NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Research Operations For NSTX-U

Stefan Gerhardt

Research Staff

Head of Experimental Research Operations

Thanks to Brent Stratton, Bob Kaita, Masa Ono, Jon Menard, Charlie Gentile, & Larry Dudek

NSTX-U Ready for Operations Review

B-318

December 9th, 2014

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
ORNL
PPPL
Princeton U
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Think Tank, Inc.
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U Colorado
U Illinois
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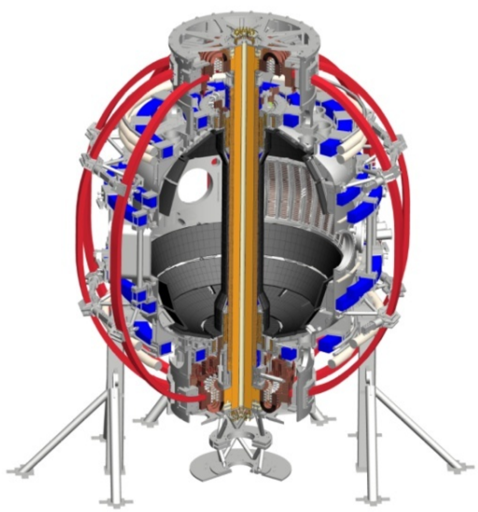
U Tulsa
U Washington
U Wisconsin
X Science LLC



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

Outline

- Long Term NSTX-U Research Agenda
- Recent Operations Work to Support Research Agenda
- Operations with Aquapour/CTD-425 Composite Material
- Schedule for the 1st Research Campaign
- Process for Execution of the First Research Campaign

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Long-Term Research Agenda For NSTX-U is Defined in the 5-Year Plan

- Available on the web at:
- http://nstx-u.pppl.gov/five-year-plan/five-year-plan-2014-18
- 11 Chapters, written by the entire NSTX-U team, describing
  - the research goals
  - future upgrades to the facility
- Reviewed over three days in May 2013.
- Accepted by DoE.

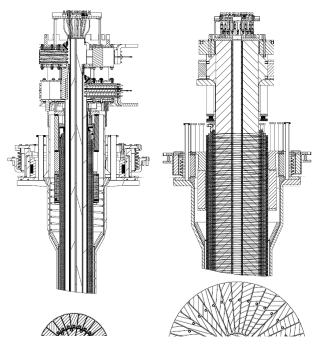
Five Year Plan Described Five Highest Priority Research Goals

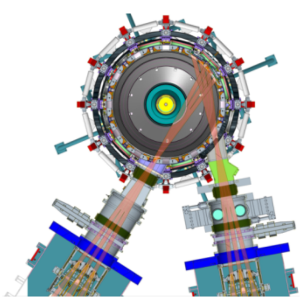
Present Upgrade **Future Upgrade (See Backup Slides)**

1. **Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF**
   - 2nd neutral beam, higher TF
   - Cryopump (future upgrade) , NCC (future upgrade)
2. **Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding**
   - 2nd neutral beam, higher TF, higher I_P
   - Cryopump (future upgrade), NCC (future upgrade)
3. **Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid**
   - 2nd neutral beam, higher TF
   - ECH (future upgrade)
4. **Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes**
   - Expanded PF-1 coil set, new divertor gas injectors
5. **Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps**
   - Metal PFCs and flowing lithium systems (future upgrades)

FY2015-16 Research Milestones Target Exploitation of New Capabilities, Exploration of New Regimes

Previous center-stack | New center-stack





Present NBI | New 2[nd] NBI

Incremental (full ops)

Expt. Run Weeks:	FY2015: 12 / 14	FY2016: 16 / 20
Macroscopic Stability		
Transport and Turbulence	R15-1 Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	IR16-1 Assess confinement and local transport and turbulence at low ν^* with full range of B_T, I_P, and NBI power
Boundary Physics	Develop snowflake configuration, study edge and divertor properties	R16-1 Assess heat-flux mitigation and PFC response using advanced divertor configurations + radiation at high $q_{\|\|-div}$
Materials & PFCs	IR15-1	
Waves+Energetic Particles	R15-2 Characterize effects of NBI injection angle on fast-ion distribution and NBI-CD profile	R16-2 Assess fast-wave SOL losses and core thermal / fast ion interactions at increased B_T, I_P
Solenoid-free Start-up/ramp-up		R16-3 Develop high-non-inductive fraction NBI H-modes for ramp-up & sustainment
Adv. Scenarios and Control	R15-3 Develop physics+operational tools for high-performance discharges (κ, δ, β, EF/RWM)	
ITER Needs + Cross-cutting		
Joint Research Target (JRT)	Quantify impact of broadened J(r) and p(r) on tokamak confinement and stability	Assess disruption mitigation, initial tests of real-time warning and prediction techniques

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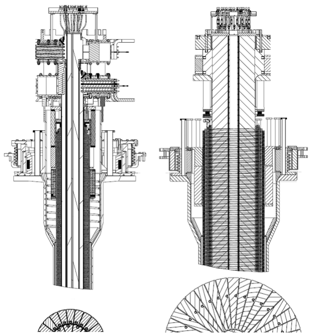
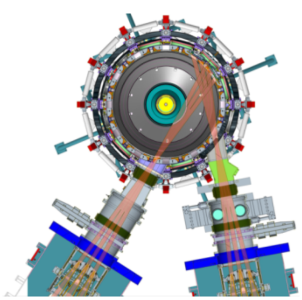
Previous center-stack | New center-stack





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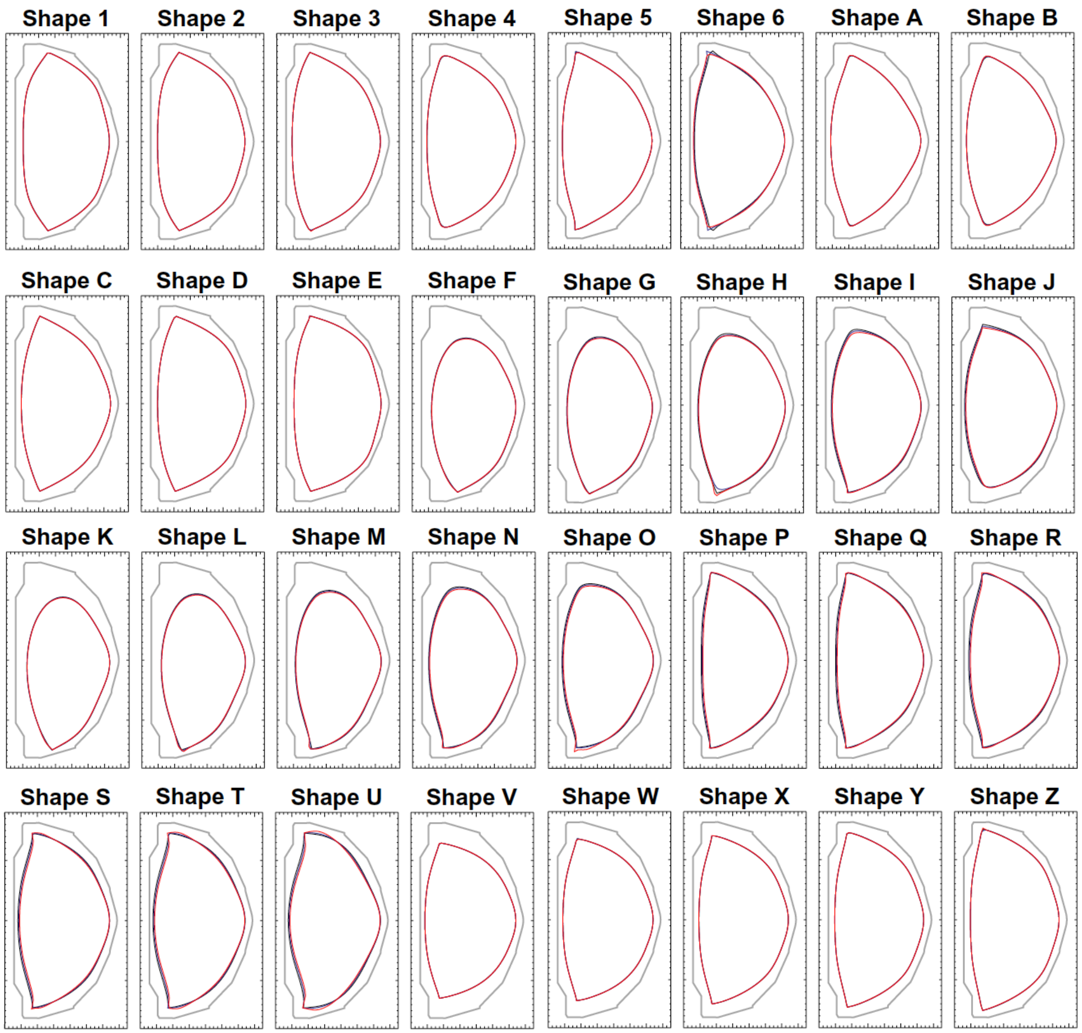
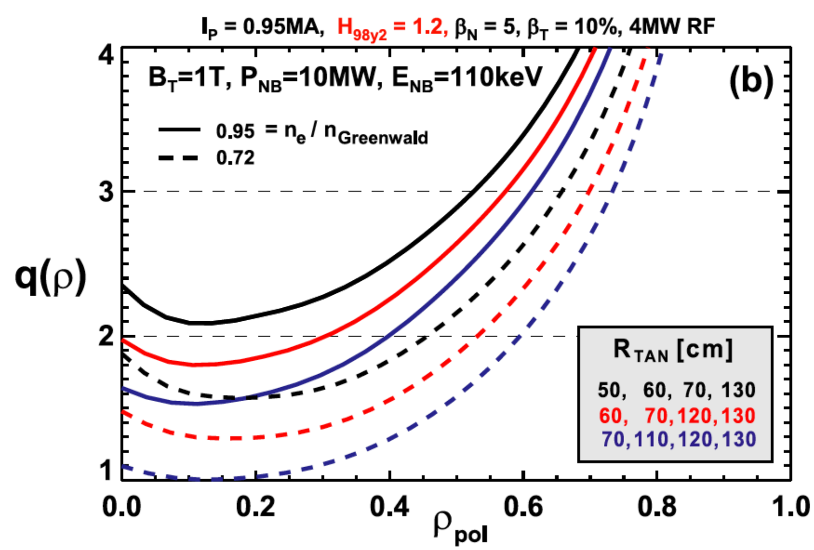
Engineering Design Driven By Physics Considerations



J. E. Menard, et al., Nuclear Fusion **52**, 083015 (2012)
S. P. Gerhardt, et al., Nuclear Fusion **52**, 083020 (2012)

- Poloidal field set consistent with a set of 96 plasma equilibria at 2 MA, 1T.
  - High and low triangularity & elongation, conventional and snowflake divertors, range of OH flux states
  - Defines CS coil locations, power supply requirements, vessel/coil forces/stresses that must be managed, some DCPS limits
- Beam tangency radii determined by integrated modeling with TRANSP.
  - Provides a range of current profiles.



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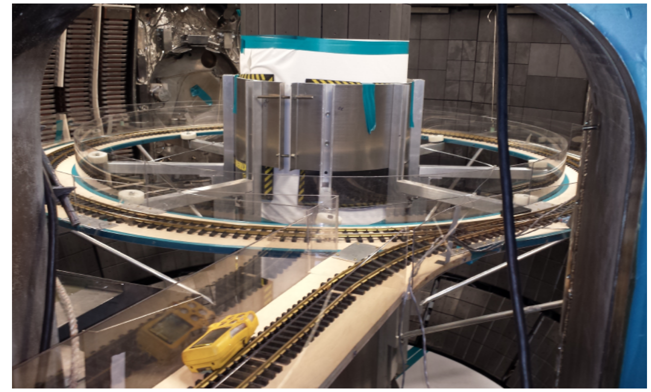
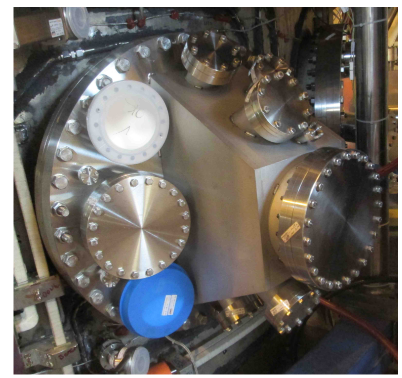
Research Prep. Has Been Accomplished in Concert With the Upgrade Project: Diagnostics

- Neutron detectors installed, and calibrated with in-vessel train track.
- Thomson scattering collection optics aligned, vacuum boundary established.
  - On track to calibrate & support experiments on the schedule to be presented later
- New diagnostics in final stage of fabrication/installation:
  - Three new SSNPAs (UC-Irvine)
  - Bolometer, multi-energy SXR system (PPPL & JHU)
  - EUV spectroscopy systems (LLNL)
- Other major profile diagnostics reinstalled, spatially calibrated, intensity calibrated where appropriate:
  - CHERS, FIDA, T-FIDA, P-CHERS. MSE, MSE-LIF
- Magnetic diagnostics on CS expanded as part of the upgrade project.
  - And legacy magnetics on the outer vessel tested, repaired.
- Three new large port covers fabricated, installed, populated to accommodate systems displaced by vessel modifications.

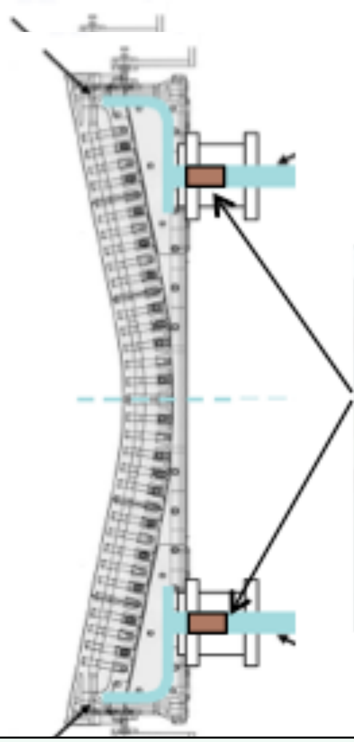




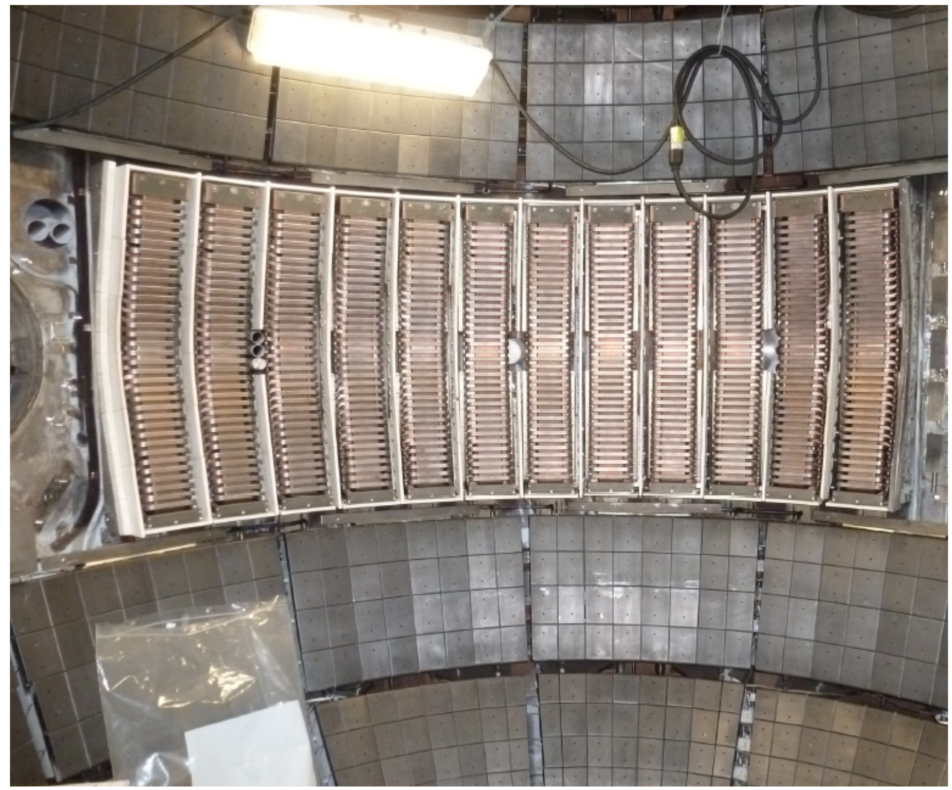
All work follows the same procedure/JHA/work package system as the Upgrade scope.

Research Prep. Has Been Accomplished in Concert With the Upgrade Project: HHFW Operations

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



Prototype electroformed compliant section



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

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

Remaining tasks:

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

Research Prep. Has Been Accomplished in Concert With the Upgrade Project: Boundary Physics Operations

- New boronization (dTMB) system will be used.
  - System designed through successful FDR.
  - Components have been ordered.
  - Electric service 85% complete…will use vacuum system PLC for controls.
  - Plan for it to be available for initial research operations.
- LIThium EvaporatoR (LITER)
  - LITERs were carefully stored during the outage.
  - Mounting locations are being repositioned.
  - New fume hood and other laboratory upgrades complete for LITER filling and maintenance.
  - Plan for LITER to be available for research operations.
- High-conductance divertor gas injection lines (2) have been installed
  - Supports radiative divertor studies
- Gas delivery system upgrades.
  - Moving to a uniform system of valve drive technologies.
  - All valves to be commanded from PCS.
- Materials Analysis Particles Probe (MAPP) probe has been fit-up w/ a new stand.
  - Allows material samples to be exposed to the plasma and then examined in-situ with surface science techniques.

All work follows the same procedure/JHA/work package system as the Upgrade scope.

Research Prep. Has Been Accomplished in Concert With the Upgrade Project: Physics Ops. And Plasma Control

- New firing generators for transrex recifiers designed, tested, fabricated, deployed.
- New in-house design for realtime digitizer completed, in fabrication.
- New I_P measurement systems and associate permissive generators designed, fabricated, in testing.
- Magnetics racks re-wired to support Upgrade operations, integrators now being tested.
- All low-level plasma control software has been revisited, upgraded.
  - Includes moving power supply control software from stand-alone code to an algorithm within PCS.
  - Integration of the “FCC DCPS” with associated inputs/outputs is ~85% complete.
  - System is in the final testing stages to support power supply dummy load testing.
- In the process of revisiting all physics algorithms
  - Have assigned a cognizant physicist to each algorithm to provide accountability.

All work follows the same procedure/JHA/work package system as the Upgrade scope.

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Background: We Have Plans to Increase the Field, Current & Pulse Duration Over 3 Years

	NSTX (Max.)	FY 2015 NSTX-U Operations	FY 2016 NSTX-U Operations	FY 2017 NSTX-U Operations	Ultimate Goal
I_P [MA]	1.2	~1.6	2.0	2.0	2.0
B_T [T]	0.55	~0.8	1.0	1.0	1.0
Allowed TF I^2t [MA^2s]	7.3	80	120	160	160

1st year goal: operating points with forces up to ½ the way between NSTX and NSTX-U, ½ the design-point heating of any PF/TF coil (~75% for OH)

2nd year goal: Full field and current, but still limiting the PF/TF coil heating

3rd year goal: Full capability

1st and 2nd year goals not affected materially by composite material

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3rd year goal: Full capability

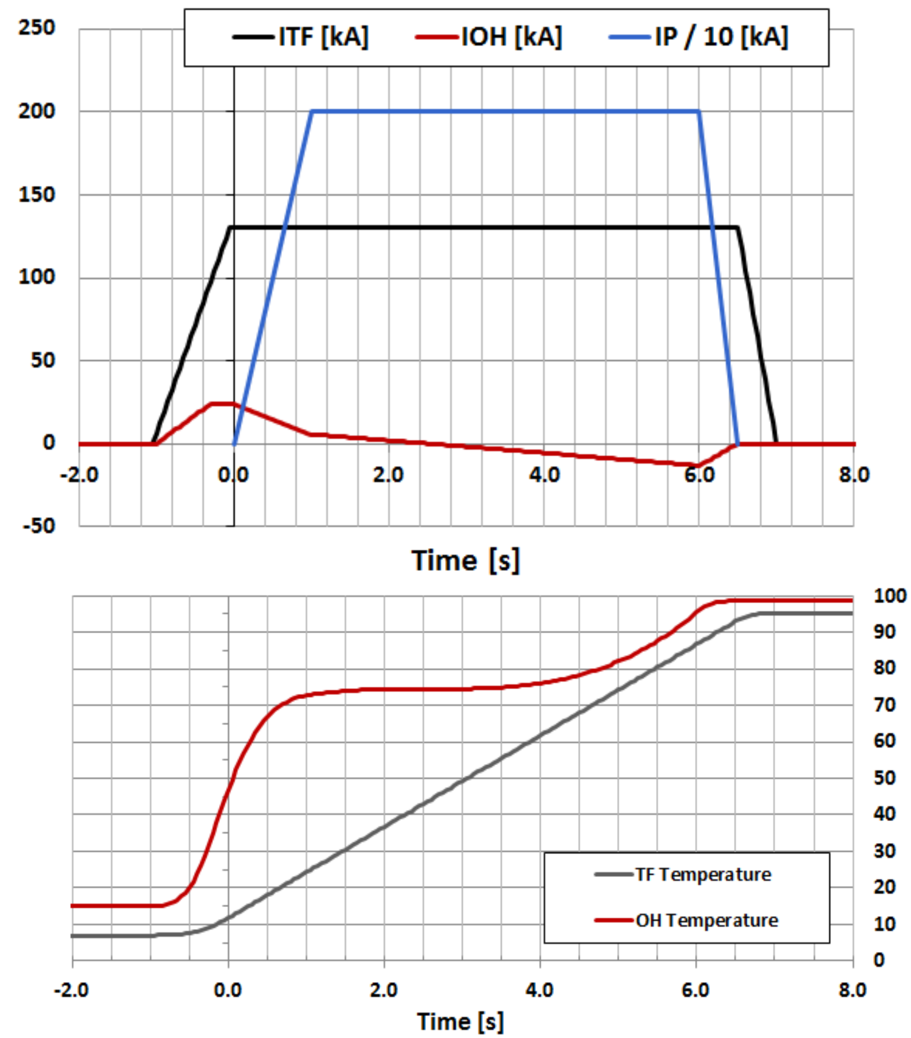
This scenario most likely to be affected

1st and 2nd year goals not affected materially by composite material

Summary Statement:
Physics Program Largely Unaffected By Requirement $T_{TF}<T_{OH}$

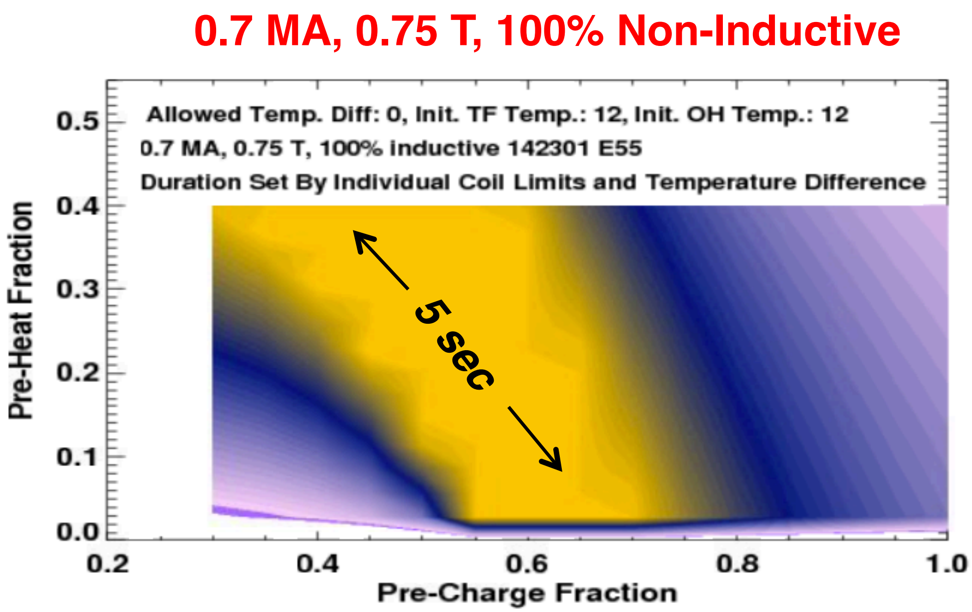
- Illustrative Example: 2 MA, 1T, 5 second.
- TF Coil:
  - Current is constant
  - Temperature is linear
- OH Coil:
  - current has a zero-crossing
  - Temperature has an "S-Shaped" curve.
- Options for maintaining $T_{TF}<T_{OH}$.
  - ***Pre-heat the OH coil*** using currents (or water) before the TF turns on.
  - Control the shape of the OH S-curve by ***adjusting the amount of pre-charge***.
- In this example,
  - Full 24 kA pre-charge
  - Pre-charge duration is extended to provide heating.

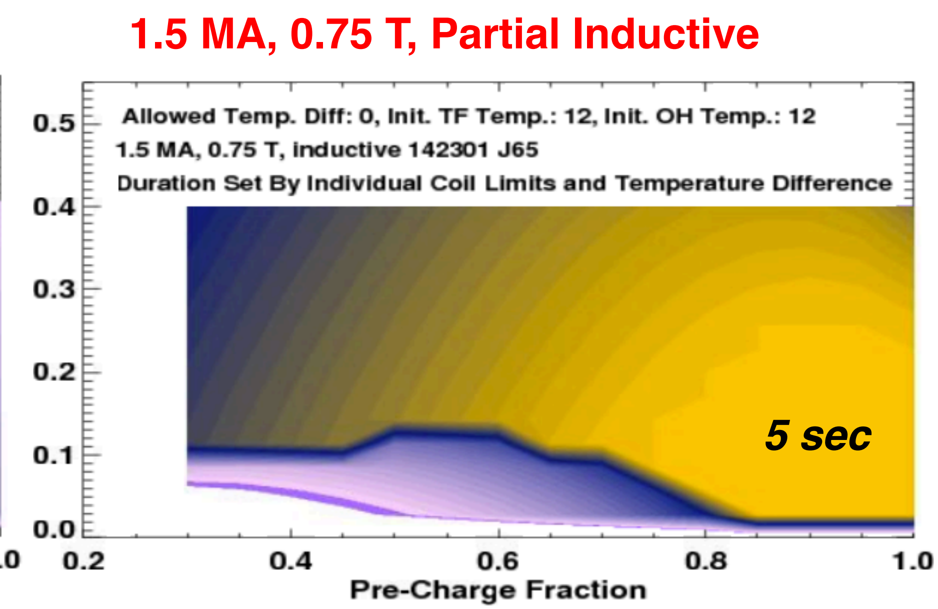
H_{98} = 1.2, $f_{Greenwald}$ = 0.75, P_{NBI} = 8MW, β_N = 4.6



Initial Operations Will Be Largely Unaffected By Aquapour/CTD-425 Composite

- Scan two variables in these studies:
  - Pre-heat level, quantified as the fraction of the full OH coil I^2t limit used before the shot starts.
  - Pre-Charge fraction, quantified as the fraction of 24 kA used.



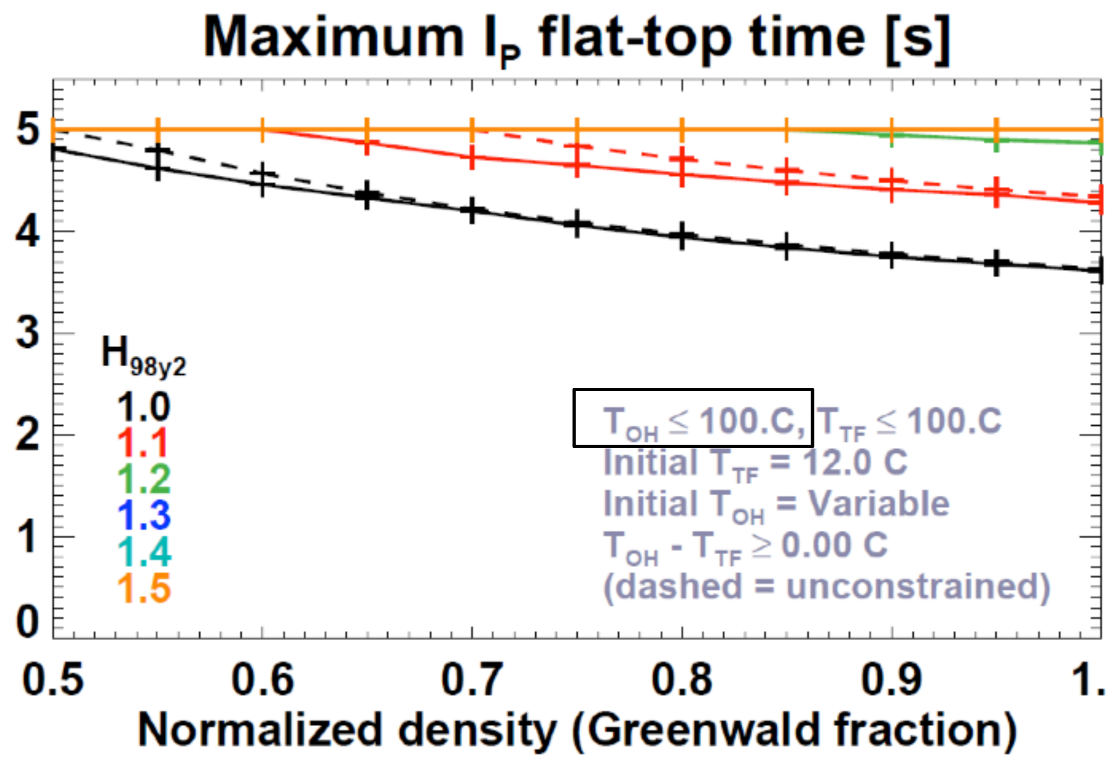


- Resistive pre-heat of ~15% provides operating room for 0.75 T scenarios typical of the first year.
  - Same as starting the coil at ~23 C

Limitations Become Apparent, but Manageable, for 2 MA Cases
Reason: These Often Required the Full OH I^2t

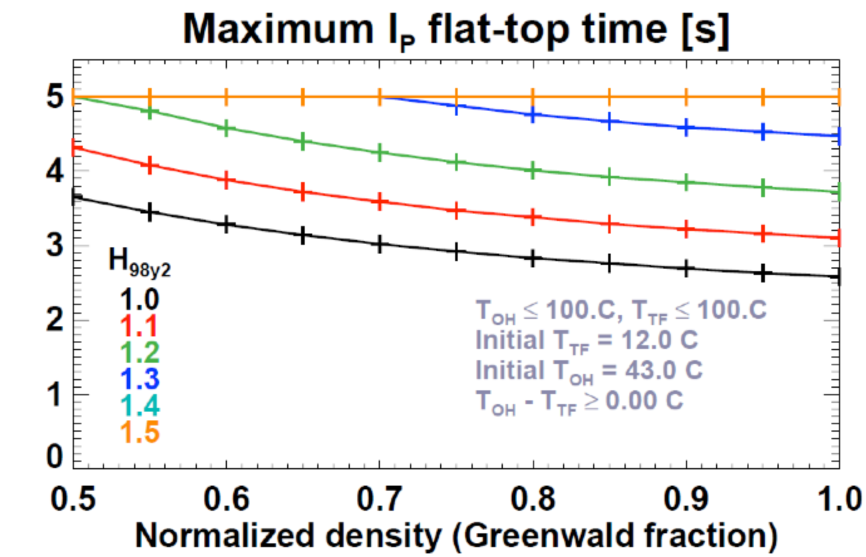
- 0D study as a function
  - Confinement (H_{98})
  - Density (Greenwald)
- Determine via optimizer the optimum initial OH temperature, *limiting the maximum to 100 C.*
- Result:
  - Typically only a 0.2 second (or less) reduction in pulse length, provided the pre-heat is optimized
  - H_{98}~1.2 needed for reliable 5 sec operation for any constraint on relative temperatures.

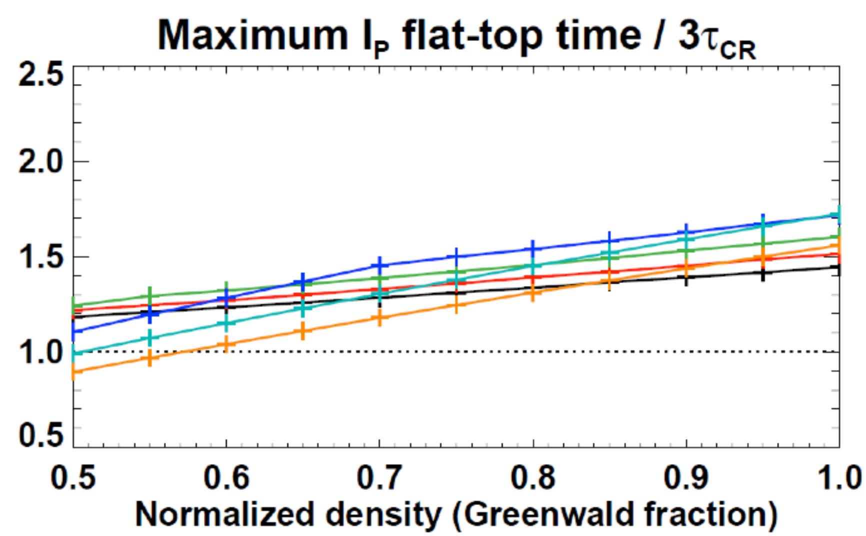
Solid:
$T_{TF}<T_{OH}$ applied as a constraint
Dashed:
No constraint on relative temperatures



Second Optimization: Find Initial OH Temperature that Guarantees Current Profile Equilibration for a range of 2 MA Configurations

- Two assumptions in this study:
  - The important normalization for the discharge duration is the $3\tau_{CR}$.
  - It will be an imposition to change the initial OH temperature all the time, so need to find an optimal single value.
- Fix the initial OH temperature to 43 C
  - Could be achieved, for instance, by a "standard" OH current pulse, or the water pre-heater.
- Durations in physical units lowered for H_{98}=1, but are *greater than $3\tau_{CR}$ for essentially all densities and confinement*.
- 110 C operation on the OH largely eliminates the composite material as an issue.
  - Optimal initial temperature drops to 36 C.
  - Plasma thermal energy confinement and CD physics, not the composite material, would have the dominant impact on the pulse duration at 2 MA.
  - Under engineering evaluation, looking quite feasible.





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Activities between CD4 and Research Run

Important to optimize them to start the timely research run

March 2015			April 2015		May 2015		June 2015			
ISTP	CD-4	Short vent, Facility Work	MPTS Rayleigh Raman	Bake Out	ISTP	Commisioning	Run Week	Run Week	Maint.	Run Week

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

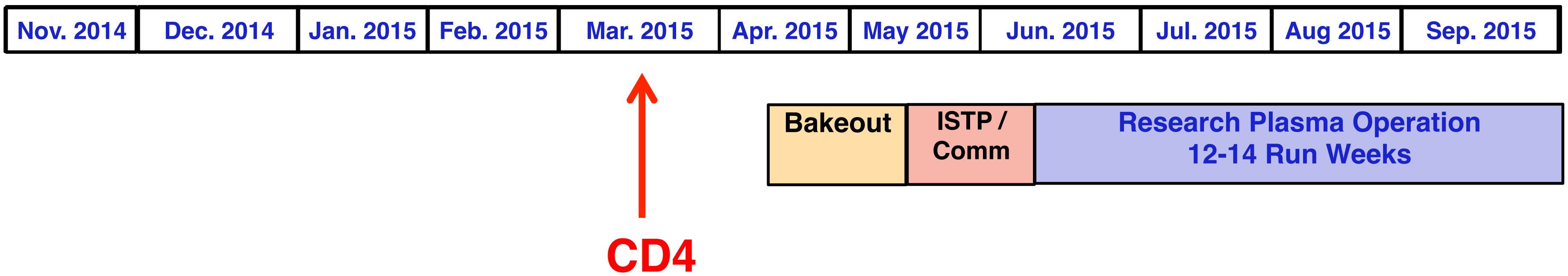
Calibrations:
Magnetic
MSE
CHERS
Neutrons

Boronization / GDC

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

If some tasks can be moved before the CD-4 date without impacting that schedule, we will do so.

Nominal NSTX-U run schedule for FY2015



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

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NSTX-U Experimental Program Organizational Structure is Clearly Defined

NSTX Upgrade Department

- **Project Director**: Masayuki Ono
- **Program Director**: Jon Menard; Deputy: Stan Kaye
  - Run Coordination: Jon Menard, Stefan Gerhardt (deputy)
  - Engineering Ops: Al von Halle; Project Engineer: Peter Titus
    - Device Operation: A. von Halle
    - Heating Systems: T. Stevenson
    - Auxiliary Systems: W. Blanchard
    - Power Systems: J. Lacenere
    - Central I&C: P. Sichta
    - Construction: E. Perry
  - Experimental Research Ops: Stefan Gerhardt; Deputy: Robert Kaita
    - Physics Operations: D. Mueller
    - RF Systems: J. Hosea
    - Diagnostic Ops & R&D: B. Stratton
    - Diagnostic Design/Fab: R. Ellis
    - Boundary Physics Operations: R. Kaita
  - Physics Analysis: Stan Kaye
    - Publications & Presentations
    - Computational Support: B. Davis
    - Theory & Simulation: A. Bhattacharjee
  - **Science Groups**
    - Boundary Science: R. Maingi
    - Core Science: S. Kaye
    - Integrated Scenarios: S. Gerhardt
    - Particle Control Task Force (FY2015-16): R. Maingi

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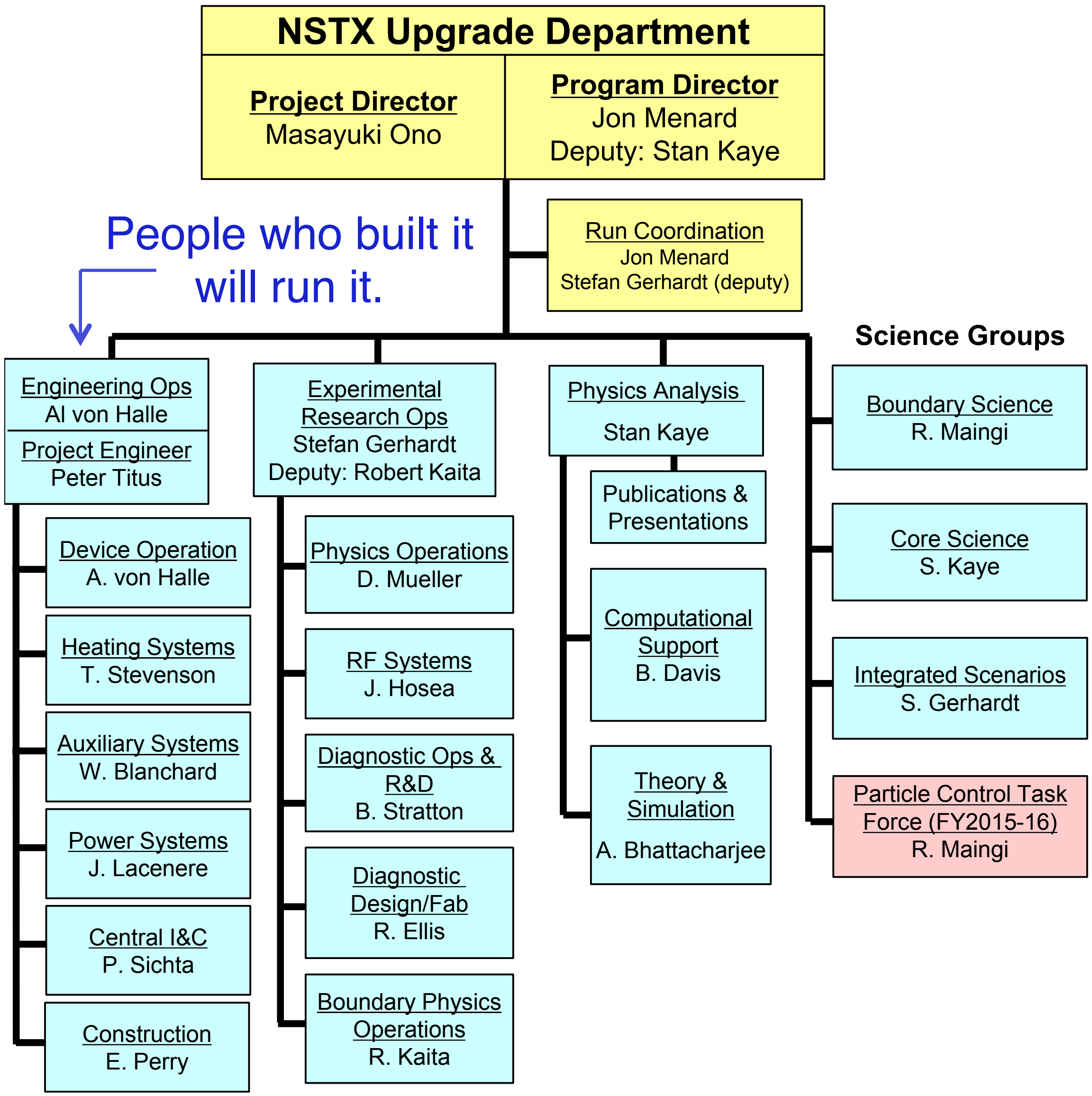


Work at D-Site is governed by the WCC & OP-AD-56, which defines the chain of command and various rolls (COE, D-Site supervisor, Health Physics,…).

Experimental program management goes through Engineering Ops. division to get work done.

NSTX-U Research Program Will be (re-)Organized Along 3 "Science Groups" and 9 TSGs for the FY15 run

NSTX Upgrade Science Program

Project Director
Masayuki Ono

Program Director
Jon Menard
Deputy: Stan Kaye

Physics Analysis
Stan Kaye

Run Coordination
Jon Menard
Stefan Gerhardt (deputy)

Cross-Cutting XMP/XPs

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

Collaborators in Science Program Leadership:

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

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

Pedestal Structure and Control
A. Diallo, R. Maingi
Theory/Modelling: J. Canik[1]
University Rep: D. Smith[2]

Divertor and Scrape-Off-Layer
V. Soukhanovskii[3], J.-W. Ahn[1]
Theory/Modelling: D. Stotler
University Rep: O. Schmitz[2]

Materials and PFCs
M. Jaworski, C. Skinner
Theory/Modelling: B. Wirth[4]
University Rep: J.-P. Allain[5]

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

Macroscopic Stability
J. Berkery[6], J.-K. Park
Theory/Modelling: S. Jardin
University Rep: D. Brennan[7]

Transport and Turbulence
W. Guttenfelder, Y. Ren
Theory/Modelling: W. Wang
University Rep: K. Tritz[8]

Energetic Particles
M. Podestá, D. Liu[9]
Theory/Modelling: N. Gorelenkov
University Rep: N. Crocker[10]

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

Advanced Scenarios and Control
D. Battaglia, S. Gerhardt
Theory/Modelling: F. Poli
University Rep: E. Kolemen[7]

Solenoid-free Start-up & Ramp-up
D. Mueller, R. Raman[11]
Theory/Modelling: F. Ebrahimi[7]

Wave Heating and Current Drive
R. Perkins, J. Hosea
Theory/Modelling: N. Bertelli
University Rep: P. Bonoli[12]

Particle Control Task Force (FY2015-16)
Leader: R. Maingi, **Deputy:** J. Canik[1]

Goal: Develop pumping and fueling tools, operating scenarios, and control systems to achieve main-ion and impurity density control for long-pulse

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

Topical Sub Groups (TSGs) play major role in governing the research program

- Led brainstorming, organization, writing of 5 year plan
- Address highest priority scientific issues through discussion and consensus at open meetings
- Organize the NSTX-U Research Forum sessions.
- Draft scientific milestones
- Propose and execute experiments
- Define facility and theory resources to achieve research goals
- Aid dissemination of results with Physics Analysis Division
  - Journal publications, invited talks, seminars, colloquia, conferences, ITPA, BPO
- Provide summaries of scientific progress at NSTX-U team meetings and other venues to promote discussion
- Assist and report to the NSTX-U Program and Project directors

Details of the Research Program Will Be Defined By The Team in a Series of Meetings

- Research Prep. Meeting: Jan. 28th and 29th
  - Designed to notify the scientific team of facility status
  - Day #1 talks:
    - Gerhardt : Intro, Magnetics
    - Von Halle : Engineering Operations (Power systems, NBI, this review,…)
    - D. Mueller : Physics Operations (operator training, PCS,…)
    - Kaita : Boundary Operations (GDC, LITER, Boronization,…)
    - Stratton : Diagnostic Operations
    - Hosea : RF Operations
  - Day #2: Update from SG/TSGs on research goals and XMP/XP solicitations
- Experimental proposals (XPs) submitted by through a dedicated web site.
  - Historically 1.5-2x more run times requested than is available.
- Research Forum (Feb 24th -27th, PPPL)
  - Opening plenary session summarizes anticipated run schedule & programmatic goals.
    - Include run time allocations, typically 1/3 of the available run time held in reserve.
  - Breakout sessions for each TSG allow open discussion of research proposals and preliminary XP prioritization.
  - Summary plenary session presents the preliminary prioritization.

What Exactly is An XP?

- What is an XP?
  - It is an official PPPL document, archived in the ops. center.
    - Process defined in OP-ADX-03
  - Subject both optional TSG and mandatory team reviews.
  - Author is the scientist who leads the XP.
  - Signed by SG or TSG leader
  - Run coordinator signature takes the place of the RLM.
  - Describes both required machine configuration and individual steps of the experiments.
  - Typically describes 1-2 days of run time.
  - Successful completion of an single XP should lead to a publication or invited talk.
- We also have XMPs.
  - ~2-4 hour blocks of run time designed to test a specific piece or hardware or control software.
  - Process defined in OP-ADX-02
- Weekly "program/ops" meeting where the run coordinator provides a draft ~2-3 week schedule, which is then iterated with the research and engineering team before posting.

Physics Operations Staff+Collaborators Will Be Ready to Execute the NSTX-U Research Program

- Three NSTX physics operators will return to NSTX-U.
  - D. Mueller is a world-recognized tokamak driver.
    - Operated TFTR
    - Has collaborated on EAST and K-STAR control development over the last year.
    - Author of the CD-4 XP.
    - Author of the machine commissioning XP.
  - D. Battaglia has spent the last 2 years as a DIII-D operator
  - R. Raman (U. of Washington) provides leadership in CHI, MGI areas + physics operations.
- D. Mueller will hold a training/refresher course following CD-4.
  - Plan to train an additional 2-3 operators.
  - Slides from previous course:
    - http://nstx.pppl.gov/DragNDrop/Operations/Physics_Operations_Course/
- Major diagnostics have primary and backup support.
  - Magnetics: S. Gerhardt + new post-doc.
  - CHERS: R. Bell + M. Podesta
  - Thomson Scattering: B. LeBlanc+A. Diallo+new post.-doc.

Summary

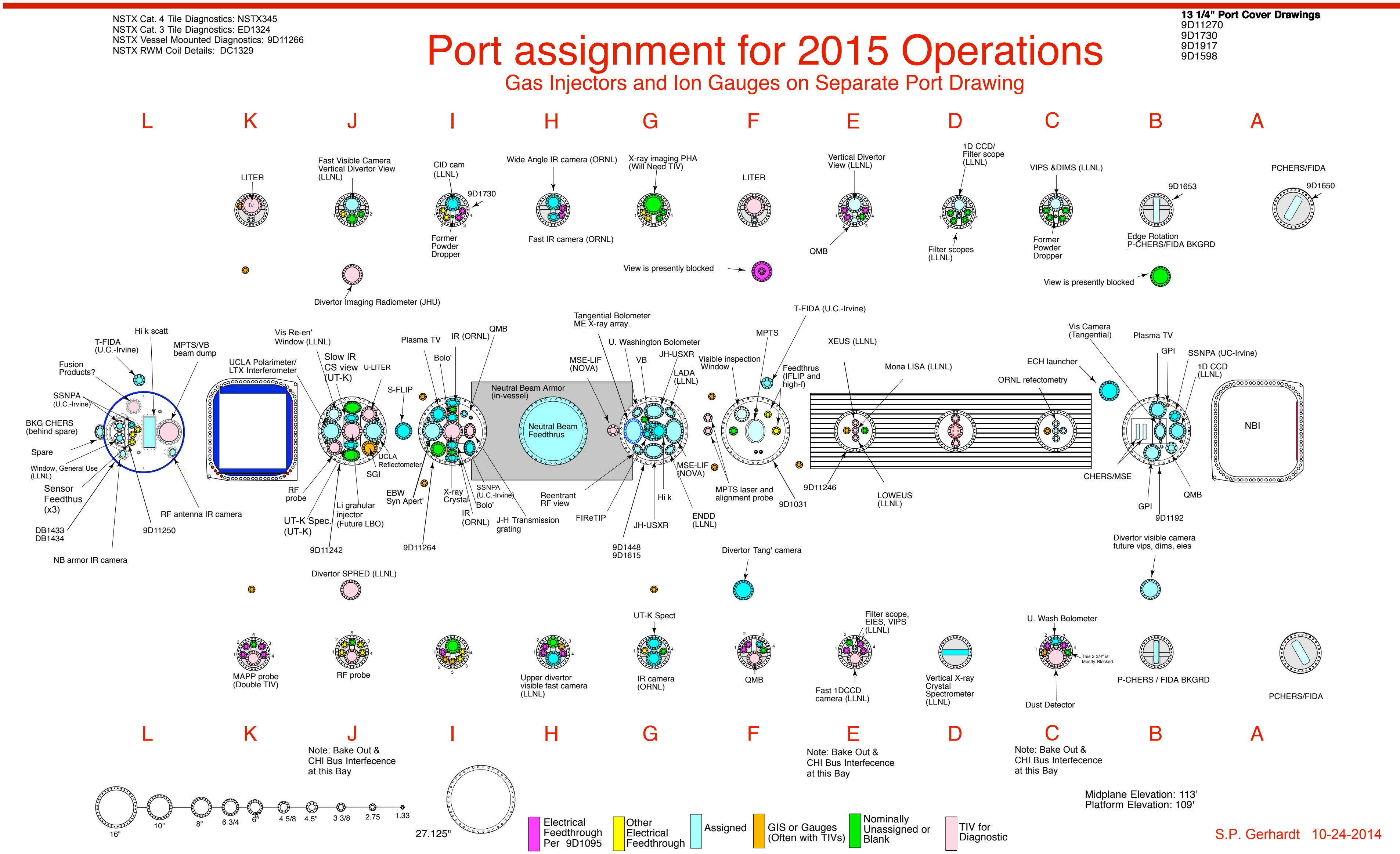
- NSTX-Upgrade project directly feeds the long term goals for the facility.
- Operations work, in concert with the Upgrade scope, has progressed well.
- Operations scenarios compatible with the Aquapour/ CTD-425 composite have been identified.
- The process for defining the research run is in place.

The NSTX-U team is excited and prepared to move to research operations!

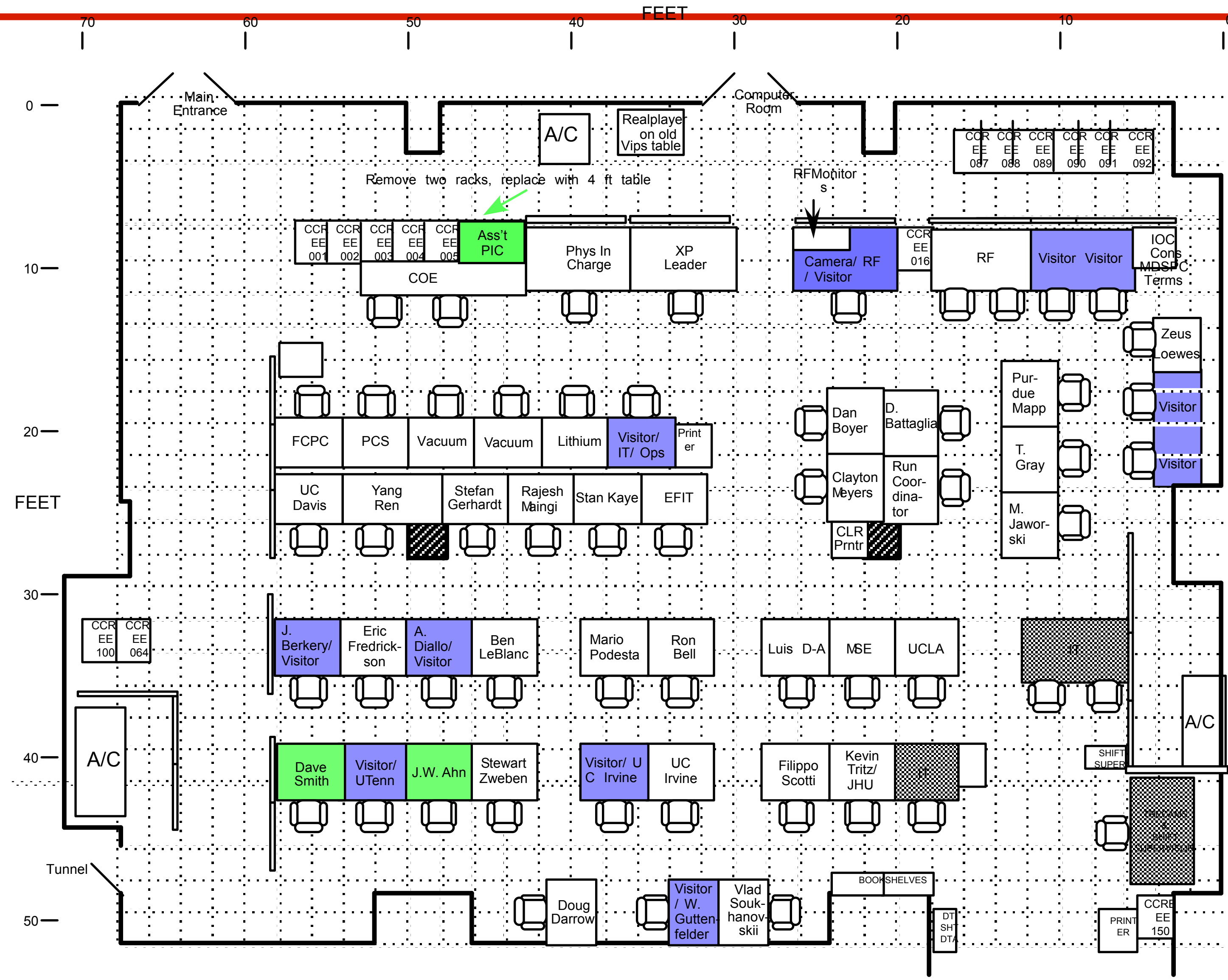
Backup

Some Configuration Information

NSTX-U Ports are Assigned to Diagnostics



Seat Assignments in the Control Room Have Been Updated

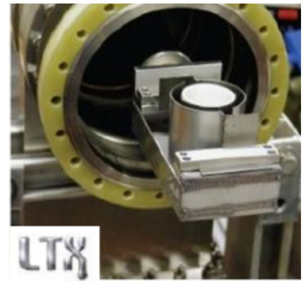


Long Term Upgrades

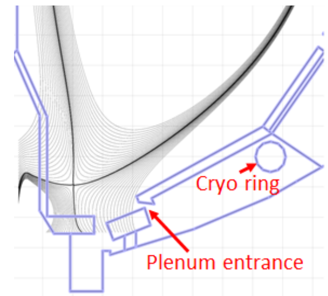
NSTX-U facility enhancements proposed for 5 year plan support FESAC Tiers/Priorities

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

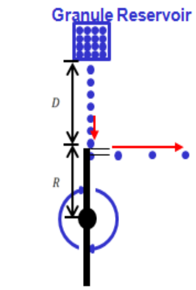
Upward Li evaporator

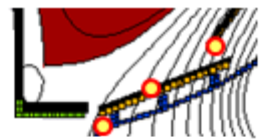


Divertor cryo-pump



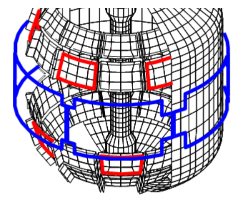
Li granule injector (LGI)

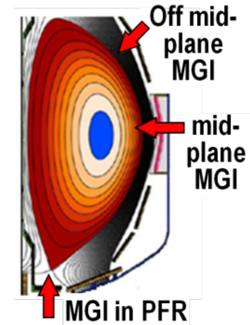




Extended low-f MHD sensor set

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

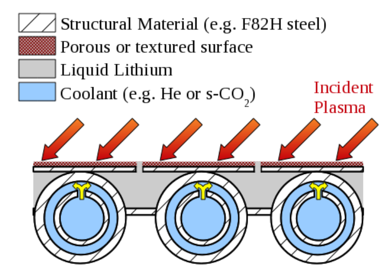




1MW 28 GHz gyrotron

High-Z tiles

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



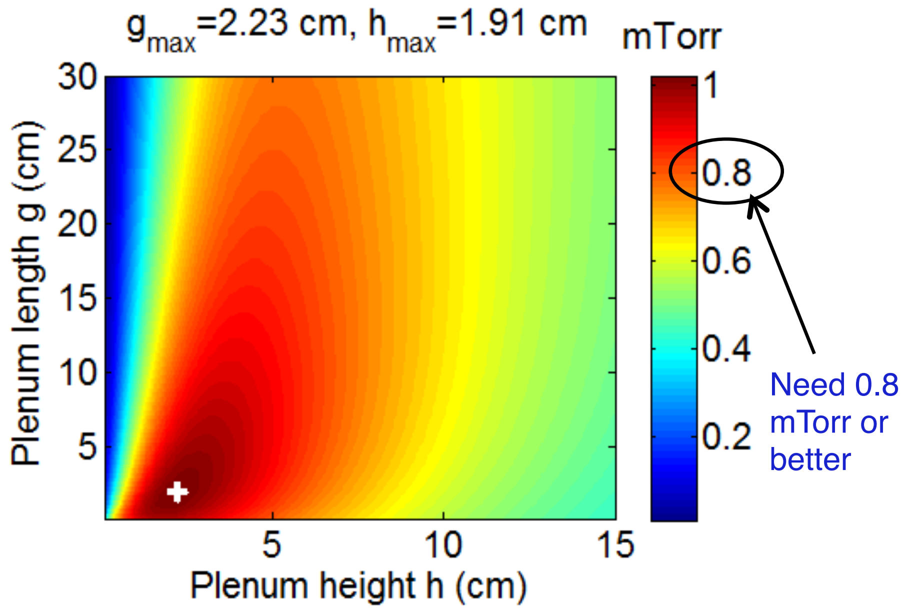
4 Major Upgrade Are Being Considered for the next 5 Years

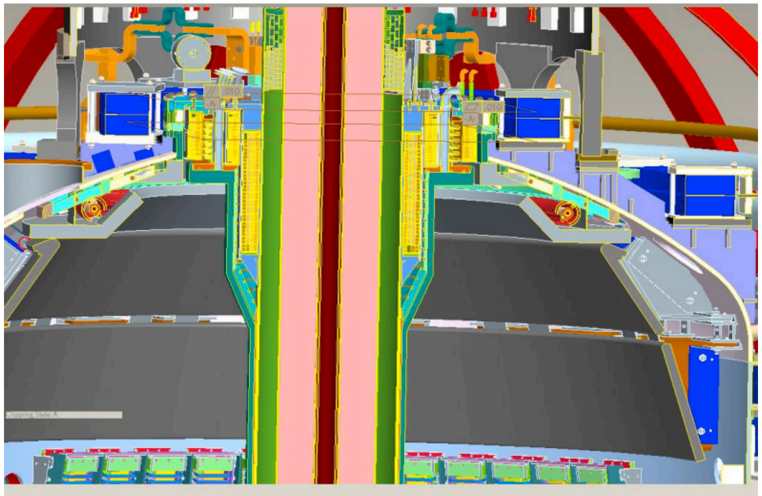
- We need robust density control.
  – Proposed Upgrade: ***Divertor cryopump***
- We need to develop high-performance ST scenarios compatible with reactor relevant plasma facing components (PFCs).
  – Proposed Upgrade: ***High-Z PFC upgrade***
- We need to understand how a CHI formed plasma can be ramped to full current without solenoid induction.
  – Proposed Upgrade: ***ECH system***
- We need to better understand and optimize error field correction, resonant magnetic perturbations for pedestal control, fast feedback for RWM control, rotation profile control.
  – Proposed Upgrade: ***Additional 3D field coils***

For detailed justification, see: http://nstx-u.pppl.gov/five-year-plan/five-year-plan-2014-18

Cryopump Physics Design to Provide Pumping over a Wide Range of Divertor Geometries and Core Densities

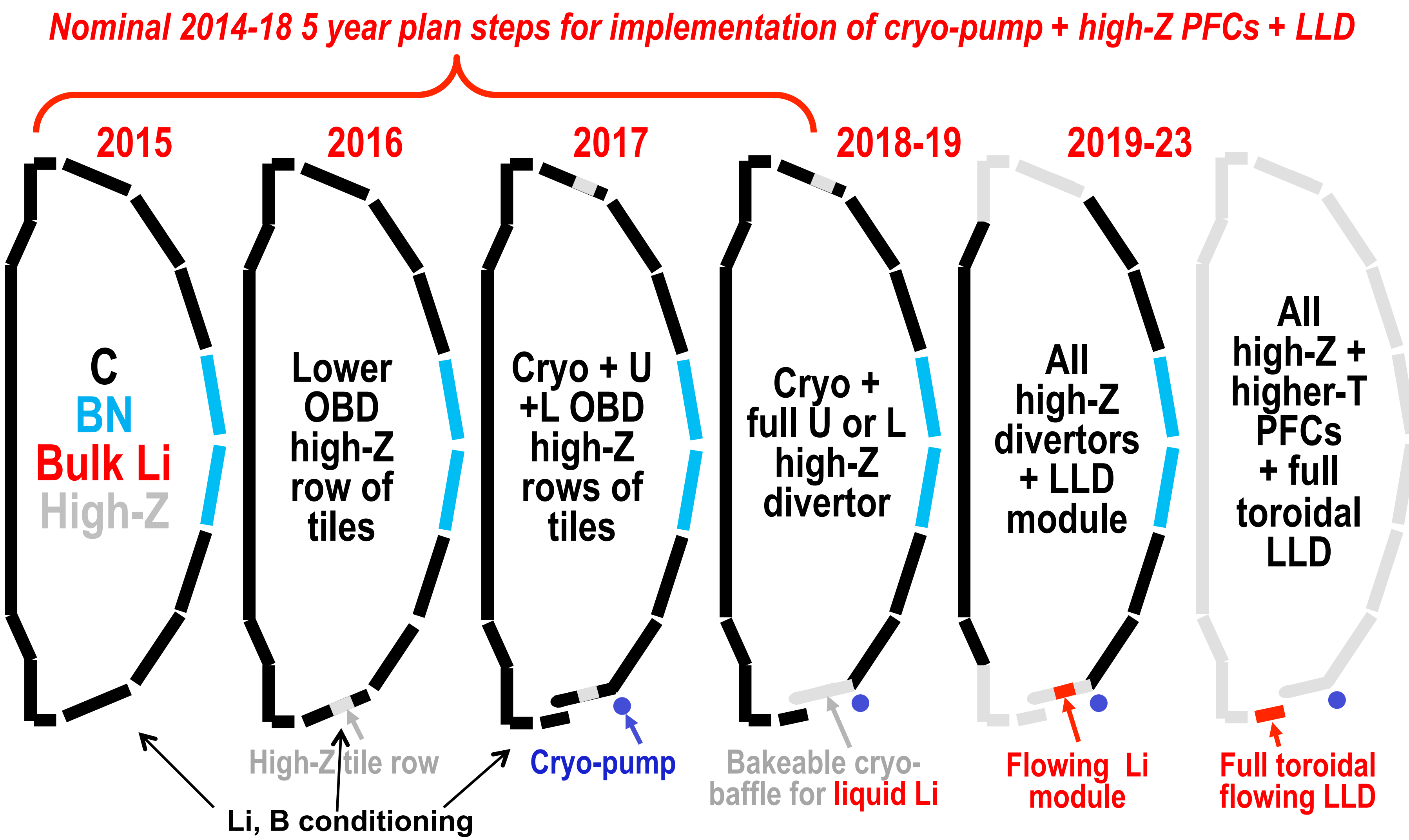
- Physics design completed in collaboration with ORNL[1].
  - Defined the geometry, plenum sizes, ability to pump various geometries.
- Conceptual design process has been initiated:
  - Draft GRD has been formulated.
  - Initial designer sketches of in-vessel implementation completed.
  - Potential refrigerator systems and associated elements identified.
  - Goal is to to have the system available for the 2017 run campaign.



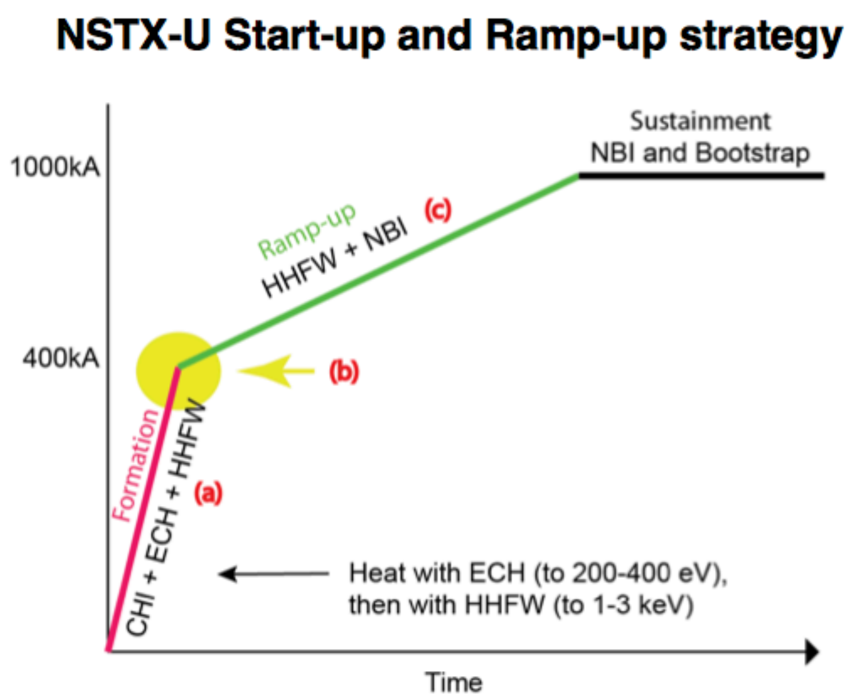


[1] http://nstx.pppl.gov/DragNDrop/Scientific_Conferences/APS/APS-DPP_12/Contributed_Posters/PP8.00030_Canik_APS2012.pdf

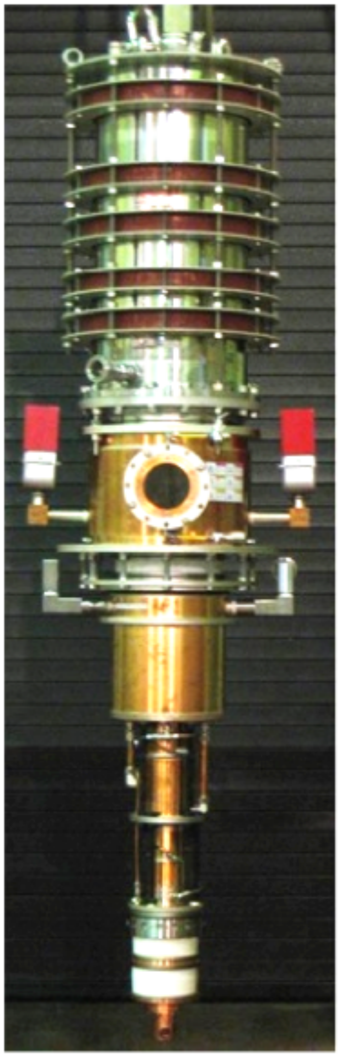
Stages Plan Has Been Developed to Implement High-Z PFCs & Flowing Liquid Metal Systems



28 GHz Gyrotron System Will Facilitate Non-Inductive Ramp-Up



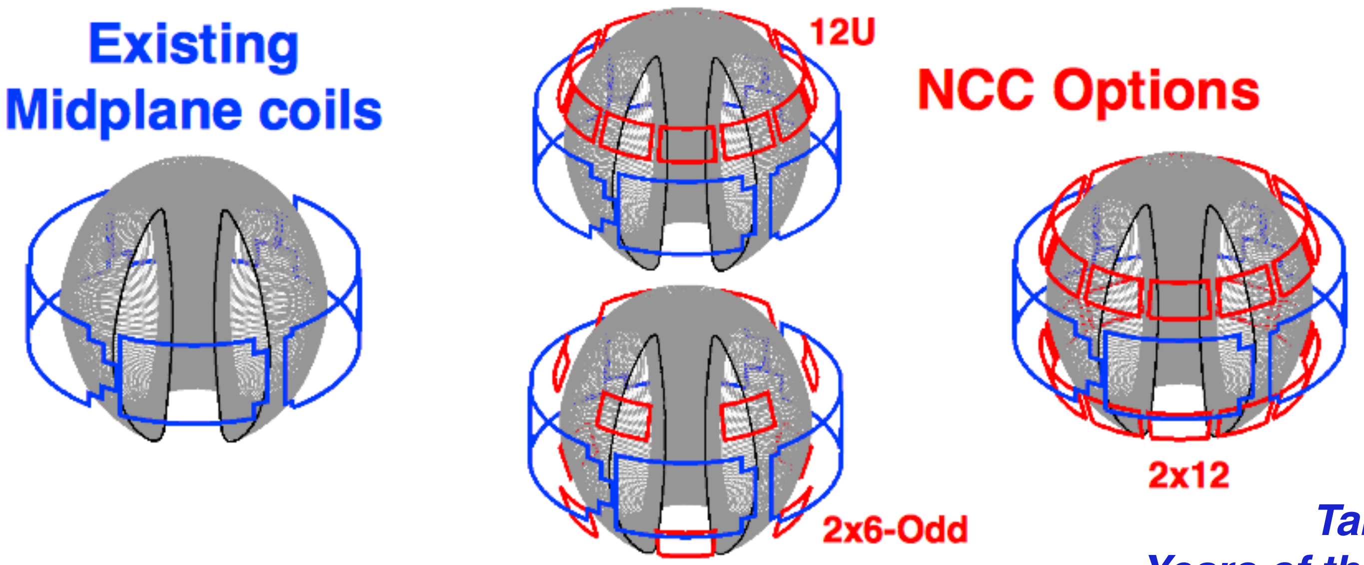
- Coaxial Helicity Injection can form a 200-400 kA seed plasma, but it is too cold and quickly decays.
- Use of ECH can "bridge the gap", to where HHFW and then NB current drive can support the ramp and sustain the current.
  - 20-40% first pass absorption predicted by GENRAY.
- Goal of first ECH power in 2017 run



1 MW Tube Developed for Gamma 10

3D Coil Physics Design Targets a Range of Physics Objectives

- NCC = Non-axisymmetric Control Coil
- Evaluated three upgrade options based on numerous physics criterion
  - Magentic breaking, error field control, fast RWM control, RMP applications.
- Initial findings shows that while the 2x12 options is best, a phase implementation starting with the 2-6-Odd approach may be a good intermediate step.



Targeting the Out Years of the 5 Year Period

Collaborators Play a Key Role in the NSTX-U Research Program

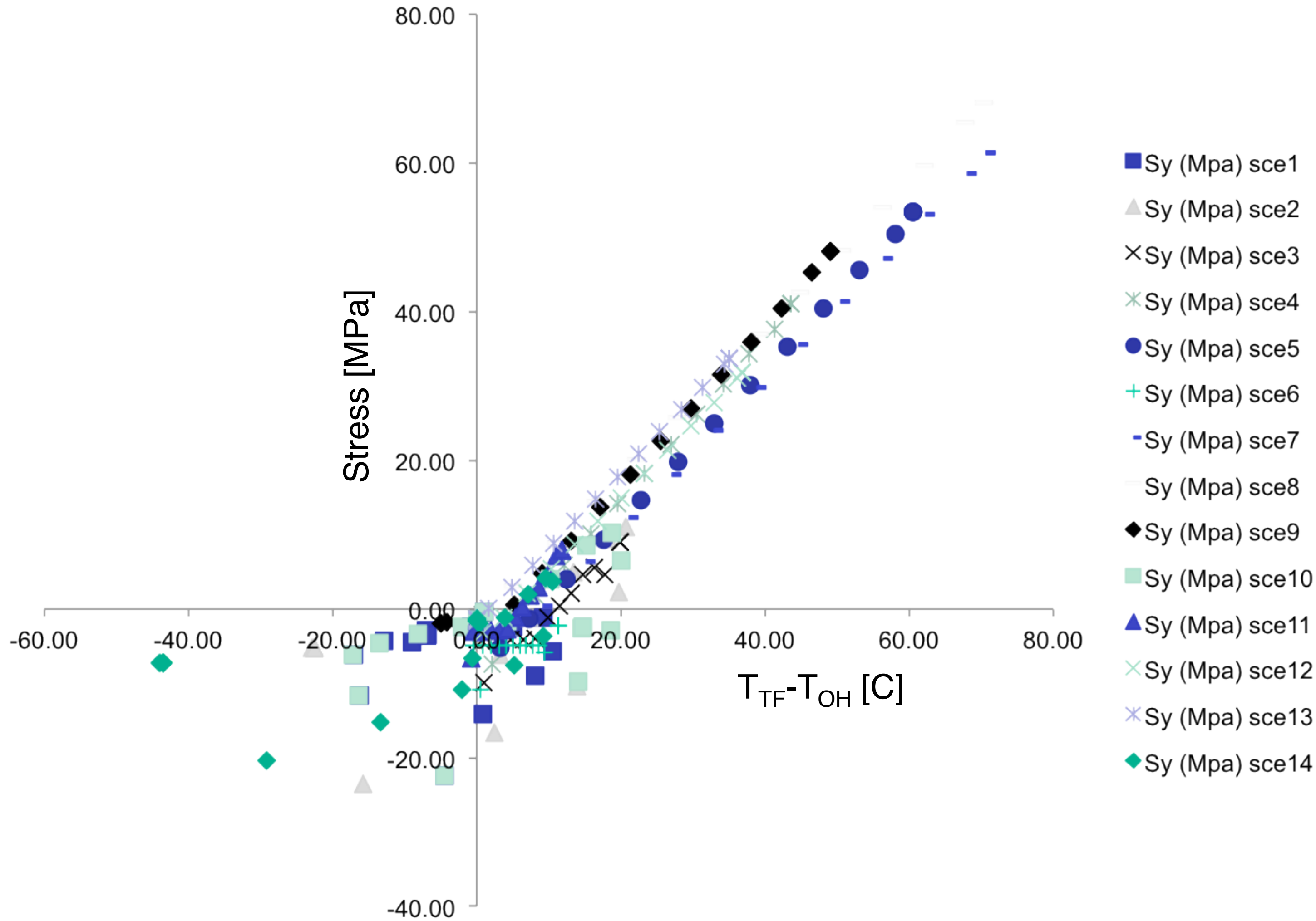
- University, national lab, and business collaborations for both data analysis and facility upgrades (diagnostics, gas injectors,…).
  - Are ***X of X*** topical science group leaders, 2 of three science group deputies.
- Collaborations reviewed & renewed on a 3-4 year cycle.
- Key documents:
  - Record of Discussion: documents communications between PPPL and collaborator during the formulation of DOE proposal, including estimates of PPPL resources to support collaboration is funded
  - Record of Agreement: agreed commitments of resources, equiptment, and facilities by collaborator and PPPL.
  - Data Usage Agreement: access to and publication of data.
- PPPL generally provides the vacuum interface, floor space, AC power & other services for diagnostics.
  - Collaborator provides the diagnostic itself, typically including data acquisition.
- Collaborators have the same safety & training requirements as PPPL employees.
  - And their systems have the same design reviews and work package requirements.

Analysis Justification for $T_{TF}<T_{OH}$ Rule

Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Method

- Created 14 different discharge scenarios.
  - Mostly 2 MA, 1T, but a few at lower field and current.
  - Many variations in the pre-charge and pre-heat.
  - All had the TF temperature eventually exceed the OH temperature, sometimes by a large amount.
    - So are useful for defining protection scheme.
  - Had a wide range of OH states during the time when T_{TF} exceeded T_{OH} by 0-10 C.
- Used ANSYS to analyze the OH stress at 18 times in each of the discharge scenarios.
  - 14x18=252 combinations of stress, temperature difference, OH state
- Motivation: Find a bounding curve for the OH stress that is a function of only the temperature difference.

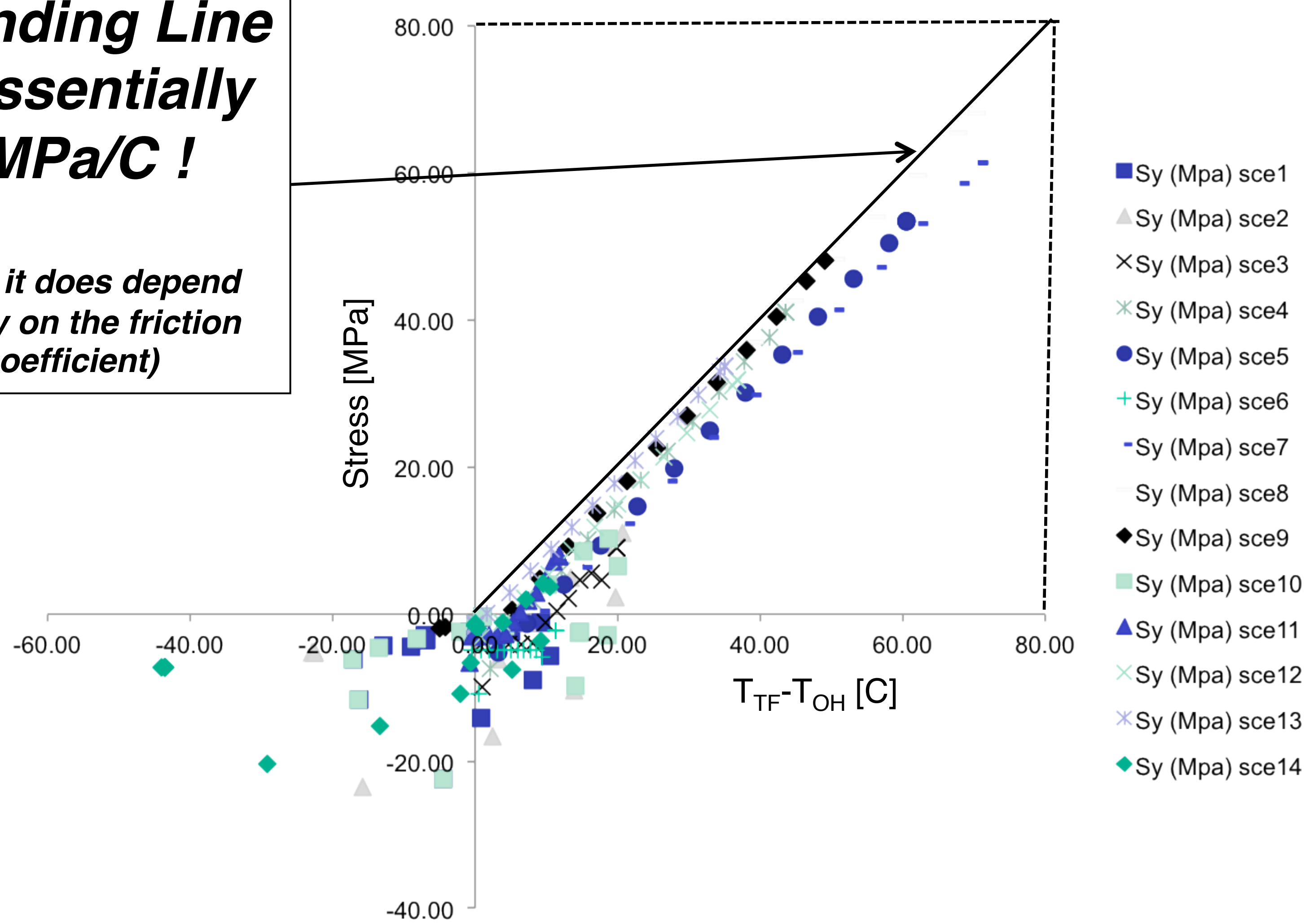
Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Result (I)



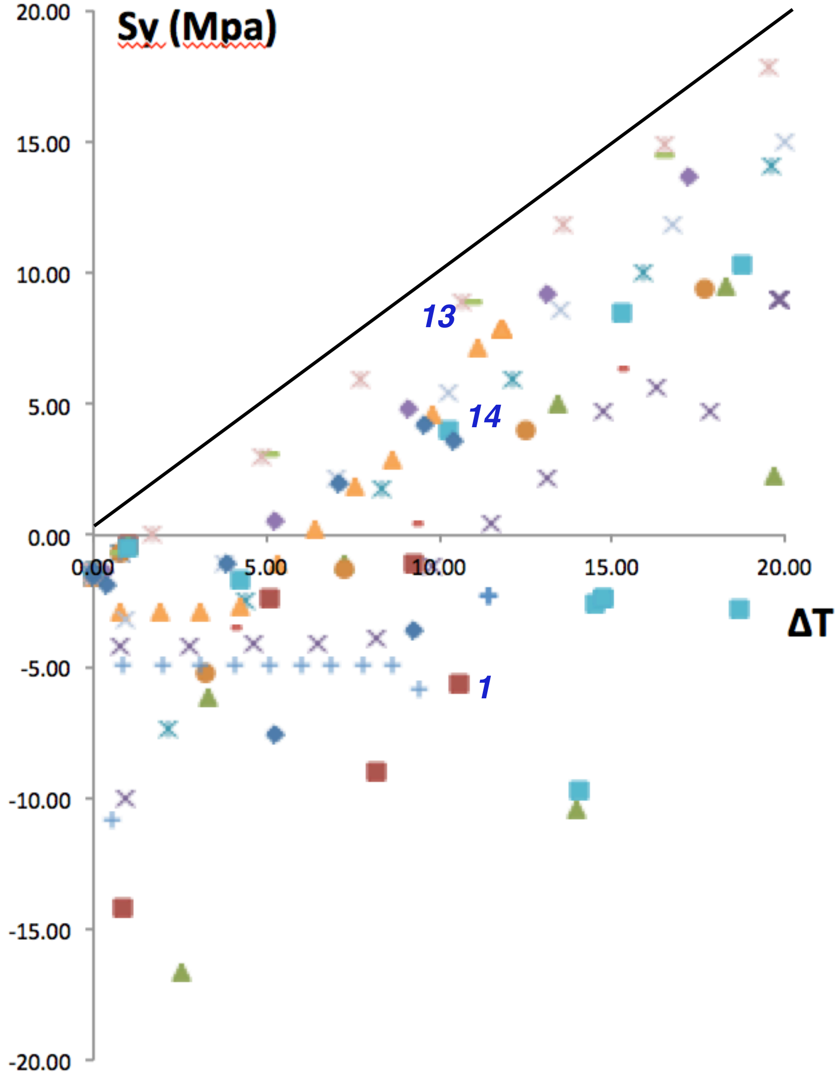
Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Result (I)

Bounding Line is Essentially 1MPa/C !

(Note, it does depend weakly on the friction coefficient)



Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Result (II)



- Unity-slope bounding line holds over the temperature different region of interest ($0<\delta T<\sim 20$).
- Large variation under that line, due to:
  - The OH state
  - Path dependence.
- Future work: evaluate this data as a function of δT and I_{OH}

Benefits of Operations with T_{OH} up to 110 C

What Happens if the OH is Allowed to Operate up to 110 C? 1: Kinder Operating Window

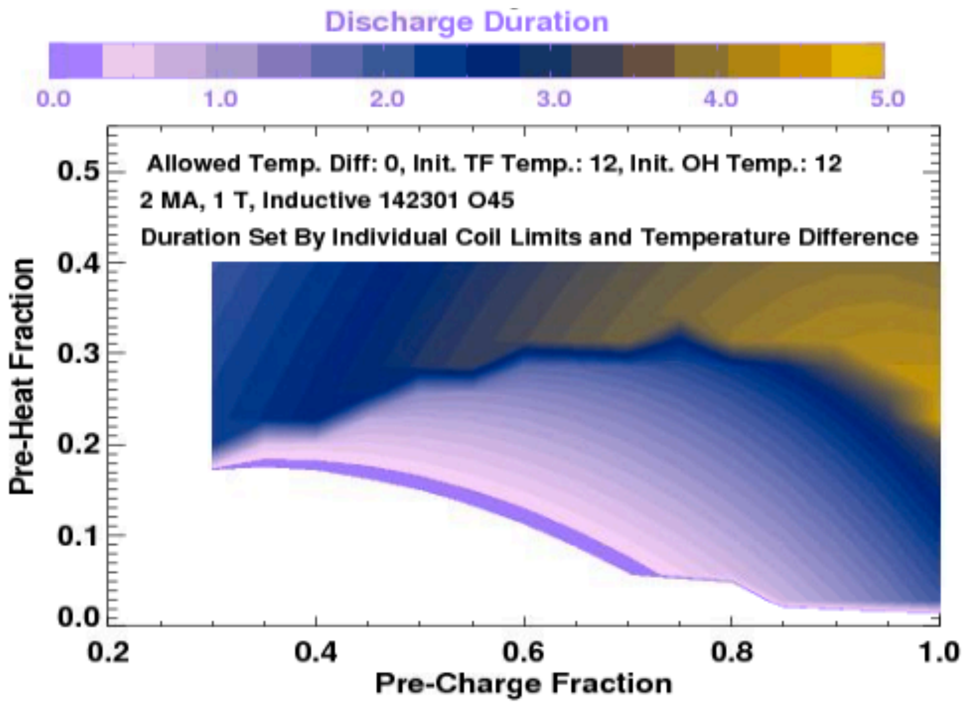
Both Simulations

Initial Coil Temperatures of 12 C, with Resistive Pre-Heating Method

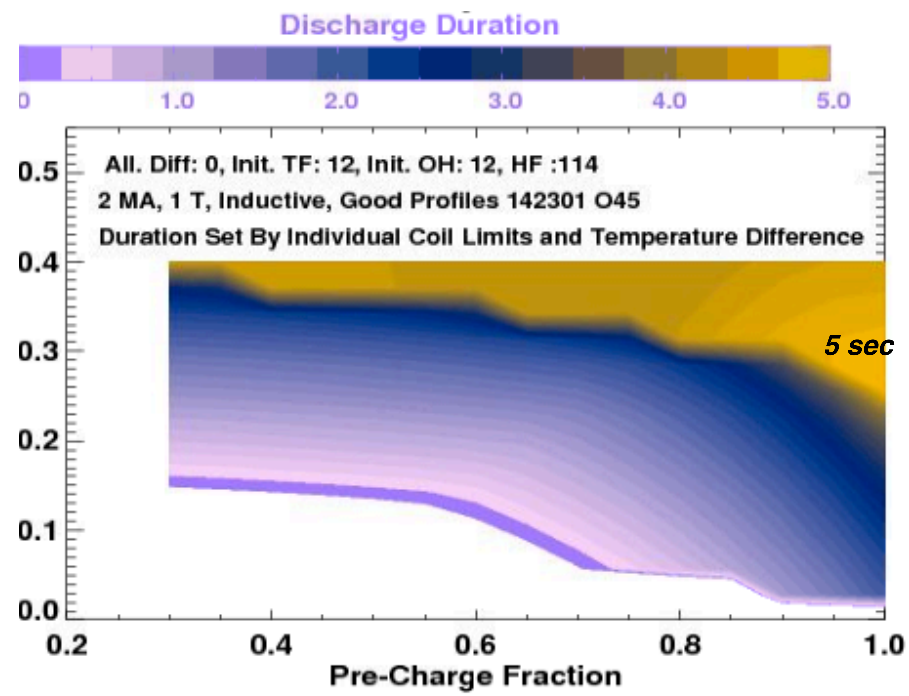
$T_{TF} < T_{OH}$ maintained

2 MA, 1T, H~1.05, allows 5 sec. shot *without* relative temperature constraint

T_{OH} limited to 98 C



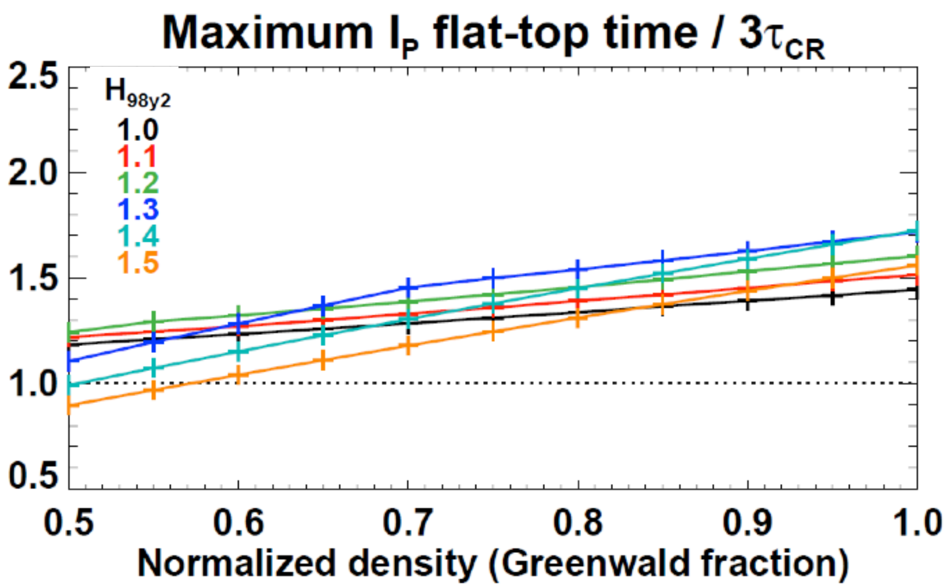
T_{OH} limited to 110 C



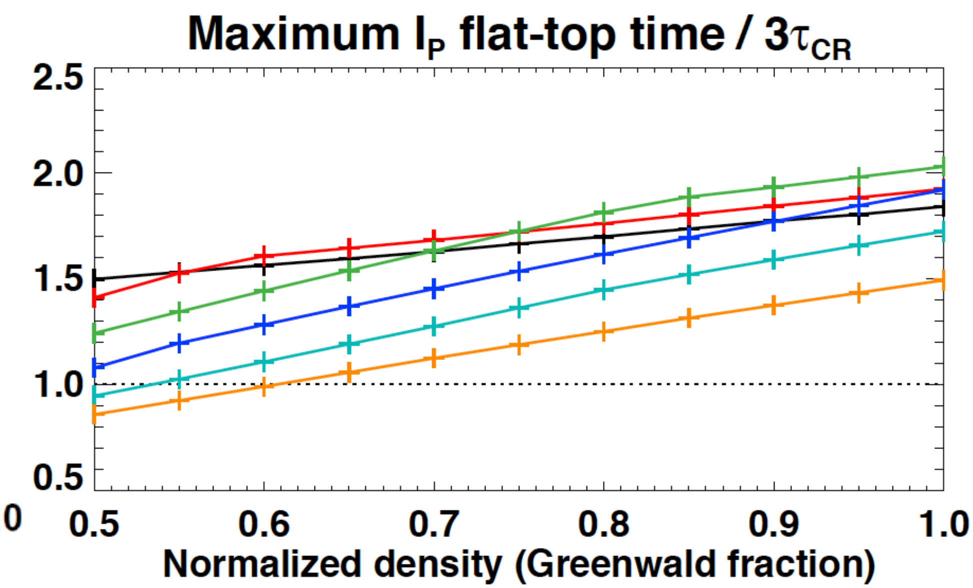
For this confinement multiplier, 5 sec. operation restored with with 110 C max. OH temperature

What Happens if the OH is Allowed to Operate up to 110 C?
2: More robust access to $t_{discharge}$>3τ_{CR}

T_{OH}<100 C, T_{TF}<100 C
Initial TF temperature: 12 C
OH Pre-heat to 43 C



T_{OH}<110 C, T_{TF}<100 C
Initial TF temperature: 7 C
OH Pre-heat to 35 C



In this configuration, only 0.2-0.4 sec of absolute discharge duration lost, despite the fixed initial OH temperature

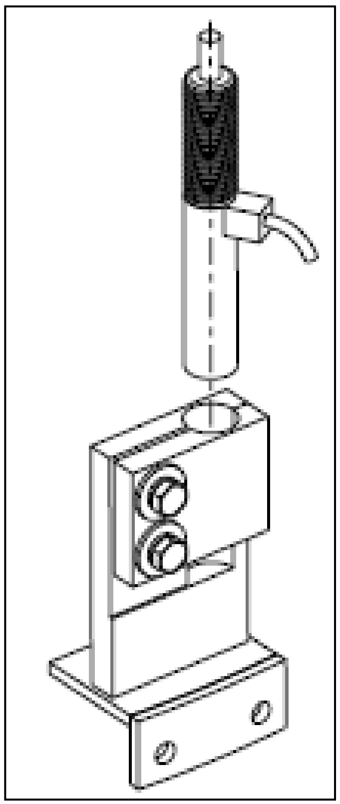
Aquapour/CTD-425 Engineering Thoughts

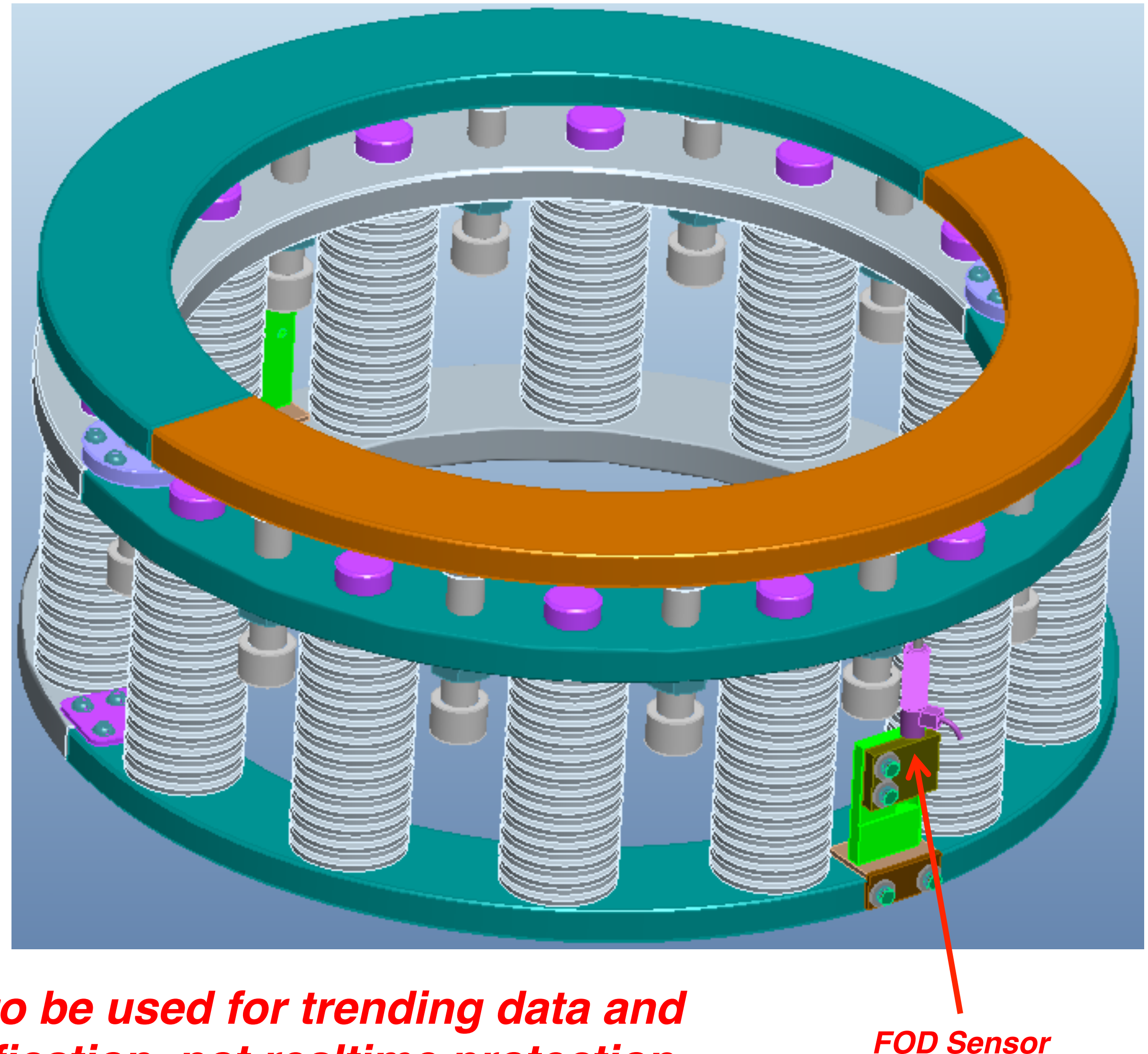
DCPS Will Be Used to Enforce This Temperature Difference

- Operating engineer & water-systems PLC enforce that the coils be cooled to a pre-defined set-point at the start of the discharge.
- Coil temperature evolution computed in DCPS based on current measurements.
  - Compute the temperature difference at the i^{th} step: $\delta T_i = T_{TF,i} - T_{OH,i}$
- Consider the heating that would occur in the event of a fault:
  - $\delta T_{TF,fault,i} = I_{TF,i}^2 C_{TF}$, $\delta T_{OH,fault,i} = I_{OH,i}^2 C_{OH}$ (OH may or may not heat up more than the TF)
  - $\delta T_{i,fault} = (T_{TF,i} + \delta T_{TF,fault,i}) - (T_{OH,i} + \delta T_{OH,fault,i})$
- At each cycle, compare both δT_i and $\delta T_{i,fault}$ to the defined limit (0 in the first year).
- Algorithm accounts for both instantaneous heating, and fault heating, while only relying on coil current measurements.
- Temperature evolution algorithm will be calibrated against outlet water temperature and potentially other measurements.

OH Solenoid Thermal Growth Sensors Implemented
FOD sensors will monitor OH solenoid growth

- Originally motivated by desire to monitor the pre-load.
- Two fiber optic displacement (FOD) sensors to be installed at 180° apart.
- The fixtures can be installed now and the sensors will be installed after the center stack is installed.





Intent these to be used for trending data and analysis verification, not realtime protection

Permanent Aquapour/CTD-425 Composite Does Have Some Advantages

- OH coil will stay well centered on the TF bundle.
  - Eliminates the need for centering shims.
- OH pre-load mechanism is more robust.
  - OH pre-load provided by Belleville washer stack pushing on the TF coil flags.
  - 20 klb limit on the OH F_Z determined by the hot-TF, cold-OH case.
  - By eliminating this case, the F_Z limit is increased to 30 klb.
    - Provides additional headroom for control oscillations.