U.S. DEPARTMENT OF ENERGY | Office of Science

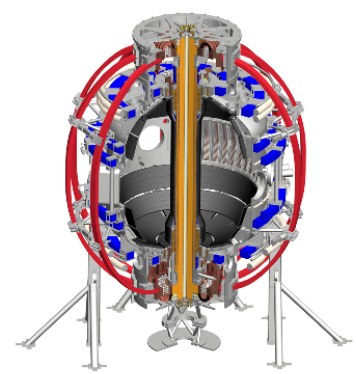
NSTX-U

Overview of NSTX-U Facility and Diagnostic Status and Plans

Masa Ono

NSTX-U PAC 37
January 26 - 28, 2016

PPPL



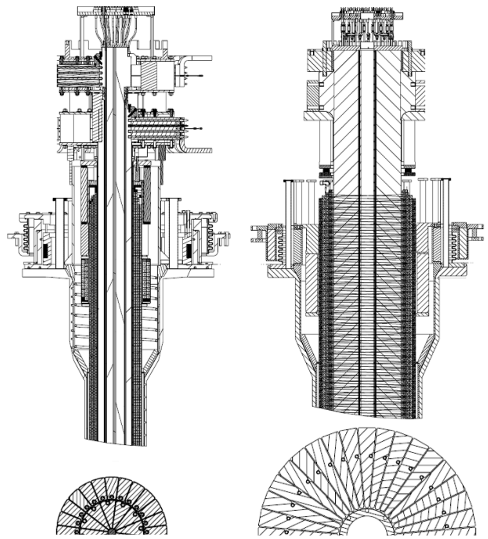
Presentation Outline

- Completion of NSTX Upgrade Project
- NSTX-U Facility Commissioning
- Facility Operations Status and Plan
- Facility Enhancement Status and Plan

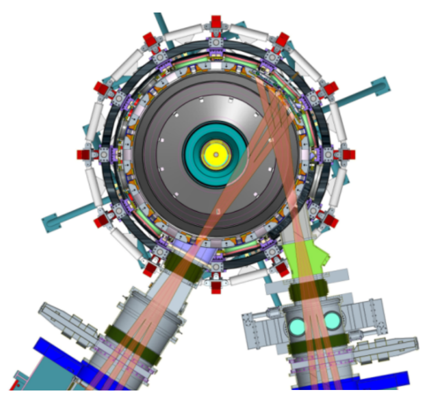
New CS and 2nd NBI are two main upgrade elements

to provide data base to support ST-FNSF designs and ITER operations

Previous center-stack | **New center-stack**



TF OD = 20cm | **TF OD = 40cm**



Present NBI | **New 2nd NBI**

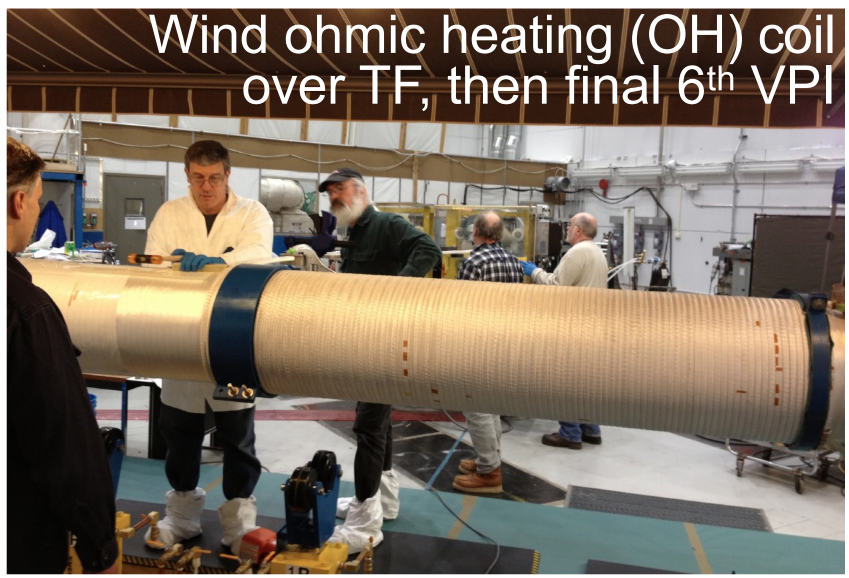
- New CS provides higher x2 B_{TF} (improves stability), 3-5s needed for J(r) equilibration
  - **CS Fabrication: 1T, 5s TF and 2 V-S OH**
  - **Structural enhancement due to x 4 E&M forces**
  - **Ancillary systems – power systems & I & C**
- More tangential injection provides 3-4x higher CD at low I_P for full non-inductive operation
  - **Relocate 2nd NBI from refurbished TFTR NBI system**
  - **Tangential port installation**
  - **Port relocation and test cell rearrangement**

Upgrade Project completed on budget and on schedule in September 2015.

Central magnet construction was complex, multi-stage, multi-year effort

Built 4 toroidal field (TF) quadrants

4 vacuum pressure impregnations (VPI)

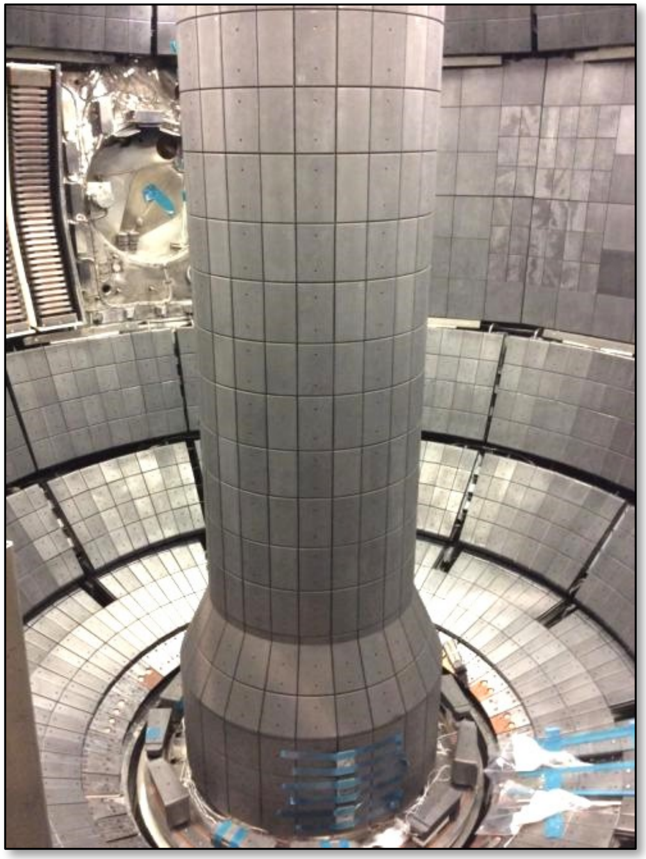


Fabrication and installation of central magnet ultimately successful

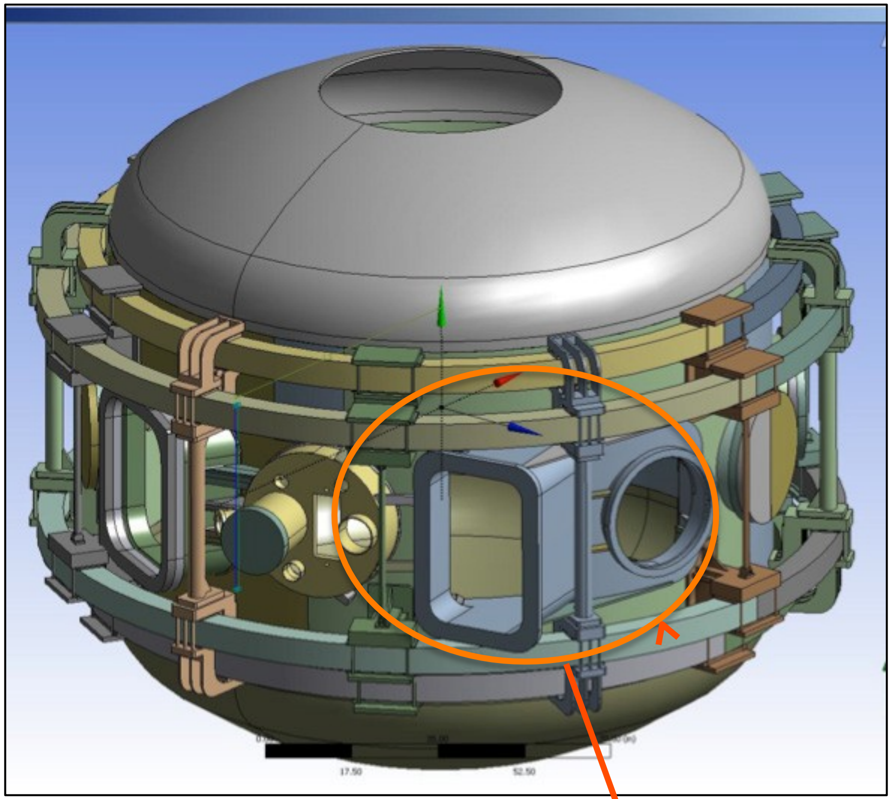
Over the machine

Over shield wall

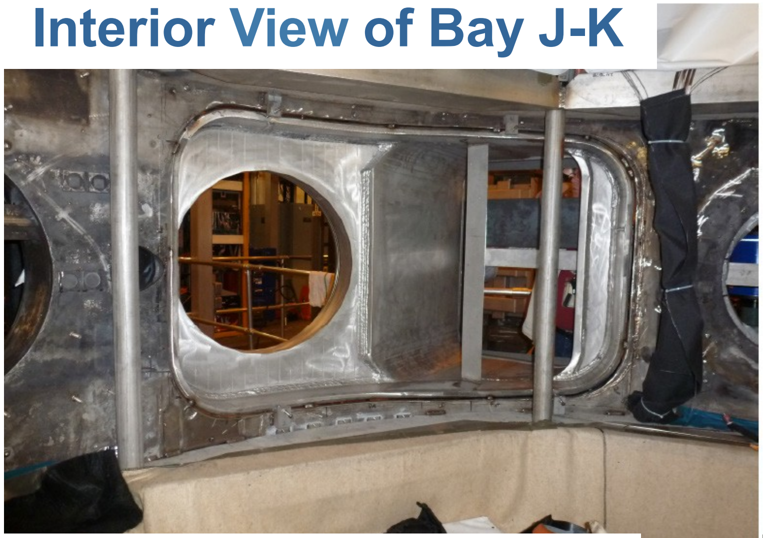
Inside NSTX-U!



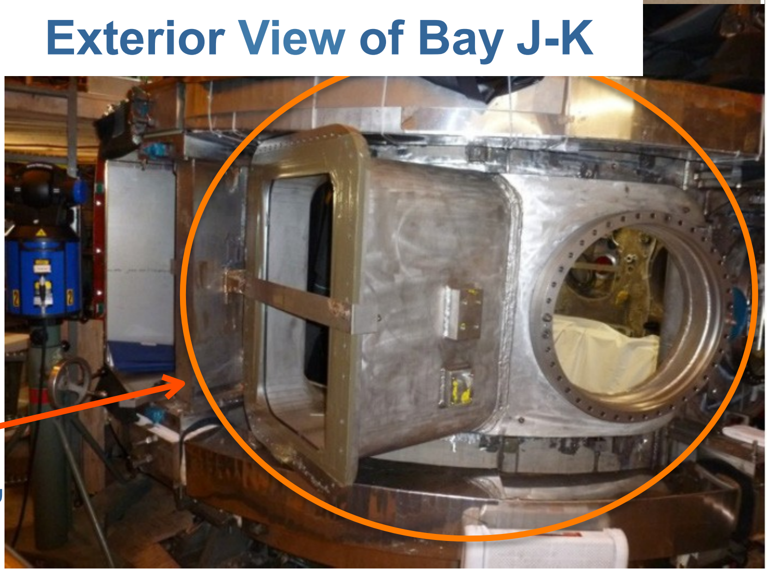
Tangential neutral beam required major vacuum vessel modifications



Interior View of Bay J-K



Exterior View of Bay J-K



2nd NBI "Bay Window"

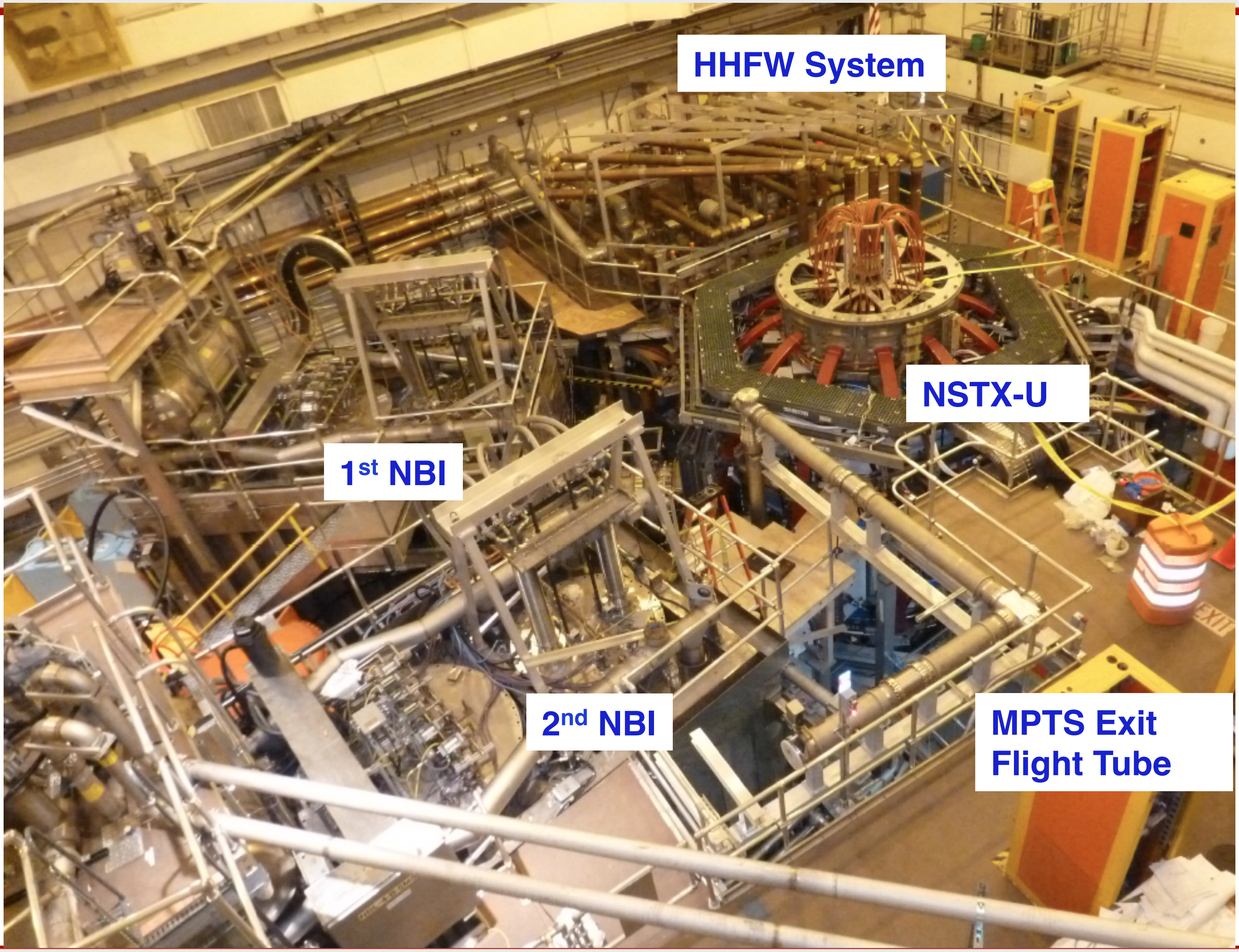
2nd beam (from TFTR DT campaign) required T-decontamination, NSTX test-cell re-arrangement

Beam Box being lifted over NSTX

Beam Box placed in its final location and aligned

Beam Box being populated with components

NSTX-U Facility Is Now Operational
Achieved First Plasma on August 10, 2015



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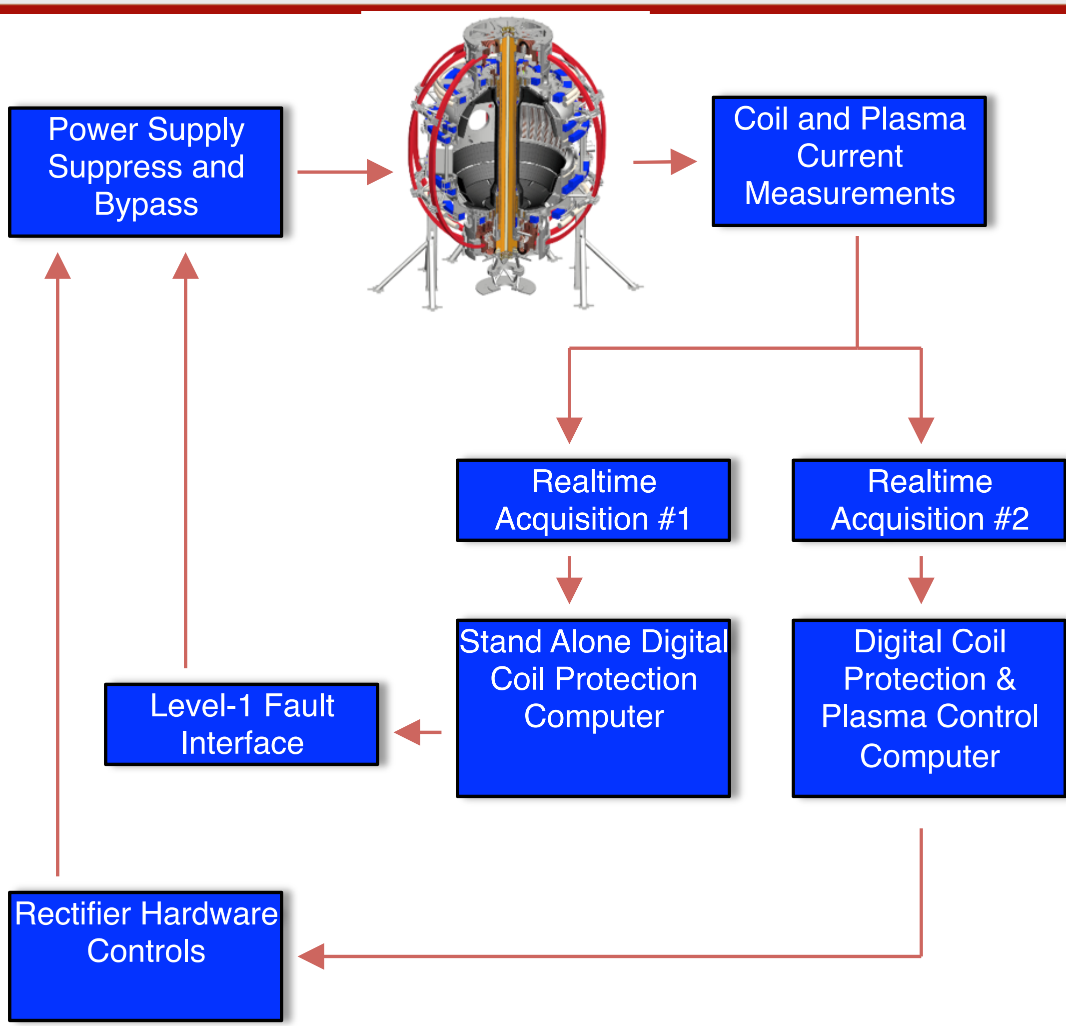
Digital System Provides Electromechanical Coil Protection
DCPS supporting the research operation very nicely



Protects the NSTX-U coils and mechanical structure against electromagnetic loads

Computes forces and stresses in realtime based on reduced models of the full mechanical structure

Redundant systems

Full commissioning of the system went very well; DCPS is now routinely supporting operations.

Discussions on going with ITER for collaboration

Excellent Progress on Magnetic Diagnostics

- **Plasma current, loop voltage, poloidal flux and field measurements in good shape supporting EFIT.**
  - **All integrators recalibrated**
  - **Rogowski coils fully calibrated, and pickup compensations established**
  - **All Mirnov sensors and flux loops have had their position determinations refined based on calibration shots.**
- **New diamagnetic loop system is now operational also supporting EFIT.**
  - **Based on using the Rogowski return loop as a diamagnetic loop.**
  - **Successfully implemented and eliminated the old TF-coil diamagnetic system.**
- **High-n and high-f array is taking data.**
  - **Used for detecting rotating Kink/Tearing modes, *AE modes.**
- **RWM sensors are writing mode fit data to the tree.**
  - **Realtime RWM sensor codes have also been upgraded, now in testing.**

Significant Progress in Plasma Control System
Now supporting the research operations

- **PCS has been supporting plasma operations.**
  - **Pre-programmed PF control & simple radial and vertical position control, I_P control.**
  - **Gas injection and pre-fill control**
  - **Real-time magnetic sensor calibrations**
  - **Beam control from PCS**
  - **Automatic discharge shutdown following disruption detection.**
  - **rtEFIT running in the background on the control machines**
  - **RWM/EF coil current control from PCS has been restored.**
- **Some older less-reliable real-time digitizers have been replaced, and a new every-shot latency measurement system has been implemented.**
- **Near term PCS steps**
  - **Finish testing rtEFIT and begin to use ISOFLUX shape control**
  - **Finish the recommissioning of the RWM/EF control algorithms**
  - **Then move on to profile control and snowflake divertor control.**

NSTX-U diagnostics to be installed during first year
More than half are led by collaborators

Ready now/commissioning

Magnetics for equilibrium reconstruction
Halo current detectors
High-n and high-frequency Mirnov arrays
RWM / Locked-mode sensors
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)
Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
Midplane ME-SXR (200 ch)
Midplane tangential AXUV bolometer array (40 ch)
Ultra-soft x-ray arrays – multi-color
Fast Ion D_α profile measurement (perp + tang)
Solid-State neutral particle analyzer
Neutron measurements
Charged Fusion Product
Fast IR camera (two color)
Material Analysis and Particle Probe
AXUV-based Divertor Bolometer
Tile temperature thermocouple array
Fast visible cameras
Visible bremsstrahlung radiometer
Visible and UV survey spectrometers
VUV transmission grating spectrometer
Visible filterscopes (hydrogen & impurity lines)
Wall coupon analysis
1-D CCD H_α cameras (divertor, midplane)
2-D divertor fast visible cameras (4)
Two-color intensified 2D cameras TWICE (2)
Edge neutral density diagnostic ENDD
IR cameras (30Hz) (3)
Dust detector
Edge Deposition Monitors
Scrape-off layer reflectometer
Edge neutral pressure gauges

Ready by mid-run

Fast lost-ion probe (energy/pitch angle resolving)
Microwave Reflectometer
Beam Emission Spectroscopy (48 ch)
MSE-CIF (18 ch)
MSE-LIF (20 ch)
SAMI edge field pitch diagnoistc
Divertor VUV Spectrometer (SPRED)
Gas-puff Imaging (500kHz)
Langmuir probe array
Divertor fast eroding thermocouple

Ready by end of run

FIReTIP interferometer

Ready next run year

Poloidal FIR high-k scattering
Midplane metal foil bolometer
Metal foil divertor bolometer

New capability,
Enhanced capability

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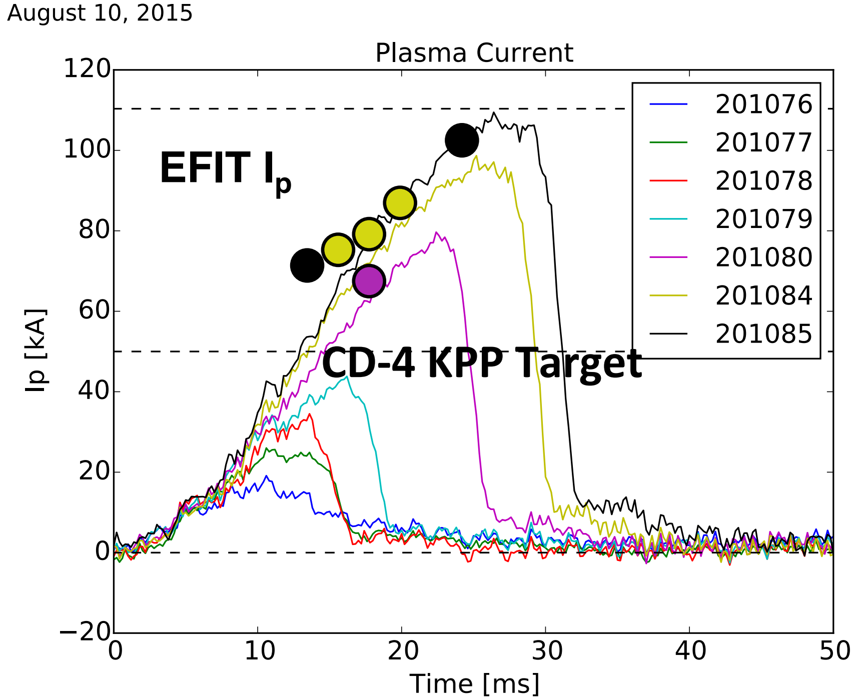
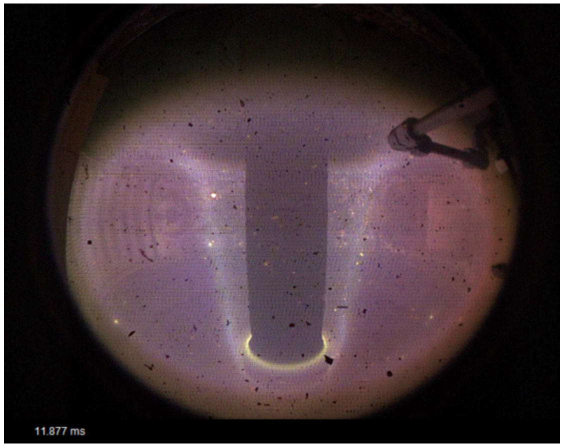
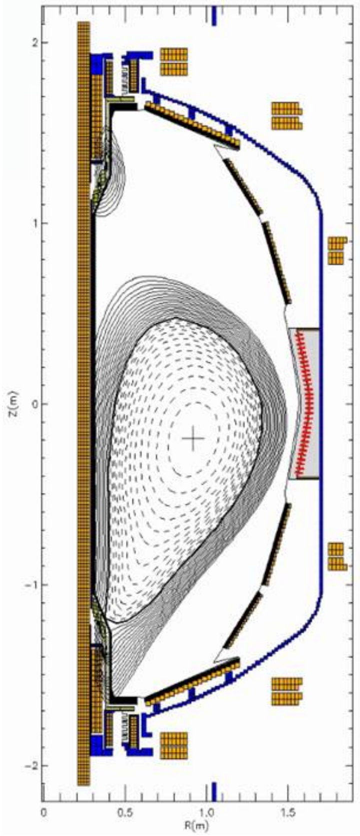
CD-4 KPP #1 Plasma achieved on August 10, 2015

Upgrade Project successfully closed on budget and on schedule







<u>Shot 201085</u>

Time: 28ms

I_p = 117 kA

B_{T0} = - 0.482 T

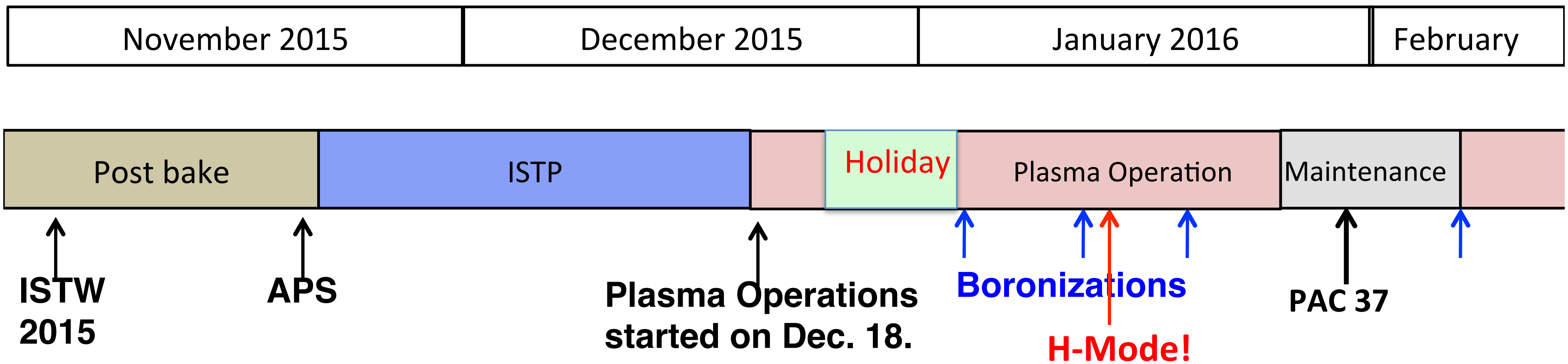
R_0 = 0.8 m

Z_0 = - 0.2 m

I_{wall} ~ 0.4 MA

Calibrated and compensated magnetics, EFITs plasma movie all showed consistent pictures

FY 2016 plasma operations started
Expecting to run 18 run weeks in FY 2016



- **After CD-4, we vented briefly to install various items before the bake.**
- **Bakeout was completed with good vacuum pressure in October**
- **During ISTP, MGs experienced control problem during ISTP. The problem resolved and MG#1 is supporting the operations.**
- **Plasma operation started on Dec. 18 and ran for 2.5 days before the holiday.**
- **The first boronization performed on Jan. 4, 2016 and performed three times.**
- **NBI injection started and H-mode access achieved quickly.**

Plasma Operations progressed rapidly as reported by D. Battaglia

NBI Heating System Status

Plan to start all sources after this maintenance period

- Neutral Beam #2:
  - **N2A and N2B Sources have experienced fault at 60 kV. The problem traced to the transmission lines between the source and the high voltage enclosure (HVE). (See the back up slide for the transmission line arc repair.) The repair should be complete during this maintenance period.**
  - **N2C Source is at 75 kV – being injected into the plasma**
- Neutral Beam #1
  - **All three NB#1 ion sources have completed arc conditioning, and are being High Voltage conditioning.**
  - **N1A Source is at ~ 80 kV – has been injecting into the plasma**
  - **N1B Source is at 60 kV - has been injecting into the plasma**
  - **N1C Source is at 87 kV – has been injecting into the plasma**

Over 4 MW level injection achieved, routine H-mode operations

Latest run plan schedule for 2016

Goal is to operate 18 run weeks

➔FY16 budgets are favorable enough to support 18 weeks

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

- **December: 0.5 run weeks (XMP)**
- **January: ~ 2 run weeks (XMP, XP), PAC-37**
- **Two week maintenance: Ar-PS, LITER, LGI, Diagnostics**
- **February: ~ 3 run weeks**
- **March ~ 3 run weeks**
  - **Mid-run assessment in March/April**
- **April – June 9.5 run weeks, complete FY16 run**
- **July: Start outage: install high-k, high-Z tiles, …**
- **Resume operations winter 2017 for FY17: ~16 run weeks**

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

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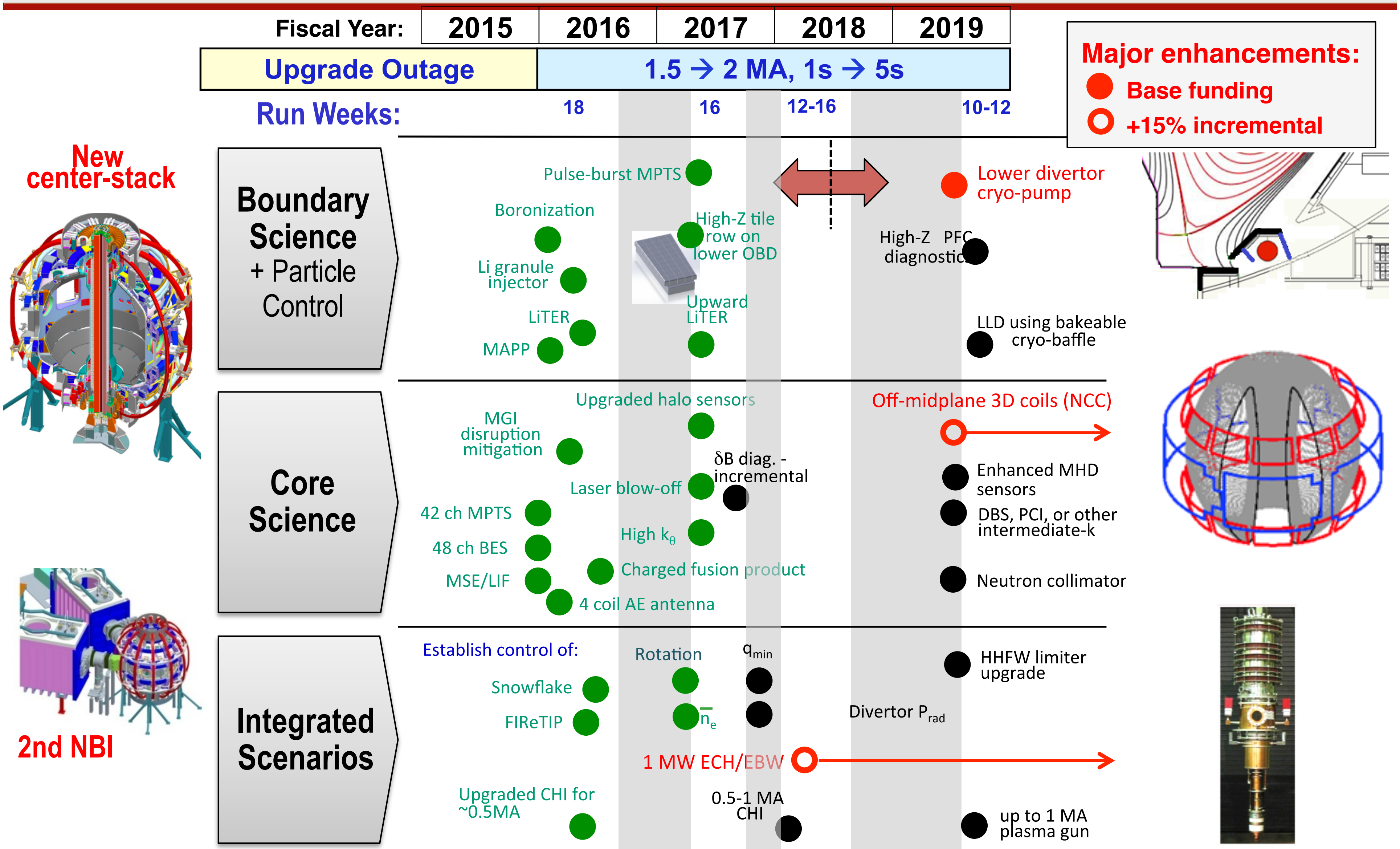
Five Year Facility Enhancement Plan (green – ongoing)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH



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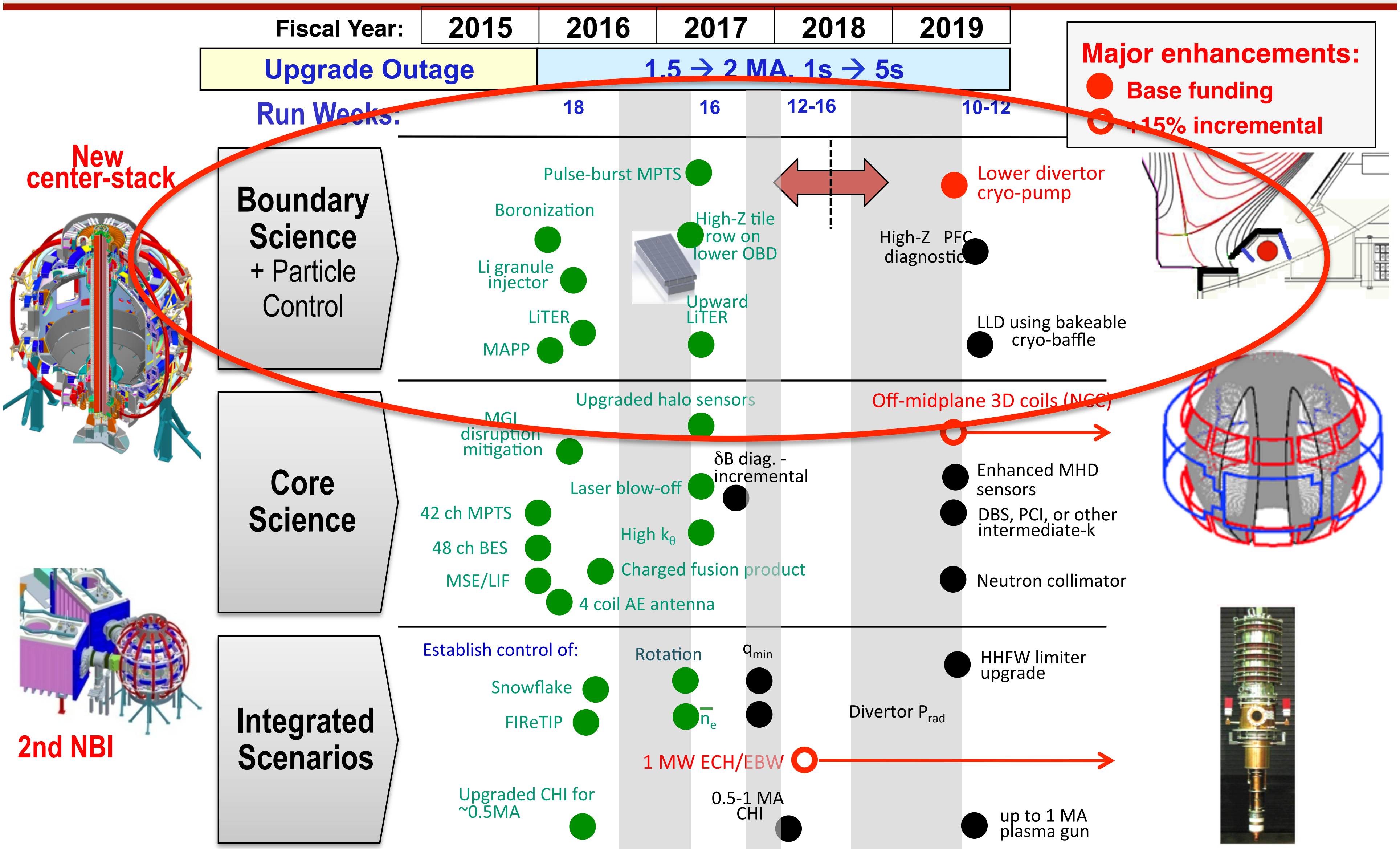
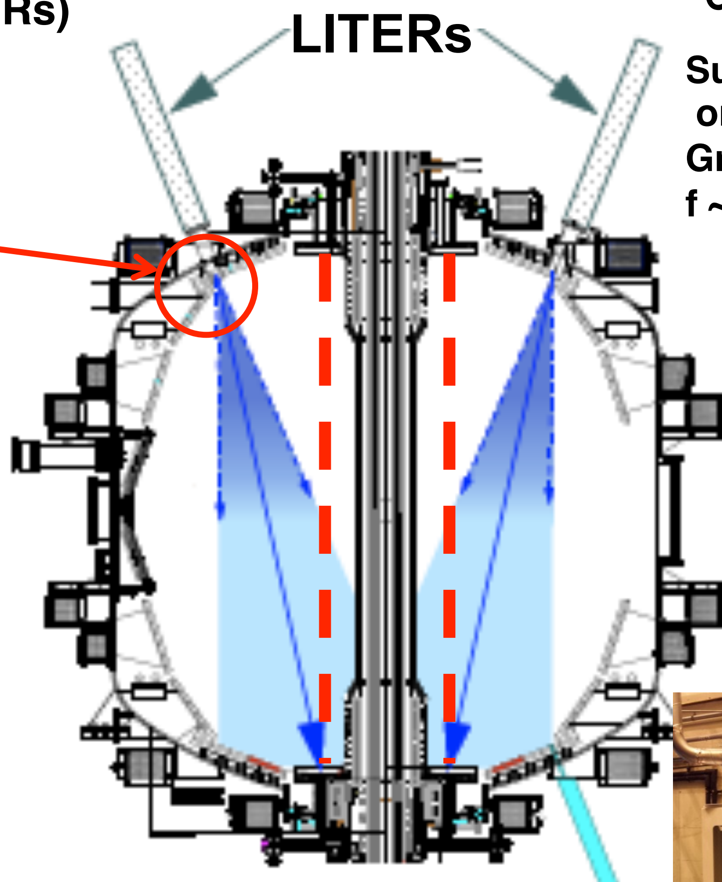


First Year Boundary Physics Tools

Boronization, Lithium Evaporators, Granule Injector

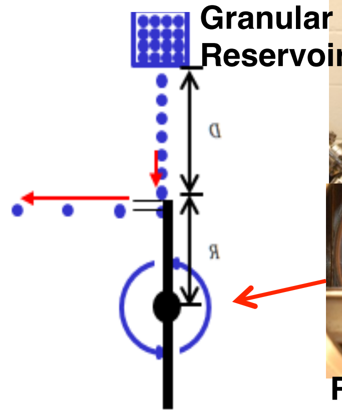
Lithium Evaporator (LITERs)

- LITERs filing set up in high bay south of NSTX-U Test Cell
- Argon purge system being implemented for safety



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

- Remote control undergoing tests
- Stand complete
- Vacuum interlock requirements identified and implementation plan specified

Boronization System

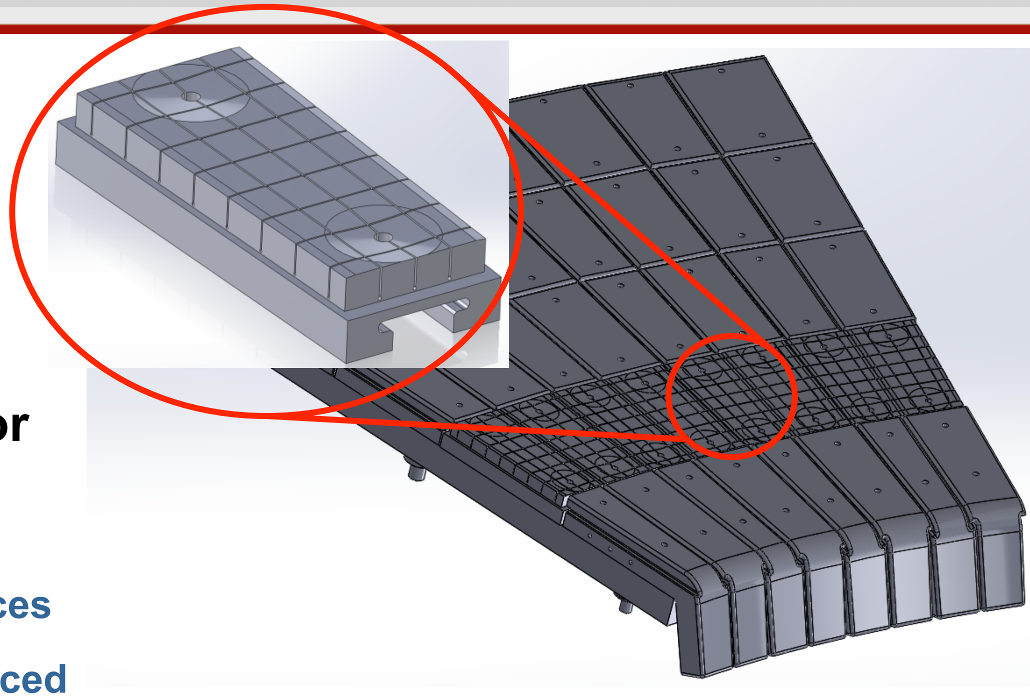
- Multiple injection and glow made more uniform boronization.
- System is working very well. Third boronization complete. Also being used for He glow discharges.

dTMB Gas Cabinet for safety

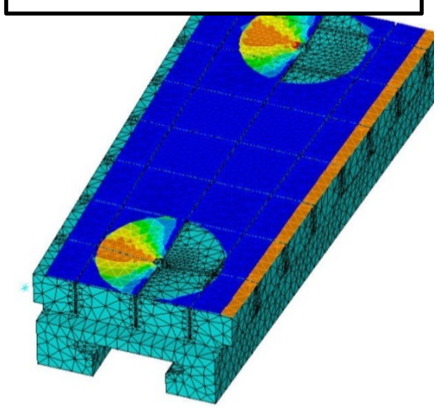
High-Z Tile Design Nearly Complete

(See M. Jaworski's PAC talk for more detail - plan to be ready by the 2016 outage)

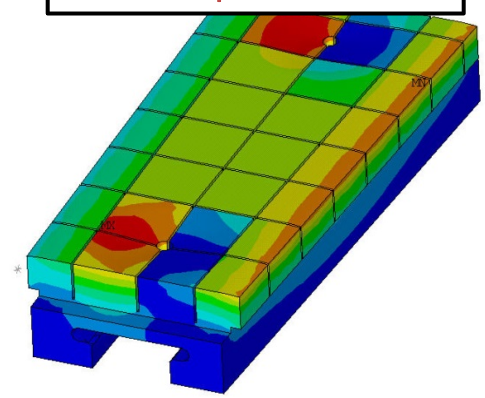
- **Successful PDR held in December**
  - **Final drawings and installation issues nearly complete (FDR mid-Feb.)**
  - **82% of raw materials on-site**
- **Final design rated to 10 MW/m² for 1s heat flux for 1000s of cycles**
  - **Installation flexibility introduced to accommodate "as built" vessel tolerances**
  - **Edge and access-way chamfers introduced to reduce heat-flux peaking**
- **Design "lesson's learned" already informing cryo-pump PFC design**
  - **Geometric flexibility emphasized to avoid stress-limited design**
  - **Tight tolerancing in sub-structure emphasized to avoid time-intensive installation tasks**



Surface heat flux

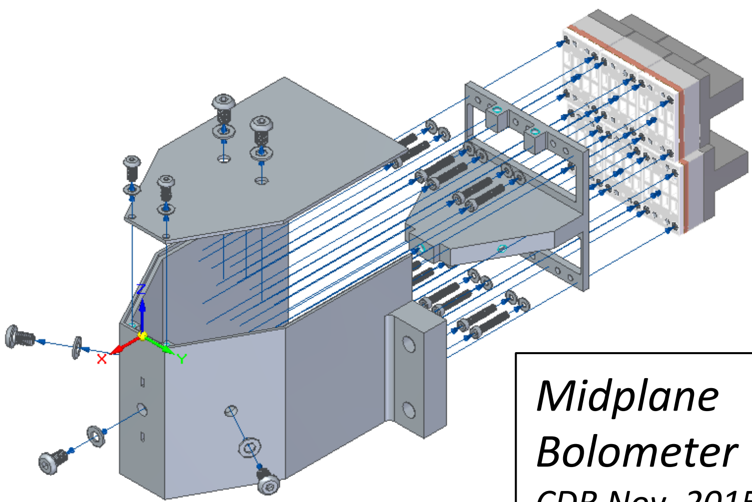


Temperature



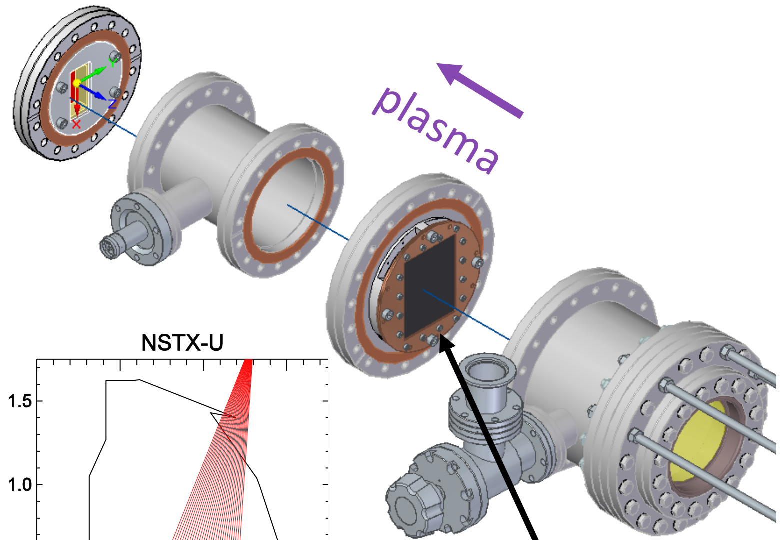
NSTX-U Developing Tools for Measuring Core and Boundary Radiation

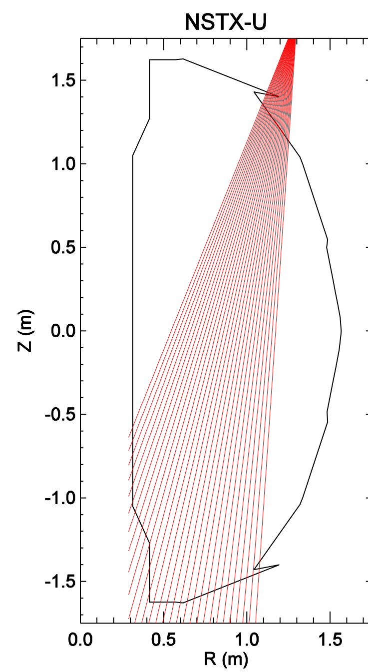
- **Redesign and expand bolometer diagnostics to support FY17 operations**
  - **16 ch of lower divertor viewing for boundary radiation**
  - **24 ch tangential midplane core radiation**



Midplane Bolometer
CDR Nov. 2015

Prototype IR video bolometer (IRVB) with NIFS and DIFFER





thin Pt foil, heated by radiation, imaged by IR camera

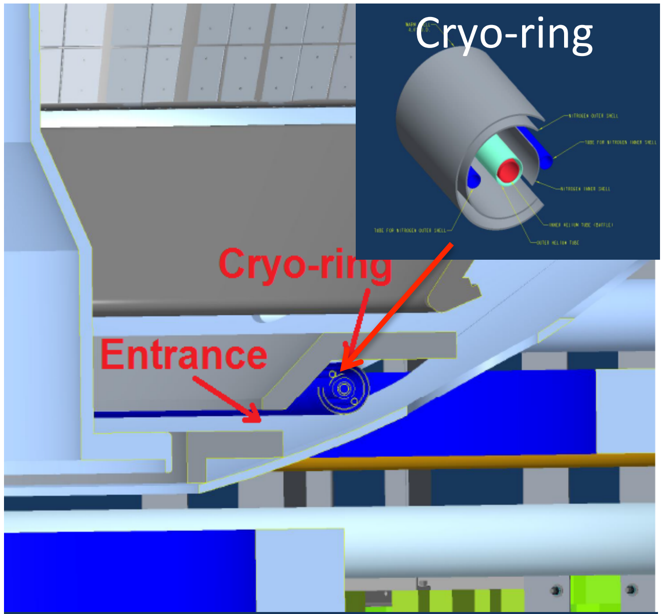
testing 32-ch system for viewing lower x-pt late in FY16 campaign

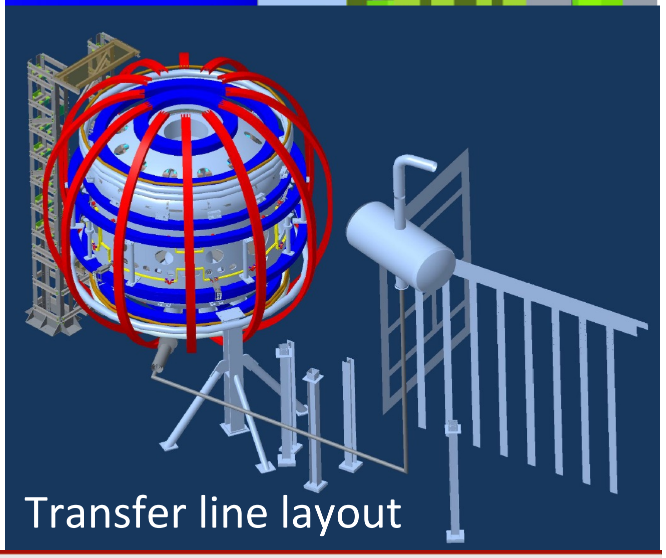
M. Reinke, ORNL

Divertor Cryo-pump Design Activities Started

Physics Design Described at PAC 33 by J. Canik, ORNL

- **Initial in-vessel geometry has been laid out. MIT will design cryo-ring.**
  - **Pump radius, throat dimensions taken from the modeling.**
  - **Is a significant perturbation, requiring a rebuild of basically the entire lower outer divertor.**
  - **High-Z tile research will contribute to the choice of PFCs (see M. Jaworski's talk)**
- **Specification in progress for the Liquid He refrigerator.**
  - **Likely suitable model found**
  - **Location in room adjacent to NSTX-U has been identified.**
- **Ex-vessel liquid He plumping and transfer Dewar is under design.**





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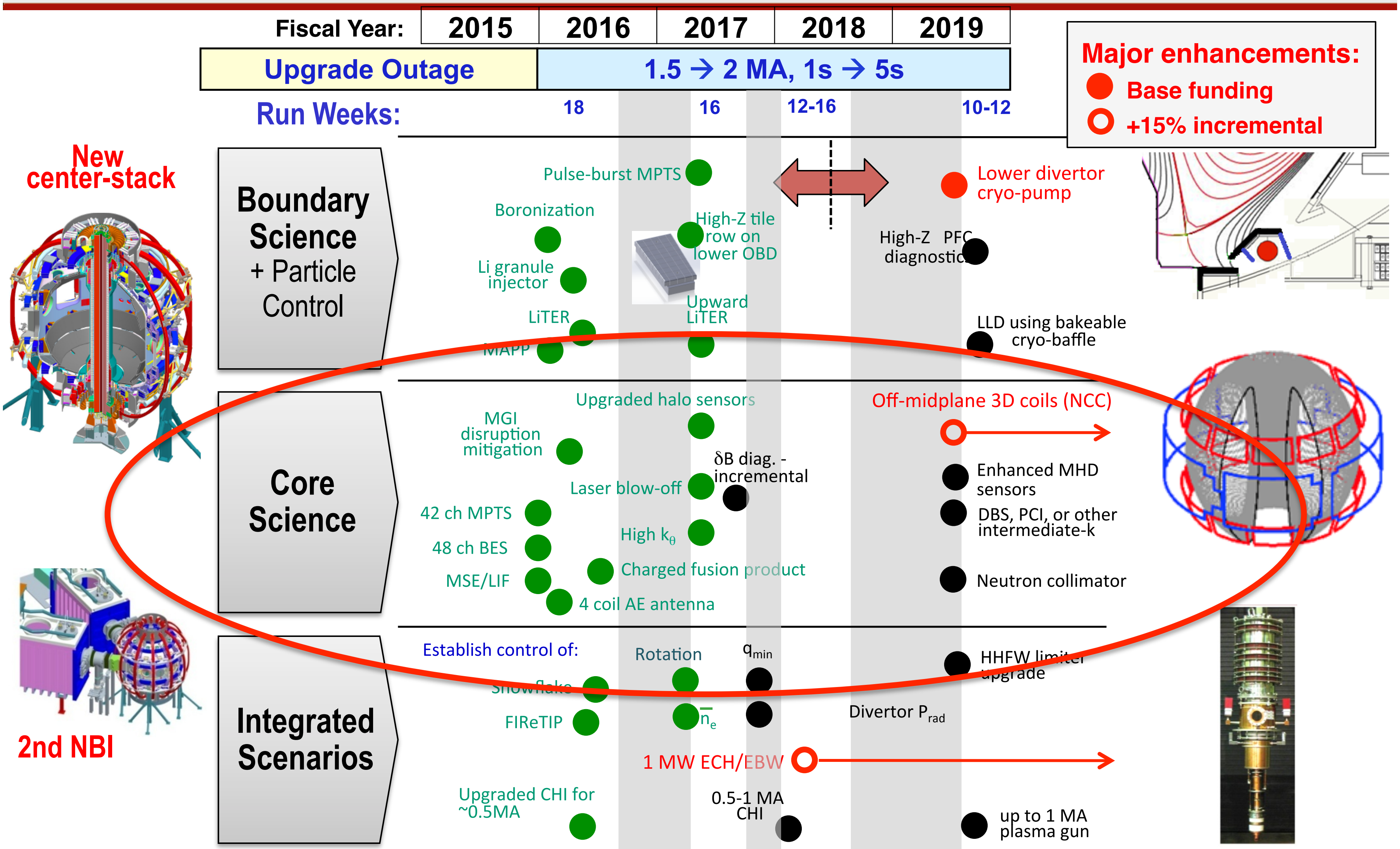
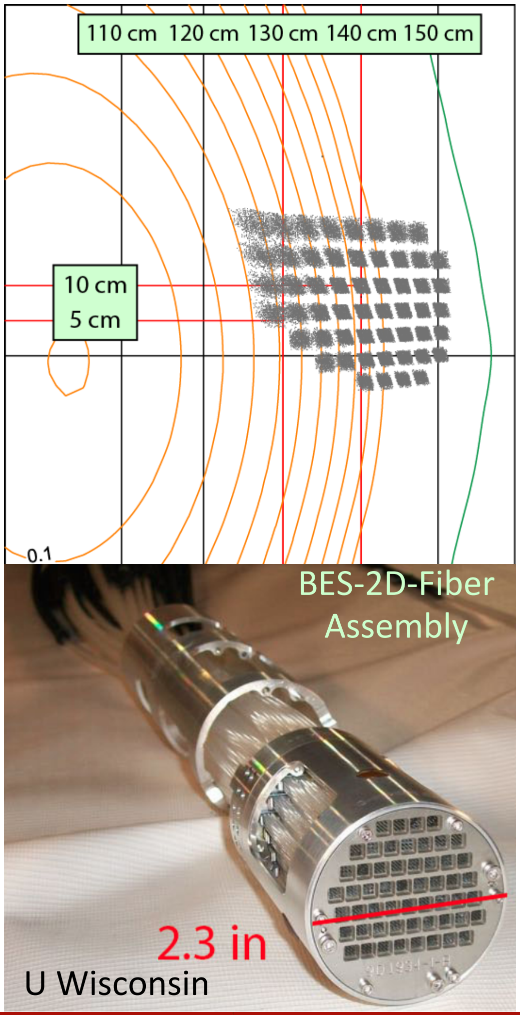
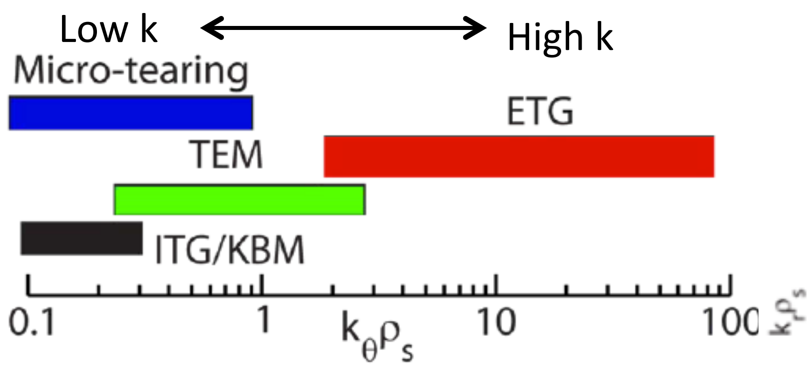


Microturbulence Diagnostics Being Enhanced

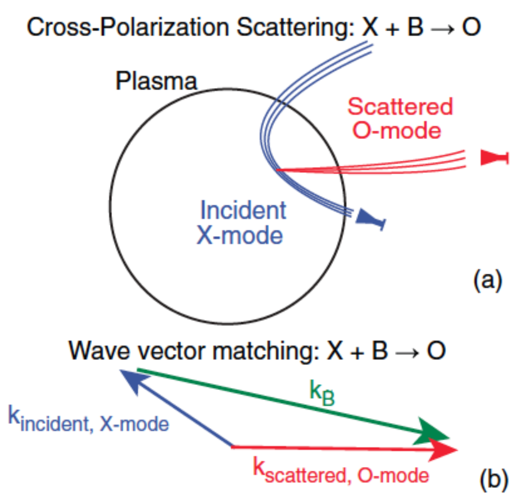
To measure ion to electron gyro-scale, magnetic fluctuations

Beam Emission Spectroscopy
for low k turbulence
48 chs being readied



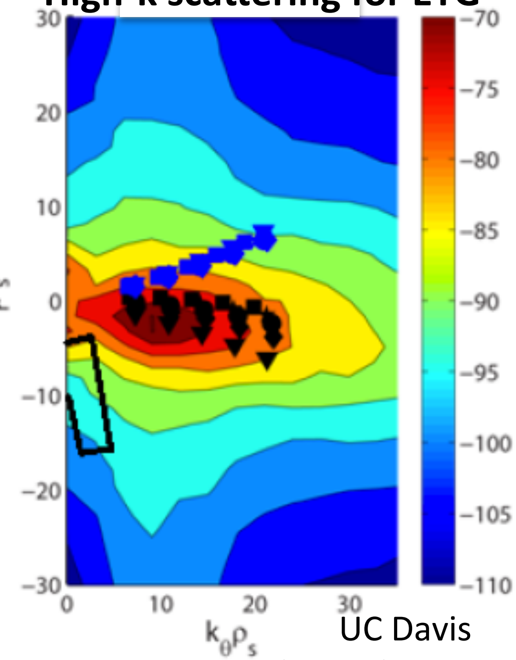


Cross-Polarization Scattering for magnetic fluctuations being developed in collaboration with DIII-D and MAST



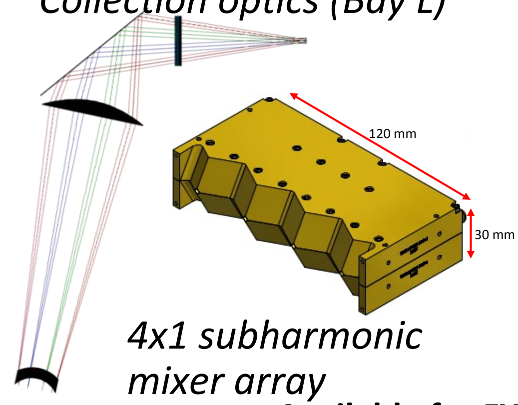
UCLA

High-k scattering for ETG



UC Davis

Collection optics (Bay L)



4x1 subharmonic mixer array

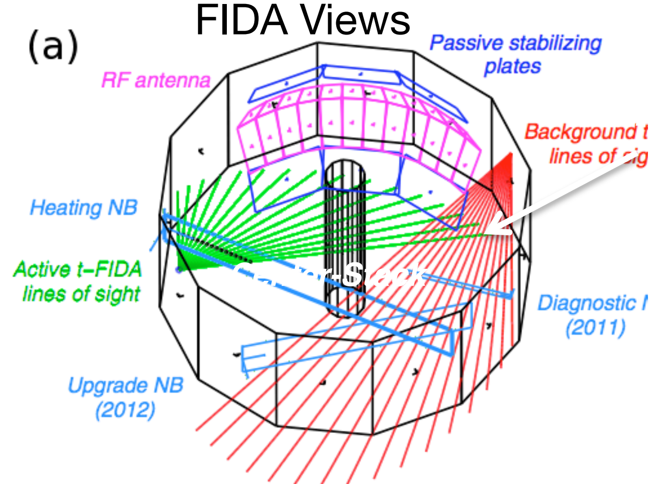
Available for FY 17

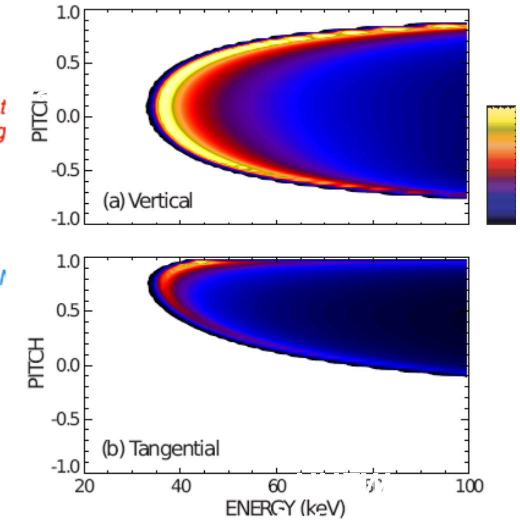
Enhanced FIDA will measure NBI distribution function
For NBI fast ion transport and current drive physics

Fast Ion D-Alpha Diagnostics

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

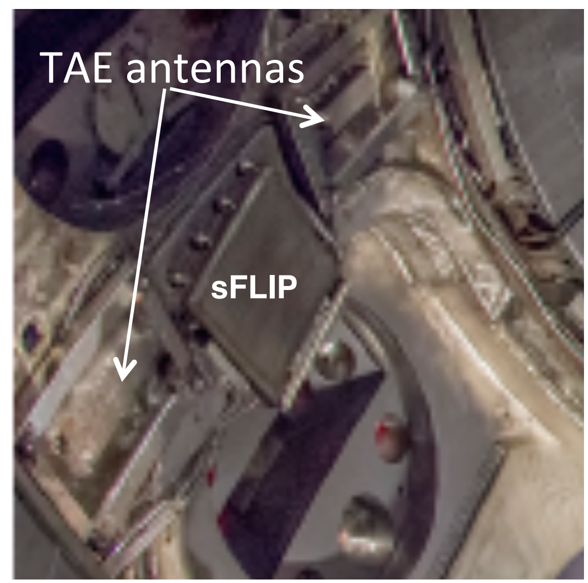
FIDA Views





FY 2016 - 2017 Energetic Particle Conceptual Design and Diagnostic Upgrade

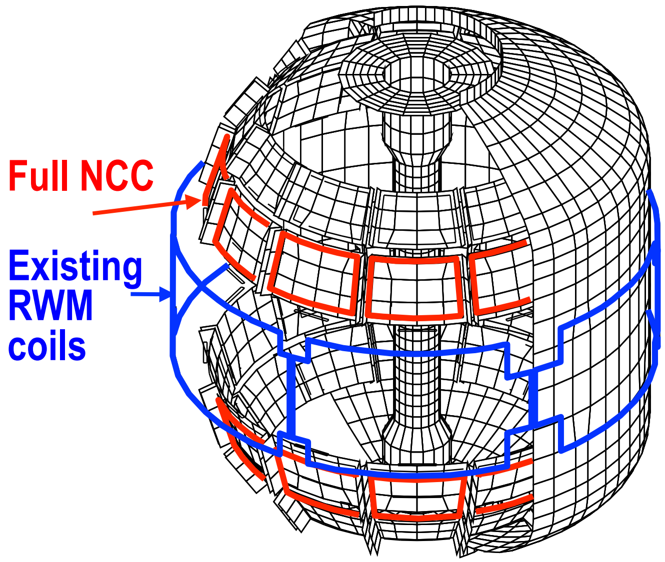
- SS-NPA installed but investigating pick-up problem. UCI
- sFLIP is installed for lost ion measurements
- Active 2 X 2 TAE antennas installed. Initially passive spectroscopy then active excitation at few kW level.
- Proto-type charged fusion product (CFP) profile diagnostic to be installed this year. FIU
- 8+8 reflectometry array available for AEs. UCLA



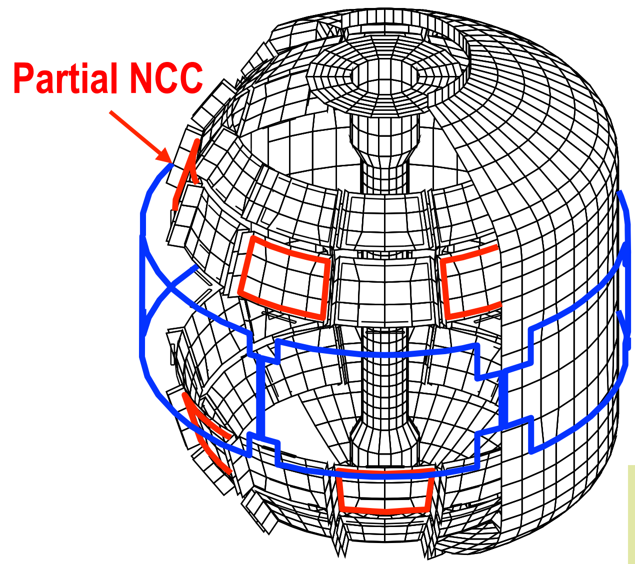
Flexible Mid-Plane Feedback Coils for MHD Studoes

NCC will greatly enhance MHD physics studies and control

Full toroidal NCC array (2 x 12)



Partial toroidal NCC array (2 x 6)



Columbia U
General Atomics

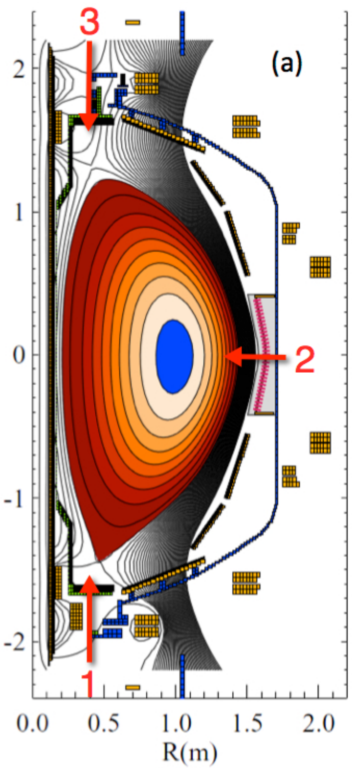
- 6-channel Switching Power Amplifier (SPA) powers independent currents in existing EFC/ RWM Coils.
- NCC (a facility enhancement) can provide various NTV, RMP, RWM, and EF selectivity with flexibility of field spectrum (n ≤ 6 for full and n≤ 3 for partial)

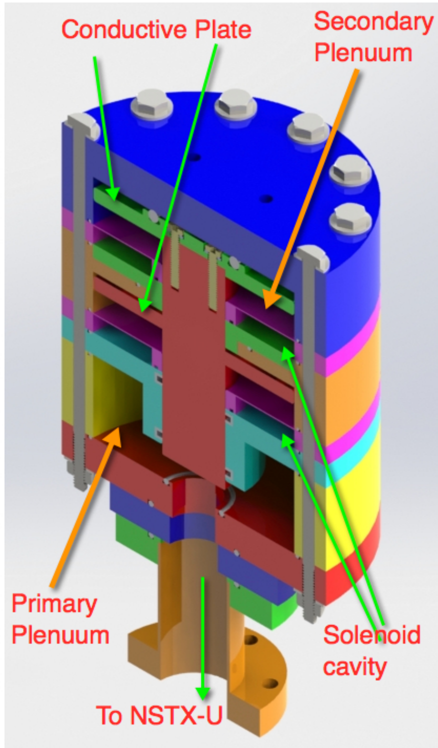
Base – Engineering design work on NCC to be performed in 2016 – 2017 to develop reliable cost and schedule.

Disruption Mitigation System for NSTX-U

Massive gas injection system at multiple poloidal positions

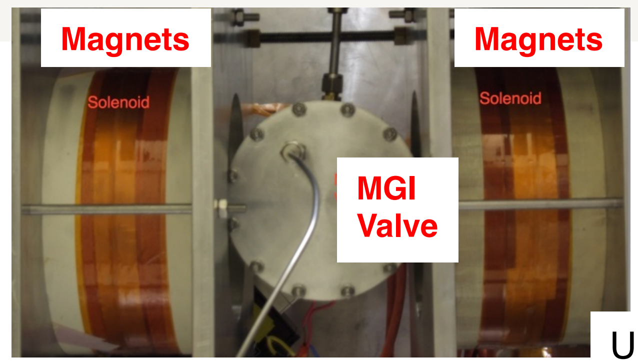
NSTX-U MGI Valve





- **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

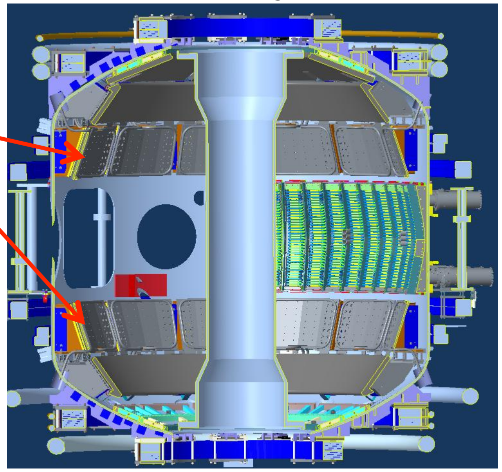


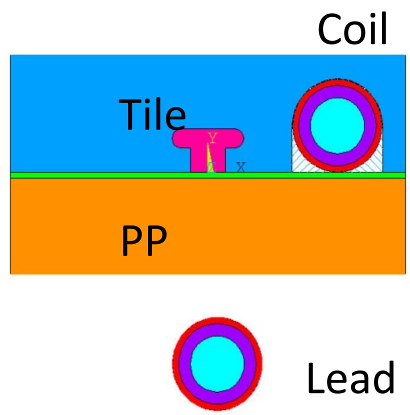
U. Washington

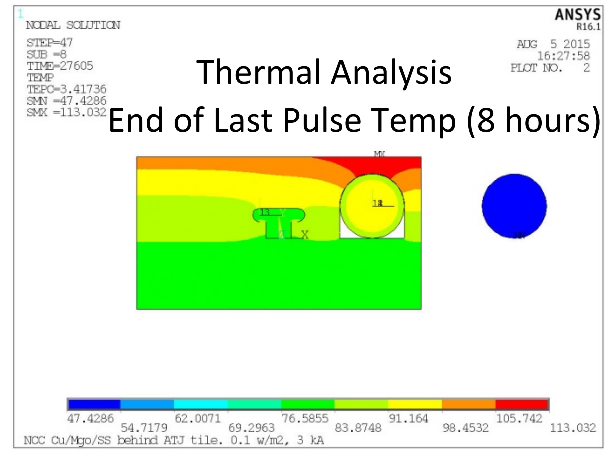
- **Conceptual Design Review of MGI system was held on October 16. Recommended changes were incorporated into the power system hardware.**
- **All the MGI components including MGI valves were delivered to PPPL from U. Washington.**
- **Preparation are being made to commission the MGI system on NSTX-U this year.**

NCC Coils Design Activity Made Significant Progress
NCC Physics Design Presented by J-K Park at PAC 33

NCC = Non-axisymmetric Control Coil

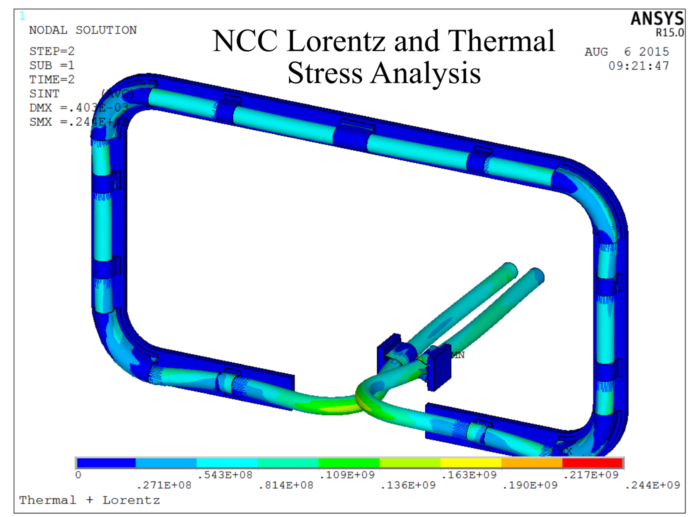






3 kA,0.1 MW/m2 Plasma Heating,5s pulse,1200 s reprate

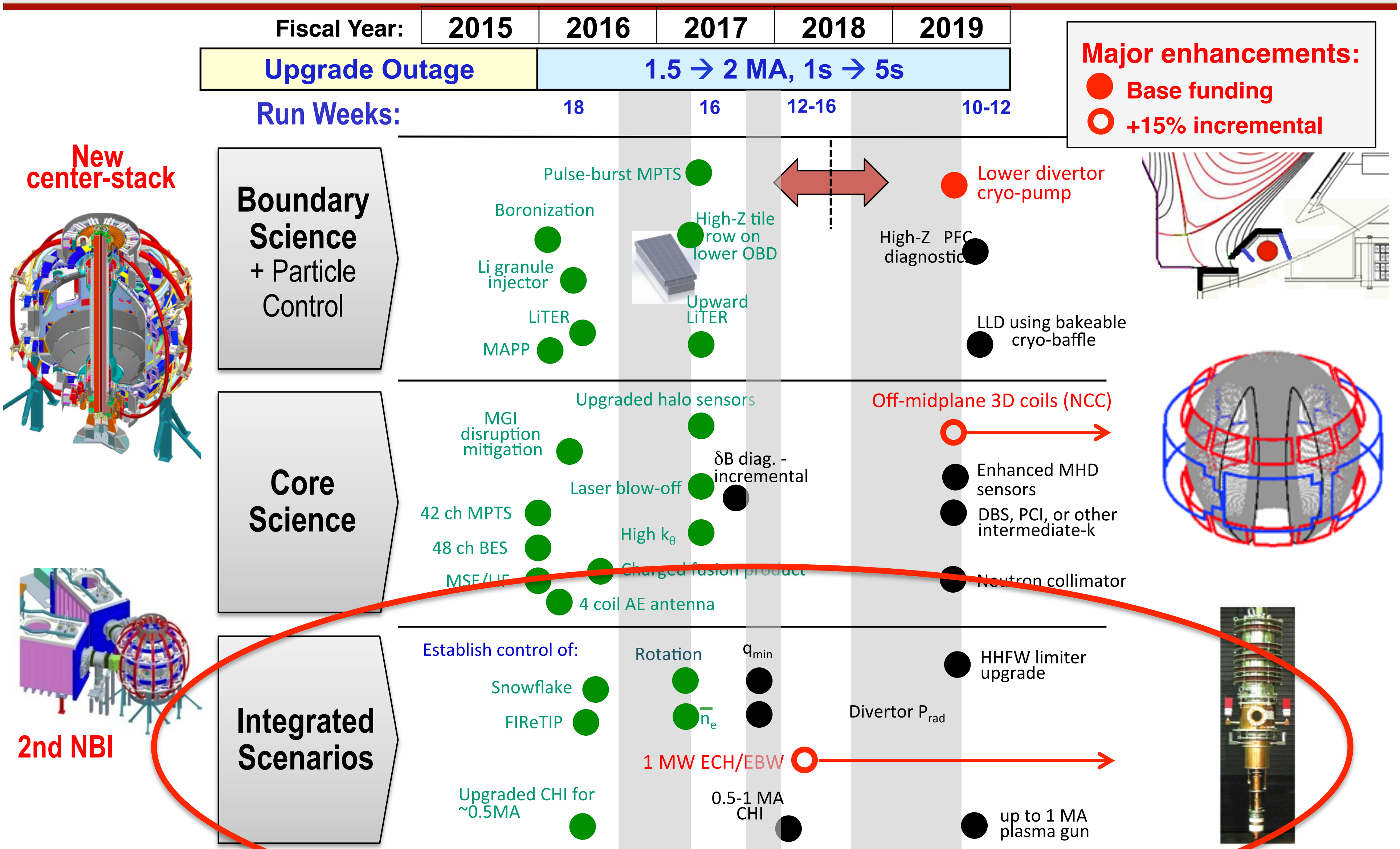
- **Selected candidate conductors and test sample received for R&D.**
- **The R&D selection criteria include thermal capability, manufacturability, impact on interfacing objects, fabrication lead time and cost.**
- **Helium cooling system or no direct cooling options will be quantified.**
- **Cost and 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)

2015: Engineering design for high-Z tiles, Cryo-Pump, NCC, ECH



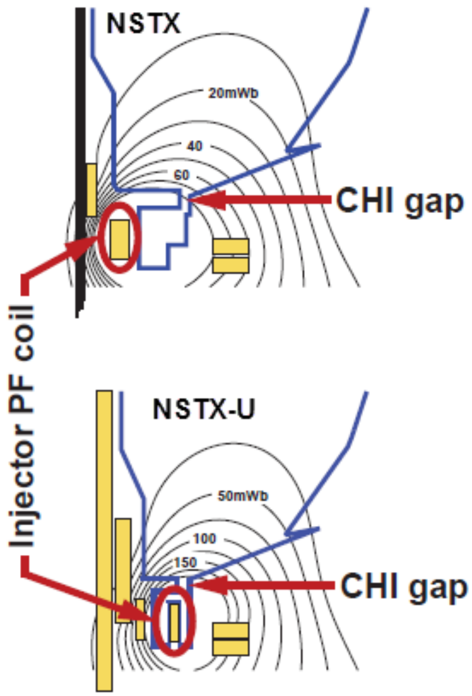
Solenoid-free start-up in support of ST-FNSF

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

CHI Start-Up in NSTX-U

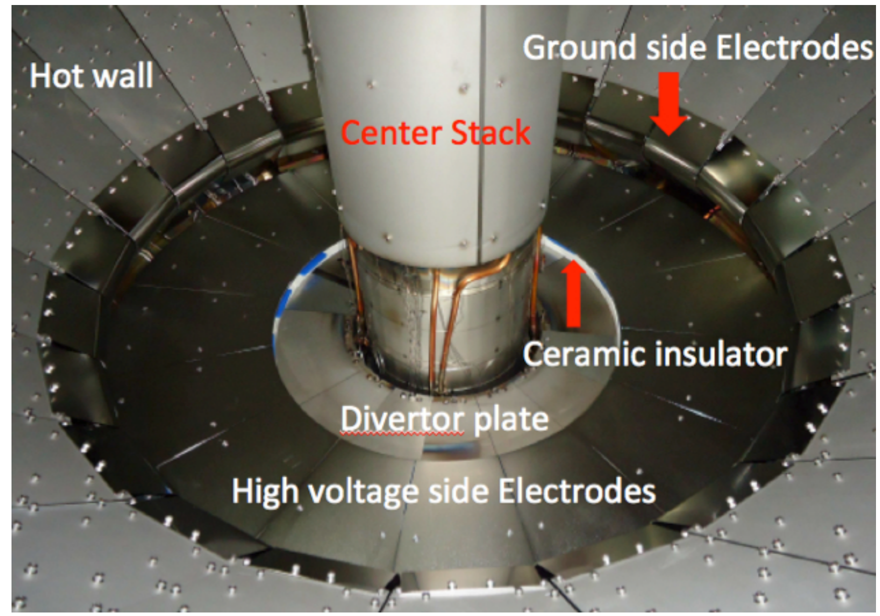
- **Inj. Flux in NSTX-U is about 2.5 times higher than in NSTX**
- **NSTX-U coil insulation greatly enhanced for higher voltage ~ 3 kV operation**

U. Washington



- **CHI will start with the present 2 kV capability then enhanced to higher voltage as needed.**
- **Control system updates for the CHI cap bank have been completed, and the system is ready for remote testing.**
- **The CHI control room procedure has been updated.**

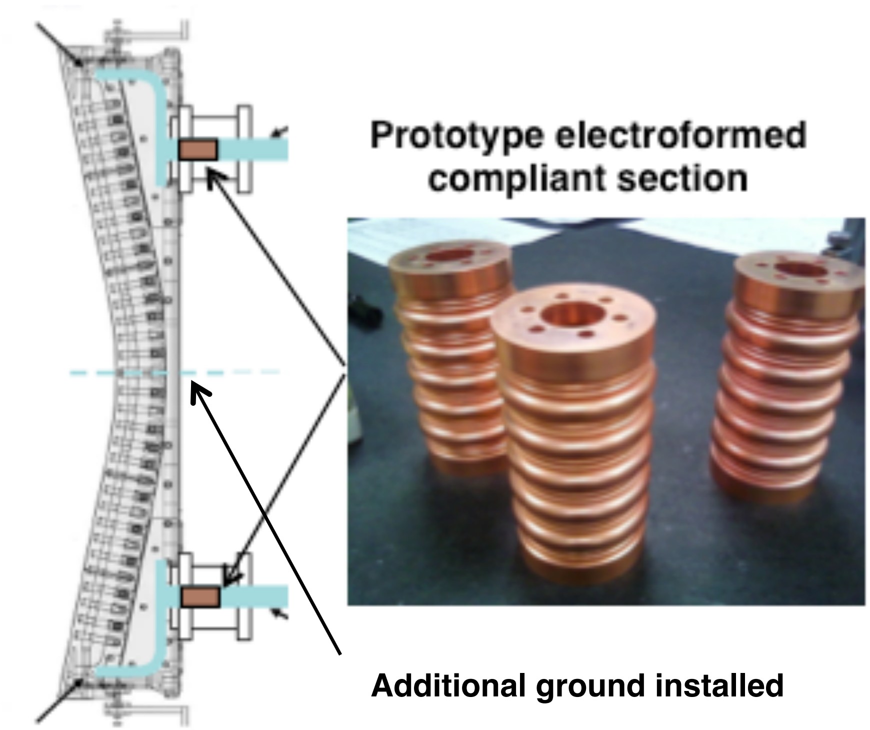
QUEST CHI Experiment to test high-Z electrode operation



- **An ST-FNSF like CHI configuration will undergo plasma tests on QUEST after FY 2016 NSTX-U operation**
- **CHI electrodes installed in QUEST, CHI power supply and gas injection system fabricated at U-Washington**

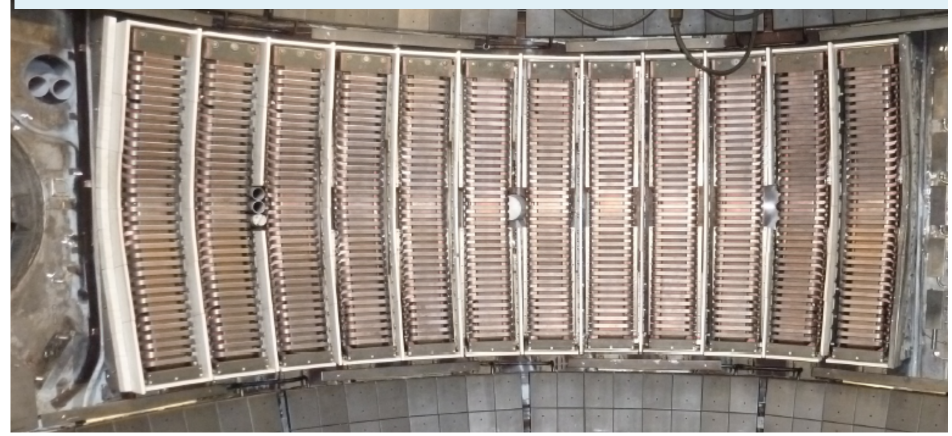
HHFW system will be ready for operation in March
All sources are ready to start antenna conditioning

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.

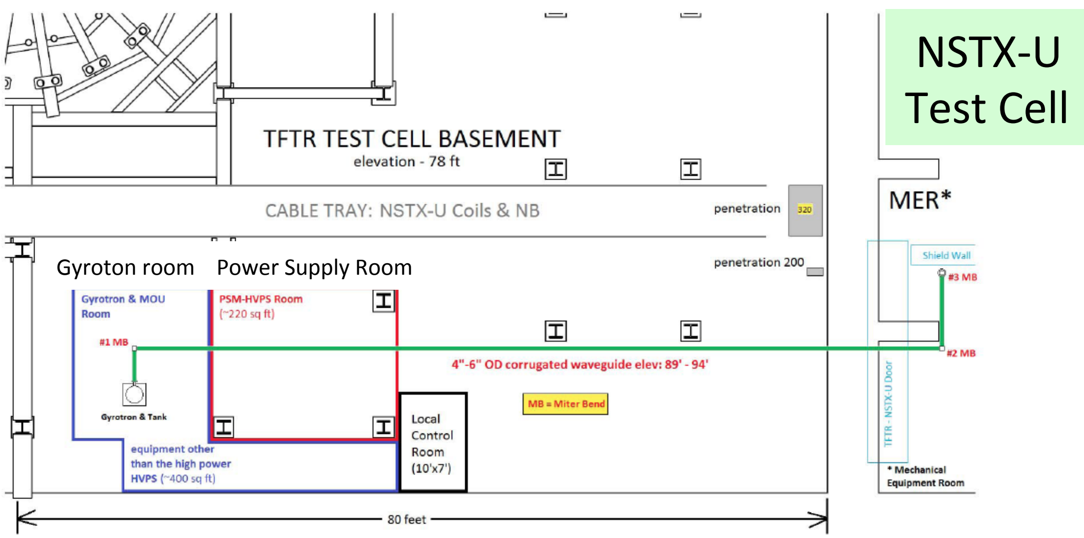
- **All sources will be ready to support HHFW operation in March.**

28 GHz ECH System Design Progressing Well

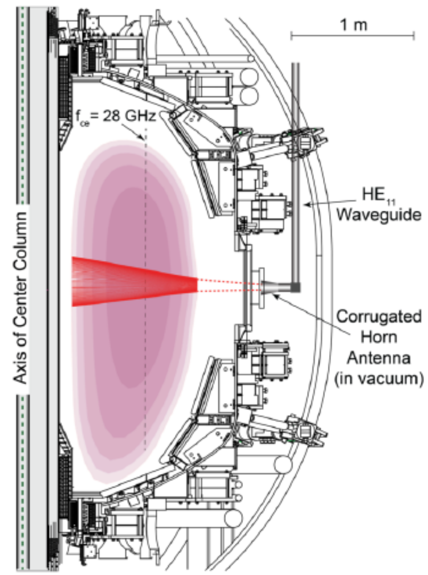
Develop engineering design and cost/schedule this year

- **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 - Talk by F. Poli at this PAC.**
  - **Good first pass absorption predicted.**
- **Goal of first ECH power in 2019 run with 15% incremental funding.**

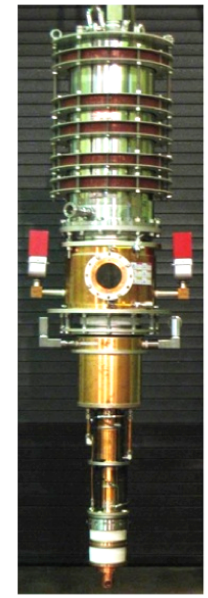
28 GHz Gyrotron Room



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)**
- **The gyrotron is being constructed. Will be tested this summer.**

Summary of Facility and Diagnostics
Research operations successfully started

- **CD-4 KPP#1 Plasma successfully achieved on August 10, 2015. The upgrade project was closed in September 2015.**
- **Bake-out has concluded on October 20, 2015.**
- **Research preparation progressing well. Team is vigorously preparing diagnostics and research tools for the first year of plasma operations.**
- **Research operation started on December 18, 2015.**
- **Very good progress on the plasma control system.**
- **Routine H-mode obtained shortly after the second boronization.**
- **Engineering design work continuing for the major facility enhancements: high-Z tiles, divertor cryo-pump, ECH, and NCC.**

Back-Up slides

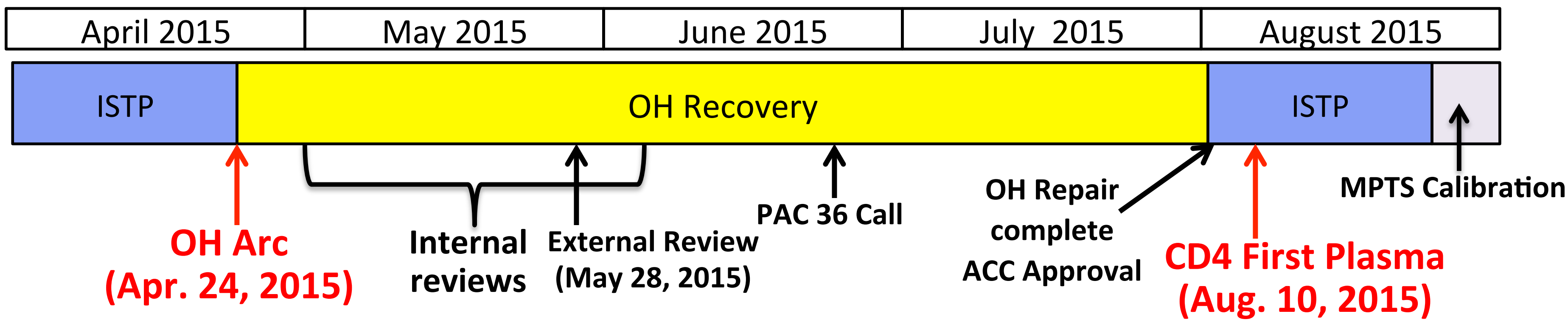
NBI 2 Transmission Line Breakdown Repair

Arc occurred at a steep bend causing inner accel to touch outer return

Inside of the NBI transmission line. Arc has occurred between the accel wire (blue) and the return wire. A strong bend caused them to touch, causing an arc damage at 60 kV.

OH Arc Recovery Activity Completed on July 31

ISTP restarted on Aug. 5 & CD-4 Plasma Achieved on Aug. 10



<u>OH Arc Related Reviews</u>

• On causes: technical, procedural, process (April 30 – May 13)

R. Ellis (chair, ME), J. Delooper (best practices), J. Hosea (phys.), C. Neumeyer (EE), M. Bell (phys.)

• On extent of condition (May 13 – May 22)

J. Hosea (chair, phys), R. Ellis (ME), N. Greenough (EE),D. Mueller (phys)

• Root cause analysis (May 4 – July)

I. Zatz (chair, ME), J. Lacenere (EE), J. Malsbury (QA), M. Mardenfeld (ME)

• External Review (May 28)

A. Kellman (Chair, GA), J. Irby (MIT), B. Merrill (INL), G. Ganetis (BNL)

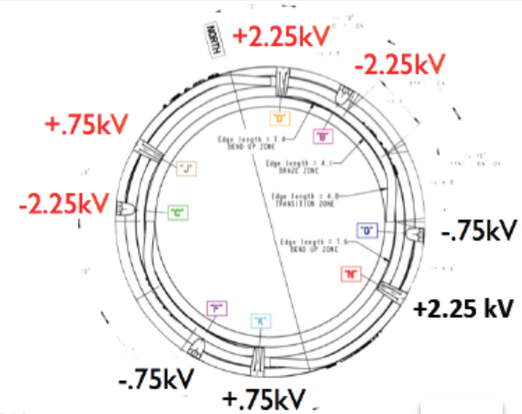
• PPPL Activity Certification Committee (August 3)

C. Gentile (Chair) et al.,

Upper OH Coil Arrangement

TF Cooling

Inner TF Conductors

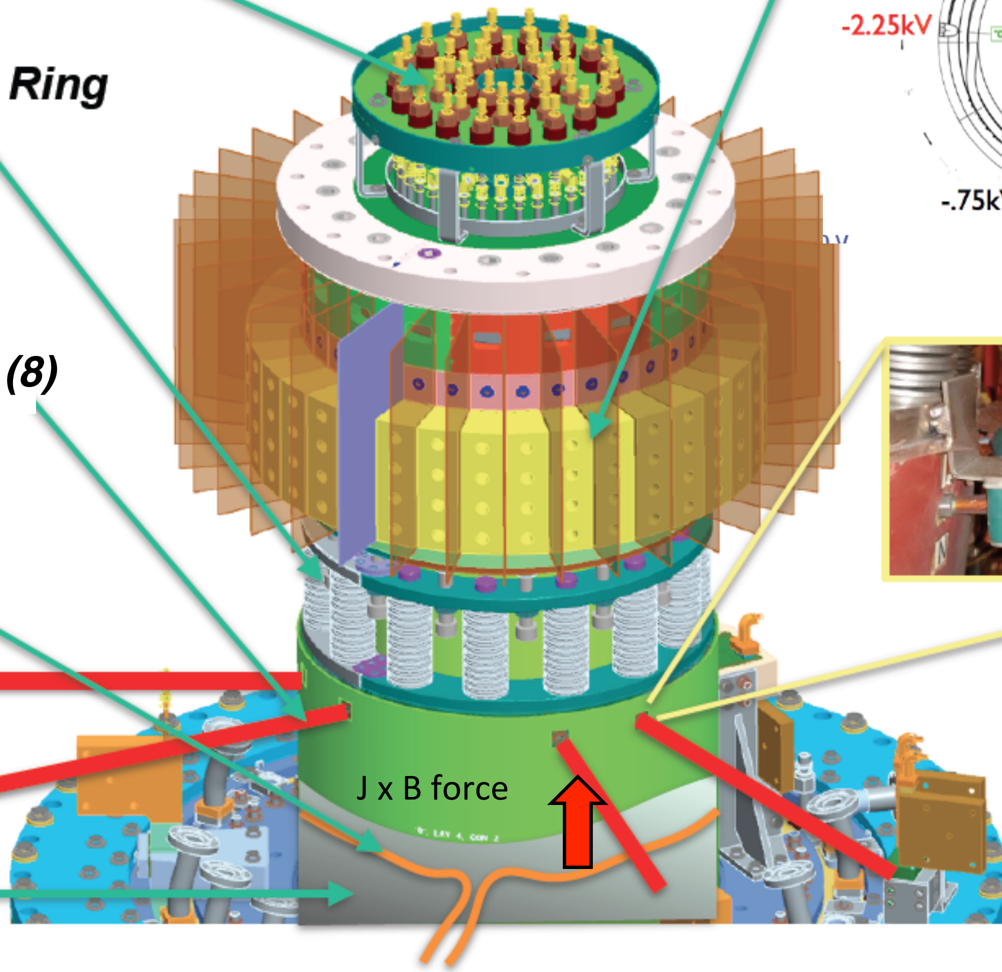


OH Compression Ring

Water Connections (8)

Ground plane ground clamp & Braid

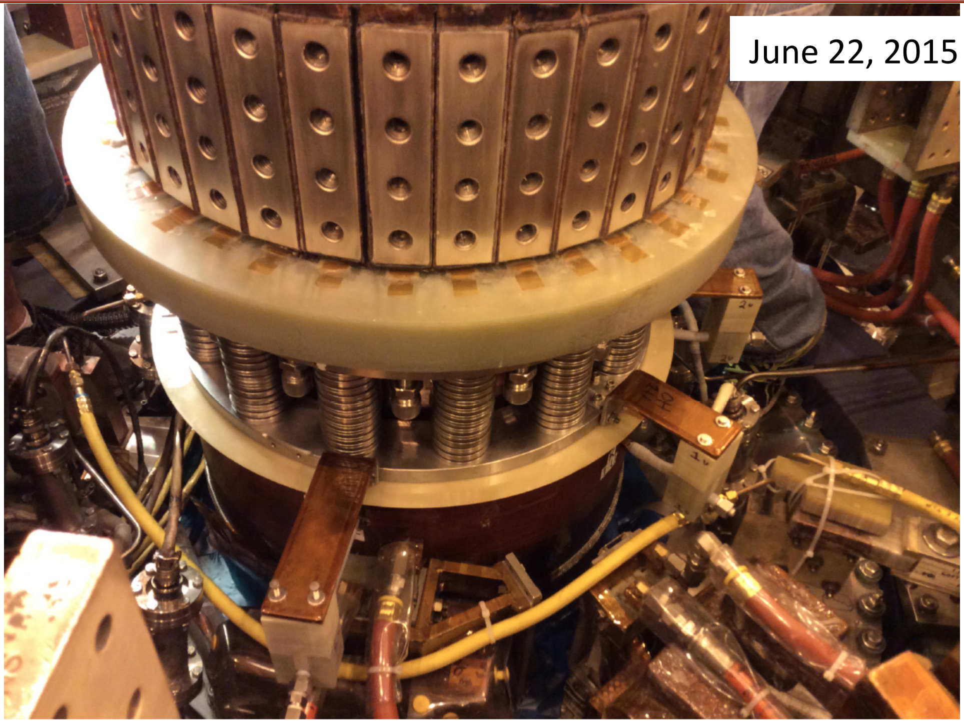
OH Coil Ground Plane Paint



OH Arc Recovery Status Summary

No significant damages and improvements implemented

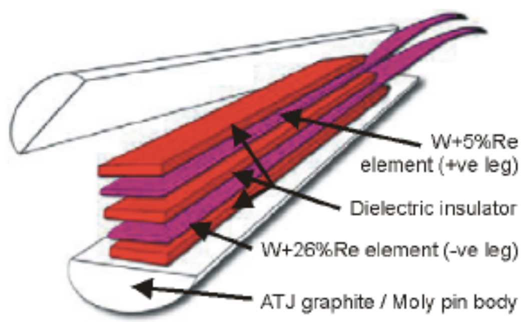
- The overall health of the NSTX-U machine appears good.
  - The damage was contained to external to OH coil (and other coils)
  - Electrical continuity/insulation and hydrostatic testing of the OH coil (and other coils nearby) indicate the coils are fine.
  - Magnetic diagnostics check out fine.
  - Bottom umbrella removed and inspected. Bottom area including support bracket improved.



- OH coil grounding loop eliminated and hose clamp improved.
- OH cooling water support bracket electrical insulation improved.
- Insulation tapes / bus supports generally improved.

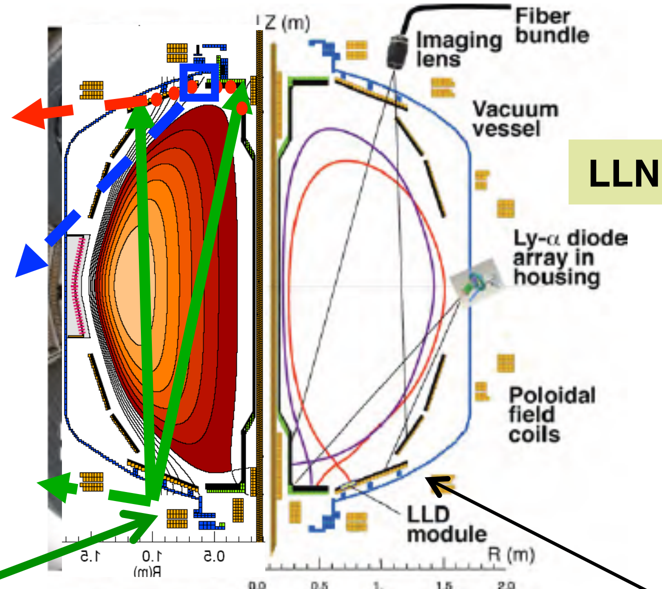
Enhanced Capability for PMI Research
Multi-Institutional Contributions

Divertor fast eroding thermocouples



ORNL

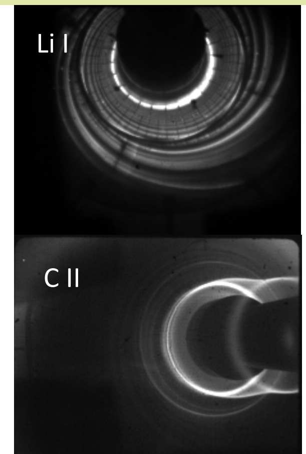
Divertor Imaging Spectrometer



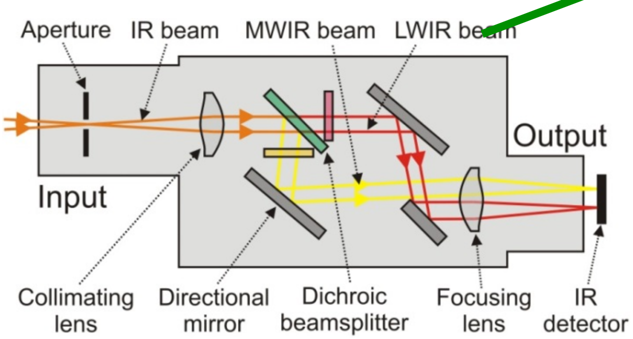
LLNL

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

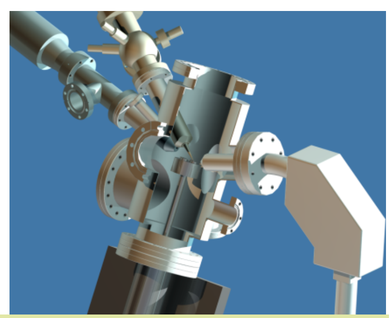
LLNL, ORNL, UT-K



Dual-band fast IR Camera



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



U. of Illinois, PPPL

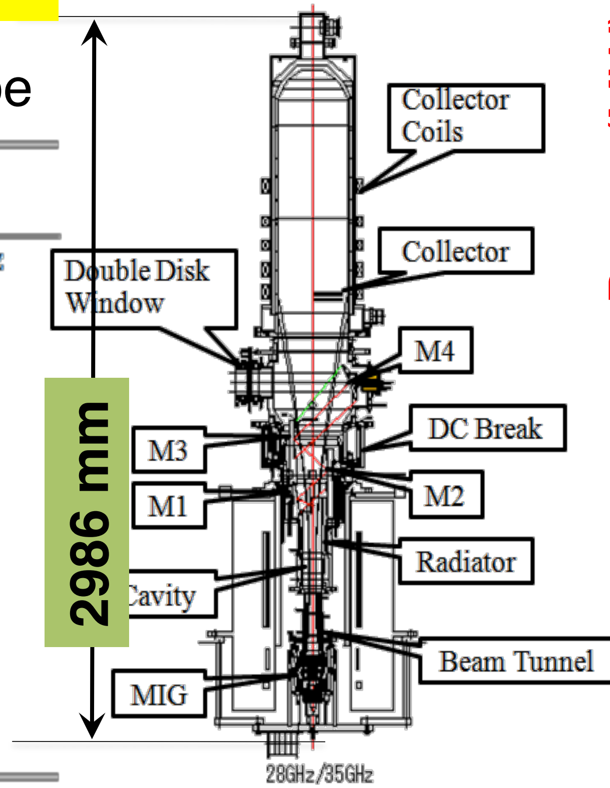
Tsukuba University is developing Prototype 28 / 35 GHz Gyrotron for NSTX-U & G-10/PDX

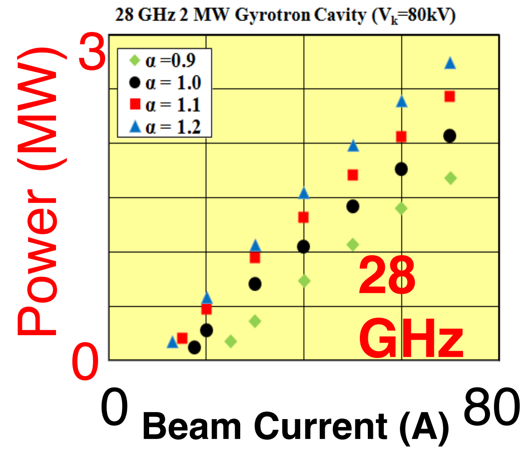
→ New design of cathode, cavity and mode converter for 1.5 – 2 MW

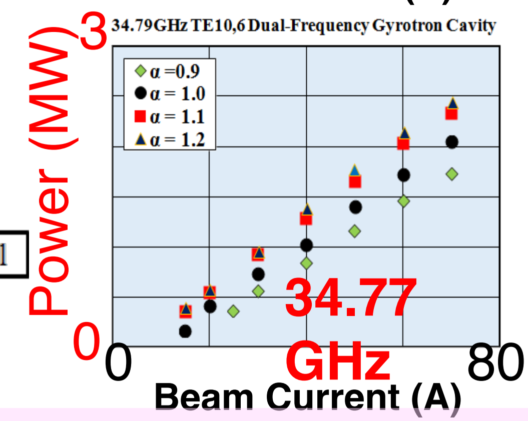
●Design Parameters of New Tube

28 GHz 2 MW Dual-frequency Gyrotron for GAMMA 10/PDX, QUEST, NSTX-U

Frequency	28 GHz		34.77 GHz
Output Power	2 MW	0.4 MW	1 MW
Pulse Width	3 s	CW	3 s
Output Efficiency	50% (with CPD)		
Beam Voltage	80 kV	70 kV	80 kV
Beam Current	70 A	20 A	40 A
MIG		triode	
Cavity mode	$TE_{8,5}$		$TE_{10,6}$
Output mode	Gaussian like		
Output Window	Sapphire Double Disk		
Collector	Depressed Collector		
	Sweeping coils		







$TE_{8,5}$ (28 GHz) & $TE_{10,6}$ (35 GHz) by the selection rule

- 2 MW calculated outputs at both 28 & 35 GHz are obtained.
- We (Tsukuba) started its fabrication and it will be tested this summer.