NSTX-U

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U.S. DEPARTMENT OF ENERGY

Office of Science

Macroscopic Stability (MS) Research Progress and Plans

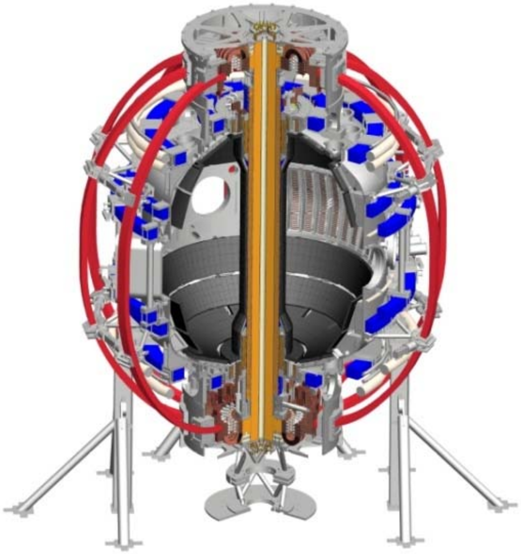
Jong-Kyu Park (PPPL)

J. W. Berkery (Columbia University)

A. H. Boozer (Columbia University)

and the NSTX Research Team

NSTX-U PAC-31
B318, PPPL
April 18, 2012



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IPP, Garching
ASCR, Czech Rep

Goal of MS research is to establish predictive capability for stability, 3D field, and disruption, in future STs and ITER

- Directly aligned with OFES research themes for "Validated predictive capability" and "3D magnetic fields" for FNSF, ITER, and next-step devices

- MS TSG milestones:
    - **R(12-1): Investigate magnetic braking physics to develop toroidal rotation control at low collisionality for NSTX-U and ITER**
    - **R(13-4): Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER**
    - **R(14-1): Assess access to reduced density and collisionality in high-performance scenarios – with new NBIs and 3D coils (NCCs)**

- NSTX-U MS researchers are active in collaborations world-wide, in both theory and experiment
    - RWM, TM, NTV, 3D field, disruption: ITPA MDC-1,2,4,7,15,17,WG7,9
    - RWM, TM, NTV, 3D field : DIII-D, KSTAR, ITER

Outline

- Research highlights and progress towards FY12 milestones
  - Importance of rotation and its control for RWM and EF correction
  - Improvement of understanding NTV braking and plan for study
  - Study on fast particle effects on RWM in NSTX and NSTX-U
- Research plans and progress for FY13-14 milestones
  - Study on disruptivity and halo current dynamics
  - Full 3D modeling of eddy currents for active RWM control
- Highlights and plans for collaborations with other devices
- Plans during years 1-2 for NSTX-U operation
- Long term research plans in years 3-5 for NSTX-U operation
  - Importance of Nonaxisymmetric Control Coil (NCC) for future research
- Summary

FY12-14 milestones: **R(12-1)** **R(13-4)** **R(14-1)**

Response to PAC29 questions: ***PAC29-##***

ITPA activity: ***ITPA ##***

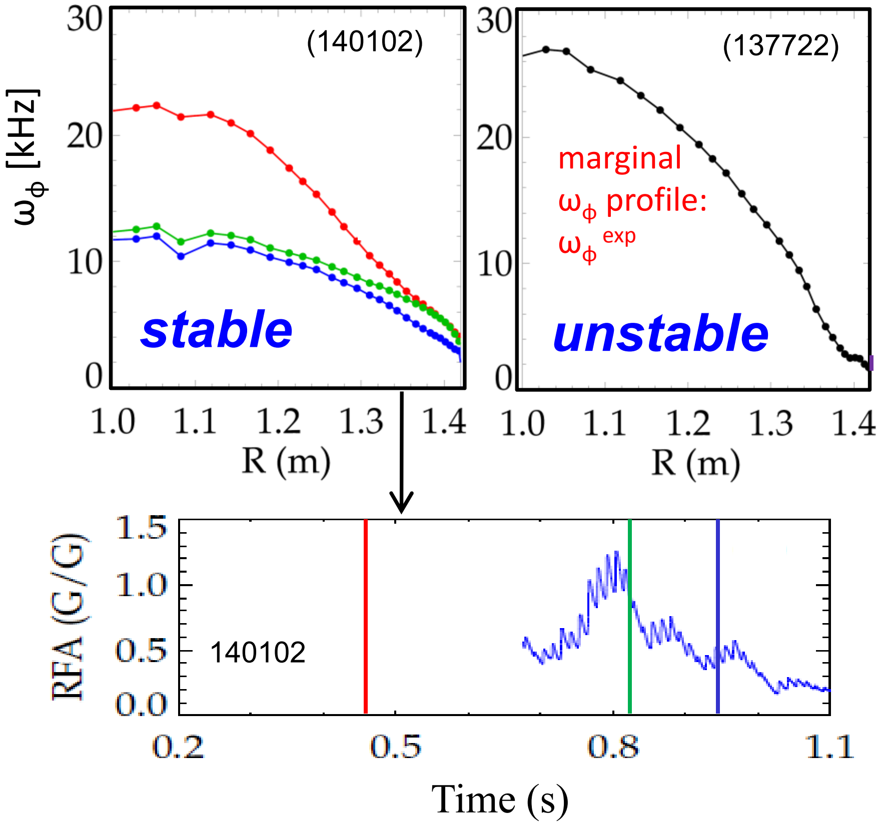
Study of RWM kinetic stabilization is unveiling complex rotation and collisionality dependence

R(12-1)

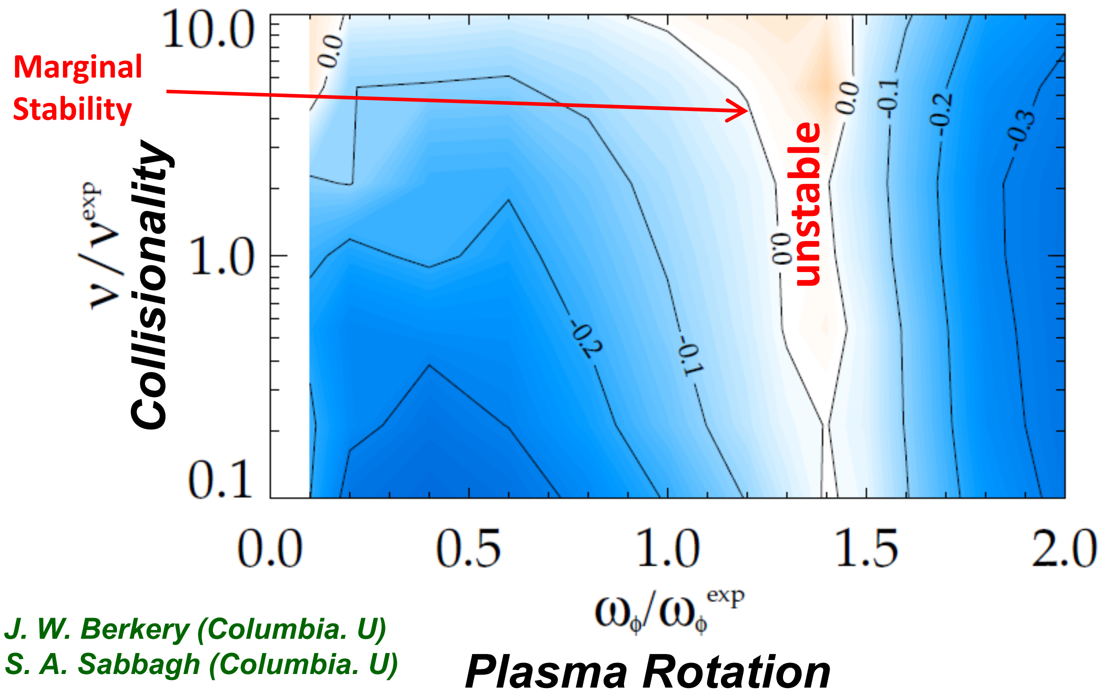
- RWM can be stabilized by kinetic effects through rotational resonance
  - **Implying importance of rotation control, NTV, NCC coils**
- NSTX-tested kinetic RWM stability theory showed that reduced $\nu*$ can be stabilizing through kinetic resonances

J. W. Berkery et al, PRL 104 035003 (2010)
J. W. Berkery et al., POP 17 082504 (2010)
S. A. Sabbagh et al., NF 50 025020 (2010)
J. W. Berkery et al., PRL 106 075004 (2011)

RWM, RFA vs. rotation



NSTX RWM stability (γ_W) vs. (ν, ω_ϕ) by MISK



J. W. Berkery (Columbia. U)
S. A. Sabbagh (Columbia. U)

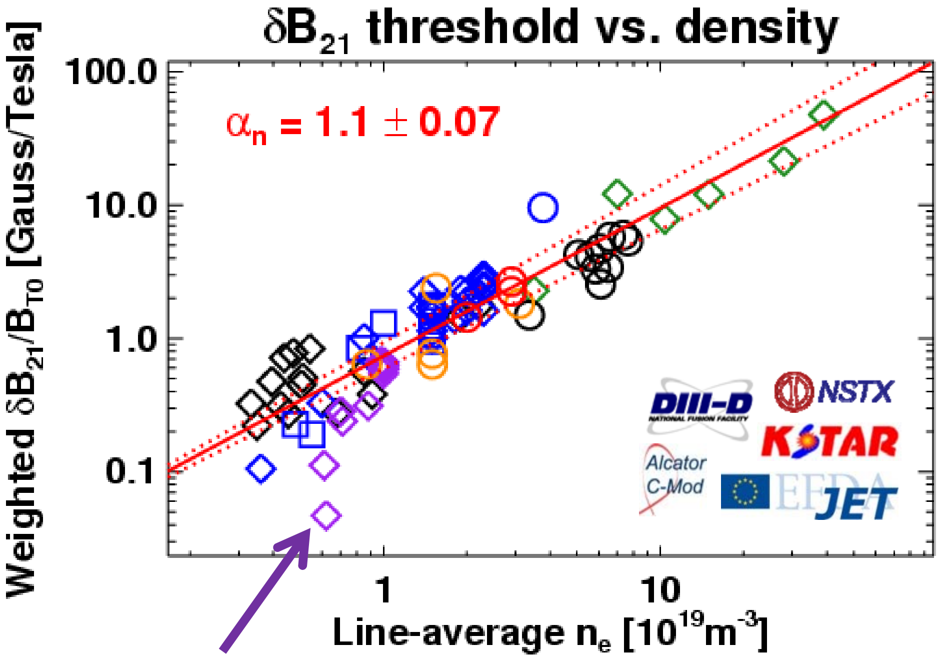
PAC29-20

Error field correction requirements more demanding due to non-resonant braking of rotation

R(12-1)

- IPEC applications are successfully combining error field threshold data across various tokamaks and are being used for ITER *J. E. Menard, J.-K. Park et al., ITER IPEC TA (2011)*
- However, error field threshold can be substantially changed when strong braking is introduced *J. -K. Park et al, NF 52 023004 (2012)*
  - **Implying importance of non-resonant field correction by NCC coils**

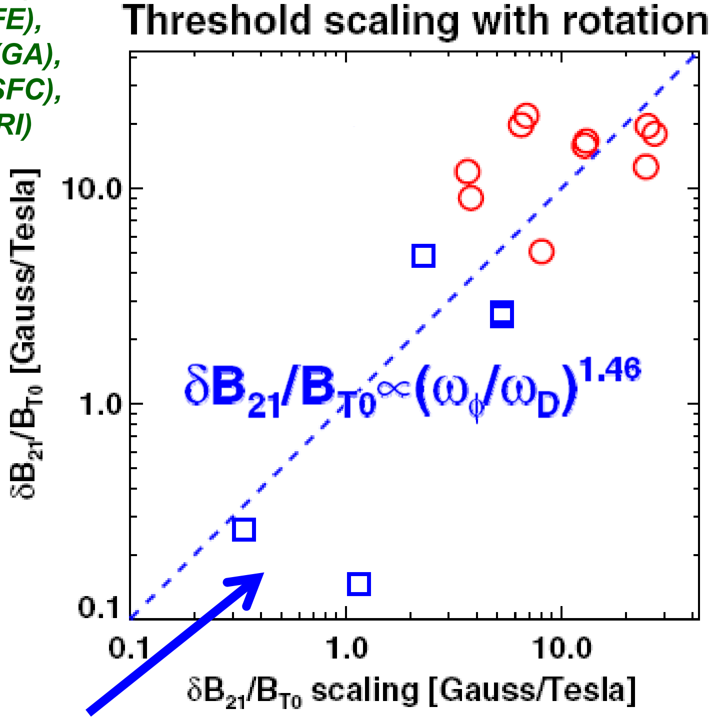
Resonant error field threshold scaling



DIII-D TBM: Locking by dB_{21}/B_{T0} ~10^{-5}

J.-K. Park,
R. J. Buttery (GA),
T. Hender (CCFE),
M. J. Schaffer (GA),
S. M. Wolfe (PSFC),
Y. M. Jeon (NFRI)

Scaling correction for rotation



NSTX: Locking by dB_{21}/B_{T0} ~10^{-5}

ITPA WG9

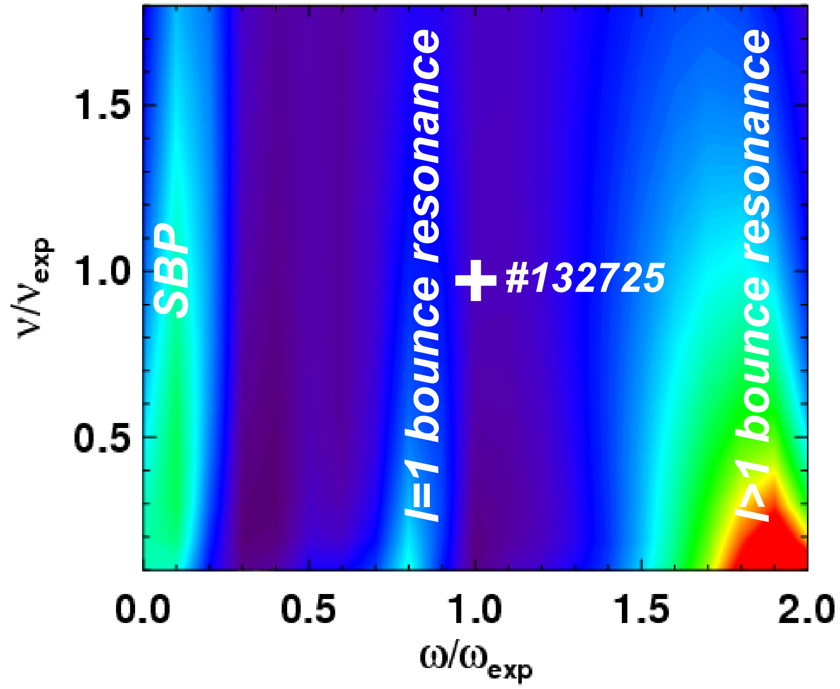
Studying effects of 3D fields on plasma rotation to develop and understand NTV braking for rotation control

R(12-1)

- NTV analysis on NSTX data shows:
  - n=1 braking has a complex but similar dependency on rotation and collisionality to the RWM kinetic stabilization (as the dissipation plays a same role to both physics)
  - n=3 braking is strongly dominated by SuperBanana-Plateau (SBP) and traditional $1/\nu$ and ν dependency on collisionality (providing qualitative explanation of NSTX data)
- Present tools will be put to the rigorous verification and validation

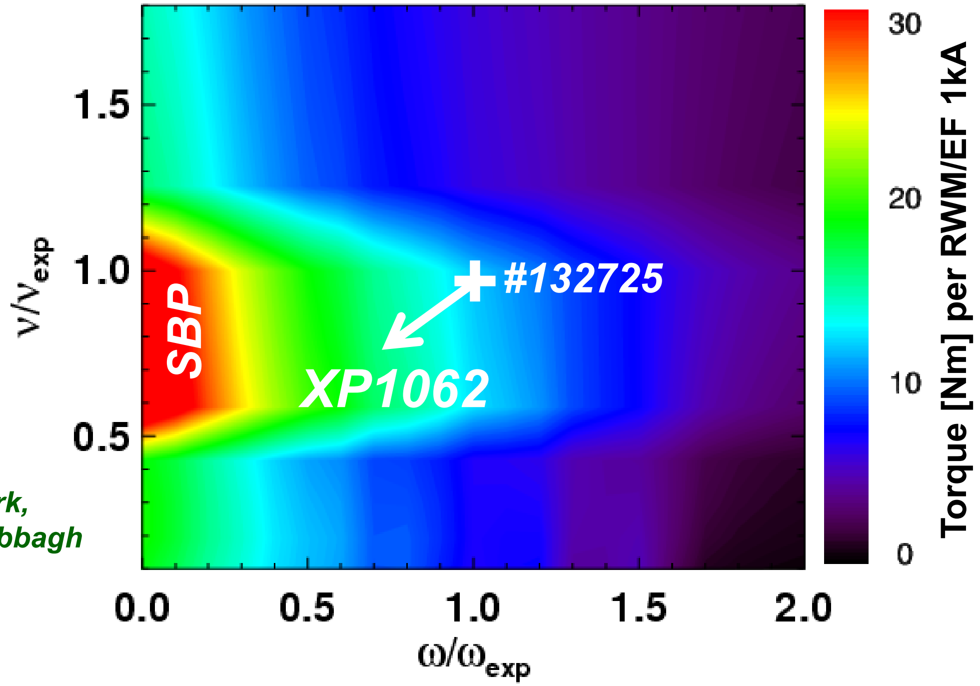
S. A. Sabbagh, IAEA 2010

NSTX NTV n=1 braking vs. (ν, ω_ϕ) by IPEC+NTV



J.-K. Park,
S. A. Sabbagh

NSTX NTV n=3 braking vs. (ν, ω_ϕ) by IPEC+NTV



PAC29-20

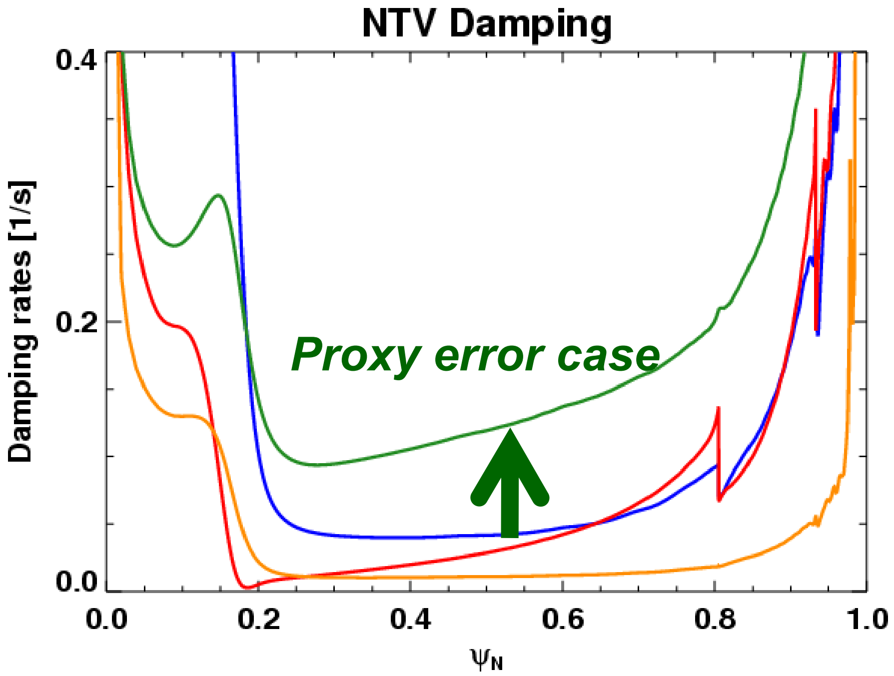
Collaboration with other facilities important and useful for NTV model validation

R(12-1)

- IPEC and NTV codes have been successfully used to
  - Explain locking by DIII-D proxy error field experiment ***J.-K. Park, R. J. Buttery, J. M. Hanson***
  - Verify NTV peaks observed in DIII-D low rotation ***J.-K. Park, for A. J. Cole, PRL 106 225002 (2011)***
  - Predict required NTV braking for DIII-D QH mode experiments ***J.-K. Park, K. H. Burrell***
  - Explain observed damping in KSTAR RMP experiments ***J.-K. Park, Y. M. Jeon***

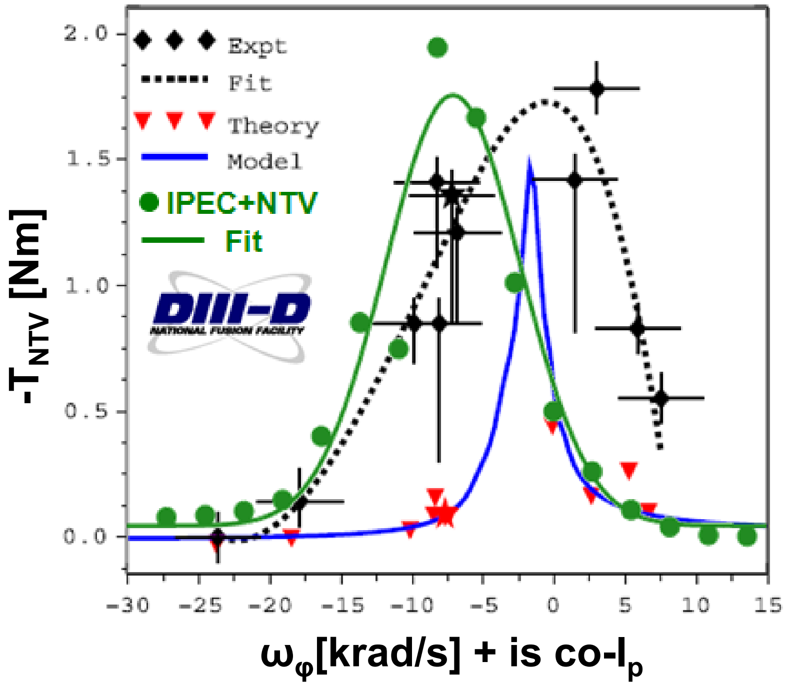
NTV increase in DIII-D proxy error correction

Providing explanation for increased locking sensitivity



NTV Experiments vs. Theories

Reproducing SBP peaks



J.-K. Park, R. J. Buttery (GA), J. M. Hanson (CU), W. M. Solomon

PAC29-20 **ITPA WG9**

Present NTV and kinetic RWM physics analysis tools are under active benchmarking and upgrading

R(12-1)

- Fundamental relation between perturbed energy (RWM) and toroidal torque (NTV) has been theoretically proved
  - **Implying both physics studies can be unified and validated all together**

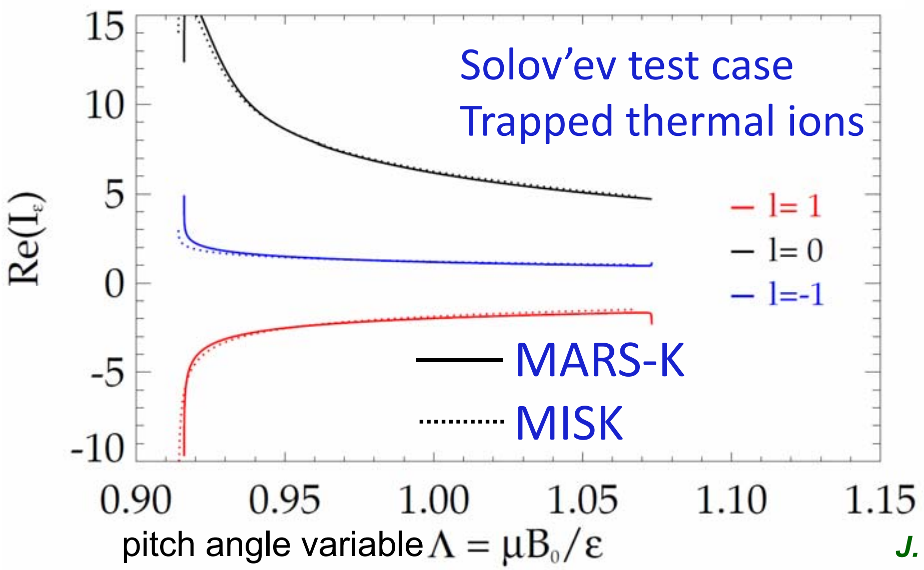
$$T_\varphi = 2in\delta W_k$$

J.-K. Park, POP <u>18</u>, 110702 (2011)

- RWM analysis tools, MISK/MARS-K/HAGIS, are under benchmark in details (ITPA MDC-2, Group leader: S. A. Sabbagh)

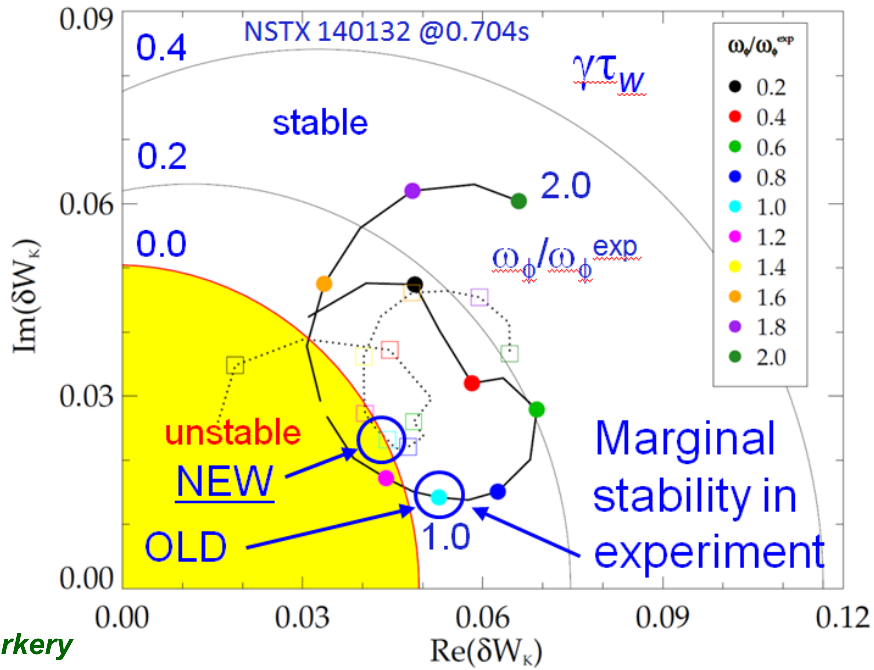
<u>MISK and MARS-K benchmark for energy integral</u>

$$I_\varepsilon = \int_0^\infty \frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega}{\omega_D + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega} \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}.$$



J. W. Berkery

<u>Marginal stability prediction by improved MISK</u>



***For improved MISK analysis through benchmark, see backup page 23**

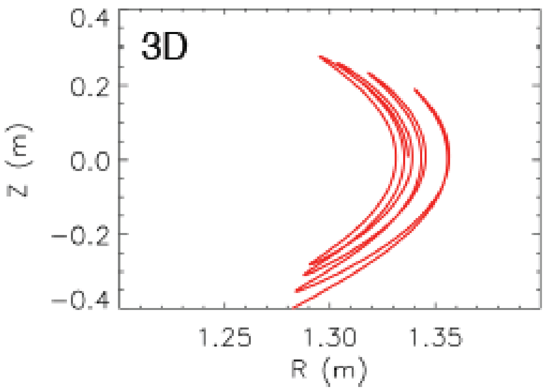
PAC29-20 **ITPA MDC-2**

Advanced NTV and kinetic RWM computations are also being developed and benchmarked

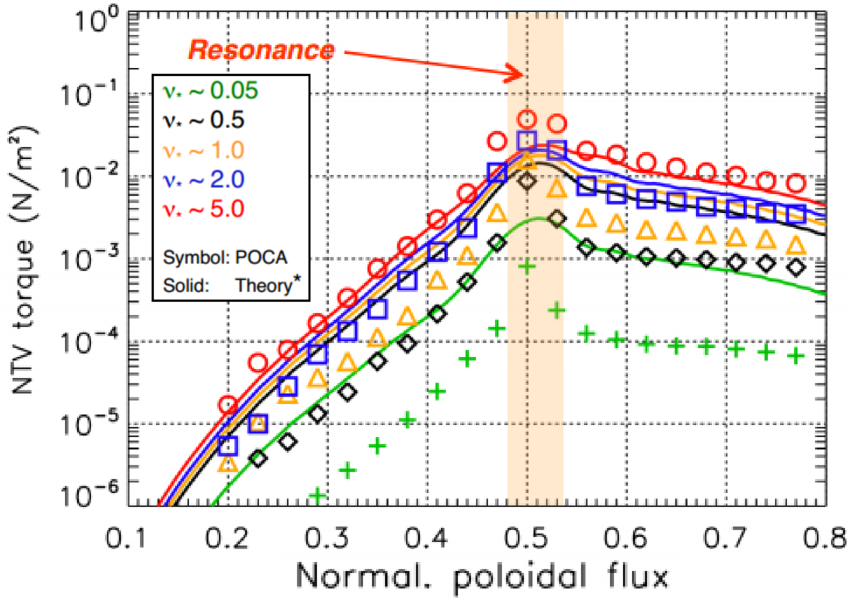
- NTV and kinetic RWM calculations can be improved by computing precise 3D orbits and perturbed distribution function
  - Particle Orbit Code for Anisotropic pressures (POCA) is under development and benchmark
  - MARS-K and M3DC-1 computations are also planned

R(12-1)

3D orbits without collision

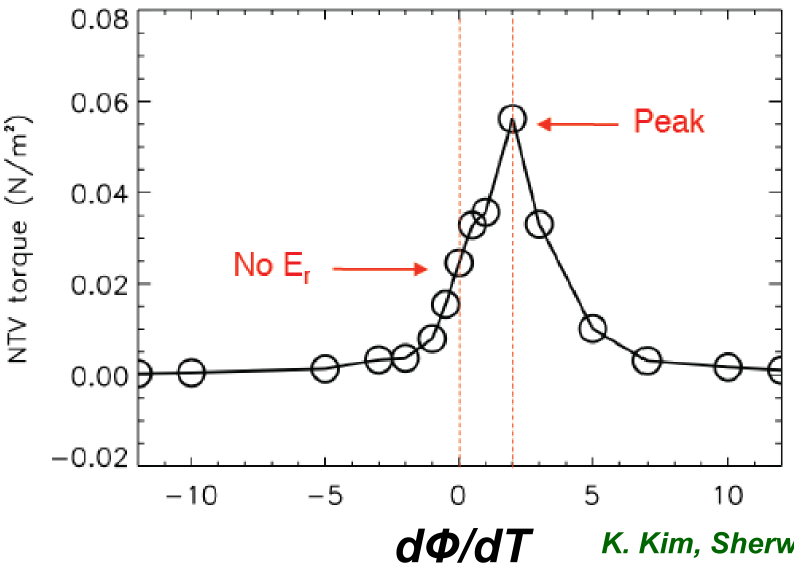


Analytic NTV and POCA benchmark



K. Kim, Submitted to POP
Benchmark for the same case on
S. Satake(NIFS), J.-K. Park, PRL 107 055011,(2011)

POCA demonstration of superbanana-plateau



K. Kim, Sherwood 2012

***For MARS-K with self-consistent eigenfunctions, see backup page 24**

PAC29-20

Extended RWM study indicates stabilizing effects of energetic particles will be modified in NSTX-U

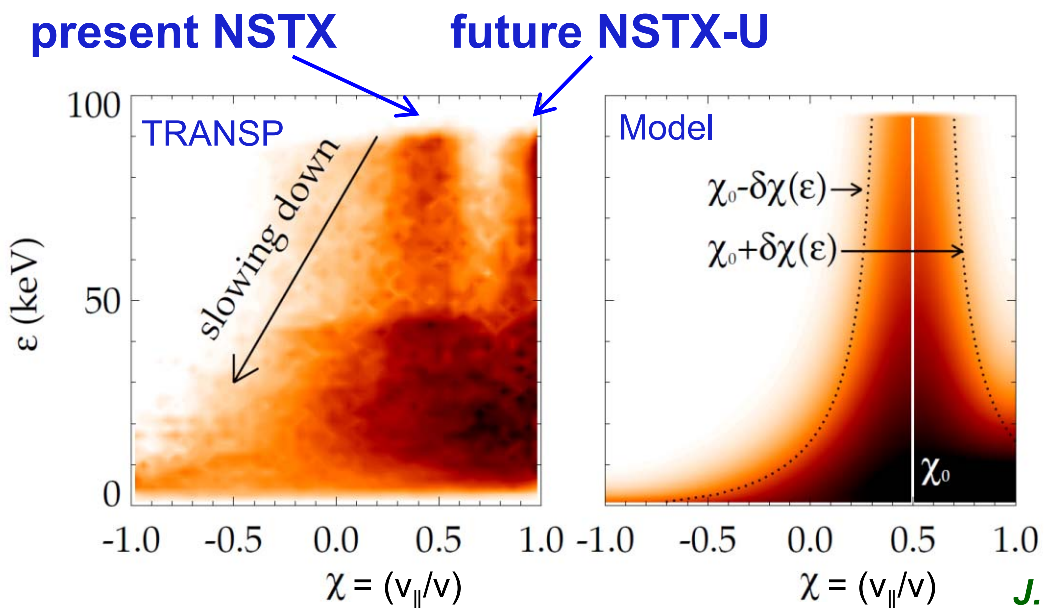
R(12-1)

- Reminder: NSTX-U will have three additional tangential beam sources
- Anisotropic slowing-down distribution function for energetic particles:

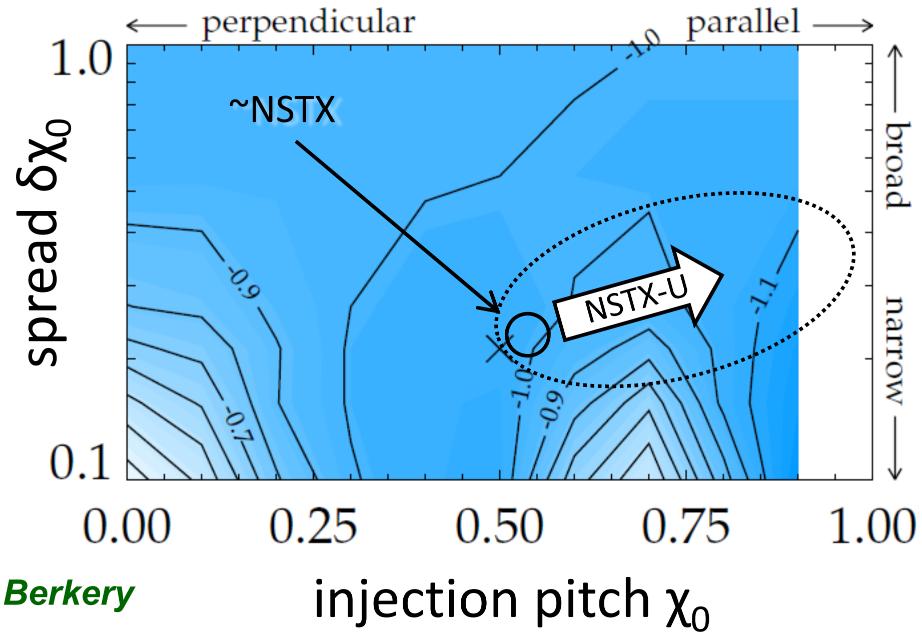
$$f_j^b(\varepsilon,\Psi,\chi) = n_j A_b \left(\frac{m_j}{\varepsilon_b}\right)^{\frac{3}{2}} \frac{1}{\hat{\varepsilon}^{\frac{3}{2}}+\hat{\varepsilon}_c^{\frac{3}{2}}} \frac{1}{\delta\chi}\left(\exp\left[\frac{-(\chi-\chi_0)^2}{\delta\chi^2}\right] + \exp\left[\frac{-(\chi+2+\chi_0)^2}{\delta\chi^2}\right] + \exp\left[\frac{-(\chi-2+\chi_0)^2}{\delta\chi^2}\right]\right)$$

  - RWM kinetic stabilization effects were tested with perpendicular vs. parallel and broad vs. narrow NB injection

Simulated distribution function by TRANSP



MISK anisotropy + fluid + kinetics for (γ_W)



J. W. Berkery

****For further highlights, see backup page 25 (RWM active control) and page 26 (Tearing mode)***

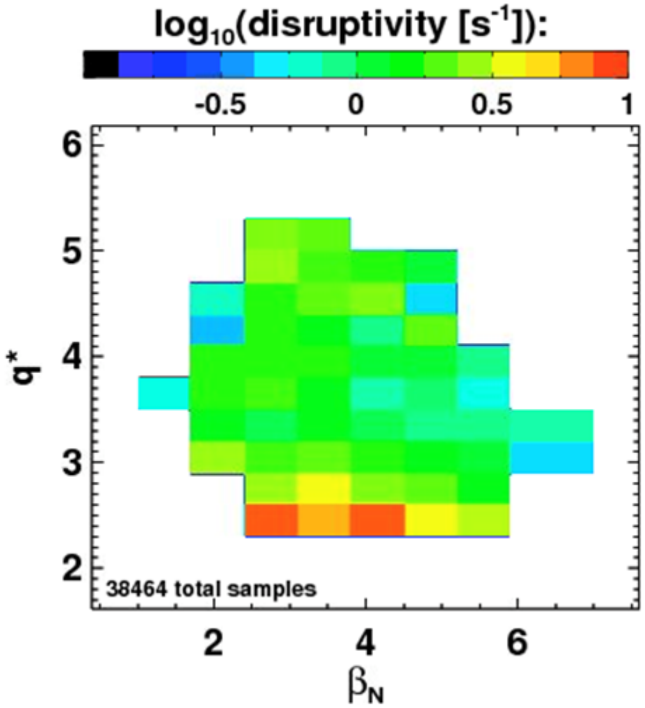
PAC29-20

NSTX database shows important correlations between disruptivity and stability variables

R(13-4)

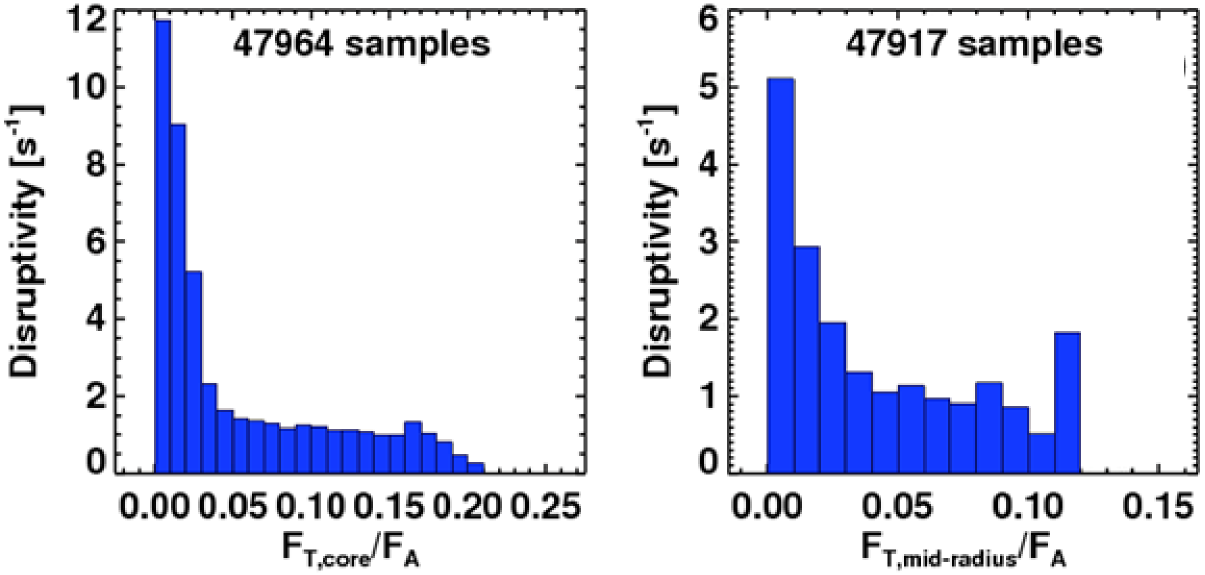
- NSTX disruptivity has been studied based on ~40000 sampled time slices, and revealed correlations with stability indices such as q, β_N, ω
  - Disruptivity increases in lower q*, as expected, but decreases in highest β_N (Consistent with “weaker” RWM stability at “intermediate” rotation)
  - Rotation decreases disruptivity, but not strongly when $\omega > 2\text{-}3\%\omega_A$

Disruptivity vs. q* and β_N



S. P. Gerhardt

Disruptivity vs. rotation (ω)



***For more statistics for disruptivity, see backup page 27**

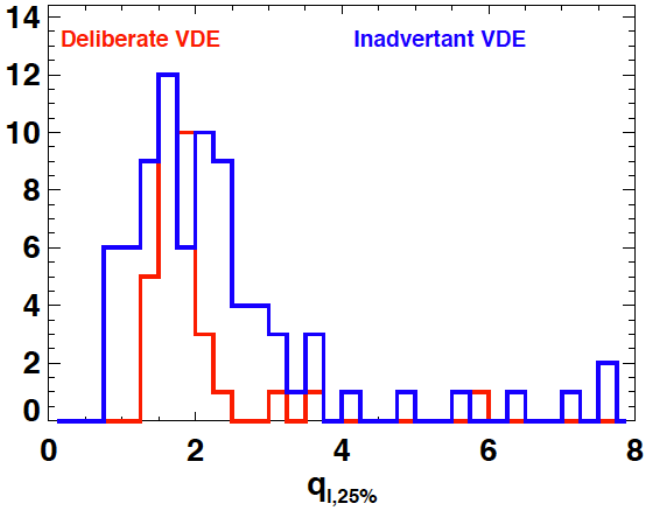
PAC29-21 **PAC29-45** **ITPA MDC-15**

Halo currents propagate toroidally and depend on evolution of q at limiter flux-surface during disruption

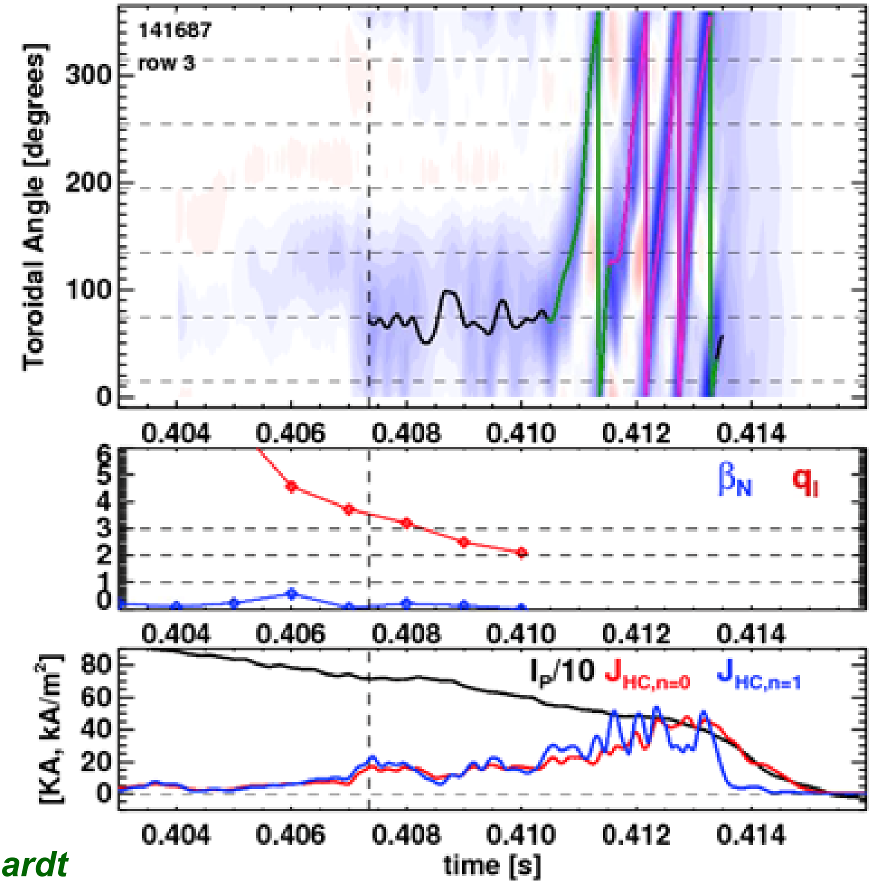
R(13-4)

- Dynamics of NSTX n=1 halo currents (Important for ITER, ITPA MDC-15)
  - Rotates 2 kHz in average during ~4ms
  - Typically rotates 1-3 times
  - Halo current tend start at about time of edge-q dropping beneath 2
  - Appears that n=1 vanishes when LCFS vanishes, n=0 a few ms later as the open field line current dies away

Statistics for q when n=1 rotates



Halo current rotation vs. q and LCFS



S. P. Gerhardt Submitted to NF

****For more about disruption studies, see back up 28-30 (including head loading)***

PAC29-45

ITPA MDC-15

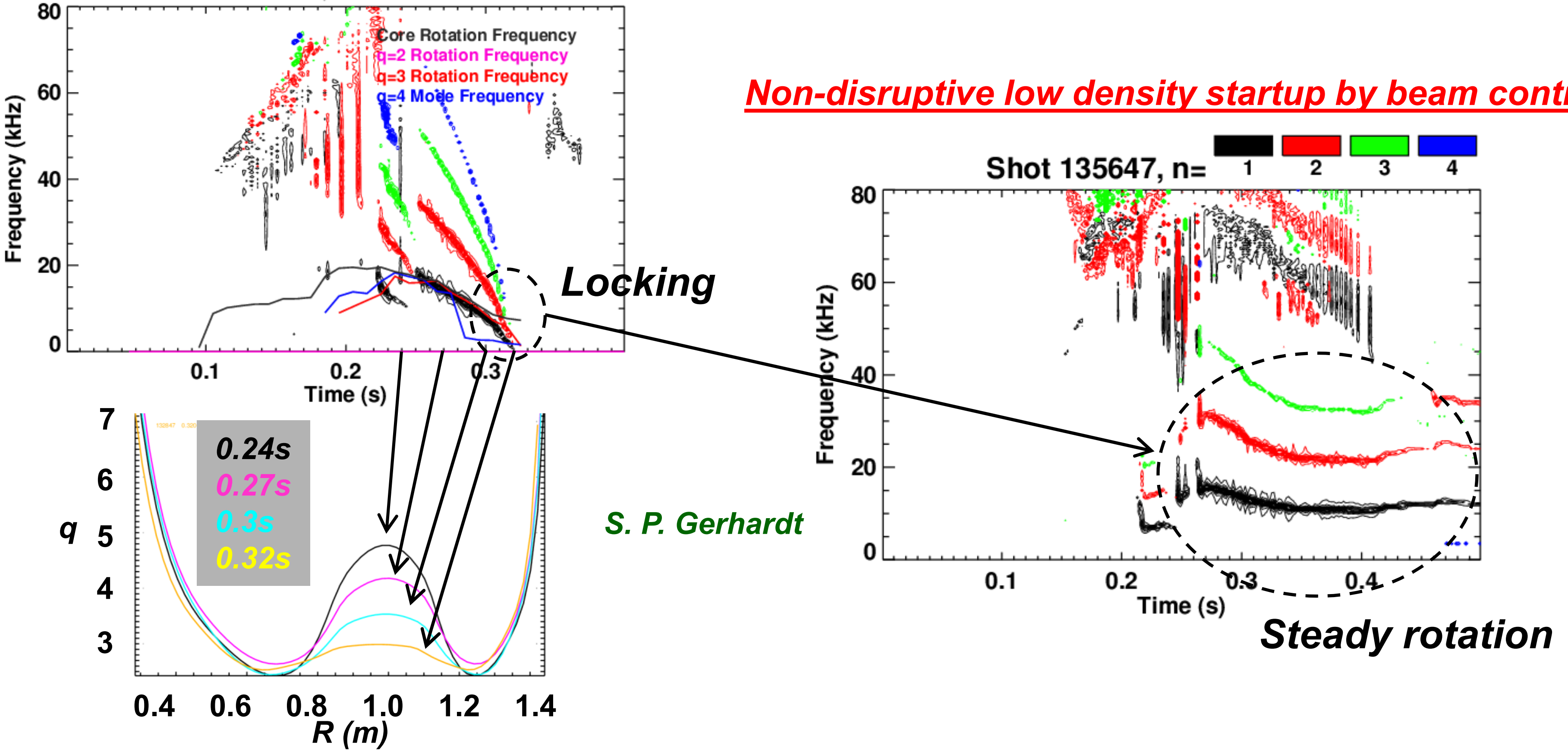
Access to reduced density in NSTX-U can be improved by early MHD mode control in startup

R(14-1)

- Reduced-density operation in NSTX was occasionally unsuccessful by early MHD modes, which could be induced by unfavorable q-profiles or error fields
  - **Implying importance of current, heating, 3D field control**
- MHD stability and control in reduced density and collisionality will be actively studied on developed NSTX-U scenarios, with new NBIs and potential NCC coils

Disruptive low density startup with early MHDs

Non-disruptive low density startup by beam control



S. P. Gerhardt

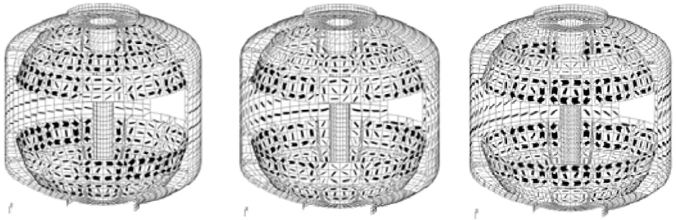
Full 3D modeling for RWM control pioneered on NSTX will be important for NSTX-U, ITER, FNSF

R(14-1)

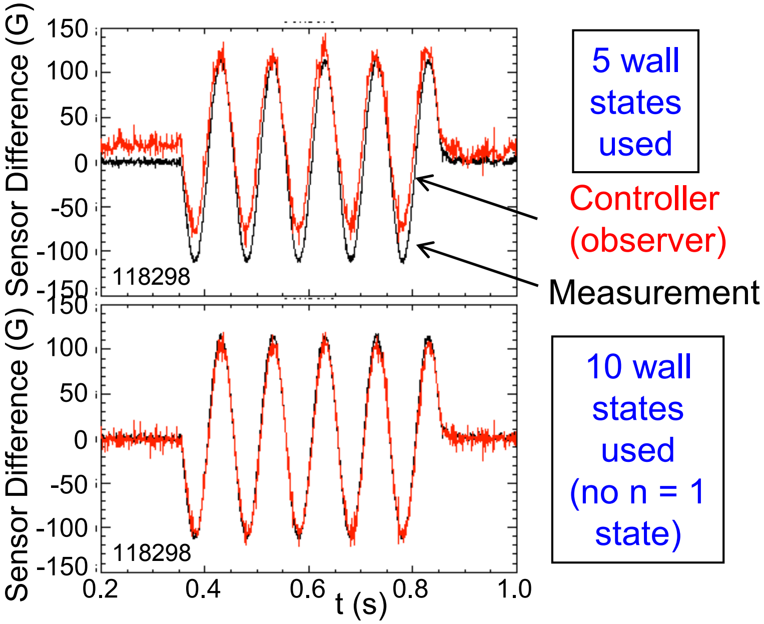
- RWM State Space (RWMSC) controller created using full 3D eddy current model (VALEN-3D code) has been implemented and successfully tested in NSTX, and will be used with independent coil control in NSTX-U

State space controller modeling

~3000 states for 3D eddy currents in total

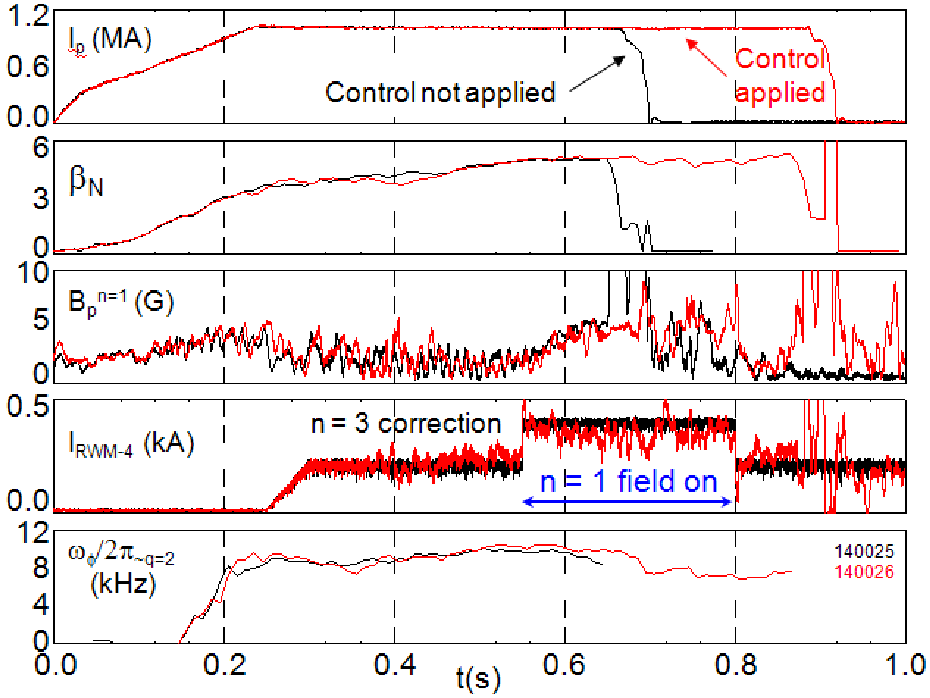


Controller reproducing rotating n=1



Use of RWM state space controller for NSTX

Controller with 12 states (including 10 wall + 2 plasma states) sustains discharge at high β_N=6.4 and β_N/l_i=13, otherwise disrupted by n=1 field



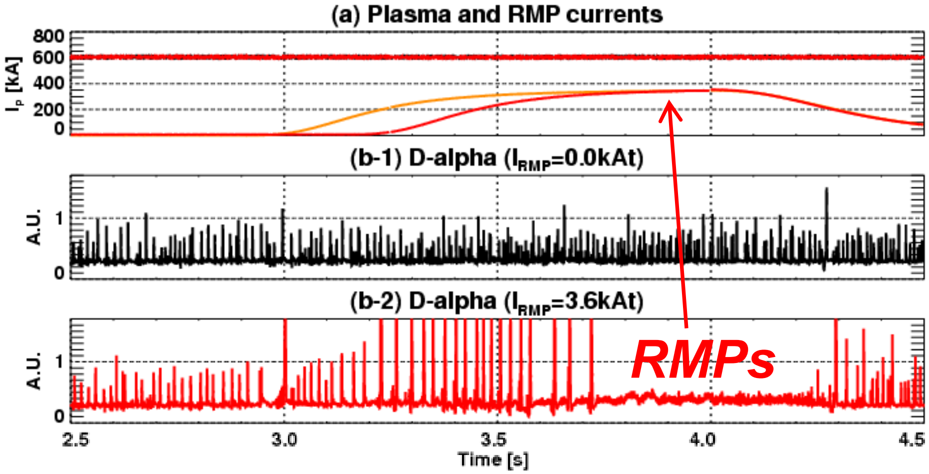
S. A. Sabbagh, O. Katsuro-Hopkins, J. Bialek (CU)

****For more about RWMSC, see backup page 31, for RWM control summary in NSTX , see backup page 32***

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

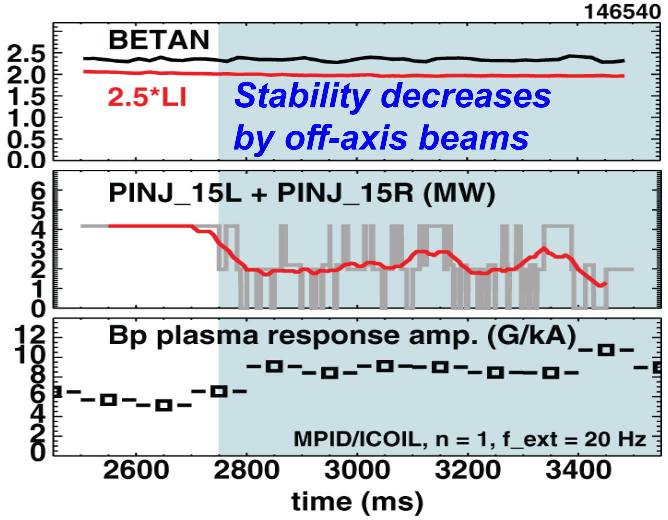
- KSTAR: Collaborations on 3D fields achieved n=1 ELM suppression, error field, tearing mode, NTV analysis, and supported equilibrium reconstruction
- DIII-D: Strong collaborations and joint experiments will be continued on RWM, NTV, error fields, and RMP suppressions
- ITER: Leading RWM and error field physics analysis efforts for recently requested ITER control group needs

ELM suppression by 3D fields in KSTAR



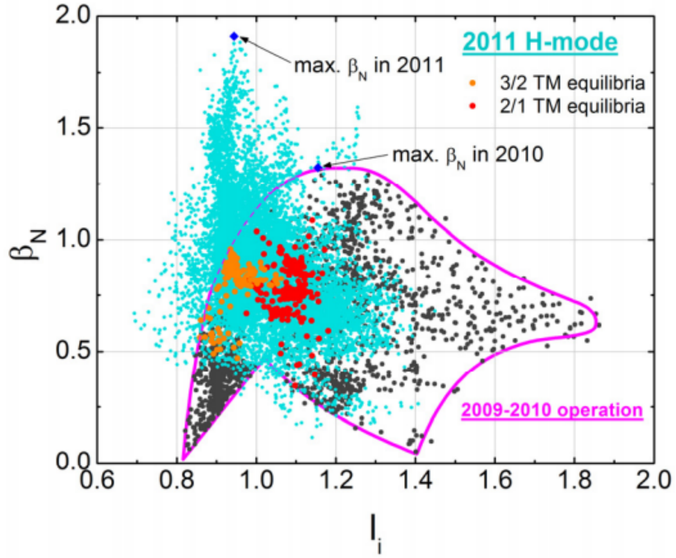
Y. M. Jeon, J.-K. Park, Submitted to PRL

Joint RWM experiments in DIII-D



J. M. Hanson (CU), S. A. Sabbagh, J. W. Berkery

KSTAR operation window



S. A. Sabbagh, Y.-S. Park (CU), IAEA2012

**For MISK calculations for ITER, see backup page 33*

MS research will exploit new 2^{nd} NBI and upgraded SPA capabilities during years 1-2 of NSTX-U operation

- Focus in Year 1 of NSTX-U operation:
  - Recover and explore NSTX MS control capabilities
  - Identify n=1,2,3 error fields and optimize corrections with new SPAs
  - Assess the β_N or q limit with new shaping control and off-axis NBCD
  - Recover and upgrade RWM B_P+B_r and state space control with SPAs, including n>1 and multi-mode control
  - Revisit disruptivity and study halo current dynamics and heat loads on divertor
  - Apply MGI mitigation and explore dependency on injection locations*
- Focus in Year 2 of NSTX-U operation:
  - Explore NTV physics with new NBIs and SPAs
  - Begin implementation of rotation control with new NBIs and SPAs
  - Validate RWM physics in reduced ν^* and varied fast ion populations
  - Utilize off-axis NBCD to vary q-profile and applies to RWMs and tearing modes
  - Identify disruption characteristics in various scenarios obtained by off-axis NBCD
  - Test and optimize MGI techniques by varying positions and actuators

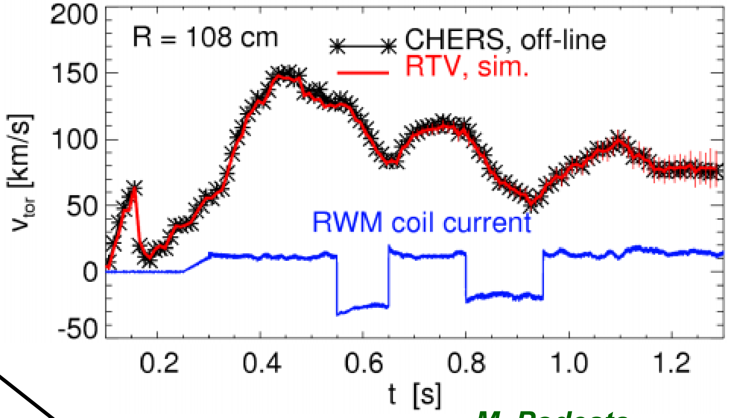
For MGI plans and present modeling efforts, see backup page 34

Key diagnostics have been identified and are being developed or proposed to support MS research

R(14-1)

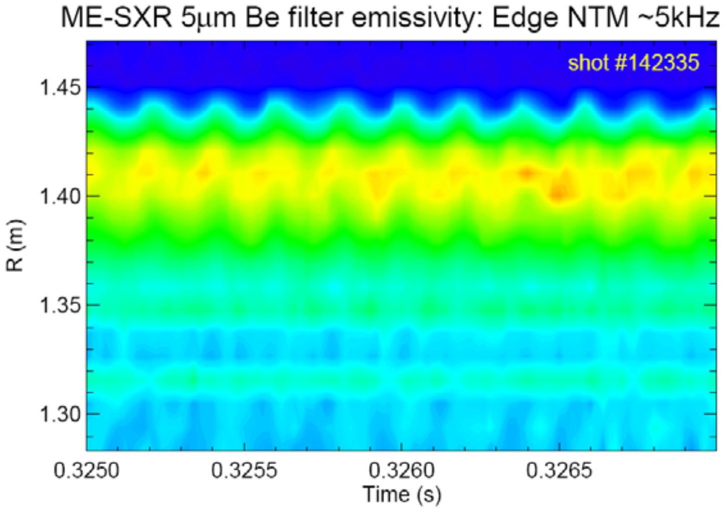
- Key diagnostics identified for MS study:
  - **Real-Time Velocity measurement** for successful implementation of rotation control, and disruption detection
  - **Toroidally displaced multi-energy SXR** to study 3D physics including island dynamics, and RWM eigenfunctions
  - **Core X-ray imaging spectrometer** to study rotation effects on error field and early MHD without NBIs
  - **Internal magnetic fluctuation measurement** for island structures in details
  - **Real time MSE and MPTS** for fast and precise kinetic equilibrium reconstruction
  - **Magnetic sensors including B_P and B_R sensors** will be refurbished and upgraded

Algorithm test for RTV with off-line CHERS



M. Podesta

Edge islands by single ME-SXR



K. Tritz (JHU)

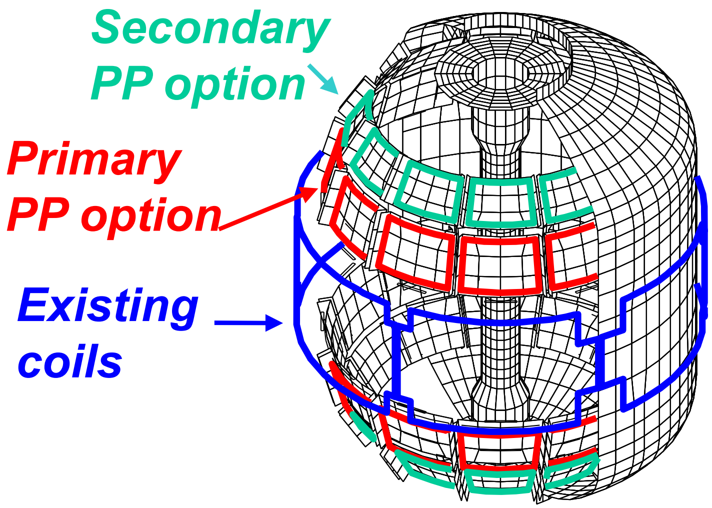
****For present identification for key diagnostics, see backup page 35***

Long term research plans for next 3-5 years will be focused on integrated MS study in NSTX-U

- Year 3 NSTX-U operation:
  - Optimize rotation feedback control for improving RWM and TM stability
  - Assess and optimize tradeoffs between q, rotation, β to improve stability
  - Explore the lowest ν^* regimes and optimize RWM and TM stability
  - Explore disruption precursors and avoidance scenarios with various MHD origins
  - Explore MGI triggering for real-time actuation for disruption mitigation
- Year 4 NSTX-U operation:
  - Combine rotation and β feedback control to maximize performance
  - Provide FNSF/Pilot projection on RWM and TM stability and disruption
  - Couple MGI triggering techniques to mitigate disruptions
- Year 5 NSTX-U operation:
  - First use of NCC (if resources permitting)
  - Integrate MS control to avoid RWM, TM, ELM instability, disruption, with disruption mitigation protection
  - Integrate validation of models for FSNF/Pilot

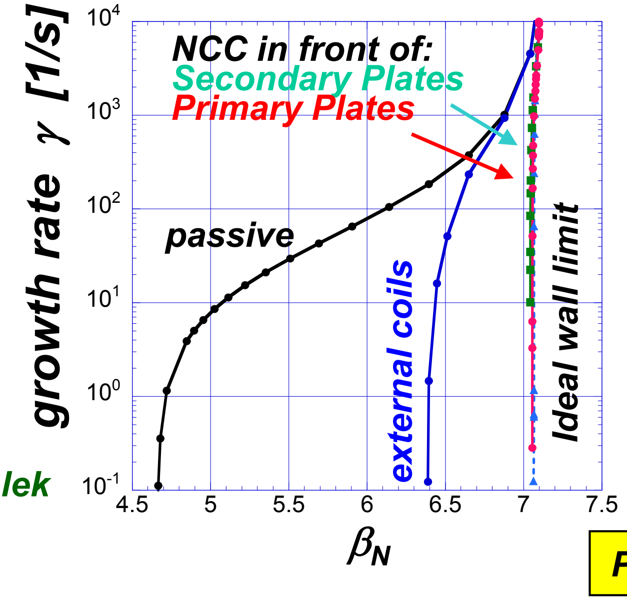
Non-axisymmetric Control Coil (NCC) would greatly improve control capabilities on stability and 3D fields

- Non-axisymmetric Control Coil (NCC) will play an important role in each
  - Rotation control, and thereby RWM kinetic stabilization, error field correction, tearing mode stabilization
  - RWM active control for significant multi-mode spectrum
  - ELM control and stabilization
  - Prediction for ITER 3D coil capabilities
- NCCs may prove essential to achieve integrated MS control
  - Simultaneous control for rotation, RWM, error field, TM, ELM
- IPEC, NTV, VALEN-3D, RWMSC codes will be actively used for 3D physics studies with NCCs



VALEN3D prediction

Showing substantial improvement on RWM stability by NCCs



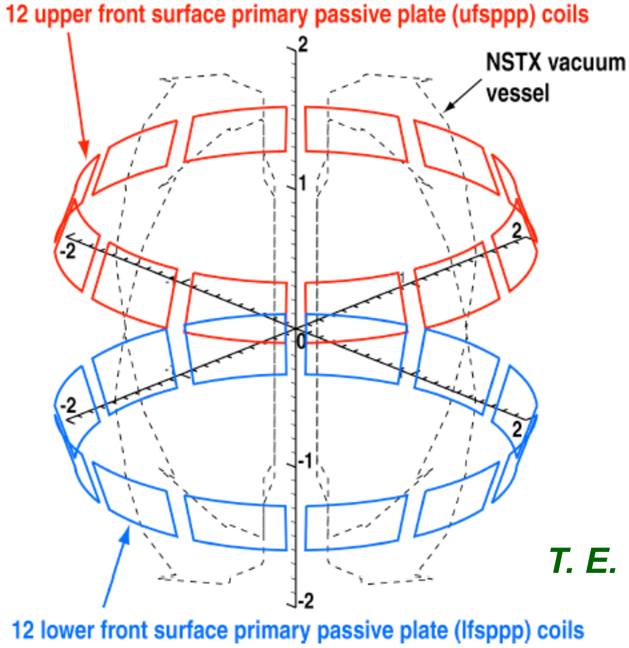
J. Bialek

PAC29-5e

NCCs can maintain edge stochastic layer over a wide range of q_{95} by varying n=6 toroidal phase

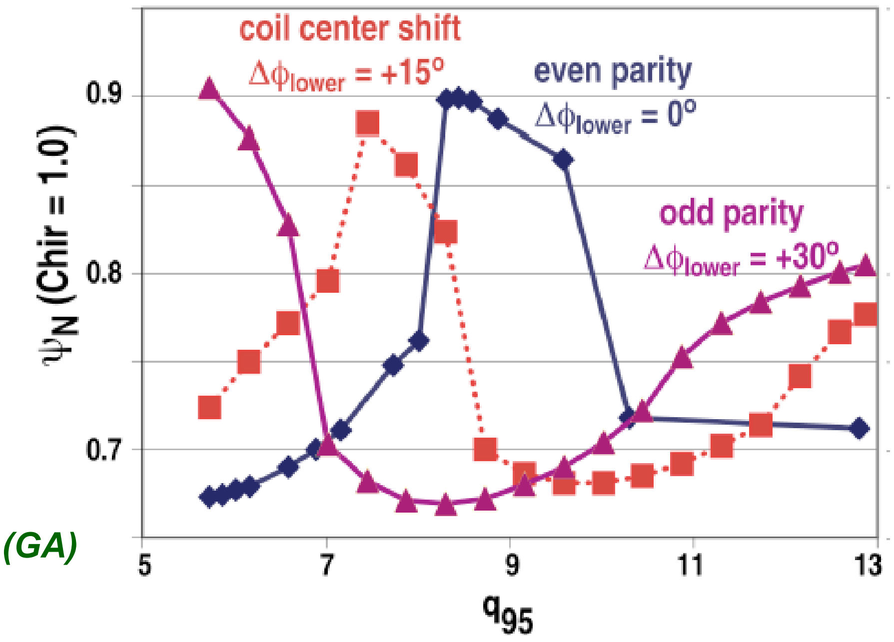
- TRIP3D code analysis on NCCs for various target plasmas showed:
  - In high shaping NSTX plasmas, n=6 fields produce a wider edge stochastic layer than n=3 I-coil fields in DIII-D, over a wide range of q_{95} ($5.3<q_{95}<12.8$)
  - Combined n=6 and existing n=3 field line loss fractions exceed those combined n=3 I-coil and n=1 C-coil fields in DIII-D

NCC model in TRIP3D



T. E. Evans (GA)

Stochastic layer by n=6 NCC fields



- Next step: Plasma response and NTV calculations with NSTX-U scenarios

Summary of MS research progress and plans

- MS research is addressing important issues to establish predictive capability for stability, 3D field effects, and disruptions, for NSTX-U, ITER, and FNSF
- NSTX is making vital contributions in the areas of:
    - Physics understanding for complex rotation dependencies in RWM stabilization, error field correction, tearing modes, and NTV braking, in present NSTX and future devices
    - Understanding disruptivity and halo current dynamics
    - Full 3D modeling of eddy currents in RWM control
- MS research and integrated stability control of NSTX-U plasmas would be greatly enhanced with NCC coils
- Integrated MS research and control in NSTX-U will be compared and validated with upgraded analysis tools, utilizing more principle-based computations*
- Collaborations with other devices will play important role in developing MS predictive capability

For key modeling efforts, see backup page 36

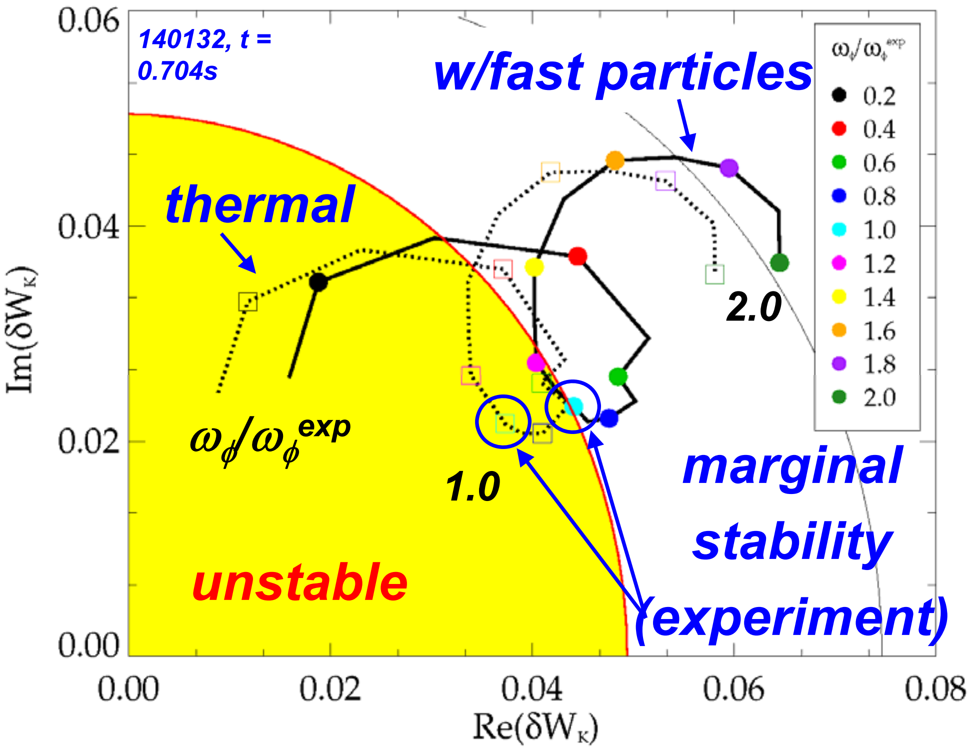
Back up

Kinetic stability calculations show reduced stability in low l_i target plasma as ω_φ is reduced, RWM becomes unstable

R(12-1)

- Stability evolves
  - Computation shows stability at time of minimum l_i
  - Region of reduced stability vs. ω_φ found when RWM becomes unstable ($l_i = 0.49$)
- Quantitative agreement between theory/experiment
  - MISK, MARS-K, HAGIS code benchmarking (ITPA MDC-2)
  - MISK calculations improved
    - (already good) agreement between theory/experiment improved (no free params.)
    - Conclusion: Best agreement with fast particle effects included

RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)



More quantitative comparison to theory

- S.A. Sabbagh, et al., IAEA FEC 2008, Paper EX/5-1
- J.W. Berkery, et al., PRL 104 (2010) 035003
- S.A. Sabbagh, et al., NF 50 (2010) 025020
- J.W. Berkery, et al., Phys. Plasmas 17, 082504 (2010)
- S.A. Sabbagh, et al., IAEA FEC 2010, Paper EXS/5-5

PAC29-20 **ITPA MDC-2**

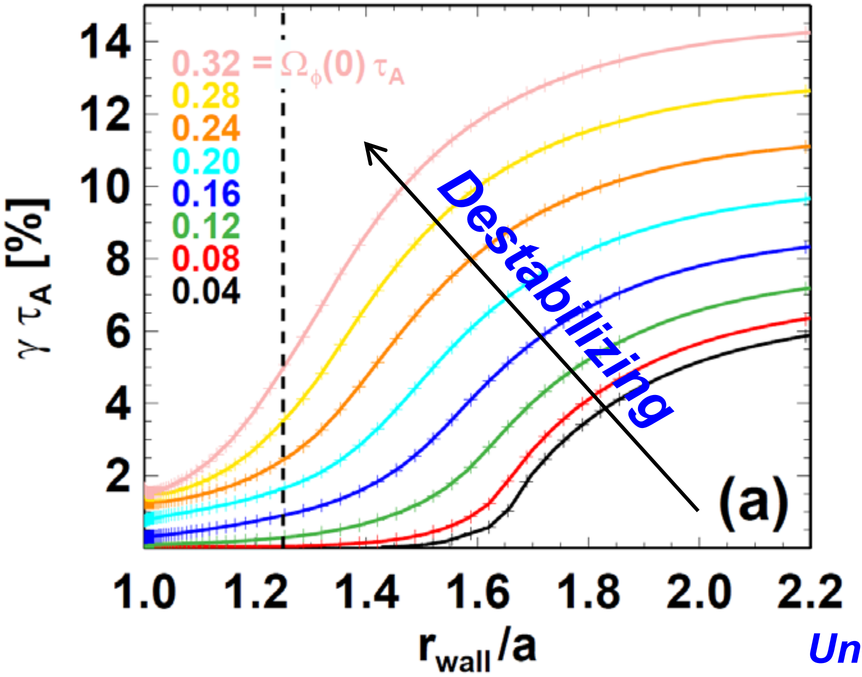
RWM stability changes not only by particle kinetic energy, but also by modified eigenfunctions

R(12-1)

- Kinetic δW can be comparable to or larger in magnitude than the fluid δW component, implying eigenfunctions can change
- MARS-K calculations showed self-consistent eigenfunctions can substantially differ by rotations and can even change ideal-wall limit

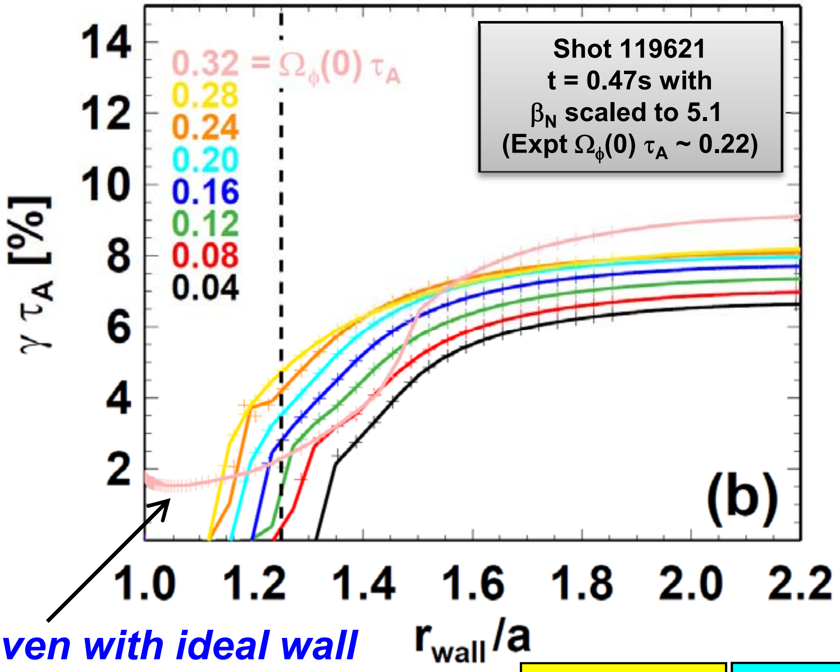
Ideal wall stability in fluid plasma

Plasma becomes unstable along with rotation, by Kevin-Helmholtz instability



Ideal wall stability in kinetic plasma

Without bounce motions, kinetic effects stabilize plasma, as expected, but can be destabilizing by rotation



Shot 119621
t = 0.47s with
β_N scaled to 5.1
(Expt $\Omega_\phi(0)\,\tau_A$ ~ 0.22)

Unstable even with ideal wall

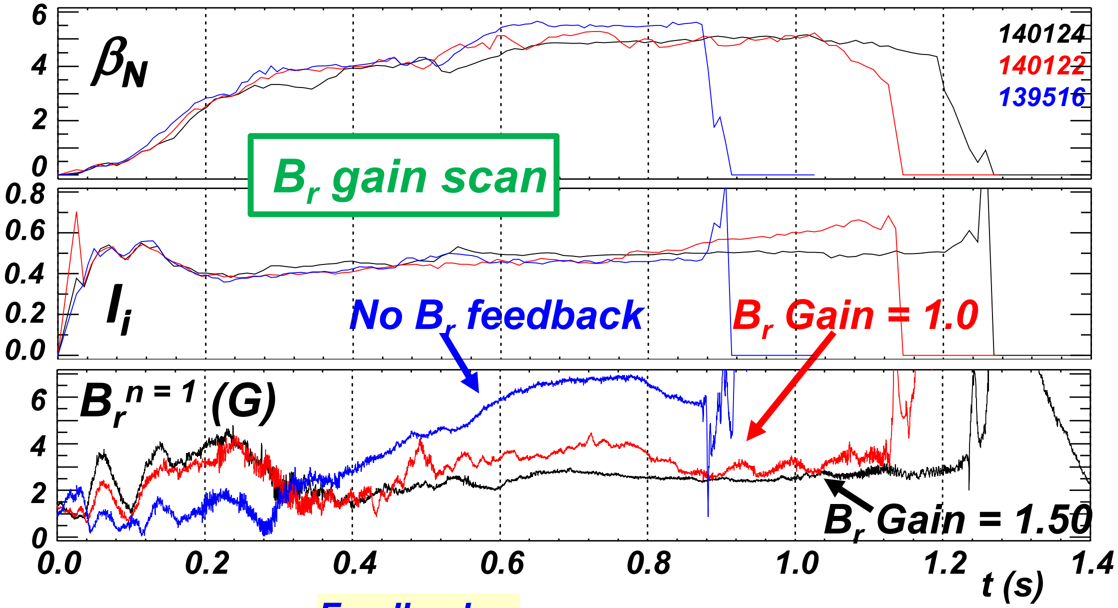
J. E. Menard, Y. Liu (CCFE), EPS2012

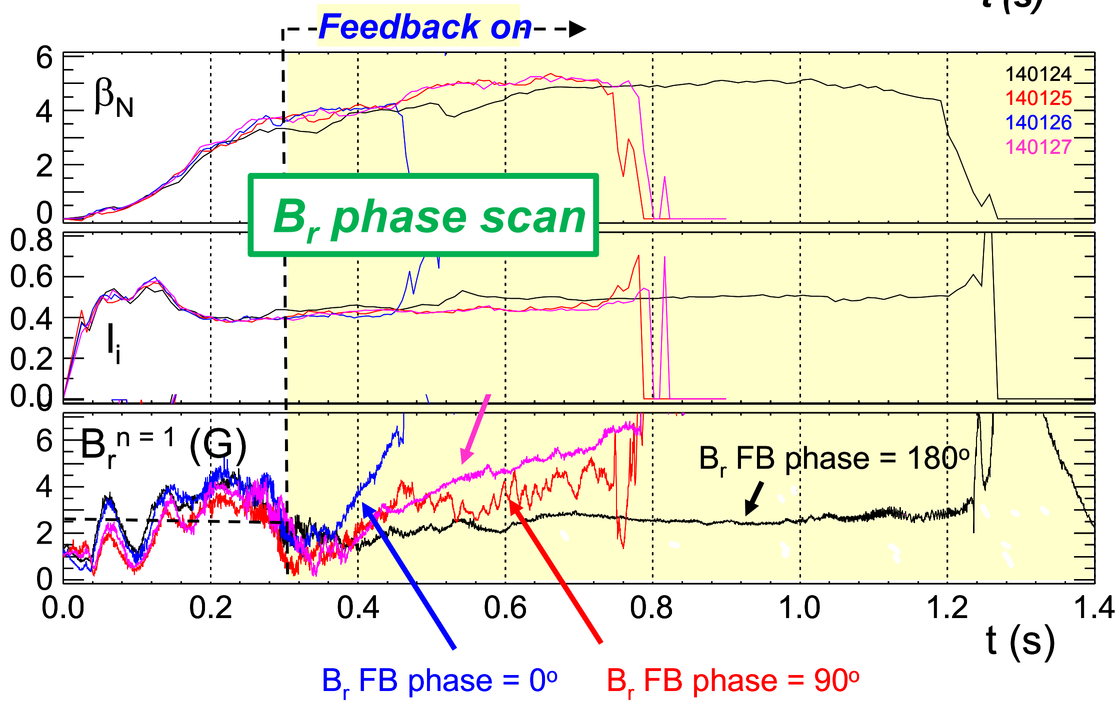
PAC29-20 ***ITPA MDC-7***

Combined RWM B_r + B_p sensor feedback gain and phase scans produce significantly reduced n = 1 field

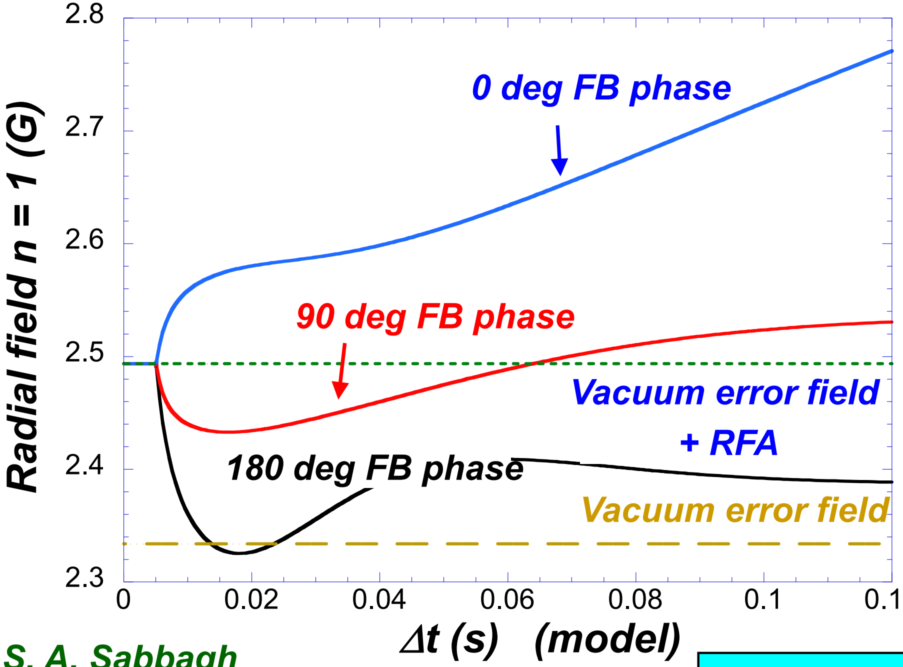
R(12-1)

- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
  - Fast RWM growth ~ 2 - 3 ms control by B_p
  - B_r feedback controls slower (~10 ms) n=1 field amplification, modes
- Time-evolved theory simulation of B_r+B_p feedback follows experiment





Simulation of B_r + B_p control (VALEN)



S. A. Sabbagh

ITPA MDC-7

Tearing stability threshold in NSTX can be explained with existing models with rotations

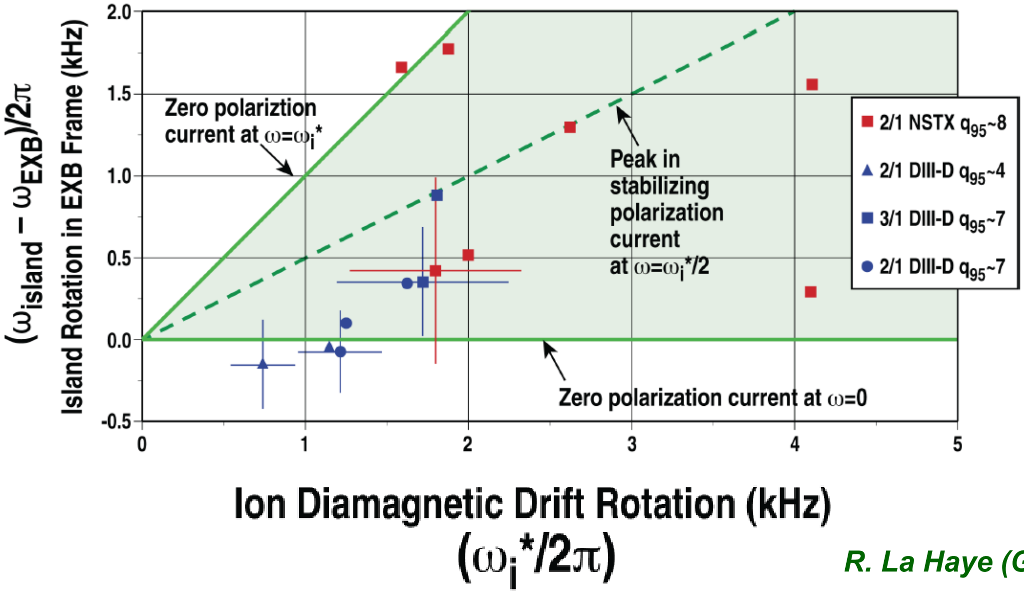
R(12-1)

- NSTX island rotations, which are faster than ExB rotations, should provide stabilizing helical polarization currents
- The polarization model gives a fair fit to the marginal island data for both NSTX and DIII-D
  - Advantageous for STs

TM stability vs. ExB and diamagnetic rotation

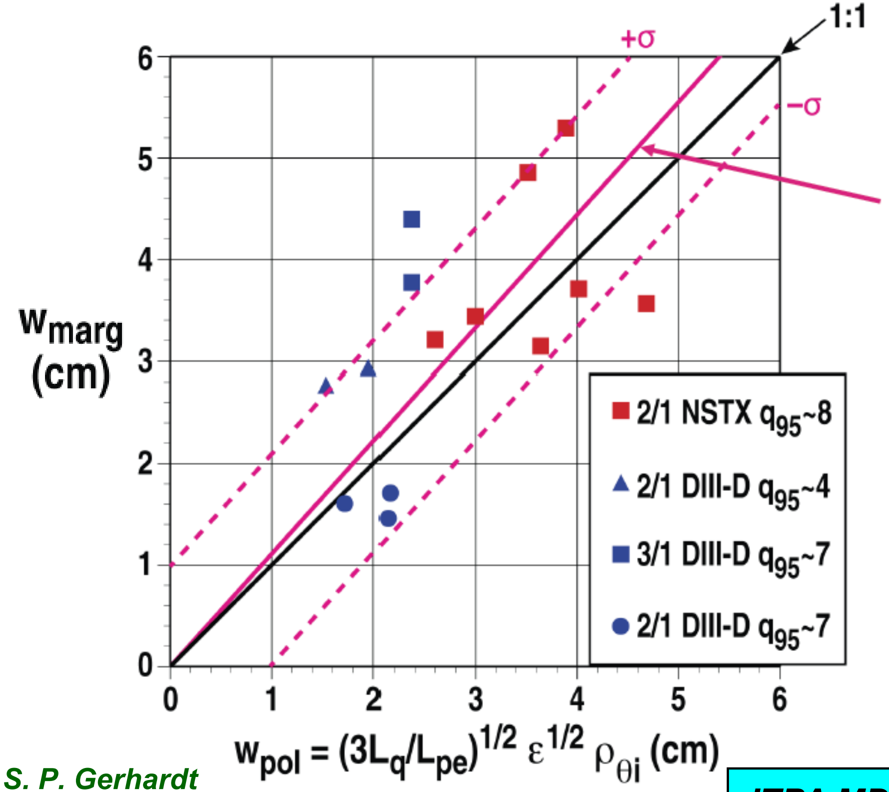
$$w_{pol} \approx (3L_q/L_{pe})^{1/2}\varepsilon^{1/2}\rho_{\theta i}\ \mathrm{x}2 \left[\frac{\omega\omega_i^* - \omega^2}{\omega_e^{*2}}\right]^{1/2}$$

for $(\nu_i/\varepsilon)/\omega \ll 1$ with $\omega=\omega_{island}-\omega_{ExB}$



Theory vs. experiments for marginal islands

Assuming $\omega \equiv \omega_i^*/2$ and $(\nu_i/\varepsilon)/\omega \ll 1$



R. La Haye (GA), S. P. Gerhardt

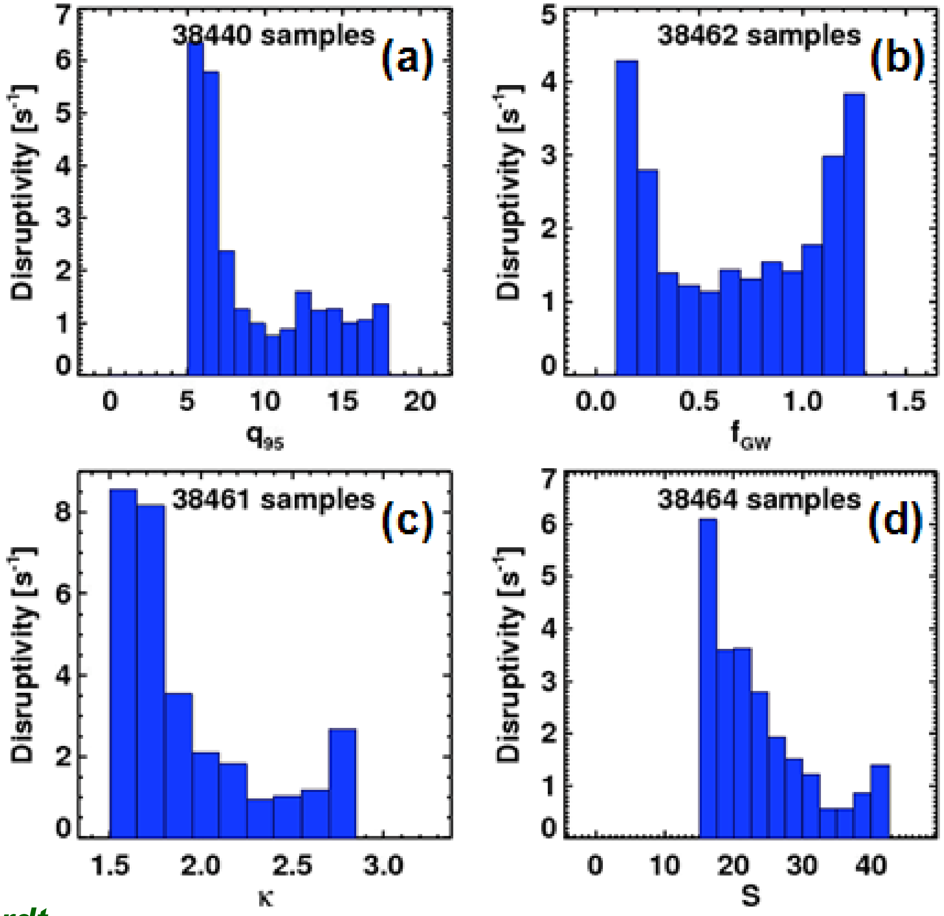
ITPA MDC-4

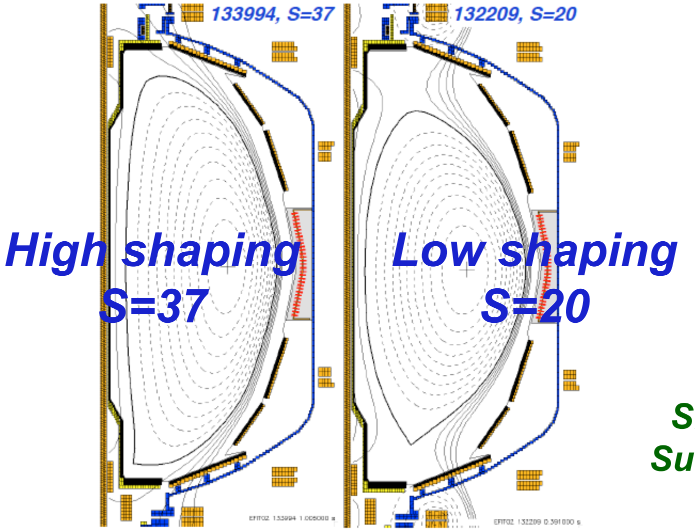
Further disruptivity study shows importance of q_{95}, density, shaping control to disruption avoidance

R(13-4)

- Disruption analysis on NSTX database additionally shows disruptivity
  - (a) dramatically increases for $q_{95}<7.5$ (as shown by q*)
  - (b) increases in low density with $f_{GW}<0.3$ by typically early disruption in the flat-top, and in high density with $f_{GW}>1.1$
  - (c) Increases in low elongation and
  - (d) increases in low shaping factor

Disruptivity as a function of macro-variables





S. P. Gerhardt
Submitted to NF

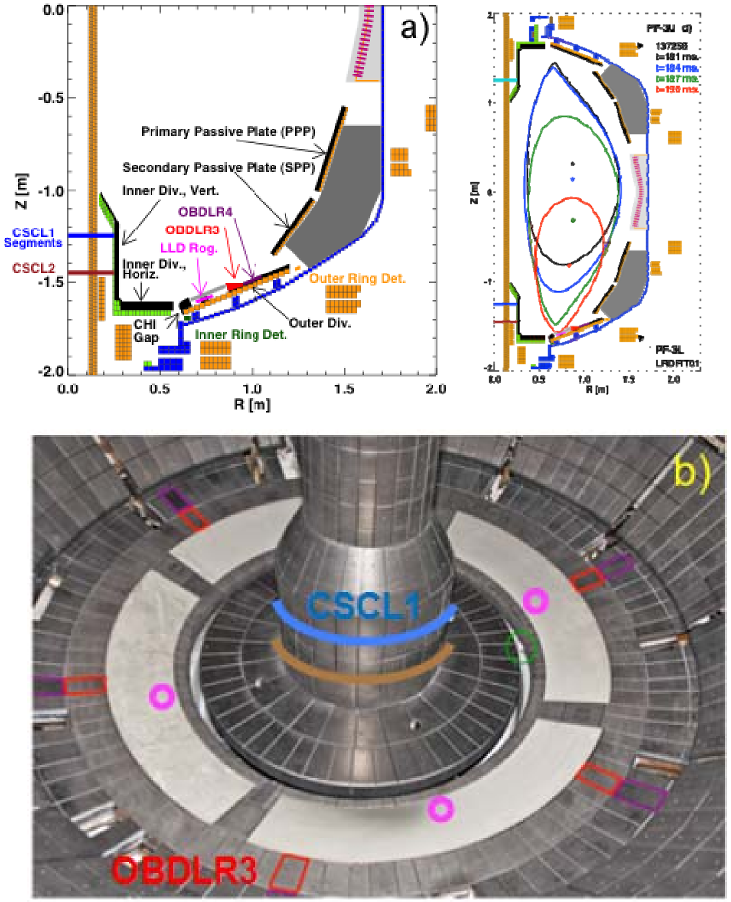
PAC29-21 ***PAC29-45*** ***ITPA MDC-15***

Halo currents in NSTX disruptions have low toroidal peaking, but get stronger in fast quench

R(13-4)

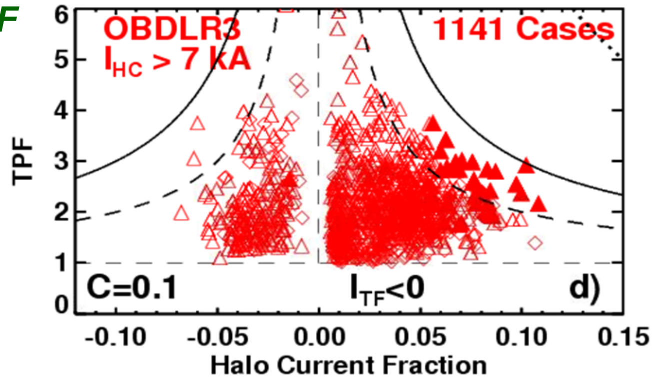
- Detailed study for halo currents showed Toroidal Peaking Factor (TPF) is anti-correlated with Halo Current Fraction, but peaking is low
- Halo Current Fraction becomes stronger in fast quench

Halo current detection system

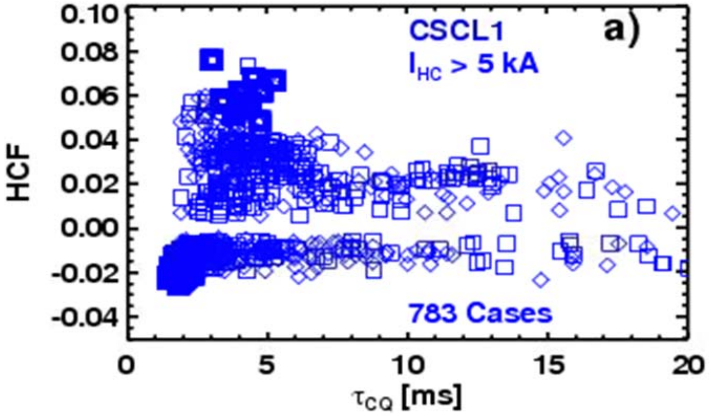


S. P. Gerhardt
Submitted to NF

TPF = 1+C/HCF, C~0.1



HCF vs. current quench



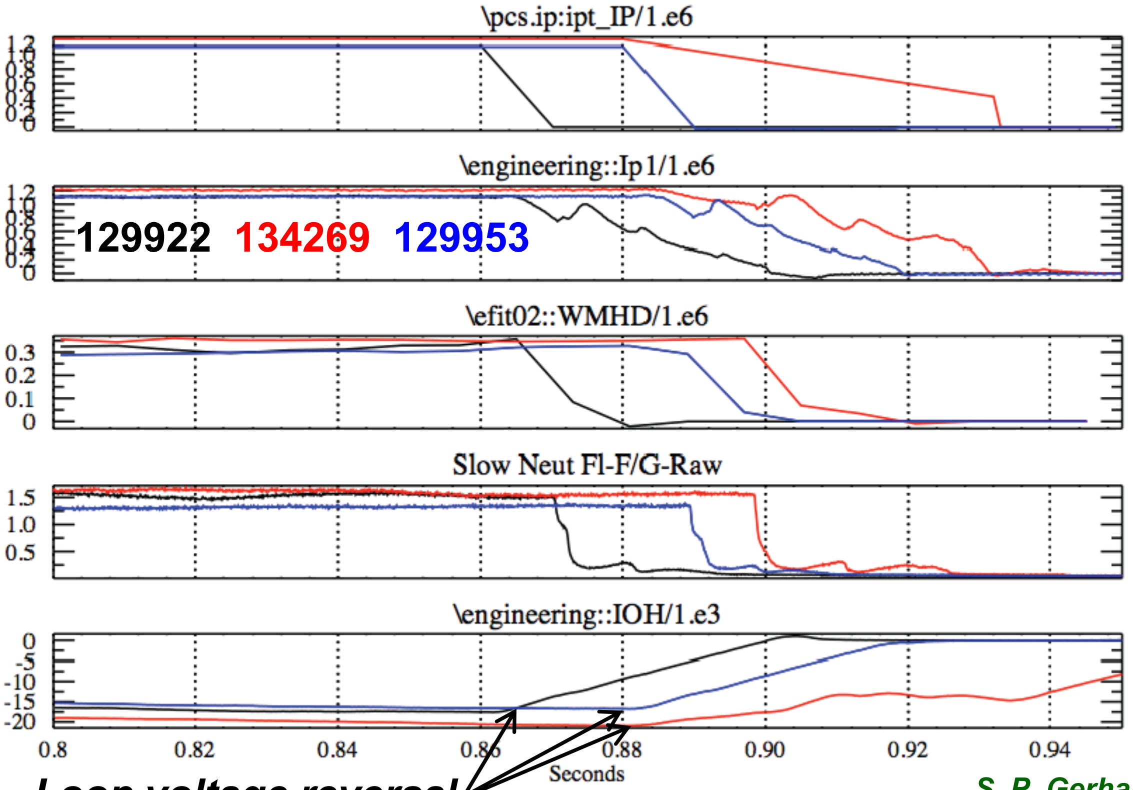
PAC29-45 **ITPA MDC-15**

NSTX high energy disruptions were investigated to study heat loading on divertor

R(13-4)

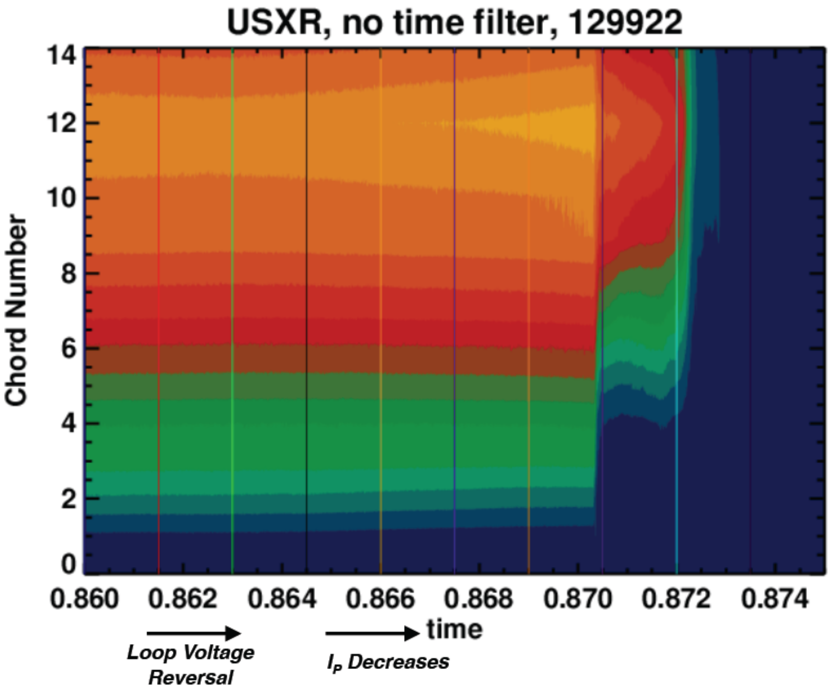
- High energy disruptions in NSTX occurred soon after loop voltage was reversed without leading RWM, TM locking, or vertical motion before TQ
- USXR analysis shows that heat is lost in two steps very rapidly
  - May provide an ideal scenario for studying disruptive heat transport through scrape off layer region

3 of the 4 largest NSTX disruptions since 2007



Loop voltage reversal

USXR before and during disruption



S. P. Gerhardt, A. Mclean (ORNL)

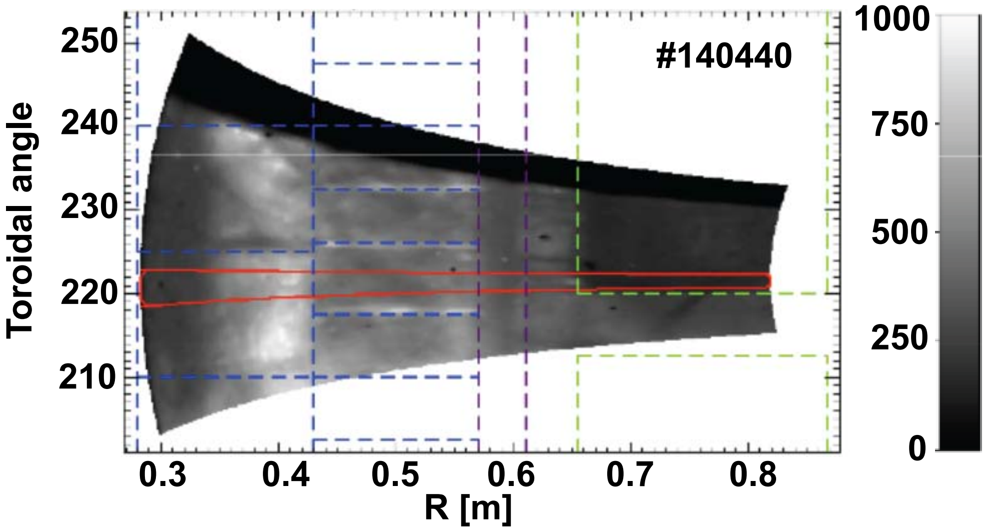
PAC29-46

ITPA MDC-15

Fast IR camera demonstrated ability to resolve disruption heat loading

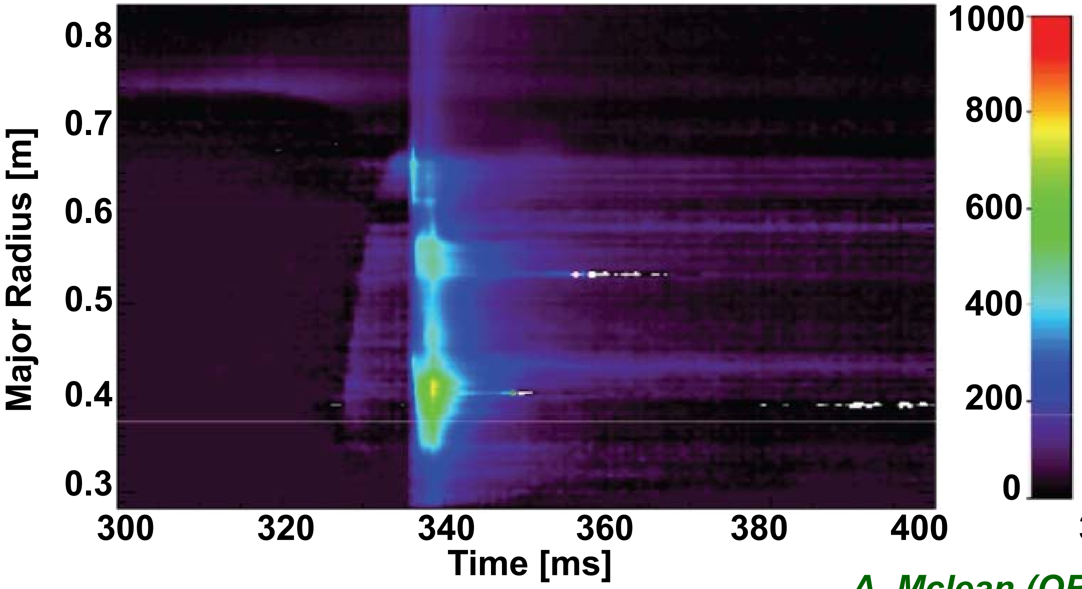
R(13-4)

NSTX fast dual-band IR temperature

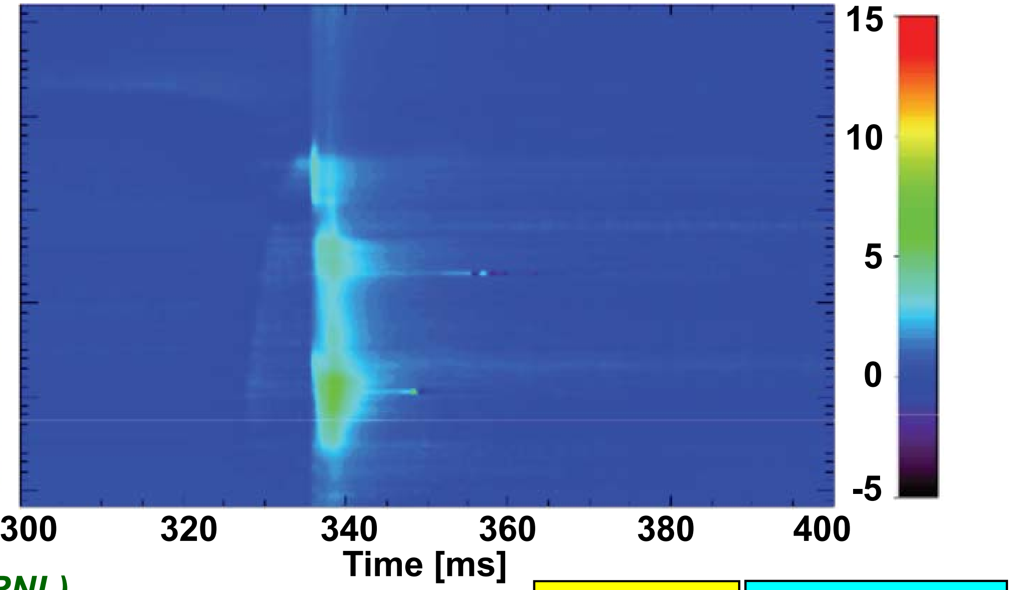


- 2-D surface temperature shows significant turbulence
- T, q in time shows interesting pre-collapse signature
  - Peak q using THEODOR shows much lower value (~10) than 1-D C&J
- Fast cooling of the surface shows that incorporation of surface layer physics is essential

Divertor temperature vs. time



Divertor heat flux (THEODOR) vs. time



A. Mclean (ORNL)

PAC29-46 **ITPA MDC-15**

Open-loop comparisons between measurements and state space controller show importance of states and 3D model

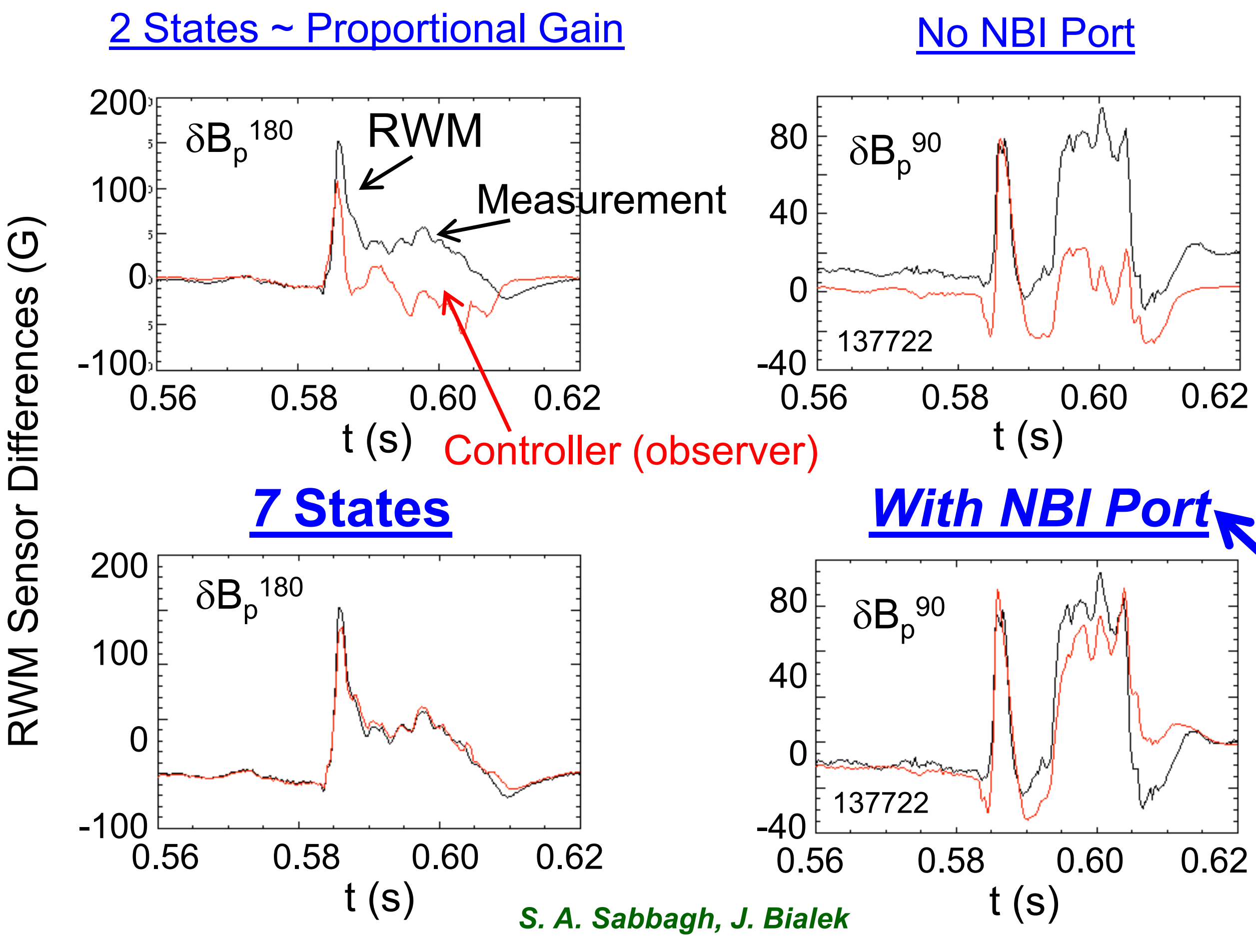
R(14-1)

- Agreement can be greatly improved with sufficient number of states and with 3D detail of model (such as NBI port)
- Extra NBI port is also included in NSTX-U prediction

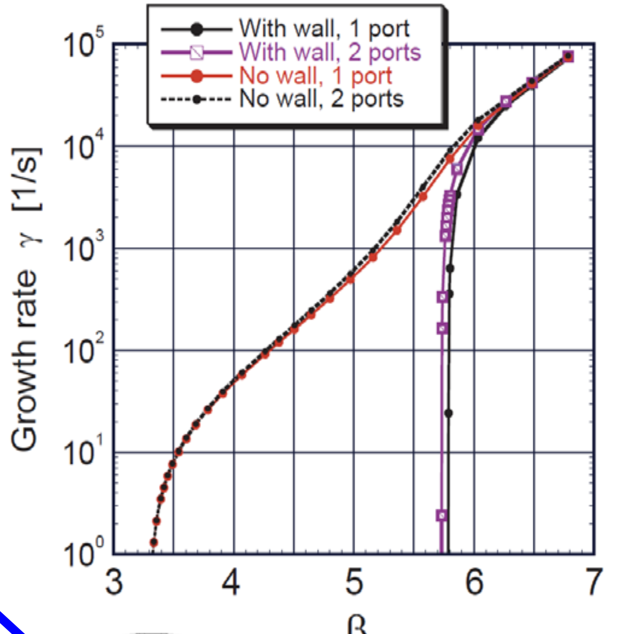
Effect of Number of States Used

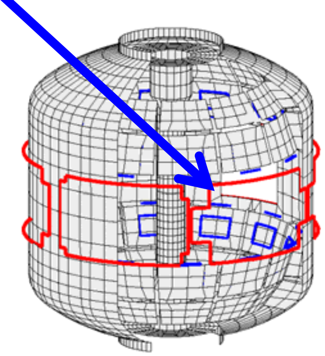
Effect of 3D Model Used

NSTX-U passive stability vs. β_N



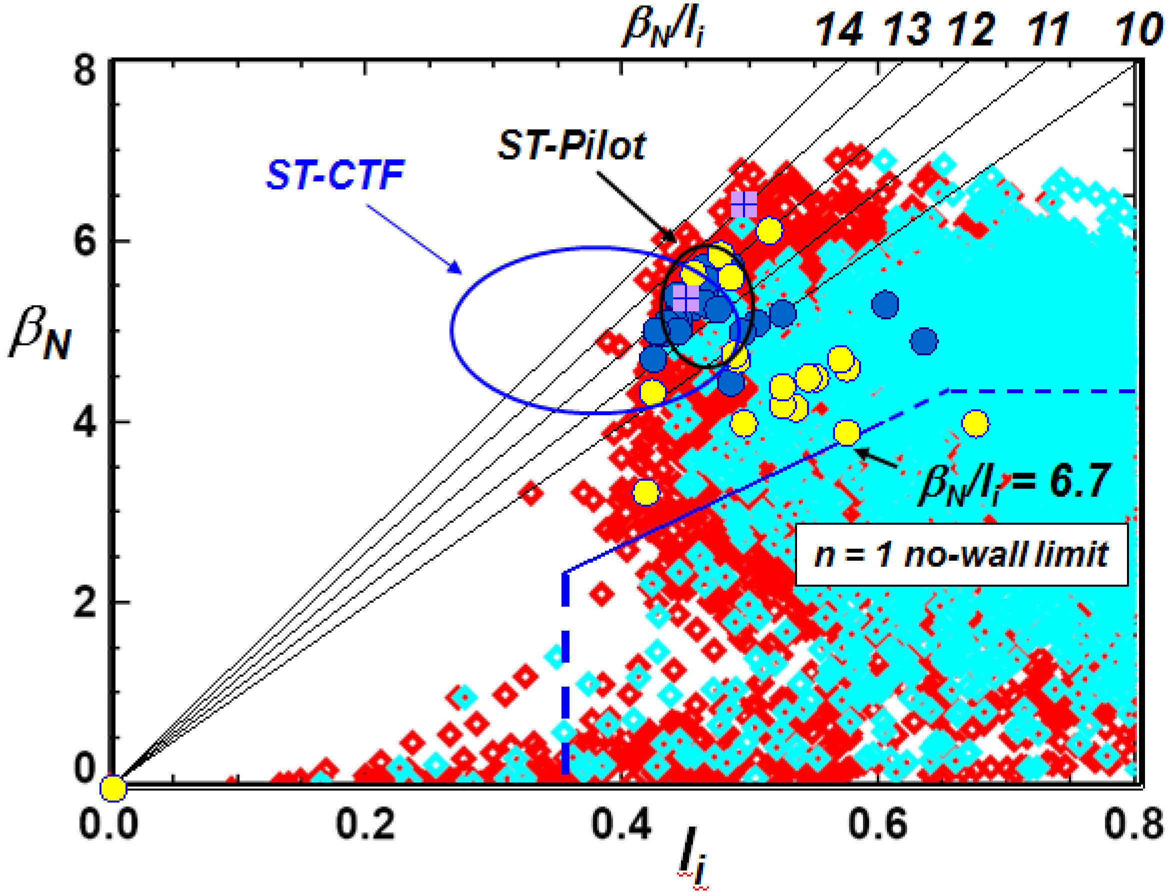
S. A. Sabbagh, J. Bialek





(R10-1) Improvements in stability control techniques significantly reduce unstable RWMs at low l_i and high β_N

- Computed n = 1 no-wall limit β_N/l_i,~ 6.7 (low l_i range 0.4 – 0.6)
- Synthetic equilibria variation: n = 1 no-wall unstable at all β_N at $l_i < 0.38$ (current-driven kink limit)
  - significant for NSTX-U, next-step ST operation



S. A. Sabbagh

- Subset of discharges
  - High $I_p \geq 1.0$MA, I_{NICD}/I_p ~ 50%
- 2009 experiments
  - 48% disruption probability (RWM)
- 2010 experiments
  - n = 1 control enhancements
  - Significantly reduced disruption probability due to unstable RWM
    - s14% of cases with $\beta_N/l_i > 11$
    - Much higher probability of unstable RWMs at lower β_N, β_N/l_i

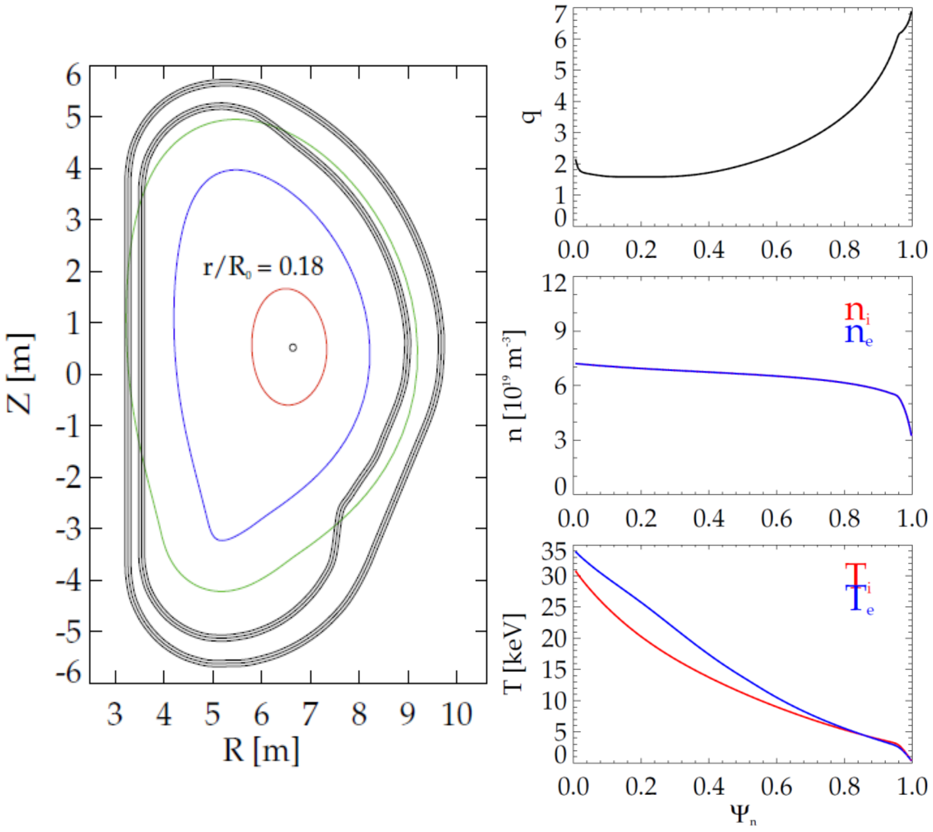
ITER advanced scenario requires alpha particles for RWM stability across all rotation values

R(14-1)

- Improved MISK calculations again shows the importance of alpha particles in ITER for RWM stability
- RWM, error field, and NTV prediction for ITER and next-step devices will be continued

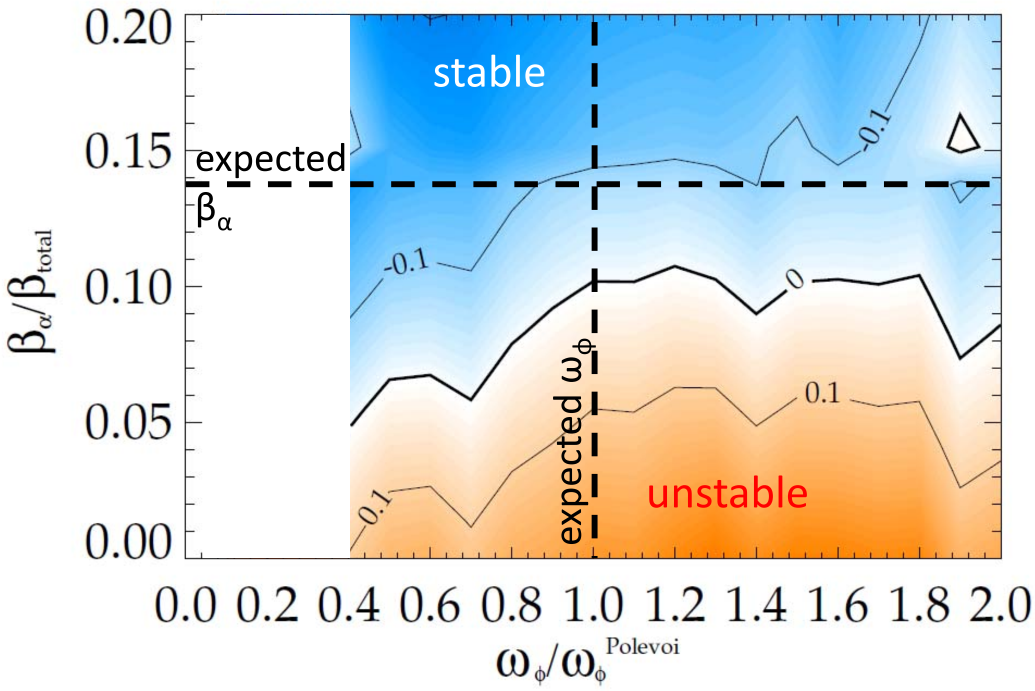
ITER equilibrium WG7

I_p = 9 MA, β_N = 2.9 (7% above no-wall limit)



MISK prediction for ITER RWM

Revisited from MARS-K benchmark and still showing importance of alpha particles



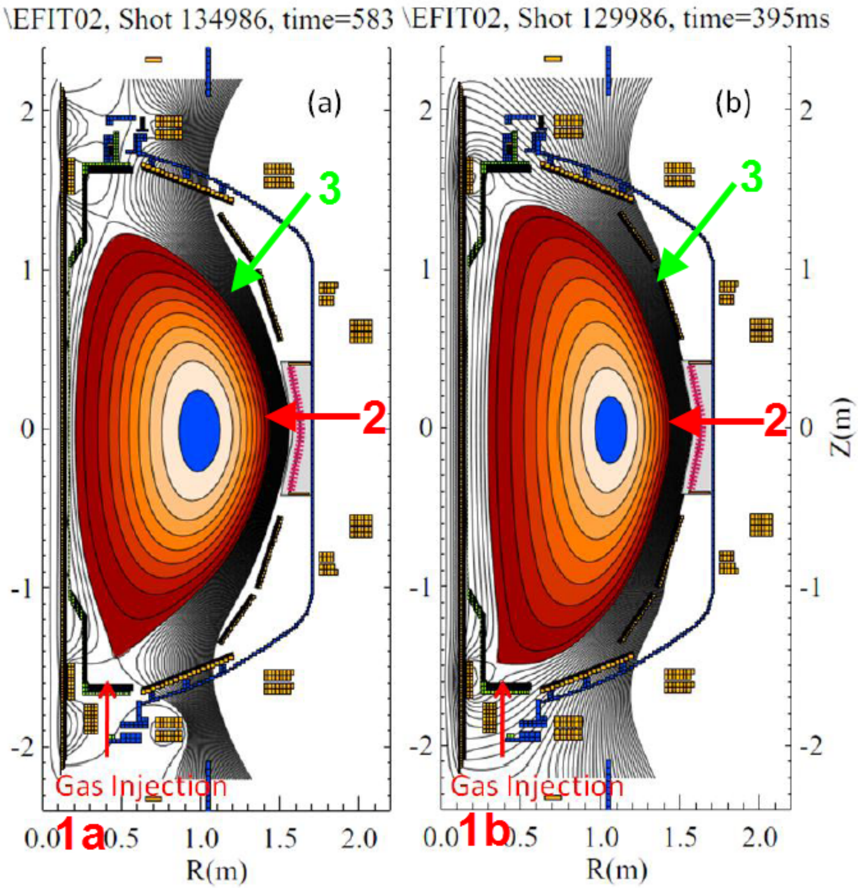
J. W. Berkery, POP 17 082504 (2010)

PAC29-20 **ITPA WG7**

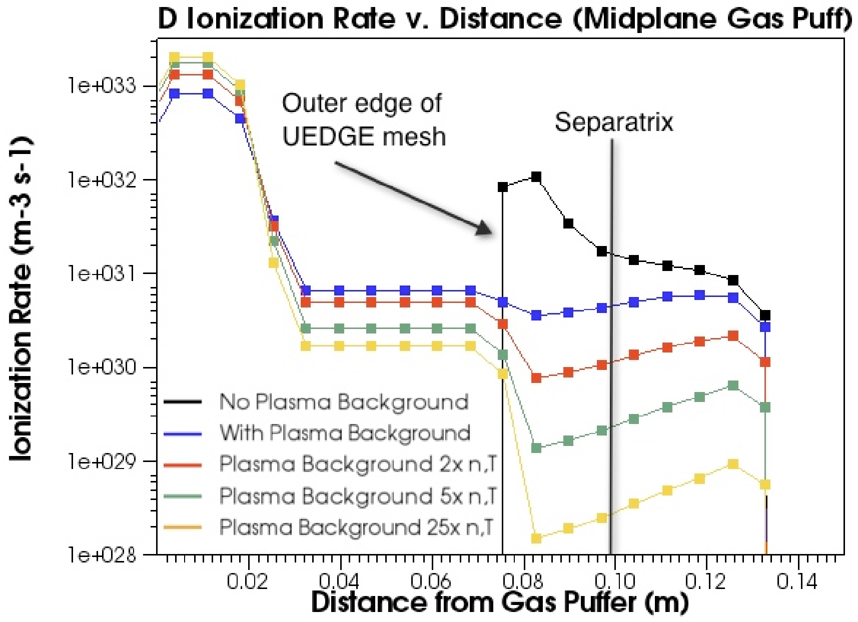
MS research will be combined to improve disruption detection, as well as mitigations

- Disruption mitigation techniques will be tested in NSTX-U, using our unique access in inboard and private flux region
- Modeling for gas dynamics has been started

MGI location variation in NSTX configuration



UEDGE+DEGAS2 gas penetration modeling



R. Raman (UW), D. P. Stotler

PAC29-45 **ITPA MDC-1**

Important diagnostics for MS topics were identified and will be under proposal and/or development

Diagnostics	Resolution	Related topics
Magnetic refurbishment	kHz-MHz	Whole MS area
Radial and poloidal magnetic sensors		3D, global
rtMSE	1-3cm, 5ms	Global, tearing
Internal magnetic fluctuation measurement	18CH, 100kHz, 5-10ms	3D, Tearing
rtMPTS	10-20CH, 11-16.7ms	Global, tearing
Toroidally displaced ME-SXR	1-3cm, 10-100kHz	3D, global, tearing, disruption
Core X-ray Imaging Spectrometer	<1cm, >5ms	3D, global, tearing
Disruption force diagnostics		Disruption
RTV (Real Time Velocity) measurements	4-6CH, <5kHz	3D, global, tearing
Neutron collimator	3-4CH, 5-20ms	Global, tearing
Tangential FIDA, High density FIDA	1cm, 5ms	Global, tearing
NPA, ssNPA	5-10cm, 1MHz, 10keV	Global, tearing
SOLC with magnetic probes, electrodes, sensors		3D, global, tearing, disruption
Additional RWM sensors near upper and lower divertors		3D, global
EBW measurements for magnetic field	1-3mm (rho=0.7-0.9)	3D, global, tearing, disruption
MSE-LIF	1-3cm, 5ms	3D, global, tearing
Radiation tomography		Disruption
Improved reflectometer system	1-10kHz	Global, ASC
Fast thermography, thermocouples	5-10cm, 1ms	Disruption
Visible bremsstrahlung imaging	1cm, 20us	Global
Error field measurements with external coils		3D

Summarized theory topics in MS

Category	Existing efforts	Associated physics issues
More robust equilibrium reconstruction and modeling including toroidal rotation and SOL, and stability analysis	- EFITs including rotation - LRDFITs including rotation - (E,LRD)FITs + FLOW - (E,LRD)FITs + FLOW + M3D-C1	- Stability boundary with toroidal rotation? - Stability boundary including separatrix? - Can be routinely available as GEQDSK in NSTX-U?
Quasi-linear 3D equilibrium modeling including islands, neoclassical, and kinetic MHD effects	- IPEC with tensor pressures and islands + POCA + Inner-layer - FLOW, MARS-F, MARS-K - M3D-C1	- 3D equilibrium with opened islands? - 3D equilibrium with rotation? - 3D equilibrium with anisotropic pressures? - Self-consistent modeling for NTV in NSTX-U?
Quasi-linear stability modeling including neoclassical and kinetic MHD effects	- MISK with anisotropic pressures and fast ions - MARS-K, NOVA-K - M3D-C1	- RWM passive stability with 2nd NBIs in NSTX-U? - Effects by Self-consistent eigenfunction? - Second RWM code with full kinetic treatment?
Non-linear (as well as linear) 3D modeling for time-evolving dynamics of islands, neoclassical, full kinetic MHD effects	- M3D-C1 with distribution function solver (Ramos theory or NTV theory) - XGC0	- Non-linear effects in 3D equilibrium and stability, including SW (q=1) and NTM? - Two fluid effects in 3D equilibrium and stability? - Full kinetic effects in 3D equilibrium and stability?
Gas penetration physics modeling including MGI and runaway electrons and disruption simulation	- DEGAS2 for gas penetration - TSC for runaway electrons - M3D for disruption simulation - Use of 3D equilibrium sequence	- Gas penetration with atomic physics? - Runaway electrons in NSTX-U? - Coupling gas and plasma modeling? - Why mode locking cause a disruption? - What is the origin of a density limit disruption?
Full 3D modeling for external structure for RWM dynamics	- Multi-mode VALEN3D - Plasma permeability with neoclassical and kinetic MHD effects - VALEN3D + Plasma permeability	- Full 3D current effects on RWM? - Effects of full 3D + kinetic plasma permeability on RMW stability and control?