NSTX-U/Theory Partnership

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NSTX-U PAC

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U.S. DEPARTMENT OF ENERGY

PRINCETON UNIVERSITY

PPPL
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PLASMA PHYSICS
LABORATORY

Charge to the NSTX-U PAC

Charge: Please comment on the plans for the NSTX-U/PPPL Theory Partnership, and how well this Partnership and the broader NSTX-U research activities support “integrated predictive capability.”

Response: To help answer this charge, we will provide a discussion of NSTX-U Theory Partnership status and future plans, and how the plans are aligned with the recent FES Workshop on Integrated Simulations for MFE Sciences.

NSTX-U/Theory Partnership well-integrated into the NSTX-U Science and Topical Group structures

- Theory Department leadership in SGs/TSGs
- $1M funding, which was incremental in ≤2014, is now a permanent part of NSTX-U budget
- NSTX-U funding of Theory Department researchers ~ 4.7 FTEs
- Synergistic support through SCIDAC/Base Theory funding/Collaborators/NSTX-U project theorists (e.g., W. Guttenfelder, J.-K. Park, Z. Wang)

- Partnership facilitates collaboration over a wide range of topics

PPPL Flagship Codes

“The committee considers the three “Flagship codes” to be a very positive step.” (Advisory Board, November 2014)

Extended MHD

M3D-*C*^{1} (supported by SciDAC project CEMM, S. Jardin, *Lead*): Extended MHD, fully implicit algorithm, enabling long runs over transport time scales.

Gyrokinetics

XGC (supported by SciDAC project EPSI---C.-S. Chang, *Lead*): full-*f* code, focused on edge physics, including X-point geometry, electromagnetic effects (implemented).

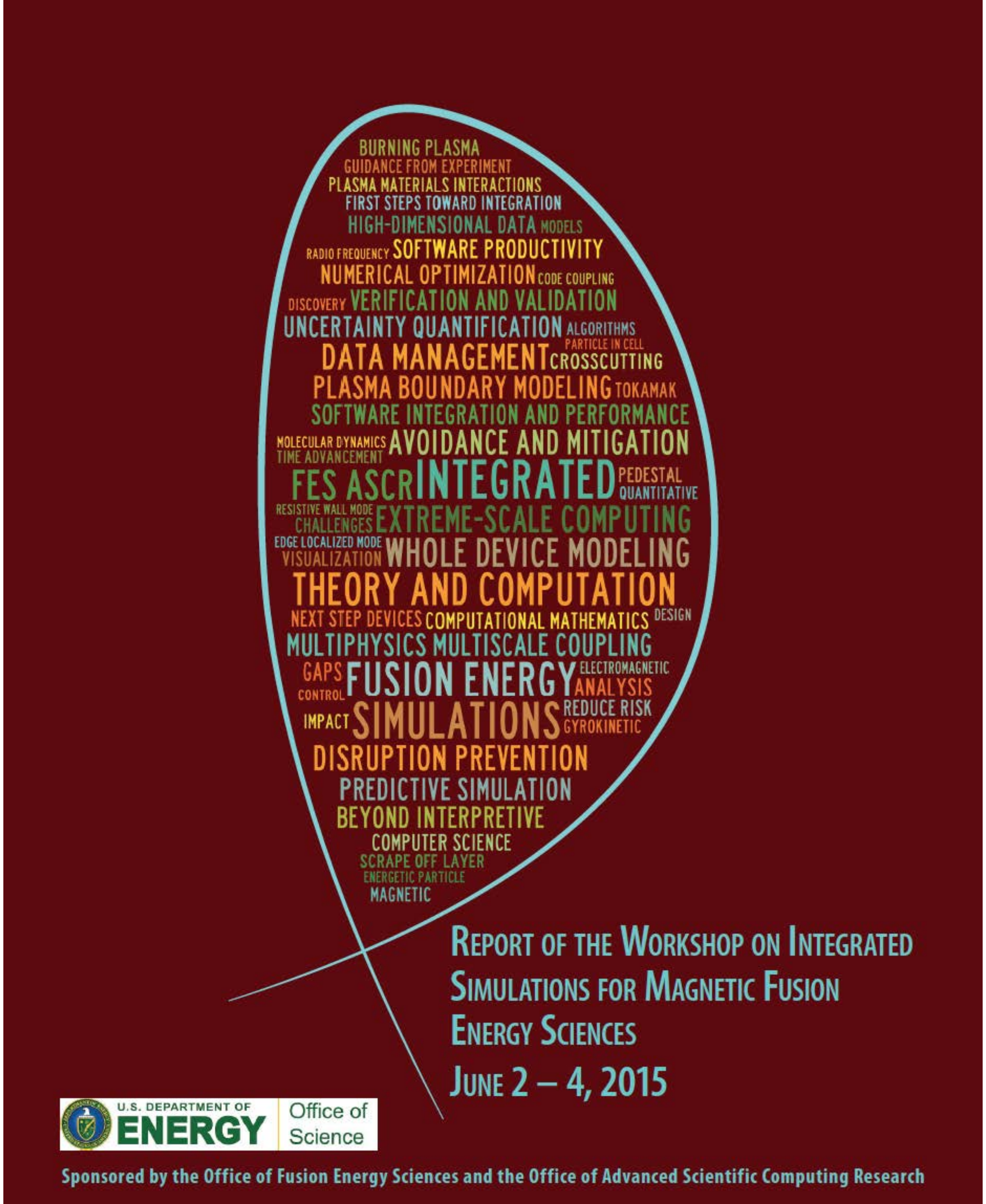
GTS (W. Wang, *Lead*): δf code focused on core physics with options for shaped boundary, electromagnetic effects (in progress).

(DOE Notable Outcome on Electromagnetic Effects in Gyrokinetic PIC codes, 2015)

Other major codes

TRANSP (Report of a new PPPL Committee, *R. Hawryluk, Chair*)

In addition to PPPL codes, we use GYRO, GENE, GS2, NIMROD, AORSA, and TORIC for design, analysis, and interpretation of experiments.



REPORT OF THE WORKSHOP ON INTEGRATED SIMULATIONS FOR MAGNETIC FUSION ENERGY SCIENCES

JUNE 2 – 4, 2015

U.S. DEPARTMENT OF ENERGY
Office of Science

Sponsored by the Office of Fusion Energy Sciences and the Office of Advanced Scientific Computing Research

FES Workshop Report, June 2-4, 2015

Assessed recent progress and gaps and challenges in fusion theory and computation directly related to theory and computation directly related to integrated simulations. The *science applications* were focused on:

- Disruption physics (aligned with goals of M3DC^1/M3DC^1-K) (*PPPL participants*: Brennan, Ferraro, Fu, Gerhardt, Jardin)
- Plasma boundary physics (aligned with goals of XGC1) (*PPPL participants*: Chang, Hammett)
- Whole device modeling (aligned with goals of TRANSP modernized) (*PPPL participants*: Grierson, Kaye, Poli)

The crosscutting ASCR areas in *mathematical and computational enabling technologies* were:

- Multiphysics and multiscale coupling
- Numerical optimization and uncertainty quantification
- Data analysis, management, and assimilation
- Software integration and performance

PPPL observers: Bhattacharjee, Zarnstorff

NSTX-U/Theory Partnership well-integrated into the NSTX-U Science and Topical Group structures

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]

NSTX-U Mission Elements
5 Highest Research Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  1. Understand confinement and stability at high beta and low collisionality
  2. Study energetic particle physics prototypical of burning plasmas

- Develop solutions for PMI challenge
  3. Dissipate high edge heat loads using expanded magnetic fields + radiation
  4. Compare performance of solid vs. liquid metal plasma facing components

- Advance ST as possible FNSF / Pilot Plant
  5. Form and sustain plasma current without transformer for steady-state ST

Theory addresses NSTX-U research priorities, using analytical and simulation tools that produce novel insights

Several aspects of NSTX-U (and more generally, ST) research require rethinking ideas and mechanisms in conventional tokamaks, leading often to new and exciting insights. Examples are:

- Energy confinement scaling at low collisionality, produced by interplay of micro-tearing, trapped electron modes, and strong sheared flows.
- Copious generation of super-Alfvenic ions due to low magnetic fields, exciting Alfven eigenmodes (AEs) which can provide new mechanisms for beam and thermal transport.
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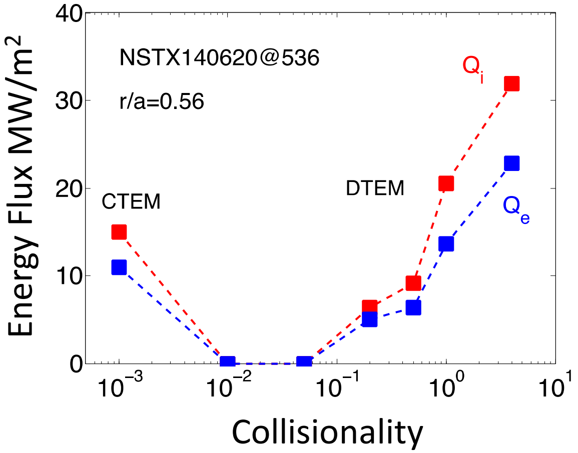
- Understanding new physics underlying pedestal structure, and SOL heat flux profiles.

- Directly ITER relevant

Global, non-linear GTS simulations giving insight into causes of thermal electron and ion transport

- Previously reported role of ITG/K-H in driving ion thermal transport in NSTX L-mode

- Recent 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 (2015)

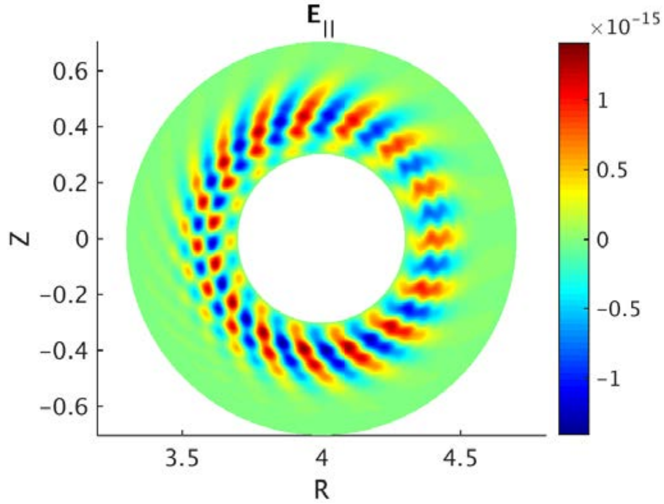
- E-M capability presently being implemented in GTS (Startsev, Wang)
  - Supported by Partnership
  - Theory “Notable Outcome” 2015 (available as a pedagogical report)
- XP1520 (Kaye): I_p/B_T scaling
  - Extend to lower ν_{*e}
  - Impact of microtearing, DTEM
- XP1521 (Ren): Validation of gyrokinetic codes in L-mode plasmas (assess importance of e-m vs. e-s modes)

R16-1, 17-3, 18-1, ITER

Latest Development of EM capabilities in GTS

- Recently, Startsev-Lee EM scheme has been extended to including key toroidal effect and ion dynamics and has been implemented into GTS.

- Currently the scheme is being tested in GTS against recently available results by A. Swamy (IPR India) for collisionless MTM and KBM eigenmodes in tokamaks with circular flux surfaces.



- Result of the GTS simulation with n=10 most unstable mode with tearing parity.

$$R/L_{Te} = R/L_{Ti} = 20, R/L_n = 5, \nu_e = 0$$

$$\beta_e = 0.5\%$$

$$R/a = 4$$

$$a/\rho_s = 50$$

$$m_i/m_e = 1836$$

- The general geometry version of the Startsev-Lee em scheme including all magnetic drifts has been formulated and is currently being implemented into GTS.

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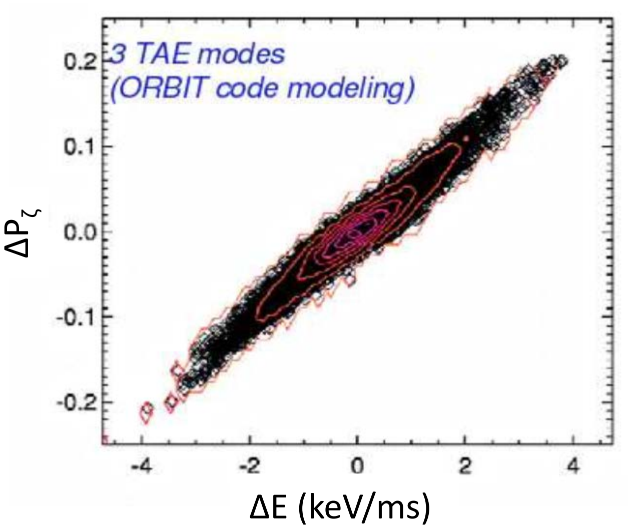
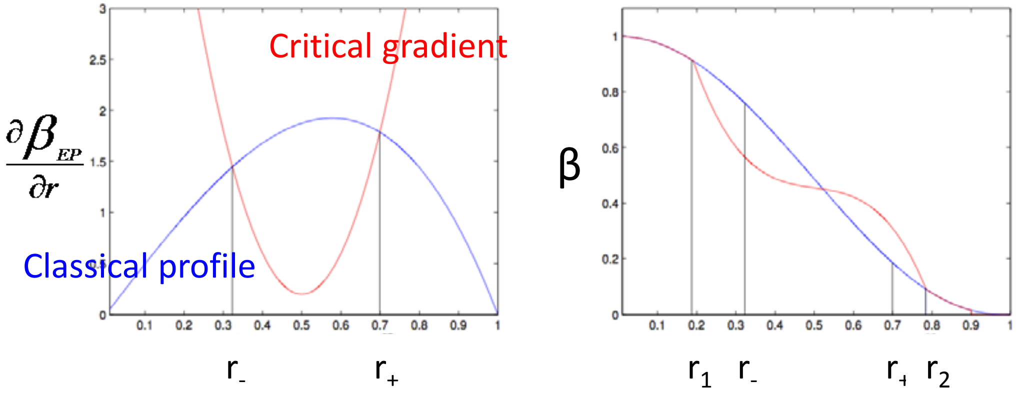
Beam ion confinement: Models for fast ion profile relaxation in presence of AEs under development

- “Kick” model (Podesta)
  - PDF computed by ORBIT (White) in presence of TAEs
  - Mode structures computed by NOVA (Gorelenkov)
  - Kicks ~ mode amplitude
  - Being used in DIII-D analysis



R16-2, R18-2, IR18-2, ITER

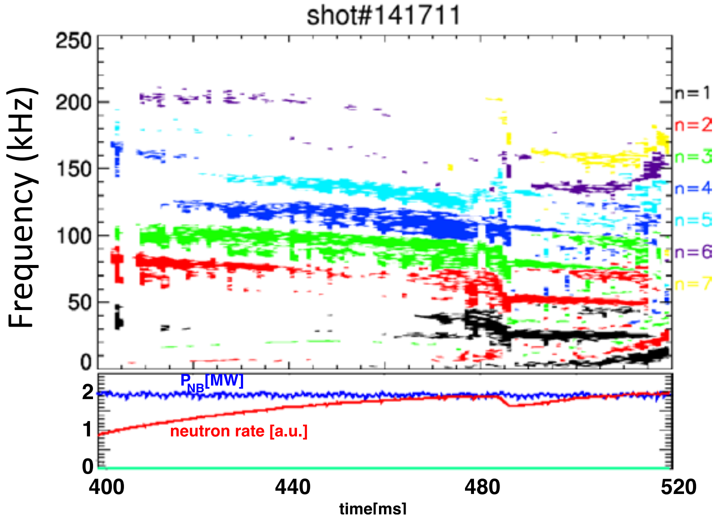
- Critical Gradient Model (Gorelenkov)
  - Compute critical $\frac{\partial \beta_{EP}}{\partial r}$ due to AE
  - Mode growth/damping computed by NOVA-K (Fu, Gorelenkov)
  - Originally benchmarked on DIII-D

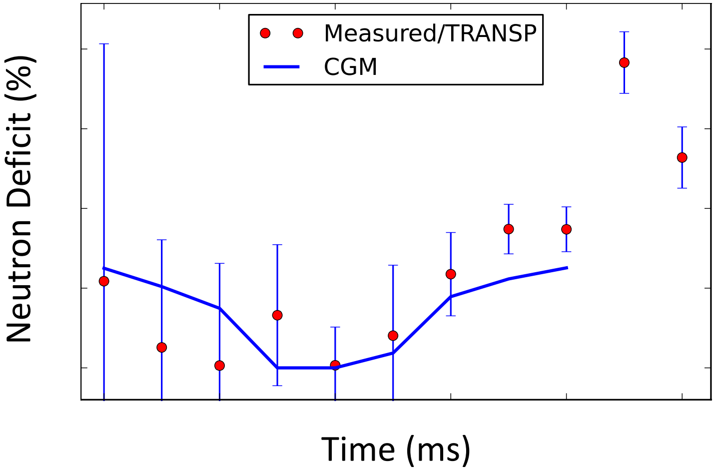


CG used to relax EP profile. It is broadened from the initially unstable one between $r_\pm \rightarrow r_{1,2}$

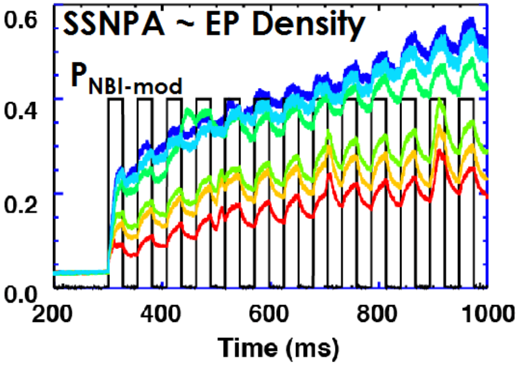
CGM recently validated for NSTX

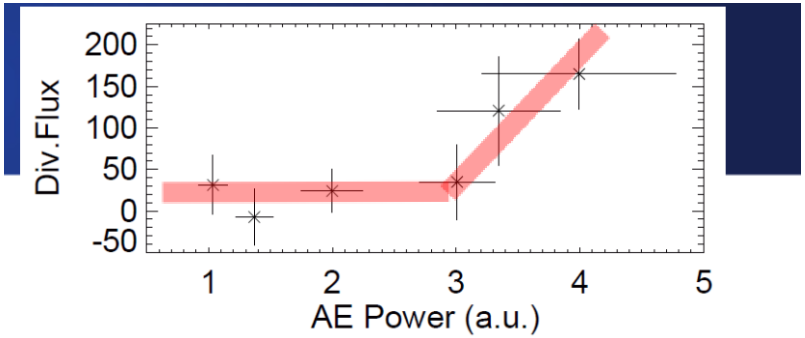
- Multiple TAE unstable discharge chosen for validation





- XP1524 (Heidbrink) directly tests CGM
  - Fashioned after successful DIII-D expt.
  - Different AE activity on NSTX(-U) crucial test for validating theory

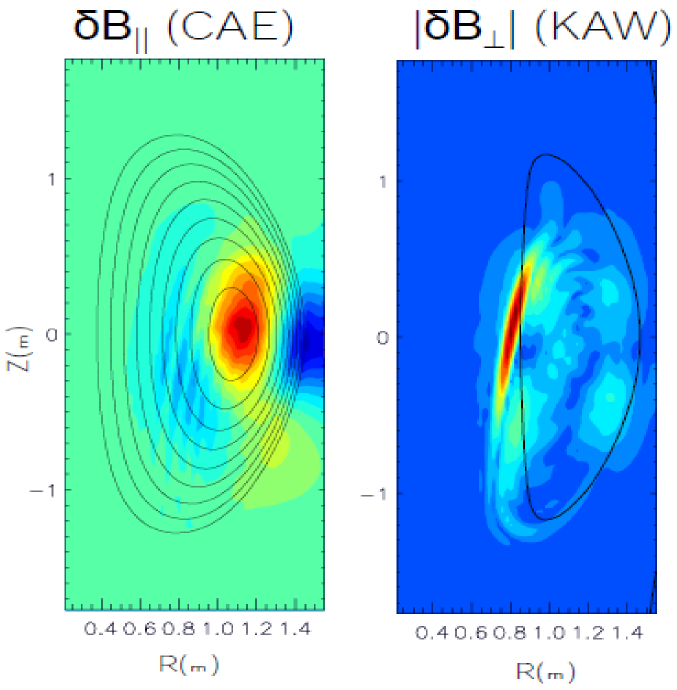




Other related XPs include XP1522, 1523 (characterize 2nd beam, beam confinement)

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

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



Belova PRL 2015

- Calculate 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 ™T_{e0})
- XP1525 (Crocker): Rotation effects on CAE/GAEs
- XP1520 (Kaye), 1523 (Podesta): Effects of collisionality, power on transport

R16-1,2, 17-3, 18-2, IR18-2, ITER

Theory addresses NSTX-U research priorities, using analytical and simulation tools that produce novel insights

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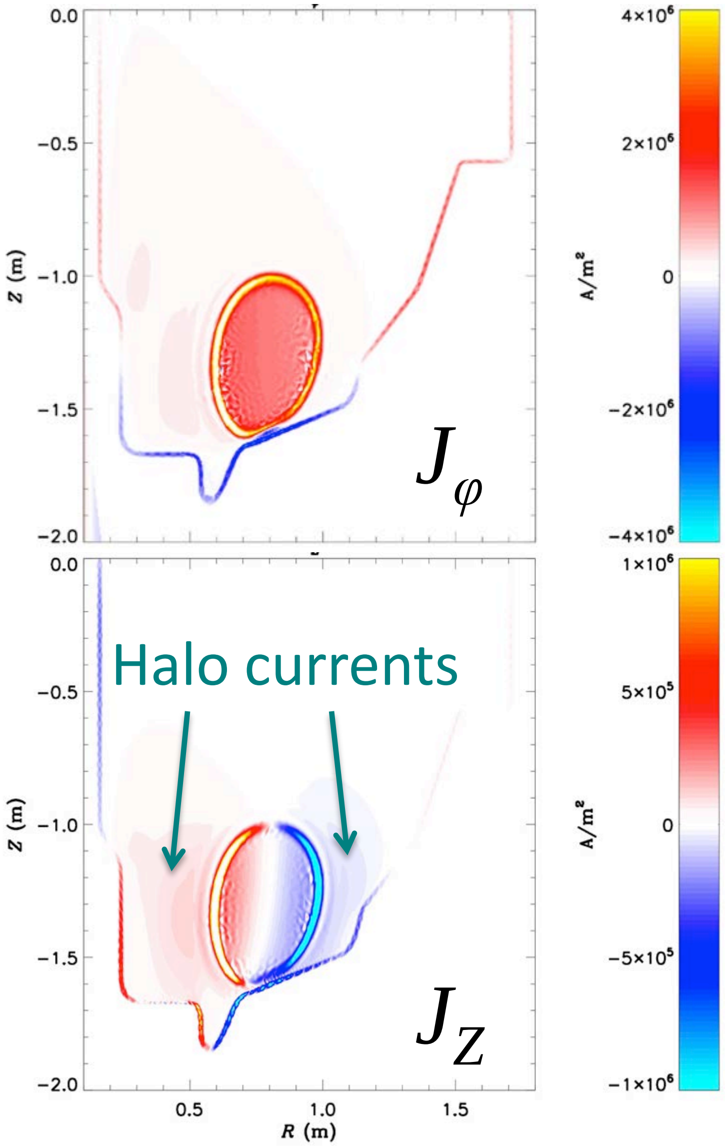
- Directly ITER relevant

Simulating Disruptions and Halo Currents Using New Modeling Capabilities

- New resistive wall model in M3D-C1 allows unique capability to simulate mode locking and current-quench

- Includes self-consistent treatment of rotation and Halo currents
  - We will seek to validate these models against NSTX-U data

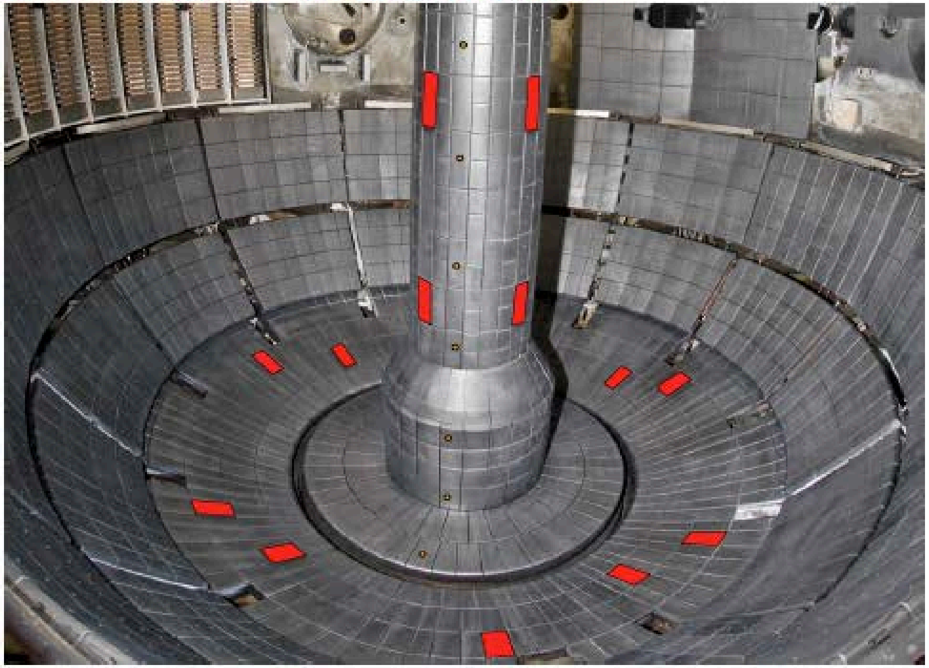


M3D-C^1 with RW capability will be used to map out optimal placement of new B-sensors to study halo currents

- Dynamics of halo currents and forces critical for ITER: particular concern are halo current asymmetries and rotation
- New sensors will measure halo currents, B-fields and JxB forces in NSTX-U
- Critical theoretical issues: (i) role of boundary conditions (ii) halo current distributions in 3D conducting structures (D. Pfefferle)

Planned NSTX-U Base Configuration

Normal Current Tiles Single Axis B Sensors

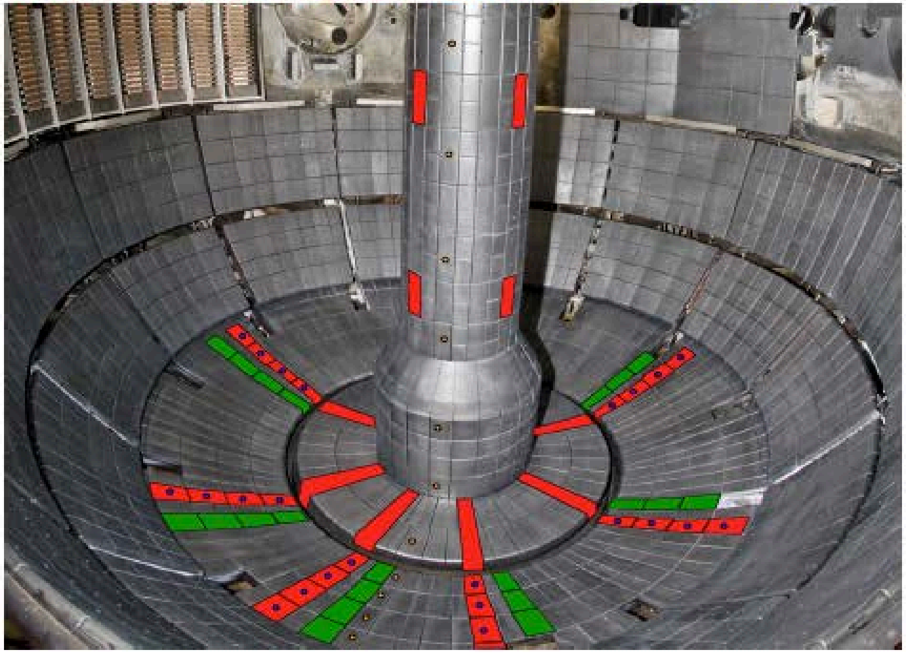


Potential NSTX-U Expanded Configuration

Normal Current Tiles Single Axis B Sensors

Tangent Current Tiles

Multi-Axis B sensors

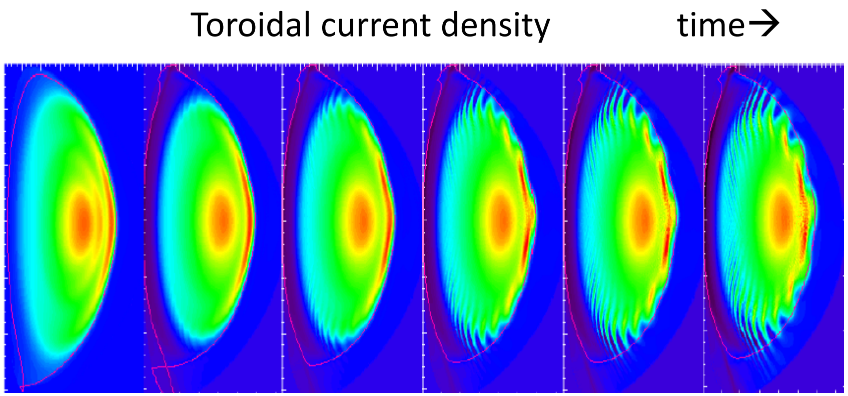


joint NSTX-U/Theory task

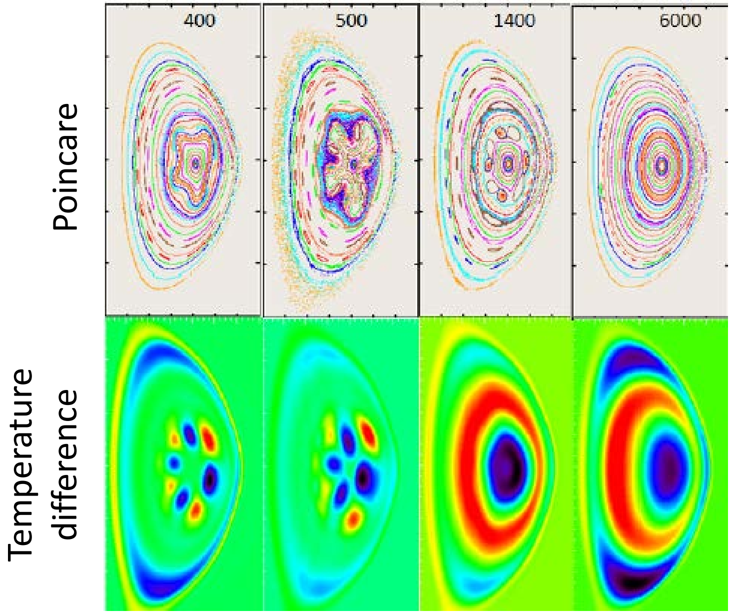
R16-3, 17-2, 18-2, 2016 JRT, ITER

Which linear instabilities lead to thermal quench and disruption?

- Rapid end-of-shot current ramp-down in NSTX led to disruption. Nonlinear modeling of this is improving understanding.

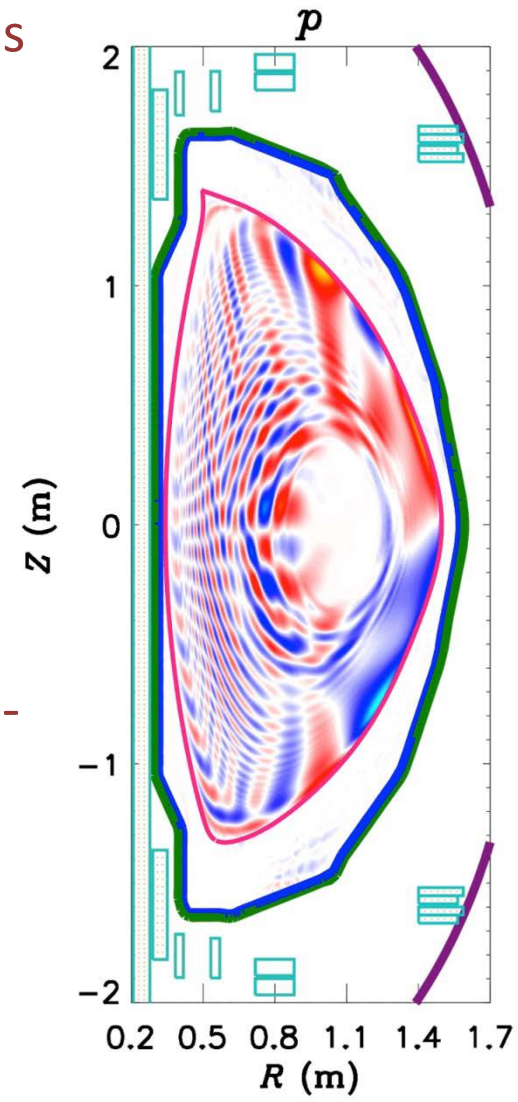


- Heating NSTX past the ideal MHD β-limit in some cases just leads to enhanced transport
  - Goal is to predict when this leads to a thermal quench



Understanding RMP ELM Mitigation in New Regimes

- ELMs in STs and tokamaks respond to applied 3D fields in opposite ways
  - Understanding this discrepancy would substantially improve our confidence in scaling RMP ELM mitigation to ITER
- NSTX-U offers a unique capability to validate ELM suppression models across the ST and tokamak regimes
- Combining models of 3D perturbed equilibrium (M3D-C1) and transport (XGC) will yield a quantitative, predictive model for transport in 3D fields
- M3D-C1 is being used to predict and optimize plasma response to NCC coils in NSTX-U



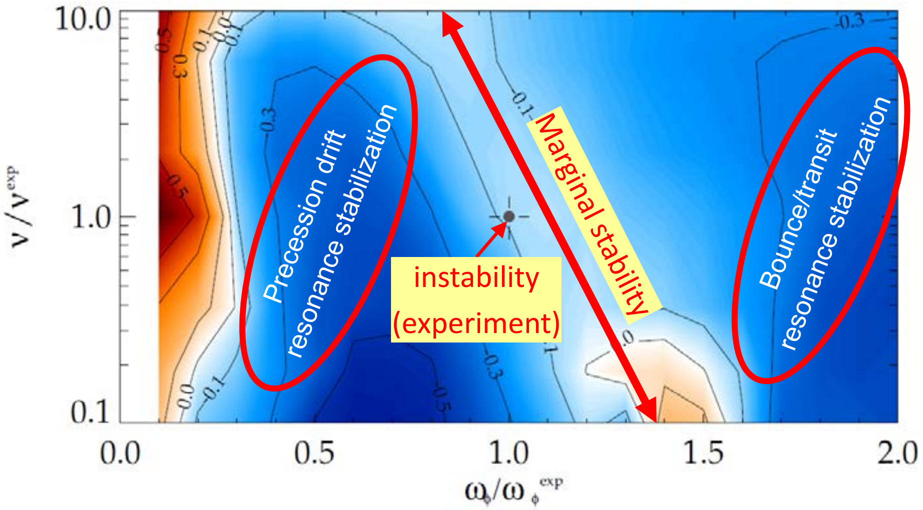
NSTX-Theory collaborations have led the advancement in kinetic global mode stability physics

RWM kinetic stability physics theory

$$\gamma\tau_w \simeq -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

(Betti, Berkery, Sabbagh)

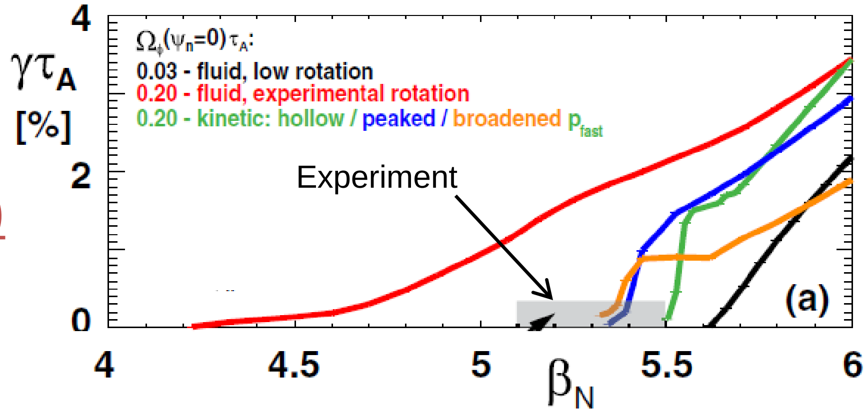
MISK: RWM kinetic stability (Berkery, Sabbagh)



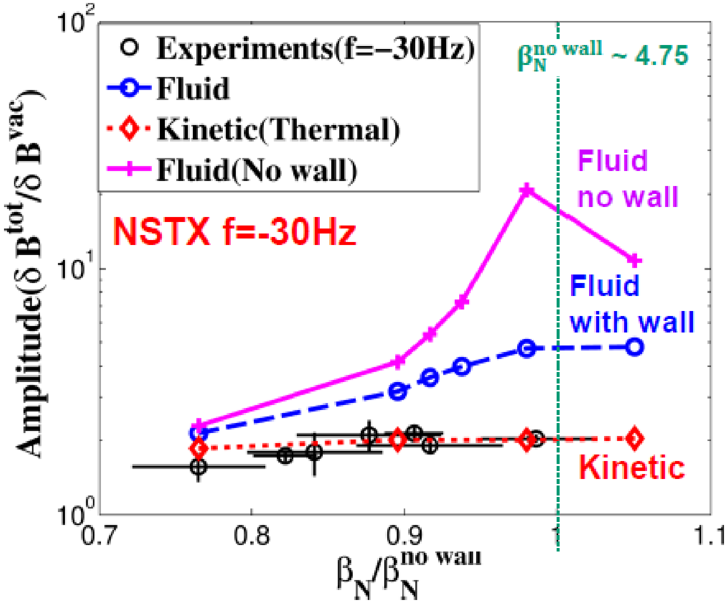
RWM physics with M3D-C^1 (Ferraro)

- Resistive wall implemented

MARS-K: Ideal wall stability (Menard)



MARS-K: Resonant field amp. (Wang)



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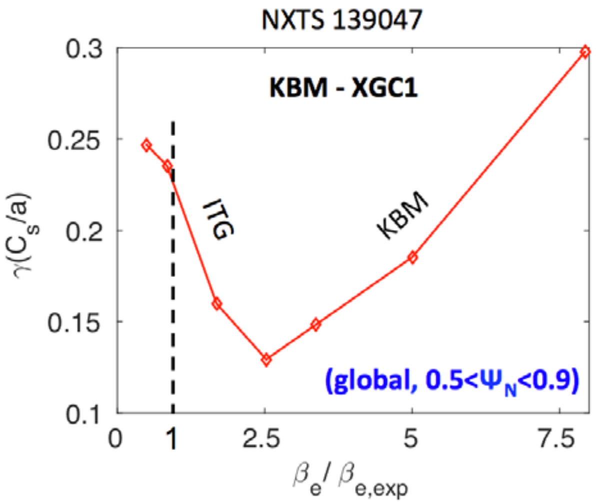
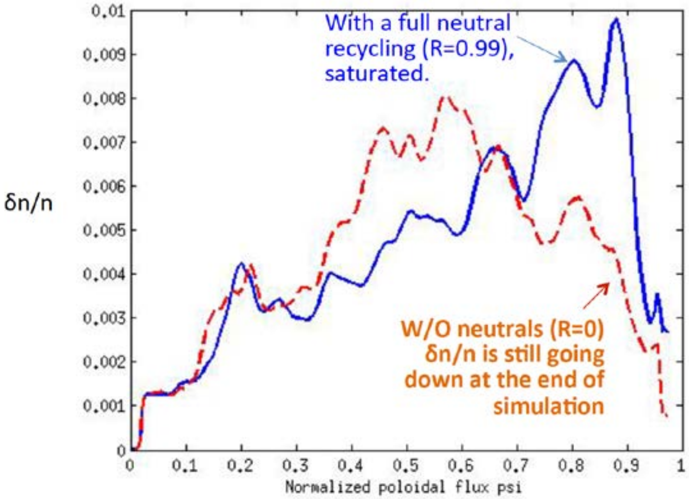
XGC results for NSTX edge plasmas

- **Understanding turbulence in NSTX edge plasma**
  - Most likely, the turbulence seen at pedestal top are ITG mo (*Diallo, Nucl. Fusion 2013*), not KBMs (*recent study*)
    - Cross verification between E&M XGC1 (*global, S. Ku*) and GYRO (*flux-tube, W. Guttenfelder*) confirmed that β is well below β_{KBM}
  - Peeling type kinetic e.m. modes can exist in steep NSTX pedestal, but KBMs are not found (*PPPL-Theory Notable Outcome report to DOE, 2015*)
  - Verified existence of blobby turbulence in extended SOL
- **Divertor heat-flux width**: The $1/I_P$ type scaling in NSTX is from neoclassical orbit spread. Only ~30% effect from blobby spread (*DOE-FES National Theory Performance Target, led by Chang; Chang, IAEA16*)
- **Bootstrap current in NSTX pedestal** is significantly different from Sauter (*Hager, submitted to Phys. Plasmas*), and can alter the NSTX edge stability diagram (*Sabbagh, Nucl. Fus. 2013*)
- **Verified importance of the neoclassical ExB shearing in L-H transition** in NSTX (*Battaglia, Nucl. Fusion 2013*)



XGC plans for NSTX-U



With a full neutral recycling (R=0.99), saturated.

W/O neutrals (R=0) δn/n is still going down at the end of simulation

Large difference in edge turbulence seen by XGC1 between zero and full neutral recycling.

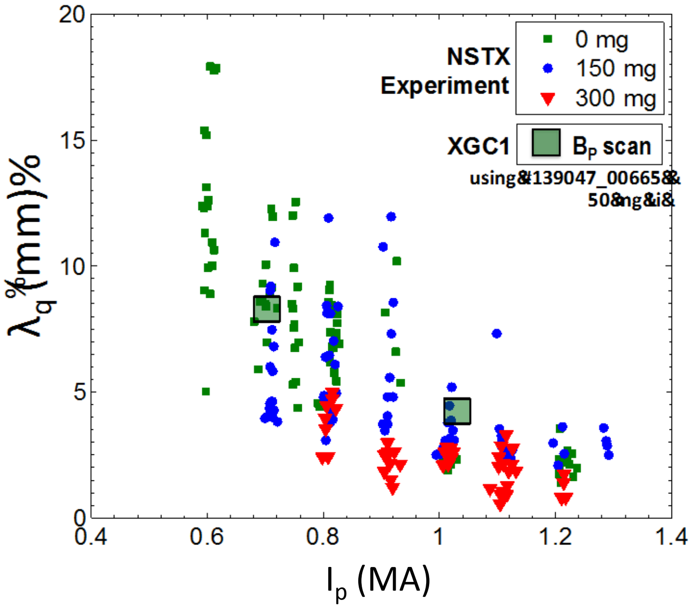
Additional plans for NSTX-U by XGC are

- Impurity studies (turbulence, including neoclassical effects)
  - How will the high and low Z impurity particles from SOL penetrate through the pedestal?
  - What will be their saturated radial profiles in the core?
  - What will be the impact of high and low Z impurities on pedestal confinement? On ExB shearing rate?
- Kinetic study of 3D field penetration into plasma, and effect on pedestal transport and shape.
- Enhancement of the XGC e. m. to include micro-tearing modes
- L-H transition physics
- Pedestal shape up against turbulence criticality and ELMs
- Incorporate DEGAS in XGC, including high-Z atomic physics

XGC1 simulations aid in understanding basis for SOL heat flux trends in NSTX

- Experiment shows contraction of SOL heat flux width at midplane with I_p as well as influence of Li conditioning

XGC1 calculations with collisions show similar trend with I_p



Heat flux width determined primarily by neoclassical processes

XP 1514:

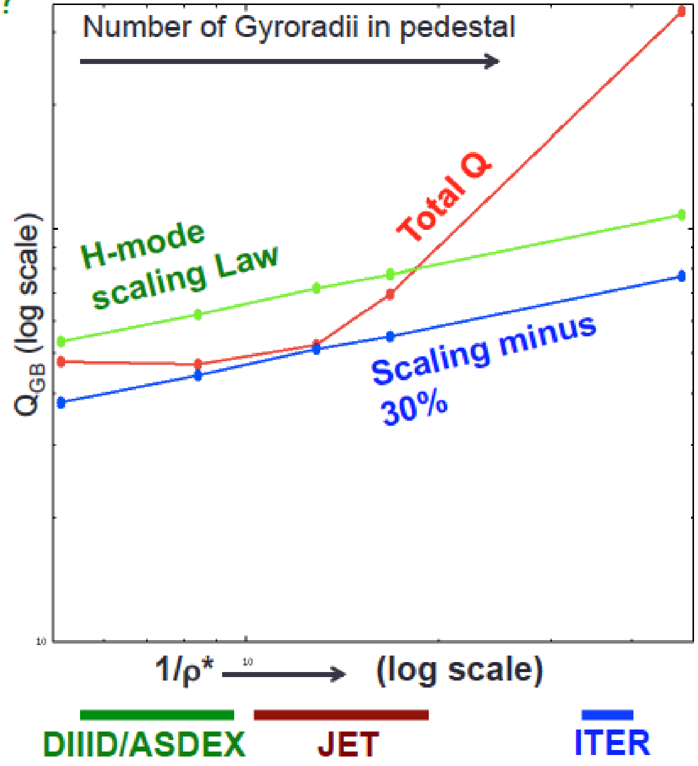
- (Gray) – Heat flux width scaling in NSTX-U; extend range of I_p, shape, Li dependence
- (Gray) – Is interchange drive responsible for SOL contraction with Li (in collaboration with LODESTAR)?

R16-1, 17-1, ITER

IFS Collaboration with NSTX-U-Theory Group

How does the magnitude of the gyrokinetic heat flux compare to typical experimental values ?

- ***Employ a rough estimate: use the H-mode scaling law to estimate the power required to produce these plasmas***
- ***The transport found in GENE for these model profiles is somewhat lower than the scaling law, but within ~ 30%***
- ***But beyond some ρ^* of JET, the transport trend is clearly much worse than the scaling law***



Kotschenreuther (2015)

Preliminary results indicate a surprisingly optimistic prediction for ST plasmas due in part to the localization of unstable eigenfunctions in the region of strong velocity shear: to be studied by XGC in a complementary study, including X-point geometry.

Flux closure and reconnection studies during CHI in NSTX/NSTX-U

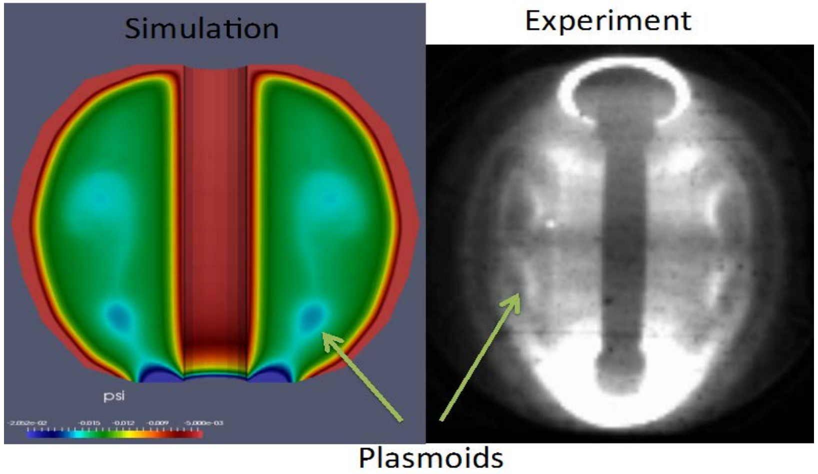


Fig2: Left: Plasmoid formation in simulation of NSTX plasma during CHI / Right: Fast-camera image of NSTX plasma shows two discrete plasmoid-like bubble structures.

- CHI experiments provide a very rich platform for studying magnetic reconnection
- Fundamental reconnection physics in NSTX-U, in particular reconnecting plasmoids physics will be explored in both the simulations and the experiment.

Comprehensive resistive MHD simulations have been conducted for the NSTX and NSTX - U:

The goals:

- To achieve maximum flux closure and CHI-generated current
- How transient CHI scales as it is extrapolated to future (larger) devices such as the ST-FNSF
- Understanding the physics of magnetic reconnection during CHI is of great importance for the viability of this concept.

Ebrahimi et al PoP 2013, 2014. PRL 2015, submitted to NF.

NSTX-U/Theory Partnership is focusing on issues central to achieving NSTX-U goals

- Both over-arching goals and specific yearly Research Milestones (RMs)
  - Matched personnel to topical choices
  - Attempted to provide mapping to Goals, Milestones
- Partnership funding now integrated into the NSTX-U budget
  - No longer incremental
- Theory work not limited to PPPL Theory/NSTX-U partnership
  - Augmented by project theorists, collaborations, SCIDAC, direct Theory coverage of personnel
- Significant synergy with work on DIII-D by same personnel – aspect ratio, β, ν_*, ρ_* leverage on theory validation
  - Confinement/effects of AE modes on fast-ion distribution, RMP/NTV/RWM physics, RF heating and current drive, pedestal/SOL characteristics, core transport

Additional Slides

Other related Theory-Experimental work

Theory	Experiment
1. Develop and implement self-consistent fast ion distribution for calculating HHFW heating and CD using TORIC/NUBEAM/TRANSP (Valeo) – R16-3, 17-4, IR17-1, R18-2, ITER	1. XP1507 (Gerhardt): High non-inductive fraction, high performance discharges
2. RMP/NTV physics for rotation control (Ferraro, Z. Wang, + CU, PU) – R16-3, 17-4, 18-2, 2016 JRT, ITER	1. Multiple XPs study effect of rotation, NTV (T&T, CAE/GAE, TAE gap structure, RWM control and disruption mitigation)
3. RWM physics with M3D-C^1 (Ferraro) – Resistive wall implemented – R16-3, 18-2, ITER	1. Multiple RWM XPs
4. Edge neutral density calculations using ENDD diagnostic + DEGAS2 (Stotler) – R16-1, 17-3, 18-1, ITER	1. Critical info for TRANSP (beam deposition, particle transport), XGC1 (collisional effects in edge)