NSTX-U

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NSTX-U Program for Advancing Theory, Model Validation, and Predictive Capability

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NSTX-U 5 Year Plan Review
LSB B318, PPPL
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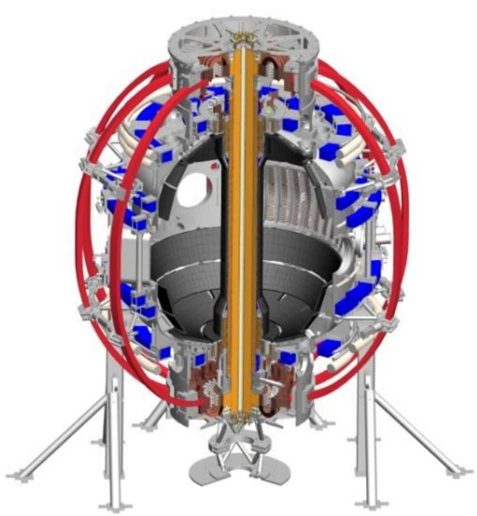

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Introductory Remarks

- NSTX-U research program will advance theory, model validation and predictive capability by connecting experimentalists, theorists, and modelers, both here at PPPL and the community at large. This will provide confidence for modeling of ITER and next-step devices.
- NSTX-U research teams consist of both experimentalists and theorists, with each Topical Science Group (TSG), co-led by two experimentalists and one theorist to facilitate synergism.
- This talk will focus on how theory has and will address the five programmatic goals of the NSTX-U Five Year Plan.
  - With apologies to the many contributors to the NSTX-U program, we will discuss only a few examples.
  - The goal of theory and computation is to identify and explore important processes and/or mechanisms that account for experiments and suggest new ones, predict their outcomes, and investigate new methods of plasma control.

NSTX-U Five Year Plan Programmatic Goals

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

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

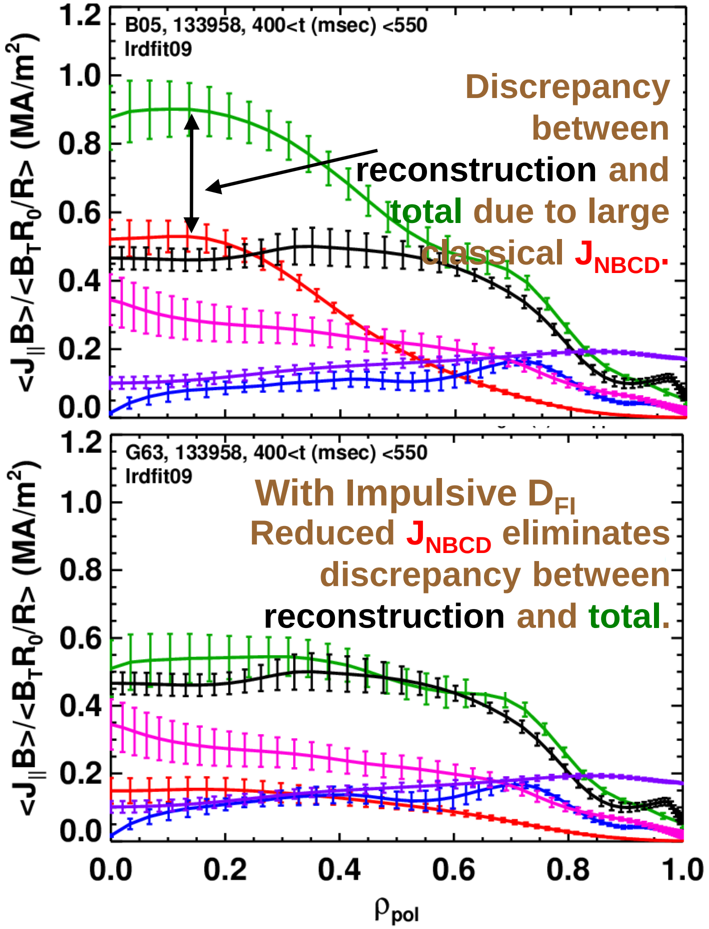
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid.

4. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment for mitigating very high heat fluxes.

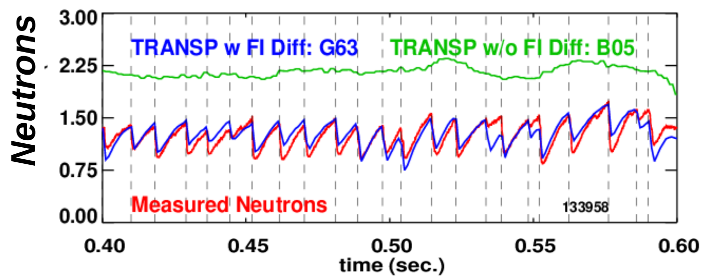
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps.

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m² neutron wall loading in FNSF

- Experiments have shown that TAE modes can have a dramatic effect on the neutral beam current drive, an important element of attaining 100% non-inductive sustainment

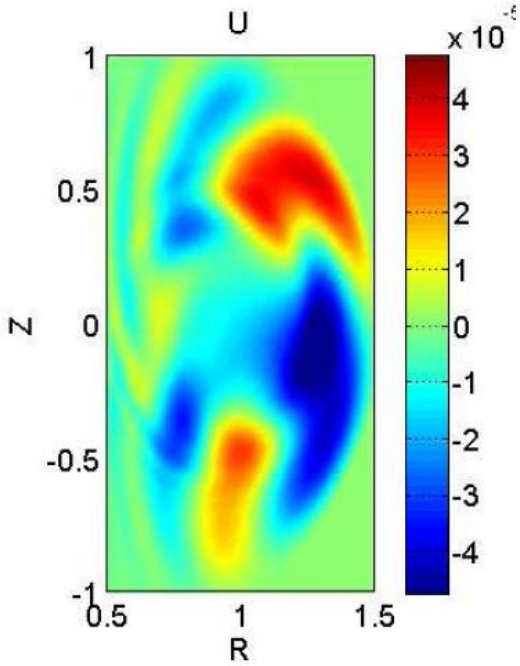


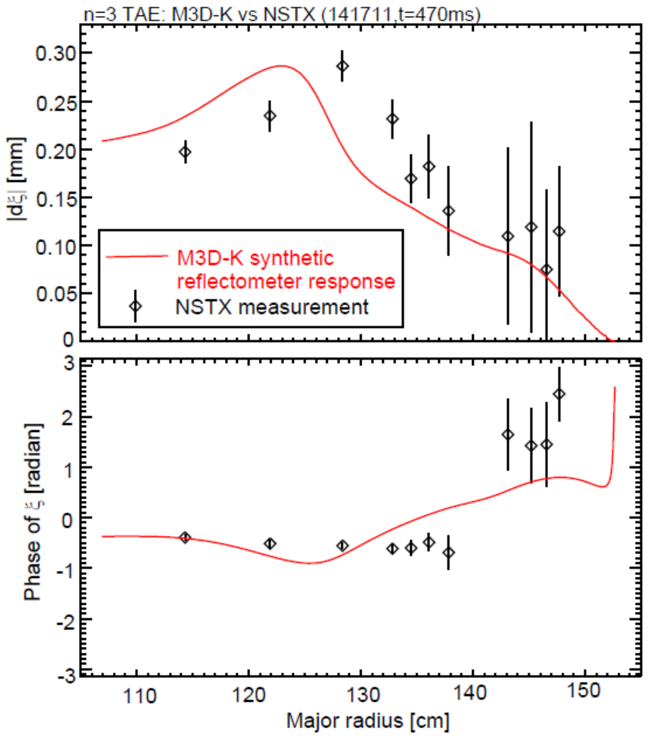
700 kA High-β_P with Rapid TAE Avalanches



- Modeled TAE avalanches using <u>ad-hoc</u> spatially localized and time-dependent fast-ion diffusivity $D_{FI}(\psi,t)$ (Gerhardt)
  - *Use S_n drops to determine $D_{FI}(\psi,t)$ details*
  - **Reinforces need for predictive modeling of avalanche transport using physics-based models**

M3D-K simulations of TAE show strong similarity to NSTX experiments



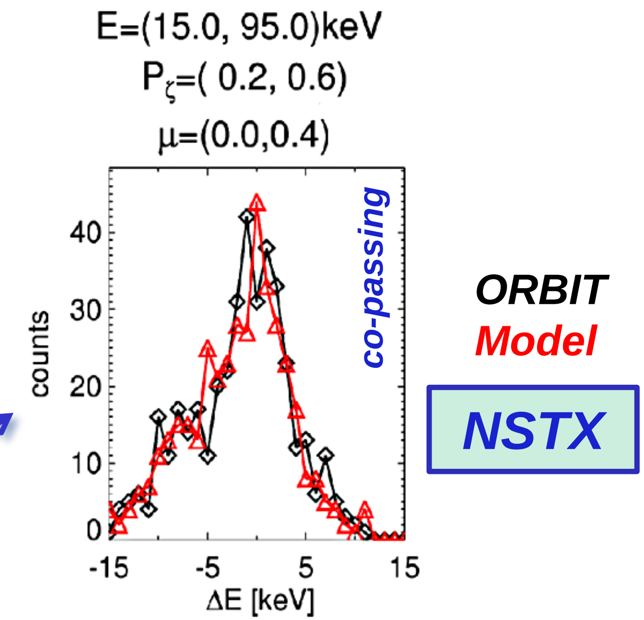


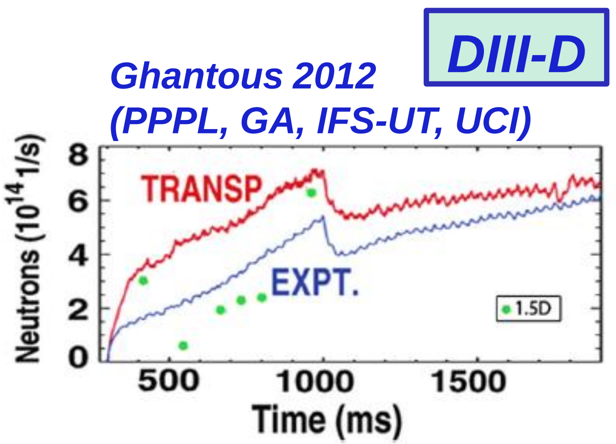
Liu 2013 (PPPL, SWIP-China, UCLA, UCI)

- Reasonable agreement between reflectometer measurement and M3D-K simulation of n=3 TAE in NSTX #141711. (f_{exp}=97kHz, $f_{M3D\text{-}K}$=106kHz)
- EP effects and plasma toroidal rotation are included non-perturbatively.
- Next step: nonlinear simulations of mode saturation and beam ion transport.

Predictive Models of AE-Induced Fast Ion Transport Are Under Development

- Resonant fast ion transport model is being implemented in NUBEAM to mimic F_{nb} modifications by resonant AEs
- Quasi-linear relaxation model
- Fast ion transport in both models rely on TAE mode spectrum and amplitudes calculated by linear/non-linear MHD codes (NOVA, NOVA-K, M3D-K) as well as unperturbed F_{NB} (NUBEAM/TRANSP)
- Reduced model being tested against full ORBIT simulations with good agreement
- QL model already developed for DIII-D with order-of-magnitude agreement
- Both models will be implemented in TRANSP, with a view to making them available for other experiments, including ITER.





Theory Plans for Goal 1

- Further development of QL theory for EP interactions with AE modes

  The application of QL theory becomes possible due to the excitation of a large number of small-amplitude of AE modes which tend to flatten the fast-ion profile. The 1.5D model, so called because it depends it includes radial dependence of density and velocity of fast ions in resonance, should be broadened to include (1) a more complete QL theory in phase space, (2) extension of the theory for ITER applications, which requires extension to include two species, and more general distribution functions.

- Phase space engineering

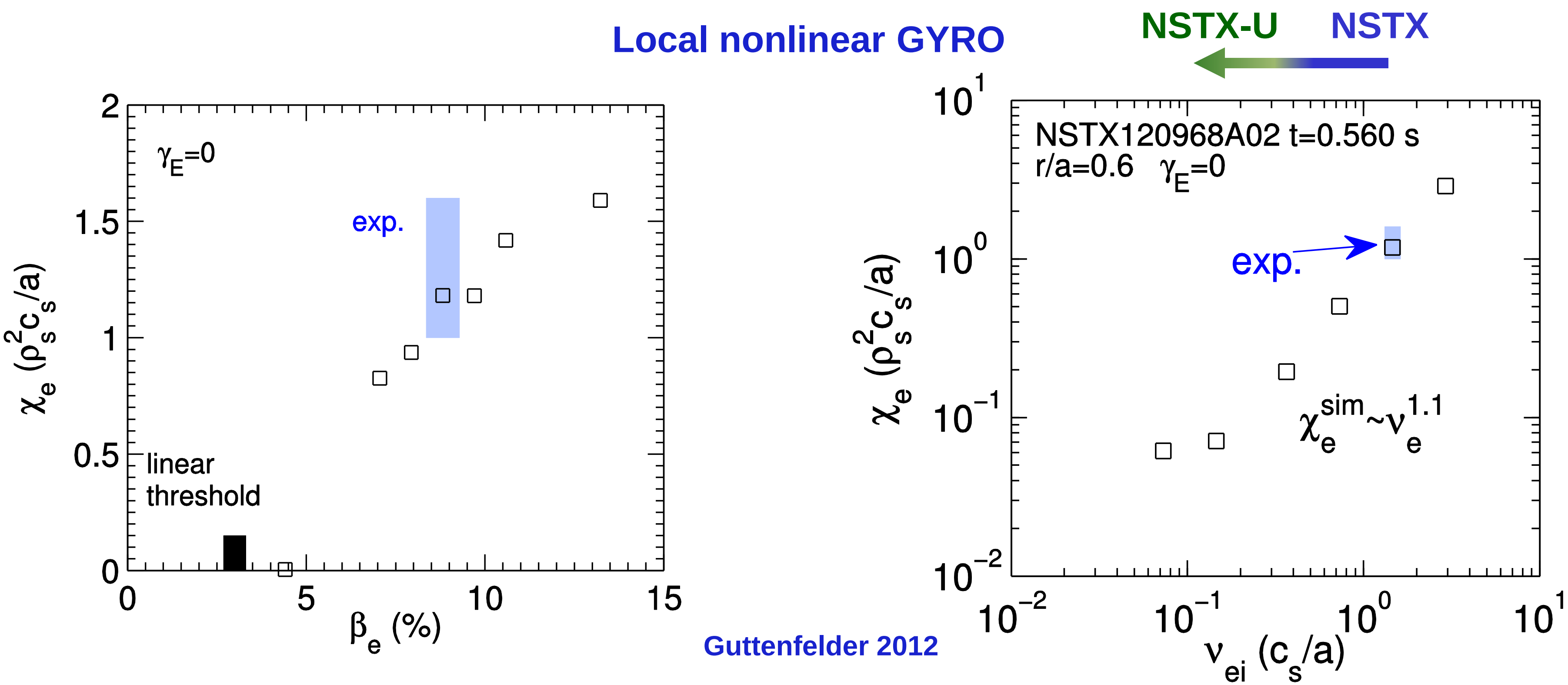
  Excite global CAE compressional mode---precise phasing is required to initiate and control diffusion.

- Nonlinear mode-coupling (including CAE, GAE, and KAW) studies and their effects on ion distribution functions (using M3D-K, HYM, and NIMROD codes).
- Effects of 3D external perturbations and microturbulence on fast ion confinement (using GTS and XGC-1)

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

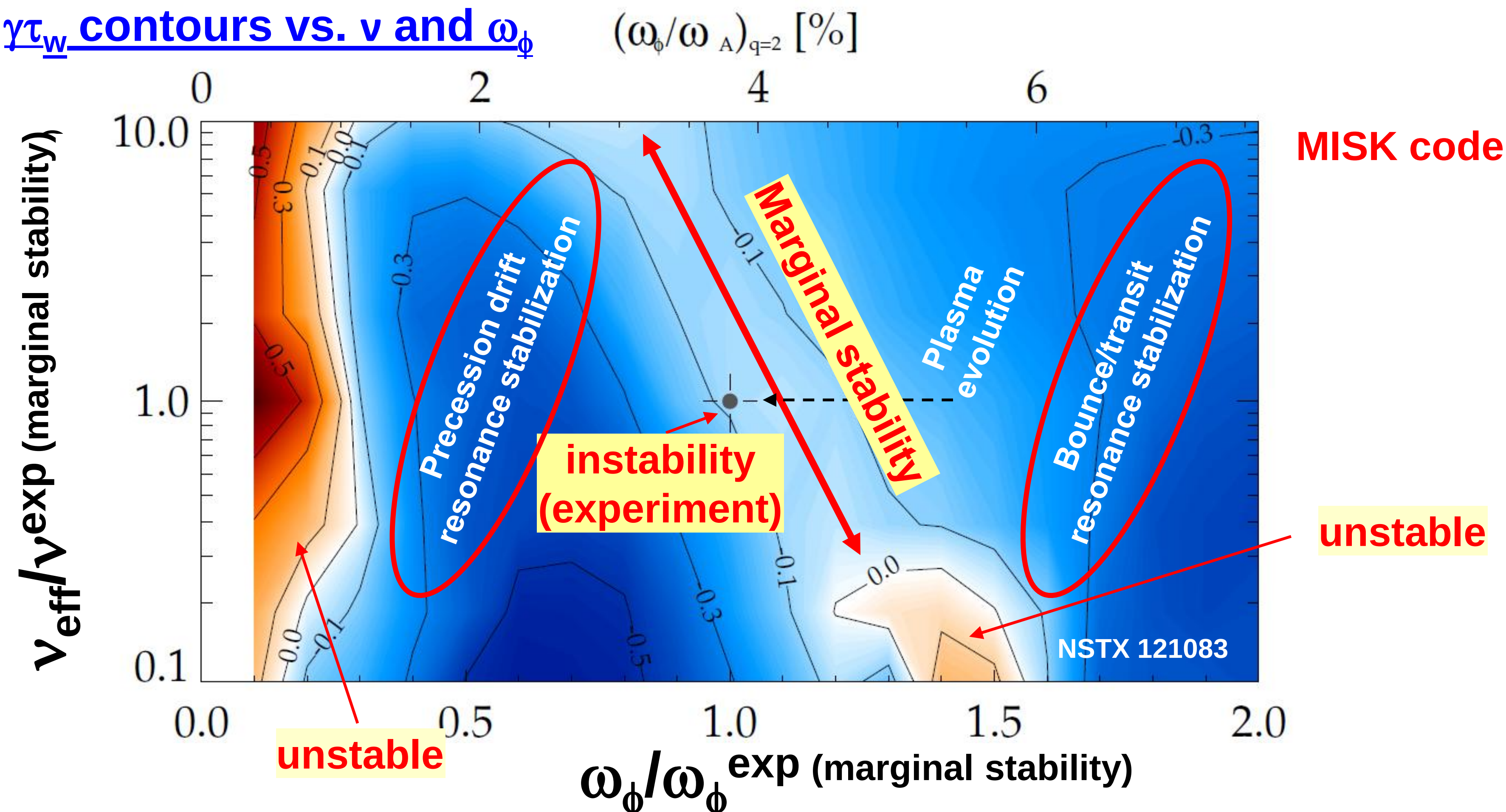
- Simulation of electromagnetic microtearing turbulence predicts significant transport at large beta and collisionality
- Extrapolation to low collisionality suggests microtearing might be weaker for NSTX-U
- Need for (1) quantitative improvement with flow shear and (2) scaling predictions of transport and thresholds

Local nonlinear GYRO



Guttenfelder 2012

Kinetic RWM theory consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality



- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

J.W. Berkery, et al., PRL 104 (2010) 035003
S.A. Sabbagh, et al., NF 50 (2010) 025020

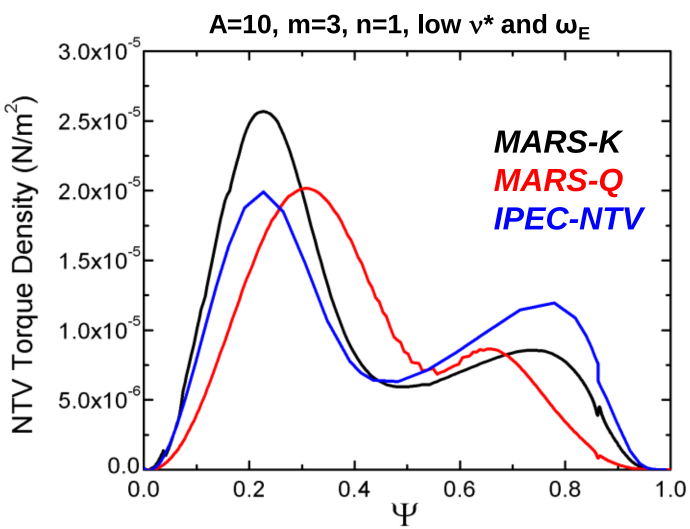
NSTX-U is an especially strong and unique laboratory for the study of neoclassical toroidal viscosity (NTV) theory

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

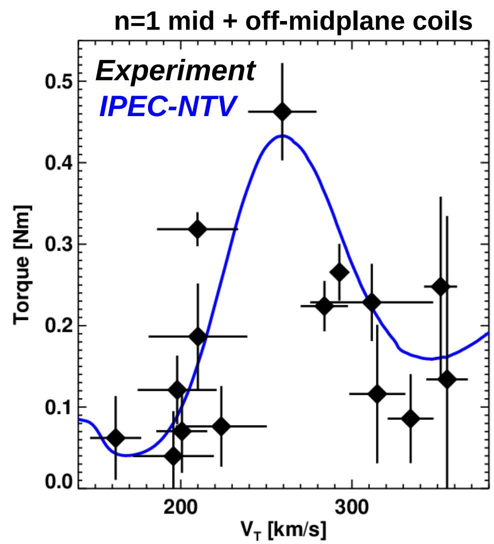
  [Boozer,Mynick,Shaing,Cole,Park] $T_{\varphi} = 2in\delta W_{K}$ [Rostoker,Rosenbluth,Porcelli,Hu,Betti]

- Verifications among 6 different codes
  - IPEC-NTV [Park,Logan], MISK [Berkery,Hu], MARS-K [Liu,Wang]
    : Bounce-averaged, Krook, Regime-combined [Park,Porcelli,Betti]
  - MARS-Q [Liu]: Bounce-averaged, ε-expansion, Pitch-angle, Pade approximation [Shaing,Cole]
  - POCA [Kim]: Exact drift orbit, Pitch-angle [Boozer]
  - FORTEC-3D [Satake] : Exact drift orbit, Fokker-Planck [Boozer]
- Total torque/torque density in KSTAR & NSTX: tests of validation (recall Zhu 2006)

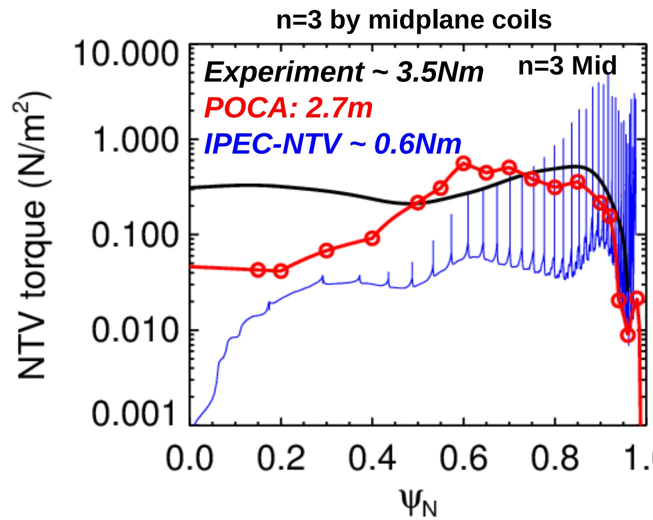
Benchmark among semi-analytic codes



Torque vs. rotation in KSTAR



Torque density profile in NSTX



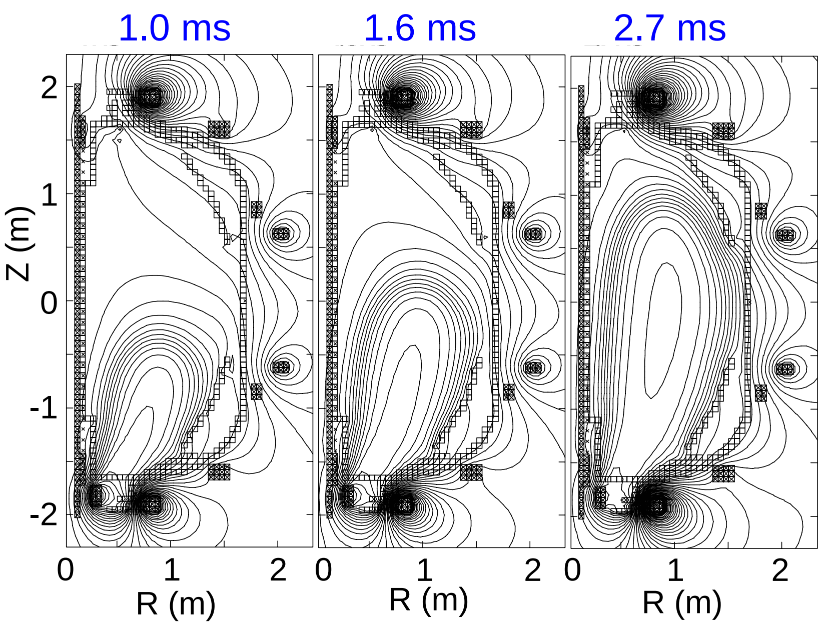
Theory Plans for Goal 2

- Global electromagnetic simulations for quantifying non-local effects and scaling of micro-tearing to low collisionality regime.
  - PPPL global PIC codes are expected to have full electromagnetic capability by 2014, including strong shaping (GTC-NEO, GTS) as well as X-point divertor geometry (XGC-1). NSTX-U provides an ideal test-bed for these codes as well as benchmarking with other continuum codes (GYRO).
  - Comparison of predictions of GTS, GYRO and XGC-1 with measurements of k-spectra and small-scale, high-frequency ZF (which represent an experimental challenge).

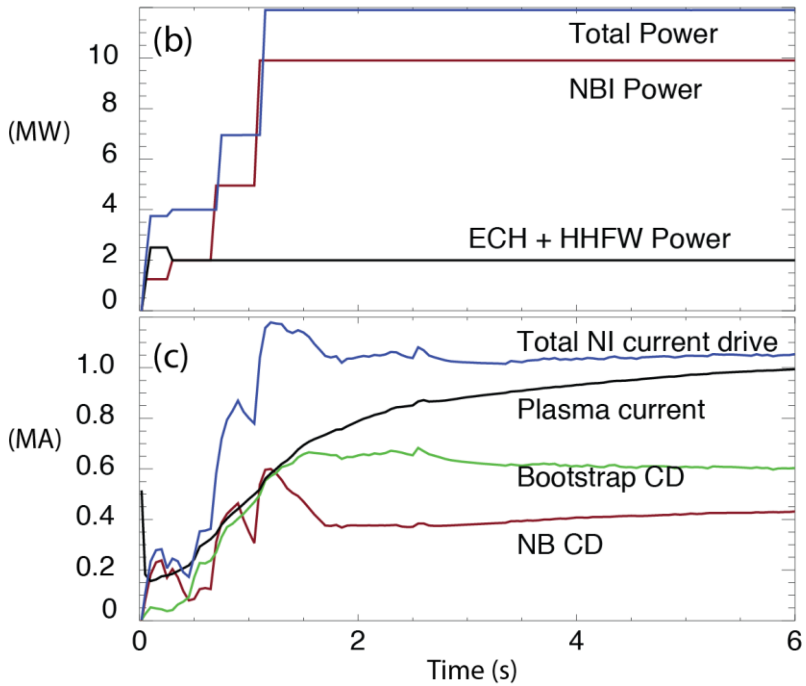
- Important issues/concepts for reliable NTV validation and predictability, and NSTX-U will provide a near-ideal environment to test theory.
  - NTV prediction for high-β, low-collisionality regime, and low-aspect ratio tokamak: discrepancies between codes and experiments tend to increase in these regimes. These are the targets of MARS-K and GPEC codes.
  - To what extent can the torques due to NTV be localized, and what are the important relevant magnetic field distributions? What are the options for coil-placement locations? Can stellarator optimization methods be useful?

- **TSC/TRANSP used to validate 2D CHI current generation model and predict non-inductive ramp-up for NSTX-U**

TSC (axisymmetric 2D) simulation of CHI startup



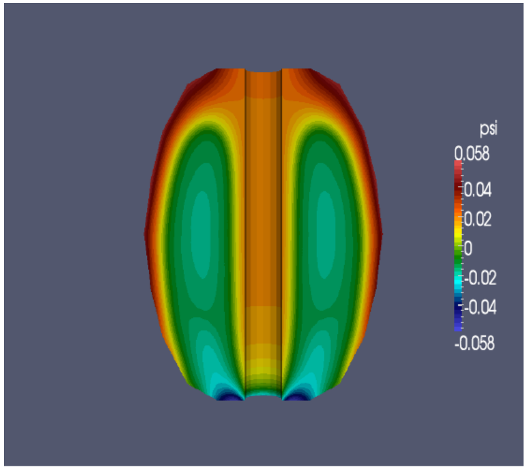
TSC/TRANSP simulation of non-inductive ramp-up from initial CHI target



Theory Plans for Goal 3

- Develop model for plasma transport during ramp-up phase
  - Use electromagnetic GTS (when ready) to determine transport
  - Model validation using NSTX results
- NIMROD investigation of CHI current generation and flux closure
  - Effects of high-Lundquist-number, and a generalized Ohm's law (Hall Current and electron pressure) on X-point formation and flux closure
  - 3D effects: field line stochasticization
  - Helicity injection using plasma guns
- Develop TSC/TRANSP capability to model non-inductive initiation, ramp-up and sustainment. (This is connected to Goal 1, specifically, to a predictive model for current profile evolution.)
  - Couple TSC directly to NUBEAM to self-consistently calculate profiles
  - Incorporate CHI model in free-boundary predictive TRANSP

Ebrahimi, Hooper, Sovinec, Raman 2013 (PPPL, LLNL, UW-Madison)

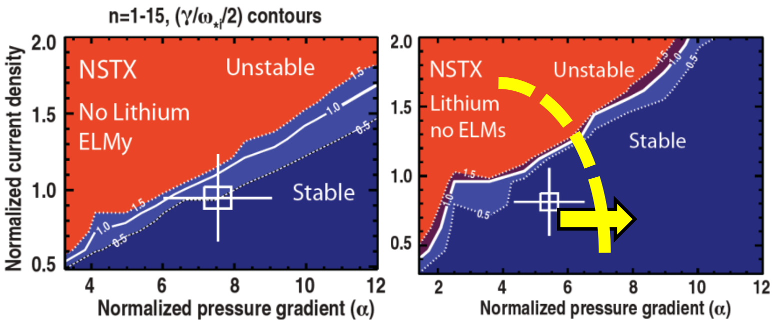


Axisymmetric NIMROD study

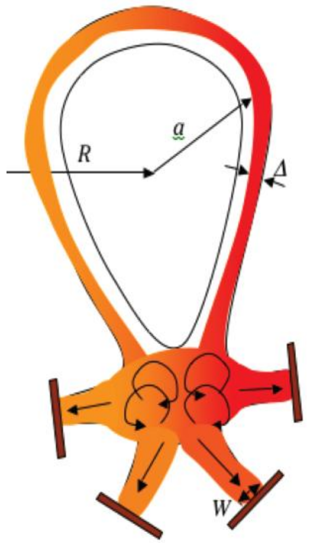
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes

"Snowflake" (SF) divertor is an example of innovative theory, which has had an important effect on setting new directions for experiments (NSTX, TCV).

- Validate peeling-ballooning ELM stability model for SF configuration
  - Magnetic shear inside separatrix may affect pedestal stability
  - ELMs are stabilized by ELM. Are they destabilized by SF?
- Validate SF null-point convective heat transport theory and null-point instability predictions
  - Heat convection in null-point region with β_{pol}>>1 results in ELM heat flux reduction by up to factor of 10
    - Heat partitioning among additional strike points

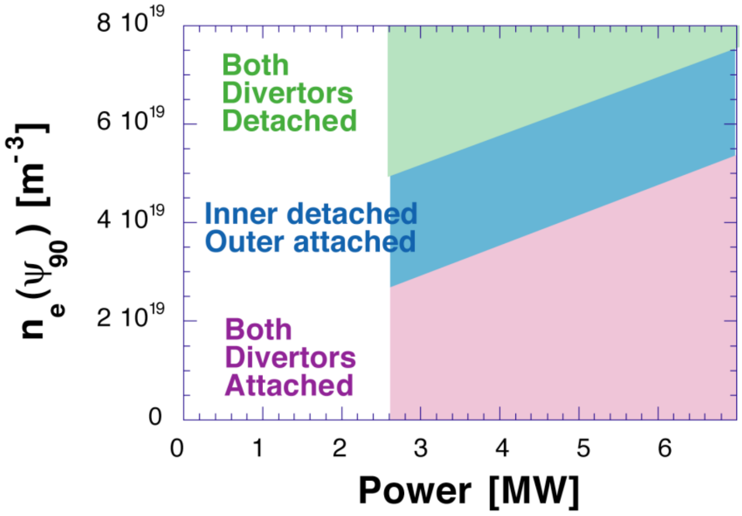


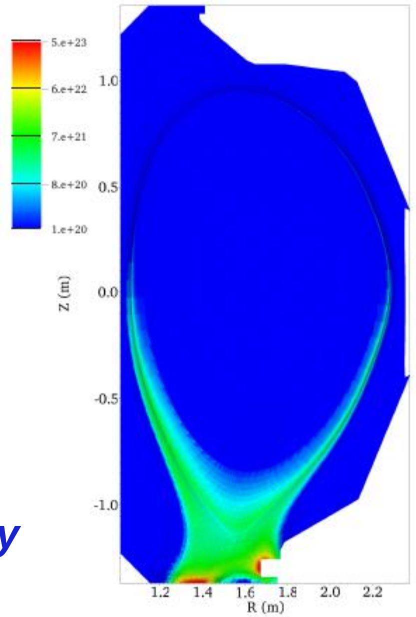
Ryutov 2007, 2012



Theory Plans for Goal 4

- Model UEDGE calculations predicted limited “window” of outer divertor detachment
  - Not inconsistent with NSTX results, but fluid models (e.g., UEDGE, SOLPS) are only as good as the input transport assumptions
- Coupling of XGC0/1 and DEGAS2 will provide self-consistent description of edge plasma and recycling
  - Background plasma descriptions critical to further modeling efforts describing transport
- Role of X-point ballooning (ideal and resistive), flute instabilities, and related transport using BOUT++ and XGC-1.
- Effect of 3D fields and stochasticity

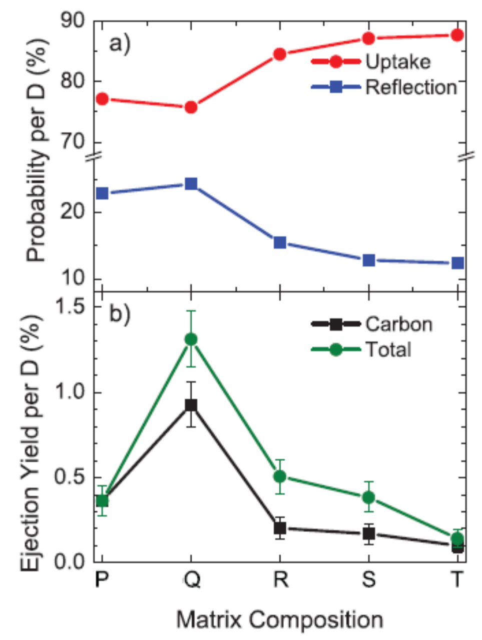




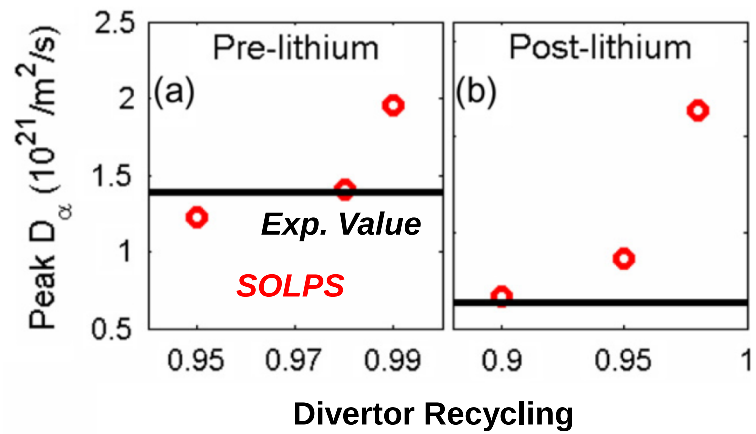
Neutral density

5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

- Material modeling provides model of erosion reduction retention with lithiated graphite
- Sample **P** is pure carbon, **R** is carbon+lithium+oxygen composite (similar to NSTX PFCs)
- Quantum-Classical Molecular Dynamics (QCMD) simulation calculates inter-atomic potentials and then simulates bombarding ions
- Predicts increased retention and reduced impurity yield with composite PFC
  - Qualitatively consistent with NSTX observations indicating reduced recycling with lithiated, graphite PFCs



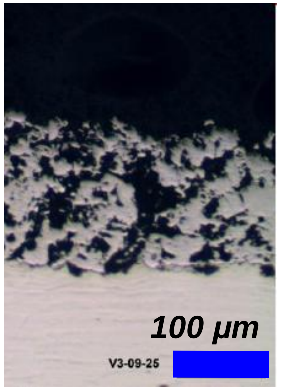
Krstic PRL 2013 (ORNL)



Canik JNM 2011

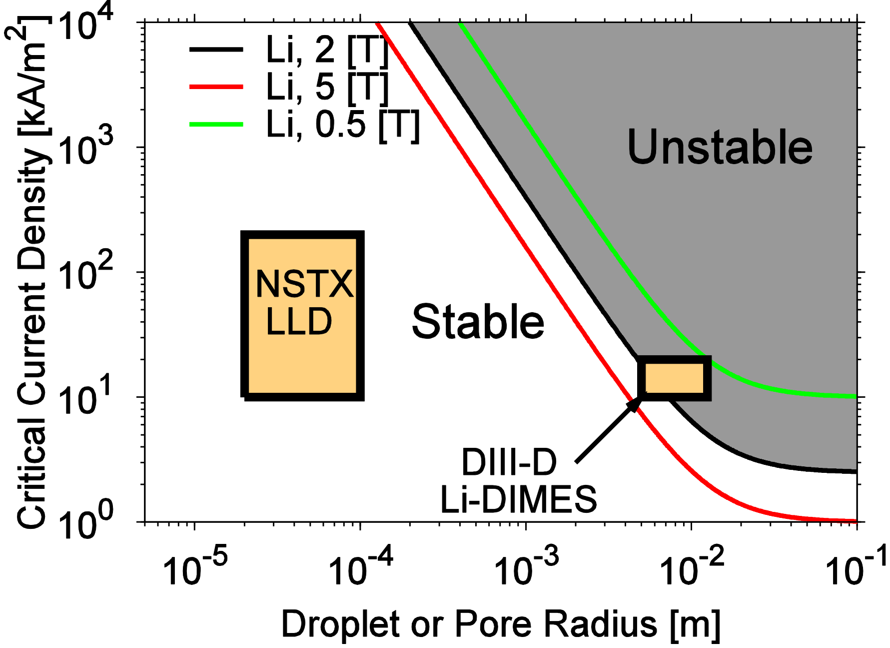
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps (cont'd)

- **Analytical modeling predicts free-surface liquid metal stability against ejection**
- Linear stability of Raleigh-Taylor droplet formation from JxB ejection forces analyzed
- Predicts stable operation with the use of porous materials and thin-layers of liquid metal
- Consistent with NSTX LLD experiments indicating no ejection events during 2010 run campaign
    - Ejection events observed on DIII-D, however



$$k_{Cr} = \sqrt{\frac{jB - \rho g}{\Sigma}}$$

For the fastest growing modes



Jaworski JNM 2011, Jaworski IAEA FEC 2012, Whyte FED 2004

Theory Plans for Goal 5

- There is a relatively new, interdisciplinary effort at PPPL, involving a developing collaboration with colleagues in academic Departments (including science, engineering and applied math) at Princeton University as well as other institutions. The goals of this program are:
  - To investigate the mechanisms of D retention in lithiated PFCs, which is fundamental to the plasma performance improvements seen in many tokamaks around the world including NSTX.
  - To investigate the nature of lithium wetting of metals and stainless steel, which is is fundamental to developing lithium coated PFCs for use in long pulse fusion devices including NSTX-U.
  - The long-term ambition is to develop liquid PFCs as a revolutionary alternative to solid PFCs such as tungsten.
- DEGAS2/XGC0/1 validation as input to fluid codes UEDGE, SOLPS

Summary

- This talk has attempted an overview of the NSTX-U Program of theory, model validation, and predictive capability. This overview has not attempted to be comprehensive, and has focused on a few important examples (with apologies for the sins of omission and commission).

- PPPL Theory and NSTX-U Theory collaborations will strongly support the high-priority research goals of the NSTX-U 5-year plan.

- The NSTX-U program has made, and will continue to make, major contributions to model validation in support of FNSF and ITER.

Backup

Validation of DEGAS 2 Simulation Code Against GPI Data

- Increase confidence in model for propagation of atoms & molecules in plasma edge.
- 3-D steady state simulations with synthetic diagnostic for GPI camera.
  - DEGAS 2 background plasma from Thomson n_e, T_e & EFIT equilibrium.
- Absolute calibration of camera & gas puff ⇒ compare photons / injected D atom:
  - GPI: 1/89 ± 34%, DEGAS 2: 1/75 ± 18%.