PAC-33 Questions – Day 1

1. What are the key physics issues and technical capabilities required to resolve the ST's suitability for an FNSF, and are any of these *not* likely to be resolved by NSTX-U? Factor in contributions from MAST and other experiments. Is the foreseen NSTX-U budget sufficient?
    - J. Menard

2. Give 2 or 3 of your best examples of how the NSTX program is advancing model validation and predictive capability, including a description of the connections between experimentalists, theorists, modelers, both here at PPPL and the community at large.
    - S. Kaye using TSG input

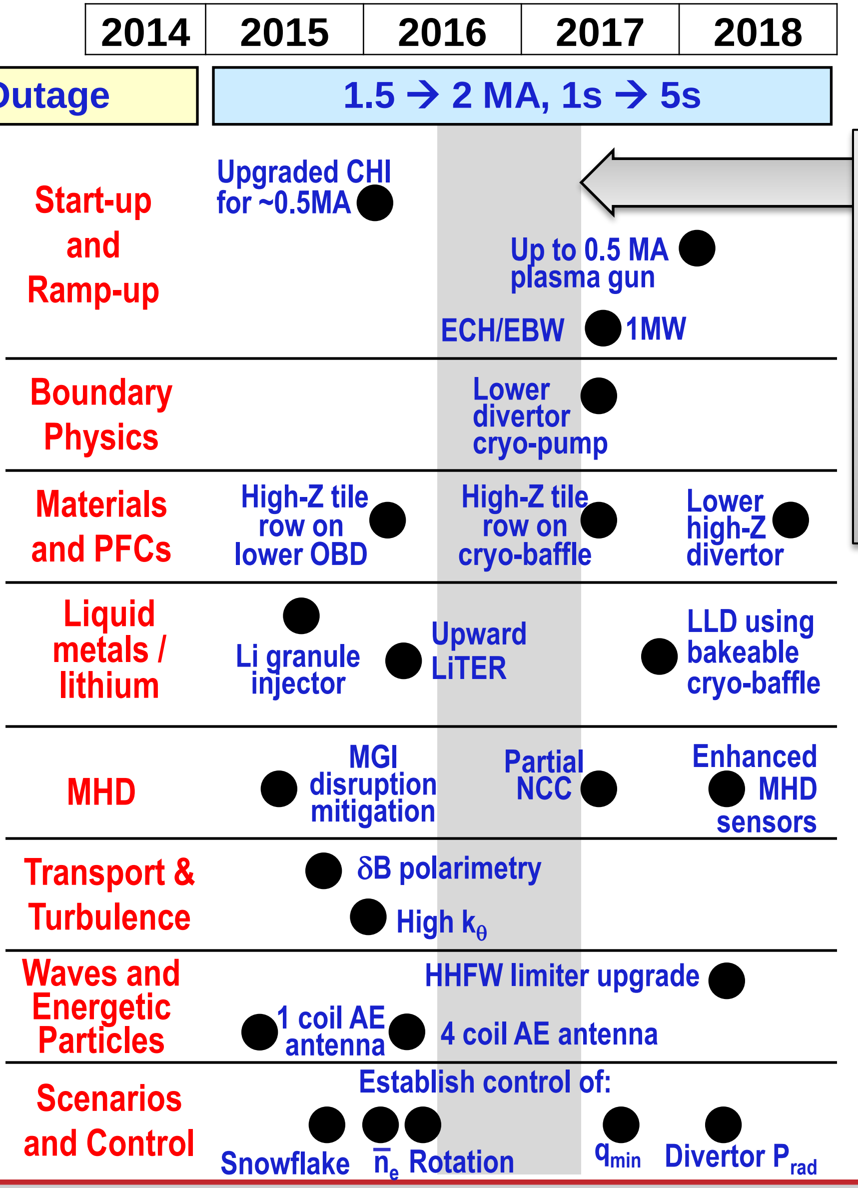
PAC-33 Questions – Day 1 – Q1

1. What are the key physics issues and technical capabilities required to resolve the ST's suitability for an FNSF, and are any of these *not* likely to be resolved by NSTX-U? Factor in contributions from MAST and other experiments. Is the foreseen NSTX-U budget sufficient?

- Quick answers:
  - NSTX-U + MAST-U plan to have the capabilities to resolve all ST-specific questions of ST suitability for FNSF
  - NSTX-U 5YP base funding should be sufficient to implement major tools: cryo, ECH, and likely the partial NCC during 5YP
  - Lower funding levels would substantially delay and/or eliminate the above major upgrades from the 2014-18 plan – would have to be implemented in follow-on 5 year plan.

5 year plan tools with 5YP base funding

(FY2012 + 2.5% inflation)

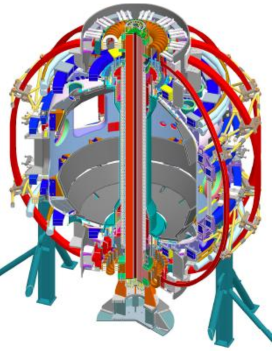


2014	2015	2016	2017	2018

Upgrade Outage

1.5 → 2 MA, 1s → 5s

New center-stack



Start-up and Ramp-up
- Upgraded CHI for ~0.5MA ●
- Up to 0.5 MA plasma gun ●
- ECH/EBW ● 1MW

Boundary Physics
- Lower divertor cryo-pump ●

Materials and PFCs
- High-Z tile row on lower OBD ●
- High-Z tile row on cryo-baffle ●
- Lower high-Z divertor ●

Liquid metals / lithium
- ● Li granule injector
- ● Upward LiTER
- ● LLD using bakeable cryo-baffle

MHD
- ● MGI disruption mitigation
- Partial NCC ●
- Enhanced ● MHD sensors

Transport & Turbulence
- ● δB polarimetry
- ● High k_θ

Waves and Energetic Particles
- HHFW limiter upgrade ●
- ● 1 coil AE antenna
- ● 4 coil AE antenna

Scenarios and Control

Establish control of:
- ● Snowflake
- ● $\bar{n}_e$
- ● Rotation
- ● q_{min}
- ● Divertor P_{rad}

2nd NBI

- Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017
  - NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

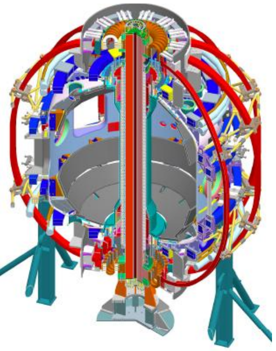
5 year plan tools with FWP base funding

(Presidential FY2013 + 2.5% inflation)

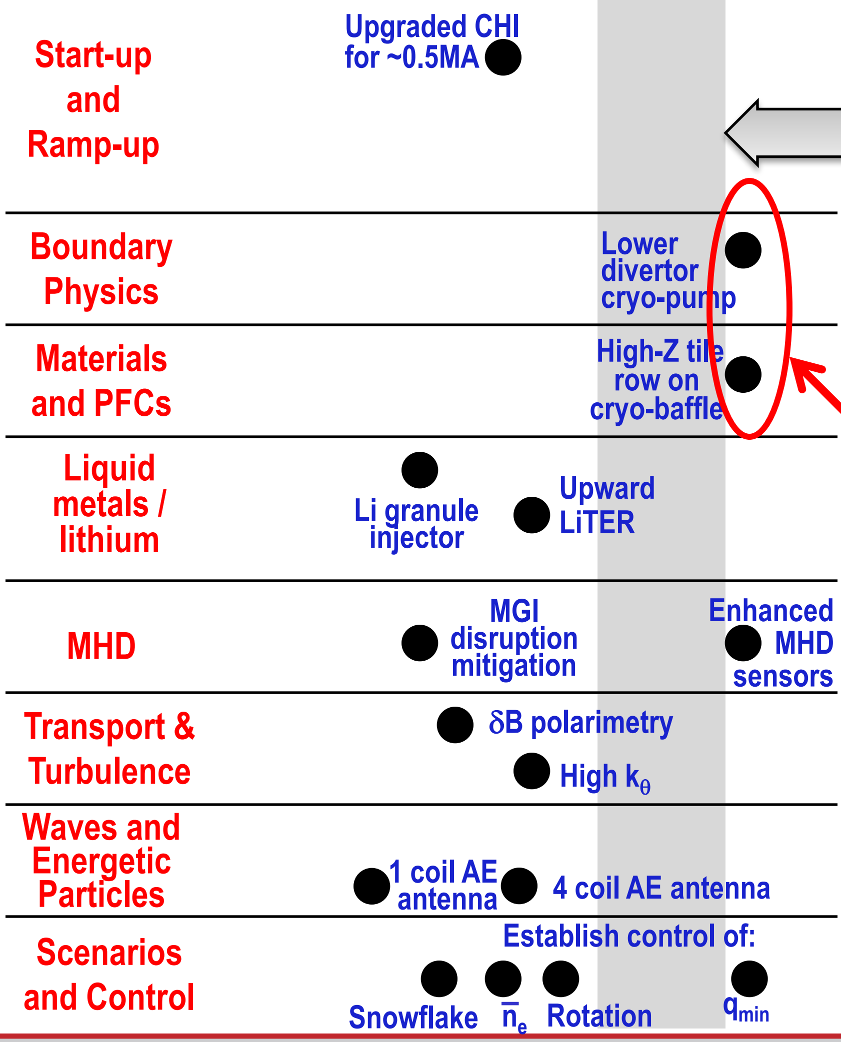
2014	2015	2016	2017	2018

Upgrade Outage | **1.5 → 2 MA, 1s → 5s**

New center-stack



2nd NBI



- **Reduction in research & ops staffing**
- **6-8 month delay**
- **≤ 1 major upgrade by end of FY18**

- Cryo-pump + high-Z tile row on cryo-baffle installed in-vessel during ~0.8 year outage between FY2018 and FY2018
  - NSTX-U would operate 1st half of FY17 and 2nd half of FY18

- *Cryo is default highest priority*
- *Could choose ECH instead to support ST start-up research – would not require extended outage*
- *Partial NCC is another option*
- *Depending on outcome of engineering cost estimates and budget profiles, could turn out that no major upgrades (cryo, ECH, or partial NCC) can be implemented before 2018*

Q1: Key physics + operational questions to be resolved to assess ST suitability for FNSF

See FESAC-TAP (2008) and ReNeW (2009) for more details
Quantitative values are NSTX-U vision/interpretation of requirements

1. Can full non-inductive CD be achieved at FNSF-relevant β_T (~10-20%?)
   - Are full non-inductive profiles compatible with high-β? Can fast-ion instabilities be suppressed/controlled, and understood to maintain acceptable/beneficial FI transport?
2. Can the plasma current (~0.3-0.4MA) be created with small or no solenoid flux and ramped up to full non-inductive operation (~0.8-1MA)?
   - Can models of current formation and ramp-up be validated for use to extrapolating to FNSF?
3. Can H-mode confinement be sustained with $H_{98} \geq 1.2$-1.3 at ST-FNSF-level β_T and approaching FNSF-level ν^* values?
   - Does the favorable ν^* dependence of confinement extend to lower ν^*
   - Which micro-instabilities are dominant for electron thermal transport at high-β + low ν^*?
   - What are implications for ST-FNSF?
4. Can FNSF-relevant β_T and NI operation sustained with low disruptivity?
5. Can divertor heat-fluxes be reduced below engineering limits, and do such heat-flux mitigation solutions extrapolate to FNSF?

Key physics + operational questions to be resolved to assess ST suitability for FNSF (1)

1. Can full non-inductive CD be achieved at FNSF-relevant β_T (~10-20%?)
   - Are full non-inductive profiles compatible with high-β? Can fast-ion instabilities be suppressed/controlled, and understood to maintain acceptable/beneficial FI transport?

Answer: NSTX-U + MAST-U will have capability to resolve this question

- Even w/ no additional upgrades to NSTX-U, facility should be able access full non-inductive transiently, i.e. several τ_E to ~1 τ_{CR} with reasonable confidence (see Gerhardt talk)
- Extending this to full 5s pulse length will require improved density and impurity control
  - Will have Lithium coatings for D control + Lithium granule injector for ELM triggering and impurity flushing
  - This evaporator + injector scheme not yet proven on NSTX/NSTX-U, but EAST results are favorable so far
  - Cryo-pump + ELMing successful on other devices – should work well for NSTX-U / MAST-U
    - There is the possibility that cryo-pumping would also eliminate ELMs similar to lithium experience…
  - MAST-U has cryo-pumps as part of Super-X divertor, may be implemented earlier than on NSTX-U
- Existing/planned fast-ion diagnostics are sufficient so support full NICD studies
- **5YP base funding is sufficient, lower funding could delay/eliminate cryo from 5YP**

Key physics + operational questions to be resolved to assess ST suitability for FNSF (2)

- Can the plasma current (~0.3-0.4MA) be created with small or no solenoid flux and ramped up to full non-inductive operation (~0.8-1MA)?
  - Can models of current formation and ramp-up be validated for use to extrapolating to FNSF

Answer: NSTX-U + MAST-U will have capability to resolve this question

- With no additional upgrades to NSTX-U, facility should be able to double CHI current from 200-400kA, and separately test HHFW+NBI ramp-up from 300-400kA (OH target) up to ~1MA
  - TSC, NIMROD, GENRAY making recent progress in modeling/interpreting helicity injection, ECH/EBW
- Coupling CHI start-up to HHFW/NBI ramp-up will likely require ECH heating of CHI target
  - High-power gyrotron would also enable tests of EBW-only plasma start-up
  - ECH/EBW tests on MAST-U combined with CHI start-up and NBI ramp-tests in NSTX-U + integrated modeling might provide acceptable basis for projecting to next-steps
  - Unclear when MAST-U will have resources to implement high-power ECH/EBW – must complete MAST-U first
- ECH would significantly lower risk to ST-FNSF to demonstrate full start-up/ramp-up solution
  - Cost/scale of FNSF arguably demands this
- **5YP base funding is sufficient, lower funding could delay/eliminate gyrotron from 5YP**

Key physics + operational questions to be resolved to assess ST suitability for FNSF (3)

- Can H-mode confinement be sustained with $H_{98} \geq 1.2$-1.3 at ST-FNSF-level β_T and approaching FNSF-level ν^* values?
  - Does the favorable ν^* dependence of confinement extend to lower ν^*
  - Which micro-instabilities are dominant for electron thermal transport at high-β + low ν^*?
  - What are implications for ST-FNSF required device size and heating power?

Answer: NSTX-U + MAST-U will have capability to resolve this question

- With no additional upgrades to NSTX-U, facility should be able to access $H_{98y2} \geq 1.2$-1.3 for many τ_E using lithium coatings, and possibly higher H_{98y2} using upward evaporation
  - Enhanced pedestal H-mode (EPH) combined with lithium accessed $H_{98y2} \sim 1.7$ at high $\beta_N \sim 6$
- Access to reduced collisionality is key. New CS (higher B_T, I_P) + 2nd NBI are foundational.
- **Simultaneous deuterium and impurity control for n_e and Z_{eff} control are critical**
  - $f_{GW} \sim 0.5 \rightarrow$ 3-5x lower ν^*, $f_{GW} \sim 0.3$-0.4 would provide ~order of magnitude ν^* reduction
  - Li evaporation + granule injection for ELM triggering appear promising (EAST collaboration)
- MAST-U may get cryos sooner, NSTX-U will access higher B_T,I_P, P_{NBI} sooner
- NSTX-U+MAST-U will have sufficient turbulence/FI diagnostics, codes to ID e-transport cause
- **5YP base funding is sufficient, lower funding could delay/eliminate cryo from 5YP**

Key physics + operational questions to be resolved to assess ST suitability for FNSF (4)

- Can FNSF β_T and non-inductive operation be sustained with low disruptivity?

Answer: NSTX-U + MAST-U will have capability to resolve this question

- NSTX-U operation near and above no-wall limit well supported by existing 3D coils and feedback control system
- Plan will implement control algorithms for boundary, n_e, rotation, q, divertor radiation
- Will implement rt-disruption warning system – see Kaye/Gerhardt talks for frame-work
- Sustaining high performance will require improved density and impurity control
- Stability concerns at reduced density/collisionality:
    - Reduced error-field thresholds, potential for increased early mode locking
    - NTV rotation damping should increase at higher T_i (lower ν^*), RWM stability modified
    - Overall, plasma stability may be more sensitive to intrinsic and applied 3D fields
- Partial or full NCC will provide greatly increased 3D control (EFC, RWM, rotation, RMP)
- **5YP base funding is sufficient, lower funding could delay/eliminate NCC, cryo in 5YP**

Key physics + operational questions to be resolved to assess ST suitability for FNSF (5)

- Can divertor heat-fluxes be reduced below engineering limits, and do such heat-flux mitigation solutions extrapolate to FNSF?

Answer: NSTX-U + MAST-U will have capability to resolve this question

- With no additional upgrades, NSTX-U will be a leader in evaluation of snowflake + detachment
  - Collaboration with DIII-D on snowflake physics and control
- MAST-U will be world-leading in evaluating Super-X divertor (+ detachment), test snowflakes
- NSTX-U will be world-leader in evaluation of liquid metals for power handling (vapor-shielding) and be ST leader in transitioning to high-Z tiles
- **5YP base funding is sufficient, lower funding could delay/eliminate NSTX-U cryo**

- **Divertor Thomson, acceleration of high-Z implementation, tests of flowing liquid metal module would be very valuable - would require 5YP incremental**

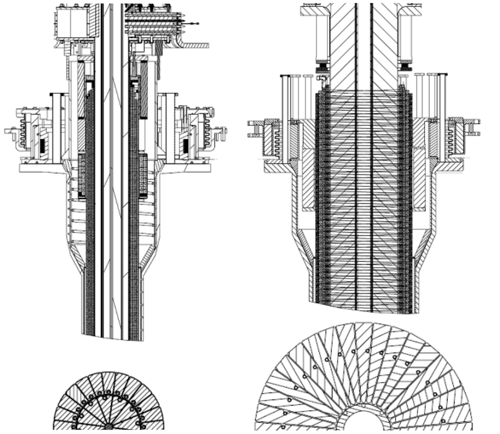
High-level goals for NSTX-U 5 year plan directly address the key physics + operational questions for ST-FNSF

1. Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
   - Note: Non-inductive goal also supports ST-based PMI facility application
2. Access reduced ν^* and high-β combined with ability to vary q & rotation to dramatically extend ST plasma understanding
3. Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid
   - Note: ST-based PMI facility could have solenoid for start-up/ramp-up
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solution for SS-PMI, FNSF, beyond

NSTX Upgrade will address critical plasma confinement and sustainment questions by exploiting 2 new capabilities

Previous center-stack

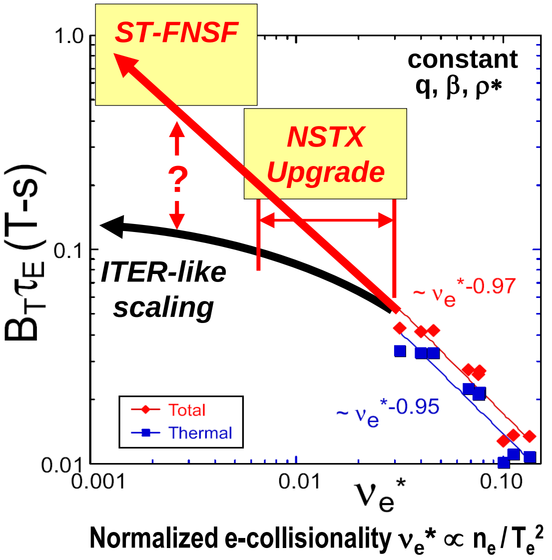
New center-stack

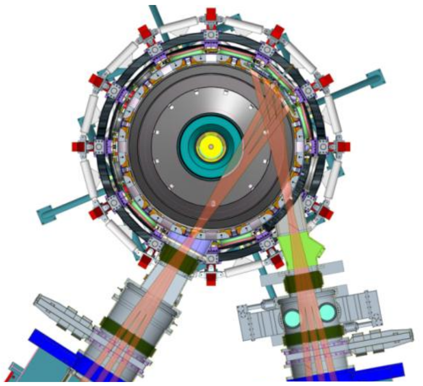


TF OD = 20cm

TF OD = 40cm

- 2x higher B_T and I_P increases T, reduces ν^* toward ST-FNSF to better understand confinement
- Provides 5x longer pulses for profile equilibration, NBI ramp-up





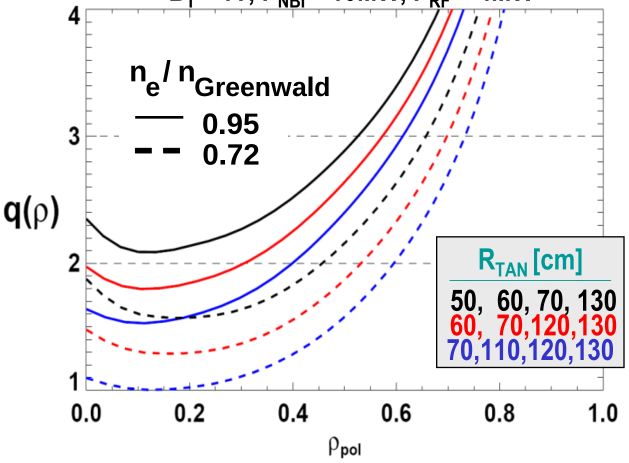
Present NBI

New 2nd NBI

- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with q(r) profile controllable by: tangency radius, density, position

I_P=0.95MA, H_{98y2}=1.2, β_N=5, β_T = 10%

B_T = 1T, P_{NBI} = 10MW, P_{RF} = 4MW



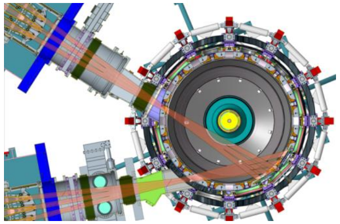
J. Menard, et al., Nucl. Fusion 52 (2012) 083015

NSTX-U plan will address key issues using cross-cutting set of existing/early tools + additional facility enhancements

Key issues to resolve:

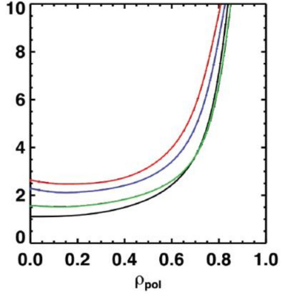
- Non-inductive current profile consistency and control, avoidance of Alfvenic modes

Present NBI



New 2nd NBI → 2 × P_{NBI}

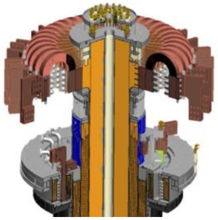
q profile control



28 GHz, 1-2MW Gyrotron

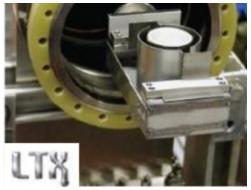
ECH / EBW for start-up (Longer-term: EBW H&CD)

- Confinement dependence on: ν^*, q, β, Ω_ϕ, means to control, increase

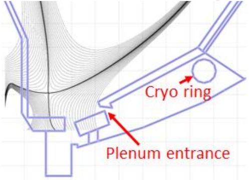


New CS: 2 × B_T, I_P
5 × longer pulse

Vary PFC Li coverage to vary recycling, $p(\rho)$, τ_E

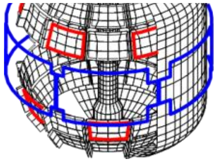


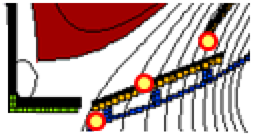
Cryo-pump for D, n_e, ν^* control w/o Li coatings



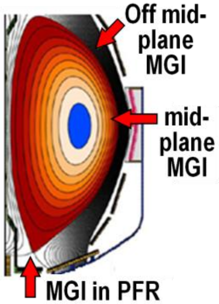
- Sustainable β w/ passive and active control, disruption prediction, avoidance, mitigation

Midplane + off-midplane non-axis. control coils (NCC) for EFC, RWM, ELM-RMP, NTV



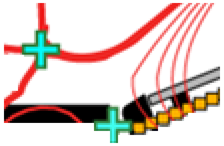


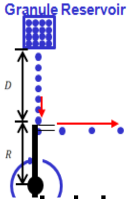
Extended low-f MHD sensor set



- Reduced power/particle fluxes, low net erosion, resilience to off-normal events/disruptions

Snowflake divertors + partial detachment





Li granule injector (LGI) for ELM pacing

Erosion & shielding of high-Z tiles + Li

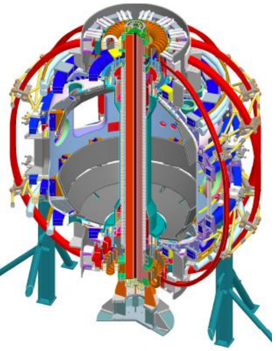
10 year plan tools with 5YP incremental funding

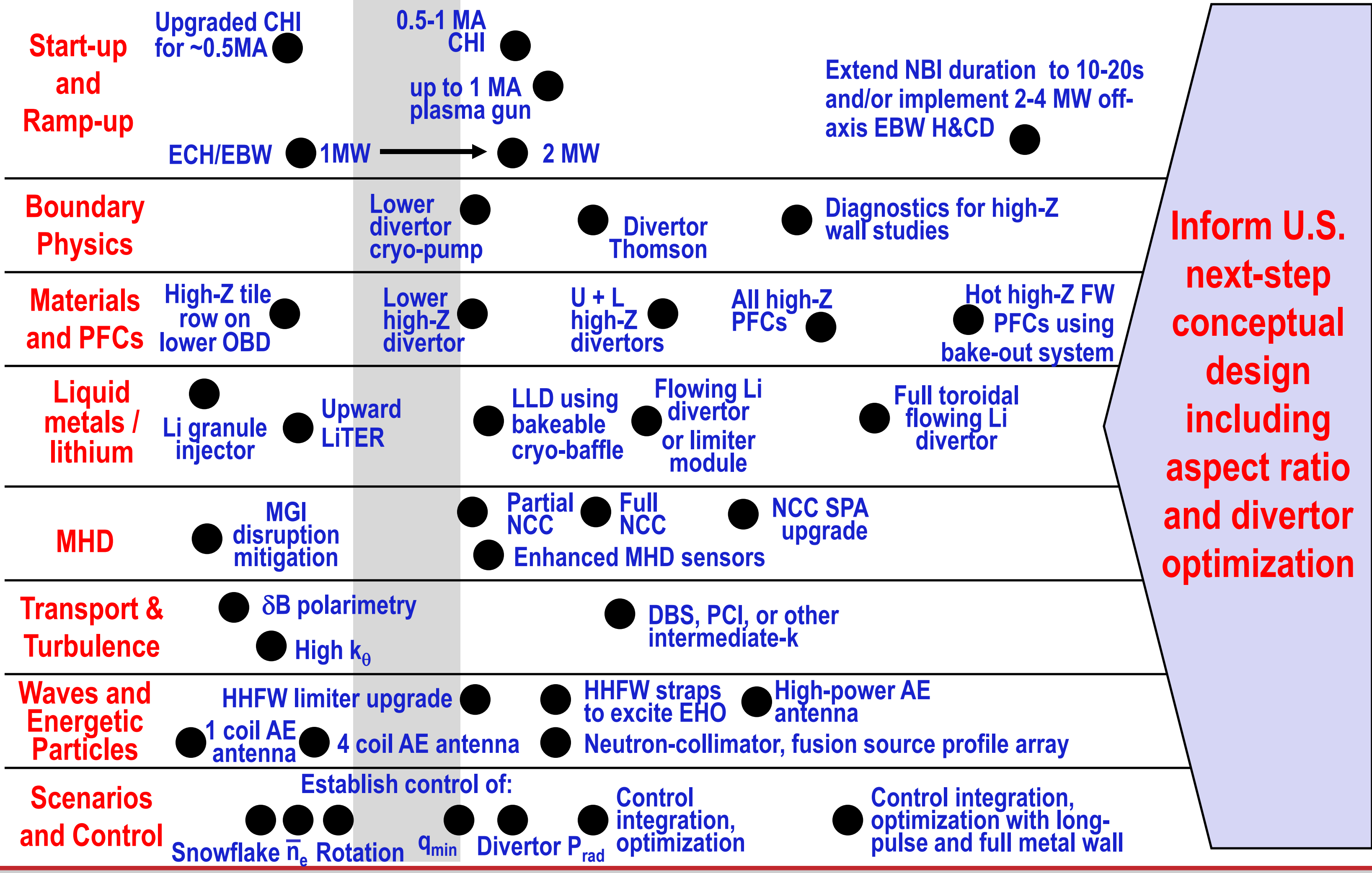
1.1 × (FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

Upgrade Outage | **1.5 → 2 MA, 1s → 5s** | **Metallic PFCs, 5s → 10-20s**

New center-stack





Start-up and Ramp-up
- Upgraded CHI for ~0.5MA ●
- 0.5-1 MA CHI ●
- up to 1 MA plasma gun ●
- ECH/EBW ● 1MW → ● 2 MW
- Extend NBI duration to 10-20s and/or implement 2-4 MW off-axis EBW H&CD ●

Boundary Physics
- Lower divertor cryo-pump ●
- ● Divertor Thomson
- ● Diagnostics for high-Z wall studies

Materials and PFCs
- High-Z tile row on lower OBD ●
- Lower high-Z divertor ●
- U + L high-Z divertors ●
- All high-Z PFCs ●
- Hot high-Z FW ● PFCs using bake-out system

Liquid metals / lithium
- ● Li granule injector
- ● Upward LiTER
- ● LLD using bakeable cryo-baffle
- ● Flowing Li divertor or limiter module
- ● Full toroidal flowing Li divertor

MHD
- ● MGI disruption mitigation
- ● Partial NCC
- ● Full NCC
- ● NCC SPA upgrade
- ● Enhanced MHD sensors

Transport & Turbulence
- ● δB polarimetry
- ● High k_θ
- ● DBS, PCI, or other intermediate-k

Waves and Energetic Particles
- HHFW limiter upgrade ●
- ● HHFW straps to excite EHO
- ● High-power AE antenna
- ● 1 coil AE antenna
- ● 4 coil AE antenna
- ● Neutron-collimator, fusion source profile array

Scenarios and Control
- Establish control of: ● Snowflake ● $\overline{n}_e$ ● Rotation ● q_{min} ● Divertor P_{rad}
- ● Control integration, optimization
- ● Control integration, optimization with long-pulse and full metal wall

Inform U.S. next-step conceptual design including aspect ratio and divertor optimization

2nd NBI

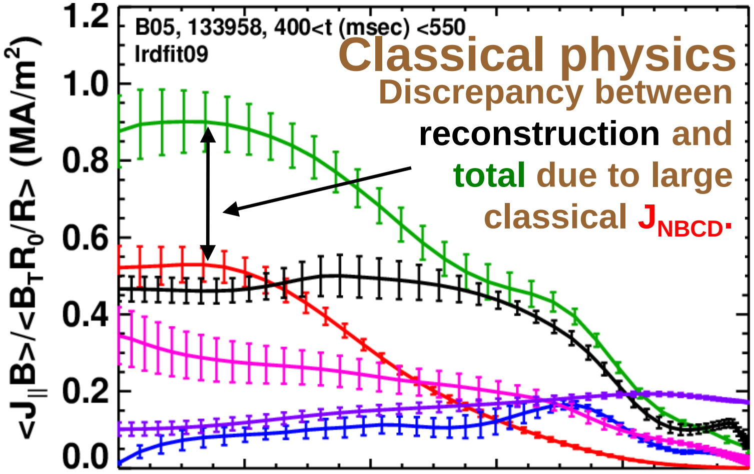
<u>PAC Question #2</u>: *Give 2 or 3 of your best examples of how the NSTX program is advancing model validation and predictive capability, including a description of the connections between experimentalists, theorists, modelers, both here at PPPL and the community at large*

Model validation/prediction development support the major research goals of NSTX-U

- Alfven modes and related fast ion transport
- Prediction of electron temperature in plasma core
- Kinetic RWM stability
- Non-inductive startup with CHI
- Non-ambipolar transport and neoclassical toroidal viscosity
- Convective ELM heat transport in the Snowflake X-point region
- Pedestal and ELM stability with the snowflake configuration
- Peeling-ballooning stability of ST pedestal

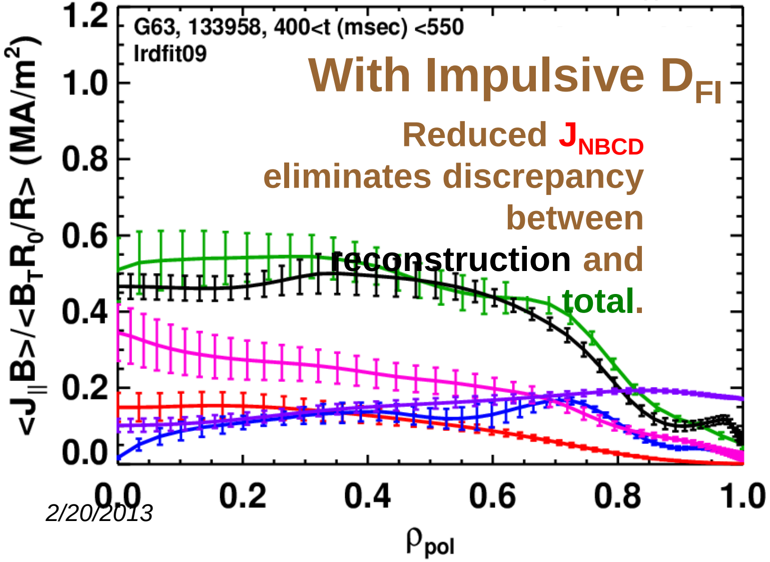
Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF

- TAE Avalanches Lead to Major Modifications of the Beam Driven Current Profile



Classical physics

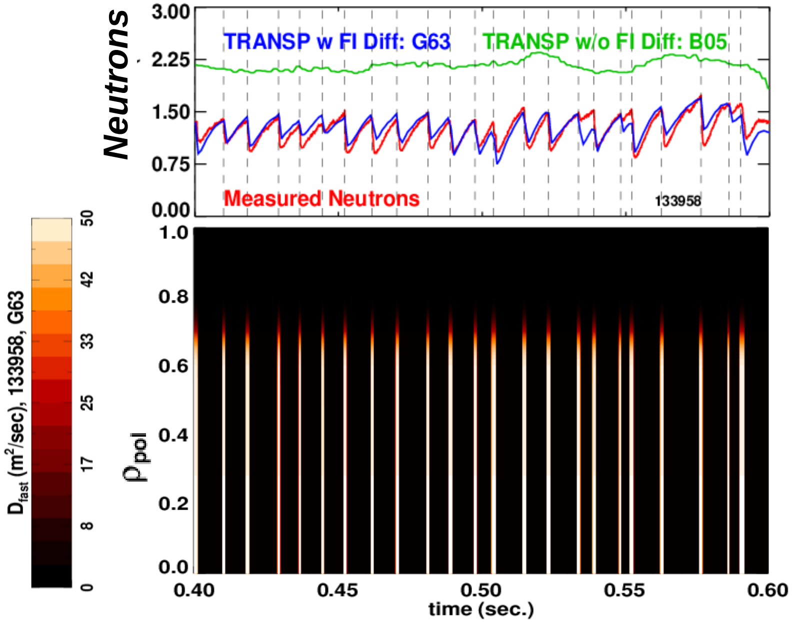
Discrepancy between reconstruction and total due to large classical J_{NBCD}.



With Impulsive D_{FI}

Reduced J_{NBCD} eliminates discrepancy between reconstruction and total.

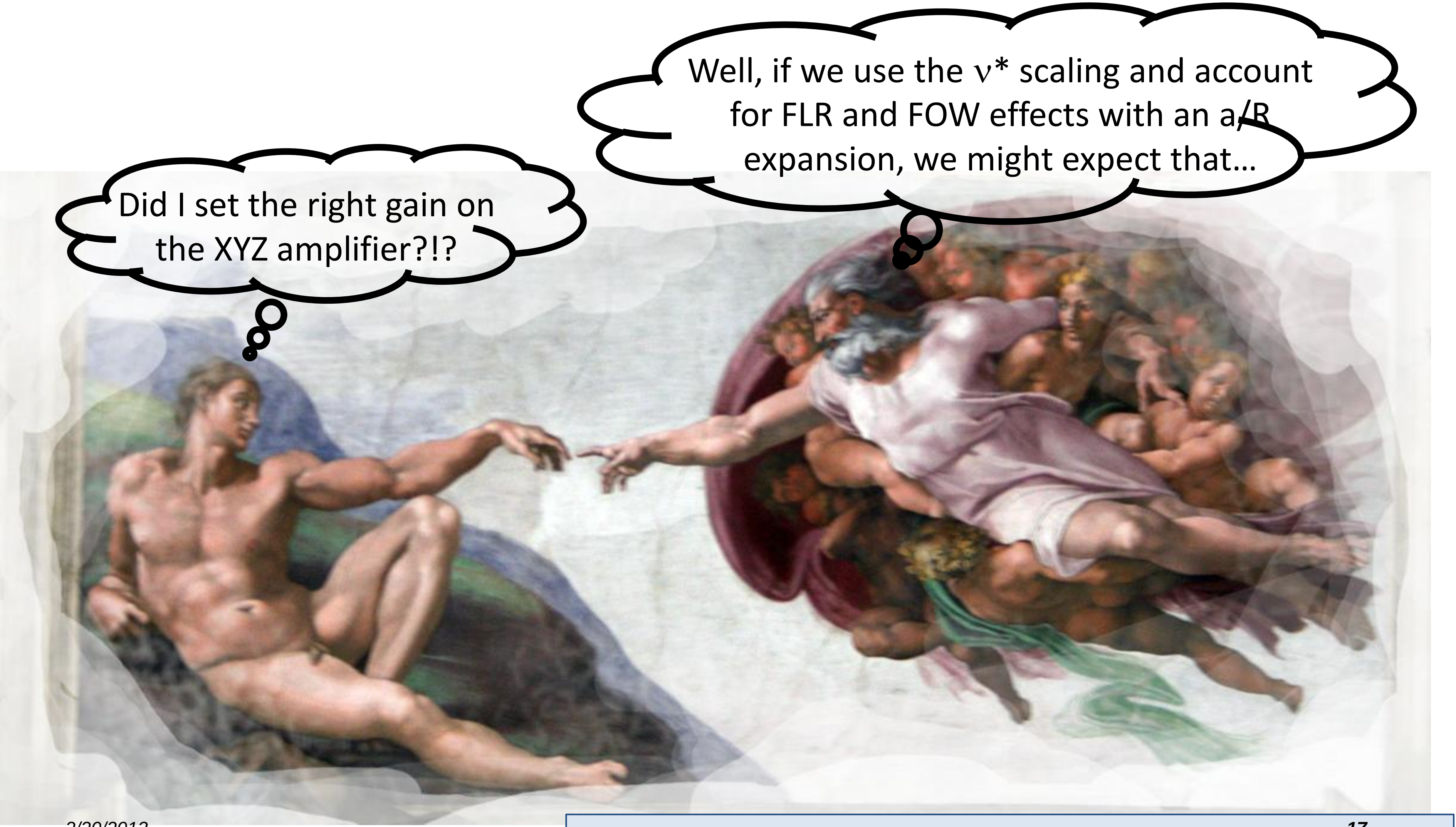
700 kA High-β_P with Rapid TAE Avalanches



- Modeled TAE avalanches using spatially and temporally localized fast-ion diffusivity $D_{FI}(\psi,t)$
  - Use S_n drops to determine $D_{FI}(\psi,t)$ details
  - Reinforces need for predictive modeling of avalanche transport

NSTX-U EP Research

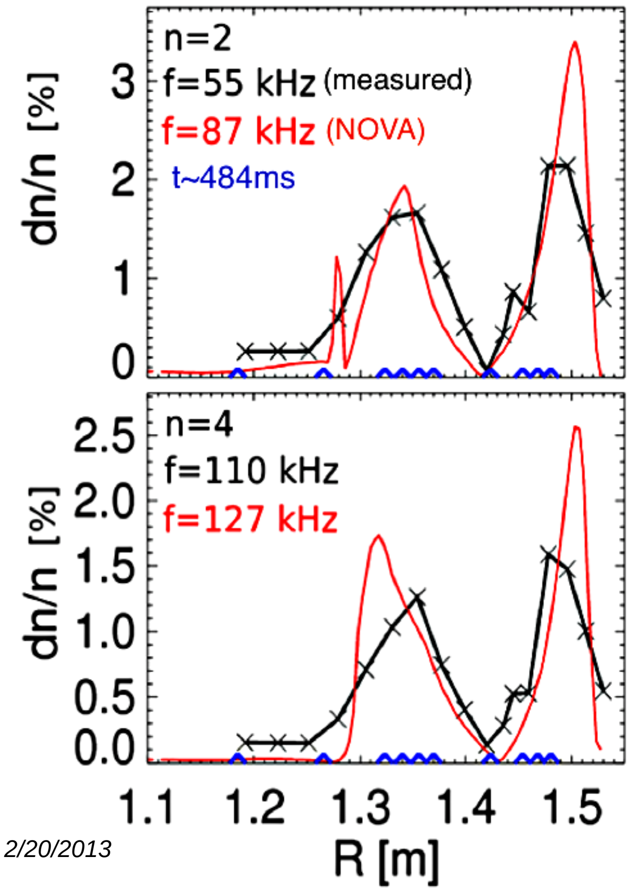
“advancing model validation and predictive capability through connections between experimentalists, theorists, modelers”



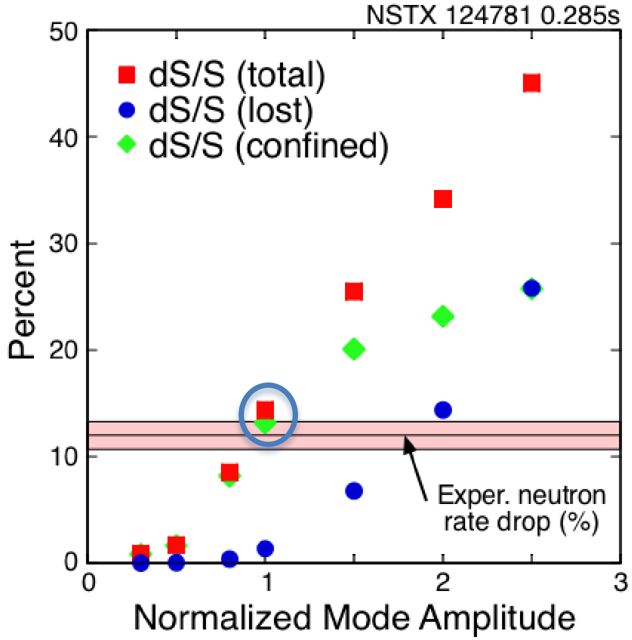
Special thanks to M. Podesta (PPPL), M.Ichelangelo (???)

Theory/experiment collaboration is advancing V&V of linear/non-linear codes for prediction of TAE mode structure, stability

First step to predict *AE-induced fast ion transport: Identify unstable modes & their properties (spectrum, structure, stability) – BES, reflectometer, NOVA-K
(D. Smith, S. Kubota, G. Kramer, N. Gorelenkov)



ORBIT simulations find threshold for fast-ion transport in agreement with experimental observations



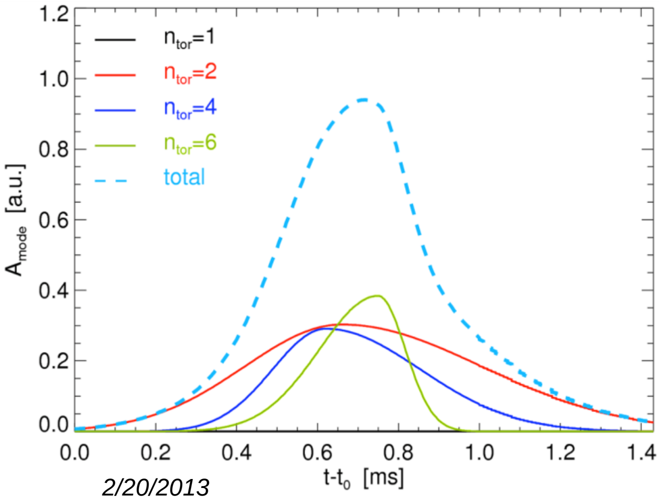
D. Darrow, R. White, G. Kramer studying nature of threshold for transport with ORBIT, SPIRAL (full orbit code)

Development of fully non-linear models (e.g., M3D-K) is focus for future work (G.Y. Fu)

Resonant fast ion transport model is being implemented in NUBEAM to mimic F_{nb} modifications by <u>resonant</u> *AEs

- Resonant/stochastic fast ion transport modeled through "probability function" for kicks in energy, canonical angular momentum $p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu, A)$
  - Probability calculated from models (e.g. ORBIT code), but *based on experimental quantities* (e.g. neutron rate, mode amplitude)
- Reduced model being tested against full ORBIT simulations
  - Good agreement, temporal evolution recovered
  - Will be implemented in TRANSP

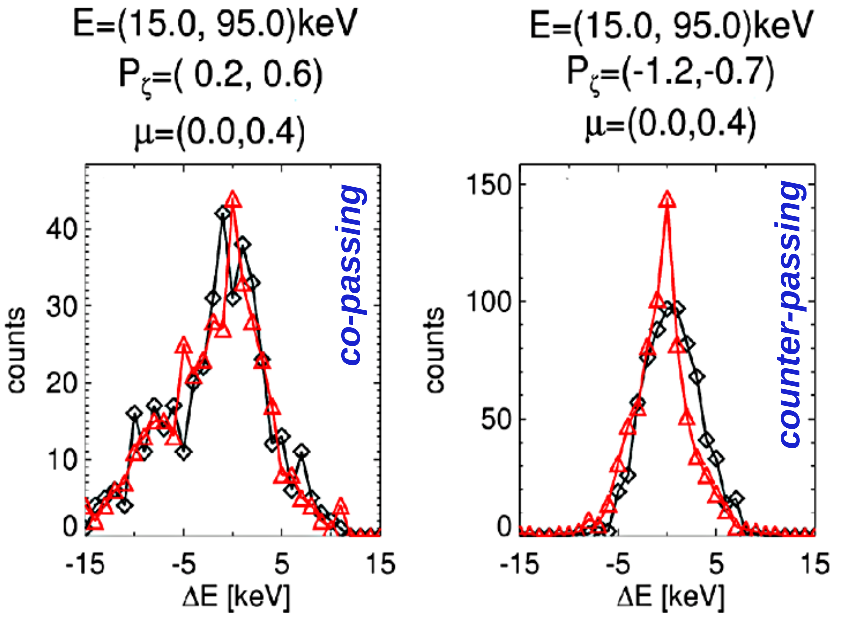
Amplitude vs. time of 4 TAE modes (from experiments)



Reconstructed fast ion "transport" (energy variation)

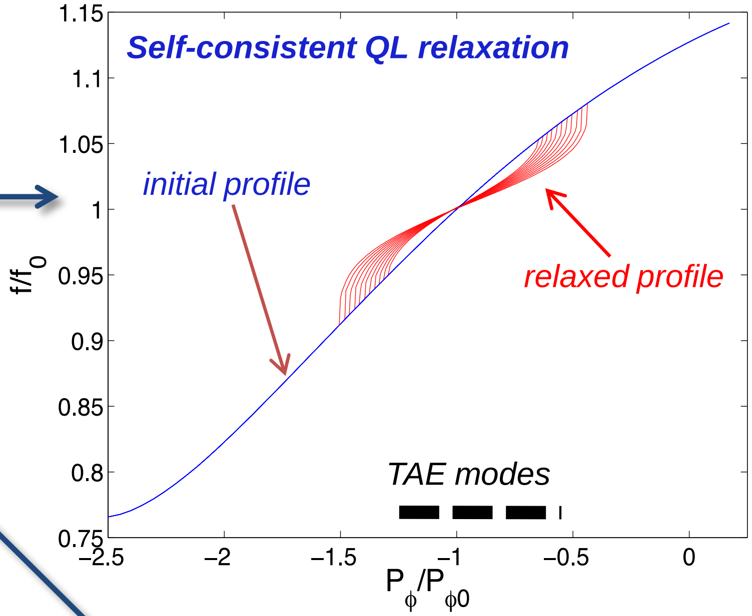
black: ORBIT

red: model

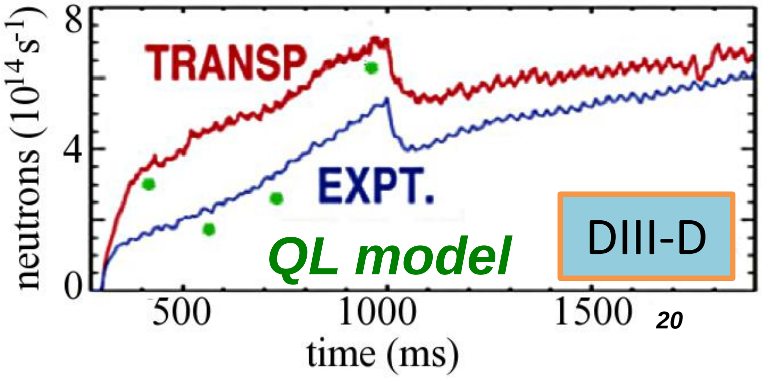


Quasi-linear relaxation model being tested, validated (DIII-D) – will compare to NSTX data (FY14) for V&V at low aspect ratio

- Quasi-linear (QL) model:
  - F_{nb} response to given set of modes
  - Compute *relaxed* radial fast ion profile, resulting fast ion transport
  - *Testing on DIII-D, then apply to* ***NSTX/NSTX-U scenarios (FY14)***

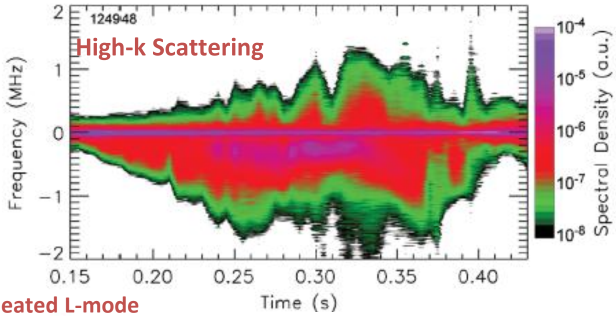


- Approach:
  - For given NSTX scenario, compute spectrum of unstable TAE modes (NOVA)
  - Compute stability (NOVA-K: growth, damping rate), unperturbed F_{nb} (NUBEAM/TRANSP)
  - Apply model to find relaxed F_{nb}, compare to data (FIDA, NPAs, neutrons)
  - Implement in TRANSP

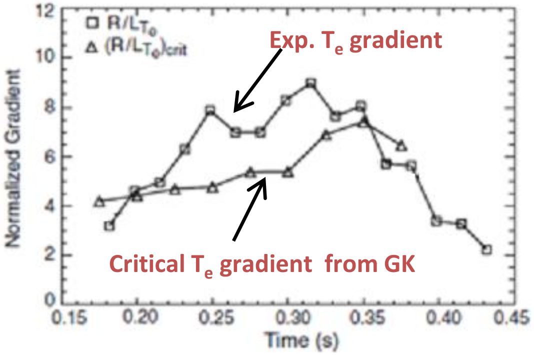


NSTX-U is making progress in validating ETG electron thermal transport model

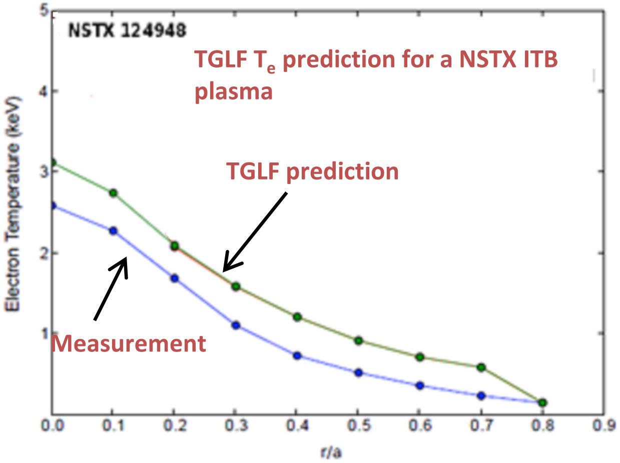
- ETG mode seen in a variety of NSTX scenarios
  - Using a unique high-k_r scattering system
  - NBI-heated H-mode; RF-heated L-mode; ITB plasmas
  - Supported by linear and nonlinear GK simulations
  - Initial TGLF model T_e prediction in a NSTX ITB plasmas shows over-prediction at edge (carried through to core)
- A FIR high-k_θ scattering system on NSTX-U to substantially improve our understanding of ETG
  - Identify streamers from 2D k spectrum measurement
- Further validation of TGLF/MMM08 against GK and GK against experiments in NSTX/NSTX-U
- A collaborative effort with multiple institutions
  - Experiments (E. Mazzucato/S. Kaye/Y. Ren/D. Smith, PPPL)
  - High-k (both k_r and k_θ) scattering (C. Domier et al., UC-Davis)
  - Theory/modeling /GK codes [W. Guttenfelder/G. Hammett/W. Wang (GTS code)/L. Peterson, PPPL;A. Kritz et al., Lehigh Univ. (MMM08); A. Pankin (Tech-X), J. Candy/G. Staebler, GA (GYRO/TGLF code)]


High-k Scattering

NSTX RF-heated L-mode


Exp. T_e gradient

Critical T_e gradient from GK

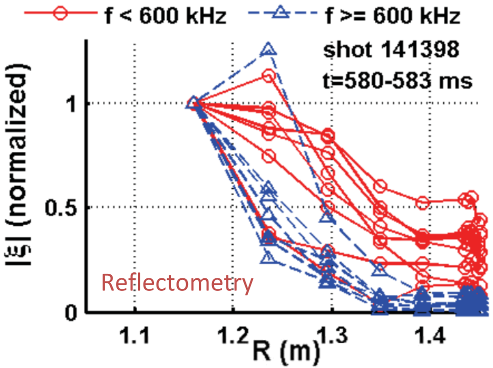

TGLF T_e prediction for a NSTX ITB plasma

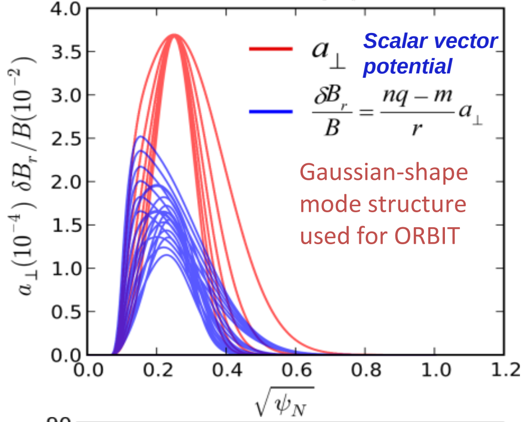
TGLF prediction

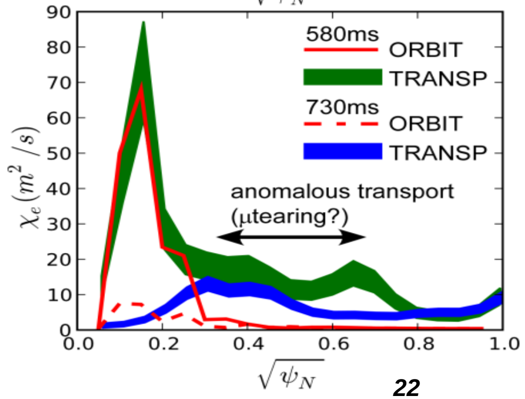
Measurement

NSTX-U T&T TSG is making progress in validation of CAE/GAE driven electron thermal transport model

- ORBIT code used for CAE/GAE driven stochastic electron thermal transport
  - Mode peak location, width, frequencies and mode numbers from measurements and dispersion equations
  - A strong scaling of transport with mode amplitude (~ $a^{3\text{-}4}$)
  - Predicted $\hat{A}_e$ matching experiment
- Moving toward predictive calculation for NSTX-U with ORBIT and HYM CAE/GAE calculations
  - First attempt planned for FY14
- A multi-institution collaborative effort
  - Experimental investigation (K. Tritz, JHU)
  - BES diagnostic (D. Smith, UW-Madison)
  - Reflectometry/polarimetry (N. Crocker, UCLA)
  - ORBIT code (R. White, PPPL)
  - Stochastic electron thermal transport theory (N. Gorelenkov, PPPL)
  - HYM nonlinear code (E. Belova, PPPL)

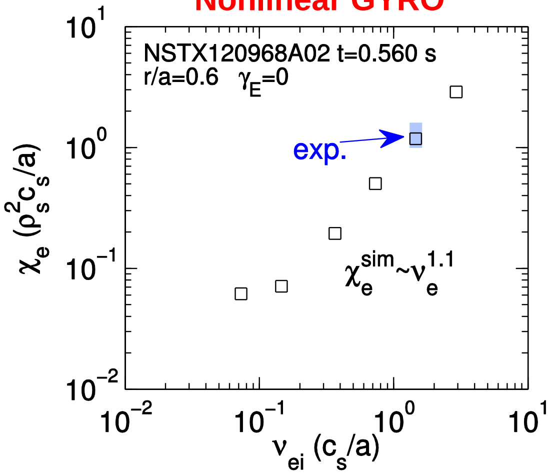




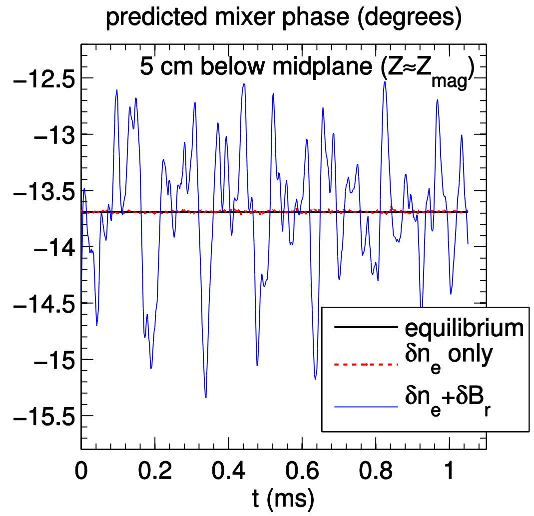


NSTX-U is making progress toward validating microtearing turbulence and transport modeling

Nonlinear GYRO



Synthetic polarimetry prediction



- Predicting scaling from nonlinear gyrokinetic simulations (w/ GA - J. Candy, PPPL- W. Wang, S. Ethier)
  - GYRO high beta simulations
  - Will verify with GTS when e-m implemented (~1 year)
- Predicting sensitivity of planned polarimetry diagnostic using simulations + synthetic diagnostic; (w/ UCLA, J. Zhang)
  - Important for validating magnetic turbulence
- Predicting sensitivity of BES using simulations + synthetic diagnostic (w/ CCFE, A. Field, Y.-C. Kim; U.W., D. Smith)
  - May provide possibility to distinguish MT from ITG, TEM
- Testing TGLF EM linear predictions of microtearing (w/ GA, G. Staebler)
  - First step in validating theory-based transport model for MT
- Improve K.L. Wong analytic to $\chi_{\mu t}$ with better $\delta B/B$ estimates

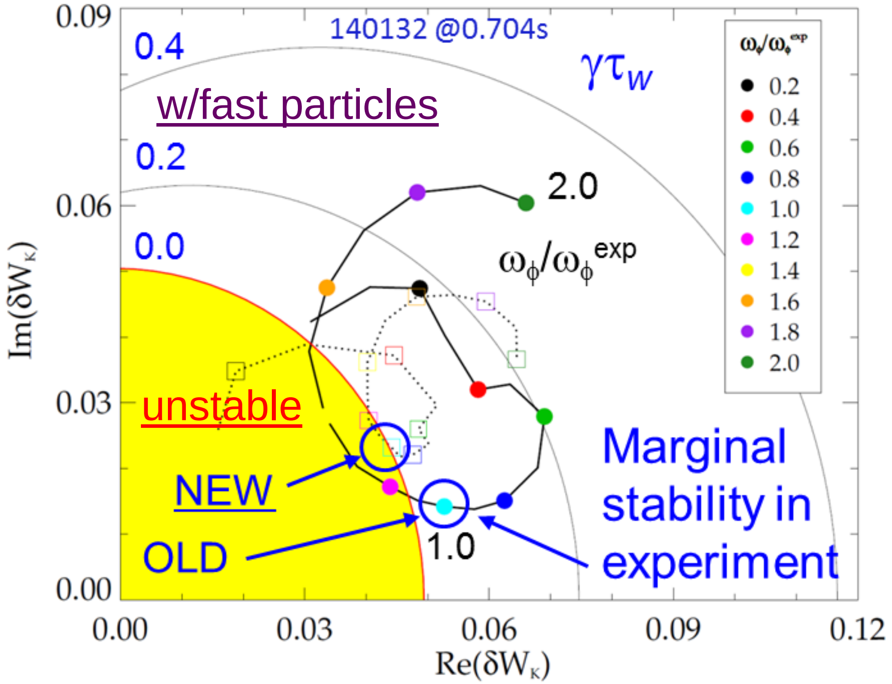
Access reduced ν^* and high-β combined with ability to vary q & rotation to dramatically extend ST plasma understanding

- Kinetic RWM Mode Theory -

- Quantitative agreement between theory/experiment
  - MISK, MARS-K, HAGIS codes being benchmarked (ITPA)
  - MISK calculation of ω_D improved
    - Agreement between theory/experiment improved
    - Best agreement with fast particle effects included

NSTX experiment / theory comparison (MISK code)

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

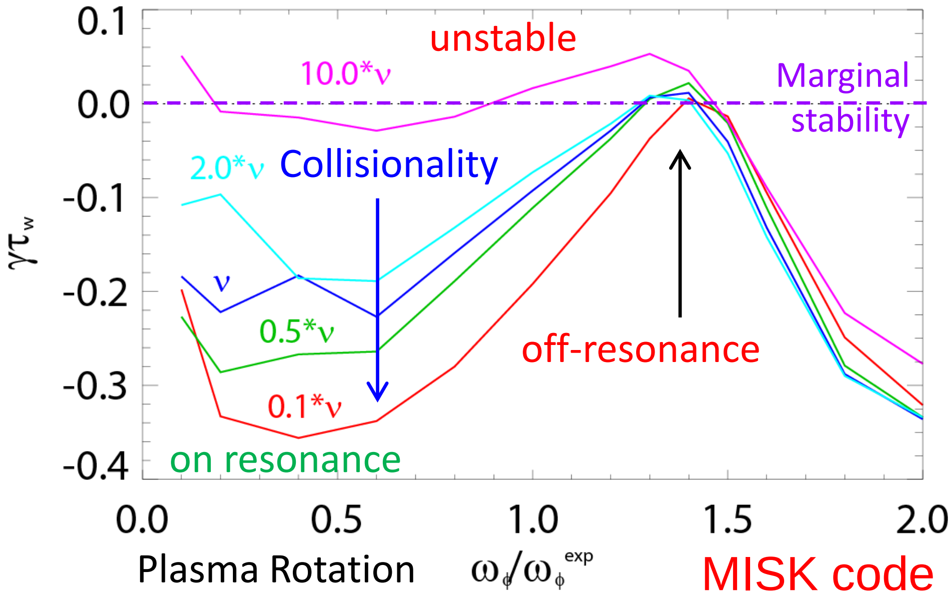


- MISK/MARS-K/HAGIS
  - B. Hu, R. Betti (U.Rochester), J. Manickam (PPPL), Y. Liu (Culham Lab), I. Chapman (Culham Lab)

- 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

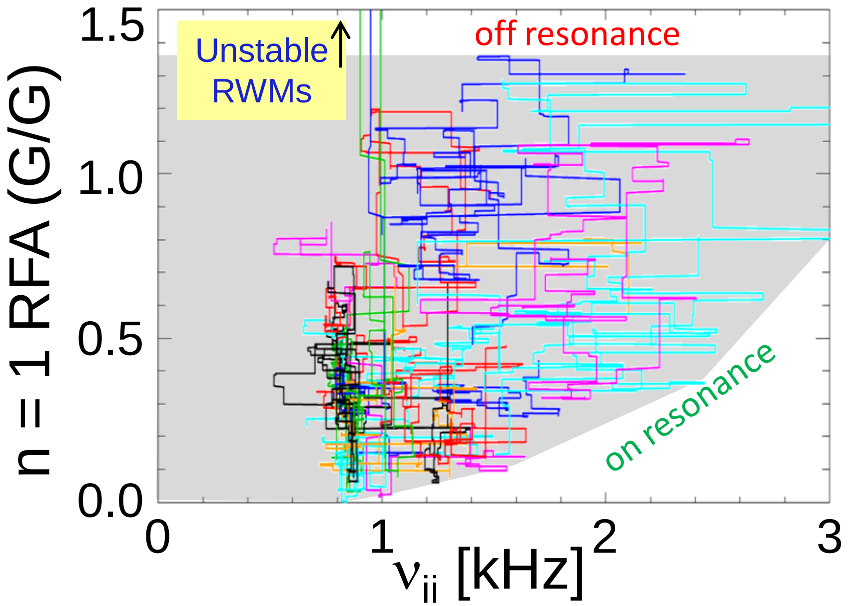
Experiments measuring global stability vs. ν further support kinetic RWM stability theory, provide guidance for NSTX-U

Theory: RWM growth rate vs. ν and ω_ϕ



MISK code

Experiment: Resonant Field Amplification vs ν



(trajectories of 20 experimental plasmas)

- ❑ Two competing effects at lower ν
  - ❑ Collisional dissipation reduced
  - ❑ Stabilizing resonant kinetic effects enhanced (contrasts early theory)
- ❑ Expectations at lower ν
  - ❑ More stabilization near ω_ϕ resonances; almost no effect off-resonance

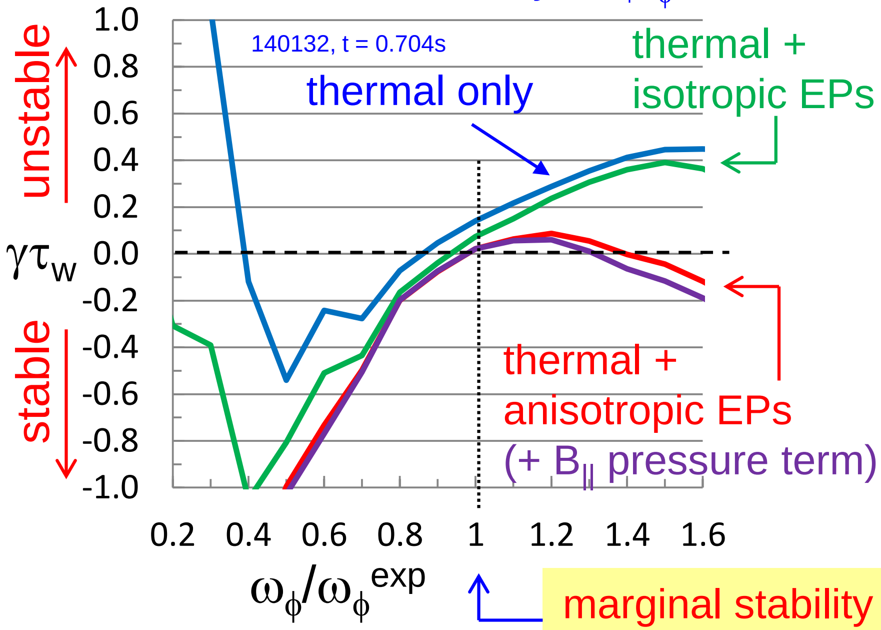
- ❑ Mode stability directly measured in experiment using MHD spectroscopy
  - ❑ Decreases with ν at lower RFA (“on resonance”)
  - ❑ Independent of ν at higher RFA (“off resonance”)

$$\mathrm{RFA} = \frac{B_{plasma}}{B_{applied}}$$

Experiments measuring global stability vs. ν further support kinetic RWM stability theory, provide guidance for NSTX-U

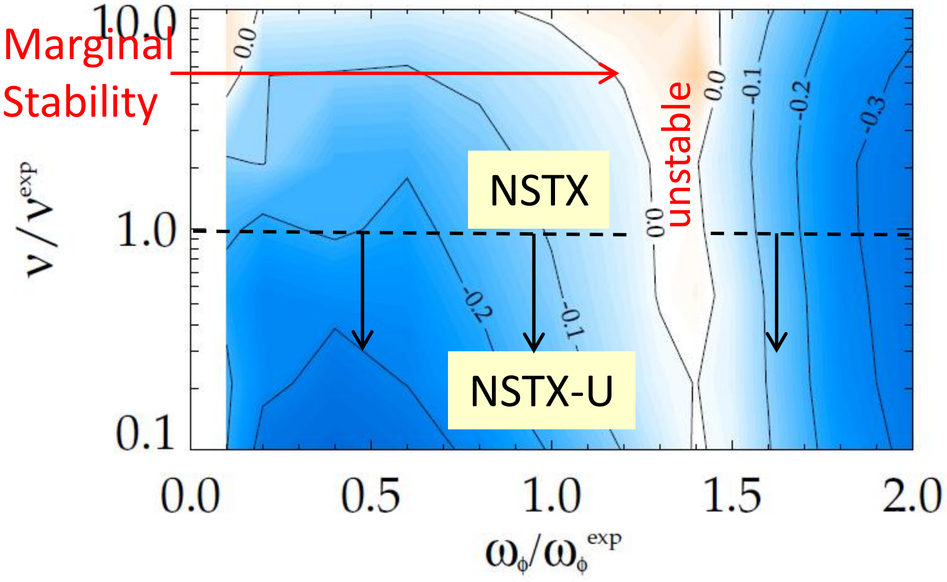
RWM stability vs. ω_ϕ

MISK code



marginal stability (experiment)

RWM growth rate contours ($\gamma\tau_w$)

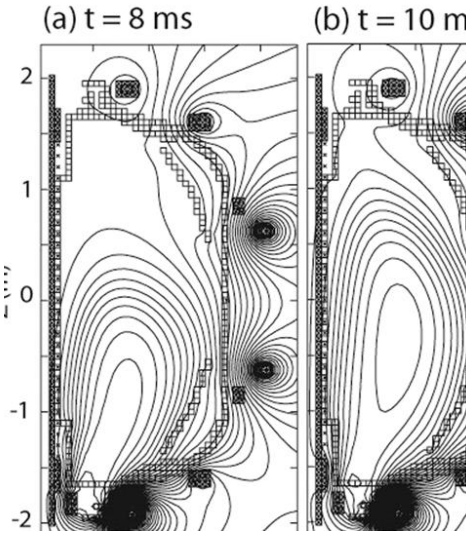


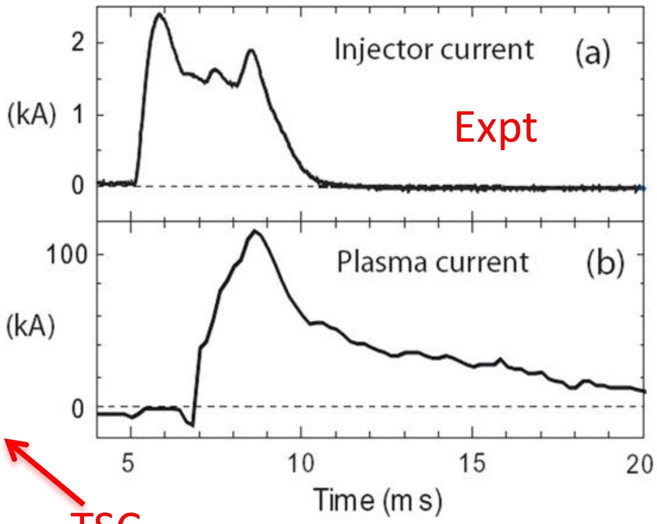
- Improvements to physics model
  - Anisotropy effects
  - Testing terms thought small
    - Already good agreement between theory and experiment of marginal stability point improved

- Two competing effects at lower ν
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)
- Expectations at lower ν
  - More stabilization near ω_ϕ resonances; almost no effect off-resonance
    - Active RWM control important

J. Berkery et al., PRL **106**, 075004 (2011)

Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid

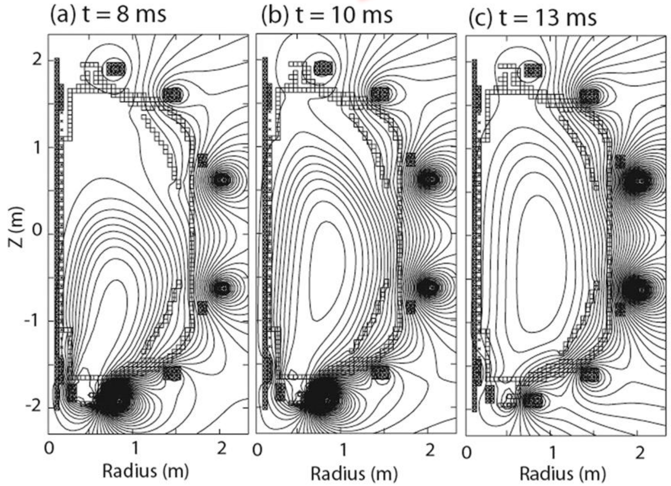




TSC

2D TSC simulations of CHI startup shows good agreement with experiment

Forms basis for prediction to NSTX-U and next-step devices



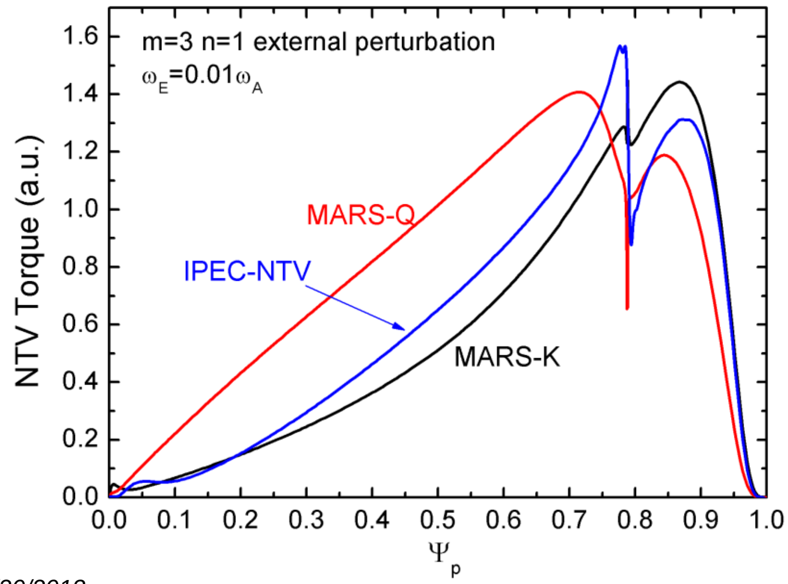
Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected Start-up current (MA)	0.2	0.4	2.0	3.6

Theory and code verifications on non-ambipolar transport and neoclassical toroidal viscosity

- Theory unification: Kinetic MHD theory is equivalent to NTV theory

[Boozer, Mynick, Shaing, Cole, Park] $T_{\varphi} = 2in\delta W_{K}$ [Rostocker, Rosenbluth, Porcelli, Hu, Betti]

- Code verifications
  - IPEC-NTV **[Park]**: Bounce-averaged, ε-expansion, Krook, regime-combined **[Park]**
  - MARS-K **[Y. Liu]**: Bounce-averaged., Krook, regime-combined **[Porcelli]**
  - MISK **[Berkery]**: Bounce-averaged, Krook, regime-combined **[Hu, Betti]**
  - MARS-Q **[Y. Liu]**: Bounce-averaged, ε-expansion, Pitch-angle, Pade approx. for regime **[Shaing]**
  - POCA **[Kim]**: Exact drift orbit, Pitch-angle **[Boozer]**
  - FORTEC-3D **[Satake]** : Exact drift orbit, Fokker-Planck **[Boozer]**



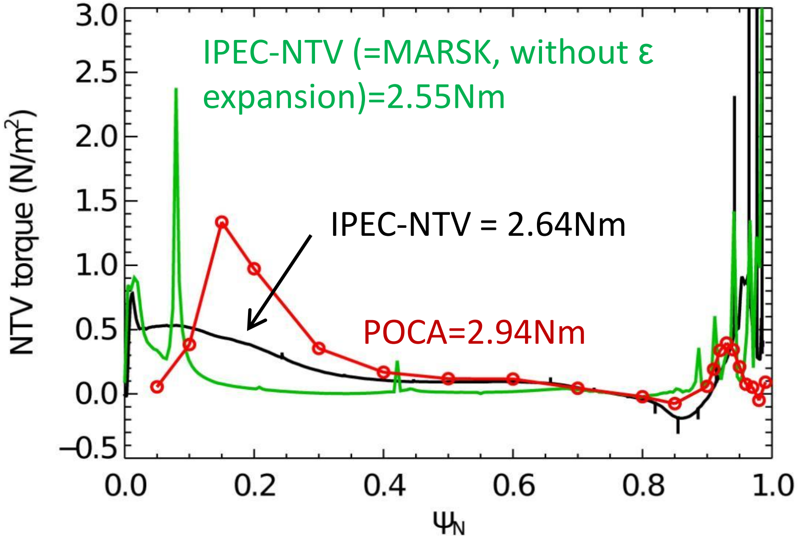
→

* MARS-Q implemented Shaing's connection formula for NTV to MARS-K, but MARS-K already has NTV from δW_k. So essentially these are comparisons between Park, Porcelli, Shaing

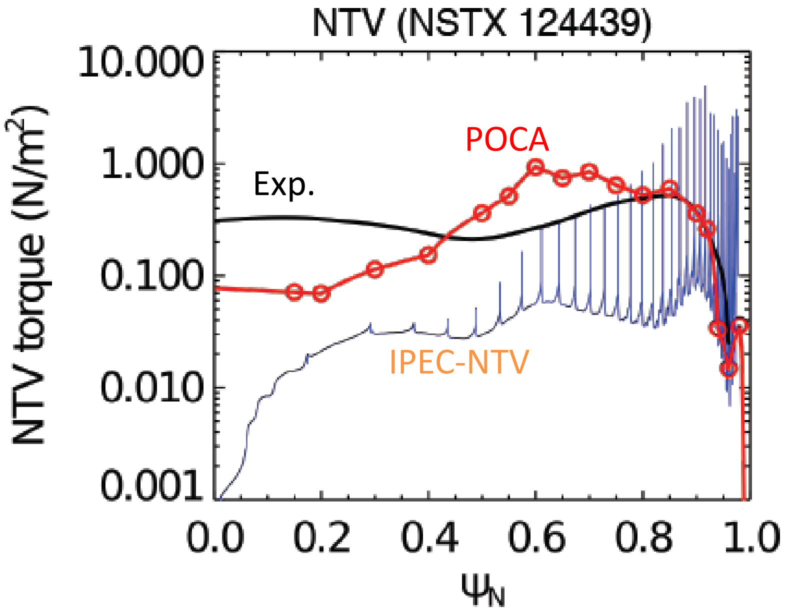
* IPEC-NTV, POCA, FORTEC-3D have been successfully compared for tokamak geometry
[Satake et al., PPCF 53 (2011) 054018]
[Satake et al., PRL 107 (2011) 055001]
[Kim et al., POP 19 (2012), 082503]

IPEC-NTV is being used for NCC analysis for NSTX-U, in parallel with cross verification & validation

- Validation for DIII-D:



- Validation for NSTX:



- Predictive capability for NTV can be increased along with computational expenses
  1. IPEC-NTV (or MARSK) is a good approximation, but not precise for low ε, or low ν*
  2. MARSQ is also a good approximation for low ν* , but not precise for low ε, or high ω
  3. POCA or FORTEC-3D should be used for low ε, low ν*, and high ω
- Existing issues to enhance predictability
  1. δB calculation is presently perturbative ⟶ self-consistent (MARSK and GPEC)
  2. Torque prediction → rotation prediction (should be combined with momentum transport)

Validation activities in the boundary physics area

- Pedestal width and structure: compare with kinetic ballooning calculations at low R/a, neoclassical predictions, and paleoclassical calculations

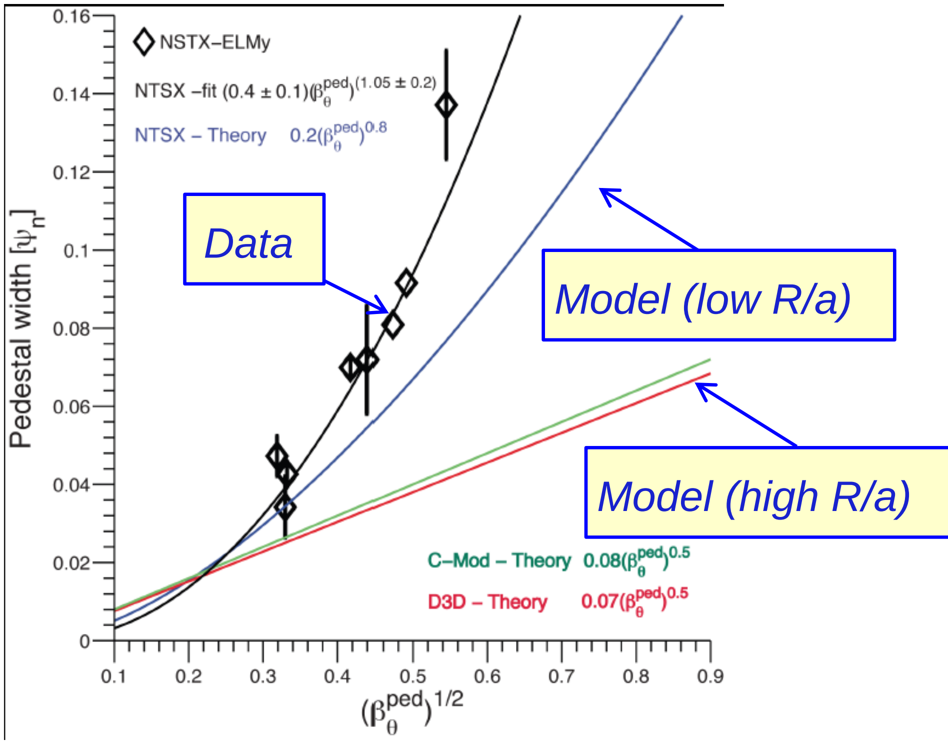
- Snowflake configuration: enhanced magnetic shear altering pedestal and ELM stability

- Snowflake configuration: predictions of enhanced X-point turbulence with analytic and 3-D fluid calculations

- Neutral transport: DEGAS-2 validation with gas-puff imaging

Several models of pedestal width being validated

- Kinetic ballooning calculation shows stronger dependence of pedestal width on pedestal β_{pol} at low R/a than high R/a
  - Reasonable agreement with NSTX data
- XGC0 calculation shows that pedestal width broader than neoclassical
  - XGC1 with turbulence to be examined
- Paleoclassical transport semi-quantitatively agrees w/NSTX pedestal gradients with and without lithium conditioning



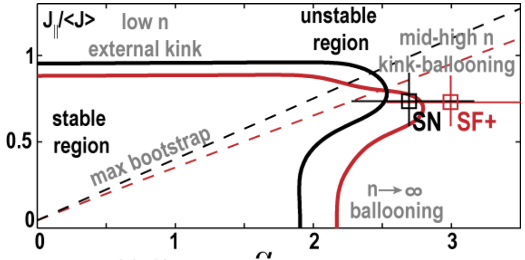
Data

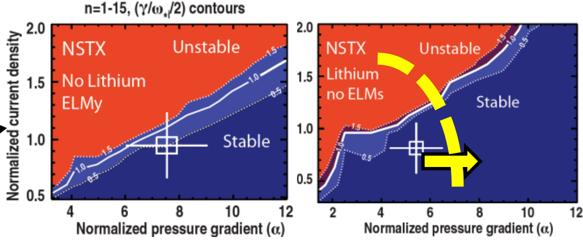
Model (low R/a)

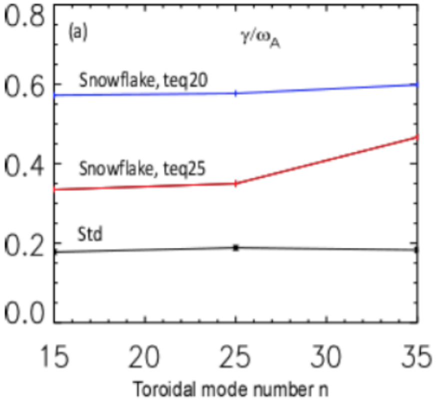
Model (high R/a)

Validate peeling-ballooning ELM stability model for the snowflake divertor configuration

- Theory: increased magnetic shear inside separatrix provided by snowflake may affect pedestal stability
- TCV tokamak with snowflake
  - Consistent with improved kink-ballooning stability
  - Type I ELM frequency increased, size decreased
- NSTX snowflake
  - Destabilized ELMs otherwise stabilized by lithium
  - Peeling/ballooning stable operating window reduced – access to second stability lost?
- DIII-D tokamak with snowflake
  - Overall stability did not appear to change
    - Slightly steeper and higher n_e, lower and flatter T_e
    - Pedestal energy did not change
    - Magnetic shear and q_{95} increased by up to 50 %
    - Change in stored energy lost per ELM (ΔW_{ELM}) is reduced



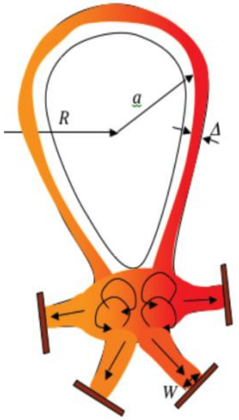


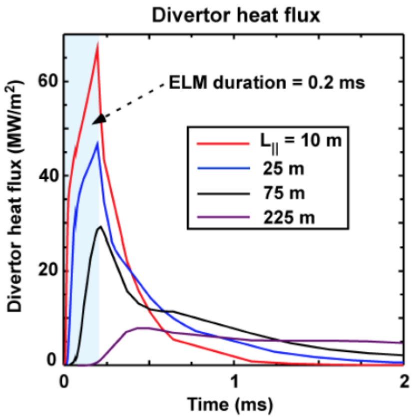


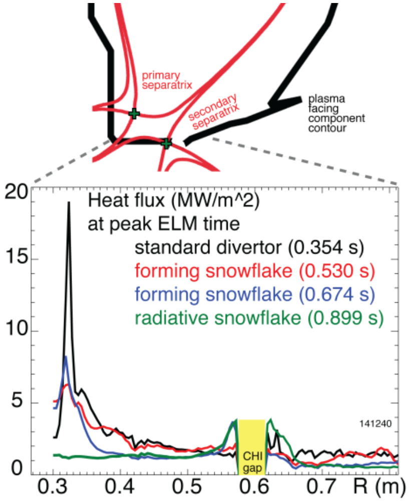
Peeling-ballooning mode stability for standard and snowflake configurations examined with BOUT++ for DIII-D-like geometry

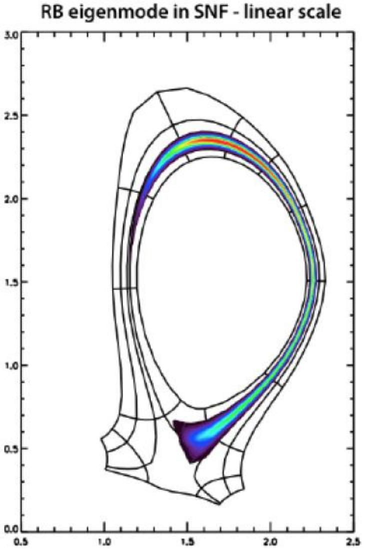
Validate snowflake null-point convective heat transport theory and null-point instability predictions

- Heat convection in null-point region with β_p>>1 (D. Ryutov, IAEA FEC 2012)
  - Heat partitioning between add’l strike point
  - Predicted ELM heat flux reduction by up to 10
  - Add’l energy loss is due to ELM energy pulse time dilution by increased L_x
  - In qualitative agreement with TCV and NSTX
- Role of X-point ballooning modes, electrostatic flute instabilities, and resistive-ballooning modes in the snowflake configuration examined with fluid turbulence BOUT++ code
  - Assess with divertor GPI









Validation of DEGAS 2 Neutral Transport Code Against NSTX GPI Data

- 3-D steady state simulations with synthetic diagnostic for GPI camera.
- Thomson n_e, T_e & EFIT equilibrium ⇒ DEGAS 2 background plasma.
- GPI data averaged over 10 ms between ELMs.
- Also have absolute calibration of camera & gas puff ⇒ compare photons / injected D atom:
  - GPI: 1/89 ± 34%, DEGAS 2: 1/75 ± 18%.

[B. Cao, D.P. Stotler, S.J. Zweben, M. Bell, A. Diallo, B. LeBlanc, Fusion Sci. Tech. (in press).]