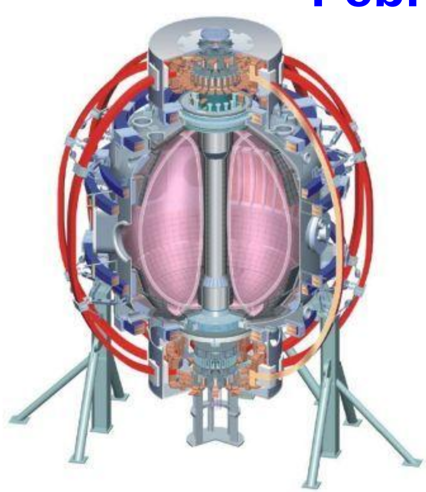
Introduction and Motivation of the Meeting

Masa Ono

NSTX-U Facility Enhancement Brainstorm Meeting
February 7 - 8, 2012



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RRC Kurchatov Inst
TRINITI
KBSI
KAIST
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ENEA, Frascati
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IPP, Garching
ASCR, Czech Rep
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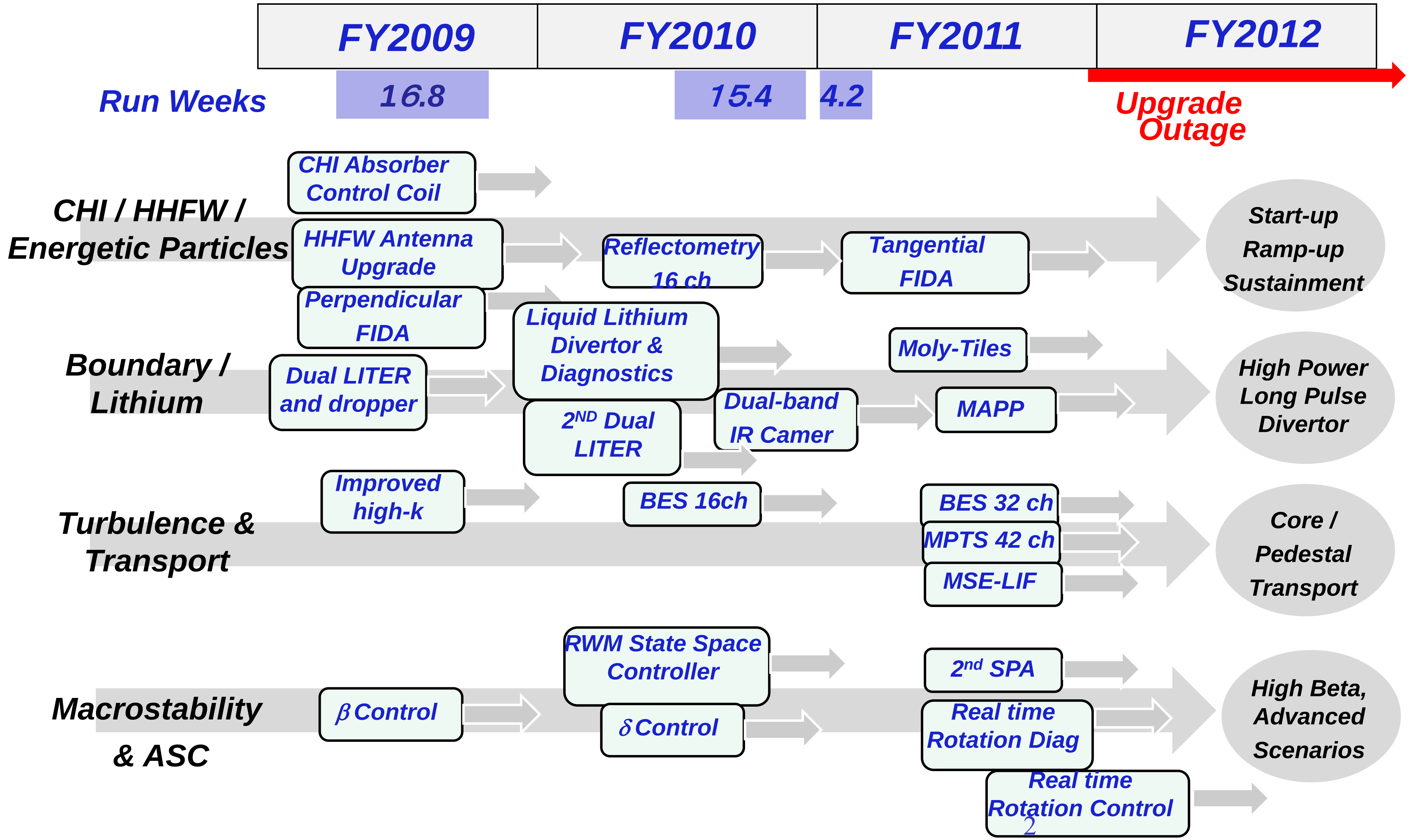
Significant Facility Enhancements Implemented
To Support NSTX Mission Elements and Upgrades

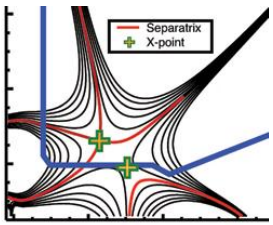


NSTX Upgrade + follow-on upgrades will enable access to broad range of new ST regimes

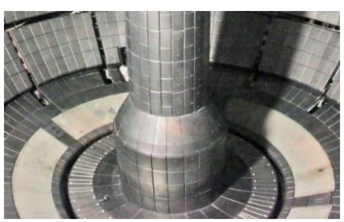
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

1 MA Plasma | **Upgrade Outage** | **1.5 → 2 MA Plasma**

- HHFW Upgrade
- LLD
- Moly-tile
- CHI Control Coils
- 2[nd] NBI

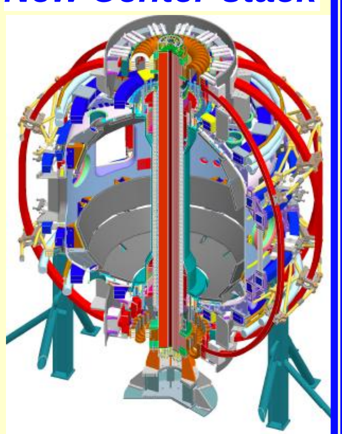


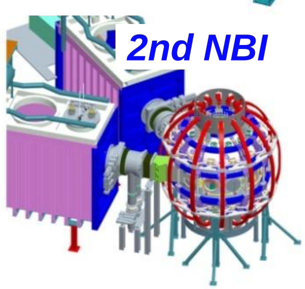
"Snowflake"



Lithium

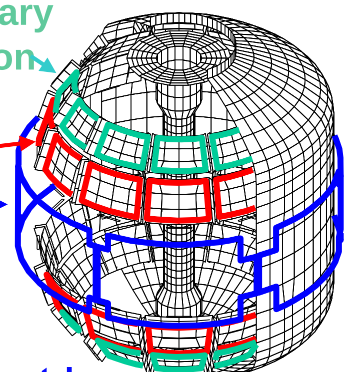
New Center-stack





2nd NBI

- 1 - 2 MW ECH/EBW
- Long–pulse Divertor
- 0.5 MA CHI
- 1 MA CHI / Plasma Gun
- 0.5 MA Plasma Gun
- NCC Upgrade



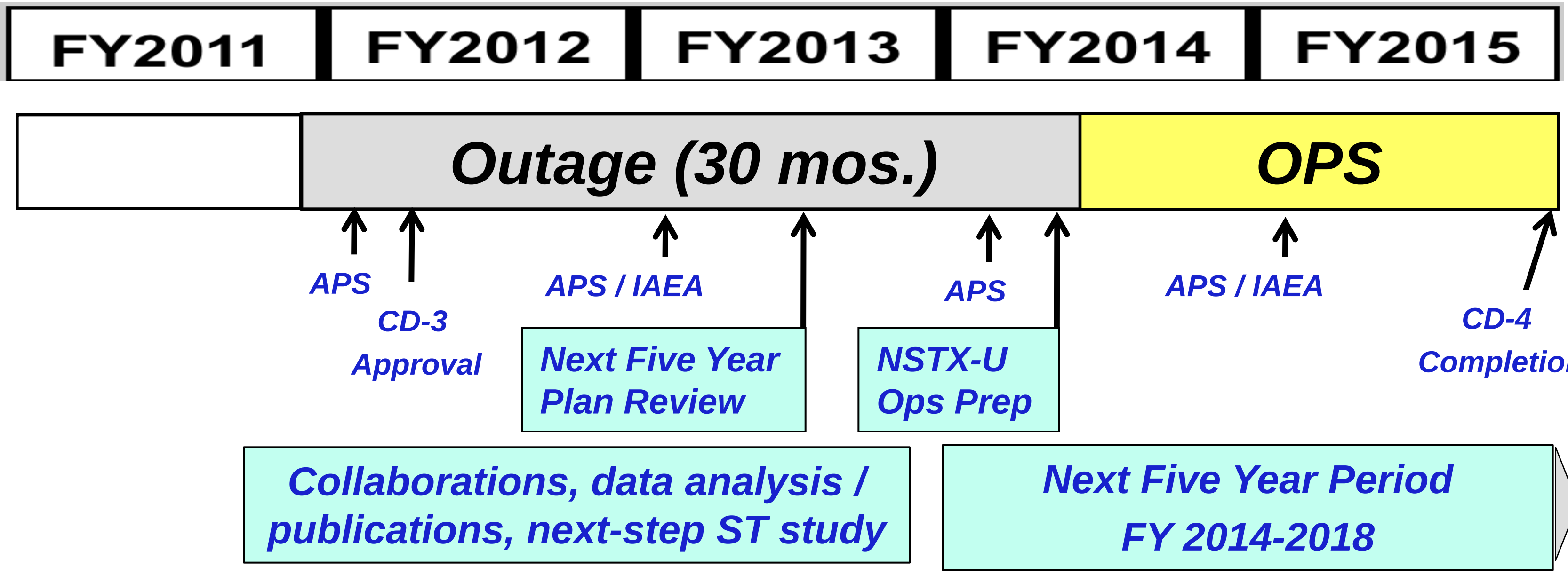
Non-axisymmetric Control Coils (NCC)

NSTX Upgrade Research Goals

- Low collisionality plasma regimes
- 100% non-inductive operation
- Long-pulse, high power divertor
- Advanced high-β scenarios

NSTX-U Outage Near Term Schedule

A rare opportunity to think broadly and innovatively!



NSTX resources are highly constrained in the near term but the need for innovation is greater than ever!

- NSTX Upgrade Project has the highest priority
- Other enhancements needed for NSTX-U Operation is next priority
  - e.g., motor generator repair, rectifier fault detector, firing generator
- Implement high priority enhancements as resources become available after completion of NSTX Upgrade Project

Facility Enhancements Brainstorming Meeting
Let us explore all innovative possibilities!

Brainstorm Facility Enhancement Possibilities:

- **Support NSTX-U operation (FY 2012 - 2014)**
- **Enhance NSTX-U operation (FY 2014 – 2016)**
- **Help achieve NSTX-U mission / goals (FY 2014 – 2018)**

Looking for new ideas to achieve NSTX-U mission elements:

- **Save $ to make best use of limited resources**
- **Significant improvement to present approach**
- **Enable new capability**
- **Enhance possibility of fusion break-through!**
- **Enhance external support for NSTX-U (community, DOE..)**

We have a full program so please adhere to allotted time!

Agenda for NSTX-U Facility Enhancement Brainstorming Meeting
Tuesday, February 7 & Wednesday, February 8, 2012

	Tuesday, February 7, 2012 – B318, PPPL	
Time	**Topic**	**Speaker**
1:00 PM	Introduction and Motivation of the Meeting	M. Ono
1:20	Programmatic Vision for NSTX-U	J. Menard
1:40	NSTX Upgrade Project Overview	R. Strykowsky
	Non-Upgrade Scopes	
2:00	Power Supply Upgrades	R. Ramakrishnan
2:10	Basic Magnetics for NSTX-U Operations	S. Gerhardt
2:20	Improved Power Handling at CHI Gap	S. Gerhardt
2:30	Hardware Upgrades Related to PCS	S. Gerhardt
2:40	HHFW Antenna Enhancement	J. Hosea
2:50	**Energetic Particle**	
3:00	*AE antenna	E. Fredrickson
	Particle Control / Divetor	
3:10	Upper Divertor Molybdenum Tiles	H. Kugel
3:20	Active Cooling	M. Jaworski
3:30	Upward facing LiTER	R. Maingi
3:40	Divertor Cryopump and Baffle	R. Maingi
3:50	PCS feedback on divertor temperature and associated diagnostics	R. Maingi
4:00	Glow Discharge Cleaning system upgrade	V.Soukhanovskii
4:10	Divertor gas injector upgrade	V.Soukhanovskii
4:20	Supersonic Gas injector Upgrade	V.Soukhanovskii
4:30	Molecular cluster injector	R. Majeski
4:40	CT fueling	R. Raman
4:50	Replaceable divertor module	S. Zweben
5:00	Fast liquid metal loop based on RDM	H. Ji
5:10	HFS gas injection shut-off valve	C. Skinner
	Mini Li evaporator concept	C. Skinner
	3-D Fields	
5:20	Off-midplane coils for improved poloidal spectrum of magnetic perturbations	R. Maingi

	Wednesday, February 8 – B318, PPPL	
Time	**Topic**	**Speaker**
	Lithium /Boundary Related Enhancements	
1:00 PM	Near Term Lithium Options	H. Kugel
1:10	LTX-style crucible evaporators	R. Majeski
1:20	FLiLi	L. Zakharov
1:30	Li injectors for real-time Li fueling	L. Roquemore
1:40	Masking of LITER evaporators to preferentially deposit Li in specified areas	L. Roquemore
1:50	Dual band thermography in NSTX-U	J-W. Ahn
2:00	Pellet injector for ELM pacing and fueling	T.K. Gray
2:10	The fast liquid lithium shower	G. Wurden
2:20	Li CPS PFCs	R. Goldston
2:30	Monitor SOLC for machine protection	H. Takahashi
2:35	Compensate for SOLC-generated error field in machine control and equilibrium reconstruction	H. Takahashi
2:40	Drive SOLC externally for machine performance extension	H. Takahashi
2:50	Surface studies to support particle control	C. Skinner
3:00	Improved tile-to-tile alignment of divertor plasma facing components	F. Scotti
3:10	Long pulse divertor biasing	D. Battaglia
	3-D Fields	
3:20	Driving EHOs	R. Goldston
3:30	Distant 3-D field Coils	S. Gerhardt
3:40	Non-axisymmetric Control Coil Upgrade and other ideas by the Columbia U. Group	S. Sabbagh
3:50	Diagnostics supporting advanced global mode stabilization studies	S. Sabbagh
	Start-Up / Current Drive	
4:00	CHI Cap. bank upgrade to higher voltage and bank energy	R. Raman
4:10	Improvements to CHI	R. Raman
4:20	NB Upgrade For Increased Pulse Length at High Power	S. Gerhardt
4:30	Plasma gun startup	D. Battaglia
4:40	Point-Source Helicity Injection Startup in NSTX-U	R. Fonck
4:50	ECH/EBW System	J. Hosea
	Other Diagnostic Ideas	
5:00	MPTS long term plans	B.P. LeBlanc
5:05	Facility modifications for Divertor Thomson Scattering diagnostic	V.Soukhanovskii
5:10	Monitor NB ions species mix	M. Podesta
5:15	Improved Magnetics IN NSTX-U	R. Raman

NSTX-U facility enhancement brainstorming meeting: Programmatic Goals and Guidance

J. Menard
for the NSTX Research Team

NSTX-U Facility Brainstorming
B318 - PPPL
February 7-8, 2012

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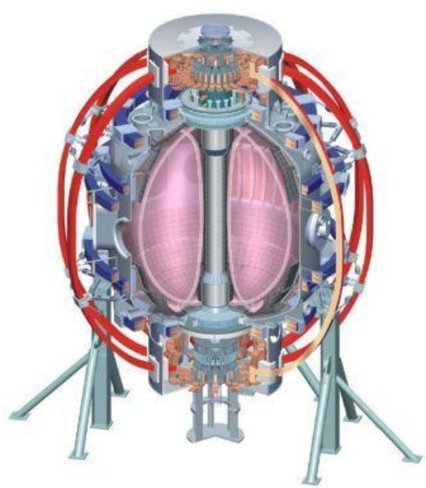

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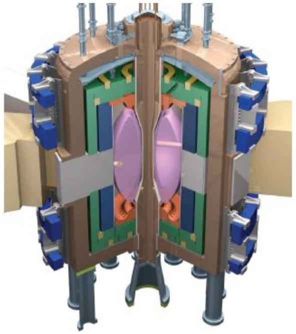
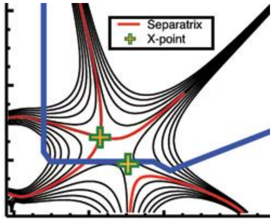
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

NSTX Upgrade Mission Elements
and associated research goals

- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
  - Advance non-inductive start-up, sustainment
  - Develop predictive capability for confinement, high-beta stability, and control
- Develop solutions for PMI
  - Inform FNSF/Pilot/Demo decisions on divertor configurations, high-Z PFCs, Li, cryo-pumping
- Advance toroidal confinement physics for ITER and beyond
  - Utilize waves/HHFW, energetic particles, 3D physics capabilities in support of ITER, beyond
- Develop ST as fusion energy system
  - Integrate + extend performance described above



ST-FNSF



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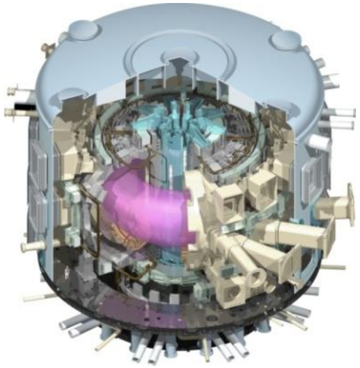

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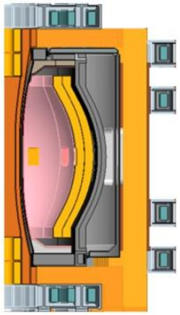
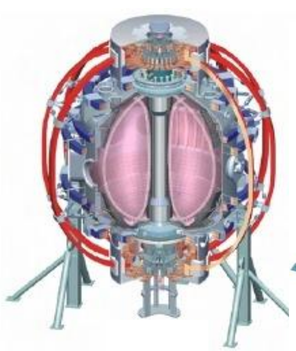


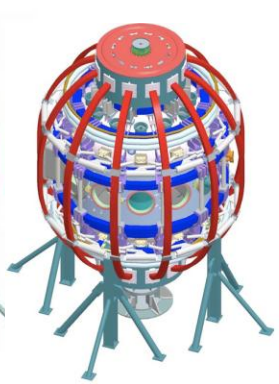
ST Pilot Plant

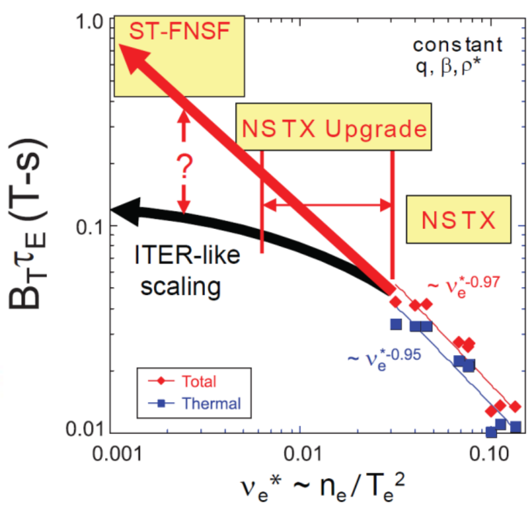
Goal of NSTX Upgrade is provide physics basis for choice of size, power, divertor, operating scenarios of next-step STs

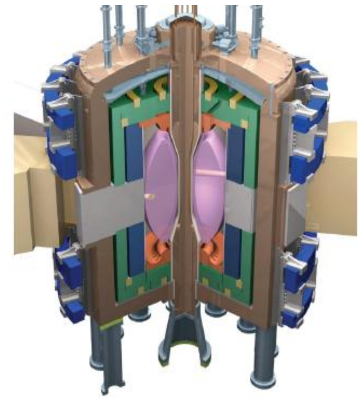
	NSTX	NSTX Upgrade	Fusion Nuclear Science Facility	ST Pilot Plant
Major Radius R_0 [m]	0.86	0.94	1.3	2.2
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.6	≥ 1.7
Plasma Current [MA]	1	2	4 → 10	10 → 20
Toroidal Field [T]	0.5	1	2-3	2-3
P/R, P/S [MW/m,m^2]	10, 0.2*	20, 0.4*	30 → 60, 0.6 → 1.2	40 → 100, 0.3 → 1
Fusion gain Q_{DT}			0 → 1-3	0 → 10-20

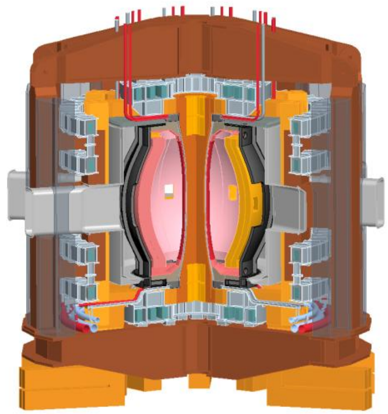
** Includes 4MW of high-harmonic fast-wave (HHFW) heating power*









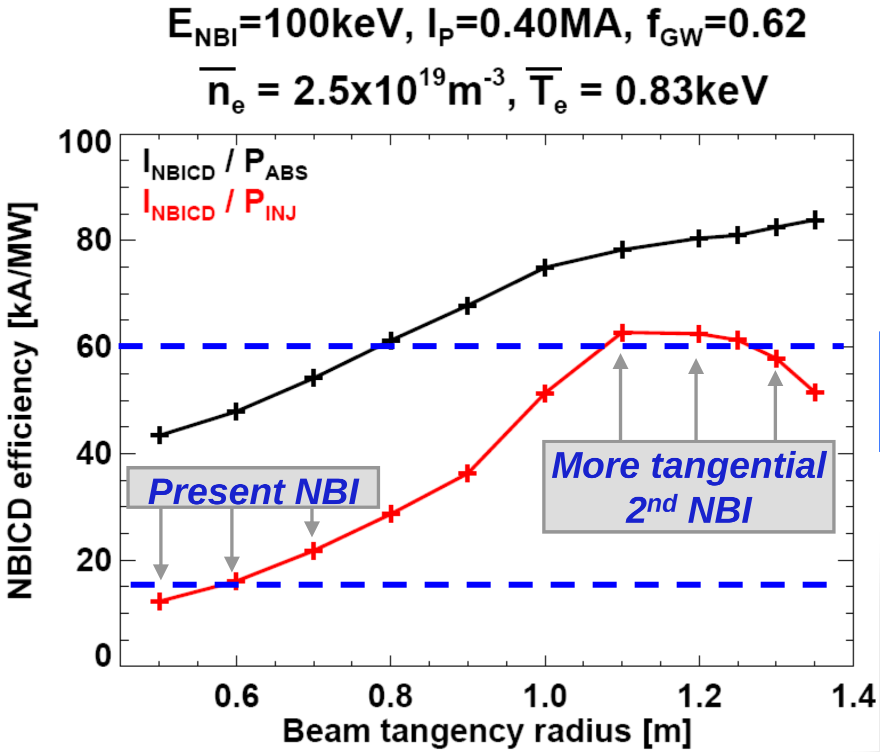


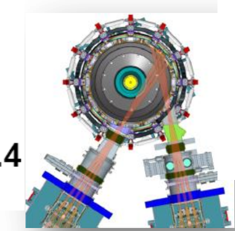
Priorities and Goals

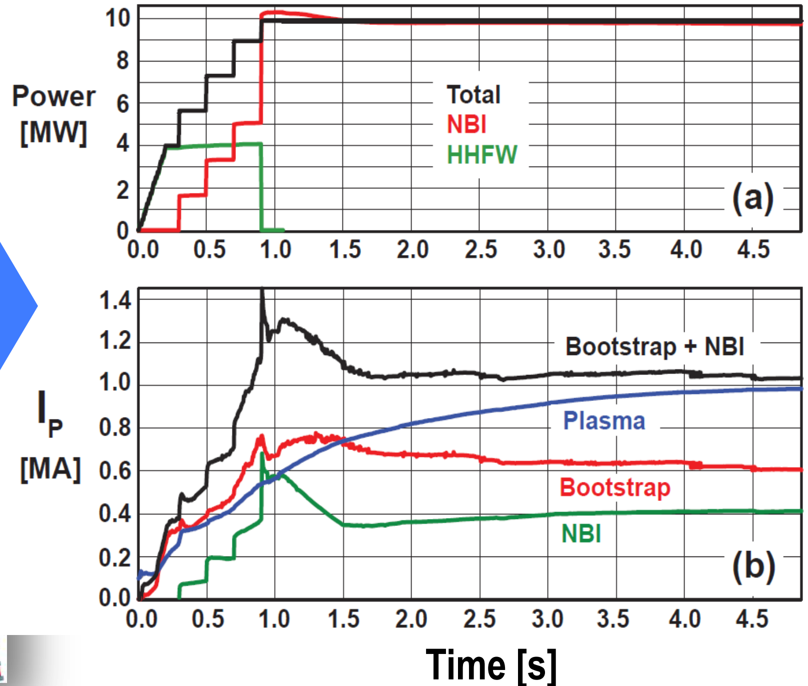
- Overall prioritization (same as Masa's talk)
  1. Successful completion of NSTX Upgrade Project
  2. Enhancements needed for NSTX-U operation
  3. Implement high priority enhancements as resources become available after completion of NSTX-U Project
- The goals that follow are long-range goals
  – To be completed by end of 5 year plan (2018)
  – Viability will be strongly influenced by available resources and NSTX-U experimental results

NSTX Upgrade will provide critical test of non-inductive current ramp-up using NBI current drive

- New CS increases B_T (improves stability) & t_{flat} (for J(r) equilibration)
- More tangential injection provides 3-4x higher CD at low I_P:
  - 2x higher absorption (40→80%) at low I_P = 0.4MA
  - 1.5-2x higher current drive efficiency







NSTX-U non-inductive start-up/ramp-up goals:

- Assess expected favorable scaling of CHI start-up with B_T
  - I_P scales linearly with B_T if higher V_{CHI} realizable (under analysis)
  - Extend/validate recent NIMROD and TSC modeling of CHI
- Test auxiliary heating and CD of CHI-formed plasma
  - Use 2nd NBI, HHFW as planned for FY2011-12, ECH (if available)
- Assess NBI ramp-up of low-I_P plasma to higher I_P
  - Model/develop optimized target plasma for NBI ramp-up
  - *AE avalanches, fast-ion redistribution potentially important

NSTX-U transport & turbulence research goals:

- Identify instabilities responsible for anomalous transport (thermal, momentum, and particle/impurity)
  - Measure scaling of local transport with relevant parameters
  - Measure turbulence characteristics (δn_e, δB_r, …) and scaling with parameters: low-k/BES, high-k/μ-wave, δB_r / polarimetry
  - Compare with linear and non-linear predictions to discriminate theoretical modes: k spectra and transport fluxes
- Establish/validate reduced transport models
  - Validate existing 0D confinement scalings: W_{core} and W_{ped}
  - Develop transport models using profile database, analytic fits to linear and non-linear GK simulations, TGLF, neoclassical
  - Validate models w/ profile data from NSTX/NSTX-U, MAST

NSTX-U macroscopic stability research goals:

- Identify & correct possible n=1-3 intrinsic error fields
- Develop validated models of RWM, NTV, and NTM
  - Vary & reduce ν^*, vary fast ion anisotropy using 2nd NBI
- Develop simultaneous control of β_N, RWM, $\Omega_\phi(r,t)$, q(r,t)
- Extend models/validation of plasma response to 3D fields
- Design, implement off-midplane 3D control coils
  - What are new/unique applications of such coils?
- Disruptions:
  - Test/optimize MGI: vary injection position, magnitude, gas
  - Identify precursors, measure disruption forces, assess avoidance
  - Relate kink stability of quenching plasmas to halo characteristics

NSTX-U boundary physics research goals:

- Investigate pedestal/SOL profiles/width, transport, and turbulence at higher B_T, I_P, P_{SOL}, reduced ν^*
- Develop, utilize snowflake divertor + real-time divertor fueling/detachment for heat-flux mitigation and control
  - Real-time multi-x-point ID, divertor temperature and P_{RAD}
- Measurements, modeling, mitigation of edge impurity sources and transport (XGC0 kinetic-neoclassical promising…)
- Design, implement cryo-pumps for D particle control
  - Provide particle pumping for scenarios w/o Li, compare to Li
- Understand, utilize advanced pedestal operating modes:
  - 'Enhanced Pedestal' H-mode, I-mode, ELM triggering with 3D δB
  - Test edge particle control w/ externally applied fields/driven EHOs

NSTX-U lithium and PFC research goals:

- Assess inboard and outboard divertor Mo PFCs as improved substrate for evaporated Li for particle control
  - If favorable, design and install high-Z PFCs for outboard walls + assess, design, implement hot wall (using bake-out) capability
- Test Li coatings for pumping longer τ_{pulse} NSTX-U plasmas
  - Assess D pumping vs. surface conditions (MAPP), PFC spectroscopy
  - Work w/ LTX to understand Li chemistry, impact of T_{wall}, Li thickness
  - Design/develop methods to increase Li coating coverage: evaporation into neutral gas, upward LiTER, Li paint sprayer
  - Assess impact of full Li wall coverage on pumping, confinement
- Develop, assess liquid Li for divertor heat-flux mitigation
  - Options: flowing Li film/jet/trenches, capillary porous system
  - Assess D/other pumping capability of these systems

NSTX-U energetic particle, wave physics, and scenario development goals:

- Measure and model fast-ion transport and loss
  - Tangential + perp. FIDA, *AE eigenfunctions: BES, reflectometers
  - Assess impact of 2^{nd} more tangential NBI on fast-ion-driven MHD
  - Linear/non-linear simulations (NOVA,M3D) of *AE, fast-ion x-port
  - Utilize AE antenna(e) to measure *AE damping rates, drive *AE
- HHFW – assess performance in Upgrade: higher B_T, I_P, n_e
  - Heat CHI start-up plasma coupled to induction and/or ECH
  - Sustain low I_P plasma 100% non-inductively for NBI ramp-up
  - Improve coupling to NBI-heated H-mode for advanced scenarios
- Scenario development will focus on 3 thrusts:

(1) 100% non-inductive, (2) rotation + q profile control, (3) high-I_P for low ν^*
  - Utilize time-dependent scenario modeling, advanced control
  - Extensive hardware & algorithm development needed (will not repeat here)

Guidance for idea submission and presentations

- Primary goal is to develop physics basis for steady-state high-performance ST for FNS applications
  - PMI/PFC innovation, ITER support, ST for fusion energy also important
- Ideas and presentations should emphasize facility enhancements that could possibly lead to:
  - New scientific breakthroughs
  - New predictive understanding/capabilities
  - New operational scenarios
  - Resolution of issues critical to the success of ITER, beyond
- Goal of brainstorming meeting is to get all ideas on the table for discussion and consideration
  - Will need to prioritize, time/stage enhancements based on:
    - Cost and schedule, likely overall benefit to research program
    - Anticipated capabilities/upgrades of other facilities

NSTXU Baseline Scope Overview
February 7, 2012

Ron Strykowsky

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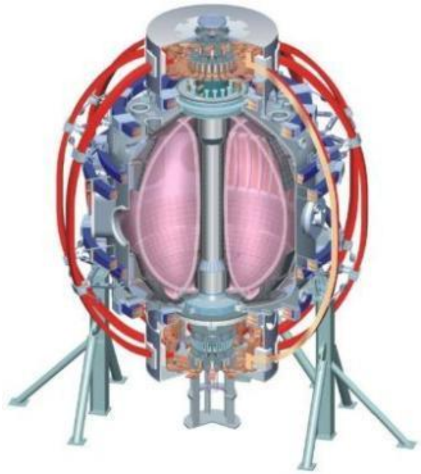

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KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Second Neutral Beam

NBI BL2 Operating Parameters meet GRD

- ***NSTX NBI operates up to 100 keV now @ approx. 2.5 MW per source (15 MW total)***
- ***NSTX NBI original spec of 80 keV 5 MW for 5 seconds retained***
- ***Approx. 3 MW per source in deuterium at 110 keV achievable…***

NBI Aiming wider tangency radii per GRD achieved

- ***Existing BL1 Tangency radii [C=50; B=60; A=70] cm unchanged***
- ***BL2 Tangency radii designed to be [C=110; B=120; A=130] cm per GRD***

✓ ***Modification of Vacuum Vessel at Bay K required… and included in design***

2 BL 6 sources 18 MW possible… 15 MW required ☑

Tim Stevenson

NSTXU NBI Overview – Scope NOT included

WBS Element: 1.2.1 **WBS Level: 3**

WBS Title: High Harmonic Fast Wave (HHFW)

Definition: The High Harmonic Fast Wave System provides radio frequency (RF) energy to the plasma for the purpose of plasma heating and current drive. The components of such a system include generators, transmission lines, tuning systems, antennas and their associated diagnostic and control systems. The system includes components inside the vacuum vessel (antennas and feed-throughs) in the test cell (transmission and tuning components) and in the RF power rooms (AC/DC power conversion system, RF generators, switches and loads). There are no changes to the HHFW System as part of the NSTX Upgrade Project.

WBS Element: 1.2.2 **WBS Level: 3**

WBS Title: Coaxial Helicity Injection (CHI) Current Drive

Definition: The Coaxial Helicity Injection System is to provide helicity injection to aid startup and provide edge current profile control. The main hardware elements required fall under other WBS's. These include a ceramic break in the vacuum vessel (WBS 1.1.3) the poloidal coil system (WBS 1.1.3) and a power supply (WBS 1.5). In this WBS element the task is to assure that the various components of the system are compatible with helicity injection and that the Central I&C required is provided. There are no changes to the CHI System as part of the NSTX Upgrade Project.

NSTXU NBI Overview – Jobs included

NSTXU NBI Project Cost (all k$)	COG
Job: 2420 - 2nd NBI Sources	Cropper
Job: 2425 - BL Relocation	Denault
Job: 2430 - 2nd NBI Decontamination	Stevenson
Job: 2440 - 2nd NBI Beamline	Denault
Job: 2450 - 2nd NBI Services	Denault
Job: 2460 - 2nd NBI Armor	Tresemer
Job: 2470 - 2nd NBI Power	Ramakrishnan
Job: 2475 - 2nd NBI Controls	Cropper
Job: 2480 - 2nd NBI/TVPS Duct	Denault
Job: 2485 - Vacuum Pumping System	Blanchard
Job: 2490 - NTC Equipt Relocations	Perry

Tim Stevenson

NSTXU NBI – Refurbish Ion Sources

2420

- ***Because BL1 did not support full 2011-2012 operations, BL1 sources are still viable and have been stored in place.***
- ***Therefore, our three spares will be used for upgrade.***
- ***Savings to project of approximately $900k.***

Arc chamber assembly and grid alignment

WBS Element: 1.2.4.2 **WBS Level: 4**

WBS Title: NBI Source Refurbishment

Definition: This WBS element includes the activities to refurbish three neutral beam ion sources for the 2nd Neutral beamline, as currently being performed for the installed Neutral beamline 1.

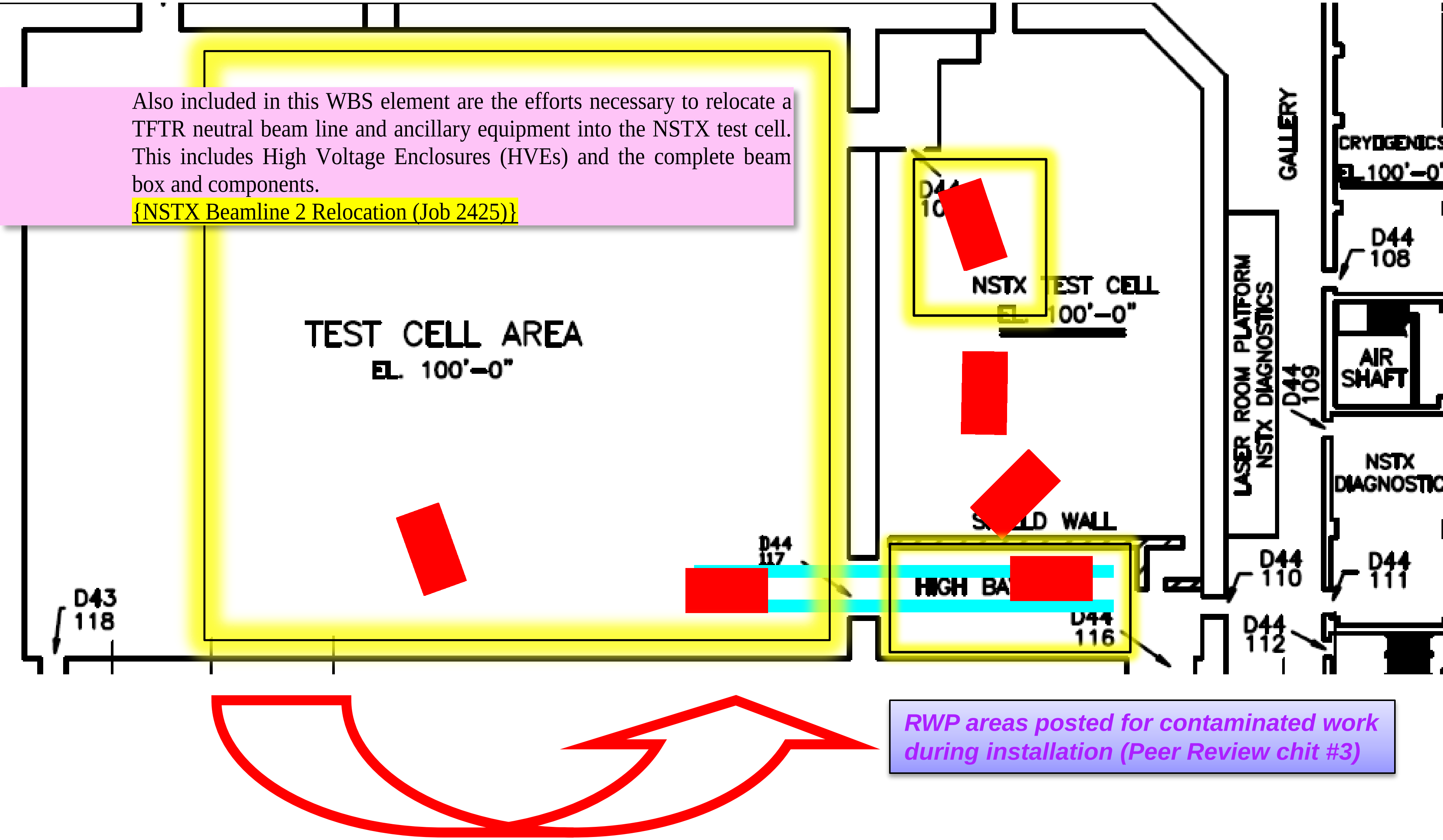
{Source Refurbishment (Job 2420)}

Tim Stevenson

BL & Component Relocation

2425

Also included in this WBS element are the efforts necessary to relocate a TFTR neutral beam line and ancillary equipment into the NSTX test cell. This includes High Voltage Enclosures (HVEs) and the complete beam box and components.
{NSTX Beamline 2 Relocation (Job 2425)}

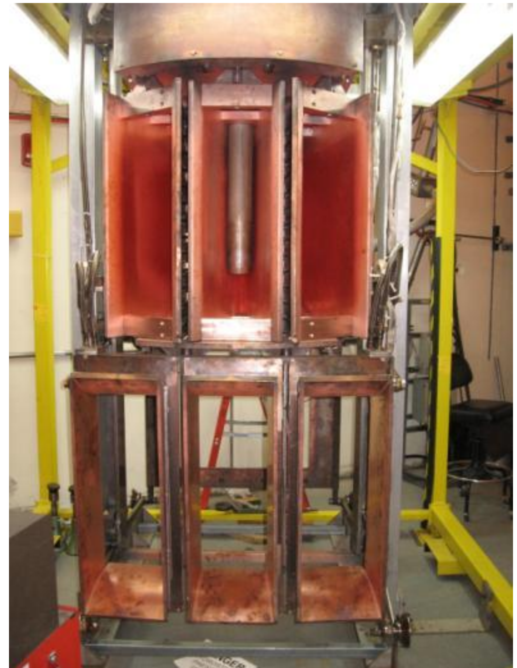


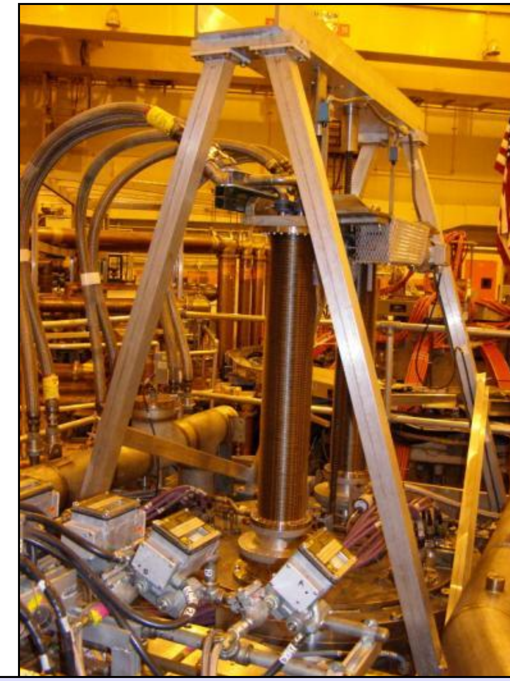
RWP areas posted for contaminated work during installation (Peer Review chit #3)

Tim Stevenson

BL Refurbishment: Ion Dump and Calorimeter – in progress

2440





Calorimeter Upgrade

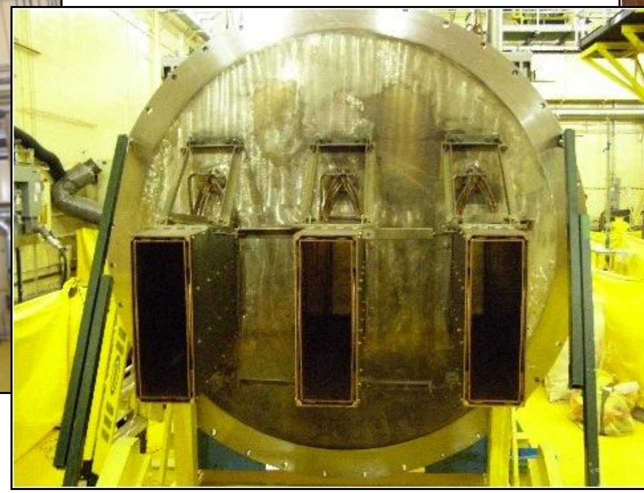
Included in this WBS element are the activities necessary to refurbish a TFTR Neutral Beam beamline for use on NSTX. This scope includes replacing the ion dump and calorimeter bellows as required and refurbishment of of the seals, thermocouple wiring, and bellows (cal and spool) as needed.
{NSTX Beamline 2 Refurbishment (Job 2440)}

Ion Dump Replacement

Tim Stevenson

BL Refurbishment: Box, Lid & Cryo panels, 90 inch Flange w/ Neutralizers, and Magnet

2440



Refurbish
Reassemble
New Seals
New TCs
More wipedowns
Package to move

Roll it into NTC
Fly it over
Fit it back together
Align it
Button it all up
Pump down…

Tim Stevenson

NBI Services – new pipes to new location but same technology…

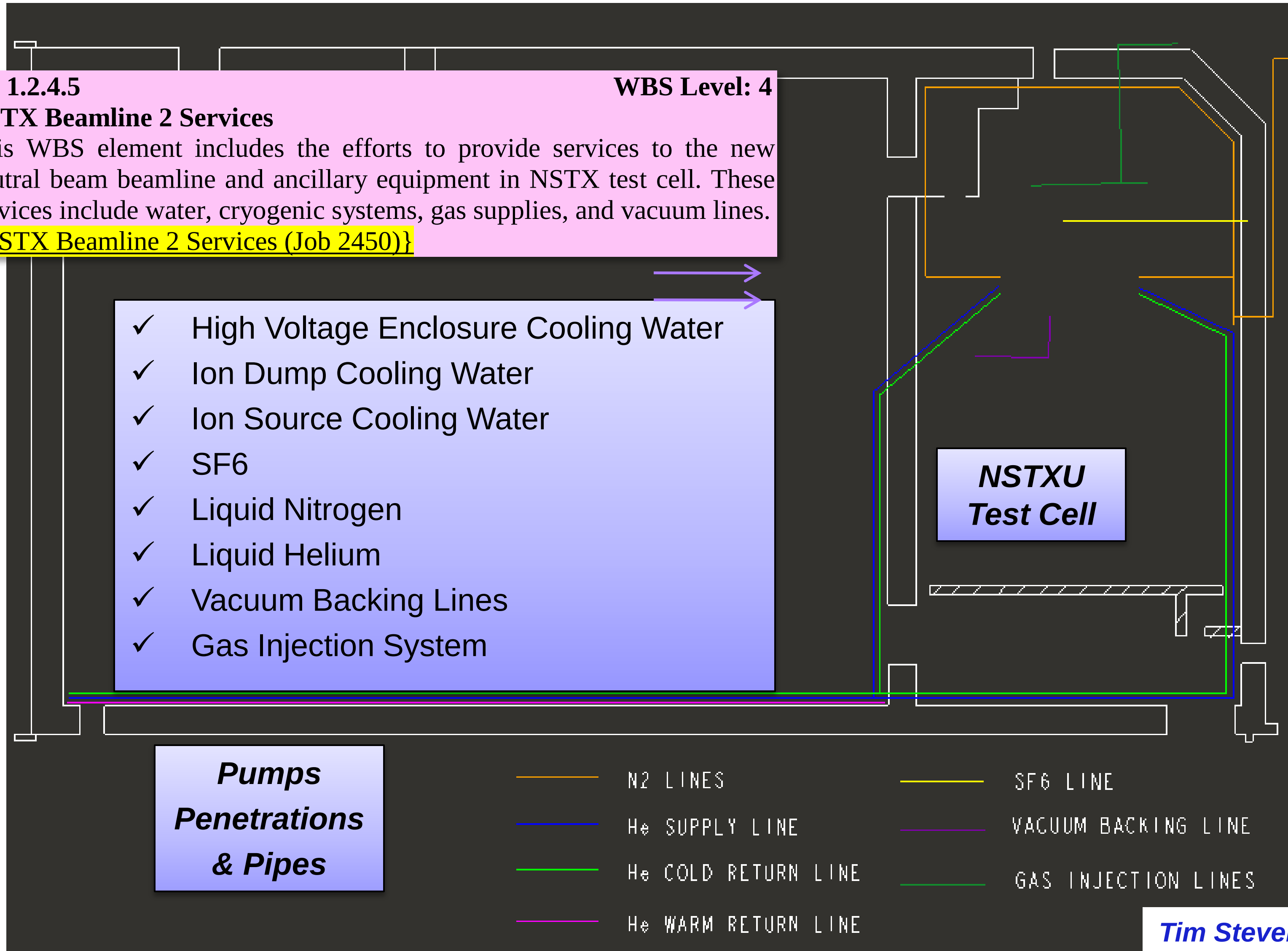
2450

WBS Element: **1.2.4.5** **WBS Level: 4**

WBS Title: **NSTX Beamline 2 Services**

Definition: This WBS element includes the efforts to provide services to the new neutral beam beamline and ancillary equipment in NSTX test cell. These services include water, cryogenic systems, gas supplies, and vacuum lines. {NSTX Beamline 2 Services (Job 2450)}

- ✓ High Voltage Enclosure Cooling Water
- ✓ Ion Dump Cooling Water
- ✓ Ion Source Cooling Water
- ✓ SF6
- ✓ Liquid Nitrogen
- ✓ Liquid Helium
- ✓ Vacuum Backing Lines
- ✓ Gas Injection System



Tim Stevenson

NBI Source Battery Diagram

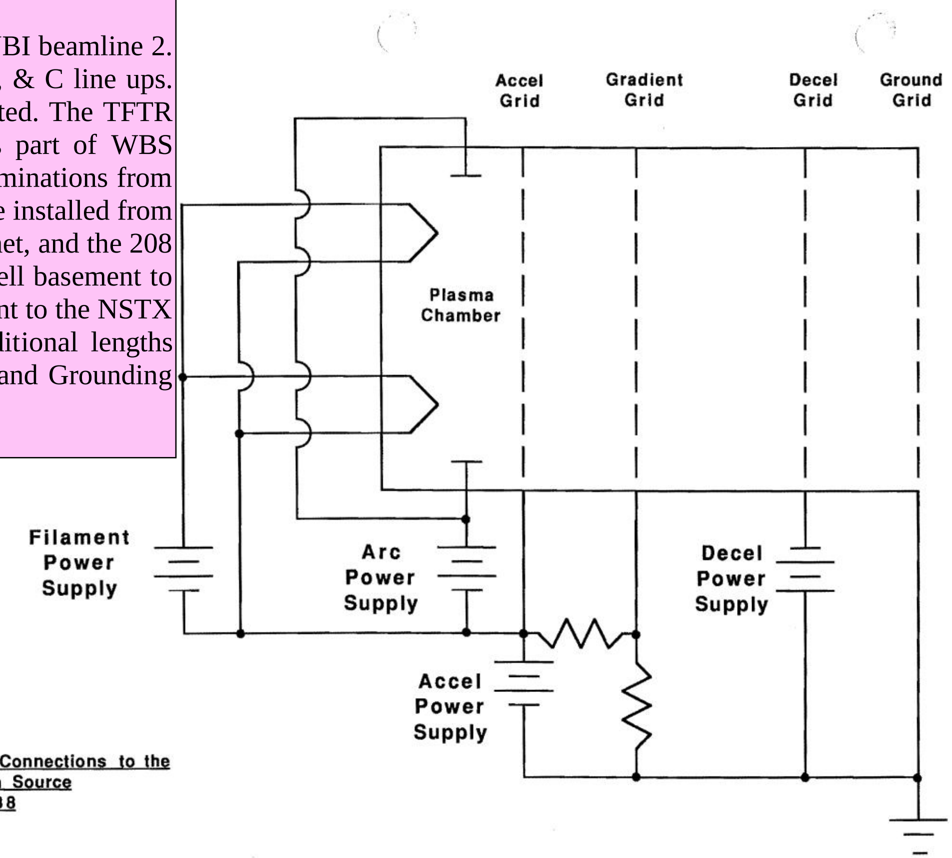
WBS Element: 1.2.4.7 **WBS Level: 4**

WBS Title: NBI Beamline 2 Power and Controls

Definition: This WBS element includes providing power, controls and instrumentation for the 2nd Neutral beamline.

Included in this WBS element is providing power for the NBI beamline 2. NB2 is planned to be powered from the TFTR NB4 A, B, & C line ups. The electrical equipment in these line ups will be reactivated. The TFTR NB4 HVEs will be relocated to the NSTX Test Cell as part of WBS element 1.2.4.4. New triax cables will be installed with terminations from the Modregs to the HVEs. New Decel coaxial cables will be installed from the Decel supplies to the Sources. The Arc, Filament, Magnet, and the 208 feeds, to HVEs cables, will be spliced in the TFTR Test Cell basement to new cabling designed and installed from the TFTR Basement to the NSTX Test Cell. The fiber cables also will be spliced with additional lengths recovered from other TFTR line ups. The AC auxiliaries and Grounding for the NB2 will be designed and installed.

{NBI Power System (Job 2470)}



Power Supply Connections to the Long Pulse Ion Source
TNS-11/03/88

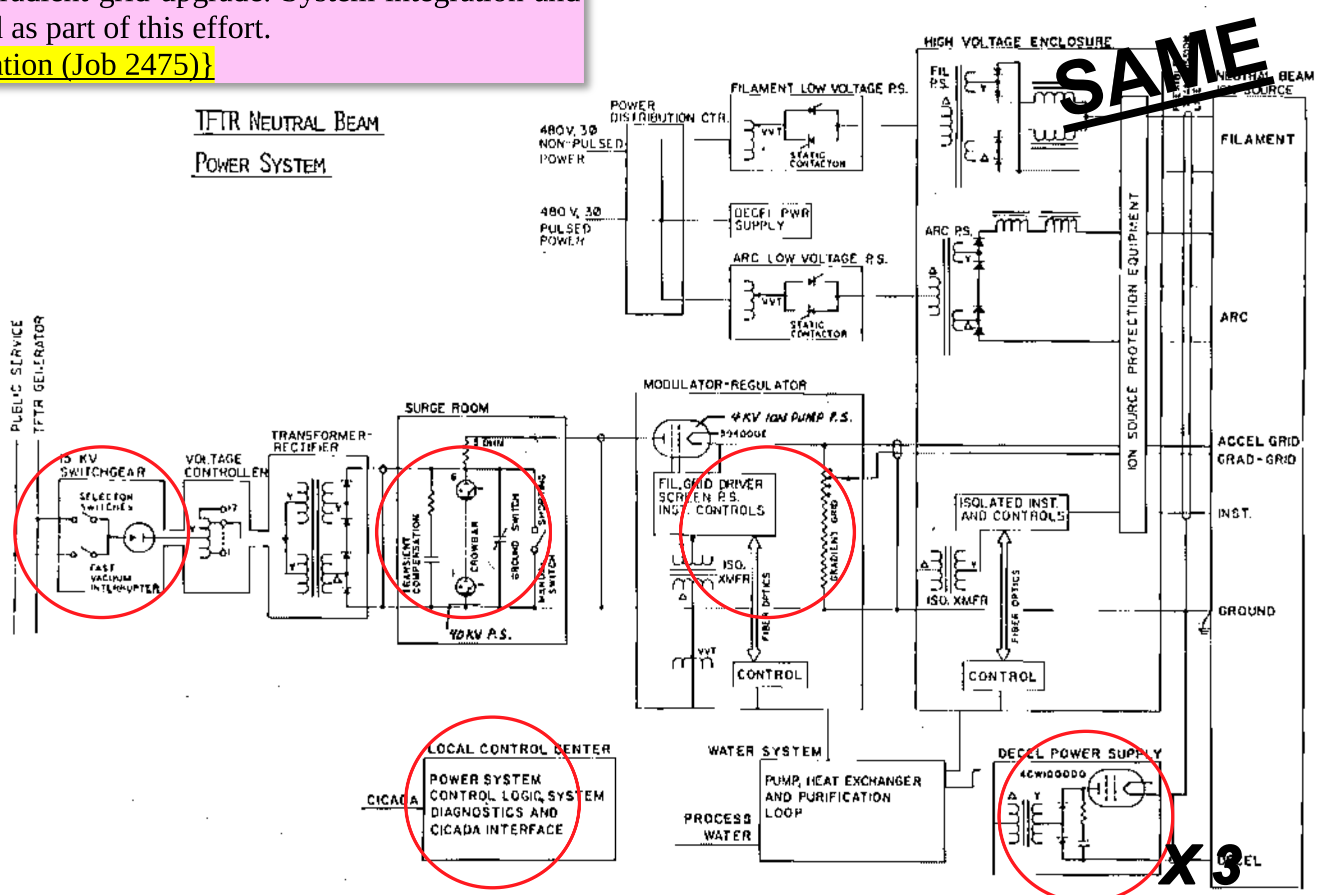
Tim Stevenson

NSTXU NBI Power & Controls - One Line Diagram

2475

Update electronics & control circuits as noted

Also included in this WBS element are the controls and instrumentation for the NB2. The work covers PLC, programming, control racks, new thermocouples, TC scanner, miscellaneous controls, and control cabling. The work also includes the gradient grid upgrade. System integration and testing will also be performed as part of this effort.
{NBI Controls & Instrumentation (Job 2475)}



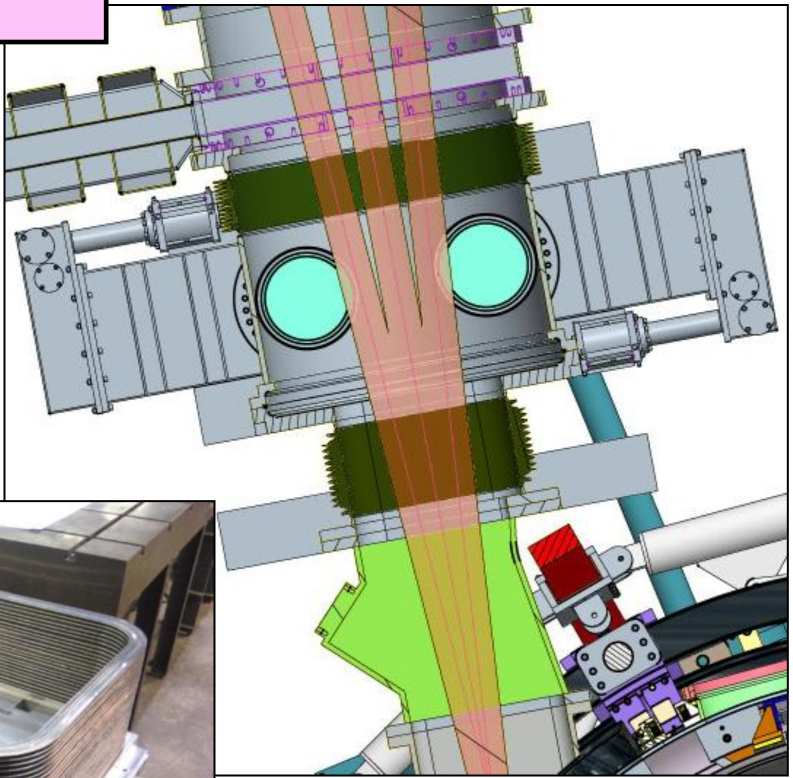
NBI NBPS One Line Diagram

Tim Stevenson

NSTXU NBI Duct – BL to VV

WBS Element: **1.2.4.8**	**WBS Level: 4**
WBS Title:	**NSTX Beamline 2 Duct & vacuum Vessel Modifications**
Definition:	This WBS element includes the design, and fabrication of all components connecting the Neutral Beam Box to NSTX, and the connecting ductwork and modifications to NSTX Vacuum Vessel to accommodate the second beamline. {NSTX NB2 Duct & VV Mods (Job 2480)}

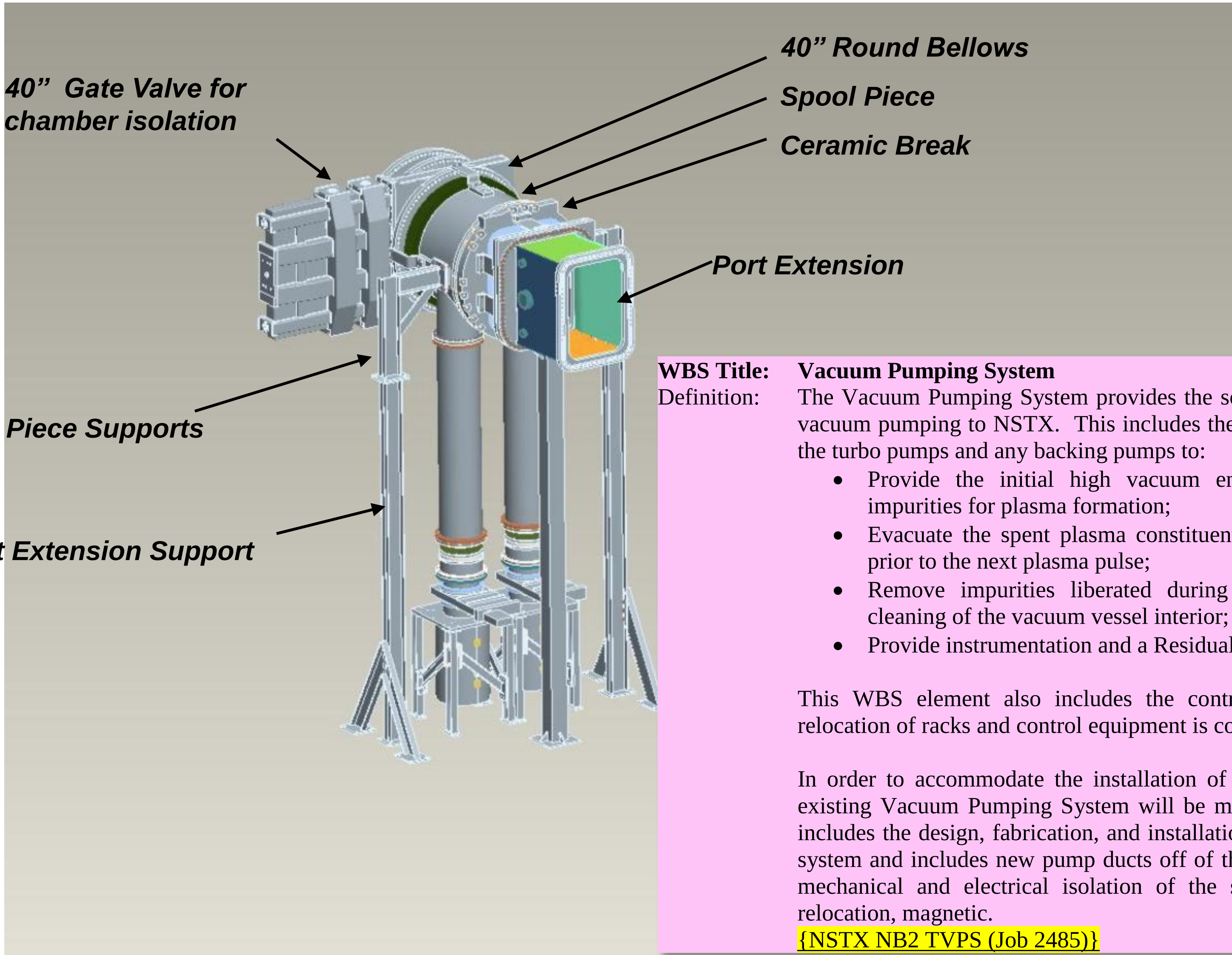
- BL2 Duct
  - Adapts from 1m TIV to NB rectangular flange
  - Contains bellows and ceramic break similar in design to NSTX NB1
- Port Extension
  - Permanently bolted up to NSTX
  - Extends NB2 Duct and Vessel Pump Duct interface past TF coils
- TVPS connection below NB duct
  - More conductance
  - Same field as existing
- Rectangular bellows ready for use on upgrade…



Tim Stevenson

BL2 Duct & TVPS modeled and drawings completed

2480
2485



WBS Title: **Vacuum Pumping System**

Definition: The Vacuum Pumping System provides the source and distribution of all vacuum pumping to NSTX. This includes the roughing pumps as well as the turbo pumps and any backing pumps to:

- Provide the initial high vacuum environment with minimum impurities for plasma formation;
- Evacuate the spent plasma constituents at the end of each pulse prior to the next plasma pulse;
- Remove impurities liberated during bakeout and/or discharge cleaning of the vacuum vessel interior; and
- Provide instrumentation and a Residual Gas Analyzer.

This WBS element also includes the controllers for all pumps. The relocation of racks and control equipment is covered under WBS 1.2.4.9

In order to accommodate the installation of the 2nd NBI on NSTX the existing Vacuum Pumping System will be modified. This WBS element includes the design, fabrication, and installation of a new vessel pumping system and includes new pump ducts off of the Neutral Beamline 2 duct, mechanical and electrical isolation of the system, vacuum diagnostic relocation, magnetic.

{NSTX NB2 TVPS (Job 2485)}

Tim Stevenson

Removals & Re-installations

2490

WBS Element: 1.2.4.9 **WBS Level:** 4
WBS Title: **NSTX Test Cell Equipment Removals/Relocations**
Definition: This WBS element covers moving of racks and diagnostics to clear space in the NSTX Test Cell (NTC) for the second Neutral Beamline. Racks to be removed and re-installed in a new location are #419, 431-435, 440-445, 447-449, 488. Racks 456 and 489 will be removed and excess. This scope also includes the fabrication and installation of five sections of platform at elevation 118' on the west side of the NTC to accommodate the racks being re-installed in the NTC. Racks #441-445 will be relocated to the Gallery east of the NTC. Diagnostics to be removed are those from the midplanes of Bay J and Bay K as well as those on the present pump duct. The diagnostics from Bay J will be re-installed ~5" outboard of their present position. IR windows and the Transmission Grating Spectrometer will be relocated to the new NB duct. Ion gages, filaments and the RGA will be relocated to the new pump duct under the NB2 duct. SPRED and LOWEUS will be relocated to Bay L. The Thomson Scattering Beam Dump Window will be relocated to between Bays K and L.
{NTC Equipment Removals/Relocations (Job 2490)}

Job 2490	1) Removal of Racks	2) Removal of Equipment	3) Re-installation of Racks	4) Re-install Equipment
Deposition monitor, fast x-ray - 488	X		X	
Fiber Optics - 447 - 448	X		X	
NPA - From Bay K	X	X		
PSI Camera - From Bay K	X	X	X	
SPREAD and VIPS - 440	X		X Need to find new location	
Transmission Grating Spectrometer -	X		X	
UCLA Reflectometer - 419	X		X	
Ultra Fast X-ray Camera -	X	X	X	
VV ion gages, RGA - 441 - 445	X		X	
X-ray Crystal Spectrometer - From Bay L pump duct	X	X		
Glow Discharge - Bay L	X	X	X	X need diagnostic to confirm will fit at bay L midplane
IR Camera	X	X	X	X need diagnostic to confirm will fit at bay L midplane
Remove Pump Duct (incl turbos) - From Bay L pump duct		X		Job 2480
Gas Delivery Systems - Miscellaneous Removals		X		Job 3400
Bolometer - Bay J		X		X
IR Windows for Camera - From Bay K		X		X
Lights, E-stops, fire alarms - Miscellaneous Removals		X		X
LOWEUS - Bay L		X		X need diagnostic to confirm will fit at bay L midplane
MPTS Beam Dump Window - From Bay L pump duct		X		X
Re-entrant Window - Bay J		X		X
Reflectometer - Bay J		X		X
RF Probe - Bay J		X		X
RGA - From Bay L pump duct to New Pump Duct		X		X
S-Flip - Bay J		X		X
SPRED - Bay L		X		X need diagnostic to confirm will fit at bay L midplane
SSNPA - Bay J		X		X
Transmission Grating Spectrometer - From Bay K		X		X
Two Gas Injectors - Bay J		X		X
Vac Vessel Ion Gages, Filaments, Micro Ion Gages - From Bay L pump duct		X		X
Cat 3 and Cat 4 bus - Miscellaneous Removals		X		
Convenience outlets - Miscellaneous Removals		X		
Fire Tips - From Bay K		X		
High K Scattering - From Bay K		X		
Remove NW section of 109' platform - Miscellaneous Removals		X		
- Fab and Install Five Sections of Platform at EL 118' on West Side of NTC				X
Install New 42 Ckt Panel in NTC and 30 Ckt Panel in Gallery				X
NOTE: Installation of new pump duc, turbos and lines to roughing pumps is covered in NB duct job - New Pump Duct				X
Platform Power (recept), grounding and lighting				X
Reconfigure AC and Diagnostic Trays -			X	
Tank farm, TMB system, Gas solenoid box & diconnects -				X

New Center Stack

Centerstack Upgrade Requirements

- Toroidal magnetic field at the major radius R0 of 1 Tesla (T) compared to 0.6T in the original NSTX
- Plasma current Ip up to 2 Mega-Amp (MA) (presently 1MA rating)
- Increase Pulse length from 0.5 to 5.0 seconds
- Plasma facing components, internal hardware (PP, OBD), CSC, VV, and RF antennae shall be designed to withstand forces due to plasma disruption.

Larry Dudek

Center Stack Jobs

DESCRIPTION	Cog
Job: 1000 - CSU Analytical Support	Titus
Job: 1001 - CS Plasma Facing Components	Tresemer
Job: 1002 -Passive Plate Analysis &Upgrade	Dudek
Job: 1200 - Structures and Supports	Smith
Job: 1300 - Center Stack	Chrzanowski
Job: 1301 - Outer TF Coils	Chrzanowski
Job: 1302 - Center Stack Assembly	Chrzanowski
Job: 1303 - TF Joint Test Stand&Test	Kozub
Job: 1304 - Inner TF Bundle (Ds/Fab)	Chrzanowski
Job: 1305 - OHMIC Heating Coil (OH)	Chrzanowski
Job: 1306 - Inner PF Coils	Chrzanowski
Job: 1307 - CS Casing Assembly	Chrzanowski
Job: 1310 - CSU Magnet Systems	Chrzanowski
Job: 2300 - ECH Analysis-	Titus
Job: 3200 - Water Cooling System Mods	Denault
Job: 3300 - Bakeout System Mods for CSU	Raki
Job: 3400 - Gas Delivery System Mods	Blanchard
Job: 4100 - Center Stack Diagnostics	Kaita
Job: 4500 - MPTS VV Modification	Labik
Job: 5000 - CSU Power Systems	Raki
Job: 5200 - DCPS	Hatcher
Job: 5501 - Coil Bus Runs-SMITH	Smith
Job: 6100 - Control Sys Data Acquisition	Sichta
Job: 8200 - Field Supervision and Oversight	Perry

Larry Dudek

Plasma Facing Components

1001
1002

Addendum-
Halo sensors;
- ***Includes additional machining for halo sensors.***
- ***Excludes external electronics and racks***

WBS Element: **1.1.1** **WBS Level: 3**

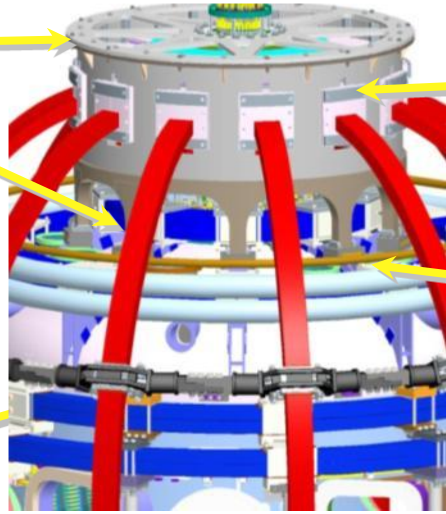
WBS Title: **Plasma Facing Components**

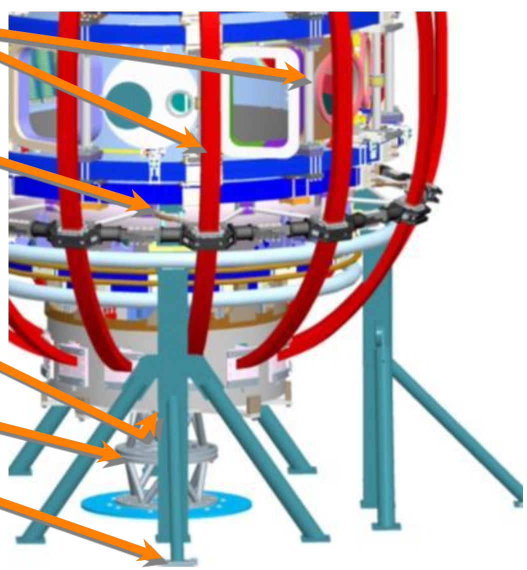
Definition: The plasma facing components (PFCs) include all the systems and related elements that serve to protect the vacuum vessel from the charged particles and radiation flux from the plasma. These include the plasma facing tiles and mounting components, passive stabilizers, inner wall protection, divertor area strike plates, and local I&C. This element consists of the engineering design, analysis, procurement activities and component fabrication.

The NSTX Upgrade Project will require new PFCs on the new Center Stack Casing (CSC) and the new Inboard divertor (IBD). This WBS element includes the design and analysis for both the CS and IBD PFCs, design modifications to the PFC tiles to accommodate surface diagnostics, including design of the tile mounting schemes and routing plans for diagnostic wires, generation of required documentation such as checked calculations, specifications and procedures, the procurement and installation of all PFC tiles and hardware on the CSC and IBD.
{Center Stack Upgrade (CSU) PFCs (Job 1001)}

In addition the NSTX Upgrade will require analysis of the passive plates for disruption and thermal loads. CDR level calculations were performed that addressed one of five disruptions. The remaining identified disruptions are to be completed during Preliminary Design. During Final design, analysis updates are expected as a result of preliminary design evolution. Modest hardware upgrades are anticipated as part of this task. Additions of accelerometers or other diagnostics to benchmark calculations with actual performance in NSTX are also anticipated. This analysis effort is included in this WBS element.
{Passive Plate Analysis and Upgrade Activity (Job 1002)}

Vacuum Vessel and Support Structure





WBS Element: 1.1.2 **WBS Level: 3**

WBS Title: Vacuum Vessel and Support Structure

Definition: The vacuum vessel & support structure (VVSS) consists of the vacuum chamber, not including the PFCs, all ports and vacuum boundary closures and the torus support structure which provides the overall supporting mechanism for the torus components to the test cell floor. This WBS element includes the engineering design, analysis, procurement activities and component fabrication.

The NSTX Upgrade Project will require that the existing VVSS be modified to accommodate the new center stack structure, including the umbrella structure and the new center stack support structure. This WBS element includes the analytical and CAD design of the support structures associated with the Magnet upgrade activities. The scope includes; the Vacuum Vessel & Structural Support, the Outer TF Structures, the Outer PF Coil Structures, the Umbrella Structural Reinforcement, the CS Support Pedestal and miscellaneous Vacuum Vessel Structural Supports. It also includes the procurement and fabrication of these structures, but does not include installation costs. Installations costs are included in WBS 1.8. {Vacuum Vessel & Support Structure (Job 1200)}

Larry Dudek

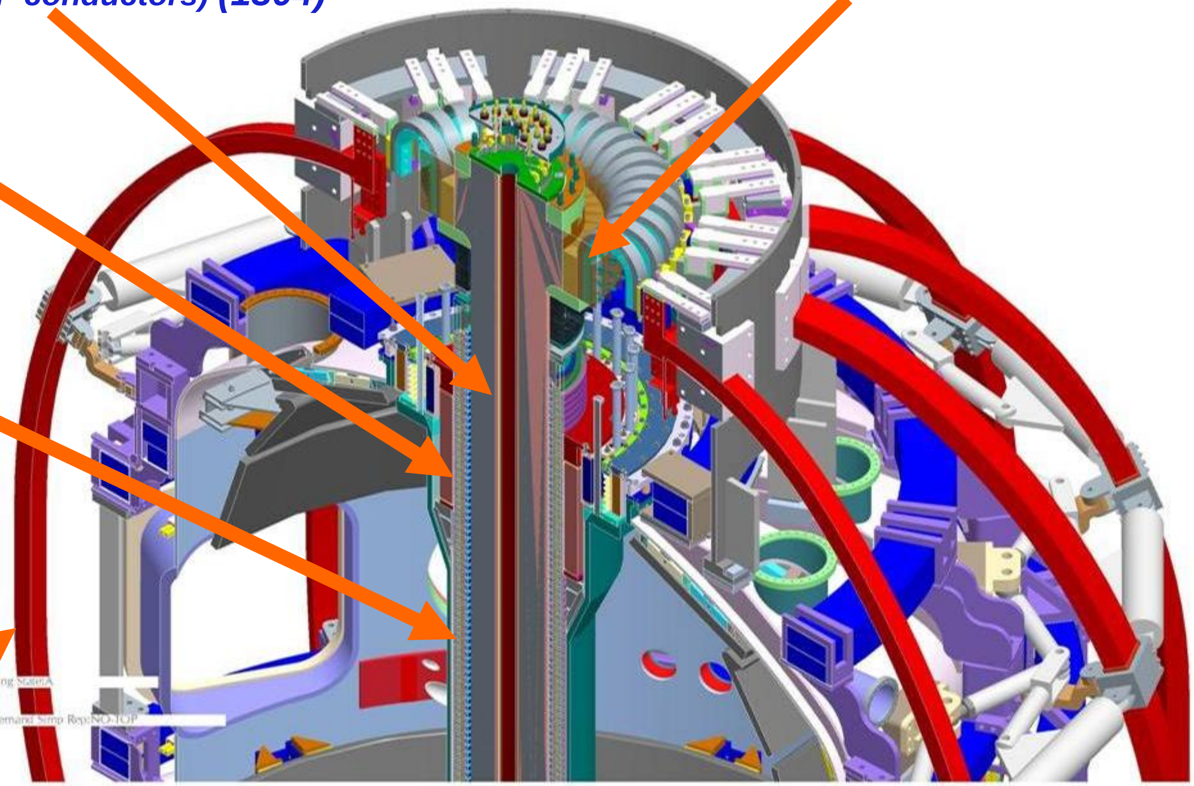
Center Stack Jobs – 1301,1304,1305,1307

Simpler Inner TF design (single layer of TF conductors) (1304)

Improved Joint Design

OH coil wound on TF (1305)

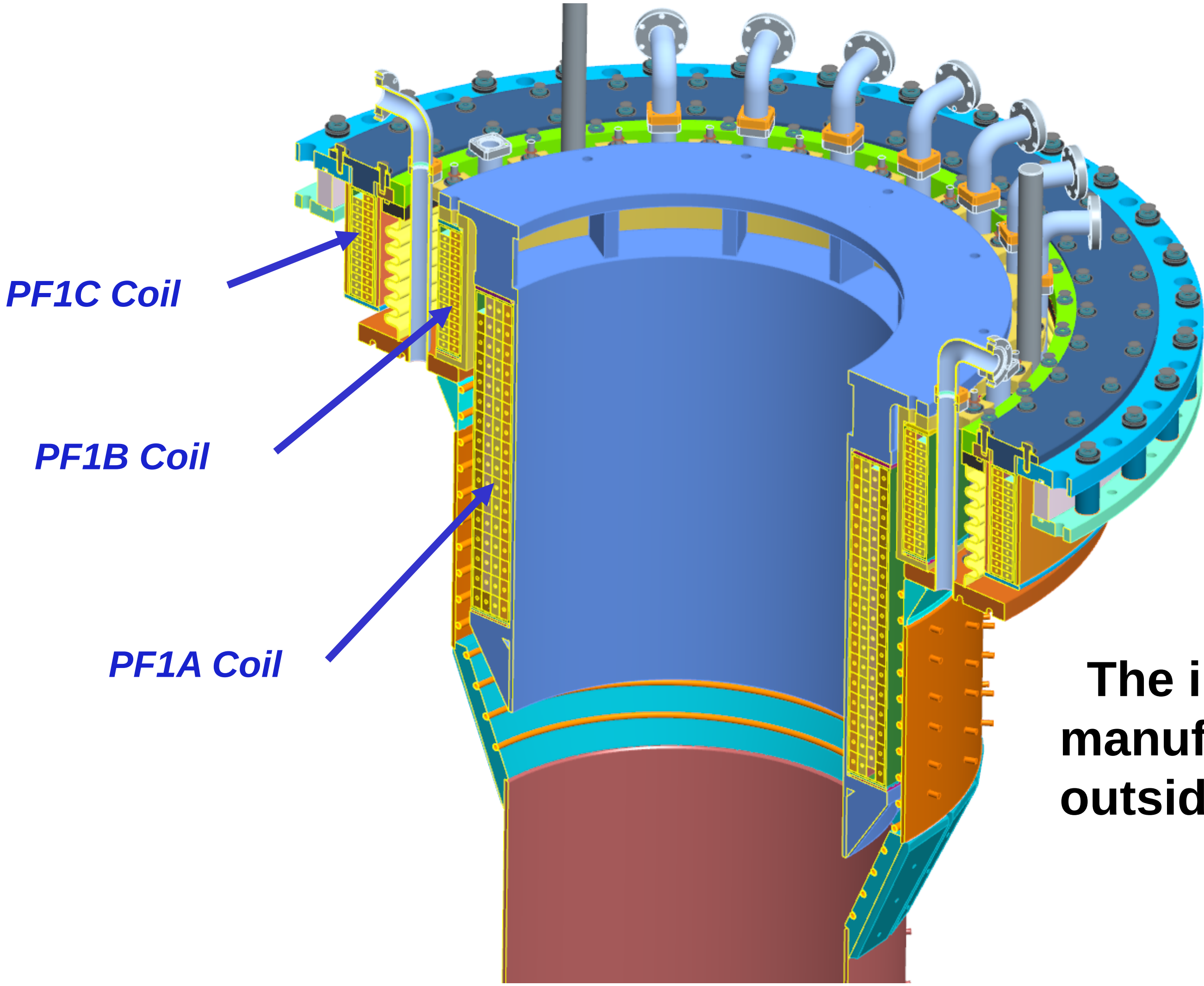
New Centerstack Casing and Tiles (1307)



Existing outer TF WITH water cooling plus 2 new TF coils being fabricated (1301)

Larry Dudek

Inner Poloidal Field Coils - 1306



The inner PF coils will be manufactured by an outside vendor.

Larry Dudek

Center Stack Jobs

WBS Title: **Outer Toroidal Field Coils**

Definition: The outer Toroidal Field coils subsystem consists of the coil sections that make up the 12 TF outer legs. This WBS element includes the design, analysis, prototypes (as required), procurement activities and fabrication. For the NSTX Upgrade Project two (2) new Outer TF coils will be fabricated to replace existing ones. This WBS element includes the fabrication of (2) new Outer TF coils to replace the existing leaking OTF#7 and OTF#11 that will be removed during the Neutral Beam port upgrade. This coil will then be used as a spare for future operations in NSTX. The scope includes the procurement of conductor, insulation material, aluminum castings and supports necessary to fabricate a new OTF coils. Coil fabrication will be performed by an outside vendor. This scope does not include costs associated with installation. Installations costs are included in WBS 1.8

{Outer Toroidal Field Coil Repairs (Job 1301)}

WBS Title: **Center Stack - TF Inner Legs/Bundle**

Definition: The TF inner leg subsystem consists of the new coil sections that will make up the TF inner bore and bundle. Also included in the scope of this WBS element is the TF coil joint (flex bus assembly) and testing of the new TF coil joint design.

For the NSTX Upgrade Project a new TF Inner Leg will be fabricated. This WBS element includes the design of the TF Bundle, the TF flex bus and flex bus supports and includes all analytical and CAD design efforts for these components. It also includes the early procurement of the TF conductor [80 lengths] and procurement of the TF flex bus and supports. It does not include the procurement/fabrication of the Inner TF bundle, which is included as part of the OH procurement in WBS 1.1.3.3.2.

{Inner Toroidal Field Bundle (Job 1304)}

. For the NSTX Upgrade Project a test stand to measure the required performance parameters on the new NSTX TF joint design will be designed and fabricated. Test parameter measurements and cyclic lifetime tests of the new TF joint materials will be performed and testing data will be compiled.

{TF Joint Stand & Performance Test (Job 1303)}

WBS Element: **1.1.3.3.2** **WBS Level: 5**

WBS Title: **Ohmic Heating Solenoid**

Definition: The ohmic heating solenoid subsystem consists of the new coils that will make up the center solenoid. This WBS element includes the design, analysis, prototypes (as required), procurement activities and fabrication.

For the NSTX Upgrade a new OH Solenoid will be fabricated. This WBS element includes the design & fabrication of a new OH solenoid and associated components including a Belleville washer spring assembly and support structures for the NSTX upgrades. It also includes all analytical & CAD design efforts. Includes advance procurement of the copper conductor and co-wound [glass/Kapton] insulation. Also includes the procurement of the Micro-therm insulation, conductive paint. Includes the in-house fabrication for the combined OH and TF bundle assembly. A single vendor will fabricate both components.

{Ohmic Heating Solenoid (Job 1305)}

WBS Title: **Inner Poloidal Field Coils**

Definition: The inner poloidal/shaping coils subsystem consists of the new coils that will make up the poloidal field coils 1A, 1B and 1C. This WBS element includes the design, analysis, prototypes (as required), procurement activities and fabrication.

For the NSTX Upgrade three new sets of inner poloidal field coils will be installed. This WBS element includes the design and procurement of the Inner poloidal field coils and supports which includes all analytical and CAD design efforts for these components. It includes the early procurement of the PF conductor and co-wound [Glass/Kapton] insulation.

{Inner Poloidal Field Coils (Job 1306)}

WBS Element: **1.1.3.3.4** **WBS Level: 5**

WBS Title: **Center Stack Casing and Assembly**

Definition: This WBS element includes the design and fabrication of the Center Stack casing and ceramic break assembly for the upgraded Center Stack as well as the assembly of the new Center Stack.

The Center Stack Casing effort includes analysis and CAD design for the casing components; the procurement of the Inconel tubing, forgings, bellows and organ pipes; the fabrication of Center Stack support legs; the procurement/fabrication of a new ceramic break assembly; the in-house assembly of the casing components; and mounting of the PF1A and PF1B structure/coils to the casing.

{CS Casing (Job 1307)}

The Center Stack Assembly effort involves all activities associated with the assembly of the Center Stack and includes design modifications and upgrade of the coil assembly stand; procedures for assembling the Center Stack and for installation; assembly of the Center Stack components including the OH/TF coil supports, mounting of the OH Solenoid surface diagnostics and thermal blanket, inconel casing and inner PF coils and setup and tear down of the Center Stack assembly area.

{Center Stack Assembly (Job 1302)}

Power Systems TF - 5000

•**REQUIREMENTS**

•**TF : 129.8 kA, 1kV, ESW 7.08 sec every 2400 sec (7.05kA rms) ;**

- **Four additional PARALLELS of Transrex power supplies to be provided to existing four parallels**
- **Each parallel - two 1 kV Transrex power supply sections in series.**
  - CLRs will be connected between the supply sections
  - One section of the supply will be used as a Diode
- **Existing four SDS of TF with additional parallel supplies will be used.**
  - two parallels to be fed via each switch.
- **Four more DC reactors (270uH) to be used in the additional 4 parallels.**
  - Since upgraded OH circuit needs reactors of higher inductance,

  the existing 270uH OH CLRs will be reconnected in the TF Circuit.
- **To install reactors in TF wing**
  - (1) Remove PF1a Ripple reduction Reactors & store; and
  - (2) Remove four CICADA Racks in the middle of isle.

➢ **DCCTs**
  - Existing eight DCCTs will be repositioned to detect current in each of the eight parallels
  - Eight additional DCCTs will be purchased and installed
  - Two new DCCTs to detect total TF Coil Current
  - The Vacuum Control Room presently empty will be used for housing the electronics boxes

➢ **CABLING**
  - Reconnect existing cabling as needed.
  - Disconnect & Remove part of existing cabling (~12000 ft)
  - Install additional power cabling within FCPC - nearly *6000* feet of 1000mcm 5kV power cables. Limited space makes bus installation difficult
  - Reconnect existing power cabling in Transition Area (TA) - in TFTR Test Cell Basement- to NSTX Test Cell for TF use.
  - Provide Control Cabling as needed

➢ **Modify Power Cable Termination Structure (PCTS) for TF to handle fault currents & to accept 3 more power cables/pole.**

Raki

Power Systems -OH PWR. LOOP DESIGN & PF PWR. LOOP DESIGN BASIS

5000

EXISTING OH PWR LOOP DESIGN:

- 6kV Anti-parallel configuration
- 24kA for 0.4 seconds every 600 seconds

UPGRADE - OH PWR LOOP DESIGN:

- 6kV Anti-parallel configuration
- 24kA for 1.474 sec every 2400 seconds

Work Required

- The DC CLR values have been optimized to the new requirement based on PSCAD analysis. These new reactors of the required values will be purchased and installed.
- All the other equipment and cabling in the power loop will be used AS IS

•REQUIREMENTS

- **OH : 24kA, ESW *1.474* sec every 2400 sec ; 6kV**
- **PF1a: Eliminate Ripple reduction reactors**
- **Other PF : Existing config. meets requirements for other PF**

PF DESIGN:

- Existing circuits for PF1b, PF2, PF3, PF4,and PF5 will be used AS IS for the upgrade.
- PF1a Changes
  - The ripple reduction reactors in the PF1aU & PF1aL circuits will be eliminated based on the newly designed PF1a Coils
  - Associated power cabling changes will be made

WILL be powered
- *PF 1 A upper & lower*
- *PF 1 B Lower*
- *PF 2-5 upper & lower*

Will NOT be powered
- *PF 1B upper*
- *PF 1C upper & lower*

Raki

Power Systems – excluded from the upgrade project scope

5000

1. **Provide power feed to a) PF1bU, b) PF1cU, c) PF1cL coils.** This involves designing the power loop and providing Power Supplies, CLRs, Disconnect & Ground Switches, DCCTs, Protective relaying etc.

2. **Upgrade PF5 feed such that PF5 coil can be injected up to 34kA**. This would require an additional branch to the existing power supply. Note that PF5 is powered up to 24kA in the current set up.

3. **Upgrade the TF feed such that TF can be pulsed every 20 minutes**. In the current scope the TF can be pulsed only once in 40 minutes. This requires additional power cabling from the Transition area to the NSTX Test Cell, additional changes in the PCTS, enhancing the feed from PCTS to coil terminals. We can also conssider providing a water cooled bus in the NSTX Test Cell Basement from the place the power cables are terminated.

4. **Make changes as needed to operate CHI from the present level of 2kV to 4kV**. In order to address this requirement we must plan right now to choose the appropriate insulation for the CHI leads and the Inner vessel. Note that the Inner Vessel to Outer Vessel will require to be hipotted at 9kV instead of 5kV as at present.

5. **Change DCCT positions such that these measure the coil currents directly.** (At the present time the DCCTs are above the SDS in some circuits.)

6. **Convert PF1a circuit from a 3- Wire scheme to a 2 - Wire scheme.**(This is required to upgrade CHI from 2kV to 4kV). The work involves additional cabling.

7. **Change FD/FG for all the suppliies needed to power NSTX. Eliminate the PC link.** (Note that we are currently performing this task under the operations budget. In this modification we are changing the FD/FG for active rectifiers which will be used for NSTX. Also a slow PLC I/O will be provided in these rectifiers to interface with the main PLC that will be provided in the Cntrol Boards.)

8. **MG Repair**

Raki

Power Systems - CONTROL & PROTECTION

5000
5200

- CONTROLS (Raki)
  - Hardwired Controls will be upgraded

- CIRCUIT PROTECTION (Raki)
  - Analog Coil Protection Units (ACPs) will be modified as needed

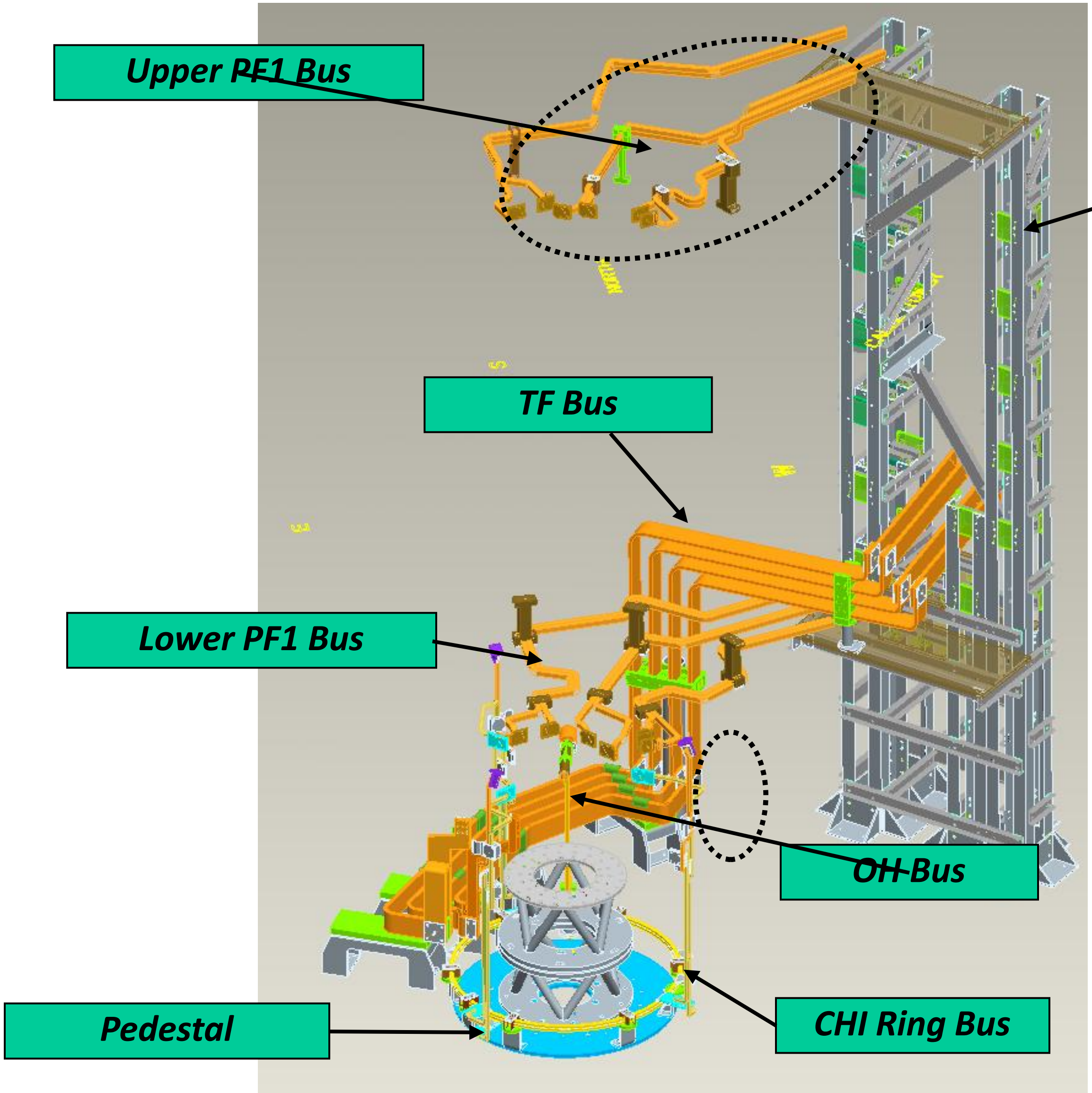
- RECTIFIER PROTECTION (Raki)
  - ACCT, DCCT & PT signals along with other interlocks will be processed in the FD. See Block diagram.
  - Fault Detector (FD) in Rectifiers
    - Overcurrent
    - Pulse duration
  - FD will generate Level 1, 2, 3 faults to trip.

- Digital Coil Protection (DCP): (Hatcher-5200)

  - DCP is designed for protecting the machine support system. Reqmnts documented updated with FDR in June 2012

Raki

Power System (Smith)- Buswork



Smith

Control Systems (Sichta) – INCLUDED Scope

~3.5x longer Pulse Length drives real-time control, data acquisition, analysis, networking, and storage.

Real Time Controls

- *Procure RT computers*
- *Migrate software to 64-bit operating system*
- *Implement new control algorithms for NSTX-U*
- *Support additional Input/Output points*

Data Acquisition: reduce role of CAMAC

Pre-upgrade (Oct. 2010)	Post-Upgrade (Sept. 2014)
(**100**) 908/3232, (**43**) 907, (9)6810, (9) TR612	(**34**) 908/3232, (**25**) 907, (9) 6810, (9) TR612
1500 channels, 77 MB	**860** channels, 70 MB
•MDSplus ACQ: 2.5 minutes •EPICS ACQ: 7.5 minutes	•MDSplus ACQ: 2.5 minutes •EPICS ACQ: 5 minutes
	•(11) D-Tacq Networked Digitizers. •(3) PXI-based systems • (24) One Mega-sample memory boards (CAMAC)

Sichta

Control Systems – EXCLUDED Scope

NOT part of upgrade scope

- **PCS real-time computer upgrade (more CPU/cores)**
- **PCS real-time software port to 64-bit OS (memory > 4 GB)**
- **FPDP_IO support for digital (Transrex) Firing Generator**
- **Diagnostic CAMAC replacements**
- **EPICS CAMAC acquisition speedup**
- **10 Gbit networking**
- **Upgrade nstxpool computers**

Diagnostics

Diagnostics –(4100 Kiata)

Relocation of Centerstack Magnetic diagnostics to new home

- **Rogowski Coils**
- **Mirnov Coils**
- **Flux Loops**
- **Langmuir Probes**
- **Thermocouples**

Halo sensors (new)

sensors and installation into PFC tiles only

Electronics , racks , other ex-vessel work EXCLUDED

Auxiliary Systems

- Gas Injection Systems – (3400-Blanchard)
  - Relocate existing center stack gas injection system to the new center stack
- Coil Cooling water modifications (3200-Denault)
  - Restoring of cooling to the outer TF legs for upgraded TF.
  - Reconnect cooling to the TF inner legs, OH and PF coils
  - Provide cooling for the coil buswork
- Bakeout system (3300-Raki)
  - the purchase of a new more powerful power supply, to replace the existing one

Multipoint Thomson Scattering (MPTS)

INCLUDED scope-

The vacuum boundaries closest to the vacuum vessel (VV) define the extent of the NSTXU scope. Vacuum boundaries include;

- *Port modifications and vessel reinforcements*
- *Torus interface valves*
- *Vacuum windows and blank covers*

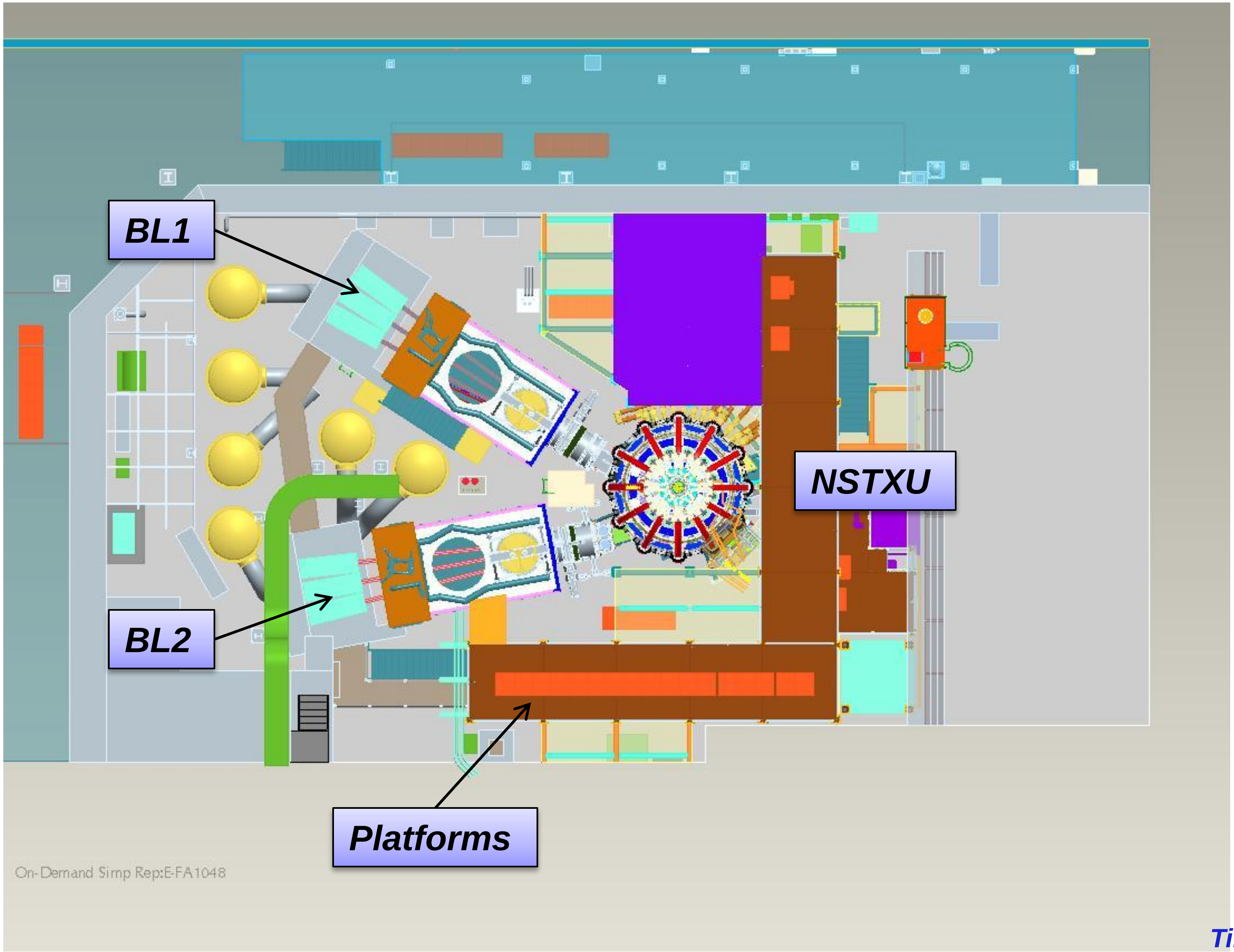
EXCLUDED scope-

- *Optics*
- *Laser optics box*
- *Laser flight tube*
- *Laser dump*

The increased diameter of the Center Stack Upgrade requires changes to the laser beam path, which requires a new laser input vessel penetration, and plugging of the existing penetration. Increasing the nozzle diameter of the L port to accommodate an external laser dump, furnishing a vacuum boundary for the extension tube. Modifications are to anticipate a third laser in the future and a new penetration for a FIDA diagnostic above and slightly offset from Bay L. The laser input location may require a special design of the PF coil support column between Bays F and G
Center Stack Diagnostic Job 4500

backup

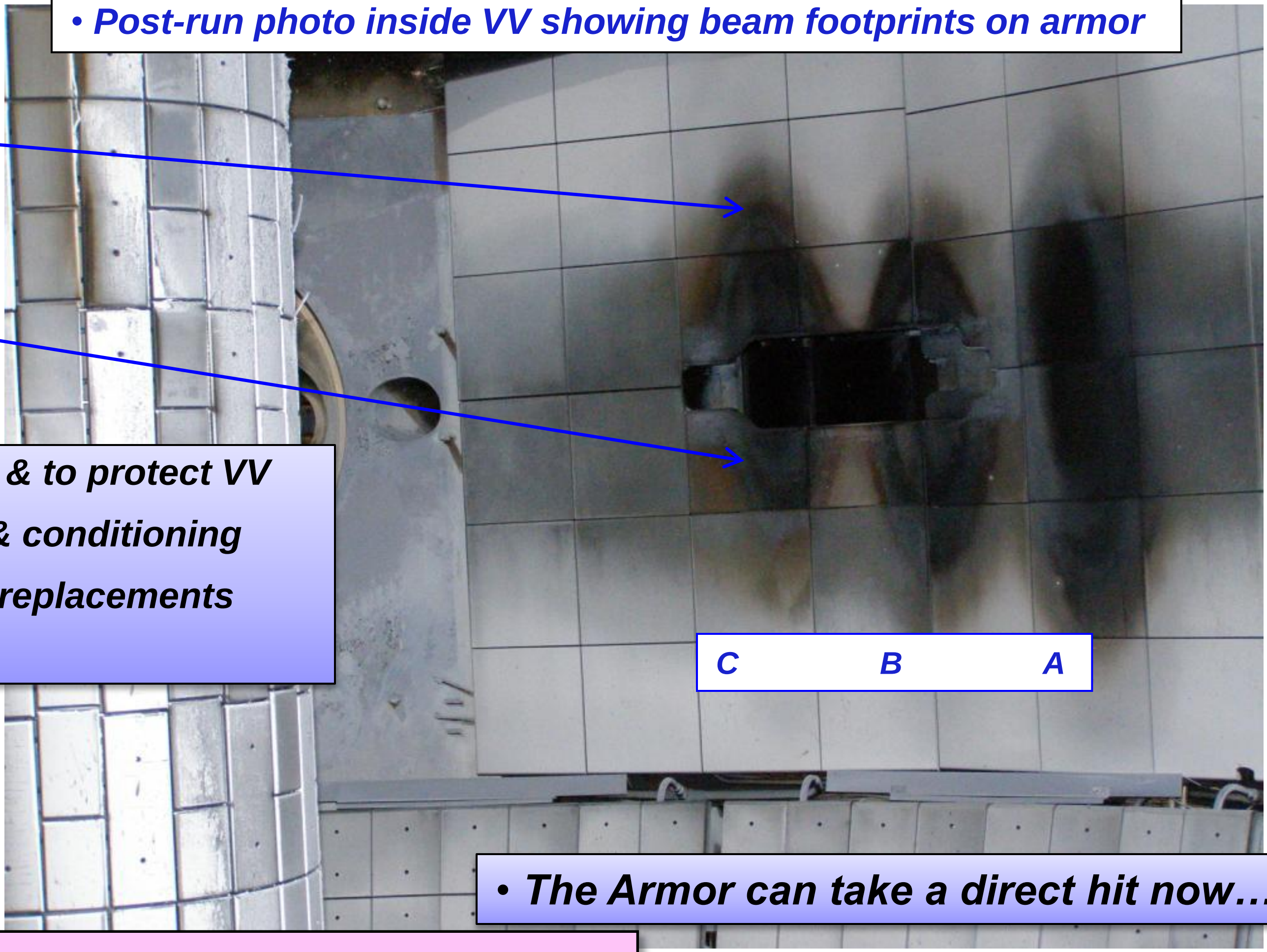
NSTXU Test Cell General Arrangement…



Tim Stevenson

Existing NBI Armor Position - 3 Beams

2460



If no plasma and no interlocks:

Takes direct hits now for Ops & to protect VV

- Alignments, MSE cal, & conditioning

Sacrificial - might require tile replacements

Interlock with Ip and R Ip

• The Armor can take a direct hit now…

WBS Title: **NBI Armor**

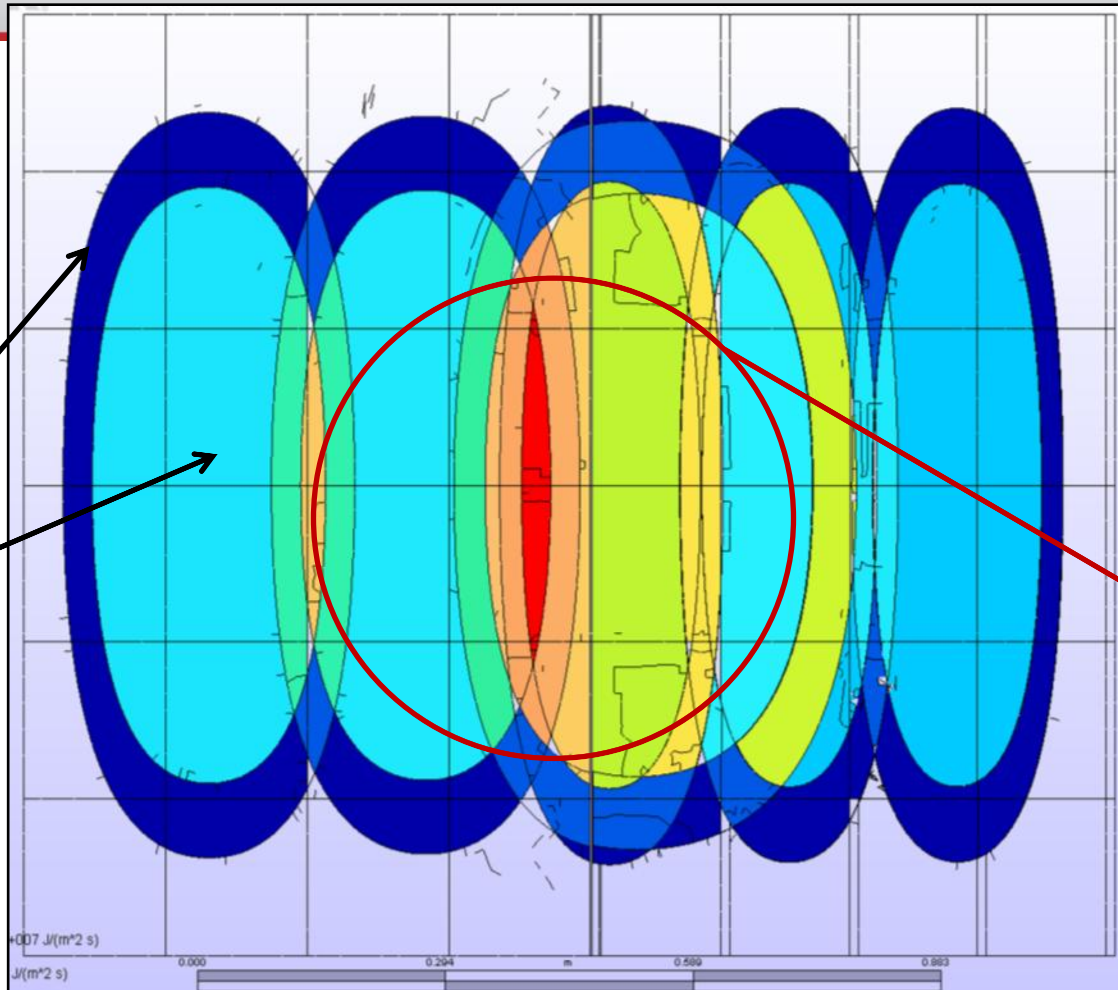
Definition: This WBS element includes the design, fabrication, and installation of upgraded and relocated neutral beam armor including cooling and instrumentation work.

{NBI Armor (Job 2460)}

Tim Stevenson

New Armor with 6 Beams: Shift location, better supports, ATJ & CFCs

2460



- **_Outer ring:_**
  - **_20% total source power_**
- **_Inner "hotspot":_**
  - **_80% total source power_**

- **_Beam overlaps create areas of intense flux_**
- **_Area of thermal investigation and use of 3D CFC from in house stock…_**
- **_ATJ everywhere else._**

- **_The Armor can still take a direct hit!_**

WBS Title:	**NBI Armor**
Definition:	This WBS element includes the design, fabrication, and installation of upgraded and relocated neutral beam armor including cooling and instrumentation work. {NBI Armor (Job 2460)}

Tim Stevenson

REQD FUTURE POWER SYSTEM CHANGES

- Following additional work is required to be performed to restore full capability of the machine:

  1. Provide power feed to a) PF1bU, b) PF1cU, c) PF1cL coils.
     - *This involves designing the power loop and providing Power Supplies, CLRs, Disconnect & Ground Switches, DCCTs, Protective relaying etc.*
  2. Upgrade PF5 feed such that PF5 coil can be injected up to 34kA
     - *This would require an additional branch to the existing power supply. Note that PF5 is powered up to 24kA in the current set up.*
  3. Upgrade TF feed such that TF can be pulsed every 20 minutes.

     (Note that we can with appropriate controls, pulse with a period < 40 / 20 minutes based on the I^2*t imposed on the coil system.)
     - *In the current scope the TF can be pulsed only once in 40 minutes. This requires additional power cabling from the Transition area to the NSTX Test Cell, additional changes in the PCTS, enhancing the feed from PCTS to coil terminals.*
     - *We can also consider providing a water cooled bus in the NSTX Test Cell Basement from the place the power cables are terminated.*

POWER SYSTEM CHANGES CONTD.

4. **Make changes as needed to operate CHI from 2kV to 4kV.**
   - *In order to address this requirement we must plan right now to choose the appropriate insulation for the CHI leads and the Inner vessel. Note that the Inner Vessel to Outer Vessel will require to be hipotted at 9kV instead of 5kV as at present.*

5. **Convert PF1a circuit from a 3- Wire scheme to a 2 - Wire scheme.**
   - *This is required to upgrade CHI from 2kV to 4kV. The work involves additional cabling.*

6. **Change DCCT positions such that these measure the coil currents directly.**
   At the present time the DCCTs are above the SDS in some circuits

*7. **Repair MG2 weld to restore normal rating**
   - *At present MG2 can be used only at about 15% of the full energy rating*

***8. Repair MG1 Welds so that it can be an effective standby.**
   - *This also increases the life of the MGs by alternating usage of the sets*

- **Following tasks are being performed at present. Part of this task was originally included in the NSTX upgrade scope but were transferred to Operations cost.**
   - *Change FD/FG for all the suppliies needed to power NSTX. Eliminate the PC link.*
   - *Note that we are currently performing this task. In this modification we are changing the FD/FG for active rectifiers which will be used for NSTX. Also a slow PLC I/O will be provided in these rectifiers to interface with the main PLC that will be provided in the Cntrol Boards.)*

(MG information from Mounir Awad)*

PWR SUPPLY TABLE

(Extracted information from CN design point spreadsheets)

Circuit	kV available	kV Required	PSS's Needed	Min Current (Reverse)	Max Current	ESW Current	ESW	Base Period	Base RMS Current	Future Period	Future RMS Current
				(kA)	(kA)	(kA)	(sec)	(sec)	(kA)	(sec)	(kA)
TF	1	1	16	0	130	130	7.08	2400	7.06	1200	9.99
OH	6	6	12	-24	24	24	1.47	2400	0.59	1200	0.84
PF1aU	2	1	4	-7	18	18	5.5	2400	0.86	1200	1.22
PF1aL	2	1	4	-7	18	18	5.5	2400	0.86	1200	1.22
PF1bL	2	1	2	0	13	13	2.1	2400	0.38	1200	0.54
PF1bU		1		0	13	13	2.1	2400	0.38	1200	0.54
PF1cU		1		0	16	16	4.34	2400	0.68	1200	0.96
PF1cL		1		0	16	16	4.34	2400	0.68	1200	0.96
PF2U	2	2	2	-11	15	15	5.5	2400	0.72	1200	1.02
PF2L	2	2	2	-11	15	15	5.5	2400	0.72	1200	1.02
PF3U	2	2	4	-16	12	16	5.5	2400	0.77	1200	1.08
PF3L	2	2	4	-16	12	16	5.5	2400	0.77	1200	1.08
PF4	2	2	2	0	16	16	5.5	2400	0.77	1200	1.08
PF5	3	3	3	0	24	24	5.5	2400	1.15	1200	1.62
CHI	2	2	1	0	15	15	0.5	2400	0.22	1200	0.31
P13	2										
P14(RWM)	2	1	1	0	2	2	5.5	2400	0.10	1200	0.14

MG REQUIREMENTS

(Extracted from CN design point spreadsheets)

		NSTX Base	Upgrade
Pulse repetition period	sec	300	2400
MG Peak active power (TF+OH)	MW	230	281
MG Peak reactive power (TF+OH)	MVAR	82	126
MG Peak apparent power (TF+OH)	MVA	244	308
MG Power NBI	MW	32	40
MG Power PF	MW	20	40
MG Energy TF+OH	MJ	101	659
MG Energy NBI	MJ	16	200
MG Energy PF	MG	10	200
MG Total energy	MJ	127	1059
#MG		1	1
MG f_end	Hz	60	60
MG f_start_min	Hz	61.9	74.2

NSTX PRE-UPGRADE CIRCUITS

NSTX Powr Supply Configuration for Coils - Pre-Upgrade							
Pwr. Sup. #	**NSTX Coil**	**Required Coil Current**	**RMS Circuit Current AMPS**	**Use TFTR PSS**	**D-Site PSS Config**	**# of PSS**	**Comments (PS tags are those of TFTR)**
1	TF	35.58kA 5.3s/300s 71.17kA 1.3s/300s	**4730**	TF1	1s x 4p	4	All Four TF1 branches, unused pss (5s x 4p) in bypass
2	OH	(+/-) 24kA 0.525s/600s	**710**	TF2	6s x 2 anti-parallel	12	Two TF2 branches 4kV, unused pss in bypass
3	PF1aU	15kA 5s/300s	**1937**	EF4*	2s x 2 anti-parallel	4	EF4 (2A&2B) supply, unused pss in bypass; EF3 & EF4 with common tie
4	PF1aL	15kA 5s/300s	**1937**	EF3*	2s x 2 anti-parallel	4	EF3 supply, unused pss in bypass; EF3 & EF4 with common tie
5	PF1b	20kA 1s/300s	**1155**	EF1	2s x 1p	2	EF4 (1A&1B) supply
6	PF2U	20kA 5s/300s	**2582**	OH5*	2s x 1p	2	OH5 supply, unused pss in bypass. OH5 & OH3 with common tie
7	PF2L	20kA 5s/300s	**2582**	OH3*	2s x 1p	2	OH5 supply, unused pss in bypass. OH5 & OH3 with common tie
8	PF3U	20kA 5s/300s	**2582**	EEF1A *; OH2*	2s x 2 anti-parallel	4	OH4 supply, unused pss in bypass; OH2 & OH4 with common tie; EEF1-PSS forward
9	PF3L	20kA 5s/300s	**2582**	EEF1B *; OH4*	2s x 2 anti-parallel	4	OH4 supply, unused pss in bypass; OH2 & OH4 with common tie; EEF1-PSS forward
10	PF5	20kA 5s/300s	**2582**	OH6	3s x 1p	3	OH6 supply, unused pss in bypass
11	PF4	10kA 5s/600s	**913**	OH6	3s x 1p	2	EF2-1 supply, unused pss in bypass
12	CHI	50kA, 30 ms every 300Seconds	**500**	OH1	1s x 1p	2	OH1 supply, unused pss in bypass
13	SPA1 DC Link	3kA 2.5s/600s	**194**	HF	1s x 1p	1	HF Section A
14	SPA2 DC Link	3kA 2.5s/600s	**194**	HF	1s x 1p	1	HF Section B

* 3-wire configuration

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NSTX-Upgrade Magnetics And Related Diagnostics

SPG

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.
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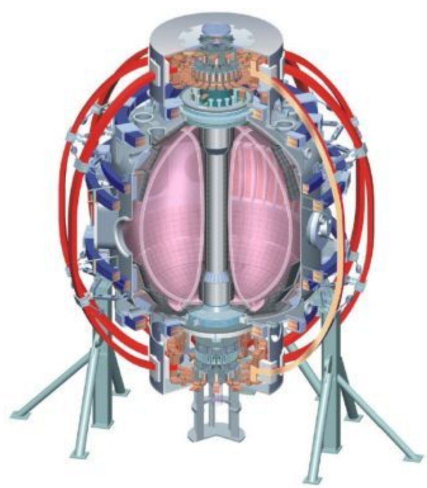
U Washington
U Wisconsin

Basic goal is to restore previous functionality and support machine operations and protection.



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Kyushu U
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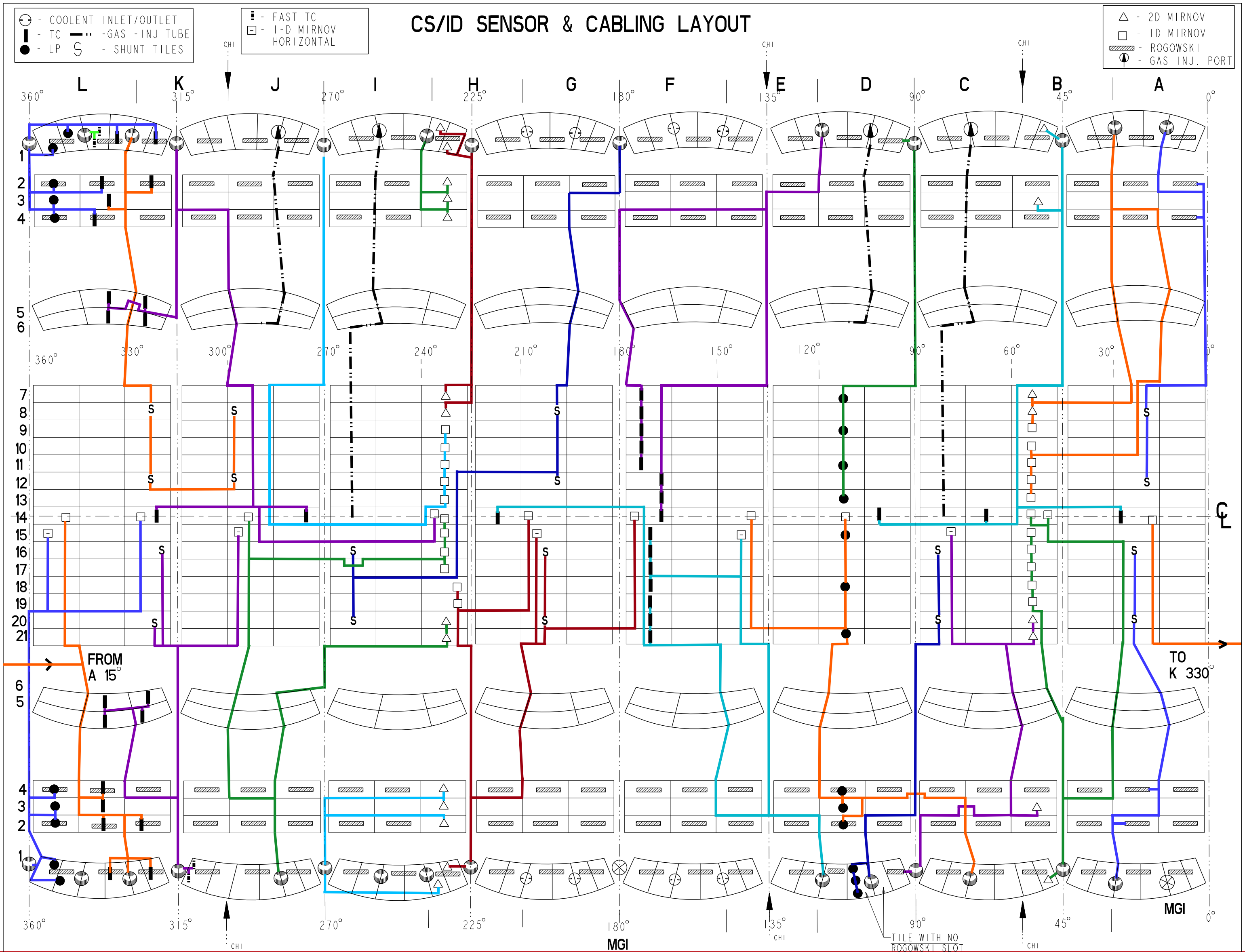
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

R. Kaita and K. Tressmer Have Lead Effort to Develop CS Magnetics Even Better than for NSTX



- 5 New B_T Sensors for CS midplane HCs.
- 18 CS shunt tiles for CS HCs.
- Additional poloidal array with 27 B_R and B_P sensors.

DCPS and Vessel Changes May Mandate Upgrades to the System

- DCPS = “Digital Coil Protection System”…realtime code calculating mechanical and thermal stresses/forces on coils and their mounting systems.
  - Rectifiers can make currents that can break the machine.
- High degree of redundancy is required in terms of both sensors and calculations.
  - Every current (coils & plasma), is measured two different ways
  - The measurements are compared, and if they differ, the shot is interdicted.
- As presently envisioned, loss of either of the two rogowskis would preclude further operation.
  - Rogowskis can fail in ways that mandate substantial machine disassembly for repair.
- *Can make a strong case that installing a 3rd Rogowski is appropriate.*
- Both rogowskis are processed through a single analog computer called the “I_P Calculator”.
  - Common loops voltages, power supplies, data transmission,…for both rogowskis.
  - May need to add redundancy in these systems.
    - For instance, when flux loops are reinstalled, install 2 (pairs) instead of a single at each location.
- Must also add channels to I_p calculator system for additional linked divertor coils, and make modifications for changes to inner-vessel resistances.
- May need to add more flux loops, I_P calculator channels, for additional conducting structures in the new CS.
- Some of this is NSTX-U scope, some maybe not…I don’t know.

NSTX-U magnetics must be considered in the context of the DCPS.

Grounding and Other Issues

- Desire to improve noise immunity for CHI, other operations. Two contributing factors are:
  - Long, fairly high-inductance ground connections for magnetics racks.
  - Multitude of diagnostics and other facility electronics mixed in with the magnetics.
- Would like to improve rack grounding.
  - Present ground both racks with #2 cables.
  - Would like to replace with bus bar.
- Cat. 3 racks moving to 119’ platform, while Cat. 4 racks staying at 100’ level.
  - Would like to connect Cat. 3 racks to inner vessel at the top of the machine.
- Want to eliminate intermixing of bolometers, stepper motor controllers, other electronics, with magnetics.
- Additional electronics needed:
  - Inner vessel: ~31 channels of new integrators, and a single SAD for bringing data to realtime system.
  - Outer vessel: None new, but some gains modified.

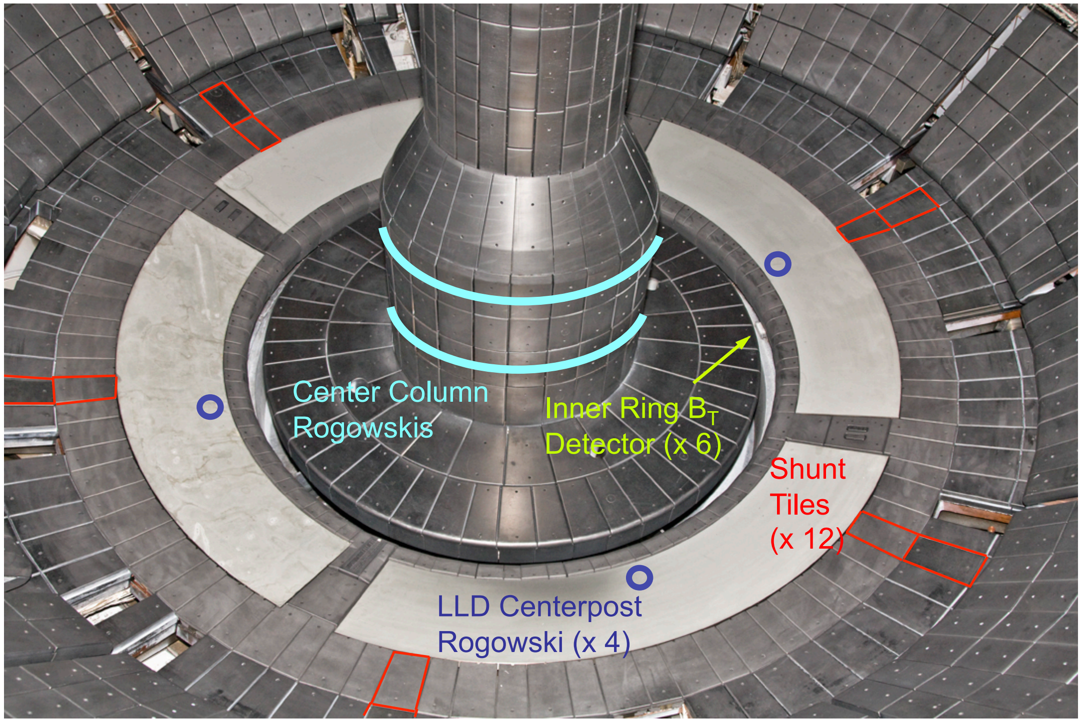
Diagnostics for Divertor/Halo/Hiro Currents on Outer Vessel Not Yet Specified

- FY-10/11 run had 12 shunt tiles and 4 LLD rogowskis.
  - Used for disruption, ELM, SOLC, HHFW studies.

See first content slide for inner vessel halo current measurements.

- LLD removal eliminates the rogowskis and 6 of the shunt tiles.

- Basic installation/restoration would be to restore 6-8 tiles per row, in each of rows 2,3, & 4.
  - Should be worked out with interested parties.



NSTX

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CHI Gap Shields

SPG, HK, RR

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
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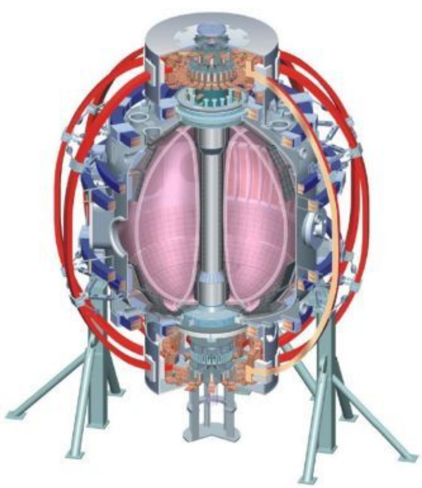

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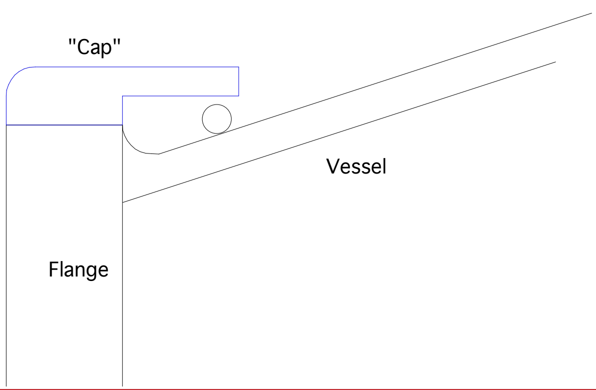
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Desire to Improve the Power Handling Capability of the CHI Gap

- Issue: Plasma & heat entering the CHI gap has been known to
  - degrade discharge performance due to heat flux on SS, and
  - damage diagnostics in the CHI gap,
- Problem may be more severe in NSTX-Upgrade, where the horizontal inner target is more narrow.
- Goal: Install armor on outboard side of CHI gap.
  - Graphite is not considered a plausible candidate due to high temperature bake-out requirement.
- Provides 2 benefits
  - For cases with OSP on OBD bull-nose tiles, armor increases tolerance to transient inboard motion of the SP.
  - For cases with OSP in the inner horizontal target, armor improves power handling of the far(ther) SOL heat flux.
- Not planning for this armor to be a primary, “steady-state” power handling component.
- Have already identified candidate concepts, and are working with engineering to implement.

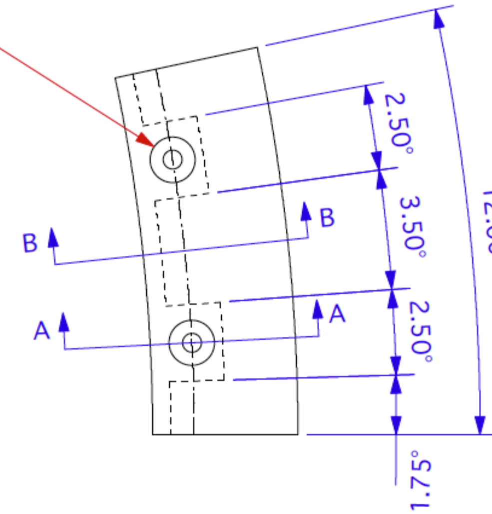
Concept for Moly. Tile

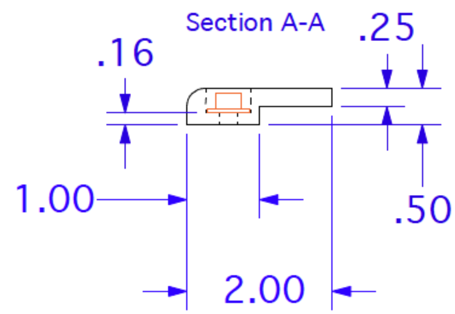


1: Hole for 1/4-20 stud and nut
2: Coutersink diamer for appropriate socket
3: Extend hole toroidally for thermal expansion?

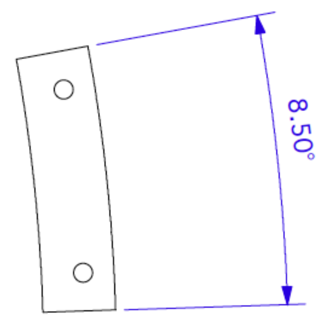
CHI Gap Armor Concept
Rev. 2
01/10/2011
Stefan Gerhardt
sgerhard@pppl.gov
243-2823

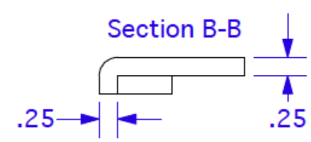
Part A: Moly Tile





Part B: Grafoil Spacer





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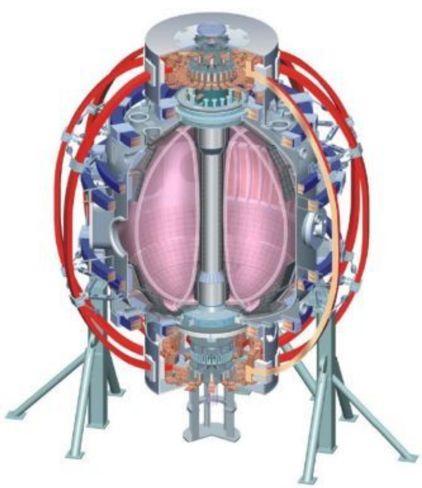
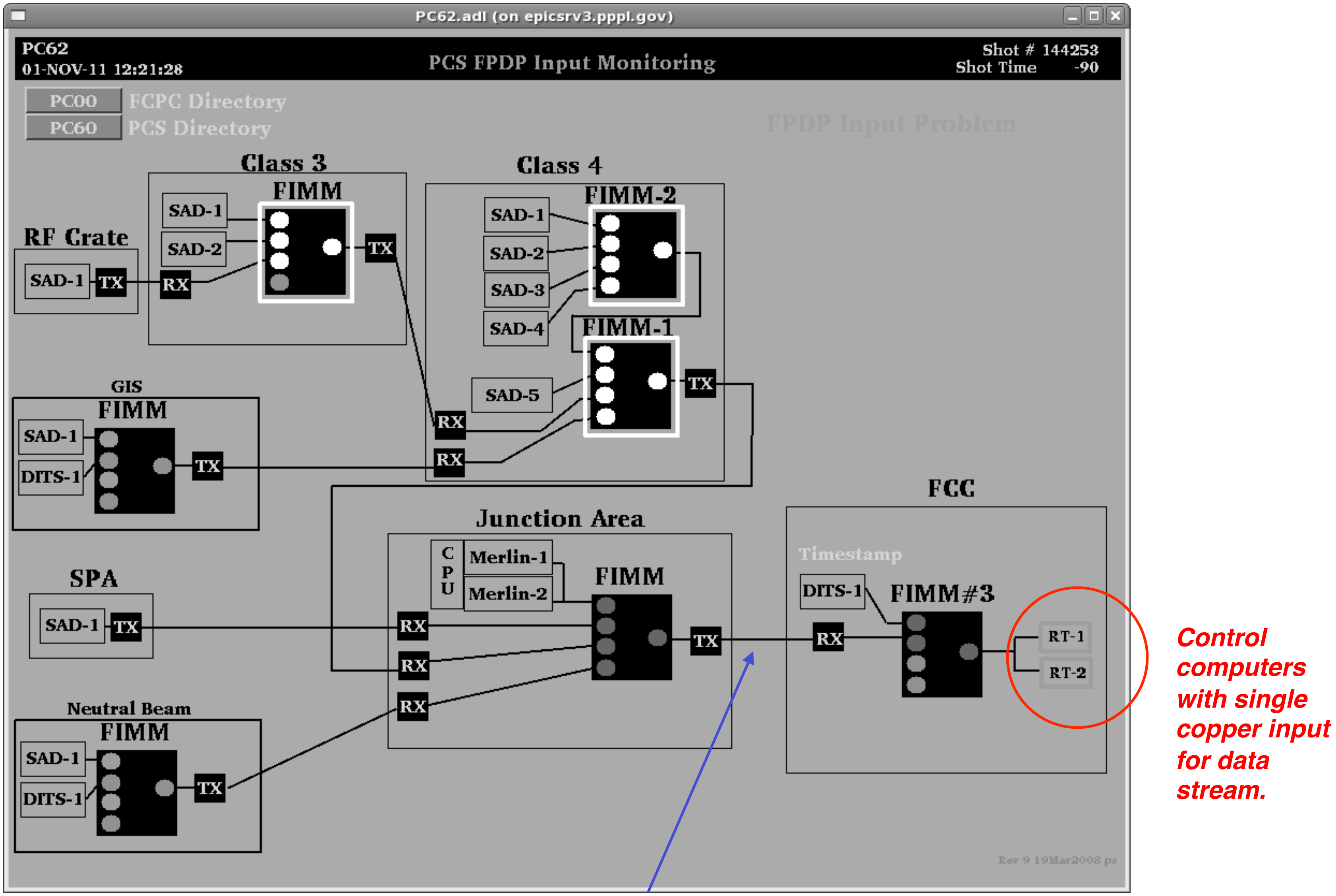
Upgrades to PCS Hardware (Incomplete)

KE, DAG, SPG, EK, DM, PS



Present PCS Data Stream Is Combined In The Junction Area for Transmission to FCC



PCS Hardware Upgrades

- Legacy power supply control link (PCLink) is being replaced as part of the firing generator upgrade.
  - This was the limiting component for the system speed.
- Have already placed requisition for new PCS computer.
  - 8 cores, 64-bit, improved realtime OS, …will purchase additional machine as operations backup as run approaches
  - New input card has 4 fiber optic inputs.
- P. Sichta's group is preparing a plan making multiple parallel input streams.
  - Goal is to increase sampling rate from 5 kHz to 40 kHz.
  - Essentially eliminate the input data stream in contributing to the system latency.
  - New Systrans, additional fiber runs, reconfiguration of the data acquisition code.

- Also need additional digitizer in Cat. 3 racks for additional IV magnetics signals.

- NSTX coil currents were displayed with ancient scopes (looks like a high school science lab) using ancient and unmaintainble data links from junction area to control room.
- D-IIID, with the same PCS, has realtime displays of relevant parameters in multiple place in the control room.
  - Coil and plasma currents, boundary shape.
  - MHD Signals, fault indicators
- Provide more flexibility about what data is displayed, where it is displayed, and how it looks.

Additional Realtime Diagnostics/Actuators That Could Be Beneficial (not complete)

- Actuators (PCS control means that settings can be restored)
  - Timing of SGI, divertor D_2 & CD_4 injection, GPI vavlues (allows pulses to be restored, use in feedback, keeps them under phys. operators control).
  - Timing of startup schemes (CHI gap-bank firing, point-source injection turn-on).

- Diagnostics
  - MPTS: Improved realtime reconstructions of things like magnetic axis radius, outer gap, pressure peaking, density control (interferometer?).
  - MSE: Necessary for realtime current profile control.
  - V-phi: Necessary for rotation profile control.
  - Divertor heat flux and/or temperature: detachment and/or balance control.
  - Rotating MHD from: Disruption avoidance or discharge shutdown.

- But recall: PCS provides “discharge protection”, not machine protection.
  - If it can break NSTX, needs additional interlocks.

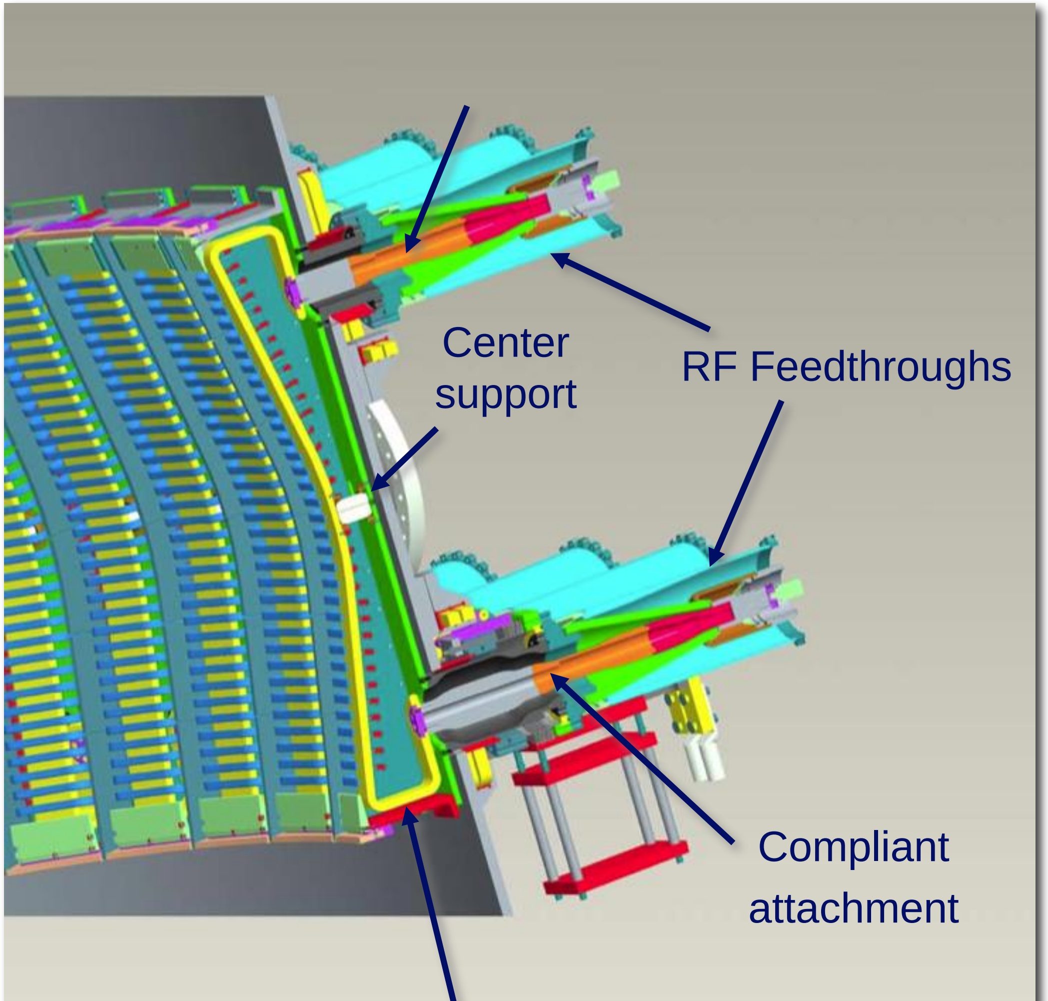
NSTX-U HHFW System and Diagnostic Enhancements

Joel Hosea

NSTX-U Facility Enhancement Brainstorming Meeting

February 7, 2012

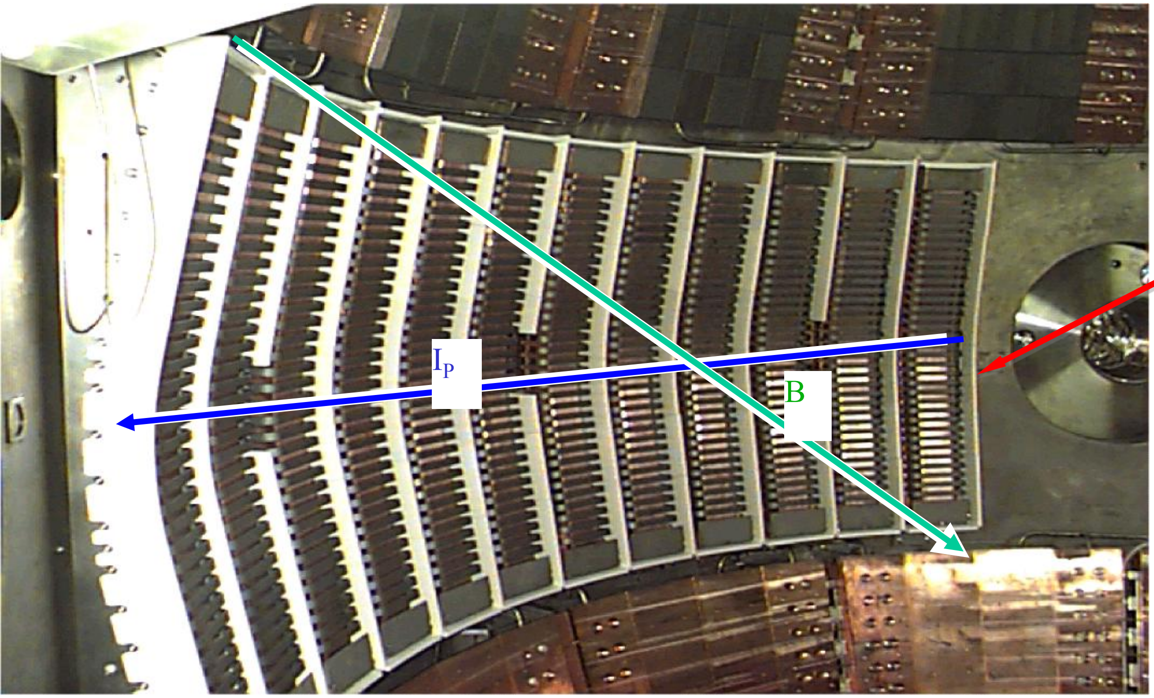
Antenna improvements needed

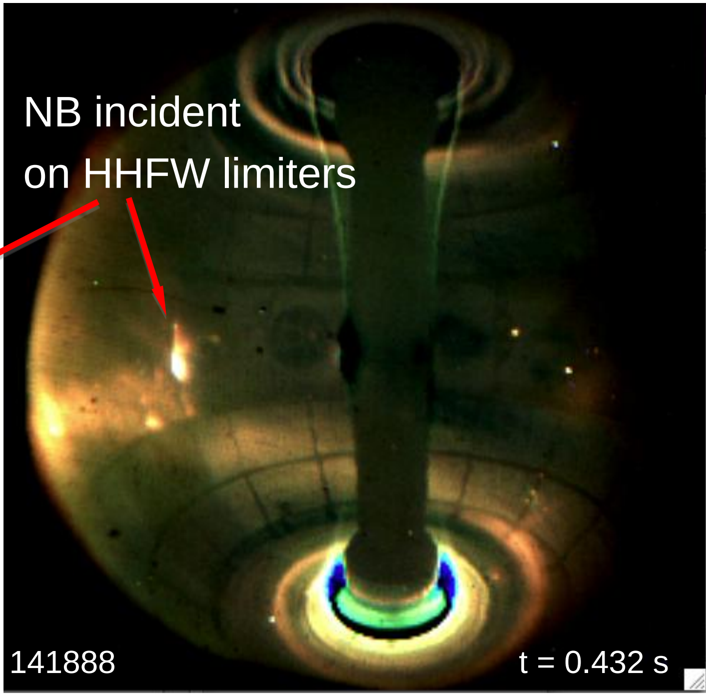


Strap ends twist during disruption

- Compliant attachments between antenna current straps and feedthroughs are required
  - B_T x 2, I_P x 2 ⇒ 4 x disruption load on strap
  - Compliant bellows being considered as first concept
  - Must be RF voltage tested on test stand to assure voltage standoff for 24 compliant attachments
- Need to improve antenna voltage standoff generally to support 5 MW operation with 8 straps in second phase of NSTX-U
  - Two antenna elements are to be tested on the test stand
  - Voltage to be improved in vacuum with aid of Microwave Studio

NSTX HHFW antenna limiter should be made more robust for high beam power operation

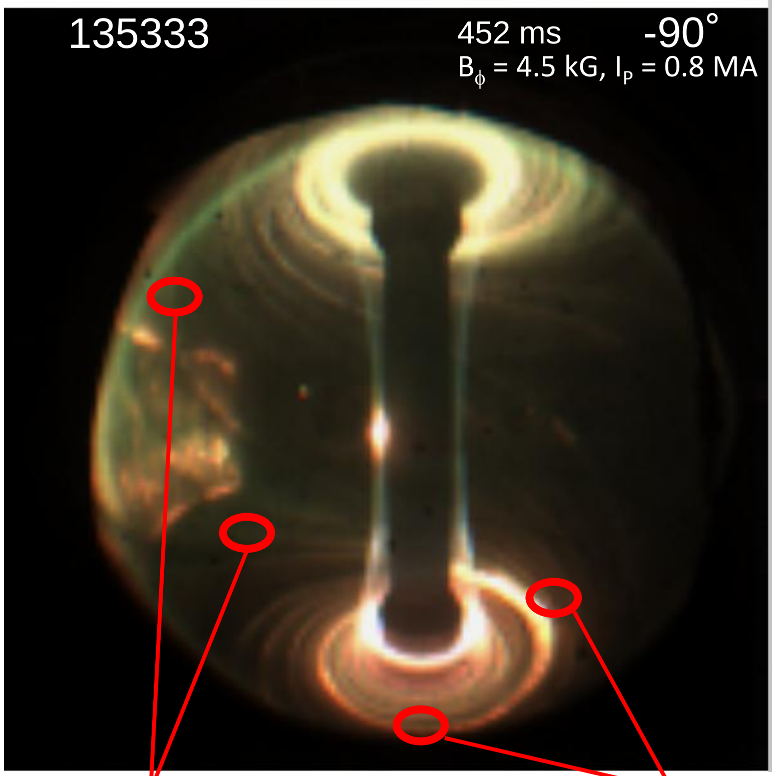




Gap = 6 cm, P_{NB} = 2 MW

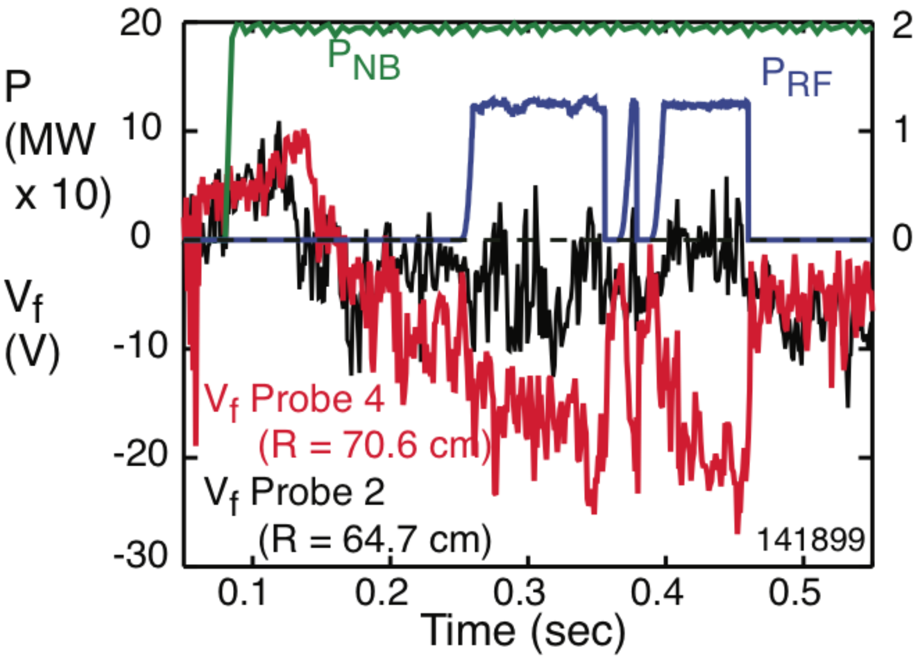
- Boron nitride limiter is impacted by beam ions with 6 cm antenna-plasma gap at modest density
  - P_{NB} in upgrade will be up to 12 MW with a large fraction deposited off-axis
- Would like to keep gap size to insure power coupling to core
  - If antenna voltage standoff can be increased, a larger gap can be used to keep energetic beam ions off the antenna limiter

IR cameras and probes are critical for documenting properties of RF edge heating to compare to advanced RF codes for SOL



Protective tile probes

Langmuir probes
(30 MHz response)



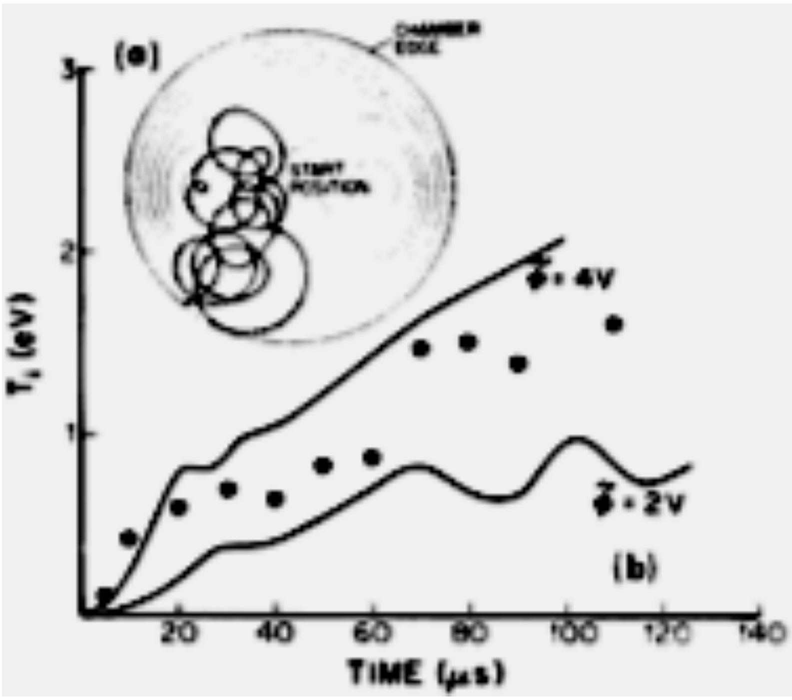
Bay B Langmuir probe measures effect of RF when the spiral is over it (Jaworski)

- Need probes in protective tiles under and above antenna and in same vertical locations away from field lines that pass in front of the antenna
  - What is RF deposition along the path of the RF power flow to the divertor regions along the magnetic field lines?

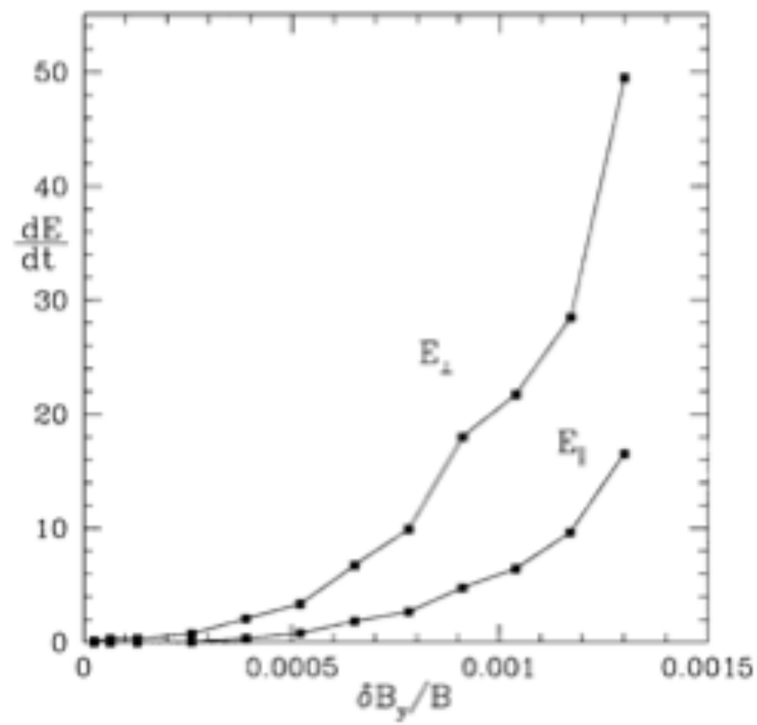
*AE Antenna Research Plan (Sketch)

- Low power (<1 kW) stability and coupling studies
  - Use existing and upgraded *AE antennae
  - Measure linear damping rate for TAE to benchmark NOVA.
  - Measure spectrum, linear damping rate of GAE and CAE (only unstable modes currently seen).
- Evaluate what is required for more active experiments
  - Power requirements
  - Antenna requirements
- Higher power experiments
  - Stochastic ion heating
  - Enhanced electron thermal transport (Te profile control)
  - Control of fast ion population with *AE (TAE, CAE, GAE)

Stochastic Ion Heating needs mode amplitude of order δB/B ≈ 1%



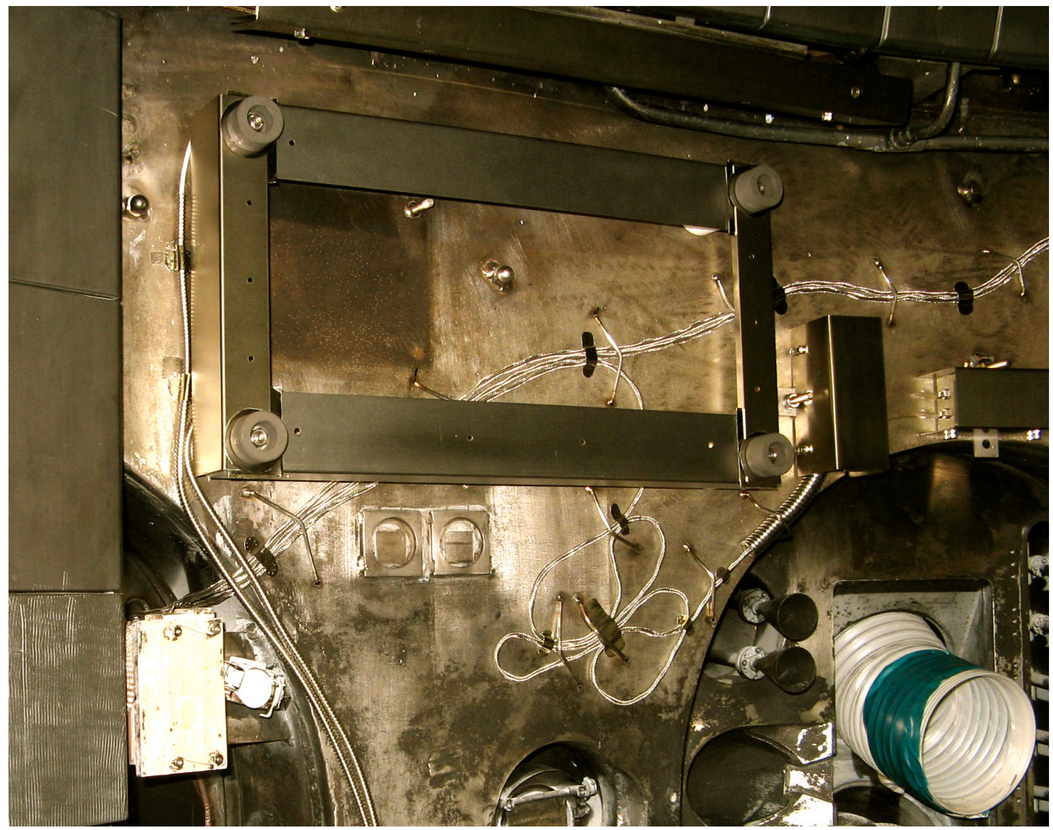
- Stochastic ion heating has been experimentally demonstrated
  - McChesney et al, PRL **59** (1987) 1436.



- Simulations for NSTX find CAE stochastic heating at order δB/B≈1%.
- Based on measured damping rate, need ≈ 1.5MW to reach δB/B≈1%.

This is opportunity for first upgrade of *AE antenna, prepare amps, controls, matching network

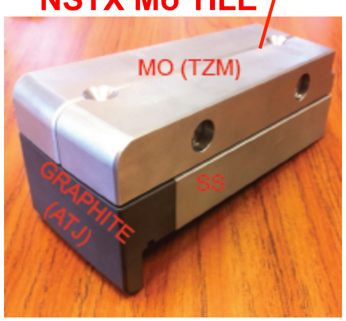
- Existing 5-turn radial antenna installed for 2011 run
- No HHFW straps in 2014; add second *AE antenna for 2014 run.
- Either different design (poloidal coil to couple to compressional wave?),
- or second antenna for spectrum control.
- ... or one antenna for TAE and a second for GAE & CAE.



Replacing the Planned Upper Inner Divertor ATJ Tiles with Molybdenum Tiles Expands NSTX-U Capabilities

- Installation of Molybdenum Tiles on the Upper Inner Divertor allows experiments to characterize:
  - Reduction of divertor carbon source term in USN discharges
    - measure effect on plasma core-carbon impurity accumulation
  - Comparison of power-handling during long-pulse DND discharge
    - measure upper and lower divertor heating and erosion
  - Prototype test for expanding molybdenum tile coverage
    - if performance enhanced, start engineering work for more Mo tile coverage

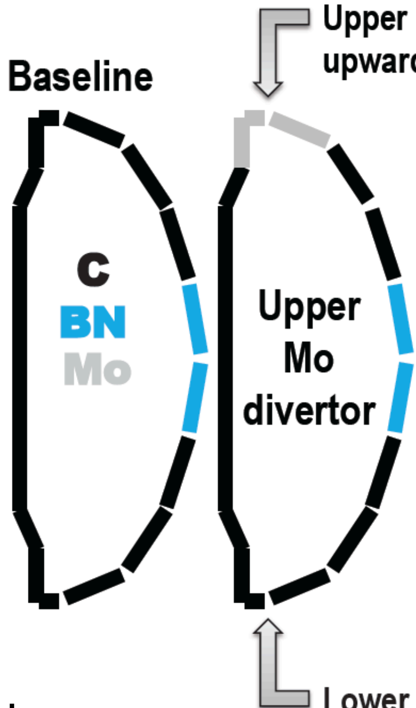
NSTX Mo TILE



- Remaining Tasks
  1. Perform fresh engineering analysis to determine NSTX-U, operating limits (Ip, Bt, NBI, rep).
  2. Design and fabricate ATJ spacer tiles.
  3. Resolve of diagnostic cabling issues.

Replacing Entire Upper Divertor ATJ Tiles with Molybdenum Tiles Accelerates NSTX-U Decision for All Metal PFCs

Upper Mo divertor to test Mo as PFC, Li on all Mo - requires upward Li evaporator and upper divertor diagnostics

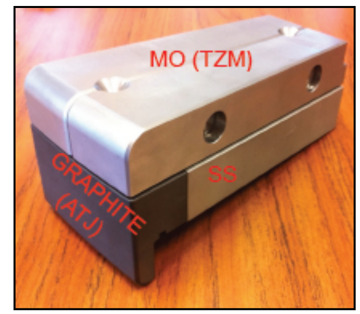


Lower C divertor enables comparison to NSTX results, reduces risk of high-Z PFCs for initial physics/long-pulse ops goals

J.Menard

- Having at least one divertor be all Mo (with Li coating capability) would:
  – Enable comparisons of Mo vs. C
  – Continue research planned for 2011-12, i.e. test effects of Li on Mo PFCs w.r.t. impurity production, possible temperature clamping
  – Inform/accelerate decisions for metal PFCs

- Number of NSTX ATJ tiles
  - Horiz Inr Div R1= 48
  - Otr Div = 916



Mo INR DIV TILE

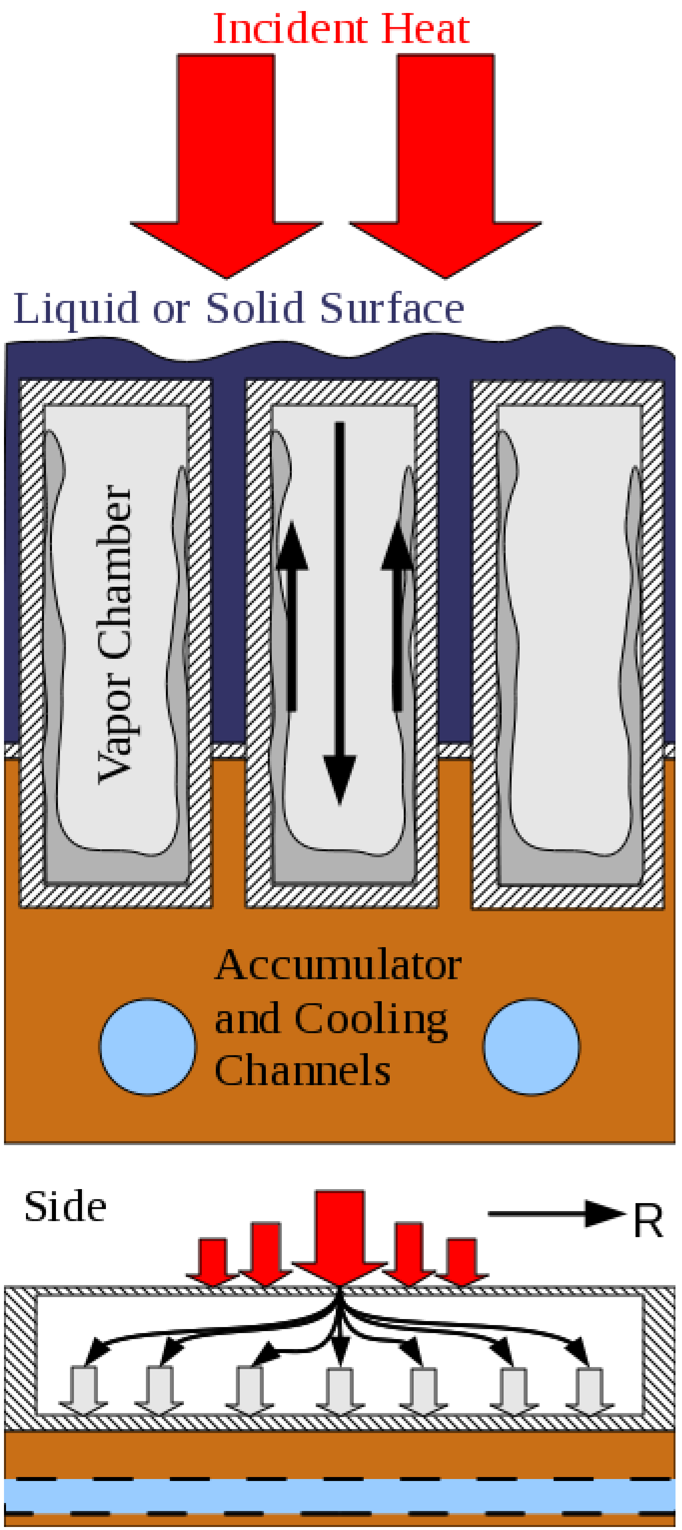
- The outer divertor has 916, ATJ tiles, 1-inch thick arrayed in 5 tile styles (on 5 conic sections), fastened with Tee-bars to tapped holes in the copper baseplates containing heating/cooling pipes
  - could use inner divertor tile design for outer divertor, but 5 different tile styles required
  - a possible tile design consisting of a standardized geometry (e.g., cubes/CMOD) could reduce the number of tile styles and fabrication cost

NSTX-U Active Cooling

- **Why consider?** Eventually active cooling is a part of every reactor concept (ReNeW thrust 11: Improve power handing through engineering innovation)
  - Nearer-term: an implicit part of the slow-flow liquid metal PFC concepts (soaker hose/Li CPS, FLiLi, LiMiT – even SnLi/Sn)
- **How urgent for NSTX-U?** First year of operation will determine new thermal response of PFC tiles to determine if NSTX-U CS cooling is adequate
- **What's available now?** Gas cooling schemes are under active development around the world improving He cooling efficacy (via T-tubes/thimbles and other clever arrangements)
- **NSTX-U divertor could provide demonstrator for these technologies or for something even more innovative...**

Concept of "Active PFC"

- NSTX-U will not be steady-state, nor is it short-pulse. 1/2" ATJ has thermal time constant of 1.7s, but inter-shot time will be >750s(12.5min) and NSTX-U PFCs still need to deal with multi-MW/m^2 heat fluxes *in some locations*
- Liquid metal heat-pipes/vapor-chambers can achieve relevant heat fluxes and **spread** incident power at modest temperatures (e.g. sonic limit of 500C sodium is $6MW/m^2$)
- Combine with thermal "accumulator" (e.g. copper block) for short-pulse storage (2cm Cu over $1m^2$ can store 7MJ with 100C rise, i.e. LLD-scale)
- Can pull energy from accumulator over longer time period via simple cooling pipes – reduces flow rate requirements and complexity
- Can extrapolate to reactor by mitigating need for intense gas cooling via spreading of incident heat flux, internal working fluid determines operating temperature range



MAJ

Proposed Facility Enhancements for FY 2014-18

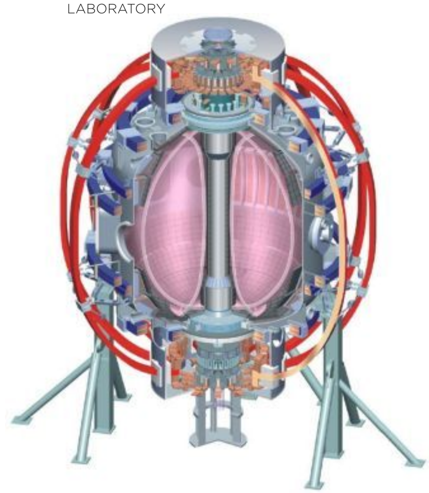
R. Maingi, Oak Ridge National Laboratory

J-W. Ahn, J. Canik, J. Lore, A. Sontag

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

NSTX Facility Enhancement Brainstorming Meeting
PPPL - Princeton, NJ
Feb. 7-8, 2012

PPPL
PRINCETON PLASMA PHYSICS LABORATORY



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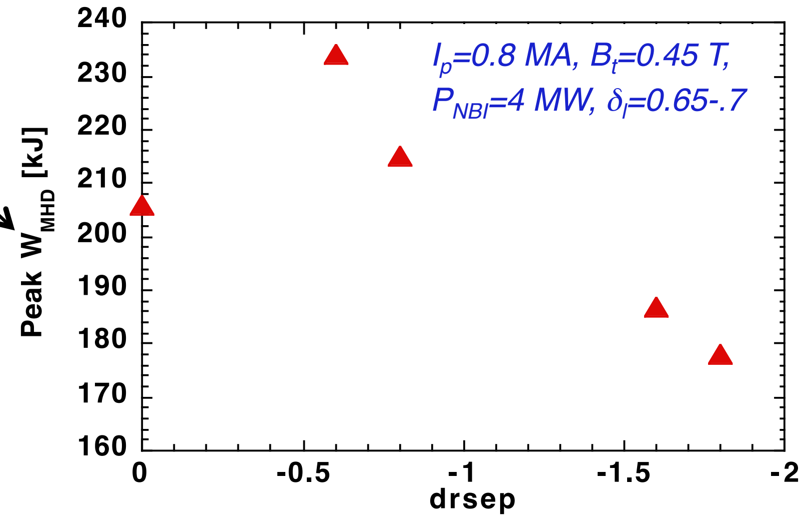
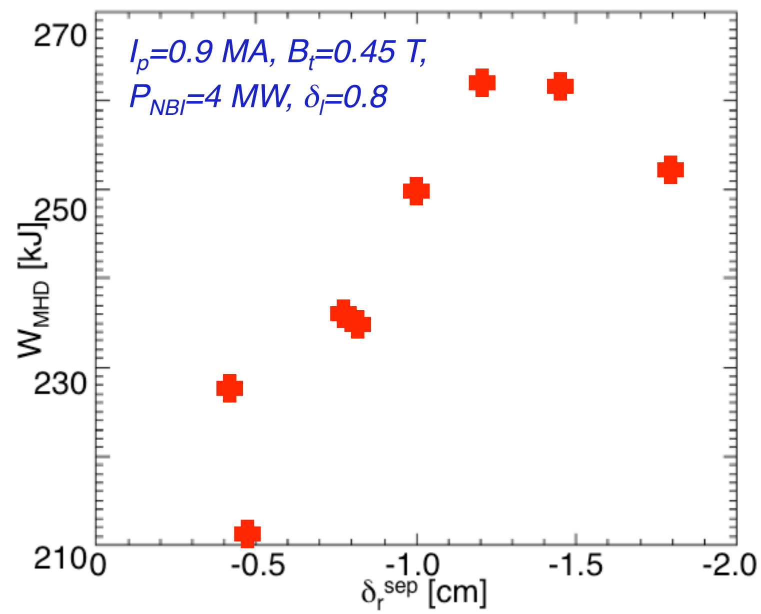
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Upward facing LiTER may further improve performance

- Discharges without lithium showed peak stored energy near $\delta_r^{sep} \sim 0$
- Discharges with lithium showed peak stored energy with more negative δ_r^{sep}, i.e. LSN
- Suggests that some method to evaporate into upper divertor should be considered, along with additional upper divertor diagnostics





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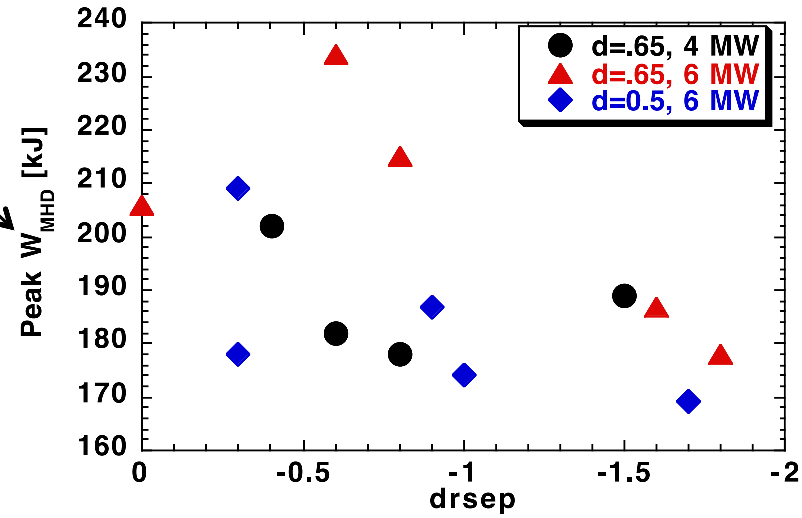
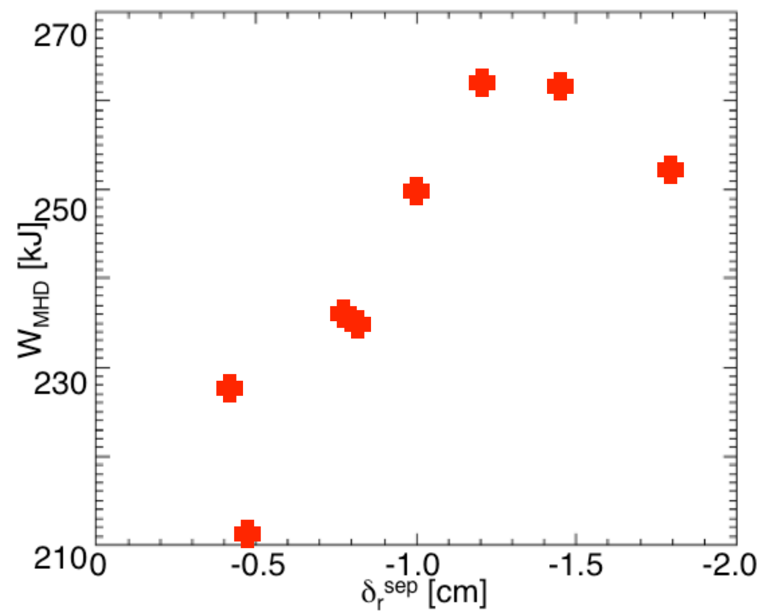
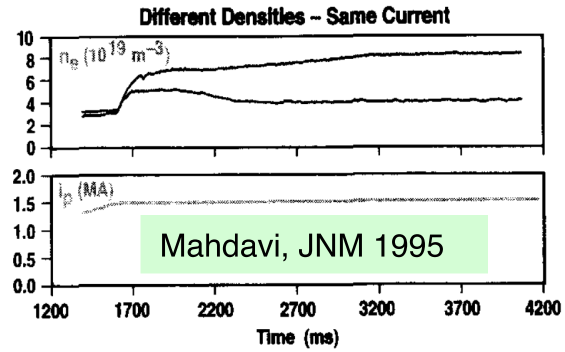
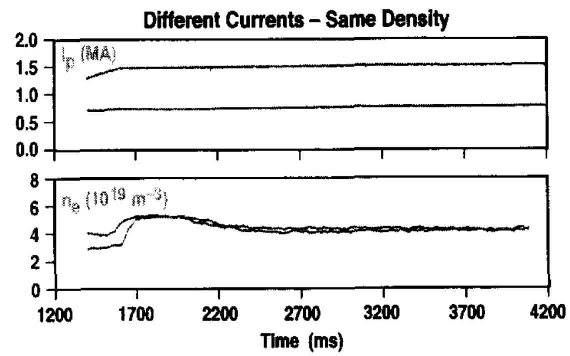


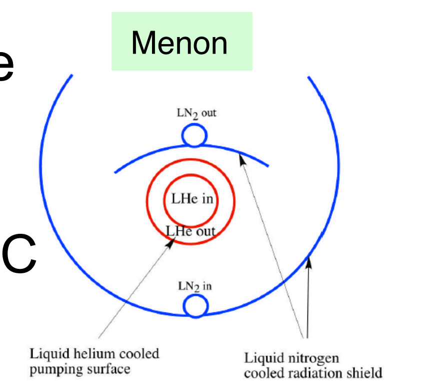


Divertor Cryopump and Baffle System: A Proven Technology for Long Pulse Particle Control

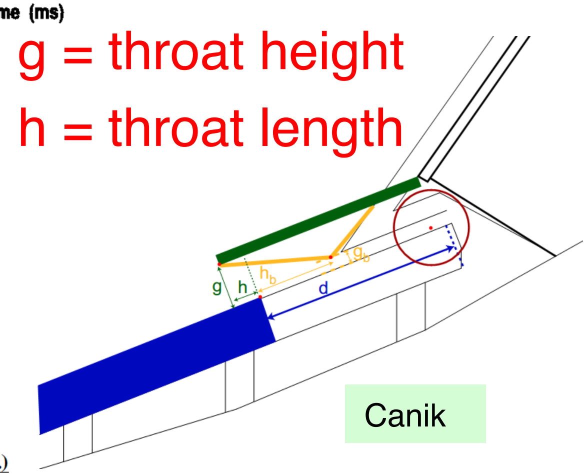
- Cryopumps have been implemented in a number of devices – *they should be viewed as a tool to provide long pulse density control*
- The basic concept is a liquid He tube surrounded by a liquid Nitrogren shroud
- A plenum system is designed to increase local neutral pressure for efficient pumping
- Preliminary design calculations are being done (by J. Canik) both with semi-analytic models and 2-D calculations, for the April, 2012 PAC meeting







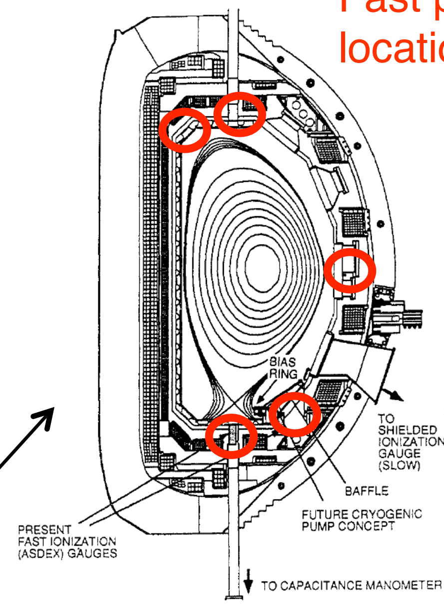
Cross-section of the pump (10 cm outer dia.)



PCS feedback on divertor temperature or neutral pressure, and associated diagnostics

- Two limits imposed on power handling: 1) critical heat flux that can dig a channel into PFCs and cause coolant leak, and 2) surface temp. below melting point and away from chemical sputtering peaks
- Unmitigated heat flux in NSTX-U predicted to be up to 25 MW/m^2; requires control of both temp. and heat flux in real time
- Propose PCS control of divertor gas injection on divertor neutral pressure from fast in-situ gauges
- Propose PCS feedback control on temp. and heat flux from fast thermocouples: actuators are δ_r^{sep} and OSP radius

Fast pressure gauge locations in D3D



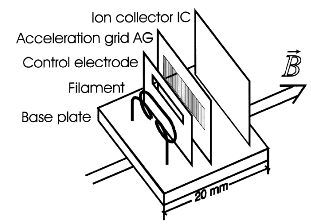
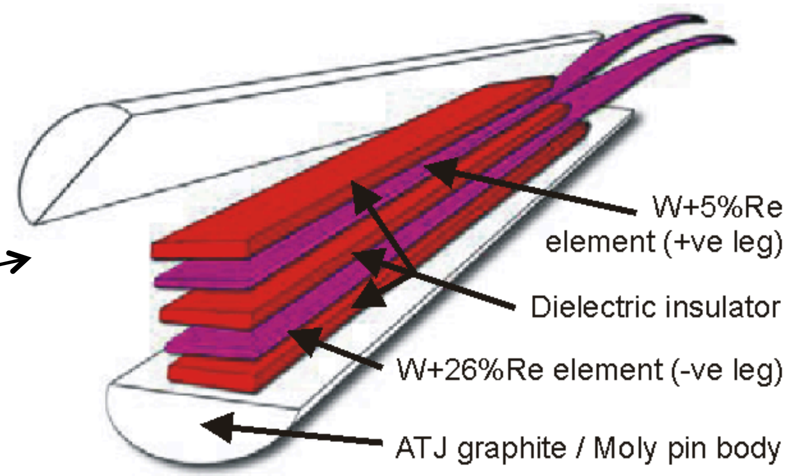


Figure 1. Electrode arrangement of the ASDEX gauge.

G. Haas, Vacuum **51** (1998) 39



McLean, Gray

NSTX Fusion Energy Sciences Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Proposed Facility Enhancements for NSTX Upgrade

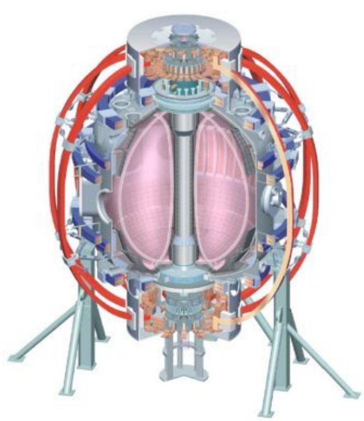
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

V. A. Soukhanovskii for the LLNL Collaboration Team

NSTX-U Facility Enhancement Brainstorming Meeting

Princeton, NJ

7 February 2012



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Kyushu U
Kyushu Tokai U
NIFS
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U Tokyo
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Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

LLNL proposals for NSTX-U facility enhancements

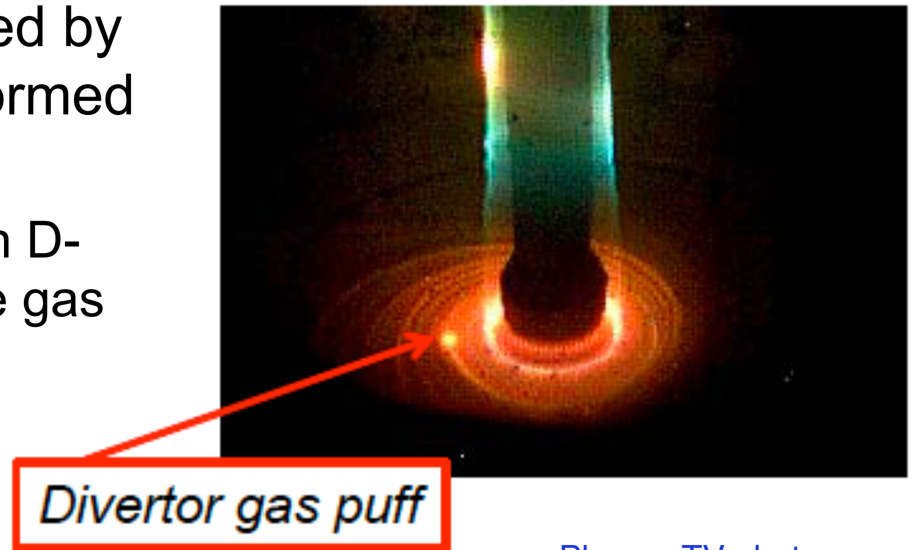
1. Divertor Gas Injector Upgrades for radiative divertor feedback control (gas actuators)
2. Supersonic Gas Injector Upgrades
3. Glow Discharge Cleaning System Upgrades
4. Vacuum vessel and Infrastructure upgrades for divertor Thomson Scattering diagnostic

LLNL proposed development of real-time feedback control of radiative divertor for NSTX-U

- Proposed and partially funded as part of DoE ECRP Award in 2010
- Goal: steady-state feedback control of divertor heat flux and detachment compatible with pedestal stability and H-mode core confinement metrics – critical for NSTX-U 12 MW 2 MA 5 s discharges
- Use diagnostic signal indicative of divertor detachment / reduced heat flux as **control parameter** and pass it on to PCS for fast gas valve control for divertor impurity seeding control (**actuator**)
- Control parameters (diagnostics side):
  - PFC temperature / heat flux monitoring (e.g., fast IR diodes)
  - P_{rad} (e.g., fast bolometers, AXUV diodes, VUV spectroscopy)
  - Recombination rate (D Balmer, Paschen lines), Divertor ion current (e.g., Langmuir probes), D or Impurity pressure (e.g., Optical Penning gauge)
  - Pedestal pressure, core impurity density, MARFE monitoring, etc
- Actuators:
  - Gas valves (midplane and divertor)

Upgrades to divertor gas injection system (D-GIS) motivated by NSTX-U divertor experiments

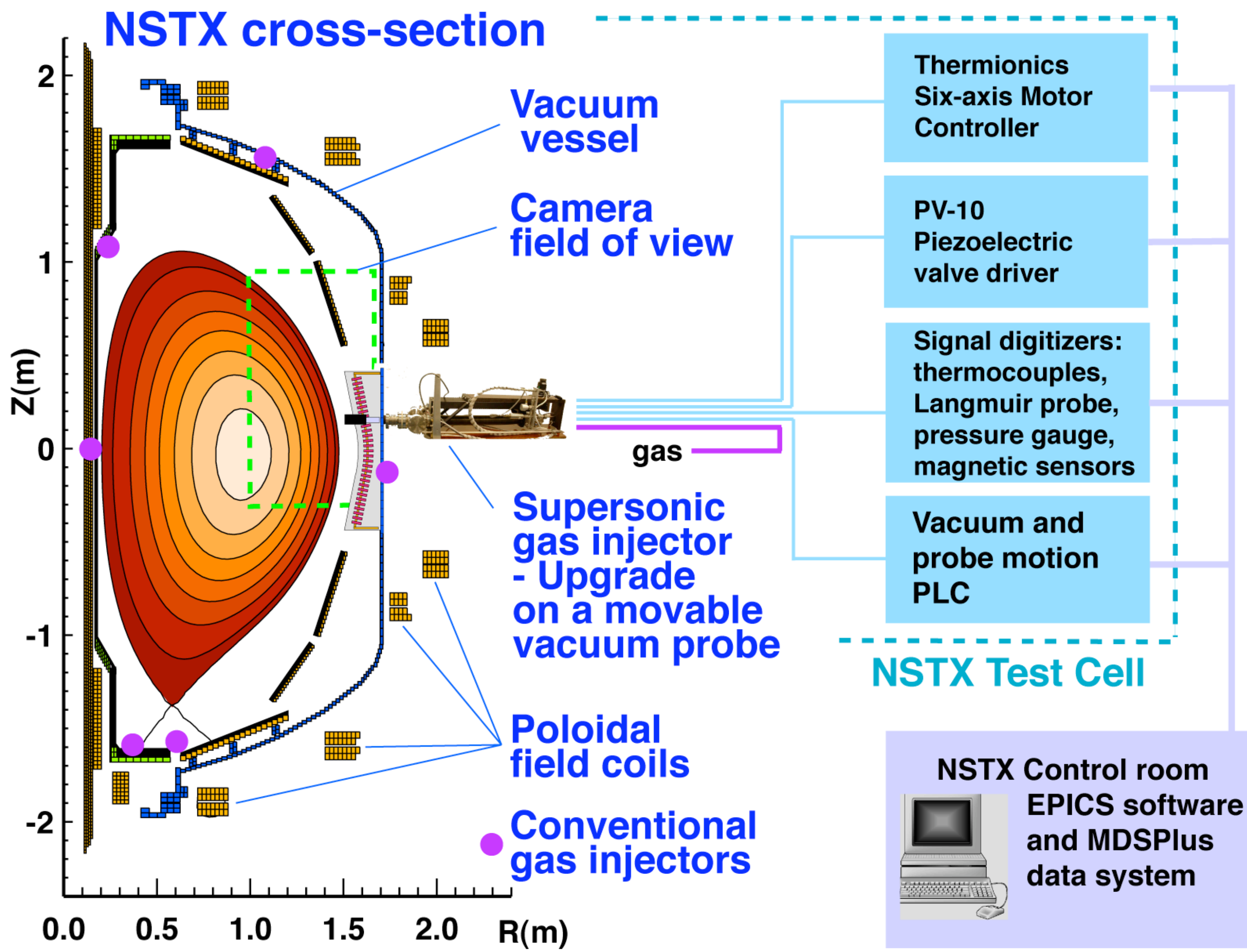
- NSTX (present) D-GIS design motivated by divertor detachment experiments performed in 2005-2008:
  - Gas delivery system is shared between D-GIS and SGI (connected to one remote gas bottle)
  - All components rated to 100 PSI
  - One divertor gas port in CHI gap
  - Pre-programmed PZV control from vacuum operator PC



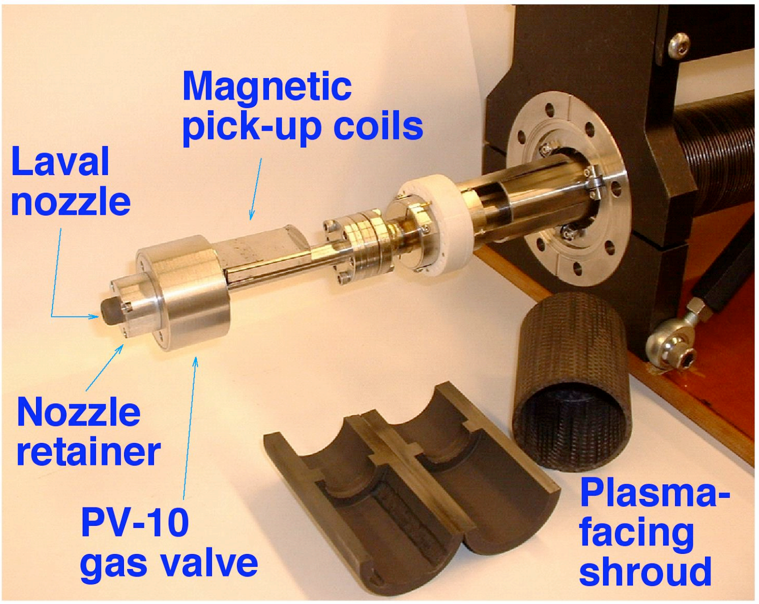
Plasma TV photo courtesy of F. Scotti

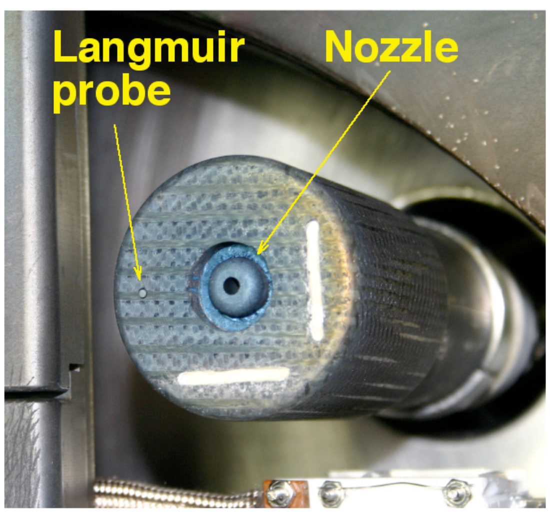
- Proposed D-GIS enhancements:
  - Make four toroidally symmetric gas ports (add in-vessel gas lines)
  - Make remotely controlled independent gas delivery system to handle several gases (D_2, He, Ne, Ar, CD_4, …)
  - Add pre-programmed control to PCS
  - Develop and implement feedback control algorithm

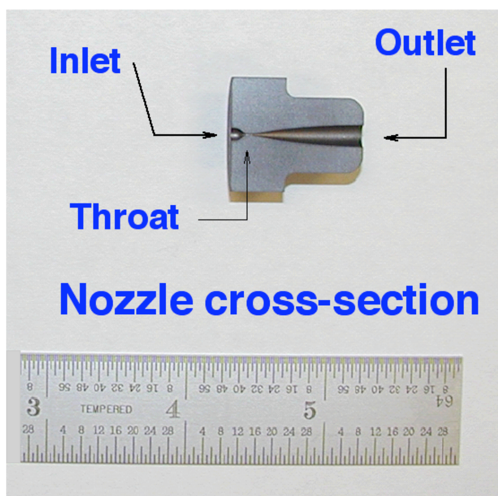
Supersonic gas injector is a complex computer-controlled high gas pressure apparatus



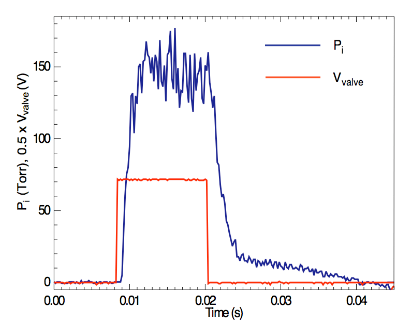
Supersonic gas injector consists of Laval nozzle and piezoelectric valve

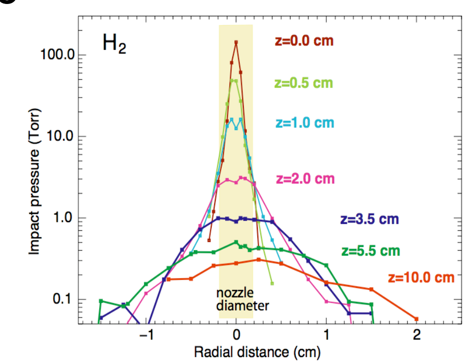






- SGI is operated at flow rates 20-250 Torr l /s
- Supersonic deuterium jet properties:
  - Jet divergence half-angle: 6^o - 25^o (measured)
  - Mach number M = 4 (measured)
  - Estimated: T ~ 60 - 160 K, $n < 5 \times 10^{23}$ m^{-3}, v_{flow} = 2.4 km/s, v_{therm} ~ 1.1 km/s
  - Nozzle Re = 6000





SGI upgrades proposed in 2008 but never implemented…

- Use present valve / nozzle for stationary SGI mounted on the wall in the shadow of limiter
- Use movable probe from present SGI to prototype cryogenic SGI
  - Design and make new metal nozzle
  - Use non-piezo valve (EM, pneumatic, others)
  - Design cryogenic cooling system (liquid N_2)
- Present limit on reservoir pressure (5000 Torr = 96 PSI) seems sufficient for fueling with present nozzle 250 Torr l / s
- Develop PCS control

Propose to re-examine present glow discharge system for optimization toward NSTX-U

Shimada, EPS 2011

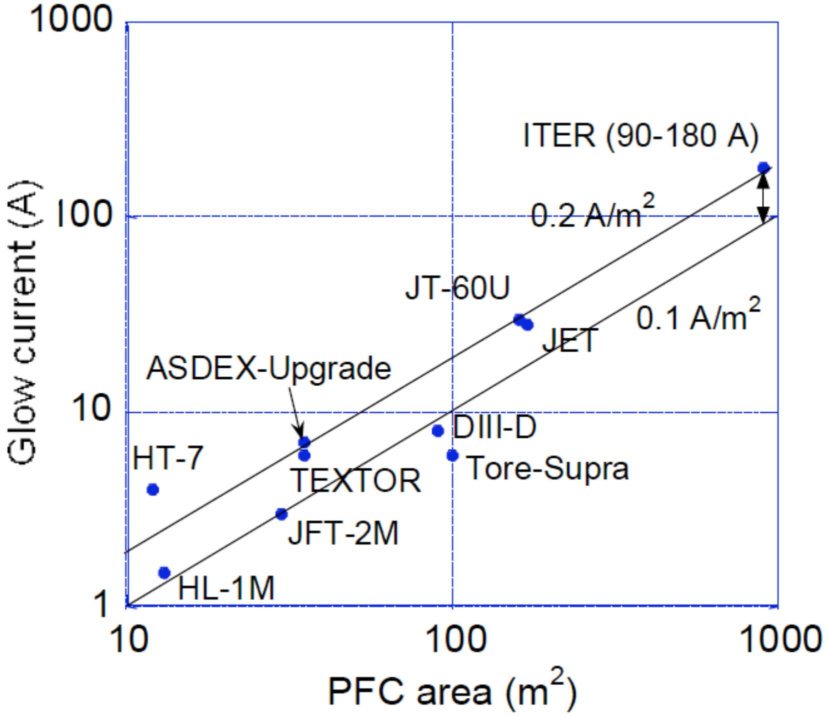


Fig. 1 Glow current vs. PFC area compiled from measurements on current devices

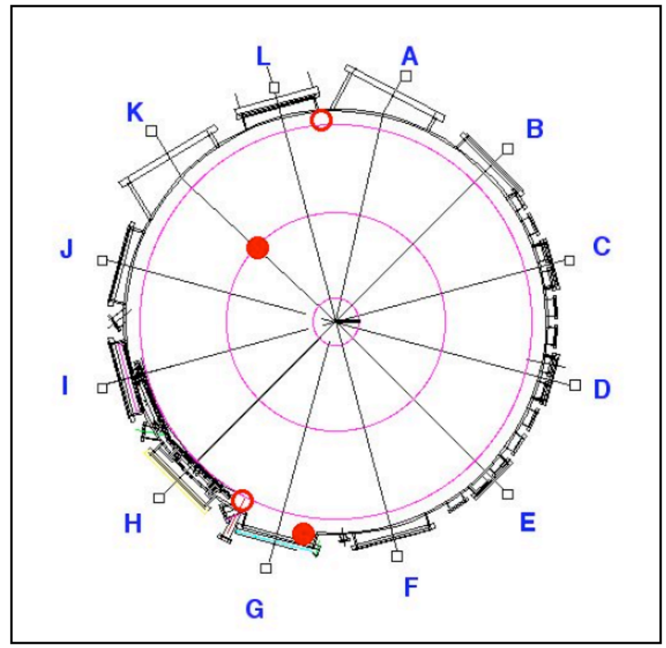
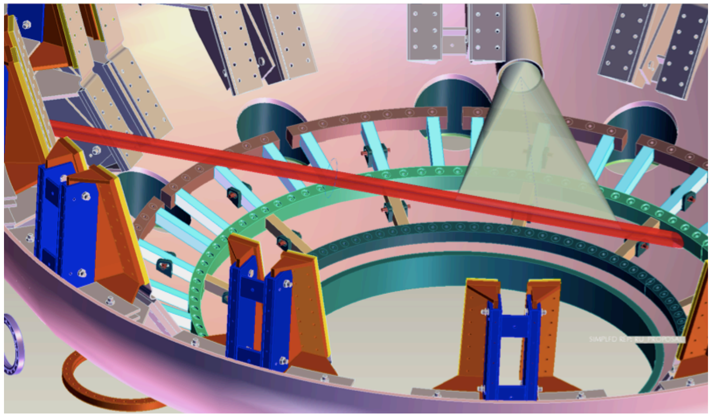


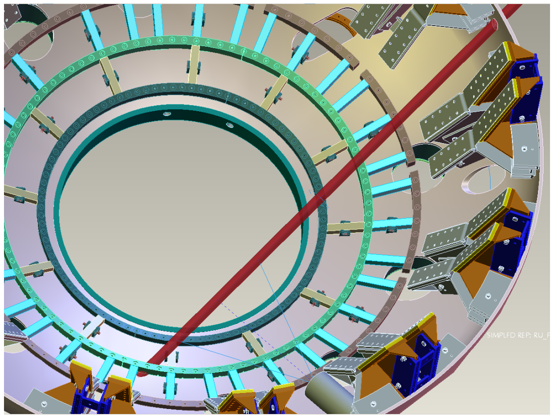
Fig. 1. Schematic diagram showing layout of inital NSTX HeGDC system (1999-2005) [open circles at Ports G and L] and the location of the upgraded HeGDC system anodes [solid circles, Ports G and K] relative to the vessel ports. The MGP is mounted at Port-K; the present fixed GDC anode is at Port-G.

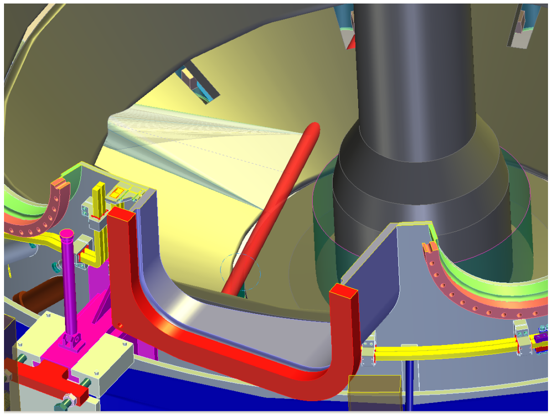
- Tokamak GDC figure of merit: 0.1-0.2 A/m^2
- NSTX PFC area 41 m^2, current ~3.5 A, two anodes
- NSTX-U: greater PFC area -> need higher current (?), more uniform coverage (?)

LLNL is proposing Divertor Thomson Scattering system for divertor and lithium studies in NSTX-U

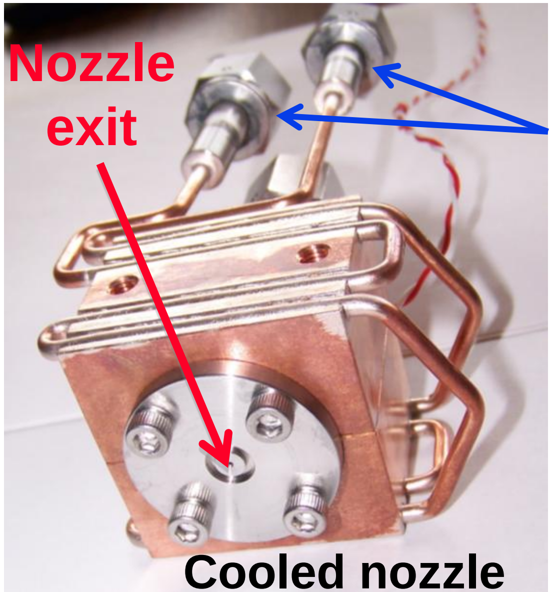
- Unique (“true”) divertor T_e and n_e measurements
  - DTS systems available only on DIII-D and TCV
- LLNL progress toward NSTX-U DTS
  - Initial identification of implementation issues on NSTX (done in 2008)
  - Maintenance and operation of DIII-D DTS (planned and performed now)
  - Conceptual design of DTS diagnostic (planned for 2013-2014)
    - Determine laser beam and collection optics geometries
    - Specify system elements and project performance
- **Need to keep DTS in mind when facility enhancements are planned**





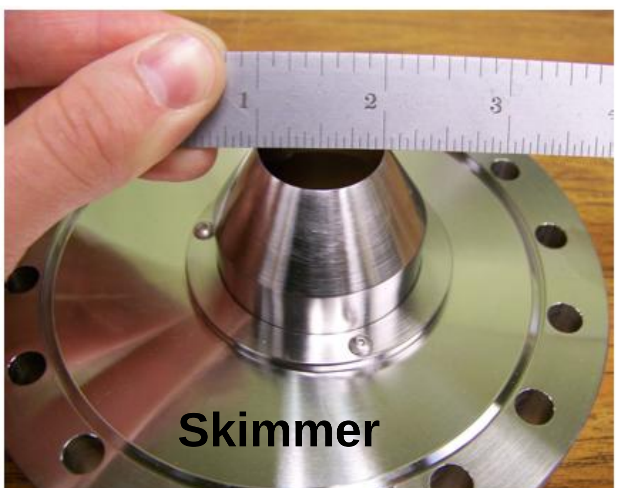


Particle fueling – molecular cluster injector (MCI)



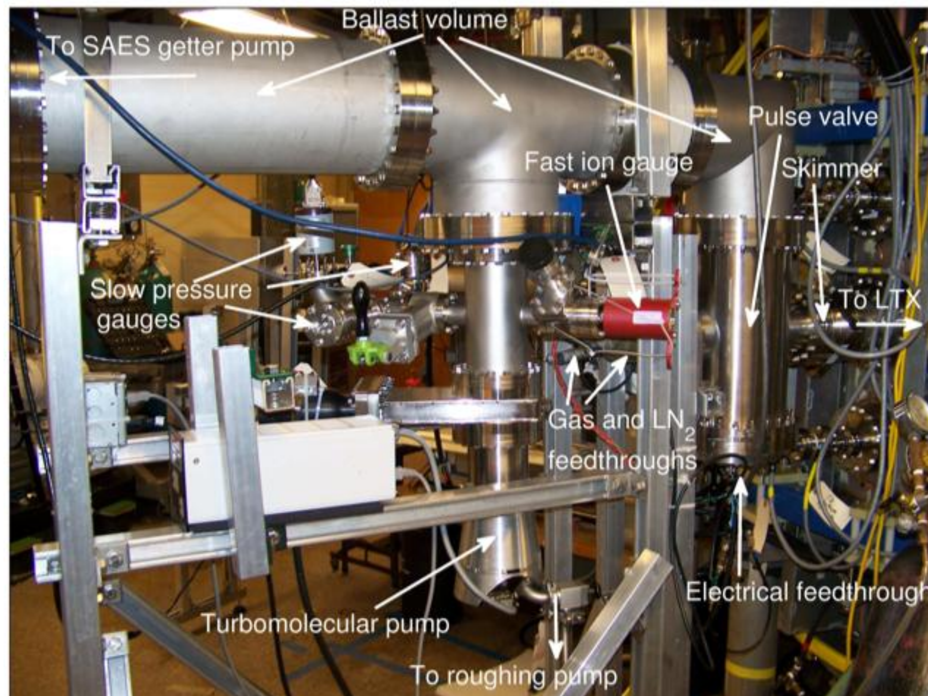
Liquid
nitrogen
inlet, outlet

Cooled nozzle



Skimmer

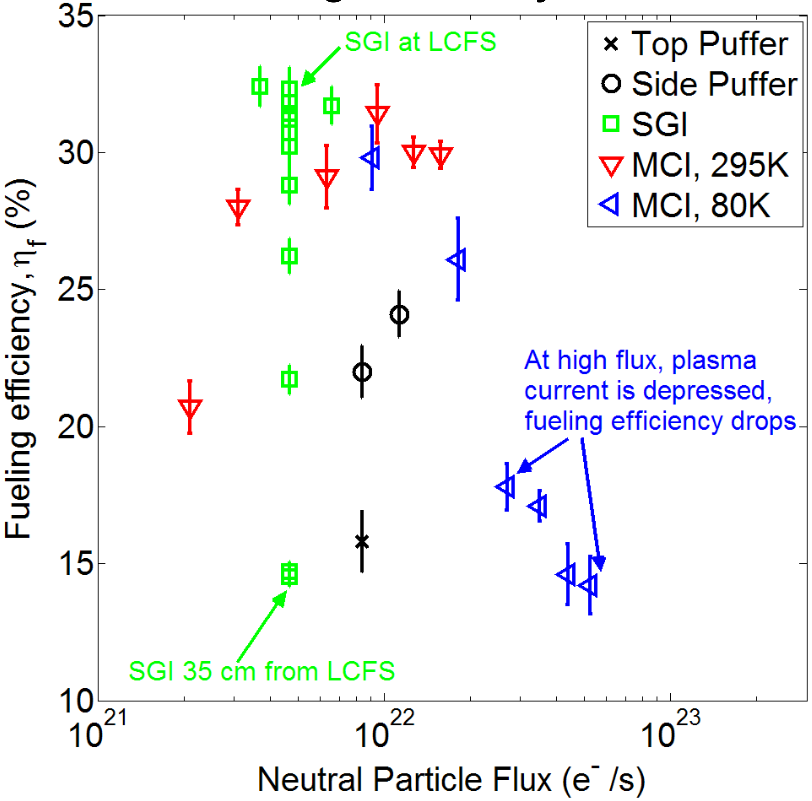
- System requirements:
  - Low divergence conical nozzle (4.5°)
  - Close-coupled fast valve
  - Skimmer
  - Pumping for skimmed gas
  - Need for cryogenic operation unclear



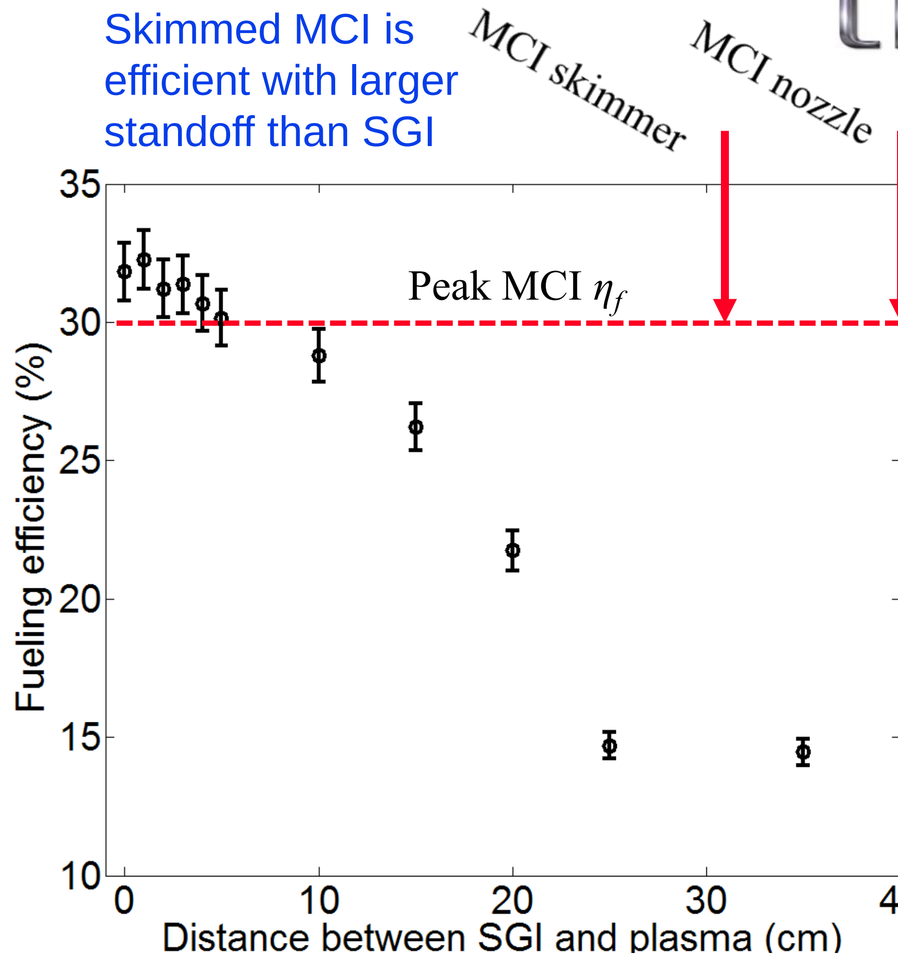
Installed on LTX with pumping

Cluster injector may provide effective discharge fueling

Fueling efficiency in LTX



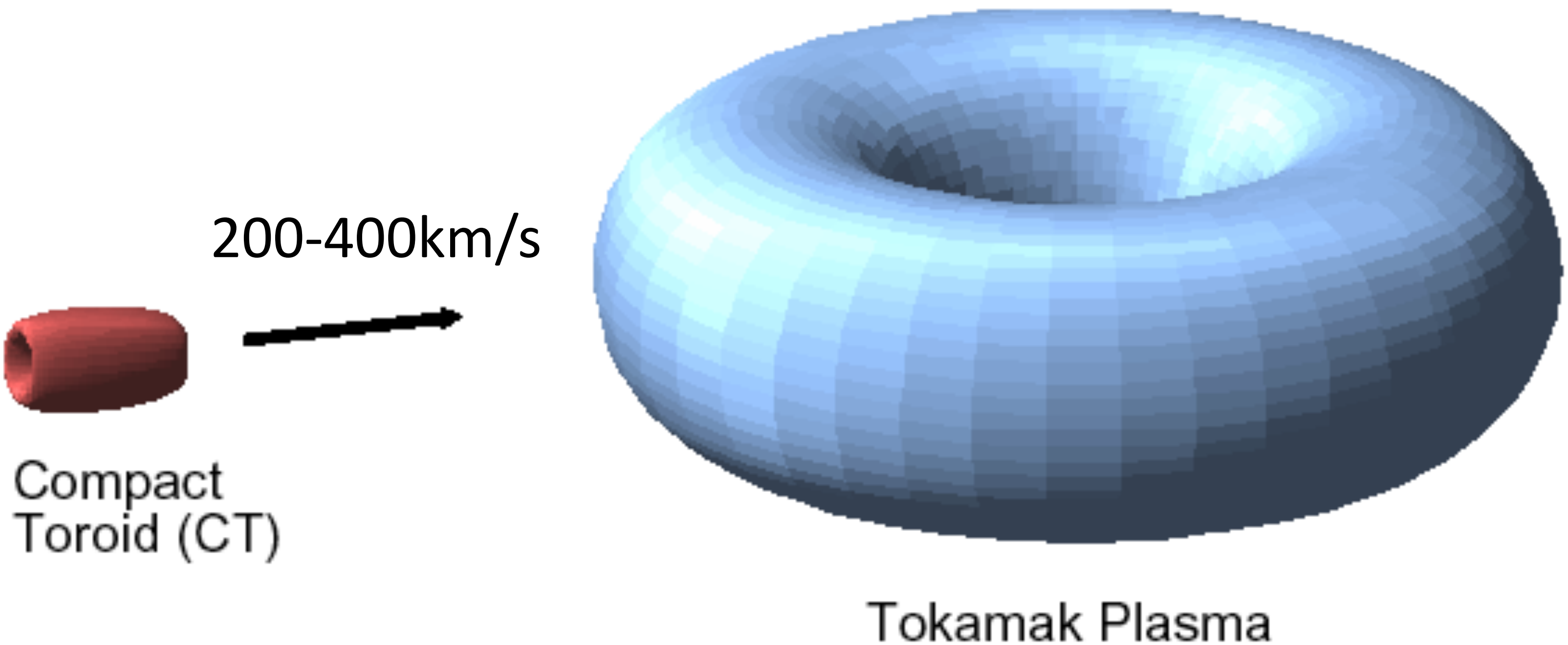
Skimmed MCI is efficient with larger standoff than SGI



- Cluster injector can provide very high particle flux
  - Highest fluxes require cryogenic operation
  - Highest particle flux overfuels LTX
- SGI efficiency drops rapidly with increased standoff from plasma edge
- Skimmed injector can maintain high fueling efficiency with increased standoff

Advanced fueling system for density profile control

In a CT injection system a CT is accelerated to high velocity and injected into the target plasma to achieve deep fueling



CT Penetration time: few μs
CT Dissociation time: < 100 μs
Density Equilibration time: 250 - 1000 μs
Variable Penetration depth: edge to beyond the core

R. Raman, T.R. Jarboe, et. al., – CT for NSTX-U -02072012

"Steady-state AT & ST scenarios rely on optimized density and pressure profiles to maximize the bootstrap current fraction. Under this mode of operation, the fueling system must deposit small amounts of fuel where it is needed and as often as needed, so as to compensate for fuel losses, but not to adversely alter the established density and pressure profiles"

- A CT injector has the potential to deposit fuel in a ***controlled*** manner at any point in the machine
- In a burning plasma device with only RF for current drive, a flexible fueling system may be the only internal profile control tool
  - Inject momentum for plasma beta and stability
  - Precise density profile control to optimize bootstrap current and to maintain optimized fusion burn conditions
  - Study core transport (He ash removal studies, ELM control)

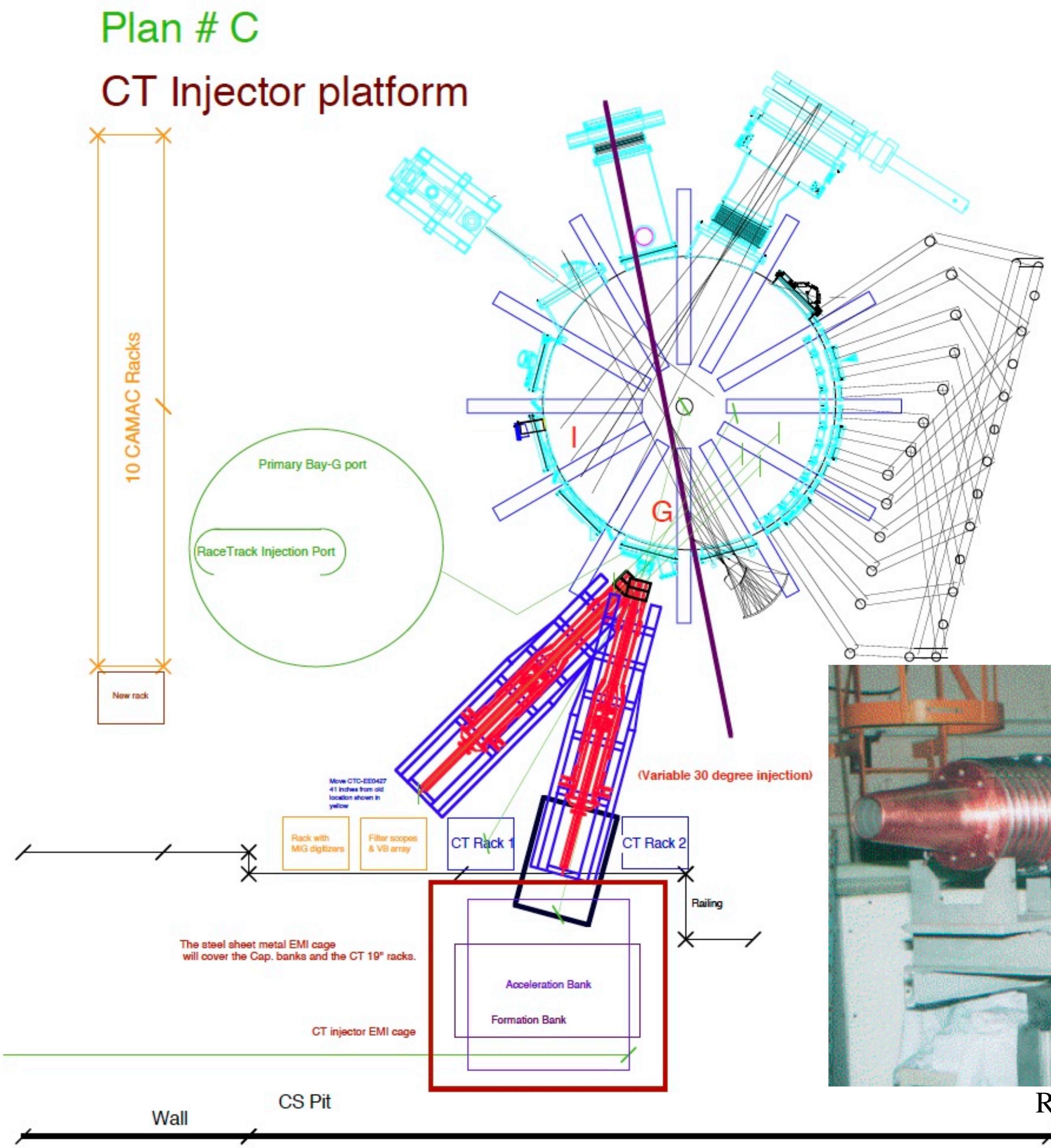
Recent publications

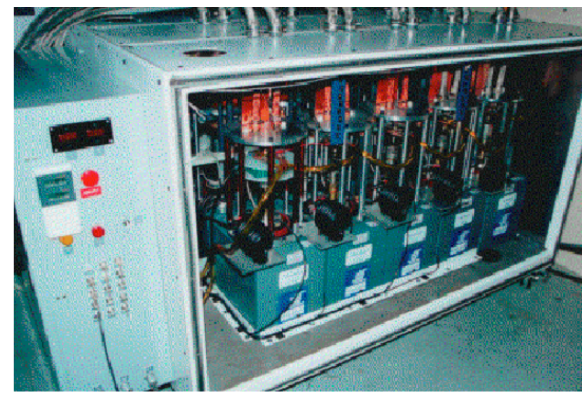
R. Raman, Advanced fueling system for use as a burn control tool in a burning plasma device, Fus. Sci. and Techn., Vol **50**, 84 (2006*) – describes density profile control*

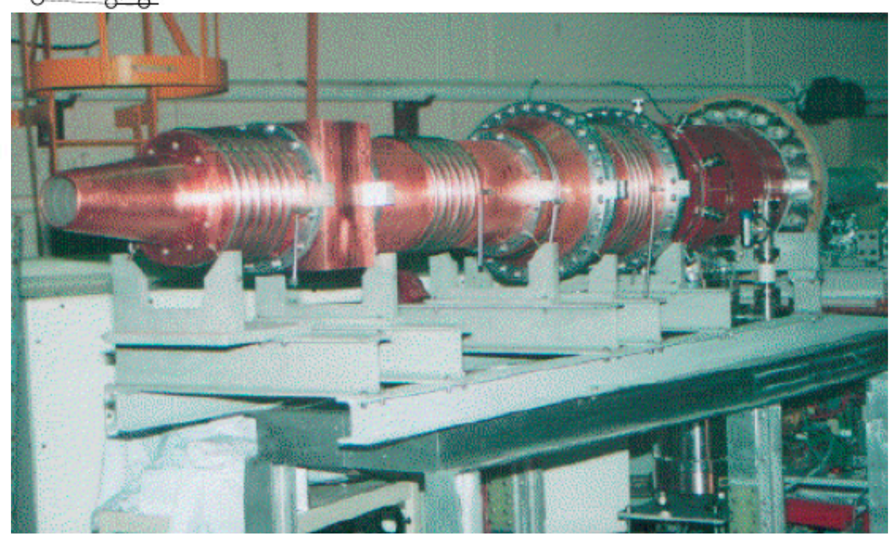
R. Raman, Advanced Fueling System for Steady-State Operation of a Fusion Reactor, Fus. Sci. and Techn., **54**, 71 (2008) *- describes improved usage of tritium*

R. Raman, Advanced Fuelling System for ITER, Fusion Engineering and Design, **83**, 1368 (2008) *– system looks attractive for ITER, should be easier in a ST reactor*

Layout in NSTX-U Test Cell





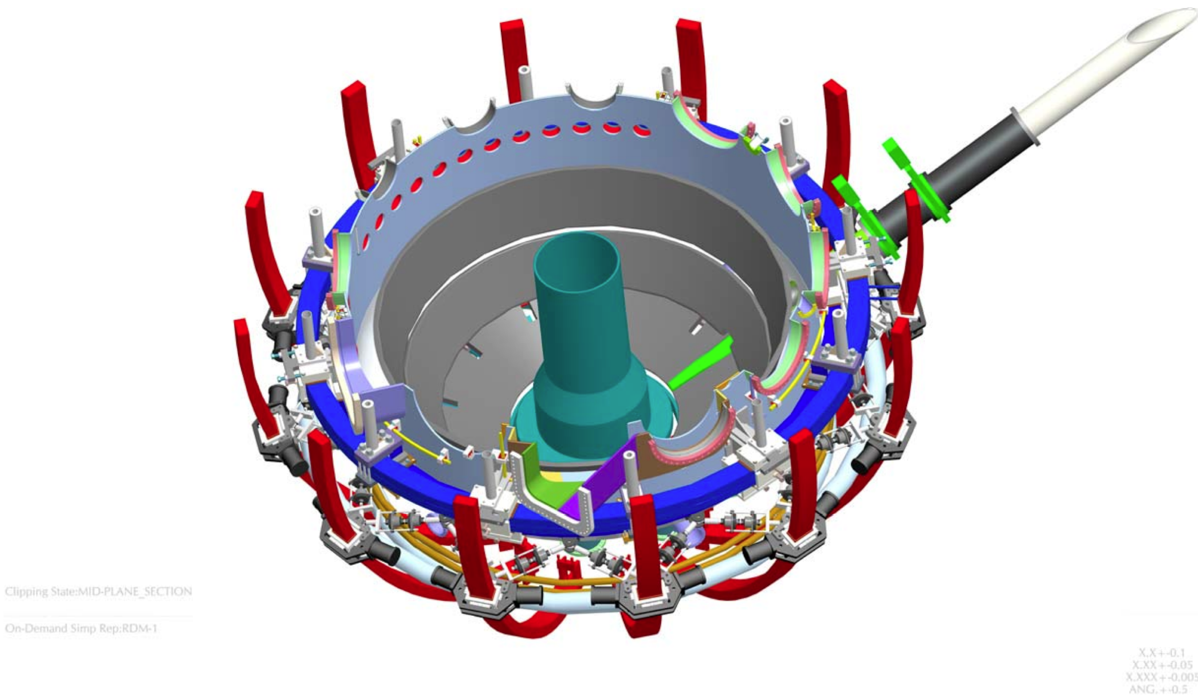


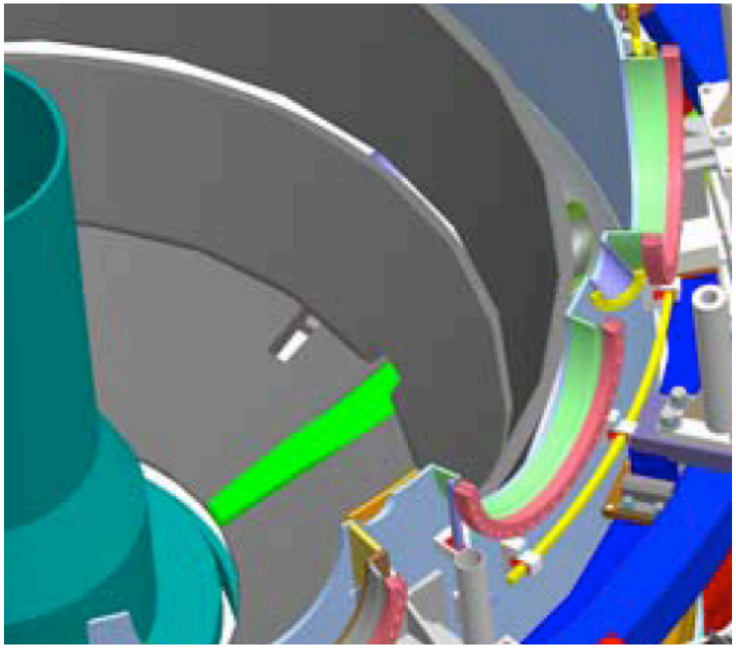
R. Raman, T.R. Jarboe, et al., – CT for NSTX-U -02072012

Replaceable Divertor Module for NSTX Upgrade

S. Zweben, R.A. Ellis, R. Goldston, H. Ji, C. Skinner, P. Titus, A. Xing
NSTX Facility Brainstorming Meeting Feb. 2012

- Small divertor segment replaced during run using bellows, for testing new PFCs, e.g. CPS or flowing liquid metal, or for new diagnostics, e.g. probes or surface samples





Conceptual Design Has Been Completed

- Divertor segment would be 7.5 cm-15 cm wide and 60 cm in radial length, with toroidal coverage ~ 6º
- An new 8” hole would have to be cut into the outer vacuum vessel wall at Bay G and some coils moved (a minor job compared with other work already being done on vessel)
- Modules could be powered and instrumented, e.g. with lithium heater or pumps, probes, and thermocouples, (or left as a carbon tile when not in use for PFC tests)
- Vacuum interlock would allow new modules to be installed and removed relatively quickly, and old modules can be kept under vacuum for later analysis

Testing Fast Flowing Liquid Metal as a PFC at NSTX-U Divertor

H. Ji, S. Zweben, R. Goldston, E. Spence, D. Majeski et al.
NSTX Facility Enhancement Discussion Feb 2012

- We have proposed to DoE to do
  a) Establish fast liquid metal channel flow across magnetic field in divertor-like geometry
  b) Characterize heat transfer properties of free-surface liquid metal pool and flow
  c) Study electromagnetic effects of side walls channel flow

- If funded, we can follow the development path of a) ➔ b) ➔ c) ➔ RDM to test and implement the idea of using flowing liquid metal to remove heat.

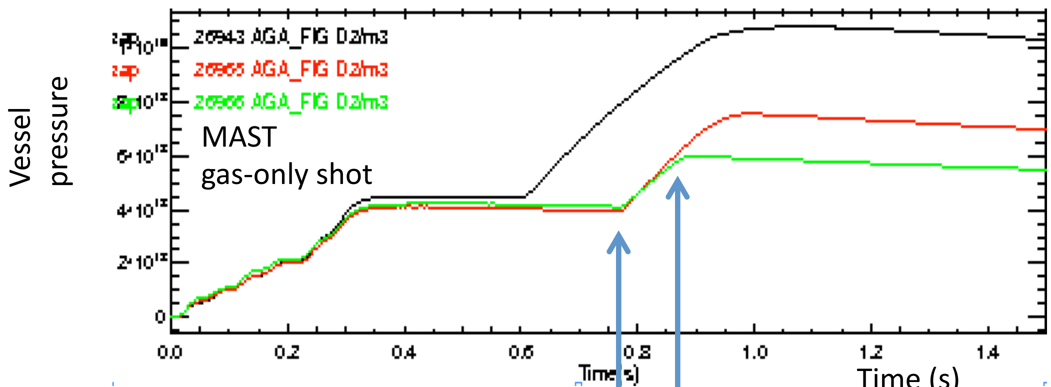
- If unfunded, we can use (limited) knowledge and expertise from LMX (Liquid Metal Experiment) and from UCLA to design and construct a liquid metal loop in RDM.

- If no RDM, the only possible option is to modify a section of divertor area to implement flowing liquid metal PFC, which should be much more “disruptive” to other activity at NSTX-U.

High Field Side Gas Injection shut-off valve

Charles Skinner

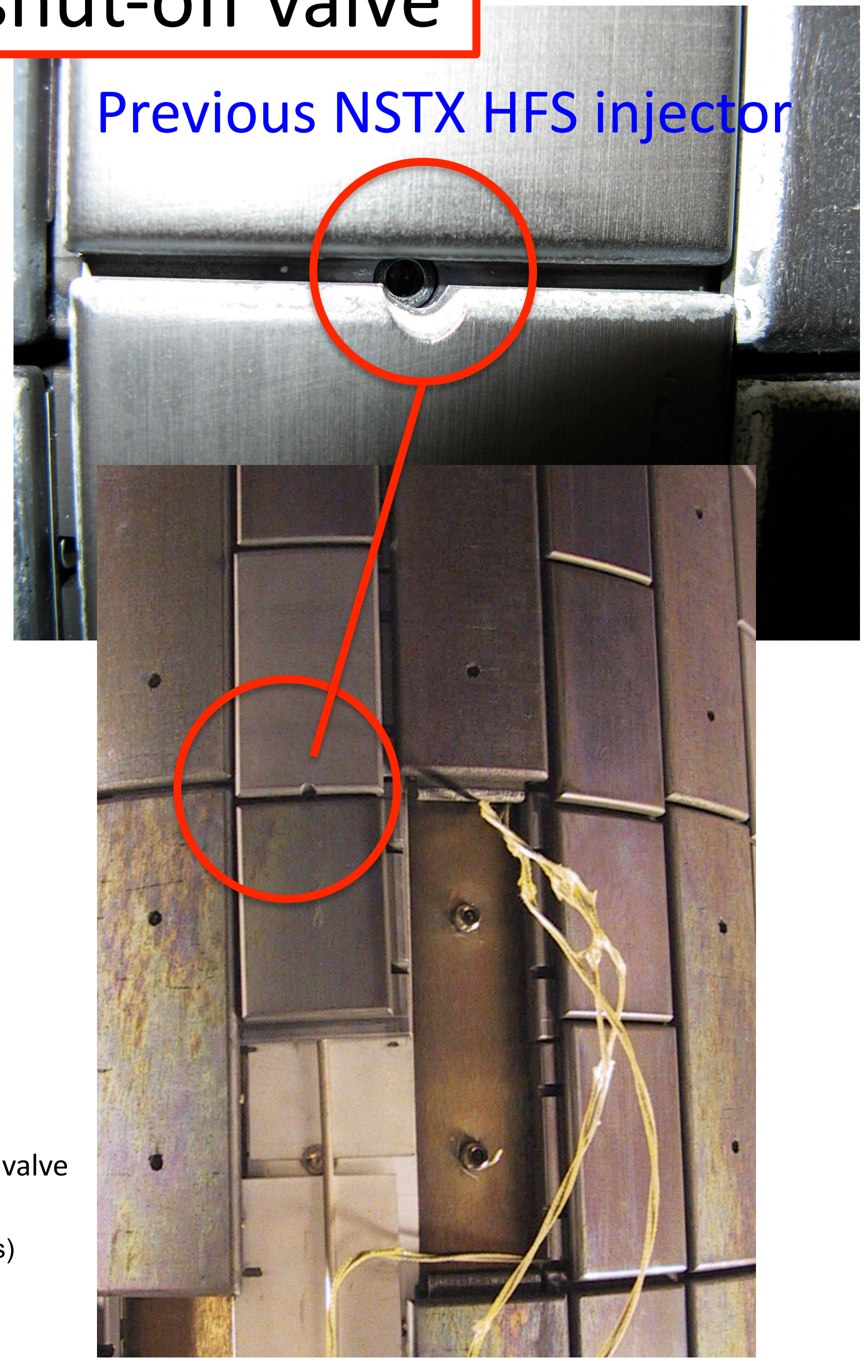
- Previous High Field Side Gas Injection had no shut-off valve complicating density control.
- Upgrade CS will have more available space.
- Propose shut-off valve actuated by in-pipe wire.
- MAST experience: (Geof Cunningham).



Gas input begins (red/green curves)

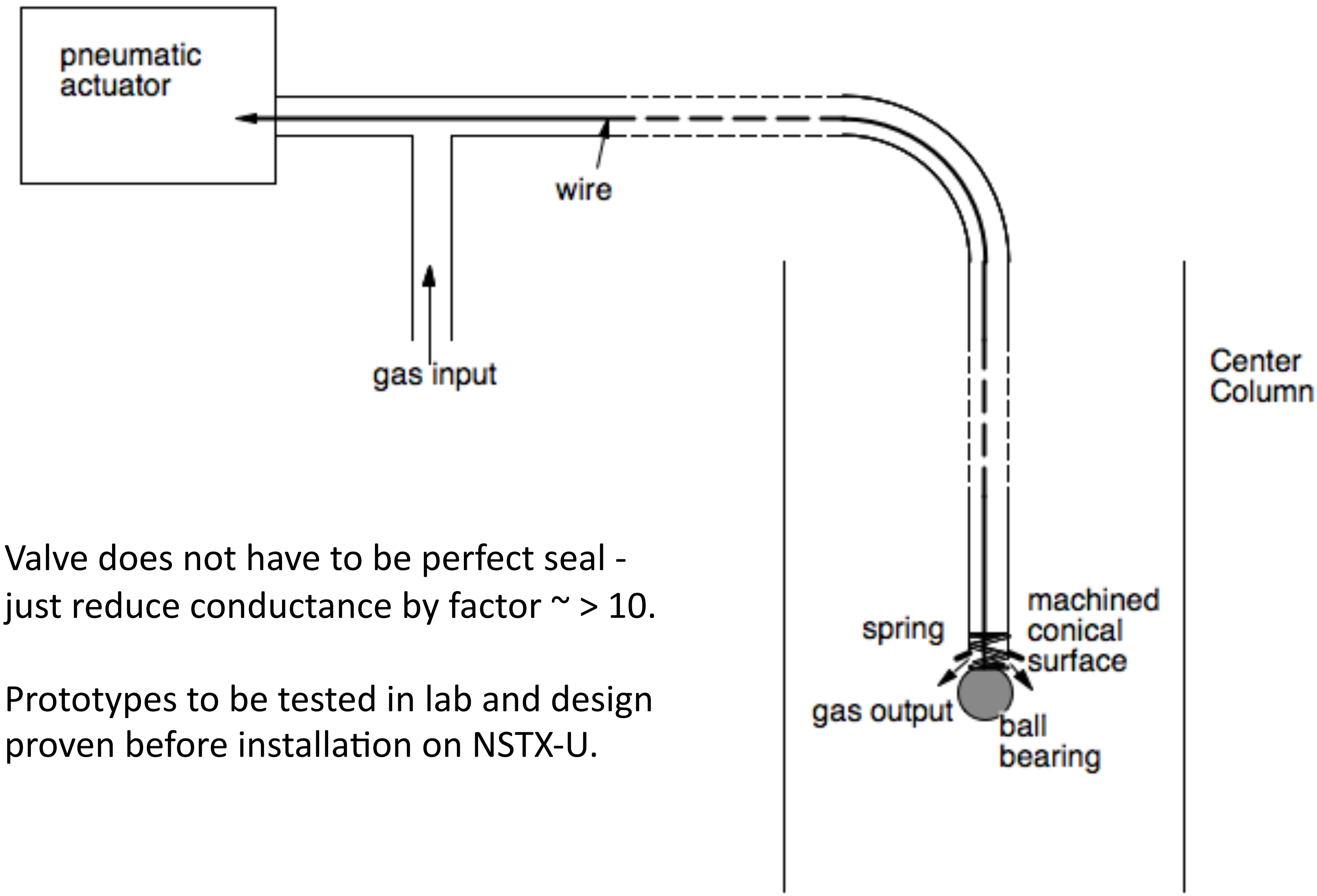
Gas input terminated by shut-off valve in 5 ms (green curve) compared to 100 ms without valve (red curve)

(The black curve was recorded the previous day prior to some mechanical adjustments)



NSTX-U facility enhancement brainstorming Feb. 7 and 8 2012.

Shut-off valve initial conceptual design



- Valve does not have to be perfect seal - just reduce conductance by factor ~ > 10.
- Prototypes to be tested in lab and design proven before installation on NSTX-U.

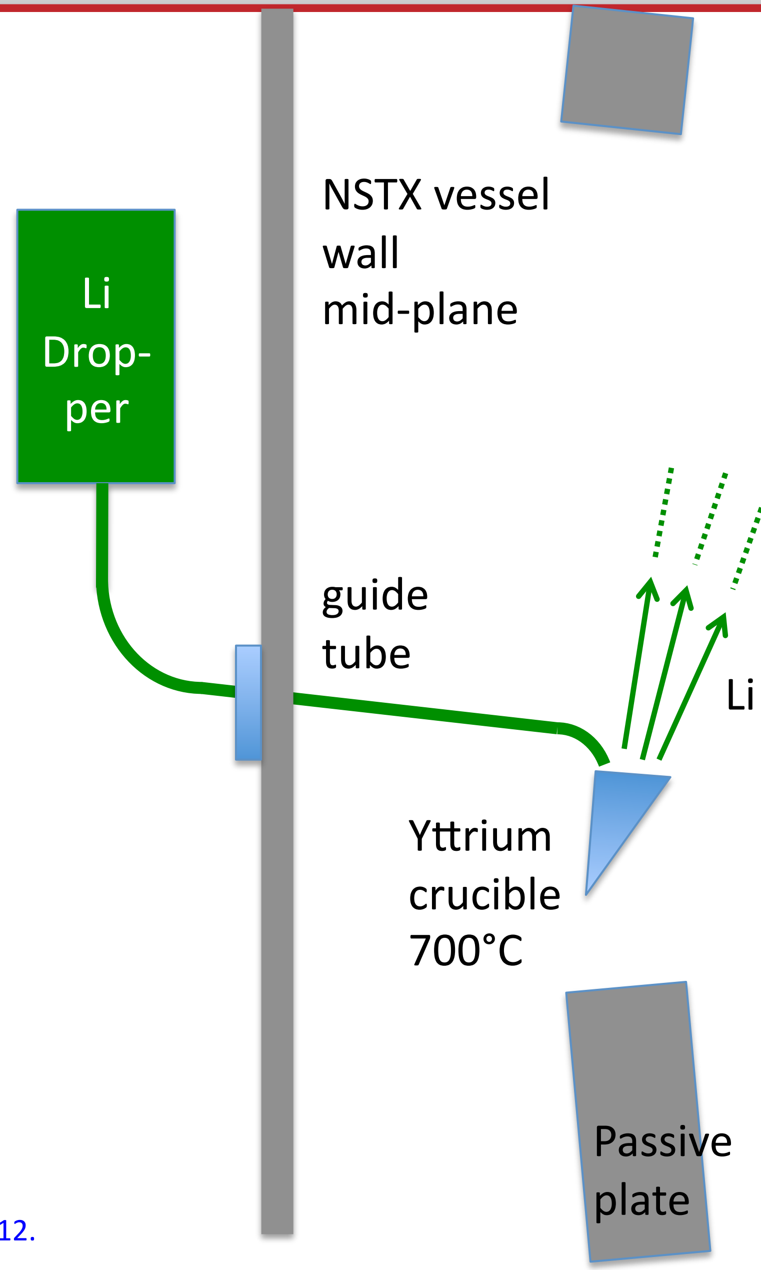
Mini Li evaporator concept

Combine Dropper and Li crucible technology

- heat mid-plane yttrium crucible
  to 700°C
- drop ~ 200 mg of Li powder into crucible after discharge.
- all Li promptly evaporated to upper vessel.

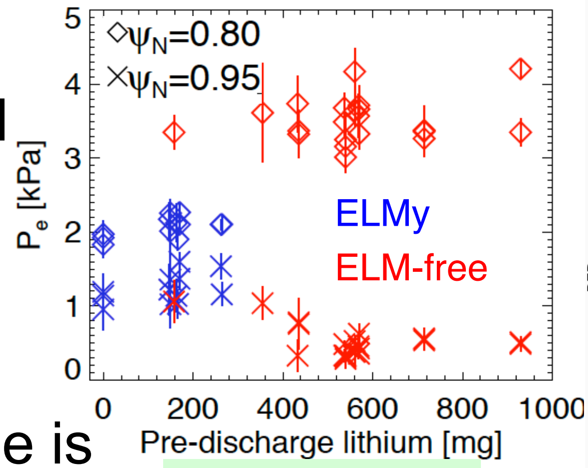
Advantages:

- no shutters
- evaporation seconds before next discharge
  – little reactions with residual gases
- 2 midplane locations cover upper vessel
- dropper technology mature.
  - Controllable Li dose
- ~ point source collimation
  - easy to avoid RF antenna
- ~ 2.75” conflat feedthrough

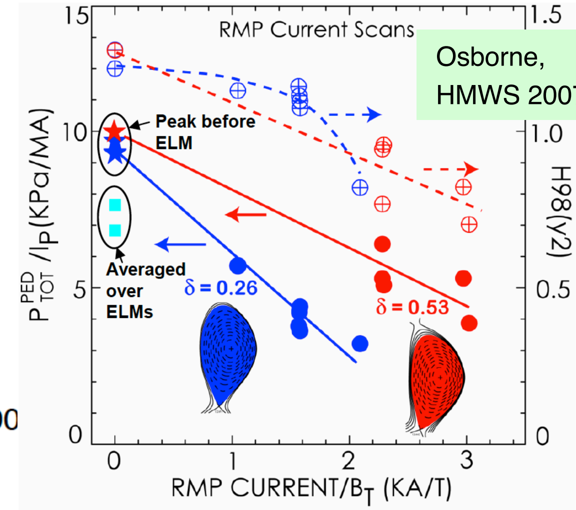


Off-midplane coils for improved control over poloidal spectrum of magnetic perturbations

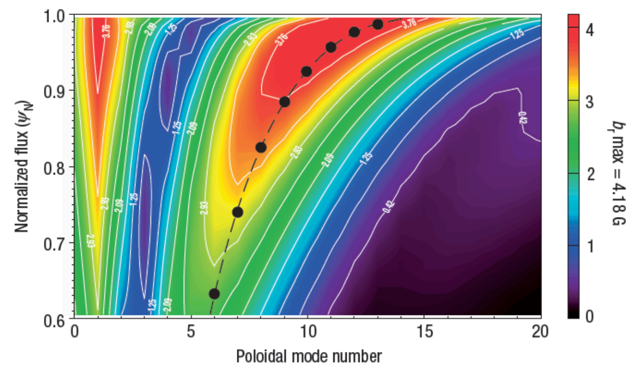
- Lithium coatings work to reduce edge density and pressure and eliminate ELMs, much like RMP
- However the particle/ impurity confinement time is too high – true ELM-free H-mode
- Off-midplane coils in NSTX-U should increase particle transport from the improved poloidal spectral control: synergy with lithium?



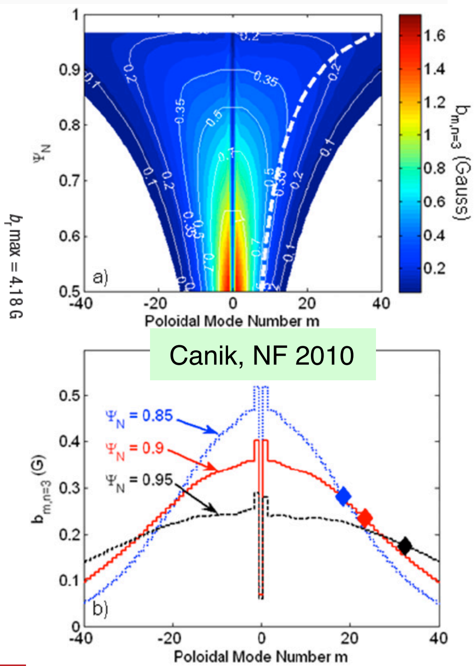
Maingi, to be submitted



Osborne, HMWS 2007



Evans, Nature Phys. 2006



Canik, NF 2010