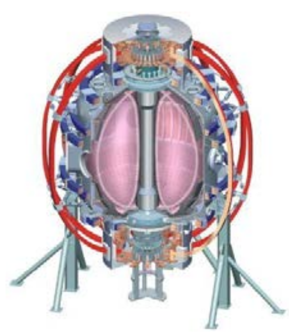
NSTX-U FY2014 Q4 Report Presentation

Vlad Soukhanovskii (LLNL)
Masa Ono
Jon Menard
For the NSTX-U Team

PPPL and FES
November 25, 2014

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



**This work supported by the US DOE Contract No. DE-AC02-09CH11466*

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

Agenda

- LLNL collaboration on NSTX-U: status and plans
  - Vlad Soukhanovskii - 25 minutes
- NSTX-U Project and Facility Status
  - Masa Ono and Ron Strykowsky - 35 minutes
- FESAC, APS highlights, FY15 research prep, FNSF
  - Jon Menard - 40 minutes

LLNL collaboration on NSTX-U: status and plans

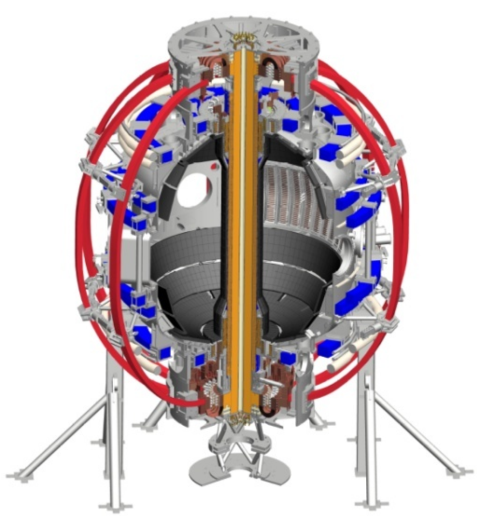
Vlad Soukhanovskii

Principal Investigator

Leader of the LLNL Collaboration on NSTX-U

FES NSTX-U Q4 Review
25 November 2014

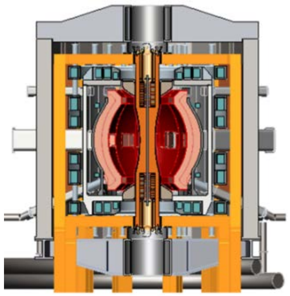
Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science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



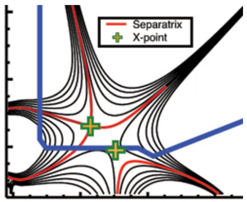
Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech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

LLNL collaboration directly supports NSTX-U mission elements and highest priority goals of NSTX-U 5 year plan

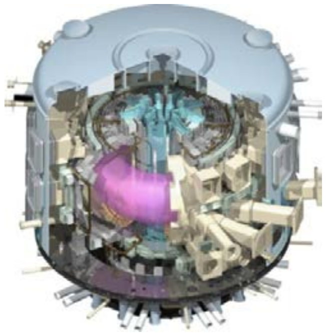
- **Advance ST for Fusion Nuclear Science Facility**
  1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
  2. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid



- **Develop solutions for plasma-material interface challenge**
  3. Develop and utilize high-flux-expansion “snowflake” divertor and radiative detachment for mitigating very high heat fluxes
  4. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps



- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  5. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding



Research elements of LLNL collaboration are funded by FES via LAB 12-03 and ECRP, and by LLNL LDRD

1. **SOL and Divertor physics** **ECRP** **LAB12-03**
   – Snowflake divertor
   – Radiative (detached) divertor and divertor control
   – SOL and divertor transport and radiation, particle balance, fueling, cryo-pumping
2. **Plasma-surface interactions and material migration** **LAB12-03**
   – Divertor and wall recycling
   – Divertor and wall erosion and sources
   – Mixed-material interactions (Li, B, C, O, Mo, W)
3. **Core impurity transport** **LAB12-03** **LLNL LDRD**
   – Low and high-Z impurity transport and particle balance
     • Laser blow-off impurity injector

LLNL collaboration includes on-site (at PPPL) and off-site LLNL staff

- Vlad Soukhanovskii, Physicist, Principal Investigator, on-site
- Peter Beiersdorfer, Senior Physicist, off-site
- Filippo Scotti, Postdoctoral Researcher, on-site
- Postdoctoral Researcher - Experiment, TBD, FY2015, on-site
- Postdoctoral Researcher - Experiment, TBD, FY2015, on-site
- Postdoctoral Researcher - Modeling, TBD, FY2015, on-site
- Staff member(s) – Modeling, off-site
- Technical staff at LLNL, as needed, on-site and off-site

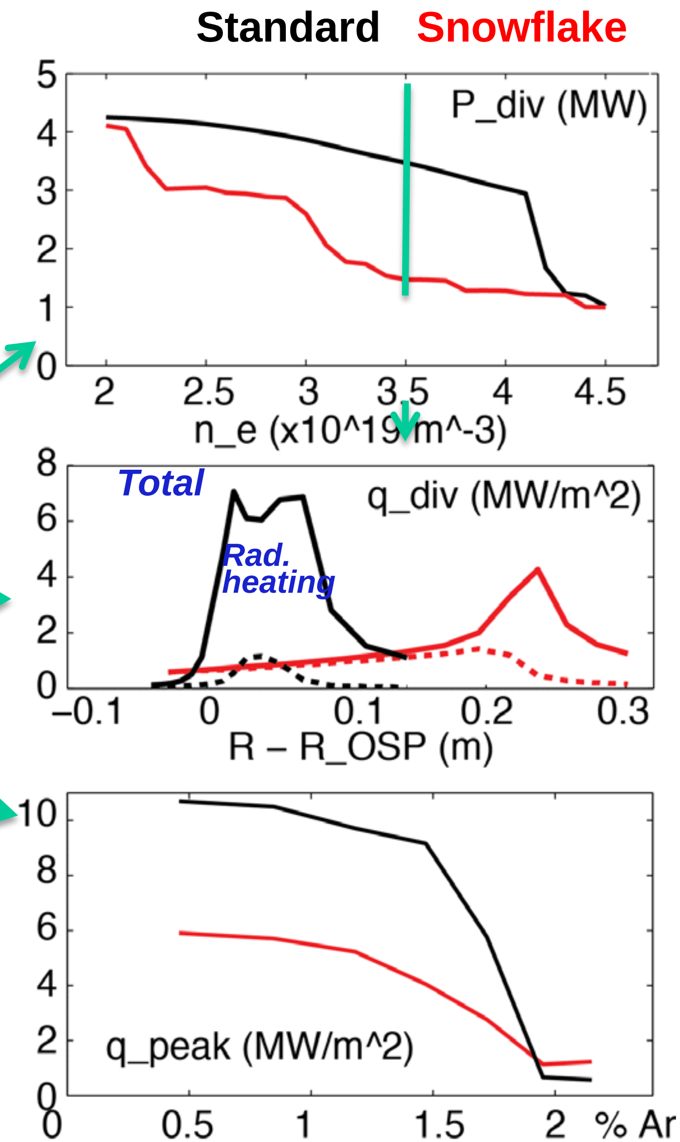
1. Support the NSTX-U high priority goal "Develop and utilize high-flux-expansion snowflake divertor and radiative detachment for mitigating very high heat fluxes"

- **DIII-D experiments elucidate on geometry and transport properties of the snowflake configuration (2012-2015)**
  - Oral talks at PSI, EPS, IAEA FEC 2014 conferences (V. A. Soukhanovskii)
  - Invited talk at APS DPP 2014 on new UEDGE model developments (T. D. Rognlien)
- **Using multi-fluid edge transport code UEDGE to understand NSTX experiments and make projections to NSTX-U and ST-FNSF**
  - PSI and IAEA FEC 2014 presentations (E. T. Meier)
- **On-going work and near-term plans**
  - Develop snowflake equilibria and discharge scenarios using NSTX-U PF coils and start-up (2014-2015)
  - Study snowflake divertor transport, turbulence, radiation and ELM/pedestal properties on NSTX-U (2015-2016, NSTX-U R(16-1))
  - Model snowflake divertor transport with UEDGE, XGC and BOUT++ (2014-2017)

ECRP

Modeling supports snowflake divertor and impurity-seeded radiative divertor as leading heat flux mitigation candidates in NSTX-U

- Upper-lower standard and snowflake radiative divertor
  - Supported by NSTX-U divertor coils and compatible with coil current limits
- Radiative snowflake with 3% carbon
  - Wide density operational window as low as $n_e/n_G \leq 0.4$
  - Peak heat flux reduced up to 50% stronger (cf. standard radiative divertor) at lower n_e
- Less impurity seeding (argon or neon) needed for lower peak heat flux
- Multi-fluid code UEDGE
  - B_t = 1.0 T, I_p = 2 MA, P_{SOL} = 9 MW
  - NSTX-like transport $\chi_{i,e}$=2-4 m^2/s, D=0.5 m^2/s



1. Support the NSTX-U high priority goal "Develop and utilize high-flux-expansion snowflake divertor and radiative detachment for mitigating very high heat fluxes"

- **Radiative divertor feedback control for long-pulse optimization (2015)**
  - Developing spectroscopic diagnostic prototypes
    - Divertor low-Z line radiation (upgraded LLNL divertor SPRED)
    - High-n deuterium series emission and photorecombination continuum for divertor T_e, n_e (new imaging spectrometer)
    - Impurity radiation front dynamics (new divertor filtered camera)
  - HTPD 2012 and 2014 presentations, two RSI papers (V. A. Soukhanovskii)
- **DIII-D Divertor Thomson Scattering operation and analysis (2012-2015)**
  - Unique T_e<1 eV measurements, detachment front dynamics for model validation
    - PSI 2014 oral talk (A. G. McLean)
  - New divertor near-infrared spectrometer (2014-2015)
- **Conceptual design of Divertor Thomson Scattering for NSTX-U**
  - Two HTPD 2014 presentations, two RSI papers (A. G. McLean, V. A. Soukhanovskii)
- **On-going work and near-term plans**
  - Install and commission radiative divertor control diagnostics on NSTX-U
  - Initial radiative divertor experiments (2015-2016, NSTX-U R(16-1)) **ECRP**
  - Finalize design of Divertor Thomson Scattering diagnostic for NSTX-U proposal

2. Support the NSTX-U high priority goal "Begin to assess high-Z PFCs and liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps"

- **Analysis of lithium and carbon erosion in NSTX shows temperature-enhanced lithium sputtering and weak reduction of divertor carbon sputtering with lithium coatings**
  - PSI 2014 presentation (F. Scotti)
- **New and upgraded spectroscopic diagnostics to enable recycling, low/high Z impurity erosion flux and divertor profile measurements in NSTX-U (2014-2015)**
  - Molybdenum erosion diagnostic moved from Alcator C-Mod to tests on LTX
- **On-going work and near-term plans**
  - Support cryo-pump physics design experiments (2015)
  - Assess role of oxygen in lithium coating pumping and effect on recycling, low and high-Z fluxes (2015-2016, R(16-2))
  - Collaborate with UIUC on MAPP probe PSI support (2015-2016)
  - Develop modeling capability of lithium coatings and vapor shielding on high-Z substrates using UEDGE, REDEP/WBC, CRETIN (2014-2017)

LAB12-03

3. Support the NSTX-U high priority goal "Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding"

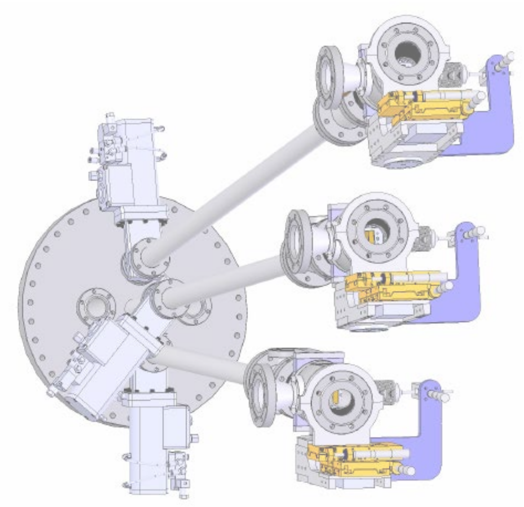
LAB12-03

- **Lithium and carbon accumulation analysis in NSTX shows complex interplay of neoclassical transport, natural or triggered ELMs and divertor sources**
  - F. Scotti, Princeton University PhD thesis
  - APS DPP 2014 presentation (F. Scotti)
- **Develop and install three extreme ultraviolet spectrometers for impurity studies (2014-2015)**
  - Spectrometers delivered to PPPL on 17 November 2014
- **Develop and install Laser Blow-Off Impurity Injector (2015)**
  - Supported in part by LLNL LDRD for edge impurity transport measurements and code validation on NSTX-U
  - Conceptual design review planned for 01/2015
- **On-going work and near-term plans**
  - Provide routine plasma impurity monitoring (2014-2017)
  - Perform impurity transport experiments using LBO (2015-2016)
  - Assess high-Z impurity transport before and after high-Z PFCs are installed

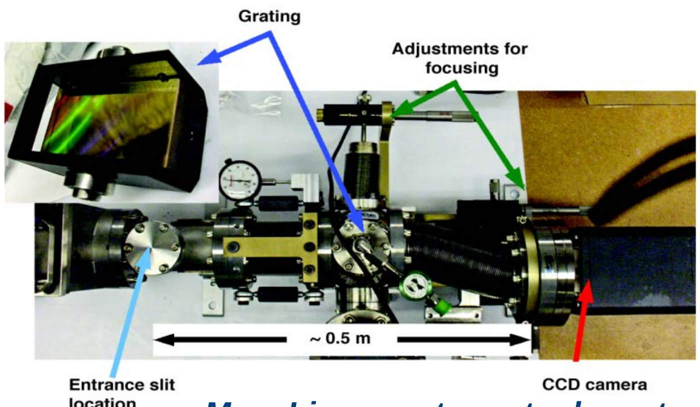
LLNL LDRD

Three XUV spectrometers will provide continuous spectral coverage from 65 to 450 A for low and high-Z line emission measurements

- Described in
  - J. K. Lepson, J. Phys. B: At. Mol. Opt. Phys. 43, 144018 (2010)
  - J. Clementson, RSI 81, 10E326 (2010)
  - J. K. Lepson, RSI 83, 10D520 (2012)
- Two NSTX spectrometers
  - XEUS, 5 to 65 Å region, 2400 gr/mm grating
  - LoWEUS, 250 to 450 Å region, 1200 l/mm grating
- New MonaLisa (Metal Monitor and Lithium Spectrometer Assembly) spectrometer, 65 to 250 Å
  - 0.5 m, 1200 l/mm grating
  - Princeton Instruments PIXIS XO 100B CCD detector
- **Delivered to PPPL on 17 November 2014**



LLNL XUV spectrometer placement on NSTX-U at Bay E midplane

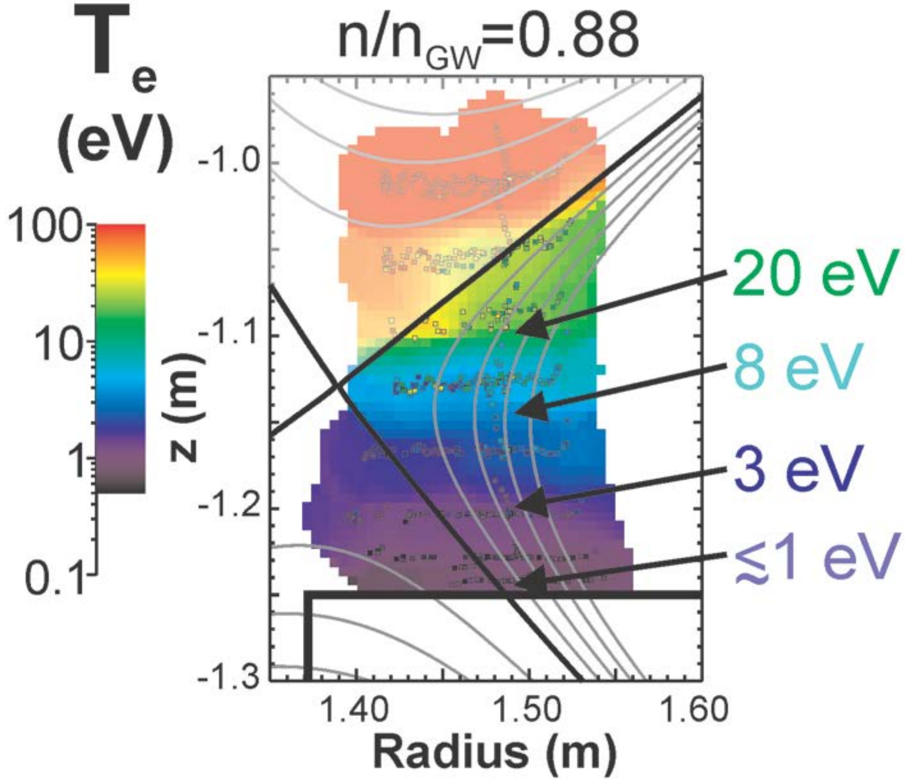


MonaLisa spectrometer layout

Backup slides

Electron pressure balance in the SOL through the transition to detachment at DIII-D (A. G. Mclean, PSI 2014)

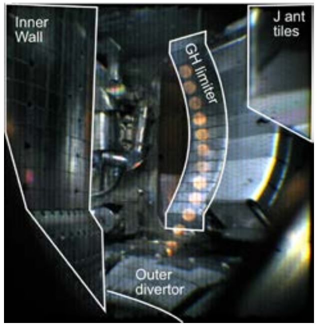
- The transition to detachment has been well characterized in DIII-D using standard diagnostics and supplemented with divertor Thomson scattering in 2D
- Low temperature capability of upgraded divertor Thomson allows precise determination where conditions exist for low temperature processes (e.g., 3-body recombination, molecular assisted dissociation/recombination)
- Plasma conditions in the divertor at detachment onset are weakly correlated to conditions upstream
- A rapid transition occurs incrementally from the target to the X-point and above as n/n_{GW} is increased

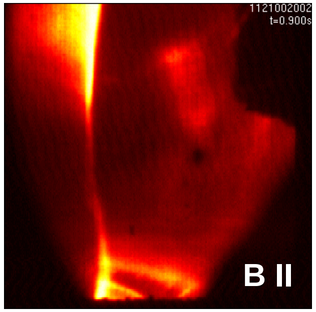


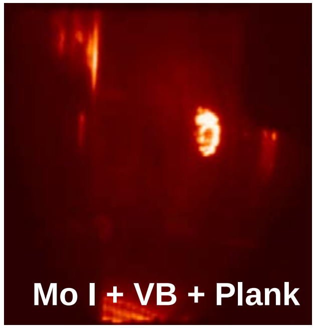
A.G. McLean, PSI-21 Kanazawa, Japan, May 2014

New CIDTEC camera will be used for measurements of Li, B coatings, oxygen emission, and high-Z erosion

- Used by LLNL at Alcator C-Mod for Mo I measurements
  - Described in A. James, Plasma Phys. Control. Fusion 55, 125010 (2013)
- Radiation-hardened intensified camera CIDTEC I3710DX9 from Thermo Schientific
  - 30 Hz, VGA resolution, UV-capable
  - Photonis XX1450UV image intensifier
  - Schott IG-154 imaging bundle
- Presently being setup for NSTX-U
  - Will be used for Li, B, O, Mo and W emission measurements where line emission is weak
  - Image splitter enables
    - simultaneous measurements of neutral and singly-ionized species for gross vs net erosion analysis
    - Line ratio measurements for T_e, etc
    - Relative impurity measurements (e.g., Li to C, B to C etc)







CIDTEC camera setup in the lab and examples of Alcator C-Mod images.

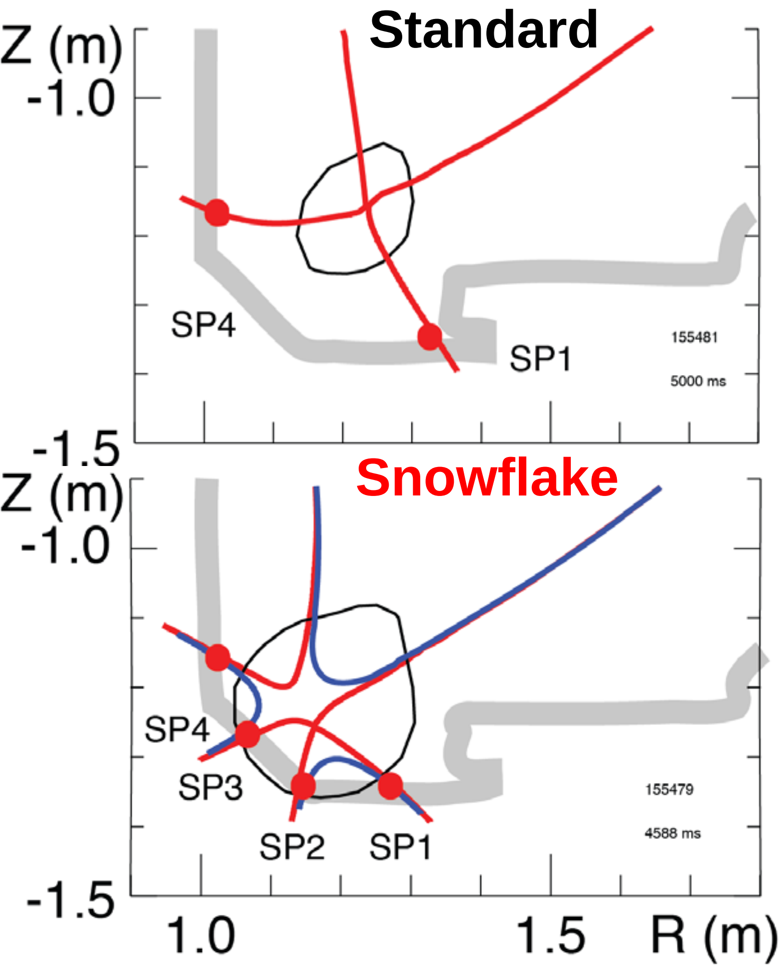
Developing the Snowflake Divertor Physics Basis For High-power Density Tokamaks at DIII-D

- SF divertor configurations compatible with high H-mode confinement and high pressure pedestal

- Snowflake geometry may offer multiple benefits for inter-ELM and ELM heat flux mitigation
  - Geometry enables divertor inter-ELM heat flux spreading over larger plasma-wetted area, multiple strike points
  - Broader parallel heat fluxes may imply increased radial transport
  - ELM divertor peak target temperature and heat flux reduction, especially in radiative snowflake configurations

Lawrence Livermore National Laboratory

Large Region of Low B_p Around Second-order Null in Snowflake Divertor is Predicted to Modify Power Exhaust



Low B_p contour: $0.1\ B_p/B_p^{mid}$

- **Geometry properties**

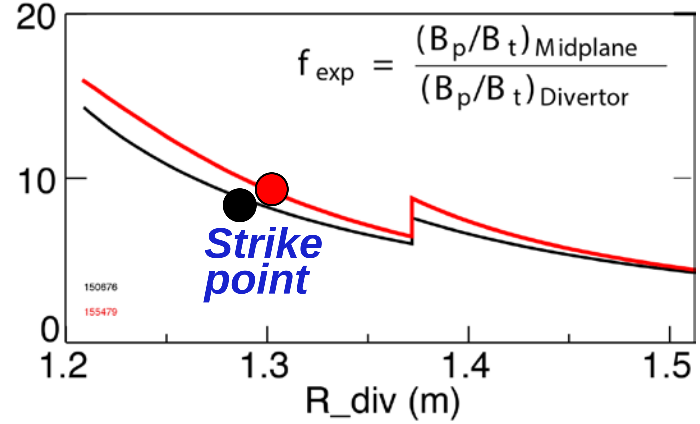
  Criterion: $d_{XX} \leq a\,(\lambda_q/a)^{1/3}$
  - **Higher edge magnetic shear**
  - **Larger plasma wetted-area A_{wet} (f_{exp})**
  - **Larger parallel connection length $L_{||}$**
  - **Larger effective divertor volume V_{div}**

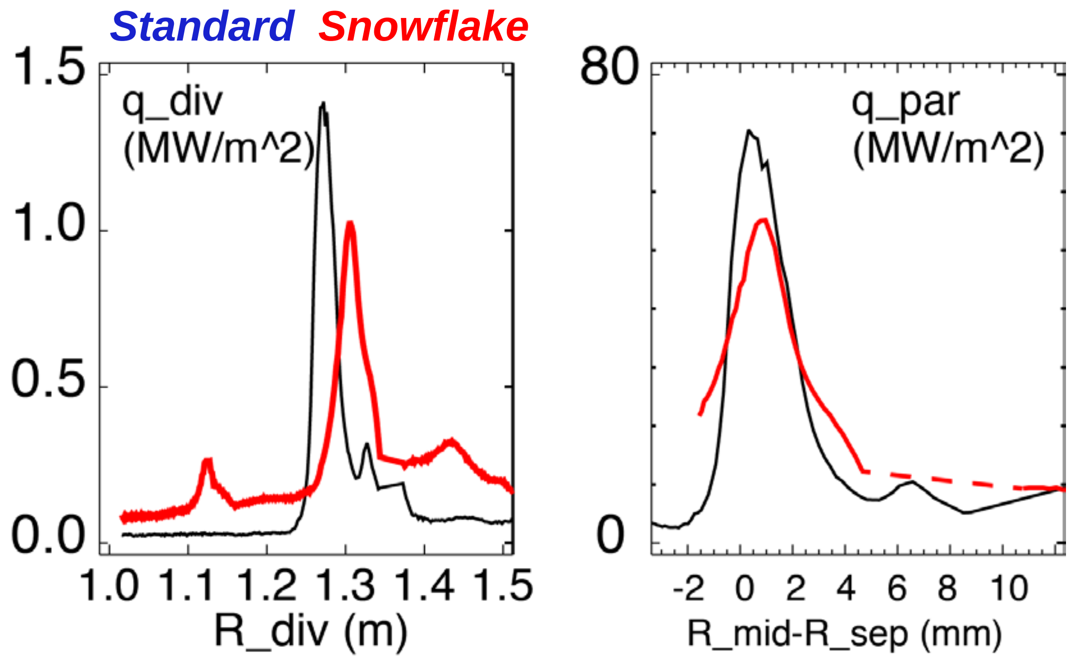
- **Transport properties**

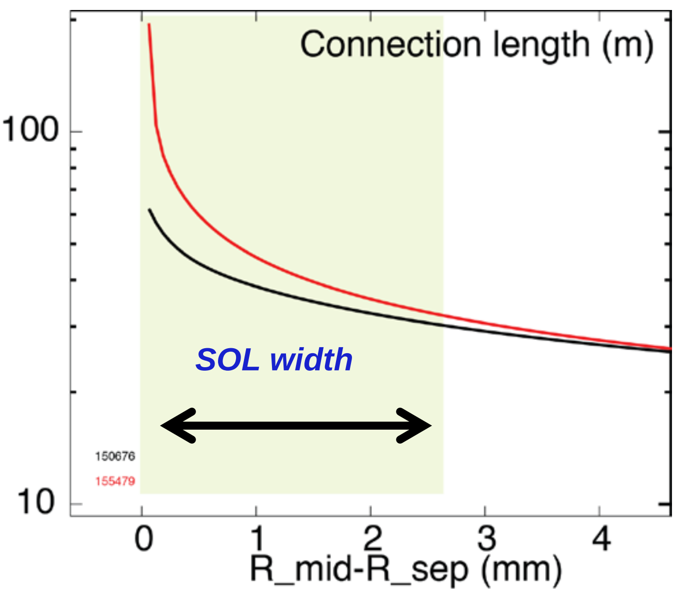
  Criterion: $d_{XX} \leq D^* \sim a\,(a\,\beta_{pm}/R)^{1/3}$
  - **High convection zone with radius D***
  - **Power sharing over four strike points**
  - **Enhanced radial transport (larger λ_q)**

“Laboratory for divertor physics”

q_{peak} Reduction in Snowflake Divertor Partly Due to Increased A_{wet} and $L_{||}$

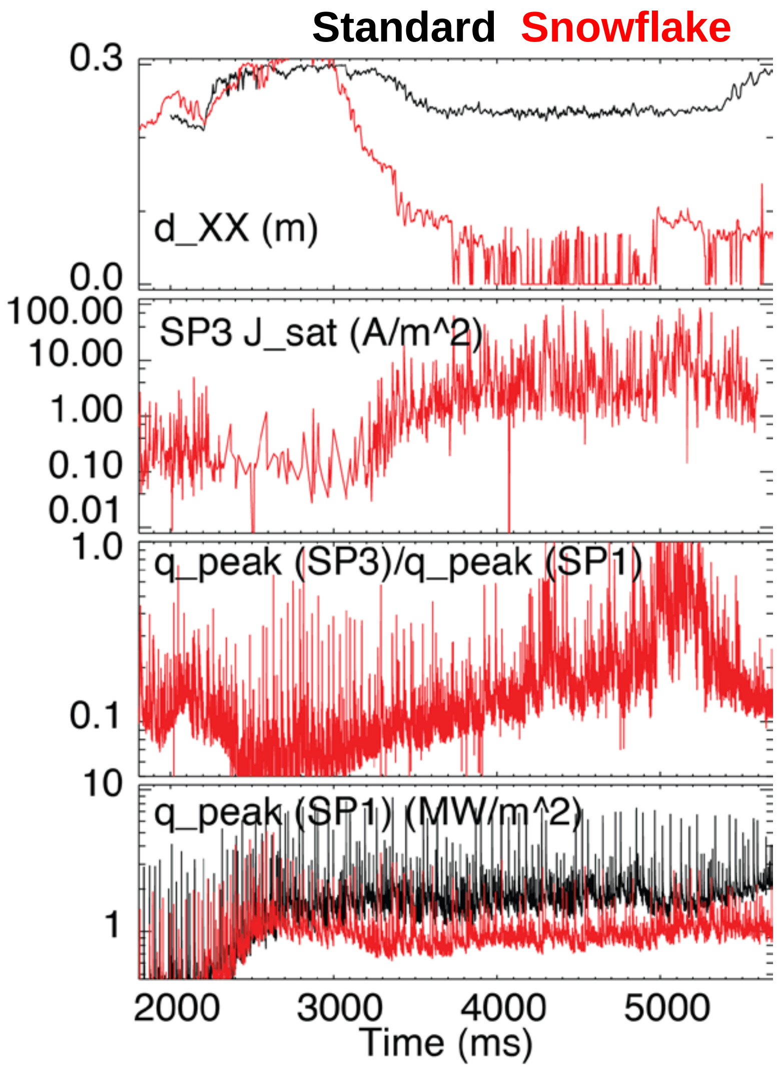






- Flux expansion increased ~20%
  - Depends on configuration, can be up to X3
- $L_{||}$ increased by 20-60% over SOL width
- Divertor heat flux reduced ~30%
- Parallel heat flux reduced ~20%

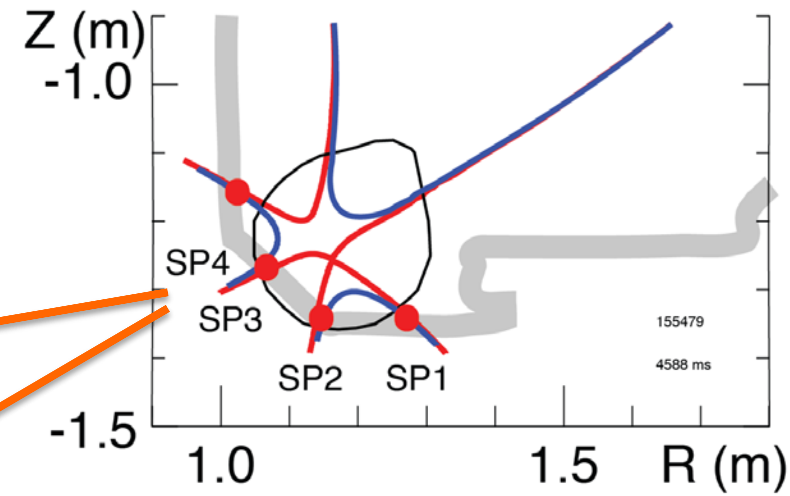
Heat and Particle Fluxes Shared Among Strike Points in Snowflake Divertor



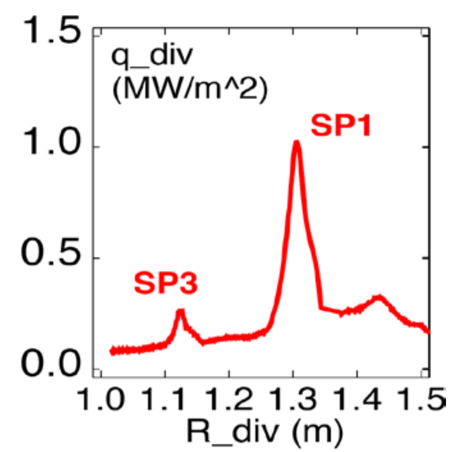
Γ_{SP3}

q_{SP3}

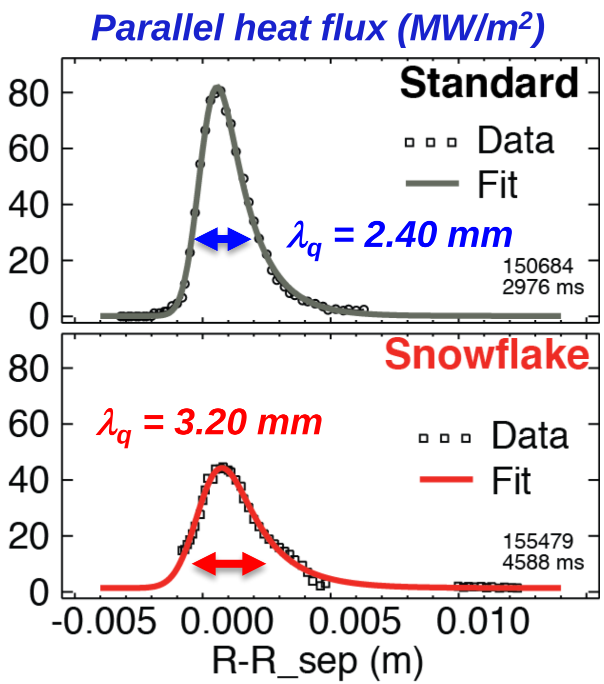
q_{SP1}

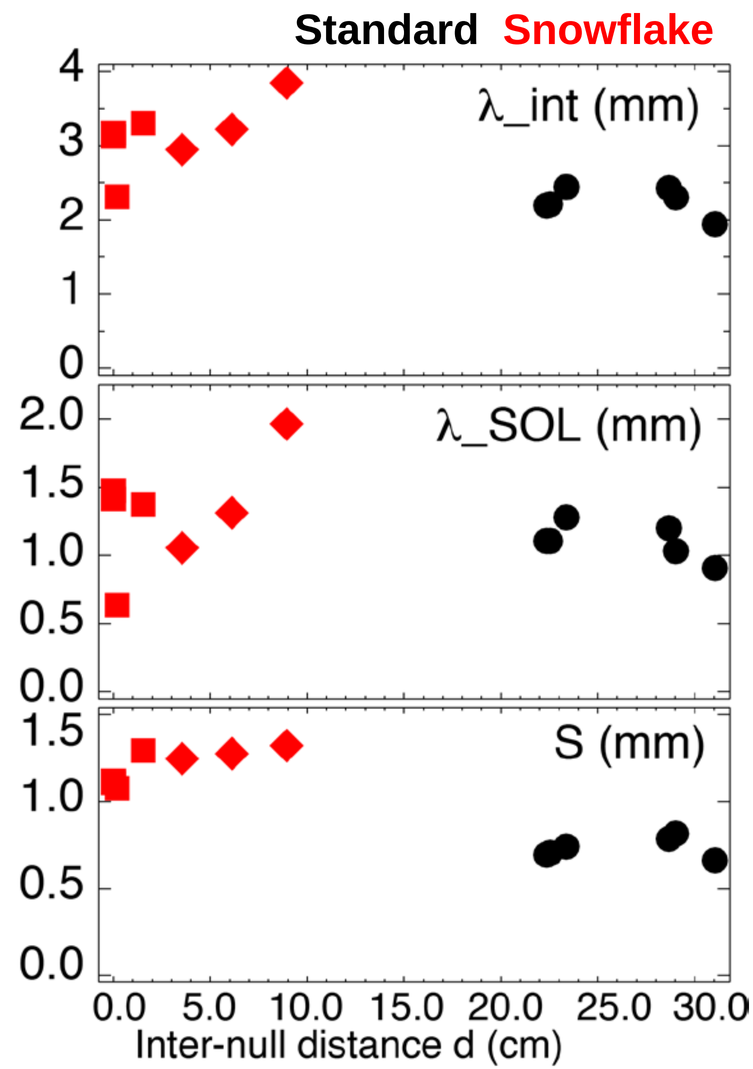


- $q_{SP3} / q_{SP1} < 0.5$
- $P_{SP3} / P_{SP1} < 0.3$
- Sharing fraction maximized at low d_{XX}



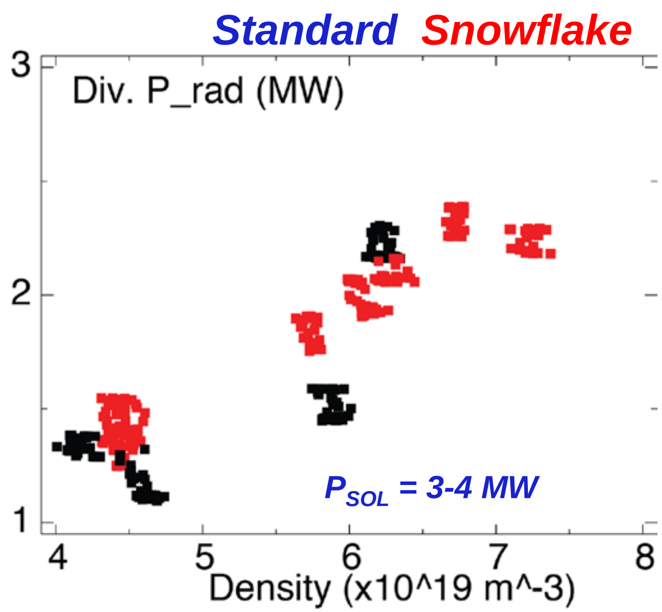
Broader $q_{||}$ Profiles in Snowflake Divertor May Imply Increased Radial Transport

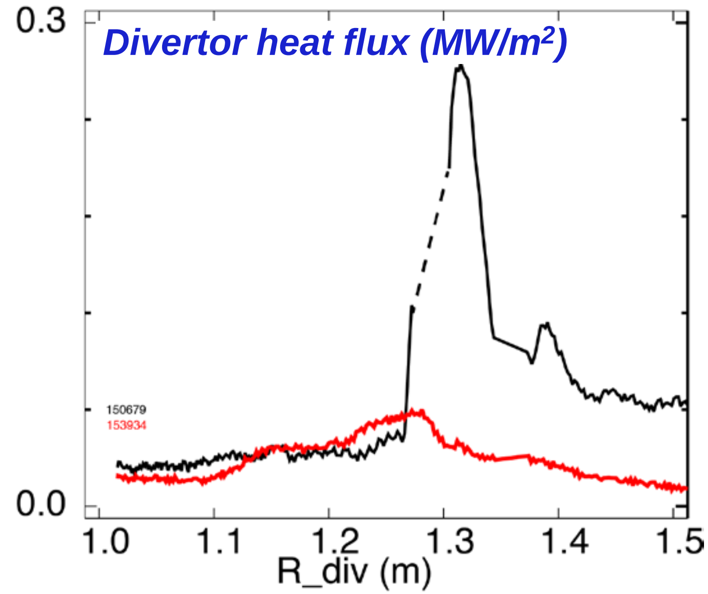


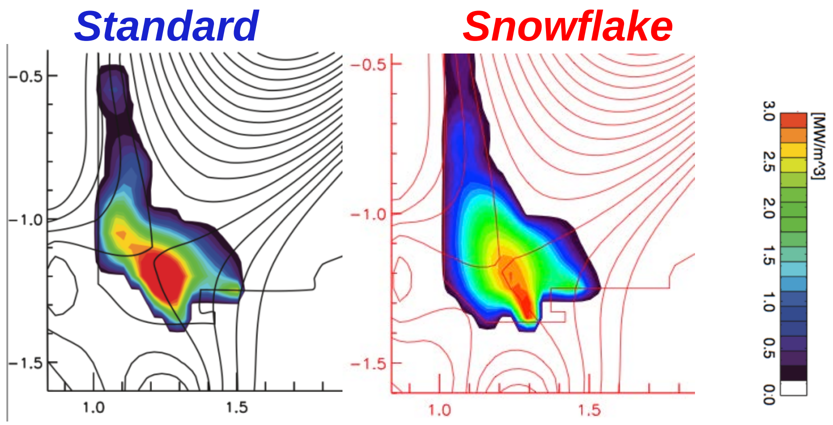


- Fit $q_{||}$ profile with Gaussian (S) and Exp. (λ_{SOL}) functions (Eich PRL 107 (2011) 215001)
- Increased λ_q may imply increased transport
  - Increased radial spreading due to $L_{||}$
  - SOL transport affected by null-region mixing
  - Enhanced dissipation may also play role

Divertor Radiation More Broadly Distributed in Snowflake for Radiative Divertor, q_{peak} Reduced by x5







- Detached radiative divertor produced by D_2 injection with intrinsic carbon radiation
- In radiative snowflake nearly complete power detachment at P_{SOL}~3 MW

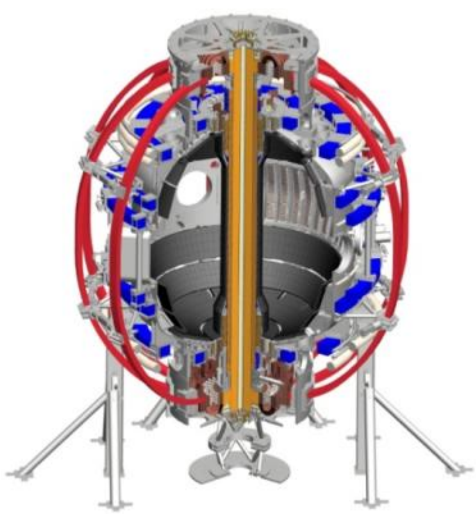
NSTX-U Project / Facility Status

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

Masa Ono and Ron Strykowsky

for the NSTX-U Team

NSTX-U FY 2014 Q4 Review Meeting
November 25, 2014

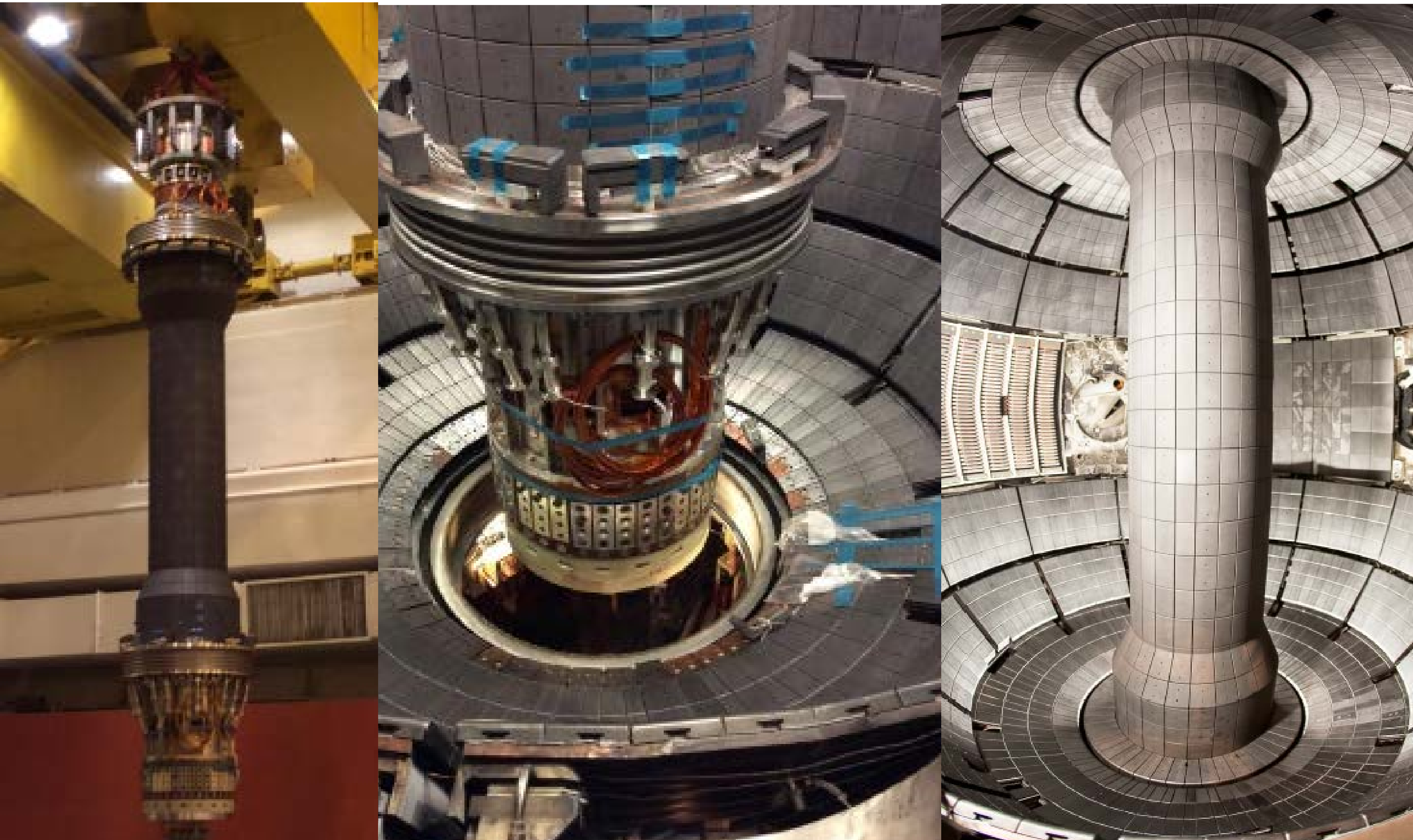


Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Tsukuba U
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
SNU
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Outline

- **Upgrade Project Status**
- **Preparation toward Operation**
- **Research Operation Schedule**
- **NSTX-U Organization**
- **Summary**

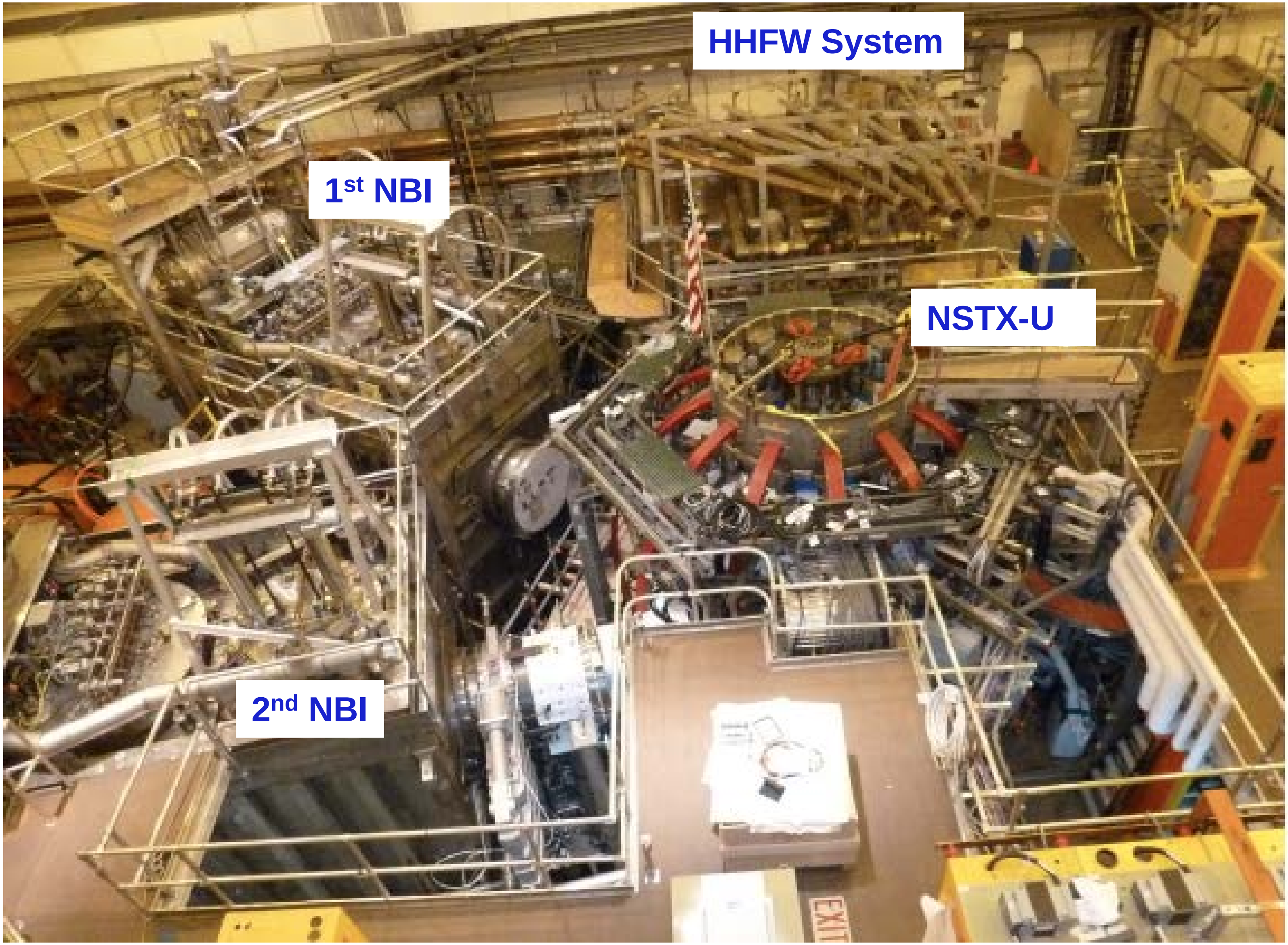
New Center-Stack Installed In NSTX-U
Vacuum pump-down is planned for December



First NBI access port duct installed last week. Smaller flanges being installed

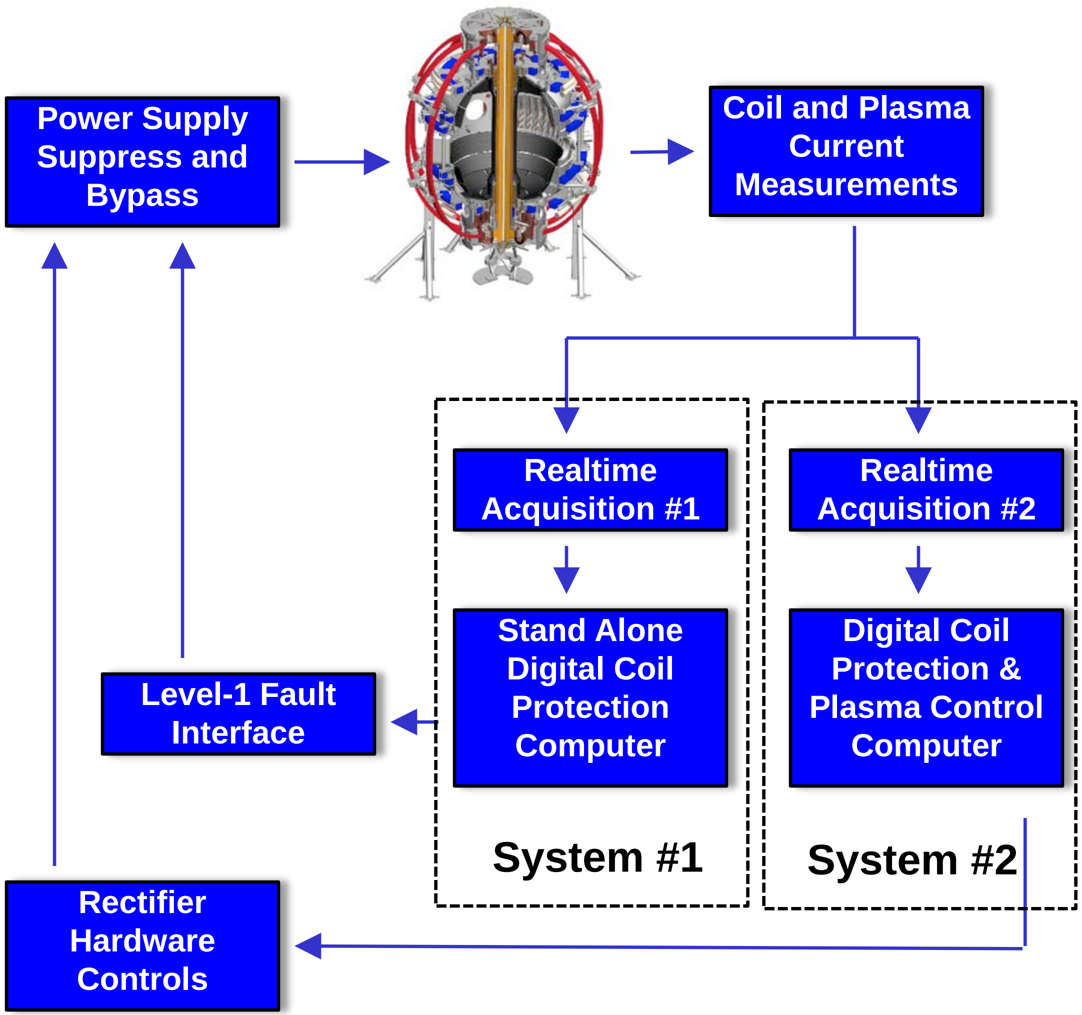
NSTX Upgrade Project Is 95% Complete

Recent aerial view of NSTX-U Test Cell (Oct. 27, 2014)



New Digital System Provides Comprehensive Coil Protection

Protects NSTX-U machine against electromagnetic loads



Computes forces and stresses in real-time based on reduced models of the full mechanical structure

Redundant systems

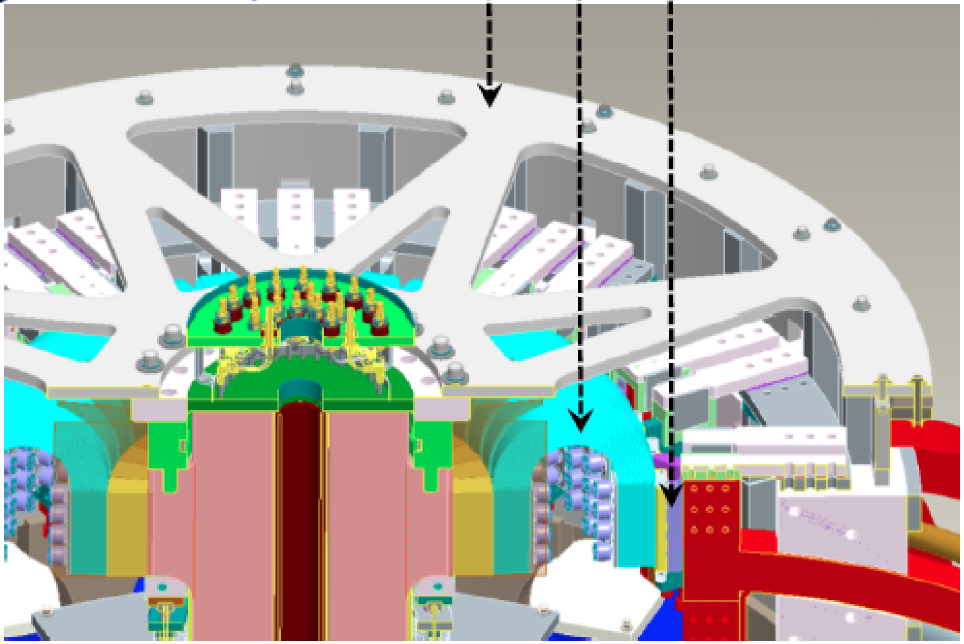
System #1 is undergoing final integrated testing, will be used during rectifier dummy-load testing in December, providing real world experience before plasma ops.

System #2 is 90% complete and it will be ready to support CD-4 and beyond.

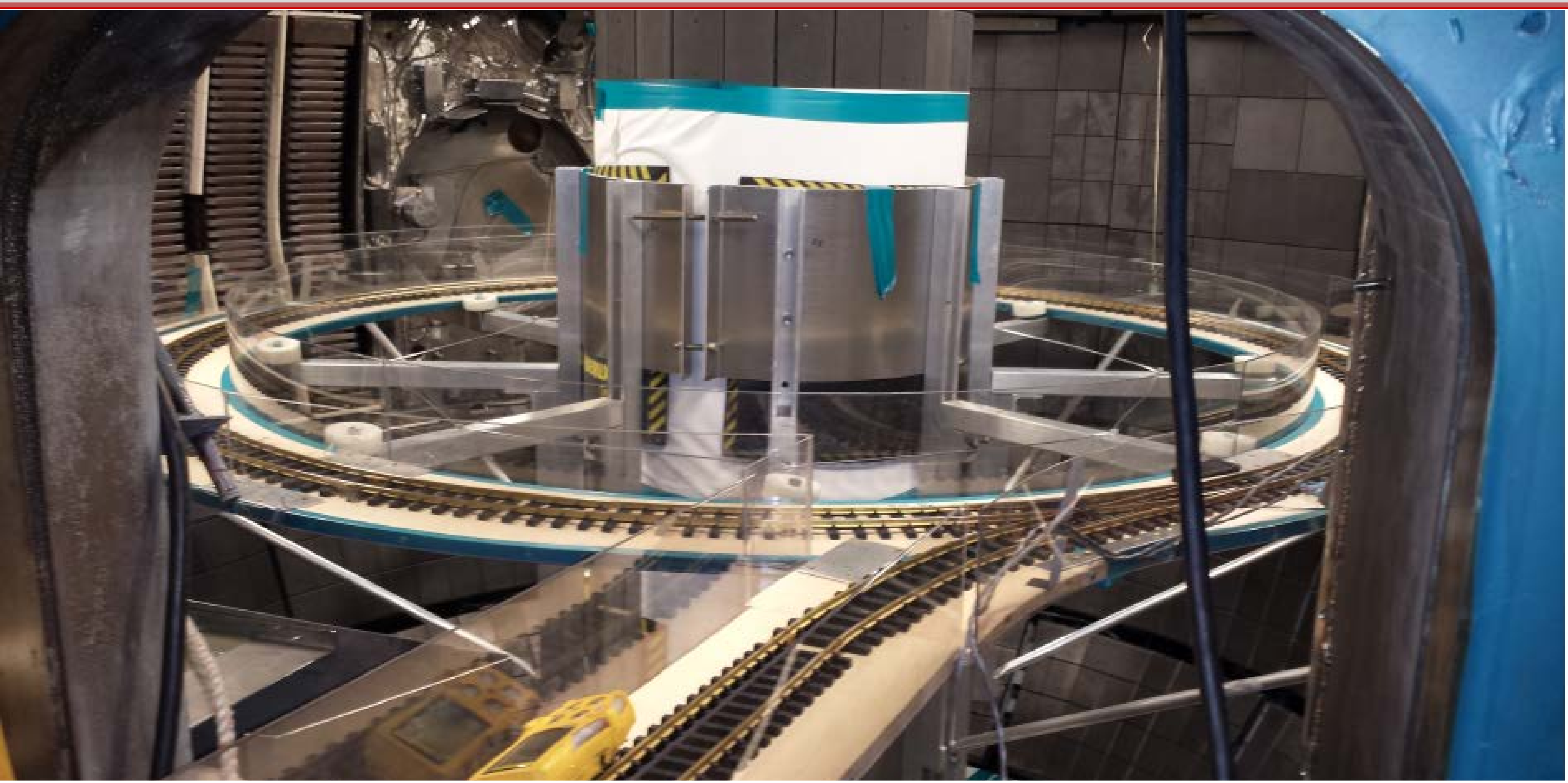
Full commissioning system will be a key part of early operations

Remaining Construction Work in NSTX Test Cell

- Pumpdown - December
- Leak check - December - January
- Install bus inside umbrella and back to racks - November - December
- Install new TF lead extensions - January
- Install TF flex bus - January
- Install new umbrella lids - February
- Install umbrella lid support rings - February
- Bakeout - February
- ISTP - March



Neutron calibration was performed safely with a stronger neutron source inside the NSTX-U vacuum chamber



- The neutron calibration was performed with two major radii with a neutron source mounted on a model train car on a set of circular tracks inside the NSTX-U vacuum chamber.
- Dr. Kunihiro Ogawa from the LHD group (NIFS, Japan) observed the calibration, in anticipation of a similar calibration that is to be done on LHD a few months from now.

Approvals for Operations

- The NSTX-U Activity Certification Committee (ACC) reviews continue, and is comprised of representatives from PPPL Engineering, Research, Safety, and the DOE PSO is currently reviewing technical and safety systems for NSTX-U

- A PPPL Internal QA Audit of NSTX-U Start-Up has been performed, and has resulted in a punch list of critical Start-Up and Test Procedures for both CD-4 and subsequent physics operations.

- A Readiness for Operations Review (Dec. 9 -11) is being arranged through the University, and is prerequisite for our safety certificate prescribing allowable operating parameters. Committee members from LANL, GA, JLAB, MIT, ORNL, CCFE & UW will be here for this review.

Preparations for Operations

- **PF1 Field Changes**
  - FCPC has been configured.
  - Connections/labeling in the test cell still required.
- **MG#1 Weld Repairs**
  - Maintenance procedures in progress with plans to spin up the set in December.
- **Field Coil Power Conversion (FCPC) Commissioning**
  - AC primary Power Systems and new rectifier firing generators ready to support Ops
  - The new PLC-based fault relaying system to replace electromagnetic relays is complete and tested. Individual rectifiers are being prepared for open circuit testing.
  - The Digital Coil Protection System (DCPS) has been installed, and is undergoing pre-operational testing.
  - The Power System Real Time Control (PSRTC) is being tested in conjunction with the rectifier firing generators. DCPS and PSRTC will be ready to support FCPC Dummy Load testing in December.

Neutral beam injection (NBI) system should be available for CD-4 and research operations

- **Neutral Beam Injection #2**
  - **Pre-operational testing in progress.**
  - **NBI#2 will be ready to pump-down in December.**
  - **Helium Refrigerator compressors have been started and clean-up of process gas in progress.**
  - **Expect to start ion source pre-operational testing (PTP-11) in December to complete the NB! #2 CD-4 in Jan/Feb.**

- **Neutral Beam Injection #1**
  - **After CD-4, will begin to re-commission NBI#1, although will attempt to make parallel progress whenever possible.**

- **Test Cell Mods**
  - **A design for a new North Door shield wall has been completed. Installation in Dec/Jan.**

Considerable Effort Being Dedicated to Plasma Control Commissioning

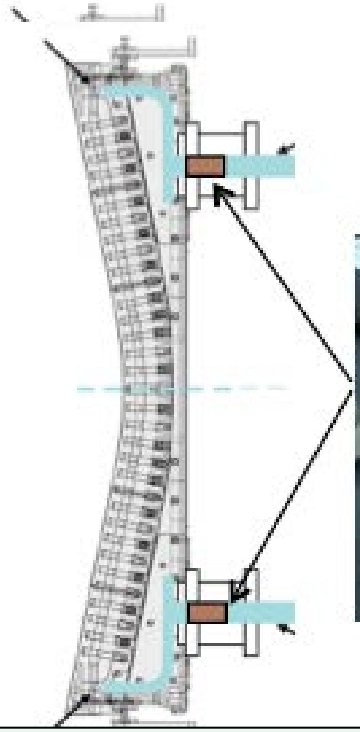
- **Critical magnetic diagnostics**
  - **Final in-vessel sensor installation and repairs completed.**
  - **Presently recommissioning the magnetic integrators.**
  - **New plasma current rogowski processing electronics nearing completion.**
  - **Excellent new magnetic diagnostics on the CS expertly installed.**

- **Making rapid progress in control software development.**
  - **New 64 core plasma control computer to be delivered in a few weeks, with plans to purchase a backup computer in January.**
    - **Supports all plasma control + DCPS System #2.**
  - **Upgrades to realtime data link successfully tested.**
    - **Presently testing new power supply control software.**
  - **Have written new gas delivery system control software, to be tested in December.**
  - **Beginning a "scrub" of remaining plasma control software to remove legacy dependencies.**
  - **Hired a replacement realtime software developer to provide expanded capability and redundancy in this critical area.**

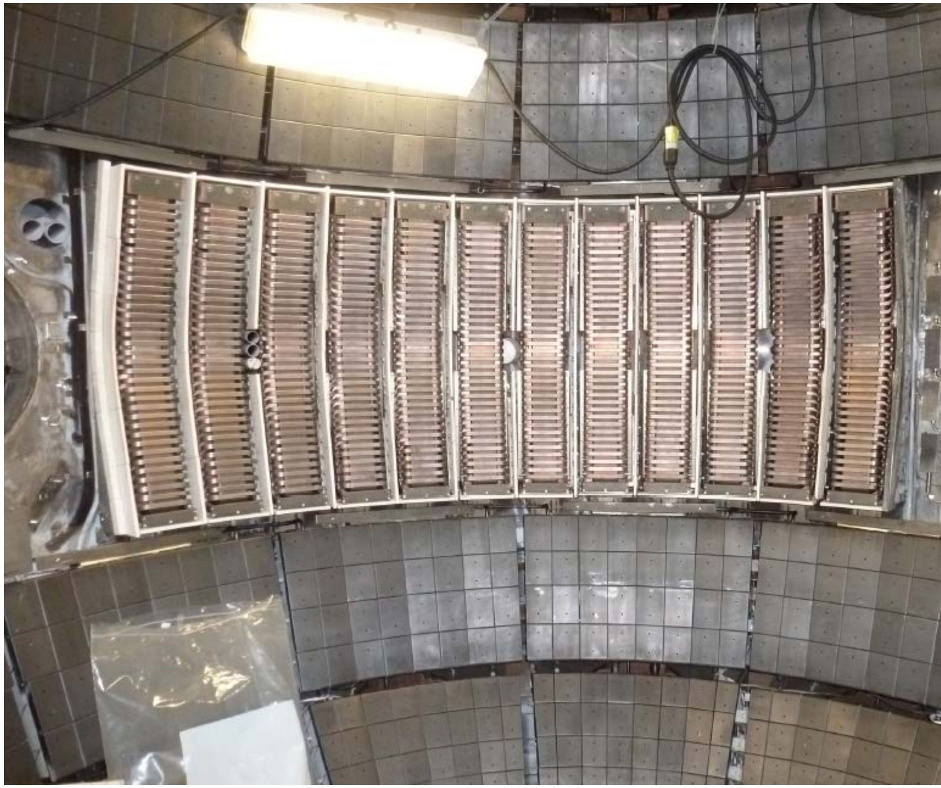
HHFW System for Electron Heating and Current Ramp-up
Improved Antennas were installed on NSTX-U

New Compliant Antenna Feeds

Will allow HHFW antenna feedthroughs to tolerate 2 MA disruptions



Prototype electroformed compliant section



- Prototype compliant feeds tested to 46 kV in the RF test-stand. Benefit of back-plate grounding for arc prevention found.
- Antennas were re-installed with the new feeds and back-plate grounding

- Transmission lines are in the process of being installed & tuned.

Remaining tasks:

- RF power supplies to be re-energized in March 2015 time frame to be ready for research operation in May 2015.

NSTX-U diagnostics to be installed during first year

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

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

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

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

Energetic Particle Diagnostics
Fast Ion D_α profile measurement (perp + tang)
Solid-State neutral particle analyzer
Fast lost-ion probe (energy/pitch angle resolving)
Neutron measurements

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

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

New capability, Enhanced capability

Considerable Success In Diagnostic Installation Before Vessel Closure With the Support of the Upgrade Project

- **Neutron detector installation & calibration (with in-vessel train track) completed.**
- **Fiber installation and in-vessel alignments for MPTS Upgrade complete.**
- **MAPP checked for interferences with outboard divertor at sample insertion point and probe drive stand secured to NTC floor.**
- **Tile on CS machined to provide reflecting surface for interferometer/polarimeter.**
- **New shutters installed for "Synthetic Aperture Microwave Imaging" (SAMI) and MSE-LIF diagnostics.**
- **Toroidal CHERS diagnostic recalibrated following window replacement.**
- **Sample coupons placed on vacuum vessel walls and quartz deposition monitors installed.**
- **All flanges required for pumpdown identified and installation in progress.**

All major profile diagnostics (MSE, MSE-LIF, CHERS, P-CHERS, MPTS, FIDA, T-FIDA) achieved spatial calibrations before pump-down.

Operations Team Continuing to Make Progress in Boundary Physics Operations to Prepare the Facility for Research

Massive Gas Injection	• Installation procedures for MGI valves have been released. • Critical valve components delivered to PPPL (from U. Washington), and support brackets fabricated. • Will be installed in parallel with the inner-PF bus work.

Fuelling and Density Control	• All gas valves will be under PCS control
	  • Allowing SGI to be used for density feedback
	  • Divertor injectors for radiation control

Boronization	• New engineer with extensive experience in hazardous gas handling completed design for trimethyl borane system • Components have been ordered with goal of availability of system for start of research operations
Lithium Evaporators (LITERs)	• Fume hood installation and other upgrades complete for laboratory for LITER filling and maintenance • Lithium handling procedures being updated – engineer responsible for boronization system involved
Granule Injectors for NSTX	• New injector expected to be available for plasma operations – new postdoc responsible for system • Lithium granules to be manufactured by UIUC

Activities between CD4 and Research Run

Important to optimize them to start the timely research run!

3/9/15	3/16/15	3/23/15	3/30/15	4/6/15	4/13/15	4/20/15	4/27/15	5/4/15	5/11/15	5/18/15	5/25/15	6/1/15	6/8/15	6/15/15	6/22/15	6/29/15	7/6/15
March 2015				April 2015				May 2015				June 2015					
23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
ISTP	CD-4	Short vent, Facility Work		MPTS Rayleigh Raman	Bake Out				ISTP	Commisioning				Run Week	Run Week	Maint.	Run Week

- Short Vent to Install New Diagnostics (no manned entry!) only if needed.
- Data Acquisition & Diagnostics Commissioning
- Ex-Vessel Diagnostic Installations
- Gas Delivery System Final Checks
- Magnetics Debugging
- Beamline #1 Final Checks

<u>Calibrations:</u>

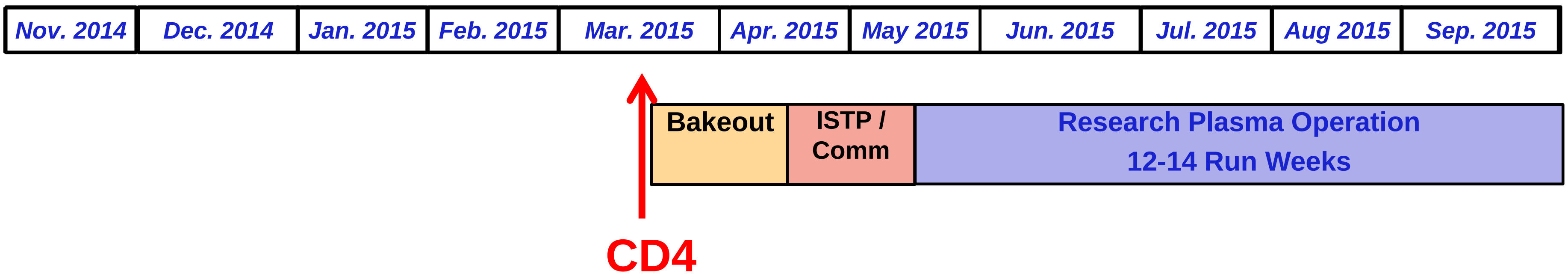
- Magnetic
- MSE
- CHERS
- Neutrons
- Boronization / GDC

<u>Commissioning</u>

- I_p<=1.0 MA, B_T<=0.5
- Breakdown and current ramp scenarios
- EFIT & rtEFIT Reconstructions
- Shape & position control
- Reliable H-mode
- Diagnostic operations
- DCPS under plasma operations
- *Boronizaton +He GDC for PFCs*

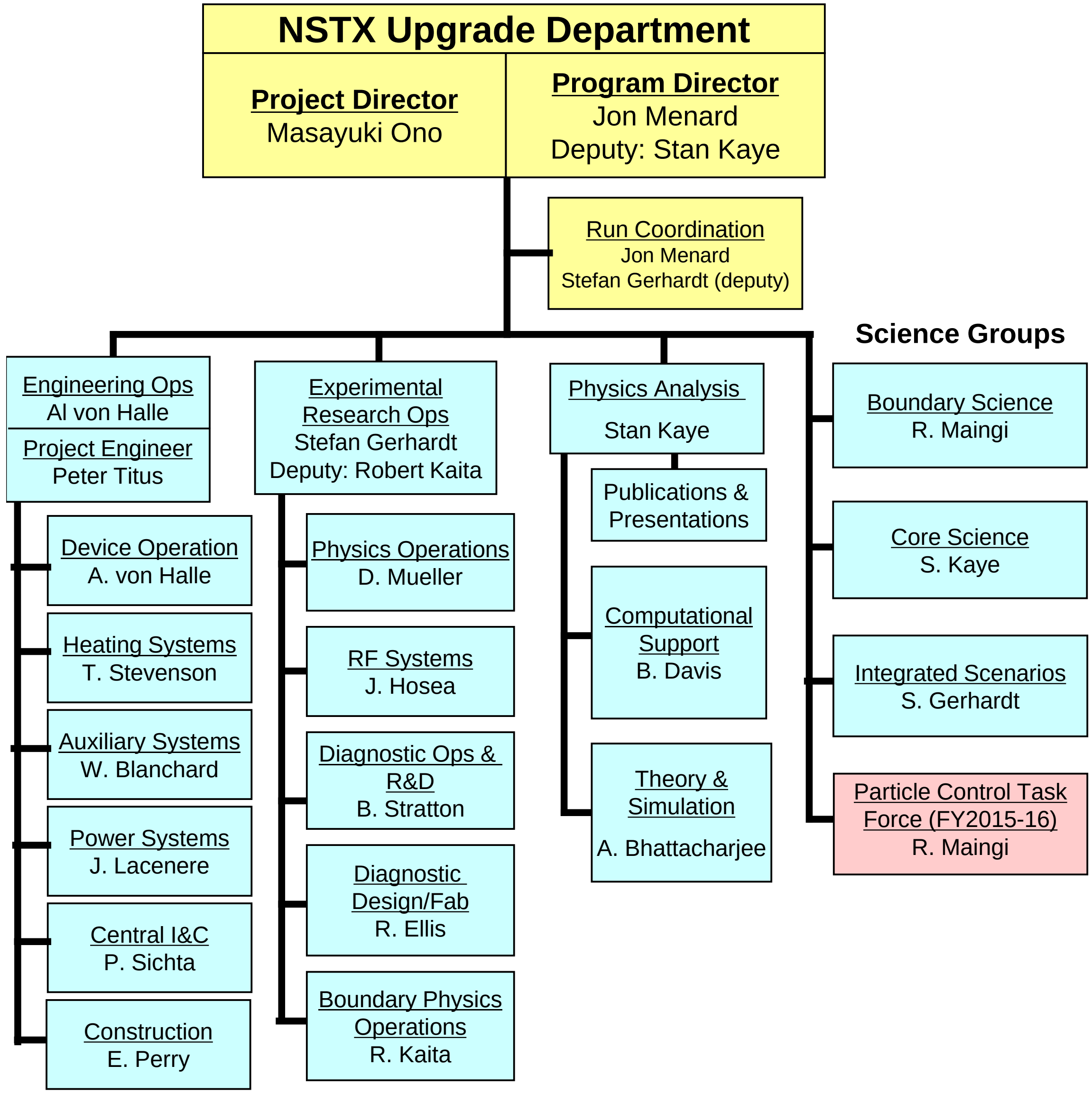
- **We will try to move the short vent before CD-4.**
- **We will also perform MPTS Rayleigh Raman before CD-4 if possible.**
- **We will try to minimize the commisioning time to move on to the research run as quickly as possible.**

Nominal NSTX-U run schedule for FY2015



- **Aquapour + CS casing installation issues caused a CD-4 delay of ~ 3-4 weeks**
- **~ 2 month period allocated between CD-4 and research plasma operations → CD-4 in mid-March, research ops in mid-May**
- **Plan: ~12-14 run weeks (assumes 1 maintenance week / month)**
- **If machine is running well at end of FY15, may run into early FY16**
  - **Provide additional data for APS 2015 and IAEA synopses for 2016**

NSTX-U Organization Chart for FY2015



Summary of Preparation toward NSTX-U Operation

- NSTX Upgrade Project is 95% complete and it has entered the final phase. The vacuum pump-down is planned for December. The coil bus installation is starting and expect to last to early February. ISTP is starting at the end of February and CD-4 early March.
- Digital Coil Protection System software implementation is progressing well. Hardware implementation is complete and it is being prepare to support the rectifier commissioning.
- Research operation schedule / commissioning – Presently planning to start research plasma operation in May 2014. Working toward minimizing the research prep time after CD-4.
- HHFW system preparation is underway. In-vessel antenna and RF probe installations were complete. The ex-vessel work is ~ 50% complete.
- Diagnostic Enhancements / Commissioning are progressing well. All of the planned diagnostics should be available during the first year of plasma operations.
- Boundary Physics Enhancement / Preparation is going well (lithium and boronization).
- NSTX-U Organization is formulated.

Backup slides

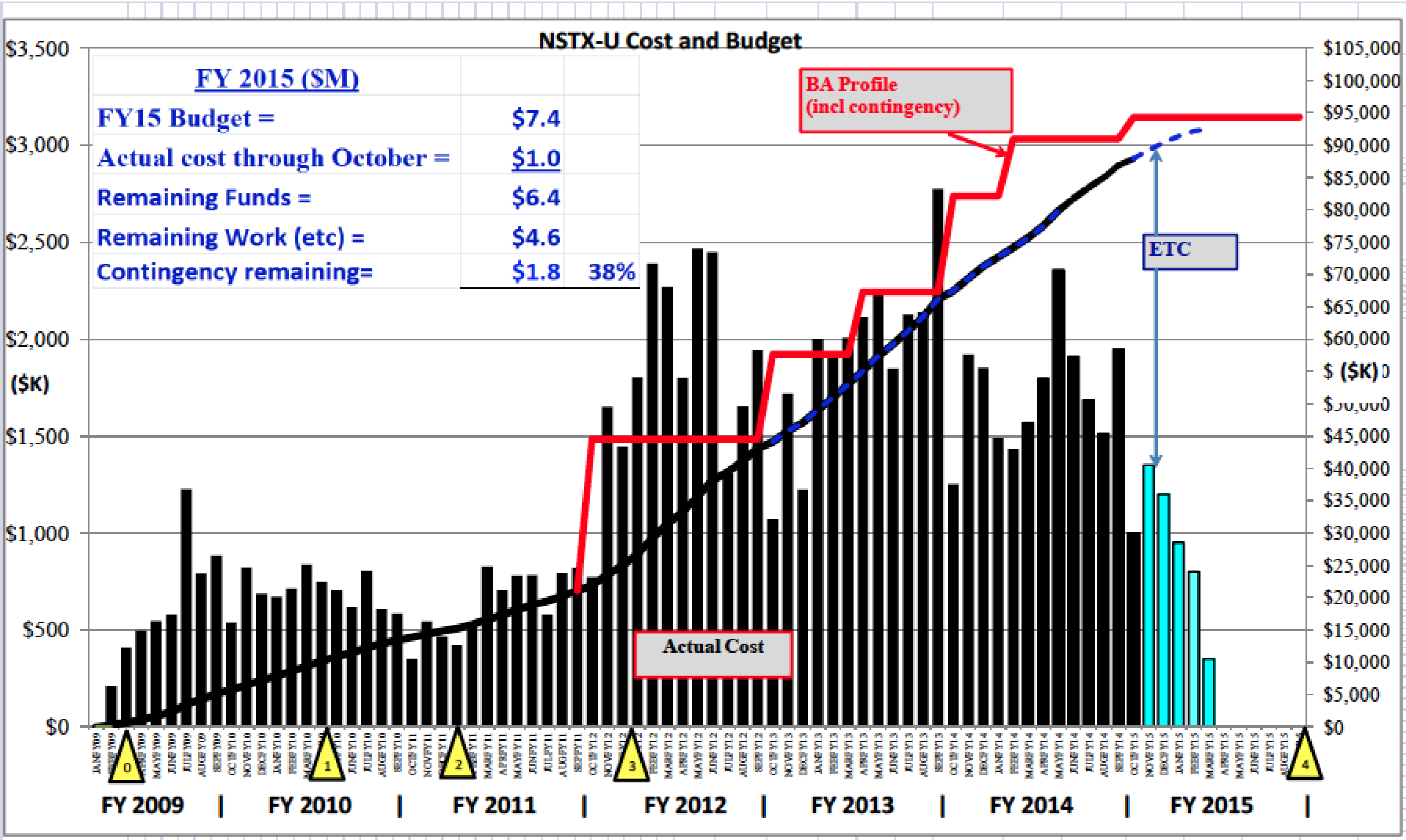
Confidence level explained – *Conclusions*

- 11 week slip in last 6 months
  - 9 weeks due to centerstack assembly.
  - Centerstack scope complete. ✓
- Project contingency started at $17.0M
  - Used to date $15.2M
  - Centerstack used $11.7M or 73% of all contingency ✓
  - Centerstack scope complete ✓
- 19 of 44 jobs closed (5 more in November) ✓
- Work remaining;
  - BCWR = $4.1M
  - CPI of remaining jobs = 1.04
  - ETC (objective CPI based) = $ 3.6
  - ➢ **ETC (subjective) = $4.6 (recently updated and discussed with CAMs** ✓

➢ **$6.4M remaining (** *11/1/14 to complete* **)**

➢ **Contingency Remaining = $1.8M** ***(38% on ETC)*** ✓ **OK**

Cost to Complete on track



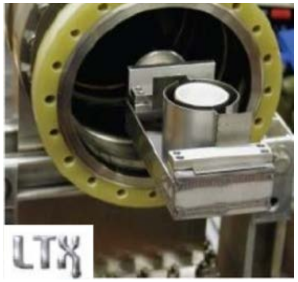
Readiness to Operate review planning underway

- Activity Certification Committee (ACC) - systems walk downs underway
- OP-NSTX-02 updated, Preoperational Test Procedures (PTP's) being executed
- QA documentation review
- SAD and FMEA underwent DOE review
- Extensive agenda for the review with dry-runs after Thanksgiving
  http://nstx-upgrade.pppl.gov/NSTX%20RR/index.html
- Readiness review December 9-11
  - Arnie Kellman, General Atomics, Chair
  - Dragaslov Ciric, Culham Centre for Fusion Energy
  - Kevin Freudenberg, Oak Ridge National Laboratory
  - Jim Irby, MIT Plasma Fusion Center
  - Ed Lessard, Brookhaven National Laboratory
  - Will Oren, Jefferson Laboratory
  - Tim Scoville, General Atomics
  - Dave Terry, MIT Plasma Fusion Center
  - Tom Todd, Culham Centre for Fusion Energy

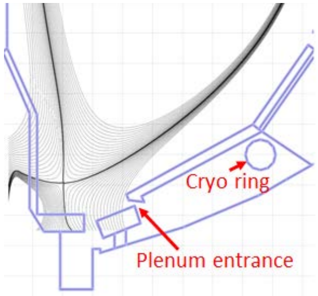
NSTX-U facility enhancements proposed for 5 year plan support FESAC Tiers/Priorities

- Improved particle control tools
  - Control D inventory, rapidly trigger ELMs to expel impurities *(Transients, PMI)*
  - Low ν* to understand ST confinement to support FNSF, validation *(FNSF, Predictive)*
- Disruption avoidance, mitigation *(Transients, Predictive)*
  - Massive gas injection, detect halos, disruptions, control v_ϕ, RWM, ELM
- ST start-up and ramp-up tools *(FNSF)*
  - ECH to raise start-up plasma T_e to enable FW + NBI + BS I_P ramp-up
  - Test EBW-CD start-up, sustainment
  - Start-up/ramp-up critical for ST-FNSF
- Begin transition to high-Z PFCs, assess flowing liquid metals *(PMI, FNSF)*
  - Plus divertor Thomson, spectroscopy

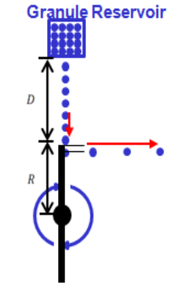
Upward Li evaporator

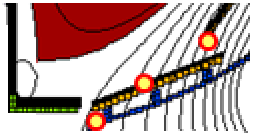


Divertor cryo-pump



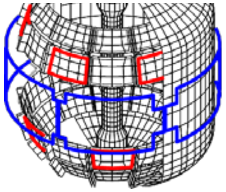
Li granule injector (LGI)

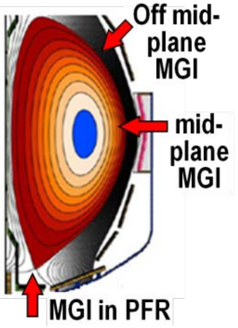




Extended low-f MHD sensor set

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

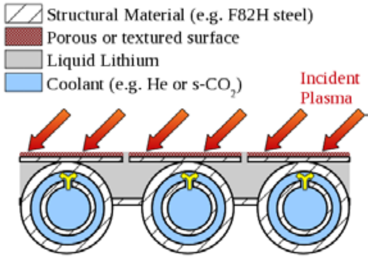




1MW 28 GHz gyrotron

High-Z tiles

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

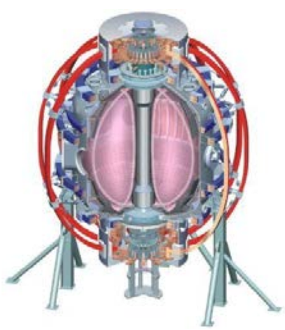


NSTX-U FY2014 Q4 - Program Highlights

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

Jon Menard
For the NSTX-U Team

PPPL and FES
November 25, 2014



**This work supported by the US DOE Contract No. DE-AC02-09CH11466*

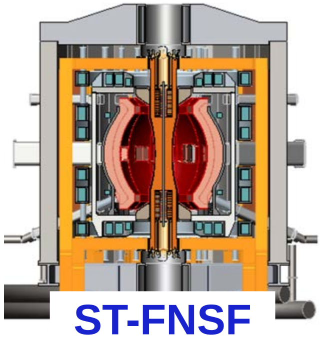
Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech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

Outline

- FESAC strategic plan and NSTX-U
- APS-DPP 2014 highlights
- FY15 research organization preparation
- ST-FNSF LDRD/IAEA/TOFE conclusions/highlights

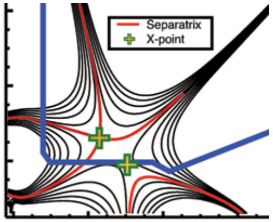
NSTX Upgrade mission elements

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
- Develop solutions for the plasma-material interface challenge
- Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond
- Develop ST as fusion energy system



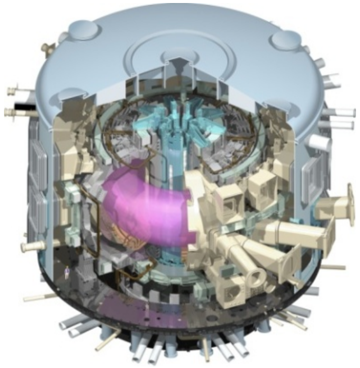
ST-FNSF

Liquid metals/Li



"Snowflake"

ITER



NSTX-U team-members proposed many innovative initiatives to FESAC SPP aligned with NSTX-U missions

FNSF

1. **Menard**, NSTX-U: ST research to accelerate fusion development
2. **Majeski**, LTX: Exploring the advantages of liquid lithium walls
3. **Fonck**, Initiatives in non-solenoidal startup and edge stability dynamics at near-unity aspect ratio in the PEGASUS experiment
4. **Raman**, Simplifying the ST & AT concepts (CT injection fueling/momentum + EBW)

PMI

5. **Maingi**, A liquid-metal plasma-facing-component initiative
6. **Jaworski**, Liquid metal plasma-material interaction science and component development toward integrated demonstration
7. **Allain**, Establishing the surface science and engineering of liquid-metal plasma--facing components

Burning plasmas, discovery science

8. **Podestá**, Development of tools for understanding, predicting and controlling fast-ion-driven instabilities in burning plasmas
9. **Sabbagh**, Critical need for disruption prediction, avoidance, mitigation in tokamaks
10. **Crocker / Guttenfelder**, Validating electromagnetic turbulence and transport effects for burning plasmas

NSTX-U missions aligned with FESAC SPP report

Quotes from the report:

- "The primary mission of the NSTX-U subprogram element is to evaluate the potential of the low-aspect ratio tokamak, or spherical torus, to achieve the sustained high performance required for a FNSF."
- "Innovative plasma-material-interaction (PMI) solutions are another important element of this program"
- "ITER-relevant research on NSTX-U includes energetic particle behavior and high-beta disruption control"
- "NSTX-U should primarily focus on resolving the technical issues underpinning the FNSF-ST design."
  - "Key issues: non-solenoidal startup, sustainment of the plasma current, and scaling of confinement with collisionality."
  - LTX, Pegasus: important support for PMI and current initiation

FESAC SPP Report Priorities:

Tier 1

- **Control of deleterious transient events:** This Initiative combines experimental, theoretical, and simulation research to understand highly damaging transients and minimize their occurrence in ITER-scale systems.
- **Taming the plasma-material interface:** This Initiative combines experimental, theoretical, and simulation research to understand and address the plasma-materials interaction (PMI) challenges associated with long-pulse burning plasma operation.

Tier 2

- **Experimentally validated integrated predictive capabilities:** This Initiative develops an integrated "whole-device" predictive capability, and will rely on data from existing and planned facilities for validation.
- **A fusion nuclear science subprogram and facility:** This Initiative will take an integrated approach to address the key scientific and technological issues for harnessing fusion power.

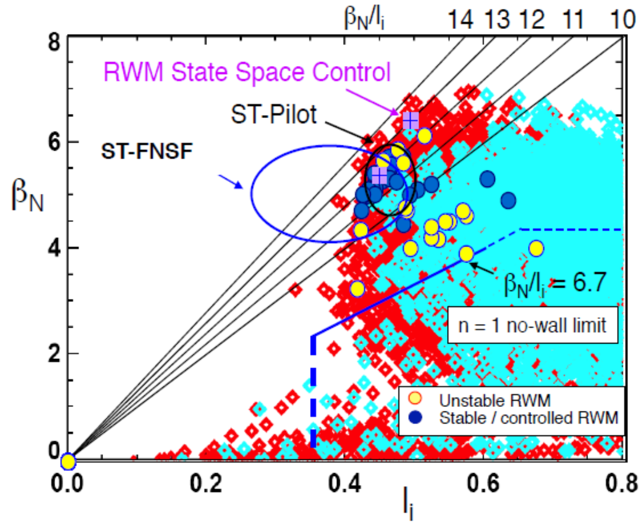
- Tier 1 Initiatives are higher priority than Tier 2 Initiatives. Within a tier, the priorities are equal.
- In concert with above Initiatives, Discovery Plasma Science will advance the frontiers of plasma knowledge to ensure continued U.S. leadership.

Outline

- FESAC strategic plan report
- APS-DPP 2014 highlights from review/invited talks
  - Talk topics are well aligned with FESAC-SP Tier topics
- FY15 research organization preparation
- ST-FNSF LDRD/IAEA/TOFE conclusions/highlights

FR-1: "Recent Progress on Spherical Torus Research and Implications for Fusion Energy Development Path" – M. Ono

Record β_N and β_N/l_i accessed using resistive wall mode stabilization



Major mission of NSTX-U is to achieve fully non-inductive

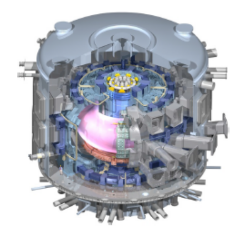
M. Ono APS ST Review

Extend Predictive Capability for ITER and Toroidal Science

High β physics, rotation, shaping for MHD, transport

Non-linear Alfvén modes, fast-ion dynamics, Electron gyro-scale turbulence at low ν*

Burning Plasma Physics - ITER

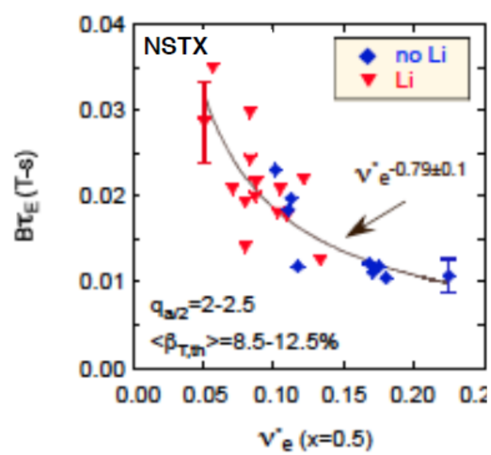


Favorable Confinement Trend with Collisionality and β found

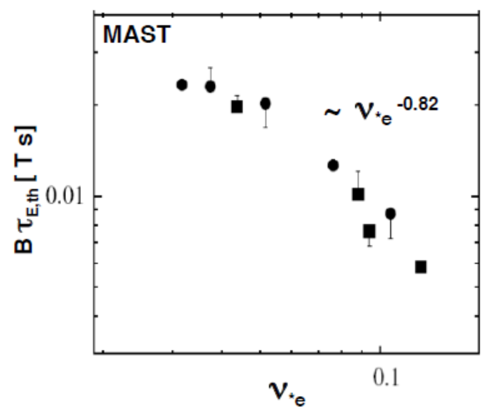
Important implications for future STs and Demo with much lower ν_*

$\tau_{E,\,th} \propto \nu_*^{-0.1}\, \beta^{-0.9}$ tokamak empirical scaling ($ITER98_{y,2}$)

$\tau_{E,\,th} \propto \nu_*^{-0.8}\, \beta^{-0.0}$ ST scaling



S.M. Kaye et al., NF (2007) (2013)



M. Valovic et al., NF (2011)

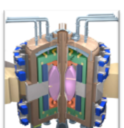
Very promising ST scaling to reactor condition, if continues on NSTX-U/MAST-U

M. Ono APS ST Review Oct. 27 - 31, 2014 19

Fusion needs to develop reliable/qualified components which are unique to fusion:

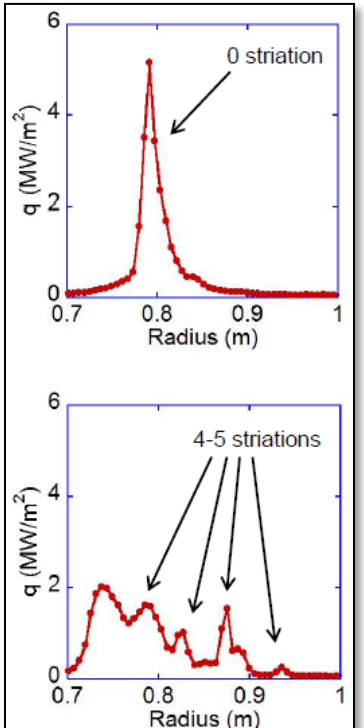
- Divertor/PFC
- Blanket and Integral First Wall
- Vacuum Vessel and Shield
- Tritium Fuel Cycle
- Remote Maintenance Components

FNSFs

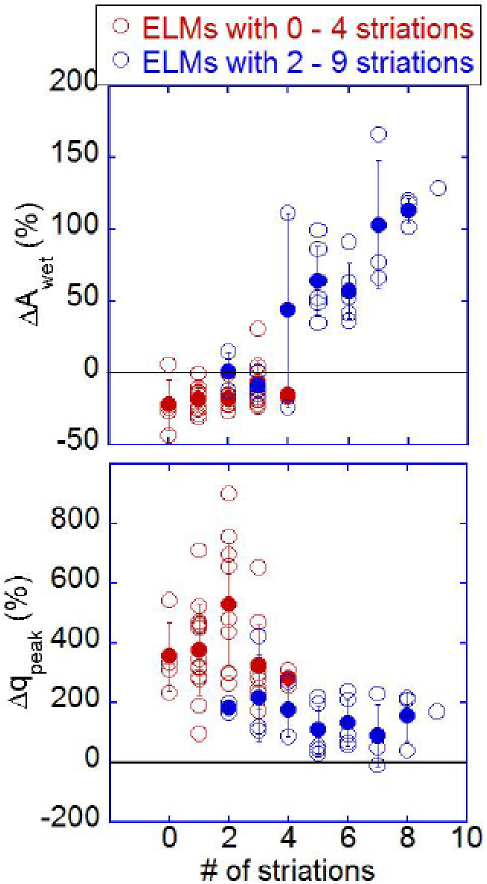


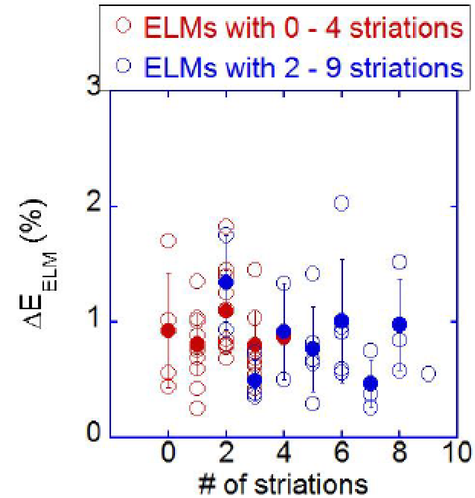
FNSF-ST

GI1.00003: "Broadening of the divertor heat flux footprint with increasing number of ELM filaments in NSTX" – J.-W. Ahn



A_{wet} increases while ELM size remains constant and q_{peak} decreases with the number of observed striations





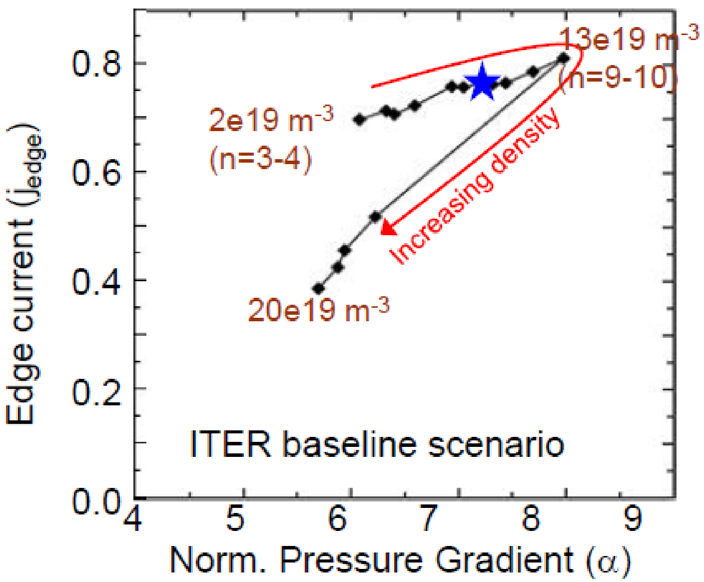
J-W. Ahn
NF 2014 (Nov)

- Two groups of ELM data
  - 0 – 4 striations for weaker shaping (κ~1.9, δ~0.5)
  - 2 – 9 striations for stronger shaping (κ~2.5, δ~0.75)
- A_{wet} increases with the # of striations but the ELM size (energy ejected by an ELM, measured by IR camera) is independent of the # of filaments → reduction of q_{peak}

GI1.00003: "Broadening of the divertor heat flux footprint with increasing number of ELM filaments in NSTX" – J.-W. Ahn

EPED model predicts ITER ELMs to be against peeling boundary with low n-number like in NSTX

EPED modeling as a function of $n_{e,ped}$



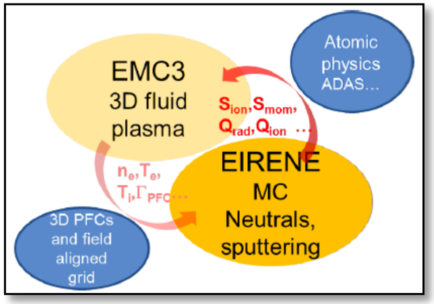
P.B. Snyder, NF 2011

- Stability analysis shows that ITER pedestal will be against current-driven kink/peeling modes due to low collisionality and shaping
- Predicted n~3 – 10, closer to NSTX → ELM profile broadening might not be as effective as in JET

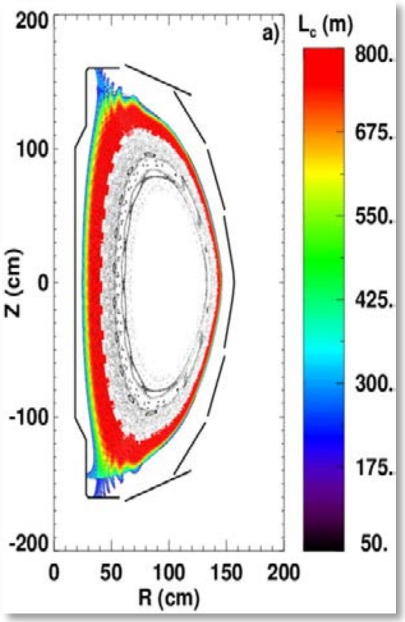
Important to better determine where ITER will sit on stability regime to estimate n-number, plus need some non-linear ELM calculations for the evolution of filament numbers

Oak Ridge National Laboratory

TI1.00001: “Simulation of 3D effects on partially detached divertor conditions in NSTX and Alcator C-Mod” – J. Lore

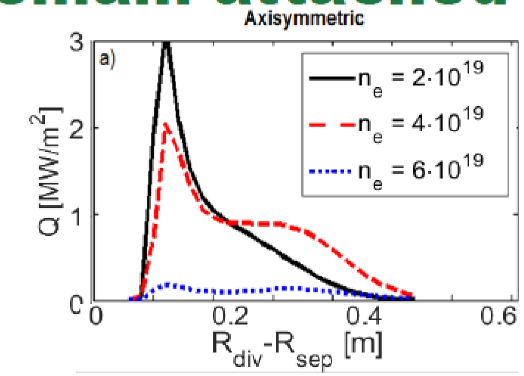


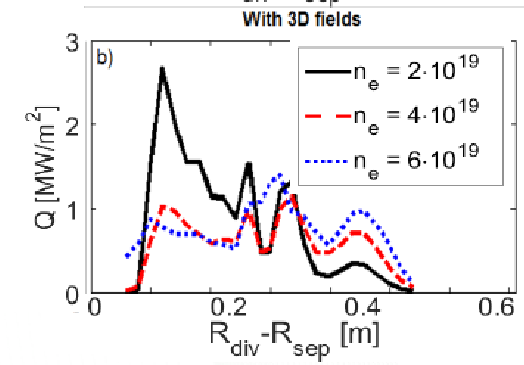
Connection Length



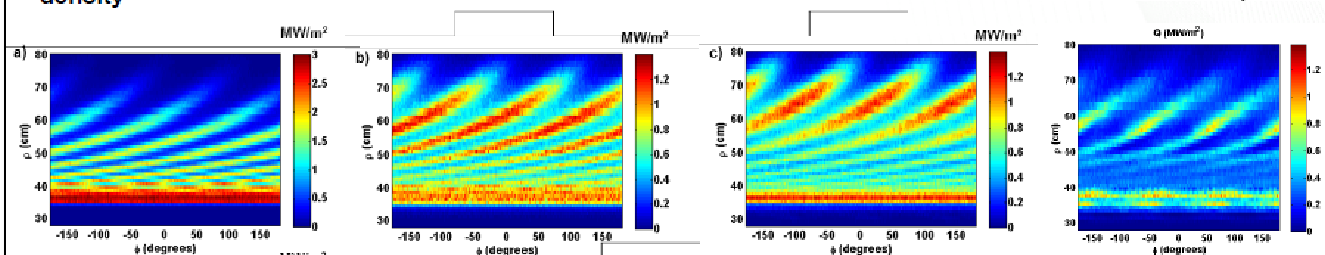
With 3D fields primary strike point detaches, but outer lobes remain attached

- Axisymmetric case shows clear reduction in heat flux with increasing density
  - Heat flux increases at larger radius due to greater effect of cross-field diffusion
- With 3D fields the maximum heat flux shifts to the outer peaks
  - Outer lobes connected to hot plasma with short connection length
  - Still in sheath limited regime at intermediate density, more heat at larger radius from cross-field diffusion





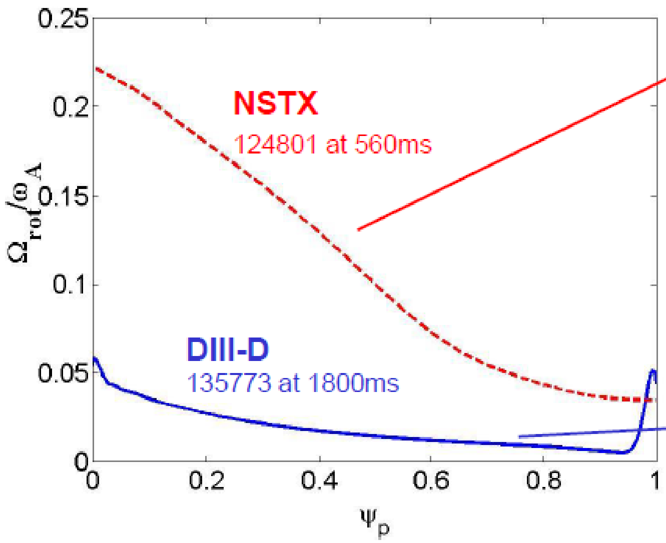
Increasing density →

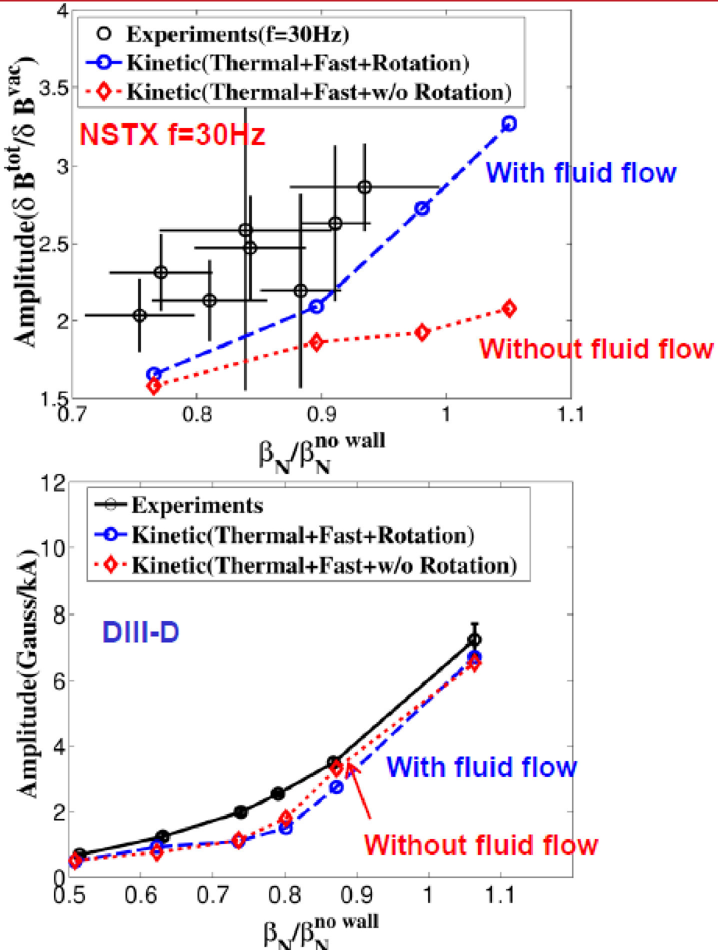


TI1.00003: "Drift Kinetic Effects on 3D Plasma Response in High-β Tokamak Resonant Field Amplification Experiments" – Z.R. Wang

Fluid Rotation Can Amplify Kinetic Plasma Response and Destabilize Plasma in NSTX

- NSTX experiments can have much higher fluid rotation than DIII-D.
- The plasma flow can significant affect kinetic plasma response and play a destabilizing role in NSTX plasmas.
- The results agree with Menard et al, BI2.00005, APS 2013



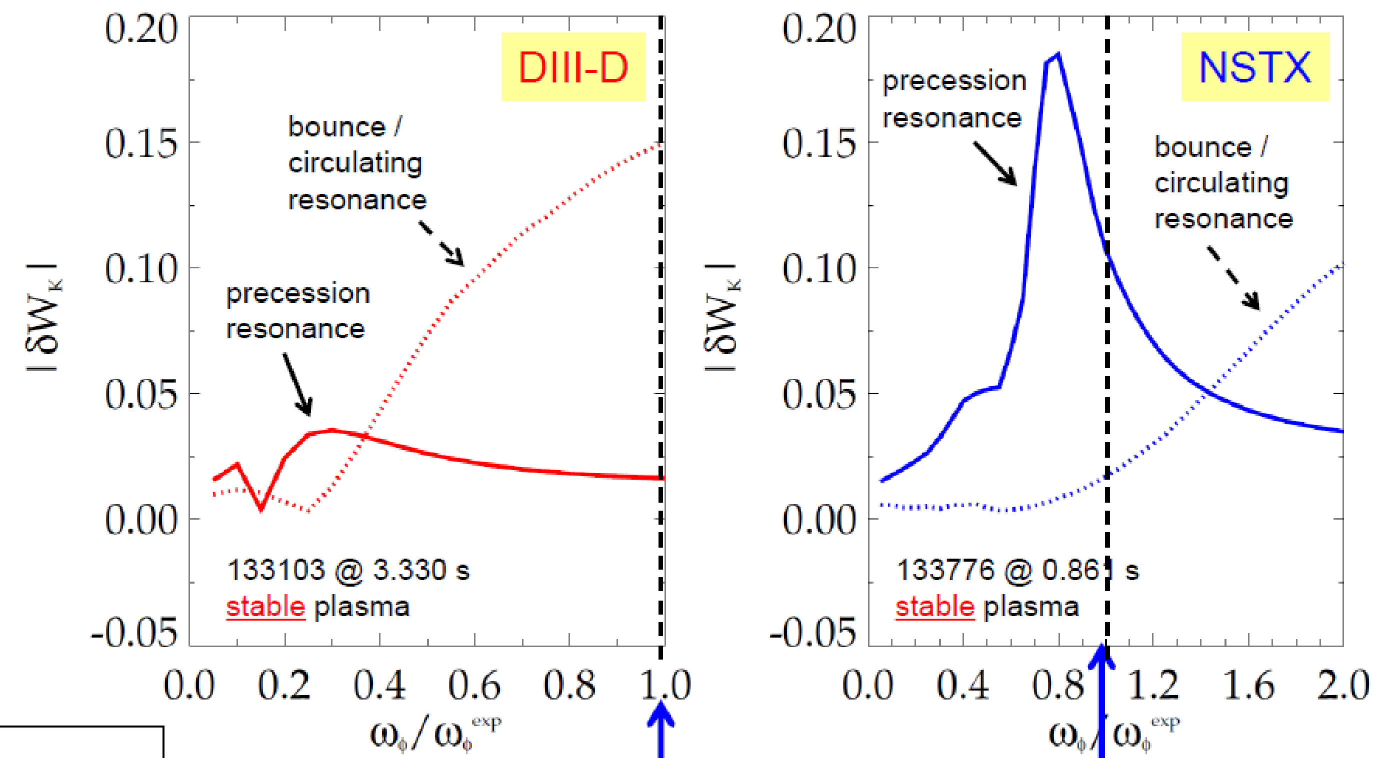


Drift kinetic effects on 3D plasma response APS DPP 2014 (Wang) 22

VI2.00002: "Unification of Kinetic Resistive Wall Mode Stabilization Physics in Tokamaks" – S.A. Sabbagh

Bounce resonance stabilization dominates for DIII-D vs. precession drift resonance for NSTX at similar, high rotation

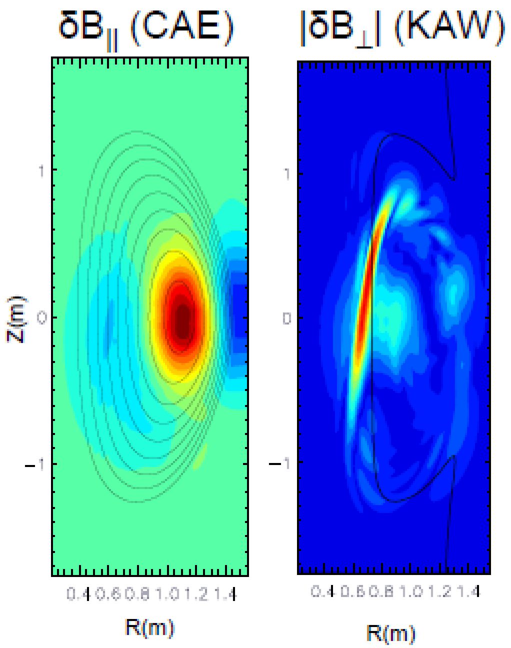
$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)



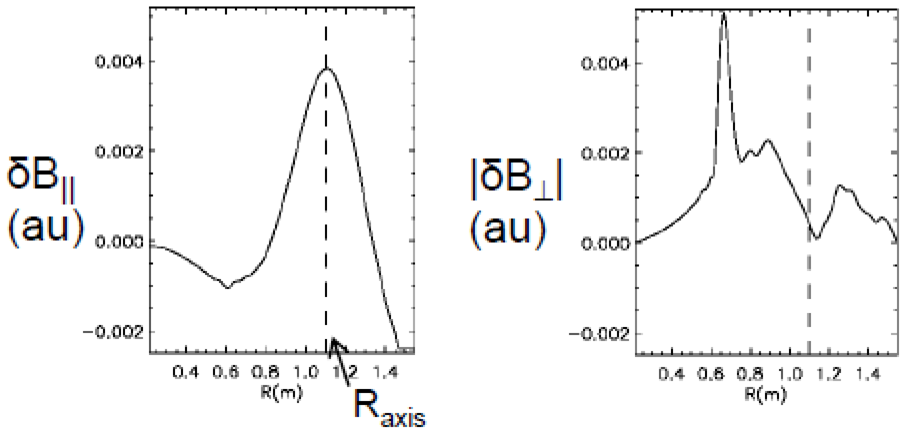
Columbia University in the City of New York

56th APS DPP Meeting: VI2.02 Unification of kinetic RWM physics in tokamaks (S.A. Sabbagh, et al.) Oct. 30th, 2014 NSTX-U 19

KAW amplitude is larger than amplitude of driving CAE mode



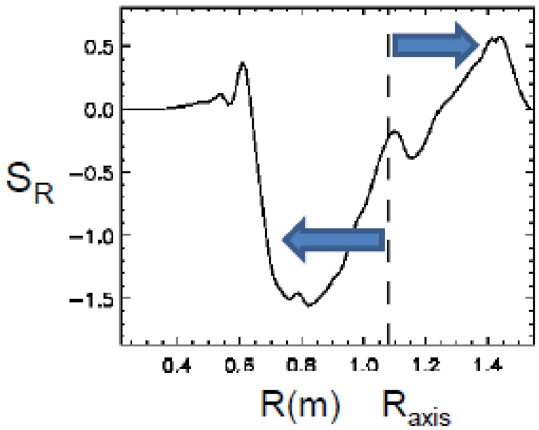
Magnetic field perturbation for n=4 co-rotating CAE. Solid line corresponds to $\omega_A(Z,R)=\omega$.



Radial profiles of magnetic field perturbation for the n=4 CAE versus major radius.

At the KAW resonance location the amplitude of KAW is larger than the amplitude of driving CAE mode.

Relation between CAE/KAW and T_e flattening?



Radial component of quasilinear Poynting vector **S**=<**E**x**B**>. Energy flux is directed away from magnetic axis, ie from CAE to KAW.

Fraction of NBI power transferred to CAE:

$$P= 2\gamma \int (\delta B)^2/4\pi\, d^3x,$$

$\delta B/B_0$= (0.9-3.4)×10^{-3} corresponds to measured displacement $|\xi|$= 0.1-0.4 mm [N.Crocker'13] (based on HYM-calculated mode structure for n=4 CAE).

For γ/ω_{ci}=0.005-0.01→ **P= (0.013 - 0.4)MW**,

- significant fraction of NBI energy can be transferred to several unstable CAEs of relatively large amplitudes.

Energy flux from the CAE to the KAW and dissipation at the resonance location can have a strong effect on T_e profile.

Outline

- FESAC strategic plan report
- APS-DPP 2014 highlights
- FY15 research organization preparation
- ST-FNSF LDRD/IAEA/TOFE conclusions/highlights

Update on increasing University engagement in the NSTX-U program

- Increasing engagement was FY2014 “Notable Outcome”
- Previously developed ideas to enhance participation:
  - Expand Early Career Research (ECR) awards to University Scientists
    - ➢ No support within DoE Office of Science to extend this beyond tenure-track
  - Support students with coordinated senior projects and targeted run-time
    - ➢ Will consider once NSTX-U resumes routine/full operation (late FY15)
  - Implementing enhanced collaboration tools (remote control rooms)
    - ➢ Will engage NSTX-U Science Groups to determine optimal tools (during FY15)
  - Implement “NSTX-U Innovative Research Award (NIRA)” with funding targeting primarily university researchers
    - ➢ No FES funding available, consider funding from NSTX-U post-Upgrade
  - Consider direct financial support for start-up and initial salary for tenure-track professor positions (Same answer as previous question)
  - More strongly engage University Principal Investigators and researchers in the management of the NSTX-U scientific program
    - ➢ **Implementing this for FY2015 run**

NSTX-U research program will be (re-)organized along 3 "Science Groups" starting with FY15 run

NSTX Upgrade Science Program

Project Director
Masayuki Ono

Program Director
Jon Menard
Deputy: Stan Kaye

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

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

Physics Analysis
Stan Kaye

Run Coordination
Jon Menard
Stefan Gerhardt (deputy)
- Cross-Cutting XMP/XPs

Boundary Science Group
R. Maingi, C.-S. Chang (deputy)

- **Pedestal Structure and Control**
  A. Diallo, R. Maingi
  Theory/Modelling: J. Canik[1]
  University Rep: D. Smith[2]
- **Divertor and Scrape-Off-Layer**
  V. Soukhanovskii[3], J.-W. Ahn[1]
  Theory/Modelling: D. Stotler
  University Rep: O. Schmitz[2]
- **Materials and PFCs**
  M. Jaworski, C. Skinner
  Theory/Modelling: B. Wirth[4]
  University Rep: J.-P. Allain[5]

Core Science Group
S. Kaye, S. Sabbagh[6] (deputy)

- **Macroscopic Stability**
  J. Berkery[6], J.-K. Park
  Theory/Modelling: S. Jardin
  University Rep: D. Brennan[7]
- **Transport and Turbulence**
  W. Guttenfelder, Y. Ren
  Theory/Modelling: W. Wang
  University Rep: K. Tritz[8]
- **Energetic Particles**
  M. Podestá, D. Liu[9]
  Theory/Modelling: N. Gorelenkov
  University Rep: N. Crocker[10]

Integrated Scenarios Group
S. Gerhardt, R. Raman[11] (deputy)

- **Advanced Scenarios and Control**
  D. Battaglia, S. Gerhardt
  Theory/Modelling: F. Poli
  University Rep: E. Kolemen[7]
- **Solenoid-free Start-up & Ramp-up**
  D. Mueller, R. Raman[11]
  Theory/Modelling: F. Ebrahimi[7]
- **Wave Heating and Current Drive**
  R. Perkins, J. Hosea
  Theory/Modelling: N. Bertelli
  University Rep: P. Bonoli[12]

Particle Control Task Force (FY2015-16)
Leader: R. Maingi, Deputy: J. Canik[1]
Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

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

Motivations for restructuring science program

- TSGs provide expertise in broad range of topics, but program would benefit from better coordination between TSGs
  - SG leader responsibility: Coordinate TSG physics research plans, experimental/shot plans, diagnostic coverage & usage
- Experiments that engage more than one TSG will receive increased priority for run-time
  - Example: experiment on 3D fields generating data for: plasma response, turbulence, energetic particle loss
- Efficient shot usage especially important during first run year (many systems need to be re-commissioned)
- Incorporate much wider set University researchers/PIs in planning + coordination of research program (FES/PPPL goal)
- NEW: Task-force for long-pulse particle control → cross-cutting goal supporting entire research program

Upcoming research planning/advisory activities

- Pre-forum meeting #1 – Early / mid Dec (~1 day)
  - Review experiments needed to support restart, physics-ops
    - Draft machine/experimental proposal (XMP/XP) list – goals, authors
    - Action: SG/TSGs to solicit people to commit to writing these proposals
- Pre-forum meeting #2 – Last week of Jan (1.5-2 days)
  - Goal: Provide up-to-date operations status to aid scheduling
  - Day 1: Diagnostics/operations readiness meeting
    - Status updates and projections for <u>all</u> systems needed for research ops
  - Day 1.5-2: Update from SG/TSGs on XMP/XP solicitations
- Research Forum – Feb 24-27th, 2015 at PPPL
  - Plenary session, TSG break-outs, SG sessions, team joint session, summary (also safety session and team photo)

- NSTX-U PAC-36 – Sept/Oct 2015 (end of/after FY15 run)

Research Forum Overview

- Science groups will nominally follow priorities/detailed plans developed for 5 year plan (until they are obsolete…)
- Abbreviated eXperimental Proposals (XPs) (developed in Dec-Jan) will be presented at the forum
  - Motivation, goal, shot plan, # of run days, diagnostics, analysis…
- Prioritization carried out at forum using abbreviated XPs
- ~70-90% of prioritization completed by end of forum
  - Highest priority research in research milestones / task forces
  - Proposals that address milestones will receive the most run time
  - If abbreviated proposal idea is "priority 1", the author is asked to develop full proposal for operational + program review/approval
- Expect ~1/3 of all XPs for year to be approved, ready at start of physics campaign (April 2015), then roll forward
  - Typically schedule XPs ~1-2 months in advance

First run year priorities support mission and 5YP goals

Mission Elements and 5YP 5 Highest Priorities

- **Advance ST for FNSF**
  1. Demonstrate full non-inductive sustainment at FNSF-relevant performance levels
  2. Advance non-inductive start-up and ramp-up (overdrive) for ST-FNSF with small/no solenoid
- **Develop solutions for PMI challenge**
  3. Develop / utilize high-flux-expansion and radiative detachment to mitigate high heat flux
  4. Begin to assess high-Z PFCs + liquid Li to develop high-duty-factor integrated PMI solution
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  5. Access reduced ν^* + high-β + varied q and rotation to dramatically extend ST understanding

FY2015 Milestones / Task Forces:

R15-3

Develop physics + operational tools for high-performance discharges (κ, δ, β, EF/RWM)

Particle Control Task Force (PC-TF)

Long-pulse main-ion and impurity control

R15-2

Characterize effects of NBI injection angle on fast-ion distribution and NBI-CD profile

IR15-1

Develop snowflake configuration, study edge and divertor properties

NOTE: IR15-1 accelerates snowflake part of R16-1 by 1 year

R15-1

Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}

JRT-15

Quantify impact of broadened J(r) and p(r) on tokamak confinement and stability

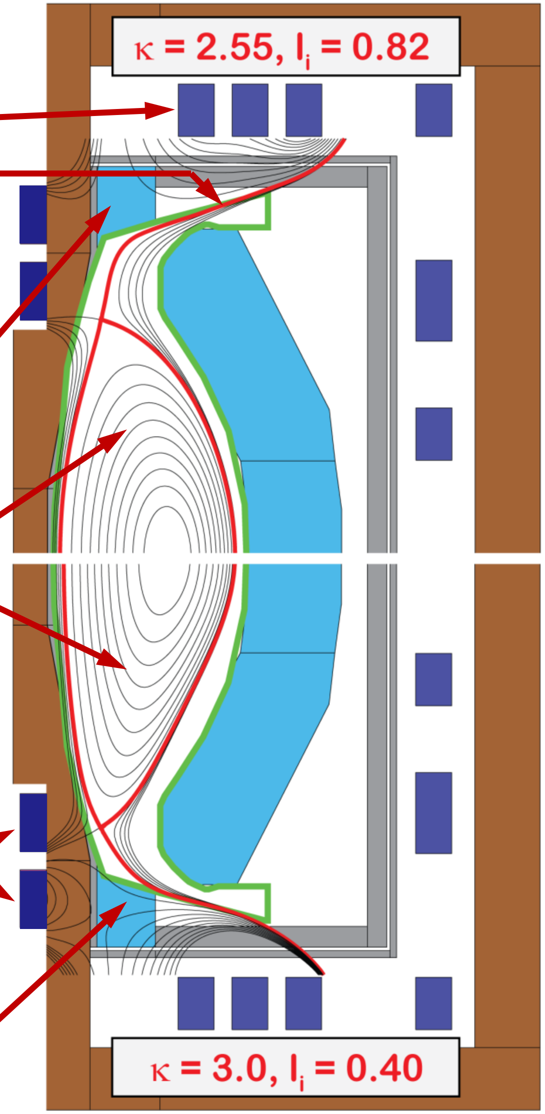
Outline

- FESAC strategic plan report
- APS-DPP 2014 highlights
- FY15 research organization preparation
- ST-FNSF LDRD/IAEA/TOFE conclusions/highlights

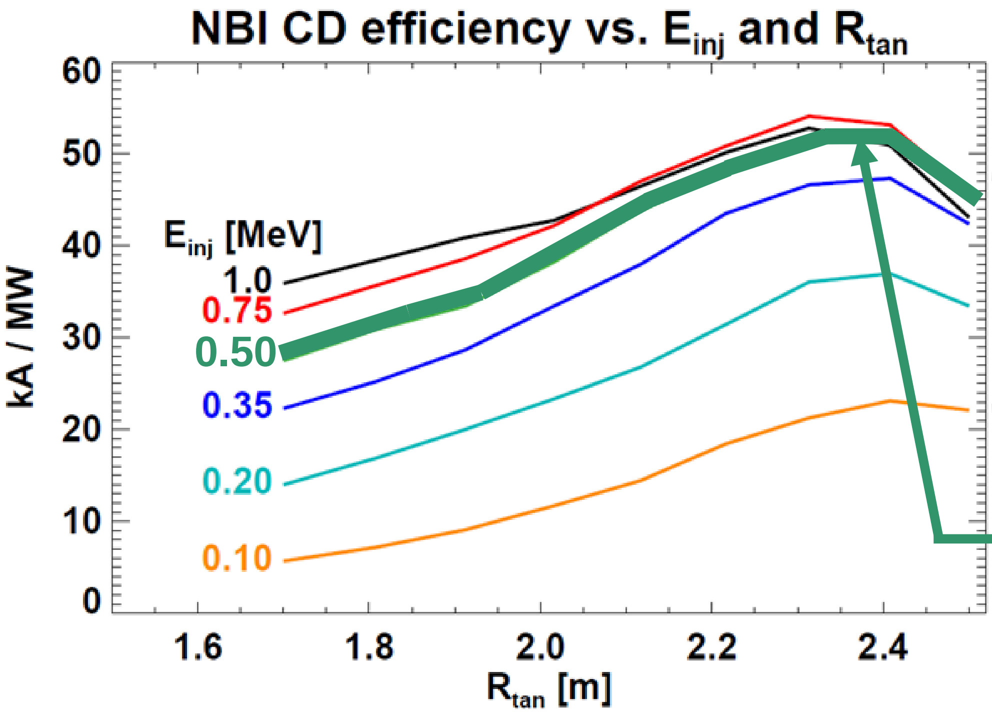
PF coil set identified that supports combined Super-X + snowflake divertor for range of equilibria

Components: TF coil | PF coil | Vessel | Blanket

- All equilibrium PF coils outside vacuum vessel
- Increased strike-point radius reduces B, $q_{||}$
  Strike-point PFCs also shielded by blankets
- 2nd X-point/snowflake increases SOL line-length
- PF coil set supports wide range of l_i: 0.4 – 0.8
  - Elongation and squareness change with l_i variation
  - Fixed strike-point R, controllable B-field angle of incidence (0.5-5˚)
- Divertor coils in TF coil ends for equilibrium, high δ
- Breeding in CS ends important for maximizing TBR



0.5 MeV NNBI favorable for heating and current drive (CD) for R=1.7m ST-FNSF



NBCD increases for $E_{inj} \leq 0.5$ MeV but saturates for $E_{inj} = 0.75$ – 1MeV

Maximum efficiency: R_{tan}=2.3-2.4m

- Fixed target parameters in DD:
  - I_P = 7.5MA, β_N = 4.5, l_i = 0.5
  - $n_e / n_{Greenwald}$ = 0.75, $H_{98y,2}$ = 1.5
  - A=1.75, R=1.7m, B_T = 3T, κ = 2.8
  - $\langle T_e \rangle$=5.8keV, $\langle T_i \rangle$=7.4keV

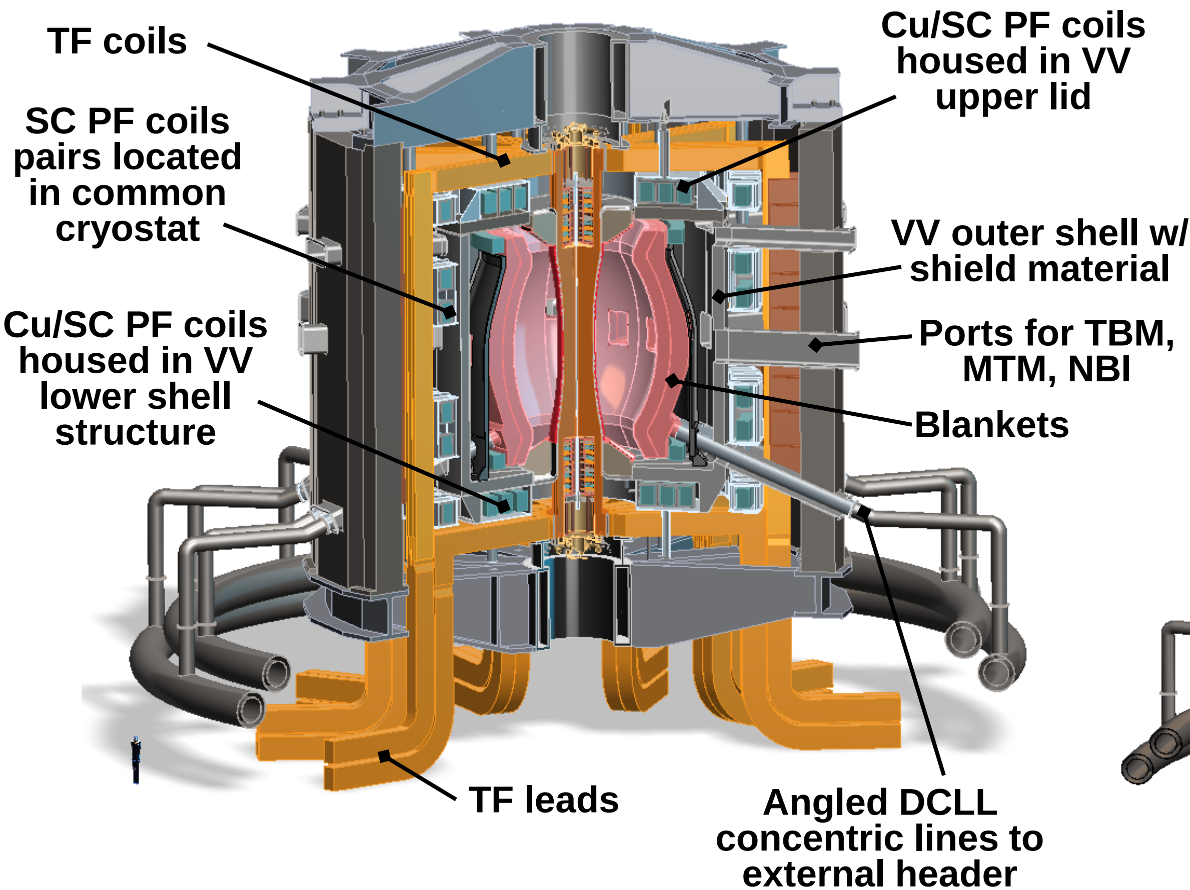
Optimal tangency radii:
1.7m ≤ R_{tan} ≤ 2.4m

Control $q(0)$, q_{min}

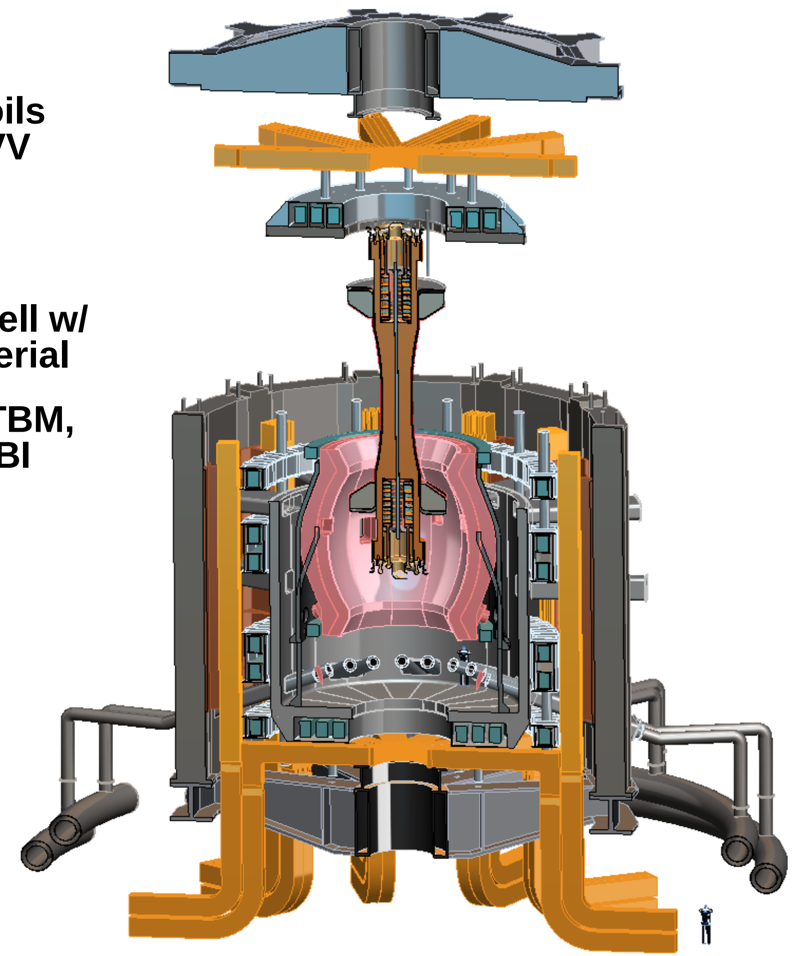
Shine-thru limit

R=1.7m configuration with long-leg divertor

Design features



Vertical maintenance



Two sizes (R=1.7m, 1m) assessed for shielding, TBR

Parameter:

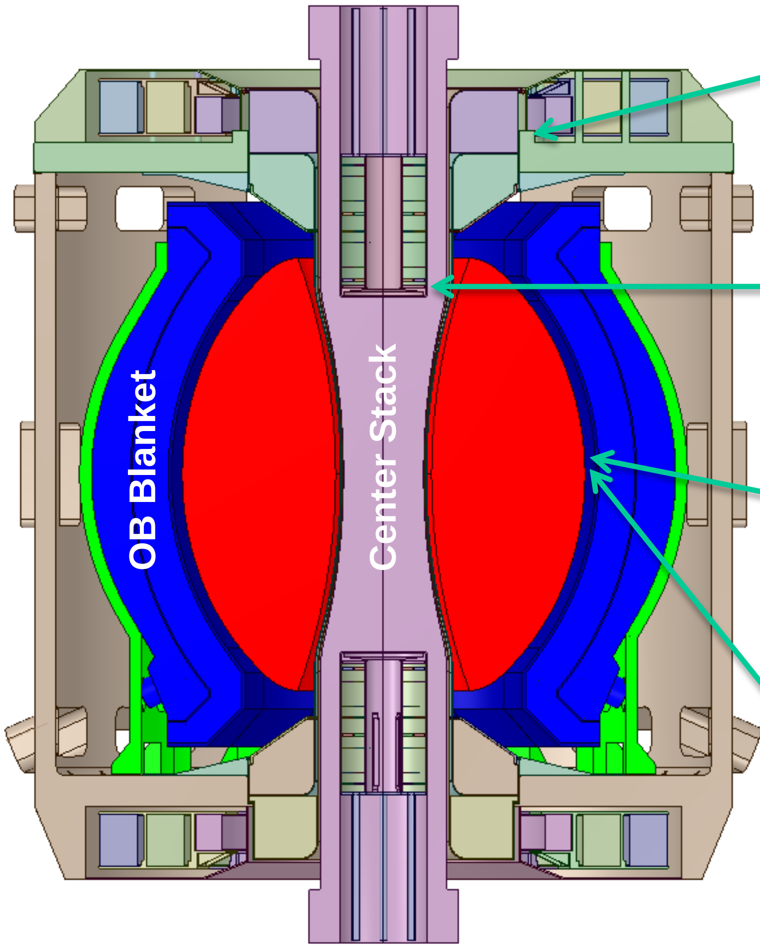
Major Radius	1.68m	1.0m
Minor Radius	0.95m	0.6m
Fusion Power	162MW	62MW
Wall loading (avg)	$1MW/m^2$	$1MW/m^2$
TF coils	12	10
TBM ports	4	4
MTM ports	1	1
NBI ports	4	3

Plant Lifetime ~20 years

Availability 10-50%, 30% avg } 6 Full Power Years (FPY)

Peak Damage at OB FW and Insulator of Cu Magnets

R=1.7m configuration



3-D Neutronics Model of Entire Torus

Dose to MgO insulator = 2×10^{8} Gy @ 6 FPY < 10^{11} Gy limit

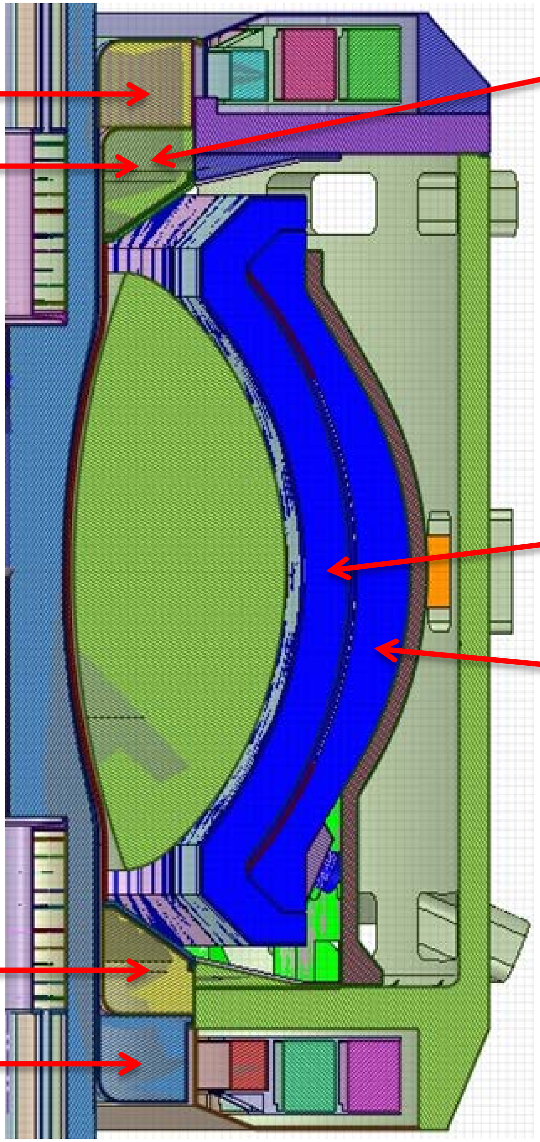
Dose to MgO insulator = 6×10^{9} Gy @ 6 FPY < 10^{11} Gy limit

Peak dpa at OB midplane = 15.5 dpa / FPY

Peak He production at OB midplane = 174 appm/FPY

$\Rightarrow$ He/dpa ratio = 11.2

TBR contributions by blanket region



Breeding at CS ends important:
ΔTBR = +0.07

Inner Blanket Segment = 0.81

Outer Blanket Segment = 0.15

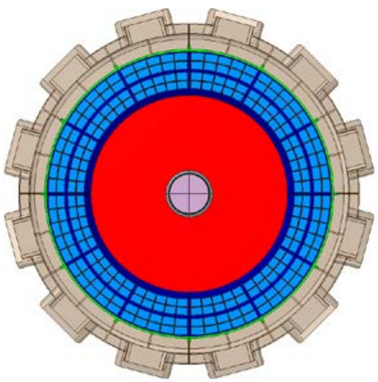
Total TBR ~ 1.03 with no penetrations or ports
(heterogenous outboard blanket)

R=1.7m configuration

Impact of TBM, MTM, NBI ports on TBR

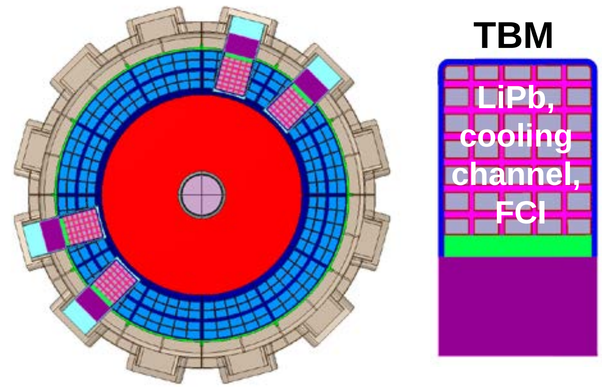
No ports or penetrations, homogeneous breeding zones:

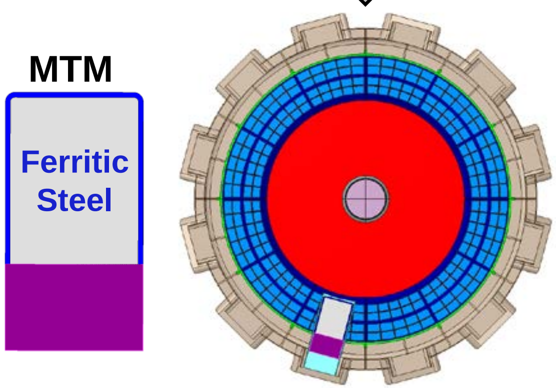
TBR = 1.03



Add 4 Test Blanket Modules (TBMs)

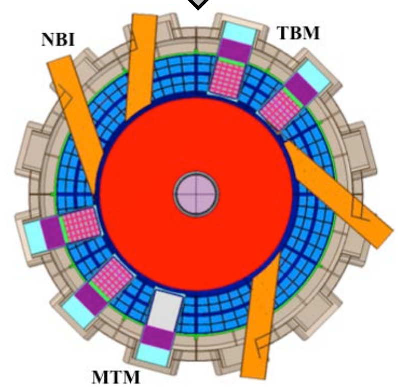
TBR = 1.02 (ΔTBR = -0.01)





1 Materials Test Module (MTM)

TBR = 1.01 (ΔTBR = -0.02)



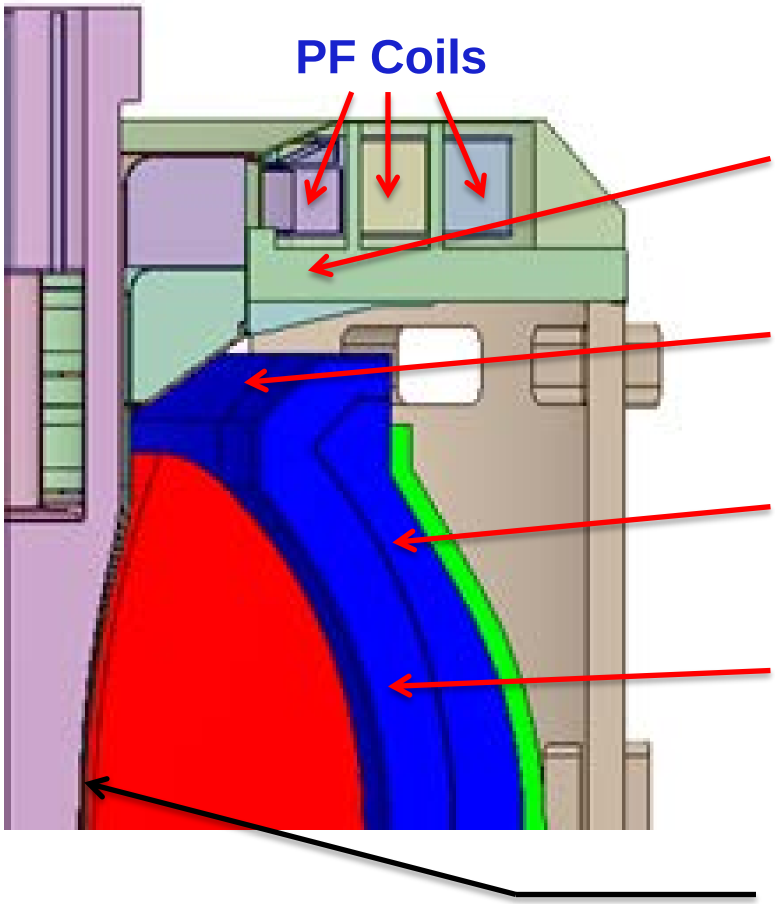
4 TBM + 1 MTM + 4 NBI

TBR = 0.97

Approx. ΔTBR per port:

- **TBM: -0.25%**
- **MTM: -2.0%**
- **NBI: -0.75%**

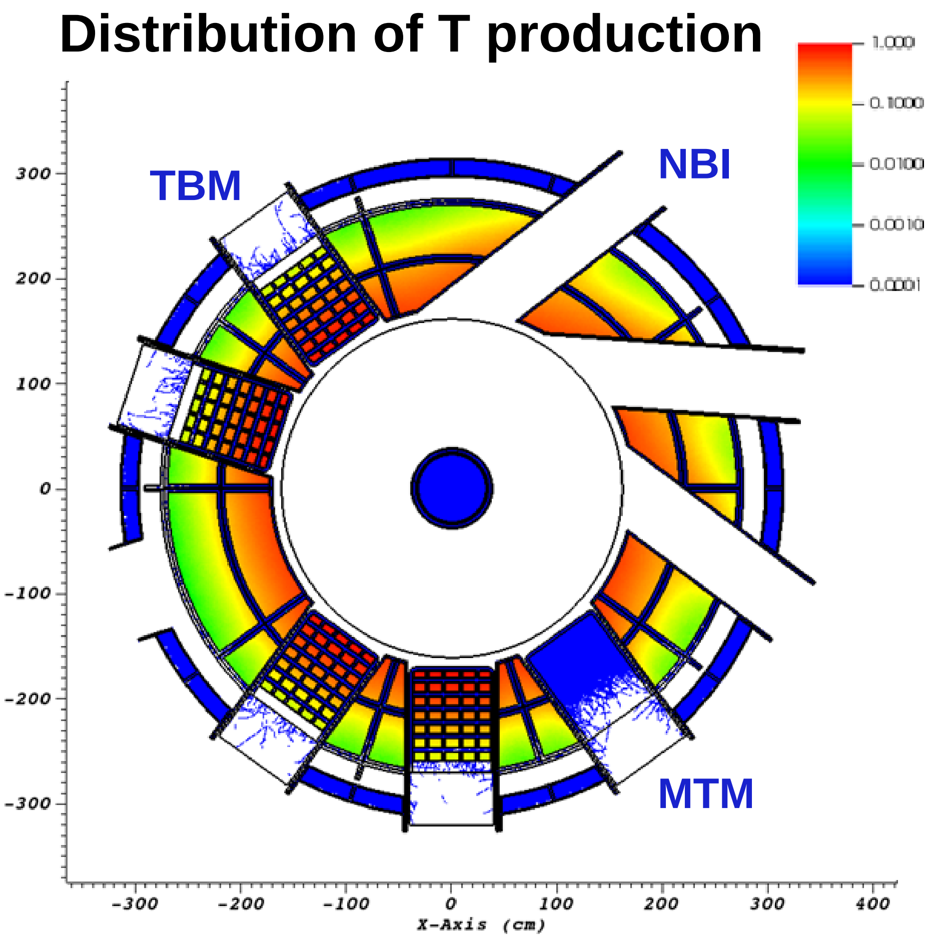
Options to increase TBR > 1

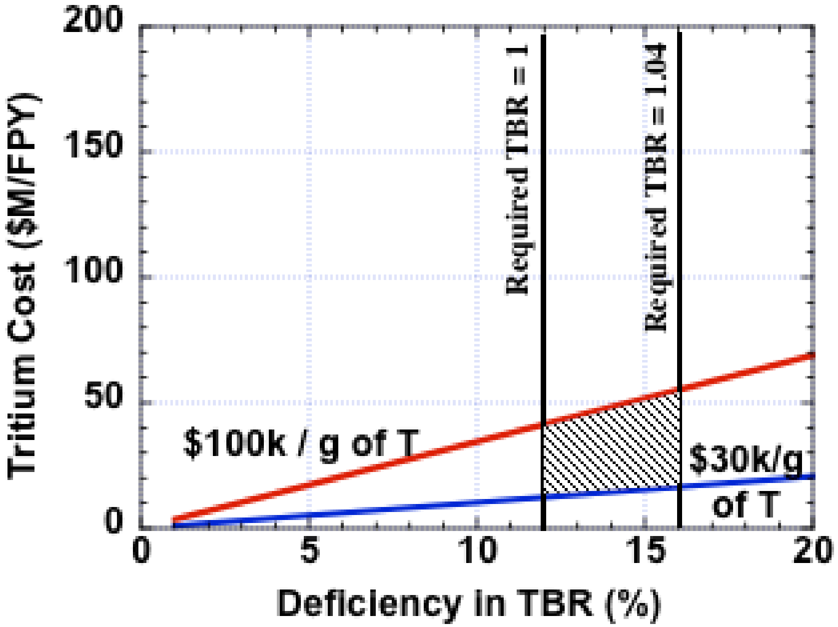


- Add to PF coil shield a thin breeding blanket (ΔTBR ~ +3%)
- Smaller opening to divertor to reduce neutron leakage
- Uniform OB blanket (1m thick everywhere; no thinning)
- Reduce cooling channels and FCIs within blanket (need thermal analysis to confirm)
- Thicker IB VV with breeding

Potential for TBR > 1 at R=1.7m

R_0 = 1m ST-FNSF achieves TBR = 0.88





- **1m device cannot achieve TBR > 1 even with design changes**
- **Solution**: purchase ~0.4-0.55kg of T/FPY from outside sources at $30-100k/g of T, costing $12-55M/FPY

Summary

- FESAC strategic plan aligned with NSTX-U missions
  - FNSF, PMI, ITER/predictive capability
- NSTX-U researchers scientifically productive in FY14
  - Led analysis for JRT-2014 / plasma response to 3D fields (reported at Q3)
  - 40 publications + 13 submitted (as of early September) for FY14
  - IAEA: 4 orals on NSTX/ST-FNSF, 2 on DIII-D, 1 on C-Mod
  - APS-DPP: 6 Invited NSTX/ST-review talks
- NSTX-U organizational re-structuring complete, preparing for Research Forum, FY15 campaign
- PPPL-led ST-FNSF LDRD completed
  - IAEA/TOFE invited talks, identified mission vs. size tradeoff (TBR vs. R)

Backup slides

NSTX-U 5 year goal: Establish ST-FNSF physics/scenarios

10 year goal: Integrate high-performance core + metal walls

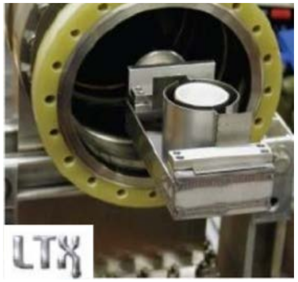
Plan presented at FESAC:

2015-2019	2020-2024
Establish ST physics / scenarios:	**High-performance + metal walls**
• Non-inductive start-up, ramp-up • Confinement vs. β , collisionality • Sustain high β with advanced control • Mitigate high heat fluxes • Test high-Z divertor, Li vapor shielding	• Convert all PFCs from C to high-Z • Static → flowing Li divertor module(s), full toroidal flowing Li divertor, high T_{wall} • 5s → 10-20s for PFC/LM equilibration • Assess ST with high-Z, high-Z + Li
Inform choice of FNSF configuration:	**Inform choice of FNSF / DEMO plasma facing materials:**
• Lower A or higher A? • Standard, snowflake, Super-X (MAST-U)?	• High-Z acceptable? or need high-Z + Li? • Assess for both divertor and first-wall

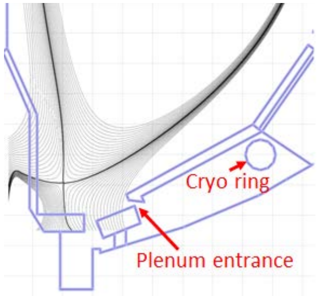
NSTX-U facility enhancements proposed for 5 year plan support FESAC Tiers/Priorities

- Improved particle control tools
  - Control D inventory, rapidly trigger ELMs to expel impurities *(Transients, PMI)*
  - Low ν* to understand ST confinement to support FNSF, validation *(FNSF, Predictive)*

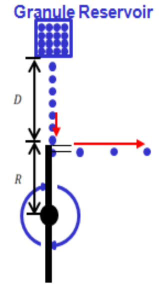
Upward Li evaporator



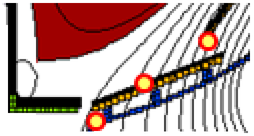
Divertor cryo-pump



Li granule injector (LGI)

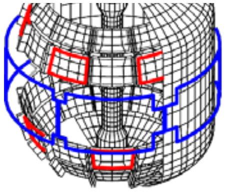


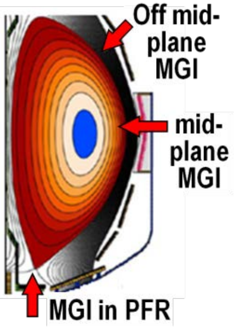
- Disruption avoidance, mitigation *(Transients, Predictive)*
  - Massive gas injection, detect halos, disruptions, control v_ϕ, RWM, ELM



Extended low-f MHD sensor set

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





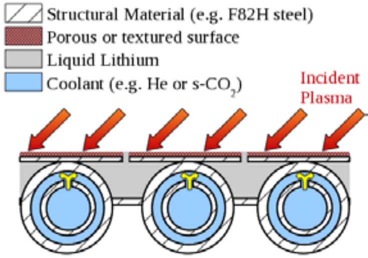
- ST start-up and ramp-up tools *(FNSF)*
  - ECH to raise start-up plasma T_e to enable FW + NBI + BS I_P ramp-up
  - Test EBW-CD start-up, sustainment
  - Start-up/ramp-up critical for ST-FNSF

1MW 28 GHz gyrotron

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

High-Z tiles

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

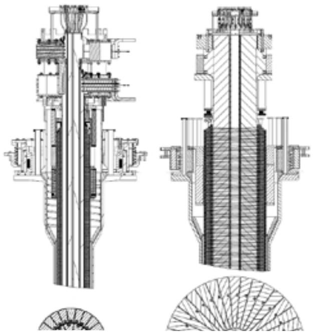


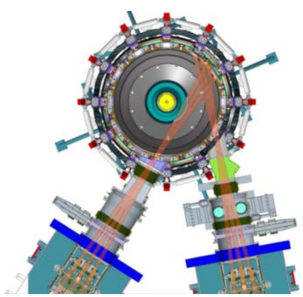
NSTX-U will continue to contribute strongly to model validation, and support development of integrated models

- **MHD**: Kinetic MHD for RWM stability, plasma response, momentum transport from 3D fields (MISK, IPEC, POCA, VALEN, PENT, MARS-K, M3D-C1, R-DCON…)
- **Transport**: High-β/electromagnetic effects on electron transport from micro-tearing, Alfvenic instabilities (GYRO, GTS, GTC, …, HYM, ORBIT)
- **Boundary**: Edge kinetic neoclassical & turbulent transport (GENE, GYRO, GS2, XGC), SOL turbulence (SOLT), snowflake/detachment: neutrals, impurities (UEDGE, SOLPS, BOUT++, EIRENE, DEGAS2, DIVIMP)
- **Fast-ions**: Gyro-center and full orbit following (ORBIT, SPIRAL), linear and non-linear Alfven instability, fast-ion transport (NOVA-K, M3D-K, HYM)
- **RF**: Heating, edge power loss (AORSA, TORIC, SPIRAL), RF/fast-ion interactions (hybrid FOW CQL3D), ECH/EBW heating & CD (GENRAY)
- **Scenarios**: 2D/3D helicity injection physics (TSC, NIMROD), time-dependent ramp-up/sustainment modeling (TSC/TRANSP/NUBEAM)

FY2015-16 research milestones target exploitation of new capabilities, exploration of new regimes

Previous center-stack | New center-stack





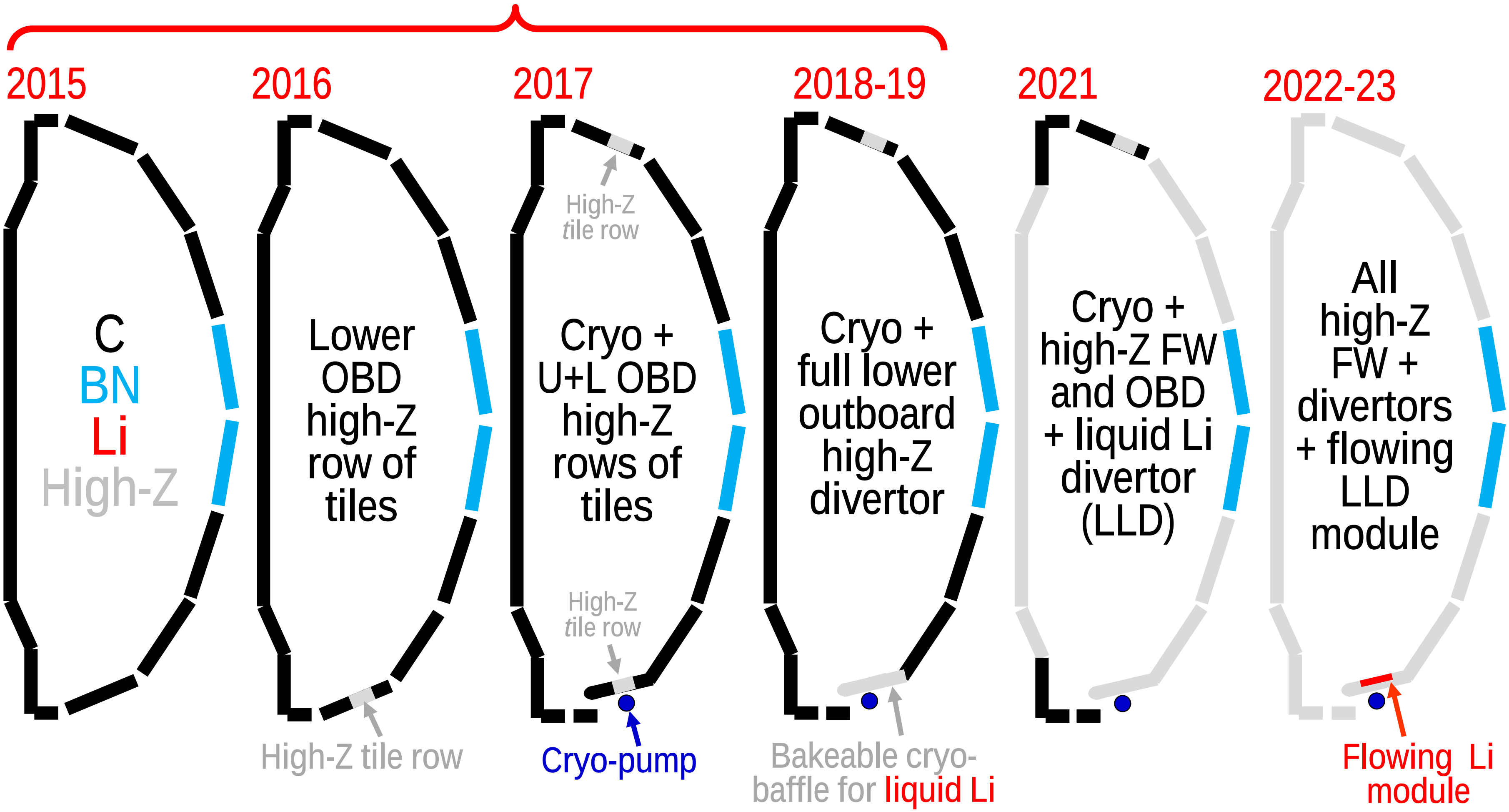
Present NBI | New 2nd NBI

Incremental (full ops)	FY2015	FY2016
Expt. Run Weeks:	18 / 20	16 / 20
Macroscopic Stability	*Support JRT on profile effects on stability*	*Lead JRT on disruption physics*
Transport and Turbulence	R15-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	IR16-1 Assess confinement and local transport and turbulence at low ν^* with full range of B_T, I_P, and NBI power
Boundary Physics	Develop snowflake configuration, study edge and divertor properties	R16-1 Assess heat-flux mitigation and PFC response using advanced divertor configurations + radiation at high $q_{\parallel\text{-div}}$
Materials & PFCs	IR15-1	
Waves+Energetic Particles	R15-2 Characterize effects of NBI injection angle on fast-ion distribution and NBI-CD profile	R16-2 Assess fast-wave SOL losses and core thermal / fast ion interactions at increased B_T, I_P
Solenoid-free Start-up/ramp-up		R16-3 Develop high-non-inductive fraction NBI H-modes for ramp-up & sustainment
Adv. Scenarios and Control	R15-3 Develop physics+operational tools for high-performance discharges (κ, δ, β, EF/RWM)	
ITER Needs + Cross-cutting		
Joint Research Target (JRT)	Quantify impact of broadened J(r) and p(r) on tokamak confinement and stability	Assess disruption mitigation, initial tests of real-time warning and prediction techniques

NSTX-U has long-term goal to assess compatibility of high τ_E and β + 100% non-inductive with metallic PFCs

5 year plan base budget case

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

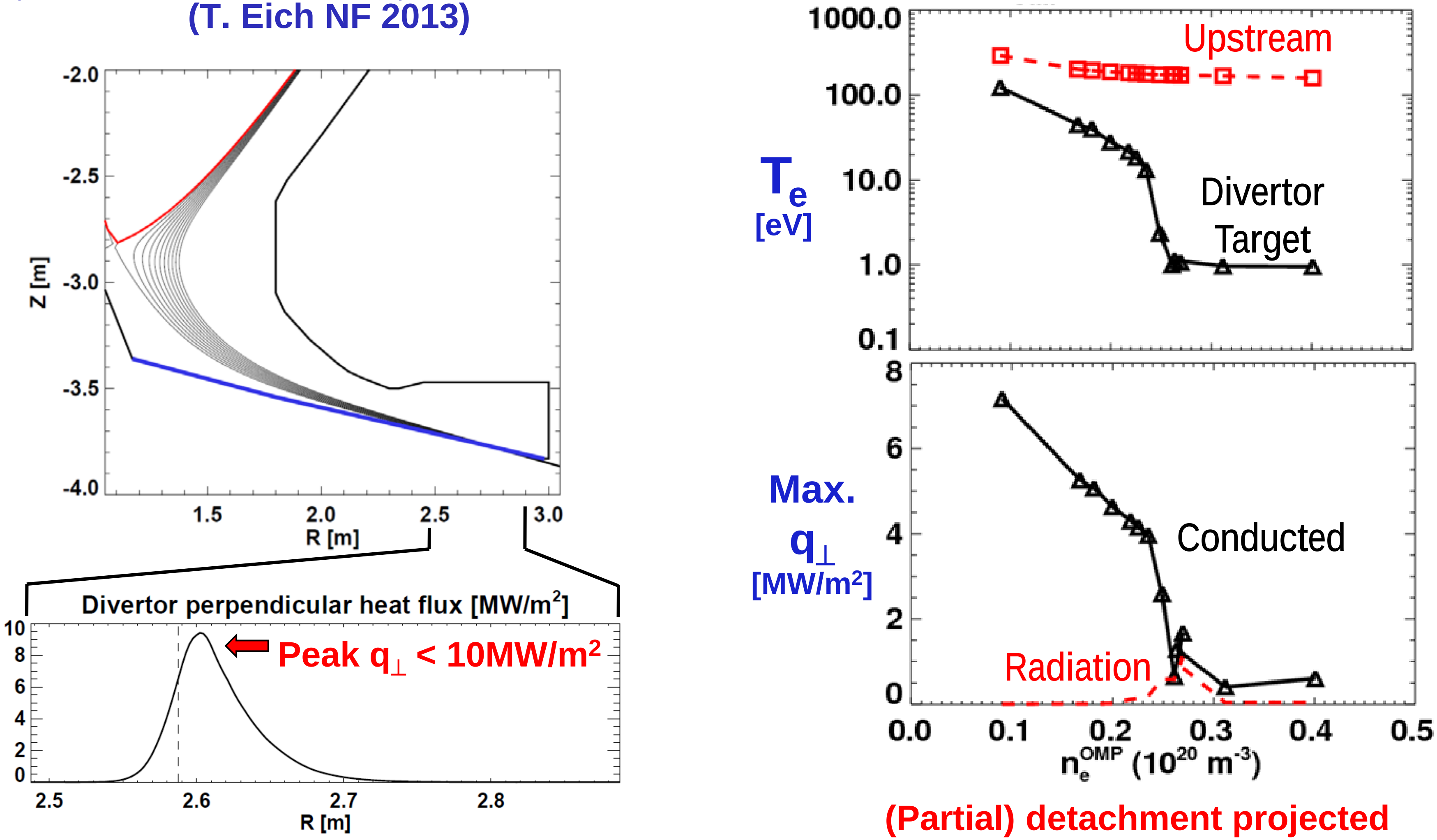


High-Z / Li implementation could be accelerated pending results and additional resources

Up/down-symmetric Super-X/snowflake projected to maintain peak divertor heat flux below material limits

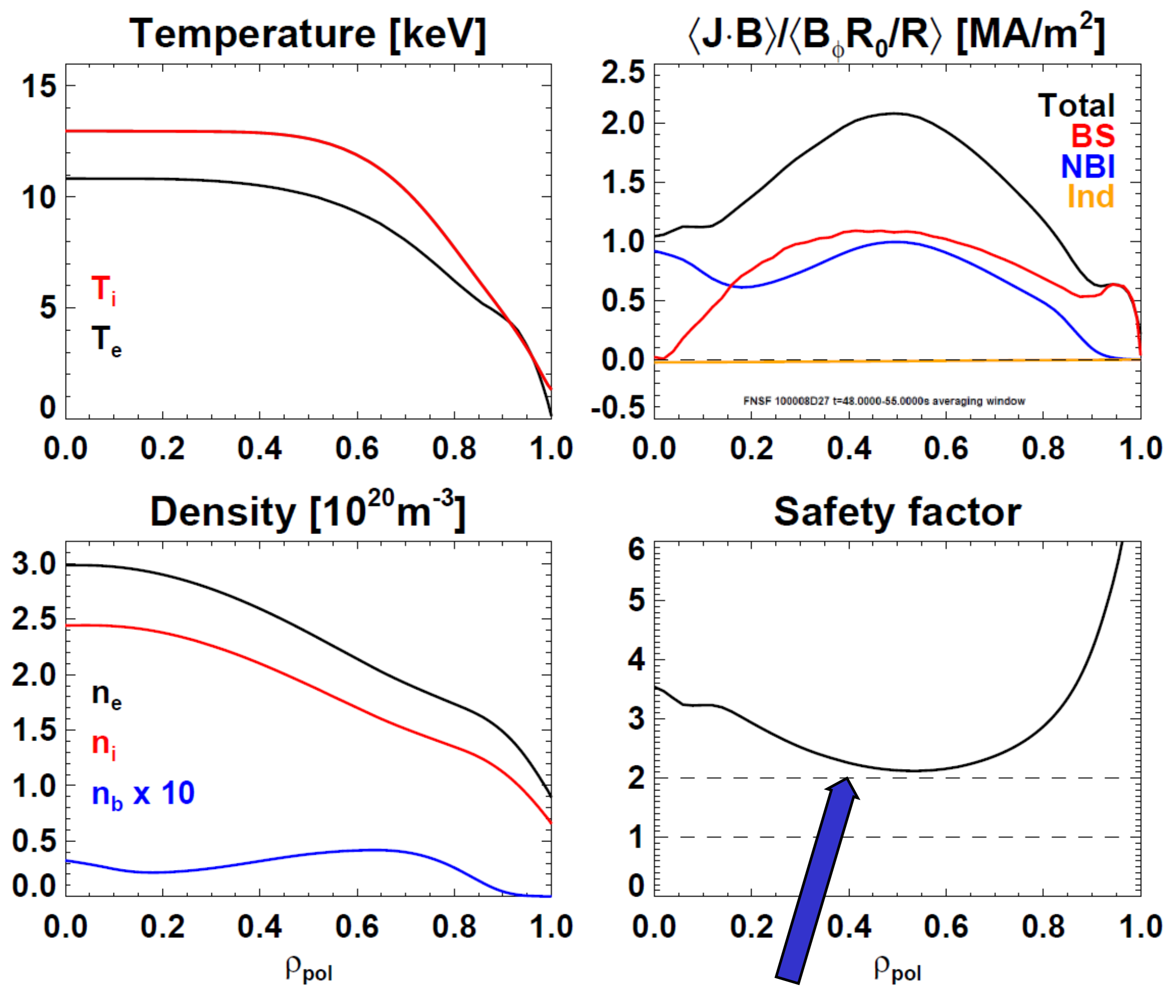
λ_q = 0.8mm, assume S ≈ λ_q (closed divertor)
(T. Eich NF 2013)

λ_q ≈ 1.2mm (J. Canik IEEE 2013)



(Partial) detachment projected to reduce peak $q_\perp$ to < 2MW/m²

Free-boundary TRANSP/NUBEAM used to compute profiles for 100% non-inductive plasmas with Q_{DT} ~2

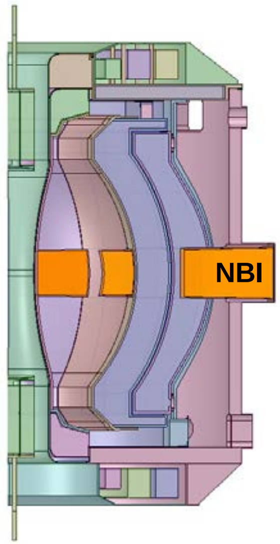


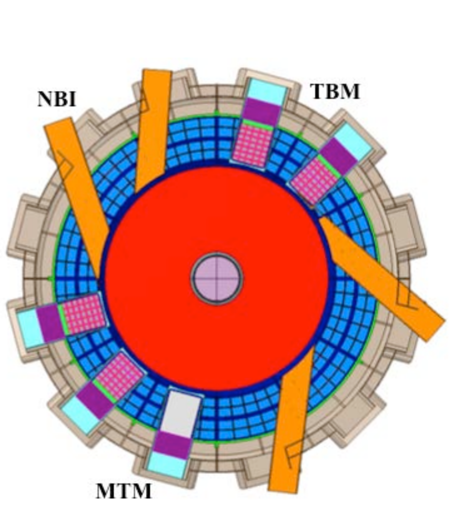
- Neoclassical χ_{ion}
- n_e / $n_{Greenwald}$ = 0.7
- $H_{98,y2}$ = 1.4
- I_P = 8.9MA, B_T = 2.9T
- f_{NICD} = 100%, f_{BS} = 65%
- P_{NNBI} = 80MW (0.5MeV)
- P_{fus} = 200MW (50-50 DT)
  - 2.6% alpha bad orbit loss
- Q_{DT} = 2.5
- β_N = 5.5, W_{tot} = 58MJ
  - W_{fast} / W_{tot} = 14%

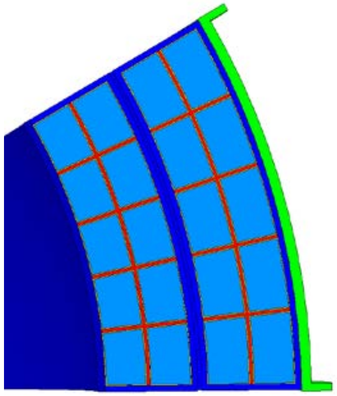
- Maintain q_{min} > 2
- q(0) / q_{min} controllable via R_{tan} and density

ST-FNSF shielding and TBR analyzed with sophisticated 3-D neutronics codes

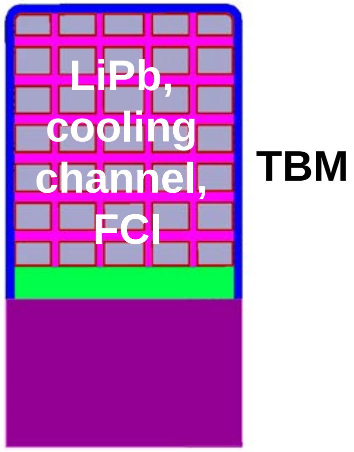
- CAD coupled with MCNP using UW DAGMC code
- Fully accurate representation of <u>entire torus</u>
- No approximation/simplification involved at any step:
  - Internals of two OB DCLL blanket segments modeled in great detail, including:
    - FW, side, top/bottom, and back walls, cooling channels, SiC FCI
  - 2 cm wide assembly gaps between toroidal sectors
  - 2 cm thick W vertical stabilizing shell between OB blanket segments
  - Ports and FS walls for test blanket / materials test modules (TBM/MTM) and NNBI





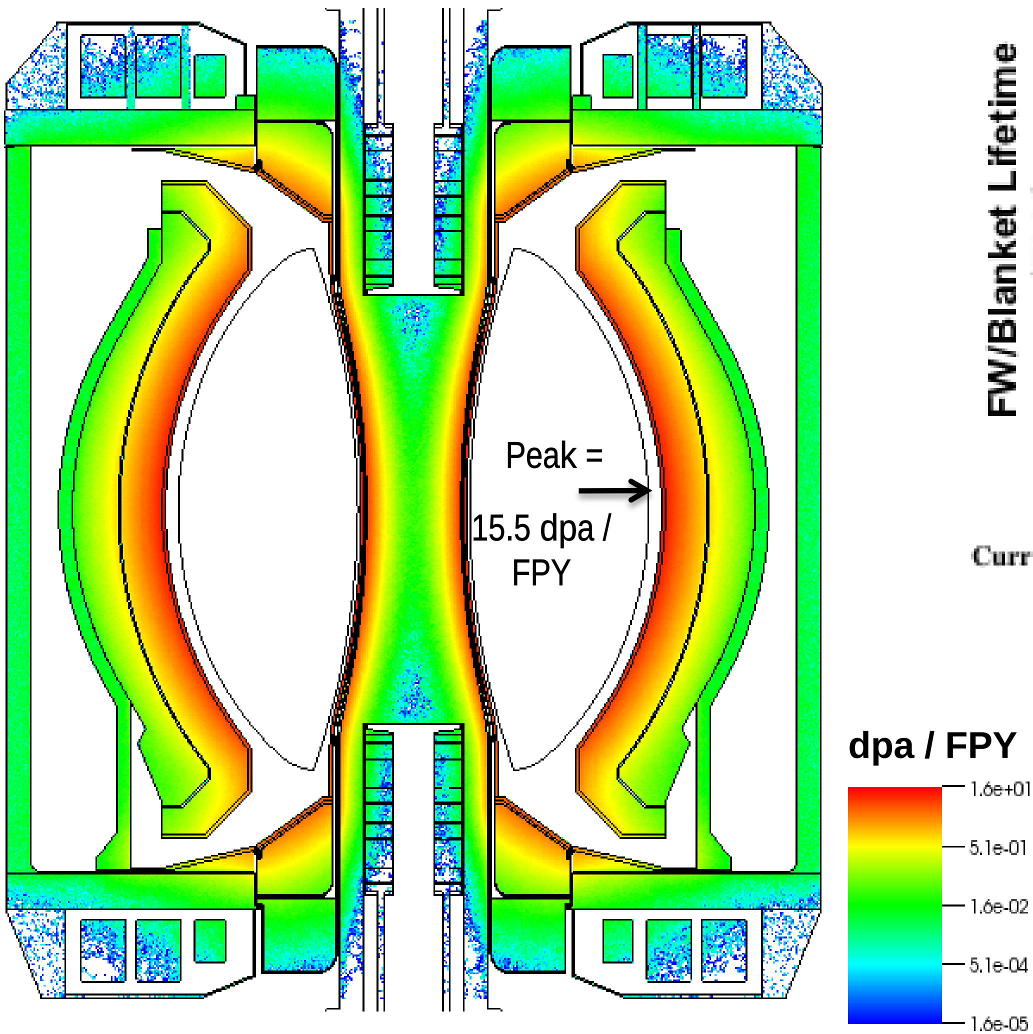


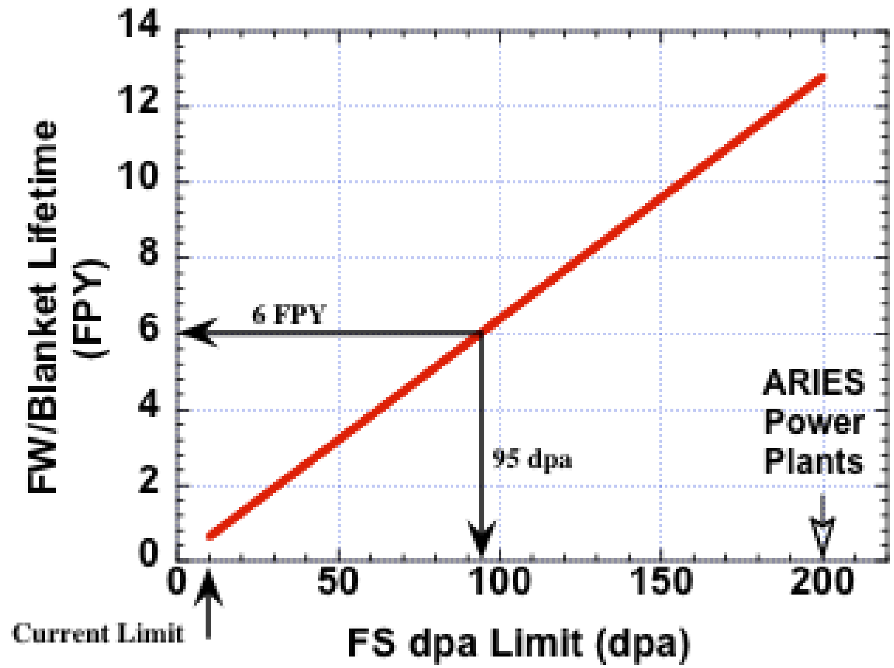
Heterogeneous OB Blanket Model, including FW, side/back/top/bottom walls, cooling channels, and SiC FCI



Mapping of dpa and FW/blanket lifetime
(R=1.7 m Device)

R=1.7m configuration



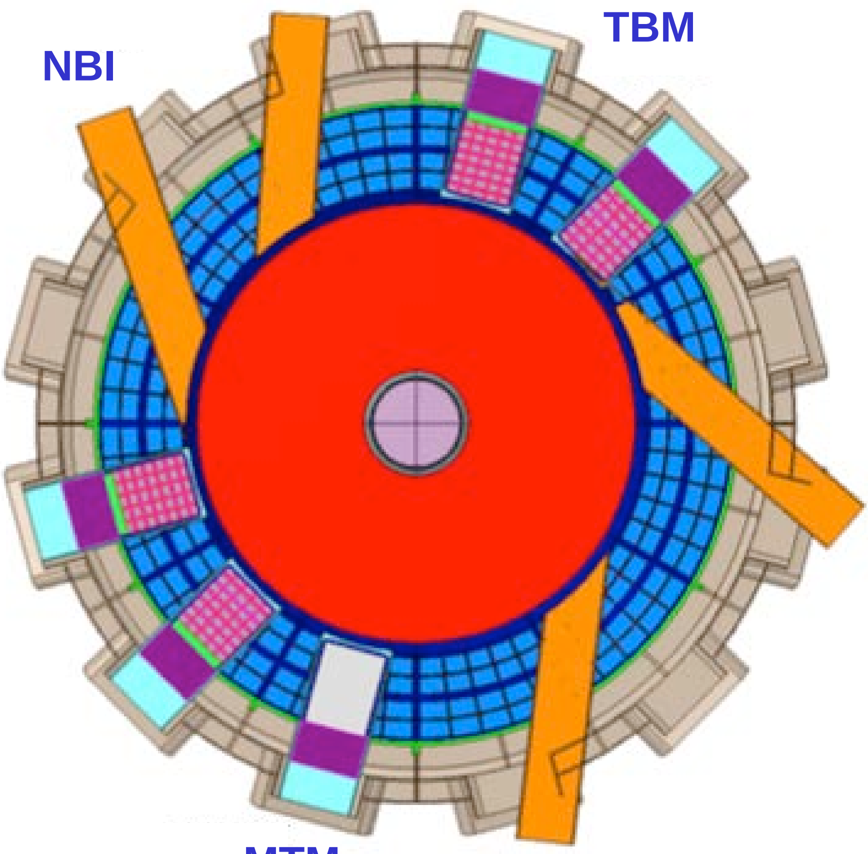


FW/blanket could operate for 6 FPY if allowable damage limit is 95 dpa

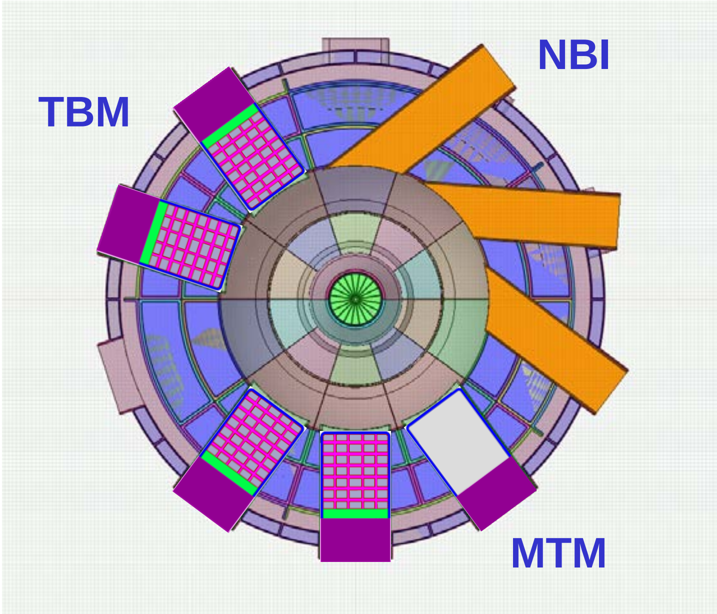
→ **Peak EOL Fluence = 11 MWy/m^2**

Summary of ST-FNSF TBR vs. device size

R=1.7m: **TBR ≥ 1**

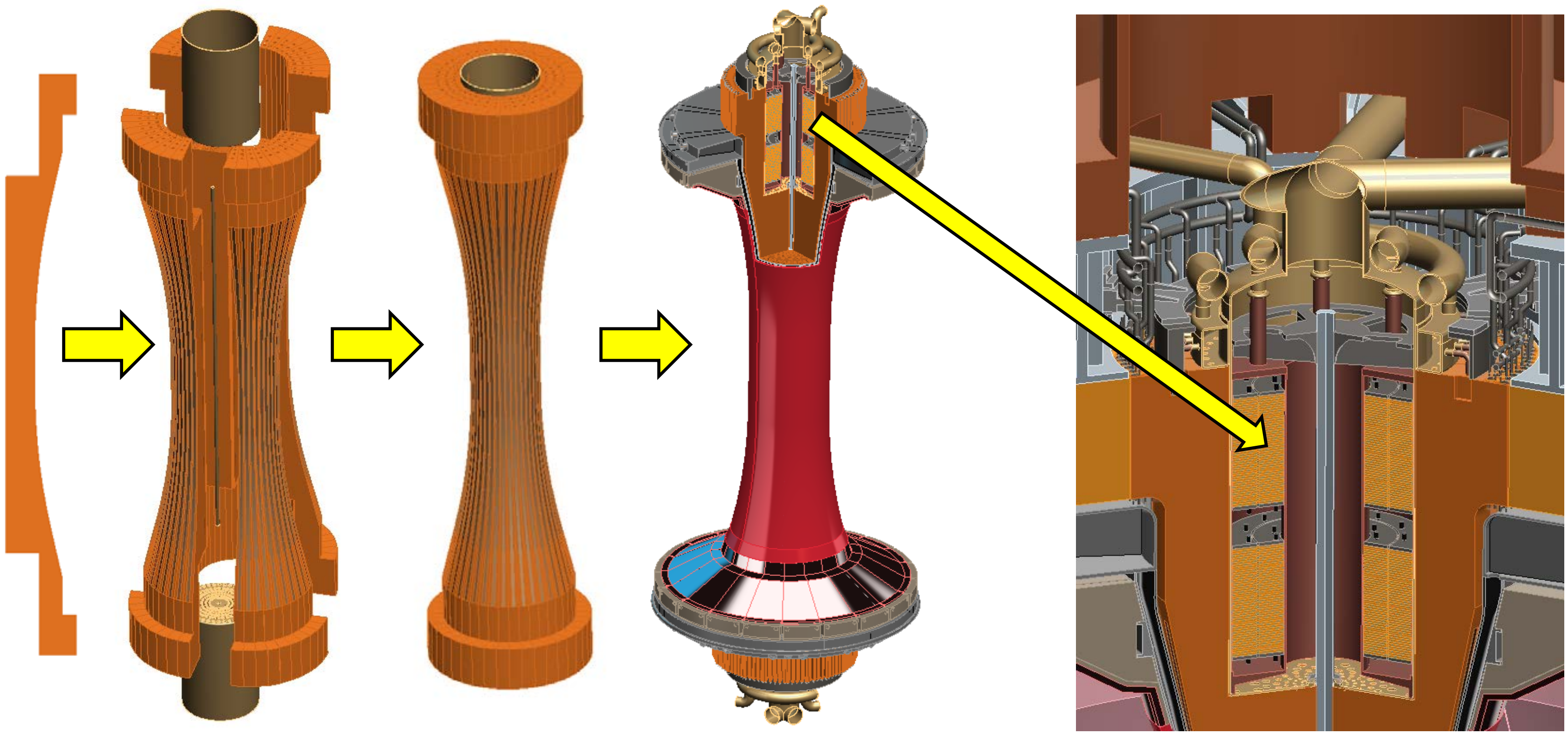


R=1.0m: **TBR < 1 (≈ 0.9)**



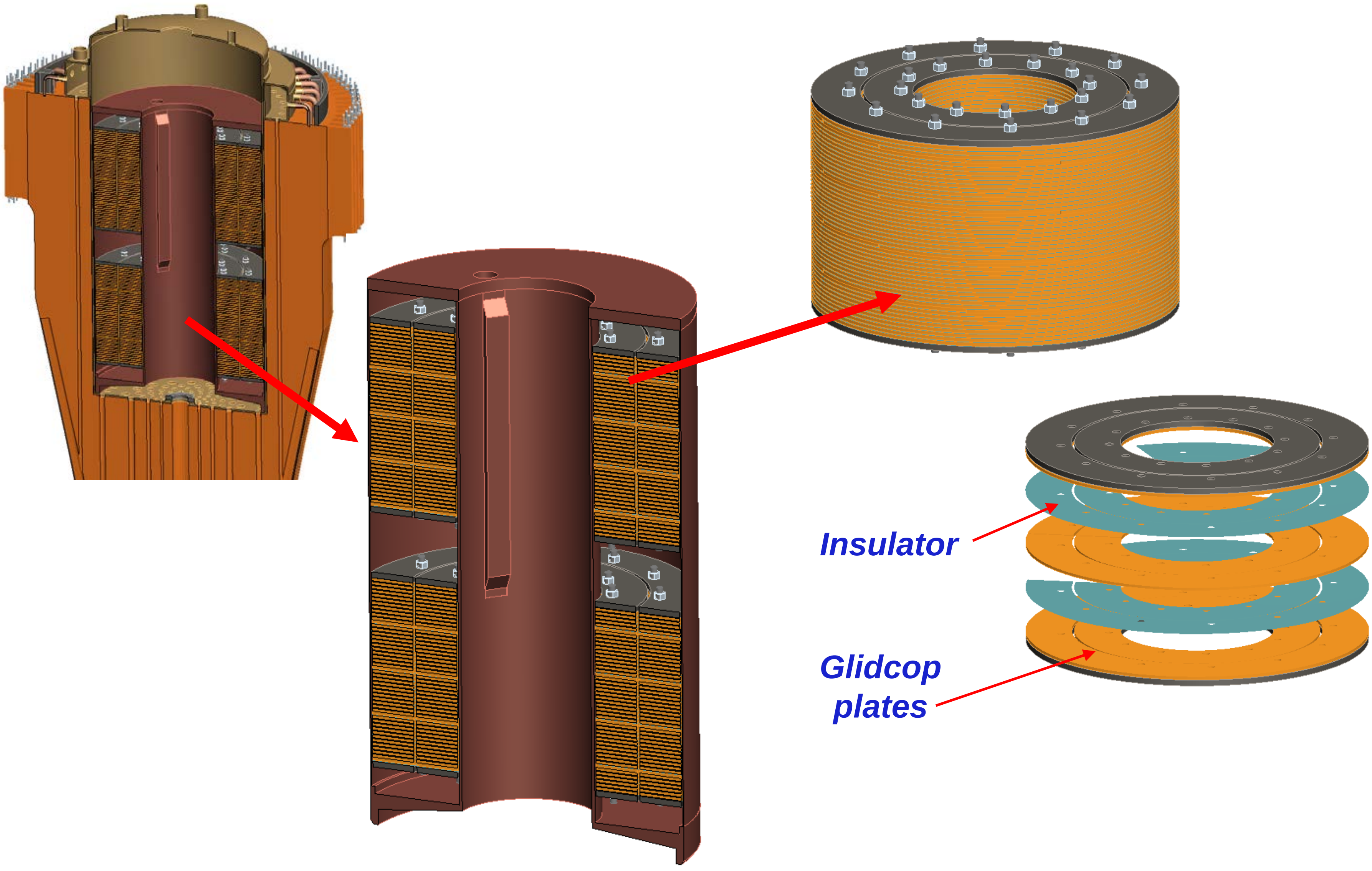
- **1m device cannot achieve TBR > 1 even with design changes**
- **Solution**: purchase ~0.4-0.55kg of T/FPY from outside sources at $30-100k/g of T, costing $12-55M/FPY

FNSF center-stack can build upon NSTX-U design and incorporate NSTX stability results



- **Like NSTX-U, use TF wedge segments (but brazed/pressed-fit together)**
  - Coolant paths: gun-drilled holes or grooves in side of wedges + welded tube
- **Bitter-plate divertor PF magnets in ends of TF achieve high triangularity**
  - **NSTX data:** High $\delta > 0.55$ and shaping $S \equiv q_{95} I_P / a B_T > 25$ minimizes disruptivity
  - Neutronics: MgO insulation can withstand lifetime (6 FPY) radiation dose

Bitter coil insert for divertor coils in ends of TF



MgO insulation appears to have good radiation resistance for divertor PF coils

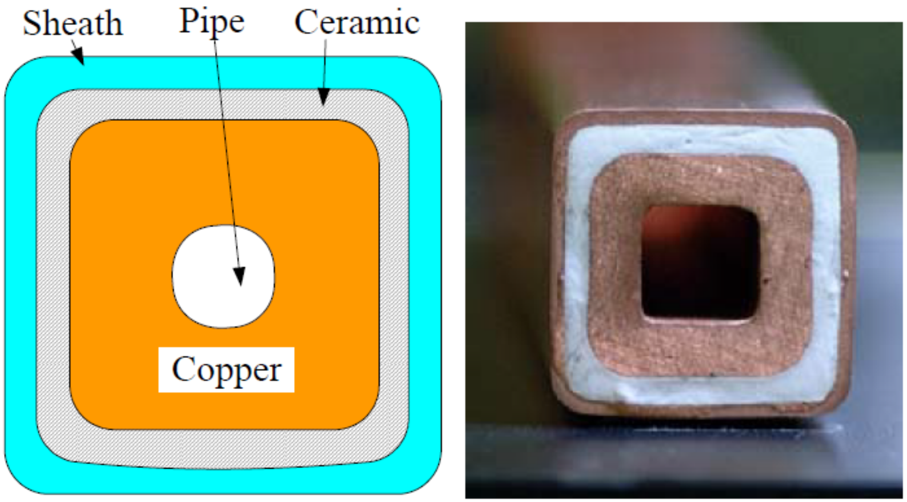


Fig. 3 Cross section of MIC

Table 1: Comparison of radiation resistant

	Organic		Inorganic
Insulation	Epoxy	Polyimide	MgO
Resistant	$>10^7$ Gy	$>10^9$ Gy	$>10^{11}$ Gy

R&D of a Septum Magnet Using MIC coil

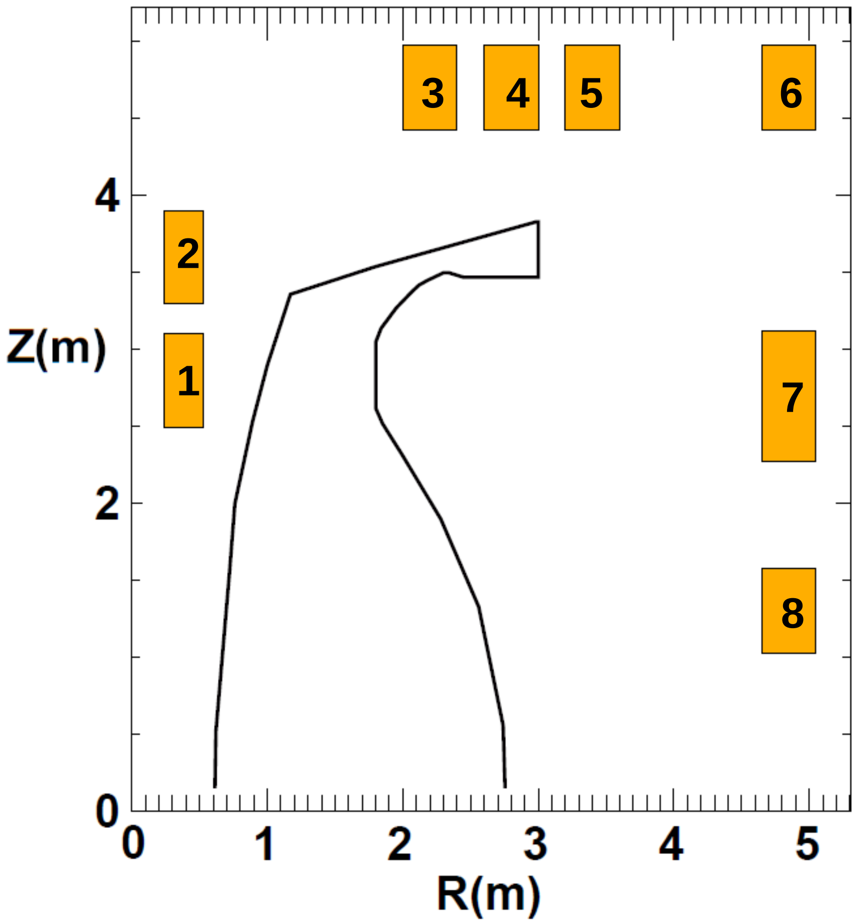
Proceedings of the 5th Annual Meeting of Particle Accelerator Society of Japan and the 33rd Linear Accelerator Meeting in Japan (August 6-8, 2008, Higashihiroshima, Japan)

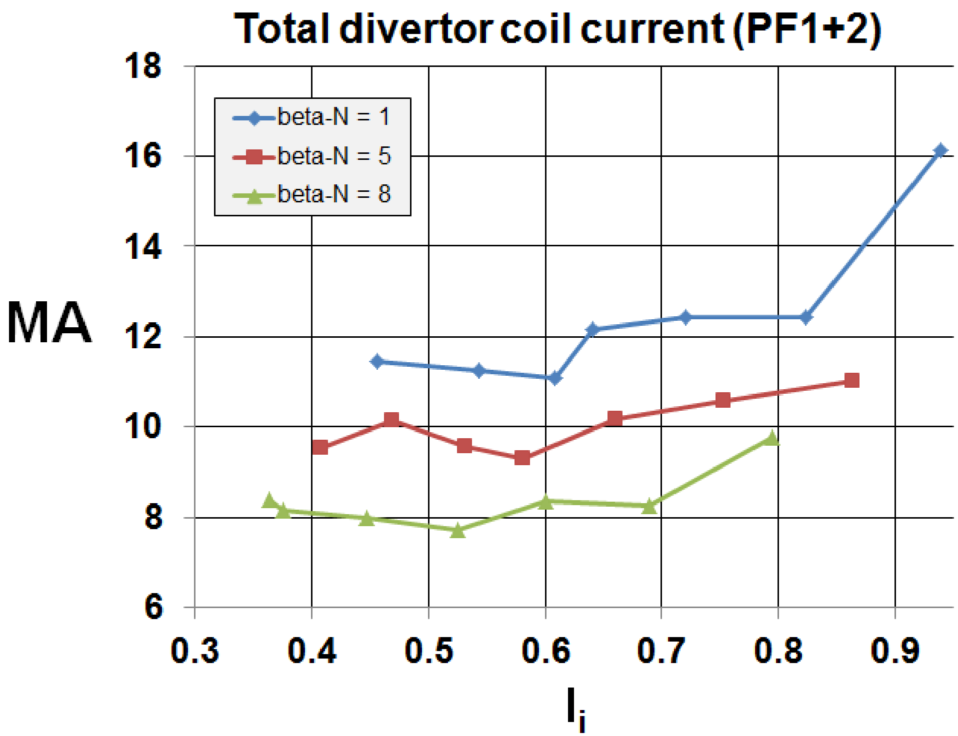
Kuanjun Fan [1,A)], Hiroshi Matsumoto [A)], Koji Ishii [A)], Noriyuki Matsumoto [B)]
A) High Energy Accelerator Research Organization (KEK)
1-1 OHO, Tsukuba, Ibaraki, 305-0801, Japan
B) 2NEC/Token

PF coil currents and current densities

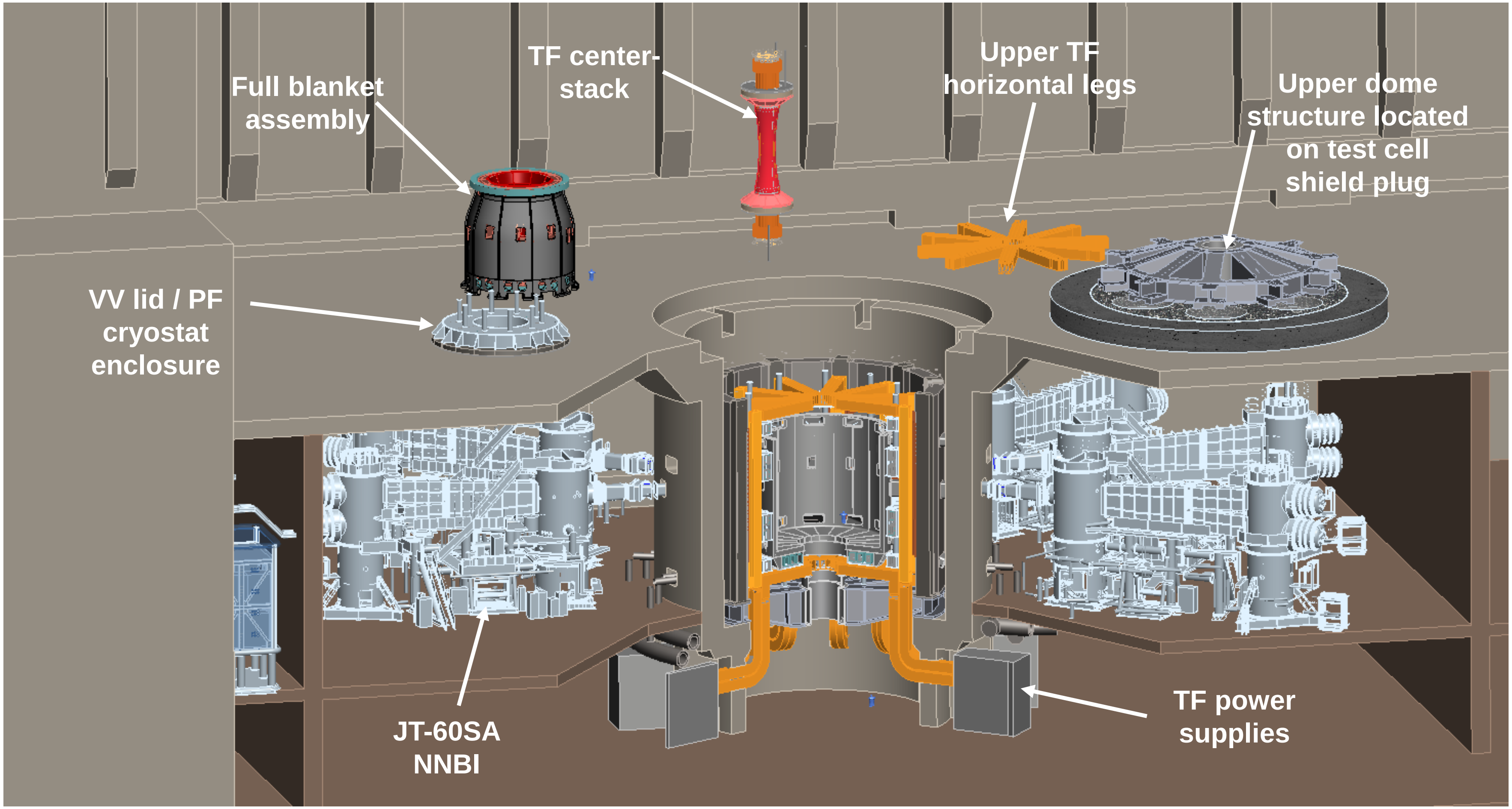
$\beta_N = 5$
$l_i = 0.58$

Coil	PF1U	PF2U	PF3U	PF4U	PF5U	PF6U	PF7U	PF8U
MA turns	2.3	7.0	1.3	0.0	6.2	-0.6	-9.7	0.4
MA/m^2	12.8	39.6	5.9	0.0	28.2	-2.7	-28.5	1.8





R=1.7m ST-FNS facility layout
using an extended ITER building



FNSF Summary: R = 1m and 1.7m STs with Γ_n = 1MW/m^2 and Q_{DT} = 1-2 assessed for FNS mission

- Ex-vessel PF coil set identified to support range of equilibria and Super-X/snowflake divertor to mitigate high heat flux
- 0.5MeV NNBI optimal for heating & current drive for R=1.7m
- Vertical maintenance approach, NBI & test-cell layouts identified
- Shielding adequate for MgO insulated inboard Cu PF coils
  - Outboard PF coils (behind outboard blankets) can be superconducting
- Calculated full 3D TBR; TBR reduction from TBM, MTM, NBI
- **Threshold major radius for TBR ~ 1 is $R_0 \geq$ 1.7m**
- **R=1m TBR = 0.88 → 0.4-0.55kg of T/FPY → $12-55M/FPY**
- R=1m device will have lower electricity and capital cost → future work could assess size/cost trade-offs in more detail