NSTX-U

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NSTX-U FY2013 3rd Quarter Report Presentation

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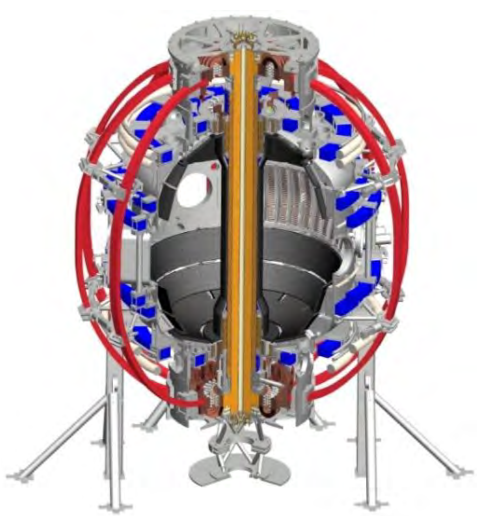
X Science LLC

Ron Strykowsky
Jon Menard
Masa Ono

FES Room G258
PPPL Room B205
July 16, 2013



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IPP, Garching
ASCR, Czech Rep

Agenda

- NSTX Upgrade progress report – R. Strykowsky
  - 20 minutes
- 5 year plan overview - including FY13 collaboration highlights relevant to 5 year plan – J. Menard
  - 55 minutes
- NSTX-U facility and diagnostic highlights – M. Ono
  - 45 minutes

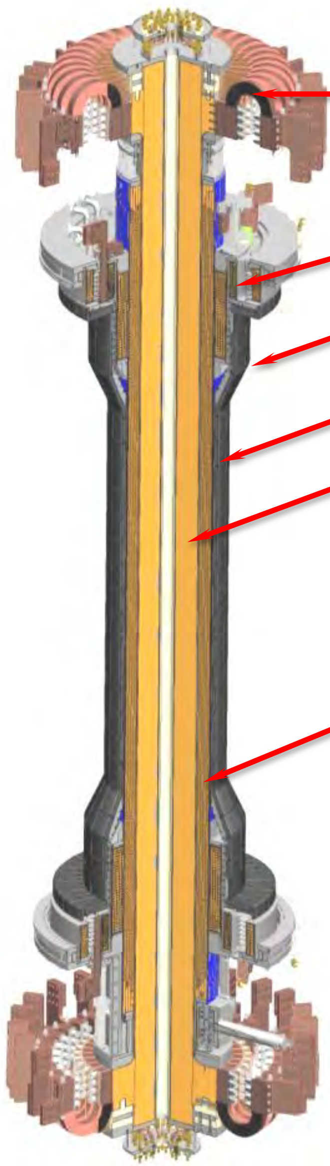
Significant progress continues to be made

- **Excellent safety record**
- **Good technical Progress**
- **On schedule and cost**

Neutral beam installation

- All 3 High Voltage Enclosures (HVE's) relocated to the NSTX-U Test Cell !
- NB water piping installation underway
- Electrical cable installation contract in procurement

Centerstack is the critical path and highest risk



- **Components & Hardware**
  - Flex connectors delivered
  - PF 1b,a,c coils- Awarded.
  - PFC Tiles-delivered and being machined
  - Casing - delivered
- **Inner TF Bundle**
  - VPI 4 Quadrants- Completed
  - VPI Full Bundle- ***August 2013***
- **OH Solenoid**
  - OH Conductor delivered
  - Begin winding OH solenoid- ***September 2013***
  - OH Mold - ***Delivery August***
  - VPI OH – ***January 2014***
- **Centerstack Assembly-**
  - Delivery to NSTX TC ***May 2014***

Center Stack Fabrication and Assembly Proceeding Well

Machined conductor by Major Tool

100% COMPLETE

Cooling tube soldered into inner TF conductor

100% COMPLETE

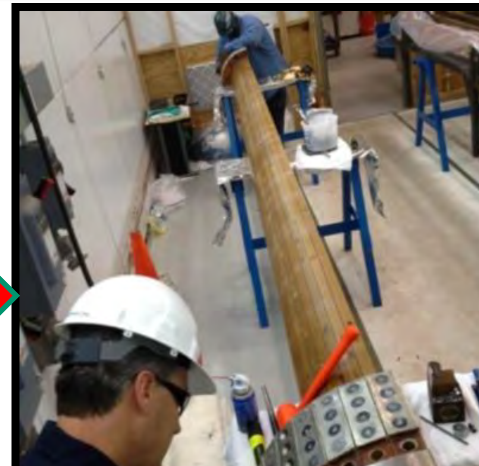
Conductor being wrapped with fiberglass insulation

100% COMPLETE

Insulated conductor being placed into mold

100% complete

Assembled TF mold ready for Vacuum Pressure Impregnation (VPI)



All 4 Quadrants successfully VPI'd and tested!

Next step - CS Inner bundle assembly

- Two of the 4 quadrants being sanded for final assembly

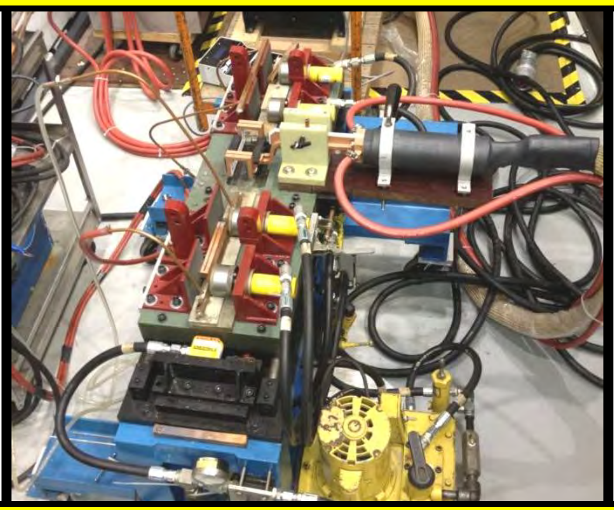
- The assembly stand ready to receive the 4 quadrants

- The full Inner TF mold positioned and leveled

- The TF mold shown with the lid installed

OH Winding Assembly & Casing tile studs

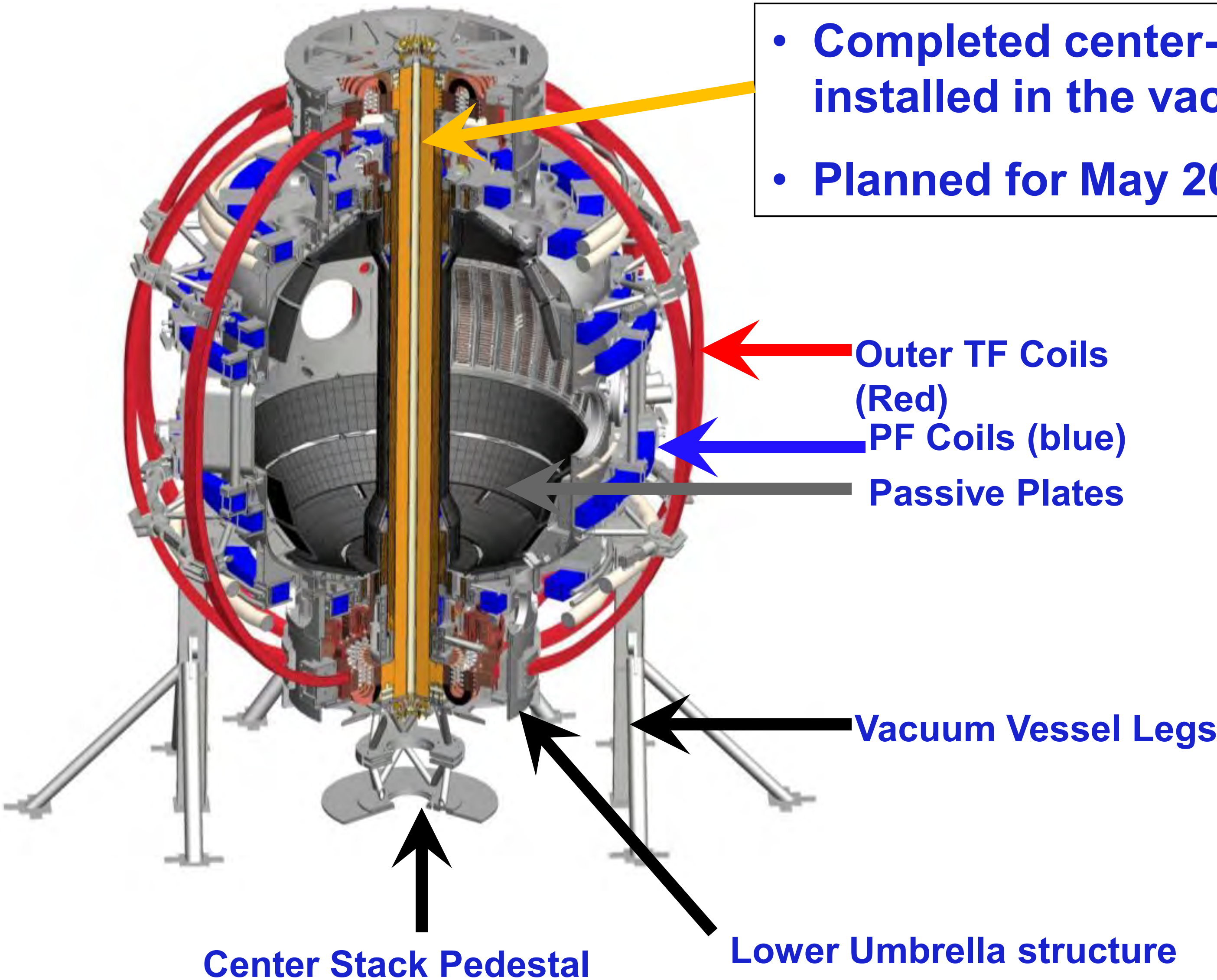
- The OH winding assembly being assembled for testing



- The OH in-line braze unit tested and ready for use

- The casing forms the inner part of the vacuum vessel and houses the inner TF/OH magnet.
- 500 Inconel studs being added to the outside surfaces.
- 696 Tiles with diagnostics will then be mounted.

New CS Installation one year away!

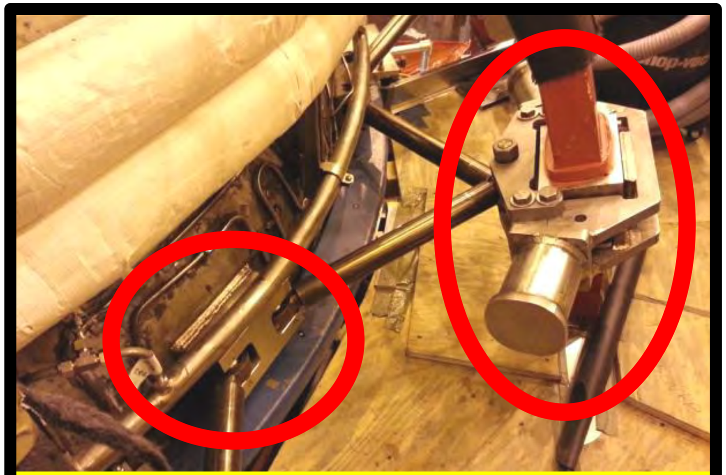


- **Completed center-stack assembly installed in the vacuum vessel**
- **Planned for May 2014**

Machine modifications making good progress

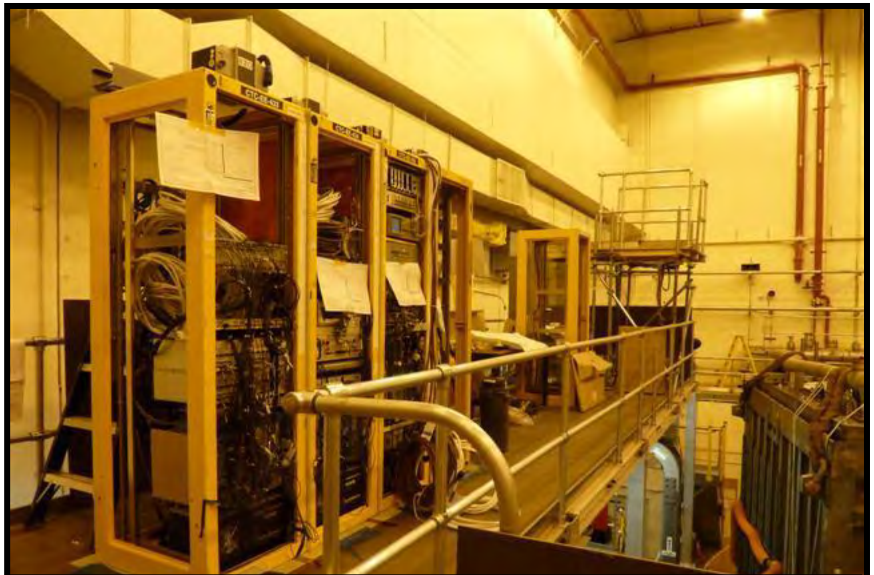
Umbrella Legs and Arch Reinforcement

Umbrella/TF Reinforcements



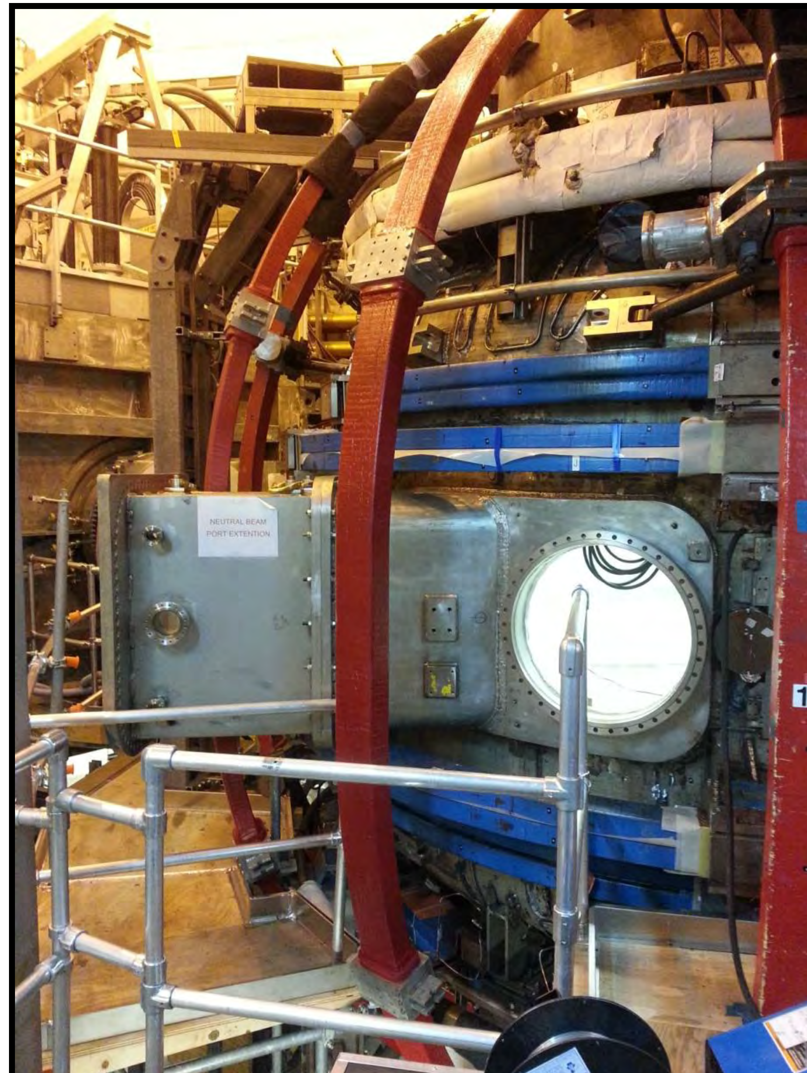
TF Outer Leg Supports

Other field work progressing well



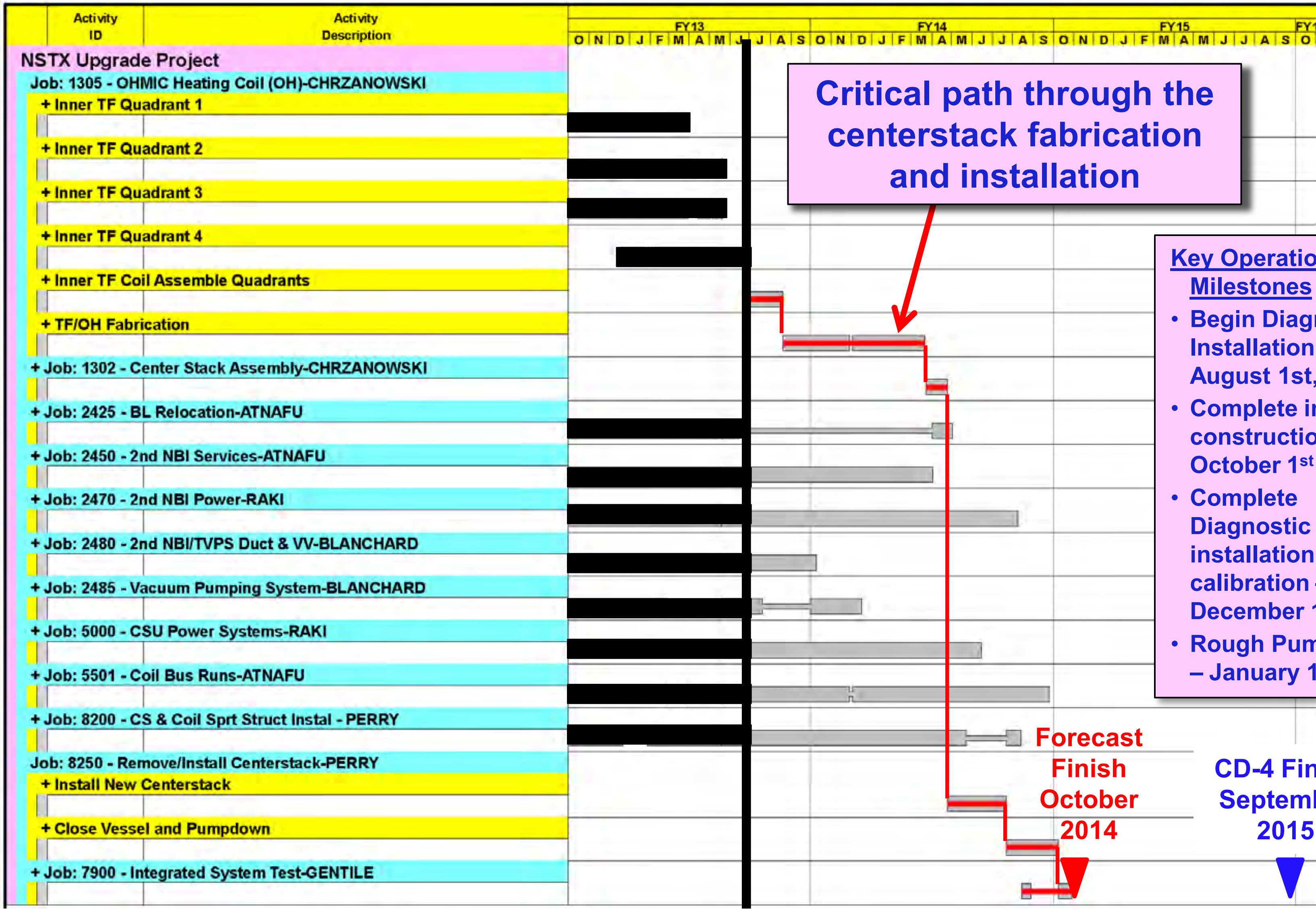
Re-installation of cable trays and racks underway

- Cable tray installations on the north wall and labyrinth underway.
- Fabrication and leak checking of NB LHe cryo lines underway.
- Installation of new gas injection ports underway
- Fabrication of NB/TVPS duct components underway.



2 New Outer TF Coils installed

Project on track for October completion



Key Operations Milestones

- Begin Diagnostic Installation – August 1st, 2013
- Complete in-vessel construction work October 1st 2013.
- Complete Diagnostic installation & calibration – December 1st, 2013
- Rough Pump down – January 1st, 2014

Performance metrics good

- **Performance** CPI = 0.97 SPI = 0.99
- **Completion**
  - Forecast = October 2014
  - CD-4 DOE Milestone (Late Finish) = September 2015
- BAC =$84.9 TPC = $94.3M
- Cost to date = $59.2 M 68% complete
- Contingency balance = 29% ($8M remaining) (26.6% at CD-2)

(1) Through March 2013

Near Term Risks & Uncertainties

SCHEDULE –

1. Center Stack Assembly
2. Vendor deliveries

TECHNICAL –

1. Centerstack VPI operations.
    - First 4 VPI's successful!
    - 2 more to follow (full TF, OH coil)

NSTX Upgrade Summary

- Project risks identified and being worked
- The project continues to make good technical progress.
- The project is currently on schedule and cost.
- Planning for start-up underway

Agenda

- NSTX Upgrade progress report – R. Strykowsky
  - 20 minutes
- 5 year plan overview - including FY13 collaboration highlights relevant to 5 year plan – J. Menard
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Key collaborations will be highlighted in light blue boxes

- NSTX-U facility and diagnostic highlights – M. Ono
  - 45 minutes

Maintaining strong team and publication and conference participation, development of early career researchers

	PPPL/PU	National Team (non-PPPL/PU)	International	Total
Total Researchers	79	166	61	306
Post-Docs	5	9	0	14
Students	3	26	4	33

Number of institutions	
Total	61
Domestic	32
International	29

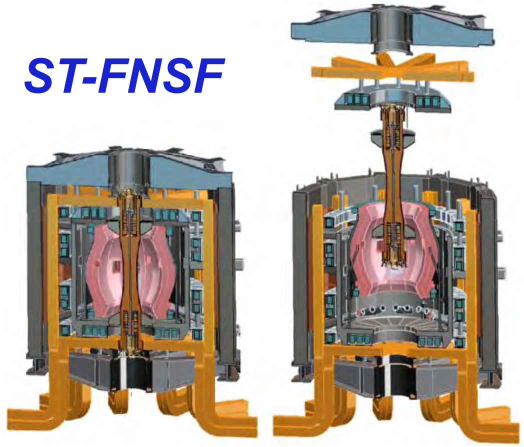
Calendar Year	Refereed Publications	PRLs	APS Invited	IAEA Papers
2009	45	6	5	
2010	63	5	10	25
2011	58	5	8	
2012	56	1	4	30
2013	34 so far	3 so far	6	

- Ahmed Diallo (PPPL) received 2013 DOE Early Career Research Program (ECRP) award for: “Edge Pedestal Structure Control for Maximum Core Fusion Performance”
- NSTX snowflake divertor team featured in October 2012 FES Science Highlights, led by V. Soukhanovskii (LLNL - 2010 ECRP) – also leading DIII-D snowflake expts.

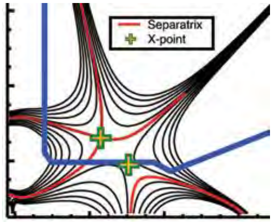
NSTX Upgrade mission elements

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

ST-FNSF



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

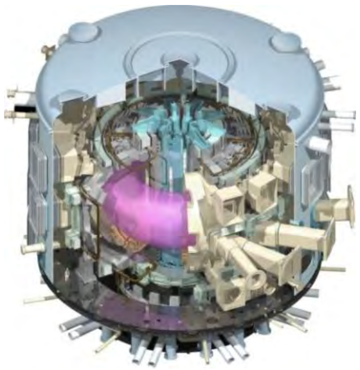


"Snowflake"

Lithium

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

ITER



- **Develop ST as fusion energy system**

Major assessments of NSTX-U since Q1 review:

- March: FESAC Subcommittee on the Prioritization of Proposed Scientific User Facilities for the Office of Science
  - Ranked importance of NSTX-U as “A” for “absolutely central”
- May: Positive debrief report of NSTX-U 5 year plan (2014-18)
  - “The quality of the proposed research is excellent, employing state-of-the-art diagnostics to obtain data that will be compared to theory using a wide variety of numerical models.”
  - “The proposed research addresses fundamental problems in magnetic fusion and will advance the state of knowledge in a number of areas.”
  - “The proposed research is essential for advancing the ST to a nuclear science mission.”
  - “NSTX-U will be a leading facility in the world fusion program, exploring unique physics of a low aspect ratio spherical tokamak, accessing high beta, large non-inductive current fractions, compact magnetic geometry, pushing to parameters not accessible to conventional tokamaks.”

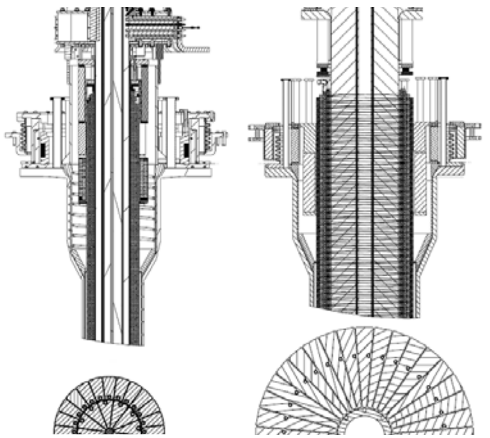
Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

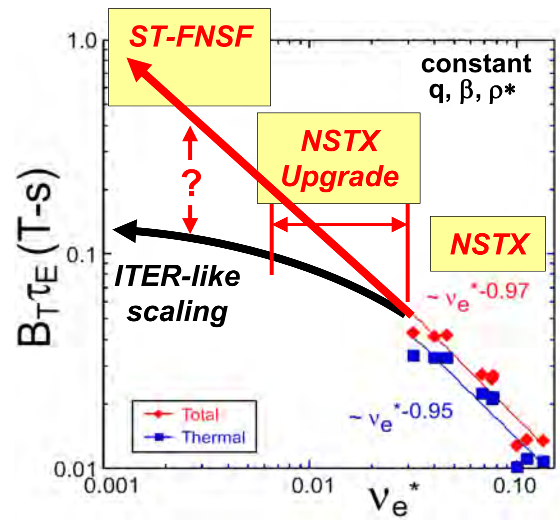
Longer-term (5-10 year) goal:

Integrate 100% non-inductive + high β and τ_E + divertor solution + metal walls

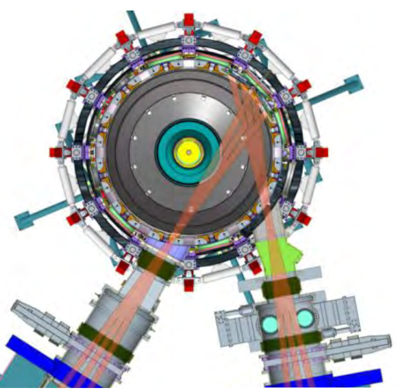
NSTX Upgrade incorporates 2 new capabilities:



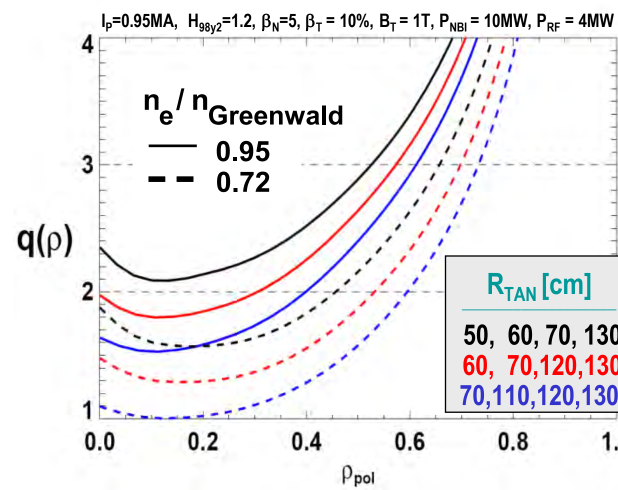
- Expect 2x higher T by doubling B_T, I_P, and NBI heating power
  - Reduces ν^* → ST-FNSF values to understand ST confinement
- 5x longer pulse-length
  - q(r,t) profile equilibration
  - Test non-inductive ramp-up



Normalized e-collisionality $\nu_e{}^* \propto n_e / T_e^2$



- 2x higher CD efficiency from larger tangency radius R_{TAN}
- 100% non-inductive CD with core q(r) profile controllable by:
  - NBI tangency radius
  - Plasma density, position (not shown)

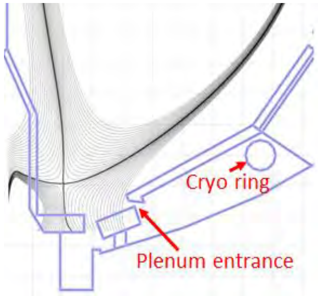


5 year plan also includes longer-term facility enhancements to fully utilize Upgrade capabilities, support ITER and FNSF

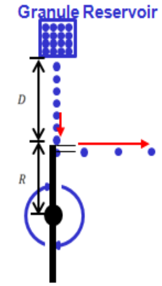
- **Improved particle control tools**
  - Control deuterium inventory and trigger rapid ELMs to expel impurities
  - Access low ν^*, understand role of Li

Upward Li evaporator

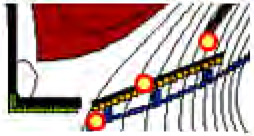
Divertor cryo-pump



Li granule injector (LGI)

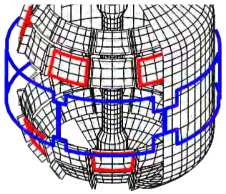


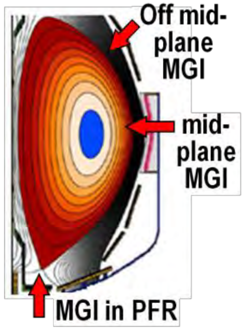
- **Disruption avoidance, mitigation**
  - 3D sensors & coils, massive gas injection



Extended low-f MHD sensor set

Midplane + off-midplane non-axisymmetric control coils (NCC)





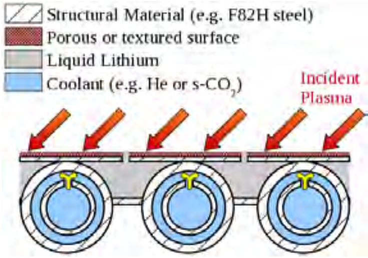
- **ECH to raise start-up plasma T_e to enable FW+NBI+BS I_P ramp-up**
  - Also EBW-CD start-up, sustainment

1-2MW 28 GHz gyrotron

- **Begin transition to high-Z PFCs, assess flowing liquid metals**
  - Plus divertor Thomson, spectroscopy

High-Z tiles

Actively-supplied, capillary-restrained, gas-cooled LM-PFC



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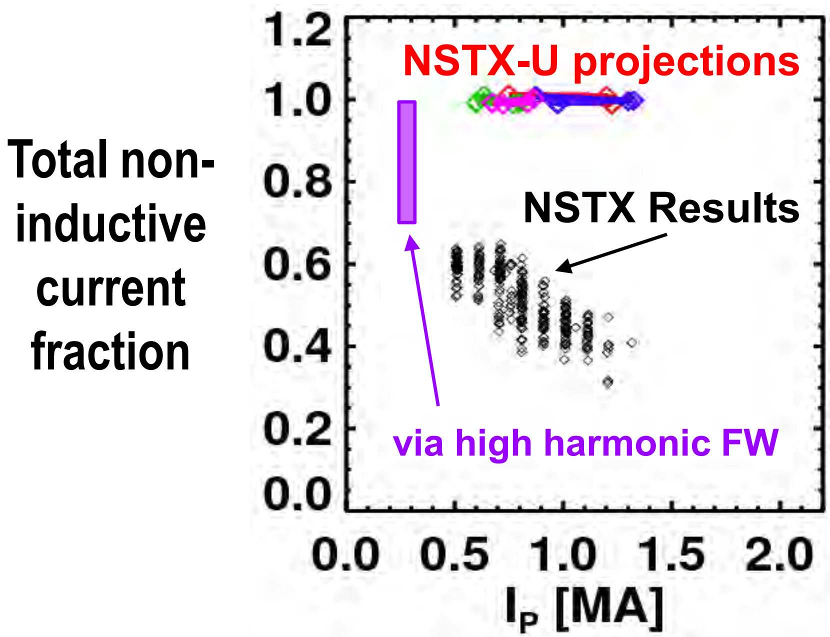
TRANSP simulations support goal of accessing and controlling 100% non-inductive plasma operation

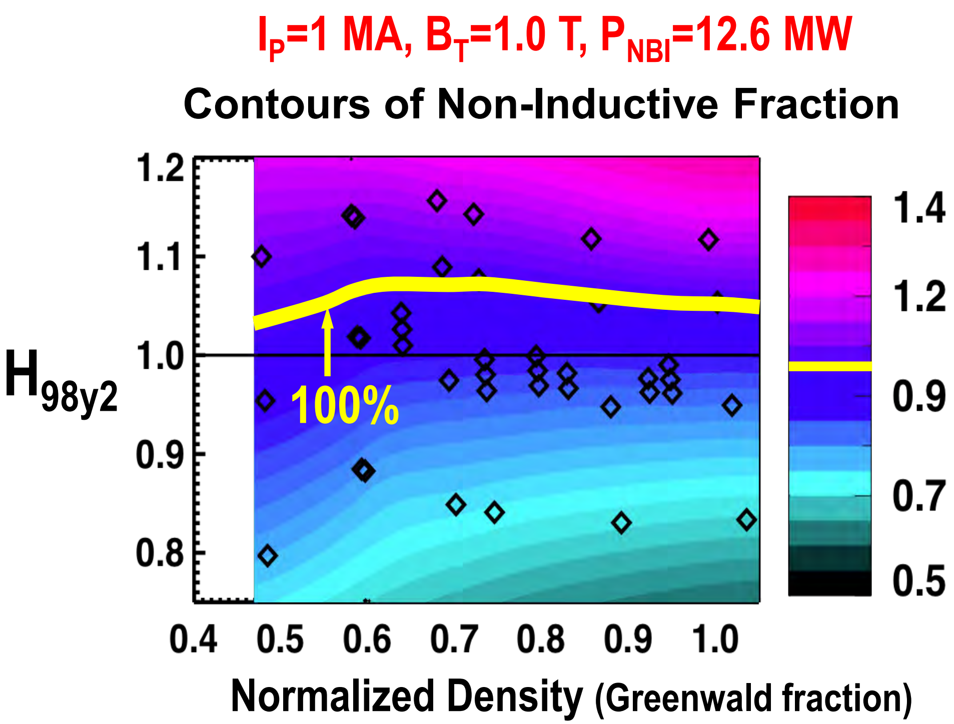
NSTX achieved:

- Maximum sustained non-inductive fractions of 65% w/NBI at I_P = 0.7 MA
- 70-100% non-inductive transiently with HHFW current-drive + bootstrap

NSTX-U projections (TRANSP):

- 100% non-inductive at I_P = 0.6-1.3MA for range of power, density, confinement

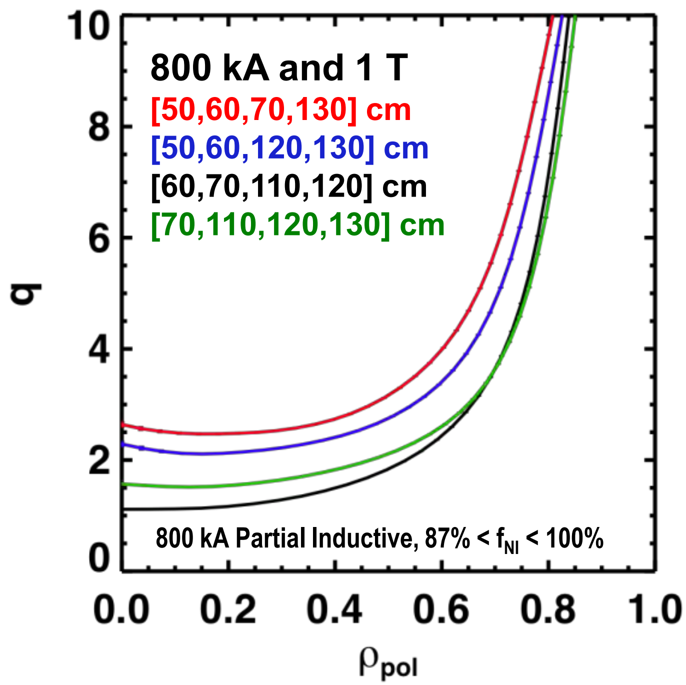




NSTX-U is developing a range of profile control actuators for detailed physics studies, scenario optimization for FNSF

q-Profile Actuators

Variations in Beam Sources

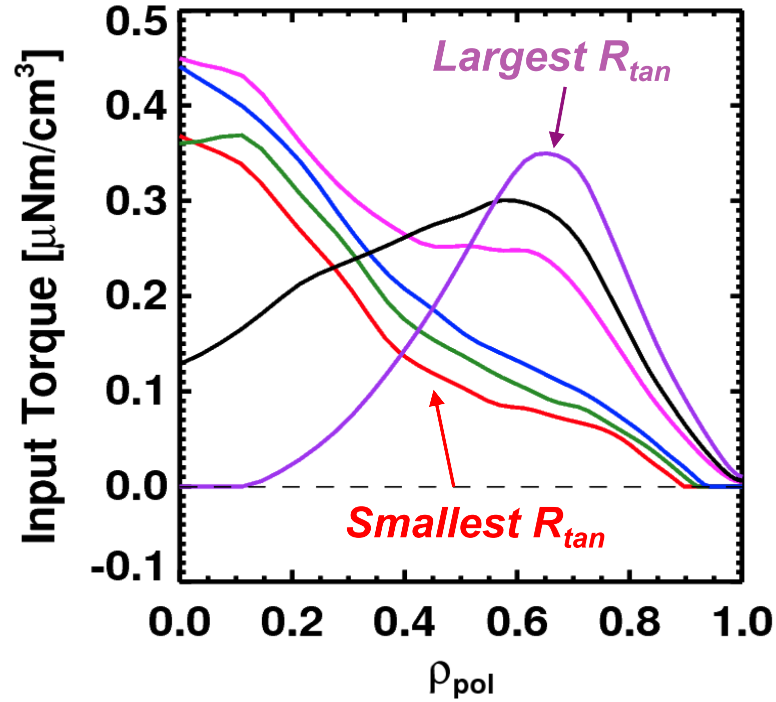


- Also density and outboard gap

Lehigh, General Atomics, Nova Photonics
(Lehigh: grad student + ORISE fellow)

Rotation Profile Actuators

Torque Profiles From 6 Different NB Sources



- Also torques from 3D fields

Princeton Univ., Columbia Univ.
(Princeton: MAE grad student)

Advanced Scenarios and Control (ASC) 5 Year Goal:

Develop basis for steady-state operation/control for next-step STs, help resolve key scenario and control issues for ITER

ASC Thrusts:

1. Develop and assess new physics scenarios
   - 100% non-inductive operation
   - Lower ν^*: high-current, partial-inductive scenarios, extend to long-pulse
2. Implement axisymmetric control algorithms and tools
   - Current and rotation profile control
   - Improved shape and vertical position control
   - Heat flux control for high-power scenarios

- **Snowflake divertor physics, control on DIII-D: V. Soukhanovskii (LLNL), Kolemen (PPPL)**
- **Radiative divertor control on DIII-D: E. Kolemen (PPPL)**

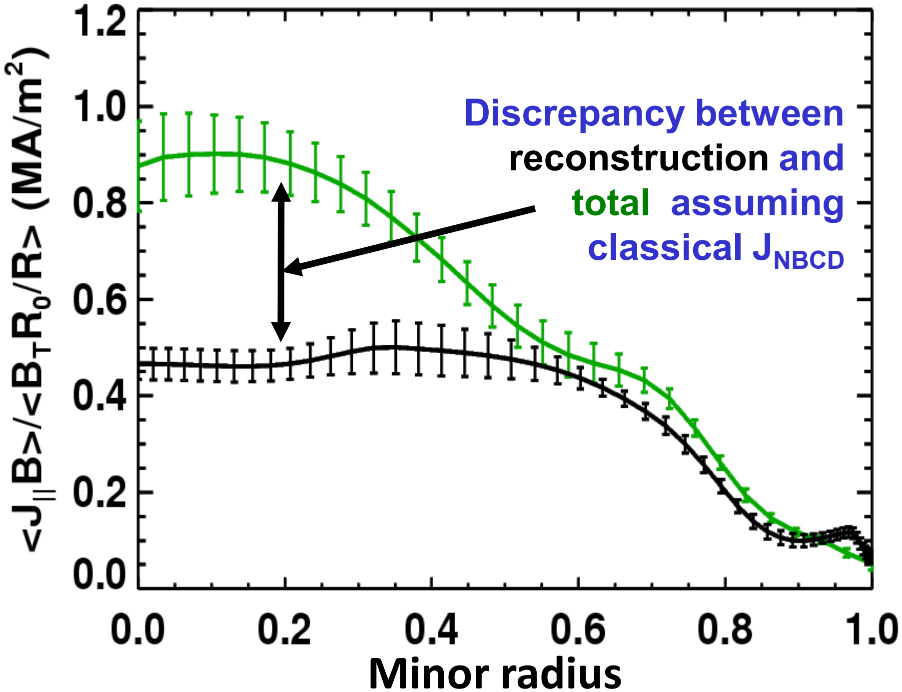
3. Develop disruption avoidance by controlled plasma shutdown

4. Assess scenario physics for next-step devices

- **D. Battaglia, E. Kolemen (PPPL) are physics operators on DIII-D – maintaining skills for NSTX-U ops**

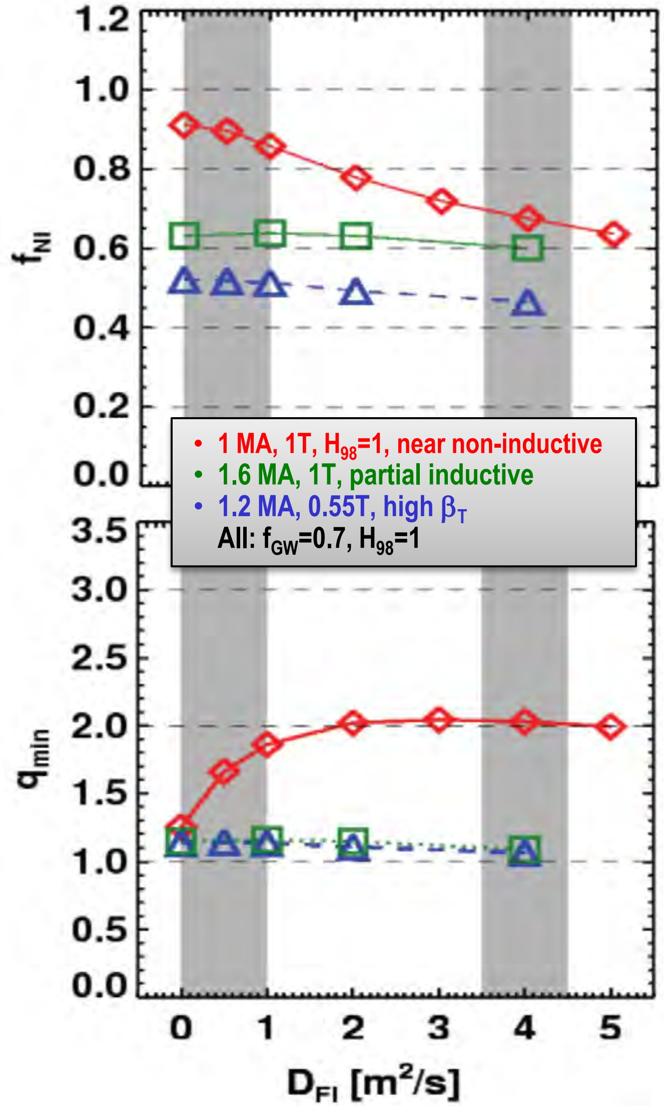
Rapid TAE avalanches could impact NBI current-drive in advanced scenarios for NSTX-U, FNSF, ITER AT

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



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

NSTX-U TRANSP simulations

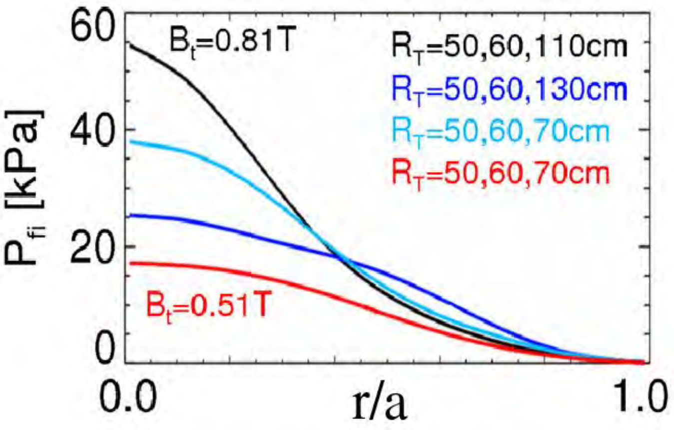


Energetic Particle (EP) 5 Year Goal:

Develop predictive capability for fast-ion transport caused by Alfven Eigenmodes (AEs), explore control of AE modes

EP Thrusts:

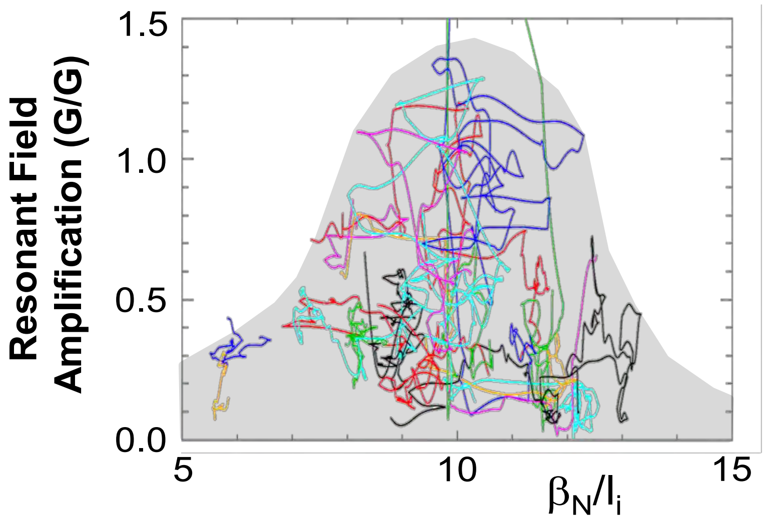
1. Develop predictive tools for projections of *AE-induced fast ion transport in FNSF and ITER
   - Vary fast-ion instability drive using NBI, q, rotation, 3D fields
   - Measure *AE mode structure
     - Magnetics, BES, reflectometry
   - Characterize fast ion transport vs. *AE type
   - Compare data to simulation, develop reduced models
     - ORBIT, NOVA-K, M3D-K, HYM to understand mode-induced transport



- **DD fusion product/rate profile measurements on MAST: W. Boeglin (FIU), D. Darrow (PPPL)**
- **TAE avalanche physics on MAST, DIII-D: E. Fredrickson and M. Podestá (PPPL)**

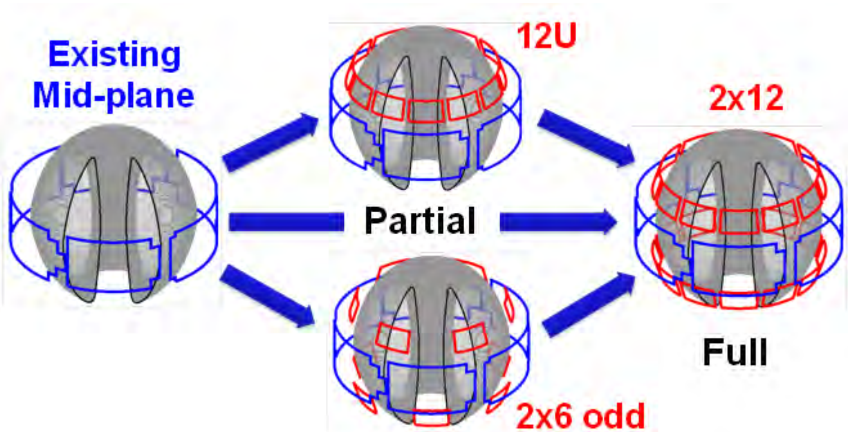
2. Assess requirements for fast-ion phase-space engineering
   - AE spectroscopy, also stability control using NBI, q, rotation, 3D fields

NSTX/NSTX-U is making leading contributions to high-β_N stability physics, and assessing possible 3D coil upgrades



- n=1 MHD spectroscopy: high β_N can be more stable
  - Combination of rotation and current profile effects at high beta
  - Important for advanced scenarios

NCC options:



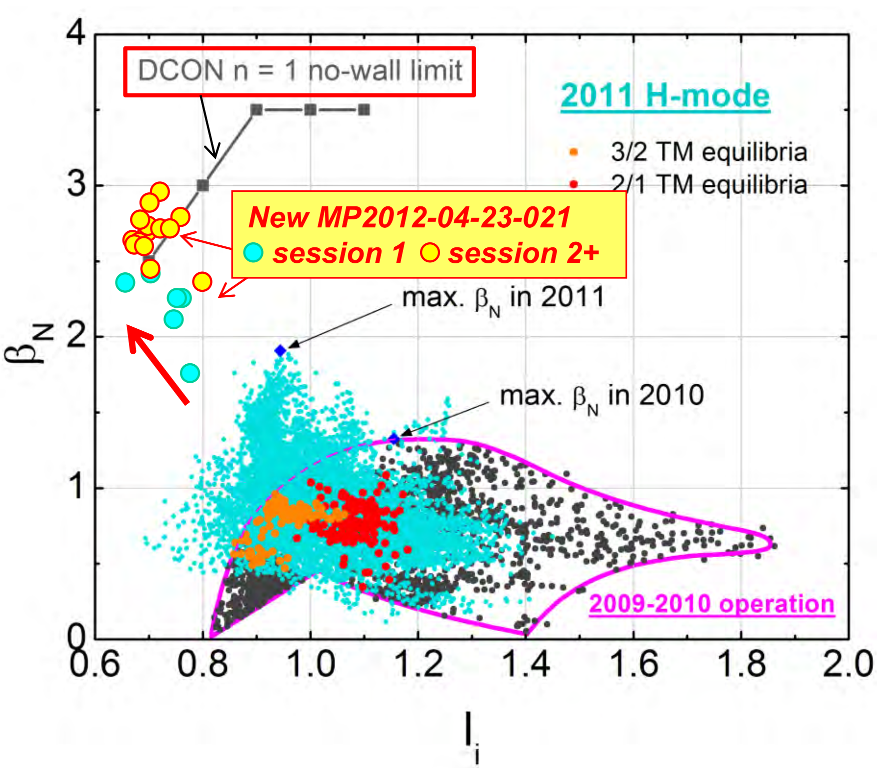
- Identified several off-midplane 3D coil sets favorable for profile and mode control
  - ~40% increase in n=1 RWM β_{active} / $\beta_{no\text{-}wall}$
  - ~5x reduction in n=1 EF resonant torque
  - ~10-100x variation in ratio of non-resonant to resonant n=3 torque in edge
    - Important for control, understanding of RMP ELM control, NTV rotation profile control

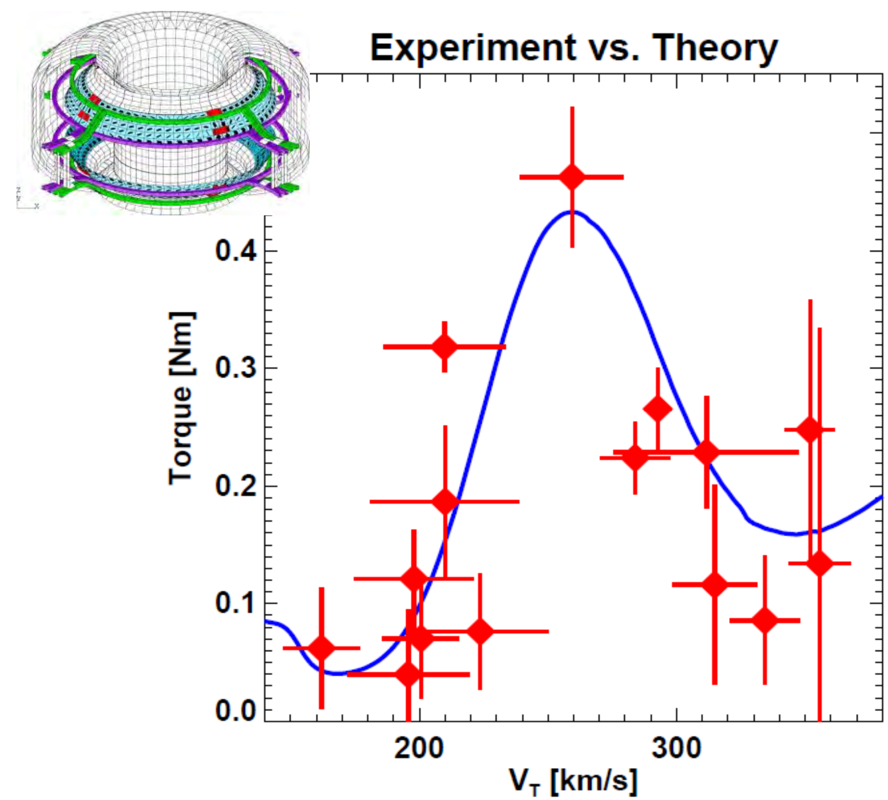
NSTX experience in scenario development, high-beta, and 3D physics is having significant impact on KSTAR research

- Improved shape control, improved access to low l_i + high κ: D. Mueller, D. Battaglia, E. Kolemen (PPPL)

- Studying MHD stability near no-wall beta limit: S. Sabbagh (CU)

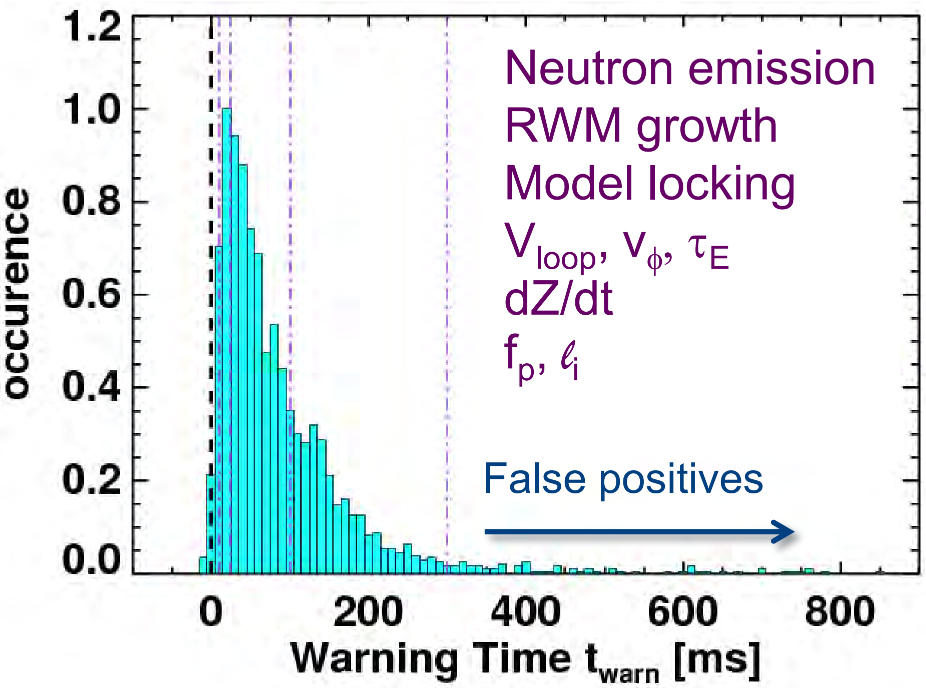
- Bounce-harmonic resonance in NTV observed in KSTAR for the first time in tokamak, and compared to theory/IPEC: J-K Park (PPPL – 2010 ECRP) *submitted to PRL*





NSTX has also making leading contributions to disruption warning research in support of ITER, FNSF

- **Disruption warning algorithms:**
  - **Based on sensors + physics-based variables (not neural net)**
  - < 4% missed, 3% false positives
  - ITER requires 95-98% prediction success for VDE, thermal quench
  - Will also assess for ST-FNSF



- **Will use to trigger ramp-down and/or mitigation in NSTX-U**

- **Will assess applicability to ITER through ITPA Joint Activity – S. Gerhardt**
- **Major topic at this week's PPPL-led workshop on *Theory and Simulation of Disruptions***

Macroscopic Stability (MS) 5 Year Goal:

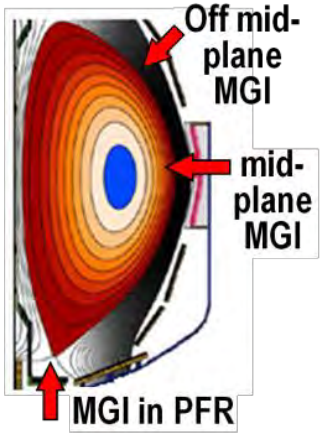
Establish the physics and control capabilities needed for sustained stability of high performance ST plasmas

MS Thrusts:

1. Understand and advance passive and active feedback control to sustain macroscopic stability
   - Study effects of reduced ν^*, also q and rotation on LM, RWM, NTM
   - Advance RWM state-space control for EF, RWM for ITER, next-steps

2. Assess 3D field effects to provide basis for optimizing stability through rotation profile control by 3D fields
   - EF penetration, rotation damping, ELM triggering and suppression

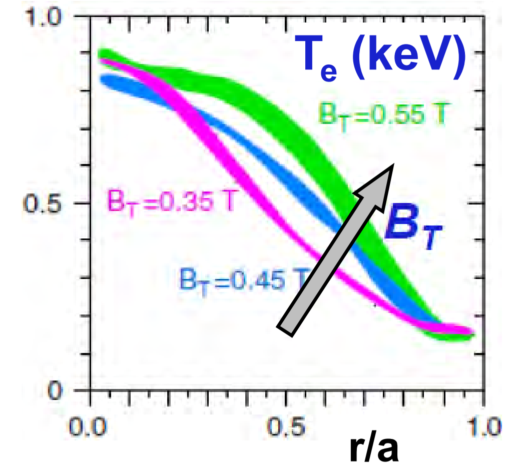
3. Understand disruption dynamics, develop prediction and detection, avoidance, mitigation
   - Enhance measurements of disruption heat loads, halos
   - Develop novel particle delivery techniques for mitigation:
     - MGI in private-flux-region (PFR), electromagnetic particle injector



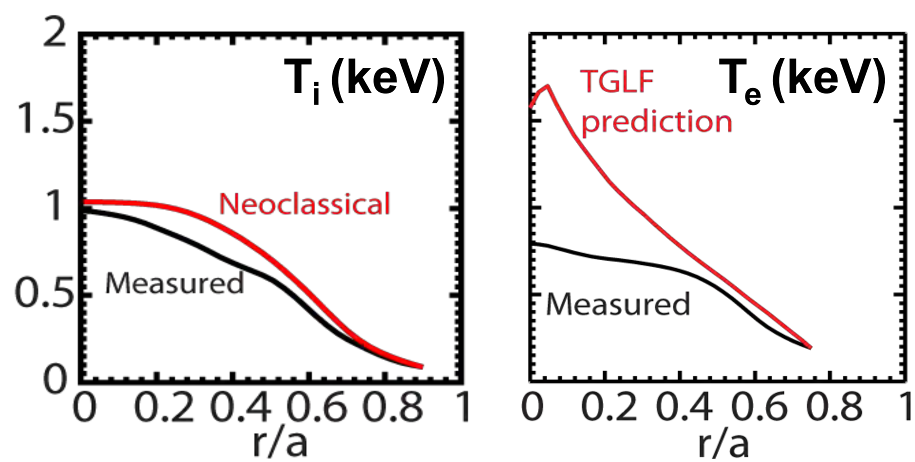
• **R. Raman (U. Washington) collaborating on DIII-D MGI experiments**

Beginning to test/utilize transport models to predict NSTX temperature profiles, identify possible missing physics

- NSTX H-modes showed broadening of T_e profile as B_T was increased
  - Similar broadening trend observed with increased lithium deposition
  - $B_T\tau_E$ scales as $\sim 1/\nu^*$ in both datasets



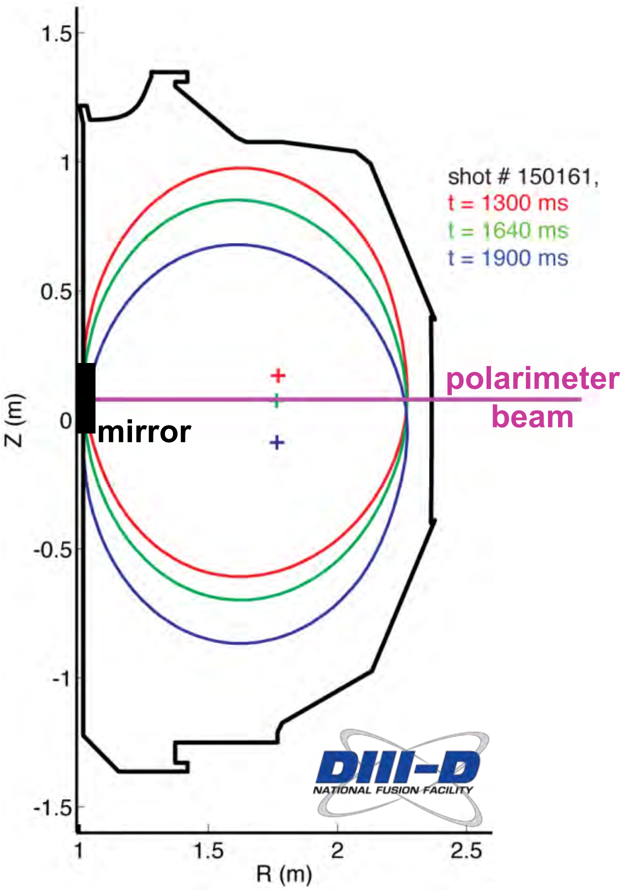
- Utilizing neoclassical + drift wave models to simulate NSTX T_i and T_e profiles (collaboration with GA)
  - Need model for χ in edge region
  - Discrepancy in core T_e prediction for beam-heated H-modes



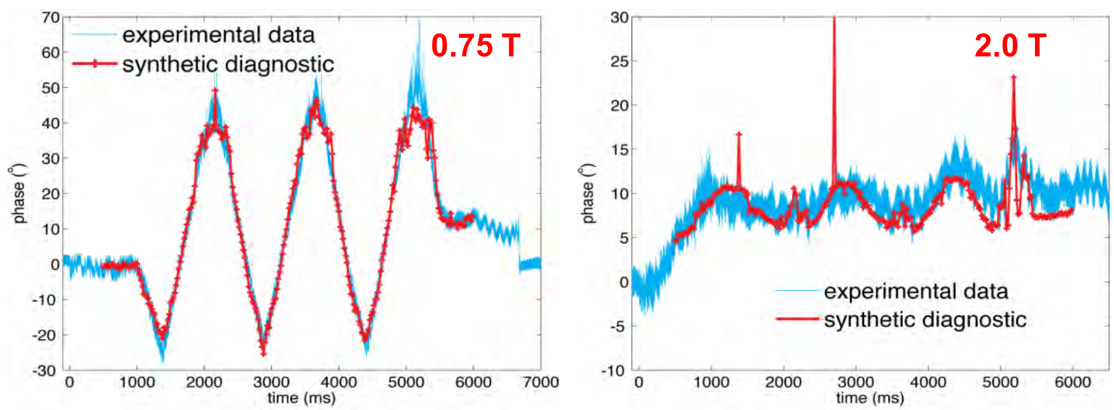
- Over-prediction of core T_e in NSTX may be due to transport from GAE/CAE modes not included in gyro-Landau-fluid model

UCLA successfully tested 288 GHz polarimeter for NSTX-U on DIII-D

UCLA Graduate Student: J. Zhang – Thesis Project



- Dedicated DIII-D run time to test polarimeter over wide range of conditions: phase response predicted to vary strongly with vertical position and B_T.
  - Moving plasma vertically → Faraday rotation due to horizontal B ranges from weak to strong
  - Wide range of B_T → elliptization (Cotton-Mouton effect) ranges from weak to strong
- Synthetic diagnostic calculations agree with measured phase over wide range of B_T (0.75-2.0 T), plasma height



Faraday rotation dominated **Cotton-Mouton effect dominated**

- **Polarimetry planned to be used to measure μ-tearing δB in NSTX-U**

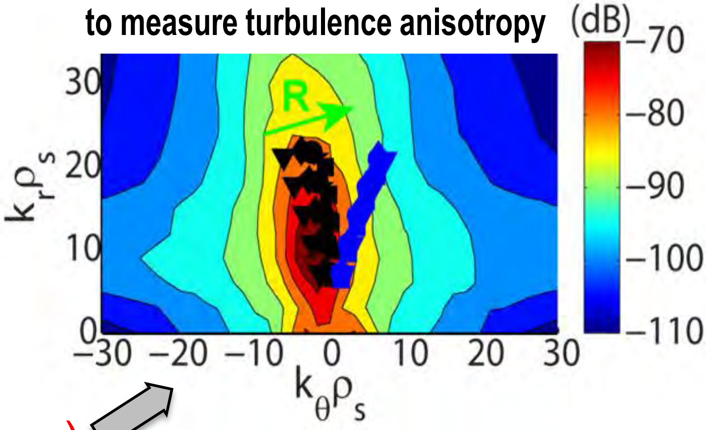
Establish predictive capability for transport in next-step devices focusing on the ST high-β + low-collisionality regime

TT Thrusts:

1. Characterize H-mode global energy confinement scaling in the lower collisionality regime of NSTX-U

2. Identify modes causing anomalous electron thermal, momentum, particle/impurity transport
   - Exploit scaling dependencies of modes
     - Example: μ-tearing $\chi_e \sim \nu^1$, ETG $\chi_e \sim \nu^0$
   - Relate predicted turbulence to data:
     - Low-k (BES), δB (polarimetry), high k_r & k_θ (μ-wave)
   - **Builds on identification of ETG w/ novel high-k_r scattering in NSTX**

New high-k scattering
to measure turbulence anisotropy



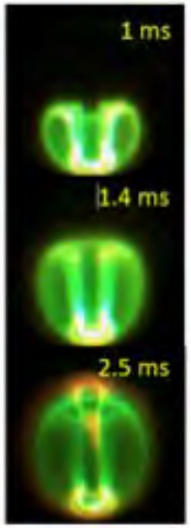
3. Establish and validate reduced transport models

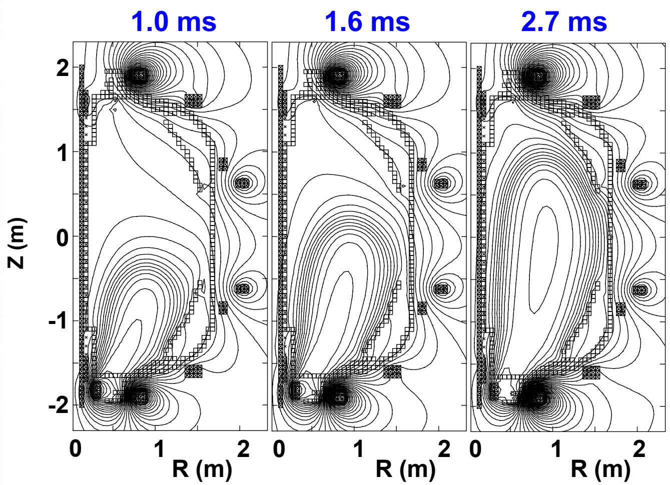
Highest priority research goals for 5 year plan:

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1MW/m^2$ neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

Simulations support non-inductive start-up/ramp-up strategy

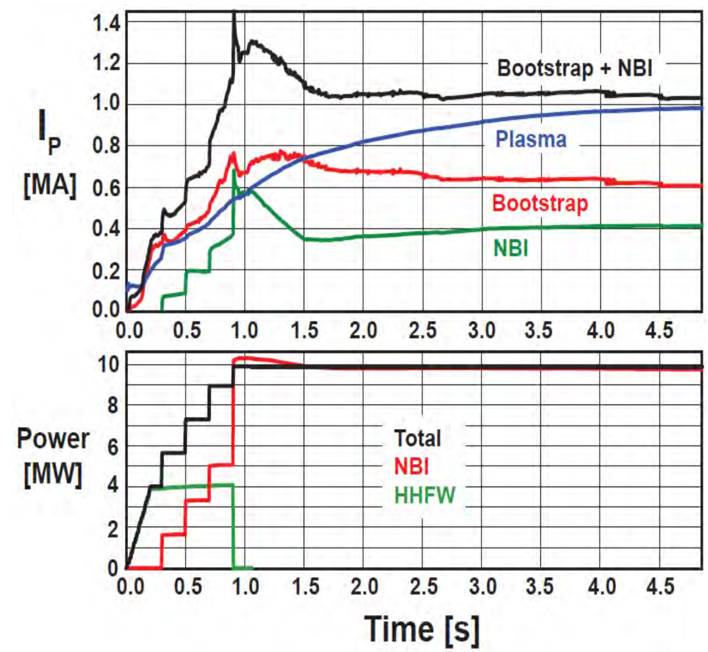
- TSC code (2D) successfully simulates CHI I_P ~200kA achieved in NSTX





- TSC + tools included in 5 year plan support CHI I_P → 400kA in NSTX-U
  - Higher injector flux, toroidal field, CHI voltage
  - 1MW 28GHz ECH (increases T_e)

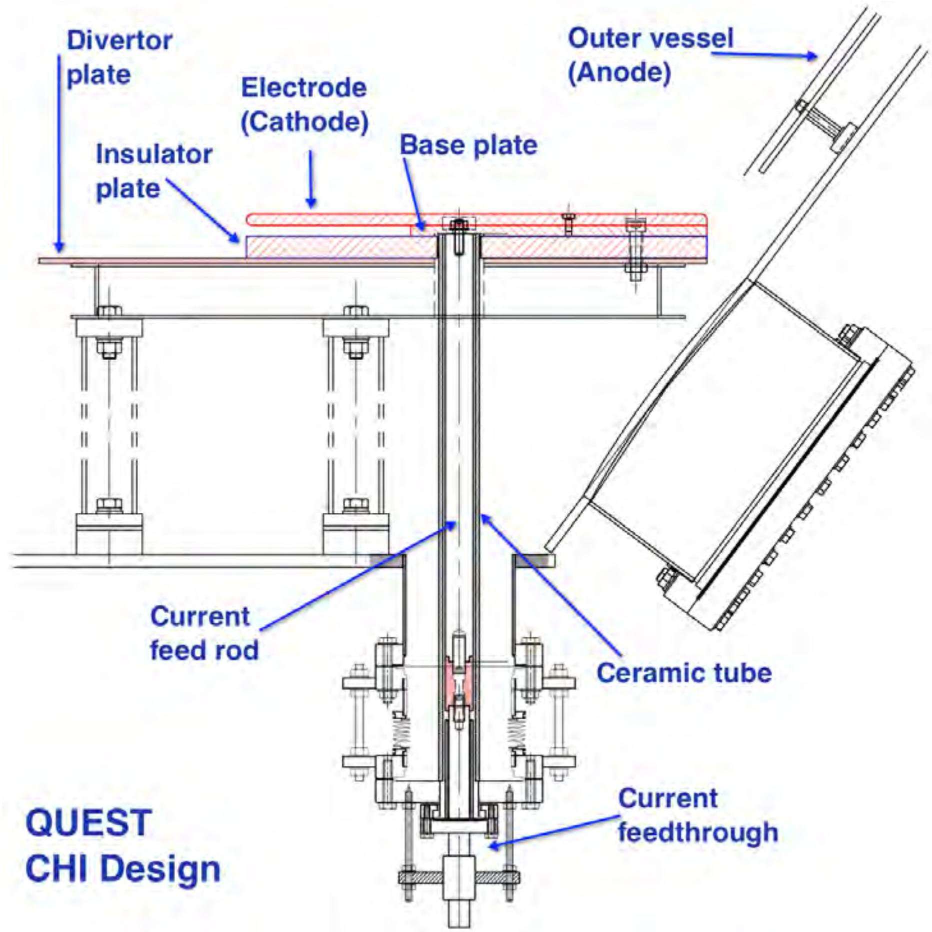
- TRANSP: NSTX-U more tangential NBI → 3-4x higher CD at low I_P (0.4MA)
- TSC: non-inductive ramp-up from 0.4MA to 1MA possible w/ BS + NBI



- But, RF heating (ECH and/or HHFW) of CHI likely required to couple to NBI

CHI design for QUEST supports NSTX-U research
(Collaboration with Kyushu University - Japan)

- Preliminary design completed (January 2013)
  - Now working on finalizing design and cost estimates
- Electrode mounted on top of divertor plate
  - Insulators not part of vacuum structure
  - CHI operation at up to 3kV
  - Metallic electrodes (SS + Mo/W)
    - Provides data for NSTX-U metal electrodes (high-Z tiles)
  - Also informs ST-FNSF CHI design

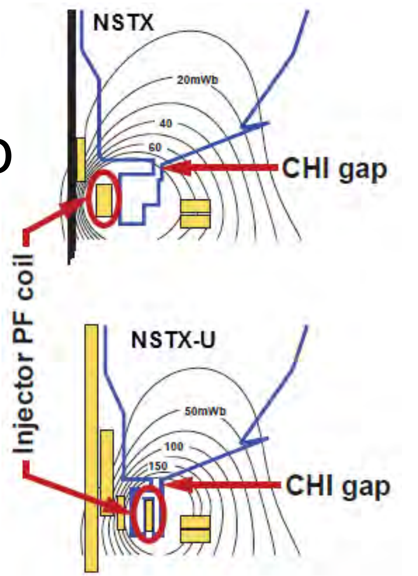


Collaboration led by R. Raman – Univ. Washington

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

PSR Thrusts:

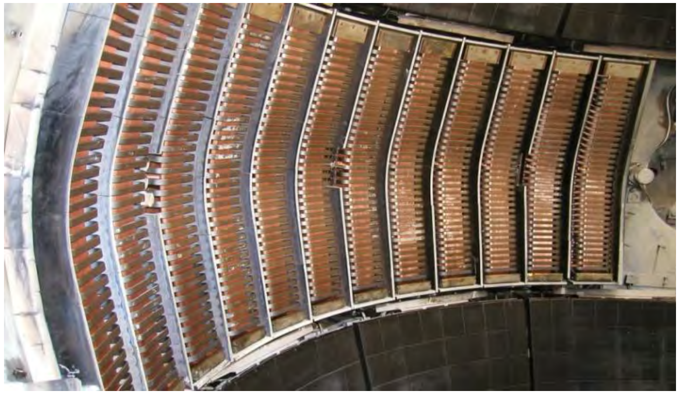
1. Initial years: Establish, extend solenoid-free plasma start-up, test NBI+BS over-drive ramp-up
   - Assess impact of new gap geometry, PF coil positions
   - Increase CHI closed-flux I_P from 200kA → 300-400kA
   - Assess NBI H&CD in 300-400kA ohmic target
   - Attempt NBI + bootstrap ramp-up: ΔI_P ~ 100-400kA



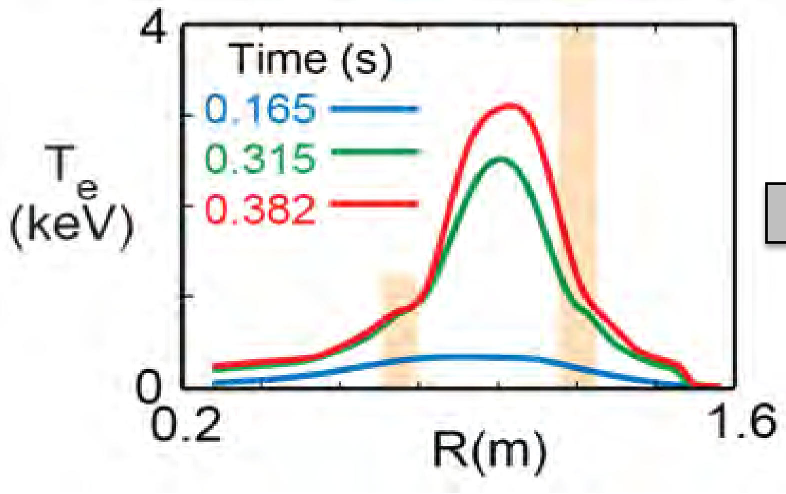
2. Later years: Ramp-up CHI plasma using ECH + HHFW + NBI, test "plasma gun" (point-helicity source) start-up
   - Maximize levels of CHI-produced I_P, extend with ECH and HHFW
   - Test NBI coupling to heated CHI, attempt full non-solenoidal start-up
   - Commission, test plasma guns (being developing on Pegasus) on NSTX-U

HHFW can efficiently heat low I_P targets for plasma start-up

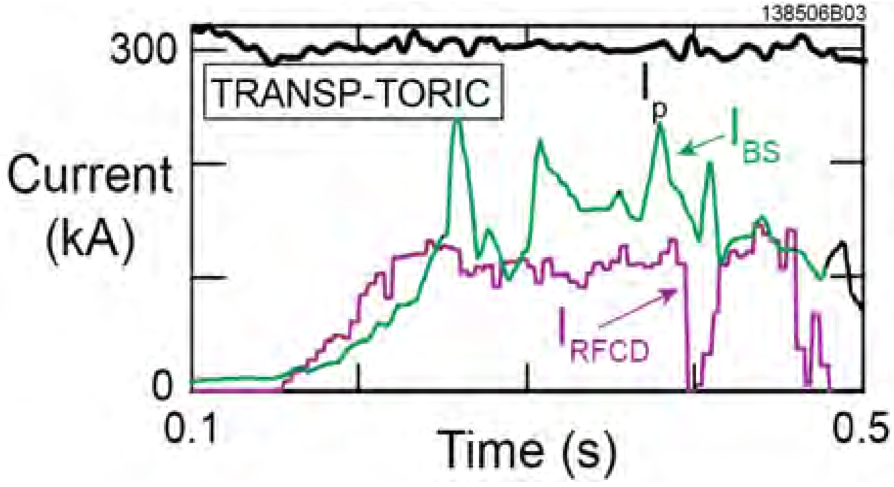
- NSTX high-harmonic fast-wave (HHFW) antenna will also be utilized on NSTX-U
  - 12 strap, 30MHz, $P_{RF} \leq$ 6MW
  - HHFW: highest ST $T_e(0)$ ~ 6keV



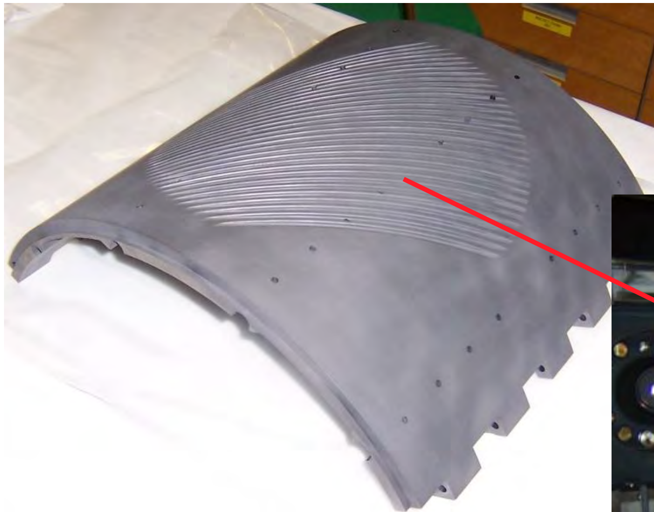
- $T_e(0)$=3keV RF-heated H-mode at I_P = 300kA with only P_{RF} = 1.4MW



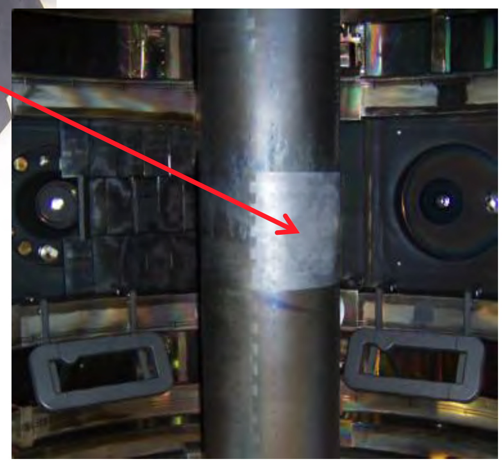
- Non-inductive fraction ≥ 70%
  - f_{BS} ~50%, f_{RFCD} ~ 20-35%

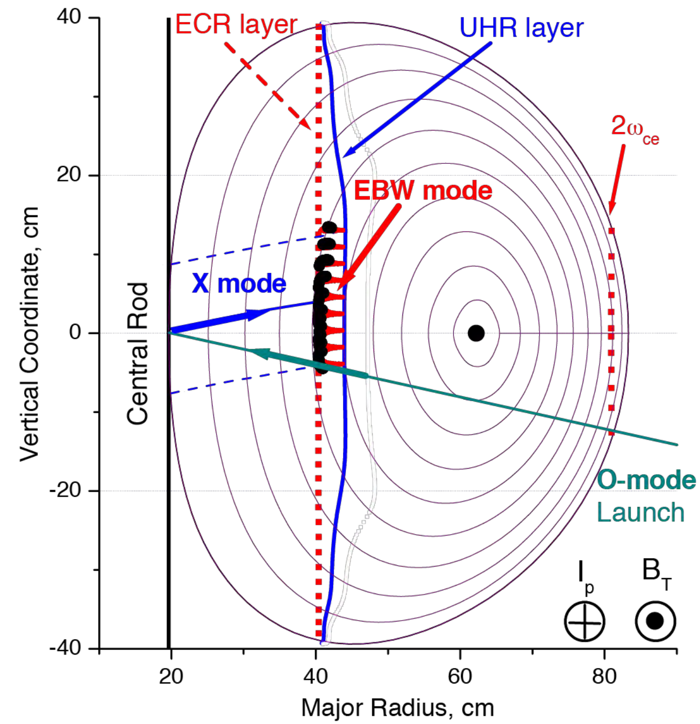


MAST: 28 GHz EBW start-up campaign in 2013 used new low-loss transmission line to achieve record plasma current



Grooved reflecting polarizer machined into center column in MAST





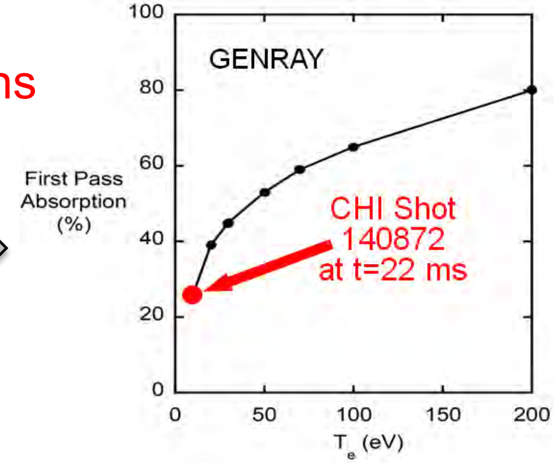
- 28 GHz O-mode weakly absorbed (< 2%) below $n_e \sim 1 \times 10^{19}$ m^{-3} cut off
- Polarizer on center column converts to X-Mode that then 100% converts to EBWs
- Previously achieved I_p~33 kA but arcs in waveguide limited RF power [Sept 2009]
- **During two one-week EBW start-up campaigns in 2013 coupled 70-100 kW for 300-400 ms achieving I_p = 50-75 kA**

G. Taylor (PPPL), with ORNL

Provide and understand heating and current-drive for full non-inductive (NI) start-up and ramp-up in support of FNSF

RF Thrusts:

1. Develop HHFW and EC heating for fully non-inductive plasma current start-up and ramp-up
   - Extend HHFW to higher power (3-4MW), demonstrate HHFW-driven 100% non-inductive at 300-400kA
     - Goal: maintain I_P to confine 2nd NBI fast-ions
   - Use ECH (~1MW, 28GHz), then HHFW to increase T_e of CHI plasmas for NBI
   - Test high-power EBW to generate start-up current - builds on MAST results



2. Validate advanced RF codes for NSTX-U, predict RF performance in ITER and FNSF

Highest priority research goals for 5 year plan:

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

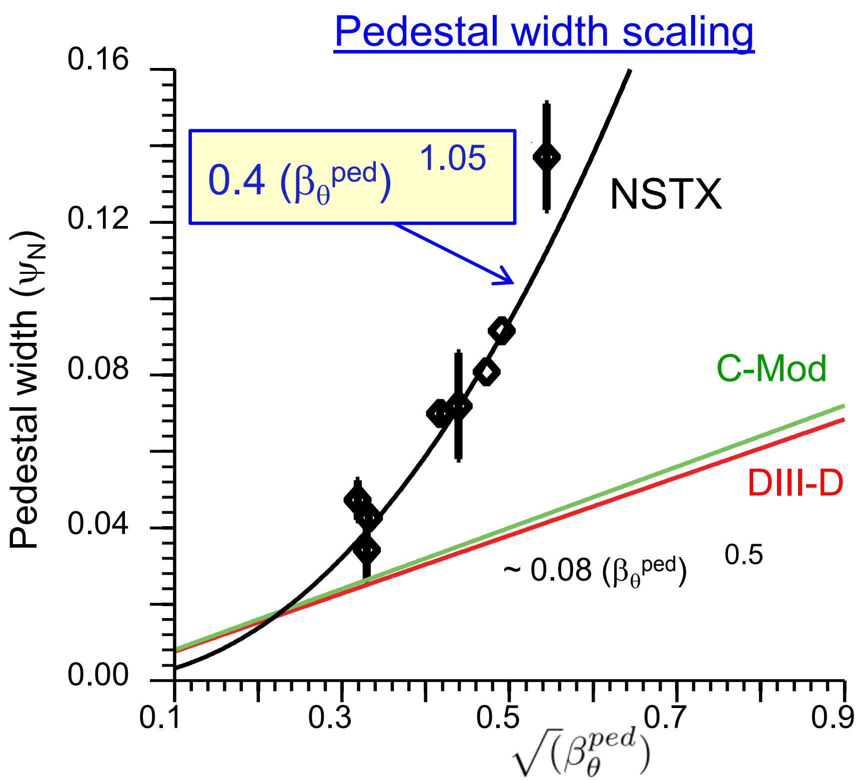
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

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

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

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

Pedestal width scaling differs from conventional aspect ratio



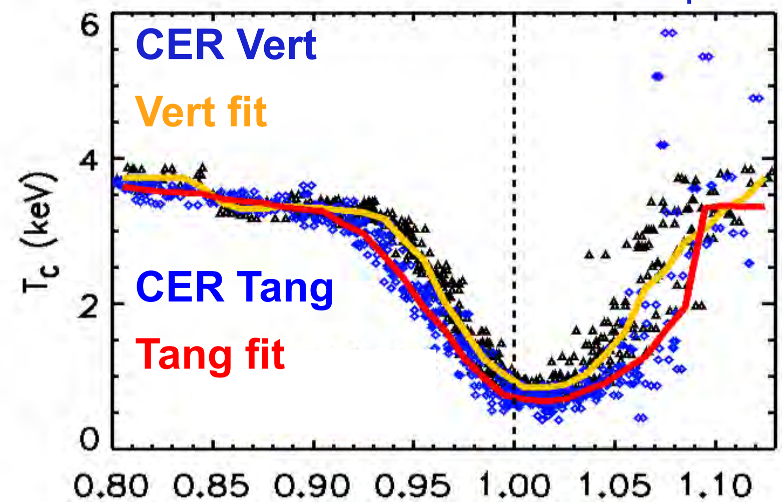
- Pedestal width scaling β_θ^α applies to multiple machines
- NSTX pedestal width is larger
  - Data → stronger scaling: $\sim\beta_\theta$ vs. $\beta_\theta^{0.5}$
  - Preliminary EPED calculations: $\sim\beta_\theta^{0.8}$
  - Measured low-k turbulence correlation lengths consistent with XGC1 turbulence predictions

Synthetic diagnostics linked to XGC0 confirm kinetic effects in high-T_i pedestals (QH-mode on DIII-D)

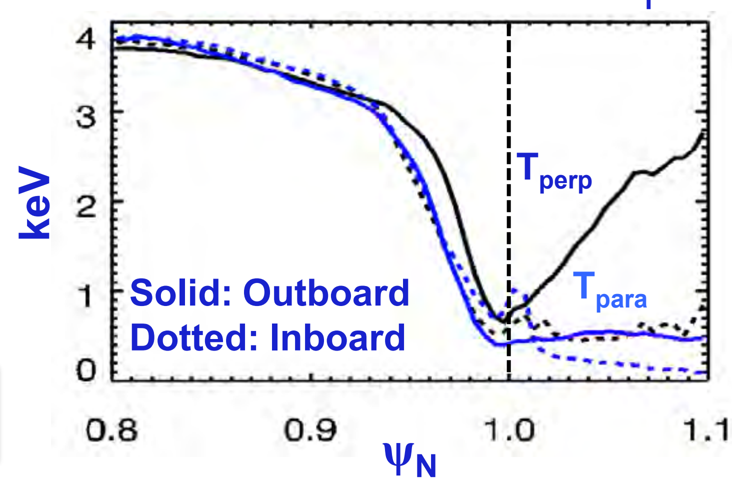
- Kinetic effects drive non-Maxwellian ion energy distributions in a high-T_i pedestal
  - Ion temperature anisotropy
  - $T_i > T_e$ in SOL
  - Increasing impurity T_i in SOL
  - Poloidal asymmetry in flows, temperatures and densities
- Improved interpretation of diagnostics modifies inferred pedestal pressure and transport
  - Important for equilibrium reconstructions, pedestal stability and transport calculations

APS-DPP 2013 invited talk on XGC0 kinetic neoclassical for DIII-D and NSTX – D. Battaglia, C-S Chang (PPPL)

Measurement: CER C^{+6} T_i

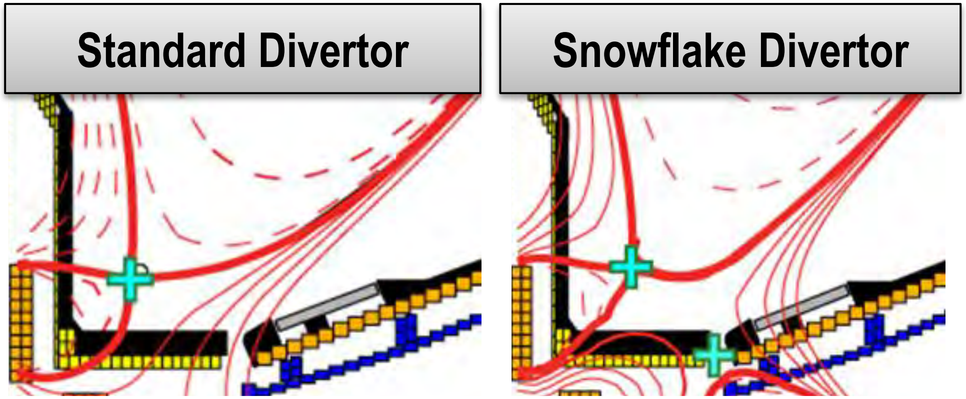


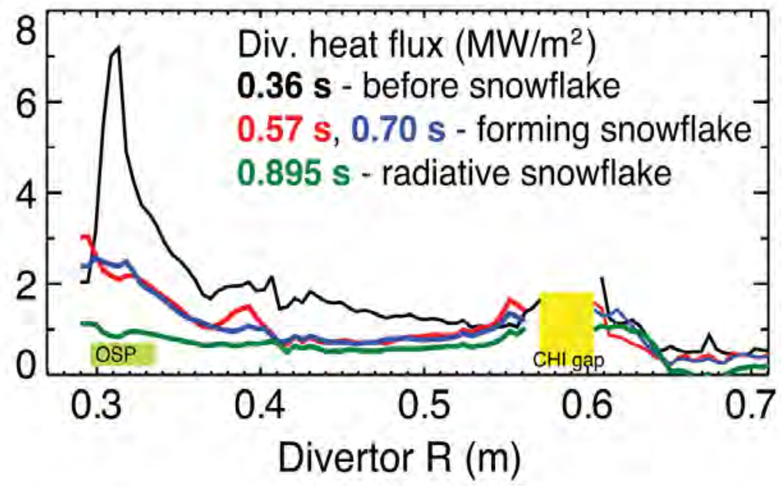
Simulation: XGC0 C^{+6} T_i



Snowflake divertor effective for heat flux mitigation

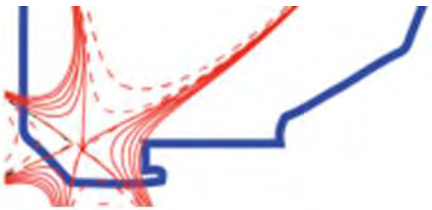
- NSTX: can reduce heat flux by 2-4 × via partial detachment
- Snowflake → additional x-point near primary x-point
  - NSTX: High flux expansion = 40-60 lowers incident $q_{\perp}$
  - Longer field-line-length promotes temperature drop, detachment



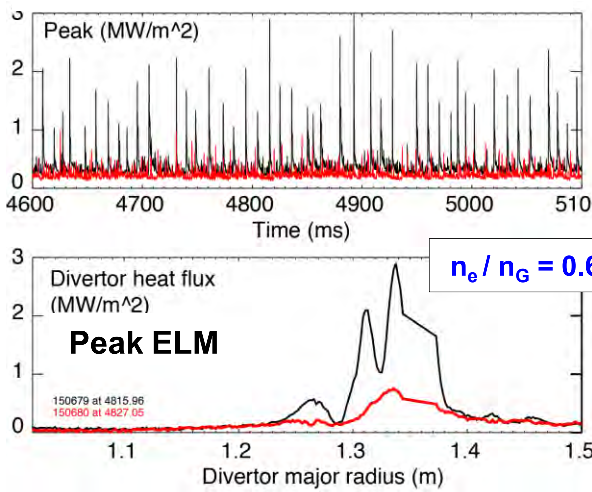


Developing snowflake and radiative detachment control on DIII-D in preparation for usage on NSTX-U

- Significant heat flux reduction between and during ELMs in DIII-D snowflake
- New expts scheduled for July
  - 1st tests of magnetic feedback control



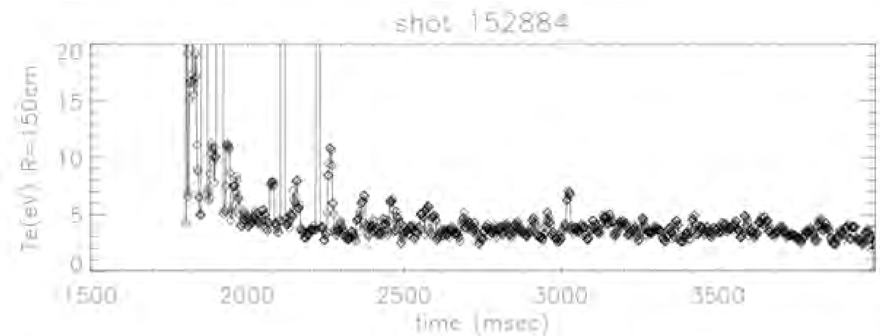
Detached - Standard **Snowflake**



$n_e / n_G = 0.60$

V. Soukhanovskii (LLNL)

- Real-time divertor radiation / detachment control developed, sustained detachment achieved



- Real-time diagnostics: bolometry, D_β, interferometry, Thomson (divertor, core, tangential)
- Actuators: D_2 and Ne gas puffing to obtain desired level of detachment and/or radiation.

E. Kolemen (PPPL)

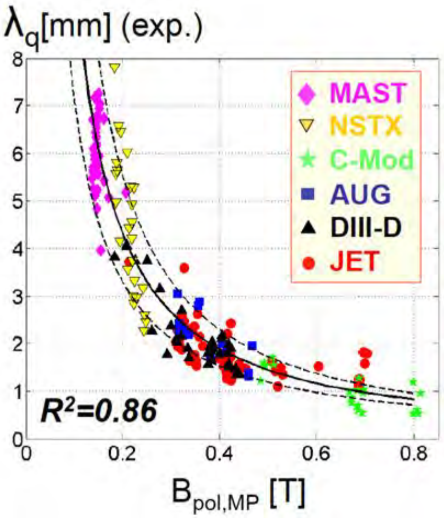
Boundary Physics (BP) 5 Year Goal:

Develop and understand integrated plasma exhaust solutions compatible with high core performance for FNSF and ITER

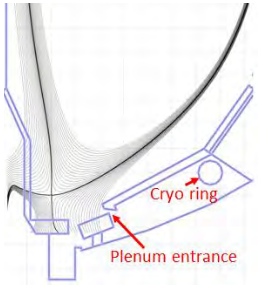
BP Thrusts:

1. Assess, optimize, control pedestal structure, transport, stability

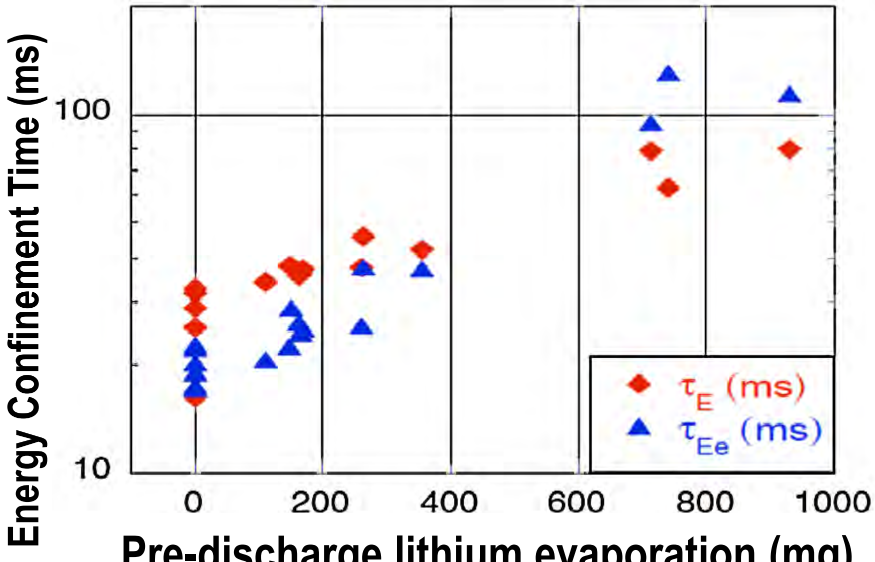
2. Assess and control divertor heat fluxes
   - Measure SOL widths at lower ν, higher B_T, I_P, P_{SOL}
     - Compare data to fluid and gyro-kinetic models
   - Assess, control, optimize snowflake divertor
   - Develop highly-radiating divertor w/ feedback control
   - Assess impact of high-Z tile row(s) on core impurities



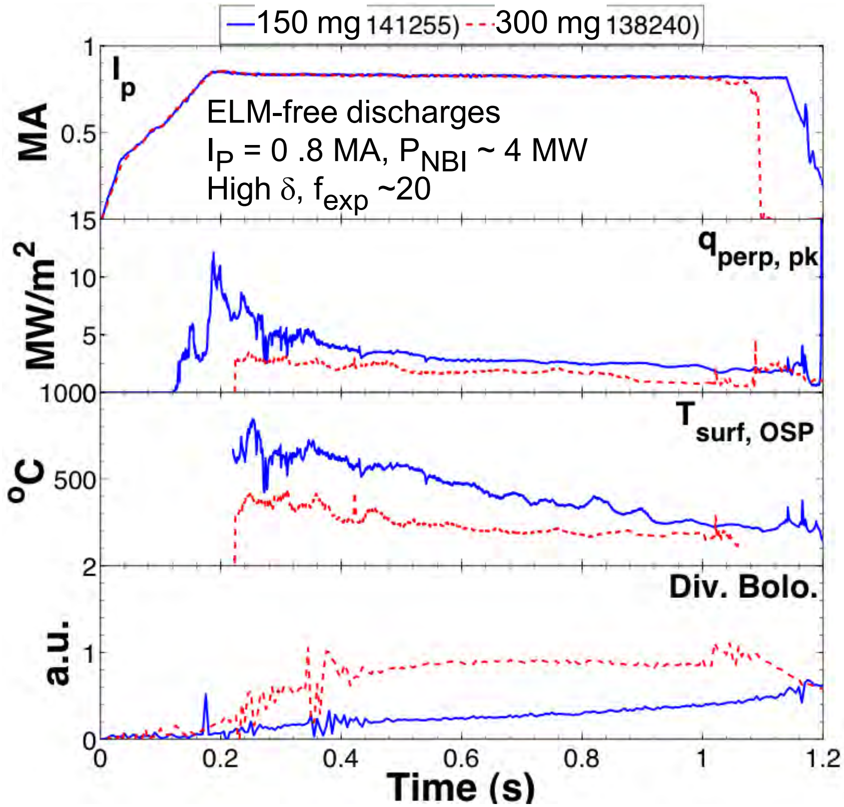
3. Establish and compare long-pulse particle control methods
   - Validate cryo-pump physics design, assess density control
   - Compare cryo to lithium coatings for n_e, impurity, ν^* control



Plasma confinement increases continuously with increasing lithium coatings; Li may also be means of heat flux mitigation



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



- Global parameters improve
  - H98(y,2) increases from ~0.9 → 1.3-1.4
  - No core Li accumulation
- ELM frequency declines to zero
- Edge transport declines
- High τ_E critical for FNSF, next-steps

What is τ_E upper bound?

- Increased Li deposition may be advantageous for power handling
  - Lower peak divertor heat flux and $T_{surface}$
  - Increased divertor radiation
- May require threshold Li level
- Motivates "vapor-shielding" research

Initiate comparative assessment of high-Z and liquid metal PFCs for long-pulse high-power-density next-step devices

MP Thrusts:

1. Understand Li surface-science at extended PFC operation
   - "Atoms to tokamaks" collaboration with PU
   - Materials Analysis Particle Probe (MAPP) (Purdue - J.P. Allain, 2010 ECRP) to identify in-situ between-shot surface composition (LTX→NSTX-U)

MAPP capabilities:

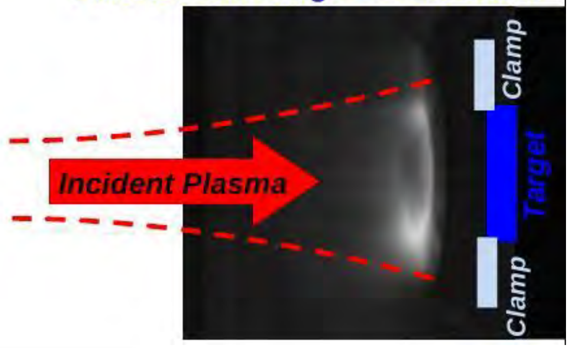
TDS LEISS
XPS DRS

Up to 4 samples exposed

2. Assess tokamak-induced material migration and evolution
   - QCMs, marker-tiles, MAPP + QCM for shot-to-shot analysis of migration

3. Establish the science of continuous vapor-shielding
   - Continue studies of Li vapor-shielding in linear plasma device Magnum-PSI
   - Extend Magnum results to NSTX-U

Fast-camera Image Li-I Emission



Magnum-PSI collaboration: M. Jaworski, T. Abrams (grad student) (PPPL)

- Lab-based R&D: flowing Li loops, capillary-restrained Li surfaces

Collaboration plans have been developed to utilize MIT expertise in boundary, RF, transport, disruptions on NSTX-U

Collaboration Topic from RoD	MIT Coordinators	MIT researchers	Research sub-topic and/or diagnostic scoping activity	NSTX-U research contacts and participating researchers
		B. LaBombard	Mirror Langmuir probe for high-f edge turbulence & transport	R. Maingi
		Design/Mech Engineer - Vieira		S. Zweben
		Electrical Engineer - Burke		R. Kaita
Diagnostics for Boundary Physics Research	Labombard, Terry	PLC/Computer Support		B. Stratton
				L. Roquemore
		J. Terry	Gas puff imaging + avalanche photo-diodes for SOL turbulence	M. Jaworski
				R. Goldston
		D. Whyte	Accelerator-based In-situ Materials Studies (AIMS) - paid by MIT	S. Gerhardt (ops impact)
		D. Whyte students		
		A. Hubbard	Analysis of existing NSTX pedestal datasets	A. Diallo, R. Maingi
		J. Hughes	Pedestal structure, transport, turbulence, stability, evolution	D. Battaglia, S. Kaye
Pedestal physics	Hubbard	S. Wolfe	L-H / H-L transition physics	T. Gray, J-W Ahn
			Search for I-modes, propose FY15 expts	J. Canik, R. Bell
			Relation between near-SOL pedestal gradients and SOL widths	
		S. Shiraiwa	Participate in design, construction, installation of ECH/EBW on NSTX-U	R. Wilson
ECH/EBW heating and current drive		G. Wallace	Participate in ECH/EBW experiments and analysis on NSTX-U	J. Hosea
	Wukitch	R. Parker	Design, construct and operate ECH/EBW diagnostics on NSTX-U	G. Taylor
		Design/Mech Eng. - Beck		N. Bertelli
		S. Wukitch	Improve performance of HHFW system	R. Wilson
	Wukitch	Y. Lin	Improve understanding of SOL rf wave propagation and power losses	J. Hosea
ICRF Activities				G. Taylor
				R. Perkins
		M. Greenwald	Scope options for laser blowoff system, X-ray crystal spectrometer (inversion	S. Kaye
			Develop analysis tools for NSTX data	W. Guttenfelder
				Y. Ren
		J. Rice	X-ray data analysis on NSTX-U	R. Maingi
			Wavelength calibration system	J.-K. Park
			Intrinsic rotation physics	W. Wang
		Student TBD	Student would start in NSE in Fall 2014, would work on data analysis, rotation	C.S. Chang
Core Transport, Turbulence and Diagnostics	Greenwald, White			L. Delgado
		J. Irby	Model/design 2.54 THz polarimeter system as enhancement to planned 288	B. Stratton
		Design/Mech Eng. - Murray		
		Student TBD	part FY14, full FY15	
		White	Analysis and modelling of high-k scattering, electron transport - paid by MIT	
		Student TBD	Student would start in NSE in Fall 2014, would work on high-k scattering, data	
		R. Granetz	Design/install foil bolometers and AXUV wall detectors for disruption MGI and	S. Gerhardt
			Test NSTX disruption warning algorithm on C-Mod data	L. Delgado
MHD and Disruption Physics	Granetz		Design halo current sensors for lower divertor plates	
			Collaborate w/L. Delgado on x-ray tomography of snakes, fishbones, etc.	
		S. Wolfe	Measurement and analysis of 3-D error fields	

Summary: NSTX-U 5 year plan goals embody world-leading research in support of ITER and FNSF

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

- **NSTX-U will be ST leader, complement AT approach (DIII-D)**

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

- **Low ν^* + high β + turbulence diagnostics unique in world**

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

- **Unique helicity injection + RF + NBI start-up/ramp-up techniques**

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

- **With MAST Super-X, STs leading development of novel divertors**

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

- **Aiming to lead development of replenishable / liquid metal PFCs**

Agenda

- NSTX Upgrade progress report – R. Strykowsky
  - 20 minutes

- 5 year plan overview - including FY13 collaboration highlights relevant to 5 year plan – J. Menard
  - 55 minutes

- NSTX-U facility and diagnostic highlights – M. Ono
  - 45 minutes

Talk Outline

- NSTX-U Operational Preparation Status
- NSTX-U Facility / Diagnostic Five Year Plans
- Summary

Successful Implementation of FY13 Milestones

Mainly Through Data Analyses, Theory/Modeling, and Collaborations

FY 2013 NSTX-U Facility Joint Research Milestone

Conduct experiments on major fusion facilities, to evaluate stationary enhanced confinement regimes without large Edge Localized Modes (ELMs), and to improve understanding of the underlying physical mechanisms that allow increased edge particle transport while maintaining a strong thermal transport barrier. … Candidate regimes and techniques have been pioneered by each of the three major US facilities (C-Mod, D3D and NSTX). … Exploiting the complementary parameters and tools of the devices, joint teams will aim to more closely approach key dimensionless parameters of ITER, and to identify correlations between edge fluctuations and transport. The role of rotation will be investigated. The research will strengthen the basis for extrapolation of stationary high confinement regimes to ITER and other future fusion facilities, for which avoidance of large ELMs is a critical issue. Stefan Gerhardt is coordinating the FY 2013 JRT and the Q3 report has been submitted.

FY 2013 NSTX-U Milestones

Research	Milestone Description	Baseline	Forecast
R(13-1)	Perform integrated physics and optical design of new high-k_θ FIR system	Sep 13	Sep 13
R(13-2)	Investigate the relationship between lithium-conditioned surface composition and plasma behavior	Sep 13	Sep 13
R(13-3)	Perform physics design of ECH and EBW system for plasma start-up and current drive in advanced scenarios	Sep 13	Sep 13
R(13-4)	Identify disruption precursors and disruption mitigation & avoidance techniques for NSTX-U and ITER	Sep 13	Sep 13

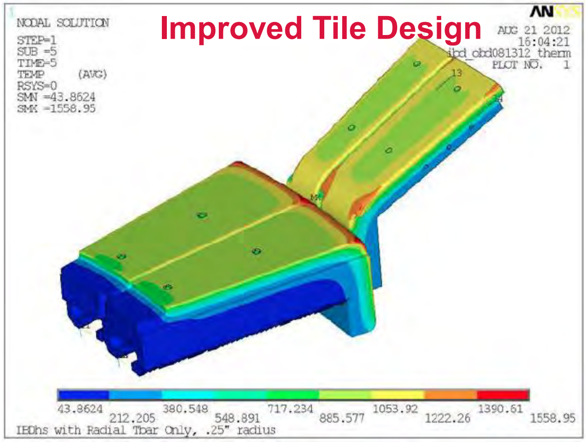
Facility	Milestone Description	Baseline	Forecast
F(13-1)	Develop conceptual designs for high priority facility enhancements for post upgrade operations	Sep 13	Sep 13

Diagnostics	Milestone Description	Baseline	Forecast
D(13-1)	Develop conceptual designs for high priority diagnostic enhancements for post upgrade operations	Sep 13	Sep 13

Engineering and Research Operations Activities
In Preparation for the NSTX-U Operations

- **Improving the PFC geometry in the vicinity of the CHI gap to protect the vessel and coils due to ~ 10x higher divertor heat loads**

New gap overhung tiles to provides necessary protection. Gap tiles being fabricated by the vendor.



- **Replacing electronics that control rectifiers - The new Firing Generator (FG) will deliver firing pulses with greater resolution, precision, and repeatability, critical for the new 8-parallel, 130kA TF system configuration.**

More than half of the 68 FG production units have now undergone power testing in rectifiers, and test results for all units have been identical, giving us confidence that we can rely on bench testing for the remaining ones. Power testing will continue to confirm current balancing on multiple rectifiers. Target completion date of Nov. 2013.

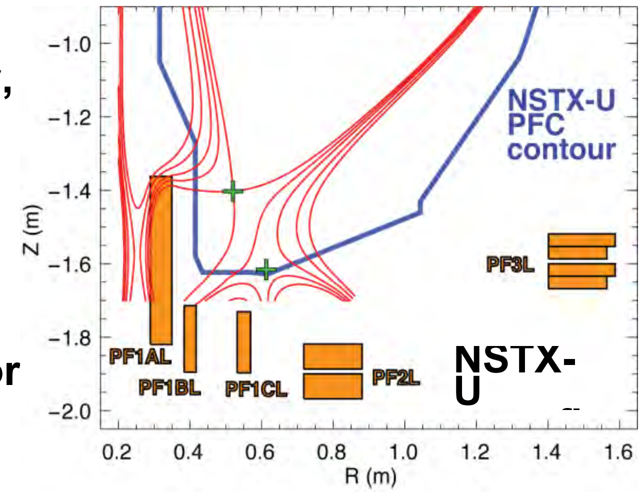
Transrex AC/DC Convertors

NSTX-U Plasma Control System Upgrade

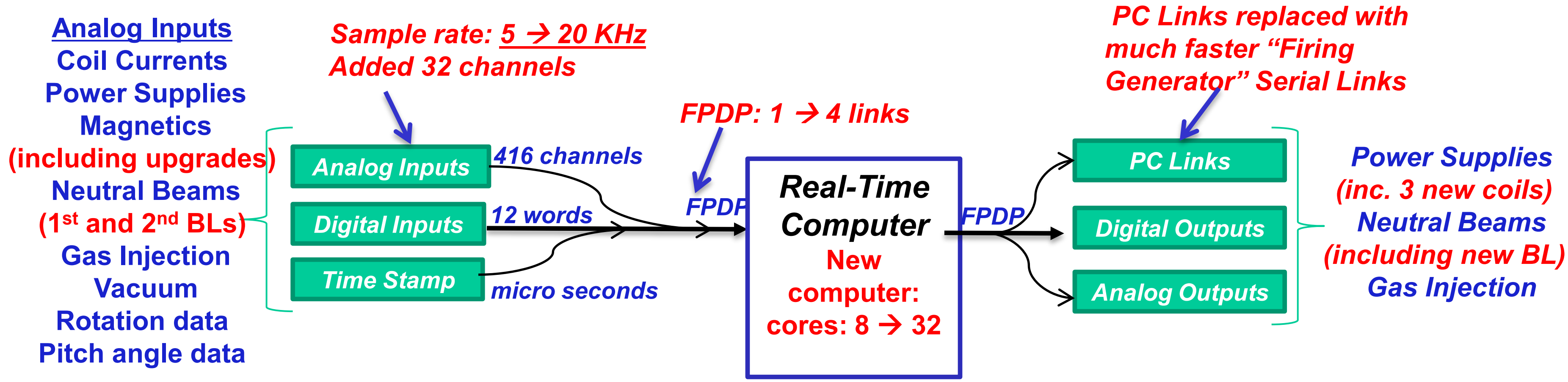
Enables real time up-down symmetric divertor control

NSTX-U PF Coil Power System Upgrade

- **The first-year power supply capabilities of NSTX-Upgrade will yield considerable experimental flexibility, via up-down symmetric PF-1C coils**
- **By powering upper and lower PF-1A & PF-1C coils, it will be possible to generate up-down symmetric snowflake divertors**
- **The new configuration should provide better control for the CHI absorber region.**

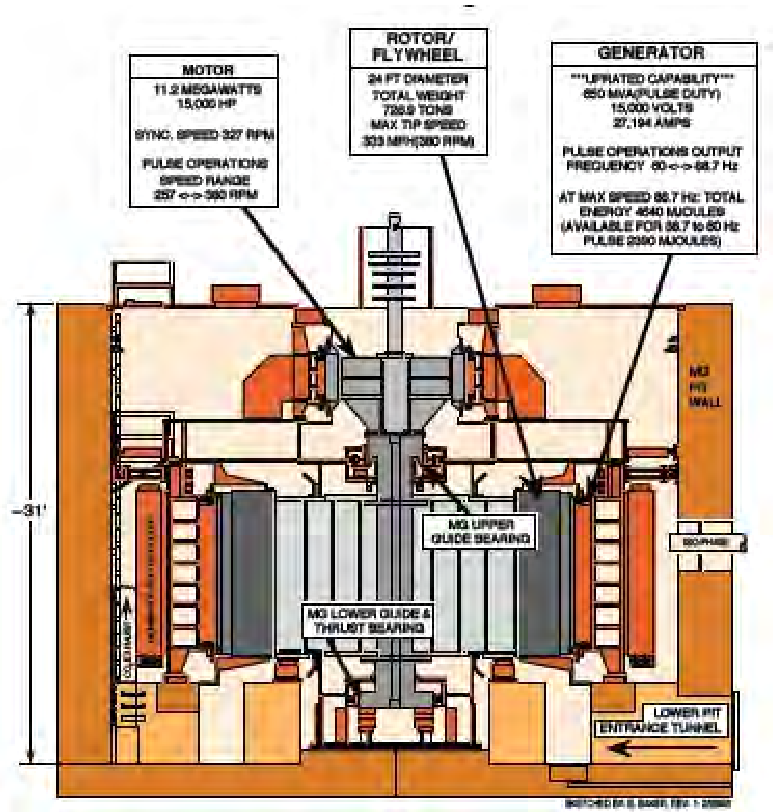


Plasma Control System Upgrade



Repair of the Motor Generator
(MG#1)

- In 2004, Magnetic Particle Inspections identified cracking in the weld fillet of multiple joints between the radial arms of MG#1. Cracks were in primary load paths, taking that set out of service. MG#2 is in limited operations (run and monitor at reduced parameters) with cracks in "stiffener" welds intended to limit elastic deformation (not in primary load paths).
  - Over 250" of welds in 19 rotor spider joints will be ground out and replaced to restore MG#1 to its original design configuration.
  - A jacking system has been engineered to relieve all loads on the rotor assembly during the repair.
  - PPPL and GE engineering collaborated on the detailed repair procedure (D/NSTX-RP-MG-07).



Status: Target completion date of Jan. 2014

A Statement of Work to perform the scope described in the repair procedure has been reviewed and approved.

Fixed-price proposals for the weld repairs have been received. A WAF capturing all project costs (PPPL and Sub-contractor) is being generated.

A draft Project Management Plan has been developed.

NSTX-U diagnostics to be installed during first 2 years

Half of NSTX-U Diagnostics Are Led by Collaborators

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 Microwave high-k scattering
Beam Emission Spectroscopy (48 ch)
Microwave Reflectometer,
Microwave Polarimeter
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

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

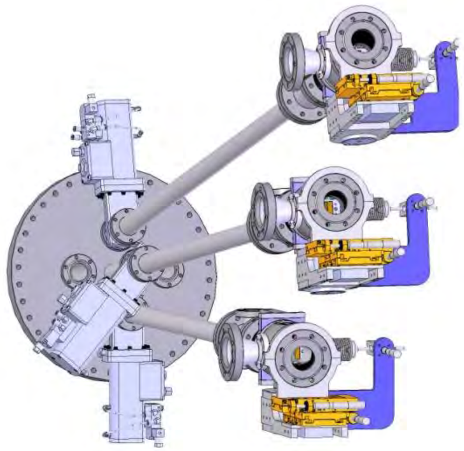
FIReTIP interferometer
Fast visible cameras
Visible bremsstrahlung radiometer
Visible and UV survey spectrometers
VUV transmission grating spectrometer
Visible filterscopes (hydrogen & impurity lines)
Wall coupon analysis

New capability, Enhanced capability

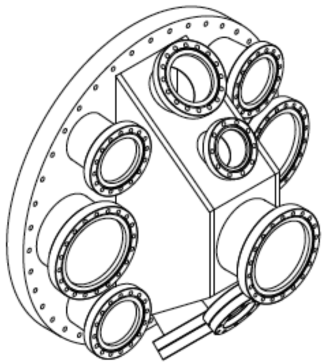
New Port Covers Have Been Designed For Bays E, I, J, and L

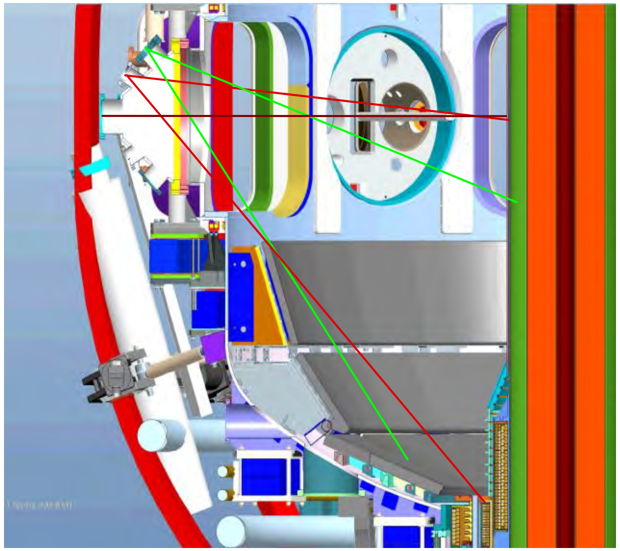
Detailed Design to Accommodate Enhanced NSTX-U Diagnostic Access Needs

Bay E Supports 3
UV Spectrometers (LoWEUS, XEUS, MonaLisa) and MIG1

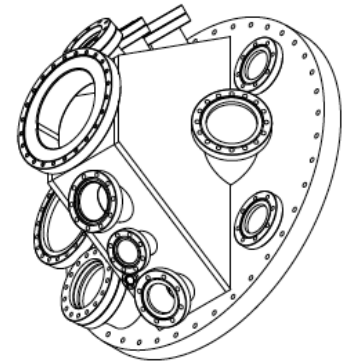


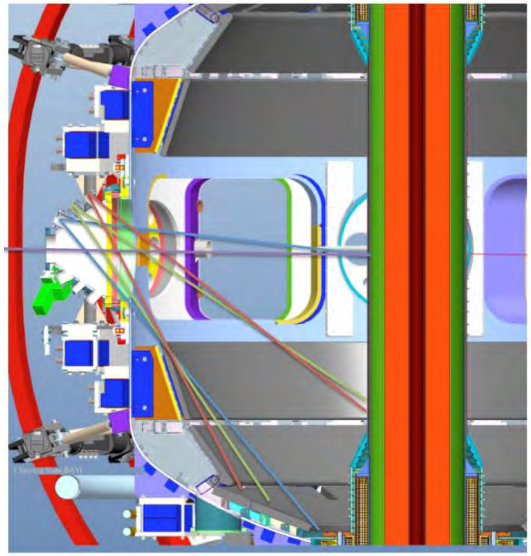
Bay J Supports
IR and Visible Cameras, UT-K and Divertor Spectrometers, Upward LITER, UCLA Reflectometer and Polarimeter, LBO, RF Probe.





Bay I Supports
XCS, TGS, IR & Visible Cameras, SSNPA, SGI, 1D CCD & EIES, Microwave Imaging, QMB, Bolometers
Design is very close to done.



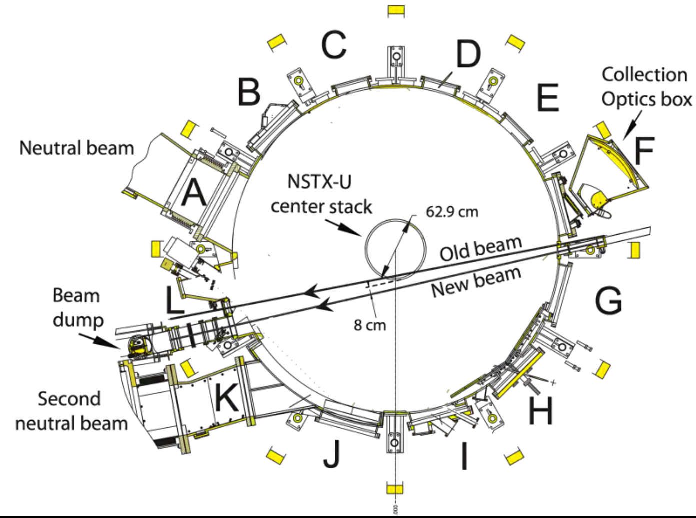


Bay-L Cap (not shown) Supports
MPTS exit window, High-k exit, plasma TV+GPI view, SSNPA, spectroscopy & CHERS view, GDC feedthroughs, magnetics feedthroughs.

Multi-Point Thomson Scattering Upgrade and Materials Analysis and Particle Probe – MAPP

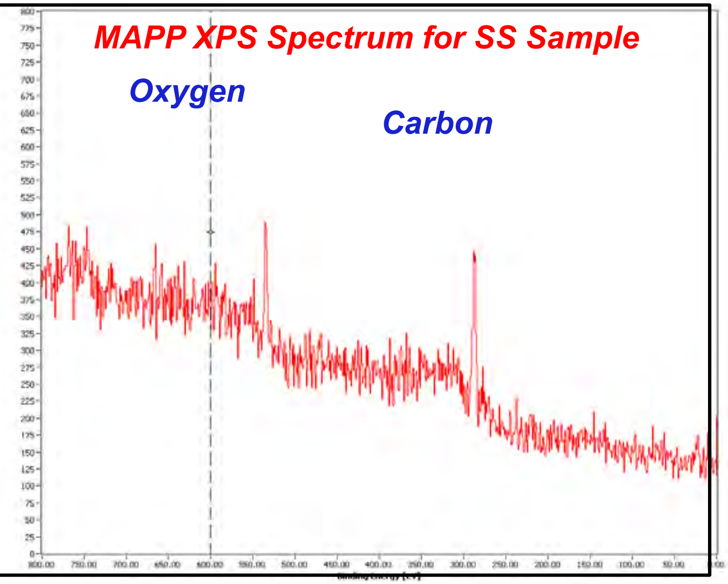
- Modification of the MPTS system is needed to accommodate the larger diameter NSTX-U Center Stack - Re-aim the laser beam, the light collection optics, redesign the beam dump, and calibration probe to be ready for the first plasma.
- Ahmed Diallo recently received an Early Career Research Program award - will install a fast rep rate (10-15 kHz) burst mode (5 ms) third laser for studies of ELMs and other fast phenomena in FY15.

MPTS Midplane Cross Section



- MAPP to relate PFC surface conditions and plasma behavior in "real time".
- PFC analysis after run is difficult to relate to plasma behavior.
- MAPP refurbished at Purdue and baseline data obtained at PPPL/LTX
- X-ray photoelectron spectroscopy (XPS) provides information on elemental composition of PFC's.

MAPP XPS Spectrum for SS Sample



Transition into operations- planning underway

NSTX-U Start-up Process Similar to NSTX

NSTX-U ISTP, Commissioning, and Startup will follow the same process as NSTX initial commissioning and startup from February 1999.

Pre-operational test of subsystems (PTP'S) → ***Activity Certification Committee (ACC) review*** → ***DOE Readiness Assessments (RA)*** → ***Integrated system test procedure (ISTP) (per OP-NSTX-02 rev 14)*** → ***CD-4 Demonstrated Performance***

Key Operations Milestones

- ***Begin Diagnostic Installation – August 1st, 2013***
- ***Complete in-vessel construction work October 1st 2013.***
- ***Complete Diagnostic installation & calibration – December 1st, 2013***
- ***Rough Pump down – January 1st, 2014***

NSTX-U Team Development of XPs for FY 2015 run → ***Shake-down*** → ***Commence Operations and run XP's***

NSTX-U Operations Team Similar to NSTX

Plans to Rapidly Recover Physics Operations Capabilities

ISTP:
(Integrated Systems Test Procedure)
Establishes facility in state of readiness for operations.

Plasma Operations with:
$I_p \leq 1.0$ MA, $B_T \leq 0.5$
Develop:
Breakdown and current ramp scenarios
Shape & position control
Reliable H-mode
Diagnostic operations

Continue to add diagnostic & control capabilities while initiating physics experiments.

$I_p \leq 1.5\text{-}1.6$ MA
$B_T \leq 0.75\text{-}0.8$

July-Sept. 2014

ISTP-1 & CD-4 Prep	MPTS Calibrations, Bake Out, CD-4	Operations Commissioning	Phys. Ops	ISTP-2	Phys. Ops

~ 2-3 Months

Attempt 50 kA CD-4 plasma before bake-out. If water in PFCs prevents success, then repeat after bake-out.

ISTP-2
Required to increase the field and current for later research phase

Formulating Strategy Toward Full NSTX-U Parameters

After CD-4, the plasma operation could enter quickly into new regimes

	NSTX (Max.)	Year 1 NSTX-U Operations (2015)	Year 2 NSTX-U Operations (2016)	Year 3 NSTX-U Operations (2017)	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

- 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

10 year plan tools with 5YP incremental funding

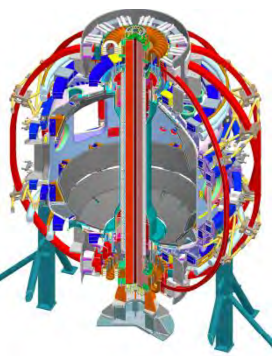
1.1 × (FY2012 + 2.5% inflation)

2014	2015	2016	2017	2018	2019	2020	2021	2022	2023

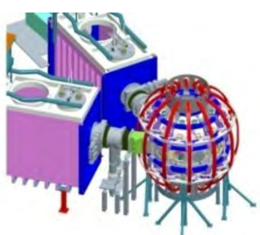
Upgrade Outage | 1.5 → 2 MA, 1s → 5s | Metallic PFCs, 5s → 10-20s

Run Weeks: 20, 16, 16, 20, 22, 6, 18, 22, 22

New center-stack



2nd NBI



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

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson
- Upper divertor cryo-pump

Materials and PFCs
- High-Z tile row on lower OBD
- High-Z first-wall + lower OBD tiles
- High-Z PFC diagnostics
- All high-Z PFCs
- Hot high-Z FW PFCs using bake-out system

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

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

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

Waves and Energetic Particles
- 1 coil AE antenna
- 4 coil AE antenna
- HHFW limiter upgrade
- HHFW straps to excite EHO
- Charged fusion product, neutron-collimator
- High-power AE antenna

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

Inform U.S. next-step conceptual design to optimize: aspect ratio, divertor, and PFCs

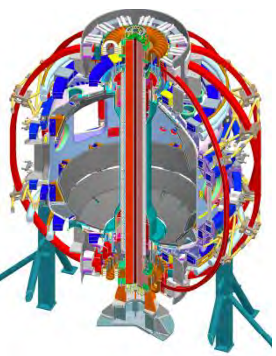
5 year plan tools with 5YP base funding

(FY2012 + 2.5% inflation)

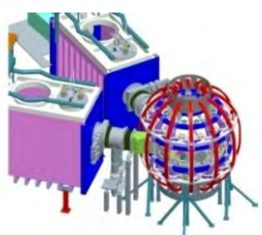
2014	2015	2016	2017	2018
Upgrade Outage	1.5 → 2 MA, 1s → 5s			

Run Weeks: 16 14 14 16

New center-stack



2nd NBI



Cryo-pump, high-Z tile row on cryo-baffle, and partial NCC would be installed in-vessel during ~1 year outage between FY2016 and FY2017

NSTX-U would operate 1st half of FY2016 and 2nd half of FY2017

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

Boundary Physics
- Lower divertor cryo-pump
- Divertor Thomson

Materials and PFCs
- High-Z tile row on lower OBD
- High-Z tile row on cryo-baffle
- High-Z PFC diagnostics
- All high-Z PFCs

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

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

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

Waves and Energetic Particles
- HHFW limiter upgrade
- HHFW straps to excite EHO
- 1 coil AE antenna
- 4 coil AE antenna
- Charged fusion product, neutron-collimator

Scenarios and Control
- Establish control of:
- Snowflake $\bar{n}_e$ Rotation
- q_{min} Divertor P_{rad}
- Control integration, optimization

Legend:
- Delayed scope
- Reduced scope
- Deferred scope

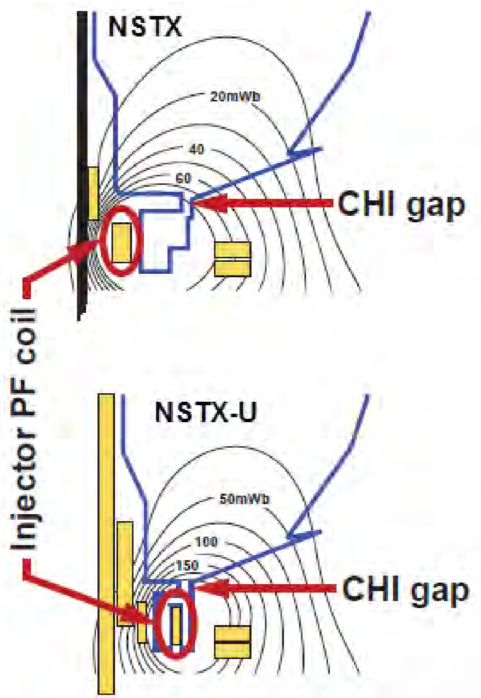
Solenoid-free Start-up

High priority goal for NSTX-U in support of FNSF

CHI Start-Up

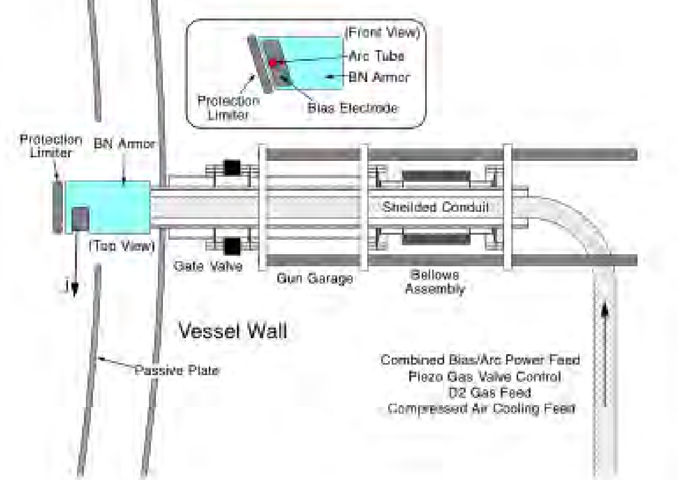
- Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX
- NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation

U. Washington



PEGASUS Point Source

PEGASUS Plasma Gun



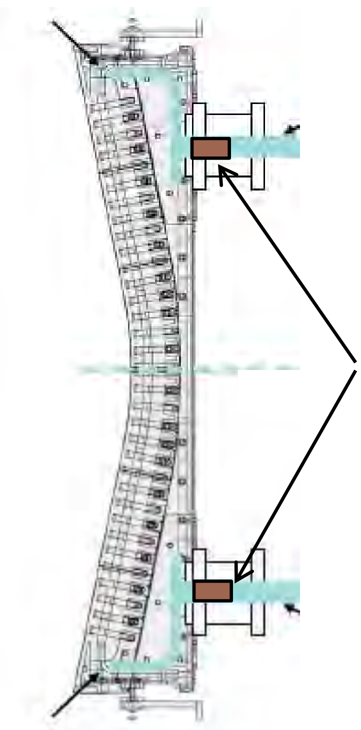
U. Wisconsin

FY 2013-14 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 current gun for the NSTX-U will be developed utilizing the PEGASUS facility in collaboration with University of Wisconsin.

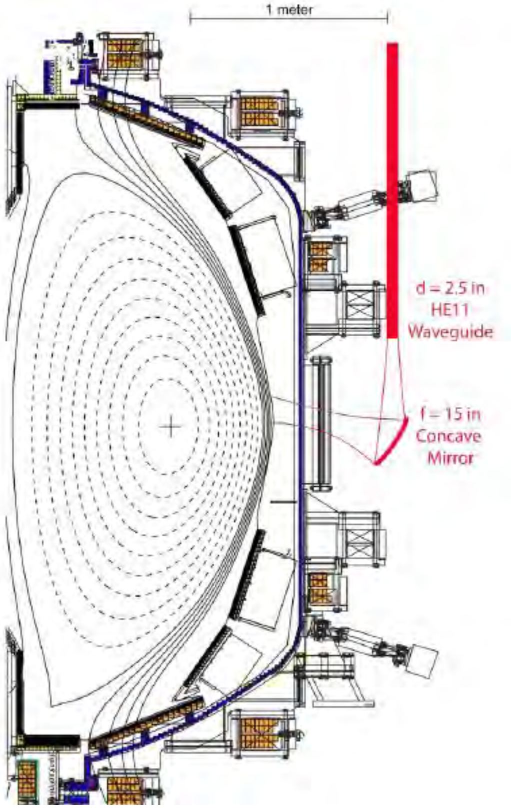
Strengthen HHFW Antenna Feeds for Disruption Load
A MW-Class 28 GHz ECH System for Non-Inductive Operation

New Compliant Antenna Feeds
Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions



C-Mod antenna electroformed compliant section

28 GHz, 1.5 MW Tsukuba Gyrotron



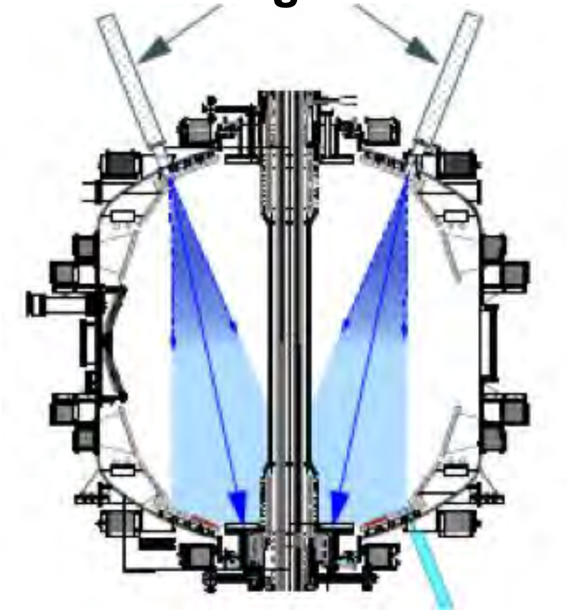
28 GHz ECH/EBWH waveguide and mirror concept

Successful CDR conducted, prototype feeds being procured.
Feeds to be tested in the RF test-stand before FDR, installation in spring 2014.

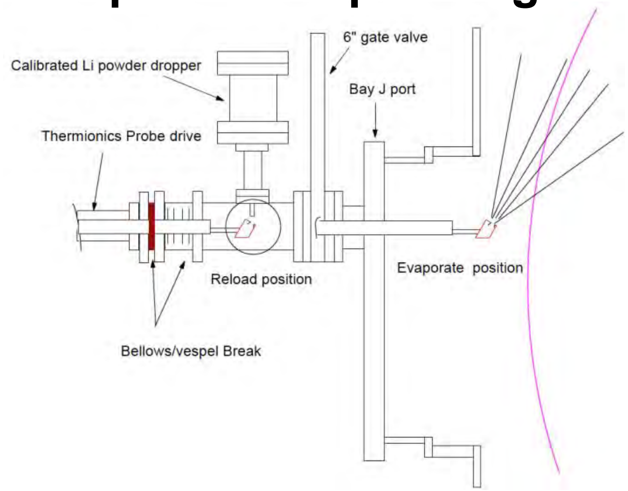
- **FY 2013/15 – Start MW-class ECH/EBW system conceptual design for non-inductive operations (MOU with Tsukuba University)**

NSTX-U Lithium Capability During Initial Two Years
Lithium Evaporators and Granular Injector

Existing LITERS



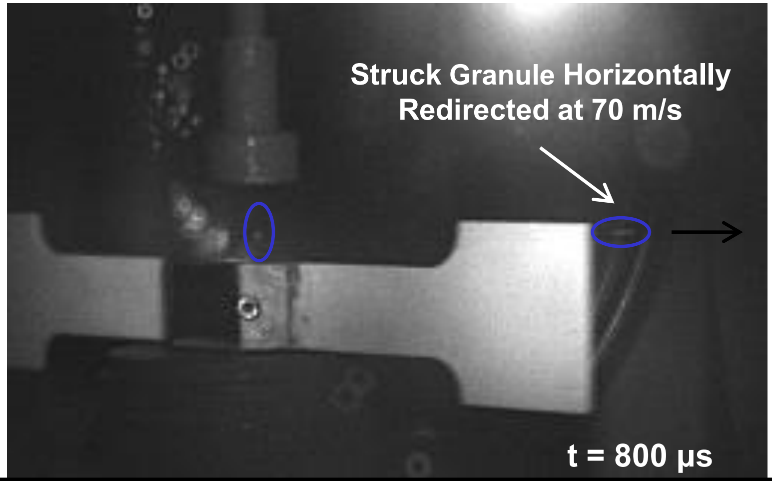
New Upward Evaporating LITER

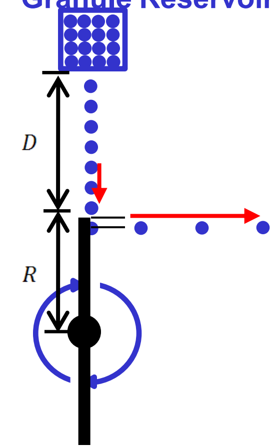


- Upward Evaporating LITER to increase Li coverage for increased plasma performance

NSTX-U lithium granular injector for ELM pacing

- High frequency ELM pacing with a relatively simple tool.
- ELM pacing successfully demonstrated on EAST (D. Mansfield, IAEA 2012)

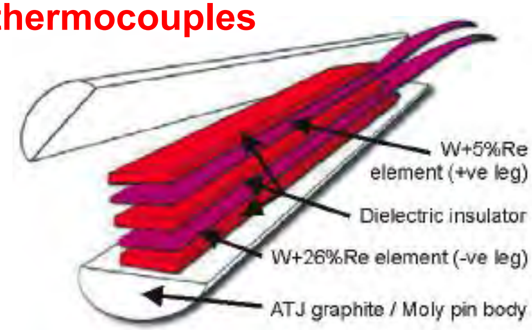




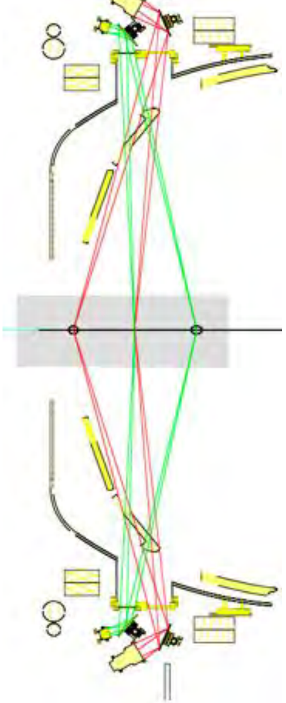
Baseline Capability for PMI Research

Supporting divertor and lithium research

Divertor fast eroding thermocouples



Lithium CHERS

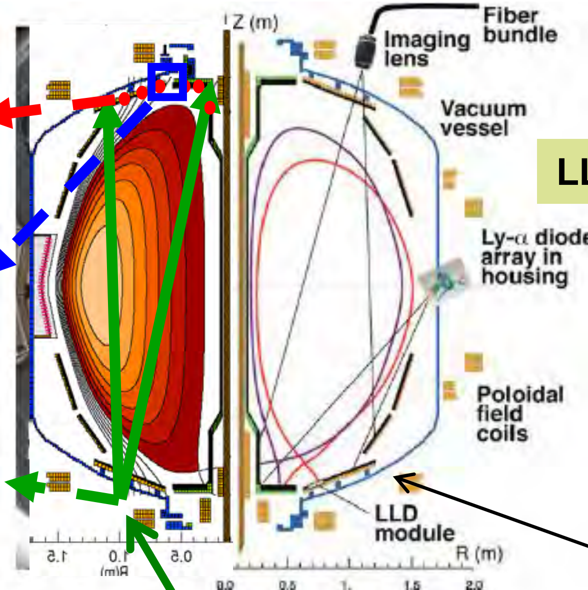


ORNL

Divertor fast pressure gauges

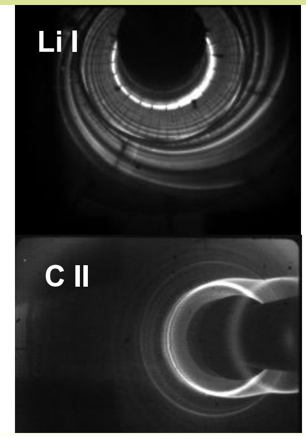
Divertor Imaging Spectrometer

LLNL

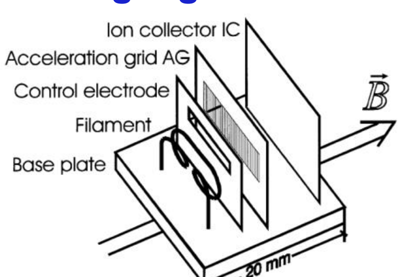


Two fast 2D visible and IR cameras with full divertor coverage

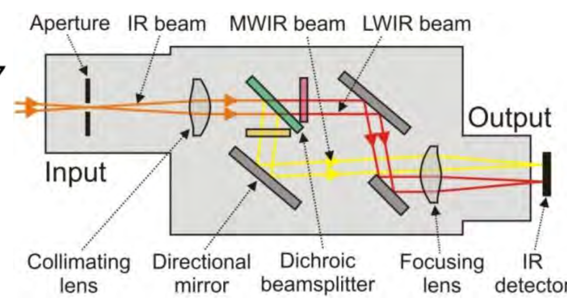
LLNL, ORNL, UT-K

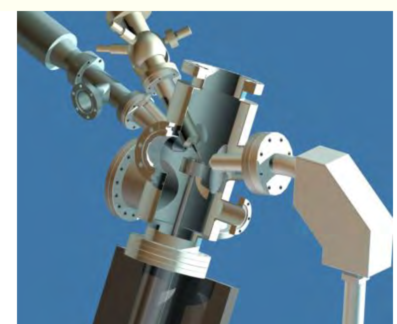


MAPP probe for between-shots surface analysis



Dual-band fast IR Camera



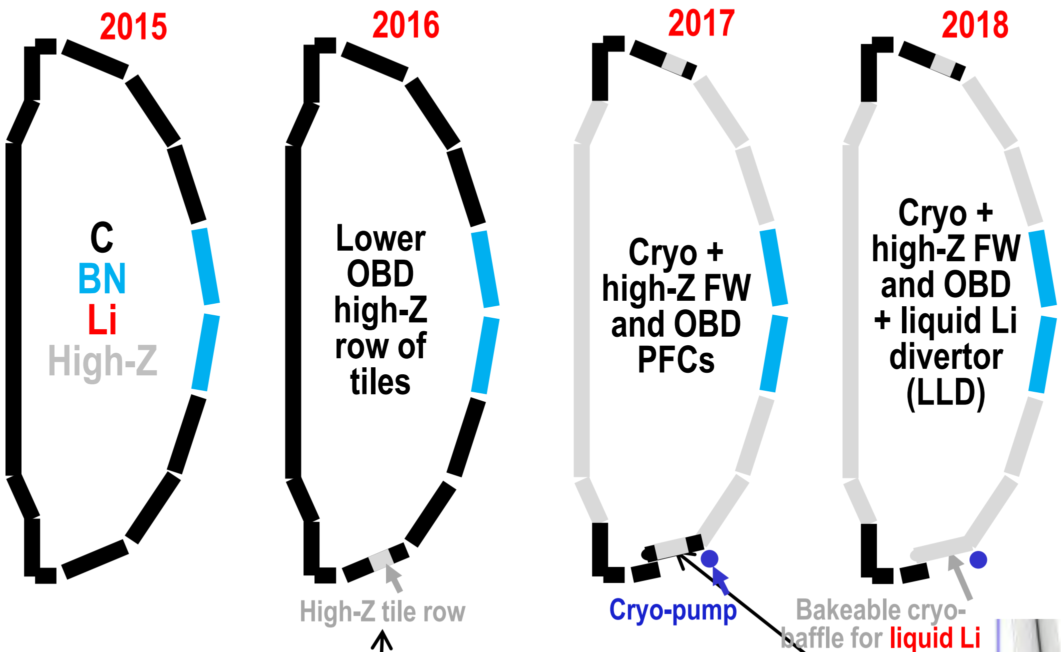


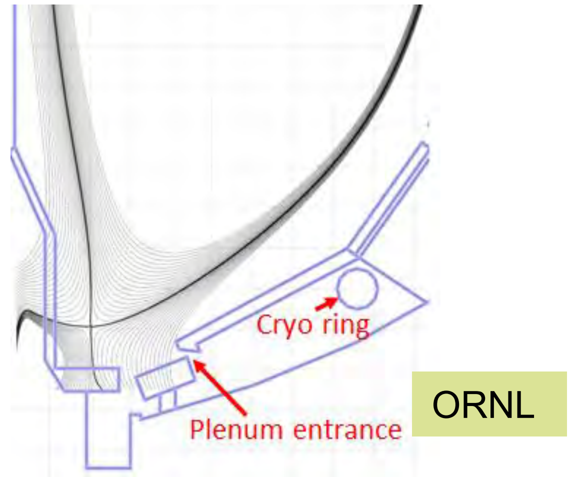
Purdue U.

(see back-up slides # 53 and 54)

Boundary Facility Capability Evolution

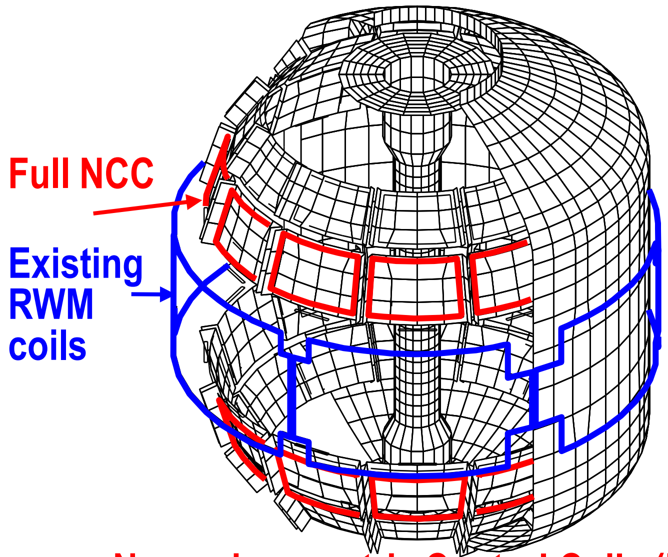
NSTX-U will have very high divertor heat flux capability of ~ 40 MW/m^2





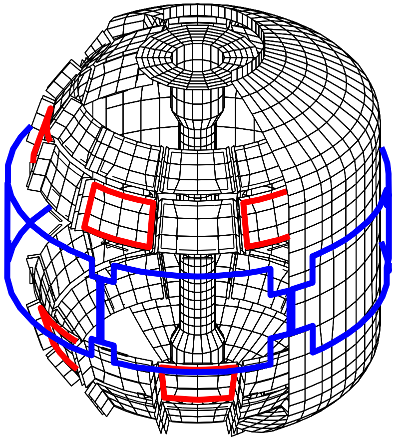
New MHD and Plasma Control Tools for NSTX-U

Sustain β_N and Understand MHD Behavior Near Ideal Limit



Non-axisymmetric Control Coils (NCC)

Partial NCC option (2 x 6 odd parity)

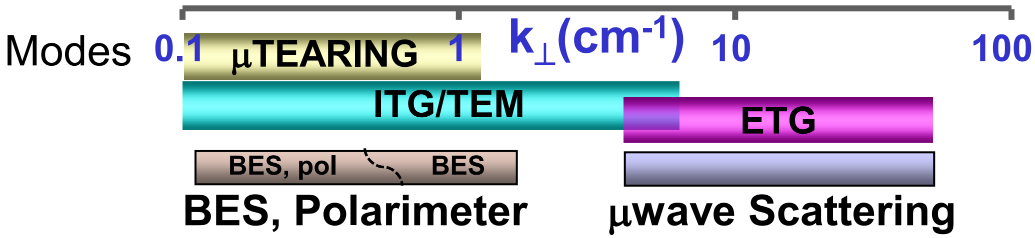


Columbia U., GA

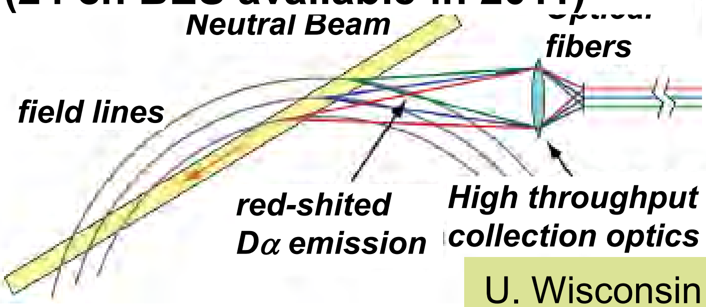
- NCC can provide expanded RWM, NTV, RMP, and EF physics studies with more flexible field spectrum (n ≤ 6, or n ≤ 3 depending on set).
- 2nd 3-channel Switching Power Amplifier (SPA) commissioned in July 2011 to power 6 independent currents in existing midplane RWM and NCC coils.
- An extended MHD sensor set to measure theoretically predicted poloidal mode structure and to improve mode control.
- A Real-Time Velocity (RTV) diagnostic in a new plasma rotation control system for active instability avoidance by controlling rotation profile.
- Multi-poloidal location massive gas injector system will be implemented.

Transport and Turbulence

BES together with high-k to provide comprehensive turbulence diagnostic



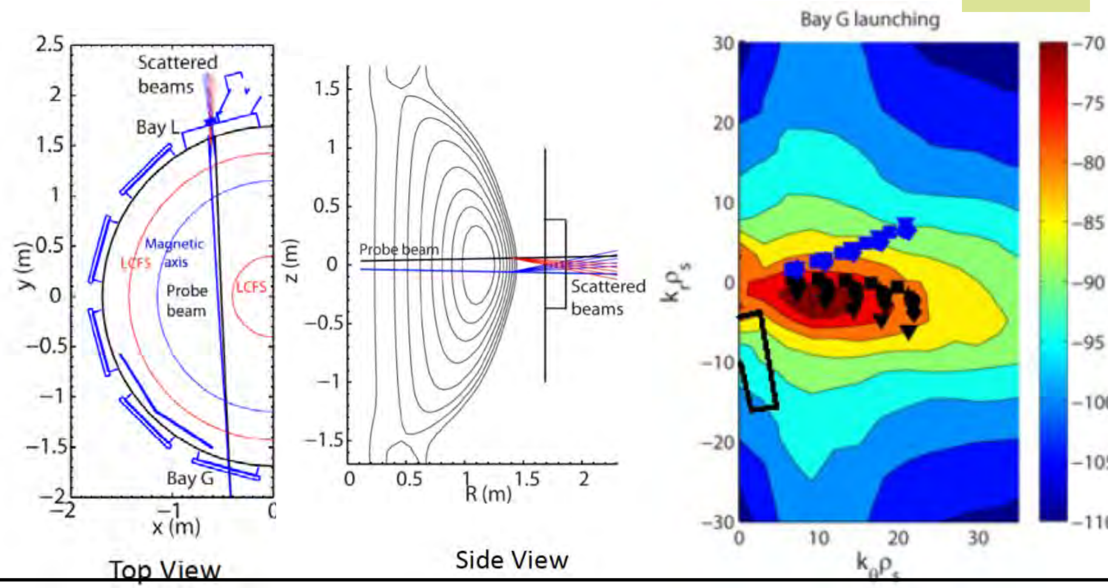
48 ch BES available for NSTX-U
(24 ch BES available in 2011)



U. Wisconsin

New high-k scattering system for allowing 2-D k spectrum

UCD



A 288 GHz polarimetry system for magnetic fluctuation measurements is being tested on DIII-D.

UCLA

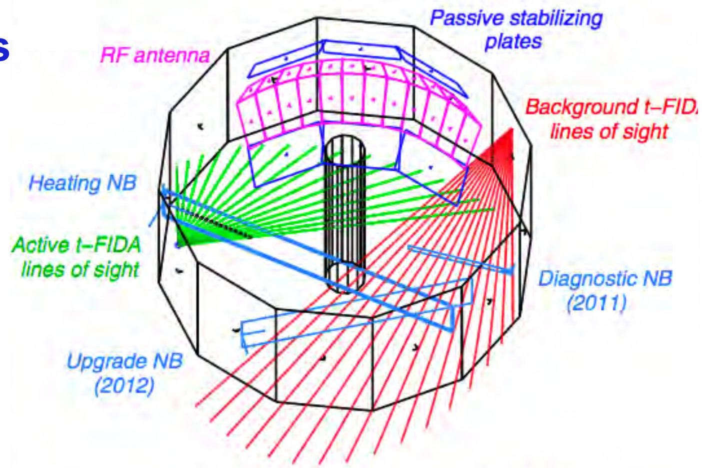
Energetic Particle Research Capabilities
For NBI fast ion transport and current drive physics

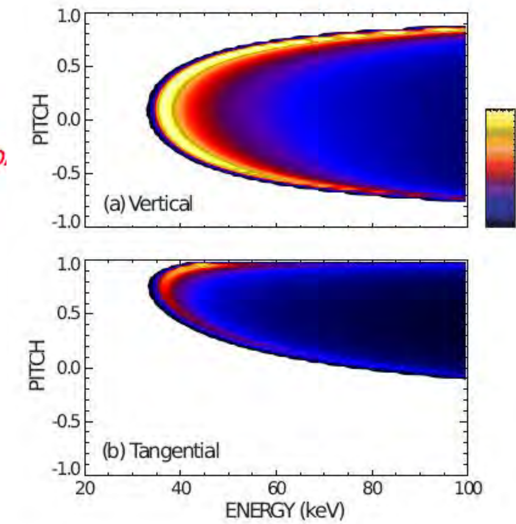
Fast Ion D-Alpha Diagnostics

- Vertical FIDA system measures trapped or barely passing (co-going) particles.
- New tangential FIDA system measures co-passing fast ions
- Both FIDA systems have time resolution of 10 ms, spatial resolution ≈ 5 cm and energy resolution ≈ 10 keV.

UCI

FIDA Views





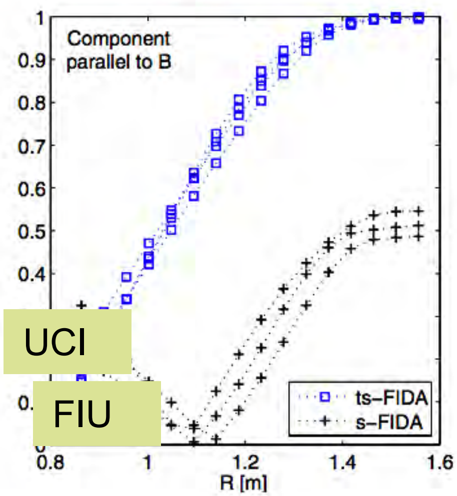
FY 2013 - 14 Energetic Partic... Design and Diagnostic Upgr...

Solid State-NPA enhanceme...

Charged Fusion Product Ar...

Proto-type active TAE anter...

(b)



UCI

FIU

5-turn radial active TAE antenna installed in 2011

NSTX Five Year Plan Budget Summary ($M)

FY 2014-15: transition years from construction to operation

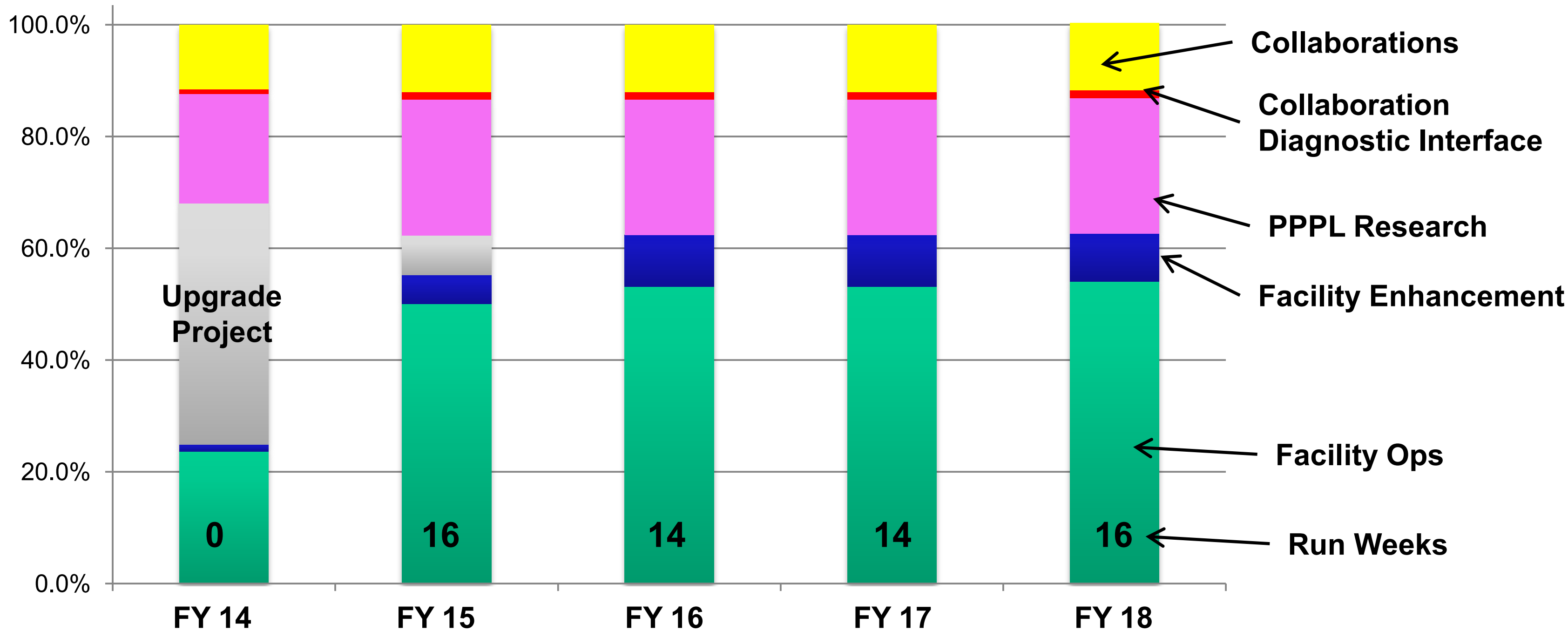
	FY14		FY15		FY16		FY17		FY18	
Budget Cases	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**
Run Weeks	0	0	16	4	14	2	14	2	16	4
Facility Ops	$12.7		$26.6	$1.0	$29.0	$0.5	$29.7	$0.5	$30.9	$1.0
Facility Enhancements	$0.7	$4.2	$2.8	$2.3	$5.0	$2.8	$5.1	$3.0	$4.9	$2.5
NSTX-U	$23.2		$3.8							
Facility Total	**$36.6**	**$4.2**	**$33.1**	**$3.3**	**$34.0**	**$3.3**	**$34.9**	**$3.5**	**$35.7**	**$3.5**
PPPL Research	$10.5		$12.9	$0.9	$13.2	$0.9	$13.5	$0.9	$13.9	$0.9
Collab Interface	$0.5	$0.5	$0.7	$0.5	$0.7	$0.5	$0.8	$0.5	$0.8	$0.5
Collaborators	$6.2	$0.6	$6.4	$0.6	$6.6	$0.7	$6.7	$0.7	$6.9	$0.7
Science Total	**$17.2**	**$1.1**	**$20.0**	**$2.0**	**$20.5**	**$2.1**	**$21.0**	**$2.1**	**$21.6**	**$2.2**
NSTX-U Total	**$53.8**	**$5.3**	**$53.2**	**$5.3**	**$54.5**	**$5.4**	**$55.9**	**$5.6**	**$57.3**	**$5.7**

- **Research and Operations team budget for NSTX-U is similar to that of NSTX FTEs of FY 2010 level.**
- **For FY 15 and beyond, the budget facility operations and PPPL/Collaboration research are based on similar operations and research staff coverage to NSTX.**
- **Base funding enables preparation and operation of NSTX-U while completing the Upgrade Project on schedule.**
- **Significant post upgrade facility/diagnostic enhancements can only start in FY 2016.**
- **Incremental scenario will enable full NSTX-U operation and timely implementation of the five year plan major facility and diagnostic enhancements.**

Base NSTX-U Five Year Plan Budget Summary

Base DOE Guidance Budget – Inflation adjusted flat FY 2012 budget

- **FY12 budget + 2.5% inflation**



- **In FY 14-15, the Upgrade Project needs to be completed.**
- **In FY 14-15, only modest budget is available for 5 year plan long lead facility enhancements (e.g., ECH, Cryo-pump, and NCC).**
- **FY 14-15 incremental budget is therefore particularly critical to start timely design and procurements for the long-lead facility enhancements.**

NSTX-U Operation Preparation Well Underway
Exciting Opportunities and Challenges Ahead

- **NSTX upgrade outage activities are progressing well**
  - Diagnostics were stored and secured for the upgrade activities. Collaborator diagnostics are being refurbished and enhanced.
  - Researchers are working productively on data analysis, collaboration, next five year plan and preparation for the NSTX-U operation.
  - NSTX operations technical staff were shifted to the Upgrade Project tasks in FY 2012 – 13. They will be shifted back to the NSTX-U operational preparation in FY 2014 as the Upgrade Project scopes are completed.
  - NSTX Upgrade Project is thus far progressing on budget and on schedule.
  - NSTX-U operational preparation is well underway.
  - Diagnostic reinstallation will be starting this coming fall.
  - Various engineering operations tools are being refurbished / upgraded including CHI gap, rectifier control, motor generator, plasma control system, and PF control.
- **Exciting 5 Year Plan (FY 2014 – 18) has been developed**
  - Aiming to provide necessary data base for FNSF design and construction.
  - Strong contribution to toroidal physics, ITER, and fusion energy development.
  - 10% incremental budget would enable timely implementation of facility capabilities to support the exciting NSTX-U Five Year Plan.

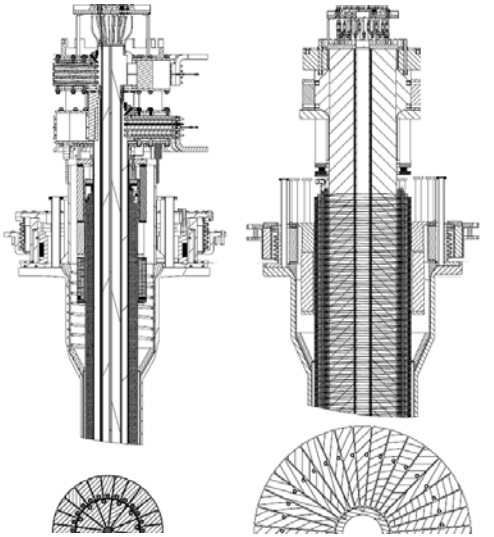
Back-up Slides

Substantial Increase in NSTX-U Device / Plasma Performance

Higher performance requires facility / infrastructure enhancements

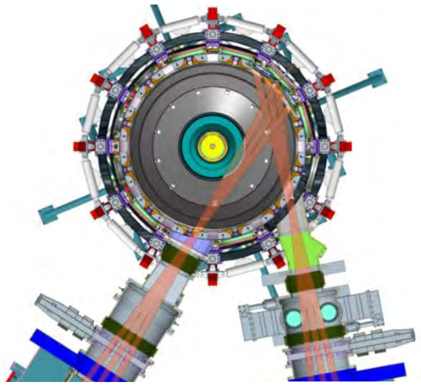
Previous center-stack

New center-stack



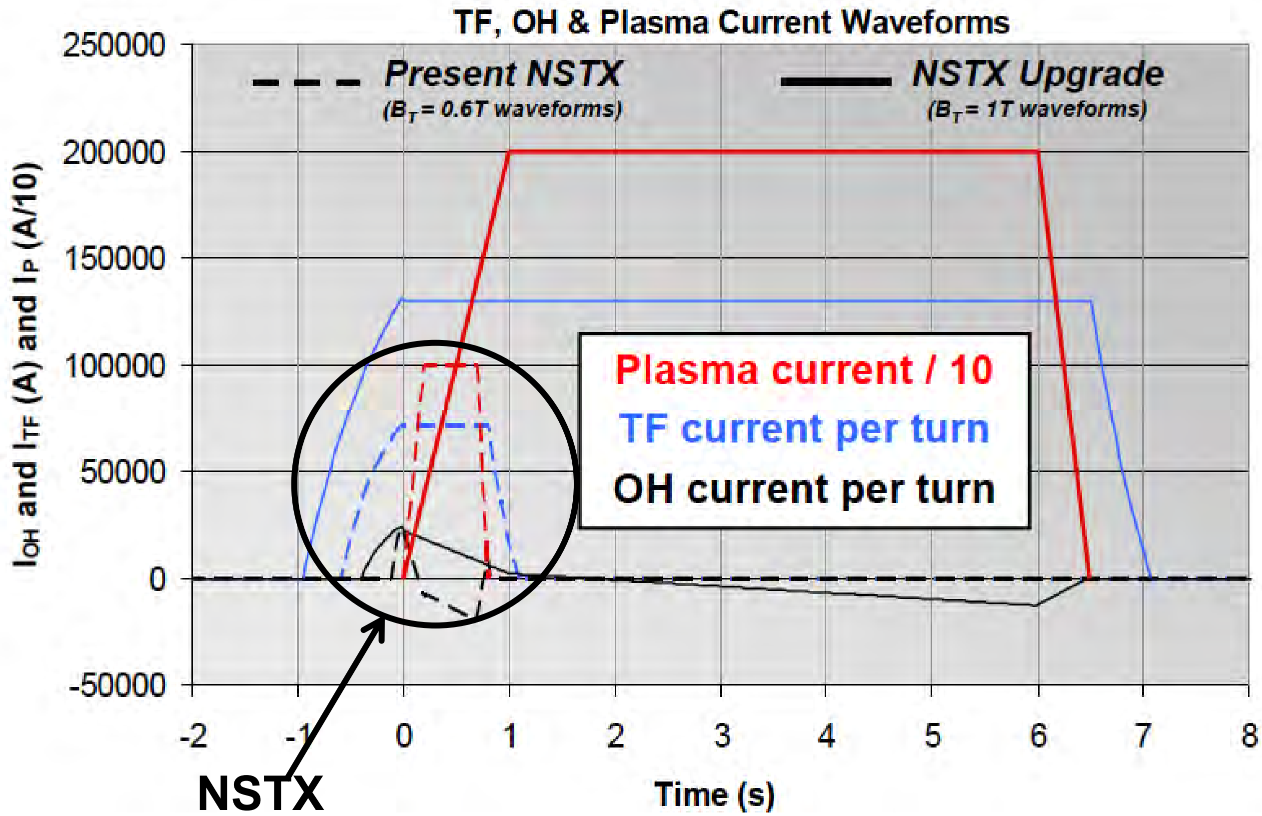
TF OD = 20cm

TF OD = 40cm



Present NBI

New 2nd NBI



	R_0 (m)	A_{min}	I_p (MA)	B_T (T)	T_{TF} (s)	R_{CS} (m)	R_{OB} (m)	OH flux (Wb)
NSTX	0.854	1.28	1	0.55	1	0.185	1.574	0.75
NSTX-U	0.934	1.5	2	1	6.5	0.315	1.574	2.1

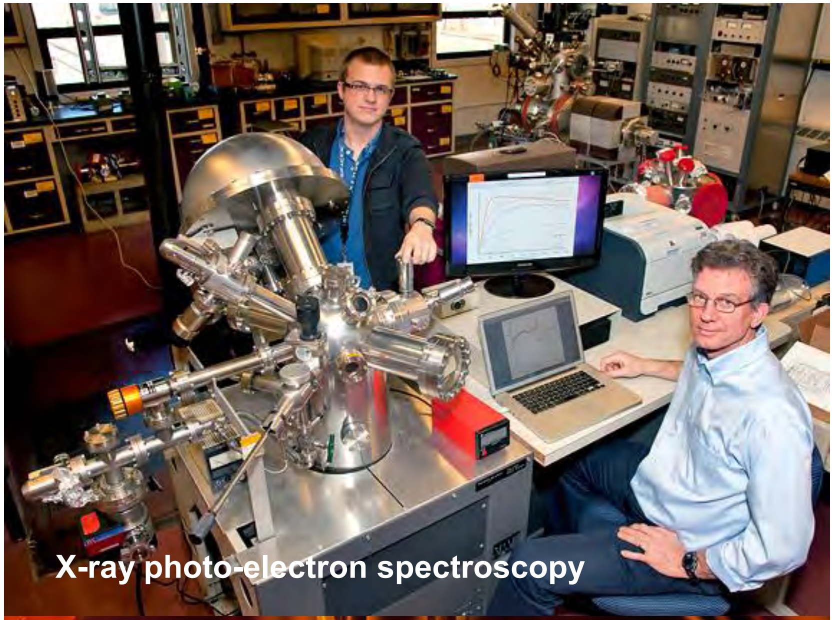
Surface Analysis Facilities to Elucidate Plasma-Surface Interactions
PPPL Collaboration with B. Koel et al., Princeton University

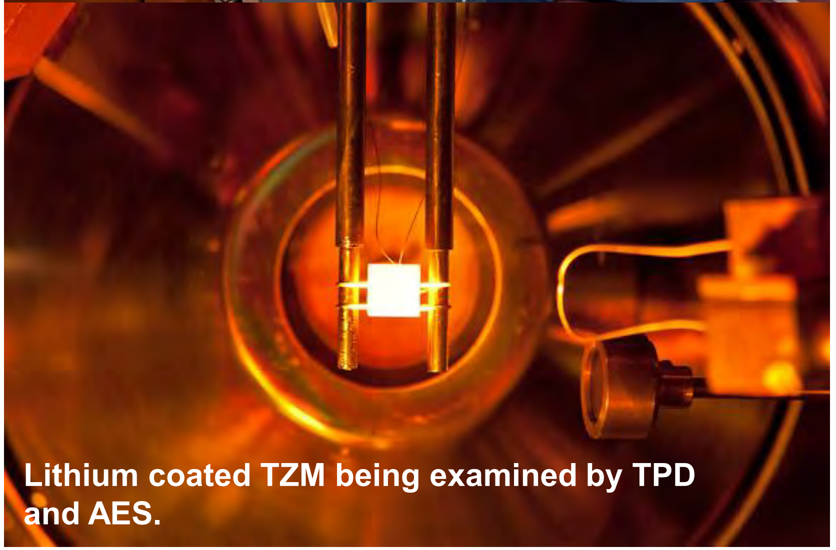
The Surface Science and Technology Laboratory (SSTL) with three surface analysis systems and an ultrahigh vacuum deposition chamber.

The Surface Imaging and Microanalysis Laboratory (SIML) with a Thermo VG Scientific Microlab 310-F High Performance Field Emission Auger and Multi-technique Surface Microanalysis Instrument.

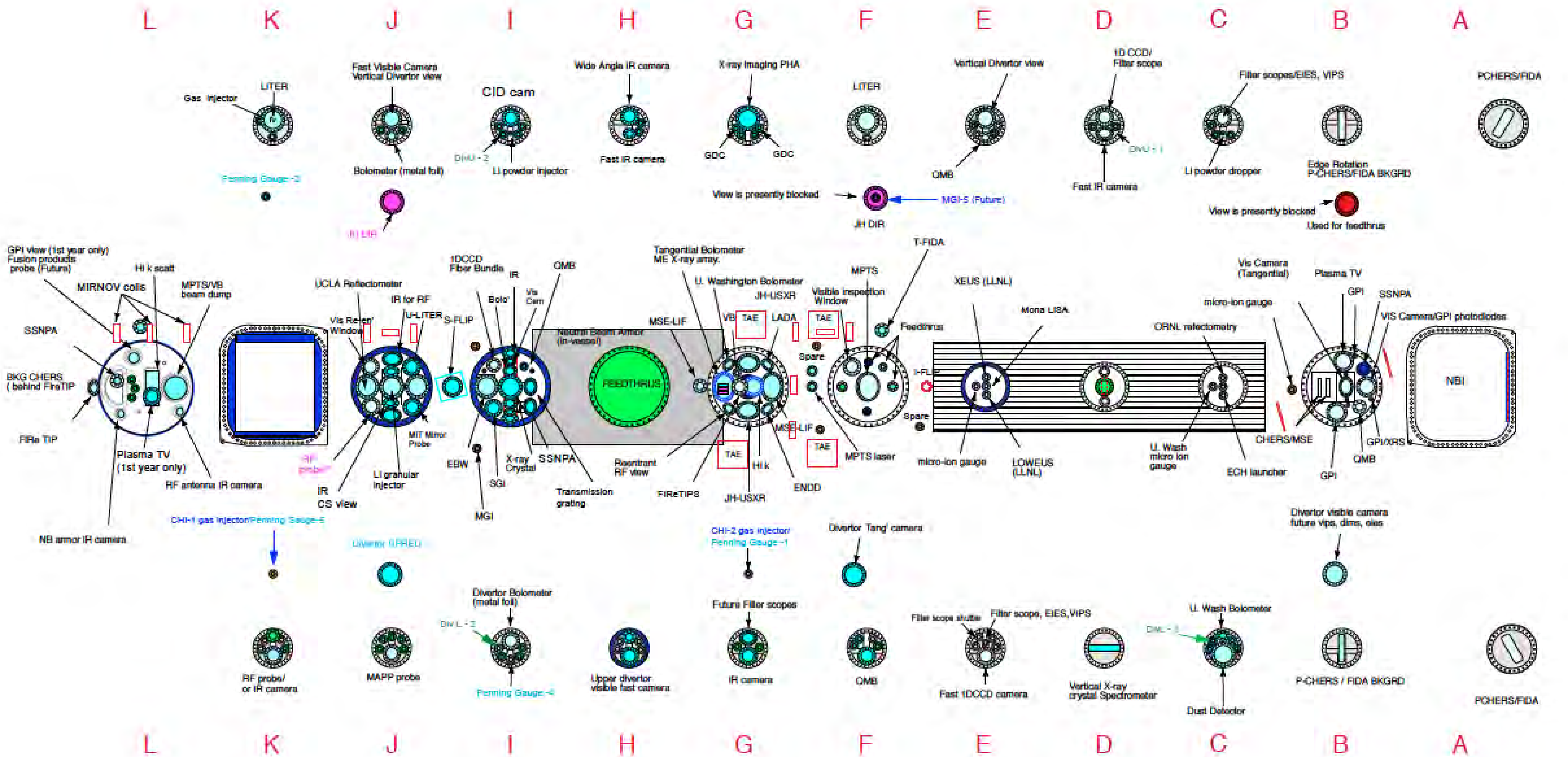
Recently solid lithium and Li coated TZM were examined using X-ray photoelectron spectroscopy (XPS), temperature programmed desorption (TPD), and Auger electron spectroscopy (AES) in ultrahigh vacuum conditions and after exposure to trace gases.

Experiment on SSTL determined that lithiated PFC surfaces in tokamaks will be oxidized in about 100 s in the expected NSTX-U vacuum conditions. (C. H. Skinner et al., J. Nucl. Mater. 438 (2013) S647)


X-ray photo-electron spectroscopy


Lithium coated TZM being examined by TPD and AES.

NSTX-U facility/diagnostics port assignment
Port flanges designed and being procured



NSTX Budget Overview for FY 08, 10, & 15
(Excluding collaborators)

	FY08	FY10	FY15
Run Weeks	15	15	16
$k	Actuals	Actuals	BA
Science	$10,118	$11,390	$13,237
Operations	$19,868	$20,478	$26,653
Capital Impr.	$1,920	$4,830	$2,317
NSTX-U	$0	$8,323	$3,766
Total	$31,906	$45,020	$45,974
FTEs	Actuals	Actuals	BA
Science	32.0	36.2	36.6
Operations	67.5	71.1	71.6
Capital Impr.	7.5	13.3	12.2
NSTX-U	0.0	29.0	7.1
Total	107.0	149.6	127.5

	FY08	FY10	FY15
Run Weeks	15	15	16
$k	Actuals	Actuals	BA
Labor	$13,080	$18,251	$16,775
Non-Labor	$4,837	$6,646	$5,710
Indirects	$13,989	$20,123	$23,489
% Indirects	44%	45%	51%
Total	$31,906	$45,020	$45,974
PPPL Total $M	79	92	84
PPPL Indir $M	32	38	40.6
% Indirects	41%	41%	48%
2% Inflation	1.000	1.040	1.149

- NSTX indirect % of budget increased from 44 % in FY 08 to 51% in FY 15.
- FY 10 budget was helped by the start of the NSTX upgrade project and the ARRA funding.
- The laboratory management change (and new contract) has occurred during FY 09.
- The overall %s of the laboratory indirect cost increased from 41% in FY 08-10 to 48% in FY 15 due partly to the overall reduction of PPPL budget and implementation of new contract.
- NSTX indirect % is greater than the lab average because of lower % indirect projects such as ITER.

NSTX Operations and Research Budget Comparison
(Excluding Collaborators)

	FY08	FY10	FY15
Run Weeks	15	15	16
Sci. + Op	$29,986	$31,868	$39,891
Normalized	1	1.06	1.33
Indirects	$13,147	$14,245	$20,381
Normalized	1	1.08	1.55
Directs	$16,839	$17,624	$19,510
Normalized	1.000	1.047	1.159
2% Inflation	1.000	1.040	1.149

Sci. + Op FTEs	99.5	107.3	108.2
Normalized	1.000	1.079	1.088

- NSTX Science + Operations budget increased from $30M in FY 08 to $40M in FY 15, an increase of $10M.
- The indirect budget has increased from $13.2 M in FY 08 to $20.4 M in FY 15, an increase of $7.2 M.
- The direct budget has increased from $16.8 M in FY 08 to $19.51 M in FY 15, an increase of $2.7 M.
- The direct budget increased roughly with inflation of 2% per year. The modest direct budget growth is due to hiring of junior researchers and technical staff together with senior staff retirement even though the total FTEs increased by ~ 9 to support enhanced NSTX-U facility and diagnostic capabilities.
- The greater than inflationary increase in Science + Operations budget can be explained by the 55% increase in the indirect cost.

NSTX Five Year Plan Budget Summary ($M)

PPPL Facility/Diagnostic Enhancement Budget Highlighted

	FY14		FY15		FY16		FY17		FY18	
Budget Cases	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**	**Base**	**10% Incr**
Run Weeks	0	0	16	4	14	2	14	2	16	4
Facility Ops	$12.7		$26.6	$1.0	$29.0	$0.5	$29.7	$0.5	$30.9	$1.0
Facility Enhancements	$0.7	$4.2	$2.8	$2.3	$5.0	$2.8	$5.1	$3.0	$4.9	$2.5
NSTX Upgrade Project	$23.2		$3.8							
Facility Total	**$36.6**	**$4.2**	**$33.1**	**$3.3**	**$34.0**	**$3.3**	**$34.9**	**$3.5**	**$35.7**	**$3.5**
PPPL Research	$10.5		$12.9	$0.9	$13.2	$0.9	$13.5	$0.9	$13.9	$0.9
Collab Interface	$0.5	$0.5	$0.7	$0.5	$0.7	$0.5	$0.8	$0.5	$0.8	$0.5
Collaborators	$6.2	$0.6	$6.4	$0.6	$6.6	$0.7	$6.7	$0.7	$6.9	$0.7
Science Total	**$17.2**	**$1.1**	**$20.0**	**$2.0**	**$20.5**	**$2.1**	**$21.0**	**$2.1**	**$21.6**	**$2.2**
NSTX-U Total	**$53.8**	**$5.3**	**$53.2**	**$5.3**	**$54.5**	**$5.4**	**$55.9**	**$5.6**	**$57.3**	**$5.7**

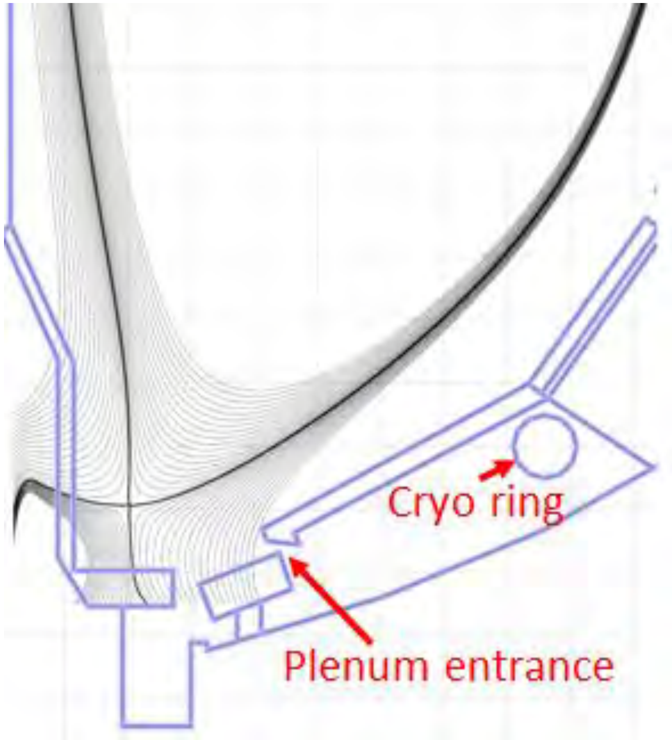
- **Highlighted #s represent PPPL facility/diagnostic enhancement budget.**
- **Design and procurement for significant enhancements will be performed in FY 2014 – 2015.**
- **Construction activities will starts in FY 2016 to be ready for in-vessel work for the FY 2016 – 2017 outage.**
- **Incremental budget increases facility enhancement budget significantly by ~ $17M enabling timely implementation of planned enhancements.**

Divertor Cryo-pump for particle control

Particle pumping for broad range of divertor parameters

Basis for Divertor Cryo-Pump Budget:

- Divertor cryo-pump is well developed. DIII-D has a long history of cryo-pump implementation.
- NSTX-U will adopt DIII-D cryo-pump design.
- Utilize DIII-D cryo-pump actual cost and adapt it to NSTX-U.



Cost Estimate Assumptions:

- No credit taken for smaller radius of NSTX-U
- SWIP cryo-pump system design achieved 14,000 hours design effort reduction. NSTX-U will take 50% of the credit.

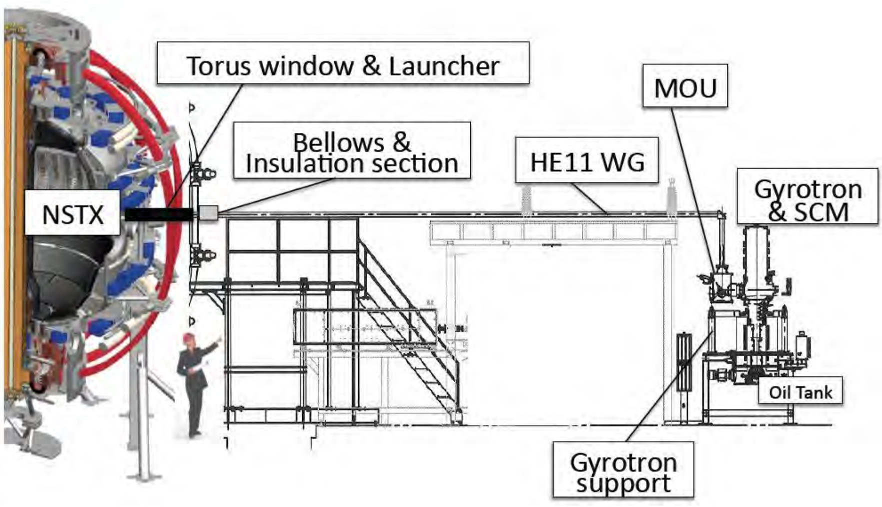
Scaling from DIII-D to NSTX-U System	$k
Inflation adjusted DIII-D actuals	$7,283
Liquid helium and nitrogen system tie in	$1,000
Credit of the design effort reduction by 7,000 hours	-$1,050
Cryo-pump tile work is covered elsewhere	-$1,000
The total estimate cost =	$6,233

1 MW 28 GHz Gyrotron System

For bridging the start-up temperature gap and EBW research

Basis for 1 MW 28 GHz Gyrotron Budget:

- System is well defined. Similar system working in Japan (Tsukuba and QUEST).
- PPPL has a collaboration with DIII-D on ECH. Some internal ECH expertise.
- ~ 50% of budget is procurement
- Antenna and waveguide is costed elsewhere.
- But with some implementation uncertainties:
  - Actual location is not finalized.
  - Power supply configuration not finalized. Utilize NBI power supply? Need for a polarity switch. Procure a new power supply?



Sub tasks	Cost Estimate (k$)	Basis for cost estimate
gyrotron system procurement	$1,760	(estimate from Tsukuba University)
water system	$560	(PPPL estimate)
power supply	$3,000	(pursuing various options)
control & instrumentation	$1,500	(previous experience on similar system)
Total Cost Estimate	$6,820	

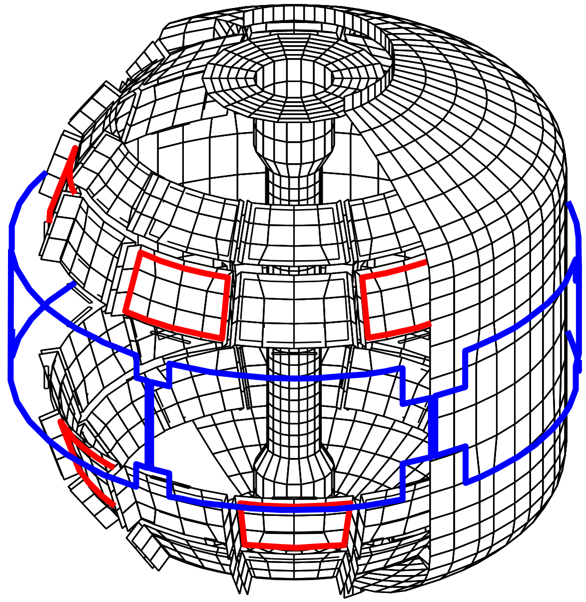
Partial NCC Coils - New MHD and Plasma Control Tools

Sustain high β_N, control rotation, modify edge transport

Basis for Partial NCC Budget:

- NCC utilized the cost actuals from the DIII-D I-Coil work.
- Actual hours spent on the I-coil tasks are the same for the NCC coils by the PPPL personnel with similar skills ($).
- M&S cost is inflation adjusted.
- DIII-D spent significant R&D and Testing of I-Coils. Assume the same level of effort for the NCC coil R&D and Testing. This may generate savings.

Partial NCC option (2 x 6 odd parity)



Cost Estimate Assumptions:

- The # of coils are the same for NCC and I-Coil systems.
- No credit taken for the NCC coil size to be half that of the I-Coil.
- NCC (RWM) diagnostics are separately funded.

Tasks	actual hours	Cost ($k)
Design	2886	$495
Fabrication	5270	$793
Installation	4102	$617
R&D Testing	8565	$1,352
M&S	inflation adj	$569
Total		$3,825

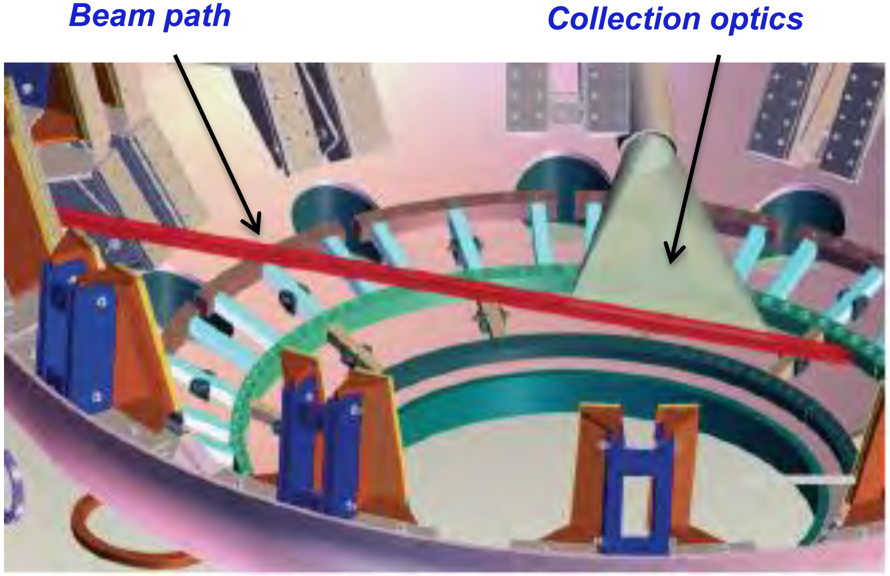
Divertor Thomson Scattering System

For divertor and SOL heat and particle transport studies

Basis for Divertor Thomson Budget:

- Relatively detailed engineering study was performed in 2008.
- A base-up cost estimate developed.
- There are two main components: Thomson scattering laser system related items and related vacuum vessel modifications and utilities.

Divertor Thomson Scattering Geometry



Cost Estimate Assumptions:

- Laser components and related items are estimated to cost ~ $950k. This includes computer, laser optics, laser safety, cooling, and 10% contingency.
- Device modification estimate is ~ $3,550k. This includes system design, laser room, AC power, interlocks, E-stop, diagnostic racks, light collection optics, laser focusing optics, vacuum vessel modification, cable tray, flight tube. We assume ~ 35% contingency due to relative complexity of the in-vessel work.
- The total cost estimate is $5.6M with overall 30% contingency.