NSTX-U

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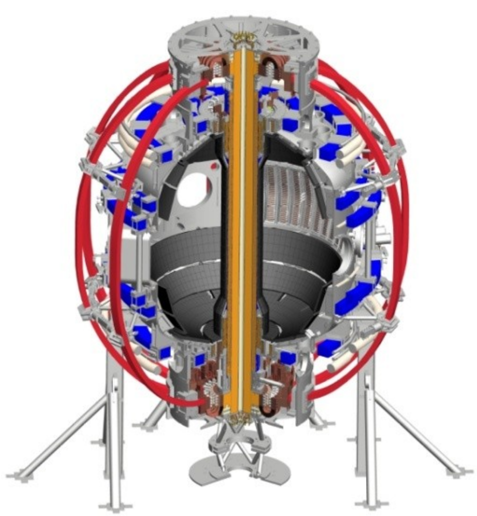
Transition to Research on NSTX-U

Stefan Gerhardt
Research Staff
Head of Experimental Research Operations

NSTX-U CD-4 Closeout
B-318
September 2nd, 2015

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



r1

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

- NSTX-U scientific goals
- NSTX-U test plasma results
- NSTX-U organization
- Preparation for the first experimental campaign
- Outline of the first experimental campaign

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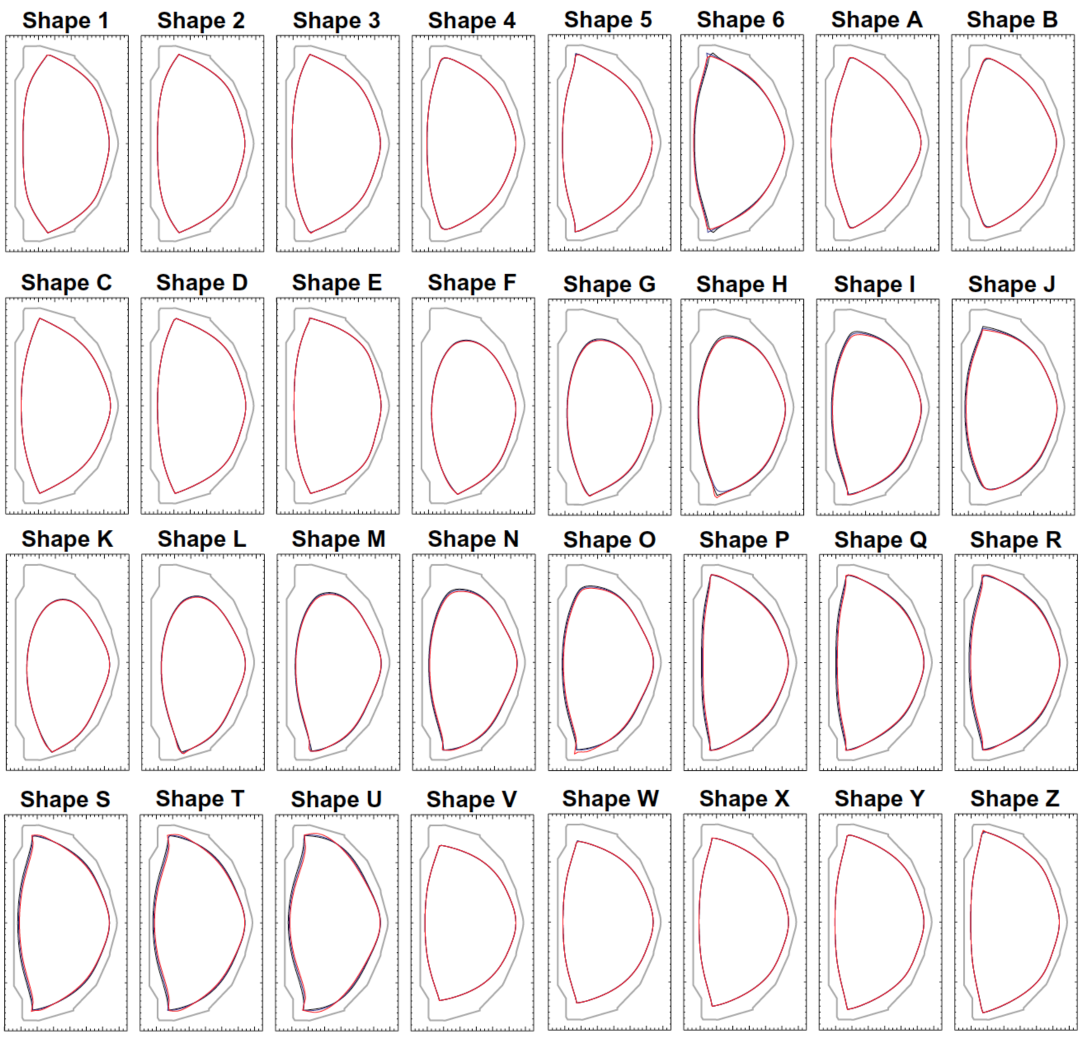
Five Year Plan Described Five Highest Priority Research Goals

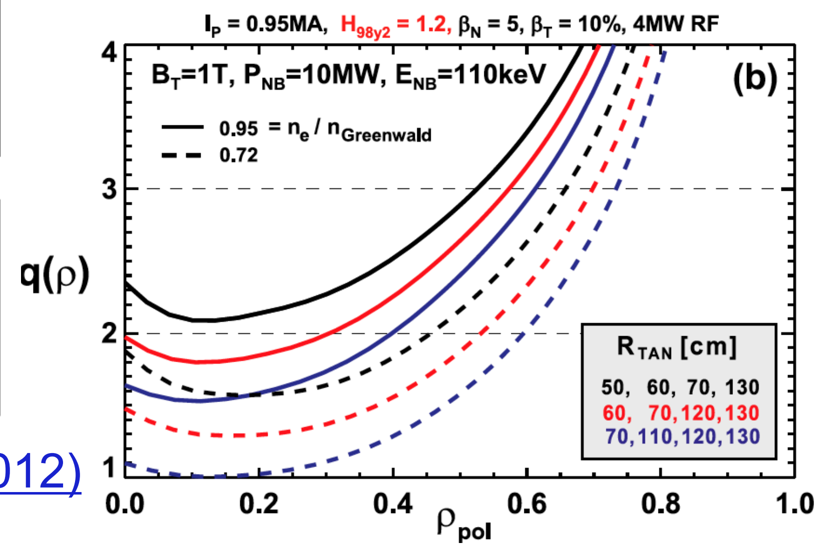
Present Upgrade **Future Upgrade (See Backup Slides)**

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)

Engineering Design Driven By Physics Considerations



- Poloidal field set consistent with a set of 96 plasma equilibria at 2 MA, 1T.
  - Defines coil locations, power supply requirements, forces/stresses on the coils & vessel, some DCPS limits
- Beam tangency radii determined by integrated modeling with TRANSP.
  - Provides a range of current profiles.



J. E. Menard, et al., Nuclear Fusion **52**, 083015 (2012)

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.

Time-Scales Involved in this Talk

- Energy confinement time: 0.04-0.1 seconds
  - The representative time-scale for energy to leak out.
- Current redistribution time: 0.2-1.5 seconds
  - The representative time scale for current to penetrate
- Expected discharge duration: 2-5 seconds
  - Set by many plasma physics and facility constraints
- Discharge repetition rate: 15-30 minutes
  - Set by OH coil or TF buss work cooling
  - Number of discharges in a day: 17-35 discharges
- Run campaign: 12-16 weeks
  - May take 16-20 calendar weeks to accumulate this time

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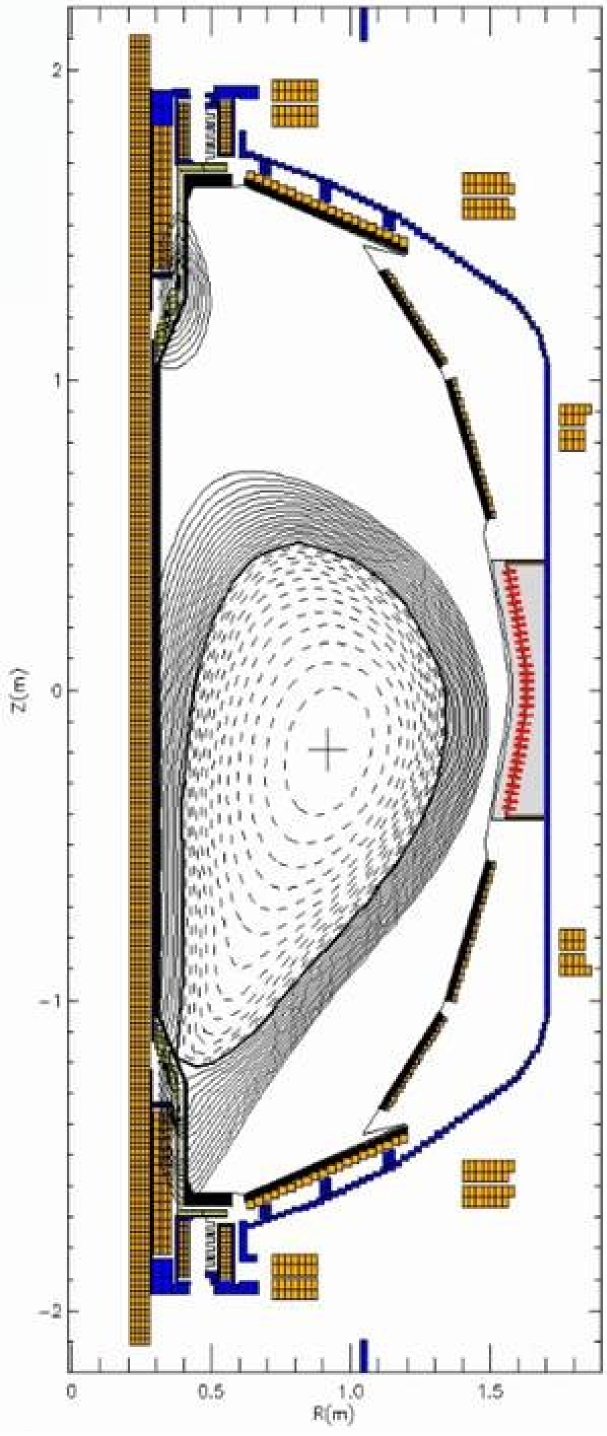
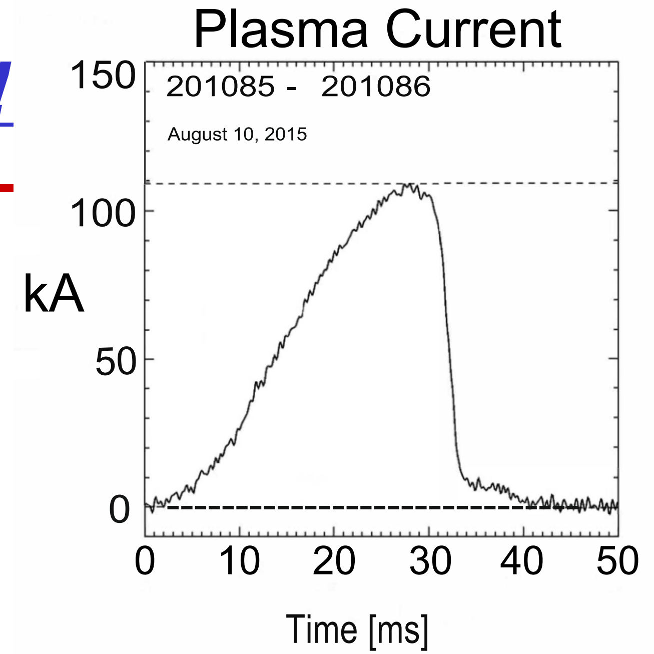
CS KPP Run-Up

- [8/3/2015] ES&H Executive Board accepted the ACC recommendation to restart the facility.
- [8/4/2015] Begin the coil system Integrated Systems Test Procedure (ISTP-001)
  - [8/4/2015] Complete Coil High-Pots
  - [8/5/2015-8/7/2015] Single Coil Test Shots
  - [8/10/2015] Combined Field Test Shots
- [8/10/2015] Begin plasma operations under XMP-100.
  - Achieved ~110 kA of plasma current
- [8/11/2015 & 8/12/2015] Continued operation on XMP-131.
  - Achieve ~140 kA, improve plasma positioning.

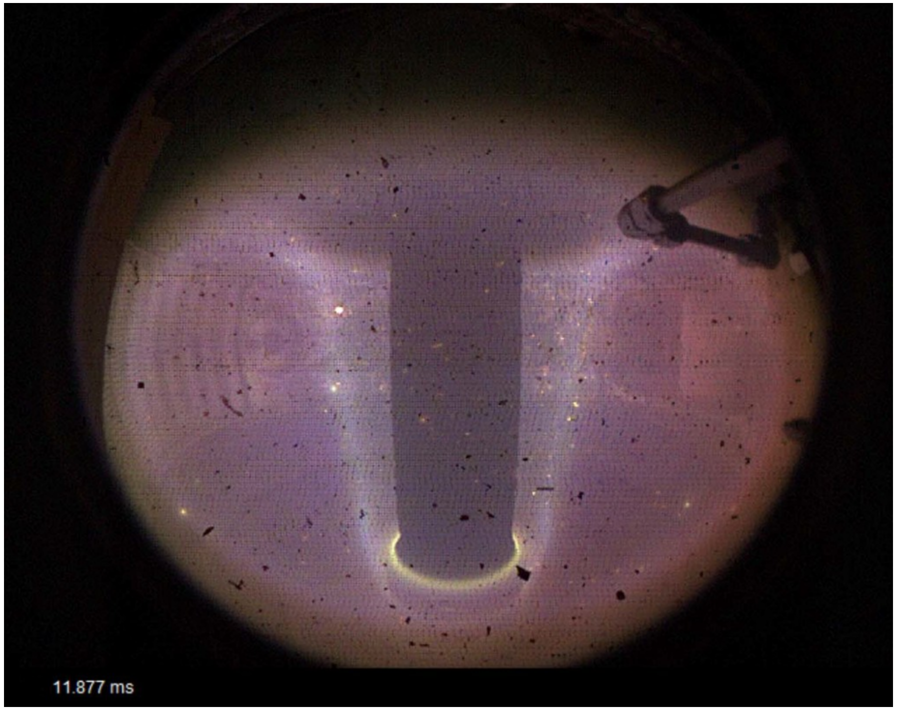


!! 110 kA Plasma !!

Measured Plasma Current



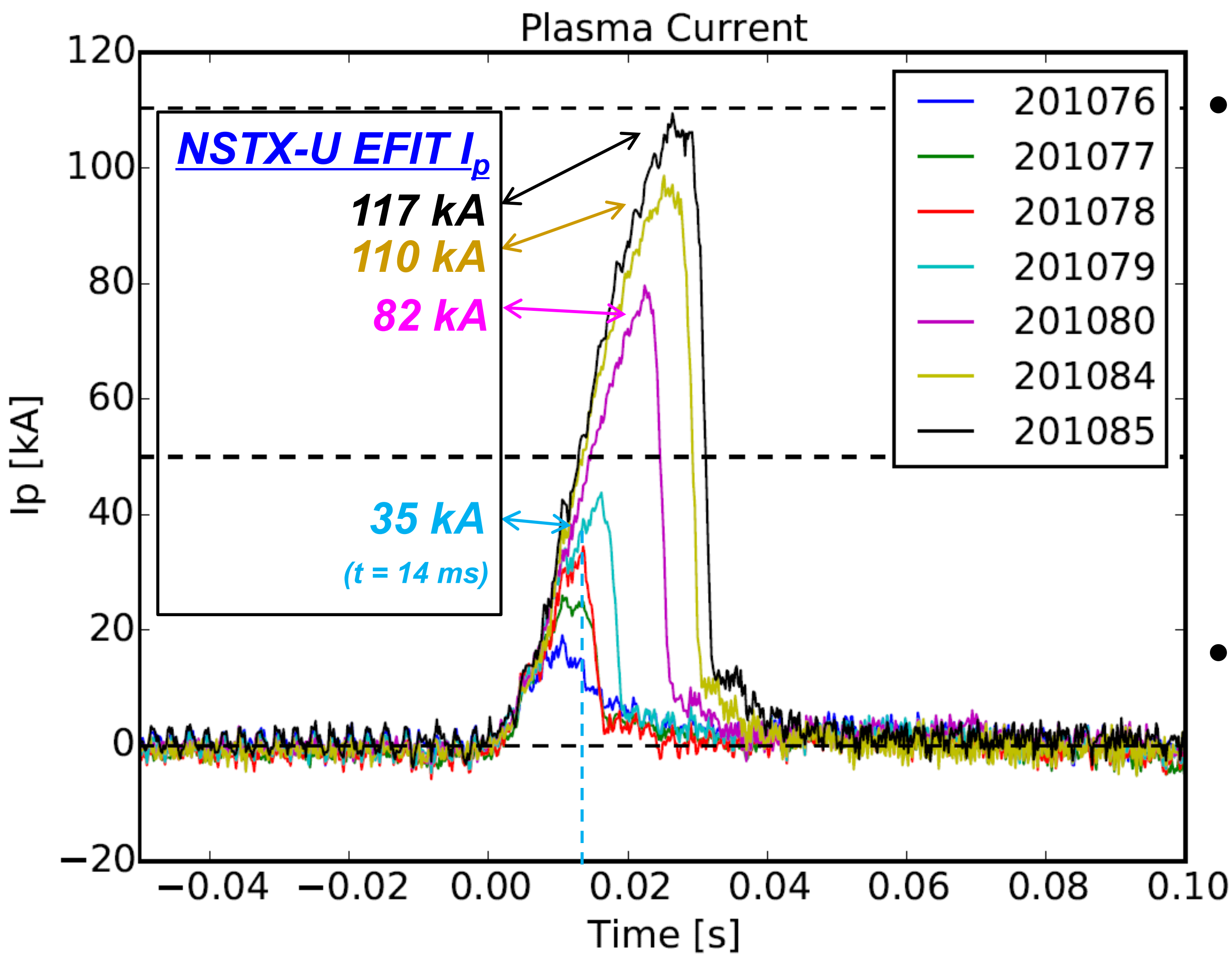
EFIT Reconstruction of the Plasma Shape
[S. Sabbagh Columbia University]



Fast Color Camera Image
[F. Scotti, LLNL]

Measured, compensated plasma current compares well to NSTX-U EFIT reconstructed current

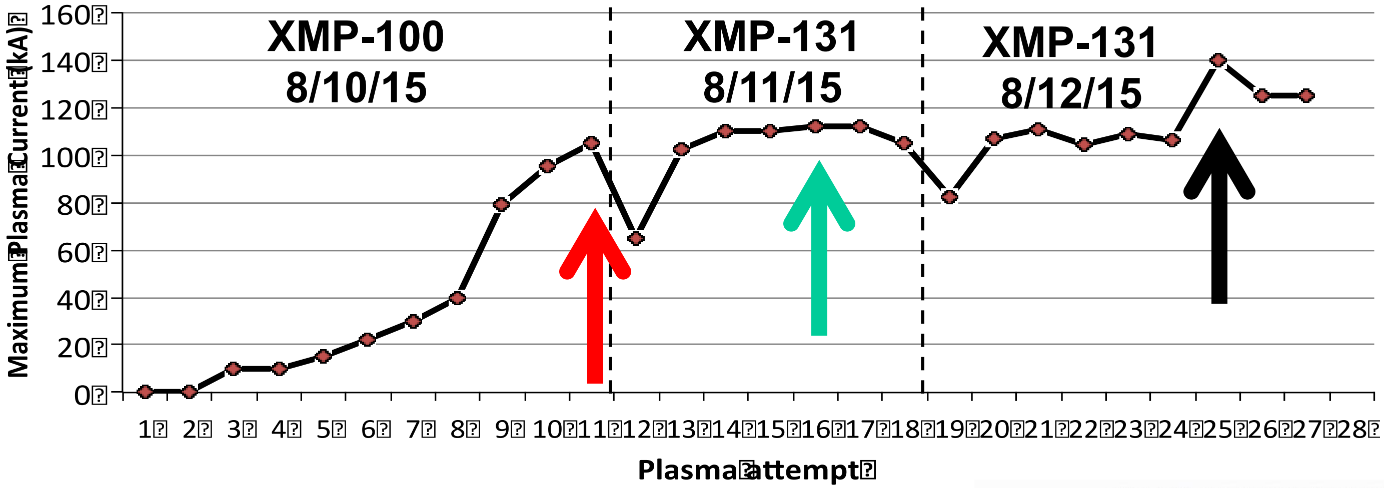
Shots from 8/10/2015



- In highest V_{loop} shots, reconstructed total wall current exceeds 0.4 MA
- Achieved highest current on last shot of day.

S. Sabbagh, Columbia University

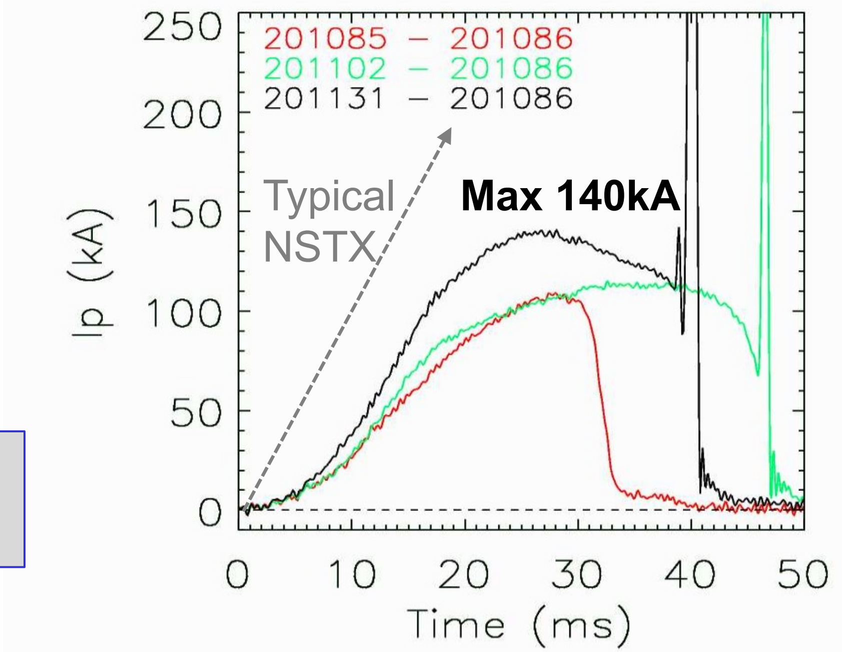
Continued Improvement in Plasma Current and Duration in Sixteen Plasma Shots over 1.5 Days



(27 out of 29 attempts were "good" over 2 days)

(First shot after morning He glow takes a hit)

- Centering plasma and shrinking outer gap lengthened discharge
- Reducing prefill fueling increased I_p ramp rate (Wed)



Performance Should be Dramatically Better Once We do the Full Vessel Bake

D. Battaglia, PPPL

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NSTX-U 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

NSTX-U Experimental 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)

People who built it will run it.

- 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
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  - Core Science — S. Kaye
  - Integrated Scenarios — S. Gerhardt
  - Particle Control Task Force (FY2015-16) — R. Maingi

This structure defines
i) science program, &
ii) engineering/operations structure to execute the activities.

Actual design, fabrication, & construction, and operations activities accomplished by PPPL engineering via their procedures and processes.

NSTX-U Research Program Is Organized Along 3 "Science Groups" and 9 TSGs for the FY16 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 Science 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 (FY2016-17)
Leader: J. Canik[1], Deputy: R. Maingi

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

er, deputy,
ıiversity rep
ticipation

NSTX-U Scientific Organization – August 2015

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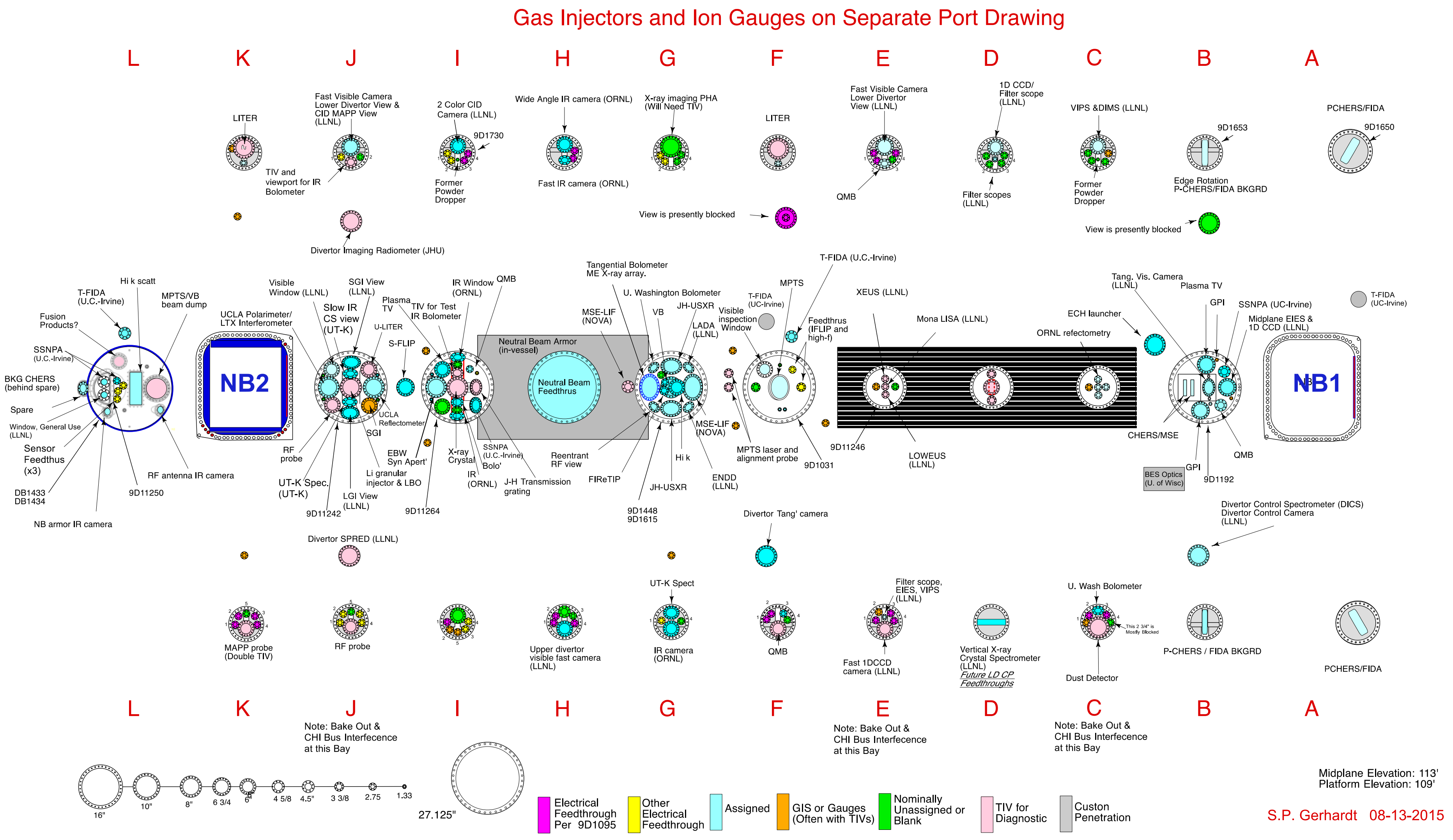
Many "Non-Upgrade" Tasks Have Been Undertaken to Prepare for the Run

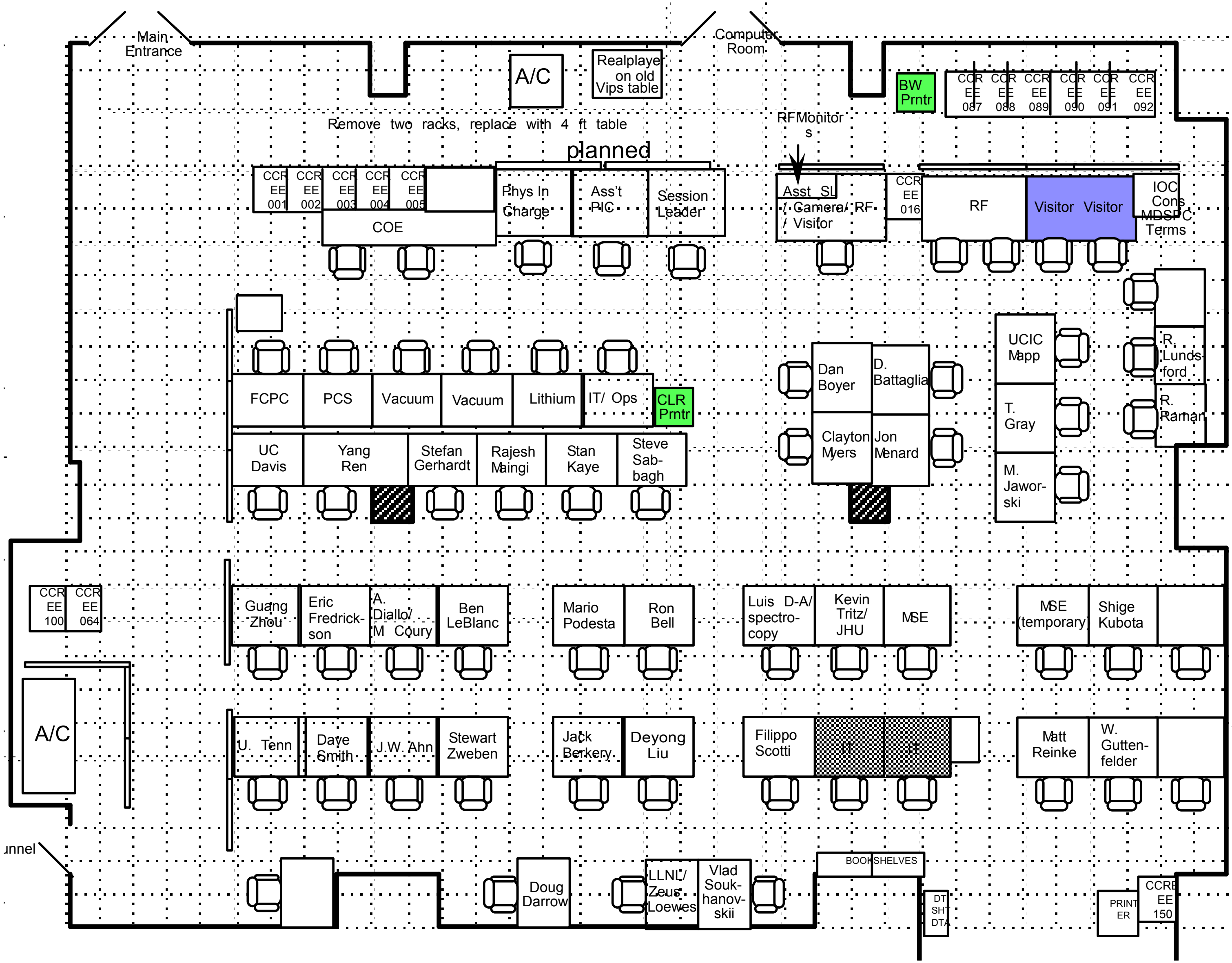
- Crucial diagnostics
  - Many upgrades to the magnetic diagnostics
  - Large changes to the critical Thomson scattering systems successfully implemented…Rayleigh/Raman scattering complete!
  - All major profile diagnostics installed and calibrated.
  - Many new or upgraded diagnostics…
- Upgrades to the High Harmonic Fast Wave (HHFW) antenna.
- New boronization systems with improved safety features.
- New rectifier control hardware, new plasma control computers and many algorithm upgrades

Many details in backup…

Most Previous Diagnostics Reinstalled or Relocated, Many New Diagnostics Installed



Seat Assignments in the Control Room Have Been Updated



We Have Three Research Milestones +JRT in FY-16

- R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}
- R16-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile
- R16-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM
- JRT: Assess disruption mitigation, initial tests of real-time warning, prediction

See: http://nstx-u.pppl.gov/program/milestones
Full 3-year set of milestones in backup

Daily Operations Directed by Experimental Proposals (XPs) and Experimental Machine Proposals (XMPs)

XPs

- Describe experimental steps to answer science questions
- Governed by OP-ADX-03
- Reviewed by
  - topical science group
  - run coordinator + research team
- Typically described 1/2-2 days of machine operations
- Expectation that each XP will lead to a publishable result

XMPs

- Describe experimental steps to qualify new machine capabilities
- Governed by OP-ADX-02
- Reviewed by
  - physics operations branch head
  - research operations division head
- Typically describe ½ -1 day of machine operations
- Expectation is that each XMP will facilitate multiple XPs

XPs and XMPs for FY-16 Defined at the Research Forum, and Subsequently Further Refined

- Research Forum was help at PPPL Feb. 24th-27th
  - Requests made for ~270 days of run time, from 84 different first authors, for ~80 available days.
  - Initial prioritizations performed within TSG and SG breakouts sessions.
  - Initial XP & XMP sequencing defined.
- Now in the process of reviewing and finalizing XPs and XMPs.
  - 6 XMPs have been approved.
  - 17 XPs have been reviewed by run coordination, 8 approved.

XP Prioritization, Anticipate Scheduling, All Posted on NSTX-U Web Site

Next unique XMP/XP number:		132	1531									Estimated fractional distribution of run time assigned to a 4 run week (RW) period						Priority 1 XMP/XP run-time				
TSG / TF	Resp. group name	XMP Number	XP Number	Title of proposal	Author last name	Priority Label	Priority 1 run time assigned at forum	Priority 2 run time requested at forum	Non-XMP CCE run time assigned after forum	Multi-TSG XP run time assigned after forum	Comments / notes	Run Weeks 1-4	Run Weeks 5-8	B--> Li (actual timing TBD)	Run Weeks 9-12	Run Weeks 13-16	Sum Chk	Run Weeks 1-4	Run Weeks 5-8	Run Weeks 9-12	Run Weeks 13-16	
						Forum Guidance:	25	0													Check	25.75
Advanced Scenarios and Control (ASC)	ASC-TSG		1501	Optimization of vertical control algorithm	Boyer	P1a	0	0	1			1					1	0	0	0	0	
	ASC-TSG		1502	Tuning of the Automated Rampdown Software	Gerhardt	P1c	0	0	0.5			1					1	0	0	0	0	
	ASC-TSG		1503	X-point control integration with shape control	Kolemen	P1a	0	0	1		SPG: This moved to CC&E	1					1	0	0	0	0	
	ASC-TSG		1504	Beam power and beta-N control	Boyer	P1b	0	0	0.5			0.5	0.5				1	0	0	0	0	
	ASC-TSG		1507	Maximizing the non-inductive current fraction in	Gerhardt	P1a	2	0					0.5		0.25	0.25	1	0	1	0.5	0.5	
	ASC-TSG		1508	Controlled Snowflake Studies	Kolemen	P1b	1	0.5	0.5				0.25		0.5	0.25	1	0	0.25	0.5	0.25	
	ASC-TSG		1509	Combined betaN and li feedback control	Boyer	P1b	0.75	0.5					0.25		0.25	0.5	1	0	0.1875	0.1875	0.375	
	ASC-TSG			Develop VERY long pulse H-mode for NSTX-U	Battaglia	P1c	1	0	0.5						0.25	0.75	1	0	0	0.25	0.75	
	ASC-TSG			Current profile controllability scoping study	Boyer	P1b	0.75	0			Myers/LaHaye inclusion...				0.25	0.75	1	0	0	0.1875	0.5625	
	ASC-TSG			Closed Loop Density Feedback	Battaglia	P2a	0	0	0.5						0	1	1	0	0	0	0	
	ASC-TSG			NB sustainment	Poli	P1c	0.5	0			Matched with 1/2 day from SFSU, so 1 tc					1	1	0	0	0	0.5	
	ASC-TSG			Rotation Control	TBD	P2a	0	0.5			Need to identify a leader for this					1	1	0	0	0	0	
	ASC-TSG			Reversed Shear Plasma with Relaxed Profiles	Gerhardt	P2a	0	0.5			Will be led by H. Yuh					1	1	0	0	0	0	
	ASC-TSG			EPH access and long-pulse development	Canik	P2b	0	0			Push to later years					1	1	0	0	0	0	
	ASC-TSG			Compare the benefits of off-axis NBI for advanc	Ferron		0	0			Most of the scope can be accomplished i					1	1	0	0	0	0	
	ASC-TSG			Combining High Non-Inductive Fraction Shot W	Gerhardt	P2b	0	0			Reconsider at mid run assessment					1	1	0	0	0	0	
	ASC-TSG			Radiation Control	Kolemen	P2b	0	0			Need the PCS capabilities. Consider aga					1	1	0	0	0	0	
	ASC-TSG			Adaptive ELM control (Can RMP ELM Control t	Kolemen		0	0			Need an EF model to even really do this.					1	1	0	0	0	0	
	ASC-TSG			3D coil based BetaN control instead of NBI bas	Kolemen		0	0			Maybe use some time out of the Boyer X					1	1	0	0	0	0	
	ASC-TSG			Vertical growth rate and maximum controllable	Kolemen		0	0			Combined this scope with the CC&E sco|					1	1	0	0	0	0	
	ASC-TSG			Measurement of Neutral beam driven current	Levinton		0	0			Combine with Podesta, Gerhardt, Boyer.					1	1	0	0	0	0	
	ASC-TSG			rampdown studies	Poli		0	0			No dedicated time this year. Use the fidu					1	1	0	0	0	0	
	ASC-TSG			Model-based Optimal Feedforward Current Pro	Schuster		0	0			Make sure the Boyer XPs offer some sup					1	1	0	0	0	0	
	ASC-TSG			Actuator Sharing and Integrated Control Demo	Snipes		0	0			Premature given our present control capa					1	1	0	0	0	0	
	ASC-TSG			Characterizing Type I ELMy H-modes in He pla	Snipes		0	0			This is a pedestal physics experiment					1	1	0	0	0	0	
	ASC-TSG			Snowflake control development	Soukhanovskii		0	0			Do with Kolemen's snowflake XP					1	1	0	0	0	0	
						Total:	6	2	4.5	0											Total:	6.00
						Forum Guidance:	6	2													Check:	6.00
Wave Heating and Current Drive (RF)	RF-TSG			Using 2D BES measurements to resolve the in-	Smith	P1c	0.25	0			XP designed to test capability, then use t		1				1	0	0.25	0	0	
	RF-TSG		1510	Characterizing the SOL Losses of HHFW Powe	Perkins	P1a	1.25	0.5			Combine with Lau/Menard XPs		0.5		0.25	0.25	1	0	0.625	0.3125	0.3125	
	RF-TSG			HHFW absorption in Neutral-Beam heated plas	Bertelli	P1b	1	0							0.25	0.75	1	0	0	0.25	0.75	
	RF-TSG			Low Plasma Current, Fully Non-Inductive, HHF	Taylor	P2a	0	0.5		1	Matching with 1/2 day from SFSU, for 1 t				0.25	0.75	1	0	0	0	0	
	RF-TSG			HHFW effects on toroidal rotation	Bertelli		0	0			Interesting, but just no time.					1	1	0	0	0	0	
	RF-TSG			HHFW CD measurements by MSE diagnostic a	Bertelli		0	0			review status at mid run assessment					1	1	0	0	0	0	
	RF-TSG			Validating HHFW coupling/loading models with	Lau		0	0			Combine with Perkins XP, piggyback on a					1	1	0	0	0	0	
	RF-TSG			Scoping study for core impurity reduction using	Menard		0	0			Combine with Perkins XP, piggyback on a					1	1	0	0	0	0	
	RF-TSG			Antenna-Plasma Interactions and HHFW Powe	Perkins		0	0			Piggyback on all other H-mode RF XPs.					1	1	0	0	0	0	
						Total:	2.5	1	0	1											Total:	2.50
						Forum Guidance:	2.5	1													Check:	2.50
Solenoid-free Start-up and Ramp-up (SR)	SR-TSG			Transient CHI Plasma Start-up in NSTX-U	Raman	P1a	1.5	0.5			Need reasonable run time this year to de				0.25	0.75	1	0	0	0.375	1.125	
	SR-TSG			Low Plasma Current, Fully Non-Inductive, HHF	Taylor	P1b	0.5	0			1/2 day from RF for 1 total day				0.5	0.5	1	0	0	0.25	0.25	
	SR-TSG			Inductive Flux Savings of Inductively-driven Tra	Nelson	P1b	0.5	0								1	1	0	0	0	0.5	
	SR-TSG			NBI overdrive without RF	Poli	P2a	0	0.5			1/2 day from ASC for 1 total day. Suppor					1	1	0	0	0	0	
	SR-TSG			Plasmoid instabiltiy during CHI startup	Ebrahimi		0	0			this can be done in piggyback, needs imp					1	1	0	0	0	0	
	SR-TSG			Impact of controlled fluctuations on current driv	Nelson		0	0			Can be applied to the Transient CHI start					1	1	0	0	0	0	
	SR-TSG			NBI overdrive with RF	Poli		0	0								1	1	0	0	0	0	
	SR-TSG			Characterization of the scrape off layer density	Reusch		0	0			Piggyback. Can benefit from MPTS meas					1	1	0	0	0	0	
	SR-TSG			HHFW Heating of CHI-Only Discharges	Taylor		0	0								1	1	0	0	0	0	
	SR-TSG			Impact of the edge current produced by CHI on	Diallo		0	0								1	1	0	0	0	0	
	SR-TSG			HHFW Ramp-up of Inductively Initiated Plasma	Taylor		0	0								1	1	0	0	0	0	
						Total:	2.5	1	0	0											Total:	2.50
						Forum Guidance:	2.5	1													Check:	2.50
	PS-TSG		1511	Multi-machine studies of the L-H power thresho	Bongard	P1b	1	0			combine with Churchill, Loarte - run befo		1				1	0	1	0	0	
	PS-TSG			Investigations of nonlinear ELM dynamics	Smith	P2a	0	0			combine with Osborne - before lithium		0.75		0.25		1	0	0	0	0	
	PS-TSG		1512	Characterization of the Pedestal Structure as fu	Diallo	P1a	0.5	0		1	run before and with lithium		0.5		0.5		1	0	0.25	0.25	0	
	PS-TSG			Resonant ELM frequency behavior as a functio	Lore	P1b	1	0			combine with Ahn, Canik - P1 before lithi		0.5		0.5		1	0	0.5	0.5	0	

We Plan to Increase the Field, Current & Pulse Duration Over 3 Years

	NSTX (Max.)	FY 2016 NSTX-U Operations	FY 2017 NSTX-U Operations	FY 2018 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

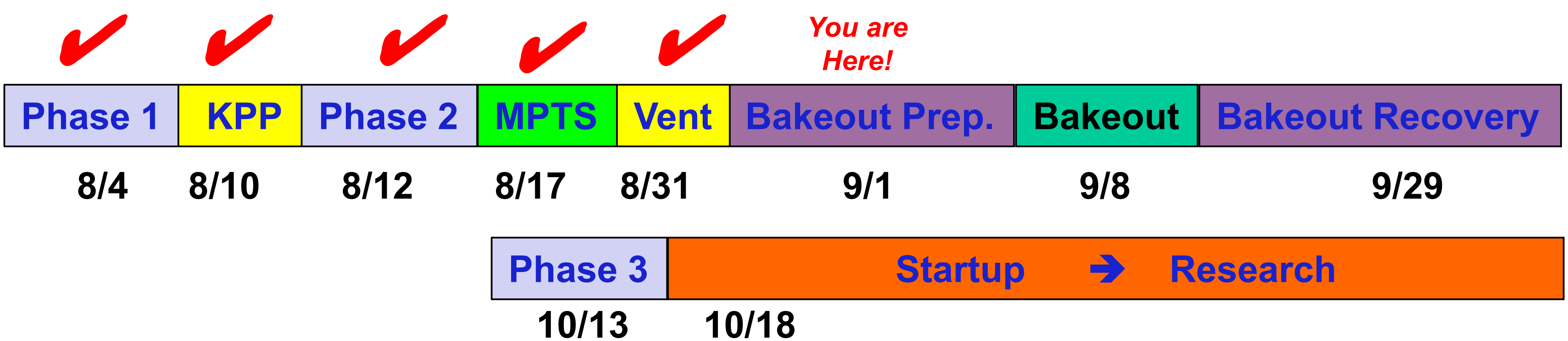
3rd year goal: Full capability

Outline

- NSTX-U scientific goals ✔
- NSTX-U test plasma results ✔
- NSTX-U organization ✔
- Preparation for the first experimental campaign ✔
- Outline of the first experimental campaign ⟸

Sequence From Test Plasma To Full Research is Well Defined

- Phase 1 Coil Testing
  - Commission TF, OH, PF coil systems required for test plasma.
- CS KPP
- Phase 2 Coil Testing:
  - Commissioned remaining coil systems
- MPTS Rayleigh-Raman Scattering
- Small Vent
- Bakeout
- Phase 3 Coil Testing
  - Prepare for Commissioning/Startup Phase
- Commissioning/Startup Phase
- Research Ops



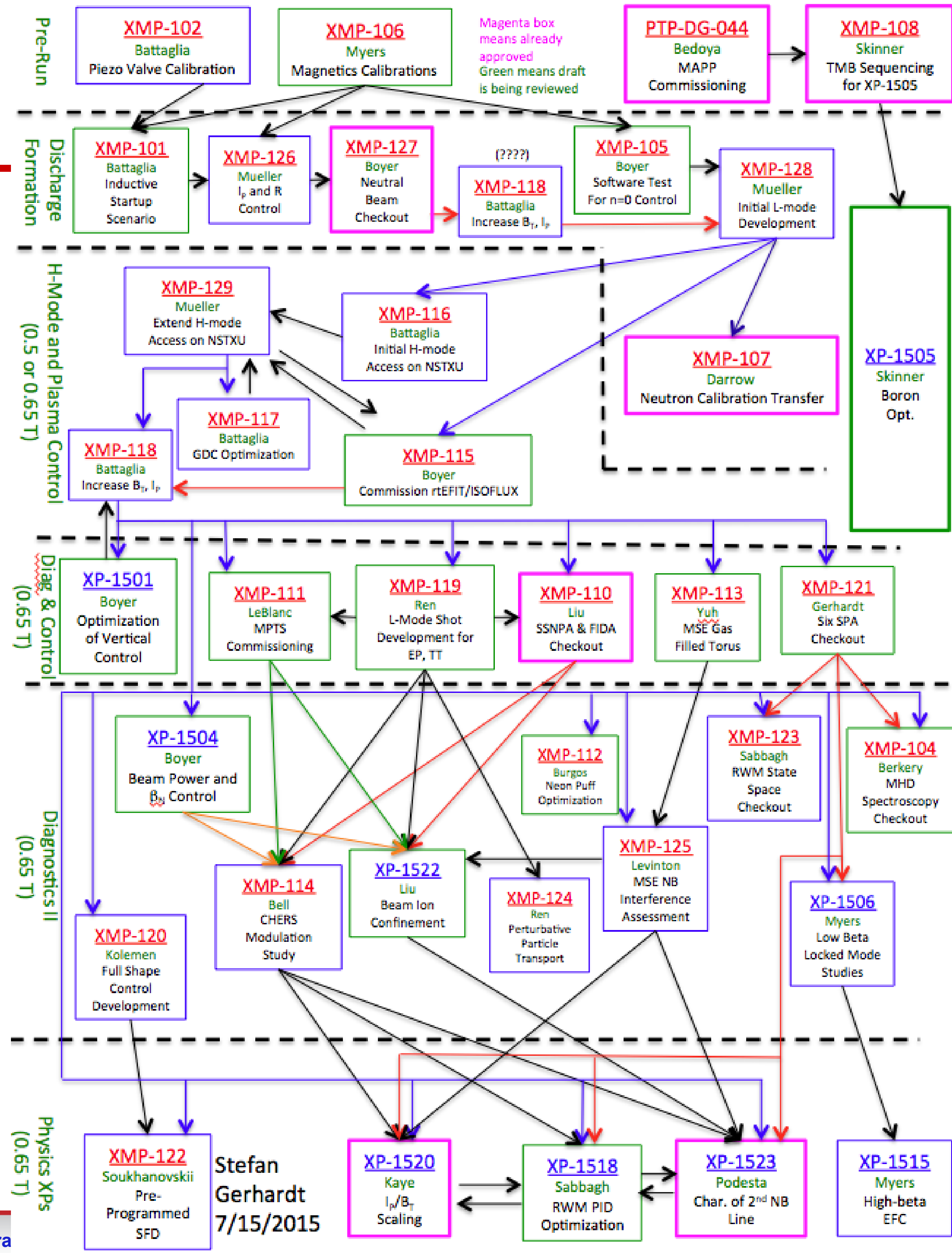
The NSTX-U Research Program Will Initiated By a Sequence of XMPs

- XMPs for pre-plasma calibrations (3)
- XMPs to reestablish basic “L-mode” plasma operations (7).
- XMPs for “H-mode” access and advanced plasma boundary control (5)
- XMPs for additional control development and initial diagnostic checkout (6)
- XMPs for advanced diagnostic checkout (6)

At the completion of this list, we will be ready to execute the critical XPs (I_P & B_T Scaling, Characterization of the 2nd NB Line)

The Linkages of the First XMPs and XPs Have Been Defined

- Obviously, not going to discuss this in detail.
- Engineering requirements are consistent with present facility plans.
  - 2 beam boxes
  - Full set of TF, OH, PF coils
    - TF to 0.65 T.
  - 6 SPAs (for RWM coils)
  - Boronization



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
    - NSTX and NSTX-U Physics Operations Branch Head.
    - Has collaborated on EAST and K-STAR control development over the last years.
  - D. Battaglia has spent the last 2 years as a DIII-D physics operator
    - Was responsible for the test plasma XMPs
  - R. Raman (U. of Washington) provides leadership in CHI, MGI areas + physics operations.
- D. Mueller holding a physics operator course.
  - ½ in July, ½ in September.
  - Plan to train an additional 2-3 physics operators.
  - Slides for course:
    - http://nstx.pppl.gov/DragNDrop/Operations/Physics_Operations_Course/
- Major diagnostics have primary and backup support.

Operating Period Likely Runs Through April, in Order to Achieve 14-16 Run Weeks

➔ If FY16 budgets are favorable enough, may run more run weeks

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

- October: 2 run weeks (XMPs)
- November: 2 run weeks (XMPs → XPs)
  - May want to slow/pause for ST workshop (Nov. 3-6), APS (Nov 16-20), Thanksgiving (Nov. 26)
- December: 3 run weeks
- January: 2-3 run weeks
  - Mid-run assessment (if applicable), PAC-37
- Feb-Apr: 6-8 run weeks, complete FY16 run
- Apr/May: Start outage: install high-k, high-Z tiles, …
- Resume operations fall/winter 2016 for FY17

Outline

- NSTX-U scientific goals ✔
- NSTX-U test plasma results ✔
- NSTX-U organization ✔
- Preparation for the first experimental campaign ✔
- Outline of the first experimental campaign ✔

Summary: NSTX-U is Well on the Way To an Exciting First Run Campaign

- Upgrade was designed to facilitate the research program.
  - And successfully built (Ron's talk).
- The test plasma activity was very successful.
- The scientific team, and management team, are in place to develop and exploit the facility.
- The sequence of events leading to research operations is well defined, and we are well along the way.

Backup

Operations-Side Facility Enhancements

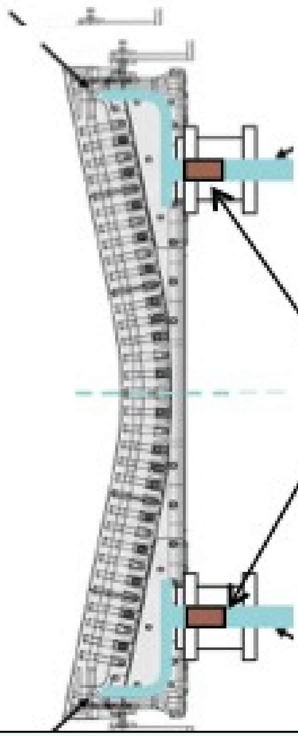
Operations-Side Activities to Support Operations: Plasma Diagnostics

- Thomson scattering ready for operations:
  - Vessel modifications
  - New flight tubes
  - Rayleigh/Raman scattering is complete
- Neutron detectors installed, and calibrated with in-vessel train track.
- New diagnostics in final stage of 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.
- Considerable activity now being spent on special purpose diagnostic development.

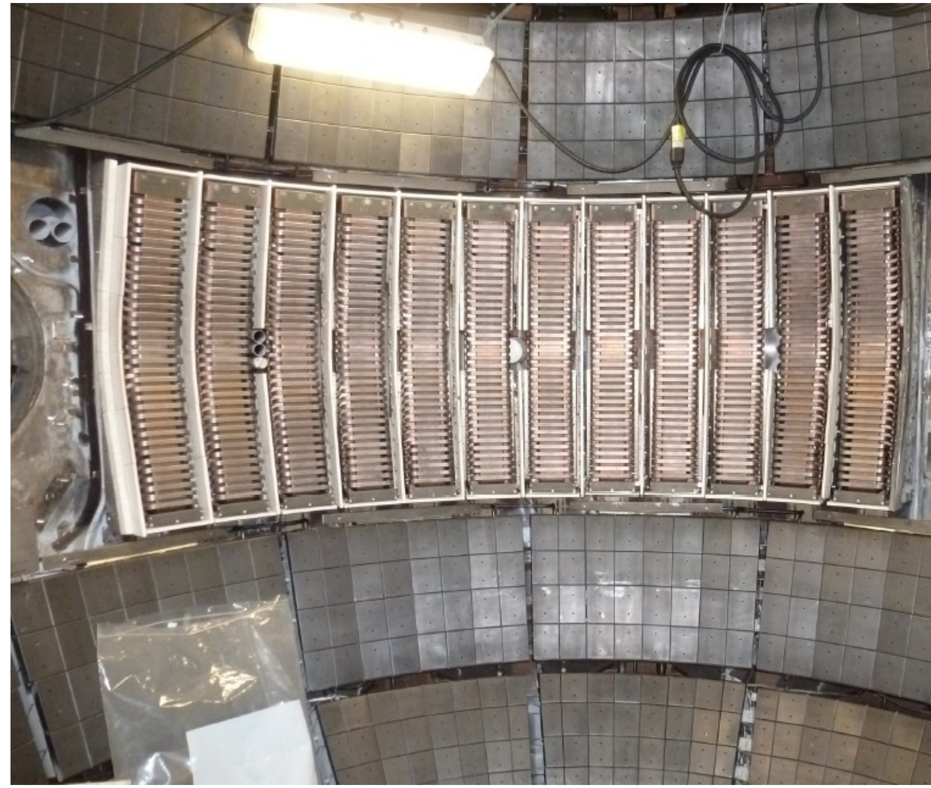
Operations-Side Activities to Support Operations: HHFW Heating and Current Drive System

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 have been installed and tuned
- 4 of the 6 transmitters have been tested into dummy load.
- Final 2 transmitters are being brought up now.

Operations-Side Activities to Support Operations: Physics Operations & Plasma Control

- New firing generators for transrex recifiers designed, tested, fabricated, deployed.
- New in-house design for realtime digitizer designed, tested, fabricated, ready for deployment.
- New I_P measurement systems and associate permissive generators designed, fabricated, deployed.
- Plasma Control System (PCS)
  - All low-level control software has been revisited, upgraded.
    - Includes moving power supply control software from stand-alone code to an algorithm within PCS.
  - Physics algorithms required for commissioning have all been revised, updated, tested.
  - Now working on more advanced physics algorithms to support research.

Operations-Side Activities to Support Operations: Boundary Physics Operations

- New boronization (dTMB) system will be used.
  - Designed, fabricated, installed…awaiting only final PLC software.
  - Plan for it to be available for initial research operations.
- LIThium EvaporatoR (LITER)
  - LITERs were carefully stored during the outage.
  - Mounting brackets have been reinstalled.
  - New Argon Dump system being designed for installation before LITER use.
    - Vessel has been prepped to accommodate that system.
- High-conductance divertor gas injection lines (2) have been installed
  - Support 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 installed.
  - Allows material samples to be exposed to the plasma and then examined in-situ with surface science techniques.

Projected Impact of the Aquapour/CTD-425 Composite Material

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

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

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3rd year goal: Full capability

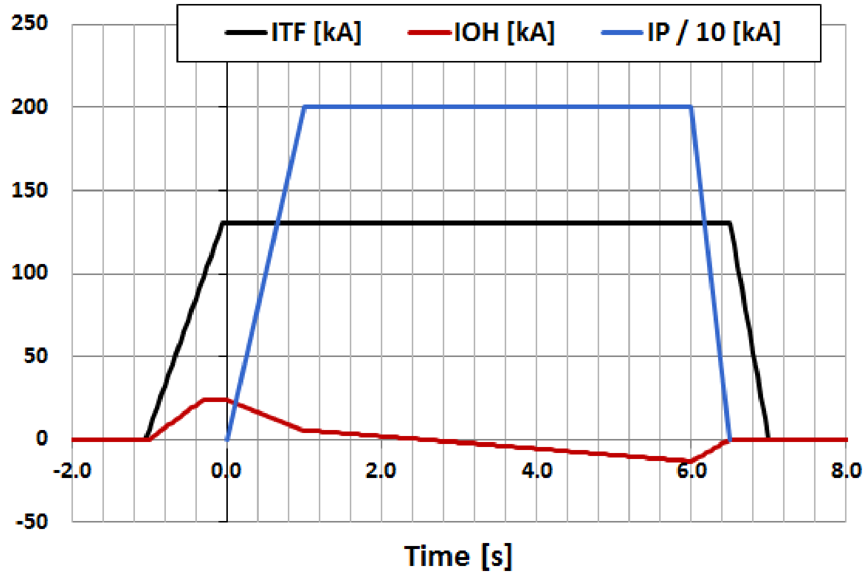
This scenario most likely to be affected

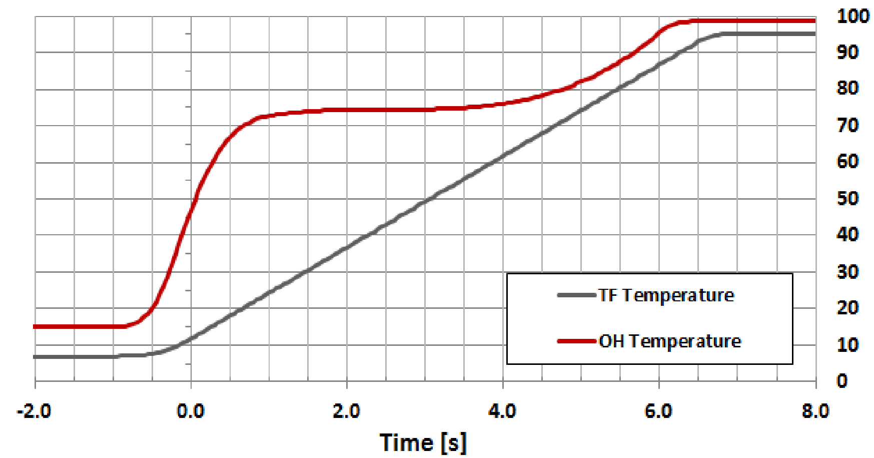
1st and 2nd year goals not affected materially by composite material

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

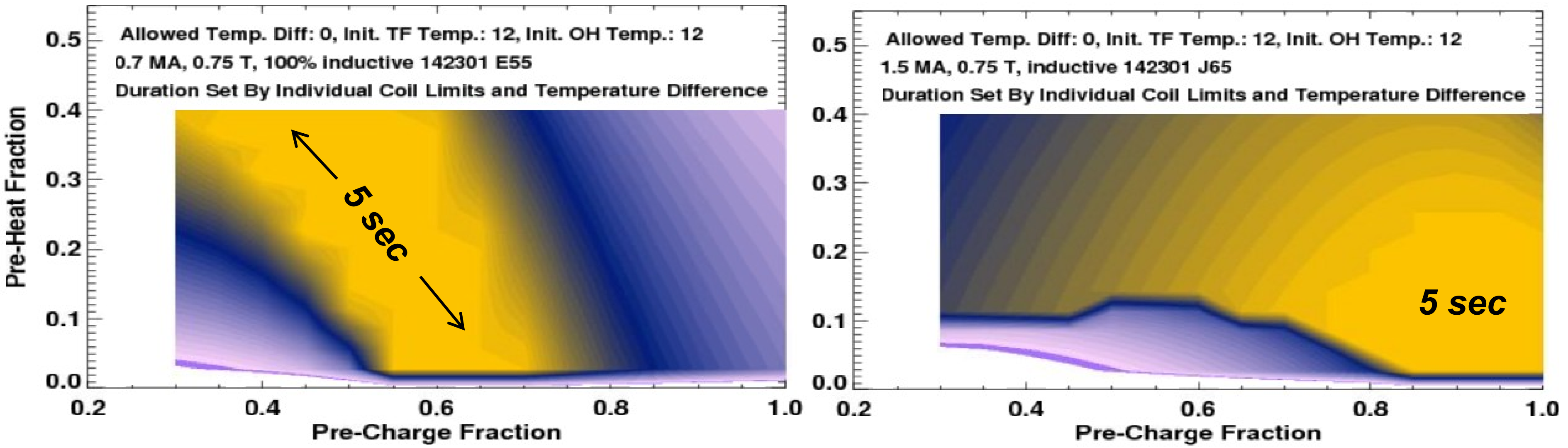




Initial Operations Will Be Largely Unaffected By Aquapour/CTD-425 Composite

- 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.

0.7 MA, 0.75 T, 100% Non-Inductive **1.5 MA, 0.75 T, Partial Inductive**



- 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

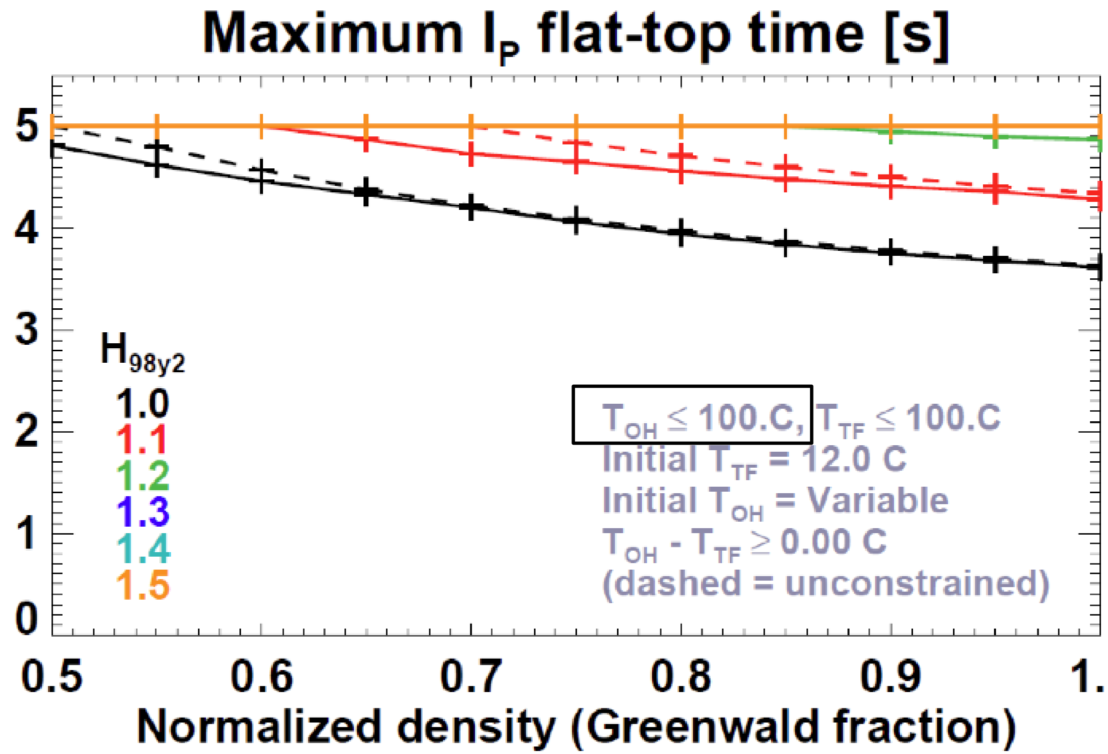
- 0D study as a function
  - Confinement (H_{98})
  - Density (Greenwald)
- Determine via optimizer the optimum initial OH temperature, *limiting the maximum to 100 C.*
- Result:
  - Typically only a 0.2 second (or less) reduction in pulse length, provided the pre-heat is optimized
  - H_{98}~1.2 needed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

Solid:

$T_{TF}<T_{OH}$ applied as a constraint

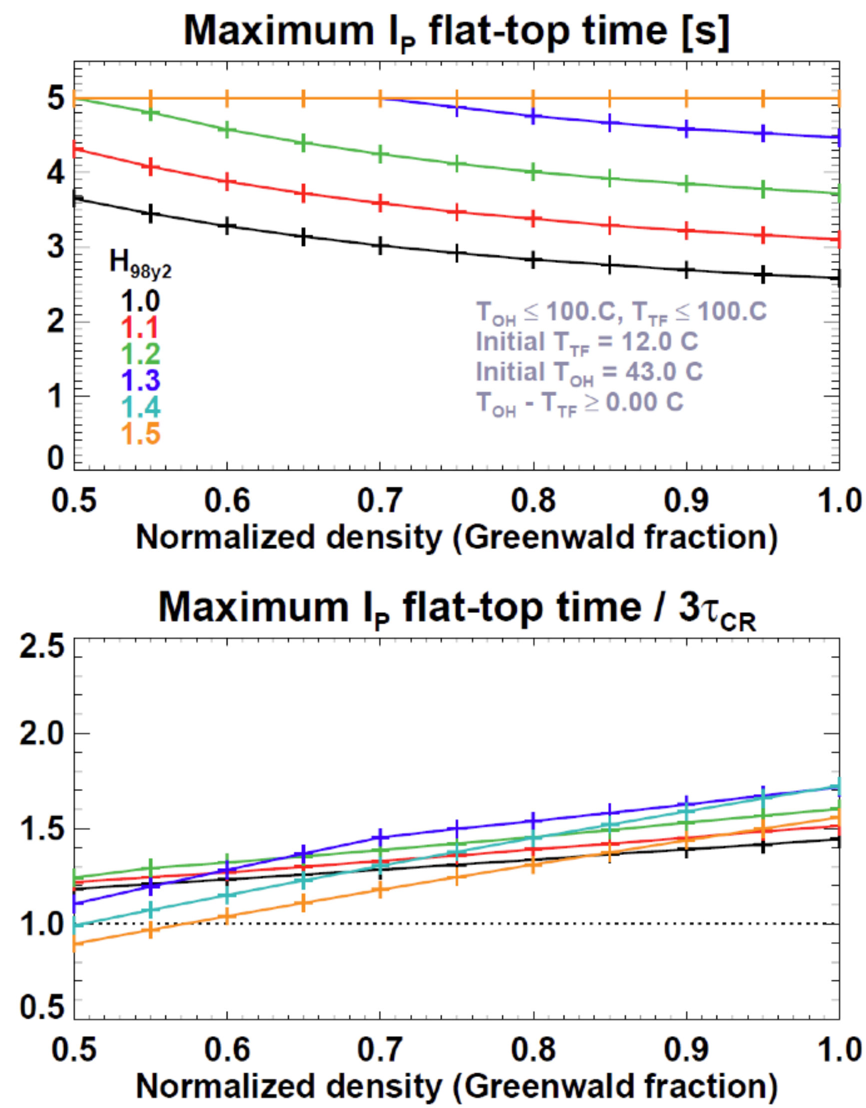
Dashed:

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.



More Scientific Organization

NSTX-U Milestone Schedule for FY2016-18

(see updated Milestone web-page for additional detail / text)

	FY2016	FY2017	FY2018
Run Weeks: Incremental	14 / 16	16 / 18	12 / 16
Boundary Science + Particle Control	R16-1: Assess H-mode confinement, pedestal, SOL characteristics at higher B_T, I_P, P_{NBI}	R17-1: Assess scaling, mitigation of steady-state, transient heat-fluxes w/ advanced divertor operation at high power density R17-2: Assess high-Z divertor PFC performance and impact on operating scenarios	R18-1: Assess impurity sources and edge and core impurity transport IR18-1: Investigation of power and momentum balance for high density and impurity fraction divertor operation
Core Science	R16-2: Assess effects of NBI injection on fast-ion f(v) and NBI-CD profile	R17-3: Assess τ_E and local transport and turbulence at low ν^* with full confinement and diagnostic capabilities	IR18-2: Assess role of fast-ion driven instabilities versus micro-turbulence in plasma thermal energy transport Begin ~1 year outage for major facility enhancement(s) sometime during FY2018
Integrated Scenarios	R16-3: Develop physics + operational tools for high-performance: κ, δ, β, EF/RWM	IR17-1: Assess fast-wave SOL losses, core thermal and fast ion interactions at increased field and current R17-4: Develop high-non-inductive fraction NBI H-modes for sustainment and ramp-up	R18-2: Control of current and rotation profiles to improve global stability limits and extend high performance operation R18-3: Assess transient CHI current start-up potential in NSTX-U
FES 3 Facility Joint Research Target (JRT)	C-Mod leads JRT: Assess disruption mitigation, initial tests of real-time warning, prediction	DIII-D leads JRT: Understanding Detachment	NSTX-U leads JRT: TBD

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

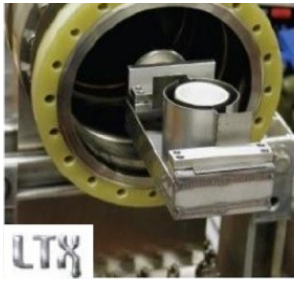
- Led brainstorming, organization, writing of 5 year plan
- Address highest priority scientific issues through discussion and consensus at open meetings
- Organize the NSTX-U Research Forum sessions.
- Draft scientific milestones
- Propose and execute experiments
- Define facility and theory resources 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

Long Term Upgrades

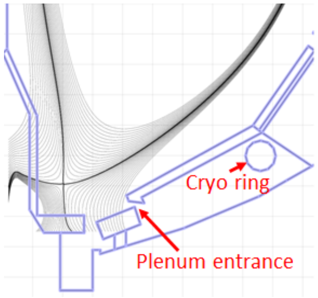
NSTX-U facility enhancements proposed for 5 year plan support FESAC Tiers/Priorities

- 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)*

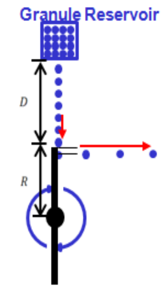
Upward Li evaporator



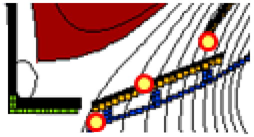
Divertor cryo-pump



Li granule injector (LGI)

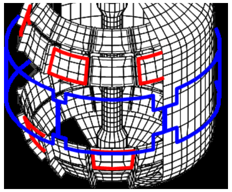


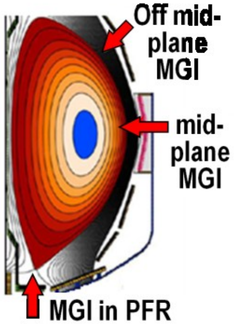
- Disruption avoidance, mitigation *(Transients, Predictive)*
  - Massive gas injection, detect halos, disruptions, control v_ϕ, RWM, ELM



Extended low-f MHD sensor set

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





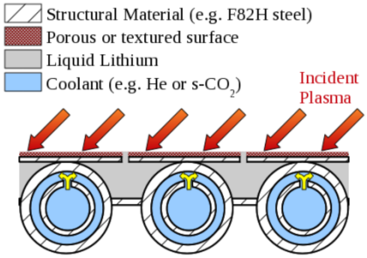
- ST start-up and ramp-up tools *(FNSF)*
  - ECH to raise start-up plasma T_e to enable FW + NBI + BS I_P ramp-up
  - Test EBW-CD start-up, sustainment
  - Start-up/ramp-up critical for ST-FNSF

1MW 28 GHz gyrotron

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

High-Z tiles

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



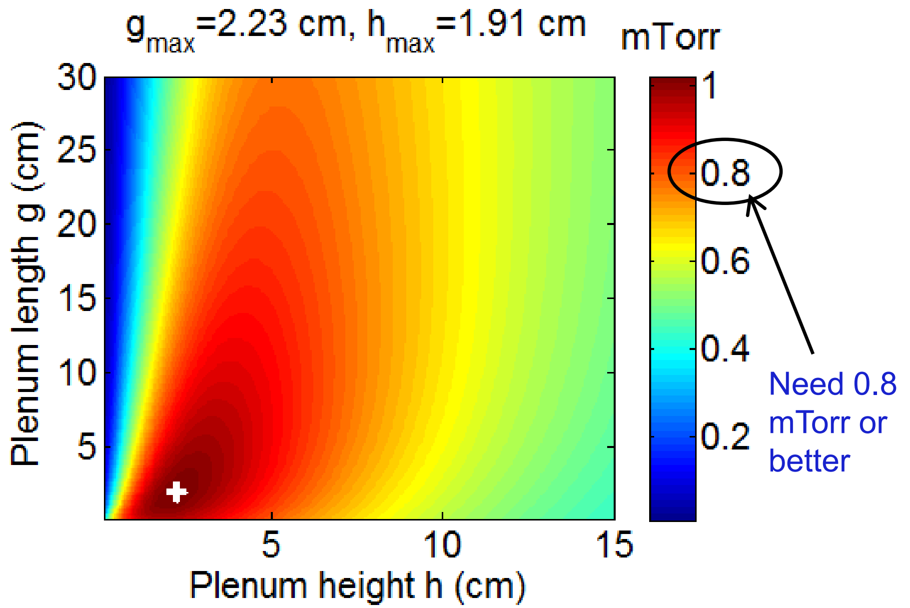
4 Major Upgrade Are Being Considered for the next 5 Years

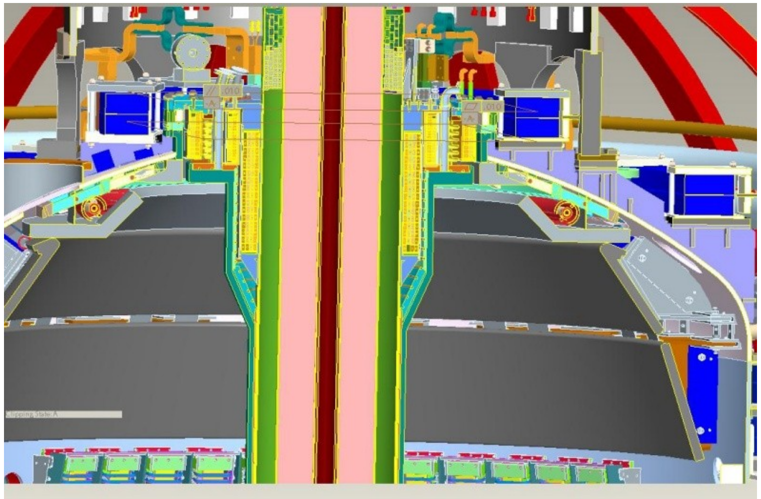
- We need robust density control.
  - Proposed Upgrade: ***Divertor cryopump***
- We need to develop high-performance ST scenarios compatible with reactor relevant plasma facing components (PFCs).
  - Proposed Upgrade: ***High-Z PFC upgrade***
- We need to understand how a CHI formed plasma can be ramped 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

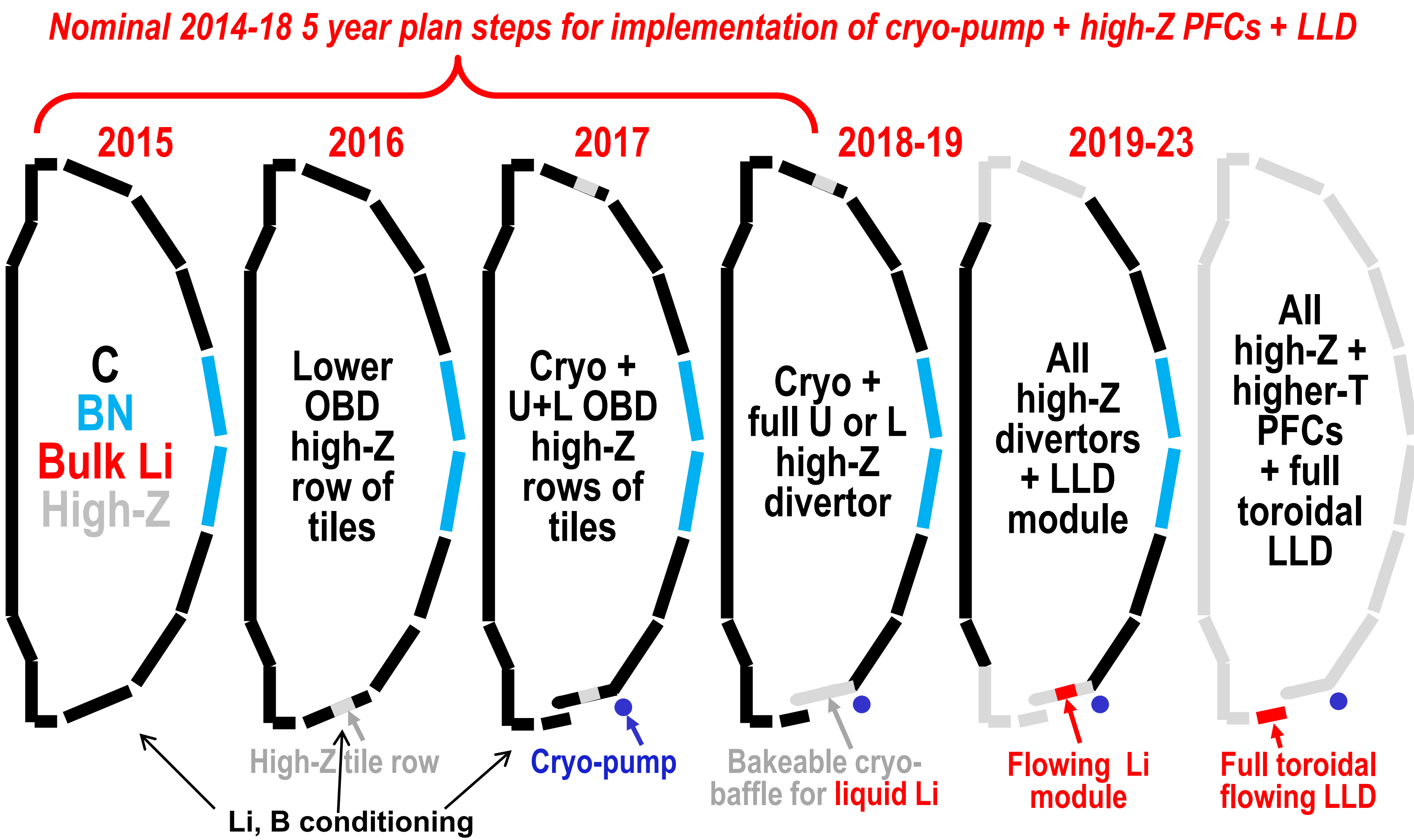
- Physics design completed in collaboration with ORNL[1].
  - Defined the geometry, plenum sizes, ability to pump various geometries.
- Conceptual design process has been initiated:
  - Draft GRD has been formulated.
  - Initial designer sketches of in-vessel implementation completed.
  - Potential refrigerator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



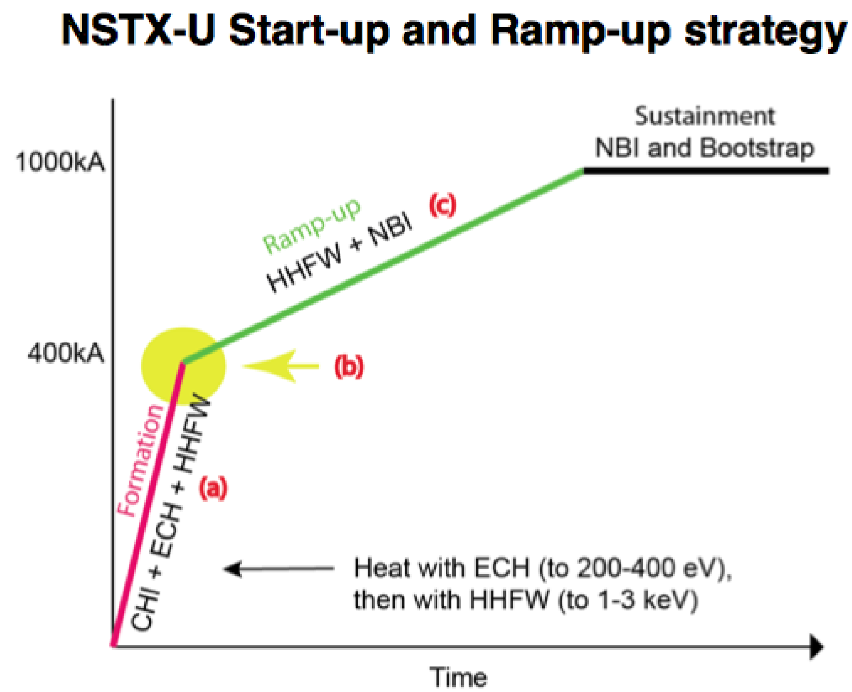


[1] http://nstx.pppl.gov/DragNDrop/Scientific_Conferences/APS/APS-DPP_12/Contributed_Posters/PP8.00030_Canik_APS2012.pdf

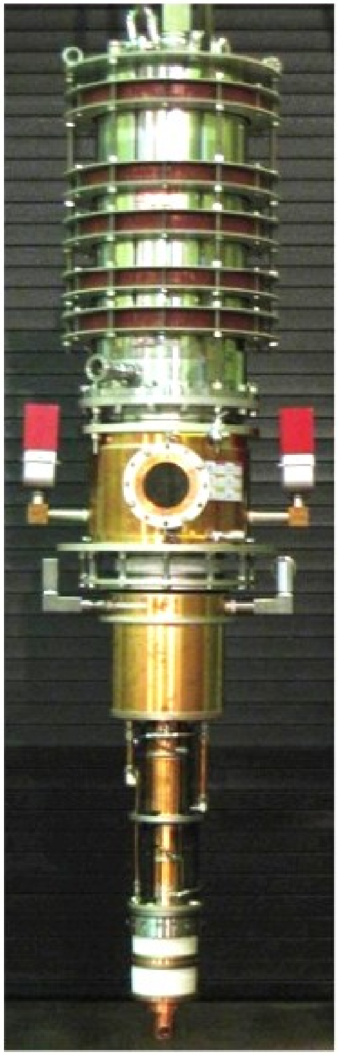
Stages Plan Has Been Developed to Implement High-Z PFCs & Flowing Liquid Metal Systems



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



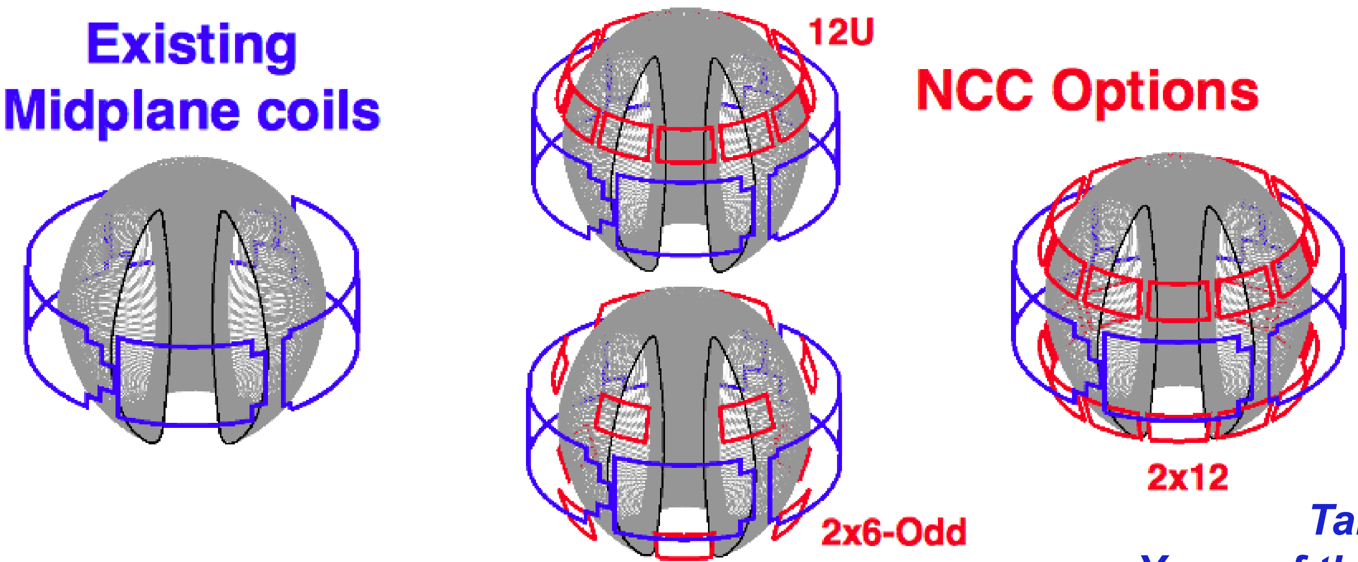
- Coaxial Helicity Injection can form a 200-400 kA seed plasma, but it is too cold and quickly decays.
- Use of ECH can “bridge the gap”, to where HHFW and then NB current drive can support the ramp and sustain the current.
  - 20-40% first pass absorption predicted by GENRAY.
- Goal of first ECH power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

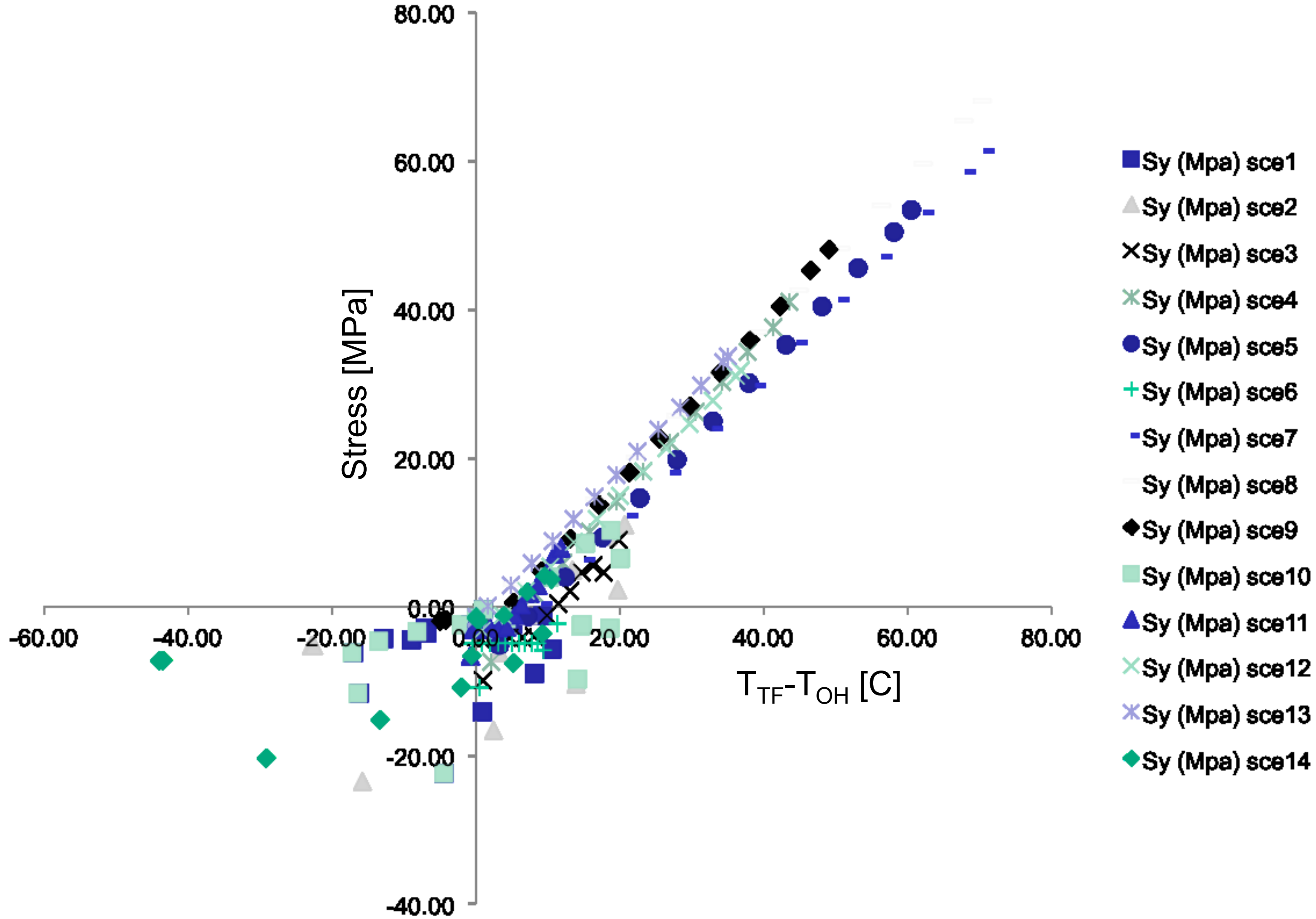
- University, national lab, and business collaborations for both data analysis and facility upgrades (diagnostics, gas injectors,…).
- Collaborations reviewed & renewed on a 3-4 year cycle.
- Key documents:
  - Record of Discussion: documents communications between PPPL and collaborator during the formulation of DOE proposal, including estimates of PPPL resources to support collaboration is funded
  - Record of Agreement: agreed commitments of resources, equipment, 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.

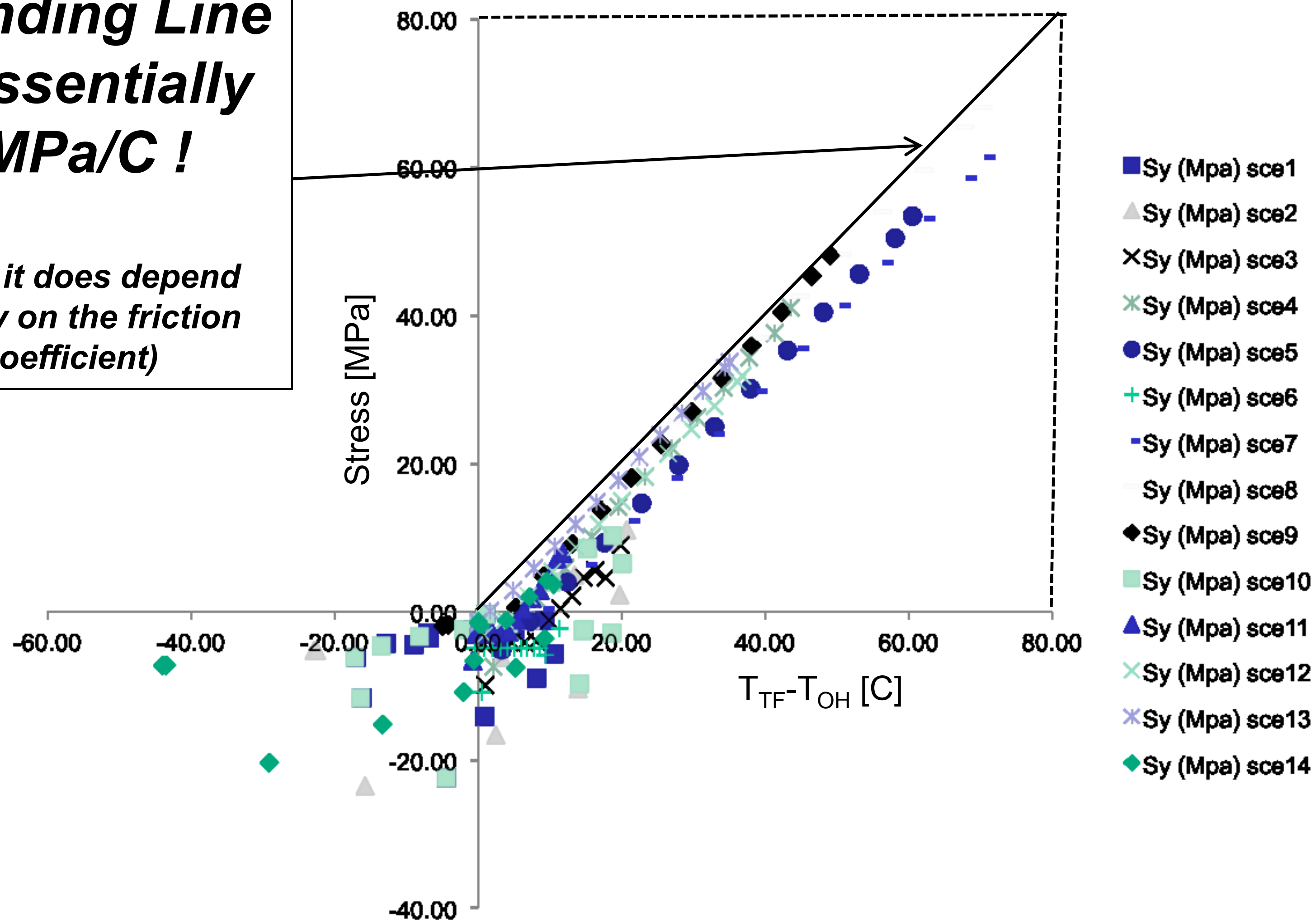
Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Result (I)



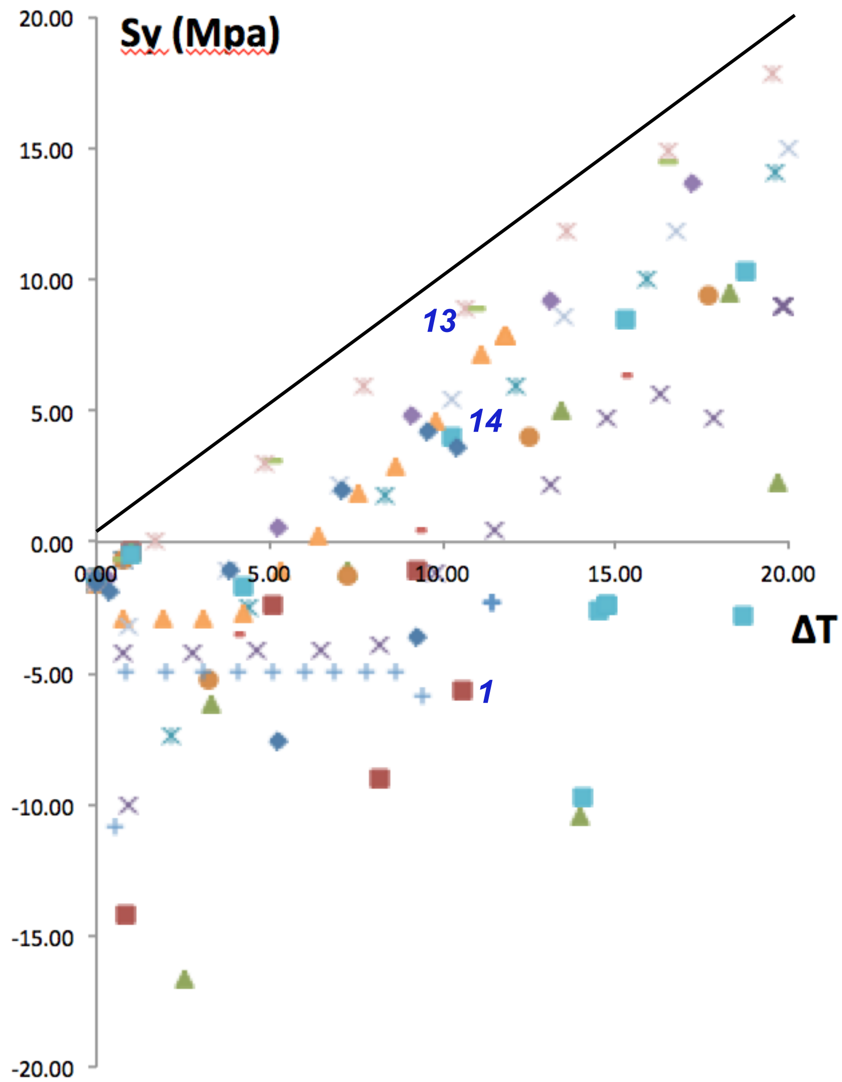
Analysis Supports the Use of Temperature Differentials for The Initial Protection Scheme: Result (I)

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<δT<~20).
- Large variation under that line, due to:
  - The OH state
  - Path dependence.

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 ith 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.

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

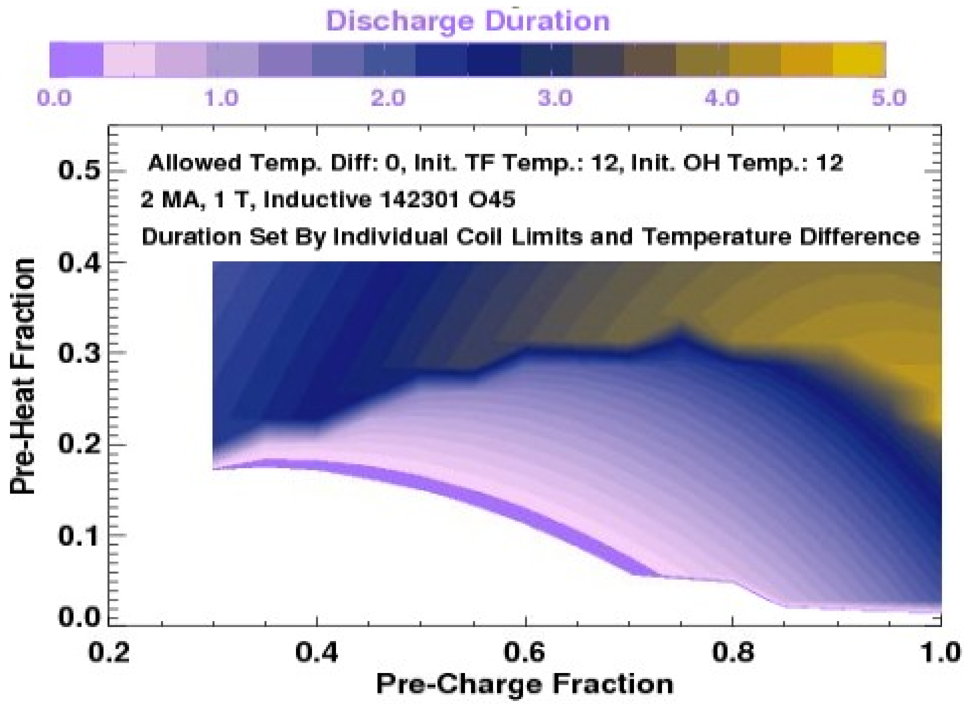
Both Simulations

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

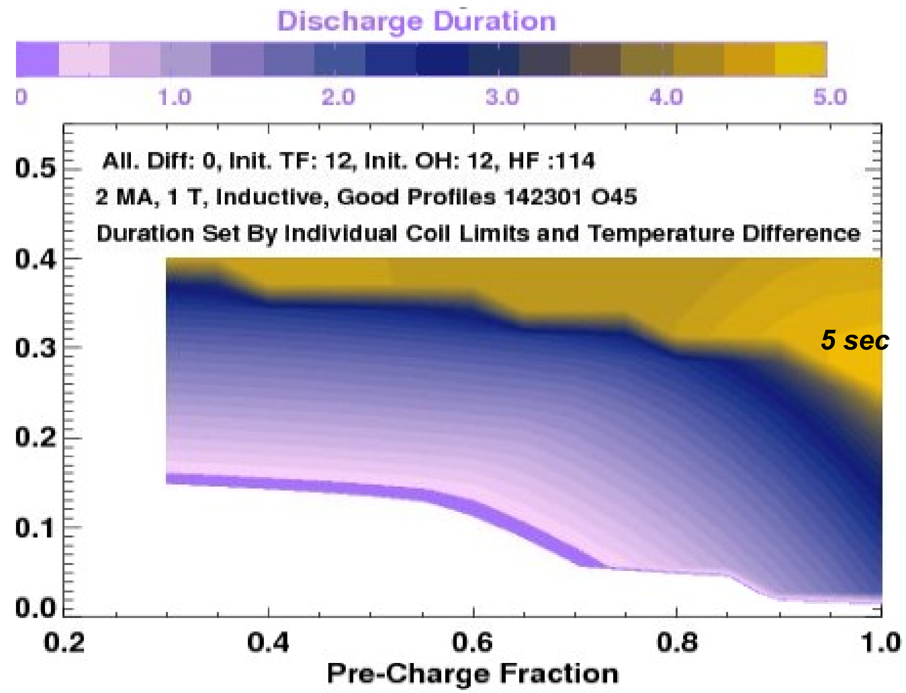
$T_{TF}<T_{OH}$ maintained

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

T_{OH} limited to 98 C



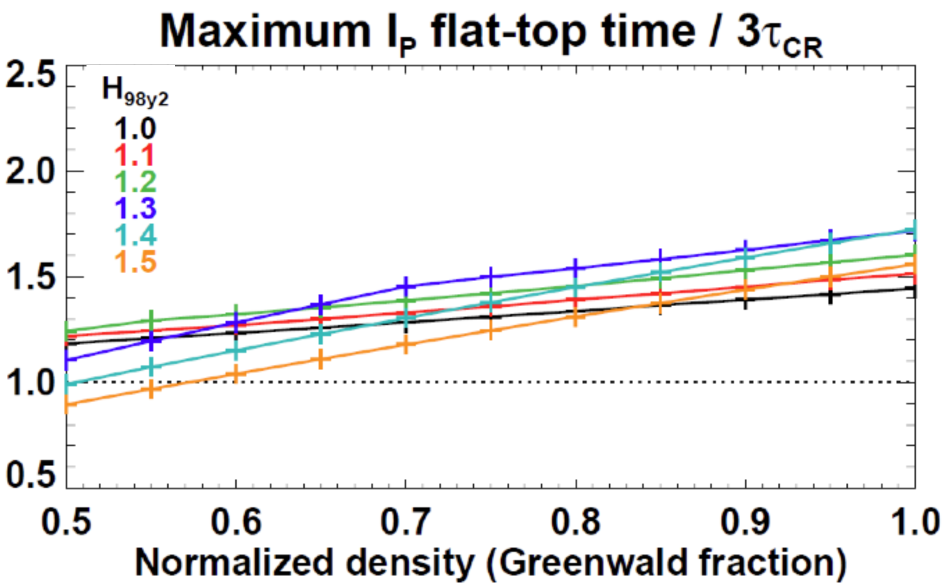
T_{OH} limited to 110 C



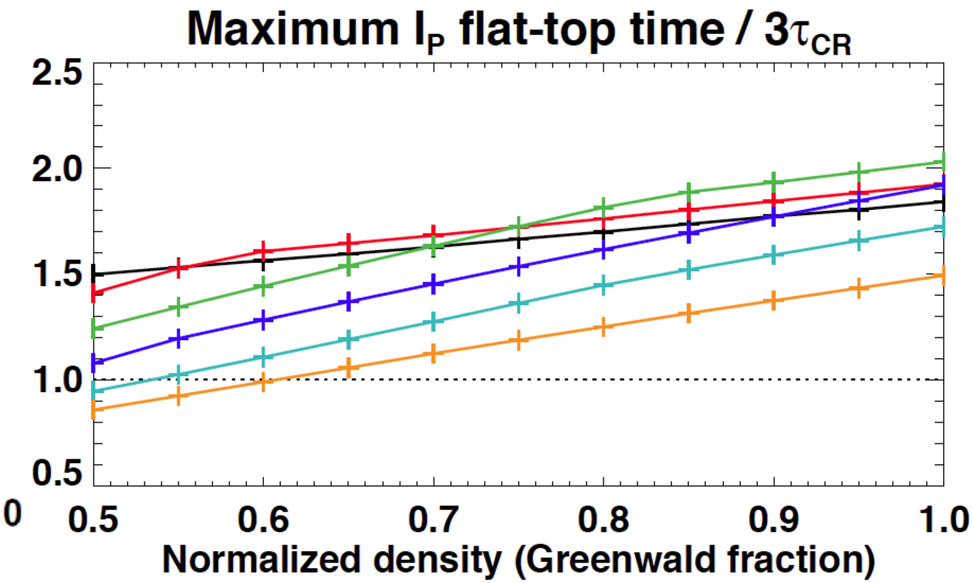
For this confinement multiplier, 5 sec. operation restored with with 110 C max. OH temperature

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

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



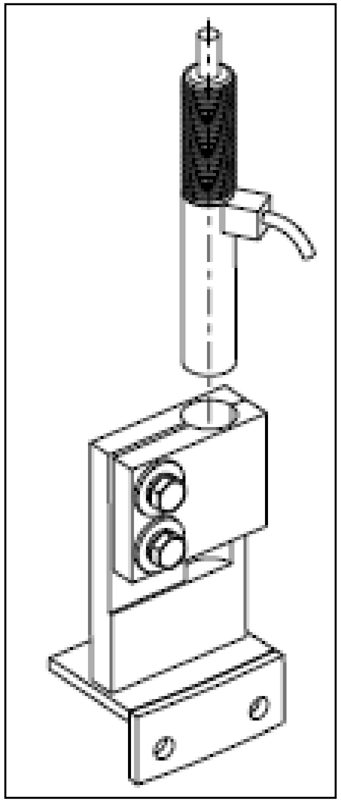
T_{OH}<110 C, T_{TF}<100 C
Initial TF temperature: 7 C
OH Pre-heat to 35 C

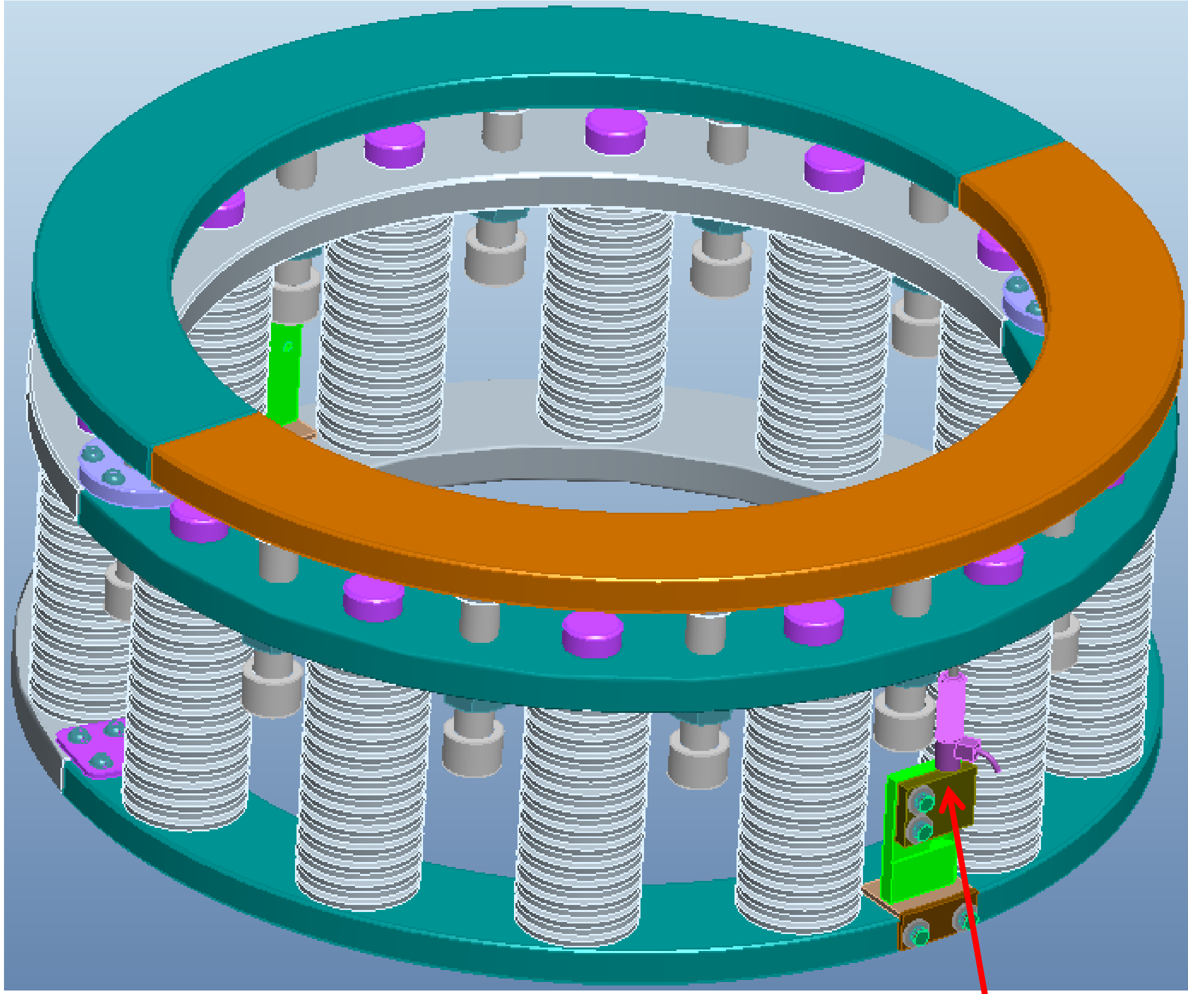


In this configuration, only 0.2-0.4 sec of absolute discharge duration lost, despite the fixed initial OH temperature

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.



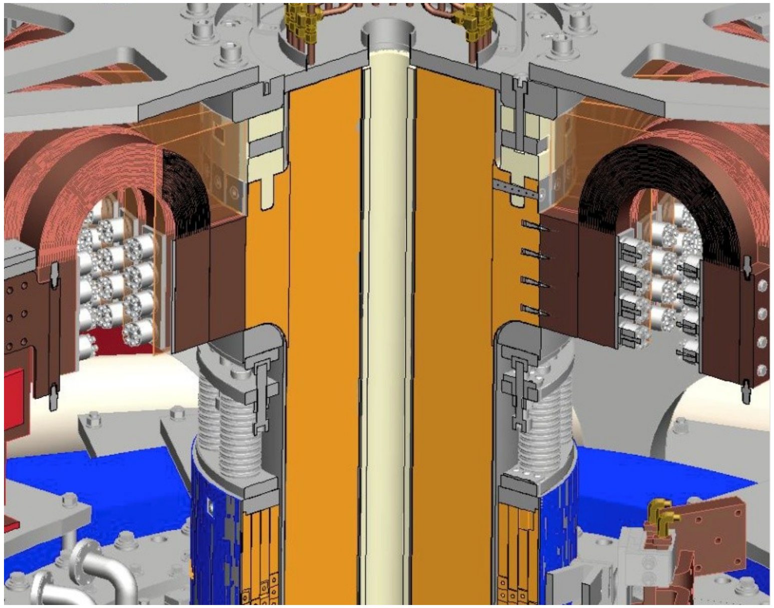


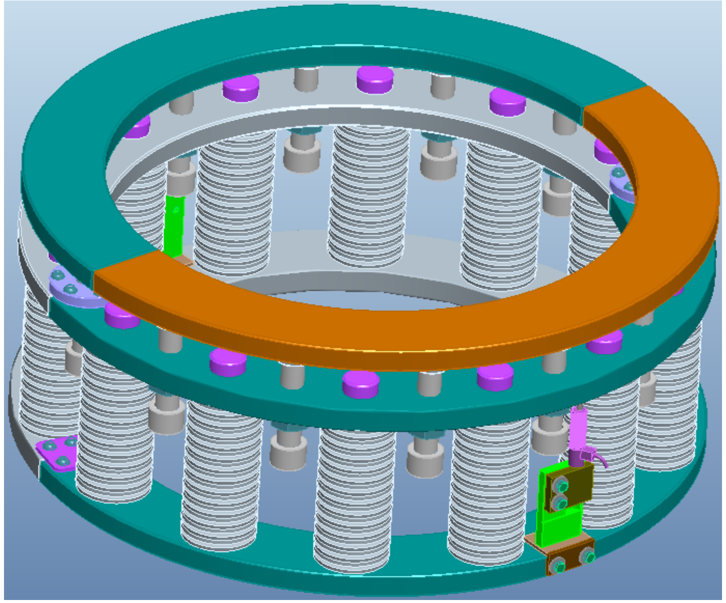
FOD Sensor

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.



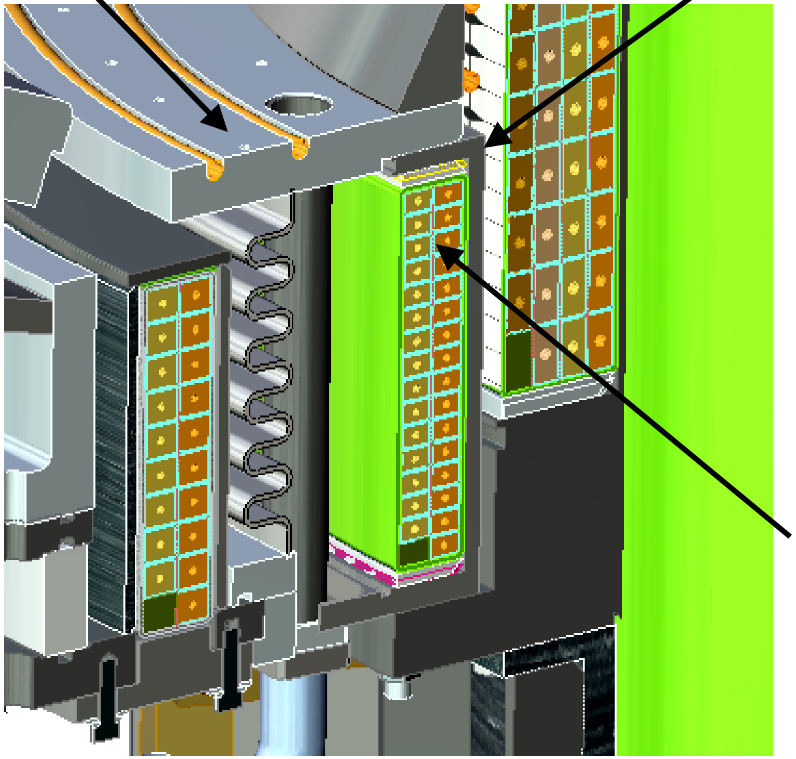


Bakeout & PF-1b

Temperature Distribution Near PF-1b and the Horizontal Target Must be Managed

We want it hot here…350 C if possible
(Where the tiles are)

We want to avoid thermal gradients here (Where there is a small stitch weld holding the casing to the PF-1b mandrel)

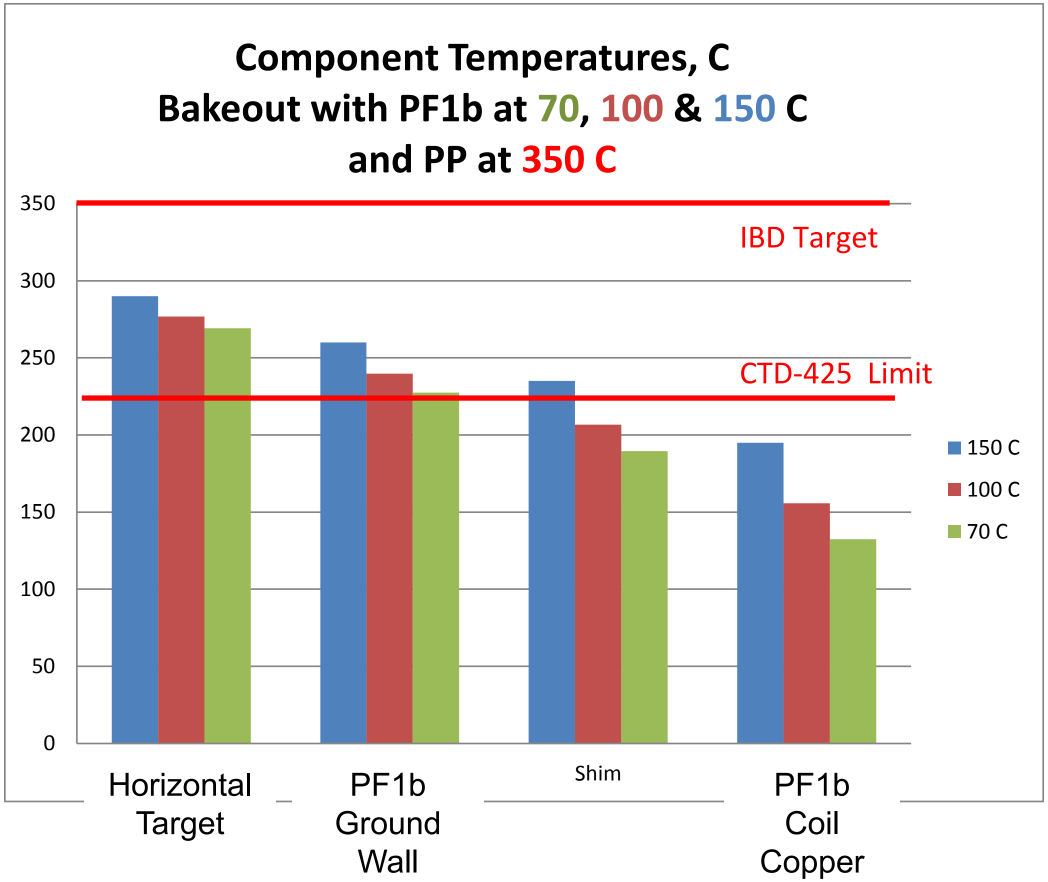


We want it cool here
(On the coil turn- and ground- insulation)

Flowing 70 C Water Through PF-1b Appears to be the Optimal Compromise

- Options for control are limited:
  - Flowing hot helium on copper cooling tubes was infeasible.
- Optimal solution appears to be 70 C water in PF-1b
  - Keeps insulation below 225 limit.
  - Limits weld stress
  - Allows the horizontal target to reach ~270 C.
- Heat exchanger solution being implemented to provide correct water to the PF-1b during next bakeout.

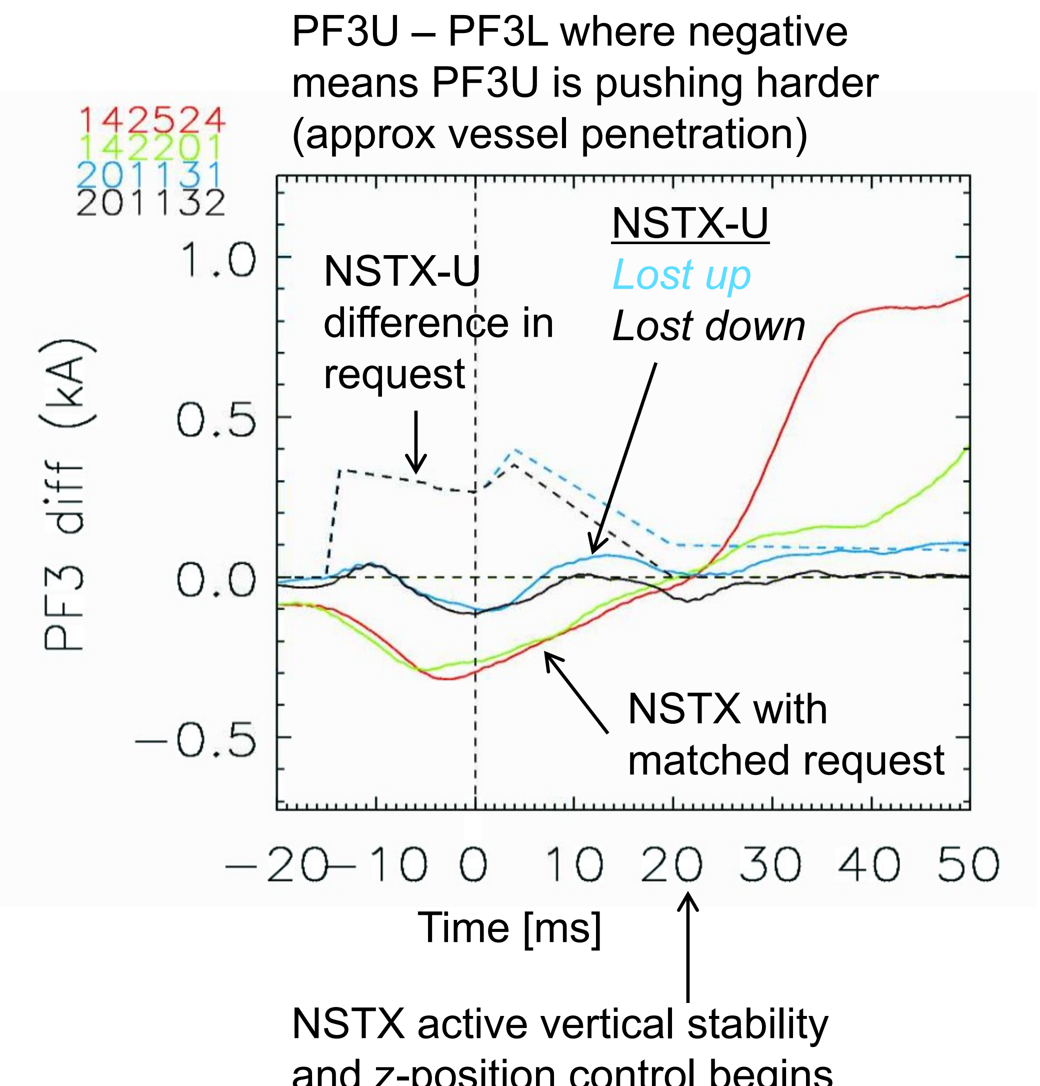
Temperature at Four Locations as a Function of the PF-1b Water Temperature



More on Plasma KPP

When we Request the Same Current in PF3U and PF3L, the Plasma Stays Below the Midplane – why?

- Factor #1: PF3U/L current control is not identical
  - Evidence that same imbalance existed in NSTX, but intrinsic vertical stability was still ok
- Factor #2: Differences between the upper and lower divertors
  - Reconstructions confirm imbalance in eddy currents



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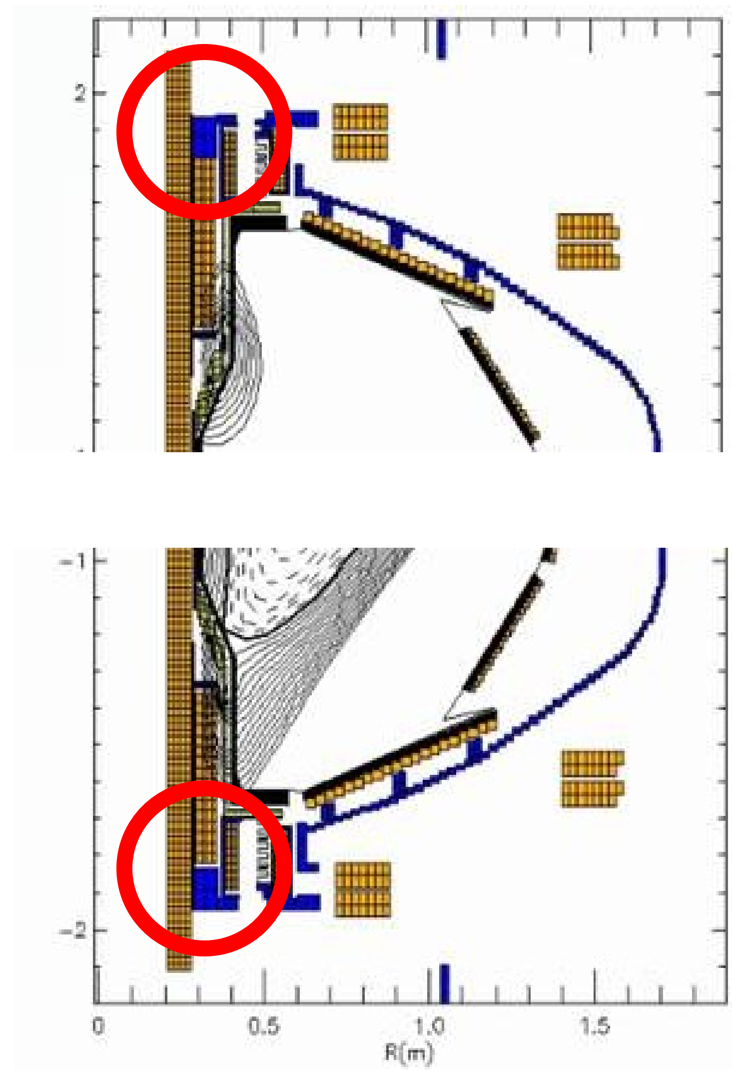

Startup Scenario Will Benefit from Reduced V_{loop} When Operations Resume after Bakeout (and later Boronization(s))

- Induced currents in divertor challenge passive vertical stability
  - V_{loop} ~ 4.5V is challenging
- It is expected that these plasmas were "dirty" due to unbaked tiles
  - CHERs sees bright C and O lines, some residual Li
  - No bright N lines
    - Good vacuum quality
- After bake, cleaner plasma will reduce V_{loop} requirements and improve intrinsic stability (lower li)
  - Energizing the PF1CU/L to cancel induced fields is an option if needed