NSTX-U

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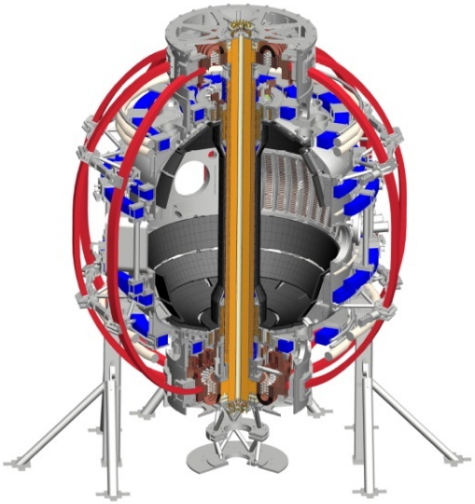
NSTX-U Research Plans for FY2015-17

J. Menard, M. Ono - PPPL

For the NSTX-U Research Team

FY2017 FES Budget Planning Meeting
Germantown, MD
March 24, 2015



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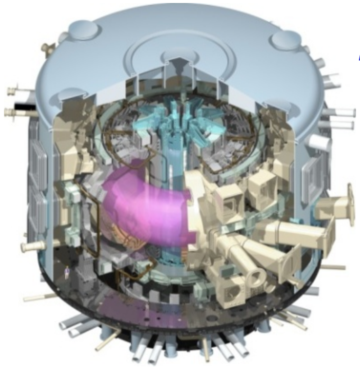
Outline

- NSTX-U mission, priorities, FY15-17 overview
- FY15-17 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF study highlights
- Summary

NSTX Upgrade mission elements

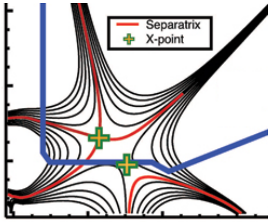
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**



ITER

- **Develop solutions for the plasma-material interface (PMI) challenge**

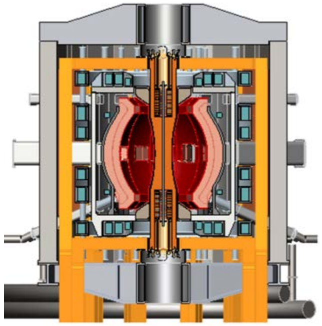
Lithium

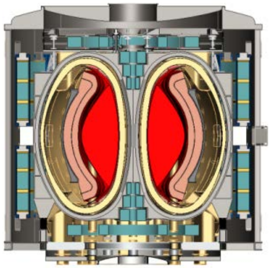


"Snowflake"

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

ST-FNSF/Pilot





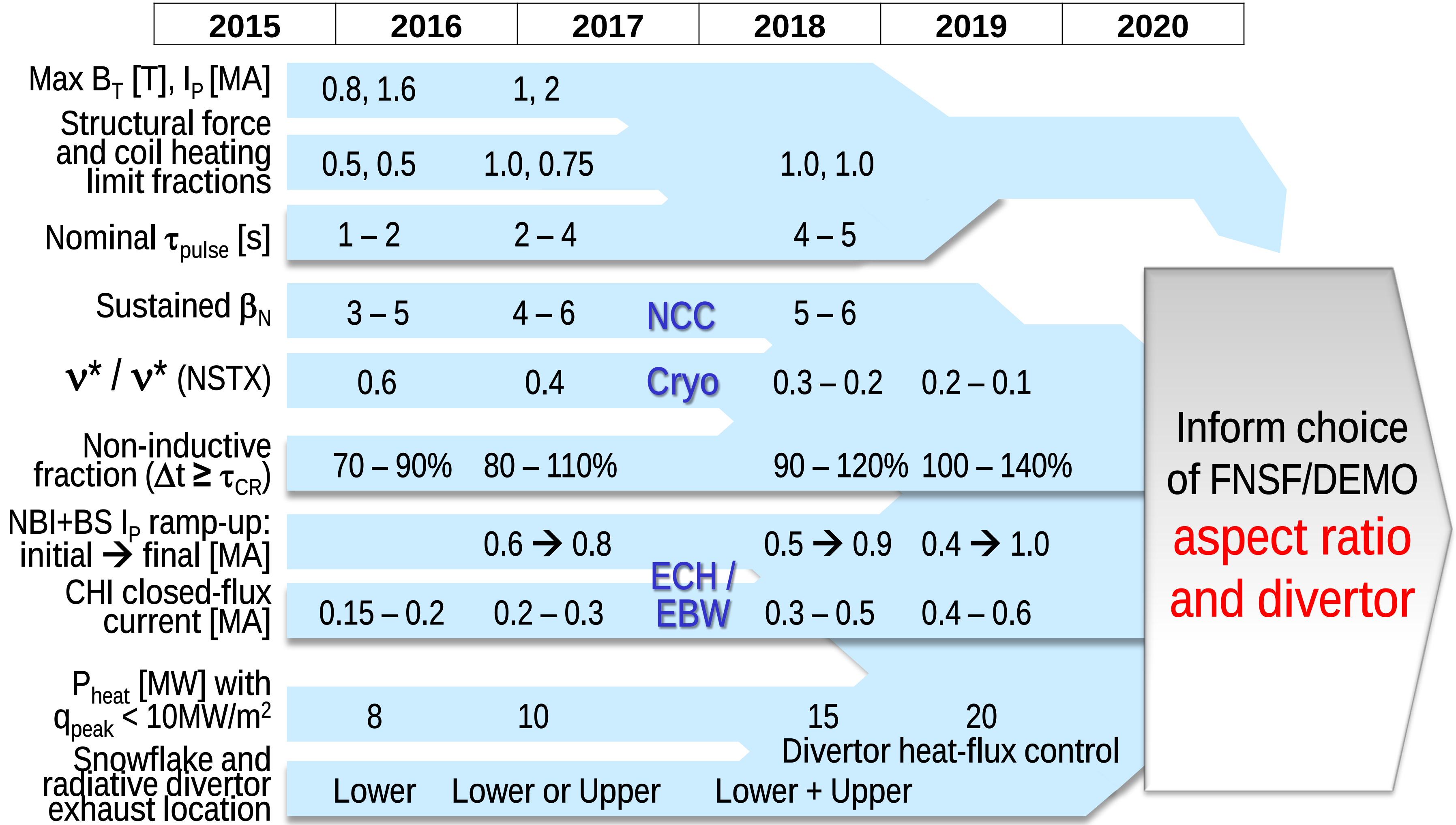
- **Develop ST as fusion energy system**

FY15-17 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

Mission Elements and 5 Year Plan 5 Highest Priorities

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Reduced ν^* + high-β + varied q and rotation to extend understanding
- Develop solutions for PMI challenge
  - High-flux-expansion snowflake/X + radiative detachment
  - Assess high-Z PFCs + liquid Li as integrated PMI solution
- Advance ST for FNSF
  - 100% non-inductive sustainment at FNSF normalized performance
  - Develop and understand non-inductive start-up, ramp-up/overdrive

NSTX-U 5 year plan: Develop physics/scenario understanding needed to assess ST viability as FNSF/DEMO, support ITER



Cryo: access lowest ν^*, compare to Li **ECH / EBW:** bridge T_e gap from start-up to ramp-up

Off-midplane non-axisymmetric control coils **(NCC):** rotation profile control (NTV), sustain high β_N

5 year goal: Establish core physics/scenarios for ST
10 year goal: Integrate high-performance core + metal walls

2015-2019

Establish ST physics / scenarios:

- Non-inductive start-up, ramp-up
- Confinement vs. β , collisionality
- Sustain high β with advanced control
- Mitigate high heat fluxes
- Test high-Z divertor, Li vapor shielding

Inform choice of FNSF configuration:

- Lower A or higher A?
- Standard, snowflake, Super-X (MAST-U)?

2020-2024

High-performance + metal walls

- Convert all PFCs from C to high-Z
- Static → flowing Li divertor module(s), full toroidal flowing Li divertor, high T_{wall}
- 5s → 10-20s for PFC/LM equilibration
- Assess ST with high-Z, high-Z + Li

Inform choice of FNSF / DEMO plasma facing materials:

- High-Z acceptable? or need high-Z + Li?
- Assess for both divertor and first-wall

NSTX-U Research Team Has Been Scientifically Productive

Very Active in Scientific Conferences, Publications, and Collaborations

- Strong APS meeting participation in the fall 2014: 1 ST review talk, 5 invited talks, 44 additional presentations. Three NSTX APS-DPP press releases available on the web.
- Significant collaboration research contributions are being made in diverse science areas by the NSTX-U research team.
- On-going active research collaboration particularly with DIII-D and C-Mod. Several activities resulted in 2014 IAEA papers.
- Strong NSTX-U and ST-FNSF related engineering / technology presentations at the 2014 PSI, SOFE and TOFE meetings.
- All of the FY 2014 milestones were completed on schedule
- 54 refereed publications for CY 2014
- NSTX-U will host next International ST workshop - November 2015

Partnering with PPPL theory to enhance NSTX-U modeling supporting high-priority research areas

- **Energetic particle research:**
  - Use the HYM, NOVA-K codes code (fully kinetic ions and drift and kinetic electrons) to study CAE, GAE, KAW effects on energy fluxes and electron transport
  - M3D-K nonlinear multi-mode TAE studies leading to avalanche production
  - Extend TAE quasi-linear model to calculate fast-ion diffusion in NSTX-U
- **Transport:**
  - Implement E-M effects in global GTS (for core) and XGC-1 (for edge) to enable studies of micro-tearing in NSTX/NSTX-U
  - *Comparative study of role of collisionality in transport in NSTX and DIII-D*
- **Stability:**
  - VDE and beta-limit disruptions using M3D/M3D-C1
  - Use stellarator tools for 3D equilibrium and coil optimization for proposed NSTX-U off-midplane non-axisymmetric control coils (NCC)
  - Halo current diagnostic planning, future implementation and measurements

Overview of FY2014-15 NSTX-U research activities

- Collaborations supporting NSTX-U, ITER, FNSF
  - DIII-D: Snowflake/detachment control, core transport
  - C-Mod: Boundary - pedestal structure/KBM, high-Z PFCs
  - KSTAR: MHD - NTV physics, kink stability, plasma control
  - York/MAST: Synthetic aperture μ-wave imaging (DBS, BXO)

- Prepare for NSTX-U operation
  - Finish data analysis, publications from NSTX, collaborations
  - Physics ←→ engineering design of facility enhancements:
    - Row of high-Z tiles on outboard divertor
    - Lower divertor cryo-pump
    - Non-axisymmetric control coil (NCC) specification
    - ECH/EBW for start-up/ramp-up
  - Prepare diagnostics, control system, analysis for NSTX-U ops

New NSTX-U Science organizational structure for 2015:
3 Science Groups, 9 Topical Science Groups, 1 Task Force

Science Group (SG)
- Topical Science Group (TSG)

Task Force (TF)

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]

Particle Control Task Force (FY2015-16)
Leader: R. Maingi, **Deputy:** J. Canik[1]

Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

Each TSG will have a leader, deputy, theory rep, and at least 1 university rep to enhance university participation

Collaborators in Science Program Leadership:

1 ORNL
2 University of Wisconsin
3 LLNL
4 UT Knoxville
5 University of Illinois
6 Columbia University
7 Princeton University
8 Johns Hopkins University
9 UC Irvine
10 UC Los Angeles
11 University of Washington
12 MIT

12 collaborating institutions engaged in NSTX-U science program leadership

Operations goals for first 2 run-months of FY15

- Machine Commissioning ~1 month (run weeks 1-4)
  - Develop basic breakdown, current ramp, shape/position control, diverted plasmas, H-mode access, basic fuelling optimizations
  - Goal: 1 MA, 0.5 T, NBI-heated H-mode (i.e. ~NSTX fiducial levels)
  - Diagnostic commissioning
  - Boronized PFCs
  - Mostly eXperimental Machine Proposals (XMPs)

- 1st Month of Science Campaign (run weeks 5-8)
  - Boronized PFCs, possibly begin lithium coatings
  - Operations and basic profile diagnostics, neutron rate,…
  - Operation up to 1.4 MA and 0.65 T, 2 seconds
  - 6 beam sources up to 90 kV
  - HHFW available for commissioning
  - **Begin early critical XPs**

Overview of FY2015-17 NSTX-U research activities

- FY2015
  - Obtain first data at 60% higher field/current, 2-3× longer pulse:
    - Re-establish sustained low l_i / high-κ operation above no-wall limit
    - Study thermal confinement, pedestal structure, SOL widths
    - Assess current-drive, fast-ion instabilities from new 2^{nd} NBI
- FY2016
  - Extend NSTX-U performance to full field, current (1T, 2MA)
    - Assess divertor heat flux mitigation, confinement at full parameters
  - Access full non-inductive, test small current over-drive
  - First data with 2D high-k scattering, high-Z tiles
- FY2017
  - Study low-Z and high-Z impurity transport
  - Assess causes of core electron thermal transport (micro-instability vs. *AE)
  - Test advanced q profile and rotation profile control
  - Assess CHI plasma current start-up performance

FY15-17 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

R1#-# → **Purple boxes indicate Research milestone year and number in this presentation and FWP**

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Reduced ν^* + high-β + varied q and rotation to extend understanding
- Develop solutions for PMI challenge
  - High-flux-expansion snowflake/X + radiative detachment
  - Assess high-Z PFCs + liquid Li as integrated PMI solution
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FY15-17 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

Core Science
- Macroscopic Stability
- Transport and Turbulence
- Energetic Particles

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Reduced ν^* + high-β + varied q and rotation to extend understanding
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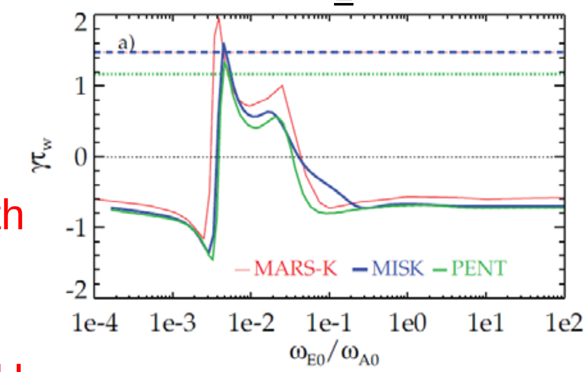
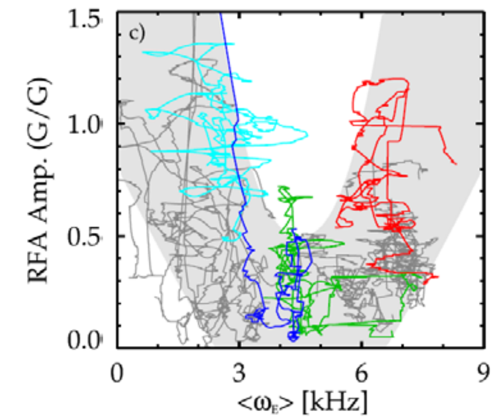
Kinetic stability theory and comparison to NSTX is setting the stage for practical use in NSTX-U for disruption avoidance

- Moving kinetic RWM stability theory from successful theory/experiment comparison to actual implementation
  - MISK (perturbative) benchmarked with other leading codes
  - A simplified model based on these results will be implemented in NSTX-U disruption avoidance algorithm

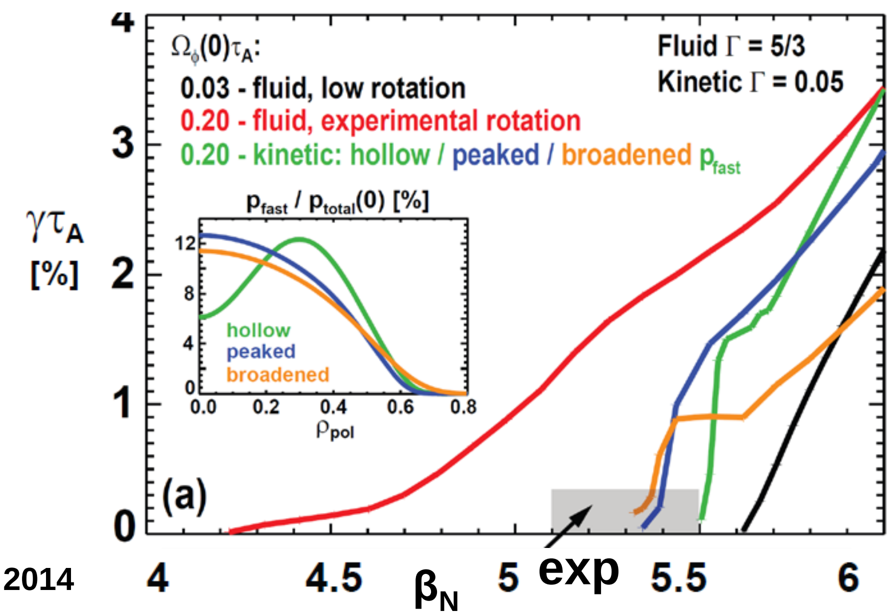
Growth rate vs. ω_E for ITER case



Instability measure (RFA) vs. exp. ω_E for NSTX



- Ideal Wall Mode destabilization by rotational shear vs. stabilization by kinetic effects explained with MARS-K
  - Also may help explain low-density/ramp-up disruptions in NSTX in prep for low ν operation (fast ions important)

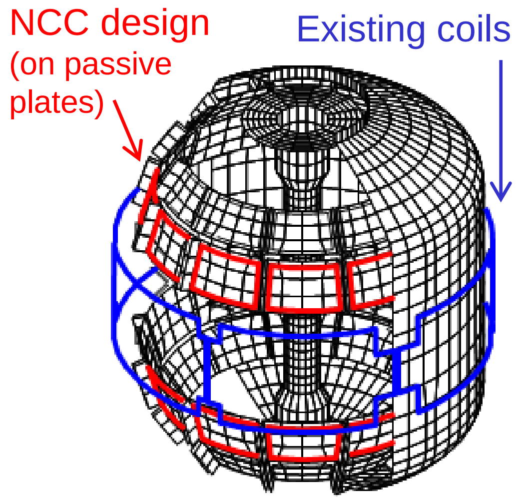


PRL 2014

Non-axisymmetric control coils (NCC) (incremental) will enhance physics studies and control

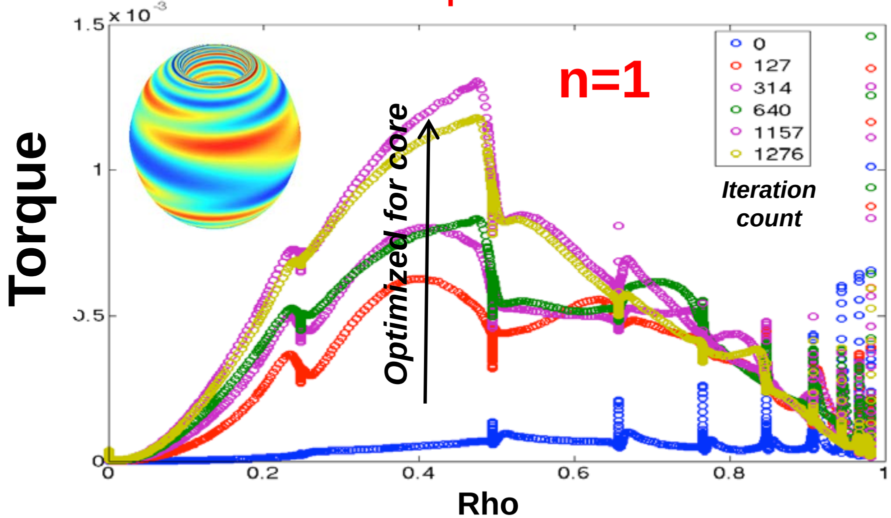
- NCC designed with multiple physics metrics for:
- error field, RWM, rotation control by NTV, RMP
  - Analysis updated with IPEC-PENT and more NSTX-U targets

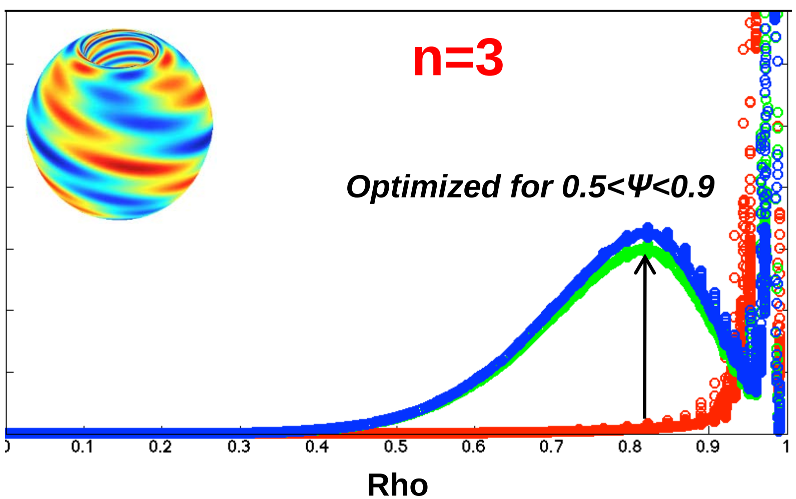
- Utilizing stellarator optimization tools for NCC design
  - The IPECOPT code developed (from STELLOPT) to optimize IPEC equilibrium for core and edge NTV Torque



PPPL Theory Partnership, JRT-14

Examples of initial IPECOPT NTV torque profile localization optimization



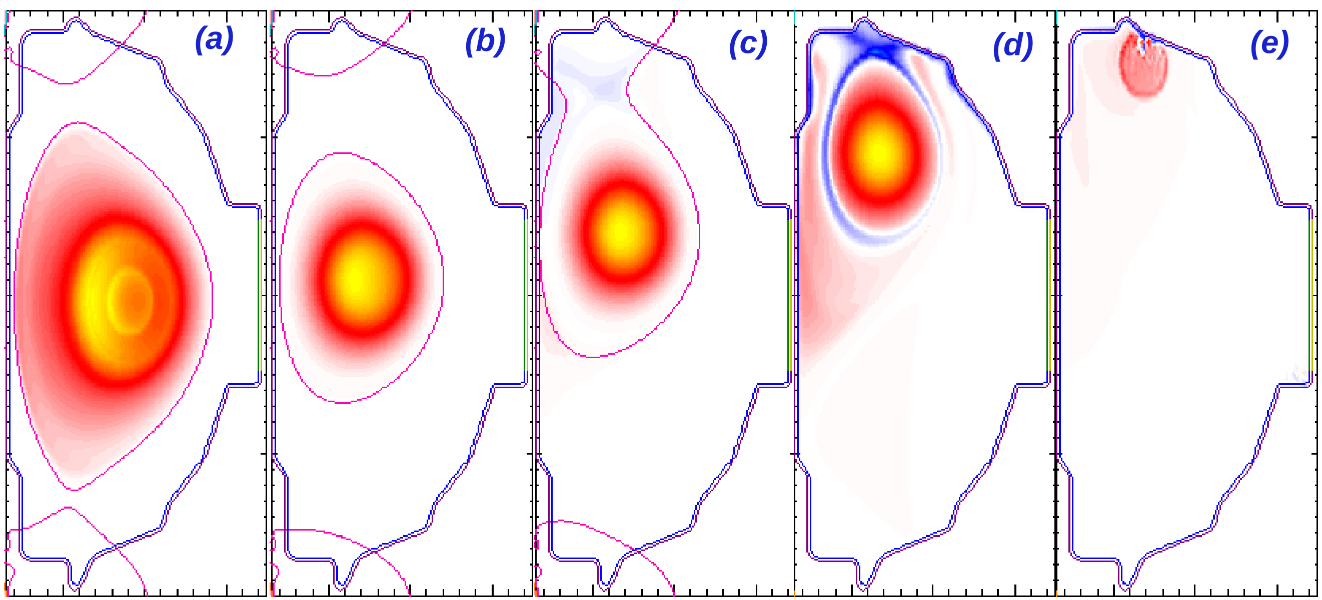


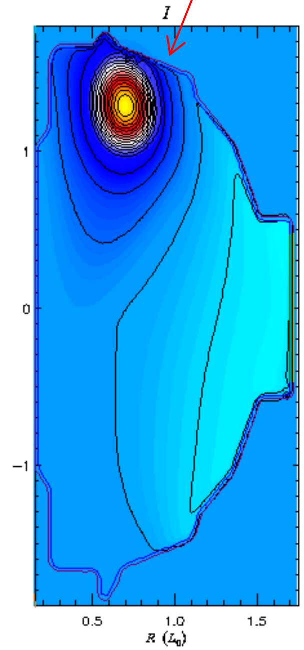
Simulations of VDEs have begun using M3D-C^1

- Initial simulations from 2D low resolution calculation
  - Benchmark against earlier TSC results
- New capability is finite thickness wall

Note halo currents

Toroidal Current Density Evolution

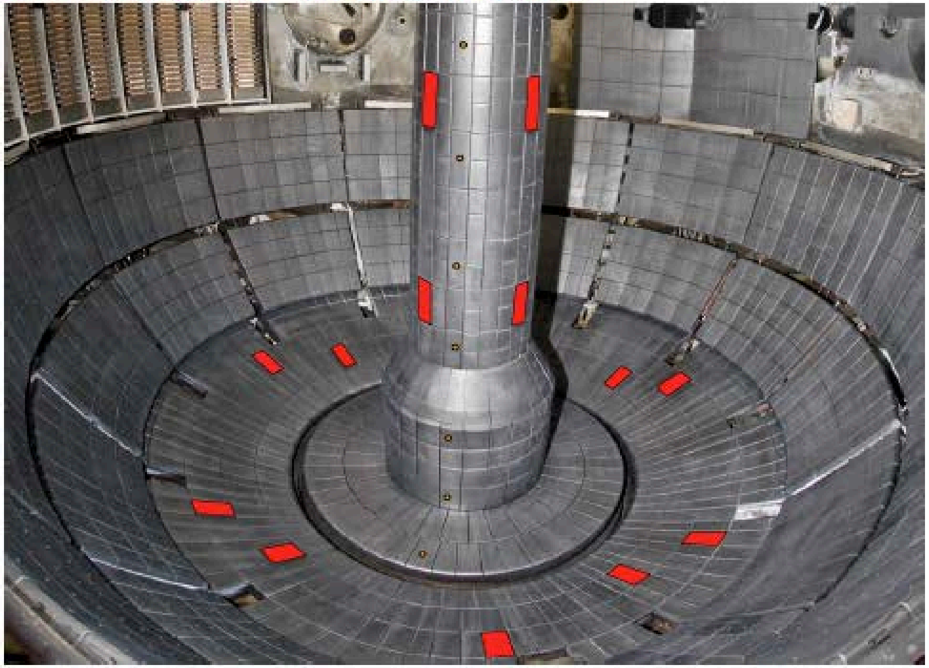


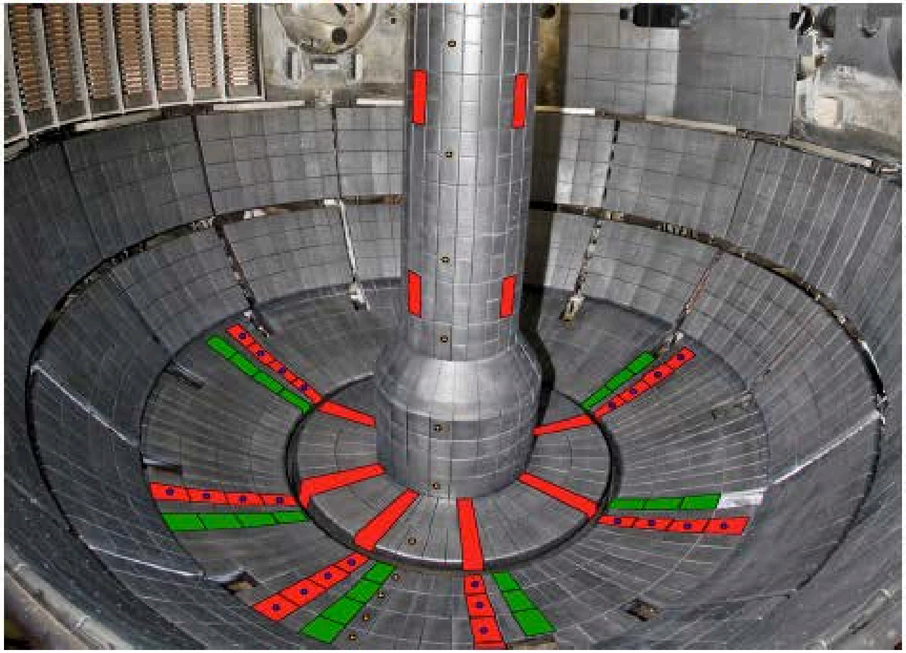


Jardin

<u>Future work:</u> Extend to 3D and realistic η to compute non-axisymmetric halo current distribution for validation against experimental measurements

Halo current diagnostic upgrade planned



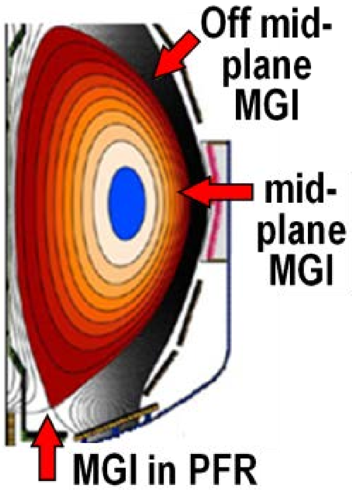


- Definition of expanded configuration in progress
  - Experimental post-doc hired for magnetics/disruptions/halo currents
  - Hiring theory post-doc for modeling support (NSTX-U/theory partnership)

Macroscopic Stability Research Plans for FY2015-17:

Complete 3D coil design, re-establish high-β ops, assess MGI and halos

- **FY15**: Finalize NCC coil specs for engineering design
  - Re-establish n=1-3 error-field correction, RWM control, minimize EF rotation damping, sustain operation above no-wall limit **R15-3**
  - Test poloidal dependence of Massive Gas Injection (outboard vs. private flux region)



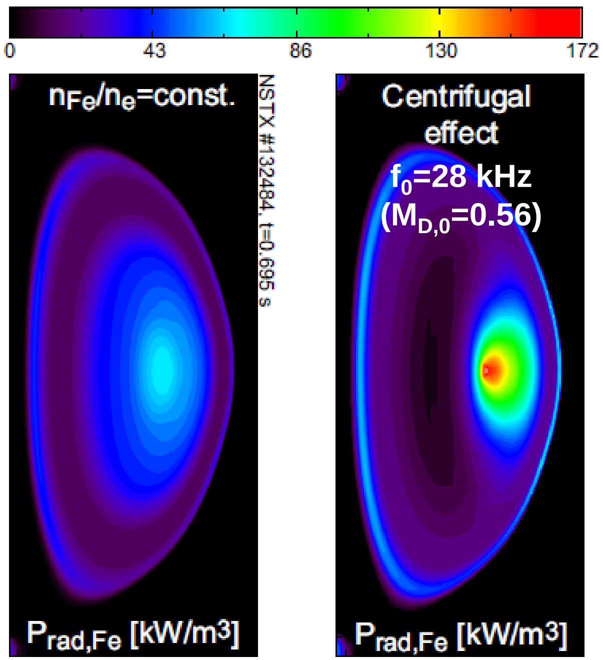
- **FY16**: Contribute unique MGI data (low-A, injector location) for mitigation + warning, prediction
  - Assess mitigation triggering via real-time warning in NSTX-U **JRT-2016**
  - First data from upgraded halo diagnostics
- **FY17**: Control of current and rotation profiles to improve global stability limits and extend high performance operation **R17-3**

NSTX-U will study low- and high-Z impurity transport to assess potentially strong rotation effects

$$n_j = n_{j,0} \exp\left(\frac{\frac{1}{2}m_j\omega^2(R^2 - R_0^2) - eZ_j\Delta\Phi}{k_B T_j}\right)$$

- Will investigate if high-Z transport follows neoclassical including centrifugal effects
  - Use 2nd NBI + NTV to vary rotation
- Investigate particle transport using edge neutral measurement (D_α from MSE, BES; D_β camera) + DEGAS2 calculations
  - Assess perturbative capability using TS, ME-SXR
  - Perturbative particle transport measurements led on MAST in 2013 (Ren) – analysis ongoing

Collaboration with CCFE



Delgado-Aparicio, HTPD (2014)

- Impurity transport studies: gas-puff (Ne, Ar), laser blow off (Ca, Mo, W – FY16, LLNL/JHU) and several diagnostic enhancements:
  - Survey x-ray spectrometers (LLNL)
  - XCIS: $V_{\varphi,Z}$, T_Z, n_Z (Ca, Ar, Mo, W) (PPPL)
  - 1D tangential mid-plane + 2D poloidal bolometers (PPPL)

Testing reduced χ_e models for micro-tearing turbulence
ST providing unique access to high-β electromagnetic effects

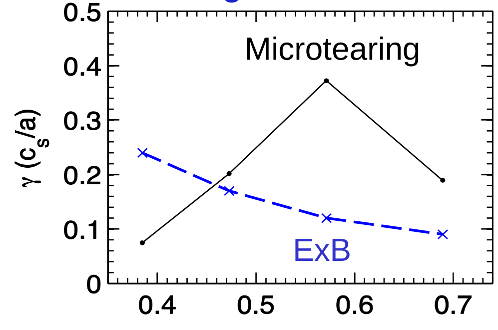
- Microtearing (MT) instability dominant in <u>high-collisionality</u> H-modes

- T_e predictions using Rebut-Lallia-Watkins (1988) microtearing model show agreement
  - Poor agreement for lower ν_* discharges
  - Will test physics-based TGLF transport model in FY15 (GA)

- Beginning to investigate global EM effects ($\rho_*=\rho_s/a$~1/120)

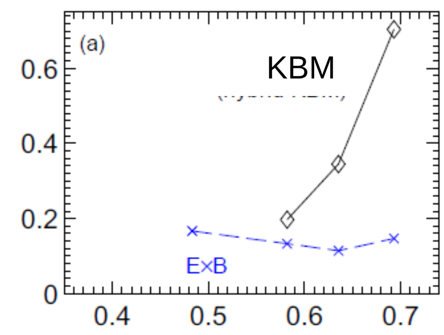
Collaboration with UC-Boulder, GEM (Chowdhury), EM in XGC1 (Lang, Ku) & GTS (Startsev, Wang) in FY15 (PPPL-Theory)

high-ν_* H-mode



ρ

low-ν_* H-mode



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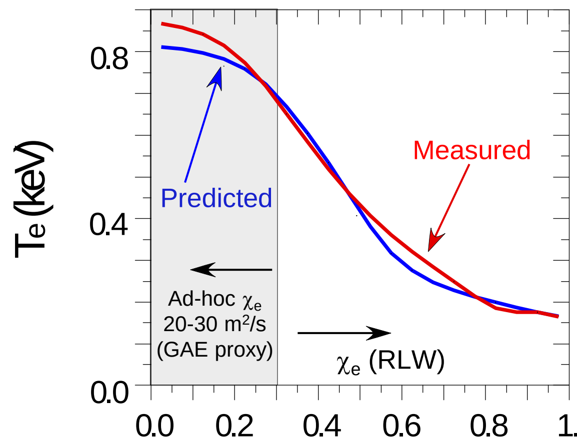
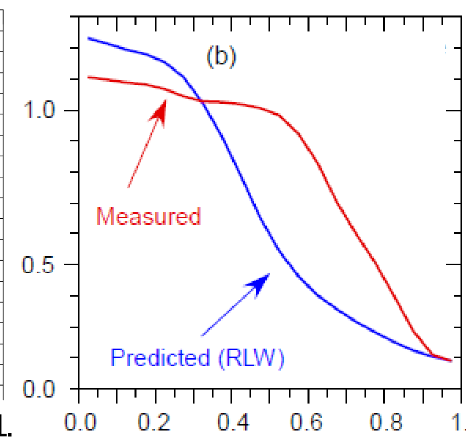


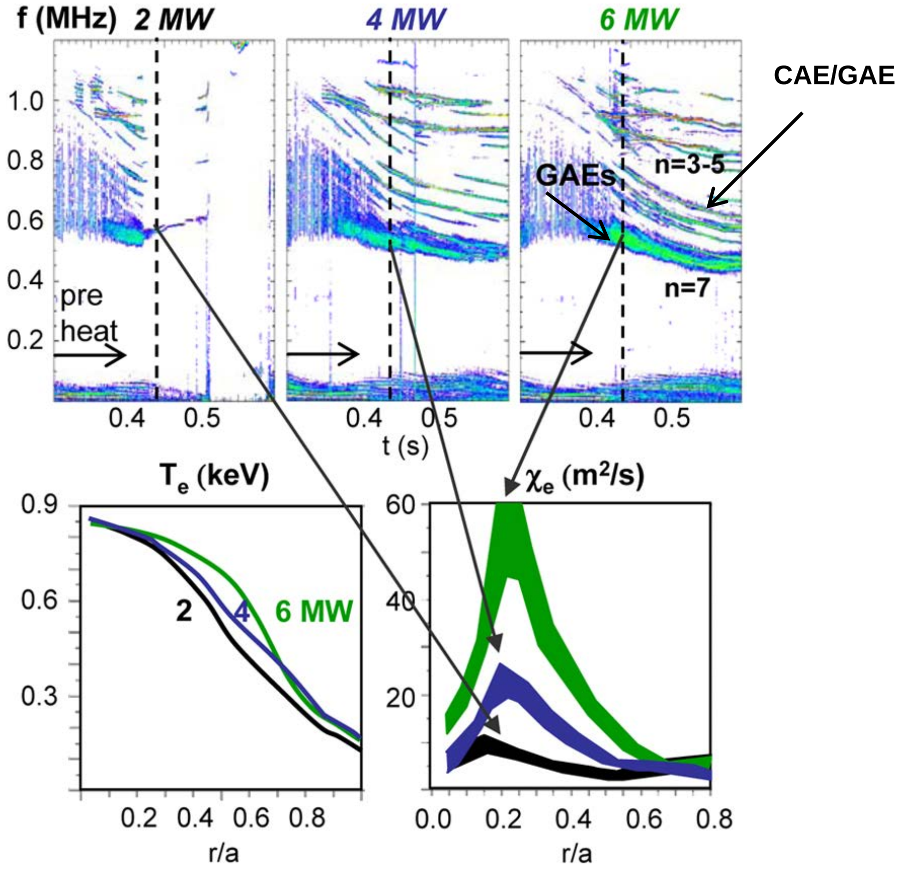


ρ *Kaye (2014)* ρ

- **No drift wave instability predicted near axis – influence of GAE/CAE?**

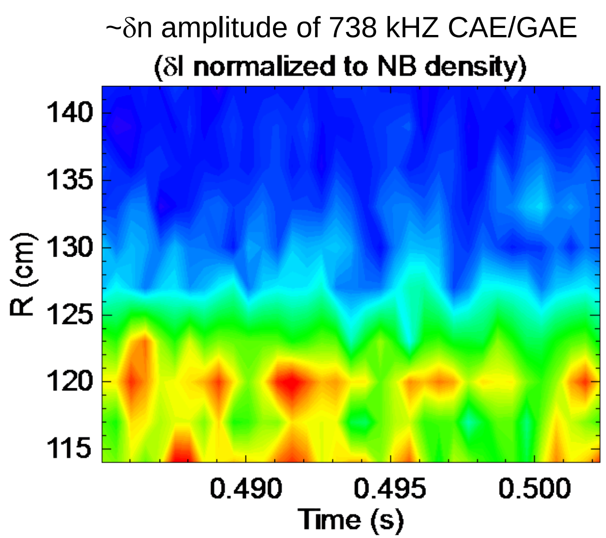
Large inferred anomalous core electron transport in presence of CAE/GAEs

- Observation of high frequency CAE/GAE modes in plasma core associated with flattening of T_e profile (Stutman et al., Tritz et al.)
  - High level of transport (10-100 m^2/s) inferred assuming classical beam physics



Stutman

BES spectra show mode amplitudes peaking from R=115 to 120 cm (r/a~0.2 to 0.3), in region of enhanced transport



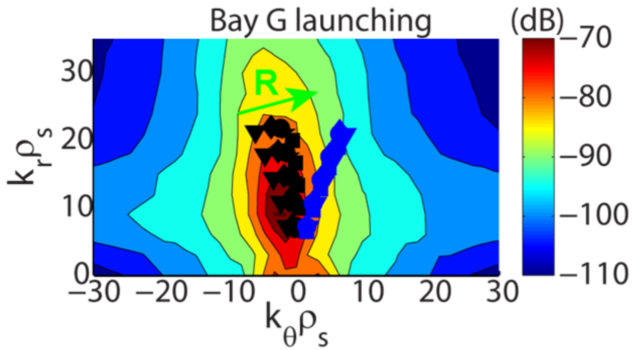
Smith

Is enhanced transport the full picture?

Transport and Turbulence Research Plans for FY2015-17:

Develop reduced χ_e models, first τ_E data at higher B_T, I_P + turbulence

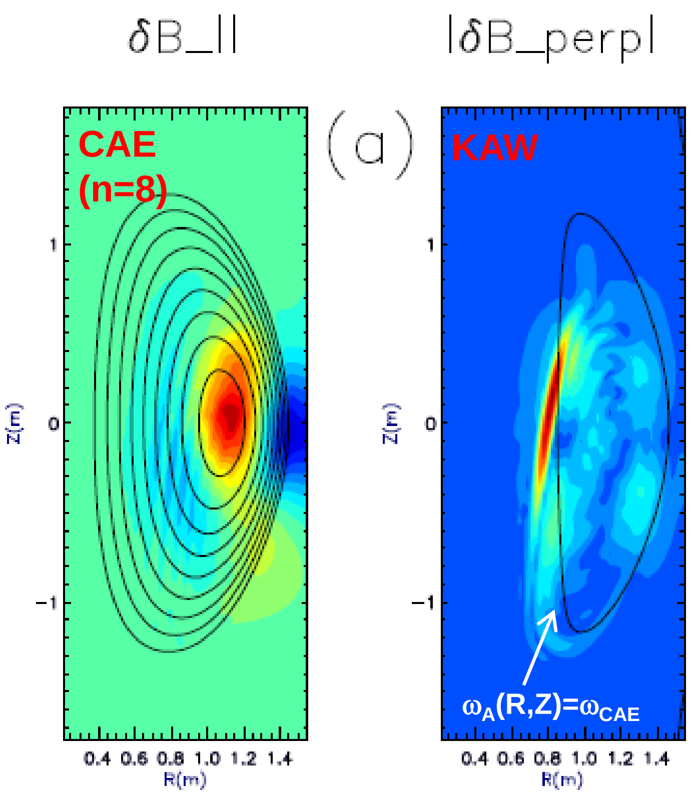
- **FY15**: Extend ST confinement scalings and understanding with up to 60% increase in B_T and I_P **R15-1**
  - Measure low-k δn (BES w/ increased edge channel count), 1st polarimetry data
- **FY15-16**: Develop and validate reduced transport models using ST data + linear and non-linear gyro-kinetic simulations
- **FY16**: Extend confinement studies to full B_T, I_P → 2-3× lower ν*
  - Initial utilization of new high-k FIR scattering system for ETG turbulence
    - Measure k_r & k_θ to study turbulence anisotropy
  - Incremental: Study turbulence vs. ν*, rotation, q with high-k + BES + polarimetry **IR16-1**



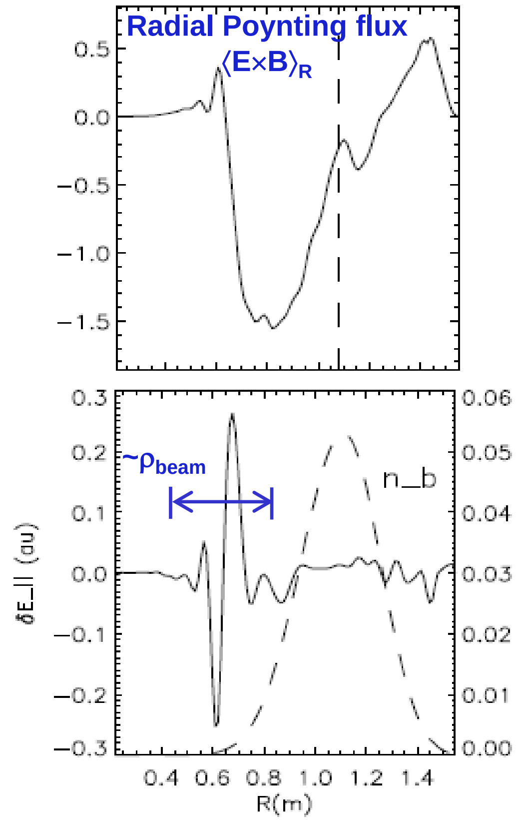
- **FY17**: Assess impurity sources, edge/core impurity transport
  - Utilize new laser blow-off system (LLNL) for edge impurity injection **R17-1**

Investigating coupling of CAEs to kinetic Alfvén waves (KAW) as additional energy "loss" mechanism

1) GAE/CAEs cause large χ_e through stochastic orbits [Gorelenkov, NF 2010]
2) CAEs also couple to KAW - Poynting flux redistributes fast ion energy near mid-radius, $E_{||}$ resistively dissipates energy to thermal electrons
   - $P_{CAE\rightarrow KAW}$~**0.4 MW** from QL estimate + experimental mode amplitudes (Belova,IAEA 2014)
   - $P_{e,NBI}$~**1.7 MW** for ρ<0.3, NBI power deposited on core electrons



Up to 25% of electron heating power transferred to KAW off-axis?

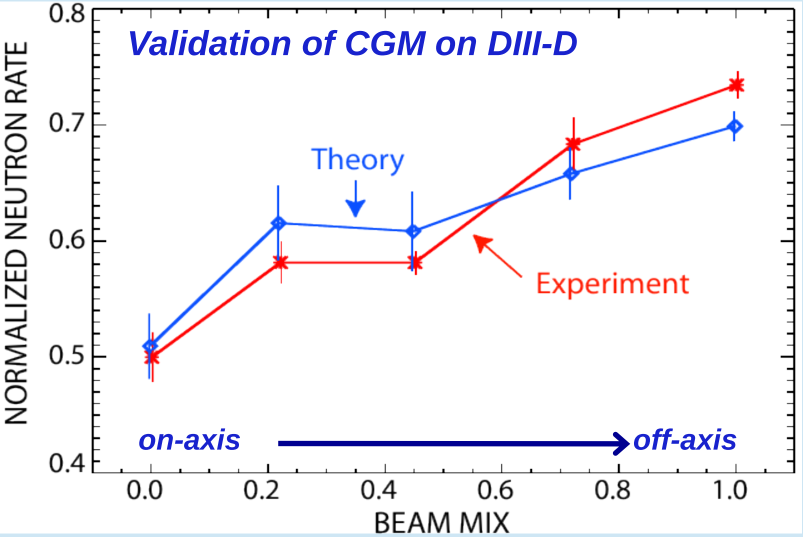


E. Belova – HYM code (PPPL Theory)

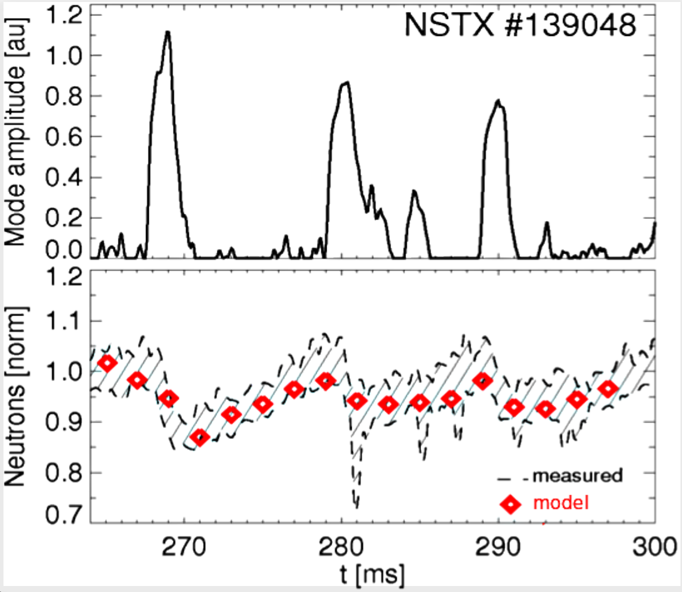
Validated reduced models for EP transport; extend validation beyond present DIII-D collaboration

- "Critical Gradient" 1.5D model predicts relaxed fast ion profiles for given instabilities
- Being validated on DIII-D, NSTX → NSTX-U
- Motivates 2D, more accurate quasi-linear model
  - Improve treatment of resonances in velocity space
  - Working towards inclusion in TRANSP
- Promising tool for ITER predictions

N. Gorelenkov, APS 2012



W. Heidbrink, N. Gorelenkov, NF 2013



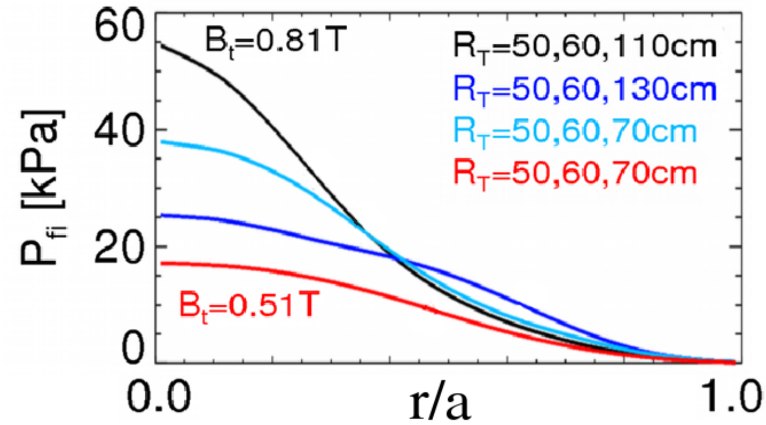
M. Podestà, PPCF 2014

- New "kick" model being implemented in NUBEAM/TRANSP for low-f AEs (μ conserved)
  - ➢ Uses a probability distribution $p(\Delta E, \Delta P_\zeta | P_\zeta, E, \mu)$ to model phase-space *kicks* by instabilities
  - ➢ Provides detailed evolution of $F_{nb}(P_\zeta, E, \mu)$, hence accurate estimates for NB-driven current
- Can handle multiple instabilities with arbitrary, time-varying mode amplitude
- Initial validation with stand-alone NUBEAM successful for TAEs, kink-like modes on NSTX

Energetic Particle Physics Research Plans for FY2015-17:

Develop full + reduced fast-ion transport models, characterize new 2nd NBI

- **FY15:** Measure fast-ion (FI) density profiles, confinement, current drive, AE stability R15-2
  - Exploit new 2nd NBI and higher B_T, access to reduced v_{fast} / v_A
  - Complete reduced model for AE-induced fast ion losses in TRANSP
    - Needed for NBICD in STs/ATs/ITER



- **FY15-16**: Develop model $\chi_{e, AE}$ using measured CAE/GAE mode structures and HYM/ORBIT simulations (w/ T&T group)

- **FY17:** Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport R17-2
  - Joint milestone between transport / energetic particle groups

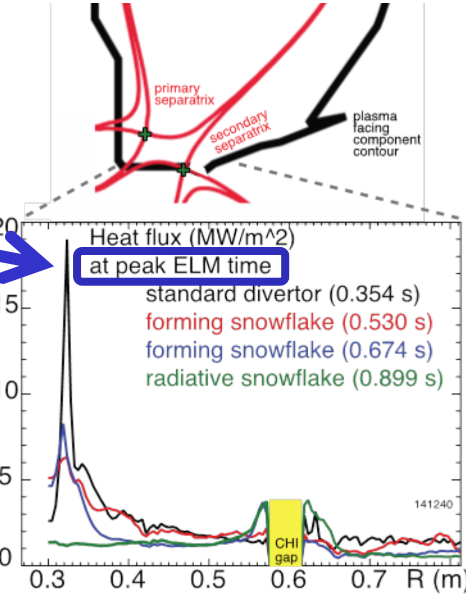
FY15-17 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

Boundary Science
- Pedestal
- Divertor / SOL
- Materials and PFCs

- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Reduced ν^* + high-β + varied q and rotation to extend understanding
- Develop solutions for PMI challenge
  - High-flux-expansion snowflake/X + radiative detachment
  - Assess high-Z PFCs + liquid Li as integrated PMI solution
- Advance ST for FNSF
  - 100% non-inductive sustainment at FNSF normalized performance
  - Develop and understand non-inductive start-up, ramp-up/overdrive

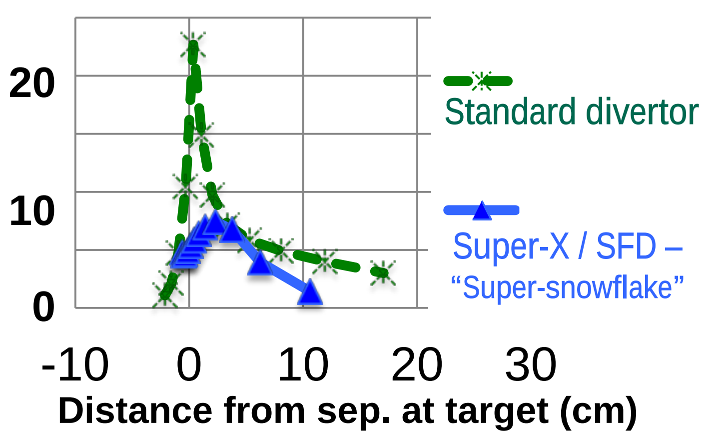
Modeling of radiative snowflake being performed in preparation for NSTX-U operation and design of ST-FNSF

- ELM heat deposition from fast thermography
  - – A_{wet} decreases during Type-I and III ELMs
  - – A_{wet} decrease leads to q_{peak} increase with increase of ELM energy loss – mitigation needed **(e.g., with rad. snowflake)**

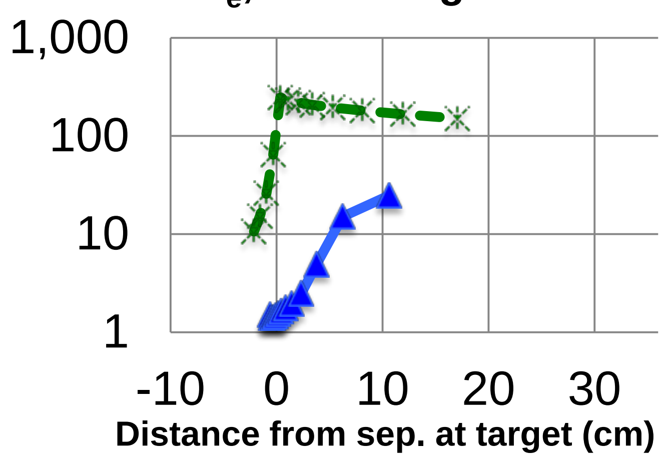


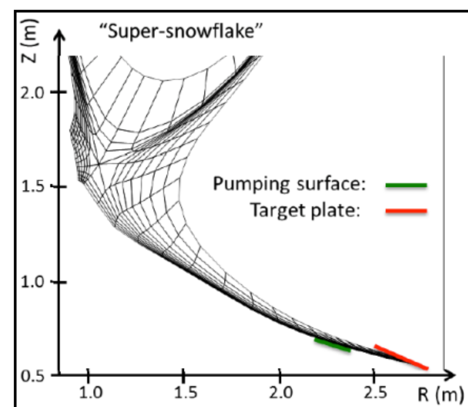
- UEDGE modeling of ST-FNSF divertor
  - – Nitrogen-seeded tilted-plate and long-legged snowflake divertor provided 3x reduction in heat flux from ≤ 25 MW/m²
    - NSTX-like transport $\chi_{i,e}$= 2-4 m²/s
    - P_{SOL}=30 MW, 4% nitrogen, R=1 (saturated metal plate)

Outer target heat flux (MW/m²)



T_e, outer target

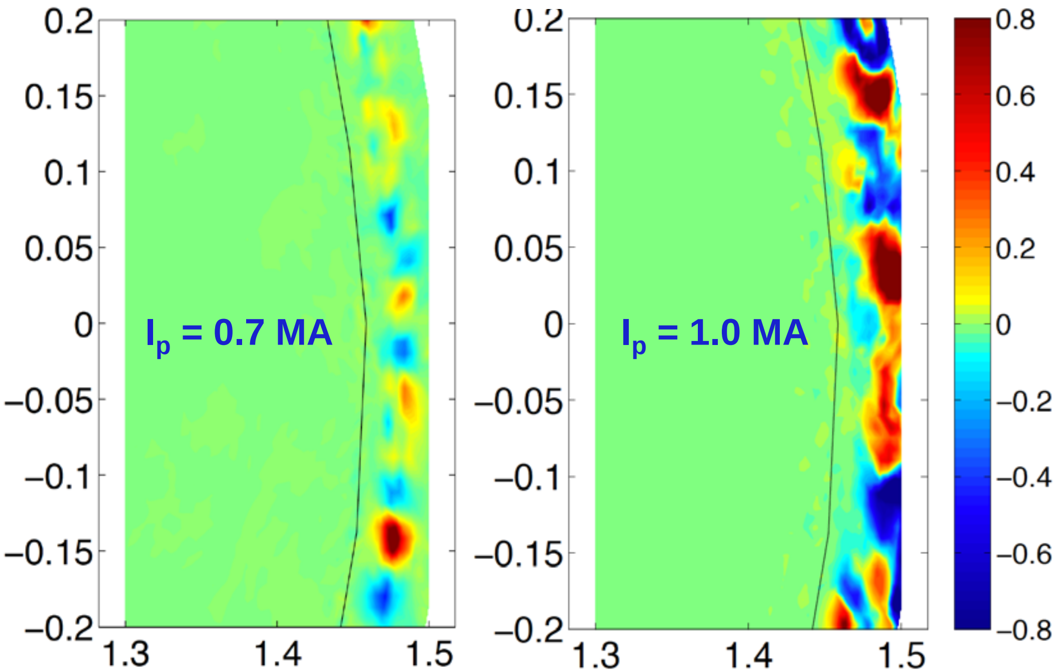


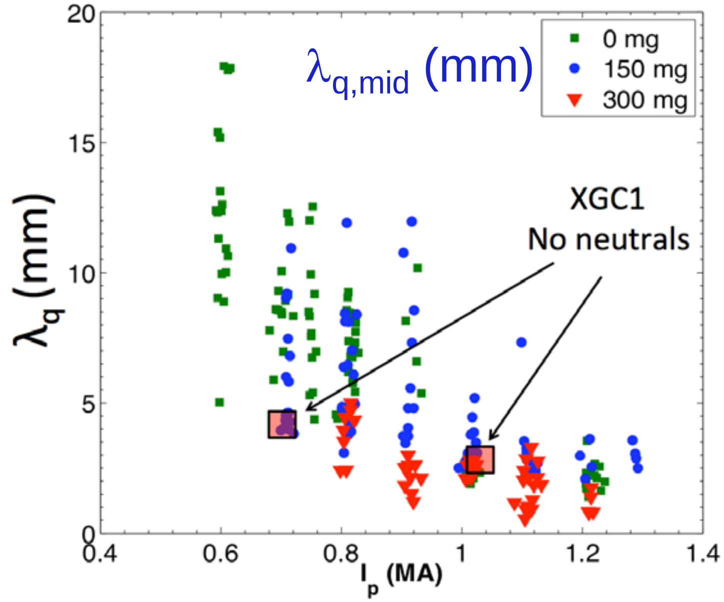


Collisionless XGC1 simulations indicate that the SOL heat flux width is set primarily by neoclassical processes

- XGC1 (collisionless) predicts "blob" related turbulence
  - Blobs stronger in SOL than in pedestal
  - Stronger at higher I_p
- Blobs do not appear to widen the heat load width above the neoclassical width ($\sim\Delta_{banana} \sim 1/I_p$ from XGC0)
- Predicted variation of $I_p^{-0.8}$ is consistent with observation (for 300 mg Li dep.)

300 mg Li deposition



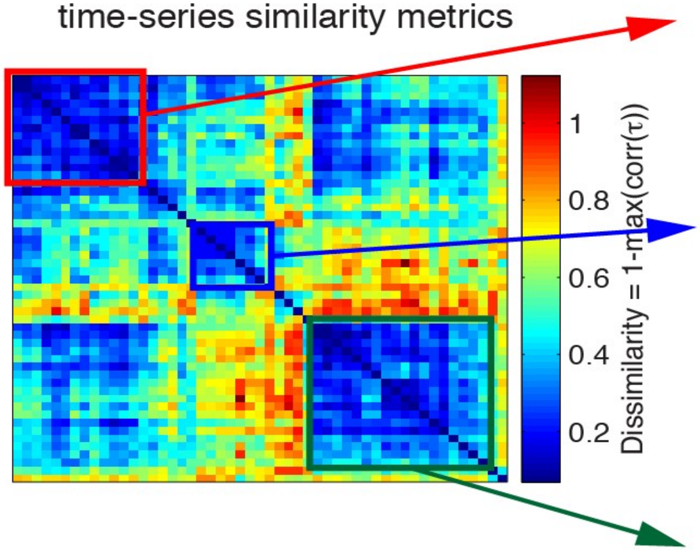


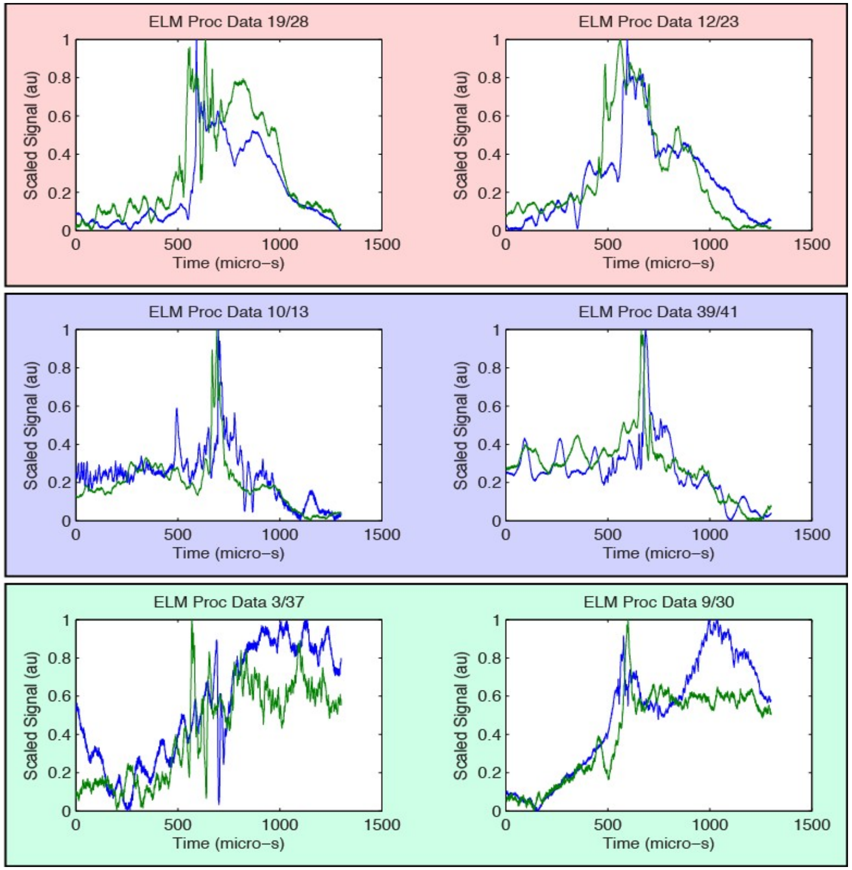
Future Work: Extend to finite collisionality and recycling to determine effect on SOL λ_q

NSTX BES measurements used to identify 2 or 3 ELM groups with distinct nonlinear evolution patterns

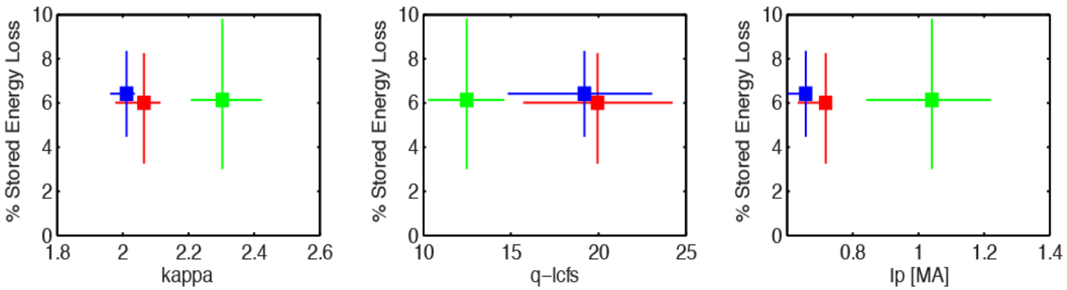
Smith (UW)

Unsupervised machine learning analysis
of ELM events with
time-series similarity metrics





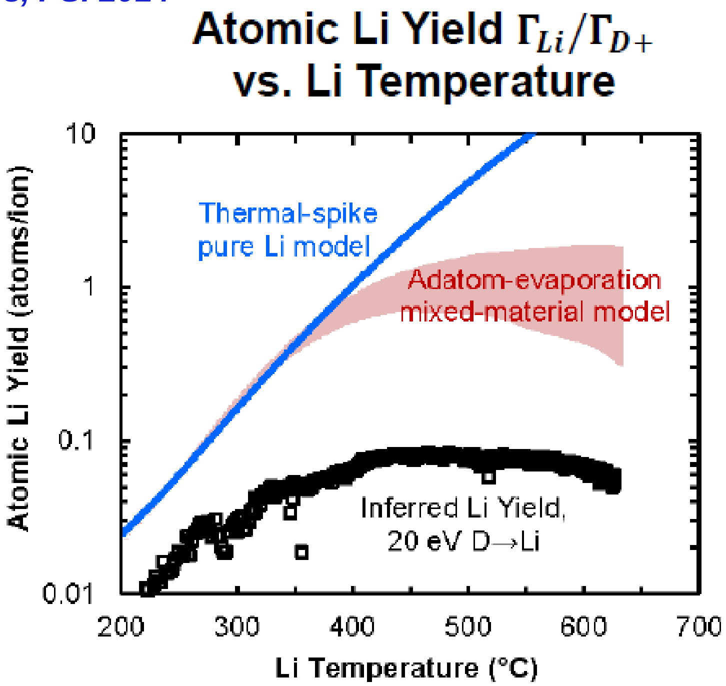
NSTX ELM groups occur in distinct regions of parameter space:



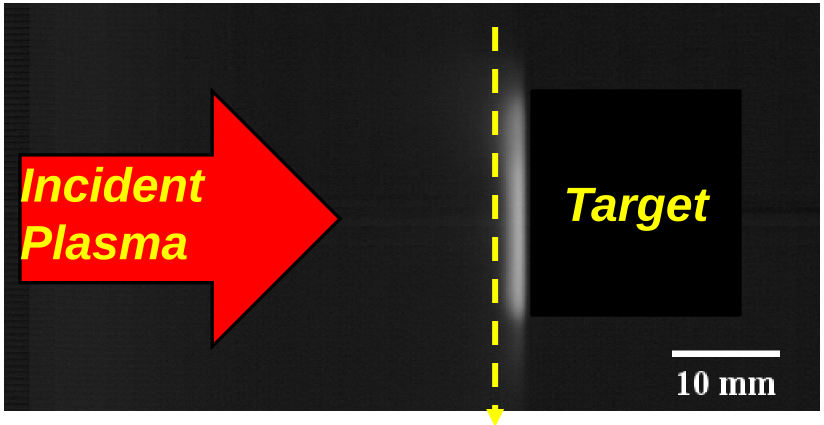
Magnum-PSI experiments on high-temperature Li show strongly reduced erosion and stable cloud production

- Gross erosion measured spectroscopically in divertor-like plasma
  - Neon plasma reproduces Langmuir Law
  - Deuterium *suppresses* erosion
- Reduced gross erosion and strong re-deposition result in 10× longer lifetime of 1 micron coating
  - Consistent with Li trapping in pre-sheath
  - Pre-sheath scale length consistent with neutral Li emission region (~3mm)

Abrams, PSI 2014



Neutral Li emission, t=2.5s

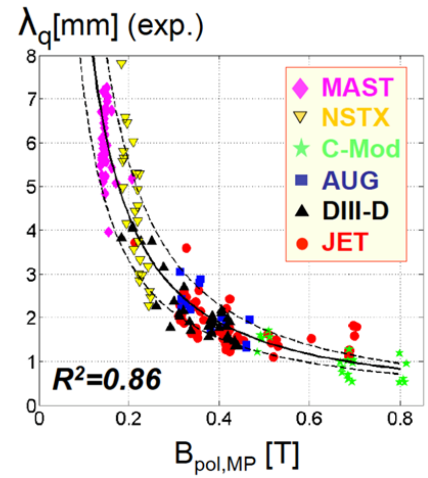


Jaworski, PSI 2014

Boundary Science Research Plans for FY2015-17:

Advance snowflake, cryo, pedestal, SOL studies, extend to higher B_T, I_P

- **FY15**: Measure pedestal structure, SOL width, ELM types, snowflake performance at up to 60% higher I_P, B_T, 2× higher P_{NBI} R15-1
  - Lithium granule injector (LGI) ELM triggering for impurity control, Li coating performance in NSTX-U - compare to EAST/DIII-D results
  - EAST: assess long-pulse particle/impurity control with triggered ELMs, cryo-pumping, lithiumization, high-Z PFCs



- **FY16**: Increase I_P → 2MA → test snowflake, detachment, PFCs with $q_{||}$ up to 4-5× higher than NSTX R16-1
  - Assess high-Z + lithium coated PFC performance with 1 row of high-Z tiles on outboard divertor (at large R) R16-2
- **FY17** (incremental): Investigate power/momentum balance for high density divertor operation (vapor shielding baseline) IR17-1

FY15-17 planned research supports 5 highest priority goals of NSTX-U 5 year plan:

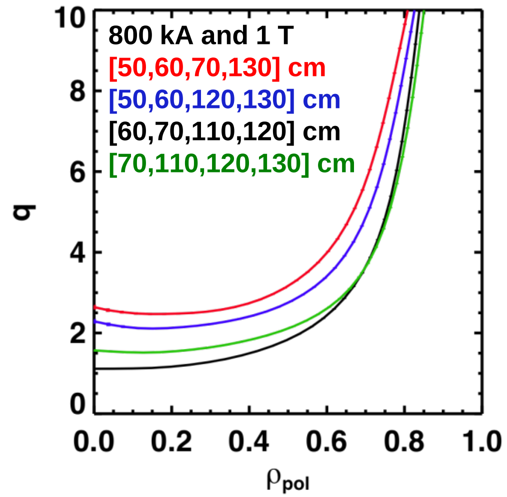
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
  - Reduced ν* + high-β + varied q and rotation to extend understanding
- Develop solutions for PMI challenge
  - High-flux-expansion snowflake/X + radiative detachment
  - Assess high-Z PFCs + liquid Li as integrated PMI solution
- Advance ST for FNSF
  - 100% non-inductive sustainment at FNSF normalized performance
  - Develop and understand non-inductive start-up, ramp-up/overdrive

Integrated Scenarios
- Adv. scenarios and control
- Start-up
- Wave heating and CD

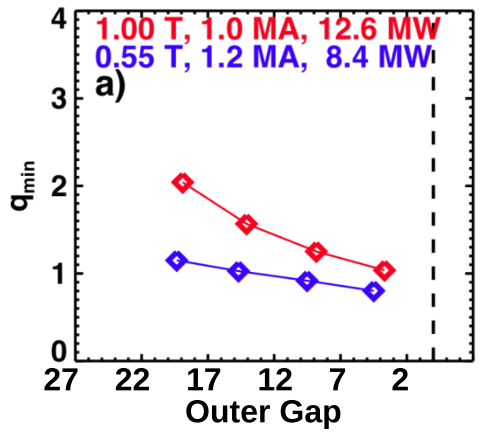
NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

q-Profile Actuators

Variations in Beam Sources
800 kA Partial Inductive, 87% < f_{NI} < 100%

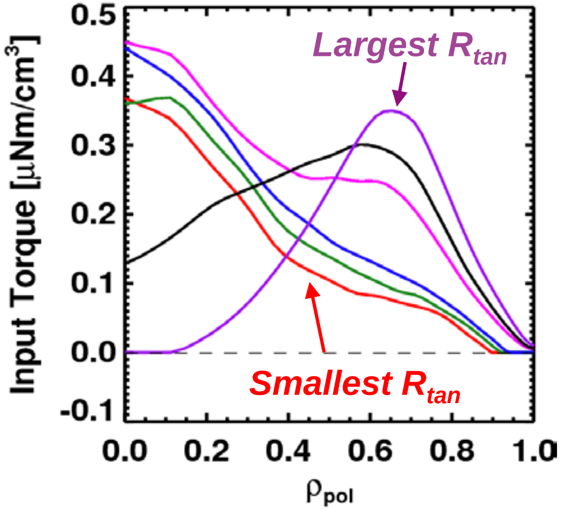


Variations in Outer Gap

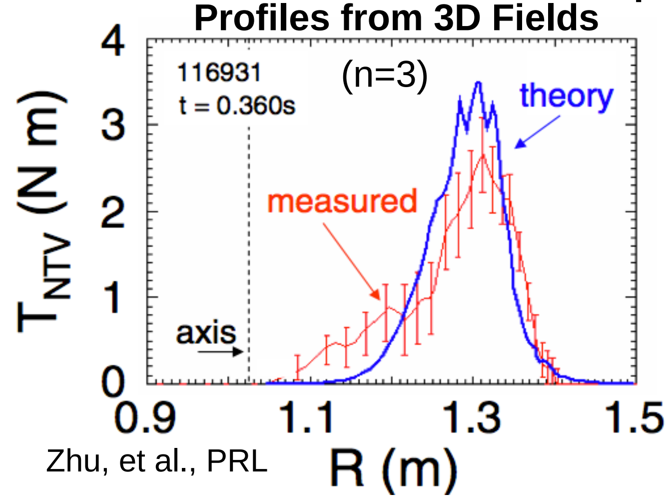


Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



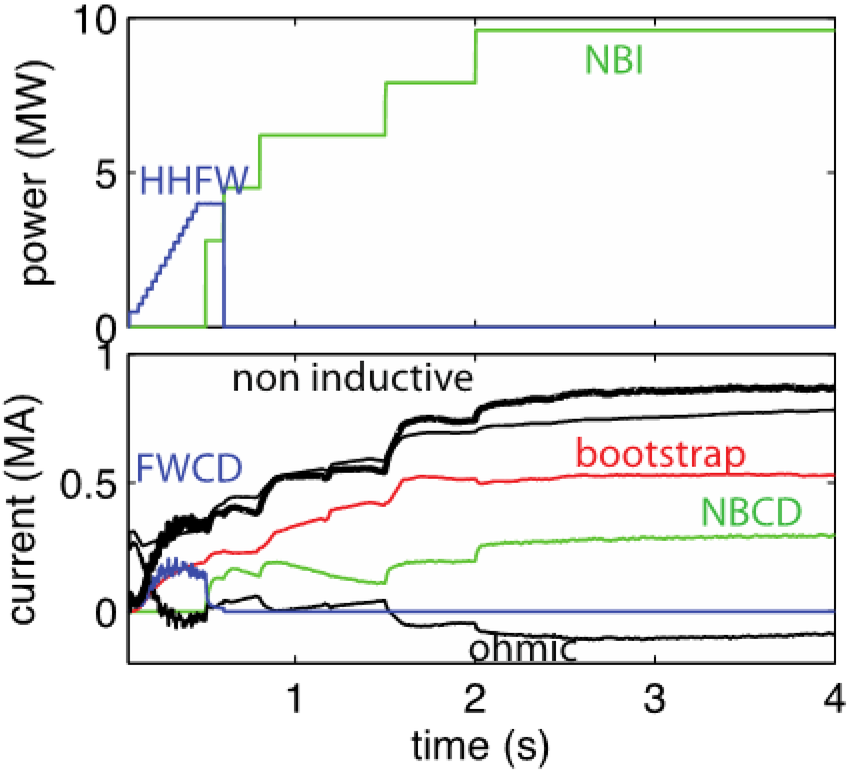
Measured and Calculated Torque Profiles from 3D Fields



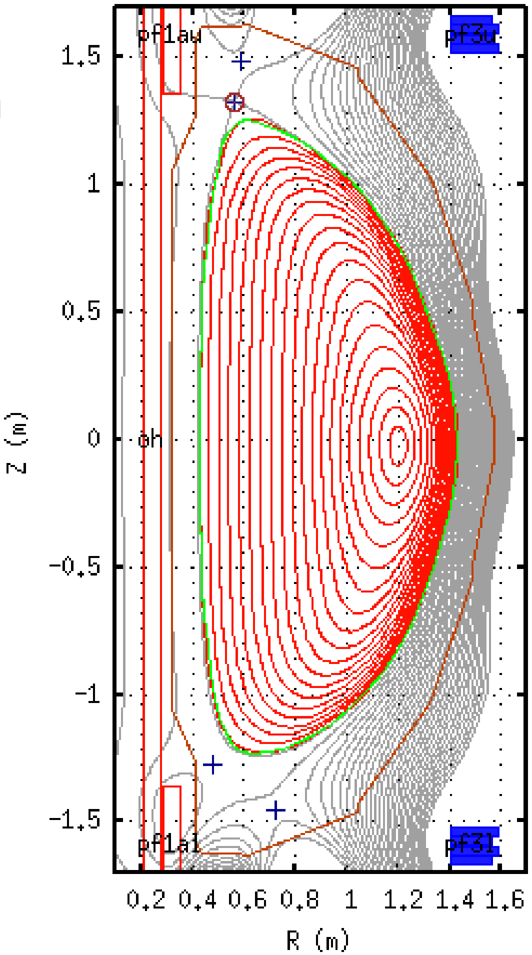
Zhu, et al., PRL

Free-boundary TRANSP now being used routinely to model NSTX-U non-inductive ramp-up (+ other scenarios)

- First ramp-up modelling with self-consistent NBI → **2nd NB line can ramp-up current from HHFW-heated plasma and sustain stationary 900kA**

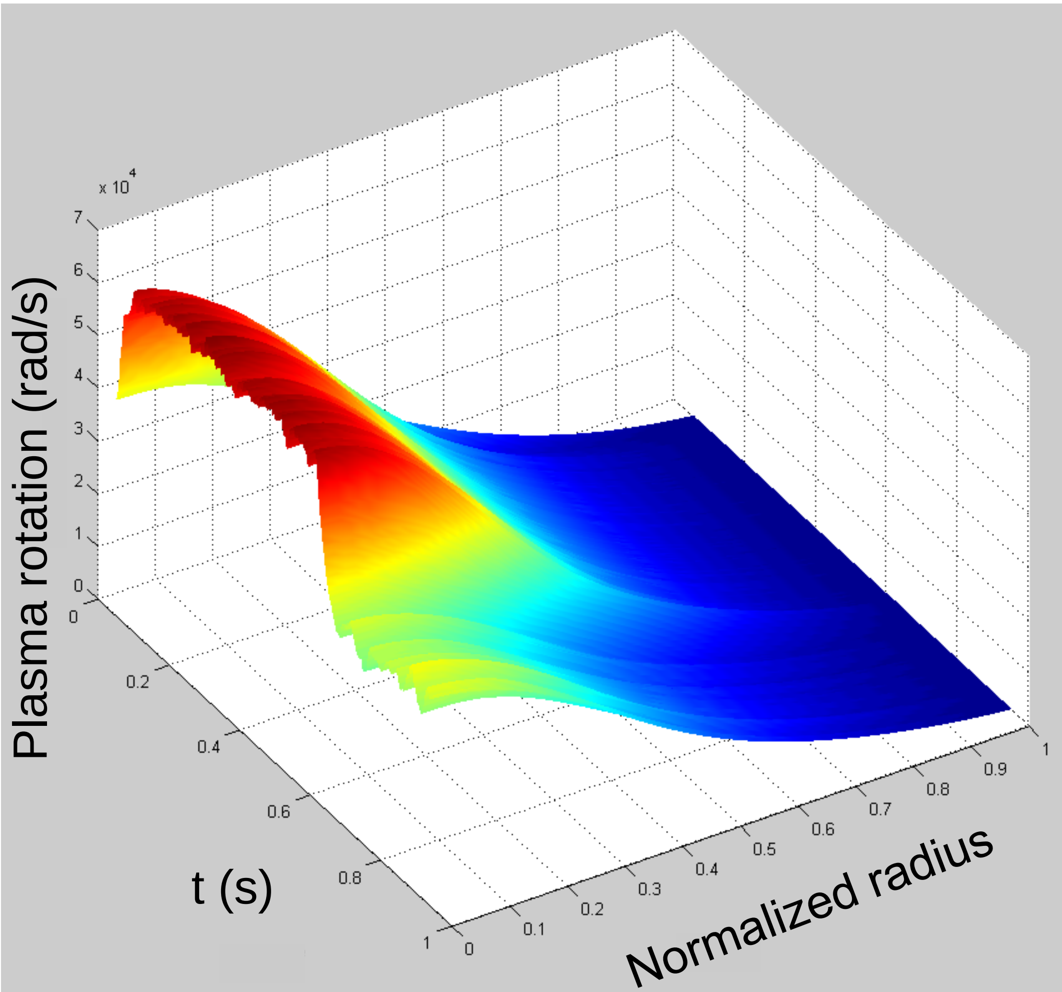


ISOLVER equilbrium
t = 3.5s
κ~2.50
δ~0.75

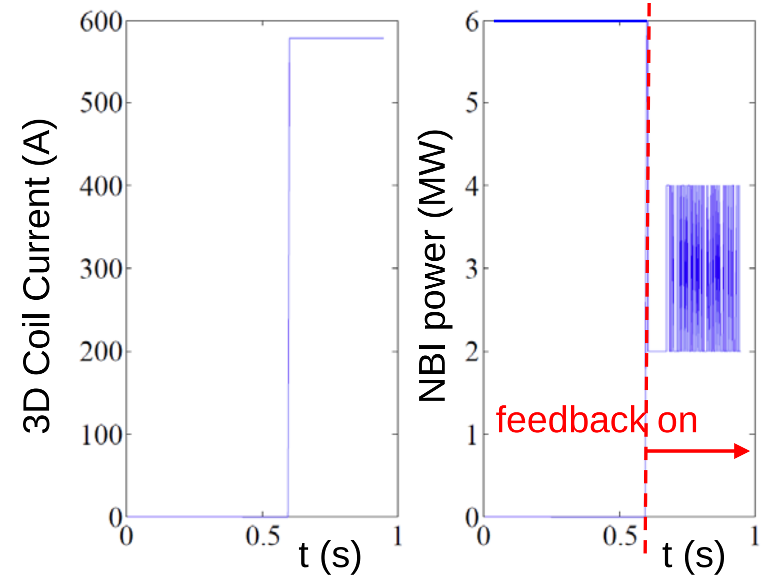


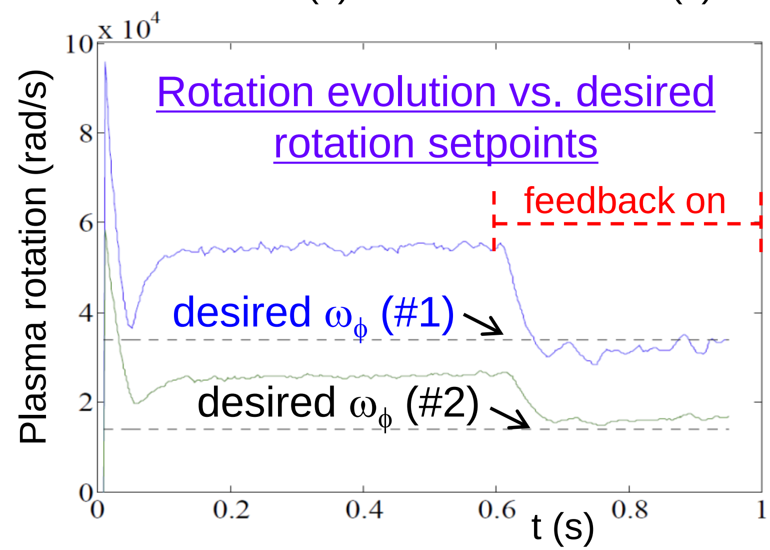
- HHFW used at t < 0.5 to ramp to ~400kA and heat target plasma
- Final state: $n_{e,lin} = 8\times10^{19}$ m^{-2} → ~900kA non-inductive, ~60% bootstrap
- β_T~7%, β_P~6%, β_{FAST} / β_{TOT}~0.25-0.35, H_{98}~1.2 (τ_{98}~70ms)

TRANSP used for simulating toroidal rotation control using NBI and magnetic braking (NTV) as actuators



3D coil current and NBI power (actuators)

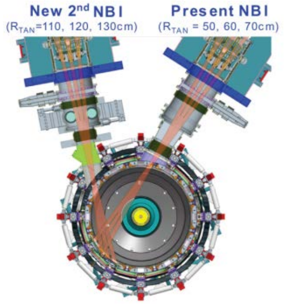


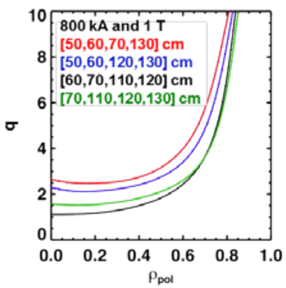


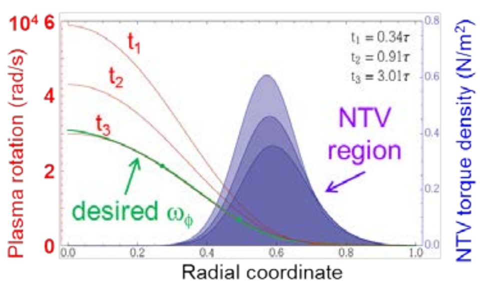
- This case uses pre-programmed 3D coil current and NBI feedback

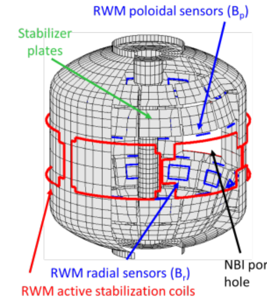
Advanced Scenarios and Control Research Plans for FY2015-17:
Implement advanced controls, explore high non-inductive & I_P scenarios

- **FY15**: Re-establish NSTX-U control and plasma scenarios **R15-3**
  - Vertical/shape control, NBI beta feedback control, EF/RWM control
  - Assess new 2nd NBI current-drive vs. R_{TAN}, n_e, outer gap
    - Push toward 100% non-inductive at higher B_T, P_{NBI}
    - Quantify impact of broadened J(r), p(r) on confinement, stability **JRT-2015**
  - Explore scenarios (τ_E, l_i, MHD) at up to 60% higher I_P, B_T
- **FY16**: Explore scenarios at full I_P and B_T capability of NSTX-U
  - Goal: Access 100% non-inductive, test small I_P overdrive **R16-3**
- **FY17**: Control of current and rotation profiles to improve global stability limits and extend high performance operation **R17-3**



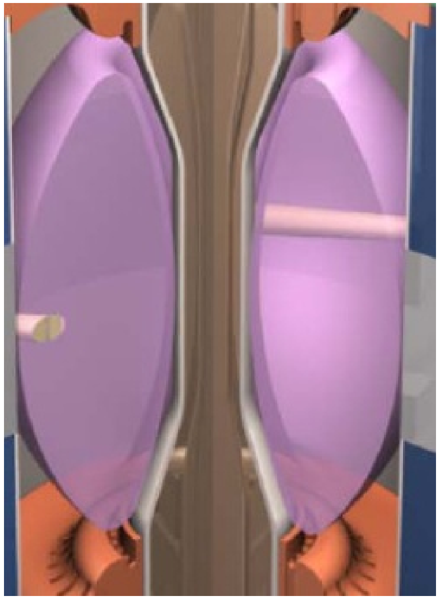




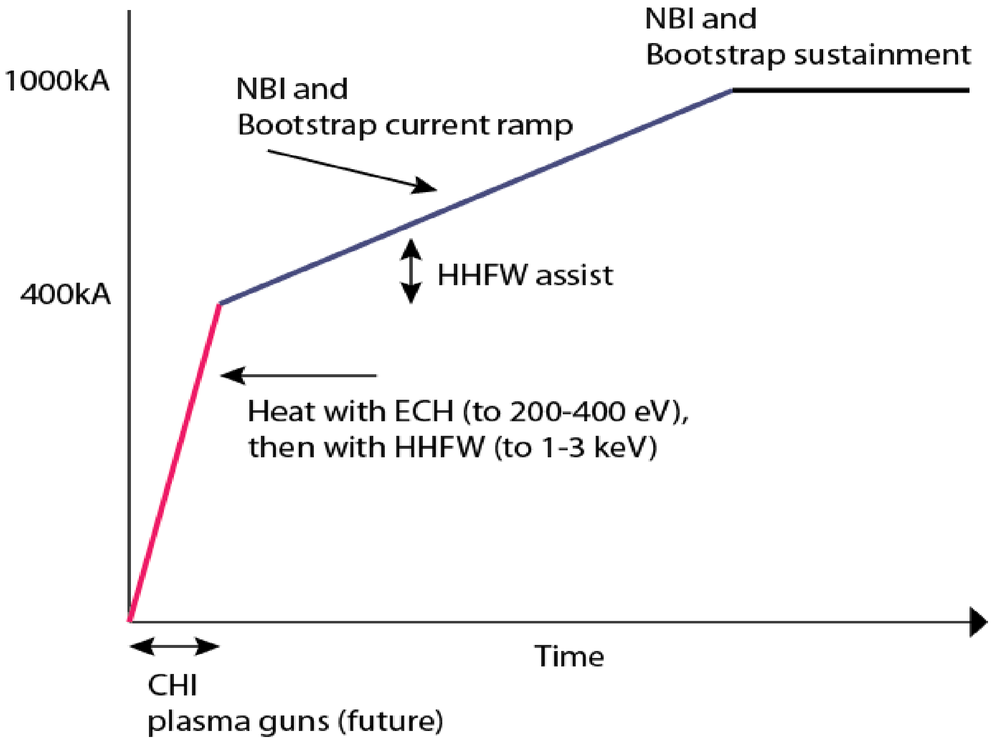


Plasma initiation with small or no transformer is unique challenge for ST-based Fusion Nuclear Science Facility

ST-FNSF has no/small central solenoid



NSTX-U Non-Inductive Strategy:

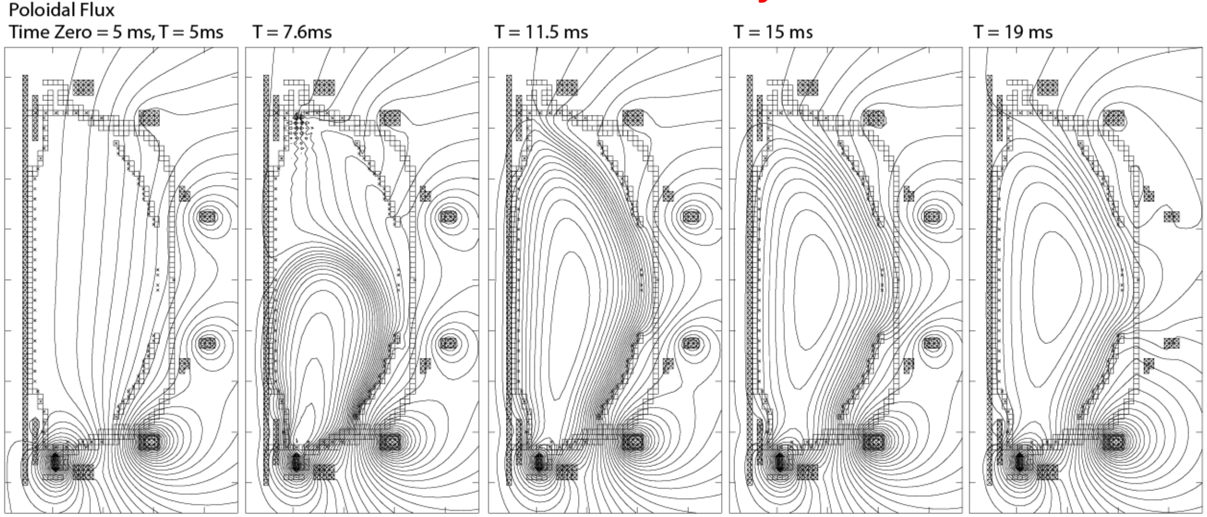


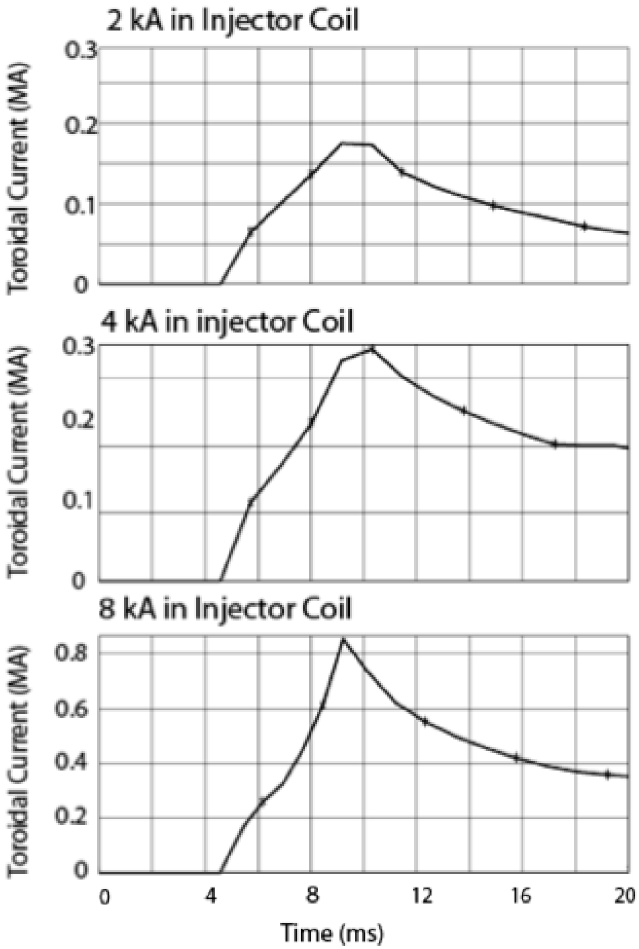
- **NSTX-U 5 year plan goal:**
  - Generate ~0.4MA closed-flux start-up current with helicity injection
  - Heat CHI with ECH and/or fast wave, ramp 0.4MA to 0.8-1MA with NBI

TSC code successfully used to interpret NSTX, now using to optimize NSTX-U coil currents for CHI operation

- **Favorable PF coil current evolution for NSTX-U transient CHI identified:**
  - Initiate CHI with PF1C injector coil
  - Grow CHI plasma into magnetic well
  - Provide buffer flux with PF1CU (absorber coil)
  - PF1AL, PF2L, PF3L adjusted as needed to reduce/optimize injector currents

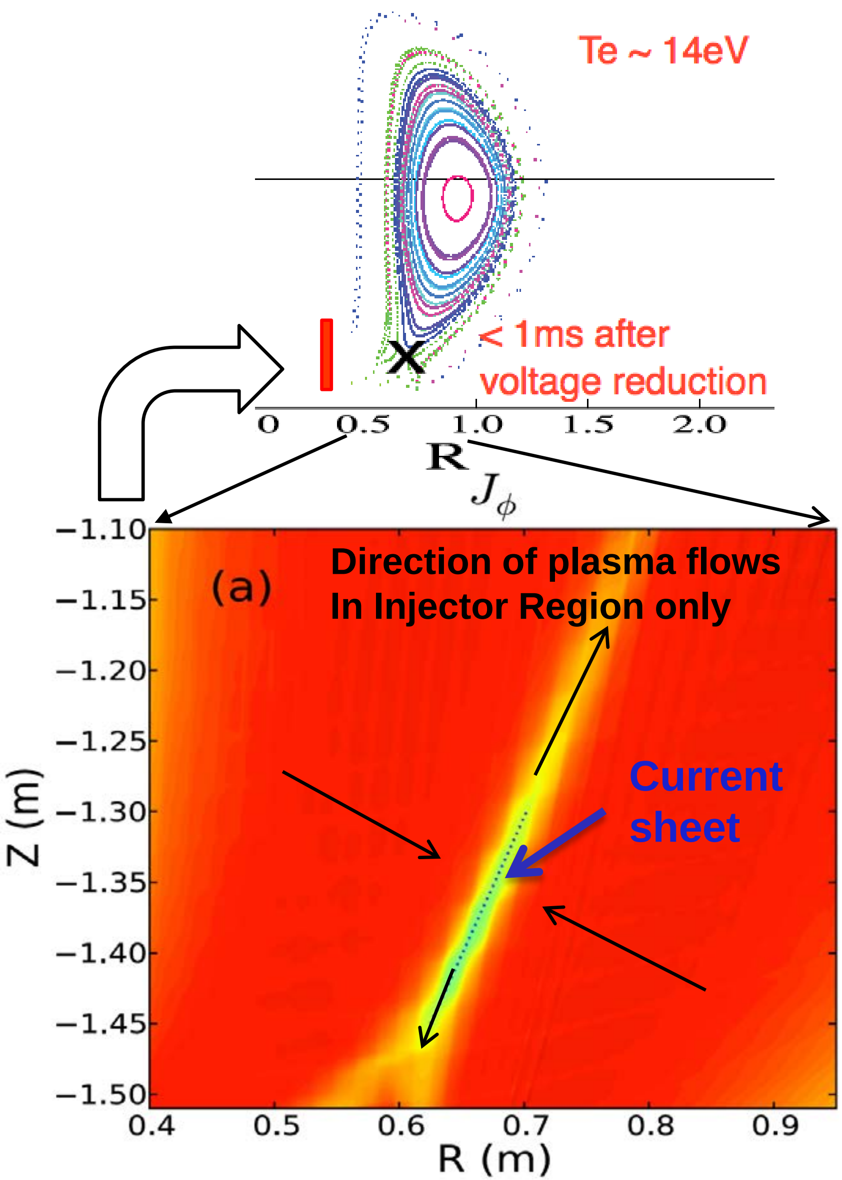
NSTX-U Vessel Geometry, 100 eV





CHI generated toroidal current increases approximately linearly with injector flux as expected

NIMROD simulations suggest Transient CHI has resemblance to 2D Sweet Parker-type reconnection



- With reduction of injector voltage & current a toroidal E-field is generated in the injector region
  - $E_{toroidal}$ X $B_{poloidal}$ drift brings oppositely directed field lines closer and cause reconnection generating closed flux

- Elongated Sweet-Parker-type current sheet forms in injector region

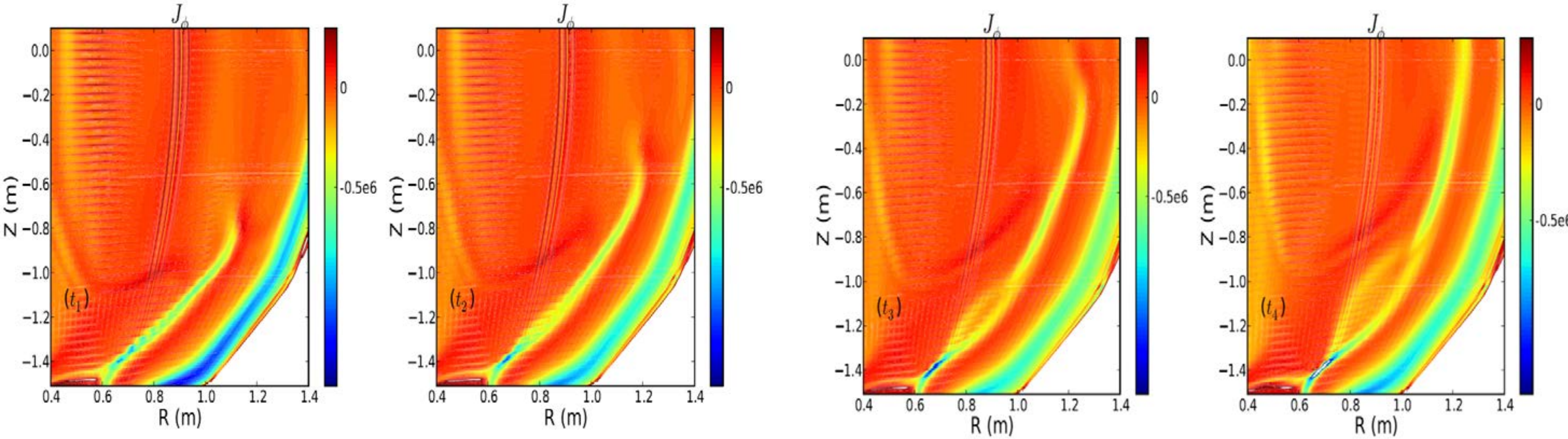
- Higher-n modes/MHD not strongly impacting 2D reconnection and closed-flux current generation

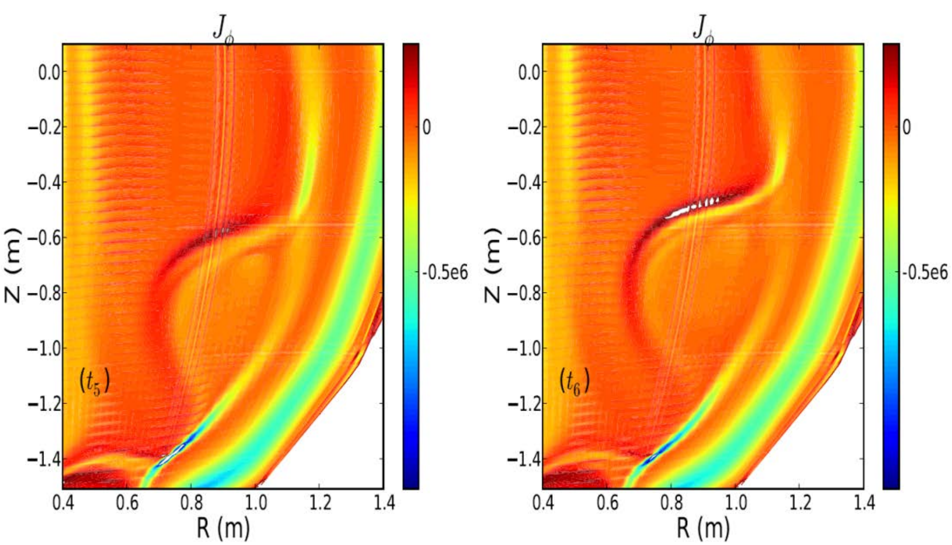
F. Ebrahimi, et al., PoP (2013)
F. Ebrahimi, et al., PoP (2014)

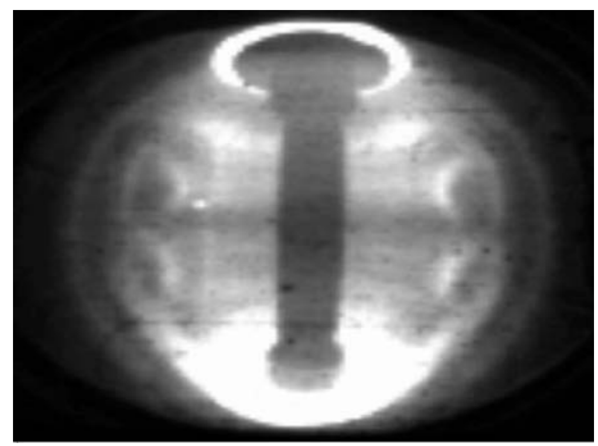
CHI current sheet unstable → formation of plasmoids → merging

NSTX may provide first lab observation of plasmoids - relevant to astrophysics

Current sheet shown in the lower half of the device.





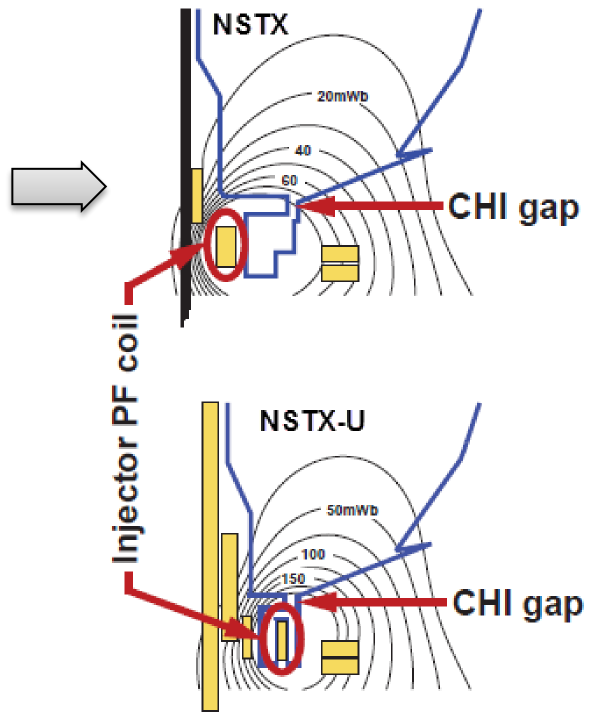


Possible NSTX plasmoids during CHI

Ebrahimi and Raman – submitted to PRL (2015)

Prepare CHI for NSTX-U, assess CHI/NBI start-up/ramp-up

- **FY15:** Establish NSTX-U CHI, assess impact of new injector, gap, higher B_T
- **FY15-16:** Initial tests of small NBI+BS overdrive ramp-up using new 2nd NBI and higher B_T
- **FY17:** Assess transient CHI current start-up potential in NSTX-U **R17-4**
  - Characterize maximum start-up current vs. injector flux, CHI voltage, toroidal field, high-power ECH (if available – incremental)
  - Study reconnection region and plasmoid instabilities with improved cameras/imaging



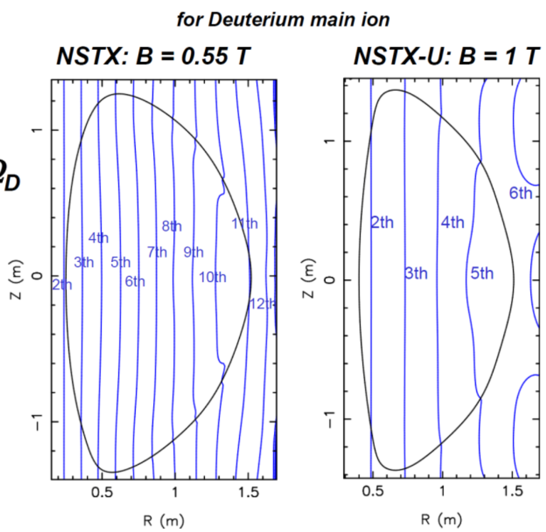
Finalize ECH/EBW design, simulate & develop reliable FW H-mode

- **FY15**: Support 1MW/28GHz ECH/EBW engineering design
  - ECH to heat CHI, form target for HHFW/NBI
  - EBW H&CD for start-up, sustainment
- **FY16**: Assess fast-wave SOL losses and core thermal and fast ion interactions at increased B_T, I_P R16-2

$B_T \rightarrow$ 2 x B_T

$\omega/\Omega_D \rightarrow$ 0.5 x ω/Ω_D

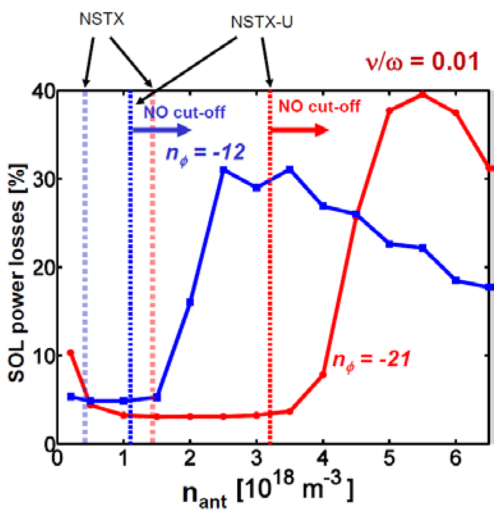
High harmonic regime in NSTX ↓ *Mid harmonic regime in NSTX-U*



AORSA modeling: higher B → lower SOL losses

$$n_{e,\mathrm{FWcut-off}} \propto \frac{k_{\parallel}^2 B}{\omega}$$

N. Bertelli



- **FY17**: Utilize ECH/EBW (incremental) for non-inductive start-up studies – couple to CHI → HHFW heating → NBI ramp-up

Outline

- NSTX-U mission, priorities, FY15-17 overview
- FY14-16 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF configuration study
- Summary

Administration FY2016 request-level provides run-time and full field + current to exploit most new Upgrade capabilities

	FY2015	FY2016	FY2017
Run Weeks:	12	14	14
Boundary Science + Particle Control	R15-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R16-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R16-2: Assess high-Z divertor PFC performance and impact on operating scenarios	R17-1: Assess impurity sources and edge and core impurity transport
Core Science	R15-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile		R17-2: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport
Integrated Scenarios	R15-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	R16-3: Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R16-4: Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R17-3: Control of current and rotation profiles to improve global stability limits and extend high performance operation R17-4: Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	NSTX-U leads JRT: Quantify impact of broadened J(r) and p(r) on tokamak confinement, stability	C-Mod leads JRT: Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT: TBD

Incremental accelerates transport and divertor research, strongly utilizes facility, supports 5YP enhancements

	FY2015	FY2016	FY2017
Run Weeks:	12	14 / 16	14 / 16
Boundary Science + Particle Control	R15-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R16-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R16-2: Assess high-Z divertor PFC performance and impact on operating scenarios	R17-1: Assess impurity sources and edge and core impurity transport IR17-1: Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R15-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	IR16-1: Assess confinement and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	R17-2: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport
Integrated Scenarios	R15-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	R16-3: Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R16-4: Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R17-3: Control of current and rotation profiles to improve global stability limits and extend high performance operation R17-4: Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	NSTX-U leads JRT: Quantify impact of broadened J(r) and p(r) on tokamak confinement, stability	C-Mod leads JRT: Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT: TBD

Outline

- NSTX-U mission, priorities, FY14-16 overview
- FY14-16 research plans
- Milestone summary
- ITPA contributions
- ST-FNSF mission and configuration study
- Summary

Supporting ITER through ITPA participation

- Representatives in every Task Group, leadership in several:
  - R. Maingi: chair of Pedestal and Edge Physics TG
  - S. Sabbagh: Leads WG on RWM code benchmarking, RWM stability & control
- Active in 31 JEX/JACs with many contributors from NSTX-U

Pedestal, Scrape-Off Layer, Divertor			
PEP-26	Critical edge parameters for achieving L-H transitions	PEP-37	Effect of low-Z impurity on pedestal and global confinement
PEP-28	Physics of H-mode access with different X-point height	DSOL-31	Leading edge power loading and monoblock shaping
PEP-29	Vertical jolts/kicks for ELM triggering and control	DSOL-34	Far-SOL fluxes and link to detachment
PEP-30	**ELM control by pellet pacing in ITER-like conditions**	DSOL-35	In-out divertor ELM energy density asymmetries
PEP-31	Pedestal structure and edge relaxation mechanisms in I-mode		
Energetic Particles			
EP-6	Fast ion losses + associated heat loads from edge perturbations (ELMs, RMPs)		
Integrated Operating Scenarios			
IOS-1.2	Divertor heat flux reduction in ITER baseline scenario	IOS-3.3	Core confinement for q(0)=2
IOS-1.3	Operation near P_{LH}	IOS-5.2	Maintaining ICRH coupling in expected ITER regime
IOS-2.1	Compare helium H-modes in different devices		
Macroscopic Stability and Control			
MDC-1	Disruption mitigation by massive gas jets	MDC-18	Evaluation of axisymmetric control aspects
MDC-8	Current drive prevention/stabilization of NTMs	MDC-19	Error field control at low plasma rotation
MDC-15	**Disruption database development**	**MDC-21**	**Global mode stabilization physics and control**
MDC-17	**Active disruption avoidance**	MDC-22	Disruption prediction for ITER
Transport and Turbulence			
TC-9	Scaling of intrinsic plasma rotation with no external momentum input	**TC-15**	**Dependence of momentum and particle pinch on collisionality**
TC-10	**Experimental ID of ITG, TEM, ETG turbulence and comparison with codes**	**TC-17**	**ρ^* scaling of intrinsic torque**
TC-11	He and impurity profiles and transport coefficients	TC-19	Characteristics of I-mode plasmas
TC-14	RF rotation drive	**TC-24**	**Impact of resonant magnetic perturb. on transport, confinement**

Maingi (chair), Ahn, Canik, Chang, Diallo, Goldston, Jaworski

Fredrickson, Fu, Gorelenkov, Heidbrink, Kramer, Podestá

Gerhardt, Kessel, Poli, Gates, Boyer

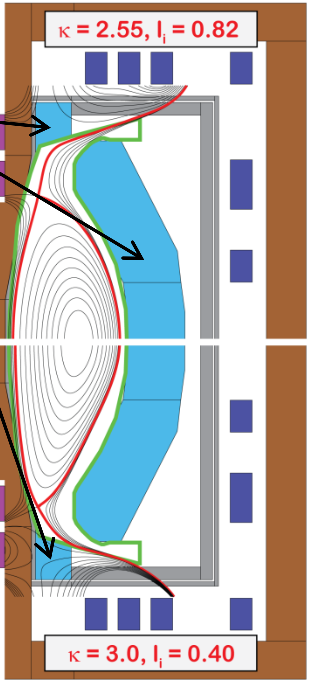
Sabbagh, Berkery, Jardin, Park, Zakharov, Gerhardt, Menard

Kaye (previous chair), Ren, Guttenfelder, McKee/Smith

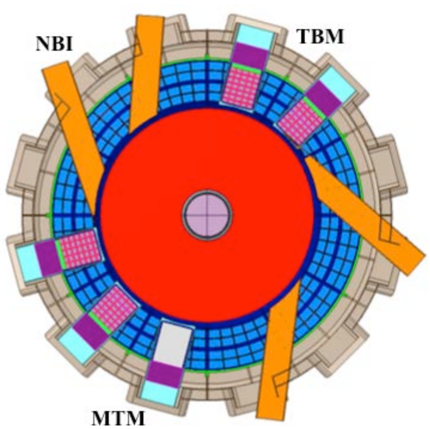
NSTX-U / U.S. ST researchers led LDRD-funded study of Mission and Configuration of an ST-FNSF

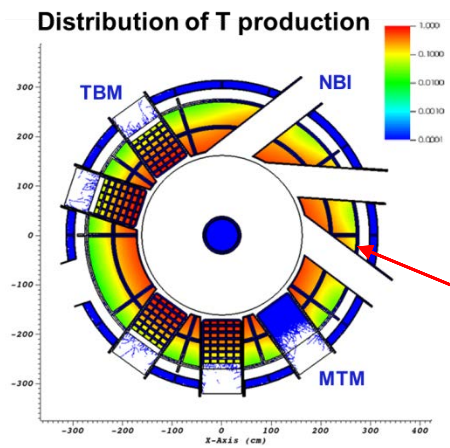
- FY2014 / Final Results:
  - Identified coil configuration compatible with:
    - Breeding in CS end region + vertical maintenance
    - Ex-vessel PF coils on outboard, can be S/C, support range of l_i and β_N
    - Divertor power exhaust: q_{peak} ~ 3-5MW/m^2, partially detached
  - p, $J_{BS}(r)$ important for l_i / κ / PF coils – assess in NSTX-U
  - Carried out free-boundary TRANSP simulations for NNBI+BS current drive, fusion performance, neutronics
  - Tritium breeding ratio (TBR) ~ 1 requires large enough R_0 and breeding blankets near top + bottom of centerstack

Blanket regions



R_0 = 1.7m
TBR ~ 1





R_0 = 1m
TBR ~ 0.9

Breeding at back of blanket important for tangential NBI ducts

Outline

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NSTX-U program well-aligned with priorities of upcoming FES workshops

NSTX-U contributions:

- Plasma material interactions
  - Scrape off layer / divertor physics ◀Low-A, advanced divertors
  - PMI and long pulse divertor simulators ◀MAPP + surface science
  - Engineering innovations for plasma exhaust ◀Liquid metal PFCs
  - Plasma core-edge integration ◀Long-term NSTX-U goal
- Transients
  - Disruption prediction, avoidance, mitigation ◀Kinetic MHD, PCS, MGI
  - ELM suppression with RMP ◀NCC RMP (incremental)
  - Naturally ELM-free operation ◀Li-wall scenarios, EPH
  - ELM pacing ◀Granule injector, 3D fields
- Integrated Simulations
  - Disruption prevention, avoidance, mitigation ◀Kinetic MHD codes
  - Plasma boundary (Ped, SOL, PMI) ◀XGC, UEDGE, Walldyn, …
  - Whole device modeling ◀TRANSP, control models
- Plasma science frontiers ◀EM turbulence, plasmoids

Summary: NSTX-U FY2015-17 research plan strongly supports FES vision, scientific organization

- **Foundations**
  - Expect transport, stability discoveries in new high-β + low-ν^* regime
  - Core: Non-linear AE* / fast-ion dynamics, disruptions, response to 3D δB
  - Boundary: SOL-widths & turbulence, advanced divertors, Li-based PFCs

- **Long-Pulse**
  - PMI: EAST collaboration: long-pulse performance of high-Z, liquid metals
  - FNSF: NSTX-U provides critical data on confinement, stability, sustainment

- **High-Power**
  - Robust Control: Goal: high-β + full non-inductive, disruption avoidance

Incremental funding needed to fully utilize NSTX-U facility and implement 5YP facility enhancements

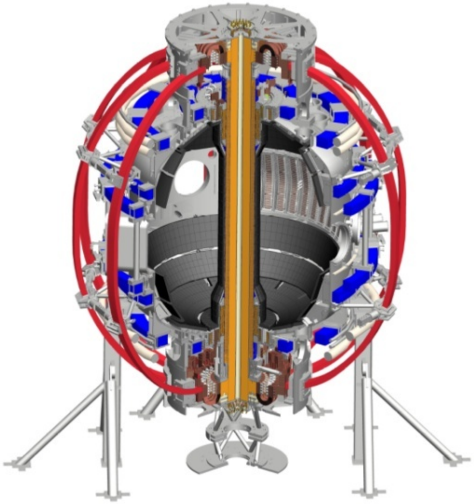
NSTX-U Facility and Diagnostics Plans for FY2015-17

Masa Ono and Jon Menard

for the NSTX-U Team

FWP 2017 Budget Planning Meeting
March 25, 2015

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
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

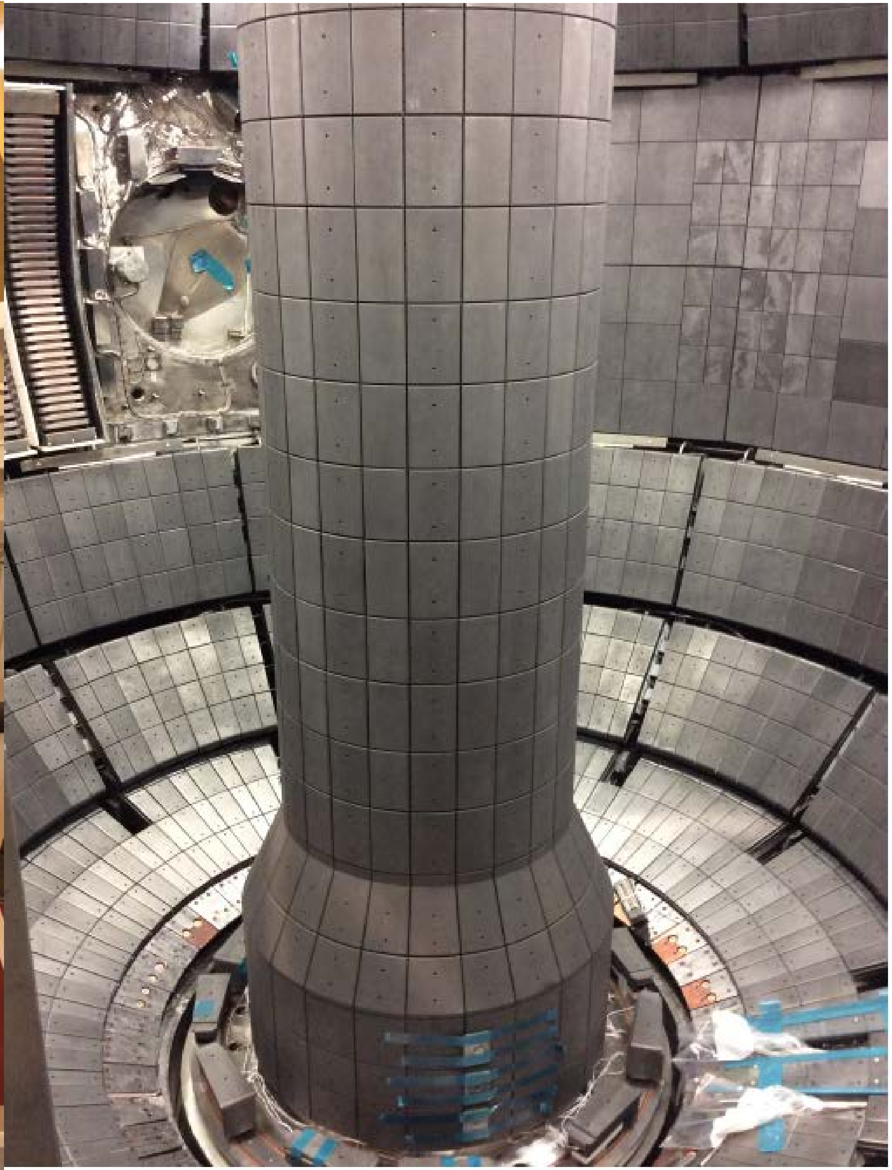


Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
Tsukuba U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching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

Talk Outline

- **NSTX-U Commissioning and Operations Plan**
- **FY2015-17 Facility-Diagnostic Plan**
- **Budget / FTEs**
- **Summary**

New Center-Stack Installed In NSTX-U (October 24, 2014)

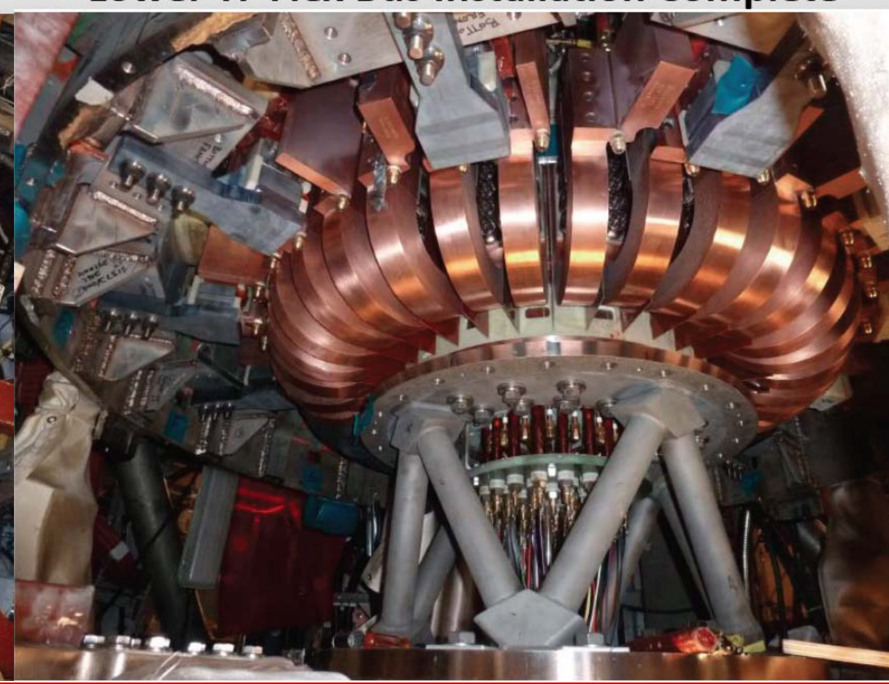


Construction Complete and Preparing for ISTP
CD-4 date depends on how quickly ISTP is complete

- Pumpdown/leak check – continuing since December
- Install TF flex bus / lead extension – January – March (complete)
- Install umbrella lids/support rings – February – March (complete)
- Bakeout – April
- ISTP/CD-4 - April

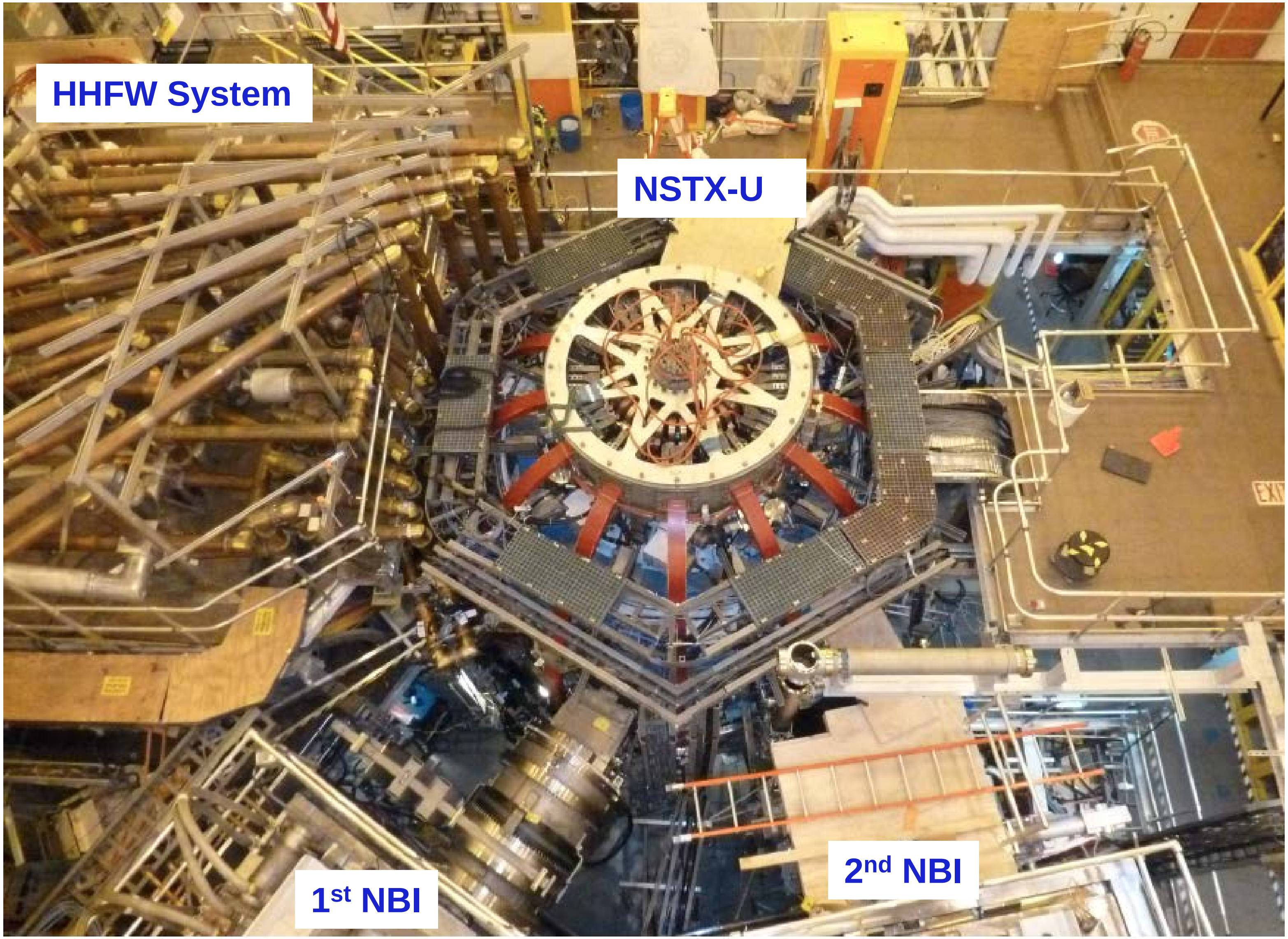
NSTX-U Top View (March 8, 2015)
Upper TF Flex Bus Installation Complete

NSTX-U Bottom View (March 13, 2015)
Lower TF Flex Bus Installation Complete

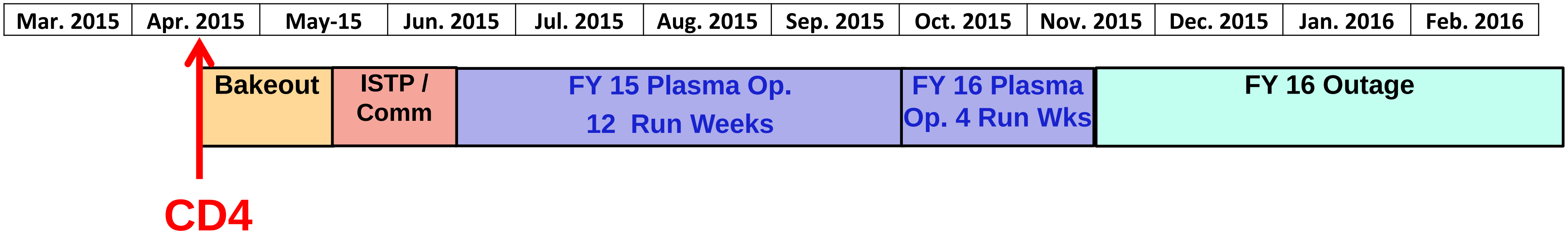


NSTX Upgrade Construction Is Complete

Recent aerial view of NSTX-U Test Cell (March 23, 2015)



Nominal NSTX-U run schedule for FY2015



- **CD-4 is now projected to be in mid- April 2015.**
- **~ 2 month period allocated between CD-4 and research plasma operations → Research ops begin in mid-June**
- **Plan: ~12 run weeks (assumes 1 maintenance week / month)**
- **Planning to run into early FY16**
  - **Provide additional data for APS 2015 and IAEA synopses for 2016**
- **FY16 outage tasks include high-Z tile installation, high-k scattering and full field/current operation preparation.**

Strategy for Achieving Full NSTX-U Parameters

After CD-4, the plasma operation could quickly access new ST regimes

	NSTX (Max.)	FY 2015 NSTX-U Operations	FY 2016 NSTX-U Operations	FY 2017 NSTX-U Operations	Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160
I_P Flat-Top at max. allowed I^2t, I_P, and B_T [s]	~0.4	~3.5	~3	5	5

Note: #s are simultaneous values

- 1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any coil
  - Will permit up to ~5 second operation at B_T~0.65
- 2nd year goal: Full field and current, but still limiting the coil heating
  - Will revisit year 2 parameters once year 1 data has been accumulated
- 3rd year goal: Full capability

The motor generator weld cracks repaired and generator tested to full specification, which enables support of full NSTX-U operation.

Five Year Facility Enhancement Plan (green – ongoing)

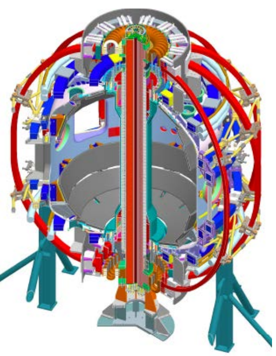
Engineering design for ECH, Cryo-Pump and NCC performed in 2015

2014	2015	2016	2017	2018

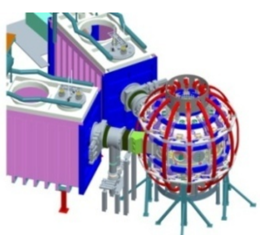
Upgrade Outage | 1.5 → 2 MA, 1s → 5s

Run Weeks: 12 4 10 14 12

New center-stack



2nd NBI



Boundary Science + Particle Control

- Pulse-burst MPTS
- Boronization
- Li granule injector
- MAPP
- Upward LiTER
- High-Z tile row on lower OBD
- High-Z PFC diagnostics
- Lower divertor cryo-pump
- LLD using bakeable cryo-baffle

Core Science

- MGI disruption mitigation
- Upgraded halo sensors
- Laser blow-off
- 42 ch MPTS
- 48 ch BES
- MSE/LIF
- High k_θ
- Charged fusion product
- 4 coil AE antenna
- δB diag. - incremental
- Partial (maybe full) NCC →
- Enhanced MHD sensors
- DBS, PCI, or other intermediate-k
- Neutron collimator

Integrated Scenarios

Establish control of:

- Snowflake
- FIReTIP
- Rotation
- $\bar{n}_e$
- q_{min}
- Divertor P_{rad}
- 1 MW ECH/EBW →
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- HHFW limiter upgrade
- up to 1 MA plasma gun

● *- Major upgrades (Requires 15% increment)*

NSTX-U diagnostics to be installed during first year

All center stack sensors mounted & ex-vessel terminations in progress

MHD/Magnetics/Reconstruction

- Magnetics for equilibrium reconstruction
- *Halo current detectors*
- *High-n and high-frequency Mirnov arrays*
- Locked-mode detectors
- RWM sensors

Profile Diagnostics

- MPTS (42 ch, 60 Hz)
- T-CHERS: $T_i(R)$, $V_\phi(r)$, $n_C(R)$, $n_{Li}(R)$, (51 ch)
- P-CHERS: $V_\theta(r)$ (71 ch)
- *MSE-CIF (18 ch)*
- *MSE-LIF (20 ch)*
- *ME-SXR (40 ch)*
- Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics

- *Poloidal FIR high-k scattering (installed in 2016)*
- *Beam Emission Spectroscopy (48 ch)*
- Microwave Reflectometer,
- Microwave Interferometer
- Ultra-soft x-ray arrays – multi-color

Energetic Particle Diagnostics

- *Fast Ion D_α profile measurement (perp + tang)*
- Solid-State neutral particle analyzer
- Fast lost-ion probe (energy/pitch angle resolving)
- Neutron measurements
- *Charged Fusion Product*

Edge Divertor Physics

- Gas-puff Imaging (500kHz)
- Langmuir probe array
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- *1-D CCD H_α cameras (divertor, midplane)*
- *2-D divertor fast visible camera*
- Metal foil divertor bolometer
- AXUV-based Divertor Bolometer
- IR cameras (30Hz) (3)
- *Fast IR camera (two color)*
- Tile temperature thermocouple array
- *Divertor fast eroding thermocouple*
- Dust detector
- Edge Deposition Monitors
- Scrape-off layer reflectometer
- Edge neutral pressure gauges
- *Material Analysis and Particle Probe*
- *Divertor VUV Spectrometer*

Plasma Monitoring

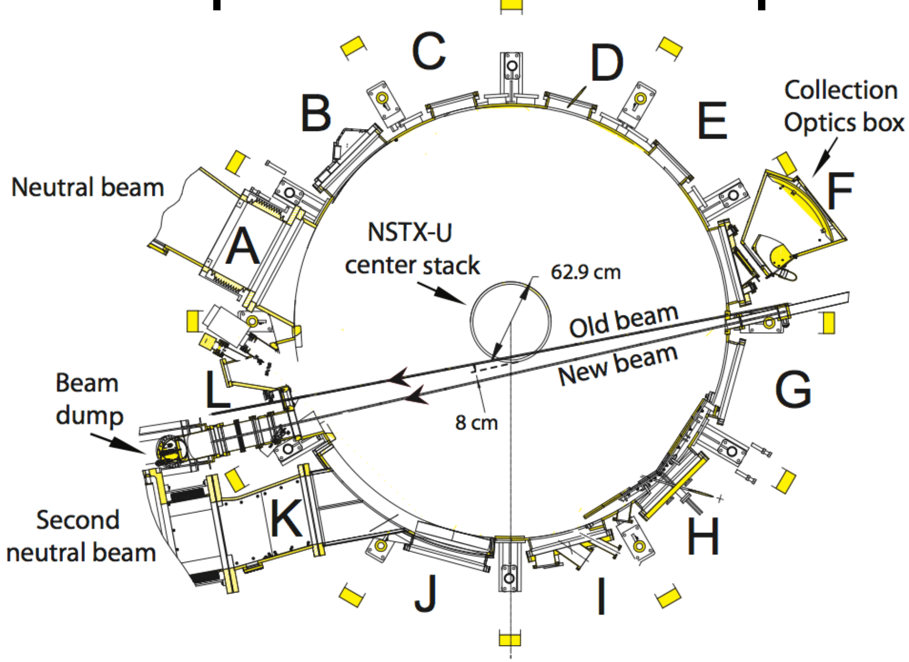
- FIReTIP interferometer
- Fast visible cameras
- Visible bremsstrahlung radiometer
- *Visible and UV survey spectrometers*
- *VUV transmission grating spectrometer*
- *Visible filterscopes (hydrogen & impurity lines)*
- Wall coupon analysis

New capability,
Enhanced capability

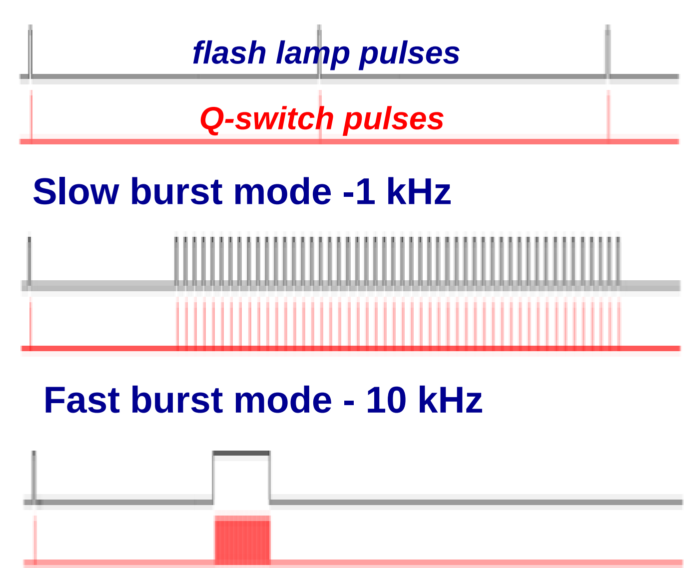
Multi-Pulse Thomson Scattering System
New pulse burst MPTS system being prepared

- **Realignment of MPTS nearing completion**
- **42 spatial channels – improved spatial resolution in pedestal**
- **Plan to have MPTS ready for calibration in May, 2015**
- **Pulse burst MPTS (Early Career Research Proposal Award) to be available for FY 2016 run to investigate e.g. fast pedestal phenomena.**

Top view of MPTS laser path



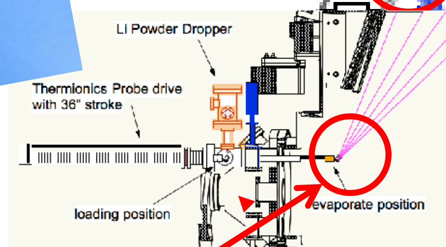
Pulse burst MPTS (FY 2016)

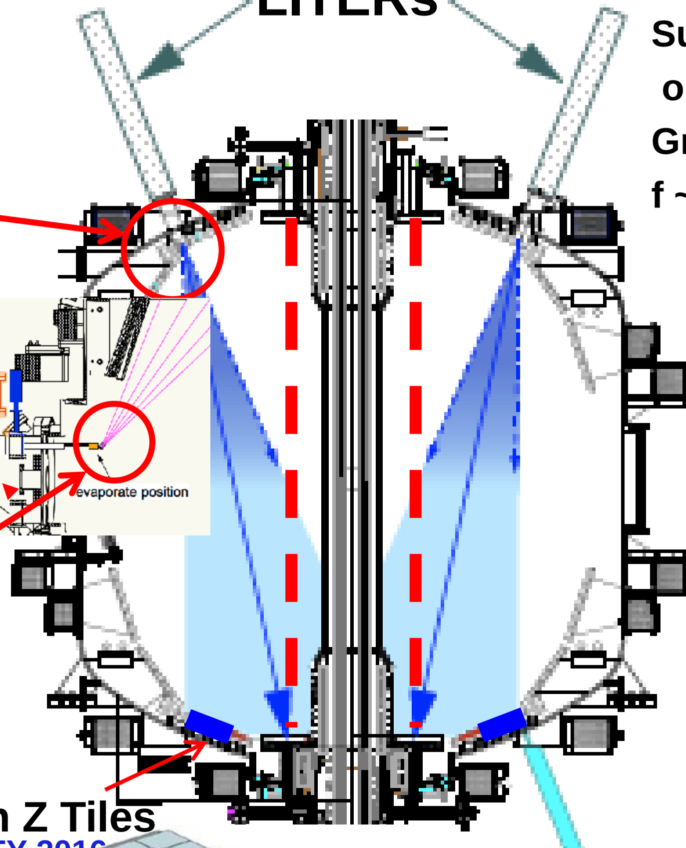


Comprehensive Boundary Physics Tools

Boronization, Lithium Evaporators, Granule Injector, High Z tiles

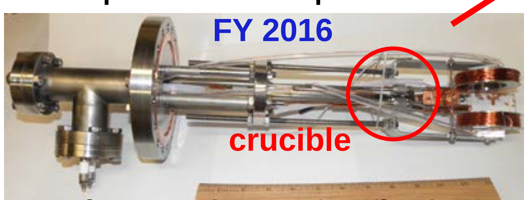
Lithium Evaporator (LITERs)





Upward Li evaporator

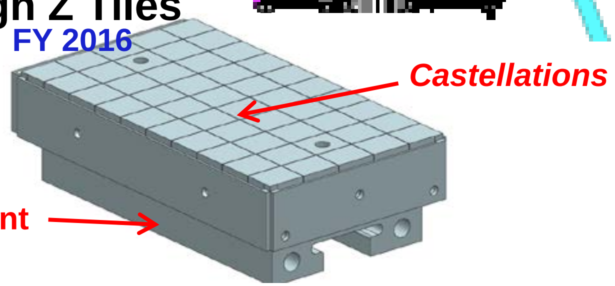
FY 2016



Electron beam for flash evaporation

High Z Tiles

FY 2016

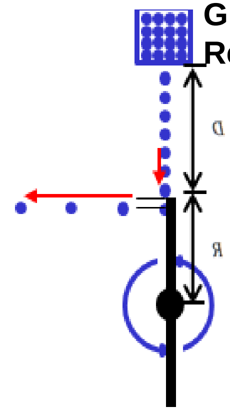


Granule injector (GI) for ELM pacing

Successfully tested on EAST and DIII-D

Granules: Li, B_4C, C

f ~ up to 500 Hz

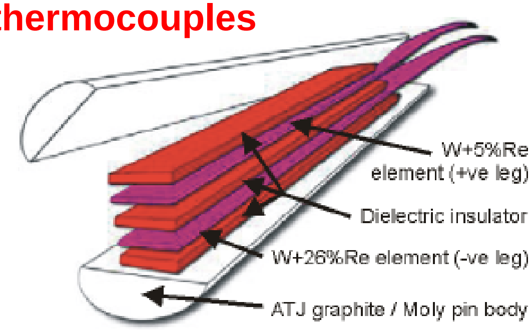


Boronization System

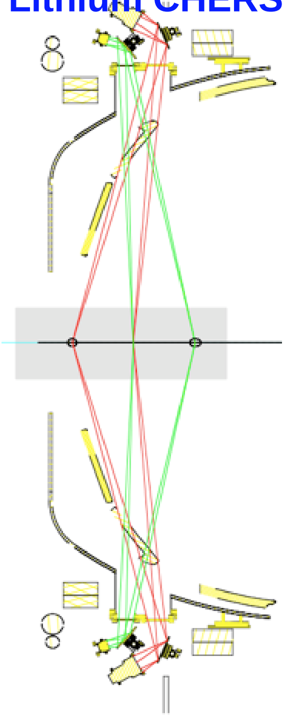
dTMB Gas Cabinet.

Enhanced Capability for PMI Research
Multi-Institutional Contributions

Divertor fast eroding thermocouples

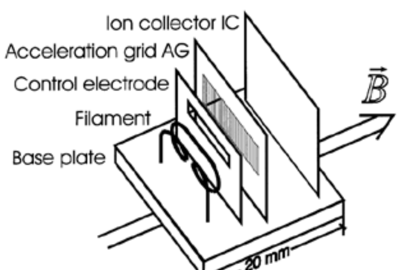


Lithium CHERS



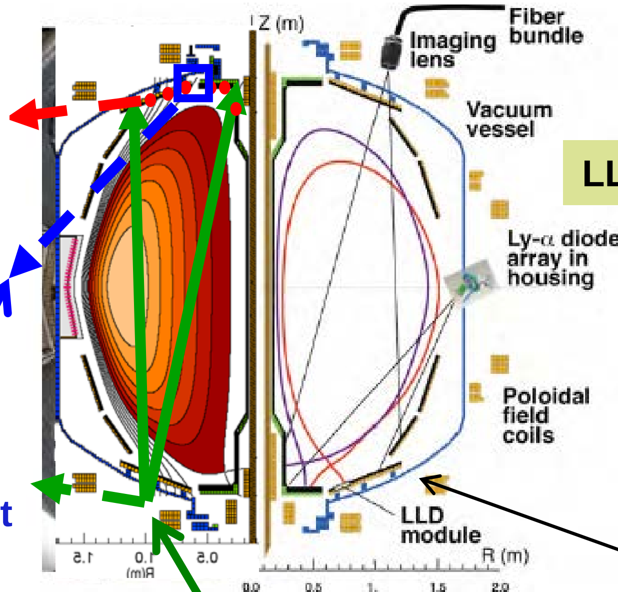
ORNL

Divertor fast pressure gauges

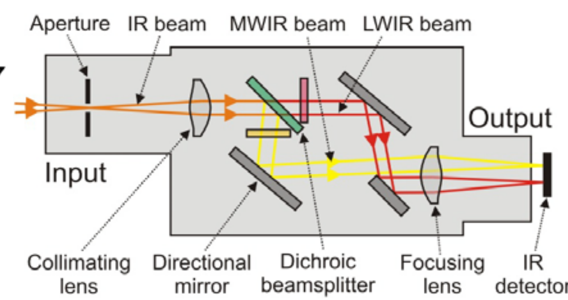


Divertor Imaging Spectrometer

LLNL

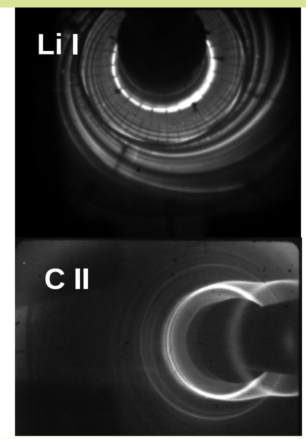


Dual-band fast IR Camera



Two fast 2D visible and IR cameras with full divertor coverage

LLNL, ORNL, UT-K



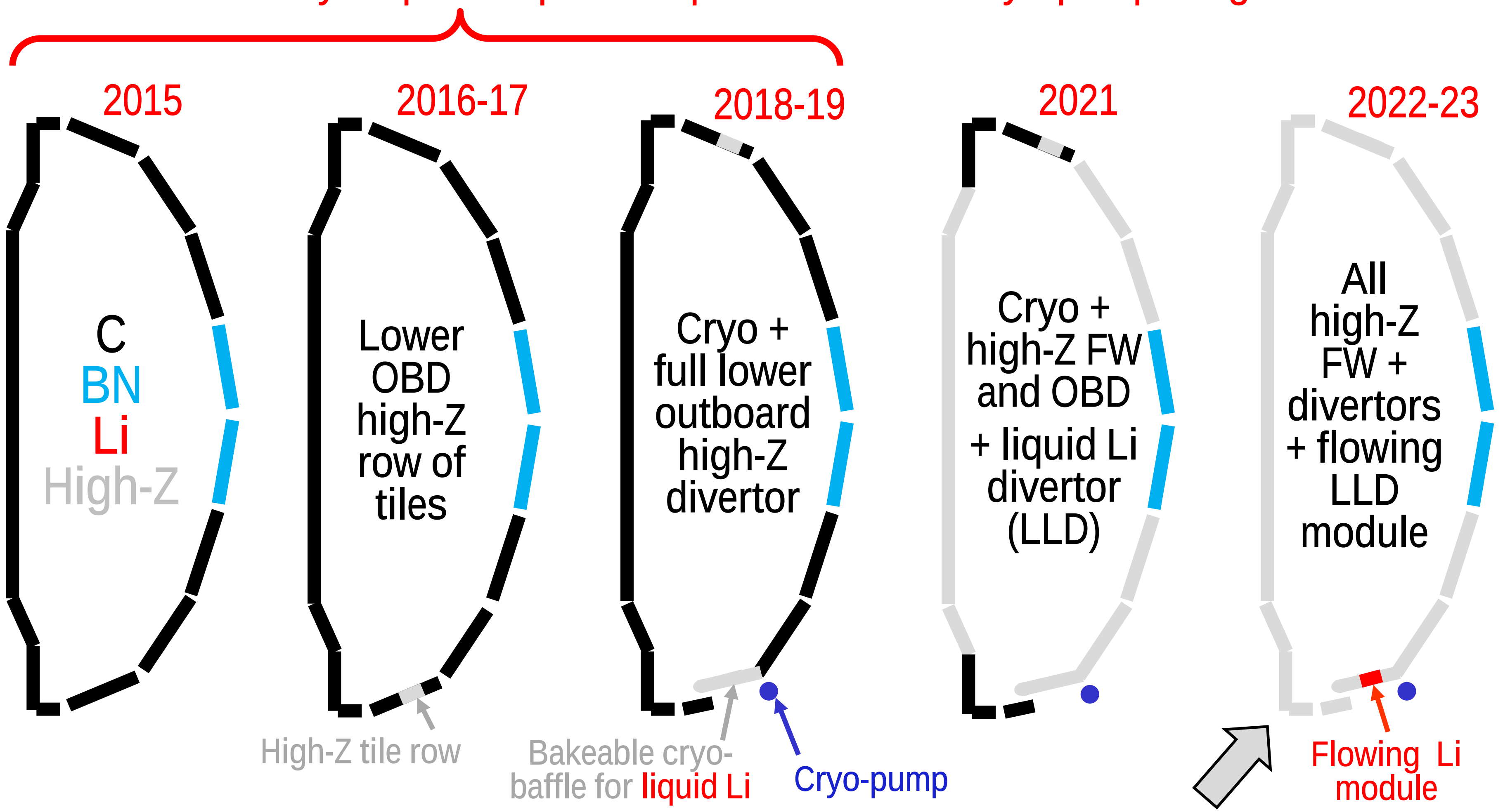
MAPP probe for between-shots surface analysis – Tested in LTX

U. of Illinois

NSTX-U plans to transition from all carbon to all metal PFCs

High Z tile row is being prepared for FY 2016

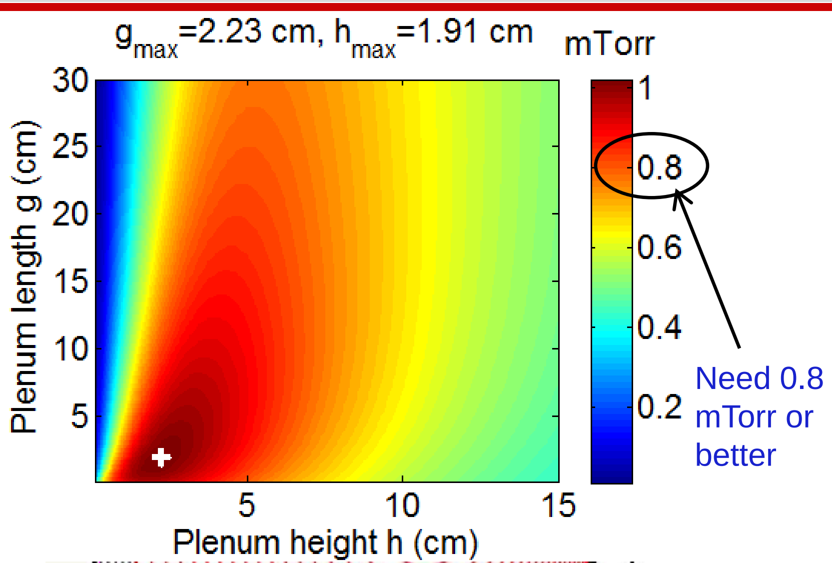
Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD

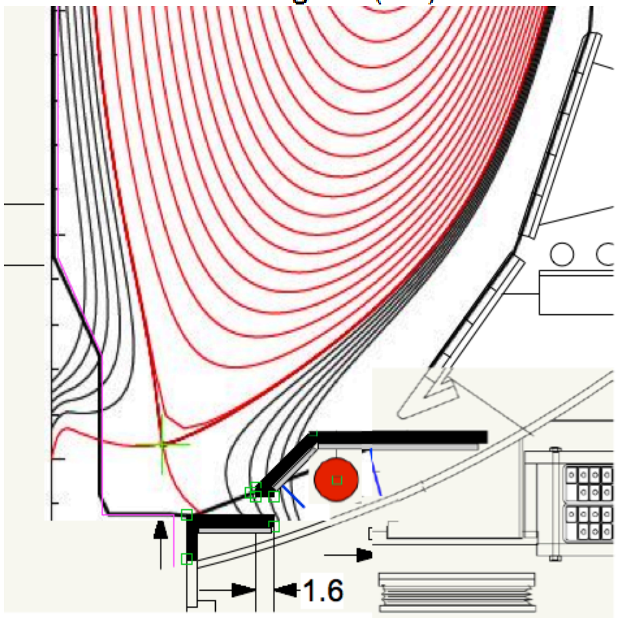


Increased funding / priority could accelerate full high-Z by ~2 years

Cryo-pump Physics Design to Provide Pumping over a Wide Range of Divertor Geometries and Core Densities

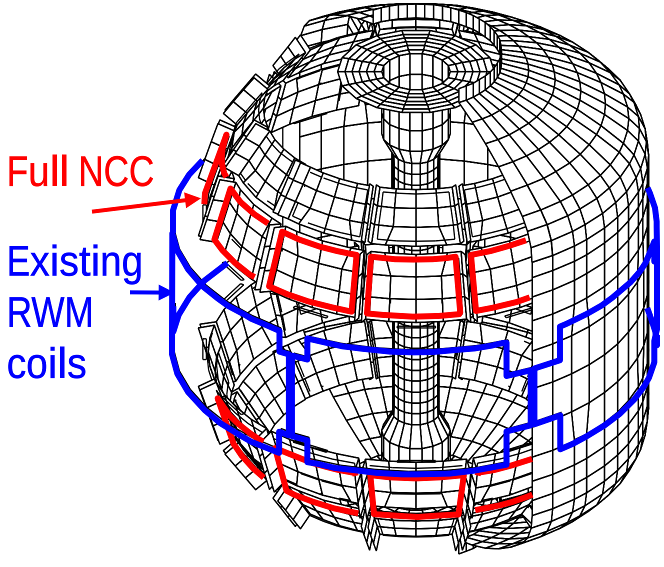
- **Physics design completed in collaboration with ORNL.**
  - **Defined the geometry, plenum sizes, ability to pump various geometries.**
- **Conceptual design process has been initiated:**
  - **Draft GRD has been formulated.**
  - **Initial designer sketches of in-vessel implementation completed.**
  - **Potential refrigerator systems and associated elements identified.**
  - **Goal is to to have the system available for the 2018 run campaign under base funding.**



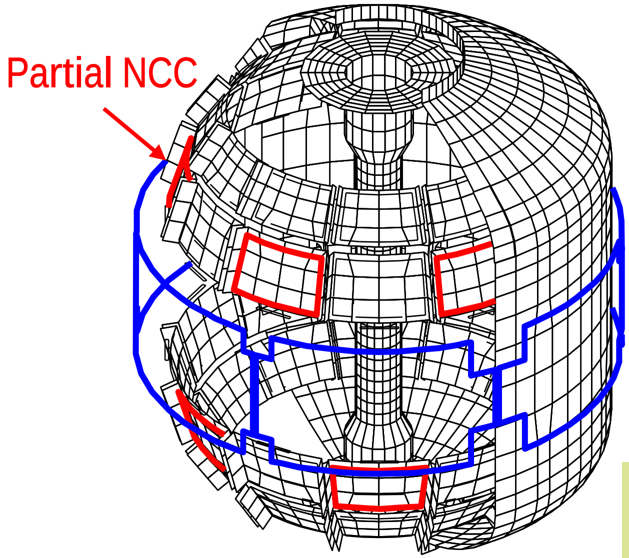


Flexible Mid-Plane Feedback Coils for MHD Studoes
NCC will greatly enhance MHD physics studies and control

Full toroidal NCC array (2 x 12)



Partial toroidal NCC array (2 x 6)

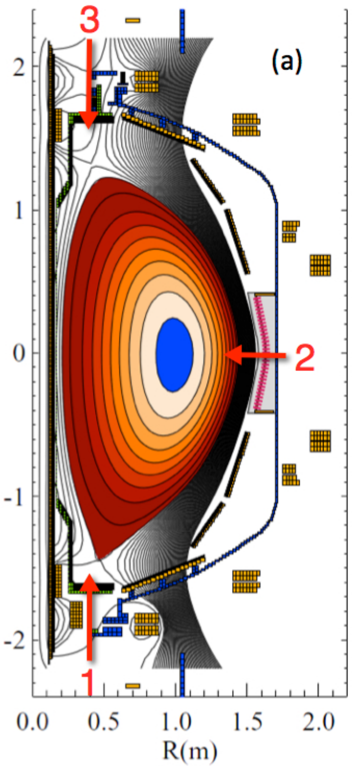


Columbia U
General Atomics

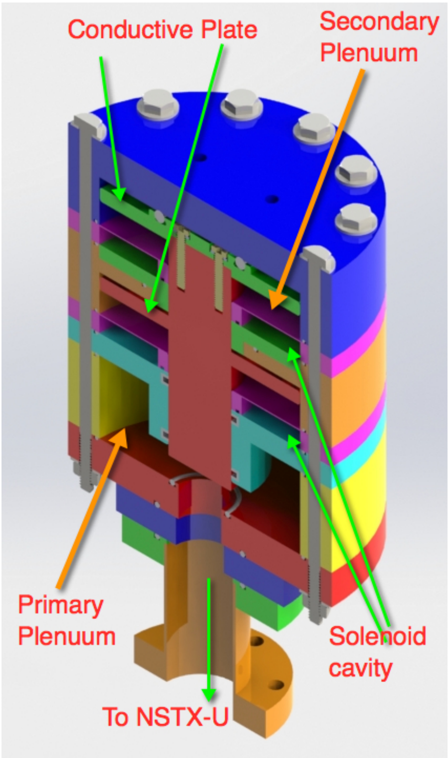
- **6-channel Switching Power Amplifier (SPA) powers independent currents in existing EFC/RWM and NCC coils.**
- **NCC (a facility enhancement) can provide various NTV, RMP, and EF selectivity with flexibility of field spectrum (n ≤ 6 for full and n≤ 3 for partial)**

Base – Engineering design work on NCC to be performed in 2015. 10% incremental funding enables start of procurement in FY 2016 and installation in FY 2017 to be available in FY 2018.

Disruption and Plasma Control Tools for NSTX-U
Massive gas injection system for disruption mitigation study

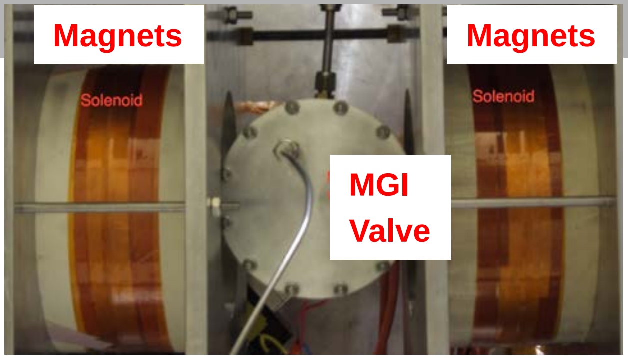


NSTX-U MGI Valve



- **Massive gas injector system installed at multi-poloidal location with identical injection set-up.**
- **A new double solenoid MGI design (zero net J x B torque) based on the ORNL ITER MGI design.**

MGI also being tested on the U. Washington test stand with magnetic field.



FY 2015-16:

- **Multi-poloidal location massive gas injector system for disruption mitigation will be implemented to test the efficiency vs location.** U. Washington
- **A Real-Time Velocity (RTV) diagnostic will be incorporated into the plasma control system for feedback control of the plasma rotation profile.**

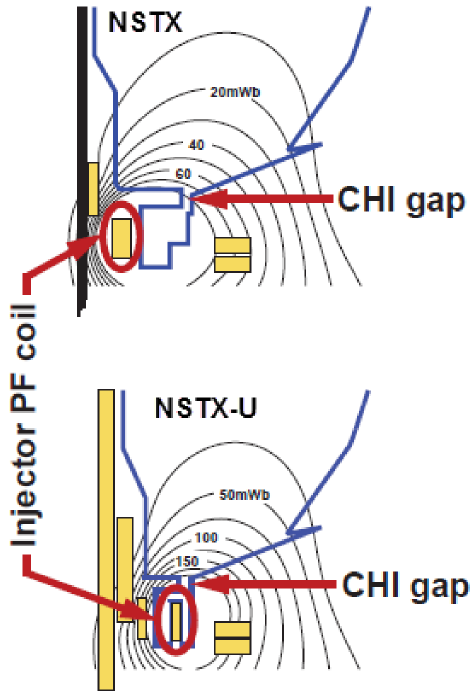
Solenoid-free start-up in support of ST-FNSF

NSTX-U CHI configuration permits ~ 400 kA level start-up

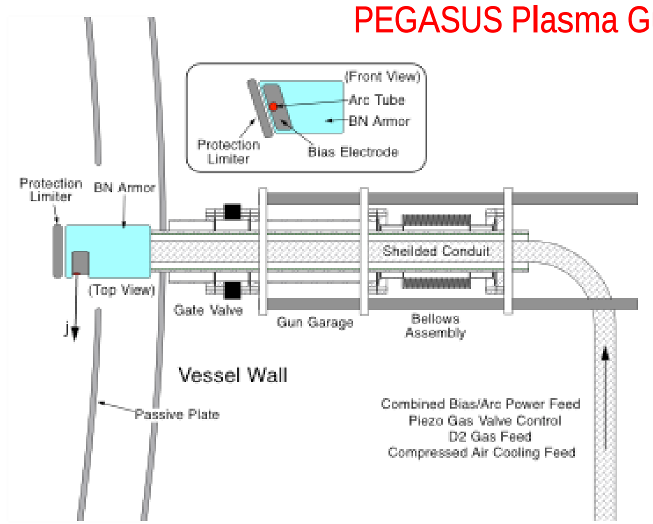
CHI Start-Up

- Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX
- NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation

U. Washington



Point Source Being Developed

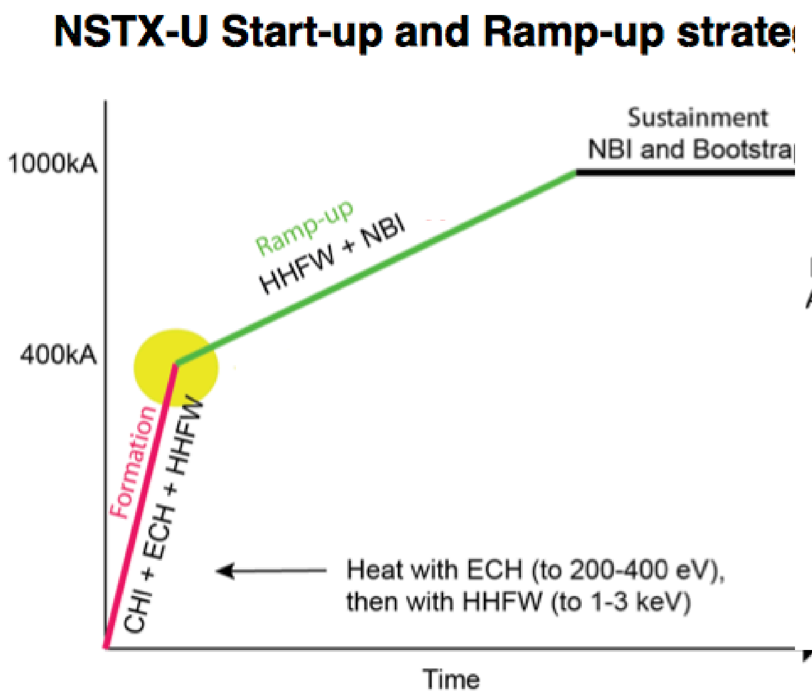


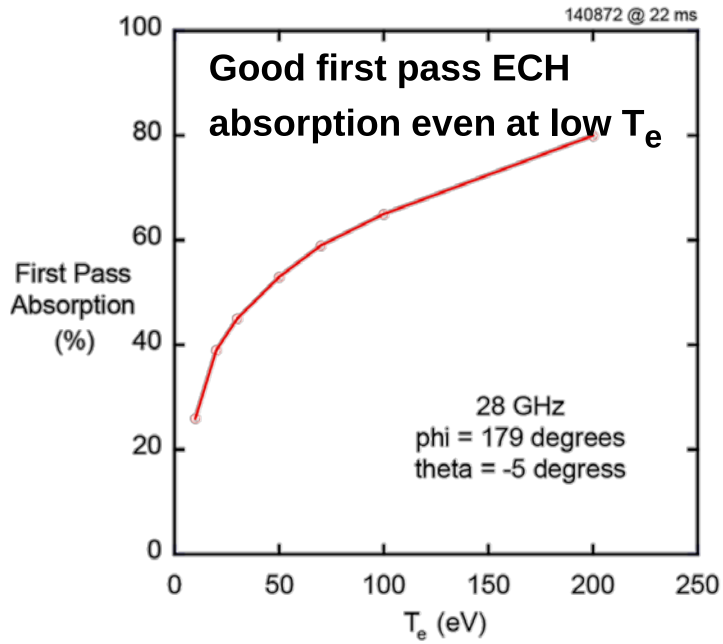
U. Wisconsin

FY 2015 - 2016 Non-Inductive Start-up Systems Design for Post-Upgrade Operations

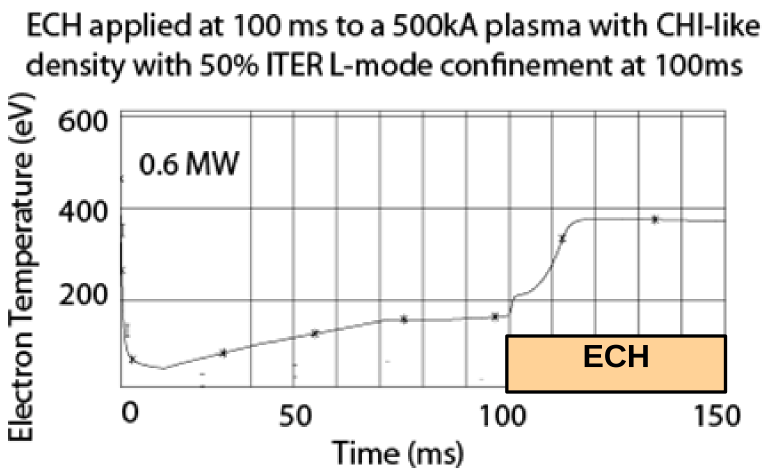
- CHI will start with the present 2 kV capability then enhanced to ~ 3 kV higher voltage as needed.
- PEGASUS gun start-up producing exciting results Ip ~ 160 kA. The PEGASUS gun concept is technically flexible to implement on NSTX once fully developed. High voltage gun for the NSTX-U will be developed utilizing the PEGASUS facility in collaboration with University of Wisconsin.

28 GHz Gyrotron ECH System Will Facilitate Non-Inductive Ramp-Up





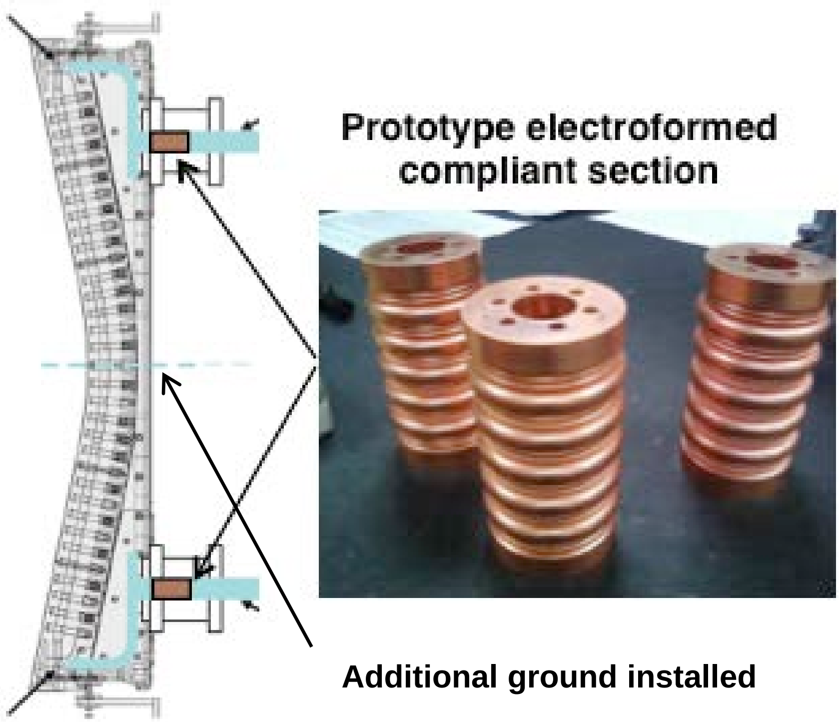
- CHI can form a 200-400 kA seed plasma, but it is too cold for HHFW absorption.
- Use of ECH can "bridge the T_e gap" to where HHFW and then NB current drive can support the ramp and sustain the current – crucial for OH solenoid-free compact STs.
  - Good first pass absorption predicted.
- Goal of first ECH power in 2017 run with 15% incremental funding.



HHFW to Support Current Ramp-up Research
Efficient electron heating and CD even at low Ip

New Compliant Antenna Feeds

Allow HHFW antenna feedthroughs to tolerate 2 MA disruptions



- Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.
- RF diagnostics also installed.

Antennas were re-installed with the new feeds and back-plate grounding

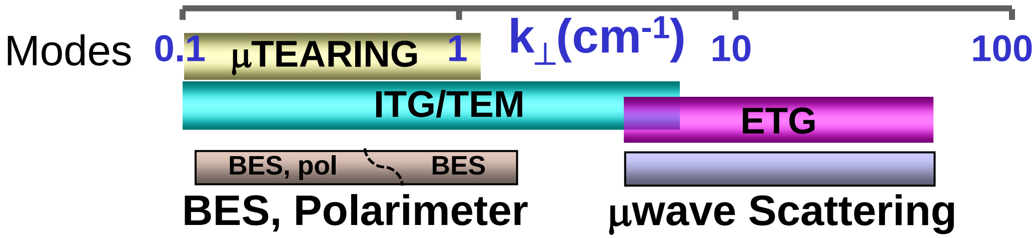
Transmission lines being installed & tuned.

Remaining tasks: Energize RF power supplies in May to be ready by June.

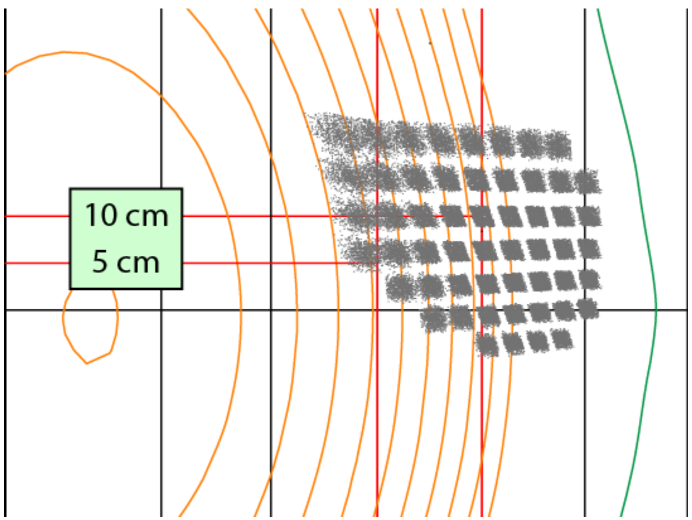
Higher B_T should improve heating efficiency

Enhanced turbulence diagnostics will give comprehensive view

MSE-CIF and MSE-LIF will provide Er information



48 ch BES available for NSTX-U (24 ch BES available in 2011)

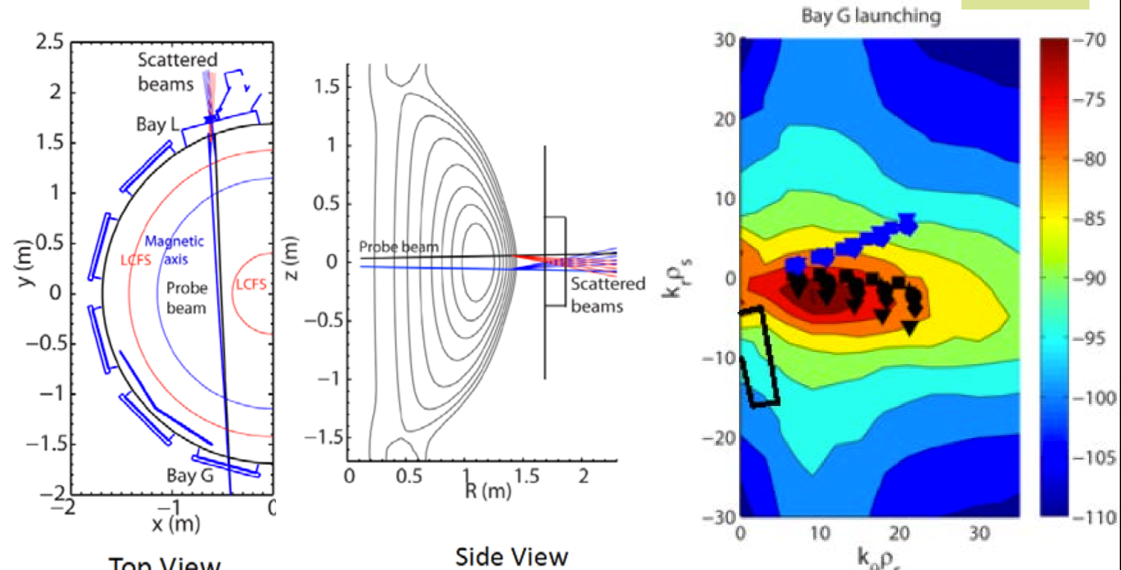


- **New 2-D fiber holder will provide better radial and poloidal coverage of r/a~0.4-SOL region**

U. Wisconsin

New high-k scattering system for allowing 2-D k spectrum in FY 2016

UCD



Preliminary magnetic fluctuation measurement concept under development at DIII-D; also initial tests performed on MAST. Proto-type on NSTX-U.

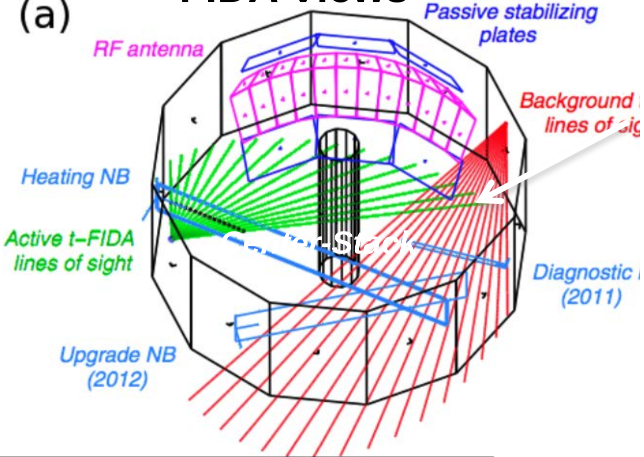
UCLA

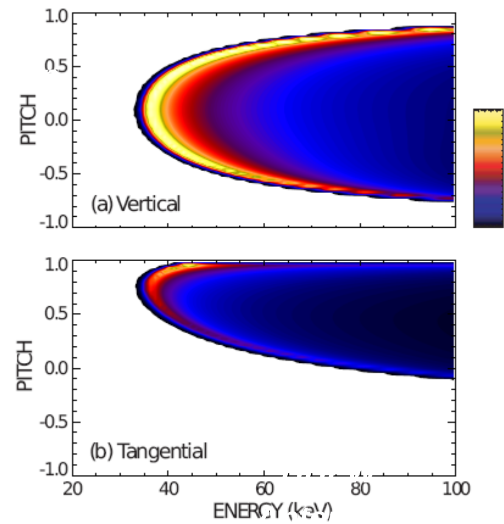
Enhanced FIDA will measure NBI distribution function
For NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics

- Both vertical (perpendicular) and new tangential (parallel) FIDA systems are ready.
- Both FIDA systems have 10 ms, 5 cm, ≈ 10 keV resolutions.

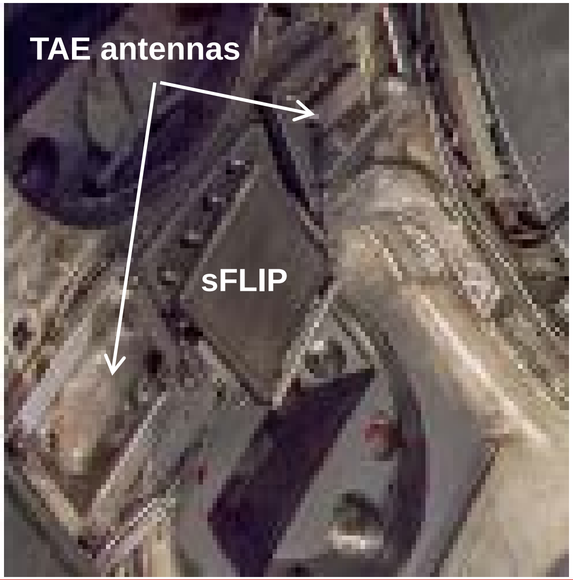
FIDA Views





FY 2015 - 2016 Energetic Particle Conceptual Design and Diagnostic Upgrade

- SS-NPA enhanced due to removal of scanning NPA (neutral particle analyzer). UCI
- sFLIP is installed for lost ion measurements
- Active 2 X 2 TAE antennas installed. Initially passive spectroscopy then active excitation at few kW level.
- Proto-type charged fusion product (CFP) profile diagnostic to be installed this year. FIU



Base NSTX-U Facility/Diagnostic Milestones

To complete Cryo-pump, NCC, and ECH/EBW Engineering Designs in FY 2015

Facility	Milestone Description	Baseline
F(15-1)	Complete 12 run week research operation	Sep 15
F(15-2)	Complete high-Z tile design and begin procurement	July 15
F(15-3)	Develop ECH engineering design and preliminary cost and schedule	Sep 15
F(15-4)	Develop cryo-pump engineering design and preliminary cost and schedule	Sep 15
F(15-5)	Develop NCC engineering design and preliminary cost and schedule	Sep 15
F(16-1)	Complete 14 run week research operation	Sep 16
F(16-2)	Install and commission high-Z tiles	Sep 16
F(16-3)	Complete cryo-pump engineering design and begin component procurement	Sep 16
F(17-1)	Complete 14 run week research operation	Sep 17
F(17-1)	Complete cryo-pump component procurement and begin installation	Sep 17
Diagnostics	**Milestone Description**	**Baseline**
D(15-1)	Install and commission Material Analysis Particle Probe (MAPP)	Sep 15
D(16-1)	Install and commission high k_θ diagnostic system	May 16
D(16-2)	Install and commission pulse –burst MPTS	Sept. 16
D(17-2)	Install and commission δB diagnostic system	Sep. 17

NSTX-U Optimized Plan Is Proposed for FY 2015 – 17

Incremental funding will enable timely implementation of 5 year plan

- **The NSTX upgrade completed its construction phase and began the commissioning phase. Schedule to complete CD-4 in April 2015, and the research operation in planned to start in June 2015.**
- **FY 2015 budget will enable the timely NSTX-U research operations start while completing the upgrade project, and implementing near term 5 year plan facility enhancements. It also allows engineering design work on the high priority Five Year Plan long term facility enhancements: divertor cryo-pump, ECH, and NCC.**
- **FY 2016-17 base budget guidance will enable the NSTX-U research operations with a row of high Z tile while prepare for the divertor cryo-pump installation in 2017.**
  - **~ 10% Incremental budget will enable full facility utilization and implementation of an additional major Five Year Plan enhancements(ECH or partial NCC).**
  - **~ 15% Incremental budget will enable full facility utilization and implementation of both ECH and partial NCC.**