Overview of the Core Science Group Status and Plans

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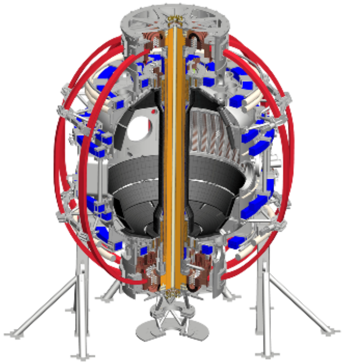
S.A. Sabbagh (SG Deputy Leader)
for the Core Science Group

37th NSTX-U PAC
PPPL, Princeton University
26-27 January 2016



Outline of talk

- Core Science Group and its components
- Core SG mission elements and TSG research thrusts and their relation to NSTX-U high-level goals
- Planned research
  - Multi-TSG XPs
  - TSG-specific
- Benefit of future facility enhancements to TSG goals
- Work directed towards FES panels' recommendations
- Summary

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This talk will address all of the PAC charges

- Assess the research planned to be carried out for the NSTX-U FY2016 experimental campaign - are there any major missing elements, or new opportunities?
- Assess the alignment between the NSTX-U research plans and goals and the FESAC / FES initiatives, research opportunities, and ITER urgent research needs
- Comment on the progress and plans for the NSTX-U / PPPL theory partnership, and how well this partnership and the broader NSTX-U research activities support “integrated predictive capability” (see talk by A. Bhattacharjee)
- Please comment on the present team prioritization of planned facility enhancements including: divertor cryo-pump, non-axisymmetric control coils (NCC), 28GHz ECH/EBW gyrotron, and conversion to all high-Z PFCs and liquid metals research

Core Science Group role is to foster communication/ connectivity among TSGs studying confinement and stability (and among other SGs)

Core Science Group consists of three Topical Science Subgroups

Boundary Science Group
R. Maingi, C.-S. Chang (deputy)

- Pedestal Structure and Control
  A. Diallo, R. Maingi
  Theory/Modelling: J. Canik[1]
  University Rep: D. Smith[2]
- Divertor and Scrape-Off-Layer
  V. Soukhanovskii[3], J.-W. Ahn[1]
  Theory/Modelling: D. Stotler
  University Rep: O. Schmitz[2]
- Materials and PFCs
  M. Jaworski, C. Skinner
  Theory/Modelling: B. Wirth[4]
  University Rep: J.-P. Allain[5]

Core Science Group
S. Kaye, S. Sabbagh[6] (deputy)

- Macroscopic Stability
  J. Berkery[6], J.-K. Park
  Theory/Modelling: S. Jardin
  University Rep: D. Brennan[7]
- Transport and Turbulence
  W. Guttenfelder, Y. Ren
  Theory/Modelling: W. Wang
  University Rep: K. Tritz[8]
- Energetic Particles
  M. Podestá, D. Liu[9]
  Theory/Modelling: N. Gorelenkov
  University Rep: N. Crocker[10]

Integrated Scenarios Group
S. Gerhardt, R. Raman[11] (deputy)

- Advanced Scenarios and Control
  D. Battaglia, S. Gerhardt
  Theory/Modelling: F. Poli
  University Rep: E. Kolemen[7]
- Solenoid-free Start-up & Ramp-up
  D. Mueller, R. Raman[11]
  Theory/Modelling: F. Ebrahimi[7]
- Wave Heating and Current Drive
  R. Perkins, J. Hosea
  Theory/Modelling: N. Bertelli
  University Rep: P. Bonoli[12]

Experiment, theory and university reps constitute SG+TSG leadership

SG successful in optimizing run time for XPs that span multiple TSGs

Core SG addresses high-level research goals and priorities of NSTX-U

- Explore unique ST parameter regimes to advance prediction capability
  1. Understand confinement at high normalized pressure and at low collisionality*
  2. Study energetic particle physics prototypical of burning plasmas*

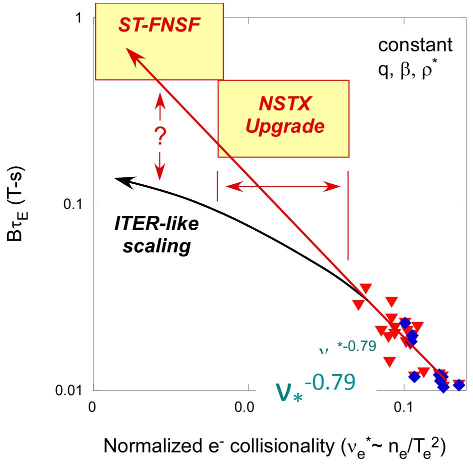
- Develop solutions for PMI under high heat flux conditions

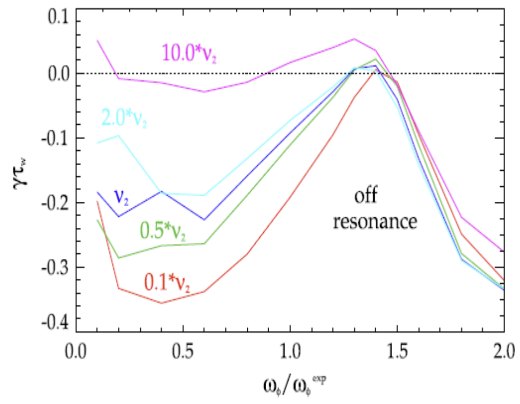
- Advance concept for Fusion Nuclear Science Facility (FNSF) by demonstrating 100% non-inductive ops at high performance
  3. Form and sustain plasma current without transformer for steady-state ST*

* Directly ITER relevant

Major upgrades allow the Core SG to accomplish its major research goals

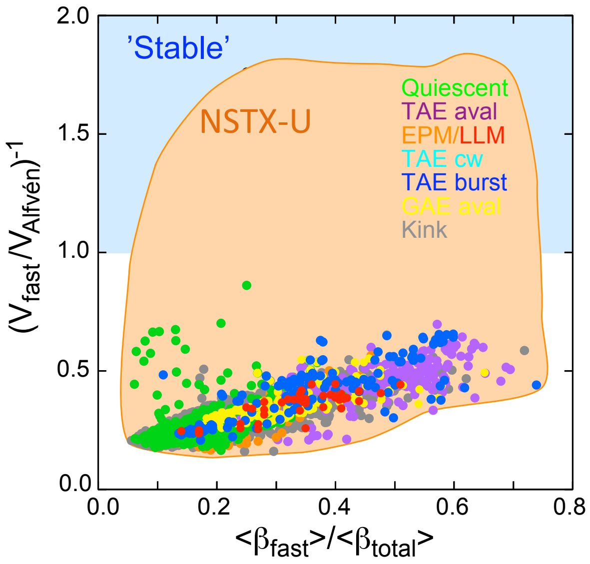
- Extended I_p, B_T range
  - Allows for reduction in ν_*
    - Confinement scaling (T&T)
    - Stability optimization (Macro)
  - Allows for leverage on varying q, $v_{fast}/v_{Alfvén}$, β_{fast}/β_{tot} for fast ion instability studies (EP)





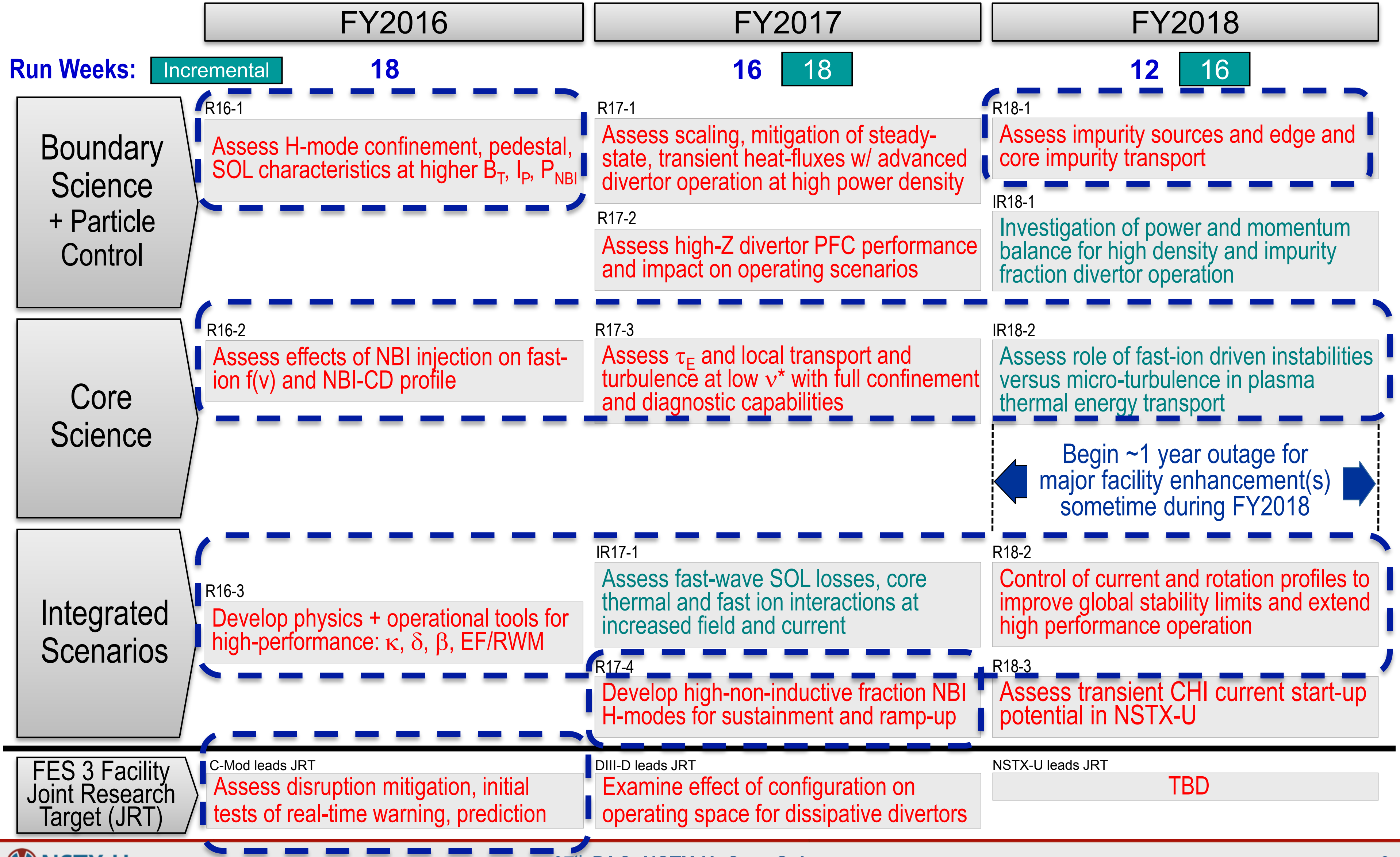
Kinetic effects important for RWM stability

- 2^{nd} NB
  - Modifies q, flow profiles
    - Transport, NTV, stability, fast ion confinement (T&T, Macro, EP)
  - Affects fast ion distribution function directly for AE studies (EP)



Increasing B_T

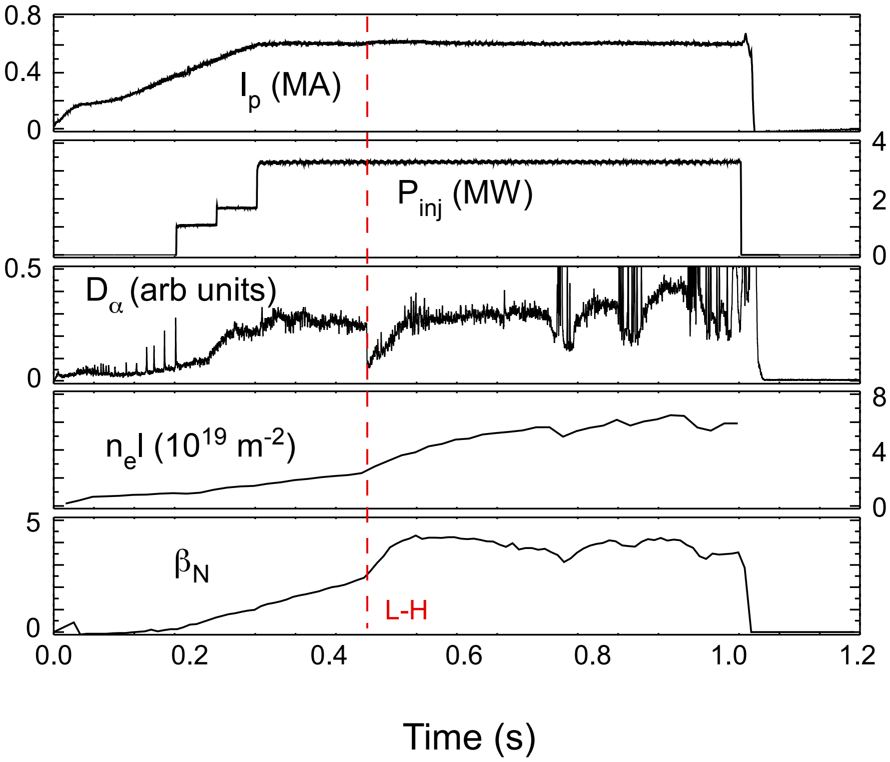
Core SG contributes to many of the 2016-2018 Yearly Milestones

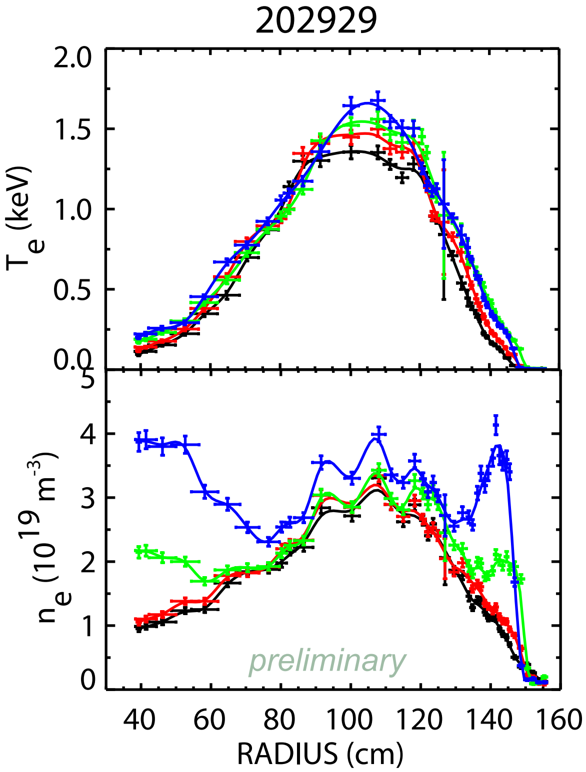


	FY2016	FY2017	FY2018
Run Weeks: Incremental	18	16 18	12 16
Boundary Science + Particle Control	R16-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1 Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2 Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1 Assess impurity sources and edge and core impurity transport IR18-1 Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2 Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3 Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	IR18-2 Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for major facility enhancement(s) sometime during FY2018
Integrated Scenarios	R16-3 Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1 Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4 Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2 Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3 Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT Examine effect of configuration on operating space for dissipative divertors	NSTX-U leads JRT TBD

Early NSTX-U results show promise for physics experiments that address Core SG goals

- Long-lived, good performing H-mode achieved after boronization





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TSG objectives and research thrusts define research for 2016-2018

- Transport and Turbulence: Establish predictive capability for the performance of FNSF and future devices
  - Characterize H-mode global energy confinement in lower collisionality regimes in NSTX-U
  - Identify mechanisms responsible for χ, D: explore parametric dependences with q, v_φ using 2nd NB and 3D coils
  - Establish and validate reduced transport models for establishing predictive capability
- Macrostability: Establish the physics objectives and control capabilities needed for sustained stability of high performance plasmas
  - Understand and advance passive and active control to sustain macroscopic stability
  - Understand 3D effects for optimizing stability through profile control
  - Understand disruption dynamics and techniques for avoidance and mitigation

TSG objectives and research thrusts for 2016-2018 (cont'd)

- Energetic particles: Enable predictions of fast ion behavior and associated instabilities in high-β super-Alfvénic regimes (ITER/FNSF)
  - Assess effects of NB injection parameters on fast ion distribution function, NB-driven current profile
  - Develop predictive tools for *AE-induced fast ion transport
  - Develop phase space engineering tools/techniques for fast ion distribution and mode control

Color Coding

Transport and Turbulence

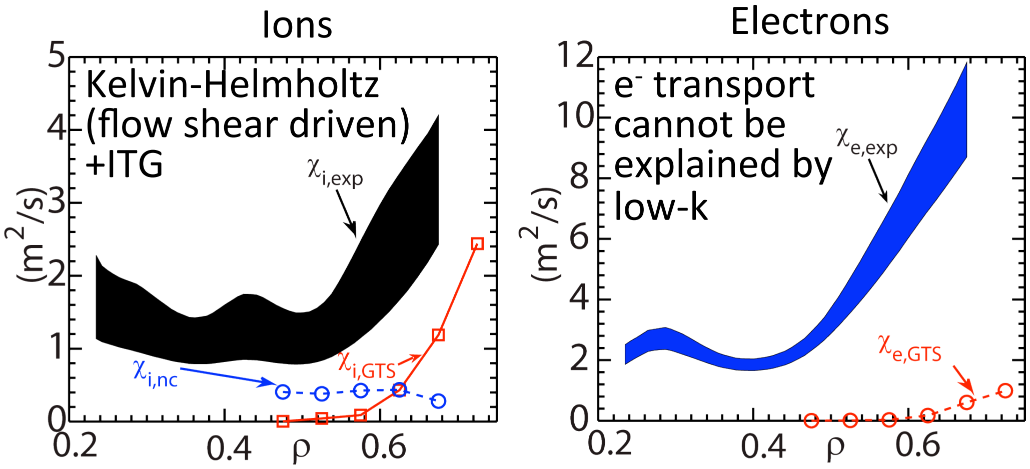
Macrostability

Energetic Particles

T&T research thrusts map directly to NSTX-U research priorities; recent results support future work

1. Understand confinement at high normalized pressure and at low collisionality
   - Characterize H-mode global energy confinement in lower ν_* regimes
   - Identify mechanisms responsible for χ, D: explore parametric dependences with q, v_φ using 2nd NB and 3D coils
   - Establish and validate reduced transport models for establishing predictive capability

Non-linear GTS indicate low-k ion fluxes within a factor of two of experimentally inferred ones



Wang PRL & PoP (2015)

- Shear-flow modification by 2nd NB, NTV from 3D coils
- Low-k turbulence will be diagnosed with expanded, 48-channel, BES array

Macro research thrusts map directly to NSTX-U research priorities; recent results support future work

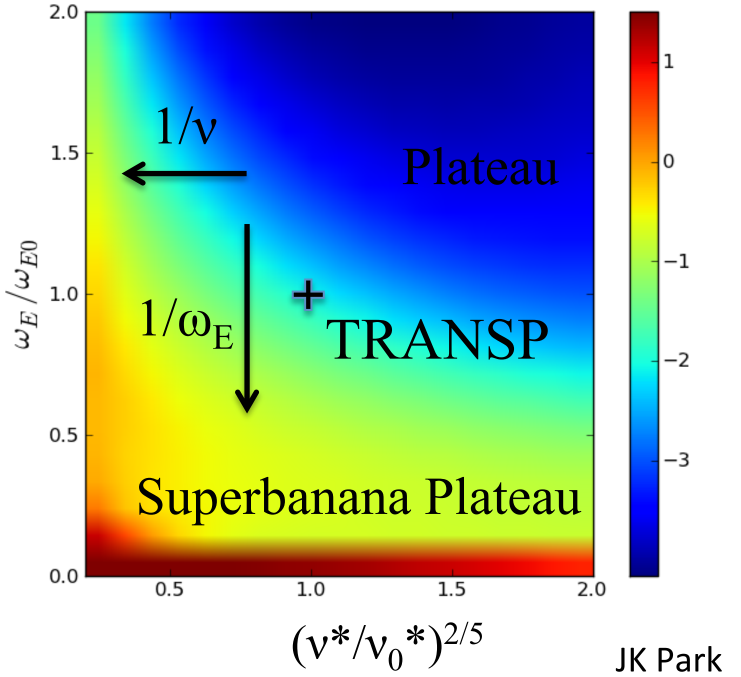
1. Understand confinement at high normalized pressure and at low collisionality
   - Understand and advance passive and active control to sustain macroscopic stability
   - Understand 3D effects through profile control
   - Understand disruption dynamics and techniques for avoidance and mitigation
     - S. Sabbagh talk on disruption PAM

- Shear-flow modification by 2nd NB, NTV from 3D coils
- Rotation, current profile control algorithms
- Joint NSTX-U/Theory study of halo currents using tile current measurements
- MGI for disruption mitigation

NTV depends on both collisionality and rotation (IPEC-PENT)

NTV by n=3 core-optimized NCC in NSTX-U

$\mathrm{Log}(T_\phi[\mathrm{Nm}])$



JK Park

EP research thrusts map directly to NSTX-U research priorities; recent results support future work

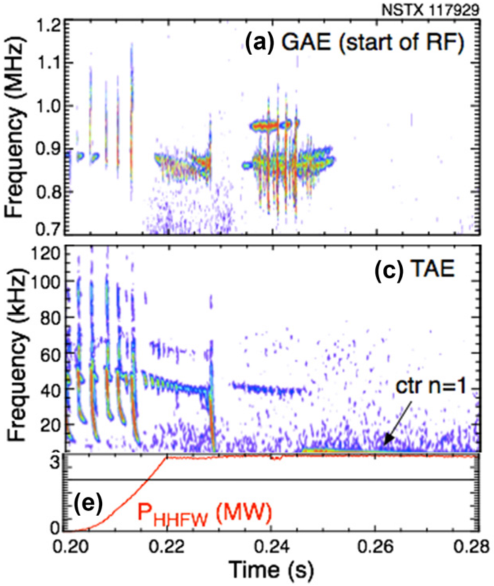
2. Study energetic particle physics prototypical of burning plasmas

- Develop predictive tools for *AE-induced fast ion transport
- Develop phase-space engineering tools/techniques for f_{fi}, mode control

- Shear-flow modification by 2nd NB, NTV from 3D coils tp study effect on CAE/KAW coupling
- HHFW + 3D fields for *AE suppression
- Expanded FIDA views, ssNPA for measuring energetic particle distribution

Suppression of TAE/GAE with HHFW

- Developing self-consistent NB+RF code to understand



Fredrickson NF (2015)

Applied 3D fields modify drive and damping of *AE modes

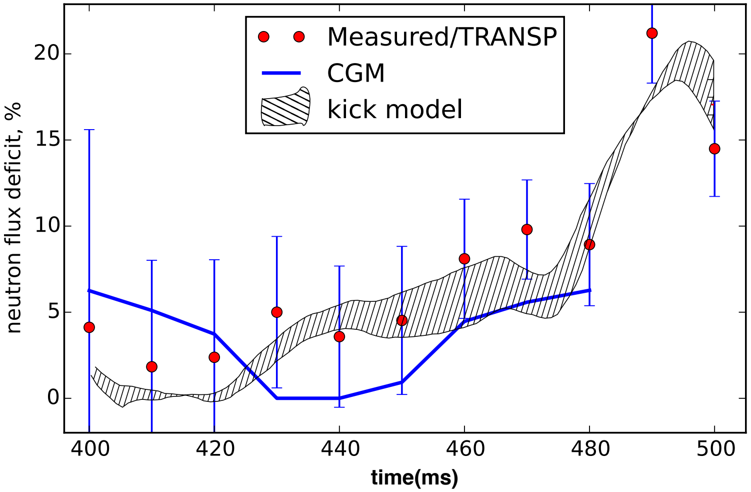
EP research thrusts map directly to NSTX-U research priorities; recent results support future work

3. Form and sustain plasma current without transformer for steady-state ST

- Assess effects of NB injection parameters on fast ion distribution function, NB-current profile
- Develop predictive tools for *AE-induced fast ion transport

- 2nd NB for adjusting NB-driven j(r)
- Expanded FIDA views, ssNPA for measuring energetic particle distribution

Critical Gradient and "Kick" models successful in reproducing effects of TAE on fast ions (Kick model implemented in TRANSP)



Gorelenkov, Podesta

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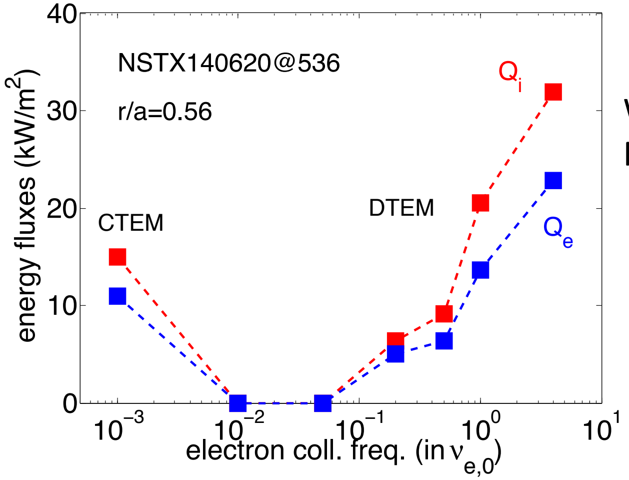
SG framework beneficial in synthesizing needs and optimizing run time among TSGs for development of major XPs

- I_p/B_T scaling (T&T) – Multi-TSG (XP1520-Kaye) [start with B, later w Li] directly addresses two Yearly Milestones **R16-1, 17-3**, 18-1, IR17-1, ITER
  - **R16-1**: Assess H-mode (and beam) confinement, pedestal and SOL characteristics at higher I_p, B_T, P_{NBI}
  - **R17-3**: Assess confinement and T&T at low ν_* with full confinement and diagnostic capabilities (full I_p, B_T, high-k scattering in 2017)
  - In addition, apply perturbations at end of discharge to study
    - Impurity transport neon puffs (T&T)
    - Particle transport with SGI (T&T)
    - NTV studies with 3D fields (Macro)
  - Overlap with Boundary SG: Scaling of pedestal structure and transport, SOL widths, transport and turbulence, L-H, H-L threshold studies

Non-linear GTS indicate low-k DTEM leads to ν^* dependence, in addition to µtearing

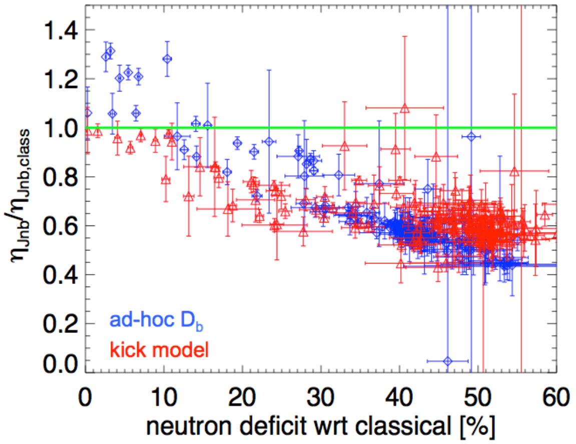


Wang PRL & PoP (2015)

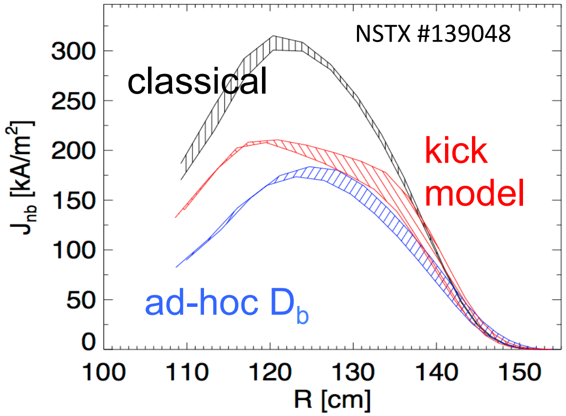
SG framework beneficial in synthesizing needs and optimizing run time among TSGs for development of major XPs

- 2nd NB characterization (EP) – Multi-TSG (XP1523-Podesta) [start with B, later w Li] **R16-2**, 3, 17-1, 4, 18-2, IR18-2, ITER
  - **R16-2**: Assess effects of NBI injection on fast ion f(v) and NBI-CD profile
  - Vary beam source (R_{tan}) injection, power to understand beam ion confinement to modify current, pressure and flow profiles for optimizing plasma confinement, stability and non-inductive current drive
    - Energy transport and confinement power scan (T&T)
    - NTV studies with varying P_{NBI} and profile (Macro)
  - Pedestal structure, L-H threshold dependence on P_{NBI} and heating profile (Boundary SG)
  - SOL widths and associated transport and turbulence (Boundary SG)
  - β_N, l_i, rotation control (Integrated Scenarios SG)

Podesta **JRT15,** NF (2015)



Profiles of NB-driven current



Critical to use proper model for calculating NB-driven j(r) (ad-hoc is radial diffusion only)

T&T research thrusts and plans 2016

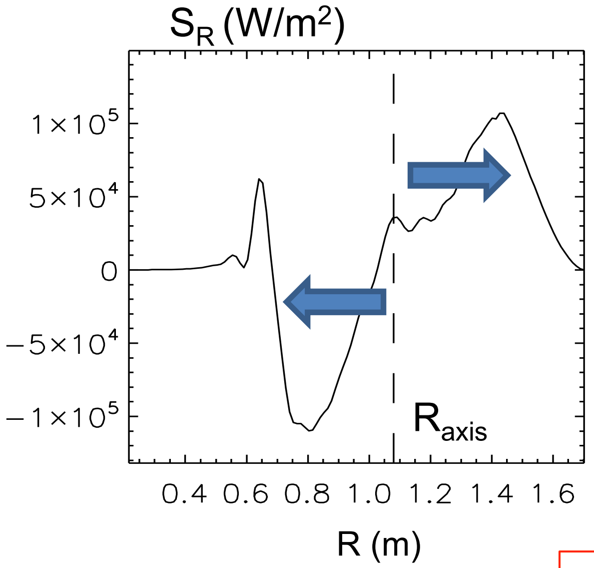
1. Characterize H-mode global energy confinement in lower collisionality regimes in NSTX-U
   - **I_p/B_T scaling – Multi-TSG (XP 1520-Kaye) [B now, later Li]**
2. Identify mechanisms responsible for χ, D: explore parametric dependences with q, v_φ R16-1, 17-3, 18-1, ITER
   - Characterize transport and microturbulence from (1): couple to g-k sims
   - Perturbative particle transport using SGI (XMP-Ren)
   - Perturbative momentum transport (XP1549-Guttenfelder)
   - 3D effects on momentum transport (XP1585-JK Park)
   - Impurity transport
     - Ne puff (XP1551-Munoz-Burgos), vs torque (XP1550-Delgado-Aparicio), intrinsic (Scotti)
   - Turbulence studies
     - Effect of reverse shear (XP1575-Yuh), q-profile (Ren)
     - AE bursting and effects on electron transport (XP1574-Tritz)
     - 2D GAMs and ZFs with extended BES (XP1584-Smith)

Priority 1 XPs

T&T research thrusts and plans 2016

3. Establish and validate reduced transport models for establishing predictive capability R16-1, 16-2, 17-3, ITER
   - Validation of gyrokinetic codes in L-mode (XP1521-Ren)
   - Develop and test reduced microtearing based electron transport model
   - Develop $\chi_{e,EP}$ using ORBIT and measured CAE/GAE structures (w/EP); move toward coupling with non-linear HYM simulations

- Non-linear HYM calculations indicate an up to 0.5 MW power channeling from the center of the plasma to the CAE-KAW conversion radius (about 2/3 of the way out
- Consistent with lack of central electron heating and broadening of the T_e profile with higher CAE activity



Belova PRL (2015)

Priority 1 XPs

Macrostability research thrusts and plans 2016

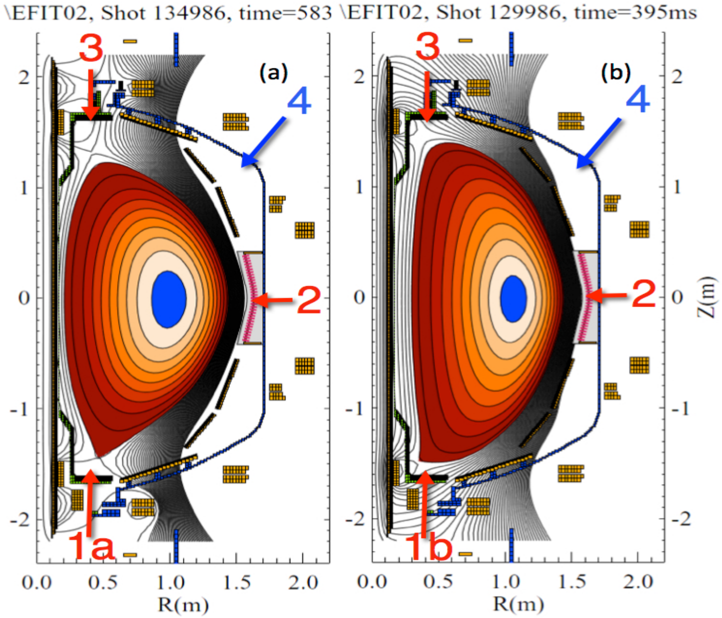
1. Understand and advance passive and active control to sustain macroscopic stability R16-2, 16-3, 18-2, ITER
   - PID and state-space control (XP1518,1545-Sabbagh)
   - RWM stability dependence on NB (XP1546-Berkery)
   - Effect of reduced collisionality on NTV (XP1517-Sabbagh)
   - TM/NTM physics
     - n=1 stability (XP1544-LaHaye), radiation-induced islands (XP1547-Delgado-Aparicio)
2. Understand 3D effects for optimizing stability through profile control
   - EF thresholds and control (XP1506,1515,1516-Myers, XP1543-JK Park, XP1570-Sabbagh)
   - 3D plasma response (XP1548-Evans, XP1571-Z Wang)
   - 3D effects on TM/NTMs (XP1572-Okabayashi, XP1573-YS Park)
   - Low rotation effects on RWM stability (XP1582-YS Park) and NTV (XP1583-Sabbagh)

R16-2, 16-3, 18-2, ITER

Priority 1 XPs

Macrostability research thrusts and plans 2016

3. Understand disruption dynamics and techniques for avoidance and mitigation **JRT16**, ITER
   - Explore poloidal angle dependence and private flux region injection of MGI (XP1519-Raman)
   - Validation of M3D-C^1 for VDE and disruption modeling (Jardin)
   - Halo current asymmetries, rotation (Joint NSTX-U/Theory task)
   - Implement real-time physics models for disruption forecasting and avoidance (S. Sabbagh talk)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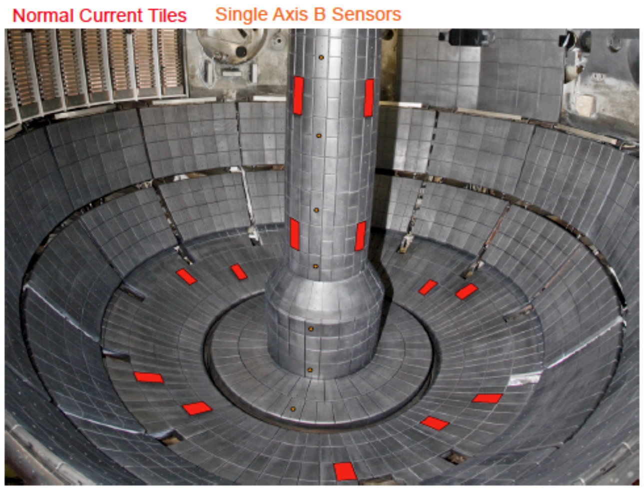
Planned NSTX-U Base Configuration



Priority 1 XPs

EP research thrusts and plans 2016

1. Assess effects of NB injection parameters on fast ion distribution function, NB-driven current profile R16-2,3, 17-4, IR17-1, R18-2, IR18-2, ITER
   - **2nd NB characterization – Multi-TSG (XP1523-Podesta)**
   - Beam ion confinement (XP1522-Liu)
2. Develop predictive tools for *AE-induced fast ion transport
   - AE critical gradient (XP1524-Heidbrink) R16-2, IR17-1, R18-2, IR18-2, ITER
   - Use Upgrade capabilities to vary mode properties (frequency, spectrum, structure, regime) for development and validation studies
     - NOVA-K, ORBIT, SPIRAL, M3D-K, HYM
3. Develop phase space engineering tools/techniques for f_{fi}, mode control R16-3, IR17-1, R18-2, IR18-2, ITER
   - Rotation effects
     - Effect on CAE/GAE modes (XP1525-Crocker), TAE modes and gap structure (XP1552-Fredrickson, XP1528-Podesta)
   - HHFW (XP1553-Fredrickson)
   - 3D fields (XP1577-Liu)

Priority 1 XPs

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Future facility enhancements will benefit Core SG research

1. Cryopump will allow for reduced collisionality and n_e control
   - T&T: Decouple ν_* and ρ_* dependences with n_e control, isolate transport changes due to j-profile evolution at constant n_e
   - Macro: Modify effect of kinetic resonances for RWM control
   - EP: Improved flexibility to manipulate fast ion distribution through density control
2. NCC: Flow profile modification, modification of f_{fi}
   - T&T: Effect of flow shear on turbulence suppression
   - Macro: EF/Locked mode thresholds and control, plasma response model validation, effect of flow shear on mode stability, NTV physics, use for active mode control
   - EP: Impact on mode drive ($f_{fi,}$ flow shear) and mode damping (3D field modification of continuum/gap structure)
3. ECH/EBW
   - T&T: Effect of RF vs NBI on plasma and impurity transport
4. High-Z tiles and flowing metal divertors
   - T&T: Effect of different PFC (C vs High-Z) on plasma and impurity transport, core-edge coupling

Core SG activities support the priorities identified by the Whole Device Modeling panel

- PRD-1: Increase development and support for modular WDM frameworks
  - Modularization of TRANSP, including development and implementation of EP transport, NTM island and impurity transport modules
  - Fast WDM capability: **BE**tween and **A**mong **S**hots **T**ransp (BEAST): NSTX-U ops

- PRD-2: Understand and distill physics of gap areas
  - Improved kinetic-fluid formulations for both drift-wave turbulence and extended MHD
    - T&T: XGC-1, GTS, GYRO with multi-scale physics **(exascale computing applications)**
    - Macro: M3D-C^1, MISK, NTVTOK, GPEC, MARS **(M3D-C^1 exascale application)**
  - Fast particle interactions with thermal (Alfvén) waves and instabilities
    - CGM/Kick, HYM, self-consistent treatment of fast ions and RF (TORIC/CQL3D+NUBEAM)
  - Couple core & edge: EPED1 lookup table coupling to TRANSP

Core SG activities support the priorities identified by the Whole Device Modeling panel

- PRD-3: Code/model validation at all fidelity levels through coupling with experiment
  - T&T
    - Reduced model testing: RLW, TGLF, MMM ↔ T(r,t)
    - GYRO, XGC, GTS ↔ T(r,t), $n_{e,i}(r,t)$, BES, high-k scattering, polarimetry
  - Macro: M3D-C^1, MISK, NTVTOK, GPEC, MARS ↔ 3D MP, v_φ, magnetics. etc.
  - EP: Kick/CGM, HYM, 3D halos (NUBEAM) ↔ FIDA, ssNPA, sFLIP, magnetics, reflectometers

Research and development on Disruption studies and modeling addresses key FES panel recommendations

- Prediction
  - RWM global stability model
    - Develop predictive understanding of kinetic effects
    - State-space controller implementation
    - MHD spectroscopy
- Avoidance
  - Develop passively stable plasmas
    - Close-fitting conducting plates
  - Extend operation range through active control
    - State-space controller
    - EF/NTM/RWM control using NBI, 3D fields for control of p, j, v_φ
- Mitigation
  - Measure effect of MGI poloidal position: testing MGI capabilities
  - Current quench forces and halo current asymmetries: toroidally/poloidally resolved current monitors (Joint NSTX-U/Theory task)
- Modeling
  - M3D-C^1 for integrated simulations throughout duration of disruption
  - Automated plasma state reconstruction and stability assessment for PAM
    - Gerhardt disruption warning algorithm
    - DECAF (See talk by Sabbagh on DECAF)

Core Science research is well-positioned to take advantage of the major device upgrades

- 2016 research activities address key programmatic goals and TSG research thrusts
- Code development and validation against experimental data with expanded diagnostic set align with FESAC/FES recommendations from the WDM and Transients panels. Core SG research also addresses needs for ITER research preparation
- Much of the accompanying model development and physics understanding of Core SG research is being carried out within the NSTX-U/Theory partnership (see talk by A. Bhattacharjee)
- The planned facility enhancements, especially the cryopump and NCC, will enable more flexibility in addressing the SG and TSG research objectives

Backup

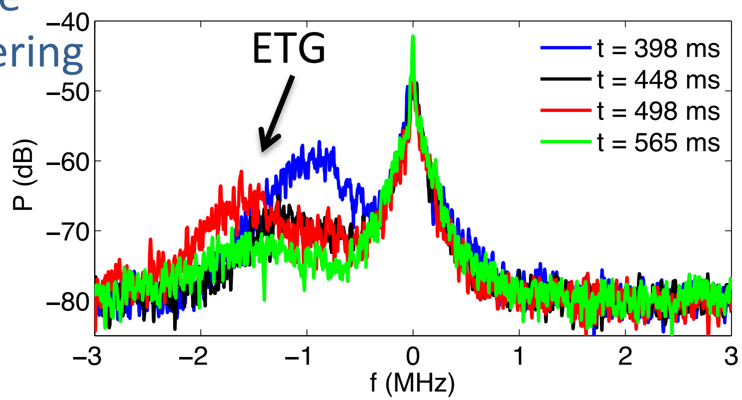
T&T highlights since PAC-35 (2014)

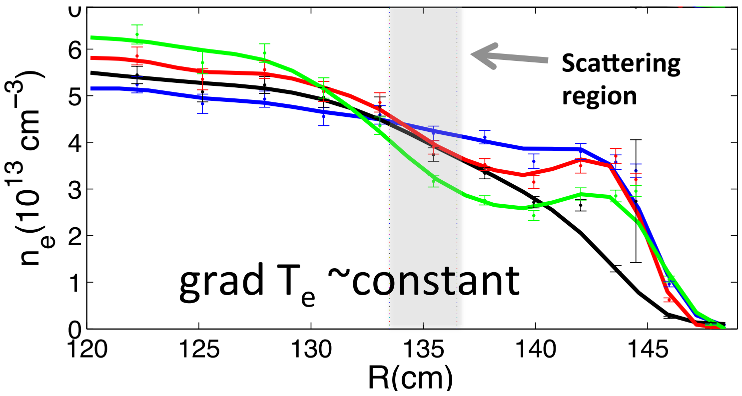
- Progress on validating core drift wave transport mechanisms
  - Identification of possible low-k-turbulence-induced transport mechanisms using global gyrokinetic codes
  - Density gradient stabilization of ETG modes and understanding through gyrokinetic simulations
  - “Stiff” electron transport cannot be explained by gradient-driven effects
  - *Investigation of roto-diffusion and centrifugal effects on impurity and momentum transport (Bucholtz et al., PoP (2015), Guttenfelder)*
- Progress on understanding the role of GAE/CAE on core electron transport
  - GAE-KAW coupling and power channeling
  - *Techniques under development to simulate electron thermal transport caused by measured CAEs/GAEs with ORBIT (Crocker)*

Linear and non-linear gyrokinetic simulations have shown the role of grad n_e in stabilizing ETG modes

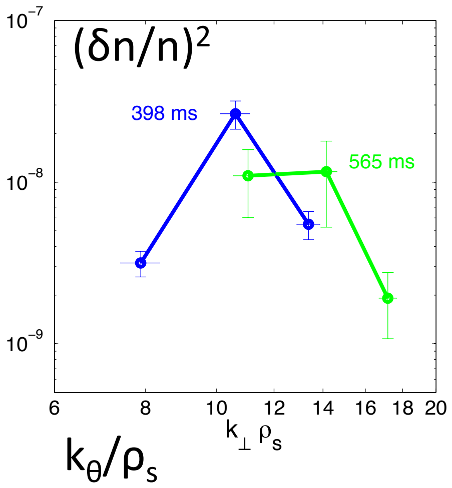
Decrease in ETG turbulence amplitude with increasing grad n_e

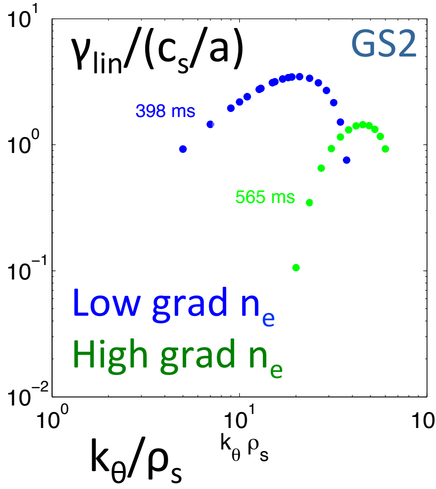
µwave scattering

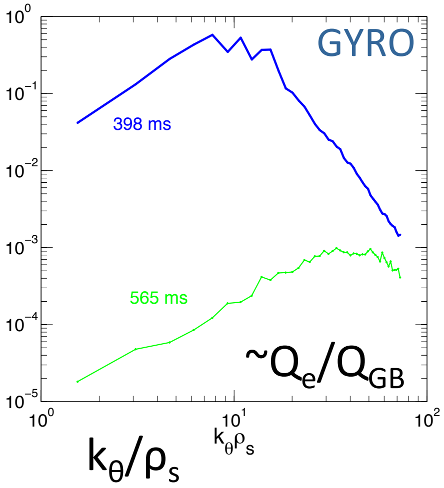




Measured δn/n, linear growth rates, non-linear Q_e behave similarly with grad n_e



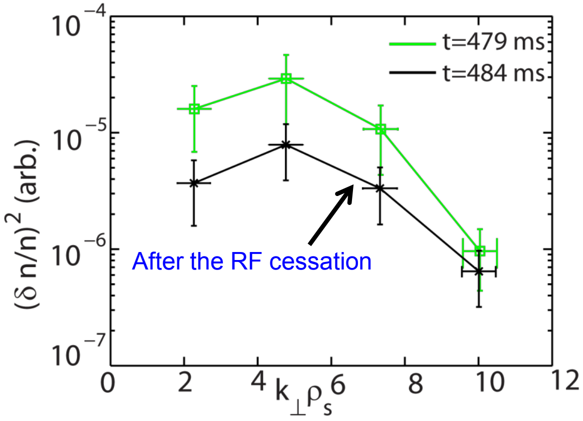


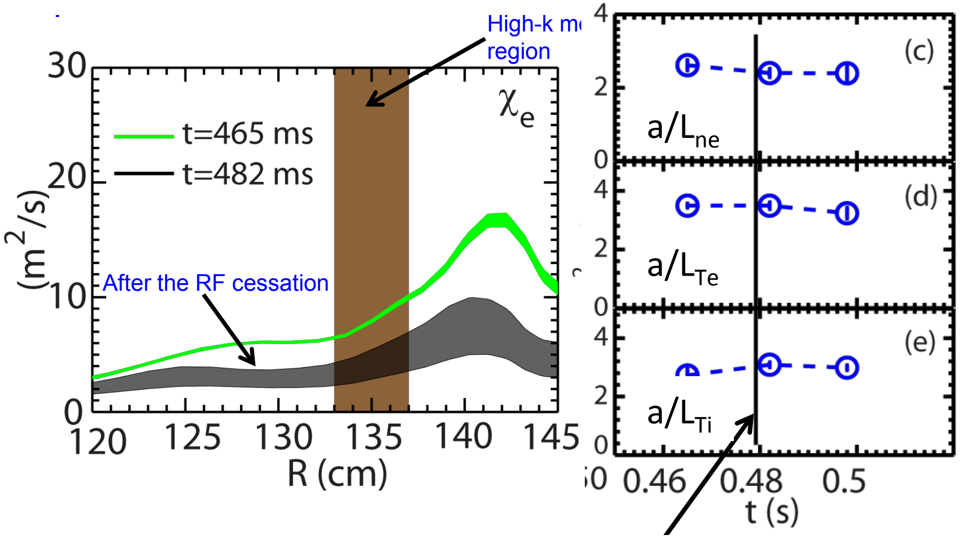


Ruiz-Ruiz et al. (MIT grad student), PoP (2015)

Non-linear gyrokinetic simulations used to study large changes in e⁻ transport in RF discharges

Factor of 4 decrease in high-k turbulence with no change in local gradients when RF shuts off

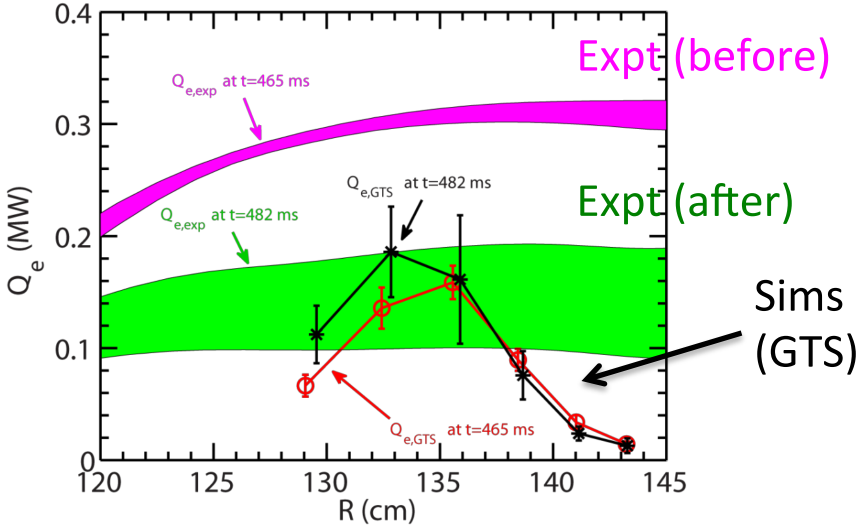




Factor of 2 decrease in electron transport with no change in local gradients

Gradient driven global g-k simulations do not predict high enough stiffness to explain transport

$Q_{e,sim}$ matches expt after RF-turnoff, but not before



Non-local flux-driven transport may be important

Ren et al., PoP (2015)

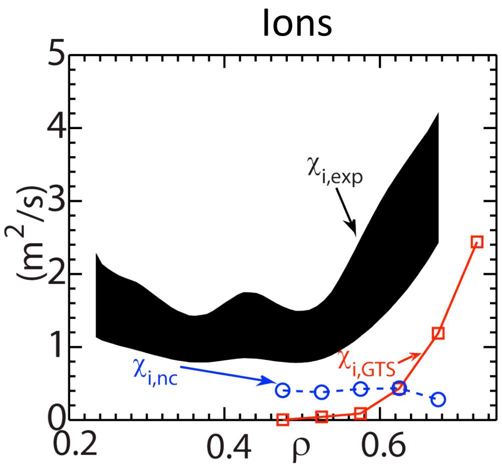
Global non-linear GTS gyrokinetic simulations have identified multiple low-k turbulence transport mechanisms

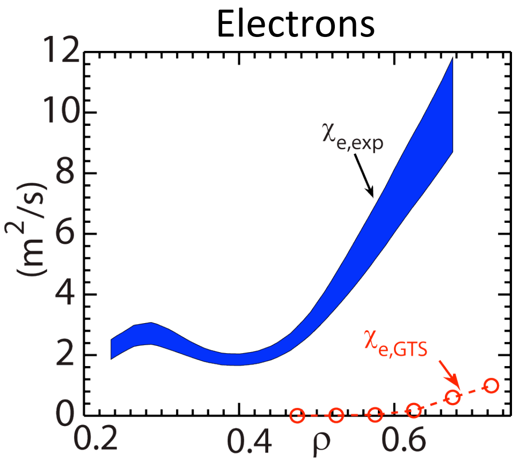
Strong flow shear can destabilize Kelvin-Helmholtz instability

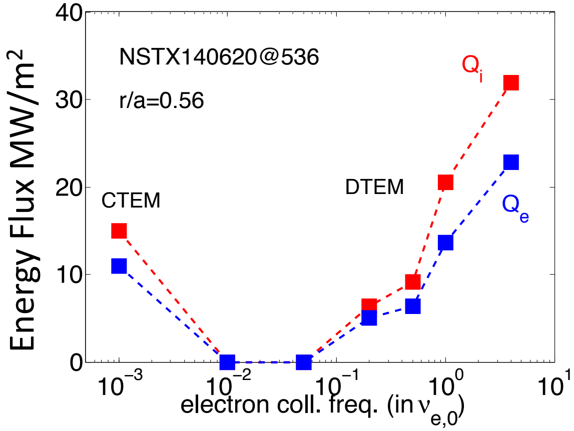
- Non-linear global GTS simulations
- K-H+ITG+Neo ion transport within factor of 2 of expt'l level
- Cannot account for electron transport

Recent GTS simulations have shown possible role of DTEM in contributing to observed favorable collisionality scaling ($B\tau_{th} \sim \nu_{*e}^{-0.8}$)

- In addition to microtearing
- Synergy with DIII-D work





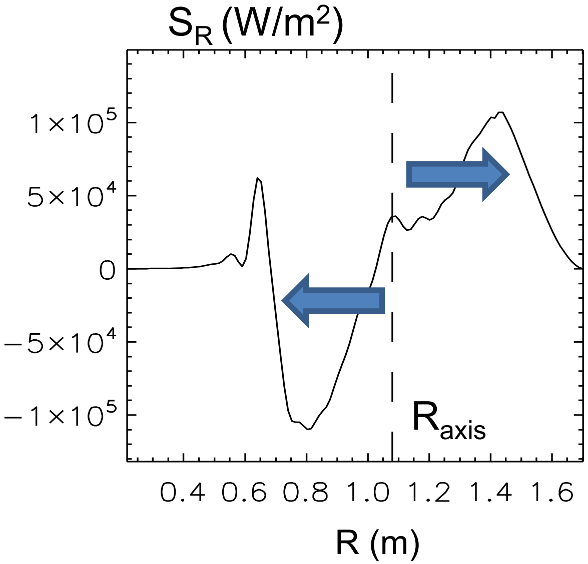


W. Wang et al., NF Letters, PoP (2015)

Non-linear HYM simulations of CAE/KAW coupling address power channeling and effect on T_e profile

- Full non-linear simulations including multiple (n≥4) unstable modes have been performed
- n=4 (largest mode) saturation amplitude (δB/B~6.6e-3) comparable to that inferred from reflectometer displacement measurements (δB/B≤3.4e-3)

Radial component of Poynting vector



- HYM calculates channeling of 0.3 to 0.5 MW for n=4
- Can result in several hundred eV modification of T_e profile (T_e broadening observed during periods of high CAE activity, with no δT_{e0})

Belova et al., PRL (2015)

Macrostability highlights since PAC-35 (2014)

- Progress in passive and active control to sustain macroscopic stability
  - Joint NSTX/DIII-D experiments to unify kinetic RWM theory
  - *DCON ideal limits and implications for NSTX-U (Berkery)*
- Understanding 3D field effects and optimizing stability through profile control
  - State-space algorithm for rotation control
  - GPEC development for more self-consistent NTV optimization
  - *Use of stellarator optimization tools+VALEN for RWM control with NCC (Lazerson, Bialek)*
- Understanding disruption dynamics, prediction, avoidance and mitigation
  - 3D non-linear simulations of VDEs in NSTX with M3D-C^1
  - MGI valves for injection in different poloidal locations tested
  - *DECAF being developed for PAM (see S. Sabbagh talk)*
  - *Multi-machine analysis of non-axisymmetric and rotating halo currents [ITPA] (Myers)*

Joint NSTX/DIII-D experiments have led to a unified picture of kinetic RWM physics

- Kinetic RWM stabilization occurs from resonances between ω_{plasma} and $\omega_{precession}$, $\omega_{bounce/circ}$, ν_*
- Plasmas free of other MHD modes can reach/exceed linear kinetic RWM stability

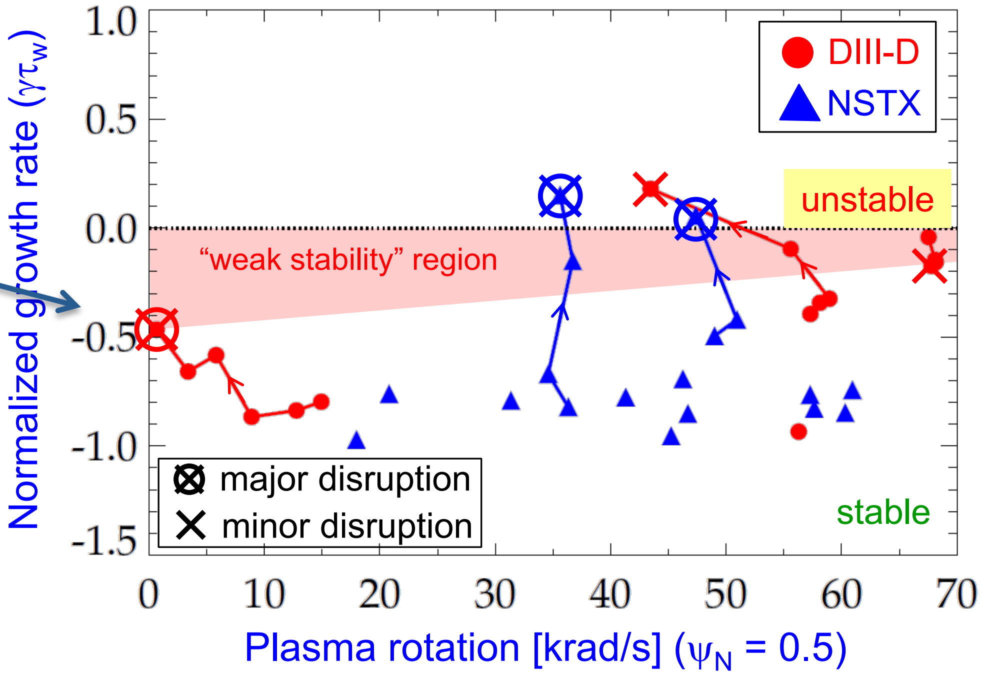
Bursting MHD modes can lead to non-linear stabilization before linear stability limits are reached

S. Sabbagh, APS Invited 2014

When RWM stable, rotation and kinetic effects important for stabilizing plasmas near the Ideal Wall Limit

J. Menard et al., PRL (2014)

Kinetic RWM stability analysis for experiments (MISK)



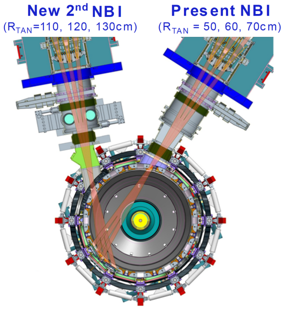
A state-space algorithm for rotation control with NBI and NTV actuators was developed

$$nm\frac{d\Omega}{dt} \propto nm\chi_{\phi}\nabla\Omega + T_{NBI} + T_{NTV}$$

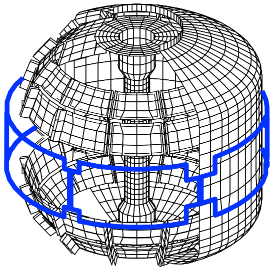
$$T_{NTV} \propto I_{coil}^{2}\Omega$$

Momentum Actuators

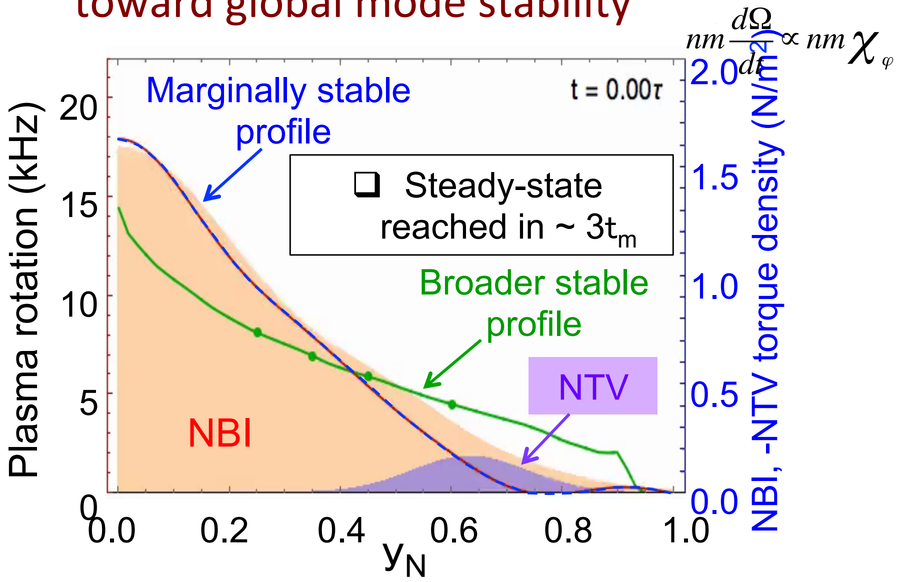
New NBI (broaden rotation)

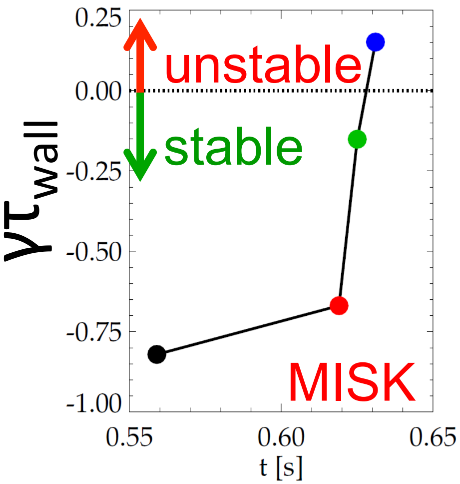


3D Field Coil (shape w_f profile)



Algorithm evolves rotation profile toward global mode stability

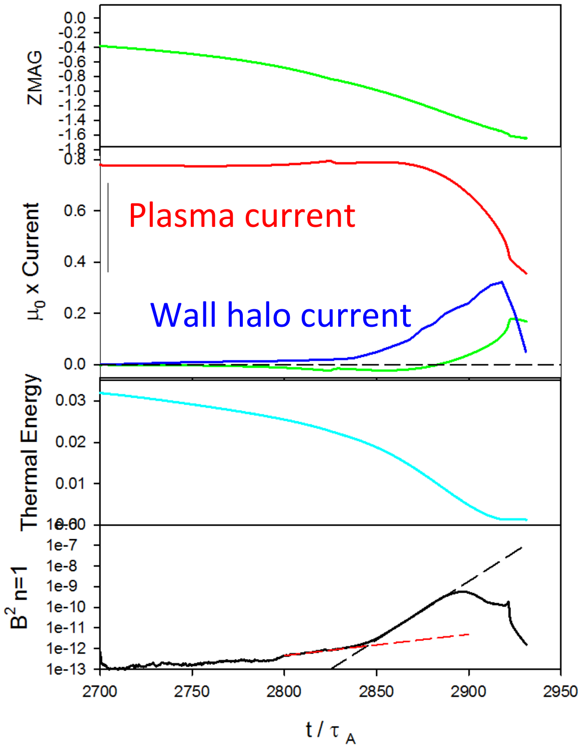


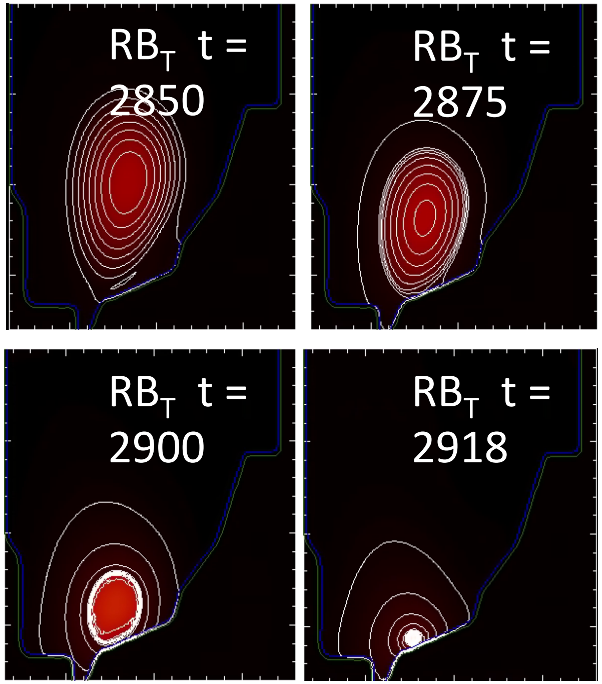


I. Goumiri (grad student, PU), S. Sabbagh, D. Gates, et al.

M3D-C^1 modeling of Vertical Displacement Events has been extended to 3D

- Implemented arbitrary thickness resistive wall
  - 3 region computational space (vacuum, RW, plasma)
- 3D modeling of NSTX VDE with realistic wall resistivity
  - Growth of n=1 mode
  - Halo currents begin to form when plasma makes contact with vessel





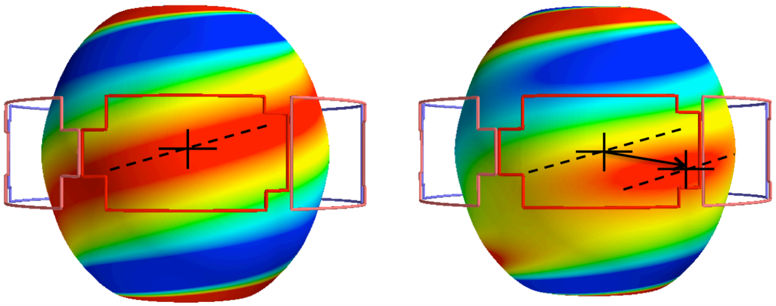
NSTX Discharge 132859

- Disruption phase: 2700 < t < 2950
- **Contours of RB_T show halo currents**

Plasma response to 3D fields has significant impact on calculated NTV profiles

- The General Perturbed Equilibrium Code incorporates plasma response in calculation of NTV (kinetic effects included)
  - 3D equilibrium modified by plasma currents induced by 3D fields

Torque creates toroidal phase shift in plasma response

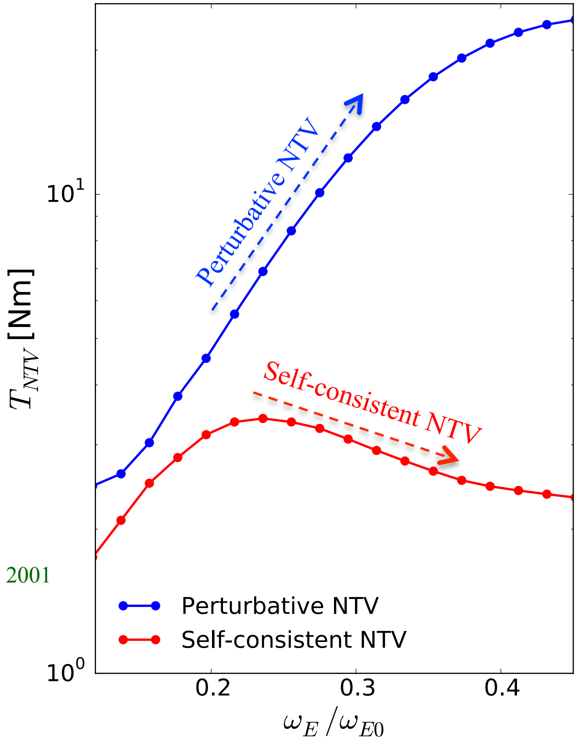

Ideal Response

Kinetic Response

(NSTX-U I_P=2MA, β_N =3.0, n=1)

With increasing phase shift, coupling between external field and plasma becomes inefficient, resulting in self-shielding process

NTV vs. $E\times B$

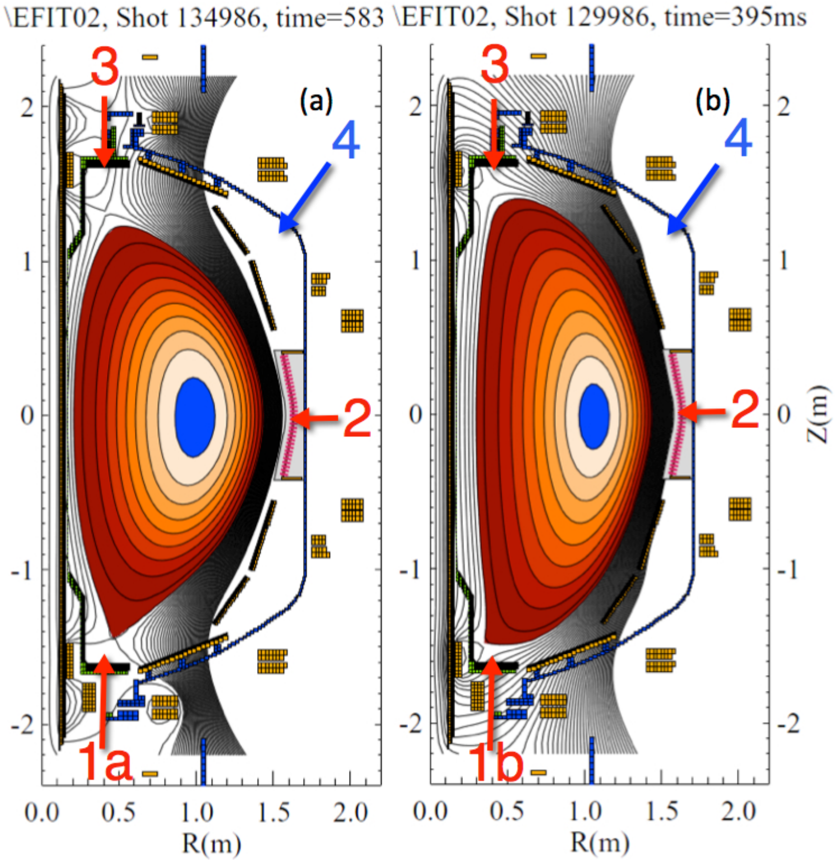


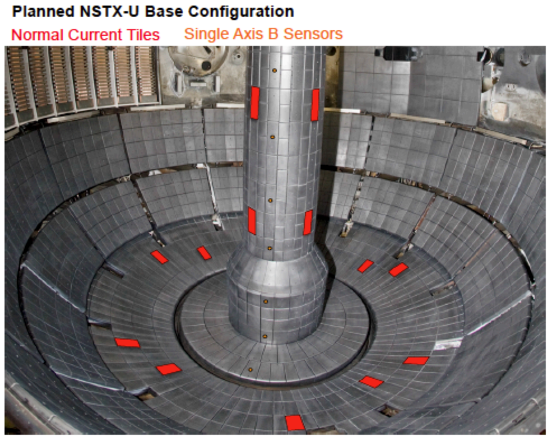
J.K. Park, APS Invited (2015)

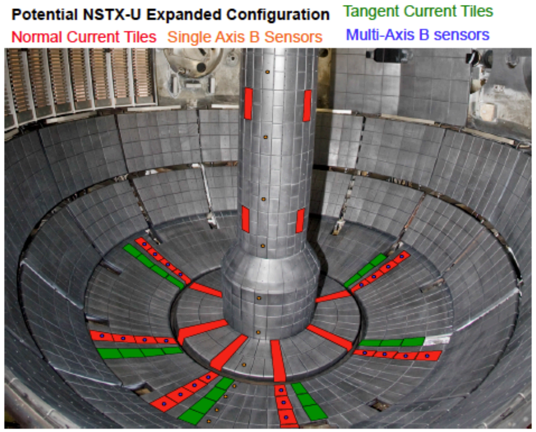
Disruption studies

- MGI will assess injection at various poloidal locations, quantify and model gas assimilation

- Joint NSTX-U/Theory study on halo current asymmetries, rotation and forces


\EFIT02, Shot 134986, time=583 \EFIT02, Shot 129986, time=395ms


Planned NSTX-U Base Configuration


Potential NSTX-U Expanded Configuration

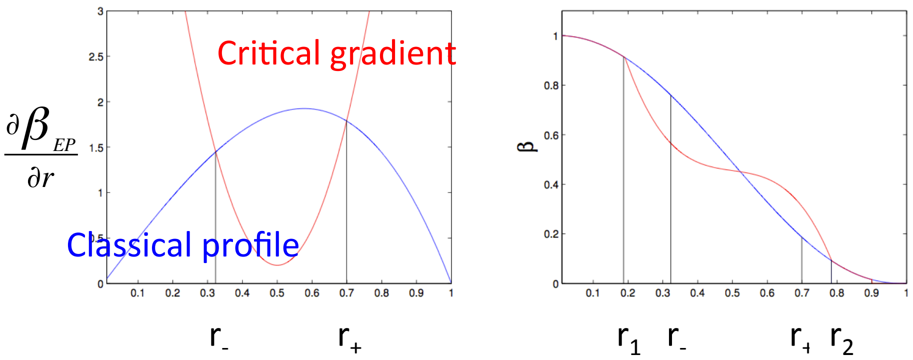
EP highlights since PAC-35 (2014)

- Further developed and validated reduced EP transport models
  - CGM/Kick models validated for NSTX & DIII-D
  - Kick model implemented in TRANSP
- Study of low-frequency EP-driven MHD
  - Found to depend on q-profile, rotation
  - Experimental results compared to M3D-K, MARS-K predictions
- Assessed roles of high-frequency AEs in thermal electron transport
  - CAE/KAW coupling (w/T&T)
  - *Compared HYM code predictions with NSTX data (Crocker/Belova)*
- Studied mitigation/suppression of AEs, fishbones with HHFW and 3D fields

Models for fast ion profile relaxation in presence of AEs are being validated

- Critical Gradient Model (Gorelenkov)
  - Compute critical $\frac{\partial \beta_{EP}}{\partial r}$ due to AE
  - Mode growth/damping computed by NOVA-K

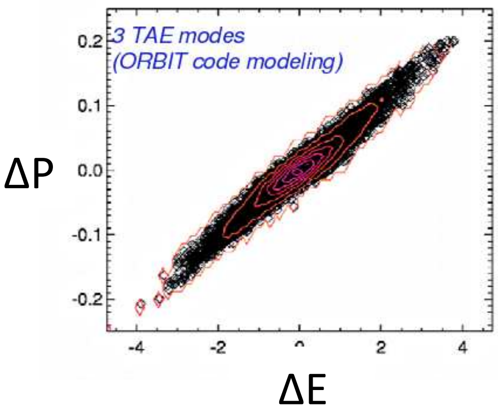
Gorelenkov



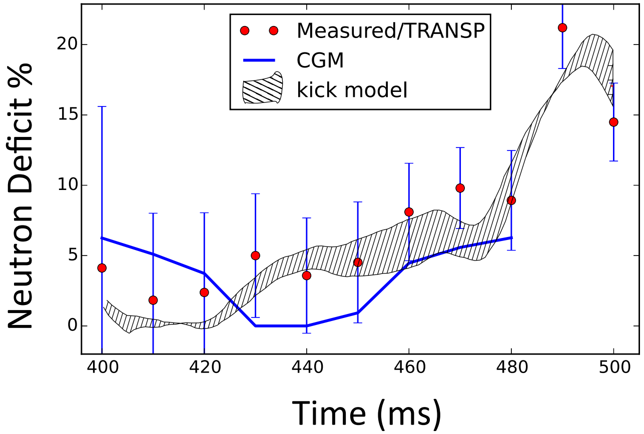
CG used to relax EP profile. It is broadened from the initially unstable one between $r_\pm \rightarrow r_{1,2}$

Both CGM and Kick models reproduce neutron deficit in an NSTX discharge with multiple unstable TAEs

- "Kick" model (Podesta et al., NF 2015)
  - PDF computed by ORBIT & NOVA
  - Kicks ~ mode amplitude

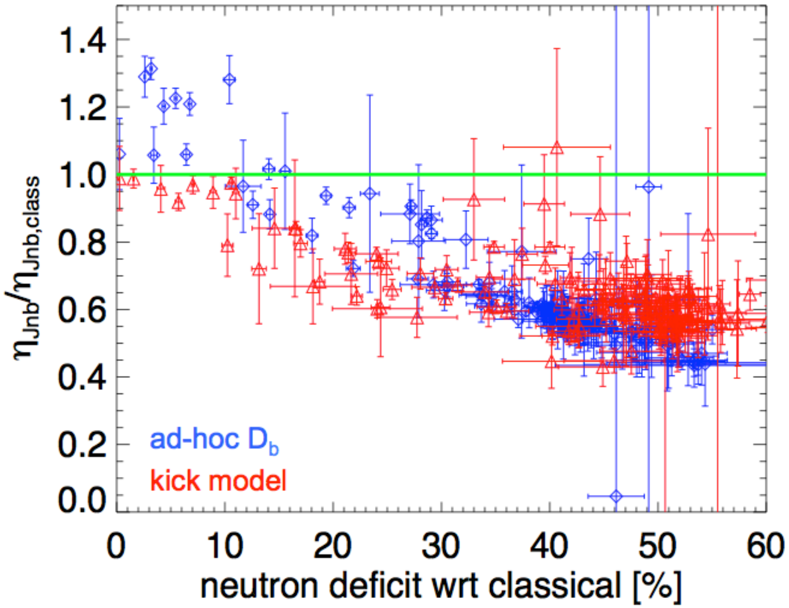


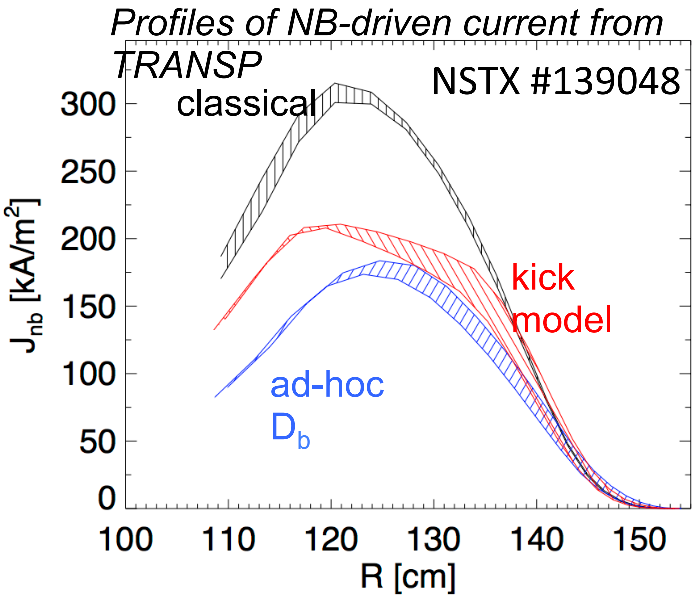
Podesta



Correct treatment of fast ion phase space evolution is relevant for consistent integrated simulations

- Two models tested for fast ion transport in integrated simulations in TRANSP
  - Ad-hoc diffusion model (radial diffusion only) & kick model
  - Ad-hoc model OK for global quantities (e.g. neutrons, stored energy)
- Substantial differences observed for profiles, time evolution of
  - Fast ion density, NB-driven current, power to thermal plasma
  - Fast ion distribution function

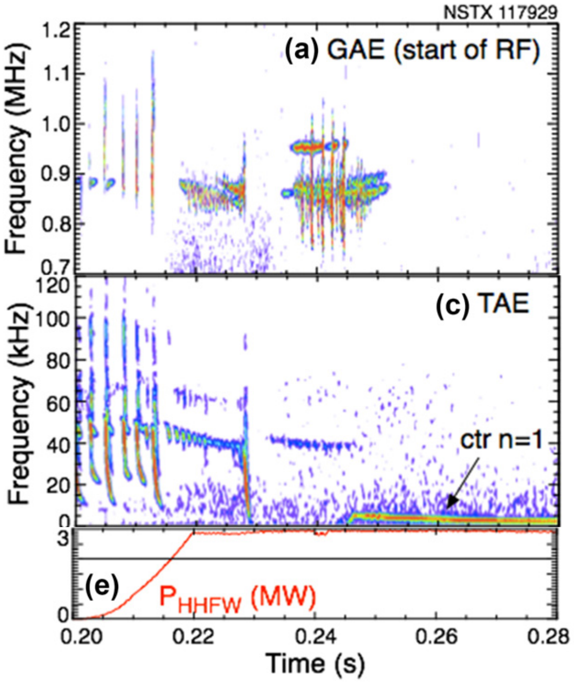



Profiles of NB-driven current from TRANSP

Podesta, **JRT 2015**, Nuc. Fusion (2015)

Techniques have been employed to mitigate Alfvén Eigenmodes

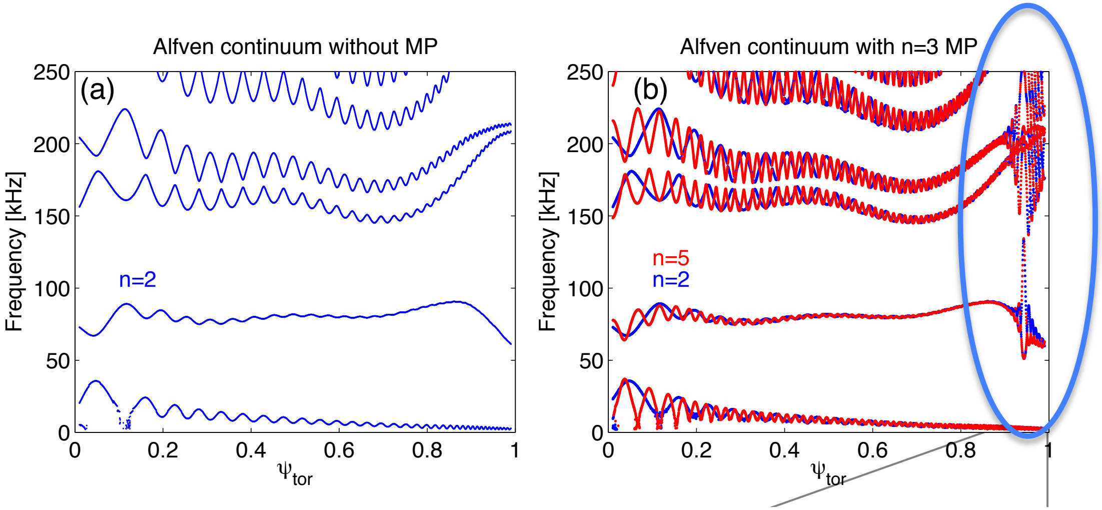
- TAE and GAE modes suppressed by application of HHFW



- Self-consistent description of HHFW/EP under development using TORIC/CQL3D- NUBEAM

E. Fredrickson et al, NF (2015)

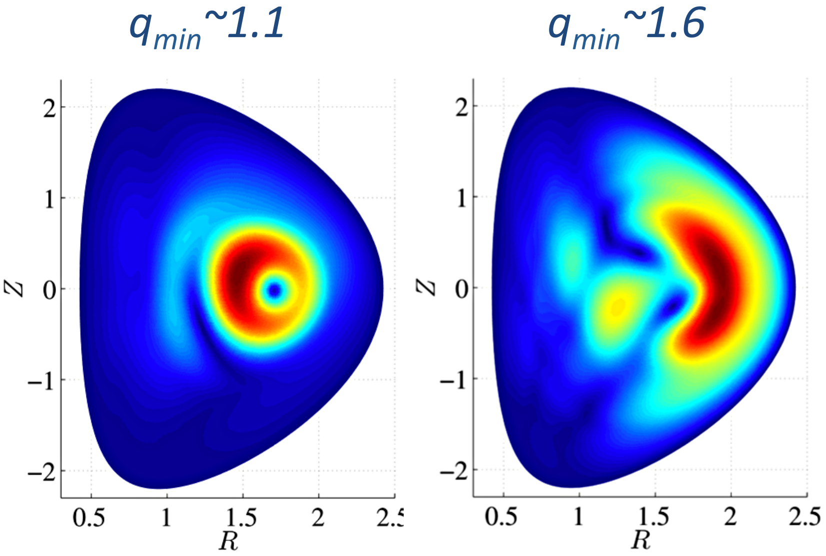
- TAE & GAE have been mitigated by application of 3D fields (Bortolon et al, PRL (2013)
  - Fast ion drive for GAE reduced due to fast ion losses (Bortolon)
  - Continuum damping of TAE increased due to reduced gap



G. Kramer et al, under prep. (2016)

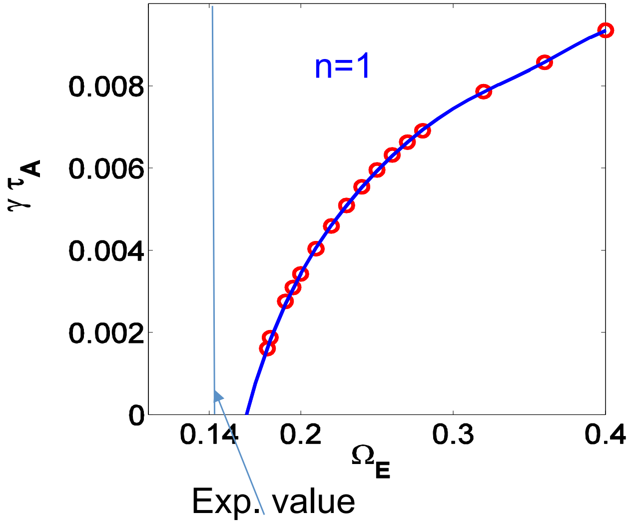
Extensive simulations investigate role of EP in determining stability and character of low-f MHD modes

- Linear & non-linear study of fishbones using M3D-K (Fu, Wang):
  - Rotation is destabilizing, favors fishbone over kink
  - Mode structure evolves with q_{min}, non-linear effects cause broadening
  - *Both passing & trapped EPs contribute to drive*
    - *Trapped particles' contribution dominant as mode evolves non-linearly*



q_{min}~1.1 q_{min}~1.6

- Complements studies of Non-Resonant Kink (NRK) with M3D-K, MARS-F (Hao)
  - MARS-F: NRK destabilized at high rotation, mode structure broadened by finite resistivity



- Fishbones and NRKs cause significant flattening of EP profile