U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

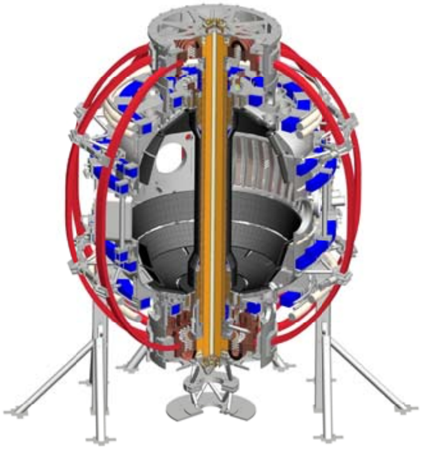
JHU Research Contributions to NSTX-U Research

K. Tritz, J. Munoz Burgos, D. Stutman

FES Quarterly Review
5/3/2016

JOHNS HOPKINS UNIVERSITY

PPPL



JHU research uses X-ray diagnostic expertise to address broad physics issues

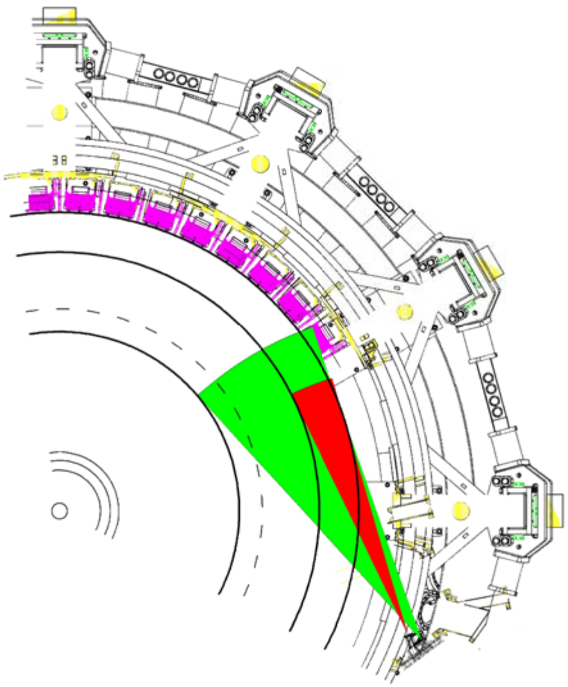
- Macroscopic Stability topics enabled by high-speed internal X-ray measurements
  - measurements of Resistive Wall Mode (RWM) internal structure
  - plasma response to external 3D fields
  - localization of rotating tearing modes, magnetic islands
  - dynamics of plasma disruption, thermal quench

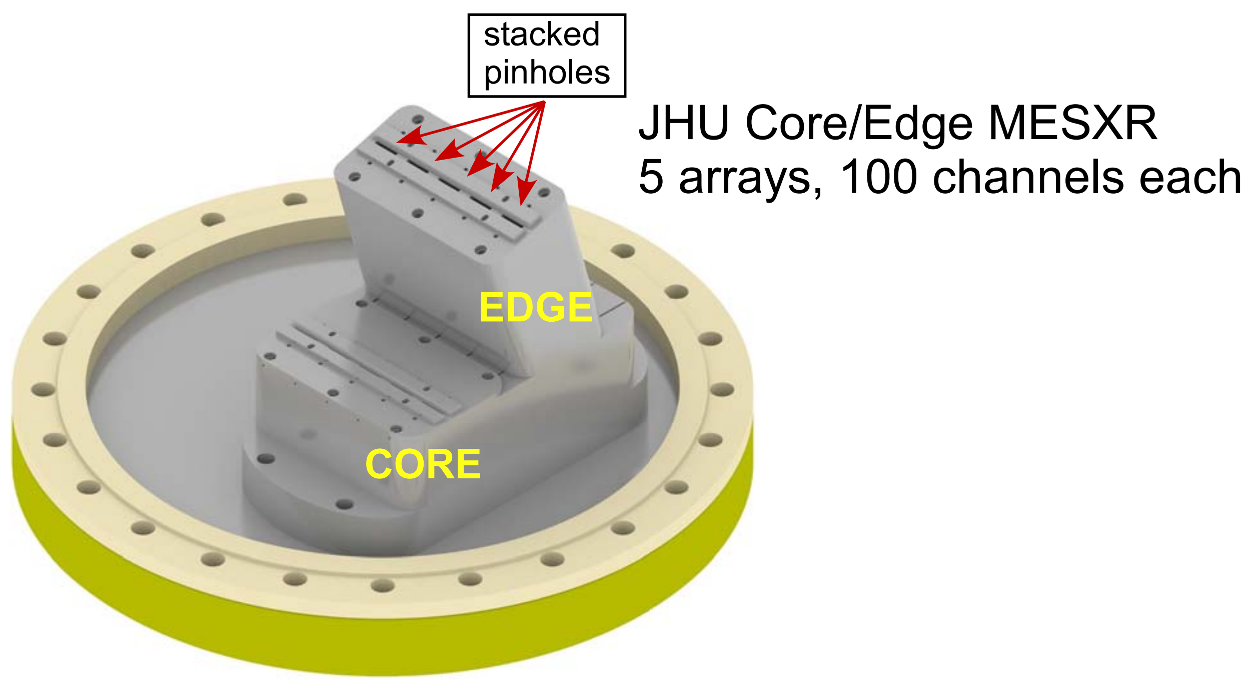
- Multi-scale Transport Physics topics enhanced using new X-ray diagnostics, fast T_e profile analysis
  - fast T_e profile diagnostic for thermal transport measurements
  - investigation of CAE/GAE effects on electron thermal transport
  - X-ray/VUV measurements of edge/core impurity transport

- Boundary Physics topics expanded with high-resolution edge measurement capabilities
  - effects of 3D fields, ELMs, Li pellets on pedestal T_e, n_e profiles
  - edge/SOL T_e, n_e profiles using advanced He line ratio analysis

JHU contributes to NSTX-U FY16 research with new diagnostic suite

- Multi-Energy Soft X-ray (MESXR) diagnostic enables 10kHz, high-resolution T_e profile measurements
  - tangentially-viewing, vertically stacked filtered diode arrays
  - complimentary core and high-resolution edge MESXR systems
  - unfiltered AXUV arrays used for diode-based bolometric P_{rad}
  - compact JHU-designed electronics selected for PPPL diode-based bolometer, UC-Irvine SSNPA



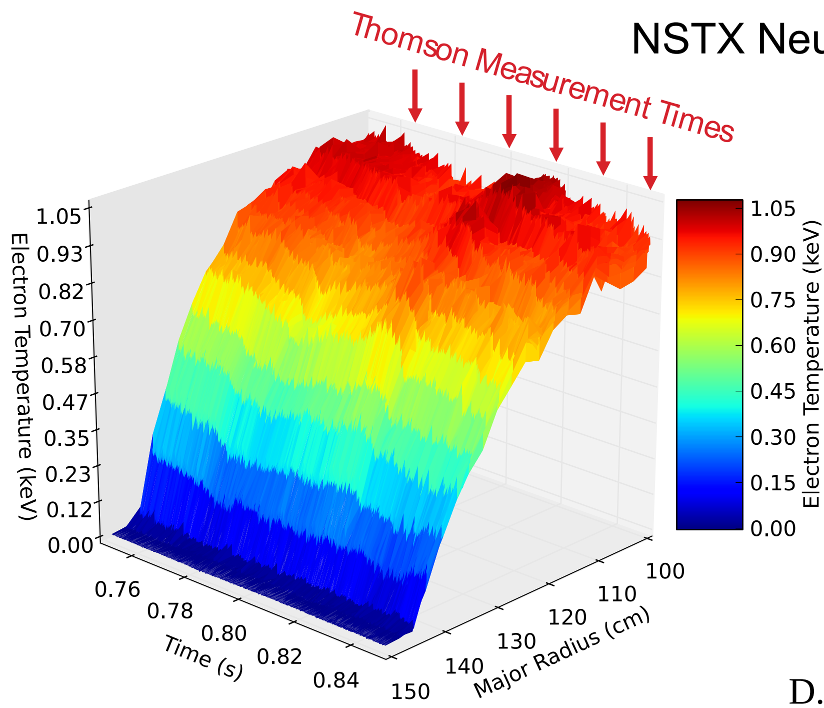


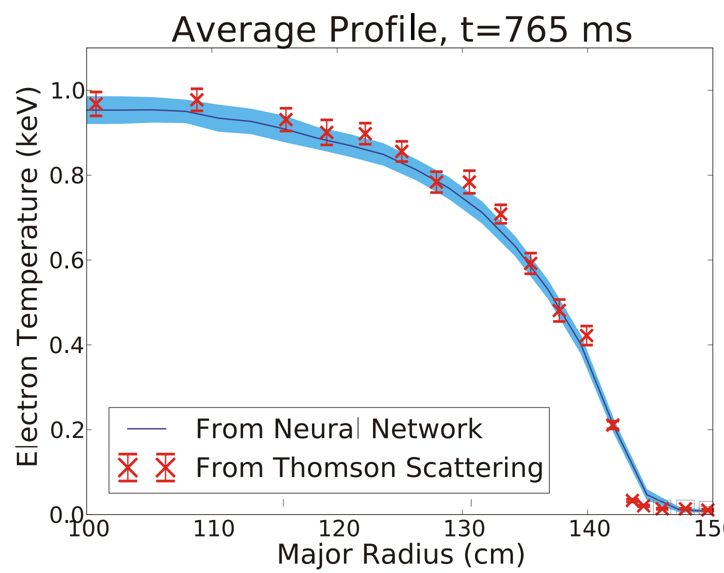
K. Tritz, et al., *Rev. Sci. Instrum.* 83, 10E109 (2012)

Neural Network (NN) analysis uses MESXR measurements to provide fast T_e

- Machine Learning discerns complex relationship between filtered X-ray measurements and T_e profile
  - NN trained using Thomson Scattering reference profiles
  - additional impurity information added from JHU TGIS
  - trained network can reconstruct 10kHz T_e profiles from MESXR
  - pseudo Monte-Carlo NN technique improves reconstruction
  - Goal: between shot fast T_e profiles for NSTX-U

NSTX Neural Network T_e profile



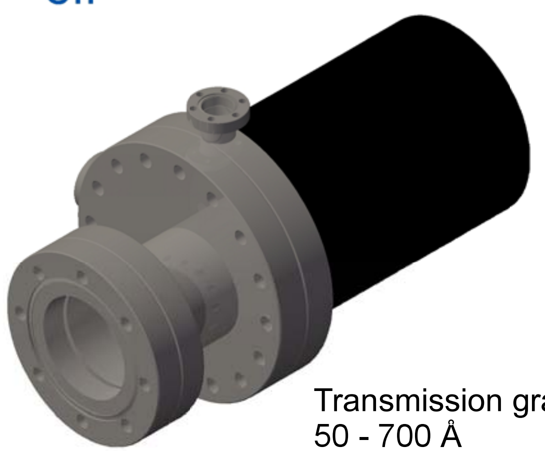


D.J. Clayton, et al., *Plasma Phys. Control. Fusion* **55** 095015 (2013)

Transmission Grating Imaging Spectrometer measures VUV/XUV impurity emission

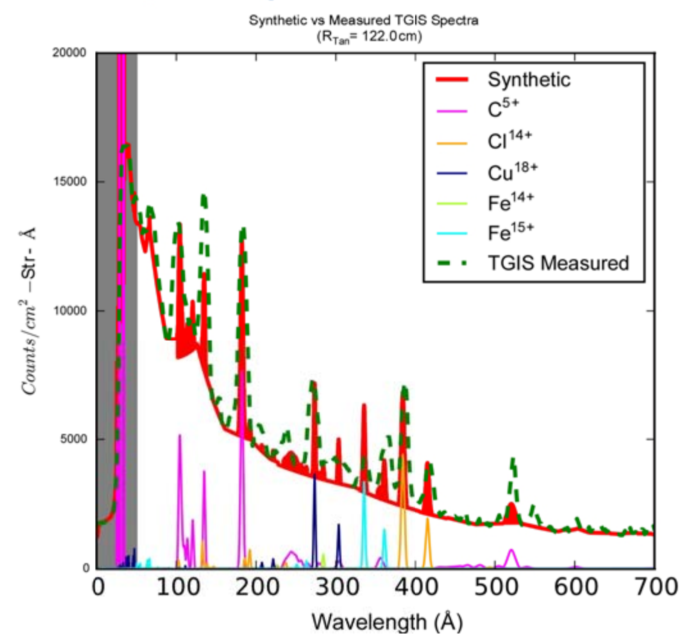
- TGIS upgrade uses high sensitivity direct detection XUV CCD
  - midplane spatially & spectrally resolved impurity measurements
  - intrinsic med. to high-Z line emission, low-Z charge exchange
  - useful monitor for core impurity accumulation, transport

- Advanced atomic collisional radiative physics modeling code developed for TGIS analysis
  - in-situ calibration using CHERS carbon impurity measurement
  - provides quantitative measurements of impurity concentration
  - Z_{eff} from Bremsstrahlung spectrum



Princeton Instruments PIXIS 400B XUV camera

Transmission grating housing 50 - 700 Å



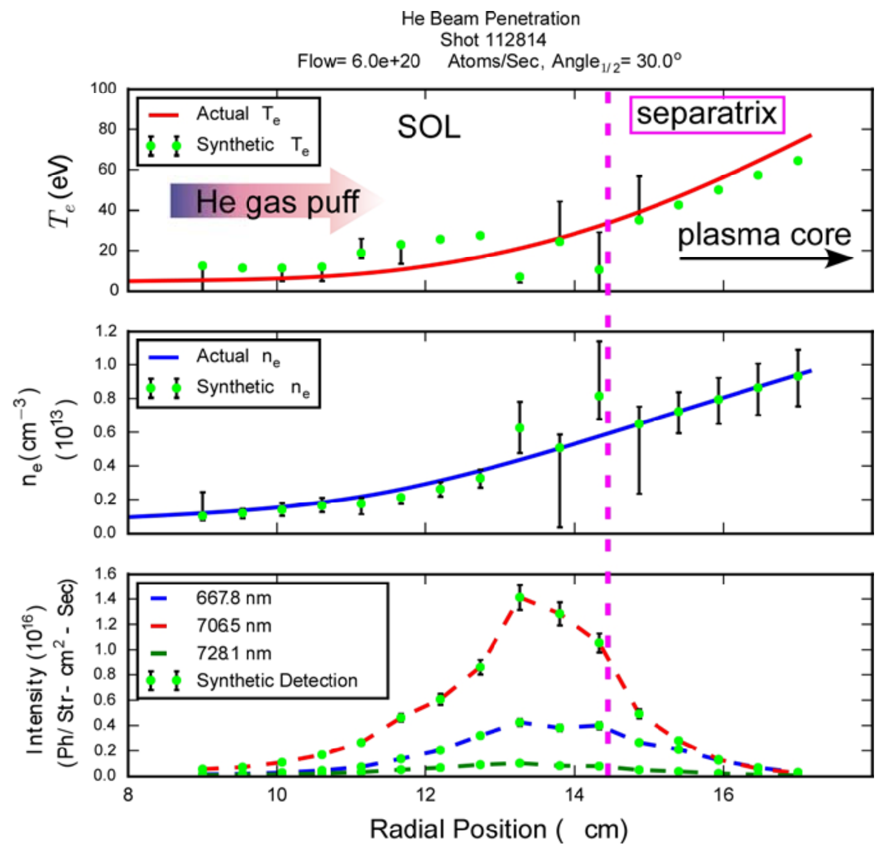
J.M. Muñoz Burgos, *Phys. Plasmas* **22**, 123301 (2015)

Advanced time-dependent atomic modeling code for He line ratio T_e, n_e profiles

- He line ratio measurements provide T_e, n_e profiles from SOL to plasma pedestal region
  - measures T_e < 100eV, compliments MESXR T_e > 100eV
  - analysis technique validated on TEXTOR, ready for NSTX-U mid-plane or divertor diagnostic

JHU provides analysis support for PPPL/collaborator hardware (FTU, ORNL, ...)

Synthetic modeling of He gas puff,
line ratio measurements, and T_e, n_e profiles



J.M. Muñoz Burgos, *submitted Phys. Plasmas* (2016)

JHU FY16 research priorities

- Lead impurity and thermal transport XPs
  - XP 1551 "Core Impurity Transport Measurements at Fixed q-Profile"
  - XP 1574 "Correlation of *AE bursts with fast core Te profiles"

- Provide crucial measurements for collaborator XPs
  - XP 1550 "Impurity transport vs torque in NBI heated H-Modes"
  - XP 1574 "Correlation of *AE bursts with fast core Te profiles"
  - XP 1554 "Make contact with NSTX for n=1 tearing mode stability"
  - XP 1547 "Stabilization of radiated-induced tearing modes (RiTMs) using off-axis-heating"
  - XP 1548 "3D plasma response data for MHD and transport code validations"

JHU near term diagnostic plans

- Optimize TGIS FOV for charge exchange measurements
  - move diagnostic to Bay K midplane view if available
  - expand FOV for complete edge to core coverage

- Test diagnostic utility of TGIS divertor view
  - previous synthetic study indicated divertor transport and spectroscopic T_e measurements with seeded impurity

- Develop radiation hardened TGIS detector
  - increased P_{NBI} and pulse length boosts neutron flux ~x10
  - will test replacement of CCD detector with optically coupled image intensifier

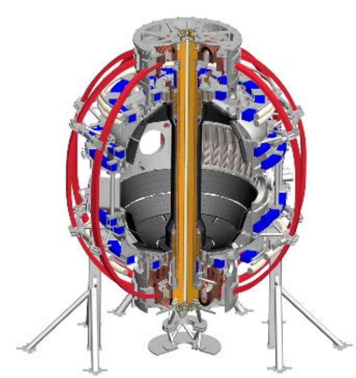
- Support incoming LLNL laser blow-off system with MESXR
  - wide range of impurity injection capability coupled with high time/spatial resolution measurements will provide fantastic opportunities for low to high-Z impurity transport studies

NSTX-U Project / Facility Status

Masa Ono and Jon Menard

NSTX-U FY 2016 Q2 Review Meeting

May 3, 2016

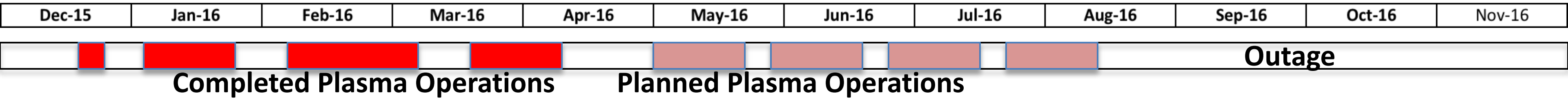


Outline

- Facility Operations Status and Plan
- On-Going Facility Enhancement Status and Plan
- Summary

Latest run plan schedule for 2016

~ 7.2 run week to date, goal is to operate 18 run weeks



➔Want as much data as possible for IAEA synopses/meeting, APS-2016

- December 2015: 0.4 run weeks (XMP)
- January 2016 (3 weeks): 2 run weeks (H-mode), PAC-37
- Two week maintenance: NBI T-line repair, Argon purge system, LITER, Diagnostics
- February – March (4 weeks): 2.4 run weeks (routine H-mode)
- Two week maintenance: BN piece recovery, NBI Auto/transformer/T-line repair, LGI, MGI, Diagnostics
- March – April: (3 weeks) 2.4 run weeks (high power H-mode)
- Three week maintenance: BPM, NBI LHe refrigeration regeneration & leak repair, LGI, MGI, Diagnostics
- May – August - 10.8 run weeks to complete FY16 run with extended run days
- August: Start outage

LHe Refrigerator Cold Box Leak

Leaks were found and repaired along with a similar piece

- The LHe Refrigerator Cold Box leak was determined to be in a piece of pipe used as a thermocouple diode well. The temperature measurement at this location was no longer in service because those types of diodes are obsolete. The pipe was cut off and capped. The cap was seal welded and QC inspected.

- A second similar well was also cut out and capped and welded as a precaution.

- Another very small leak in another location was discovered and likewise capped and welded.

- After leak checking, the Cold Box shell was replaced and vacuum restored. The LHe refrigerator was put back into service and initial operations indicate that the unit is back to full capacity. BL 1 & 2 cool down complete and operations started.

Interior of the LHe Refrigerator Cold Box

Heating System Operations
NBI system should be approaching full performance

- Cryogenics repairs completed. Restart of LHe refrigerator complete. Cooldown of BLs in progress for operations yesterday (Monday, May 2, 2016) and starting up NBI operation today.
- Neutral Beam #2
  - N2A Source had operated to 86 kV. (Hipot to 90 kV completed.)
  - N2B Source had operated to 80 kV. (High voltage investigation completed.)
  - N2C Source had operated to 80 kV.
- Neutral Beam #1
  - N1A Source had operated to 76 kV. (New source conditioning still in progress)
  - N1B Source had operated to 70 kV.
  - N1C Source had operated to 90 kV.
- RF Systems
  - HHFW #1-4 Recovery CAP completed. Ready to start antenna conditioning.
  - HHFW #5-6 CAP completed. Awaiting protective relay installation (imminent)
  - RF awaiting AC Power repairs in switchyard (completion imminent)

We are using dTMB now for PFC Conditioning, and Will Switch to Lithium in a Few Weeks

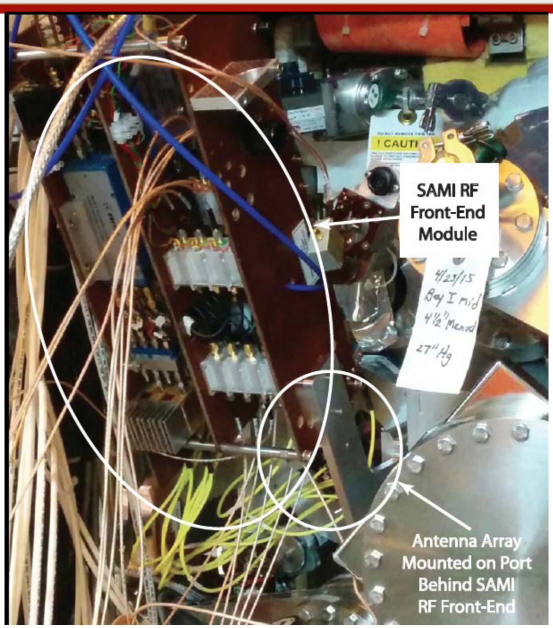
- We have been boronizing the ATJ graphite PFC at a rate of 1 bottle per week.
  - 1 bottle = 10 grams dTMB in a Helium background was the standard quanta of boronization in NSTX.
  - Started NSTX-U run with a full bottle boronization each Sunday, found conditions were degrading by the end of the week.
  - Switched to 1/5 bottle boronization late 2nd shift each evening.
    - Provides more consistent conditions day-to-day.
- We are working towards using lithium evaporators during this run.
  - Cables for motor control drives are among pacing items.
  - Still need to complete procedure revisions, do ACC reviews.
  - Installing an Ar Purge System (APS) to fill the vessel with Ar in the event of a catastrophic vent during lithium evaporation.
  - Target date for lithium use is early June.

We are Working to Deploy/Commission Additional Systems in the Remaining Duration of the Run

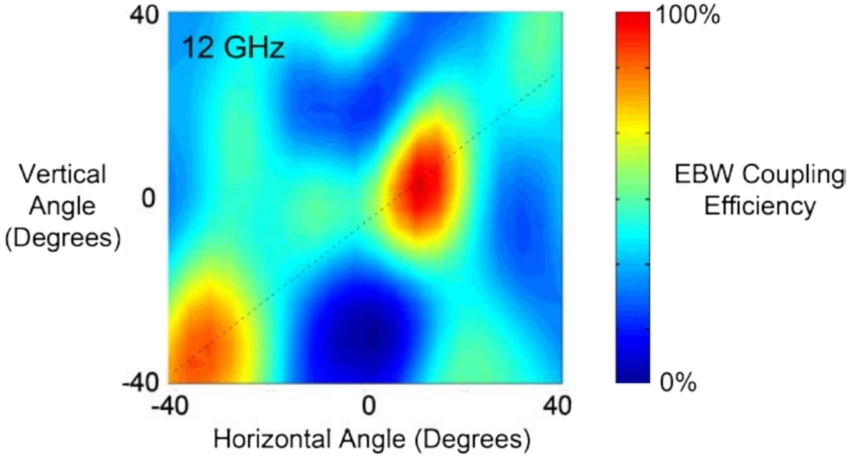
- Langmuir probe electronics
- Massive Gas Injector (UW) – disruption mitigation
- Lithium Granule Injector – ELM pacing
- SAMI (Univ. York) – EBW physics, field pitch at edge (next slide)
- High Harmonic Fast Wave Heating & Current Drive
  - AC power problem on sources delayed operation.
  - Sources 1-4 are nearing operation, 5 & 6 are ~1-1.5 months out.
- Infrared Video Bolometer (ORNL, NIFS)
- Divertor SPRED (LLNL)
- Fusion Products Detector (FIU)
- CHI Instrumentation & Gas Feeds (UW)
- TF Coil Bending Stress Instrumentation for 0.8 T Operation
  - Use existing instrumentation chassis to confirm that the outer leg bending is consistent with predictions from the mechanical analysis branch.

Synthetic Aperture Microwave Imaging (SAMI) diagnostic now calibrated and operating on NSTX-U

- SAMI* measures 10-35.5 GHz emission using 16 local oscillators and an array of antennas to image over a large field of view
  [Collaboration with Univ of York, Durham Univ & CCFE in UK]
- Two probing beams used for 2-D Doppler Back Scattering
- Emission data digitized at 250 mega samples/sec



SAMI RF front-end and antenna array installed on NSTX-U



SAMI EBW Emission Data from MAST

- First used successfully on MAST
- Image can be focused post shot
- Measures EBW coupling efficiency, plasma turbulence, and pitch angle of magnetic field in the plasma edge with high radial resolution

NSTX-U device performance progression

- 1st year: Limit forces to ½ way between NSTX and NSTX-U, and ½ of the design-point heating of any coil
  - Presently operating at $B_T \sim 0.65T$
  - Increase to $B_T \sim 0.8T$ after completing engineering analysis
- 2nd year goal: Full field and current, coil heating to ¾ of limit
- 3rd year goal: Full capability

Parameter	NSTX (Max.)	Year 1 NSTX-U Operations	Year 2 NSTX-U Operations	Year 3 NSTX-U Operations	NSTX-U Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8 (0.65)	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

NSTX Upgrade Lead Extension Qualifications
Confirmed by Calculations and Cyclic Fatigue Test

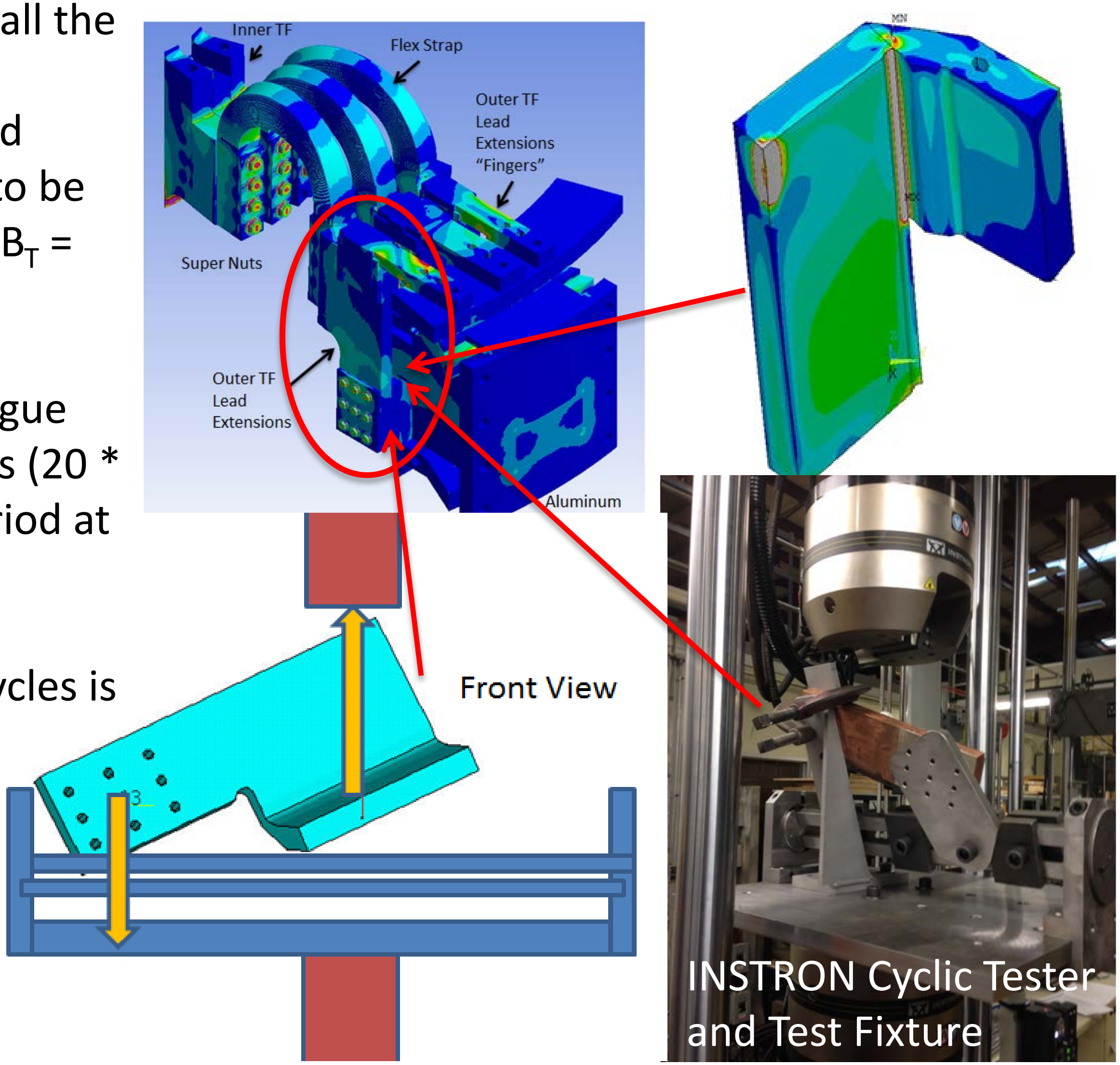
- The CuCrZr TF lead extensions and all the related parts associated with the connections between the inner and outer TF conductors are qualified to be acceptable for up to 300 pulses at B_T = 0.8 Tesla.

- It successfully passed the cyclic fatigue test to the .8 T level for 6000 cycles (20 * 300 cycles expected in this run period at 0.8T).

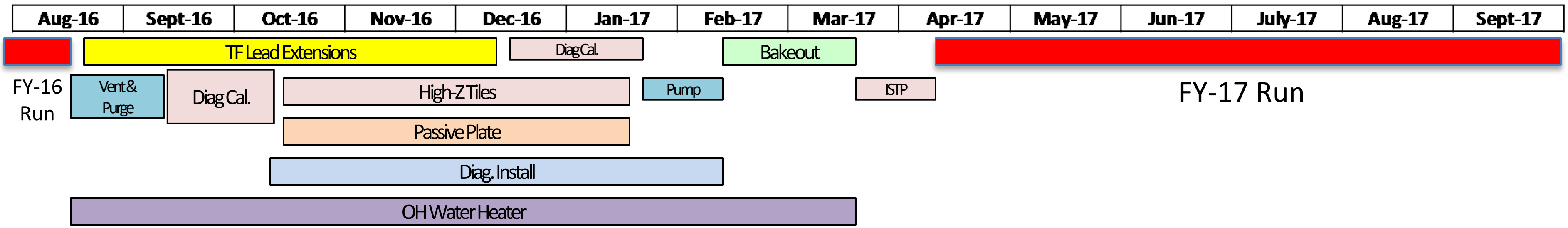
- The full 1.0Tesla level to 400,000 cycles is being conducted this week.

- Components are being inspected, analyzed tested and replaced as needed to qualify operation at full performance after the shut-down starting in August of 2016.

TF Inner to Outer Connection Details



Longer Term Plan Supports Operations in FY-17



- Present run projected to run through mid-August
- Maintenance period shown mid-August thru December 2016
  - OH Water Heater
  - Passive Plate Replacement
  - TF Coil Maintenance and Partial Parts Replacement
  - High-Z tiles
  - Diagnostic work including high-k, FIReTIP, bolometer, laser blow-off
- Diagnostic calibrations, bakeout, leak checking and coil testing through March 2017
- Operations April thru September: 5.5 months for 16 run weeks.

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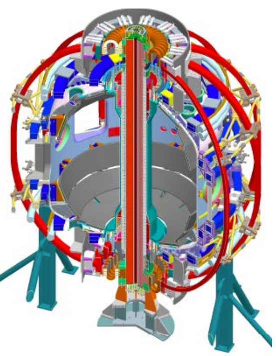
Five Year Facility Enhancement Plan (green – ongoing)

Incremental enables 5 year plan enhancements including NCC, ECH

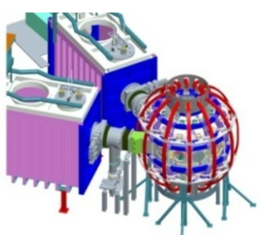
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ incremental funding

New center-stack



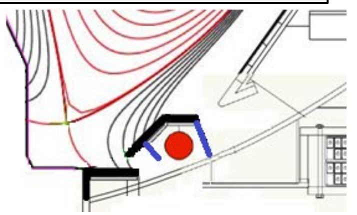
2nd NBI



Boundary Science + Particle Control

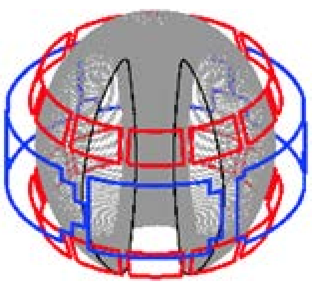
Pulse-burst MPTS
Boronization
High-Z tile row on lower OBD

Li granule injector
LiTER
MAPP
Upward LiTER
Resistive Bolometer
Scanning MLP
APD-based GPI
High-Z PFC diagnostic
Lower divertor cryo-pump
Graphite CHI/Lower Bullnose



Core Science

MGI disruption mitigation
Upgraded halo sensors
sß
XICS
42 ch MPTS
Laser blow-off
48 ch BES
High k_θ
MSE/LIF
Charged fusion product
4 coil AE antenna
CPS δB diag.
Off-midplane 3D coils (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}
Upgraded CHI for ~0.5MA
0.5-1 MA CHI
HHFW limiter upgrade
1 MW ECH/EBW
up to 1 MA plasma gun

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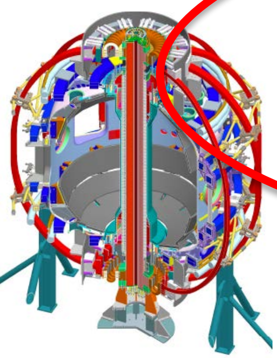

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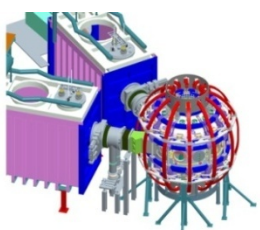

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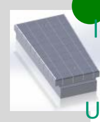
- Li granule injector
- LiTER
- MAPP
- High-Z tile row on lower OBD



- Upward LiTER
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- High-Z PFC diagnostic
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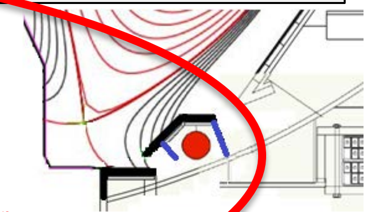
- Graphite CHI/Lower Bullnose



Core Science

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- 42 ch MPTS
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- 4 coil AE antenna
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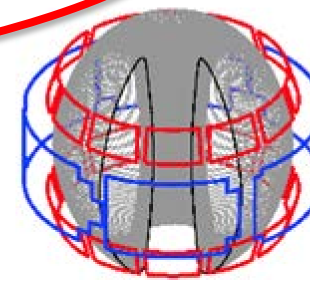

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- Rotation
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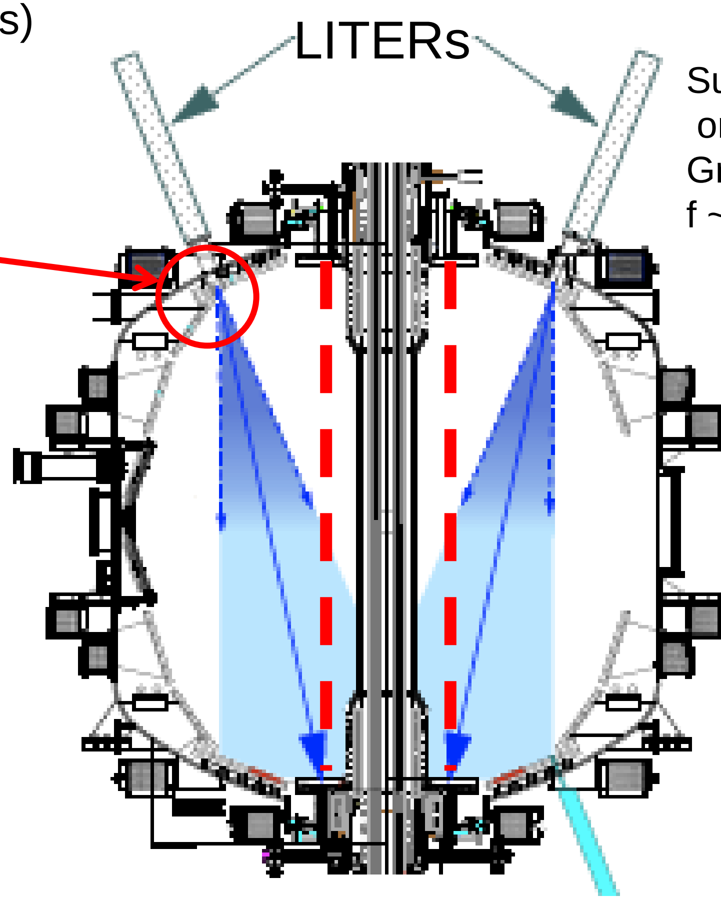
- Divertor P_{rad}
- Upgraded CHI for ~0.5MA
- 0.5-1 MA CHI
- HHFW limiter upgrade
- 1 MW ECH/EBW →
- up to 1 MA plasma gun

First Year Boundary Physics Tools

Boronization, Lithium Evaporators, Granule Injector

Lithium Evaporator (LITERs)



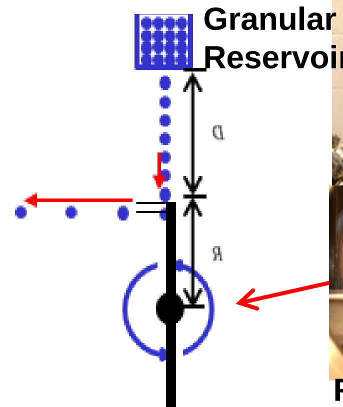
- LITERs filing set up in high bay south of NSTX-U Test Cell.
- Argon purge system implemented for Li safety, used for the quick argon vent.
- Expected to be operational in June.

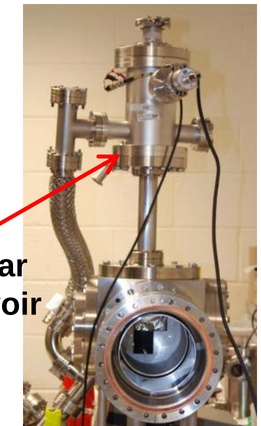
Boronization System

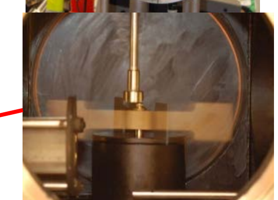
- Multiple injection and glow made more uniform boronization.
- System is working very well. Multiple # of boronization including daily ones performed. Also being used for He glow discharges.

Granule injector (GI) for ELM pacing

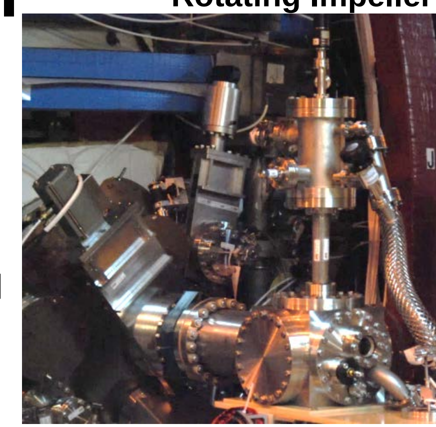
Successfully tested on EAST and DIII-D
Granules: Li, B_4C, C
f ~ up to 500 Hz







Rotating Impeller



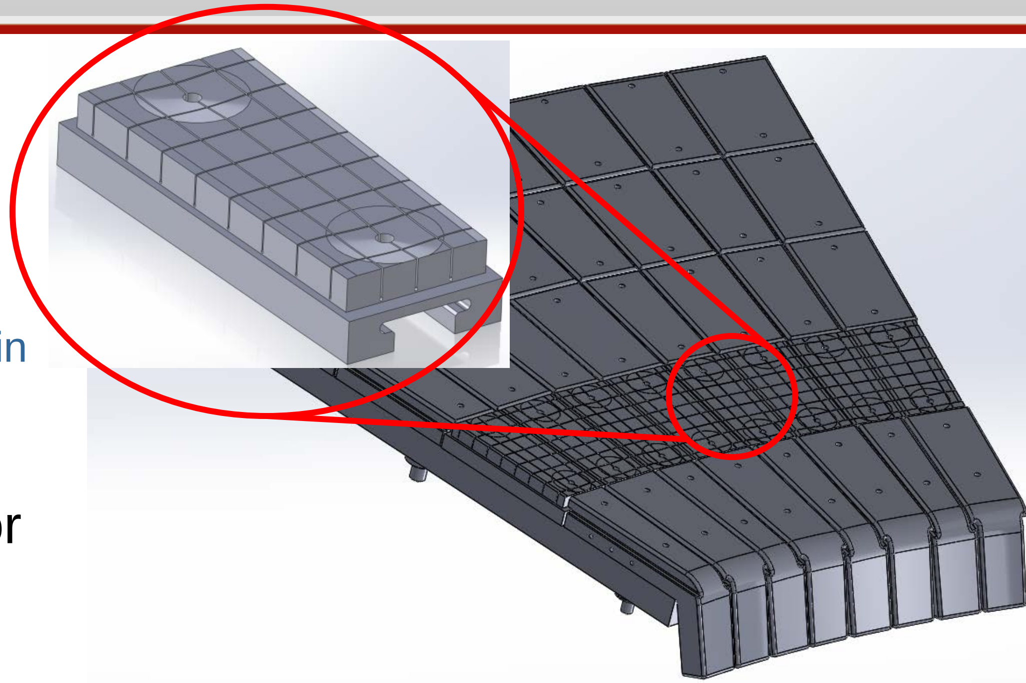
GI installed on NSTX-U

- Undergoing commissioning and initial injection during the next plasma operation.

High-Z Tile to be installed for FY 2017 run

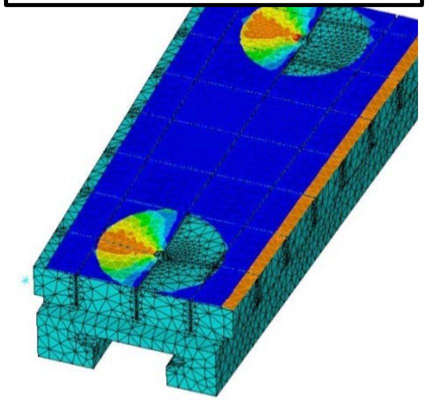
Design to replace a row of the graphite tiles in lower outer divertor

- Successful FDR held in February
  - 82% of raw materials on-site
  - Fabrication RFQ being prepared
  - Schedule to be delivered in September in time for the installation in NSTX-U

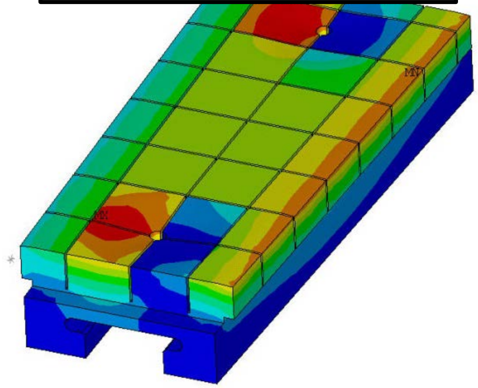


- Final design rated to 10 MW/m^2 for 1s heat flux for 1000s of cycles
  - Installation flexibility introduced to accommodate “as built” vessel tolerances
  - Edge and access-way chamfers introduced to reduce heat-flux peaking

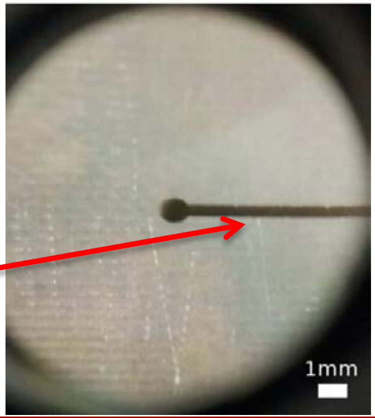
Surface heat flux



Temperature

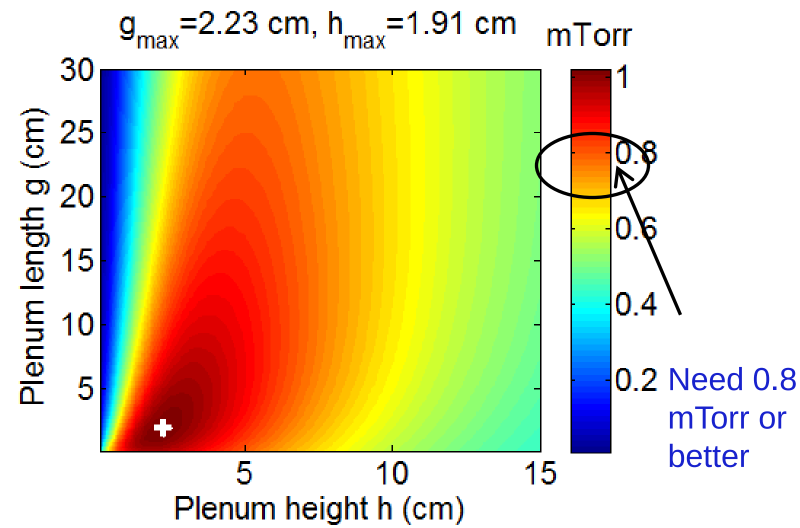


Test cut from one of the castellations performed

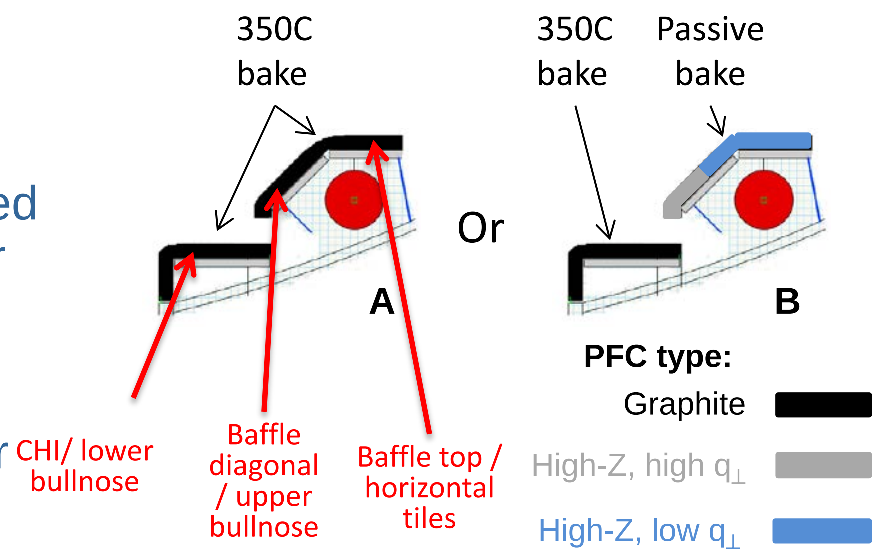


Lower Divertor Cryo-pump to Provide Pumping over a Wide Range of Divertor Geometries and Core Densities

- 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.
  - Two types of PFCs being investigated.
  - CHI/lower bullnose section may be pursued as separate job as it may be enhanced for high Z and flowing Li in the future.
  - Goal is to to have the system ready for installation in the 2018-2019 outage under base funding.



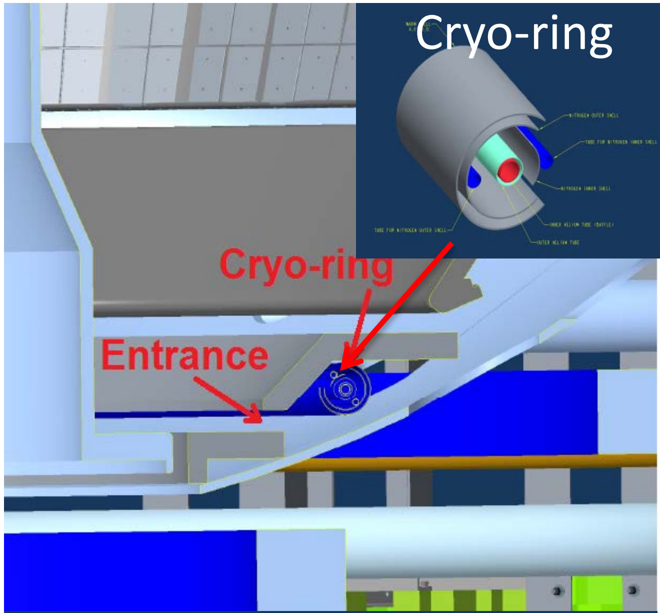
Two PFC Options for CDR

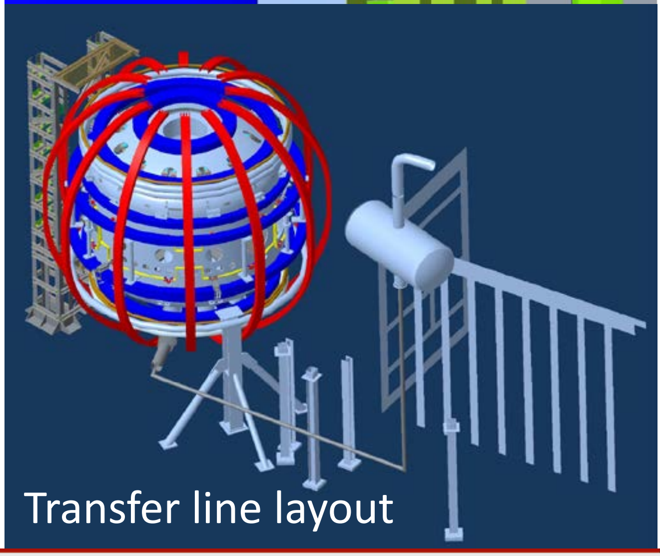


Divertor Cryo-pump Design Activities Started

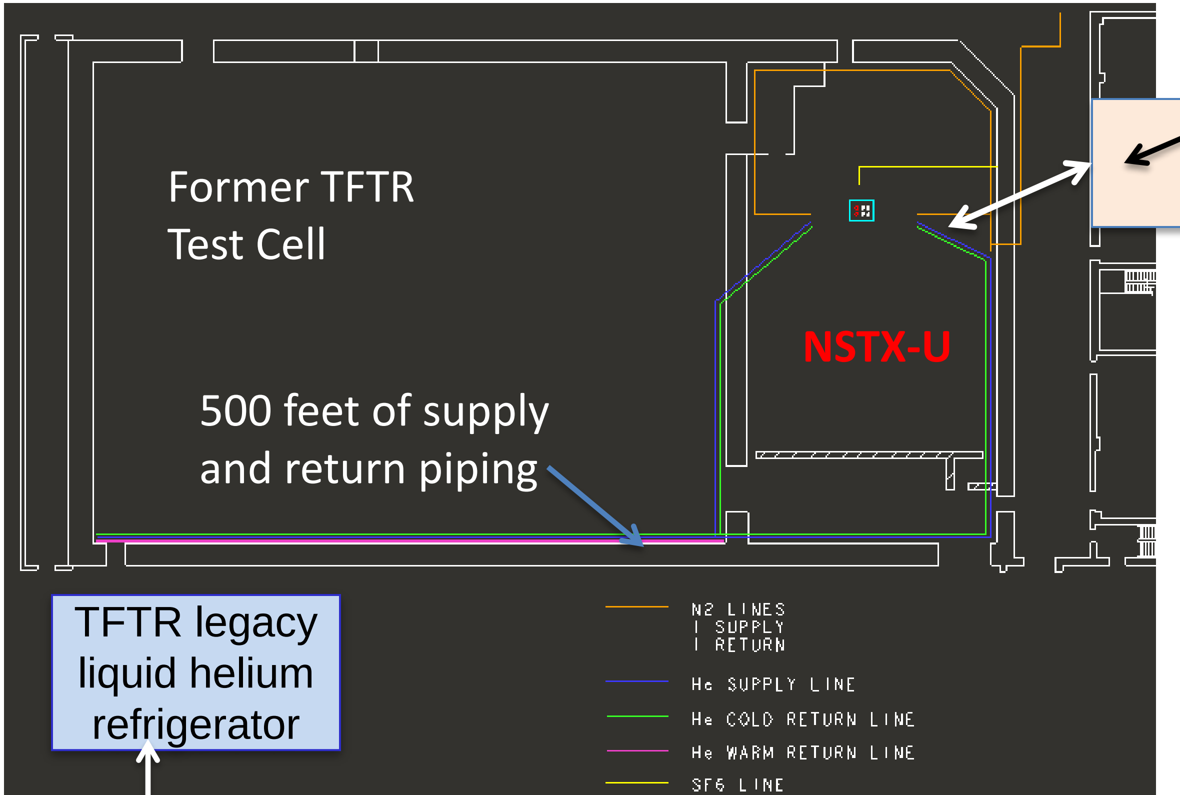
Design also includes appropriate PFCs and L-He refrigerator

- Initial in-vessel geometry has been laid out. MIT will design cryo-ring.
  - Pump radius, throat dimensions taken from the modeling.
  - The entire lower outer divertor region to be reduild.
- Cryo-baffle design to be finalized at CDR.
  - Diagnostic access and cryo-ring maintainability are major design consideration.
  - Two PFC options (Graphite or high Z) are pursued for CDR.
- A 400W liquid He refrigerator considered to reduce NBI operational risk and operational cost savings.
  - A room adjacent to NSTX-U has been identified for energy efficient location with utilities already available.
  - Replaces the outdated TFTR-era L-He refrigerator reducing risks to the NBI operations.





A new efficient 400 W liquid helium (L-He) refrigerator to minimize down time risk and reduce operating cost



Proposed 400 W L-He refrigerator ~ $2.5M

- To be located in the Cryogenics Compressor Room near NSTX-U, accommodates all envisioned loads by benefit of greatly reduced piping and heat loss (x 3-4).
- The unit would reuse power and space previously used for a 225 Watt refrigerator with all the utilities and compressors available.
- Benefit:
  - Remove down time risk
  - Increase available L-He for NSTX-U including NBI and Divertor Cryo-pump.
  - Reduced operating and maintenance cost

- 36 years old 800 W refrigerator for NBI #1 and 2 operating at near capacity due to long piping causes significant heat loss – also quite expensive to operate and maintain.
- If a cold box failure occurs, the repair will require reverse engineering and loss of several months will severely impact NSTX-U operations.

Implement Divertor Cryo-Pump with base funding

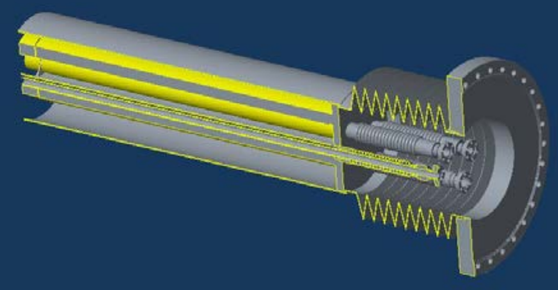
Exploring various options to minimize cost for timely completion

Schedule for Cryo-pump and PFCs:

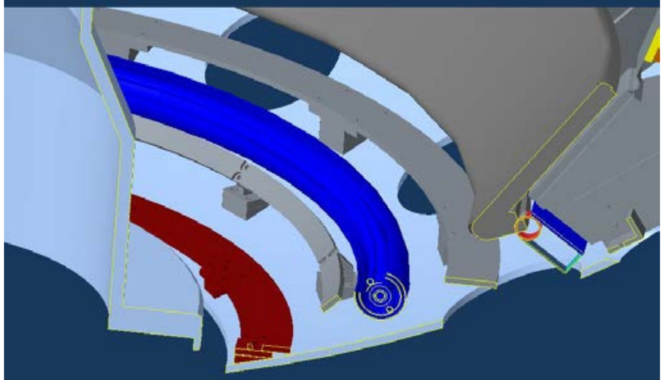
- Start formal design collaboration with MIT in Feb 2016.
- CDR – planned in July 2016 with cost and schedule developed (Notable Outcome)
- PDR – planned in Nov. 2016
- FDR – planned in March 2017
- Complete fabrication of in-vessel components – May 2018
- Complete installation of in-vessel and ex-vessel components – Feb. 2019

Schedule for L-He refrigerator:

- PDR in June 2016 with external reviewers
- Start procurement – Sep. 2016.
- Start installation – June 2017
- Commission – Oct. 2017



Cryogenic vacuum feedthrough concept.



Cryopump with redesigned divertor support structures

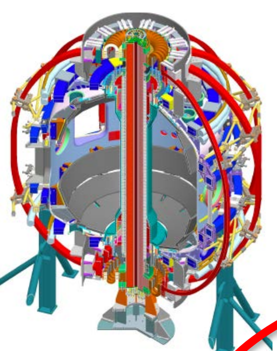
Five Year Facility Enhancement Plan (green – ongoing)

Incremental enables 5 year plan enhancements including NCC, ECH

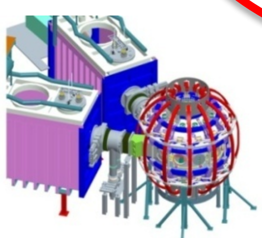
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ incremental funding

New center-stack

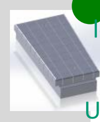


2nd NBI

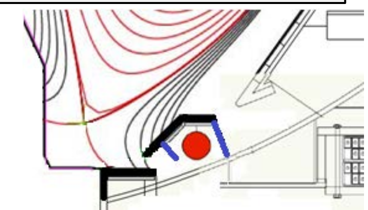


Boundary Science + Particle Control

Pulse-burst MPTS
Boronization
Li granule injector
LiTER
MAPP
High-Z tile row on lower OBD

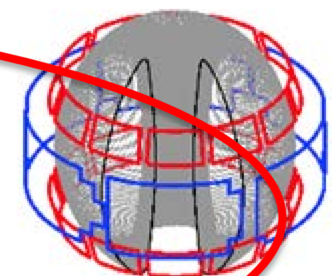


Upward LiTER
Resistive Bolometer
Scanning MLP
APD-based GPI
High-Z PFC diagnostic
Lower divertor cryo-pump
Graphite CHI/Lower Bullnose



Core Science

MGI disruption mitigation
42 ch MPTS
48 ch BES
MSE/LIF
4 coil AE antenna
XICS
Upgraded halo sensors
sß
Laser blow-off
High k_θ
Charged fusion product
CPS δB diag.
Off-midplane 3D coils (NCC)
Enhanced MHD sensors
DBS, PCI, or other intermediate-k
Neutron collimator



Integrated Scenarios

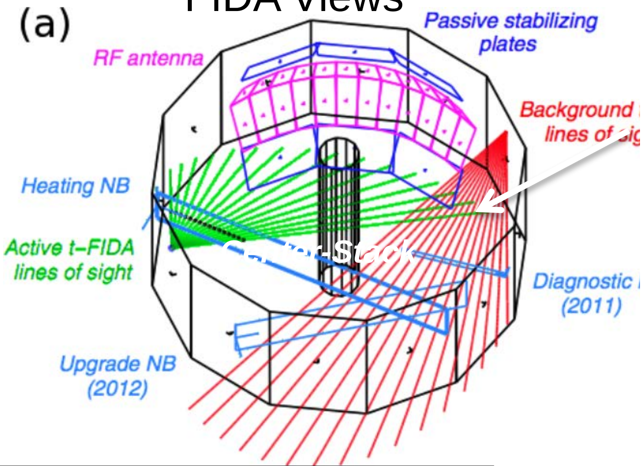
Establish control of:
Snowflake
FIReTIP
Rotation
$\bar{n}_e$
q_{min}
Divertor P_{rad}
Upgraded CHI for ~0.5MA
0.5-1 MA CHI
HHFW limiter upgrade
1 MW ECH/EBW
up to 1 MA plasma gun

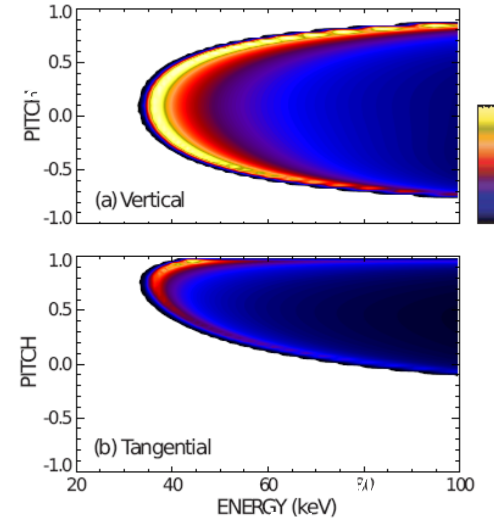
Enhanced FIDA will measure NBI distribution function
For NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics
Taking data on NSTX-U

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

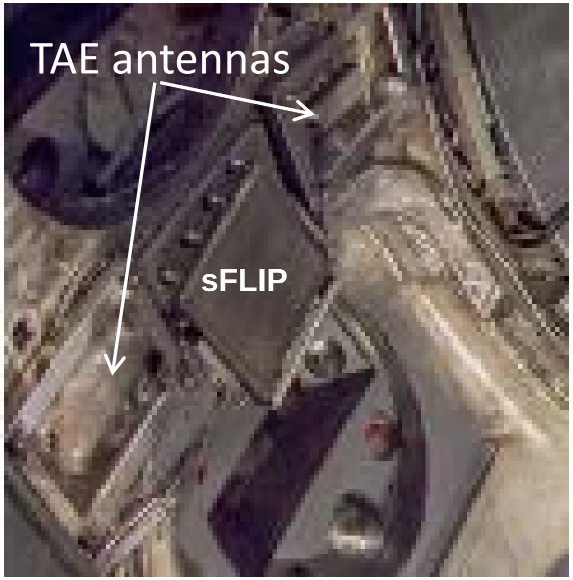
FIDA Views





FY 2016 - 2017 Energetic Particle Conceptual Design and Diagnostic Upgrade

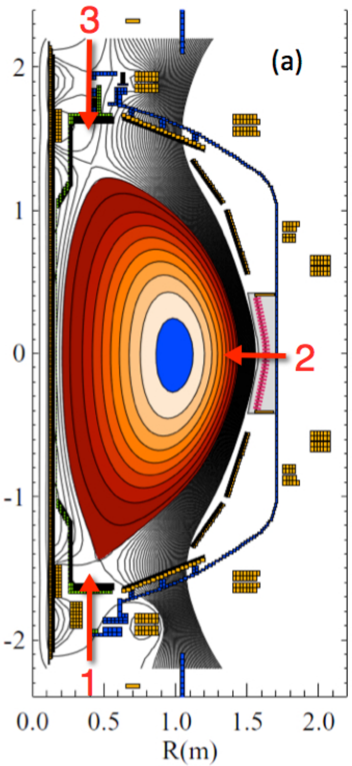
- SS-NPA installed and taking data. UCI
- sFLIP installed for lost ion measurements
- Active 2 X 2 TAE antennas installed. Initially passive spectroscopy then active excitation at few kW level.
- Proto-type charged fusion product (CFP) profile diagnostic is being prepared to be installed. FIU
- 8+8 reflectometry array available for AEs. UCLA

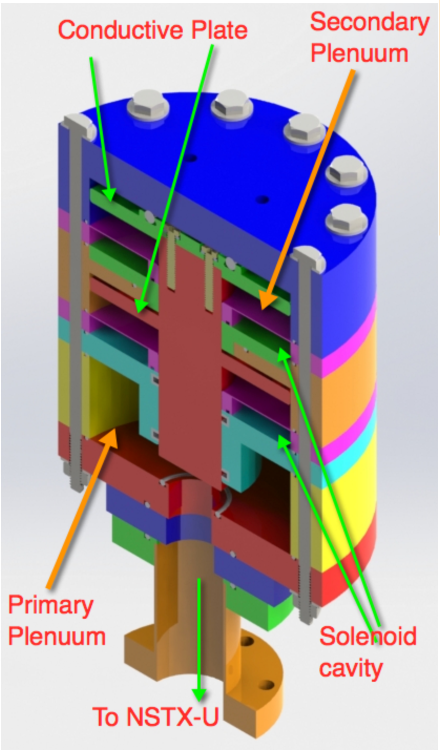


Disruption Mitigation System for NSTX-U

Massive gas injection system at multiple poloidal positions

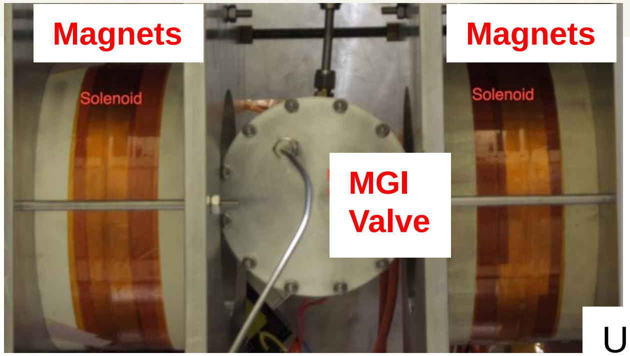
NSTX-U MGI Valve





- Massive gas injector system at multi poloidal location with identical injection set-up
- Compact power supply proto-type tested at UW
- A new double solenoid MGI design (zero net J x B torque) based on the ORNL ITER MGI design

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



U. Washington

- Successful final Design Review of MGI system was held on February 18, 2016.
- All the MGI components were installed on NSTX-U and the control is being installed.
- Preliminary MGI test is planned in May, 2016 for the initial gas pulses into NSTX-U.

Summary of Facility and Diagnostics
We are at 40% of the 18 run weeks

- The commissioning phase is nearly complete and the plasma operation is now becoming routine and the availability increasing to ~ 90 % range.
- NBI and boronization are now supporting operations with routine H-mode access. NBI is approaching the full capability. HHFW is starting up. Will switch to lithium in June.
- Very good progress on the plasma control system, quickly achieving H-mode and high performance discharges comparable to the best NSTX plasma parameters.
- Plan to achieve parameters well beyond NSTX in the near future. In preparation for the 0.8 T operation later this year, a cyclic fatigue test was successfully conducted on the TF lead extension e-beam weld joint.
- A number of enhancements are being implemented to support the NSTX-U research plan. installation of high-Z tiles and complete conceptual engineering design for divertor cryo-pump, NCC, and ECH this year.
- Divertor cryo-pump, outer lower divertor PFCs will be implemented in the base plan.

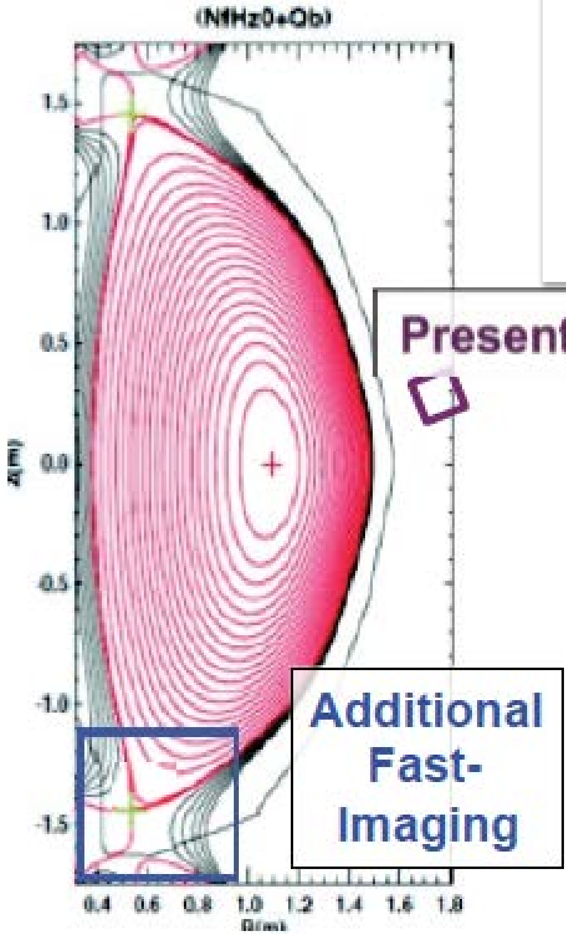
Back-up Slides

MIT PSFC Complements Well Existing NSTX-U Capabilities

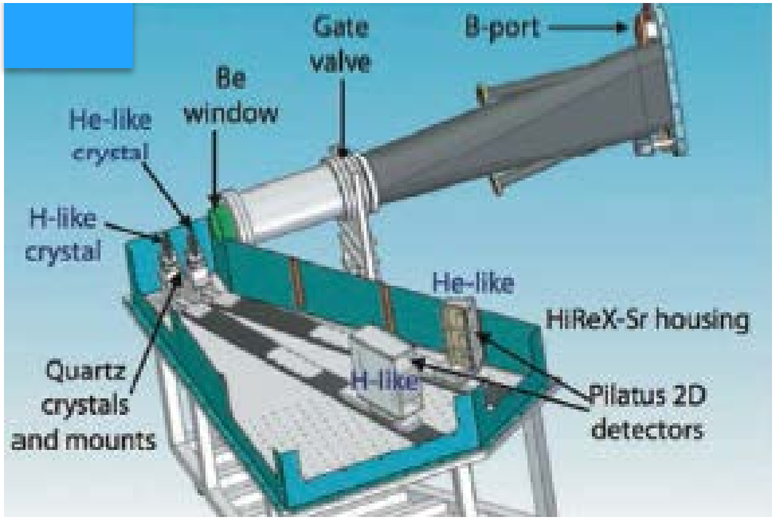
Discussions Started on Various Diagnostic Implementations

MIT will enhance NSTX-U GPI systems

Avalanche-PhotoDiode (APD)-based GPI



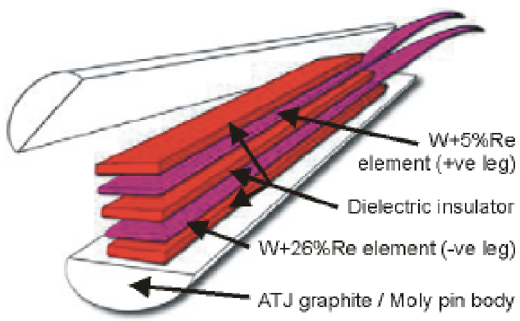
X-ray Imaging Crystal Spectroscopy



MIT is developing a next generation, servo-driven, compact scanning MLP system

Enhanced Capability for PMI Research
Multi-Institutional Contributions

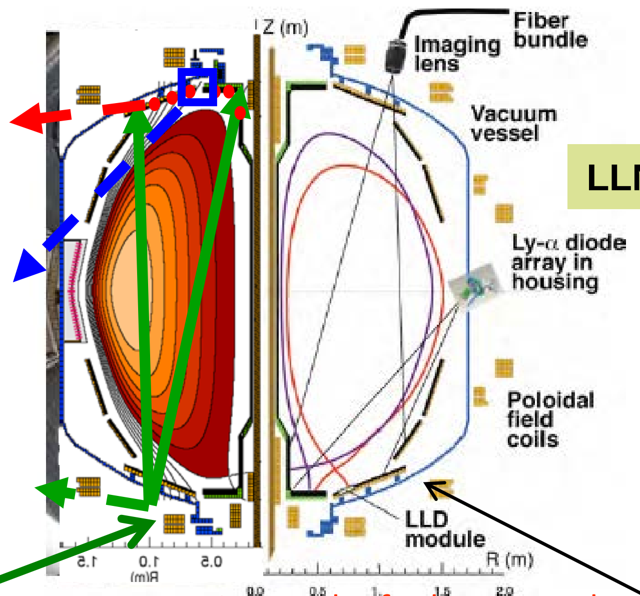
Divertor fast eroding thermocouples



ORNL

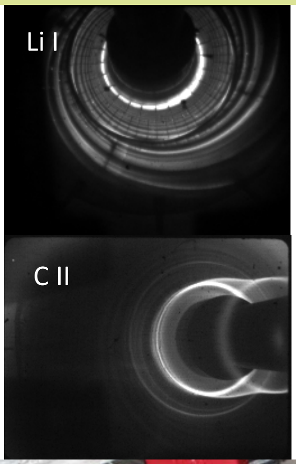
Divertor Imaging Spectrometer

LLNL

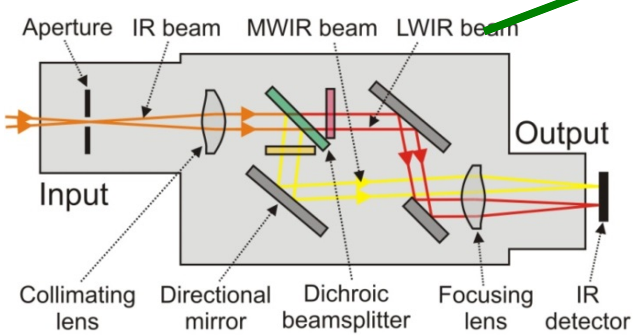


Multiple fast 2D visible and IR cameras with full divertor coverage

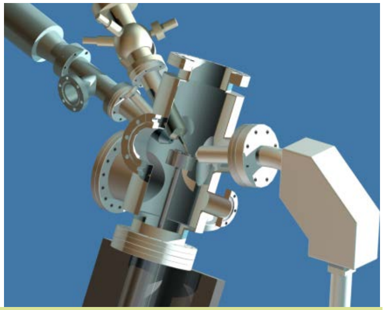
LLNL, ORNL, UT-K

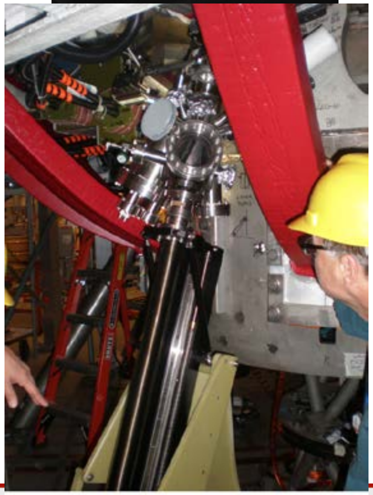


Dual-band fast IR Camera



MAPP probe for between-shots surface analysis – Now taking data



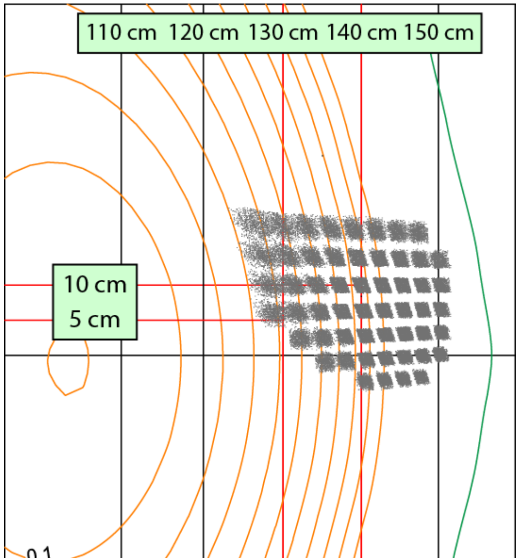


U. of Illinois, PPPL

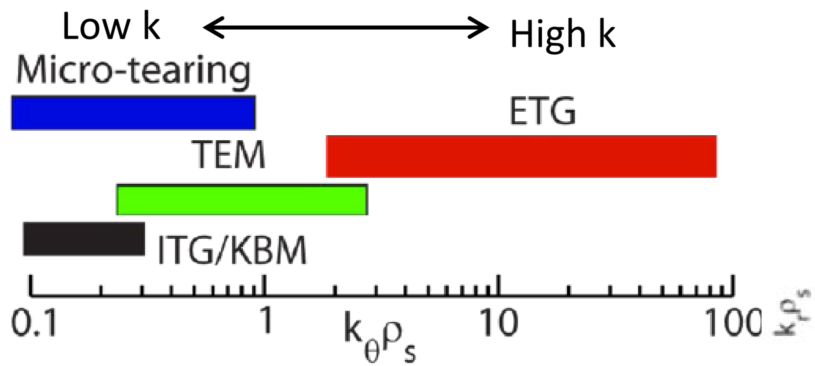
Microturbulence Diagnostics Being Enhanced

To measure ion to electron gyro-scale, magnetic fluctuations

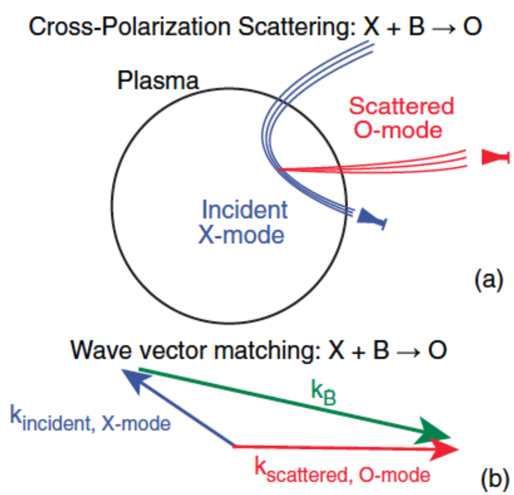
Beam Emission Spectroscopy
for low k turbulence
48 chs being readied



U Wisconsin

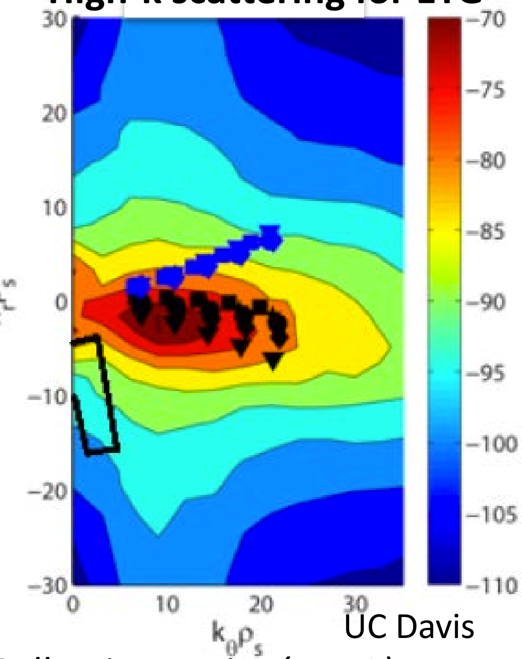


Cross-Polarization Scattering for magnetic fluctuations being developed in collaboration with DIII-D and MAST



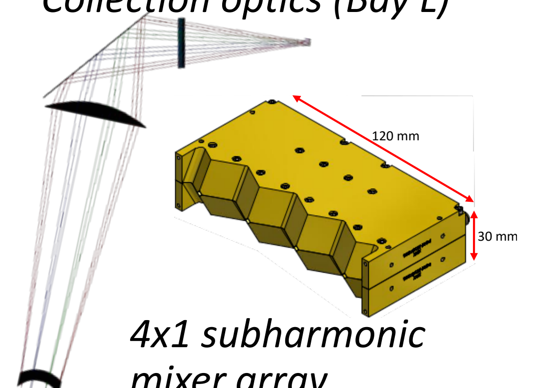
4–channel CPS system in 2017 UCLA

High-k scattering for ETG



UC Davis

Collection optics (Bay L)



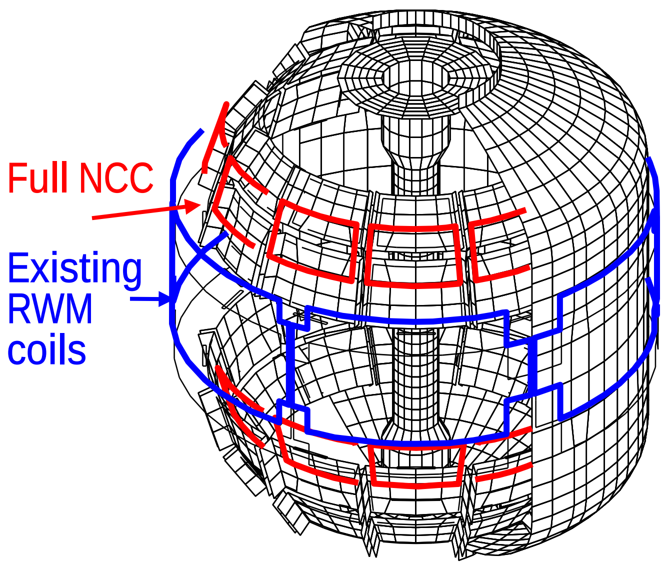
4x1 subharmonic mixer array

Available for FY 17

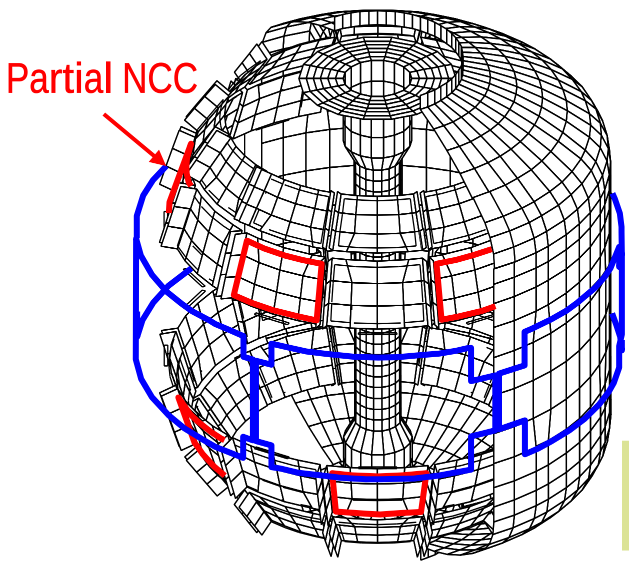
Flexible Mid-Plane Feedback Coils for MHD Studies

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

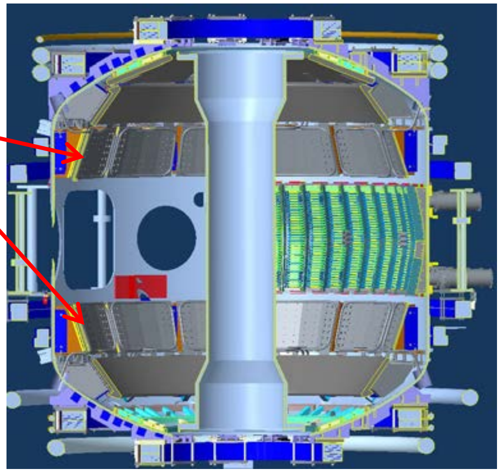
- 6-channel Switching Power Amplifier (SPA) powers independent currents in existing EFC/RWM Coils supporting experiments
- NCC (a facility enhancement) can provide various NTV, RMP, RWM, and EF selectivity with flexibility of field spectrum (n ≤ 6 for full and n≤ 3 for partial)

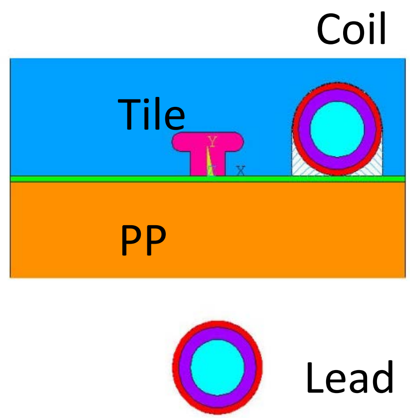
Base Budget – NCC engineering conceptual design work to develop reliable cost and schedule is being concluded to focus engineering resources to divertor cryo-pump design. CDR in May 2016.

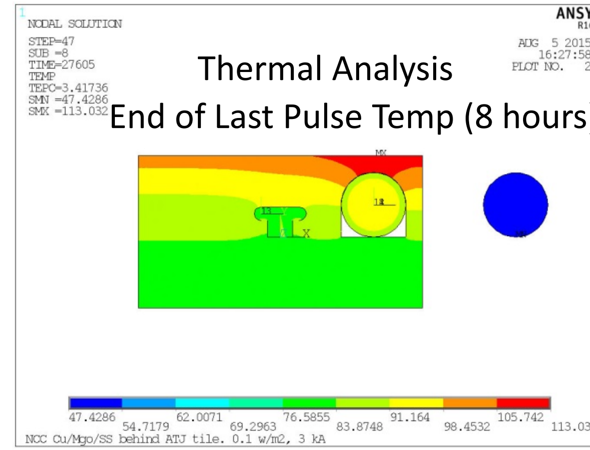
Incremental Budget – Enables continued design, development, and installation of NCC.

NCC Coils Design Activity Made Significant Progress
Test area prepared to perform conductor sample R&D

NCC = Non-axisymmetric Control Coil

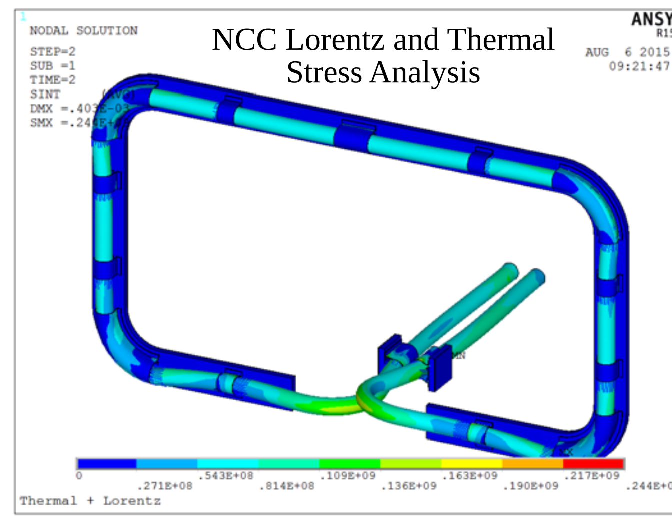






3 kA,0.1 MW/m2 Plasma Heating,5s pulse,1200 s reprate

- **Candidate conductor for test sample received for R&D.**
- **R&D facility prepared and test being conducted.**
- **The R&D selection criteria include thermal capability, manufacturability, impact on interfacing objects, fabrication lead time and cost.**
- **Cost and schedule will be prepared as part of the CDR which is targeted for May, 2016.**



With Lead Clamp, 50 C Heat-up, 3kA+ Background Field

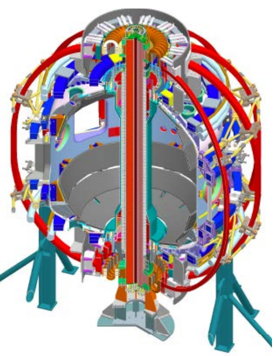
Five Year Facility Enhancement Plan (green – ongoing)

Incremental enables 5 year plan enhancements including NCC, ECH

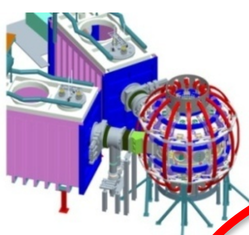
Fiscal Year:	2015	2016	2017	2018	2019
	Upgrade Outage	1.5 → 2 MA, 1s → 5s			
Run Weeks:		18	16	12-16	10-12

Major enhancements:
- ● Base funding
- ○ incremental funding

New center-stack



2nd NBI



Boundary Science + Particle Control

Pulse-burst MPTS
Boronization
High-Z tile row on lower OBD

Li granule injector
LiTER
MAPP
Upward LiTER
Resistive Bolometer
Scanning MLP
APD-based GPI
High-Z PFC diagnostic
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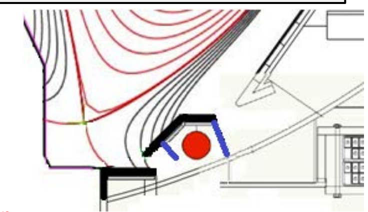
Graphite CHI/Lower Bullnose



Core Science

MGI disruption mitigation
XICS
Upgraded halo sensors
sß
42 ch MPTS
Laser blow-off
48 ch BES
High k_θ
MSE/LIF
Charged fusion product
4 coil AE antenna
CPS δB diag.
Off-midplane 3D coils (NCC)
Enhanced MHD sensors
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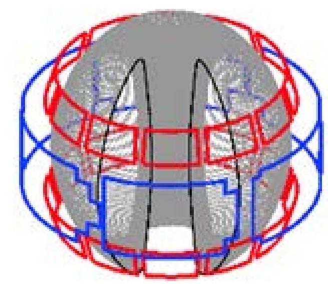
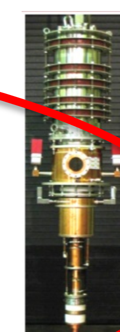


Integrated Scenarios

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



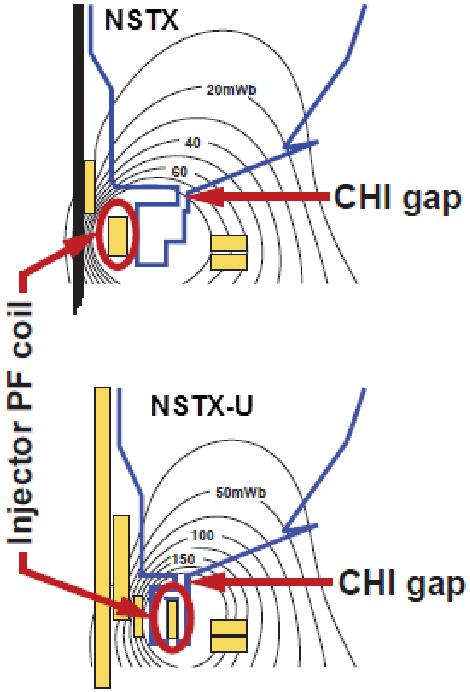
Solenoid-free start-up in support of ST-FNSF

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

CHI Start-Up in NSTX-U

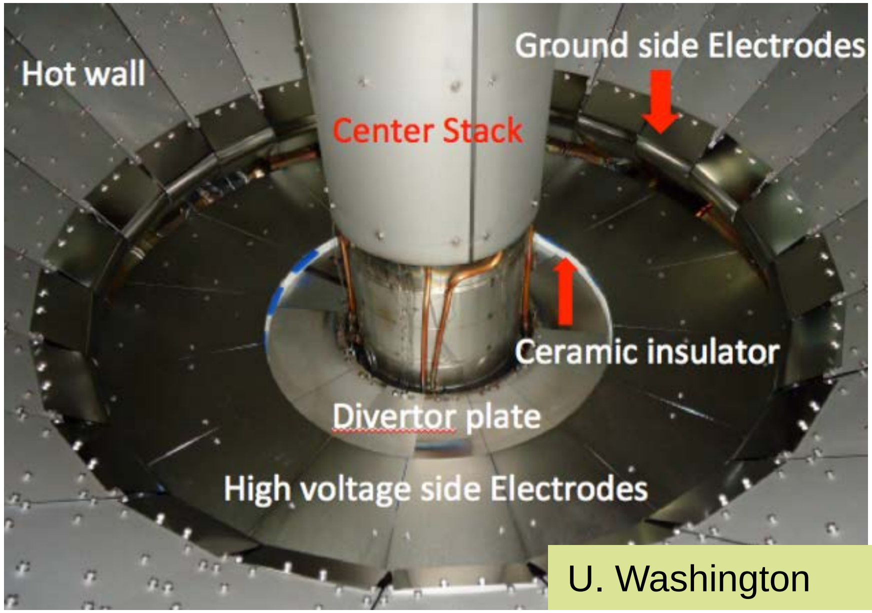
- Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX
- NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation

U. Washington



- The resistive voltage divider network was made functional, and many of the components related to a fast voltage monitoring system were installed.
- All of the connections of the gas lines to the CHI gas injection systems have been completed.
- Initial testing of the CHI system into a plasma load will begin in the near future.

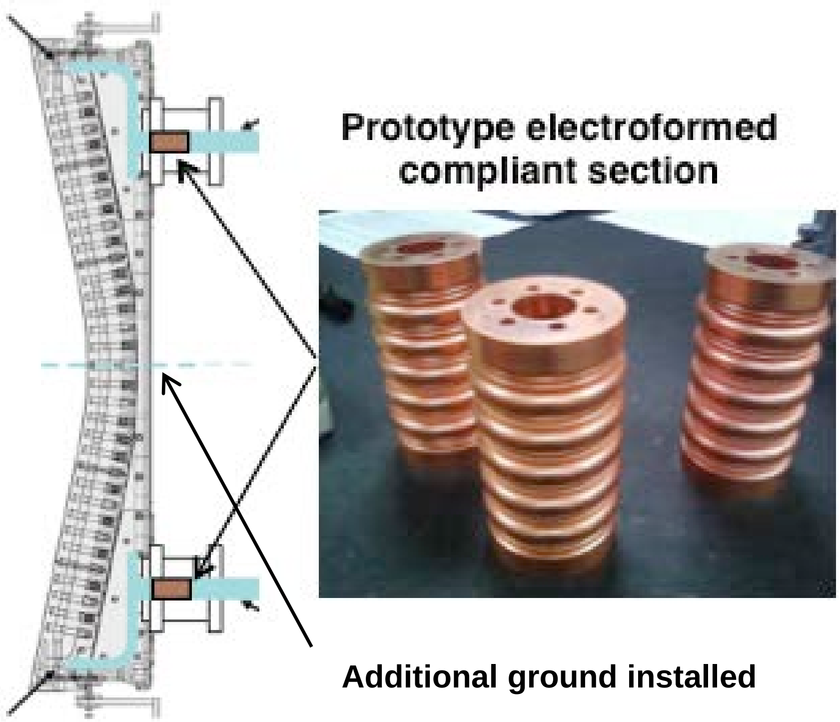
QUEST CHI Experiment to test high-Z electrode operation



- An ST-FNSF like CHI configuration will undergo plasma tests on QUEST after FY 2016 NSTX-U operation (after July 2016).
- All metal (high-Z) CHI electrodes provide valuable information for NSTX-U (presently graphite electrodes)

HHFW system will be ready for operation
Antenna plasma conditioning to start in May

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 installed & tuned.

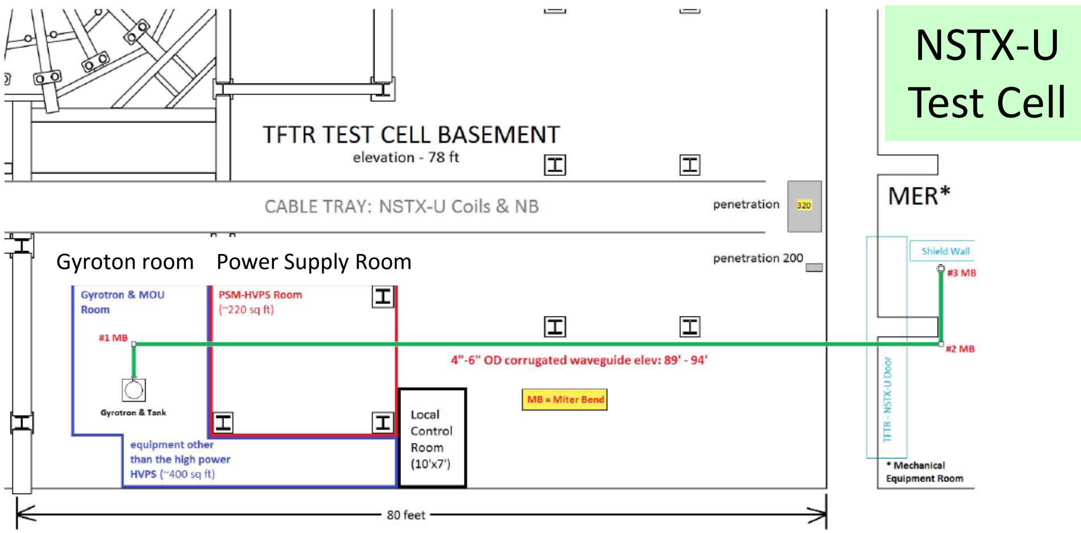
- **All sources will be ready to support HHFW operation in May.**

28 GHz ECH System Design Progressing Well

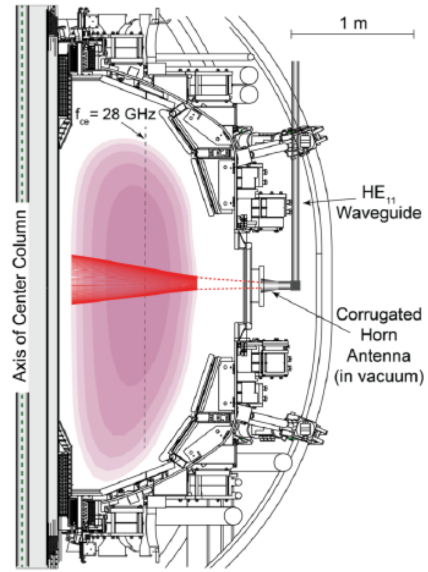
Complete conceptual design and cost/schedule this year

- 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 2019 run with 15% incremental funding.

28 GHz Gyrotron Room



Gyrotron will be located in the TFTR basement. Stray magnetic fields was measured to be negligible



28 GHz 1 MW Tube by Tsukuba

28 GHz Gyrotron Development

- 2nd generation 1.5 MW 28/35 GHz gyroton being developed at Tsukuba University. (See back-up slide). Power test to start in May.
- Incremental budget enables continued design and procurement of the ECH system.

U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

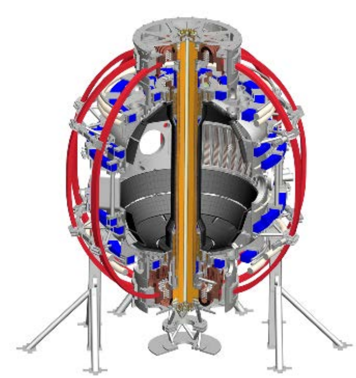
NSTX-U Program FY2016 Q2 Report

Jon Menard, Masa Ono (PPPL)

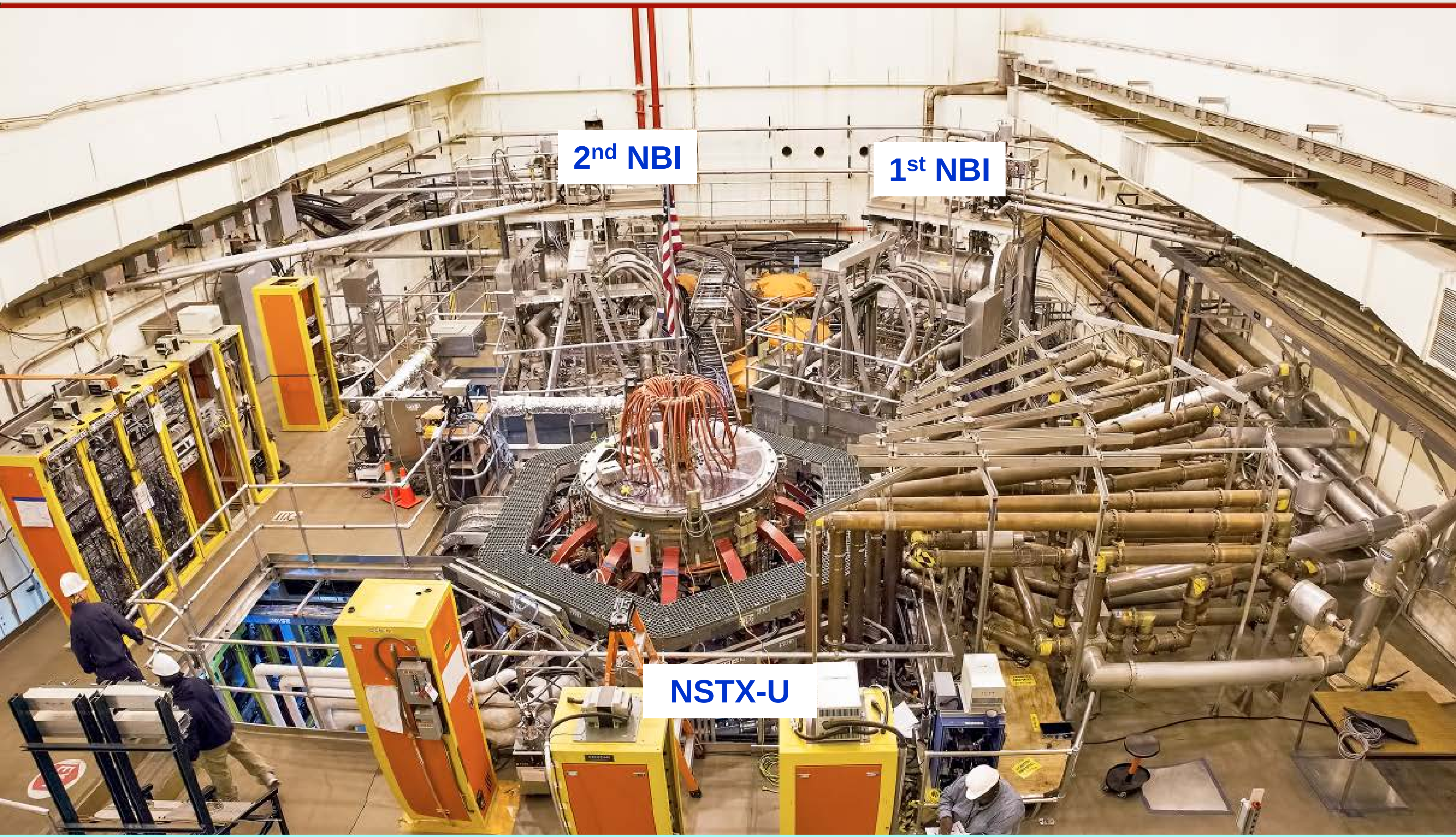
For the NSTX-U Team

PPPL and FES
May 3, 2016

PPPL



NSTX-U is a Functioning Research Facility



All six NBI sources are now operational, supporting high performance experiments

A Sequence of eXperiment Machine Proposals (XMPs) Has Been Defined to Commission the Machine

Arrow = Planned Before Run

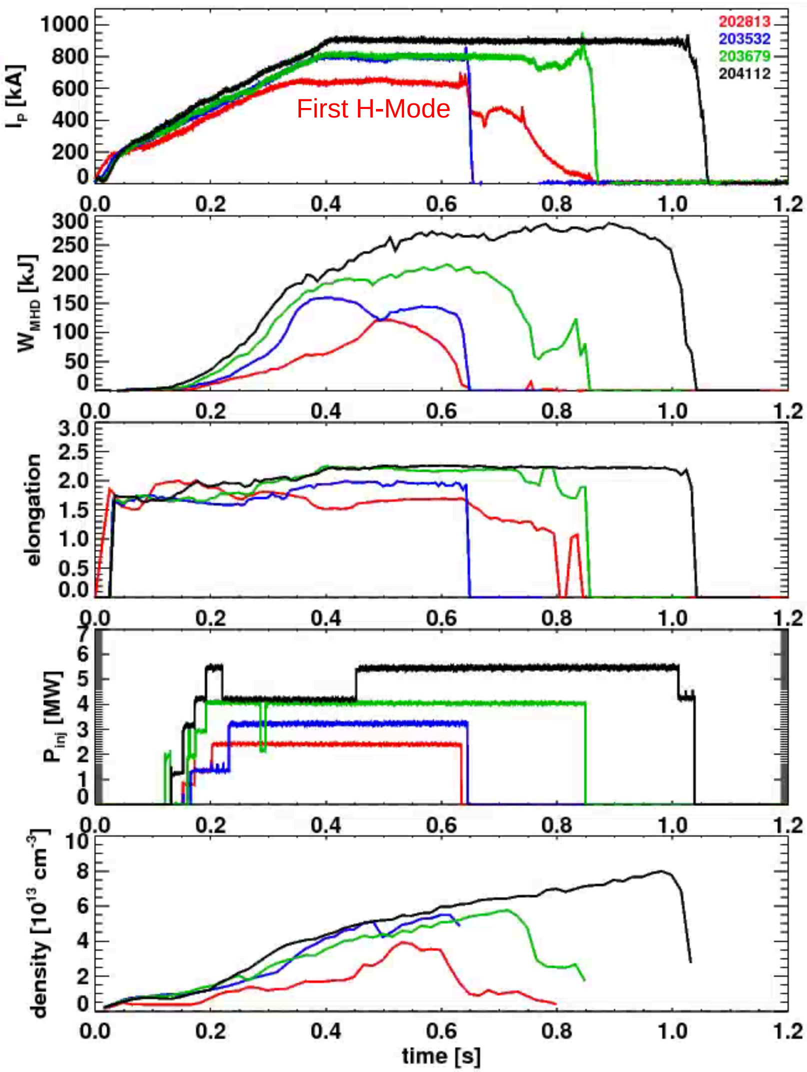
Green = Complete
Blue = Ongoing
Black=No Started

XMP-101: Breakdown Optimization	(Battaglia)
XMP-126: I_P & R Control	(Mueller)
XMP-105: Software Tests for n=0 Control	(Boyer)
XMP-115: ISOFLUX Commissioning	(Boyer)
XMP-116: Initial H-Mode Development	(Battaglia)
XMP-127: Neutral Beam Commissioning	(Boyer)
XMP-107: Neutron Calibration Transfer	(Darrow)
XMP-120: Strikepoint & X-Point Control	(Boyer)
XMP-128: Increase L-Mode Elongation	(Battaglia)
XMP-132: Fast Rampdown Sequence Commissioning	(Gerhardt)
XMP-137: Increase κ and I_P in L- and H- Mode	(Battaglia)
XMP-138: Improved Vertical Control Checkout	(Boyer)
XMP-121: SPA & RWM Control Checkout	(Gerhardt, Myers)
XMP-140: PF-5 Proportional EFC Test	(Gerhardt)
XMP-141: Proportional EFC Tests	(Myers)
XMP-142: Reduced MHD H-Mode Development	(Battaglia)
XMP-146: Higher-Order Feed Forward EFC in L-Mode	(Myers)
XMP-147: Improve L-Mode Fiducial	(Boyer)
XMP-148: Between-Shot TRANSP Validation	(Kaye)
XMP-110: ssNPA & FIDA checkout	(Liu)
XMP-150: He Density Scan for Z_{eff} Calibration	(Skinner)
XMP-151: L-Mode Development for Cora and Boundary XPs	(Guttenfelder)
XMP-114: CHERS Modulation Study	(Bell)
XMP-125: MSE-CIF 2nd NB Interference Study	(Levinton)
XP-1506: Low Beta n=1 EFC	(Myers)

*This is the complete commissioning list…**almost done**!*

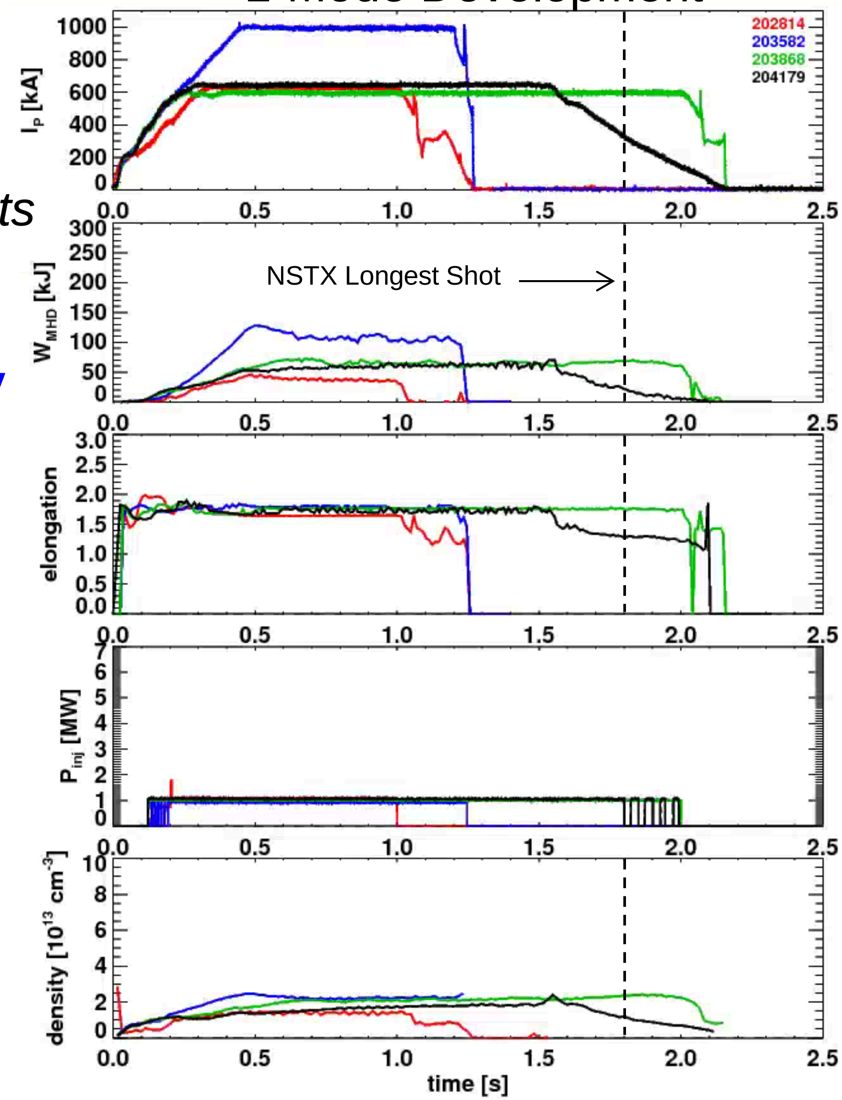
Substantial Progress in Developing L- and H-Mode Scenarios

H-Mode Development

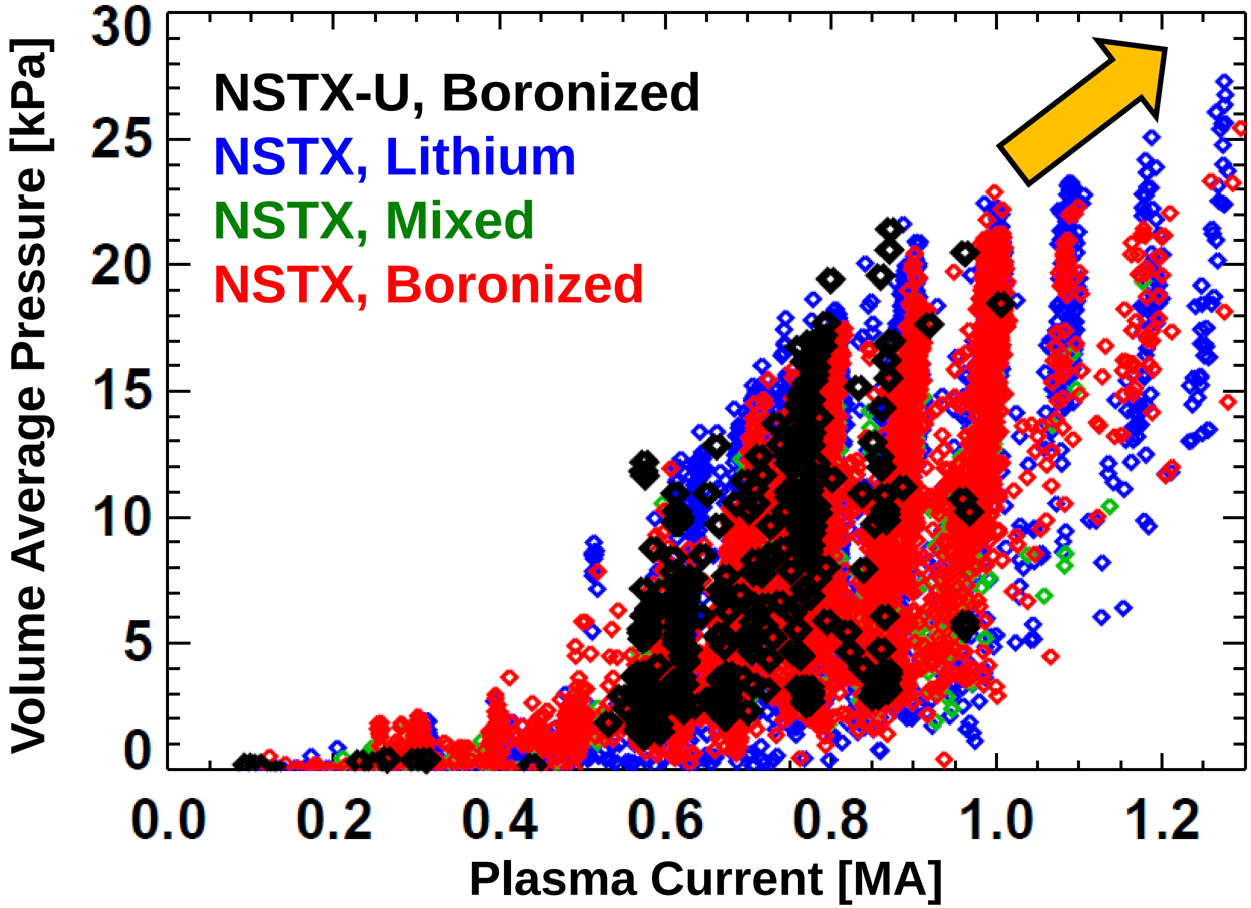


"Best" Shots From
January
February
March
April

L-Mode Development



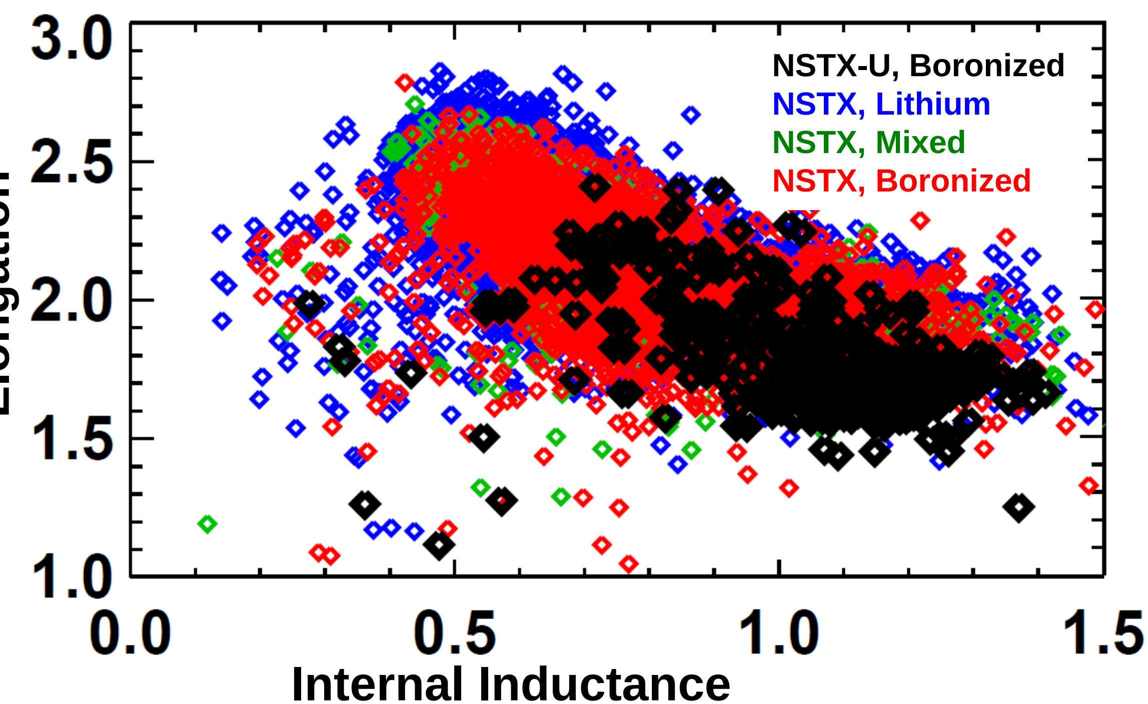
NSTX-U has matched NSTX highest flat-top pressures for plasma currents up to 0.9MA

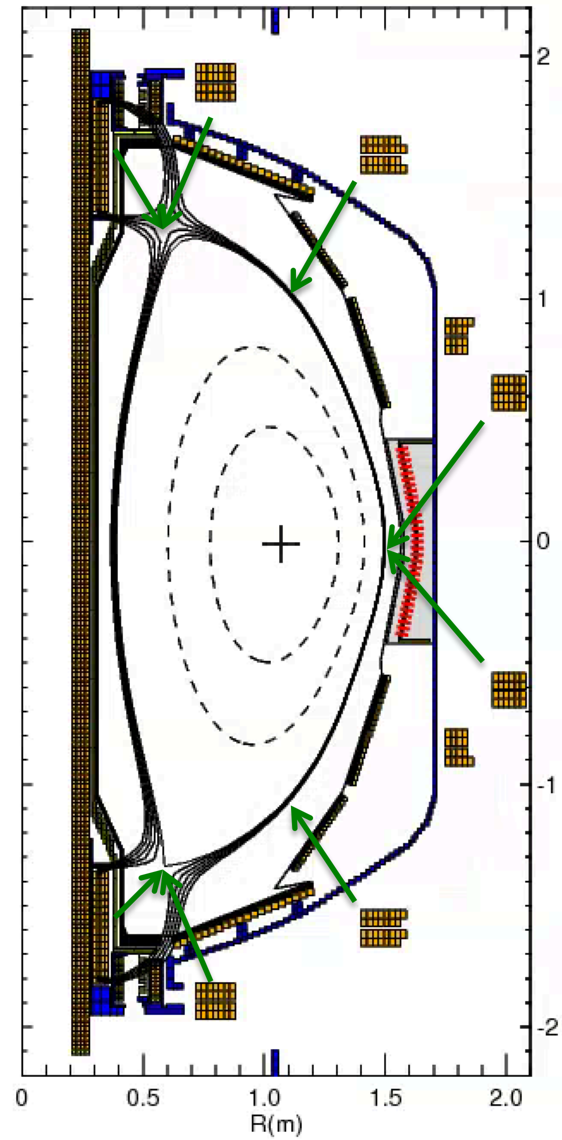


- **Near-term: I_P → 1.1 – 1.3MA**

Shape and Vertical Position Control Are In Good Position to Support the Future Experiments

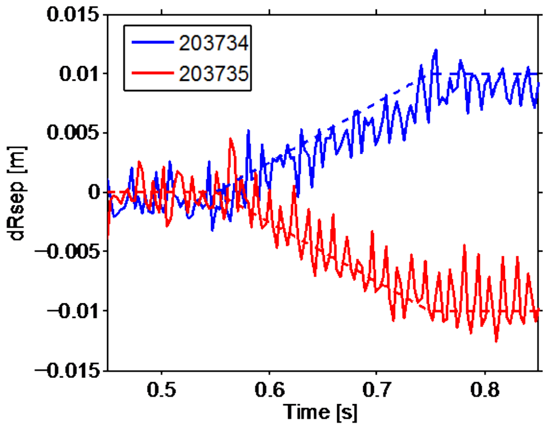
- rtEFIT/ISOFLUX control established for the plasma radius, vertical position, X-points.
  - NSTX didn't routinely do closed loop X-point control.
  - Now multi-threaded rtEFIT with greater capabilities
- New vertical control sensors & algorithms -> matching the NSTX elongation for the same l_i, but at higher A.

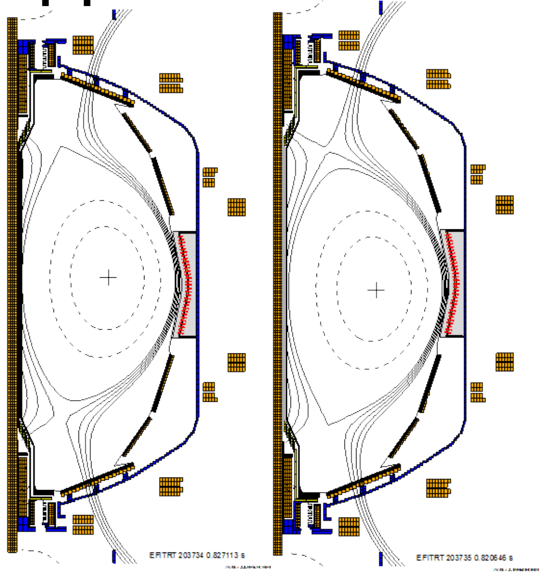


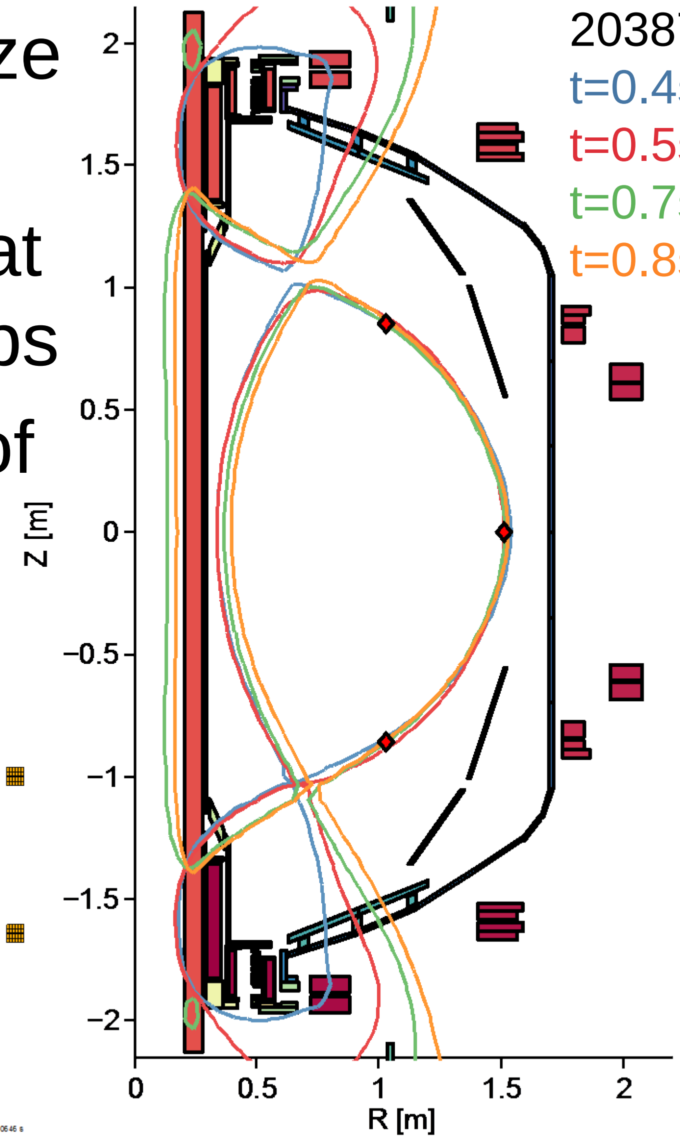


rtEFIT/ISOFLUX commissioned to control gaps and x-point/strike-point locations

- rtEFIT upgraded to 65x65 grid size
- Demonstrated ability to control steps in the strike-point location at fixed x-point height and outer gaps
- Demonstrated feedback control of drSep to produce upper/lower biased shapes

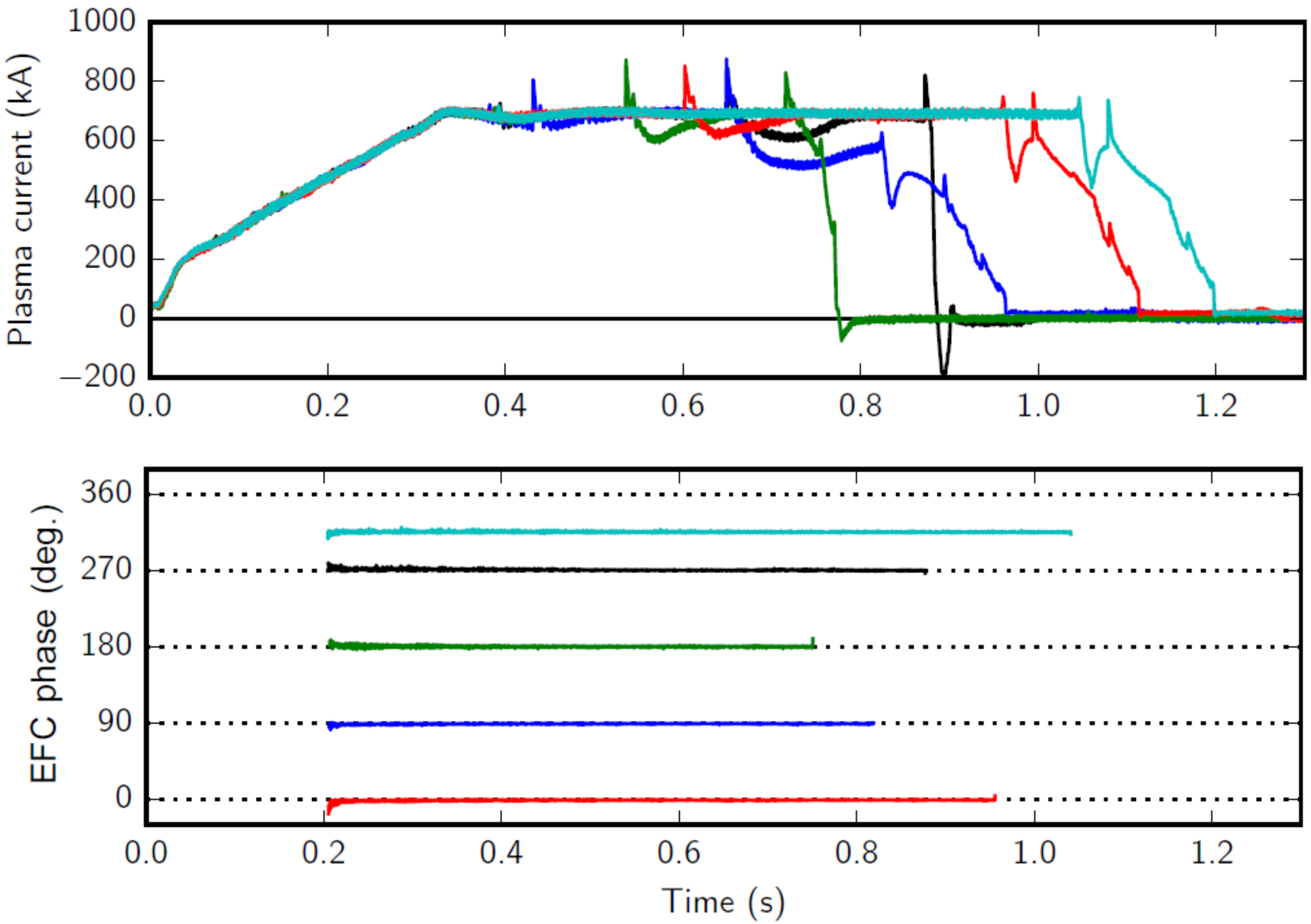






Discharge Development Aided by n=1 Error Field Correction

- Dominant error-field source: vertical field coils
- Long-pulse L-modes used to identify optimal correction amplitude, phase

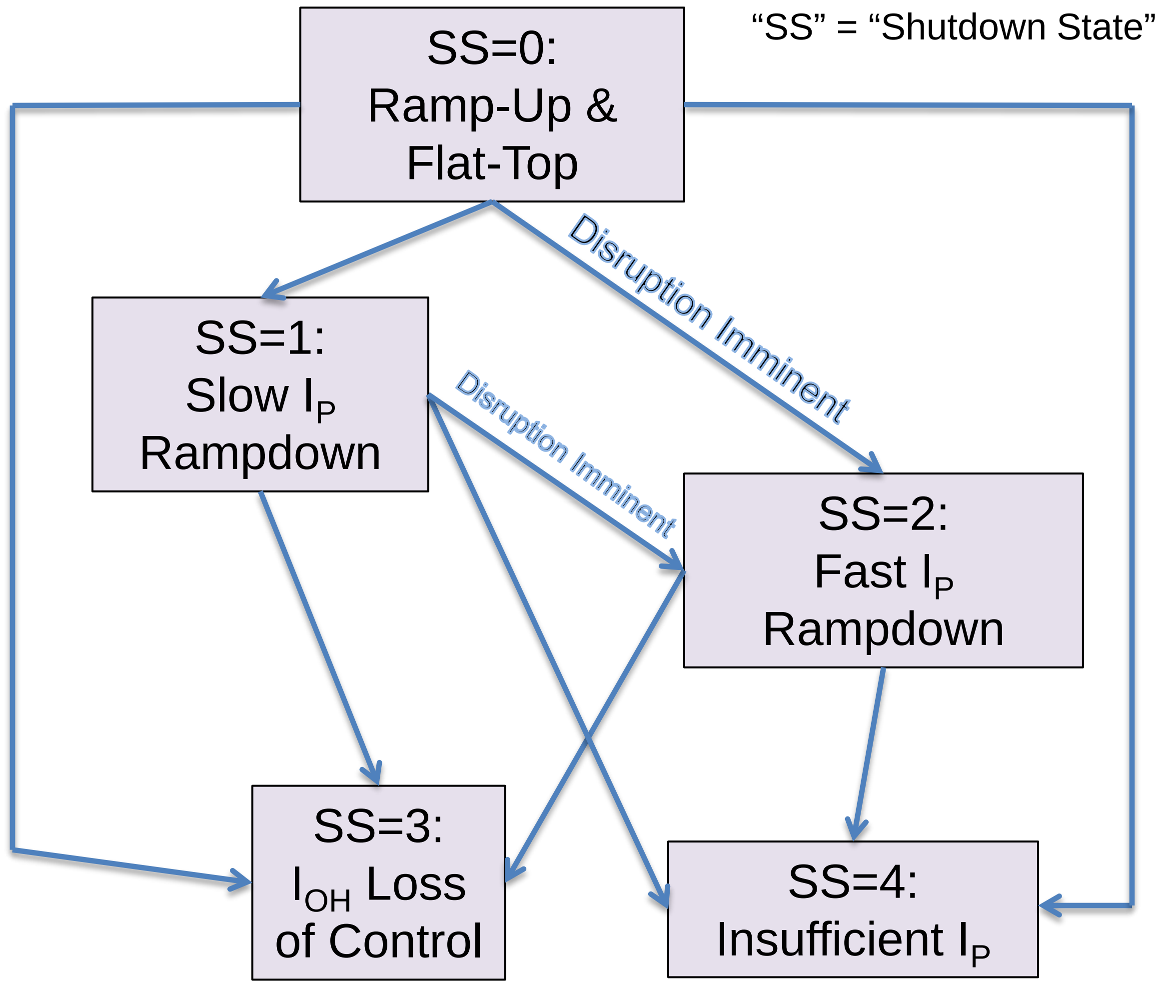


Use this EFC on every shot now

Will soon deploy feedback-based error field correction

NSTX-U Experiments Are Using a Significantly Expanded Plasma Shutdown Scheme

- **NSTX PCS**: No means of detecting a disruption, or ramping down the plasma current based on events.
- **NSTX-U PCS**: State machine orchestrates the shutdown.



NSTX-U Experiments Are Using a Significantly Expanded Plasma Shutdown Scheme

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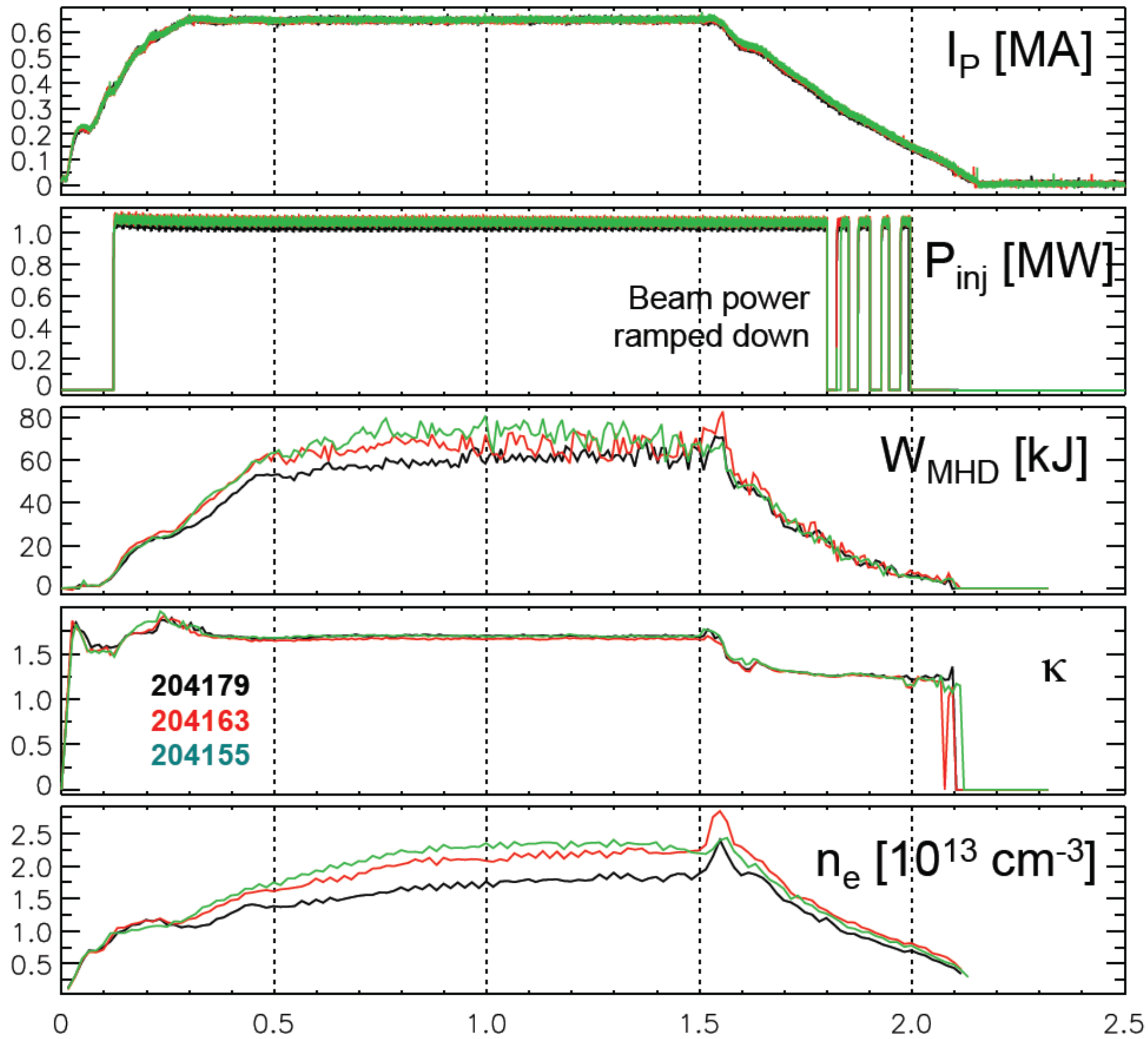
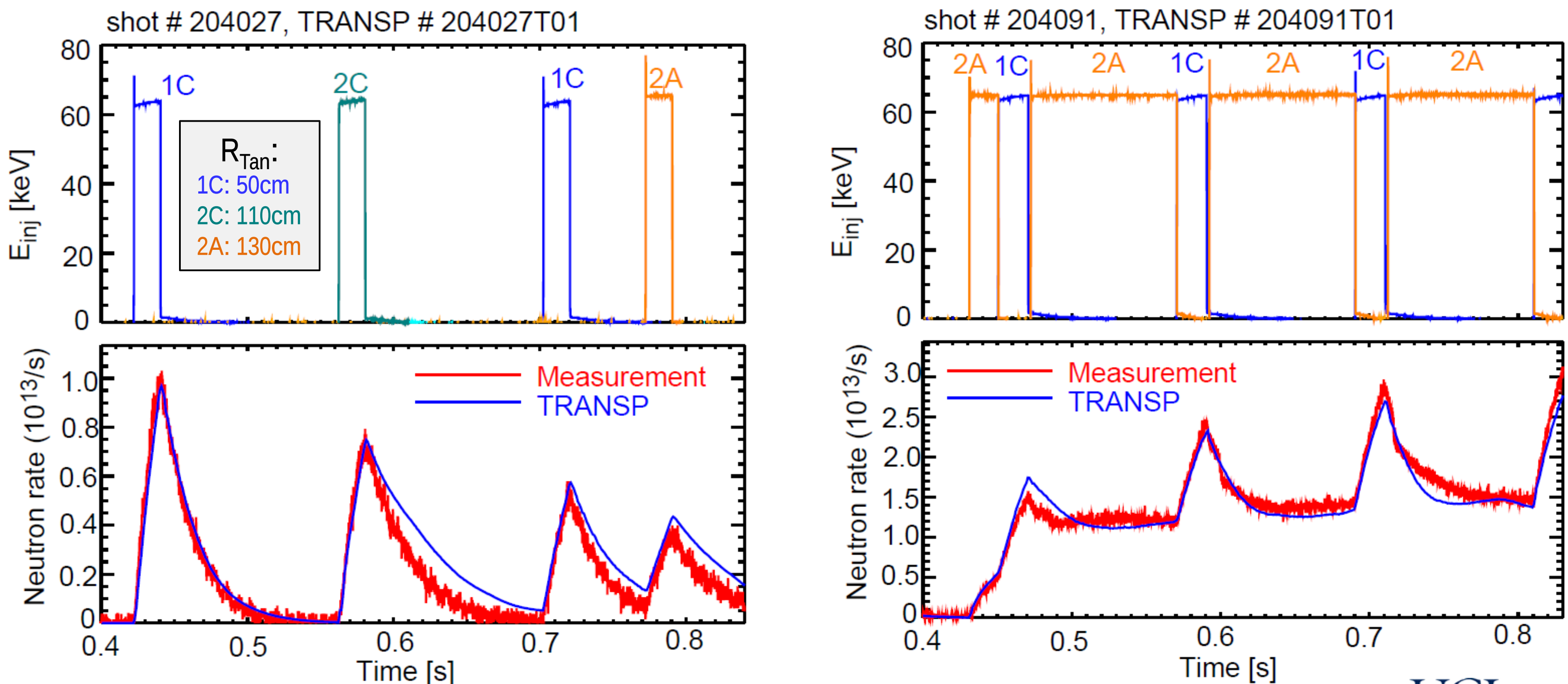
- **NSTX-U PCS**: State machine orchestrates the shutdown.

Rampdown Development and Disruption Detection/Avoidance are Key Parts of our JRT & ITER support contributions



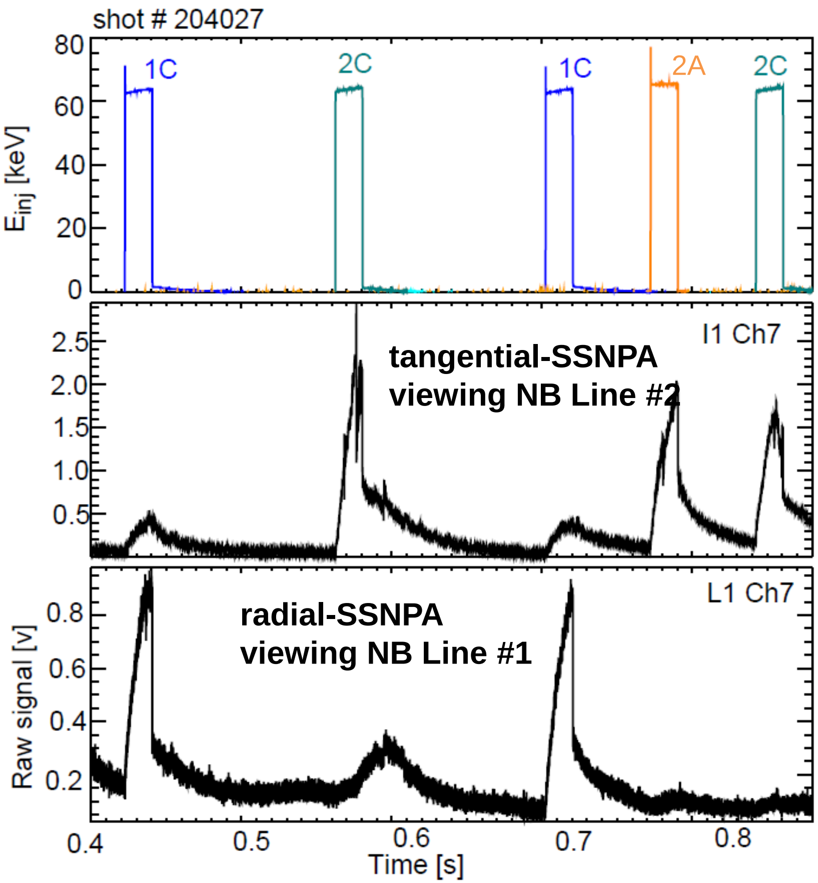
New NSTX-U result (preliminary): 2nd NBI fast-ion behavior consistent with classical slowing-down theory

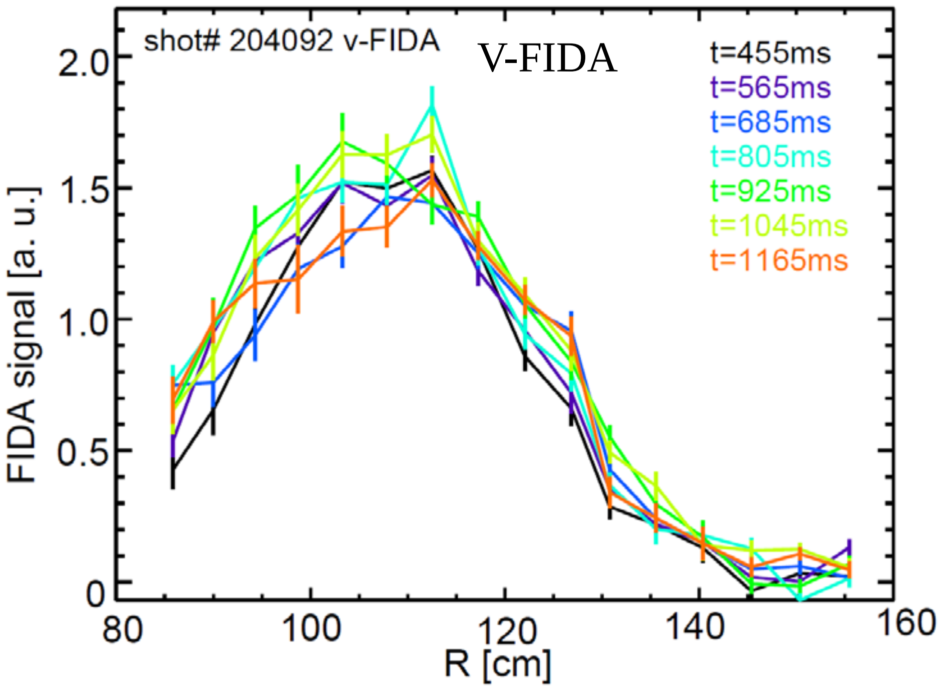


UCIRVINE

- ➢ The magnitude, rise and decay rates of neutron signal reasonably agree with the TRANSP prediction which assumes fast ions behave classically
  - Some discrepancy in decay rates → need to further refine the kinetic profile measurements

Good First Data Obtained on SSNPA and fast-ion D_α (FIDA) Diagnostics

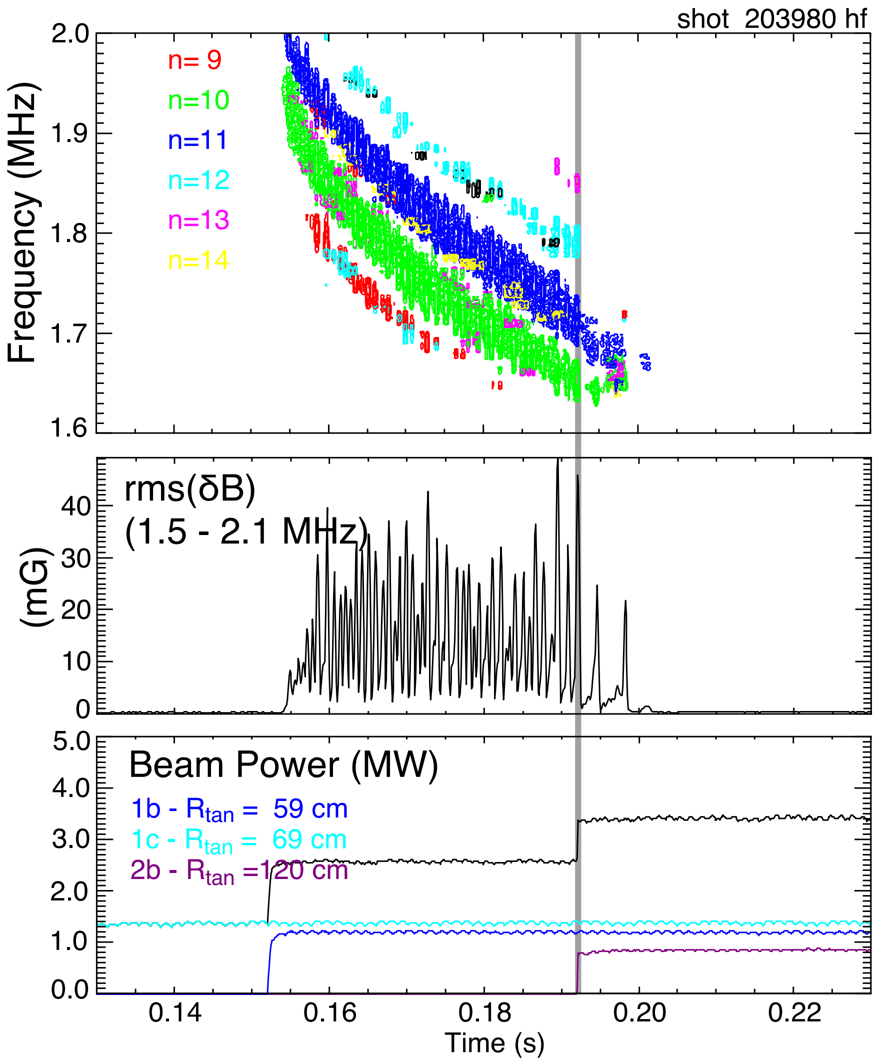




- SSNPA and FIDA diagnostics response to NB line #1 and line #2, as expected
- Active & passive responses are clearly observed
- Detailed analysis and quantitative comparison with classical theory are underway

New NSTX-U result: Suppression of counter-propagating GAE observed for large R_{TAN} 2nd NBI

- Top panel:
  - GAE excited by inboard sources 1B / 1C (blue / cyan, lower panel)
- Injection of outboard source 2B starts at 0.192s results in suppression of GAE.
  - Suppression time ~10ms
  - Suppression also with 2A, 2C
- Observations consistent with model of cyclotron-resonant drive of GAE
- Will investigate whether GAE absence impacts electron thermal transport

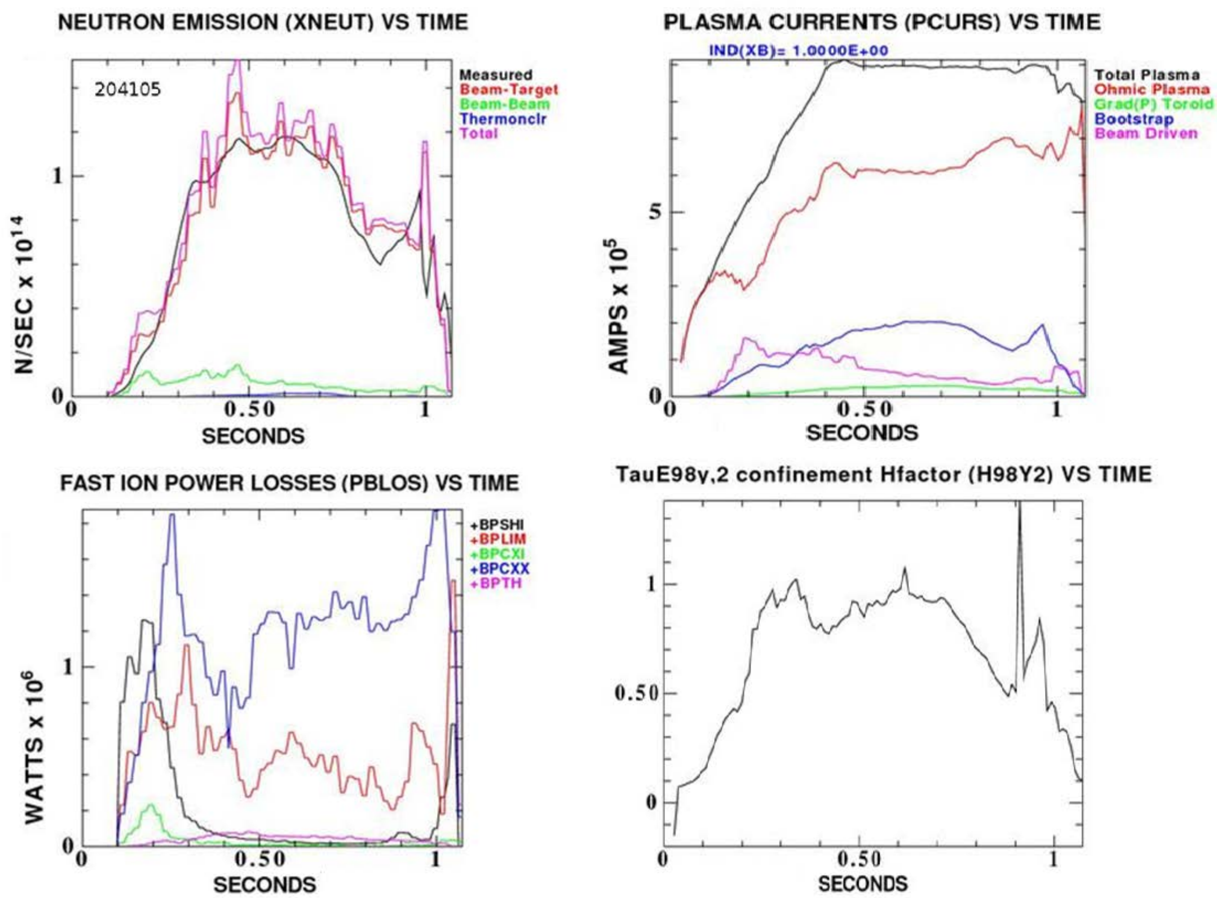


→ 2nd NBI already powerful new tool for Fast Ion and AE physics

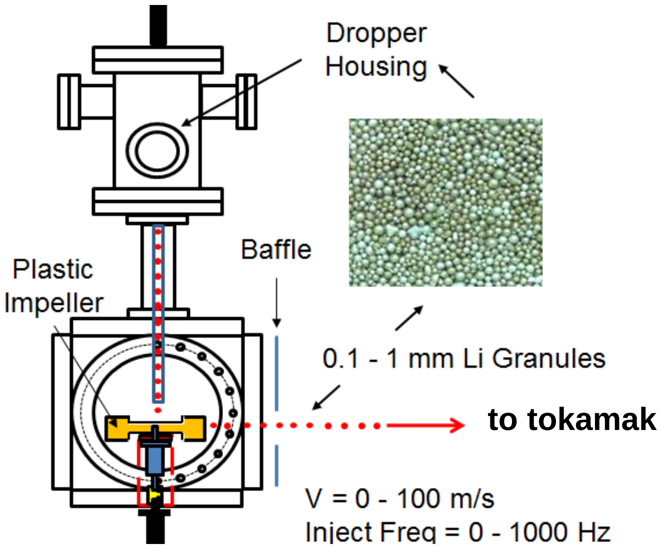
New NSTX-U tool: Between and Among Shot TRANSP (BEAST) will aid experiment execution

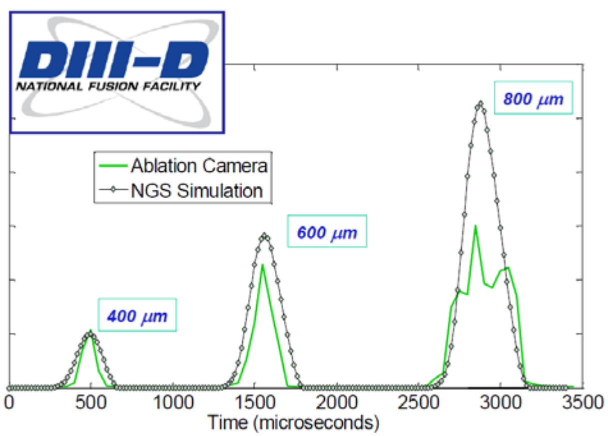
- Typical BEAST run completed in 8 mins
  - NSTX-U has 15-20 mins between shots
- In preparation for next shot, session leader can gauge:
  - Non-inductive fraction
  - Beam loss
  - Confinement quality
  - Any TRANSP quantity…

NSTX-U BEAST TRANSP run (no CHERS)



Impurity Granule Injector (IGI) will be used on NSTX-U for pedestal / ELM /density control, scenario optimization





The ablation intensity is plotted vs time, NGS field parameters (η, f_B, f_L) are set to match calculated ablation time with measurements for a typical 800 micron granule. Peak ablation intensity and NGS rate are normalized for the smallest granule size.

- Successful EAST and DIII-D demonstrations / collaborations
  - Capable of up to 0.5 kHz injection
- IGI will be tested on NSTX-U for high-frequency ELM pacing
  - Possible density control technique:
    - Combine Li coatings for D pumping with LGI for ELM-expulsion of carbon
  - Goal: reduce Z_{eff} to ~2-2.5
  - Injection of Li granules could also potentially replenish PFC Li coatings
- Using Neutral Gas Shielding (NGS) model to interpret granule ablation and penetration depth vs. mass

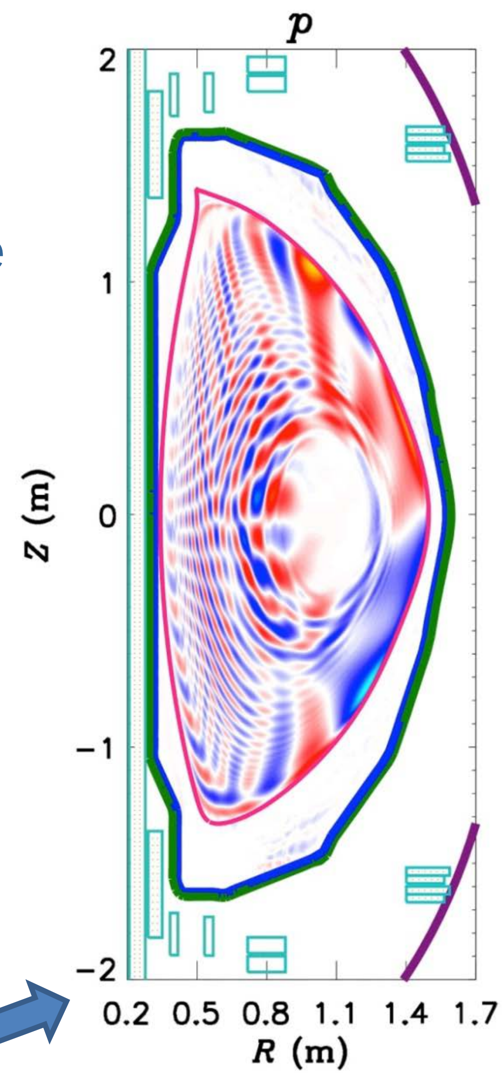
NSTX-U / STs will improve understanding of RMP ELM mitigation / suppression physics

- ELMs in STs and tokamaks respond to applied 3D fields in different ways
  - RMP ELM suppression not achieved in STs (yet)
    - 3D fields triggered ELMs in NSTX
  - Understanding such differences could greatly improve confidence in scaling RMP ELM mitigation to ITER

- NSTX-U (with MAST-U) offer a unique capability to validate ELM suppression models across the ST and tokamak regimes

- Modeling goal: Combine models of 3D perturbed equilibrium (M3D-C1) and transport (XGC) to yield a quantitative, predictive model for transport in 3D fields

- M3D-C1 is being used to predict and optimize plasma response to NCC coils in NSTX-U



Making Good Progress on Milestones (I)

- **R16-1:** Assess H-mode energy confinement, pedestal, and SOL characteristics with higher B_T, I_P and NBI heating power.
  - All key diagnostics are taking data, except MSE (waiting for NB1A at full voltage)
  - Checking data consistency via TRANSP and awaiting final H-mode scenarios.
- **R16-2:** Assess effects of NBI parameters on fast ion distribution function and neutral beam driven current profile.
  - Neutron, FIDA, ssNPA diagnostics all functional
  - Started studies of fast ion confinement vs. R_{tan} & effect of NB#2 on *AE modes.
- **R16-3:** Develop physics and operational tools for high-performance discharges.
  - Developed shape & vertical control, EFC, HFS & LFS fueling, automated shutdown.
  - Will soon commission n=1 RWM control, V_{loop} dependent EFC
- **Notable Outcome:** Perform experimental research …at magnetic field, I_P, pulse length beyond that achieved in NSTX….
  - Using discharges that exceed NSTX durations, at field exceeding the NSTX field.
  - Increasing I_P > NSTX I_P requires improved H-mode scenarios, under development.

Making Good Progress on Milestones (II)

- The JRT overlaps with a Notable Outcome:
  - **JRT:** Conduct research to detect and minimize the consequences of disruptions in present and future tokamaks
  - **Notable Outcome:** Conduct NSTX-U experiments and data analysis to support the FES joint research target ….
- We are making good progress on these tasks:
  - Automatic shutdown algorithms developed
  - Detecting disruptions in real-time via the I_P error, vertical motion, and (soon) the n=1 locked mode signature.
  - MGI will use an electromagnetic valve similar to ITER design
    - MGI valves are installed on the machine
    - Associated electronics are in pre-operational testing.

32 Priority 1 eXperimental Proposals (XPs) prepared/in-prep to complete research milestones

Will run soon / next

Already had run time

XP author first name	XP author last name	XP number and title - author (responsible group)
Dan	Boyer	XP1501 Optimization of vertical control algorithm - Dan Boyer (ASC-TSG)
Stefan	Gerhardt	XP1502 Tuning of the Automated Rampdown Software - Stefan Gerhardt (ASC-TSG)
Egemen	Kolemen	XP1503 X-point control integration with shape control - Egemen Kolemen (ASC-TSG)
Dan	Boyer	XP1504 Beam power and beta-N control - Dan Boyer (ASC-TSG)
Charles	Skinner	XP1505 Boronization Optimization - Charles Skinner (MP-TSG)
Clayton	Myers	XP1506 Low-beta, low-density locked mode studies - Clayton Myers (MS-TSG)
Stefan	Gerhardt	XP1507 Maximizing the non-inductive current fraction in NSTX-U H-modes - Stefan Gerhardt (ASC-TSG)
Egemen	Kolemen	XP1508 Controlled Snowflake Studies - Egemen Kolemen (ASC-TSG)
Dan	Boyer	XP1509 Combined betaN and li feedback control - Dan Boyer (ASC-TSG)
Rory	Perkins	XP1510 Characterizing the SOL Losses of HHFW Power in H-Mode Plasmas - Rory Perkins (RF-TSG)
Michael	Bongard	XP1511 Multi-machine studies of the L-H power threshold dependence on aspect ratio - Michael Bongard (PS-TSG)
Ahmed	Diallo	XP1512 Characterization of the Pedestal Structure as function Ip, BT, and Pnbi - Ahmed Diallo (PS-TSG)
Travis	Gray	XP1514 Relationship Between Plasma Turbulence and SOL Width Scaling in NSTX-U - Travis Gray (DS-TSG)
Clayton	Myers	XP1515 High-beta n=1,2,3 error field detection and correction - Clayton Myers (MS-TSG)
Clayton	Myers	XP1516 Optimization of PID dynamic error field correction - Clayton Myers (MS-TSG)
S.A.	Sabbagh	XP1517 Neoclassical toroidal viscosity at reduced collisionality (independent coil control) - S.A. Sabbagh (MS-TSG)
S.A.	Sabbagh	XP1518 RWM PID control optimization based on theory and experiment - S.A. Sabbagh (MS-TSG)
Roger	Raman	XP1519 Massive Gas Injection Studies on NSTX-U - Roger Raman (MS-TSG)
Stan	Kaye	XP1520 Ip/Bt scaling - Stan Kaye (TT-TSG)
Yang	Ren	XP1521 Validation of gyrokinetic codes in NSTX-U NBI-heated L-mode plasmas - Yang Ren (TT-TSG)
Deyong	Liu	XP1522 Beam ion confinement of 2nd NBI - Deyong Liu (EP-TSG)
Mario	Podesta	XP1523 Characterization of 2nd NBI line - Mario Podesta (EP-TSG)
Bill	Heidbrink	XP1524 AE Critical Gradient - Bill Heidbrink (EP-TSG)
Neal	Crocker	XP1525 Rotation effects on CAEs and GAEs - Neal Crocker (EP-TSG)
Michael	Jaworski	XP1526 Establish heat transmission pathways in high-Z reference shape - Michael Jaworski (MP-TSG)
Robert	Lunsford	XP1527 ELM pacing via multi-species granule injection and 3D field application for main ion control - Robert Lunsford (PC-TF)
John	Canik	XP1528 Characterize plasma near planned plenum entrance position - John Canik (PC-TF)
Rajesh	Maingi	XP1529 Controlled introduction of Lithium into NSTX-U - Rajesh Maingi (PC-TF)
Robert	Lunsford	XP1530 Triggering ELMs with LGI and 3-D fields in lithiated discharges - Robert Lunsford (PC-TF)
Roger	Raman	XP1531 Transient CHI Plasma Start-up in NSTX-U - Roger Raman (SR-TSG)
Stan	Kaye	XP1588 Parametric scan of L-H power threshold - Stan Kaye (PS-TSG)
Eric	Fredrickson	XP1589 CAE/GAE dynamics with NB2 - Eric Fredrickson (EP-TSG)

Summary

- Already exceeded NSTX field & pulse-length records
- Physics operations commissioning (XMPs) nearly complete – on verge of routine low/mid-l_i H-mode
  - Pre-requisite for accessing high current + long-pulse
- Implemented new disruption detection and plasma shutdown algorithms – contributes to JRT and ITER
- 2nd NBI already exhibiting interesting new physics w.r.t. fast-ion-driven instabilities
- Dedicated physics experiments will ramp up during near-term / upcoming run periods
- On track to complete research milestones for this FY