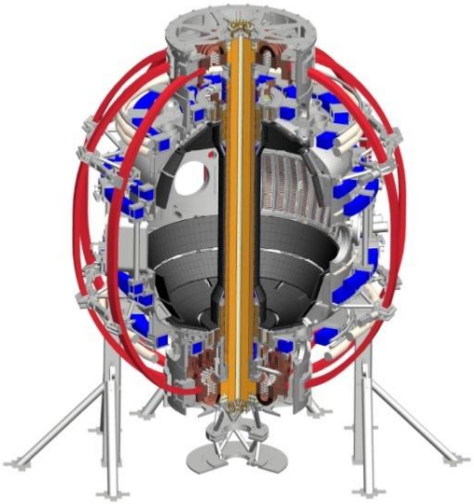
Theory needs for NSTX-U and ITER

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

J. Menard, S. Kaye, and the
NSTX-U Topical Science Group Leaders

PPPL Theory Department Retreat
Princeton University and PPPL
September 24-25 and 27, 2012



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

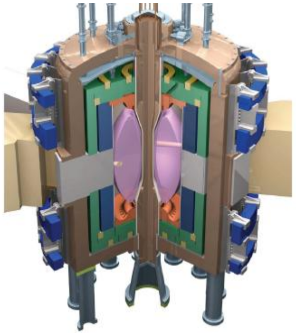
- **NSTX Upgrade – mission and Upgrade project elements**
- **Theory and modeling needs organized by topical area**
- **Some opinions on prioritization**

Note: Much of this content was developed by the NSTX-U topical science group (TSG) leaders for the NSTX-theory brainstorming meeting and for the NSTX-U PAC-31 and five year plan

- http://nstx-u.pppl.gov/five-year-plan/five-year-plan-2014-18/theory-needs-and-requirements
- http://nstx-u.pppl.gov/program/program-advisory-committee/pac-31

NSTX Upgrade Mission Elements

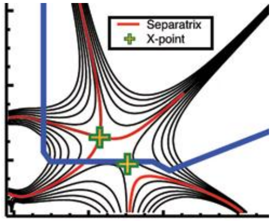
- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**



ST-FNSF

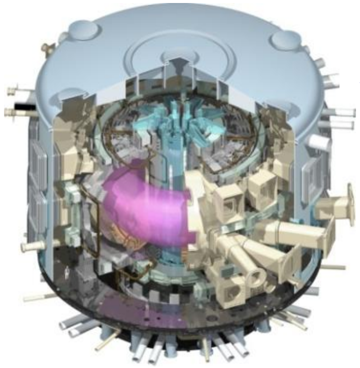
- **Develop solutions for plasma-material interface**

Lithium



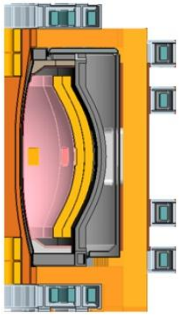
"Snowflake"

- **Advance toroidal confinement physics predictive capability for ITER and beyond**



ITER

- **Develop ST as fusion energy system**

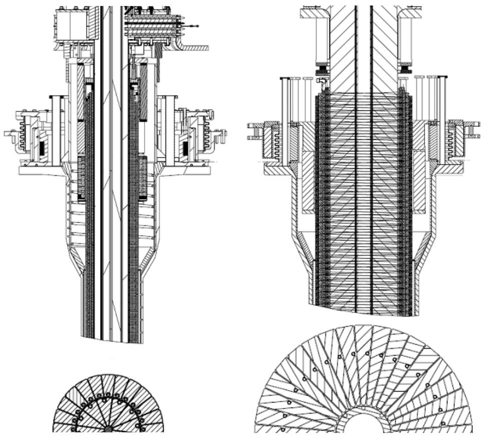


ST Pilot Plant

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

Previous center-stack

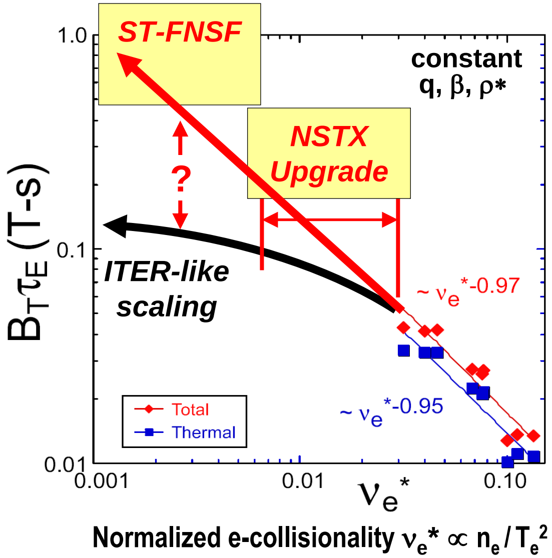
New center-stack

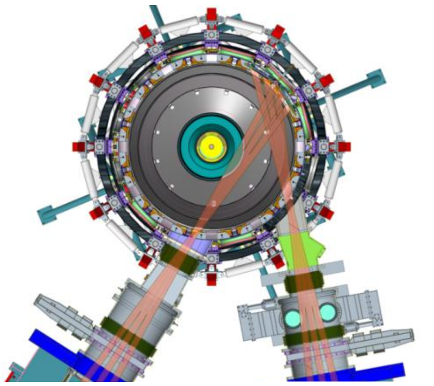


TF OD = 20cm

TF OD = 40cm

- 2 × 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





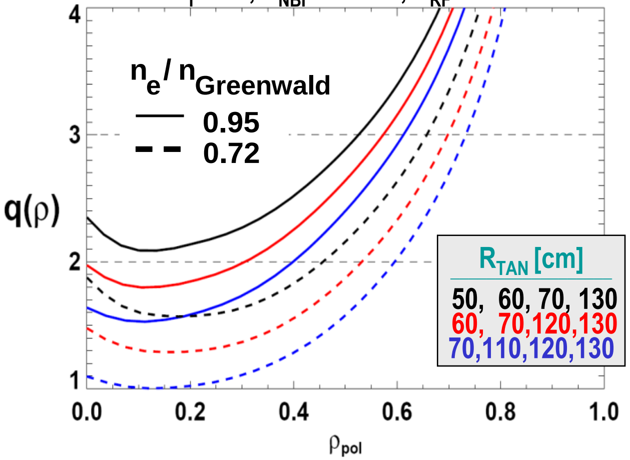
Present NBI

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



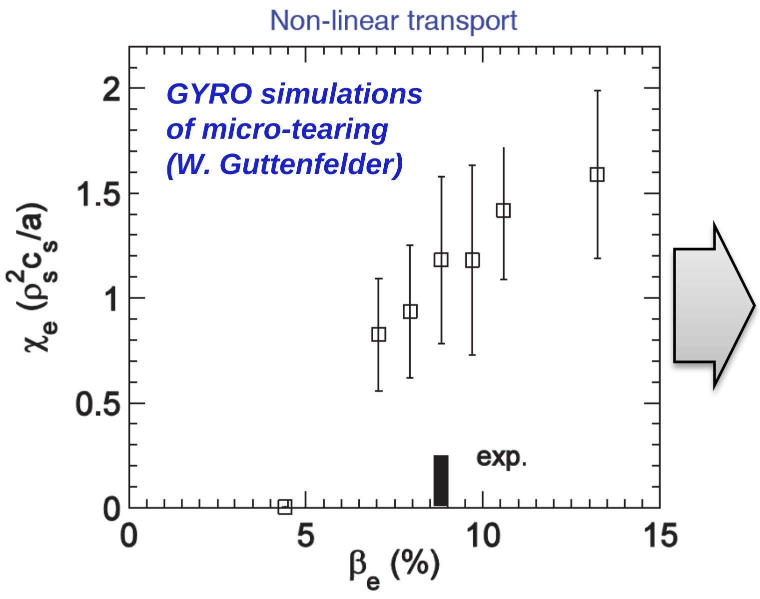
Topical Areas

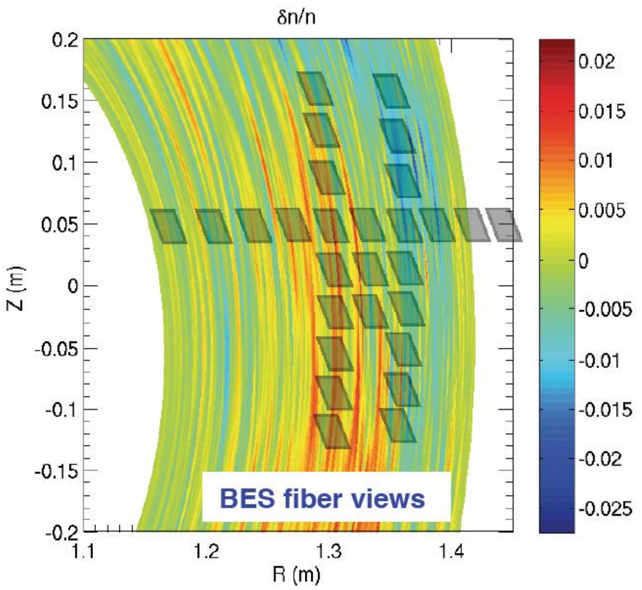
- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

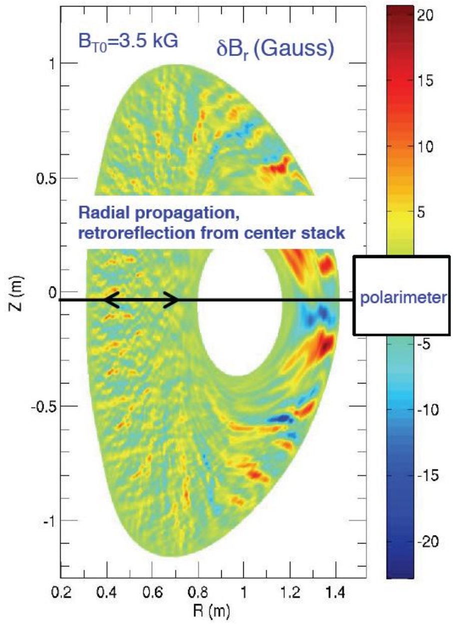
Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

NSTX-Upgrade will extend diagnosis and understanding of micro-instabilities potentially responsible for anomalous transport in STs







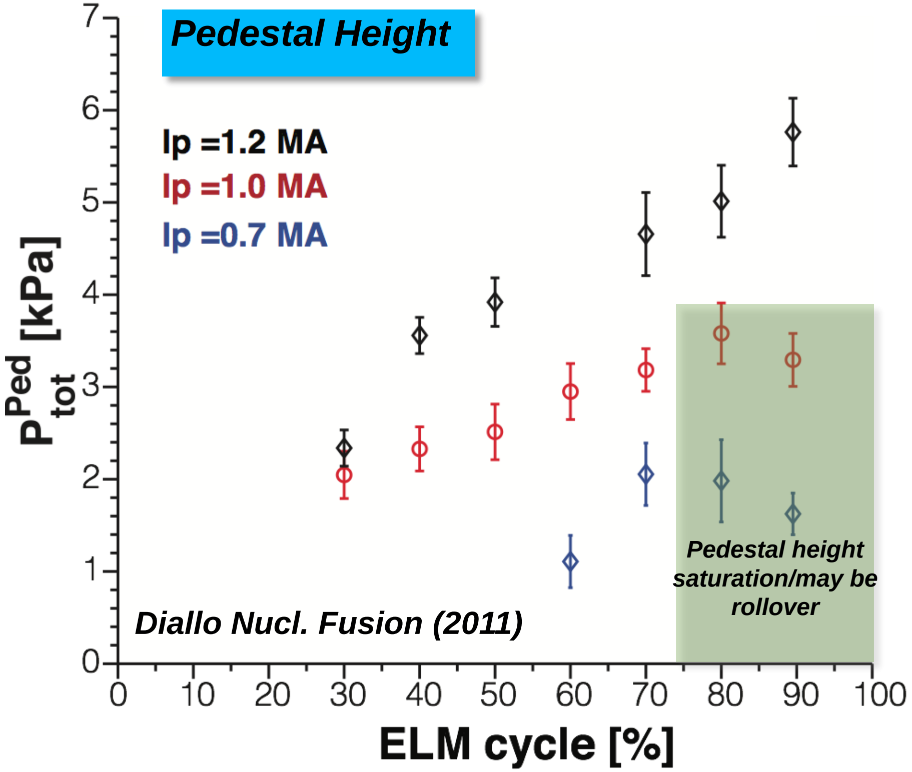
- Electrons dominant loss channel for ST thermal confinement
  - –Micro-tearing strong candidate for anomalous thermal e-transport at higher β
  - –ETG can also contribute to e-transport at lower β
  - –Alfvénic instabilities (GAE/CAE) can also cause core electron transport
- NSTX-U goal is to study full turbulence wave-number spectrum:
  - – low-k – ITG/TEM/AE/μ-tearing (BES, polarimetry) + high-k – ETG (μ-wave scattering)
- NSTX-U enables access to unique turbulence regime with high β + lower ν*

NSTX-U theory and modeling needs for Transport and Turbulence

- NBI-heated H-mode core-flat region (r/a <~ 0.4)
  - Empirical/semi-empirical scaling of core T_e profile flattening with fast ion population, gradient, β_{fast}, etc…
  - Simulations of fast particle driven instabilities and associated transport
  - Development of reduced models (theory, semi-empirical, etc…) of χ_e, χ_ϕ and $D_{j||}$ for use in predictive simulations
  - The effect of turbulence spreading from H-Mode core gradient region (r/a~0.4-0.9)

- H-Mode core gradient region (r/a ~ 0.4-0.9)
  - Identify1D profile database for model validation from relevant discharges
  - Test TGLF (or develop other reduced models) against linear and nonlinear gyrokinetics for NSTX-relevant parameters, especially for ETG, micro-tearing
  - Develop reduced models with global effects
  - May need global, multi-scale simulations due to large profile variations
  - Reconcile anomalous electron and momentum transport with neoclassical χ_i

Pedestal width and height progressively increase during ELM cycle but the peak pressure gradient remains clamped

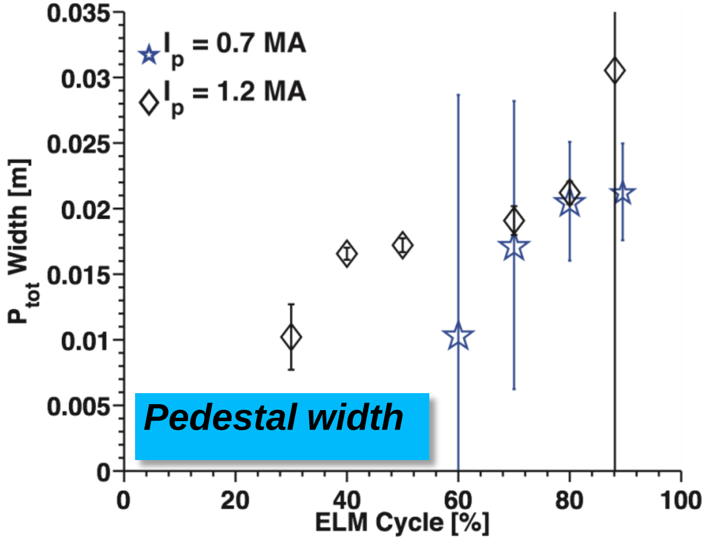


Pedestal Height

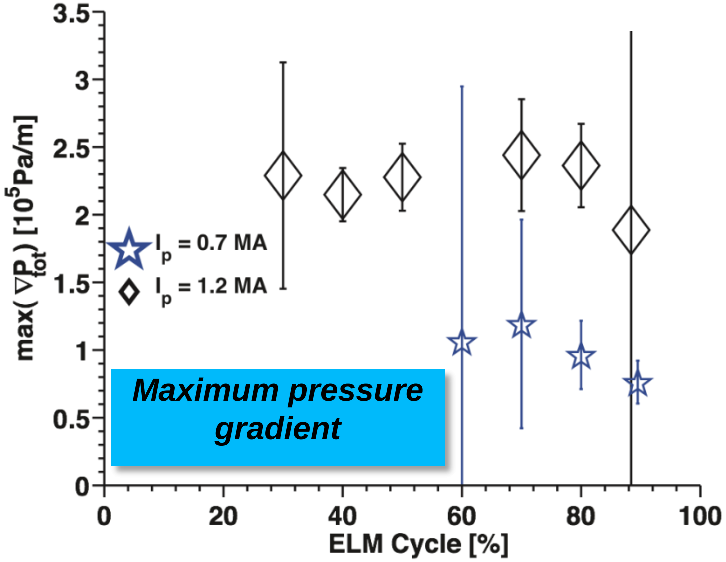
Pedestal height saturation/may be rollover

Diallo Nucl. Fusion (2011)

- Pedestal height increases by a factor ≤ 3
  - Height scales with I_p
- Pedestal width increases independently of I_p
- Gradient is clamped early in ELM cycle



Pedestal width



Maximum pressure gradient

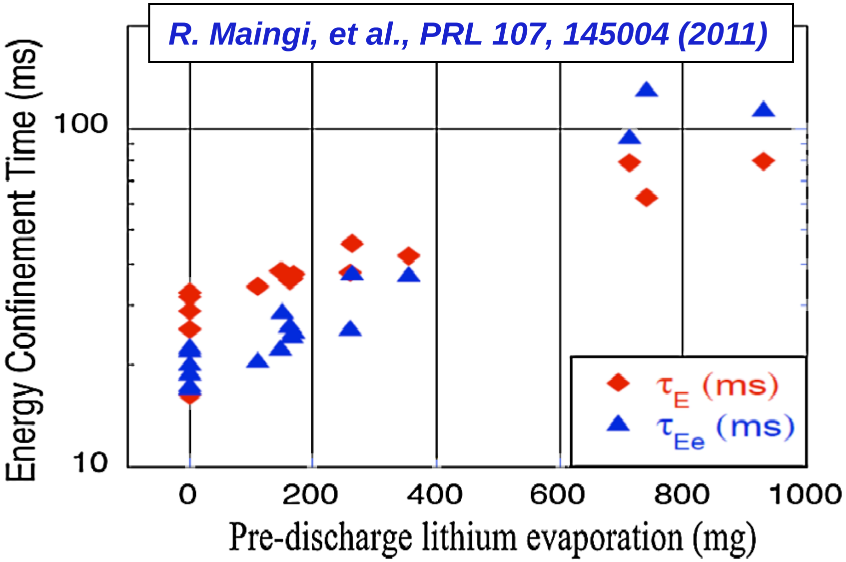
NSTX-U theory and modeling needs for pedestal turbulence, transport, stability

- H-mode pedestal (r/a>0.9)
  - Empirical/semi-empirical scaling of pedestal height & width with “engineering” parameters (I_p, B_T, n_e, Z_{eff}) and/or theory parameters (ν^*, β, ρ^*)
  - Development and validation of pedestal height models with data (EPED1, others)
  - Pedestal turbulence (Local and global gyrokinetic, fluid codes, e.g. GYRO, XGC, BOUT++, GTS, GEM)
  - Predict microstability (KBM,…) thresholds in pedestal (linear gyrokinetics, others)

- Role of Li in confinement improvement, ELM suppression
  - Energy confinement increases continuously with increased Li evaporation in NSTX
  - High confinement very important for FNSF and other next-steps

    what is τ_E upper bound?

R. Maingi, et al., PRL 107, 145004 (2011)

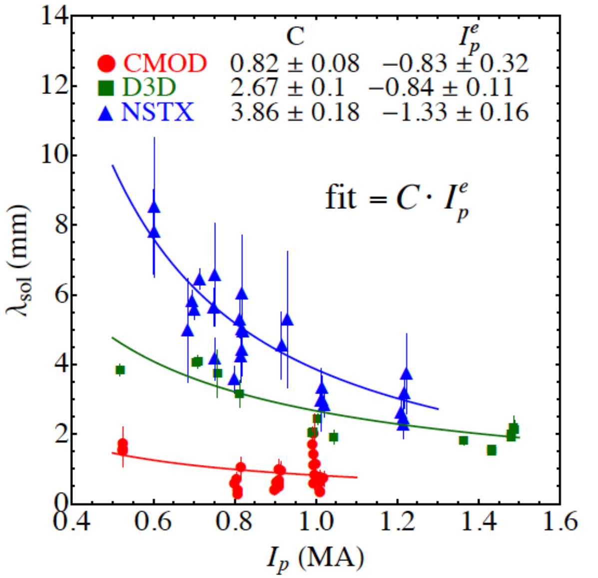


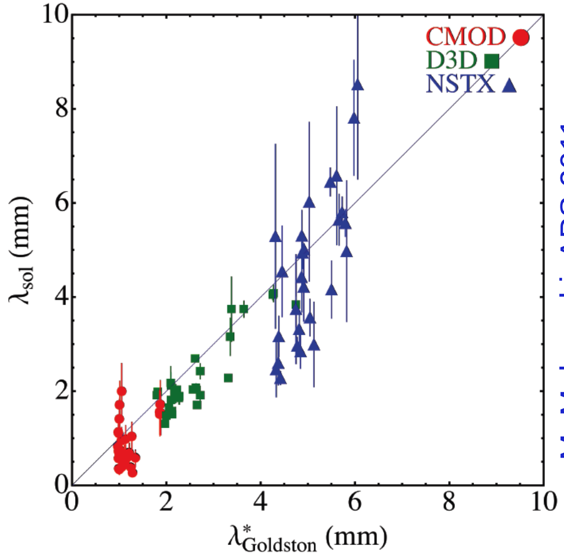
Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

SOL width and divertor heat flux studies in NSTX elucidate on divertor projections for NSTX-U, ST-FNSF and ITER

- λ_q^{mid} contracts with increasing I_p: $\lambda_q^{mid} \sim I_p^{-1.3}$
- Comparison with SOL models
  - Parallel transport: conductive/convective, cross-field : collisional / turbulent / drift
  - XGC0 reproduced I_p dependence $\lambda_q^{mid} \sim I_p^{-1.0}$
  - SOLT: I_p scaling is weaker than observed
    - P_{SOL}, collisionality, L_{II}/R set cross-field transport and turbulence structure that affect λ_q
  - Goldston drift-based model of SOL flows
    - Attached H-mode regimes, $\lambda_q \sim (2a/R)\,\rho_i$
    - ∇B and curvature drift motion sets SOL width, Spitzer thermal conduction sets T_{sep}
  - Exploring mechanisms setting steep pressure gradient region and connection to SOL width
- Projections to NSTX-U
  - $\lambda_q^{mid} = 3 \pm 0.5$ mm
  - As $q_{peak} \sim I_p$ and $q_{peak} \sim P_{SOL}$, $q_{peak} \sim$ 20-30 MW/m^2

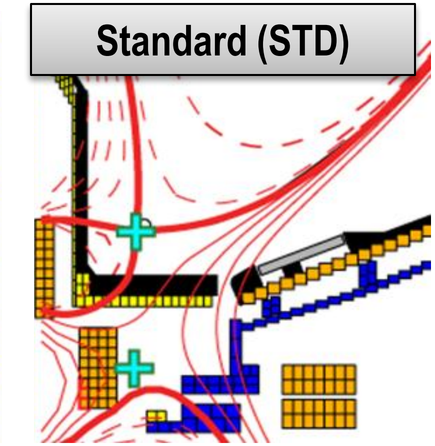




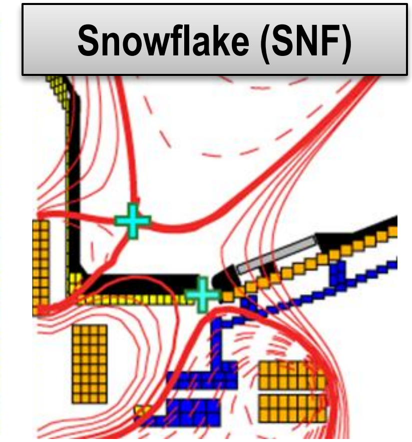
M. Makowski, APS 2011

NSTX-U theory and modeling needs for Boundary Physics

- Scrape-off layer width, transport, and turbulence
  - Role of turbulence and convective cells in setting SOL width
  - Impact of Li on the SOL width, physics of collisionless SOL
  - Characterization of the edge flows, interplay between blobs and flows
- Divertor transport, radiation and plasma-surface interactions
  - Steady state and transient transport in standard, snowflake divertors
  - Validate fluid, kinetic and gyro-kinetic edge transport models
    - Also validated radiation models including high Z atoms, PMI models

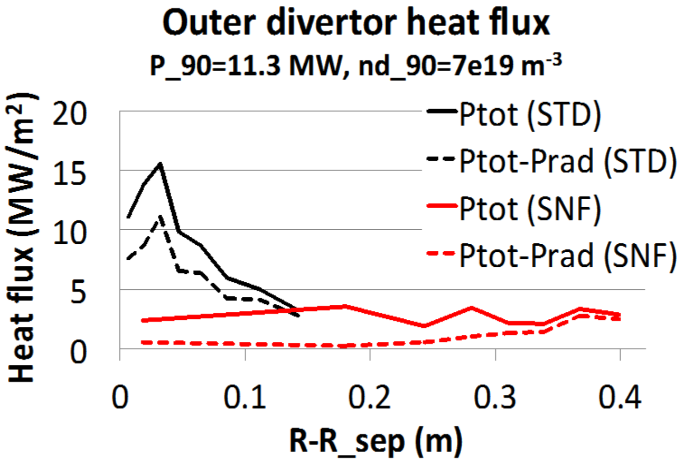


Standard (STD)



Snowflake (SNF)

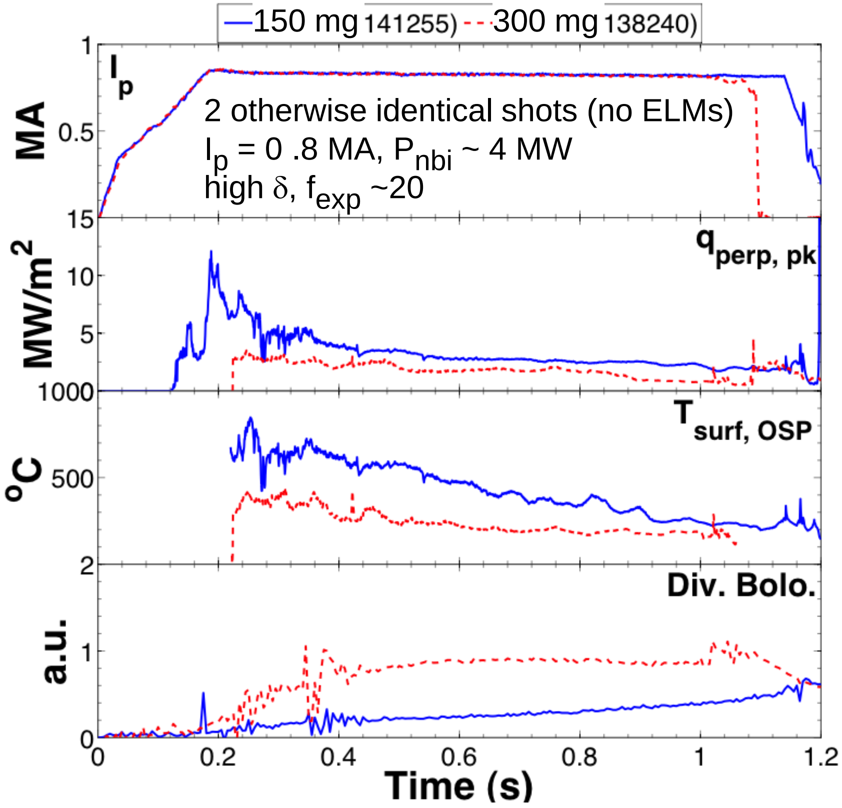
q_{peak} reduced from ~15 MW/m^2 (STD) to 0.5-3 MW/m^2 (SNF)



Liquid metals have the potential to mitigate steady-state and transient heat-loads, and protect underlying PFCs

FTU capillary porous system (CPS)

- CPS in T-11 handles > $10 MW/m^2$
  - Self-shielding radiative layers observed
- CPS e-beam tested to:
  - 25 MW/m^2 for 5 - 10 minutes
  - 50 MW/m^2 for 15s
- Plasma focus tested to 60 MJ/m^2 off-normal load



2 otherwise identical shots (no ELMs)
I_p = 0 .8 MA, P_{nbi} ~ 4 MW
high δ, f_{exp} ~20

NSTX: Increased Li evaporation correlated with lower q_{pk}
- T_{surf} at OSP = 800˚C → 400˚C with heavy Li
- q_{pk} stays < 3 MW/m^2 with heavy Li, divertor P_{rad} increases
- This occurs despite narrowing of heat-flux width at divertor

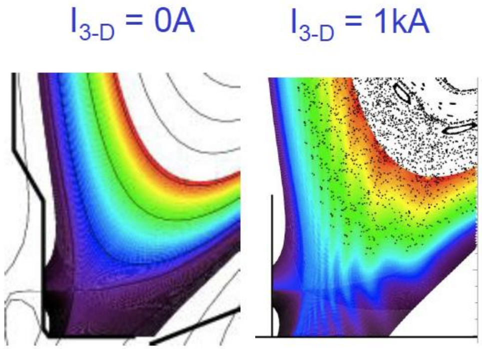
Need theory and modeling to understand roles of C, Li radiation, detachment physics, etc.

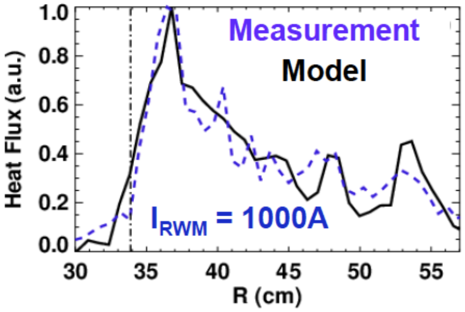
Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

NSTX studies of ELM regimes and ELM control contribute to mitigation strategies for ITER and future STs

- ELM triggering with n=3 RMP
  - Weak RMP impact on pedestal transport
  - Strong impact on stability
    - T_e, pressure gradient increase
    - PEST shows edge unstable with n=3
  - Triggered ELMs are phase locked to the imposed 3D fields for n=1 and n=3
- Small transport ELM-like events from 3D field application below ELM triggering threshold (w.r.t. duration or amplitude)
- Divertor heat and particle structures during ELMs, intrinsic and 3D fields
  - Applied 3D fields reattach detached divertor plasma
  - Developing model of toroidally non-uniform heat and particle flux structures using EMC3-EIRENE
- Collaboration with MAST in perturbed equilibria modeling
- Discussing collaboration with ASDEX in small ELM analysis, effects of 3D fields on detachment





NSTX-U theory and modeling needs for Macroscopic Equilibrium and Stability

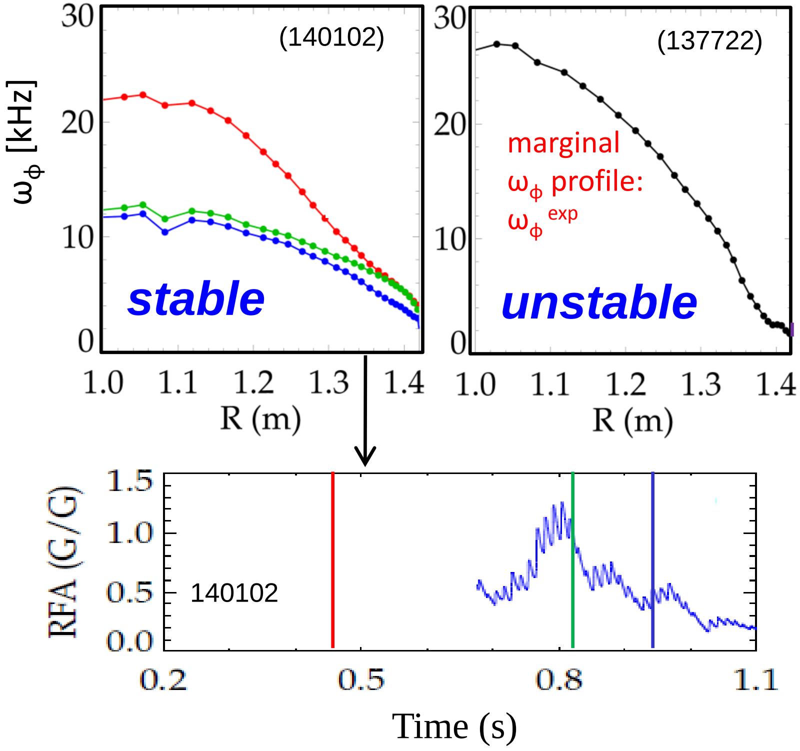
Category	Existing efforts	Associated physics issues
More robust equilibrium reconstruction and modeling including toroidal rotation and SOL, and stability analysis	- EFITs including rotation - LRDFITs including rotation - (E,LRD)FITs + FLOW - (E,LRD)FITs + FLOW + M3D-C1	- Stability boundary with toroidal rotation? - Stability boundary including separatrix? - Can be routinely available as GEQDSK in NSTX-U?
Quasi-linear 3D equilibrium modeling including islands, neoclassical, and kinetic MHD effects	- IPEC with tensor pressures and islands + POCA + Inner-layer - FLOW, MARS-F, MARS-K - M3D-C1	- 3D equilibrium with opened islands? - 3D equilibrium with rotation? - 3D equilibrium with anisotropic pressure? - Self-consistent modeling for NTV in NSTX-U?
Quasi-linear stability modeling including neoclassical and kinetic MHD effects	- MISK with anisotropic pressures and fast ions - MARS-K, NOVA-K - M3D-C1	- RWM passive stability with 2nd NBIs in NSTX-U? - Effects by Self-consistent eigenfunction? - Second RWM code with full kinetic treatment?

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

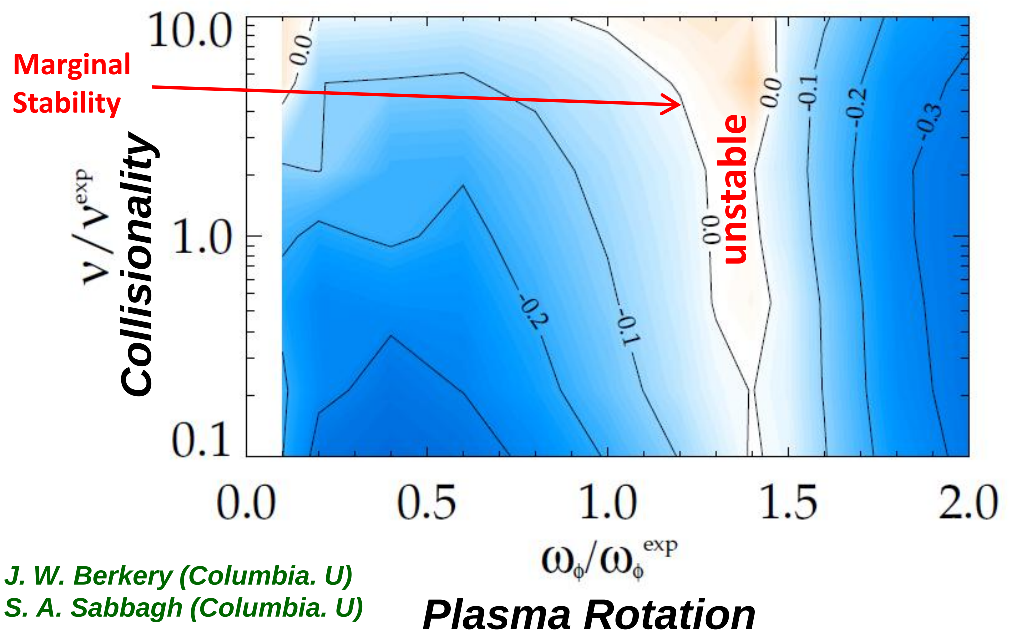
- RWM can be stabilized by kinetic effects through rotational resonance
  - **Implying importance of rotation control, NTV, NCC coils**
- NSTX-tested kinetic RWM stability theory showed that reduced ν^* can be stabilizing through kinetic resonances

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

RWM, RFA vs. rotation



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



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

NSTX-U theory and modeling needs for Macroscopic Equilibrium and Stability

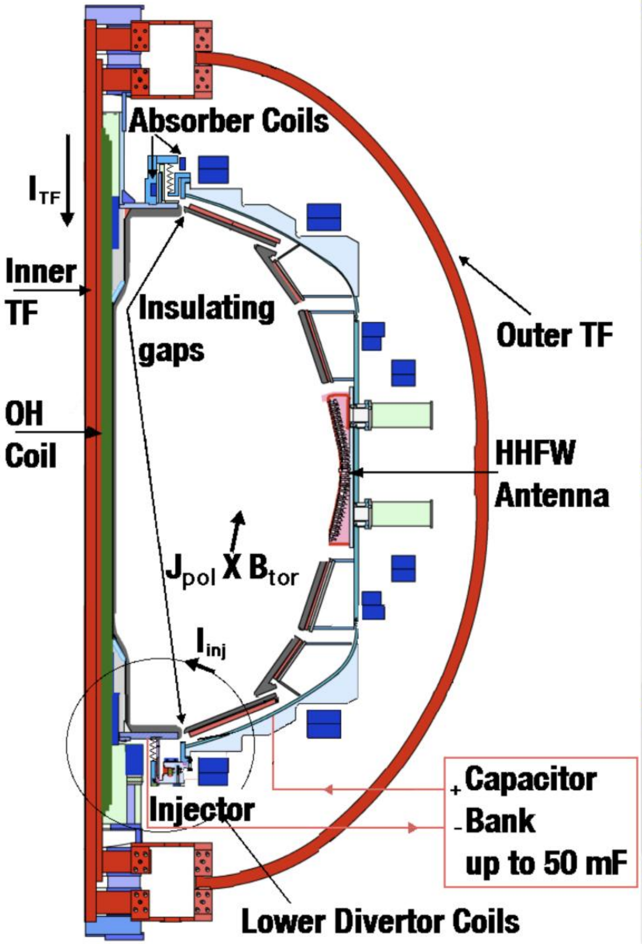
Category	Existing efforts	Associated physics issues
Non-linear (as well as linear) 3D modeling for time-evolving dynamics of islands, neoclassical, full kinetic MHD effects	- M3D-C1 with distribution function solver (Ramos theory or NTV theory) - XGC0	- Non-linear effects in 3D equilibrium and stability, including SW (q=1) and NTM? - Two fluid effects in 3D equilibrium and stability? - Full kinetic effects in 3D equilibrium and stability?
Full 3D modeling for external structure for RWM dynamics	- Multi-mode VALEN3D - Plasma permeability with neoclassical, kinetic effects - VALEN3D + Plasma permeability	- Full 3D current effects on RWM? - Effects of full 3D + kinetic plasma permeability on RMW stability and control?
Gas penetration physics modeling including MGI and runaway electrons and disruption simulation	- DEGAS2 for gas penetration - TSC for runaway electrons - M3D for disruption simulation - Use of 3D equilibrium sequence	- Gas penetration with atomic physics? - Runaway electrons in NSTX-U? - Coupling gas and plasma modeling? - Why mode locking cause a disruption? - What is the origin of a density limit disruption?

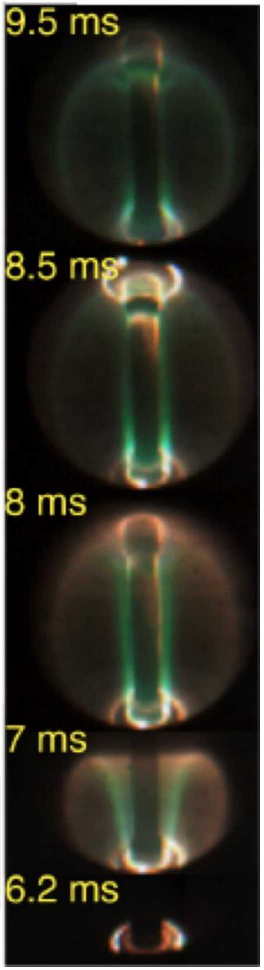
Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

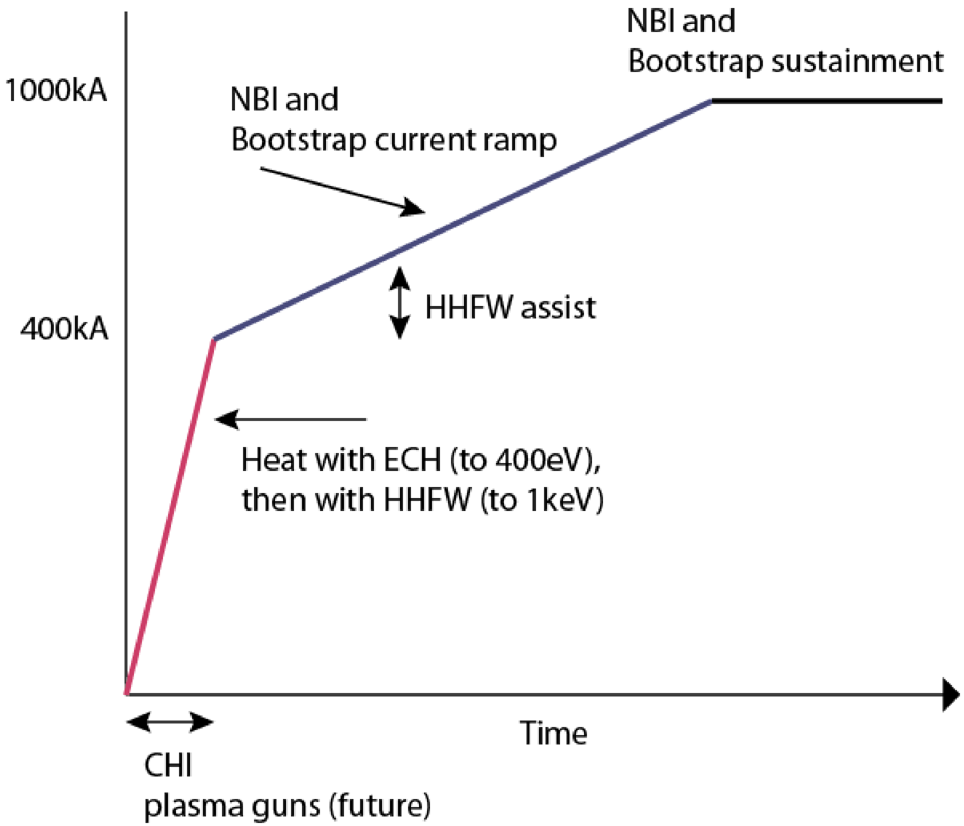
CHI planned to be used as initial current seed for subsequent non-inductive current ramp-up in NSTX-U, ST-FNSF

CHI in NSTX/NSTX-U





NSTX-U Start-up and Ramp-up strategy



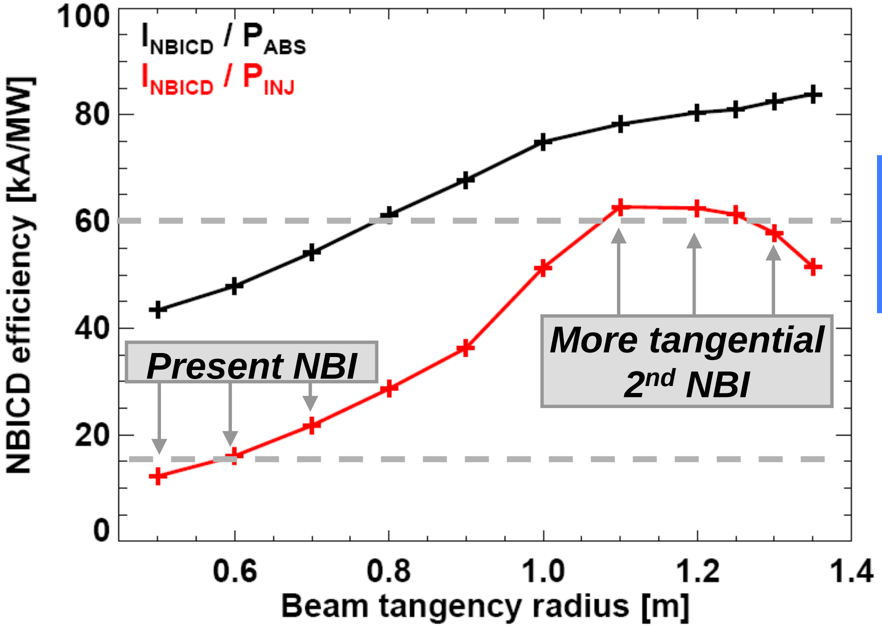
NSTX-U goal is to demonstrate and understand solenoid-free current start-up and ramp-up

Non-inductive ramp-up from ~0.4MA to ~1MA projected to be possible with new centerstack (CS) + more tangential 2nd NBI

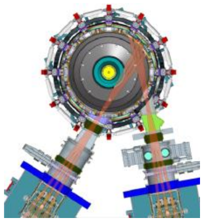
- **New CS provides higher TF (improves stability), 3-5s needed for J(r) equilibration**
- **More tangential injection provides 3-4x higher CD at low I_P:**
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
  - 1.5-2x higher current drive efficiency

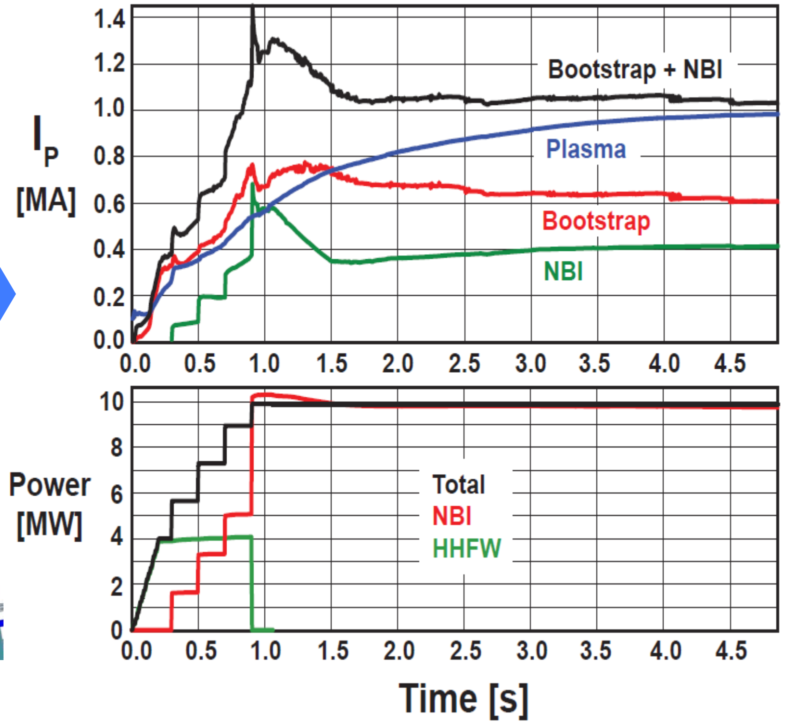
E_{NBI}=100keV, I_P=0.40MA, f_{GW}=0.62

$\overline{n}_e = 2.5\times10^{19}\,m^{-3}$, $\overline{T}_e$ = 0.83keV



TSC simulation of non-inductive ramp-up from I_P = 0.1MA, T_e=0.5keV target at B_T=1T





NSTX-U theory and modeling needs for Solenoid-Free Plasma Start-up and Ramp-up

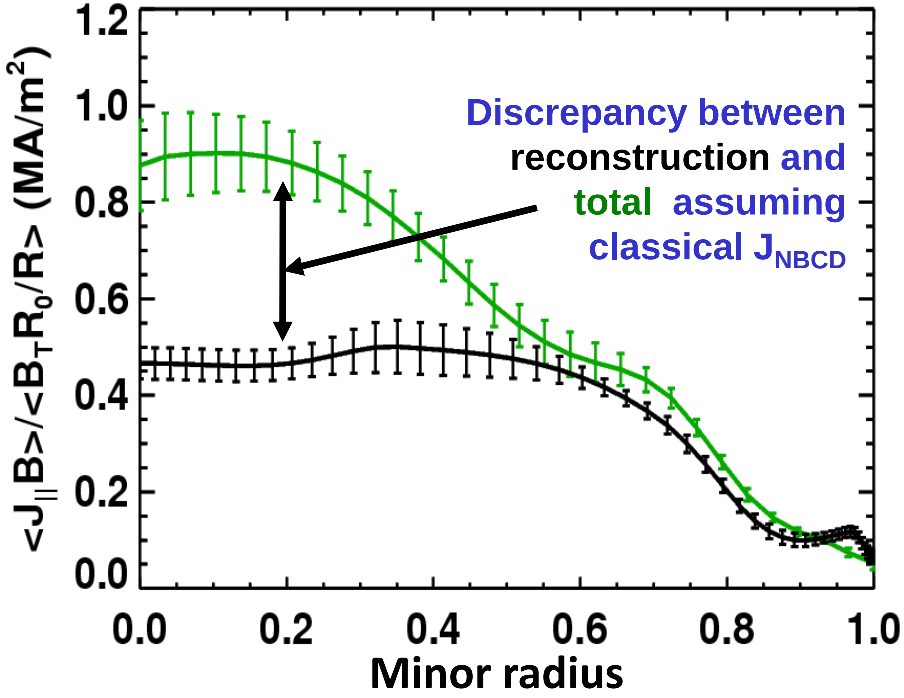
- 3-D resistive MHD model to determine conditions for generating flux-surface closure at the end of the injection time, as in the experiment.
  - e.g. resistive effects, localized magnetic fluctuations
  - Obtain quantitative comparison with experiment and quantify the influence of the time-changing flux on the dynamics of the CHI plasma
- 2-D and 3-D MHD and transport models to determine scaling of electron heating and temperature, etc., with injection parameters and χ_e and the resulting effect on I_P, size, flux-surface closure, etc.
  - Understand the relationship between electrode driven current and impurity generation and their impact on the performance of the resulting discharge
  - Develop a 3-D MHD model of point source helicity injection (plasma guns)
- Understand the scaling of CHI current generation with respect to the injected poloidal flux and injector current for extrapolation to next-steps
- Understand requirements for current drive by NBI in a helicity injection generated target; determine conditions to successfully ramp-up current

Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

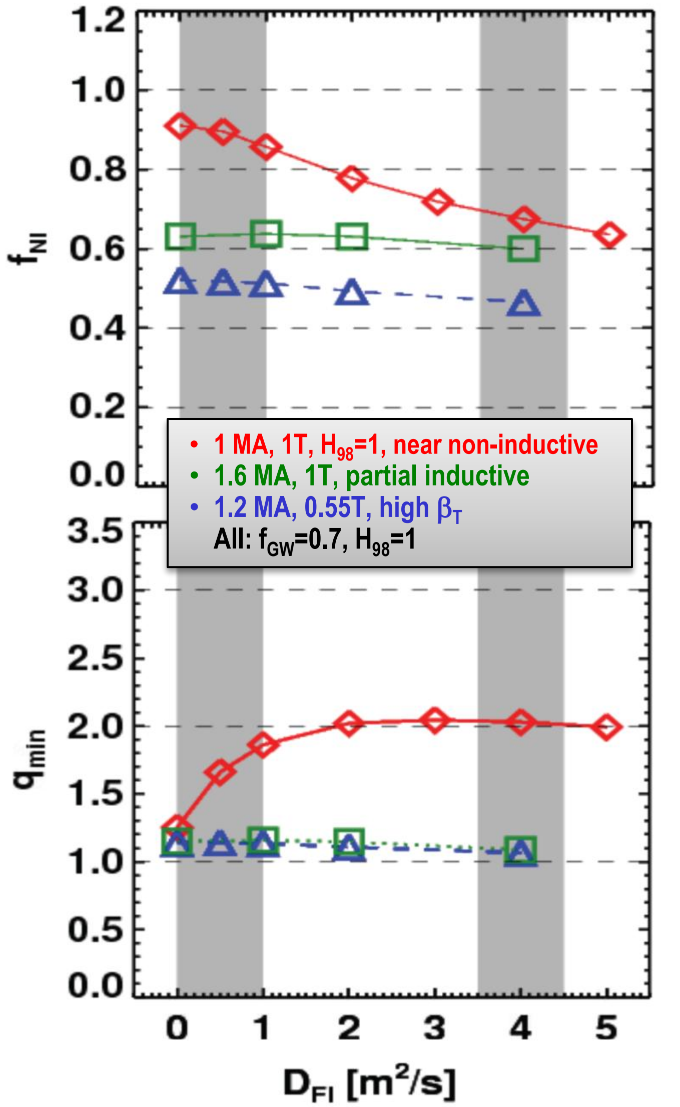
NSTX: rapid avalanches can lead to redistribution/loss of NBI current drive



Discrepancy between reconstruction and total assuming classical J_{NBCD}

700kA high-β_P plasma with rapid TAE avalanches has time-average D_{FI} = 2-4m^2/s

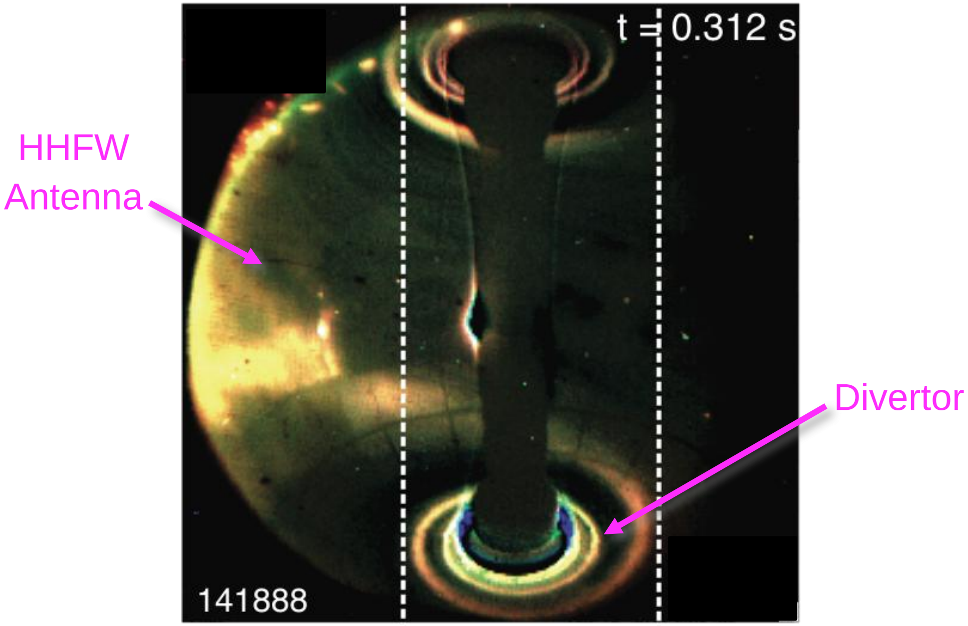
NSTX-U TRANSP simulations



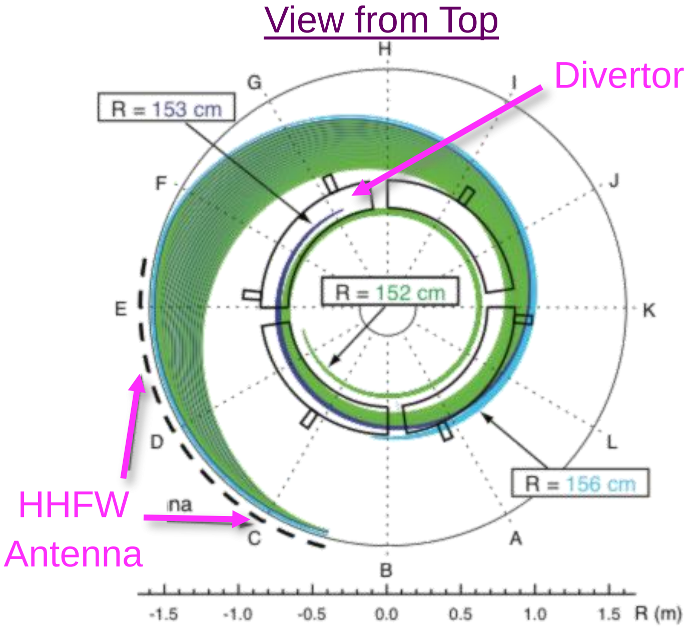
NSTX-U theory and modeling needs for Energetic Particles

- Improve and validate existing tools for *AE stability calculations, with emphasis on ST geometry (low aspect ratio)
  - Validate non-linear fast-ion instabilities and transport against NSTX data and extend to NSTX-U scenarios using M3D-K
  - Improve treatment of fast ion distribution (Fnb from NUBEAM?) in NOVA-K
  - Include rotation effects, assess effects of redistribution of fast-ions on rotation
  - Develop self-consistent models of thermal e-transport induced by *AE modes
- Include externally-driven perturbations into existing AE codes
  - Implement in NOVA, M3D-K, HYM, and/or SPIRAL to guide the design of antennae for use in experiments to characterize AE stability properties, and/or drive *AE modes for ‘phase-space engineering’
    - Implement perturbations ranging from sub-kHz (from external coils) up to CAE/GAE frequency range, including TAE band
    - Couple IPEC to SPIRAL and/or M3D-K, or include *AE antenna models in RF codes
- Improve TRANSP to model/predict the evolution of fast ion population
  - Incorporate *AE-induced fast ion transport models
  - Use fast ion diagnostics to constrain TRANSP/NUBEAM **f(r,v)** evolution

Significant fraction of the HHFW power may be lost in the SOL in front of antenna and flow to the divertor region



Visible camera image shows edge RF power flow follows magnetic field from antenna to divertor



SPIRAL results show field lines (green) spiraling from SOL in front of HHFW antenna to divertor

Field line mapping predicts RF power deposited in SOL, not at antenna face

- 3D AORSA will assess surface wave excitation in NSTX-U

Proposed DIII-D experiment to look for RF edge losses during 2012 run

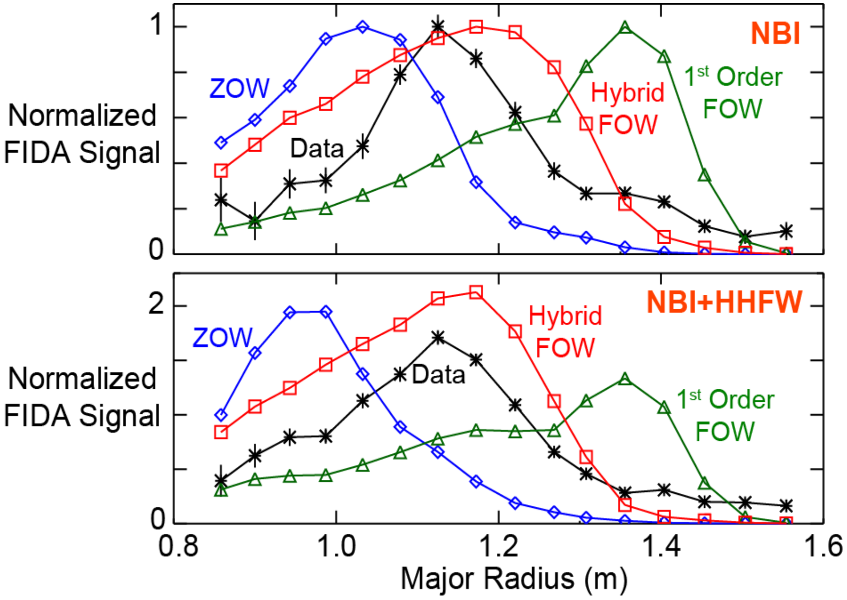
NSTX-U experiments and modeling to emphasize HHFW heating of high NBI power, long-pulse H-modes → assess effect of varying outer gap

R. J. Perkins, *et al*., PRL (2012)

NSTX-U theory and modeling needs for Wave Heating and Current Drive

- Extend RF models to include realistic model of scrape off layer
  - Predict dependence of surface wave power flows to the divertor region, RF sheaths, and parameteric decay instability (PDI).
    - The spectral solver AORSA has already been extended to the wall in NSTX.
    - An alternate approach is to couple core spectral solvers (TORIC and AORSA) to either finite element method (FEM) or particle-in-cell (PIC) codes.

- Improve models of fast-ion interactions w/ ICRF, HHFW
  - Use ORBIT-RF/AORSA, sMC/AORSA and the new CQL3D finite-orbit-width (FOW) code to model fast-wave acceleration of fast-ions and losses, compare to FIDA and NPA/ssNPA data.
  - Compare calculated spectra of energetic particles going to wall to fast-ion loss detectors.
  - Carry out couplings between AORSA and FOW code ORBIT RF, and FOW CQL3D with the HHFW version of TORIC.



Topical Areas

- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

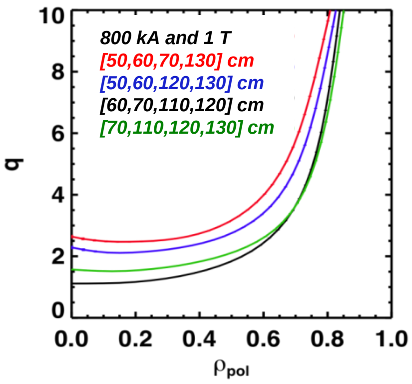
Goals of NSTX Advanced Scenario and Control (ASC) TSG

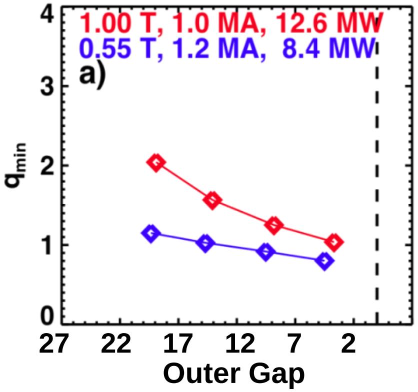
- Study, implement, optimize axisymmetric control techniques.
  - Kinetic and magnetic profiles
  - Boundary and divertor magnetic geometry control, vertical position control
- Combine various tools developed in other TSGs into integrated scenarios.
  - Examples: ELM pacing for impurity density control
- High non-inductive fraction utilizing bootstrap + NBI current drive
  - Typically coupled with optimization to low l_i, high elongation

- **Progressing towards profile control:**

q profile actuators

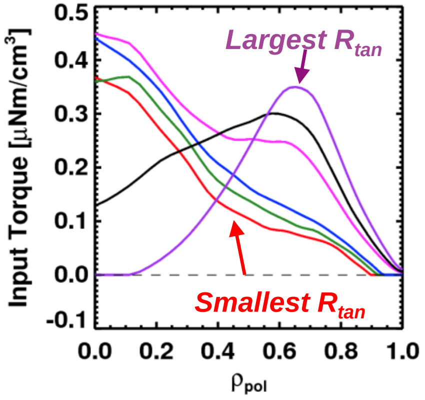
Variations in Beam Sources



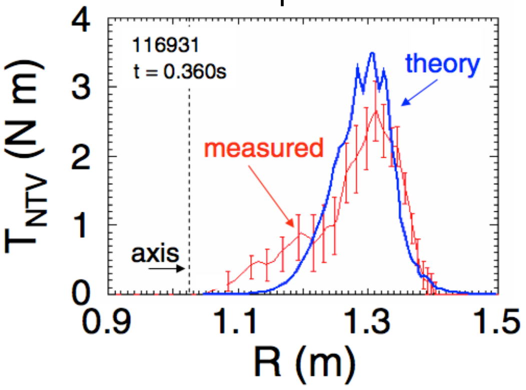


Rotation profile actuators

Torque profiles from 6 NBI srcs



Measured and Calculated NTV Torque Profiles

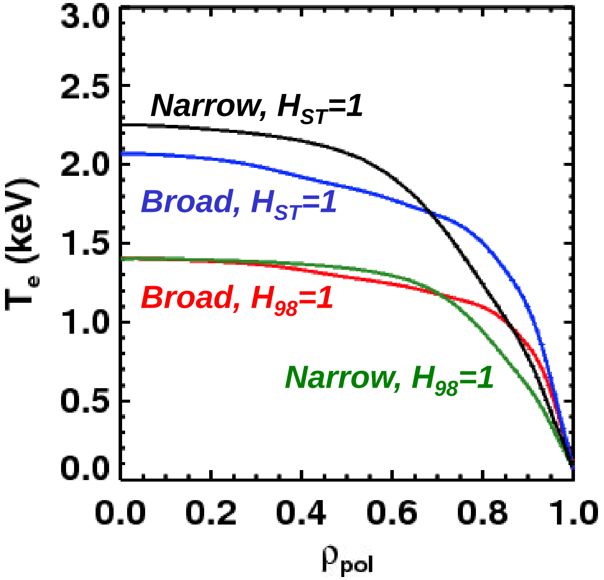


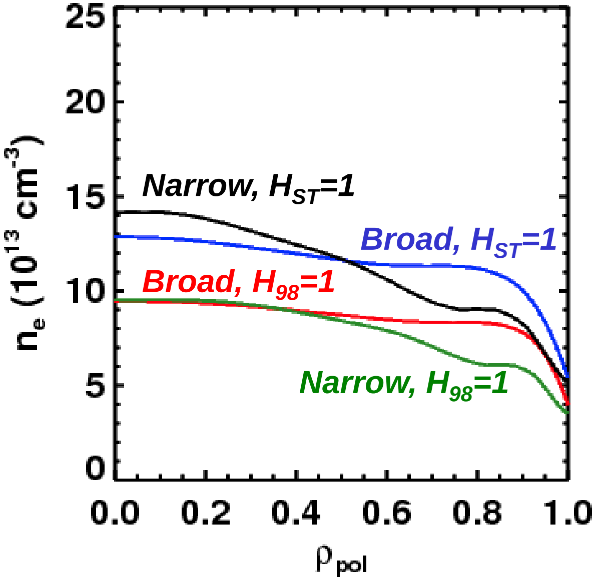
Two Overarching ASC Theory/Modeling Needs

- 1: Need advanced control algorithms for boundary shape, divertor geometry, kinetic and magnetic profiles, and divertor heat fluxes.
  - Should include actuator dynamics & saturation.

- 2: In order to tune those control algorithms, need integrated codes with fast, benchmarked models for how sources of particles, momentum, heat and current modify the kinetic and magnetic profiles and free-boundary equilibrium.

Project NSTX-U Non-Inductive Current Level at B_T=1.0 T and P_{inj}=12.6 MW To Be Between ~900 & ~1300 kA





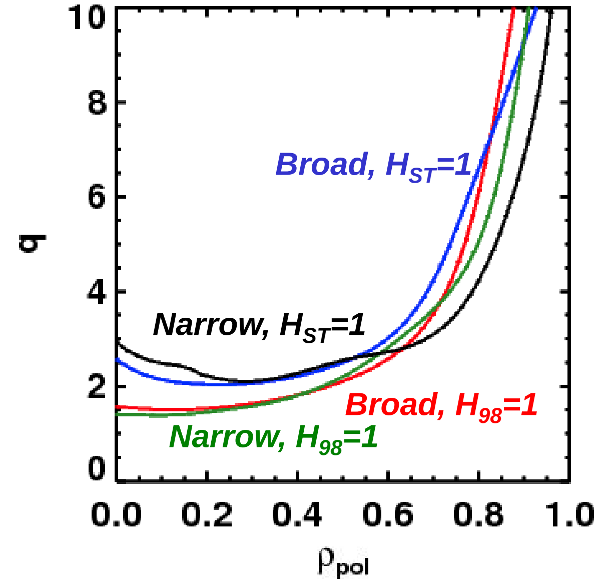
Dashed: ITER-98 confinement scaling

[illegible]

Solid: ST confinement scaling

[illegible]

(S. Kaye, NF 2005)



- **Fix: 1.0T, P_{inj}=12.6 MW, f_{GW}=0.72**
- **Fix: A=1.75, κ=2.8**
- Find the non-inductive current level for 2 confinement and 2 profile assumptions…*yields 4 different projections.*

Confinement	**Profiles**	**I_P [kA]**	**β_N**	**q_{min}**
H_{98}=1	Broad	975	4.34	1.5
H_{ST}=1	Broad	1325	5.32	2.0
H_{98}=1	Narrow	875	4.87	1.4
H_{ST}=1	Narrow	1300	5.97	2.1

Need #1: Models for Scenario Development

- NBCD with *AE modes
  - In the absence of low-f MHD, the neutral beam drive current is apparently classical.
  - At higher values of β_{fast}, *AE modes can lead to redistribution/modification of the fast ion distribution.
  - Theory is needed for when these modes will turn on, and what their effect on the pressure & current profile will be.
  - Need measurements of fast ion distribution (FIDA, neutrons, ssNPA, fusion product detector) and NBCD profile for comparison.
- Prediction of the thermal & momentum transport
  - The bootstrap current depends sensitively on the gradients in the thermal profiles. NBCD depends on T_e/n_e. Global stability depends on rotation.
  - Conversely, the transport, and hence thermal profiles, can be a strong function of the current and rotation profiles
  - Need a model for the thermal and momentum transport and its response to actuators.
  - Include both core & pedestal (and the joining region), including fast-ion MHD leading to transport.
- Need accurate, benchmarked models for HHFW and EBW H&CD within integrated codes such as TRANSP.

Need #2: Realtime Control

- Need a reliable algorithm for the individual and combined control of the current and rotation profiles, along with β_N.
  - The theory of that algorithm should help us to understand to what extent these quantities can be independently controlled given the coupled actuators V_{loop}, P_{inj}, J_{NBCD}, T_{NB} and T_{NTV}.
- Need the ability to test the actual control algorithms in simulations with high degrees of physics fidelity, i.e. flight simulator mode.
  - Could in principle be accomplished by connecting PCS to PTRANSP, CORSICA, or TSC.
- Need the ability to predict the future equilibrium and stability properties of the plasma.
  - Faster than realtime look-ahead of the evolution of the equilibrium
    - (Very) reduced transport models.
  - Stability assessments of those future states (n=0, n=1, ELM?). Future coil currents and boundary shape.
  - Control intervention based on the predictions.

Topical Areas

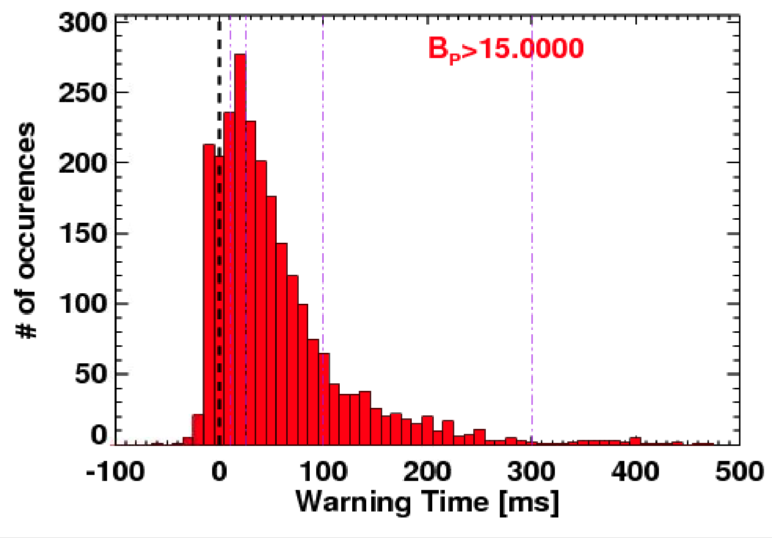
- Transport and Turbulence
- Boundary Physics
- Macroscopic Equilibrium and Stability
- Solenoid-free Start-up and Ramp-up
- Waves and Energetic Particles
- Advanced Scenarios and Control
- Disruptions

NSTX Disruption Detection Studies Show That No Single Diagnostic Can Predict All Disruptions

- Examined >20 different signals that might be used for disruption prediction.
  - Rotation, confinement, rotating MHD, RWMs and locked-modes, q^*, β_N, f_{GW}, P_{rad}/P_{tot},…
- For each signal, define limits beyond which disruptions become likely.
  - Use physics based predictions of signals if possible.

Example #1: In-Vessel n=1 RWM sensors

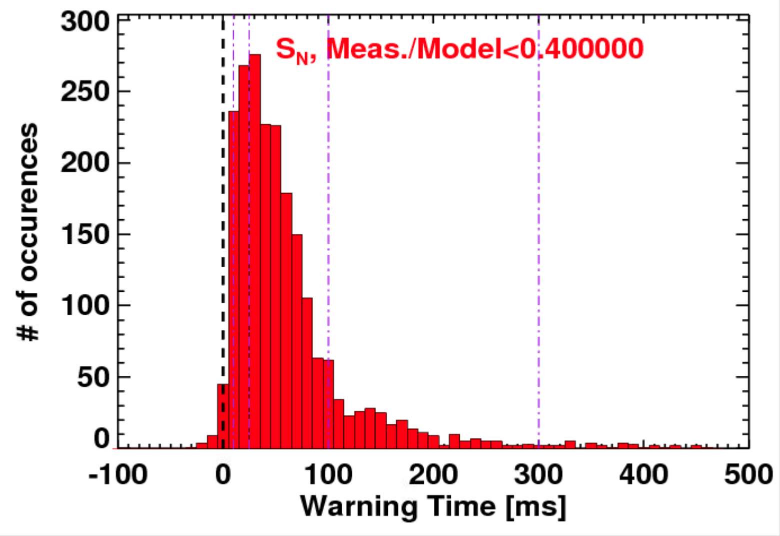
Instantaneous values >~15 G indicative of imminent disruption.



Example #2: Neutron Emission

Predict the neutron rate using a 0D slowing-down model

Measured/Model ratios <~0.4 indicative of imminent disruptions



(A short list of) theory and modeling needs for disruptions

- Continued validation of linear instability models:
  - VDE, external kink, internal kink/sawtooth, locked mode, NTM, RWM
- Non-linear MHD models to understand instability evolution
  - Does mode saturate or lead to disruption?
  - Requires at least a reduced model of transport – possibly WDM
- Improved models of thermal quench dynamics (fast reconnection) which can occur on sub-ms time-scales.
- Improved boundary conditions in MHD codes, i.e. for the interactions of the main plasma with the wall during thermal and current quench
  - Important for calculating resulting halo current resistance and width, and forces on the resistive wall/blanket components during current quench phase
- Improved models of runaway electron transport in 3D fields from plasma-driven instabilities and external 3D fields
  - Use of RMP to increase runaway electron losses observed on several devices
  - Also important for understanding impurity transport during massive gas injection
- Identify and understand new runaway electron loss mechanisms – e.g. whistler-wave instabilities for B < ~2T – potential advantage for ST?

Summary – with an opinion on priorities

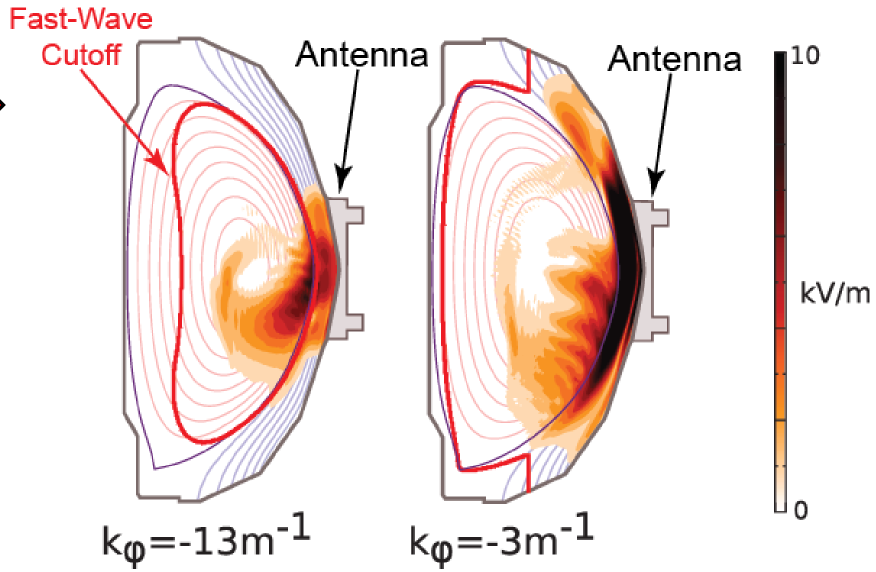
- Transport and Turbulence
  - E-M e-transport mechanisms for ST & ITER (micro-tearing, GAE/CAE)
- Boundary Physics
  - Pedestal transport and structure, SOL heat flux width, effects of lithium
- Macroscopic Equilibrium and Stability
  - Plasma response to 3D fields – including drift-kinetic/two-fluid effects
- Solenoid-free Start-up and Ramp-up
  - Role of 2D vs. 3D reconnection in transient CHI, scaling to next-steps
- Waves and Energetic Particles
  - Models of non-linear evolution of AE modes, resultant fast-ion transport
- Advanced Scenarios and Control
  - Development of (any kind of useful) reduced (electron) transport model
- Disruptions
  - Thermal quench dynamics, BCs/halo currents, RE transport by 3D fields

Backup Slides

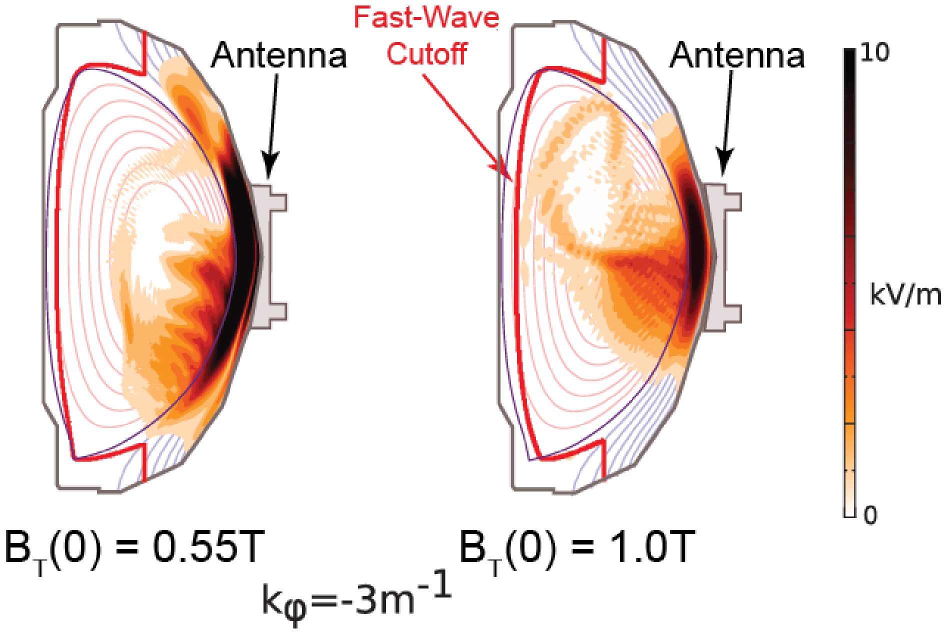
AORSA predicts large amplitude coaxial standing modes between plasma and wall in NSTX H-mode

Edge coaxial mode seen in NSTX
$B_T(0)$ = 0.55 T simulations

Edge mode significantly reduced when
$B_T(0)$ is increased from 0.55 T to 1 T



2-D AORSA simulation for HHFW in NSTX
$B_T(0)$ = 0.55T NBI H-mode shot 130608*



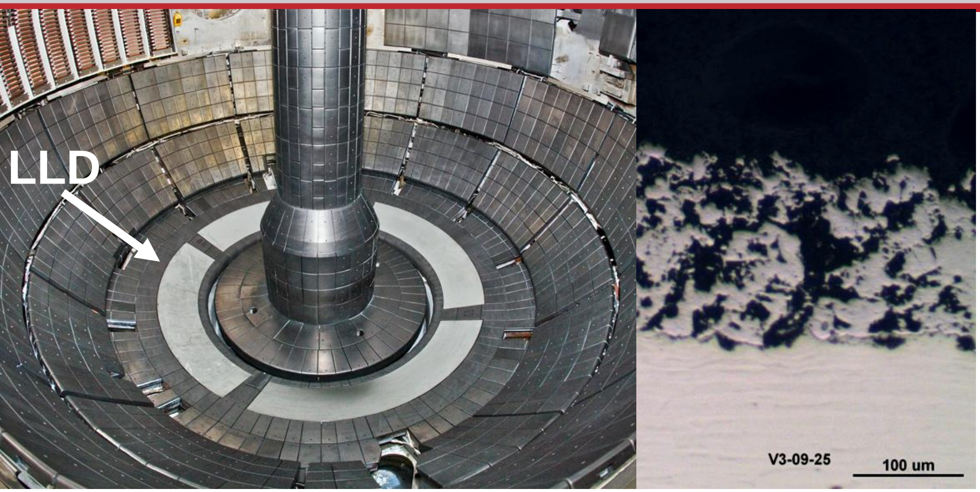
Future plans call for a quantitative comparison of predicted SOL electric fields with measurements:

- Requires better resolution in SOL and detailed antenna geometry

*D. L. Green, *et al.*, Phys. Rev. Lett. **107**, 145001 (2011)

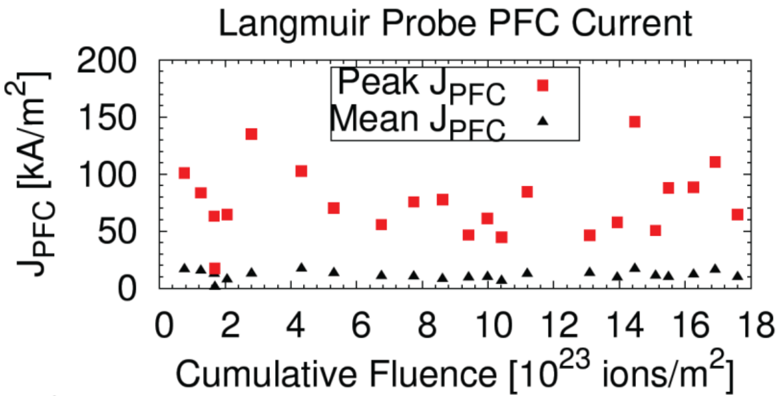
LLD with optimized pore size and layer thickness can provide stable lithium surface

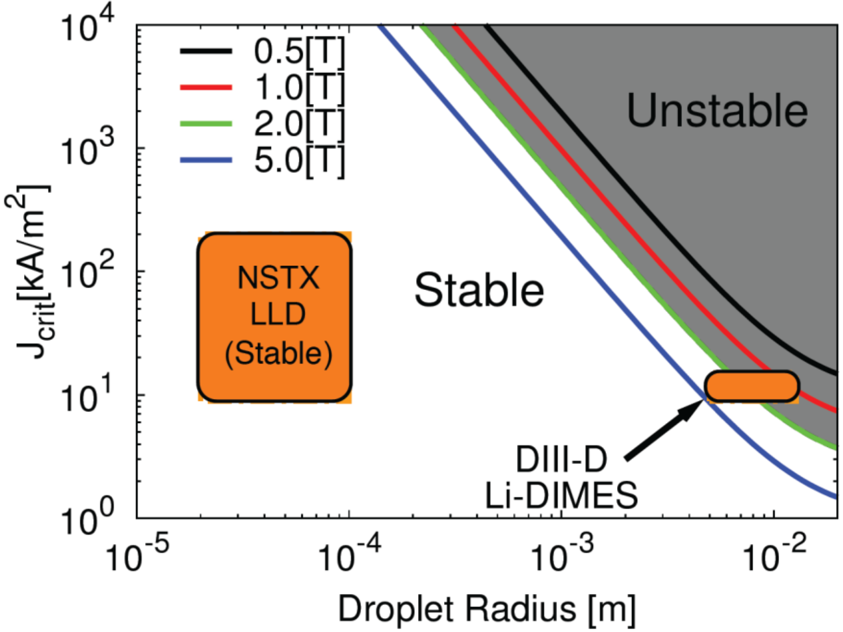
PAC29-5c



LLD surface cross section: plasma sprayed porous Mo

- LLD filled with 67 g-Li by evaporation, (twice that needed to fill the porosity).
- No major Mo or macroscopic Li influx observed even with strike point on LLD.
- No lithium ejection events from LLD observed during NSTX transients > 100 kA/m^2
  - Thin layers and small pore diameters increase critical current (J_{crit}) for ejection.
  - Modelling consistent with DIII-D Li-DIMES ejection at 10kA/m^2 and NSTX experience.

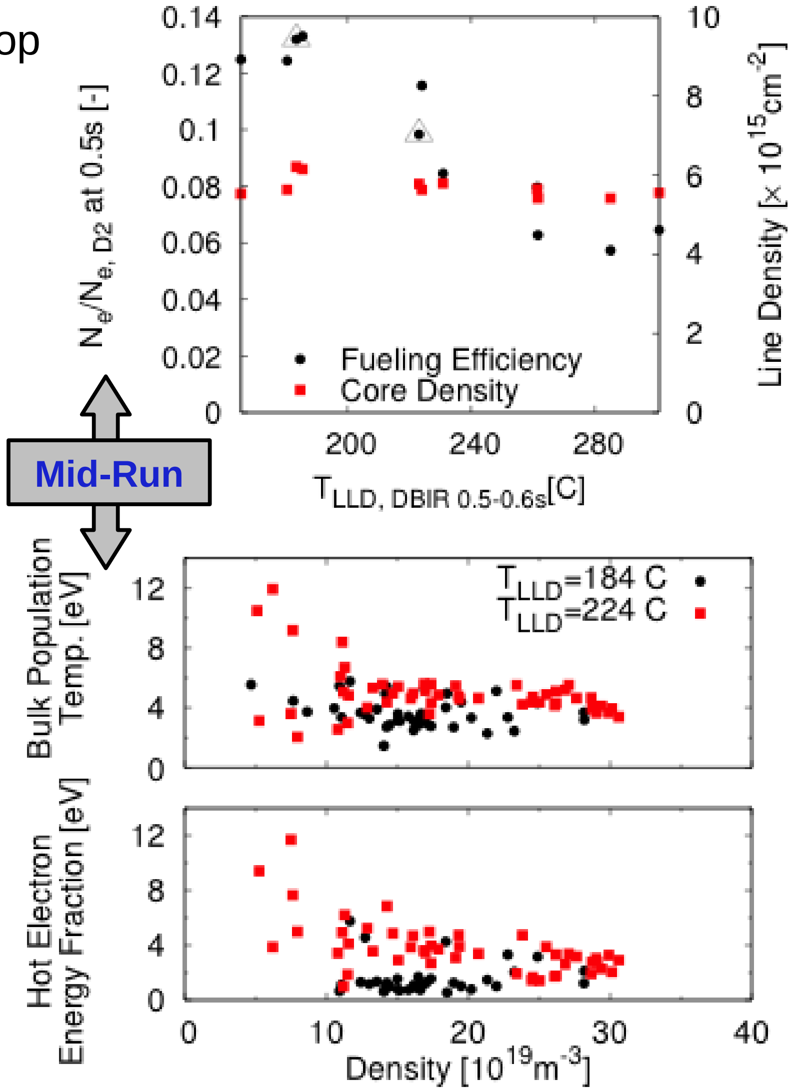


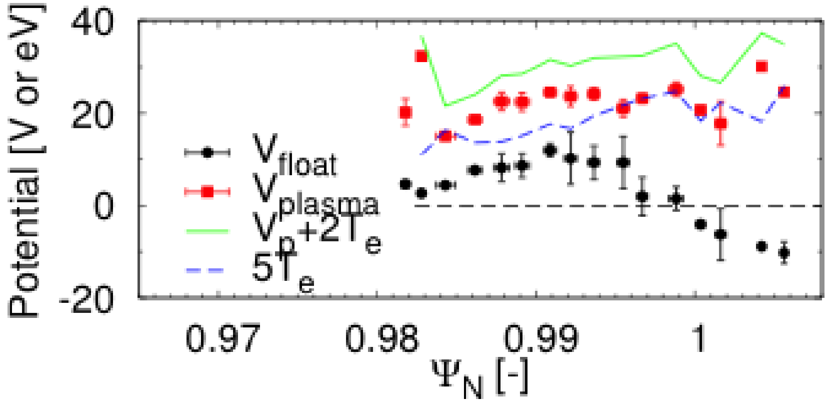


M.A. Jaworski, et al., J. Nucl. Mater. 415 (2011) S985.
D. Whyte, et al., Fusion Eng. Des. 72 (2004) 133.

Molten lithium by plasma bombardment coincided with reduced fueling efficiency and higher target T_e

- Mid-run experiments indicated fueling efficiency drop when $T_{LLD} > T_{Li,melt}$
- Increases in both bulk T_e as well as tail fraction consistent w/ absorbing surface
- Fueling efficiency decreased about 50%, but multi-variable experiment (increased gas with increased surface temperature)
- Impact energies lower than earlier estimates
- TRIM runs indicate little penetration
- Motivates flowing system to mitigate continual gettering during vacuum exposure

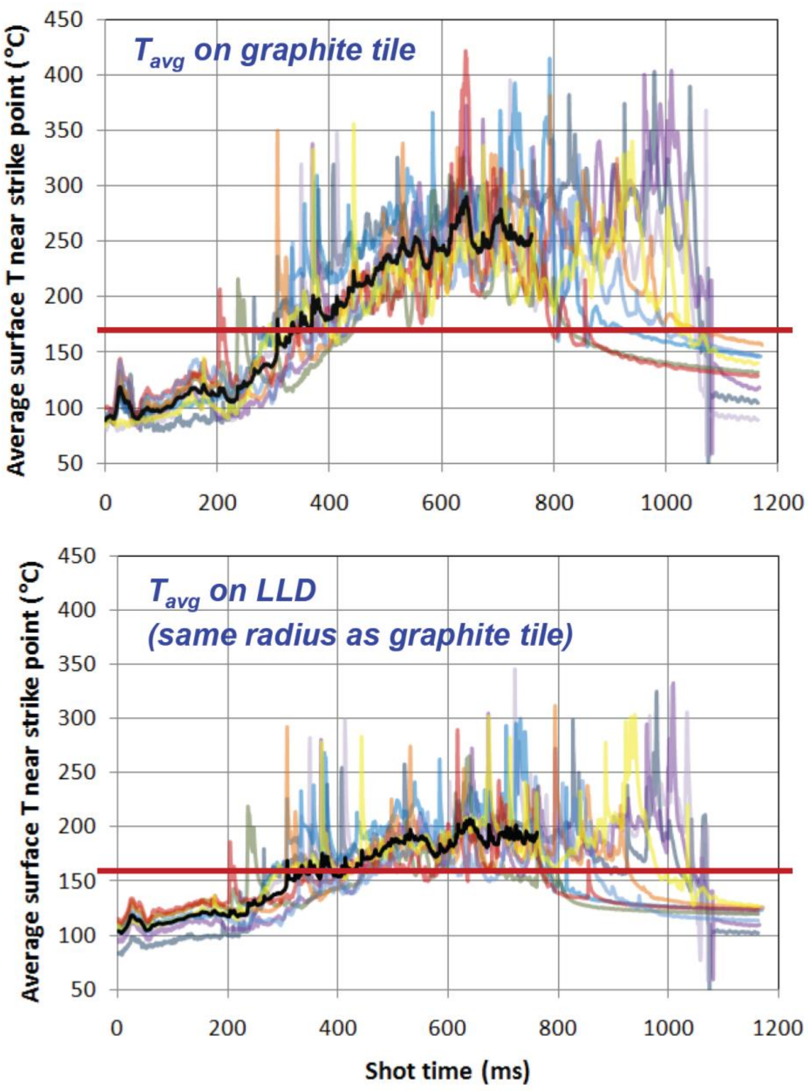




H.W. Kugel, et al., Fusion Eng. Des. 2011 in press.
M.A. Jaworski, et al., Fusion Eng. Des. 2012, in press.

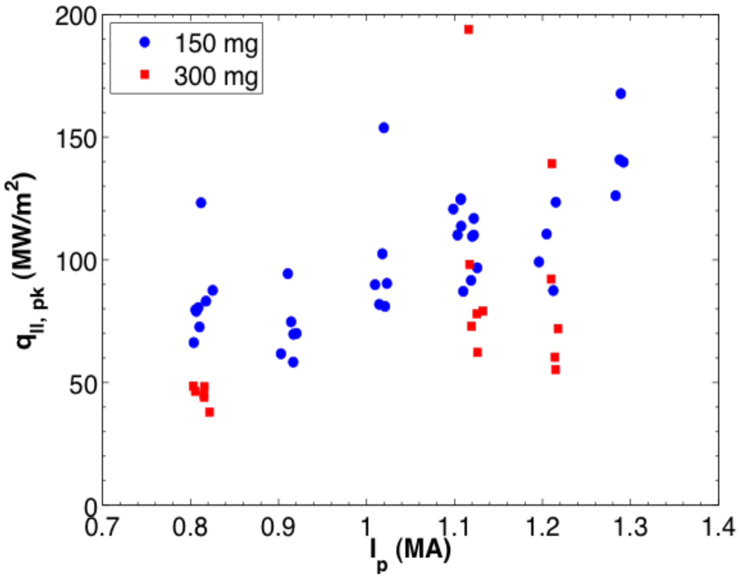
Average T_{surf} on LLD and graphite tile at equal radii suggests that T_{surf} is reduced due to improved heat removal through the LLD Cu

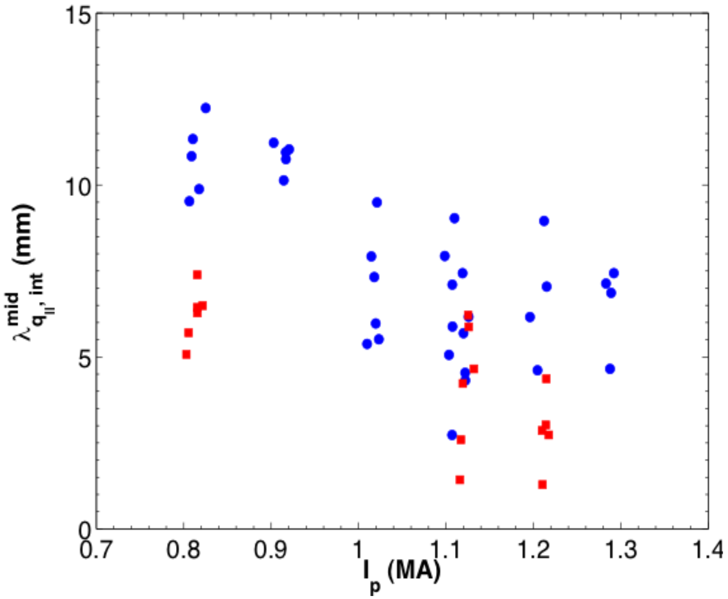
- Series of 10 repeat discharges with outer strike point on the LLD
  - Graphite and LLD in this case begin with T_{surf}~70°C
- T_{avg} on graphite gap tile increases through all shots in √t fashion
  - Average T_{surf} of ~250°C
- T_{avg} plotted at same radius, but on LLD
  - T_{surf} increases more slowly
  - Efficient heat removal through LLD depth/Cu
- However during transients such as ELMs, $T_{LLD} > T_{ATJ}$ during the transient
  - Measured T_{surf} response is dominated by thin film on the upper surface during transients [K Gan, APS 2011]



Peak Divertor Heat Flux and inter-ELM λ_q are reduced when 300 mg of Li Evaporation is Used

- Both deposited and parallel divertor heat flux is reduced when 300 mg of Li is evaporated
- $\lambda_{q,\ int}$ contracts with increased Li deposition
  - Trend is not predicted by current SOL width models
  - Suggests the importance of including divertor recycling in estimations of λ_q
- SOLPS modeling is in progress to better understand divertor physics



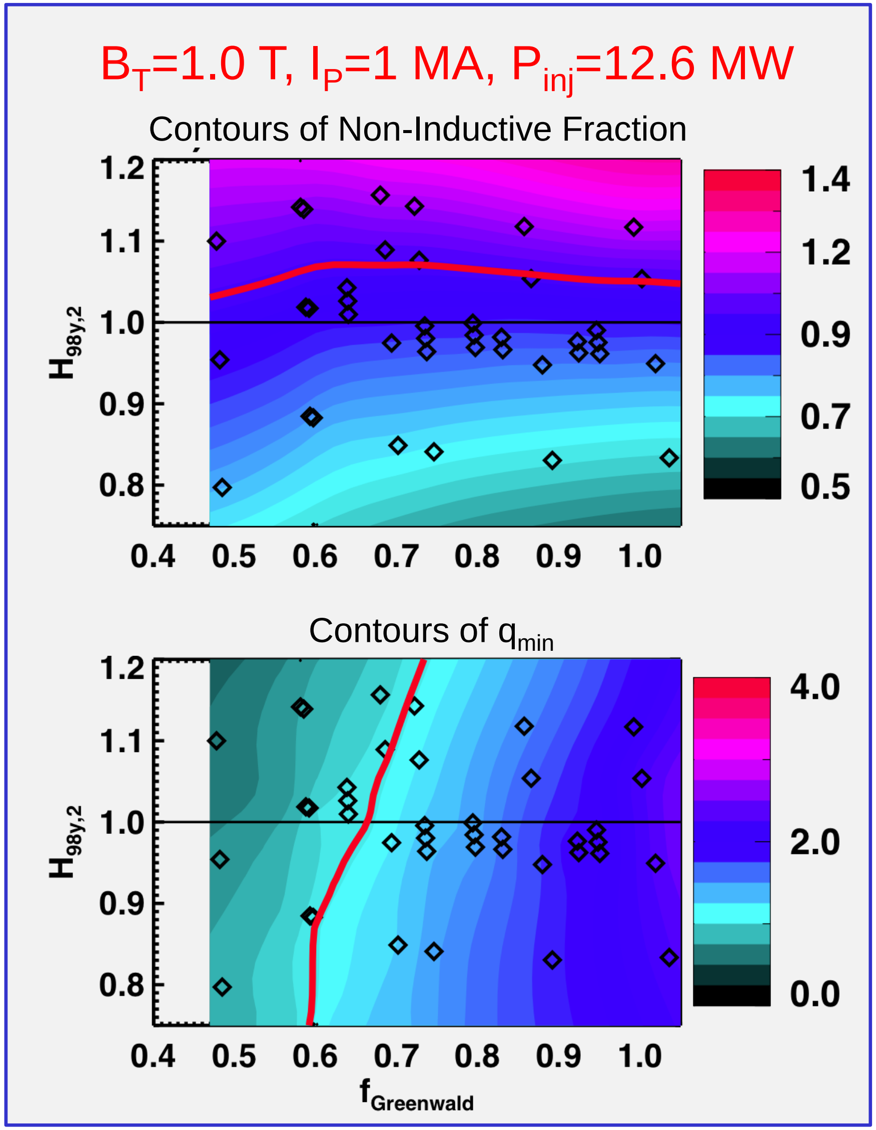


Non-Inductive Operating Points Projected Over a Range of Toroidal Fields, Densities, and Confinement Levels

Projected Non-Inductive Current Levels for κ~2.85, A~1.75, f_{GW}=0.7

B_T [T]	P_{inj} [MW]	I_P [MA]
0.75	6.8	0.6-0.8
0.75	8.4	0.7-0.85
1.0	10.2	0.8-1.2
1.0	12.6	0.9-1.3
1.0	15.6	1.0-1.5

- From GTS (ITG) & GTC-Neo (neoclassical):
  - $\chi_{i,ITG}/\chi_{i,Neo}$~$10^{-2}$
  - Assumption of neoclassical ion thermal transport should be valid.

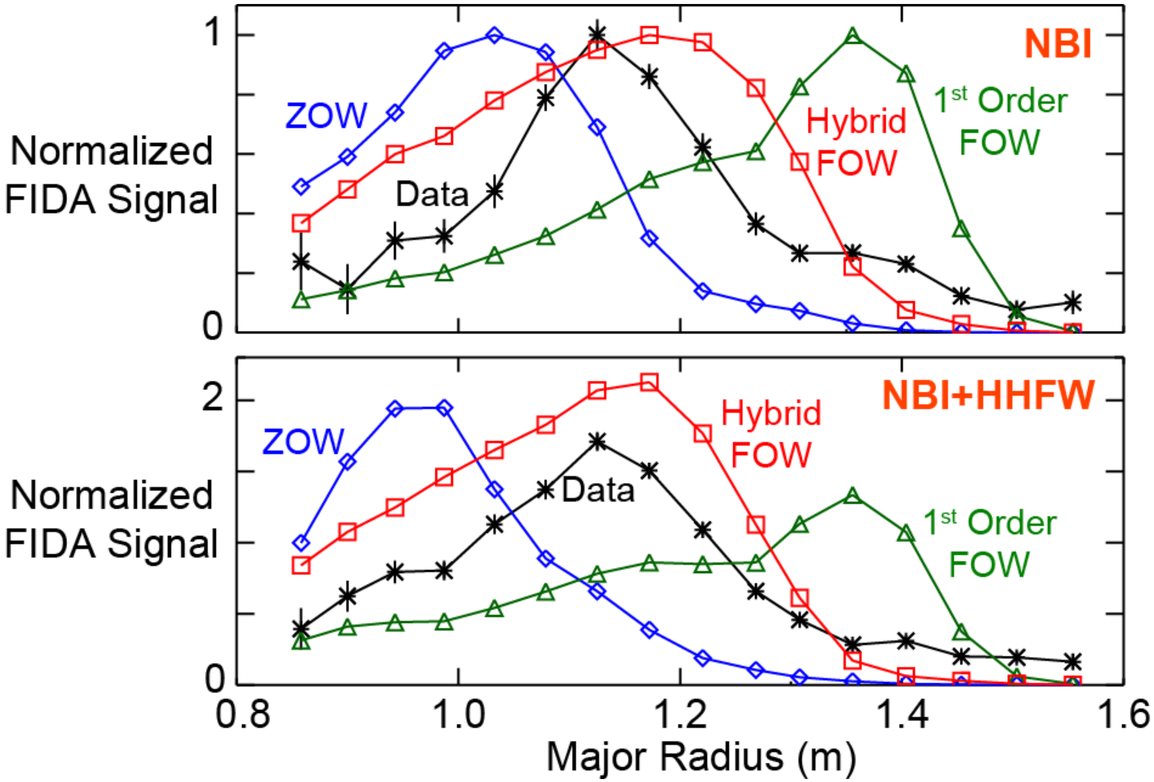


B_T=1.0 T, I_P=1 MA, P_{inj}=12.6 MW

Contours of Non-Inductive Fraction

Contours of q_{min}

Full-orbit, finite-orbit-width (FOW) CQL3D will accurately model neoclassical transport, ion loss & heat flowing to SOL



Recent FIDA simulations using "hybrid" full-orbit FOW CQL3D show much better agreement shift with FIDA data:

- "Hybrid" FOW CQL3D has full orbits but does not treat orbit topologies correctly at trapped-passing boundaries
- Expect proper treatment of orbit topologies will bring the simulations into even better agreement with FIDA data

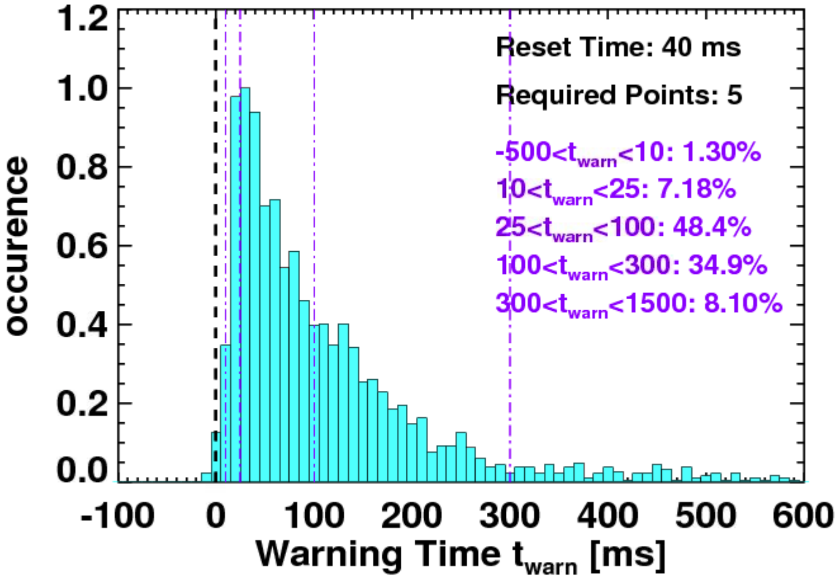
A full-orbit neoclassical transport model, and losses to SOL and wall still need to be implemented

Initial tests of full-orbit FOW CQL3D show accurate modeling of fast-ion losses, power absorption and RF-driven current profiles

CompX℠

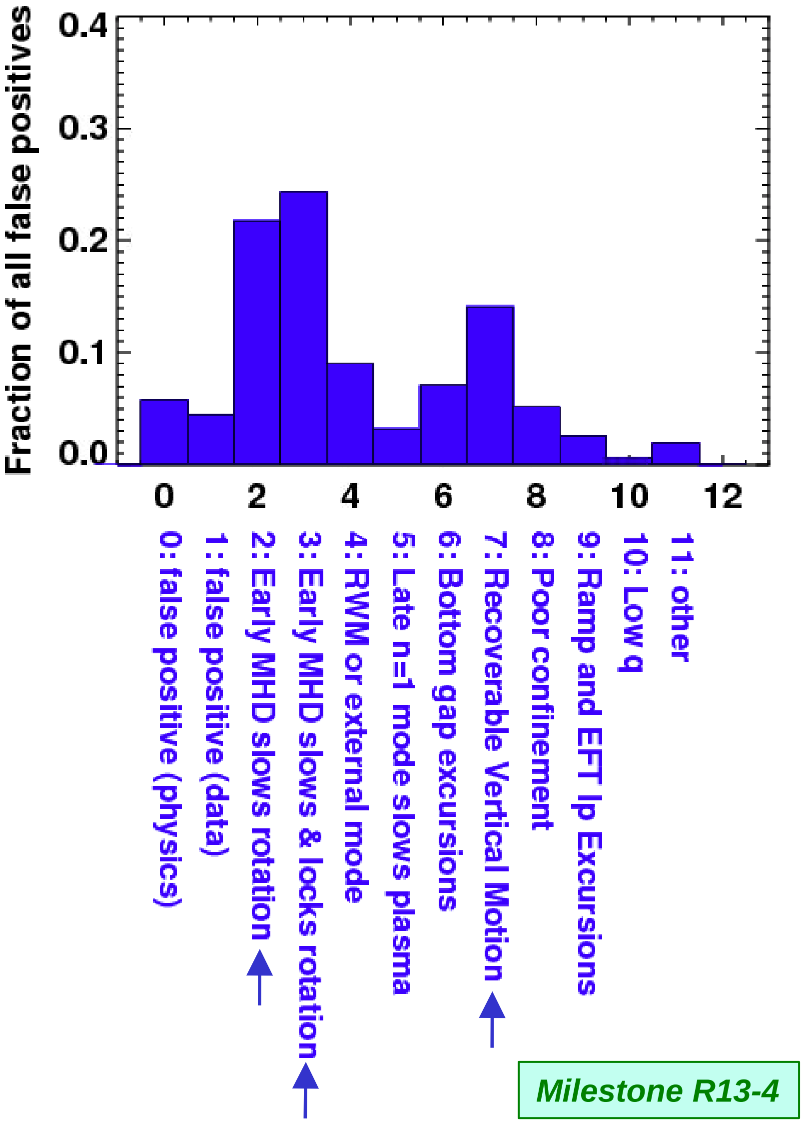
Simple Predictor Can Predict Disruptions With High Probability of Success

- Predictor based on combinations of threshold based tests.
  - Multiple thresholds for each test.
  - No machine learning
- Produces a very low missed disruption rate.



- Most false positives are due to "near disruptive" events.
- If tuned for a missed disruption fraction of 2%, then false positive rate is only 6%.

Physics Origins of "False Positives"



Milestone R13-4