National Spherical Torus eXperiment Upgrade

Project Overview

NSTX-U Recovery Project FDR – March 17-19, 2020

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NSTX-U Recovery Deputy Director

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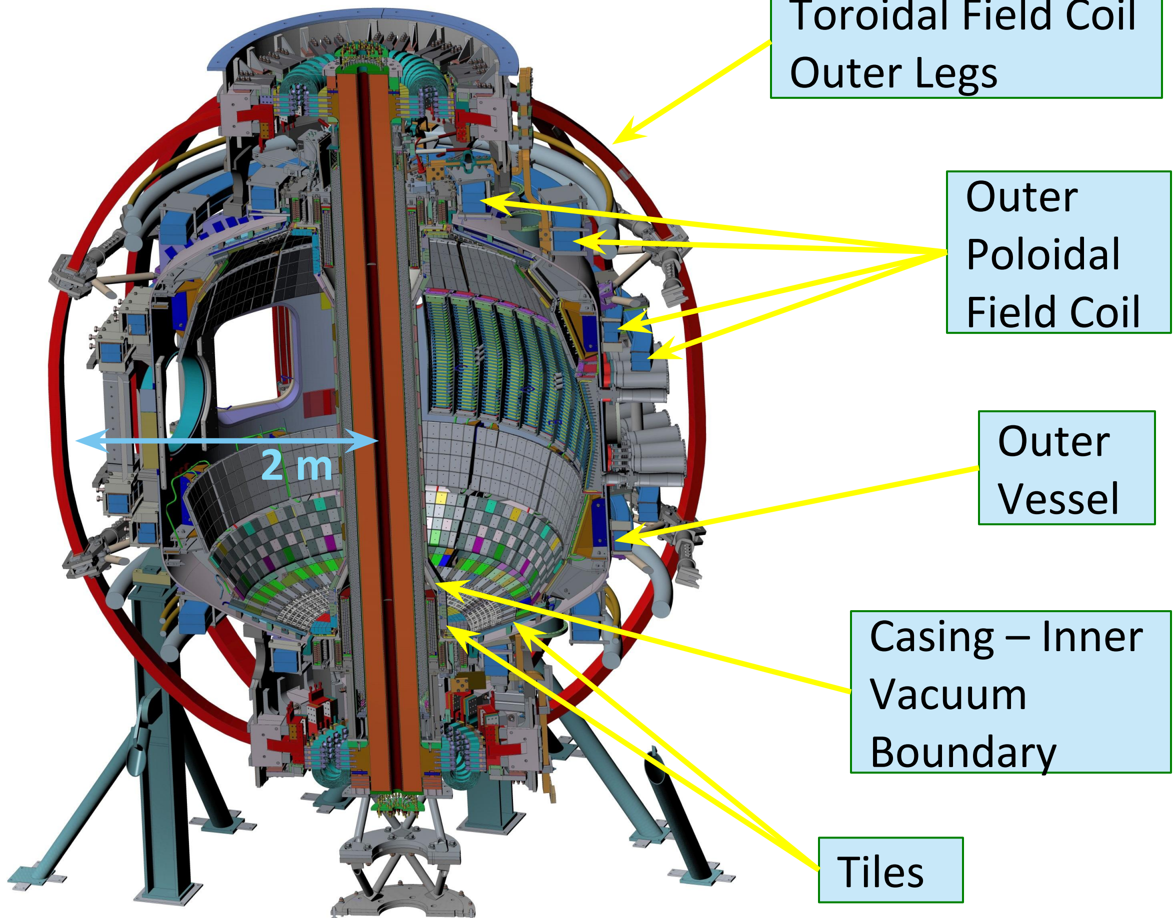
Outline

- Project Introduction and Origins
- Stakeholder Deliverables - PEP and KPPs
- Project Scope
- Project Organization
- General Requirements Document
- Safety - During and After the Project
- Outstanding Design Scope
- Answer to Charge Questions

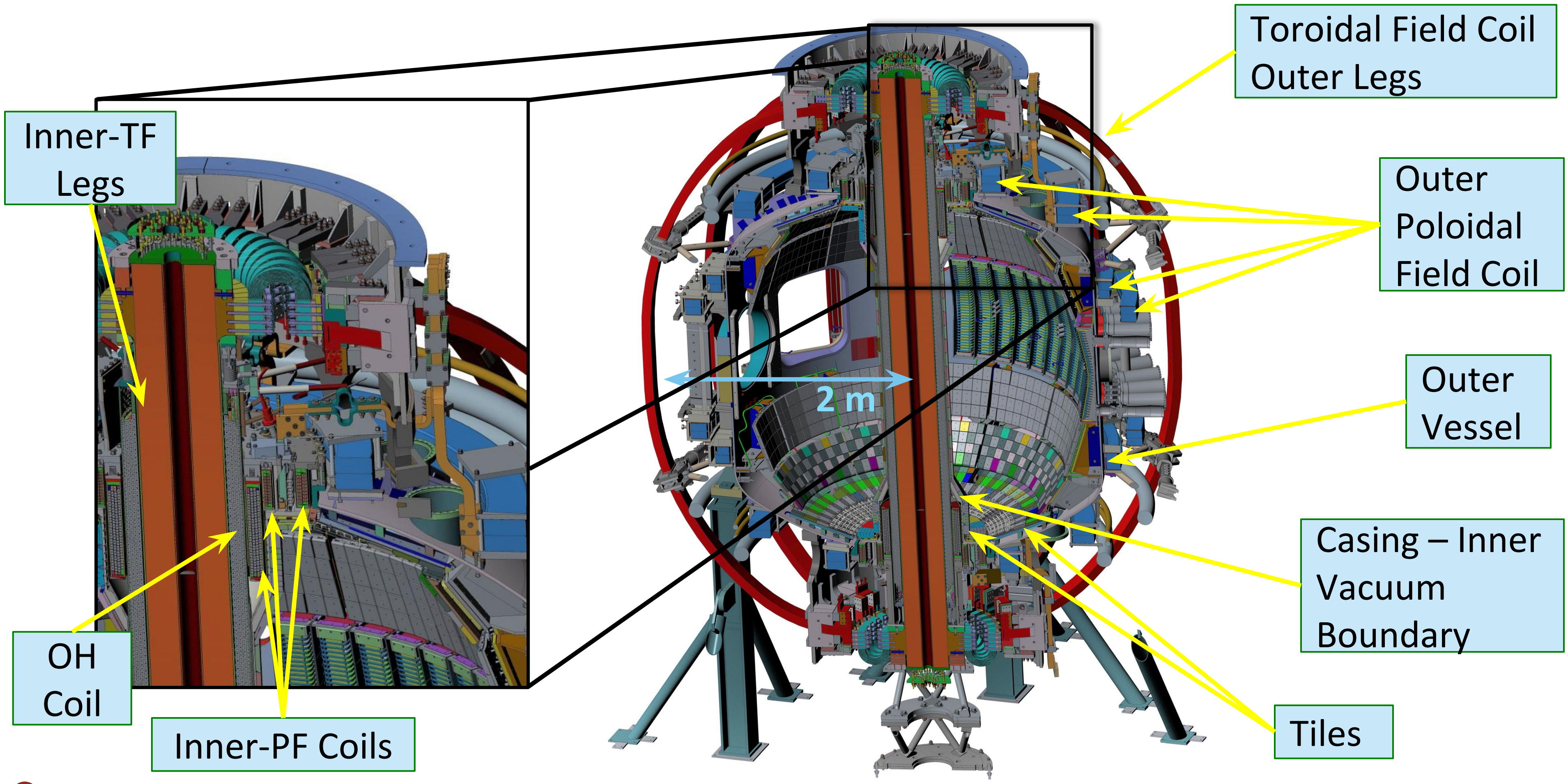
Integration and Systems Engineering will Be Further Discussed in Plenary Talks by Yuhu Zhai and Peter Dugan

NSTX-U Is a Spherical Torus

- Pulsed device: plasma of 1-5 seconds duration formed every 20-40 minutes
- Magnets provide much of the magnetic field.
  - Toroidal field of up to 1T
- Plasma current provides the remaining magnetic field
  - Plasma currents up to 2 MA
- Primary means of auxiliary heating the plasma are two "neutral beam injectors"
  - inject energetic beams of deuterium that collide with the plasma and heat it via collisions



NSTX-U Is a Spherical Torus

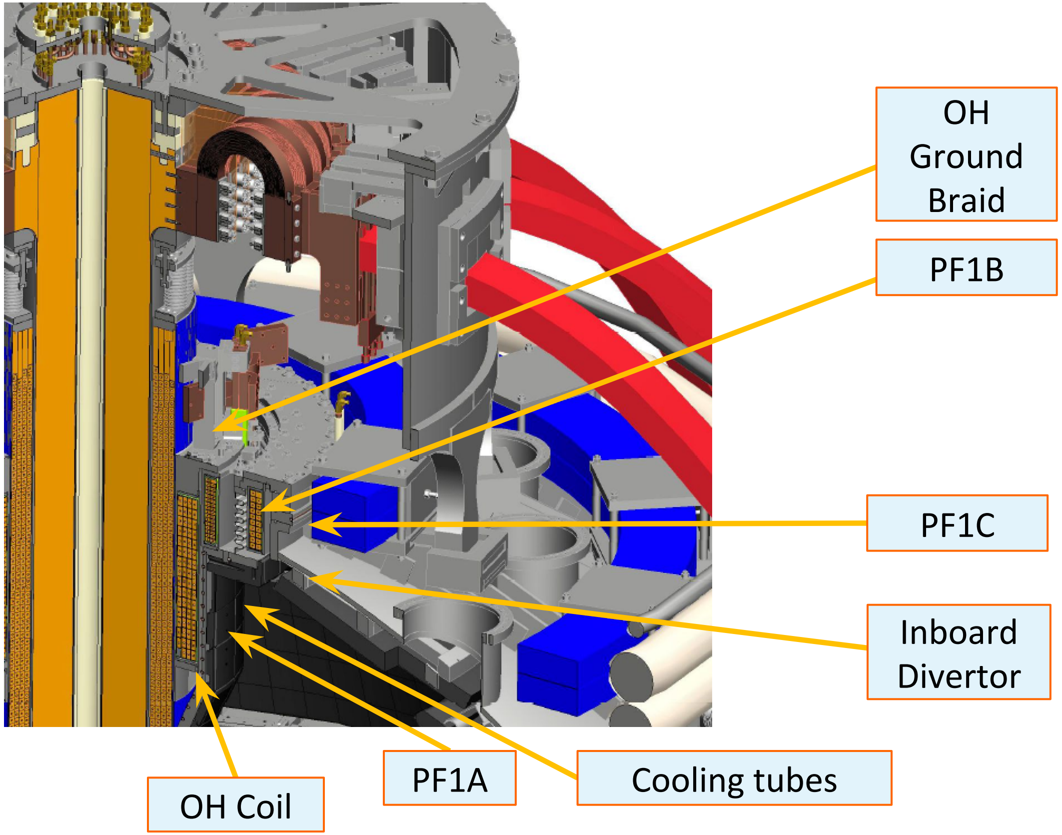


A Brief History of NSTX-U

- NSTX First Plasma – 1999
- Operated for 10 science campaigns, with operations ceasing in November 2010
- NSTX-U proposed with two major upgrades
  - New central magnet assembly for higher field and current
  - Installation of a 2nd neutral beam line (from TFTR) for more power and current drive flexibility.
- The Upgrade was a capital project
  - CD-0: February 2009
  - CD-4: September 2015
- Operated for a 10 week run campaign in FY2016

What is NSTX-U “Recovery”?

- A number of issues hindered operations in FY15&16.
  - 4/15: OH “Arc Flash” incident
  - 9/15: Inadequate inboard divertor bakeout
  - 5/16: CS cooling tubes wrong material, induced current/motion, breaches
  - 5/16: Bent PF1AU bus bar
  - 6/16: Internal short in PF1AU coil
- FY2017: DOE requested PPPL to review “Extent of Condition” and submit Corrective Action Plan (CAP) as a laboratory Notable Outcome
- **Recovery = Implementation of Extent of Condition CAP**



Series of Project-Scale Reviews Have Been Milestones on the Path to Final Design

- Extent of Condition
  - 12 Design Verification and Validation Reviews (DVVRs) (January-April, 2017)
    - Examined full technical scope of the project, from the core of the machine to the data acquisition system.
    - Internal and external reviewers
  - 2 Extent of Condition reviews (March & May, 2017)
    - External committee chaired by T. Todd assessing the DVVRs, including the proposed PPPL responses
  - Design Integration Review (April 2017)
  - Conceptual Design Review (August 2017)
  - Cost and Schedule Review (September 2017)
- Subsequent Reviews
  - DOE/SC Assessment of Recovery Plans (Winter 2018)
    - served as basis for CDE-0/1 approval
  - Project PDR (August 2018)
  - Basis of Estimate Review (March 2019)
  - CDE-2/3A Review (August 2019)
- ESAAB approval for baseline and long lead procurements in September of 2019
- "E" is for Equivalent - following the principles of 413.3b but not a line item project

Defined the Project Scope

Note: ASO added to the PPPL contract in 2016

Project Performance Goals Defined in the CD-0/1 Mission Need Documentation and the PEP

- CD-0 mission need from 2009 described “reduced collisionality, higher field, and also fully non-inductive operation” as key elements of the mission need.
  - Mission need reaffirmed by the 2018 OPA Phase 2 review
- Upgrade Project PEP (2011) translated these into engineering parameters
  - (Increase the) Toroidal field from 0.5 tesla to 1.0 tesla;
  - (Increase the) Pulse length from ~1.0 second to 5.0 seconds;
  - (Increase the) Plasma current from 1MA to 2MA;
  - (Increase the) Neutral beam heating from 5-7MW to 10-14MW.
- Recovery PEP (link) has maintained these engineering requirements while clarifying design requirements for 4000 pulses with 1 T, 2 MA, and 3-5 second duration
- Engineering design, starting from the GRD and flowing down, is aligned with achieving these parameters

Recovery Project has Four KPPs

- KPPs designed to demonstrate required technical capabilities of systems modified by the Recovery Project
  - No KPPs related to the neutral beams.
- There are no objective KPPs; they are effectively threshold KPPs.
- They are related to the following:
  - KPP #1: Magnetic Alignment
  - KPP #2: Graphite Tile Bakeout
  - KPP #3: Magnet Performance
  - KPP #4: First Plasma

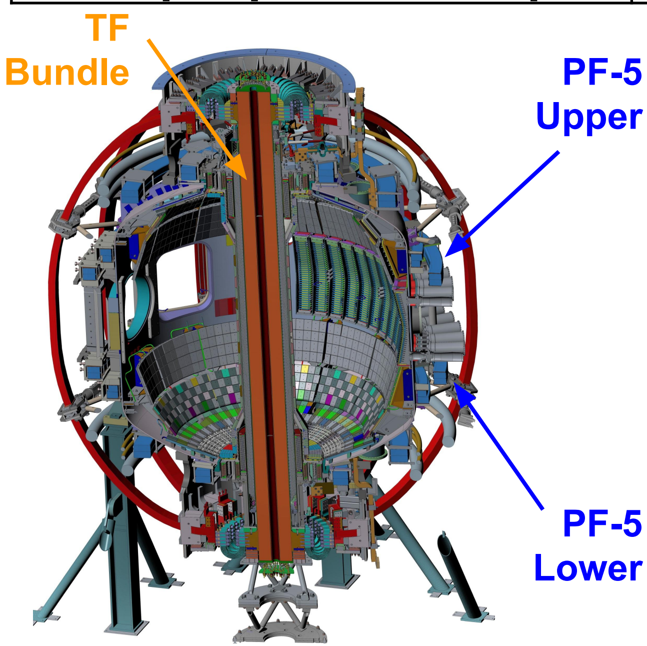
KPPs Demonstrate a Progression of Increasing Capability

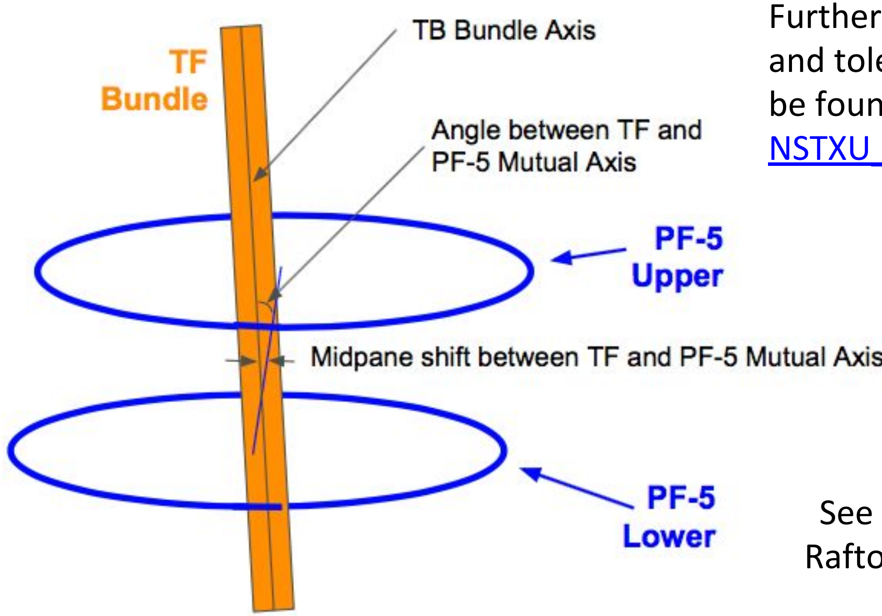
KPP	Motivation	Key WBS Elements
The inner-Toroidal Field coil axis shall be aligned to the PF-5 upper coil and PF-5 lower coil mutual axis with an accuracy bounded by a straight line through the [shift, tilt] points [0.0 mm, 6.0 mrad] and [6.0 mm, 0.0 mrad].	• Certain misalignments between magnets in a fusion machine can cause severe damping of plasma flows • KPP targets key alignment between the toroidal field and vertical field coils	PF-4/5 Realignment - WBS 1.01.02.08 **Machine Assembly - WBS 1.09.02.01**
A bakeout will be conducted in which graphite PFCs shall achieve a temperature of at least 260 degrees Celsius.	• Water trapped in graphite tiles can contaminate plasma → bake it out! • 260 °C found to be a good minimum temperature.	Machine Core Structure - WBS 1.01.02.01 Bakeout - WBS 1.03.01 PFCs - WBS 1.01.01 **Commissioning - WBS 1.09.03.01**
Without plasma, the magnetic field coils will be pulsed using OH/TF/PF waveforms expected for a 1.4MA, 0.85 Tesla, 4 second plasma with 2 second plasma current flat-top.	• Increasing the field and current results in a hotter plasma, with these parameters paving the way to new research regimes • Magnetic forces intermediate between NSTX and full NSTX-U parameters	Is achieved during **Commission (WBS 1.09.03.01)**, as a culmination of nearly all project WBS elements.

An ohmically-heated discharge shall be produced with plasma current greater than 50,000 Amperes at a toroidal magnetic field of greater than 1,000 Gauss.	• First plasma demonstrates integrated operation of the facility
	• Modest parameters:
	  ○ 0.05 MA vs 2 MA ultimate
	  ○ 0.1 T vs 1T ultimate
		Is achieved during **Commission (WBS 1.09.03.01)**, as a culmination of nearly all project WBS elements.

KPPs Demonstrate a Progression of Increasing Capability - #1

KPP	Motivation	Key WBS Elements
The inner-Toroidal Field coil axis shall be aligned to the PF-5 upper coil and PF-5 lower coil mutual axis with an accuracy bounded by a straight line through the [shift, tilt] points [0.0 mm, 6.0 mrad] and [6.0 mm, 0.0 mrad].	• Certain misalignments between magnets in a fusion machine can cause severe damping of plasma flows • KPP targets key alignment between the toroidal field and vertical field coils	PF-4/5 Realignment - WBS 1.01.02.08 **Machine Assembly - WBS 1.09.02.01**





Further physics discussion and tolerance breakdown can be found in NSTXU_1-1-2-3-2_CALC_100

See talks by Pagano and Raftopoulos in this review

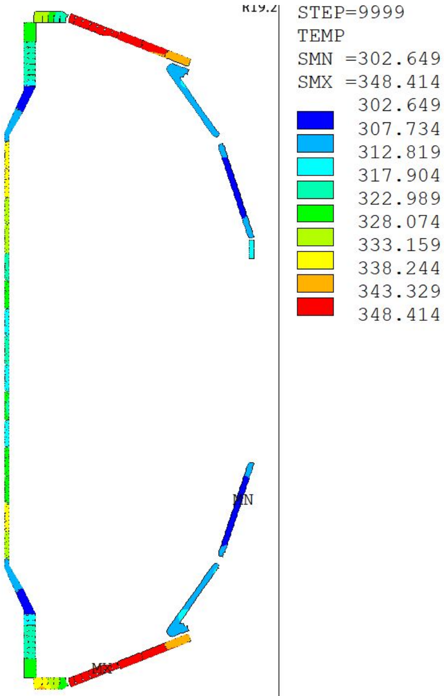
KPPs Demonstrate a Progression of Increasing Capability - #2

KPP	Motivation	Key WBS Elements
A bakeout will be conducted in which graphite PFCs shall achieve a temperature of at least 260 degrees Celsius.	• Water trapped in graphite tiles can contaminate plasma → bake it out! • 260 °C found to be a good minimum temperature.	Machine Core Structure - WBS 1.01.02.01 Bakeout - WBS 1.03.01 PFCs - WBS 1.01.01 **Commissioning - WBS 1.09.03.01**

NSTX-U interior has a large volume of graphite tiles, each of which is a reservoir of H_2O

Vessel and graphite components are heated by:

- Hot helium
- Resistive (Ohmic) heating
- Superheated Water



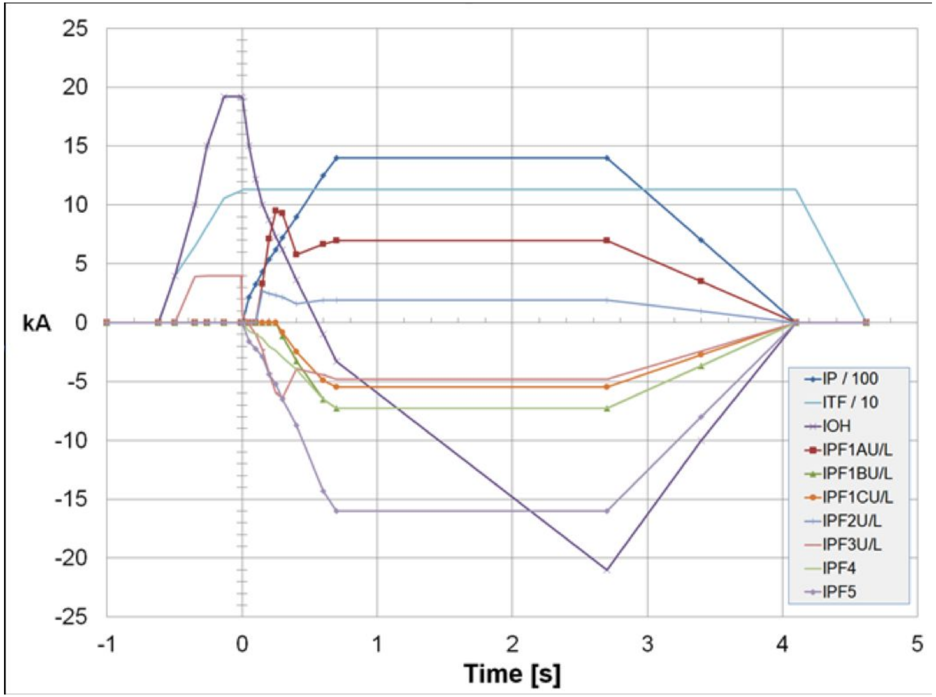
Simulation of bakeout temperatures - exceed 300 °C everywhere

KPPs Demonstrate a Progression of Increasing Capability - #3

KPP	Motivation	Key WBS Elements
Without plasma, the magnetic field coils will be pulsed using OH/TF/PF waveforms expected for a 1.4MA, 0.85 Tesla, 4 second plasma with 2 second plasma current flat-top.	• Plasmas with these parameters pave the way to [new research regimes] • Magnetic forces intermediate between NSTX and full NSTX-U parameters	Is achieved during **Commission (WBS 1.09.03.01)**, as a culmination of nearly all project WBS elements related to magnets

Mock coil waveforms for a 1.4 MA, 0.85 T plasma, as per memo and PEP

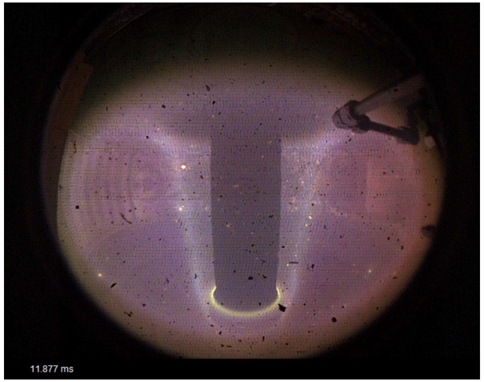
Generating these coil currents is the criteria in this KPP



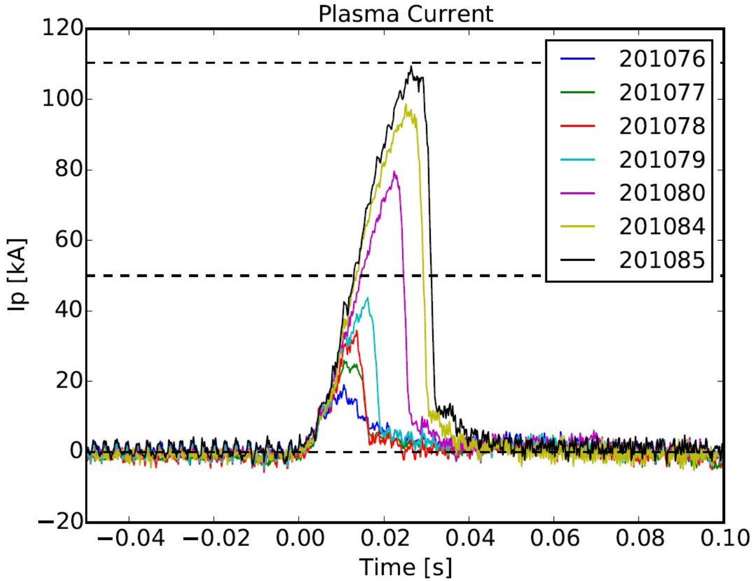
KPPs Demonstrate a Progression of Increasing Capability - #4

KPP	Motivation	Key WBS Elements
An ohmically-heated discharge shall be produced with plasma current greater than 50,000 Amperes at a toroidal magnetic field of greater than 1,000 Gauss.	• First plasma demonstrates integrated operation of the facility • Modest parameters: ○ 0.05 MA vs 2 MA ultimate ○ 0.1 T vs 1T ultimate	Is achieved during **Commission (WBS 1.09.03.01)**, as a culmination of nearly all project WBS elements.

Camera Image of 201085



Sequence of plasmas from August 10, 2015 achieving this KPP



Project Scope Divided Into Two Categories Regarding Procurement/Fabrication Authorizations

CDE-3A Scope (All FDRs Complete)	**CDE-3B Scope**	
Approved for procurement/fabrication following the August 2019 CDE-2/3A IPR	Will be approved for fabrication following CDE-3B ESAAB approval (targeting June 2020)	
Major Scope Items (Representative)	**Major Scope Items (Representative)**	
Inner-PF Magnets - 6 solenoid magnets in fabrication (Sigmaphi)	Machine Instrumentation (Stress, Strain, TF Twist)	Recovery Project Magnet Field Scope
CS Casing - large inconel weldment in fabrication (Holtec)	ODH Monitors	Recovery Project Vacuum Vessel Field Scope
Machine Core Structures (MCS) Components - in fabrication at PPPL and external shops	Personal Safety System and Central Control System	Duct Shields & Vessel Blackening
Plasma Facing Components - Graphite and metal parts being machined	Coil Bus Work	Shorted Turn Protection System
Passive Plate Brackets - Enhanced supports, electrical components being fabricated at PPPL and external shops	Vessel Seal Repairs	Bakeout Systems
Test Cell Shielding - Installations are wrapping up	Private Flux Region Fueling	BES and other Shutter

No component is fabricated until its design is complete as demonstrated by a successful FDR, signed calcs, closed chits, etc.

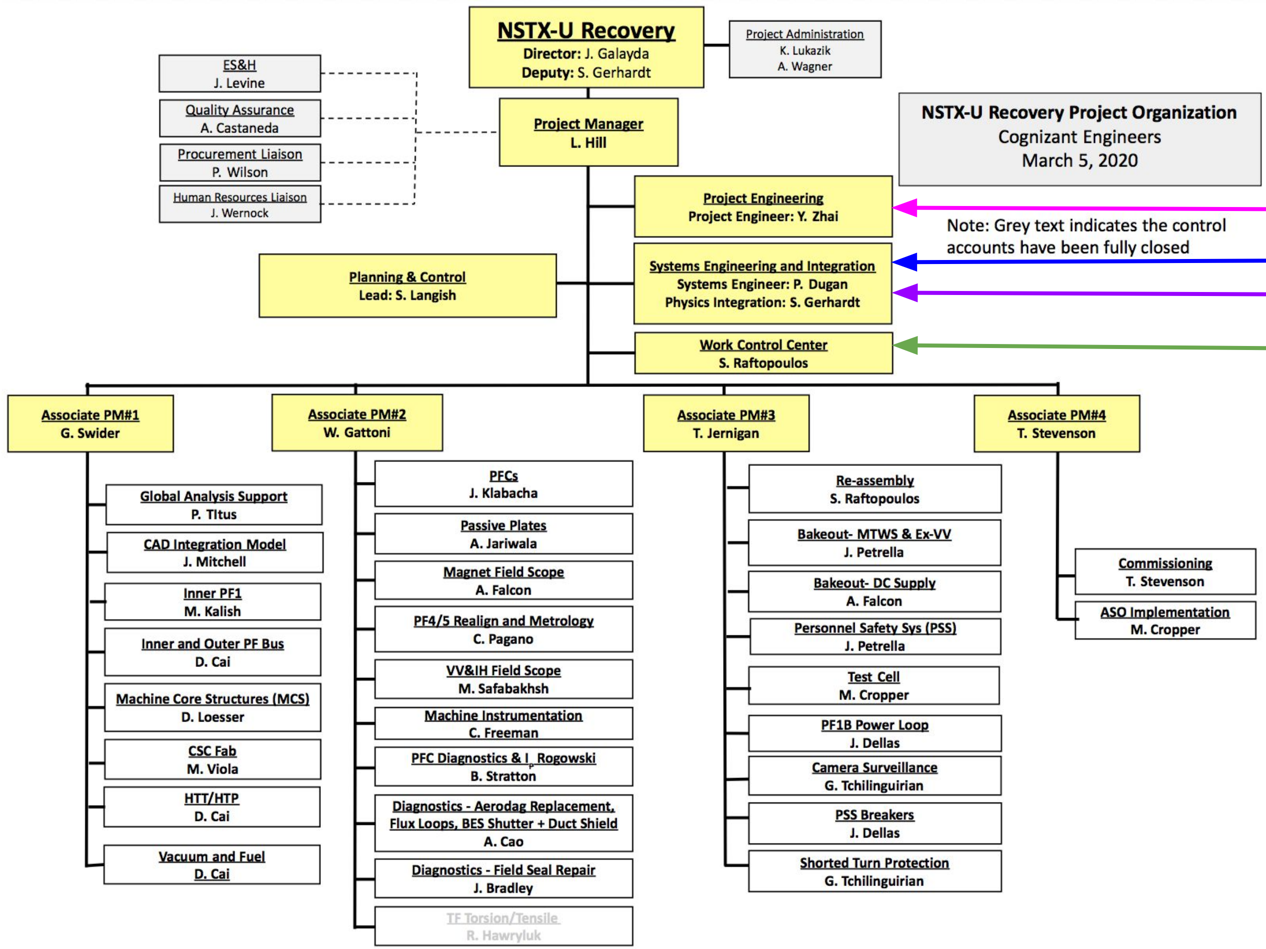
Design Status

All FDRs for the machine core, power systems, PSS, etc are complete

- Presently resolving chits from the final FDRs
- Two elements that we are exploring
  - Fission Chamber neutron detector modernization
    - Existing fission chambers date to TFTR; showing reduced reliability.
    - Work has been underway to update/relocate electronics
    - Will be BCPd onto Recovery in March; not yet FDRd
  - Balance of Plant ODH
    - In process of making a complete ODH assessment using the methods of FNAL FESHM 4240
      - the standard method of cryogenic ODH assessments in DOE SC labs
    - Will be adding additional ODH monitors in compressor, refrigerator, and other rooms
      - Will follow the methods described in the Test Cell ODH monitor talk
    - Will be adding monitoring to fans, dampers, etc

Low integration and technical risk

Recovery Project Organization: Engineering Support



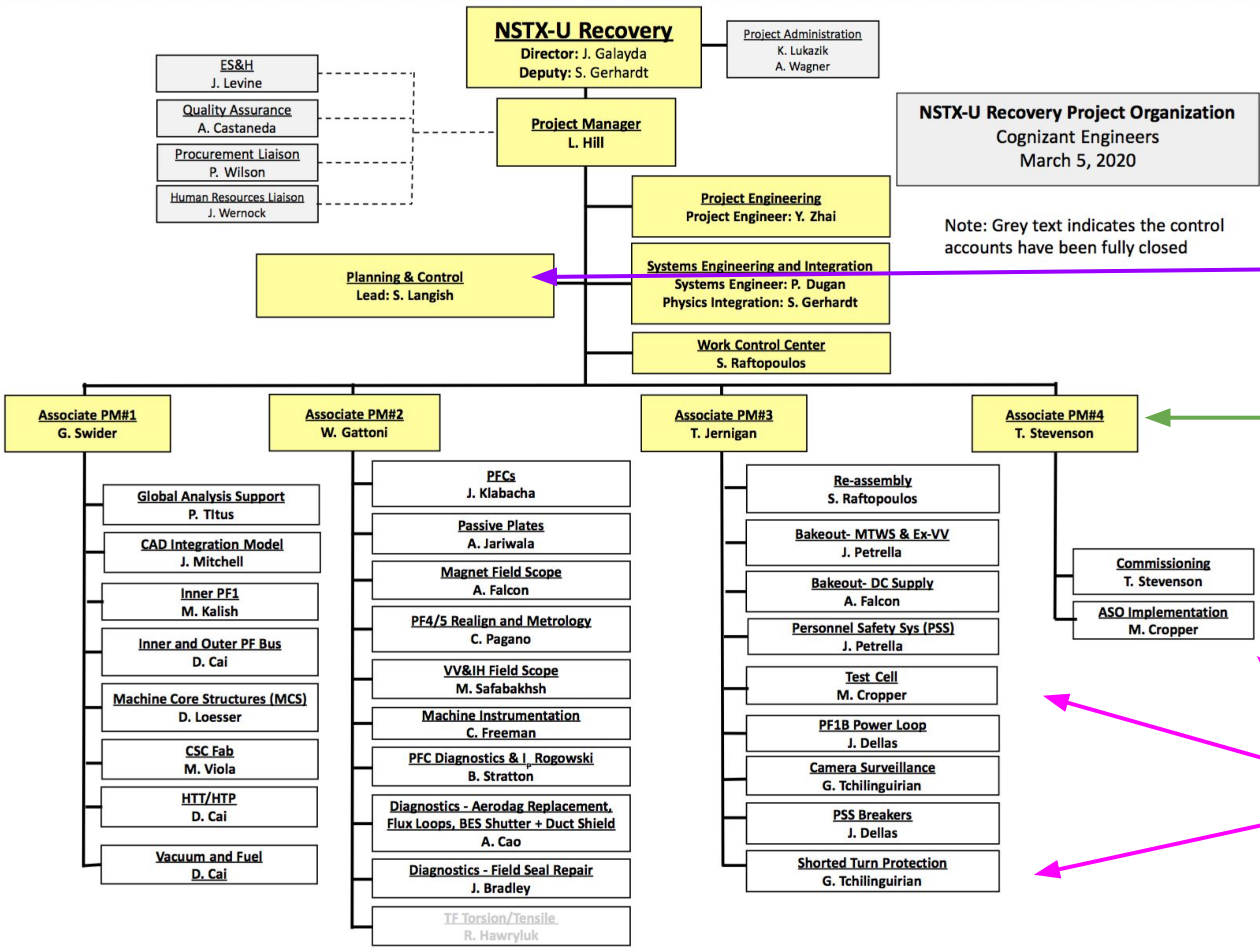
Design Assurance: Design Reviews, Calculations, Prototyping, Chit Resolution, etc

Physics Integration: Ensuring that the requirements, design, etc meets the research needs

Systems Engineering: Requirements Development, V&V, Interface Control, FMECA, etc

Work Planning and Control: Organizing work within the test cell

Recovery Project Organization: Project Support



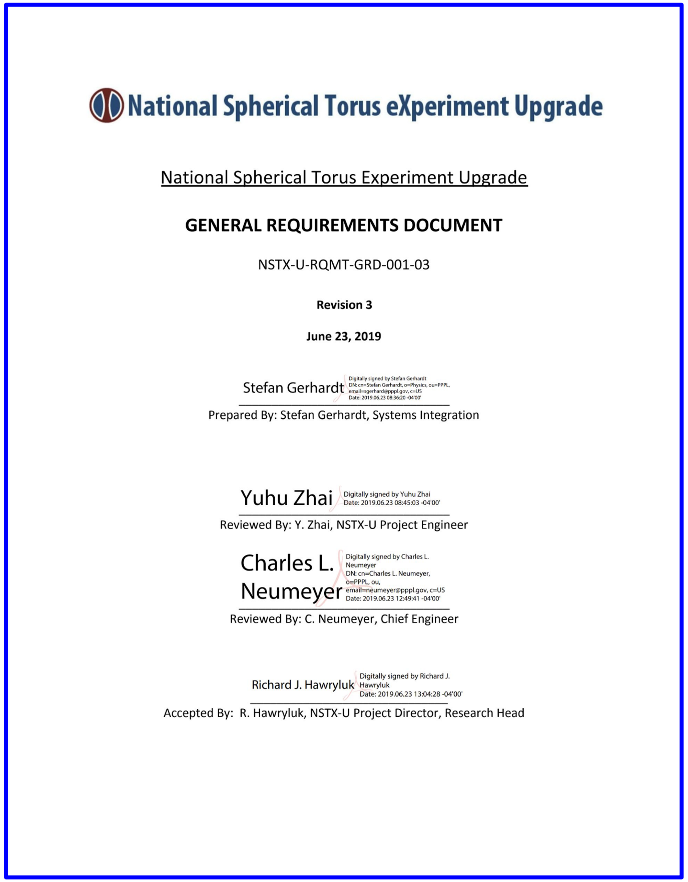
Planning And Control
EVMS, Scheduling, Risk Management Process

Associate Project Managers:
Control account managers, variance analysis, baseline change requests, EACs, etc

Project Cognizant Engineers:
Technical responsibility for design, fabrication, installation, etc.

Stakeholder Requirements Are Translated to the General Requirements Document

- Translates Stakeholder Requirements (PEP, KPPs) to engineering requirements.
  - 20000 total plasmas with parameters up to I_P=2 MA, B_T=1T, t_{pulse}=5 second, P_{inj}=10 MW
  - 300 ℃ bakeout of all in-vessel graphite
- Source material:
  - Original GRD (1997) for NSTX
  - Upgrade Project GRD
  - DVVR chits and Extent of Condition
  - Safety manual and other laboratory procedures and processes
  - PEP & KPPs
- Is the starting point for the engineering requirements flow-down
  - See talk by Dugan in Plenary



National Spherical Torus eXperiment Upgrade

National Spherical Torus Experiment Upgrade

GENERAL REQUIREMENTS DOCUMENT

NSTX-U-RQMT-GRD-001-03

Revision 3

June 23, 2019

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Click on Image or link

Project Design and Execution Follows Laboratory Safety Programs

Design

- Pressure System Standard (ES-MECH-15)
- Seismic Standard (ES-MECH-19)
- PPPL Safety Manual
- Consensus standards
  - IEC 61508/61511
  - ASHRAE

See individual talks for the specific hazards associated with each work scope

Execution - Apply ISM Principles

- Job Hazard Analysis per ES&H-004 identifies hazards for each job
  - Specific hazard mitigations are utilized per the PPPL Safety Manual, including LOTO (ES&H-016)
- Work via procedures that define the bounds of the work
- Pre-job briefs, safety and management walkthroughs, post-job briefs, used to ensure the work is done safely.
- Engineering standards also guide execution
  - Hoisting and Rigging (ES-MECH-07)
  - Wooden stairs and platforms (ES-MECH-09)
  - Forklifts (ES-MECH-10)
  - Manlifts (ES-MECH-12)
  - Anchorages (ES-MECH-16)
- STOP program used by PPPL to identify positive and negative trends, provide feedback to the workforce.

← USI screening bridges design and execution →

Project Design and Execution Follows Laboratory Safety Programs

Design

- Pressure System Standard (ES-MECH-15)
- Seismic Standard
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See in
specif
with each work scope

Execution - Apply ISM Principles

- Job Hazard Analysis per ES&H-004 identifies hazards for each job
  - Specific hazard mitigations are utilized per the PPPL
- st-job
- ...
- STOP program used by PPPL to identify positive and negative trends, provide feedback to the workforce.

Project is responsible for safety

Project management...John Galayda, Les Hill, Stefan Gerhardt, Tim Stevenson, Bill Gattoni, Tom Jernigan, Gary Swider, Yuhu Zhai...feel strongly that it is our responsibility to ensure that are staff return home without injury every day

← USI screening bridges design and execution →

CDE-3B Scope Includes Numerous Elements Defined to Ensure Safe Operations

Scope	Cog. / Speaker	Safety Impact
PSS-SIS	Petrella / Petrella	Safety Instrumented System provides IEC-61508/61511 compliant, fail-safe, redundant system for i) access control, ii) e-stops, and ii) search and secure
PSS-CMS	Petrella / D'Agostino	Protects against contact thermal & electrical hazards
PSS-TKS	Petrella / D'Agostino	Provides configuration management of personnel door, mobile shield doors, safeguards, etc
Shielding	Cropper / Cropper	Improves test cell shielding to the point where all areas outside the gallery should be beneath the requirement for dosimetry (<50 μREM/hr)
Medium Temperature Water System	Petrella / Browning	Significantly reduces volume of ~150 ℃ H_20 in the system, adds interlocks, eliminating BLEVE risk identified at DVVRs
ODH Monitors	Cropper / Cropper	Redundant ODH monitors in the NSTX-U test cell (exploring balance of plant requirements)
Radiation Annunciators	Cropper / NA	Iluminates signs outside test cell when radiation levels inside test cell exceed a threshold

Charge Questions (1 & 2)

1) Given the results of the individual FDRs, have the requirements for the Recovery Project scope defined in the GRD and the SRDs been met?

Yes. See:

- Design overview by Zhai (plenary)
- System engineering (SE) overview, and RVTM* discussion, by Dugan (plenary)
- Sections 3 & 4 of each technical talk

2) Have interfaces between project elements, and between project elements and the legacy facility, been properly identified and managed?

Yes. See:

- SE overview, particularly the interface section, by Dugan (plenary)
- Sections 3 of each technical talk

*Requirements Verification and Traceability Matrix

Charge Questions (3 & 4)

3) Have recommendations/chits from previous reviews (Project PDR, Project CDR, topical Design Reviews) been adequately addressed?

Yes. See:

- Design overview by Zhai (plenary)
- Sections 5 of each technical talk for chit closure status for each Project element

4) Have technical, interface, and integration risks to the Project been appropriately identified? Are project plans adequate to address/retire the identified risks?

Yes. See:

- Design overview by Zhai (plenary)
- FMECA overview by Dugan (plenary)
- Section 7 of each technical talk for FMECA and Project risks for each Project element

Charge Questions (5)

5) Has accelerator and industrial safety been adequately considered in completing the final design?

Yes. See:

- This talk
- Sections 8 of each technical talk for industrial ES&H concerns
- Specifically talks by Petrella, D'Agostino, Cropper, Browning for systems or Project elements with operational safety motivation

Summary

- NSTX-U is a legacy facility; present Project touches only parts of it.
  - Project scope defined in the PEP, flows from the 2017 Extent of Condition Process
- Project had a large CDE-3A approval, and fabrication of that scope is underway
- GRD flows the stakeholder requirements to the top level of the engineering requirement
- Large part of the CDE-3b scope is dedicated to operational safety.

BACKUP

Design-Point Spreadsheet is Used to Integrate Design Elements

Single large spreadsheet (multiple sheets) and documenting calculation

Physics
(equilibrium currents, flux consumption of various scenarios, ramp-up and ramp-down constraints)

Coil design point (conductor size, # of turns, cooling)

Insulation and hi-pot requirements

Static and Transient Electromagnetic Loads

Rectifier Requirements

Power System Requirements

PFC shape requirements

Key tool to ensure that physics and engineering requirements flow correctly down to the subsystems
→ Many tables in SRDs are derived from the DPSS

Requirements Flow from Stakeholder and Laboratory Level Down to Sub-Systems

CD-0/1 Mission Need

PEP & KPPs

Accelerator Safety Order

PPPL Safety Manual

PPPL Engineering, ES&H, etc procedures

Consensus Standards

NSTX-U General Requirements Document
NSTX-U-RQMT-GRD-001

Structural Design Criteria
NSTX-CRIT-0001-02

NSTX-U Disruption Requirements
NSTX-U-RQMT-RD-003

NSTX-U Thermal Scenarios
NSTX-U-RQMT-RD-012

NSTX-U Mag. Materials
NSTX-U-RQMT-RD-010

Magnets
-RQMT-SRD-002

Vacuum Vessel & Internal Hardware
-RQMT-SRD-004

Power Systems
-RQMT-SRD-006

RC&P
-RQMT-SRD-008

Test Cell
-RQMT-SRD-010

Plasma Facing Components
-RQMT-SRD-003

Auxiliary Systems
-RQMT-SRD-005

Heating and Current Drive
-RQMT-SRD-007

Central I&C
-RQMT-SRD-009

Diagnostics
-RQMT-SRD-011

Operational and Safety Systems
-RQMT-SRD-012

Systems Requirements Documents

Design Requirements Documents (examples)

PFC Diag. & Fuel
-RQMT-RD-004

CS Air Side Diag.
-RQMT-RD-005

Machine Inst.
-RQMT-RD-008

All technical requirements defined against 2 MA, 1 T, 10 MW, 5 second programmatic requirement

Requirements: link

Project Ends with Reassembly and Commissioning

- Reassemble the device - WBS 1.09.02.01
  - Sequenced installation of tiles, magnets, buswork, etc.
  - KPP #1 achieved in this phase
  - See APM talk by Jernigan
- Implement Accelerator Safety Order - WBS 1.09.01.01
  - Write the SAD and ASE, conduct Readiness Assessment and ARR
  - See APM talk by Stevenson, breakout talks by Stevenson and Malo
- Commission the device - WBS 1.09.03.01
  - Recommission power, control and protection systems, bakeout, coil operations, first plasma
  - KPPs #2-#4 achieved in this phase
  - See APM and breakout talks by Stevenson

Demonstration of KPPs Leads to Transition to Operations