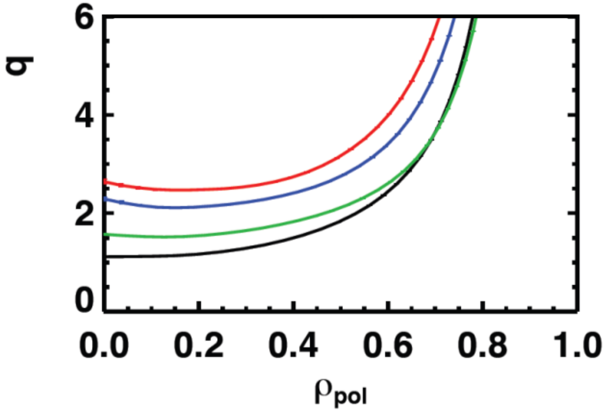


- Mode stability directly measured in experiments using MHD spectroscopy
  - Stability decreases up to $\beta_N/l_i = 10$
  - Stability increases at higher β_N/l_i
  - Presently analysis indicates consistency with kinetic resonance stabilization

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



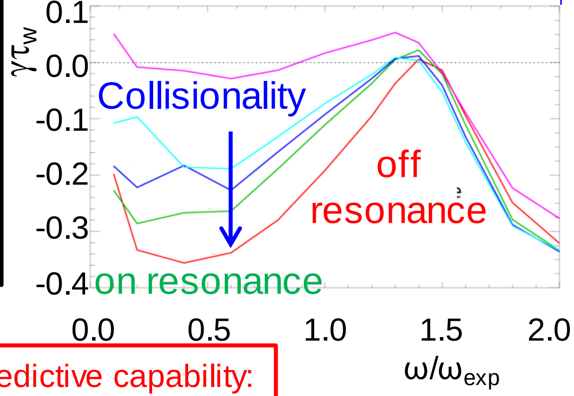


Various combinations of neutral beam sources

- 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

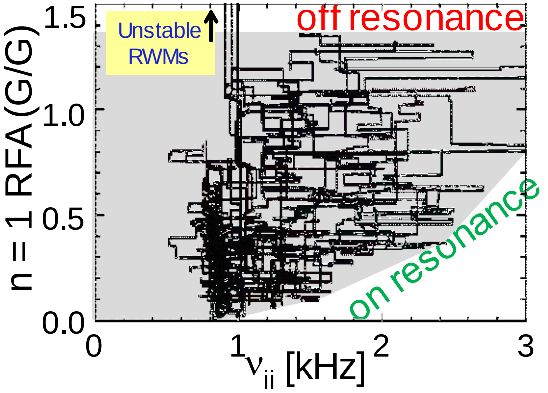
Theory: RWM γ vs. ν and ω_ϕ



Model validation and predictive capability: MISK code RWM stability calculations

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

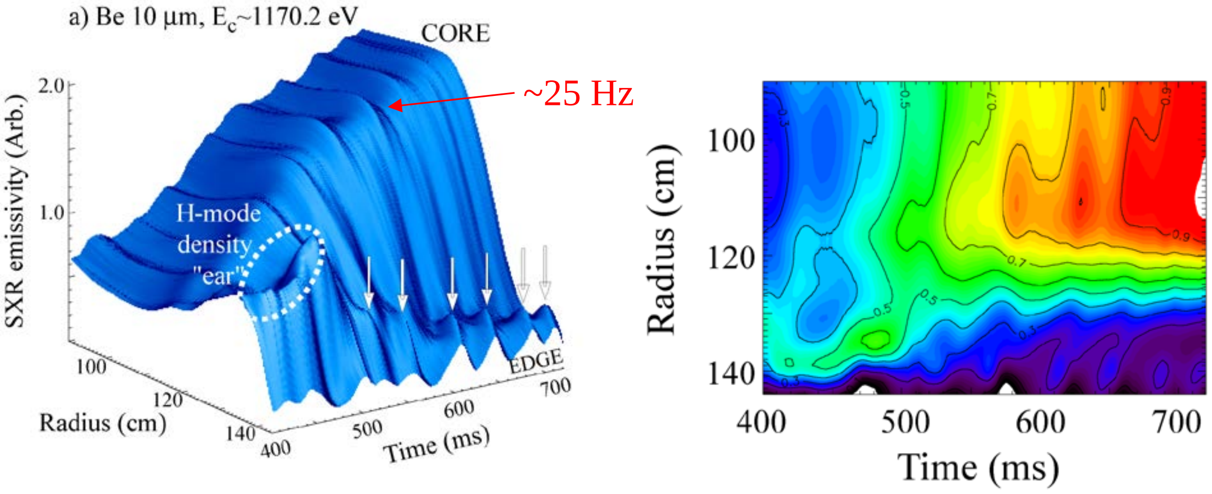
Experiment: RFA vs ν



- 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

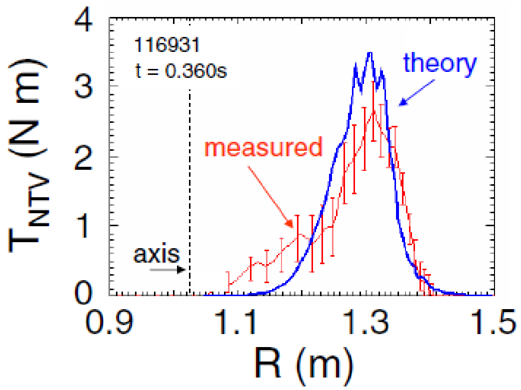


Understanding neoclassical toroidal viscosity (NTV) is crucial for rotation control

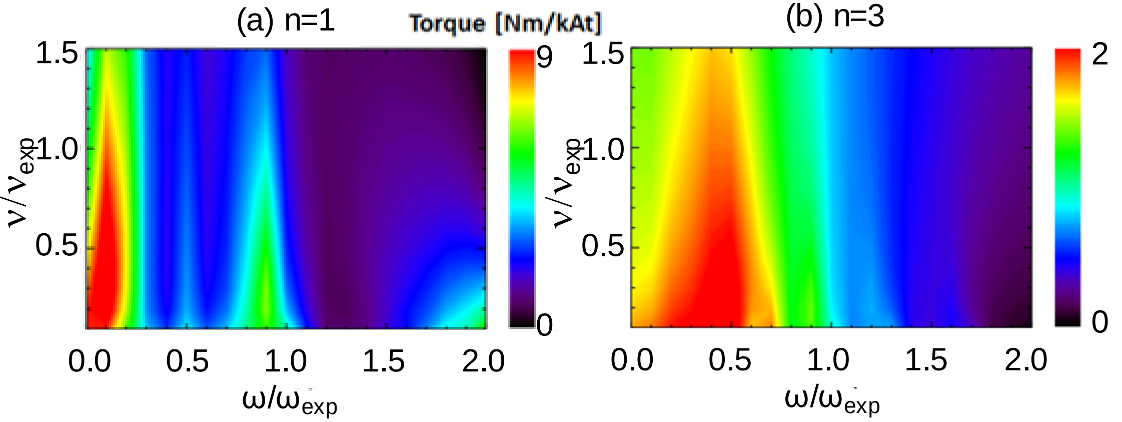
R(12-1) “Investigate magnetic braking physics to develop toroidal rotation control at low ν”

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

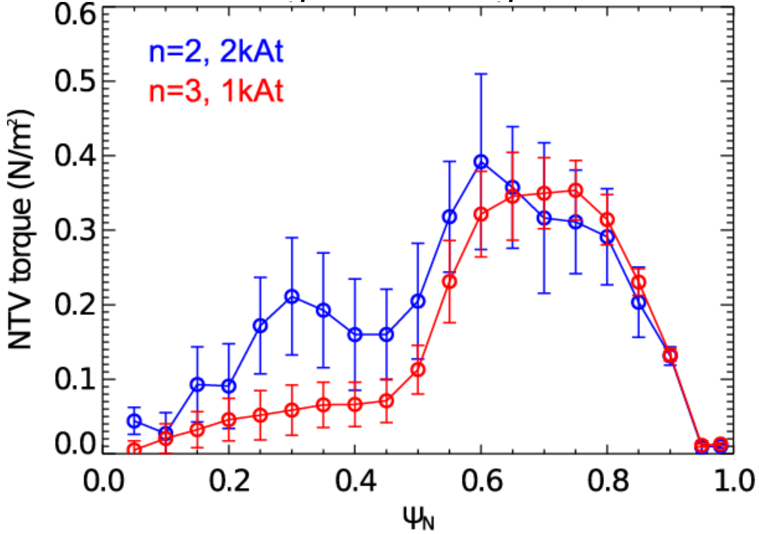


Analytic NTV calculations for (a) n=1 and (b) n=3 magnetic braking in NSTX, as a function of collisionality and rotation



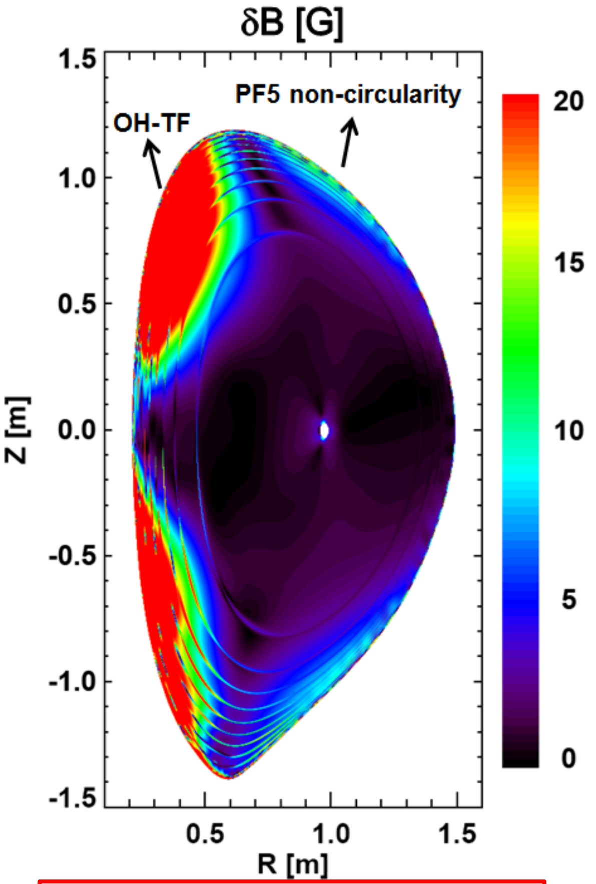
- A new δf guiding-center particle code, POCA, was developed to investigate neoclassical transport in perturbed tokamaks.
  - solves the Fokker-Planck equation with non-axisymmetric magnetic field perturbations

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



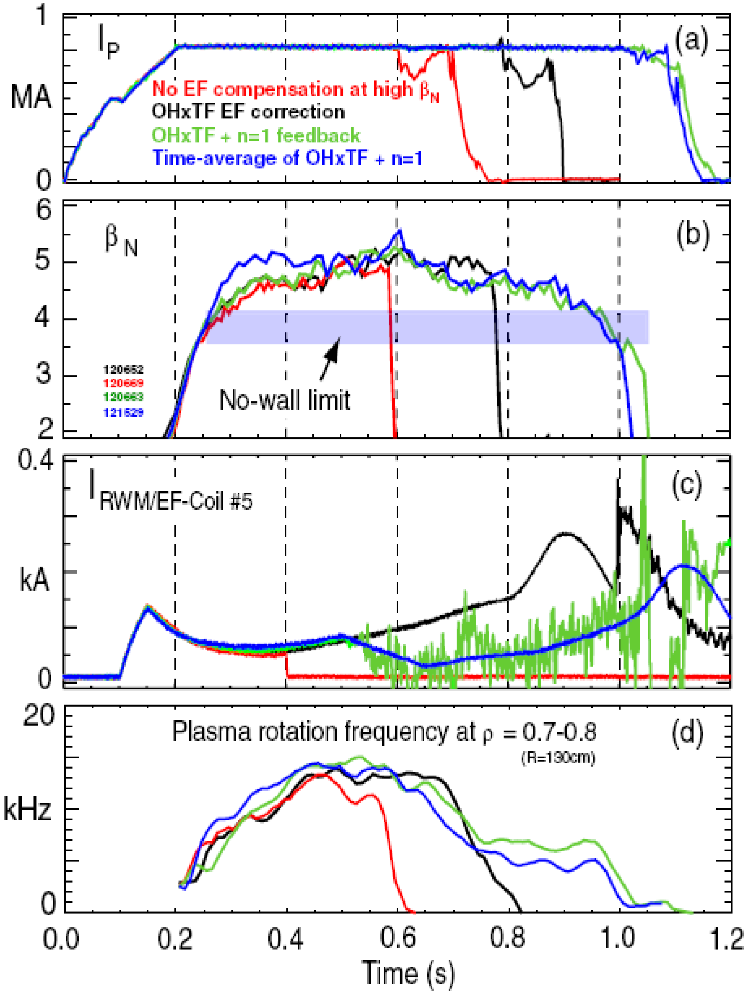
Correction of intrinsic error fields is critical for studies of 3D field physics and for performance

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



Predictive capability:
IPEC model of error fields

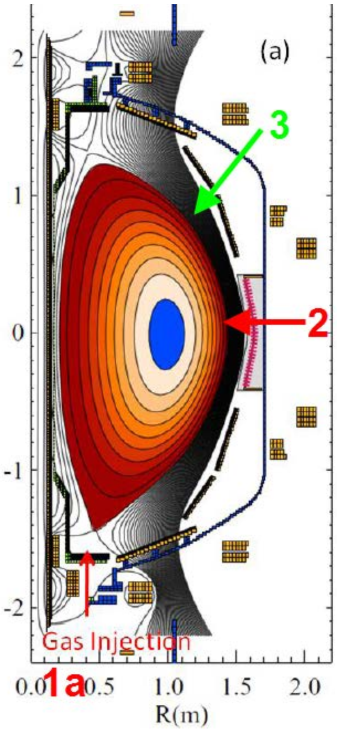
Various successful error field correction schemes in NSTX

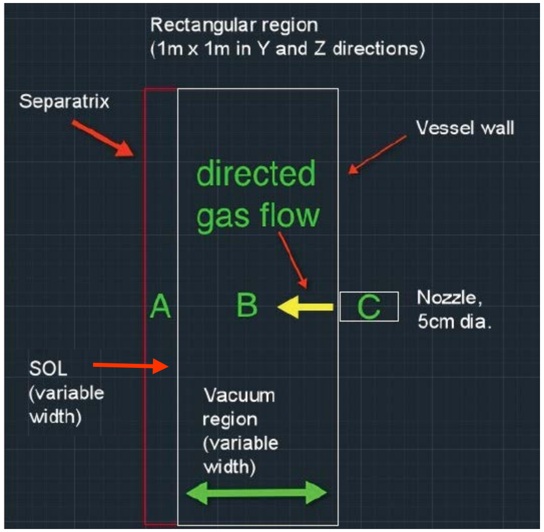


- Dynamic error field correction (green)
  - sustains β_N above the no-wall limit
  - sustains substantial toroidal rotation
- NSTX-U will have a different error field
  - Identification of error field in first year of operation
  - measure vacuum fields; revise models
  - Perform n=1,2 compass scans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

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

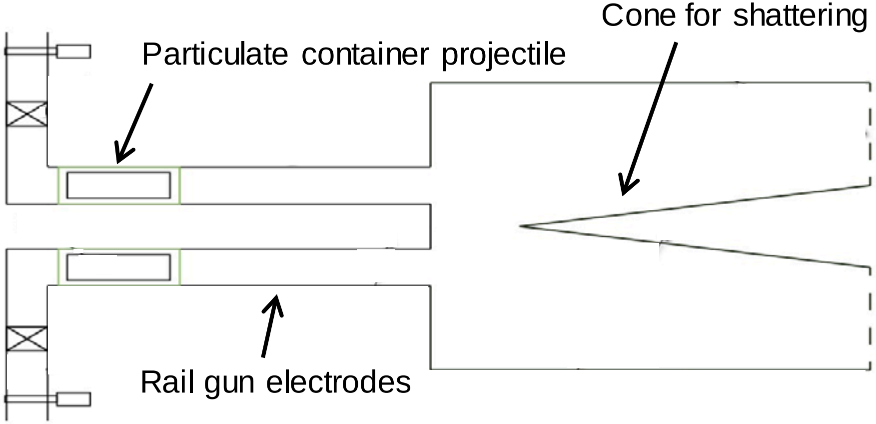




Predictive capability: Modeling using DEGAS-2 is quantifying the gas penetration past the SOL for NSTX-U

- 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

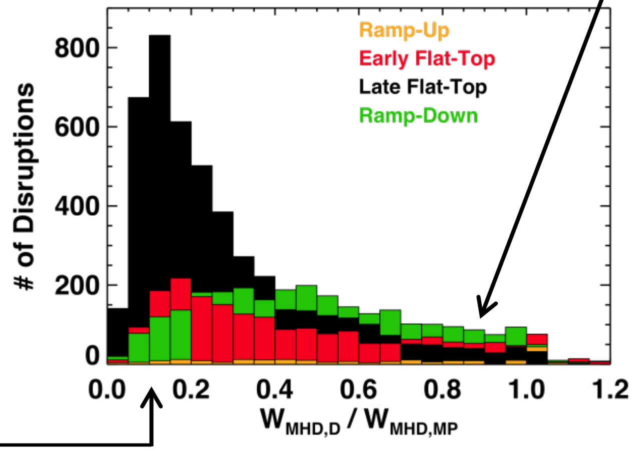


- The EPI is capable of delivering:
  - A large particle inventory
  - All particles at nearly the same time
  - Particles tailored to contain multiple elements in different fractions and sizes
  - Tailored particles fully ionized only in higher current discharges (to control current quench rates)
-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

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

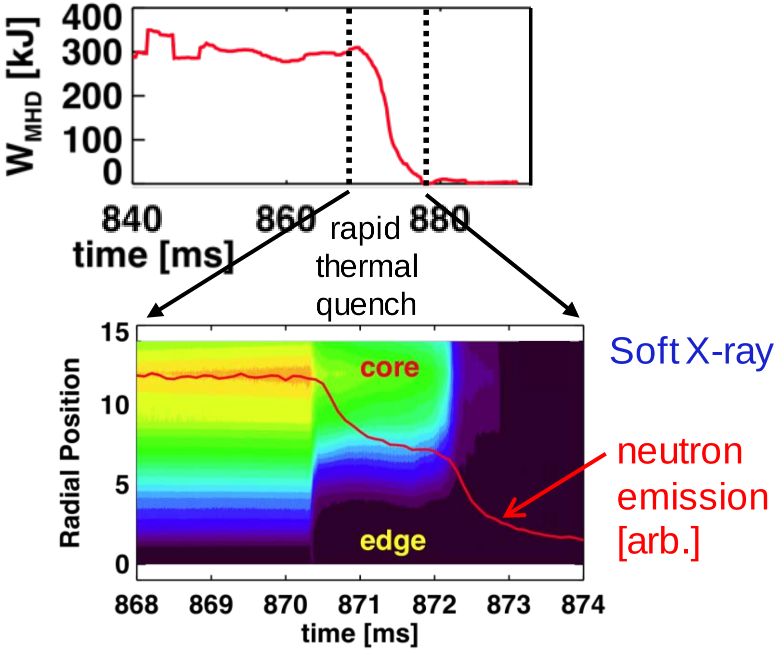
	NSTX-U	ITER	ST-Pilot	Power Reactor
Thermal Loading [MJ m^2 $s^{-1/2}$]	15	540	768	2061

- Examining assumptions:
  - How much stored energy?

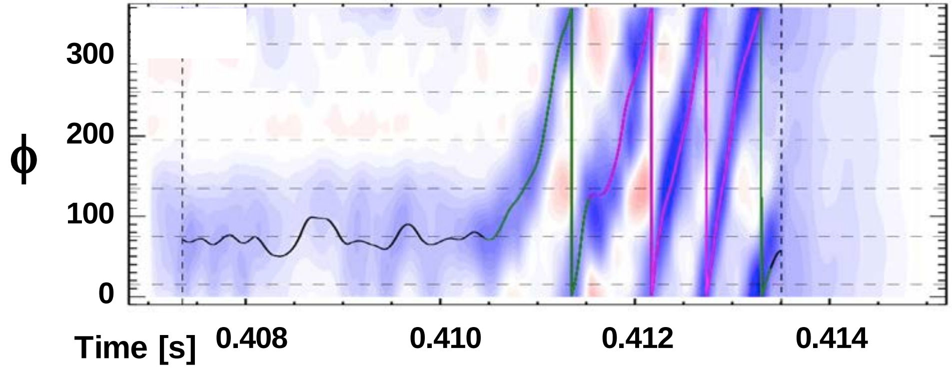


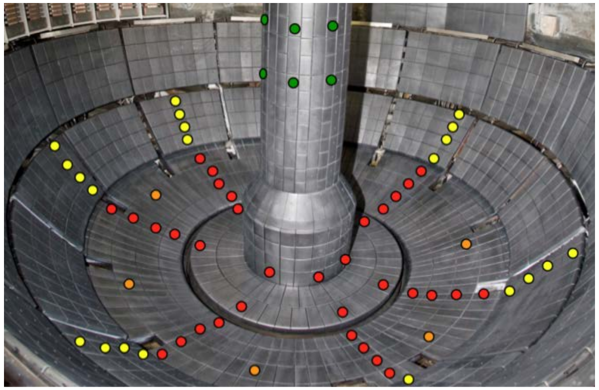
Typically only 15-20% of the stored energy remains in a late flat top disruption in NSTX

Example of rapid disruption with high stored energy



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

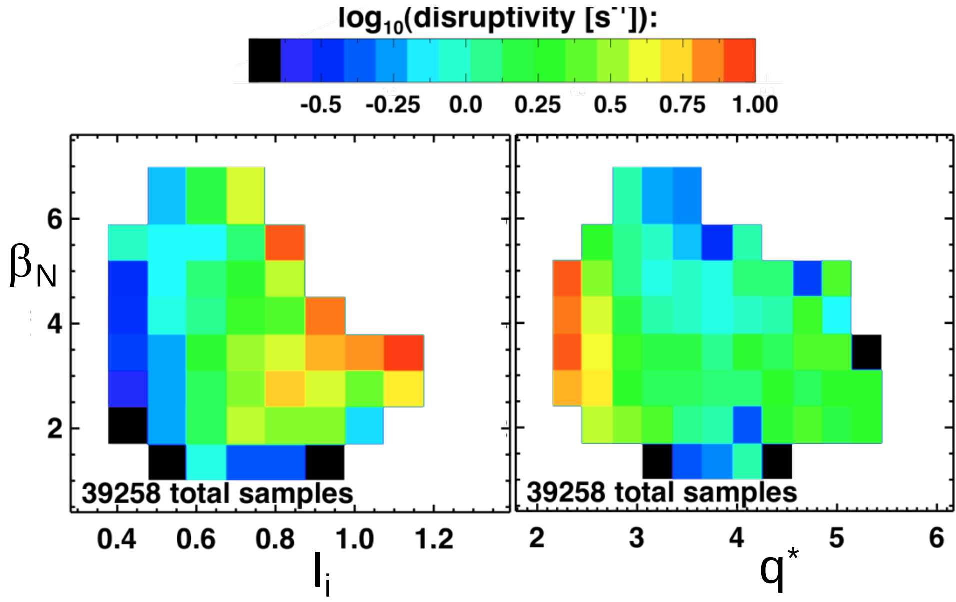




Proposed expansion of the NSTX-U shunt tile diagnostic set

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

Disruptivity

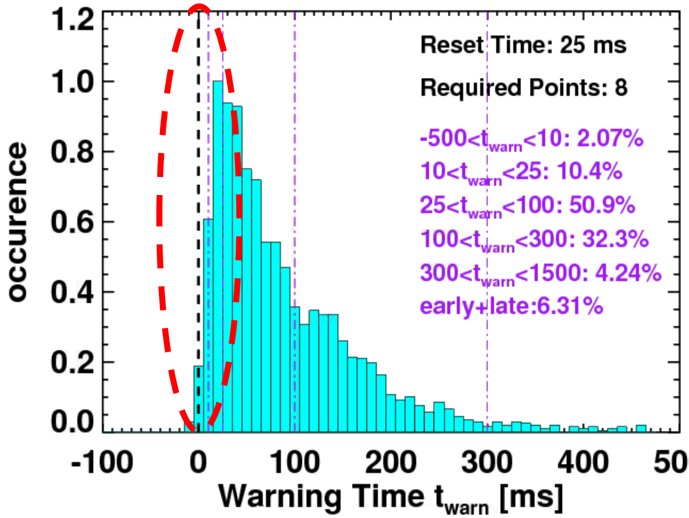


All discharges since 2006

- ❑ 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

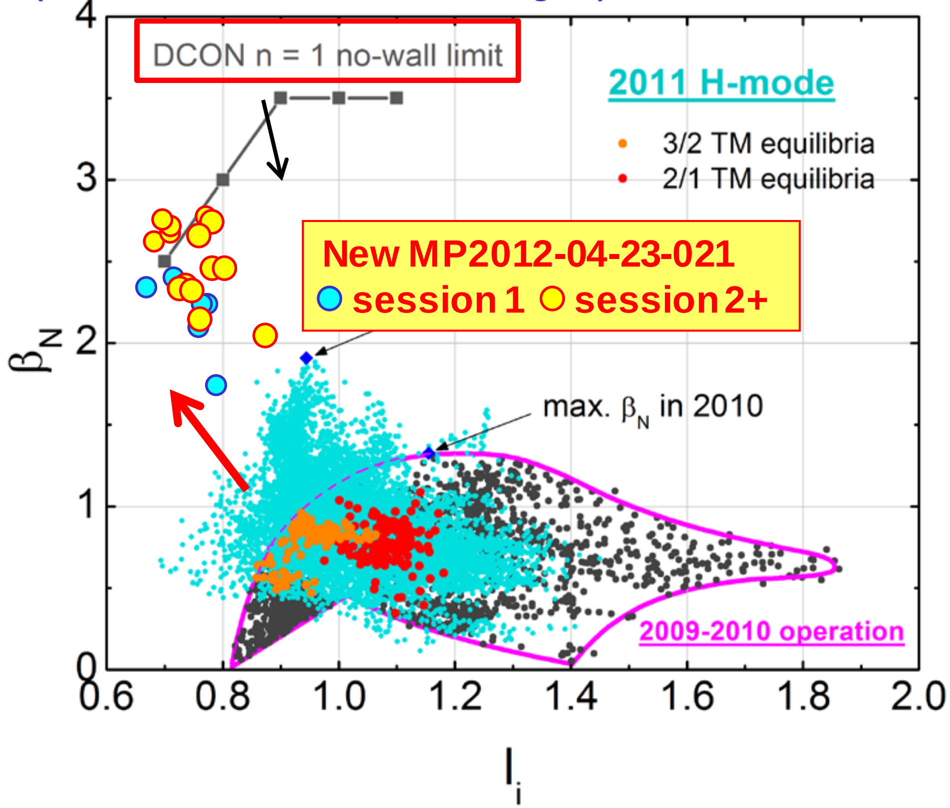


- ❑ Results
  - ❑ ~ 98% disruptions flagged with at least 10ms warning, ~ 6% false positives
  - ❑ False positive count dominated by near-disruptive events

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

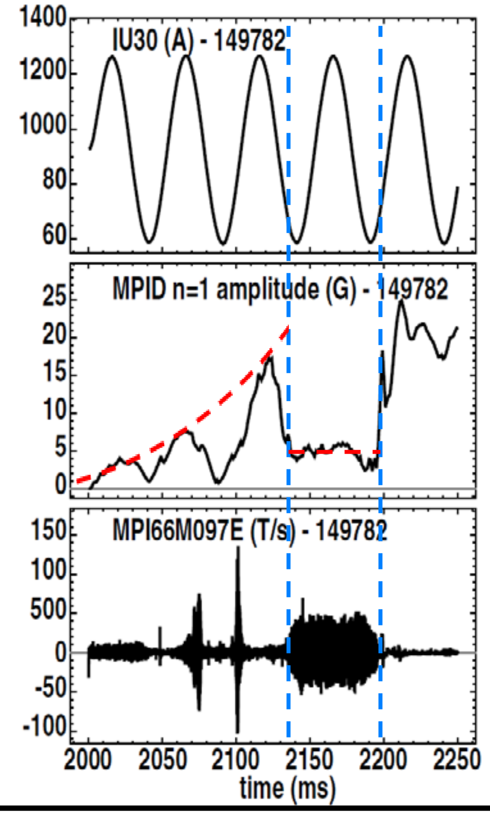
KSTAR: equilibrium operating space 2009 –11

(evolution of > 130 discharges) + new results

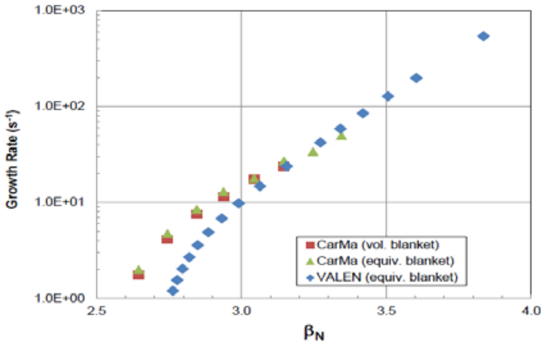


- Plasmas have passed the predicted “closest approach” to the n = 1 ideal no-wall stability limit: $l_i = 0.7$, $\beta_N = 2.5$

- **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

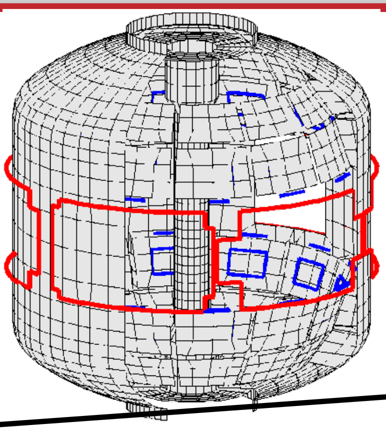


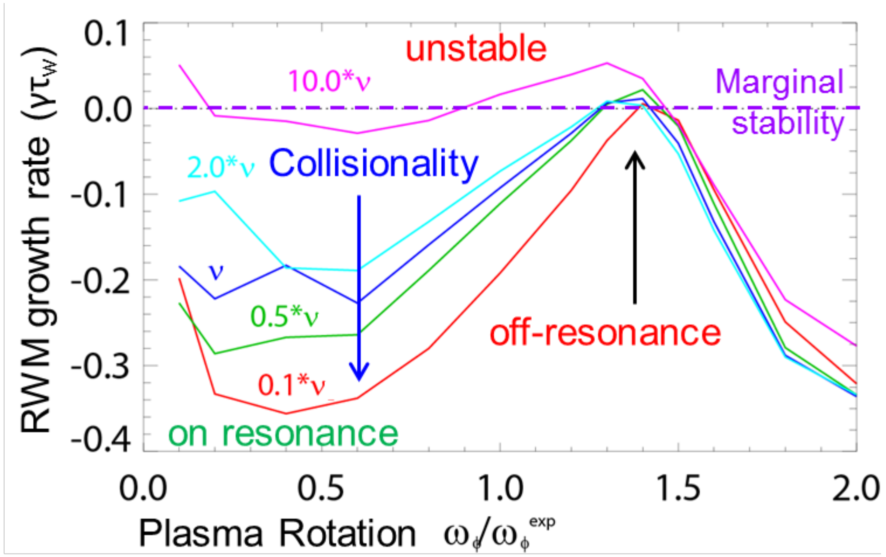
Many important computational codes are used for theory-experiment comparison on NSTX-U

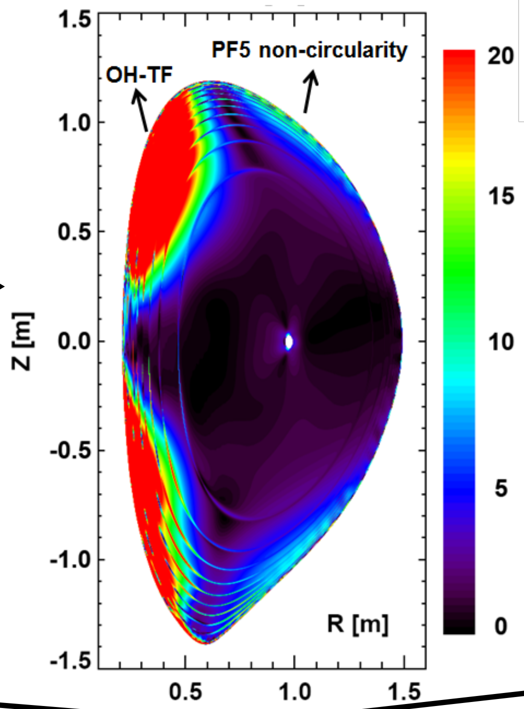
Code	Description	Scope	Improvements
VALEN	Models currents in structures with thin shell finite elements	RWM active feedback simulation, growth rate prediction with 3D walls	Multi-mode effects, study extra time delay in plasma model
RWMSC	Resistive wall mode state-space controller computations	Generate 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 equilibrium reconstruction	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	Monte-Carlo drift-kinetic physics simulation code	Non-ambipolar transport and NTV physics in general geometry	Continued integration with IPEC and application to NSTX-U
POCA	δf guiding-center orbit code	Calculation of neoclassical transport, perturbed pressures and NTV	Improved numerical scheme to enhance computation speed

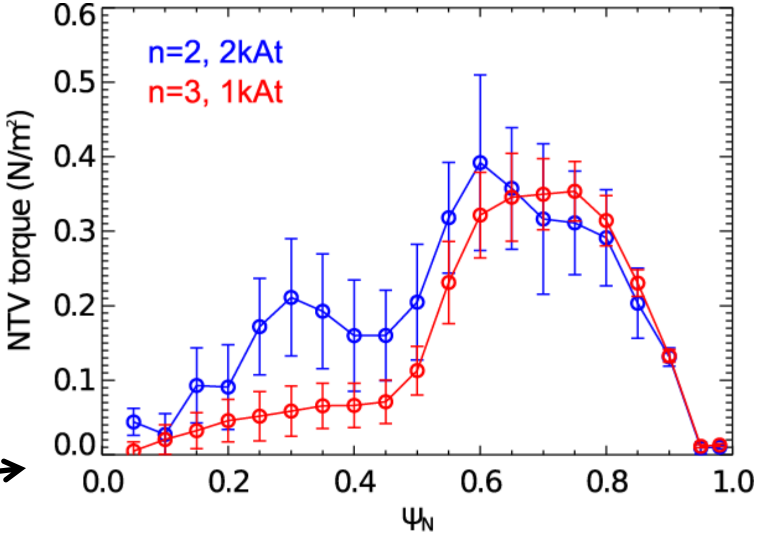
Many important computational codes are used for theory-experiment comparison on NSTX-U

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

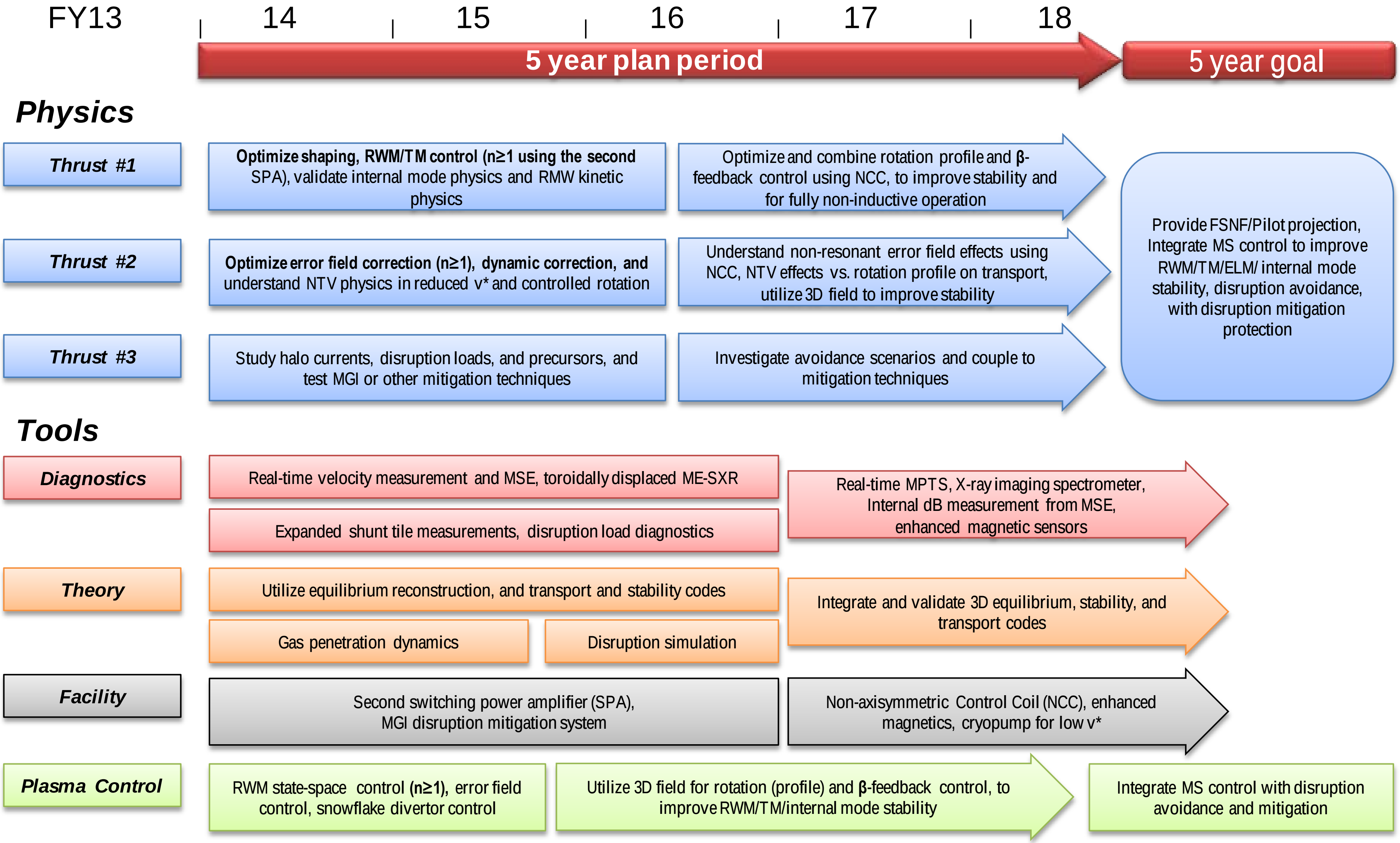








2014-18 Macroscopic Stability Research Timeline



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 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

5 year goal: 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 ν*

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