Agenda

- Steve Cowley
- John Galayda - Project Update
- Stefan Gerhardt - Bundle Update
- S. Kaye - Research Update

National Spherical Torus eXperiment Upgrade

Project Status

J. Galayda, NSTX-U Recovery Team

Project History/Status

- CDE-2/3a approved — 30 Sept 2019
- PPPL curtailment due to COVID-19 — COB 13 March 2020
- Project team continued to work remotely
- Project Final Design Review — 17-19 March 2020
- Project CDE-3b IPR — 26-29 May 2020
- CDE-3b Approved — 9 June 2020
- Baseline Update Director's Review — 3 Feb 2021
- Rebaseline Director's Review — 28 Sept 2021

Project Update

Project is

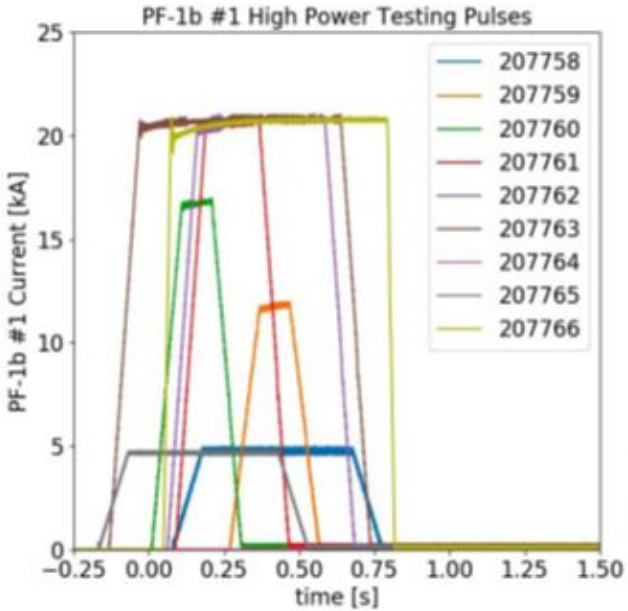
- 71% complete (Through September)
- You are accomplishing work at ~ $3.8M per month

Purchases & acquisitions largely delivered & prepared for installation

- TFTR TC chock full of components ready for installation
- PPPL shops custom-fitting components for installation in the NSTX-U vessel

All Poloidal Field Coils Delivered

- Good results in full-power tests



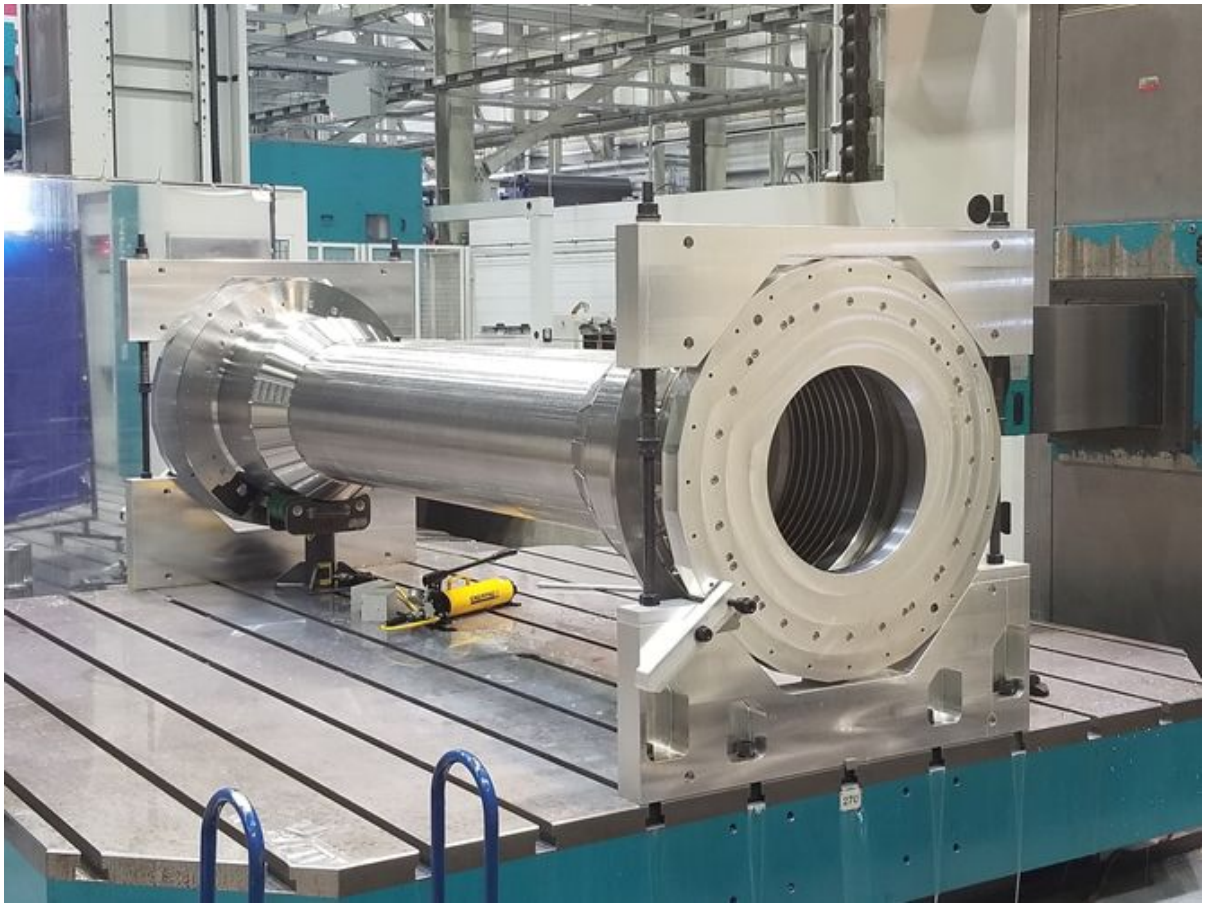
Center Stack Casing

This fabrication has taken considerably longer than the vendor had estimated-

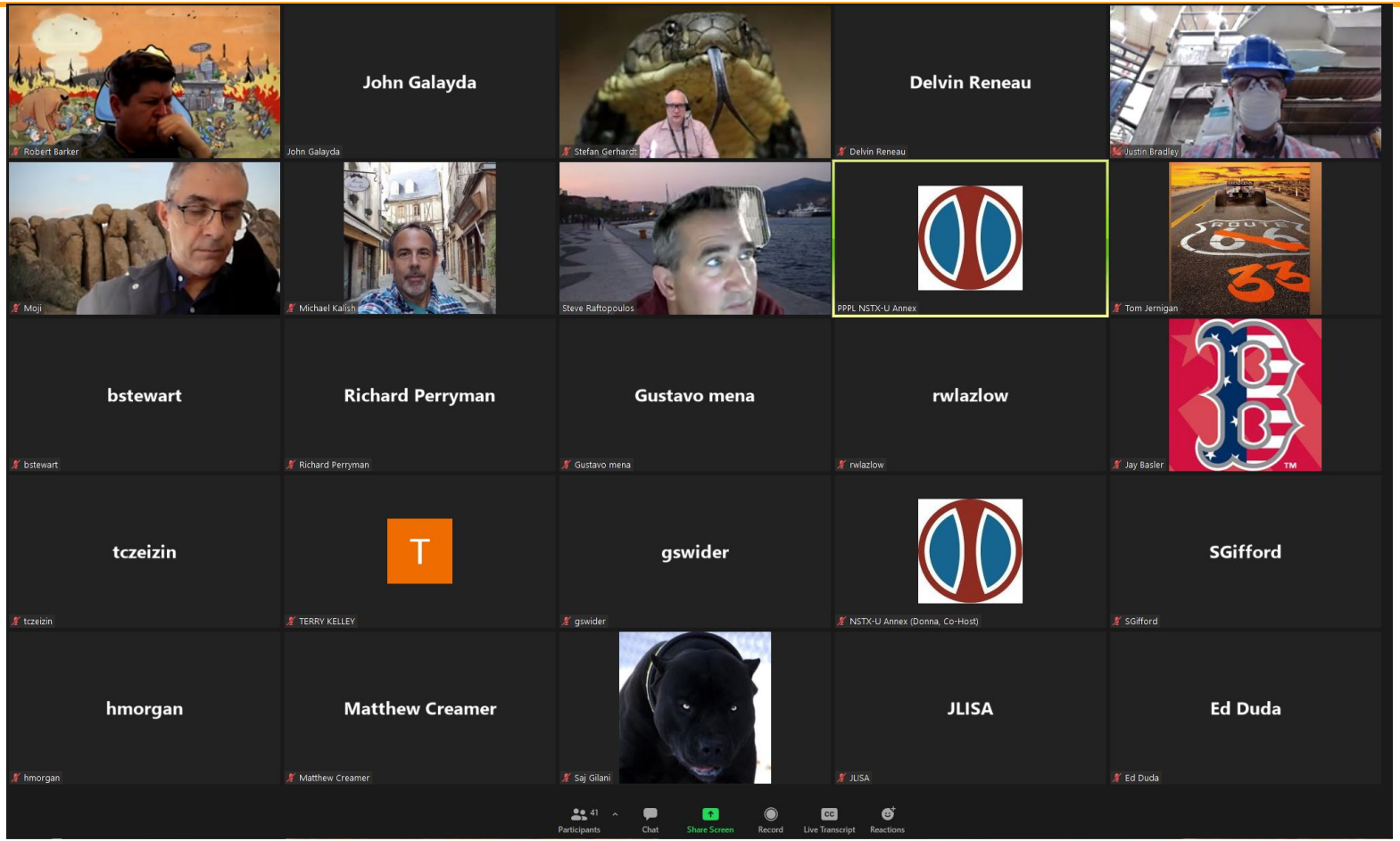
Delivery forecast 1/2022

PPPL and NSTX-U are working with the manufacturer to recover schedule

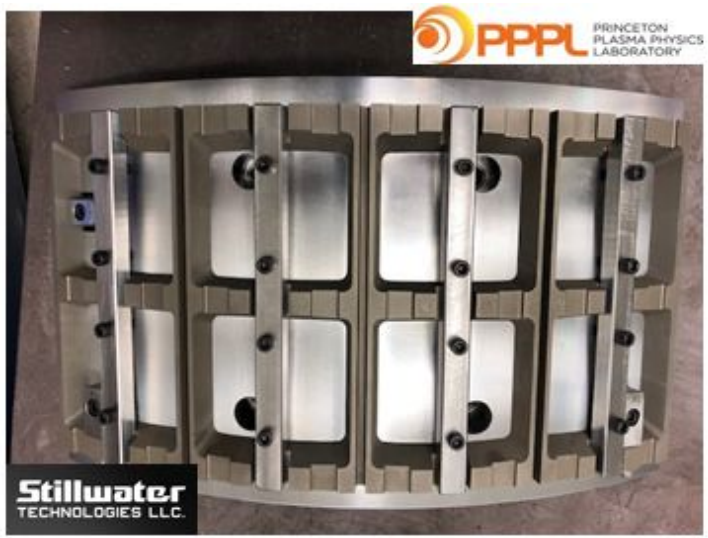
HOLTEC INTERNATIONAL

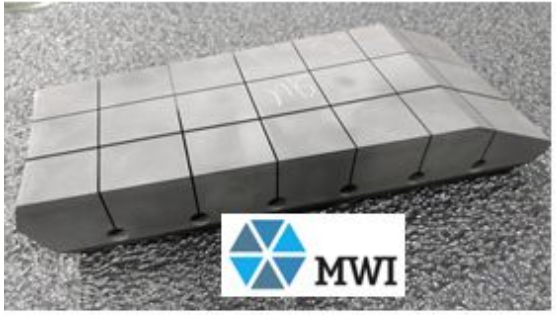


Working Together-Meeting Daily, pre- and post-shift

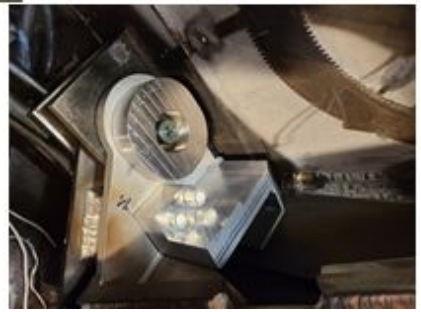


Graphite Tiles, Metal Plasma-Facing Components are Staged for Installation





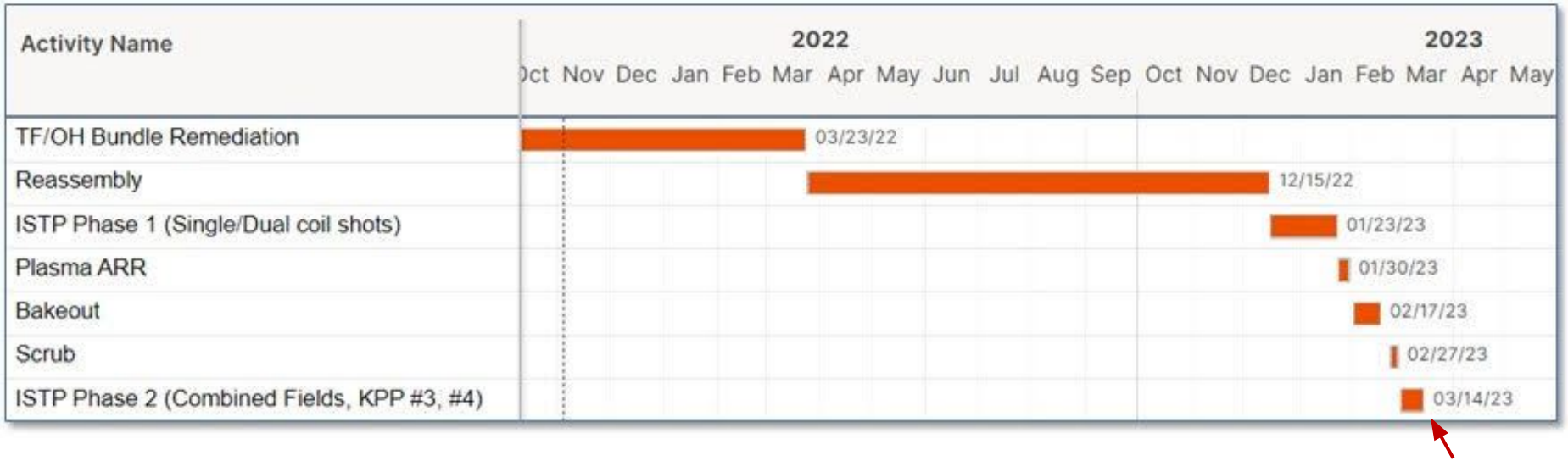
PPPL PRINCETON PLASMA PHYSICS LABORATORY



Hardware for reassembly, staged in TFTR

Schedule, Critical Path

TF bundle remediation pushes critical path (see next part of talk)



We *never* stop looking for ways to recover schedule- stay tuned

Facts of Project Life

- We try to optimize the schedule, eliminate downtime
- We try to economize
- We try to design things to be good enough, not gold-plated
  - *So technical, cost and schedule considerations are always jostling each other*

- Managing the cost/schedule/technical balance is
  - Inevitable; and
  - what makes the job challenging-

Work Planning/Control

- Written procedures to define the work
  - Thanks for writing over 100 new ones
- Preparatory walkthru's to ensure all the hazards are IDed and handled, all the preconditions are as expected
- Pre-job briefs to get the job at hand in focus
- Correct tools for the job - resist the urge to "kluge"
- PPE- shoes/glasses/gloves
  - (I like vests, too)
- STOP WORK if the situation doesn't match expectations
- Look out for your co-workers-
- COVID-19 Controls- look out for your families and your co-workers' families

National Spherical Torus eXperiment Upgrade

TB Bundle - Recent Activities

S. Gerhardt speaking

Technical contributors includes ***at least*** these people...

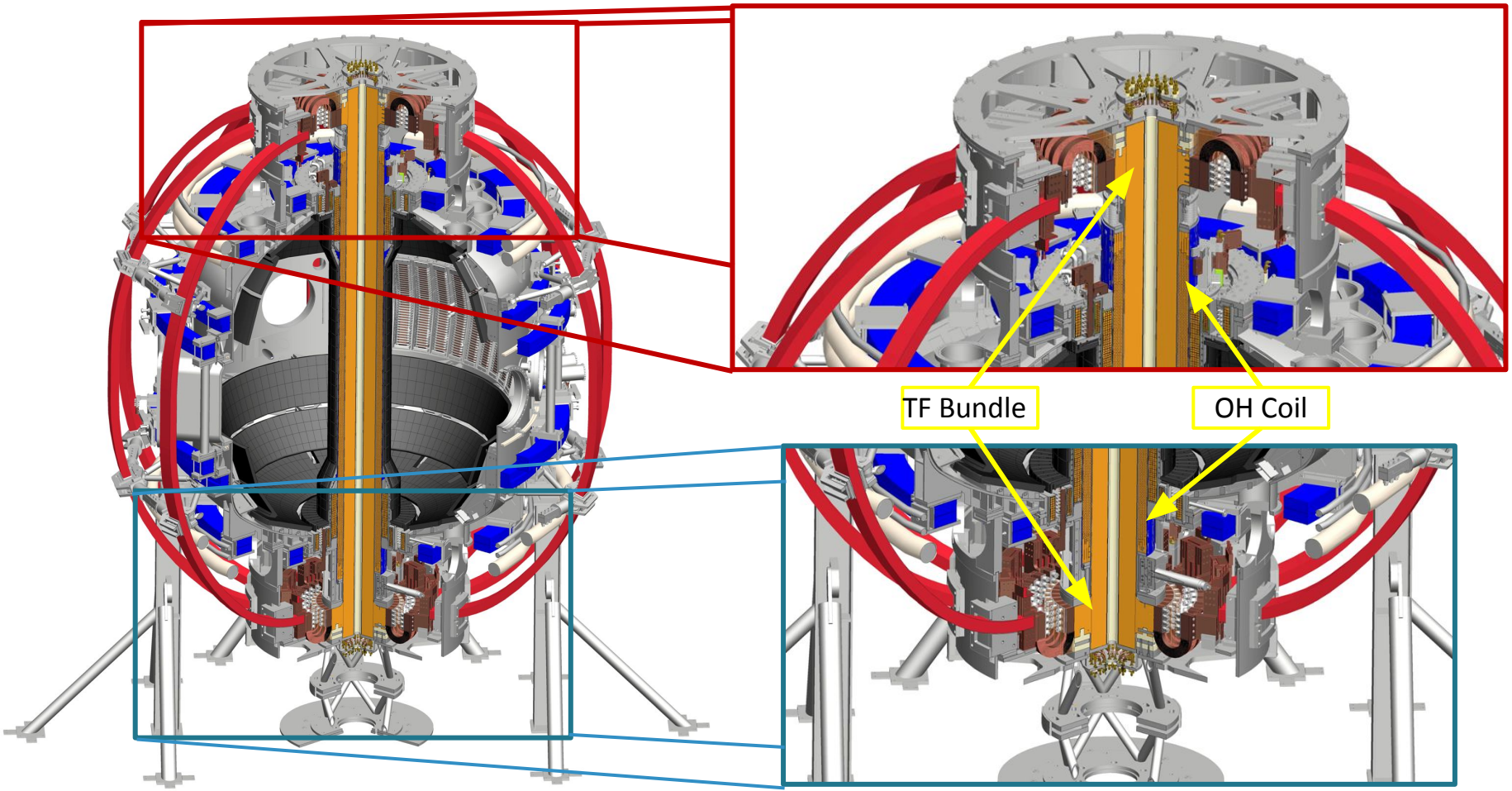
J. Alicea, M. Anderson, M. Boyer, A. Brooks, D. Cai, R. Cappelletti, J. Dellas, J. Desandro, R. Ellis, A. Falcon, R. Gutter, D. Harrison, F. Hoffmann, M. Kalish, C. Lapish, T. McLaughlin

M. Palmer, M. Pauley, J. Perich, J. Petrella, W. Que, S. Raftopoulos, W. Reese, M. Sibilia, N. Smith, P. Titus, R. Tucker, Y. Zhai (PPPL) A. Haight (CTD)

Outline

- Background 
- Work on Existing Bundle
  - Disassembly
  - Electrical Testing
  - Present and Next Steps
- Spare Bundle

Inner and Outer Legs Form a Toroidal Solenoid



Overview - 1/2: NSTX-U Project

- Upgrade Project included the fabrication of new TF/OH inner-bundle
  - Design started in 2009, fabrication wrapped up in late 2014
  - OH is wound on the TF, trapped
- Bundle supported the operations that completed the Upgrade project, and plasma operations in 2016
- On two occasions, water leaks on the machine resulted in water on the lower parts of the TF Bundle
- After NSTX-U stopped operations in 2016, the bundle was removed from the machine and stored in the two D-site test cells.

Overview - 2/2: Recent

- In early 2021, found that the insulation resistance (IR) between some bundle turns was dropping.
  - Retrospective analysis shows the initial trend was apparent in 2019
- A campaign of disassembly, cleaning, electrical testing, and bakeout followed, but has not (yet) found the cause of the problem.
- We have identified some issues on the present bundle that need to be rectified under any scenario
- We have started to examine targeted design and fabrication changes for a backup bundle.

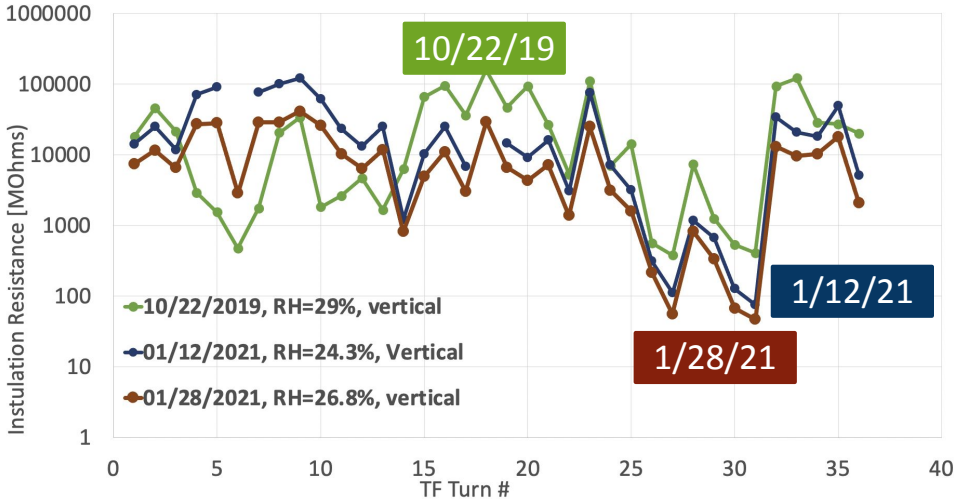
This talk: high-level summary of activities on the bundle since January 2021

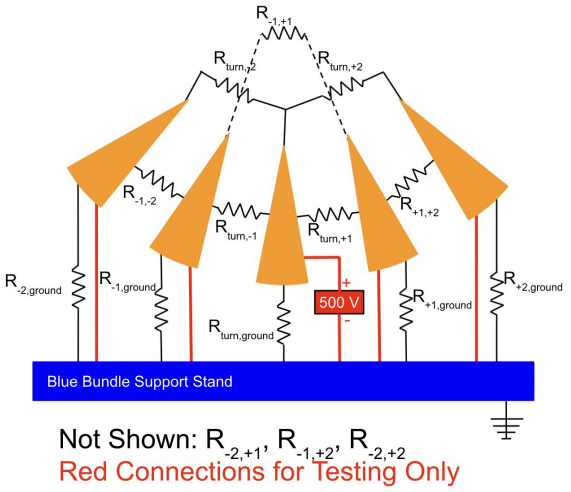
Outline

- Background
- Work on Existing Bundle 
  - Disassembly
  - Electrical Testing
  - Present and Next Steps
- Spare Bundle

Reduction of Turn IR Observed in January 2021

- Preparing to do some work, and did a set of IR tests on 1/12/2021, observed reduced IR relative to 10/22/19.
- Bundle in vertical position; did some modest cleaning and repeated tests on 1/27/21
  - Further IR reduction observed
- Viewed as likely a matter of surface contamination → disassembly and cleaning





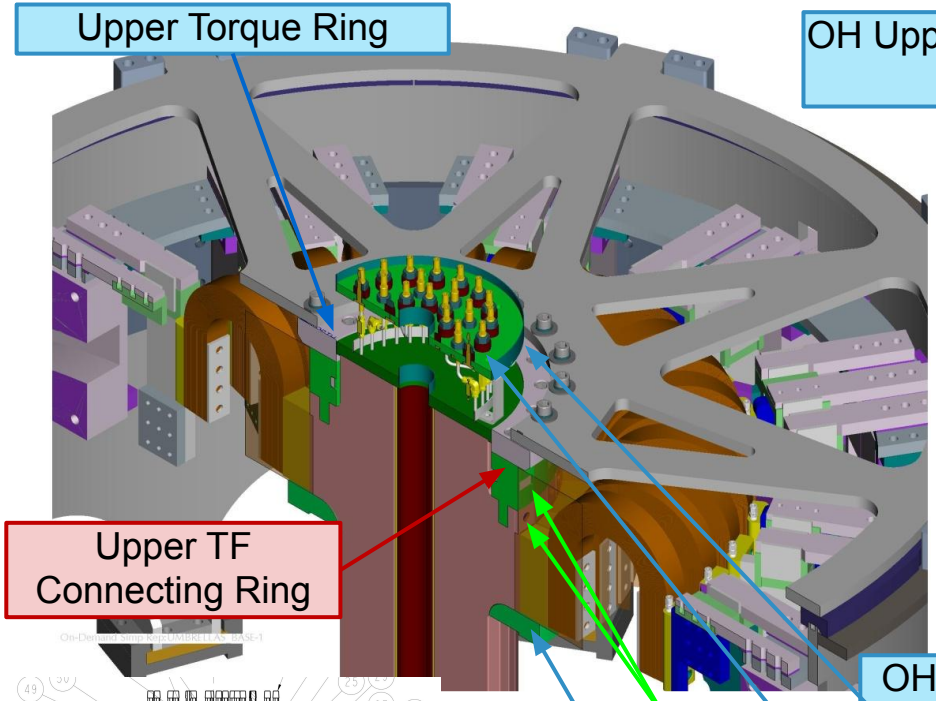
Not Shown: $R_{-2,+1}$, $R_{-1,+2}$, $R_{-2,+2}$
Red Connections for Testing Only

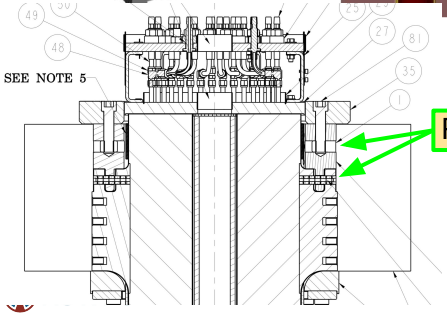
	10/22/2019	1/12/2021	1/27/2021
turn	Resistance (MΩ)	Resistance (MΩ)	Resistance (MΩ)
26	560	314	235
27	379	111	76
28	7290	1170	1100
29	1250	668	439
30	536	127	91
31	410	76	54

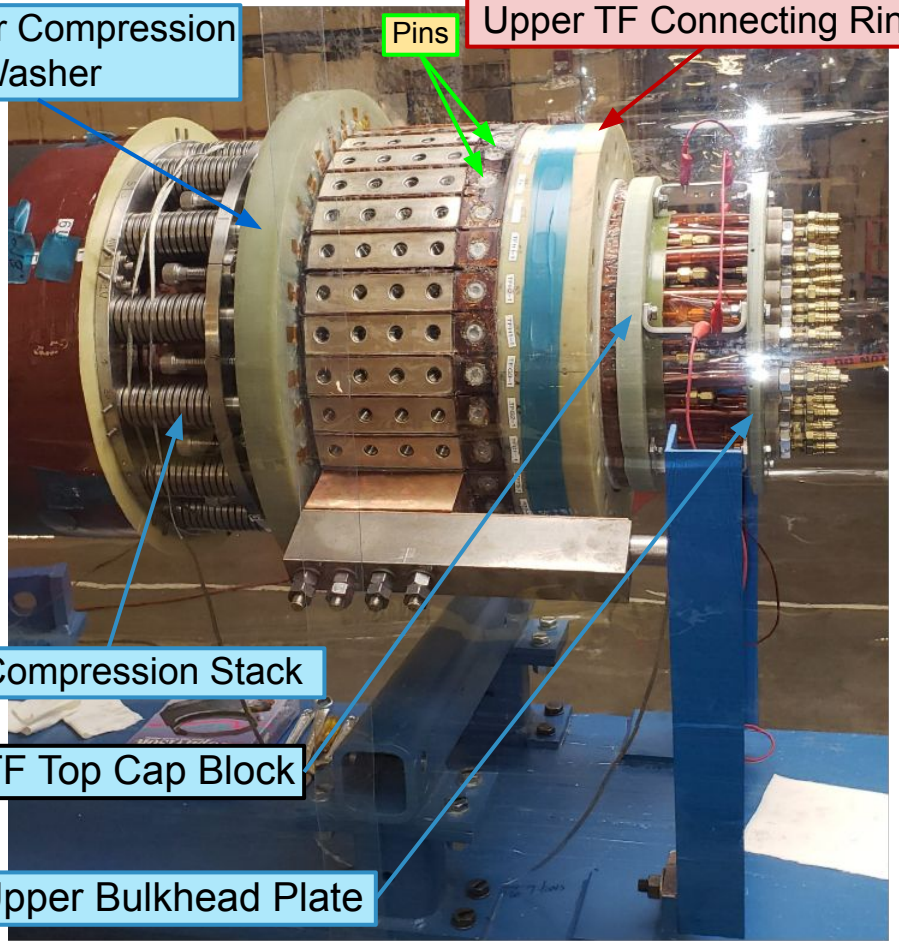
Removed as of 10/4/21

Present

Disassembly Example Bundle Top

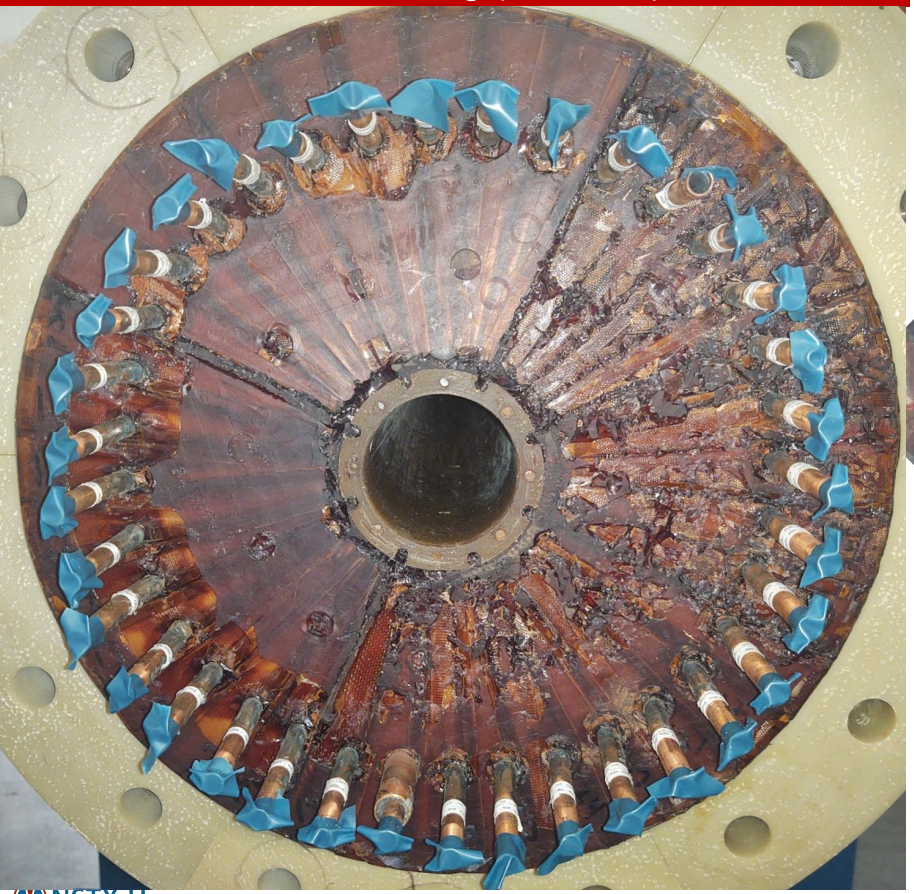




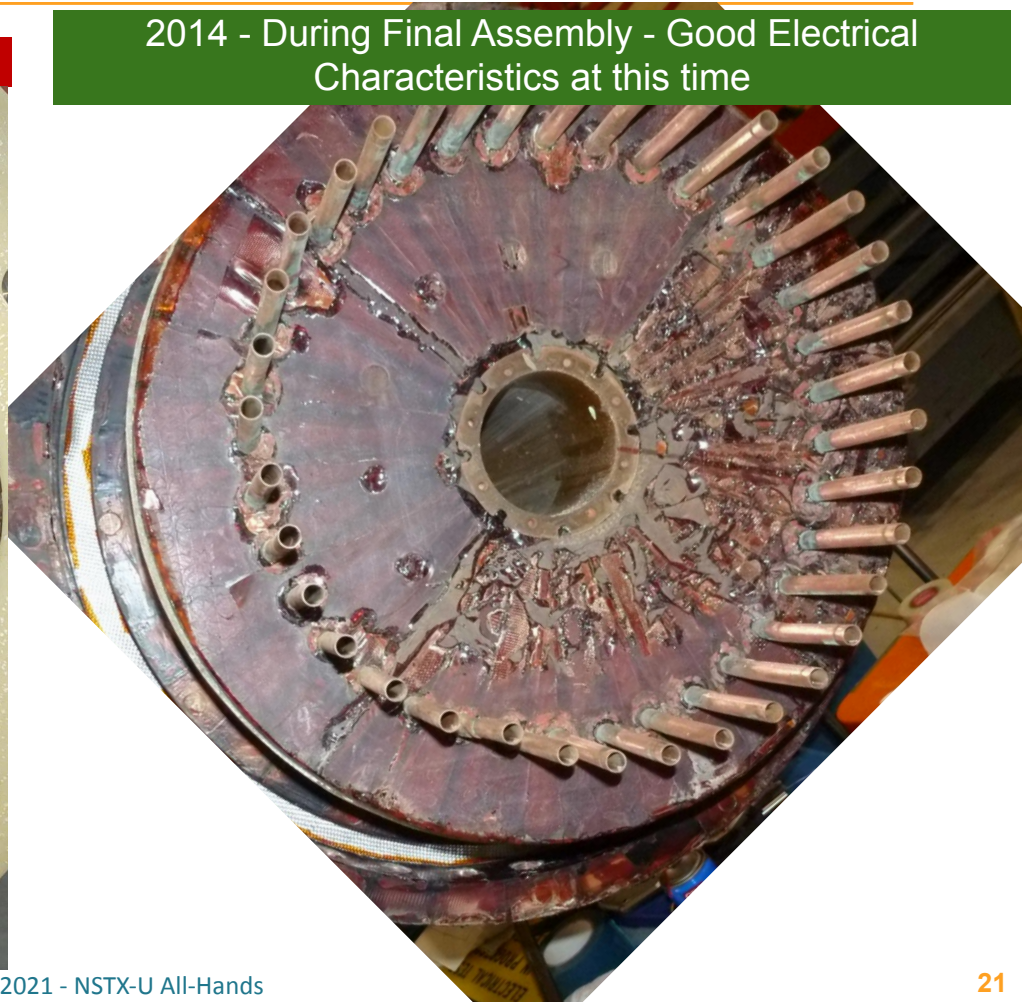


Example of Cleaning - Bundle Top 2021 vs 2021

After Cleaning (10/15/21)

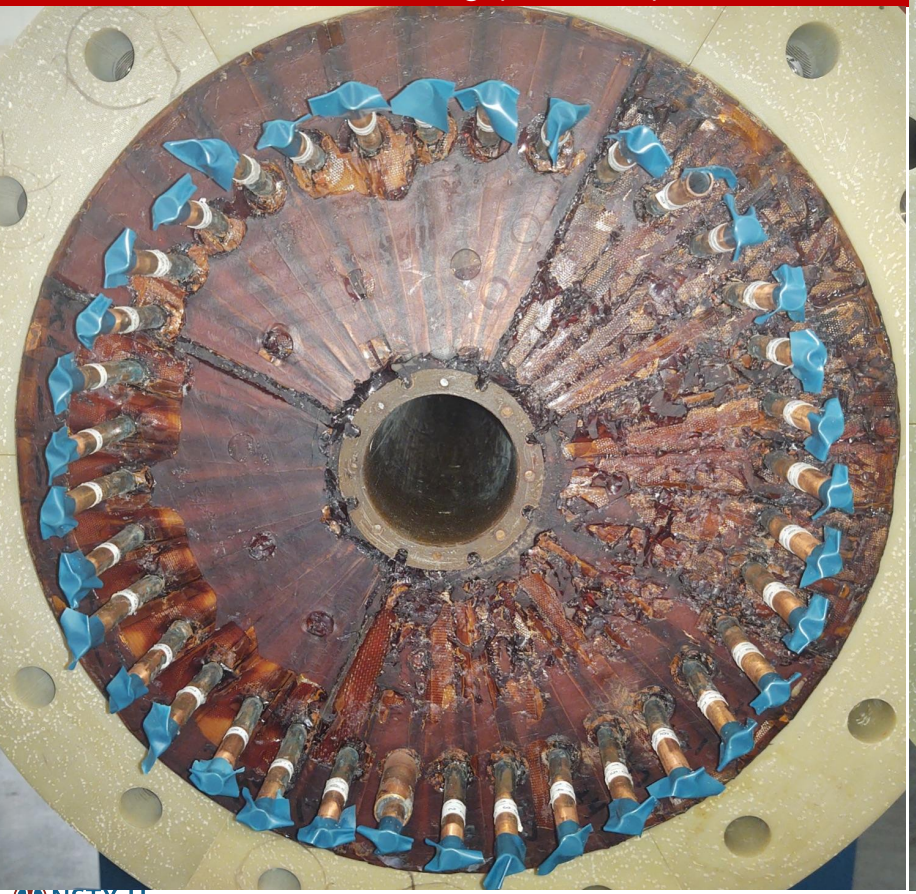


2014 - During Final Assembly - Good Electrical Characteristics at this time

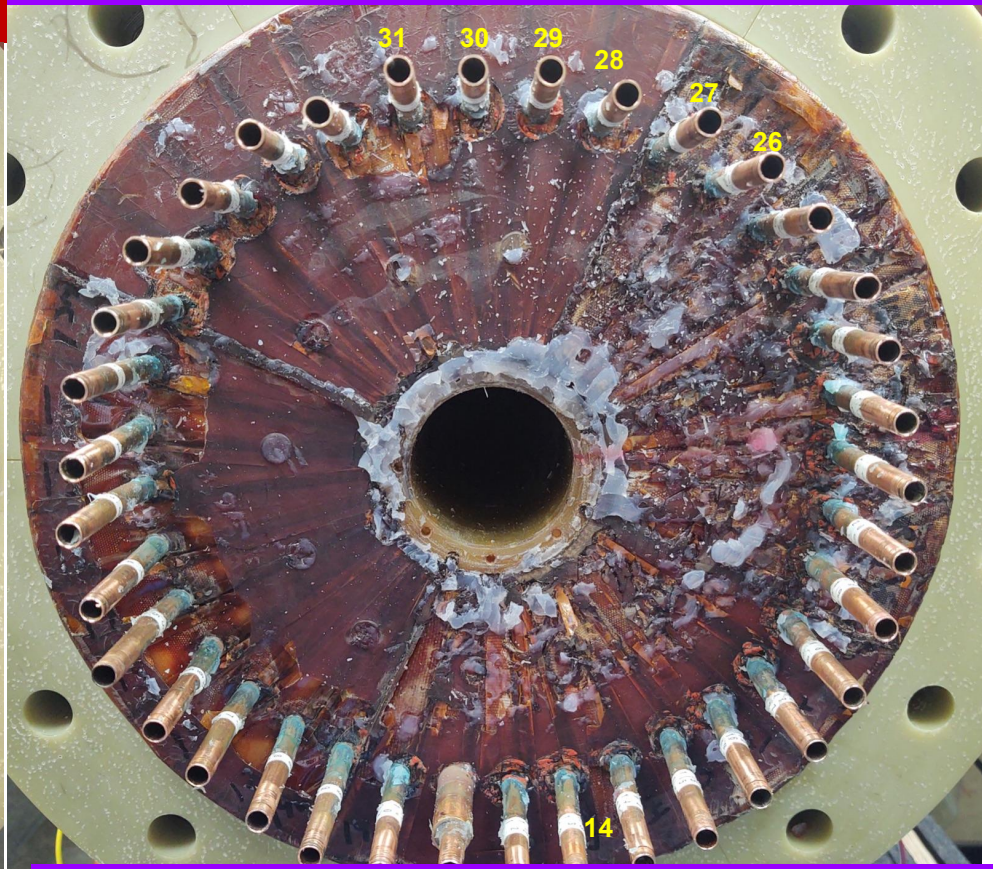


Example of Cleaning - Bundle Top
2021 vs 2021

After Cleaning (10/15/21)



Immediately After G10 Cover Removal (2021)

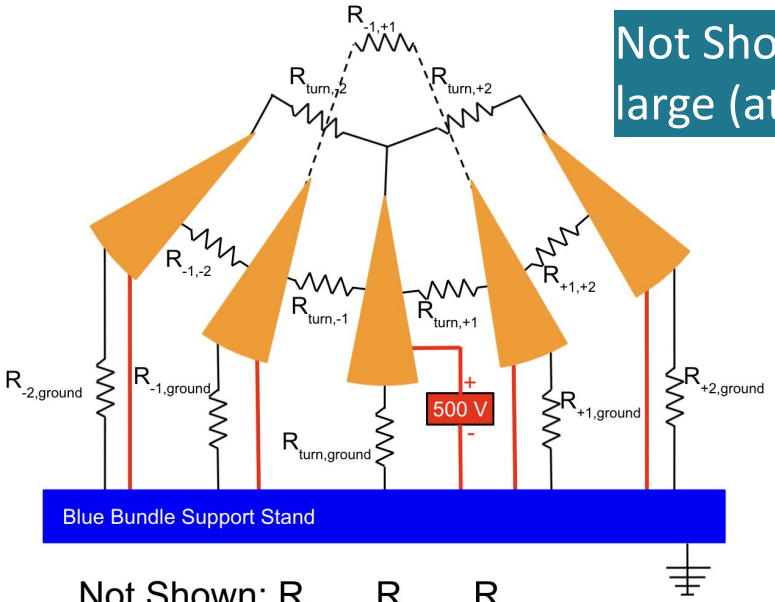


Similar Cleaning Story for the Bundle Bottom
Unfortunately - No Improvement in IR After Cleaning

Two Classes of Electrical Testing Performed on Turns; Both Challenge a Network of Resistances

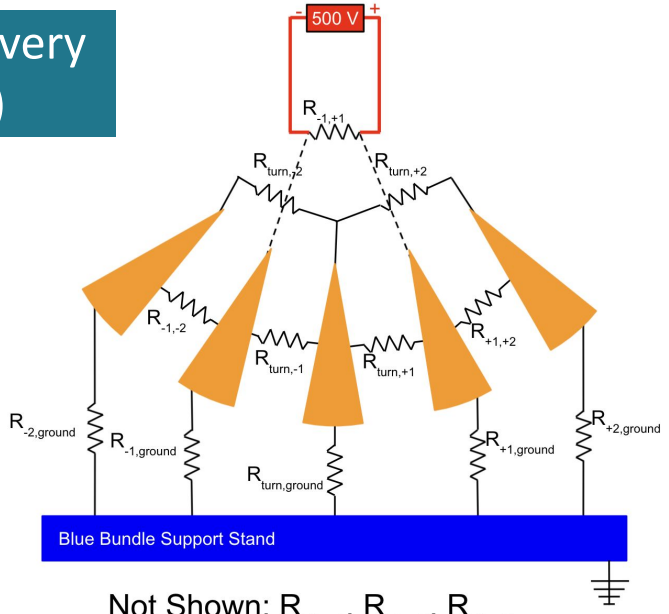
***Typical* Tests**: Ground all but one turn, apply megger voltage to that turn
Challenges: Isolation of that turn to all other turns

***Alternative* Test**: Float all turns, measure impedance between two turns
Challenges: Isolation between individual turns



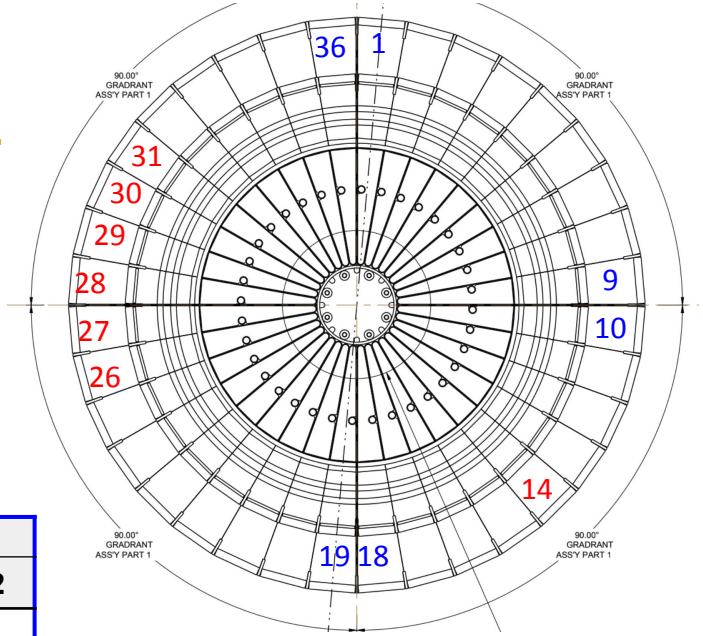
Not Shown: $R_{x,ground}$ are all very large (at least 600 MOhms)

Not Shown: $R_{-2,+1}$, $R_{-1,+2}$, $R_{-2,+2}$
Red Connections for Testing Only



Not Shown: $R_{-2,+1}$, $R_{-1,+2}$, $R_{-2,+2}$
Red Connections for Testing Only

Reduced Insulation Quality Detected Between Non-Adjacent Turns



Clear communication between turns 26 & 31 inclusive; 14 may also be communicating

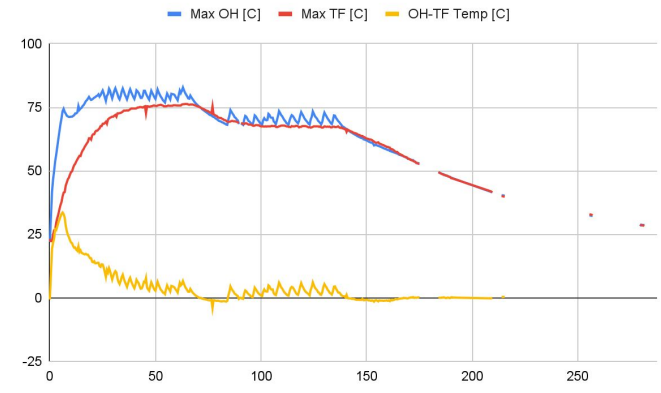
IR (Mohms), 10 min values (7/22 & 7/26)		(+) - all other floating									
		14	24	25	26	27	28	29	30	31	32
(-) - all other floating	14				369	350	758	516	390	415	
	24			7110	5070	5000		4340	4950	4820	
	25		7110		762	652	1060	679	655	652	
	26	369	5070	762		96	479	281	116	139	3770
	27	369	5000	652	96		446	279	76	78	5160
	28	758		1060	479	446		509	630	718	
	29	516	4340	679	281	279	509		206	245	
	30	390	4950	655	116	76	630	206		85	3560
	31	415	4820	652	139	78	718	245	85		3470
	32				3770	5160			3560	3470	

- Separate, unrelated test suggests the axial "centroid of resistance" is ~70% "up" between the flags.
- May be either localized, or a distributed resistance

Bakeout Preparation

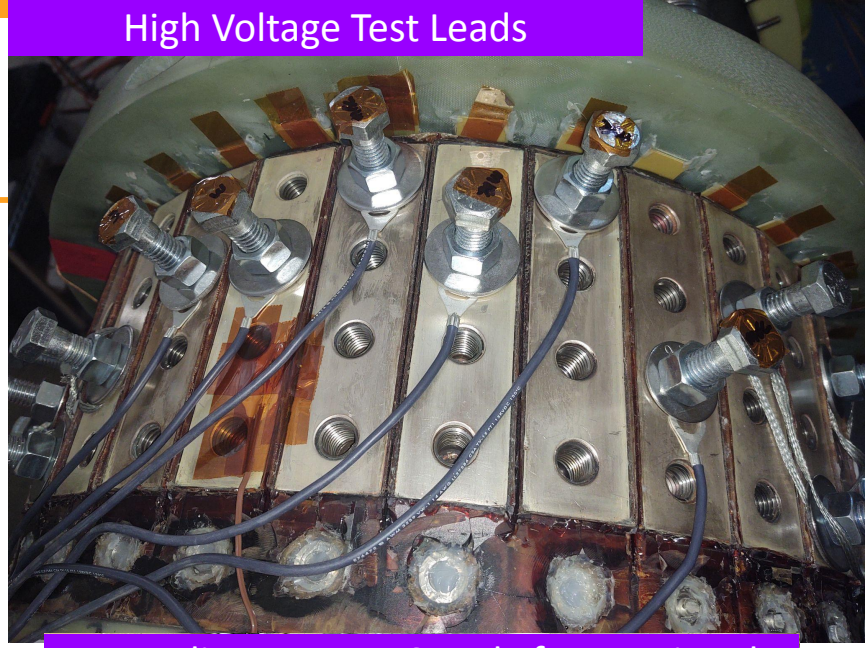
Motivation: Drive out any Residual Water

Insulation applied to the bundle
Dry N_2 feed inside the "cocoon"
RH<2% during bakeout



Maximum Temperatures on the **OH** and **TF** coils as a function of time

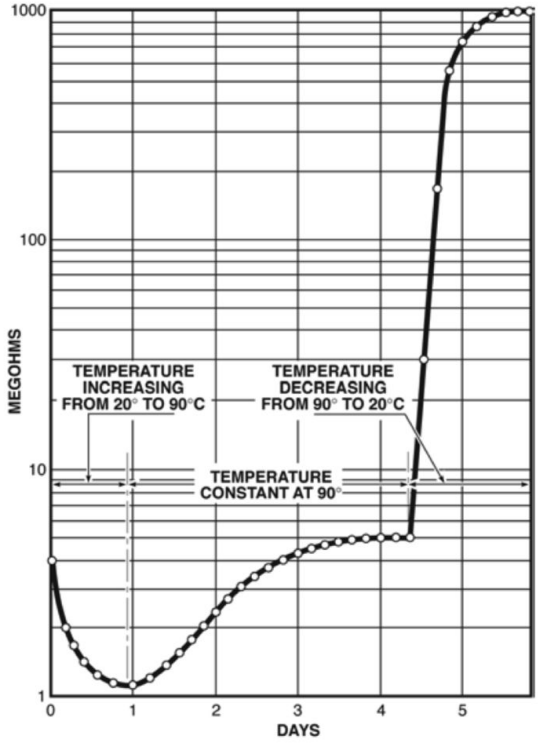
High Voltage Test Leads

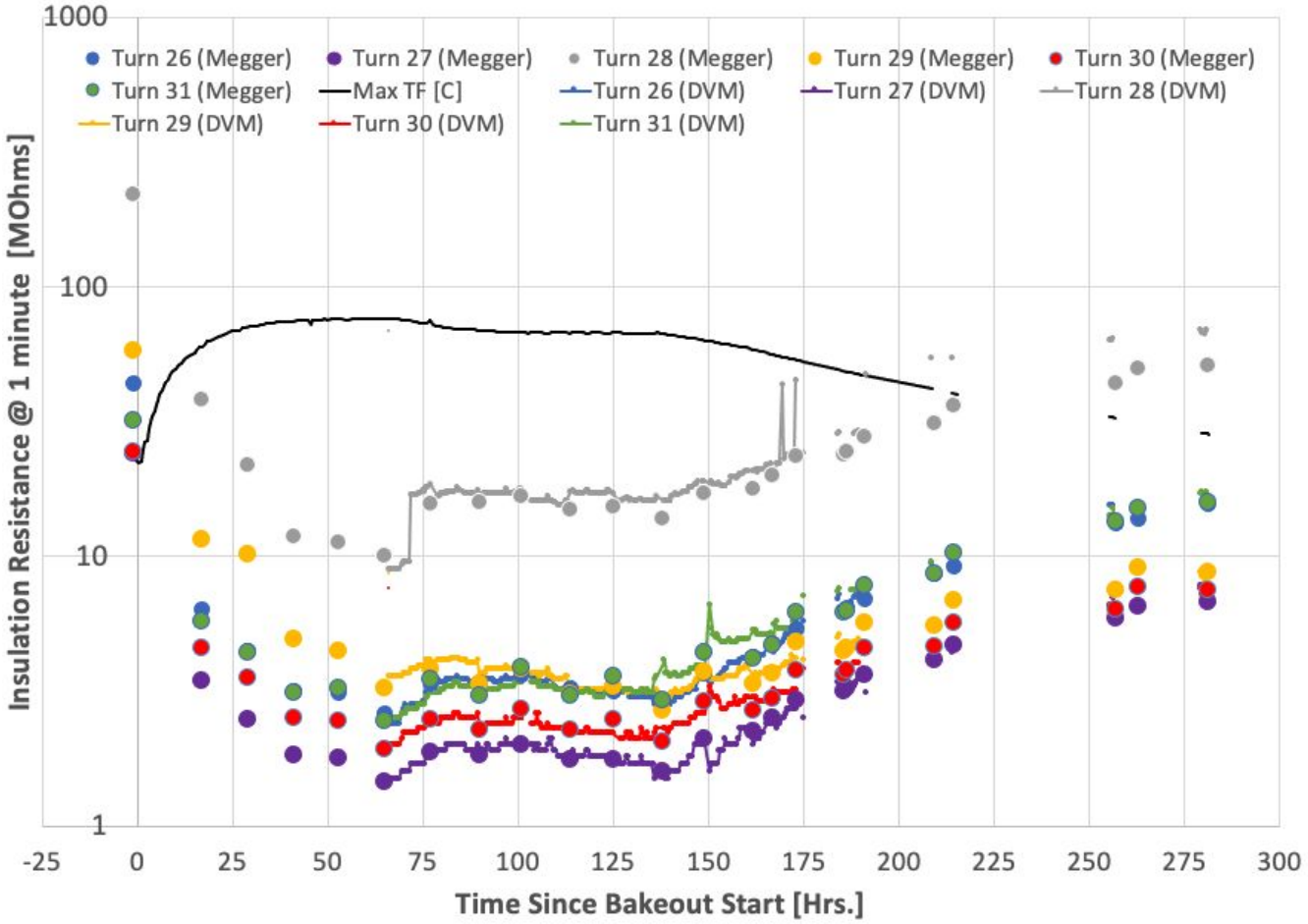


NB Bending Magnet Supply for Heating the OH Coil

IR Measurements During Bakeout Showed Apparent Reduction in IR

Typical Drying Curve for a Wet Transformer

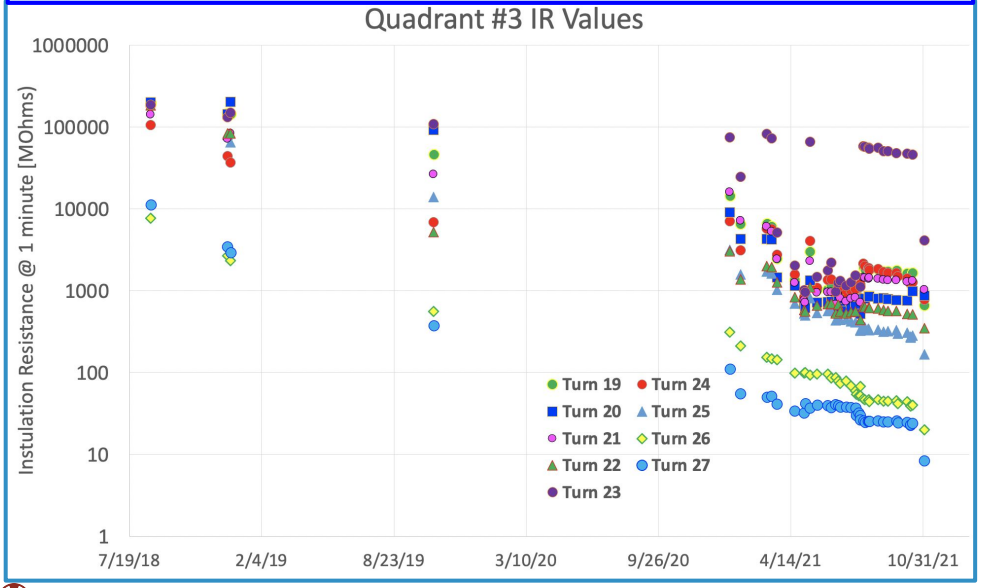


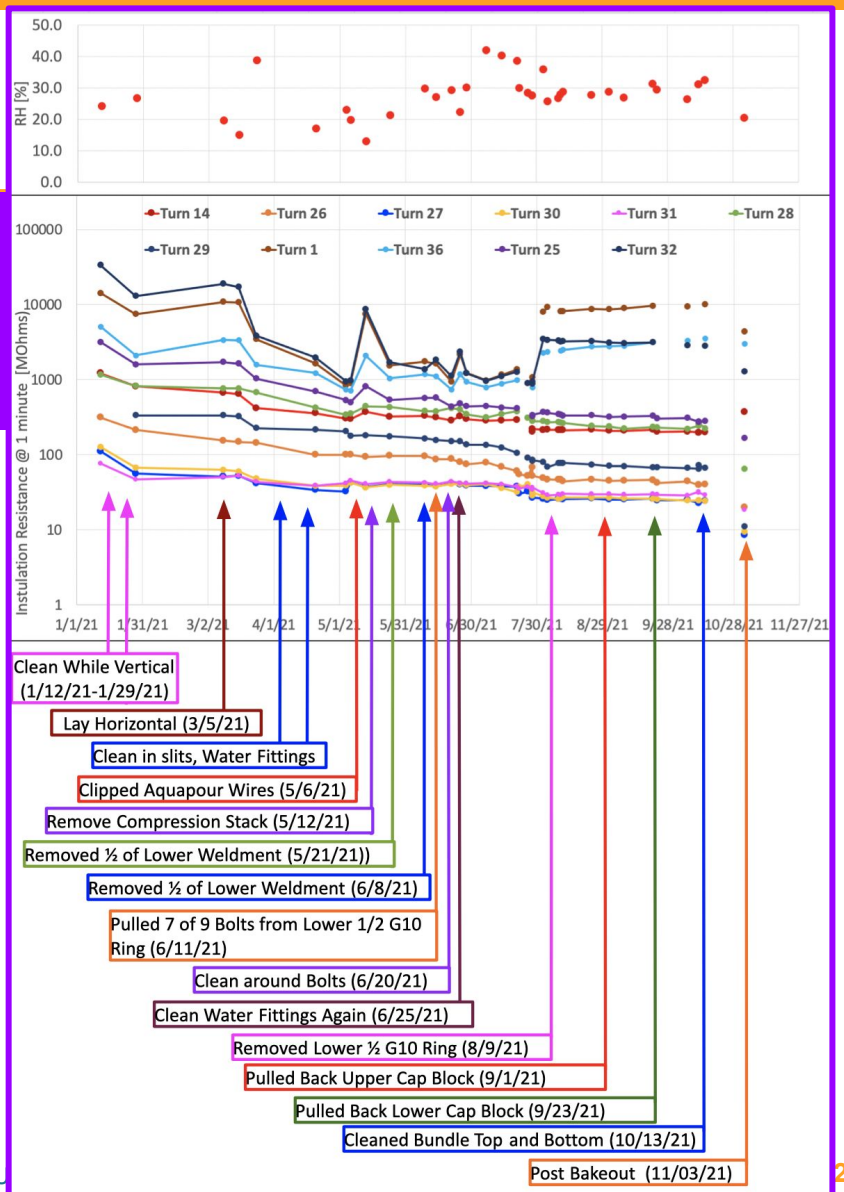


No Activity to Date Has Arrested the Downward Trend

Bottom Line - Downward trend continued over this time, despite many changes to the bundle configuration

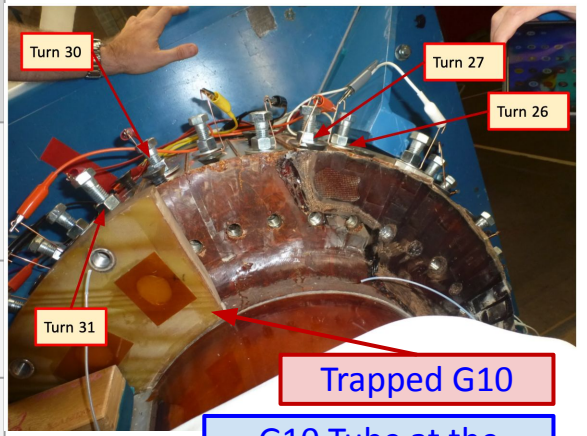
Quadrant IR Data Since 2018
Note: IR> 20 GΩ at time of fabrication

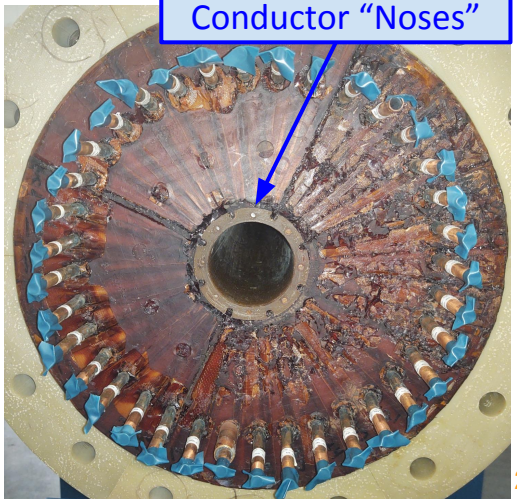




Where is the Source of the Problem?

Potential Location or Source of Problem	Action	Action included in present schedule
Contamination in cracked or patched resin on the midplane side of the flags	Carefully remove the “neat resin”*...ongoing...see next slide...*	Yes
Bundle ends, amongst water tubes	Excavate resin/glass around tubes, repair	Yes
Contamination under trapped portion of G10 ring	Remove trapped G10 ring half, either by cutting it away or by sliding the OH coil	Planning: Yes Work: No
Water trapped “deep” in the bundle	Vacuum bakeout - developing an idea for a method to do this at PPPL	Planning: Yes Work: No
Contamination or insulation degradation at the noses of the conductor	“Excavate” the G10 ring in the core of the bundle	Planning: Yes Work: No

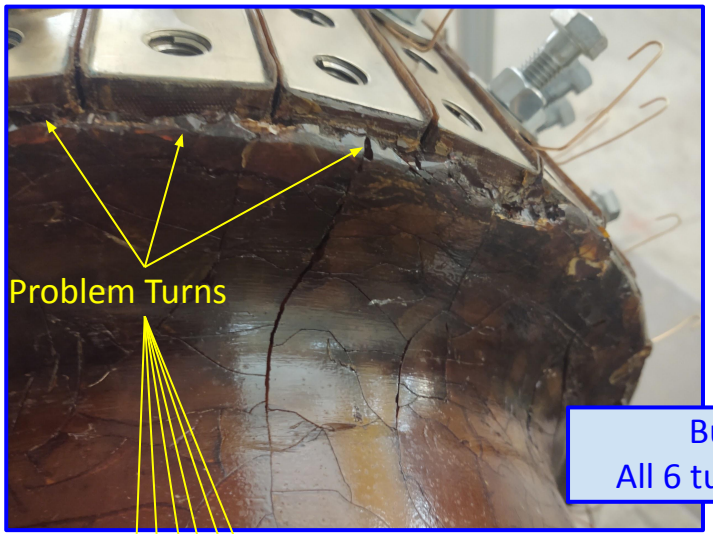




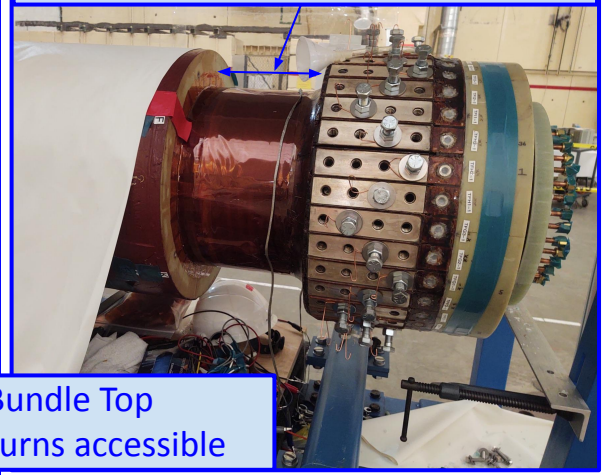
Evaluating whether these issues may be traceable to manufacturing, i.e. RTV use, kapton tape, etc.

Ongoing Now - Remediation of Fractured Resin on the "Flags"

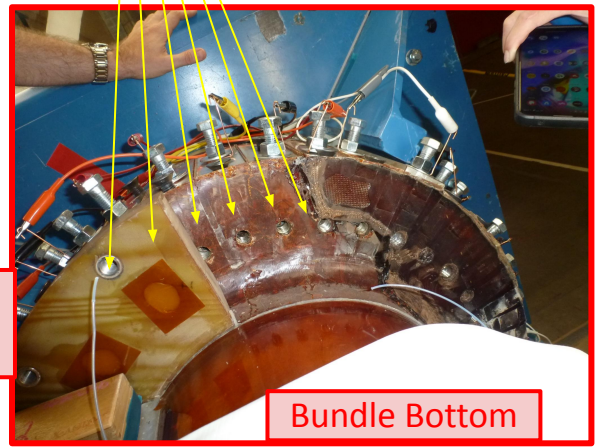
- Resin w/o glass is inherently brittle (resin rich)
- Cracks may have contamination.
- Network of cracks can allow non-adjacent turns to communicate
- Carefully sand down the cracked and extremely resin rich areas, down to the turn insulation - removal of contamination and provide a uniform bearing surface when restored.



Pre-load applied by a Belleville washer assembly in this gap at top



Bundle Top
All 6 turns accessible



Bundle Bottom

Of 6 questionable turns, 4 are accessible at the bottom

Criteria and Schedule Impacts

- Working criteria for safe bundle operations: 1 MOhm
  - Must stabilize IR value above this level.
- Present Project schedule includes flag and top/bottom insulation remediation/repair, water fitting reinstallation, bundle reassembly
- Decision point in the early spring following bundle reassembly - *can we install this bundle for NSTX-U operations* - March in the present working schedule
  - Showing March 2023 for KPP #4, i.e. first plasma, for the scenario where the existing bundle is used

Outline

- Background
- Work on Existing Bundle
  - Disassembly
  - Electrical Testing
  - Present and Next Steps
- Spare Bundle 

Tom Todd Review - October 6th

- Three independent reviews of the bundle situation: Burkhart (July), Robinson (DR, September), Todd (October)
- Tom Todd (CCFE) chaired a full-day review dedicated to the TF bundle situation:
  - Iain Dixon (NHMFL), John Last (CCFE), David Harding (FNAL), Ioannis Katramados (CCFE)
  - Scope included remediation of existing bundle, plans for backup bundle
- 31 Recommendations, including but not limited to
  - remedy visually damaged insulation
  - recommendations on design and VPI for a potential backup bundle
  - *provided we resolved the electrical concerns,* recommendation to limit to KPP #3 EM and thermal stresses for *initial operation* with the bundle
    - B_T=0.85 T, I_P=1.4 MA, τ_{FT}=2 sec ⟶ 1.19 MA·T
    - Could run 1T at reduced {current, OH pre-charge/swing, duration}

Rich Hawryluk Led a Team Charged to Identify Key Design Changes

- Also had C. Neumeyer (PPPL, ret.), Y. Zhai (PPPL), R. Fair (PPPL), G. Voss (CCFE), and A. Haight (CTD)
  - Interviewed fabrication team from old bundle, reviewed documents, drawings, etc
- Boundary condition to retain the new CS Casing and inner-PF coils.
- Identified numerous targeted design/fabrication issues to consider for modification in revised design for backup
- These + the Tom Todd Review form the technical basis for the targeted design changes we are working through.

Top-Level Design/Fabrication Changes We are Examining for Backup Bundle

- **TF Bars with Extruded Center Holes** → eliminate soldering of cooling tubes → improved operations reliability and reduced fabrication risk
- **TF-OH Gap** - alternative to the aquapour method, C-MOD and MAST developed methods; alternatively develop an engineered slip-plane
- **Targeted Insulation Changes** → reduce "thermal hoop tension" stresses in the TF insulation
- **Numerous VPI improvements** → conductor tolerances, mold release, kapton tape and RTV use, etc

- **Use an external fabricator** → including participation in the design process as part of a multi-part subcontract to ensure fabricability

Schedule For Fabrication of Backup Bundle

- Near-term priorities:
  - Identify, evaluate, implement needed design changes, including any features to improve the reliability of fabrication
  - Conduct vendor outreach, initiate design support procurement
  - Develop strategies for long-lead procurement
    - Largely raw and processed conductor materials
- These feed an Independent Project Review in February/March 2022
  - Deliverable: Baseline quality estimate for bundle fabrication

National Spherical Torus eXperiment Upgrade

NSTX-U Research Program Update

NSTX-U Team Meeting 11/5/21

S.M. Kaye

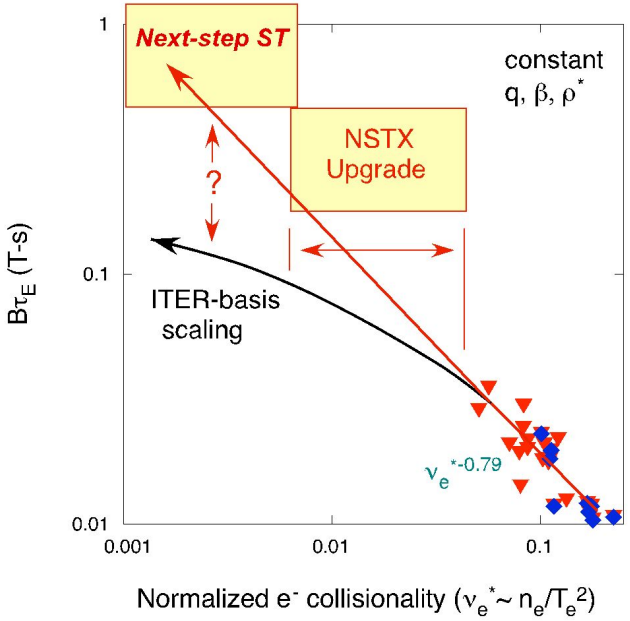
Dir. Research, NSTX-U

PPPL PRINCETON PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

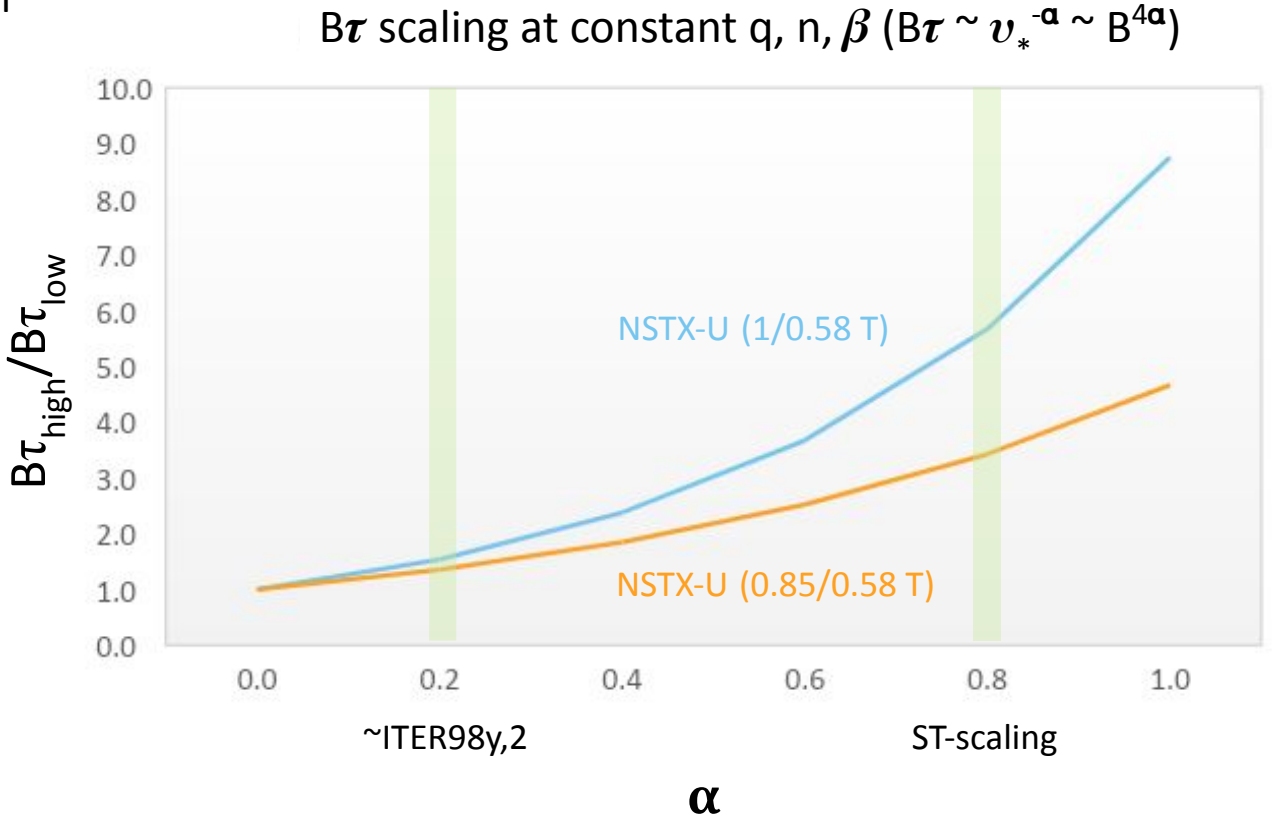
NSTX-U mission remains unchanged even with KPP3 constraints on I_p and B_T (~1.2 MA-T)

- Study ST transport/stability physics in high-β, low ν_* regimes
  - Confinement dependence on collisionality different than that in standard tokamaks
  - Does favorable scaling extend to even lower collisionality?
- Produce stable, high-performance, high-non-inductive driven current plasmas
  - Sustained operation
  - Self-driven (bootstrap) + NBI current drive
- Explore/develop power and particle handling techniques for high performance scenarios
  - Assess conventional PFCs at high heat fluxes
  - Develop and evaluate liquid lithium divertors for next 5YP

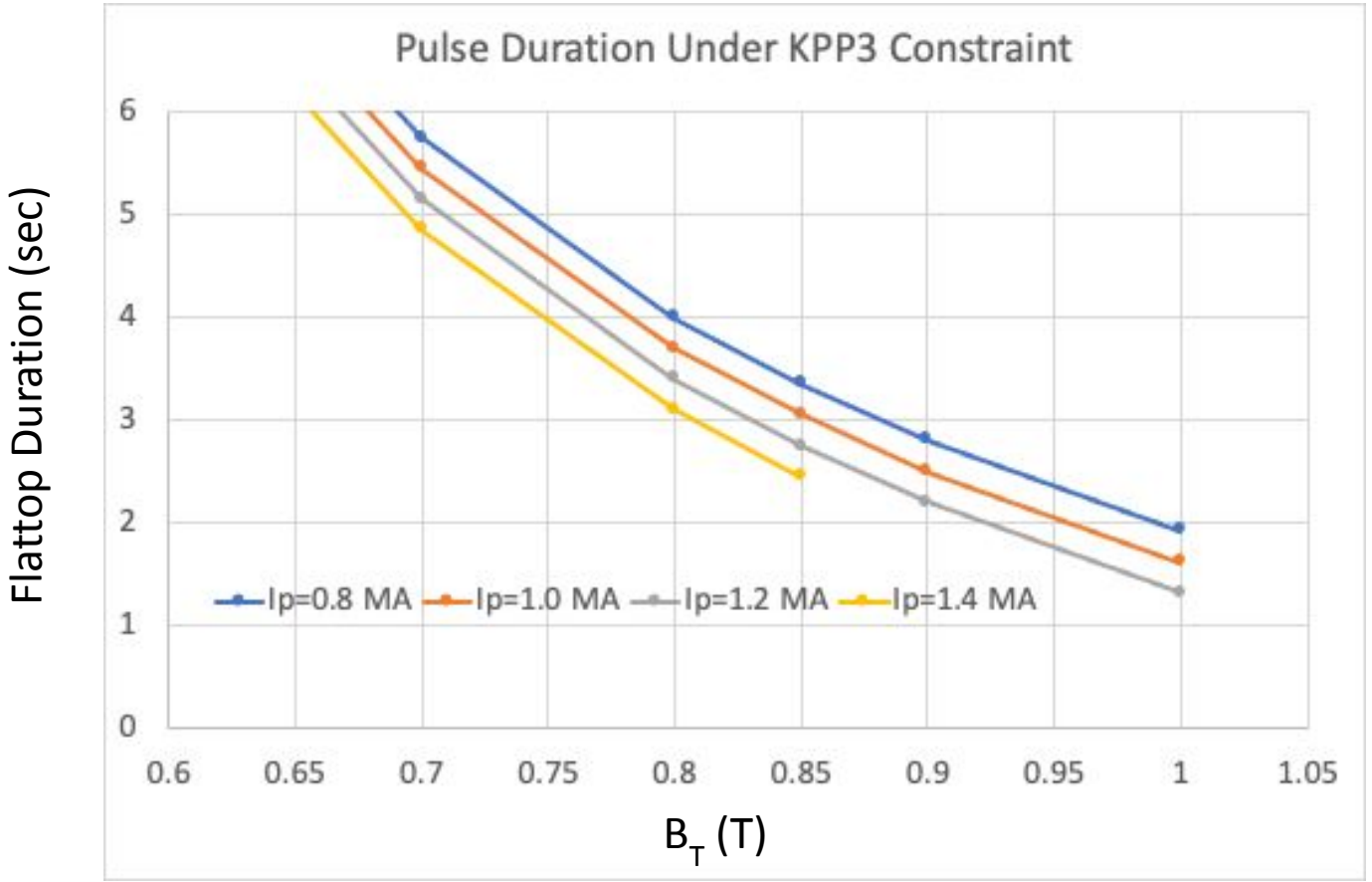


0.85-1 T allows for assessment of collisionality scaling of confinement

- 2-point B_T scans

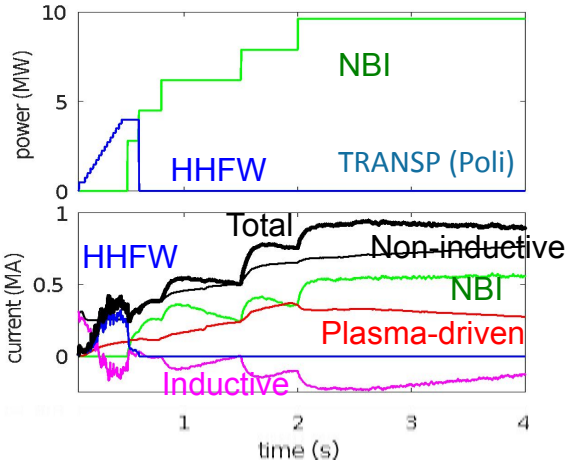


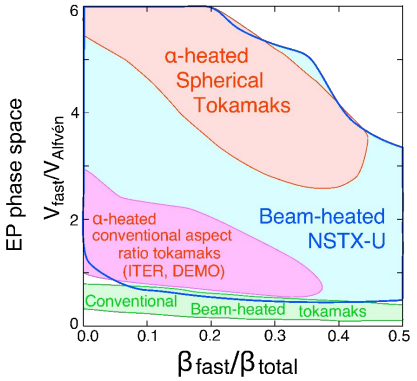
Flattop durations > 1 sec even at max I_P, B_T under KPP3 constraint



KPP3 constraint does not impact non-inductive operation mission

- High non-inductive fraction scenarios unaffected
  - High non-inductive scenarios developed for I_p ~ 1 MA
  - Develop scenarios for B_T<1 T for longer pulse duration
- EP physics essentially unaffected
  - 1 T capability most important for preserving operational NB phase space





~ (EP-instability drive)/(EP-instability damping)

There are a number of ST collaboration opportunities

- ST40 (operation up to 3 T) CRADA (see S. Kaye/R. Maingi)
  - Short pulse length (100-200 ms)
    - Core and pedestal confinement
    - Energetic Particle physics
    - Macrostability (Error Fields, low–f MHD)
    - Divertor physics
- MAST-U, Pegasus III (see D. Battaglia)
- SMART (Seville, Spain) – M. Podesta exploring this option

BACKUP