IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024.
Invited presentation given at IREF 23, November 15, 2023, Arona, Italy

Tokamak Energy

HTS fusion magnet development and irradiation considerations

Dr Greg Brittles
15th November 2023

IREF23
IRradiation Effects on HTS for Fusion
12 – 16 November 2023, Arona, Italy

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Talk Outline

1. Tokamak Energy's route to fusion

2. Update on two key live magnet development projects

3. Focus on irradiation

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Route to Fusion

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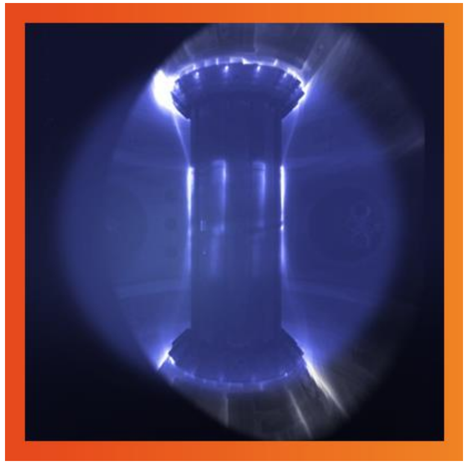
Our Technology Advantage

Spherical Tokamak + **HTS Magnets** = **Efficient Fusion**

Commercial Fusion

The Leading Global Fusion Company



2022
Highest plasma 'triple product' of any private fusion company

2022
First private fusion company to achieve 100M°C plasma ion temperature in a tokamak

2021
Robust, scaleable, quench-protected HTS magnet precisely validating our simulations

2019
World-record 24 Tesla field at 20 K with patented HTS magnet technology

2017
Designed, built and operate the world's highest-magnetic field spherical tokamak (ST40)

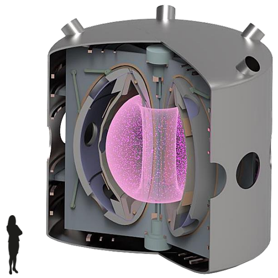
2015
First HTS tokamak sustained pulse for >24 hours (ST25 HTS)

Roadmap to commercial fusion energy

Prototype device de-risks and accelerates

Advanced Prototype Device

LATE 2020s



- **Long pulse plasma**
- **Proves new technology**

Fusion Pilot Plant

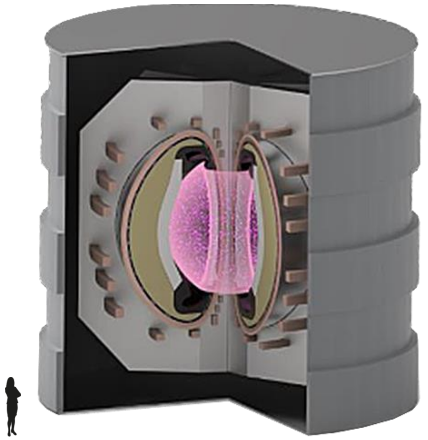
MID 2030s

- **Long pulse DT operation required for commercial fusion energy**

1st Gen Commercial Plant

LATE 2030s

COMMERCIAL



- **Commercial fusion power plant generating 500 MWe**

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Key Magnets Projects Update

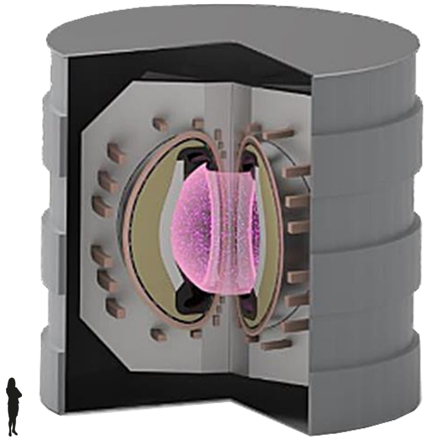
Magnet systems technology blocks

HTS Tape Quality and Robustness

HTS Coil Manufacturing

Modelling and Simulation

Stored Energy Management (Quench)



Mechanical Support

Irradiation and Shielding

Magnet Control Systems

Cryogenics

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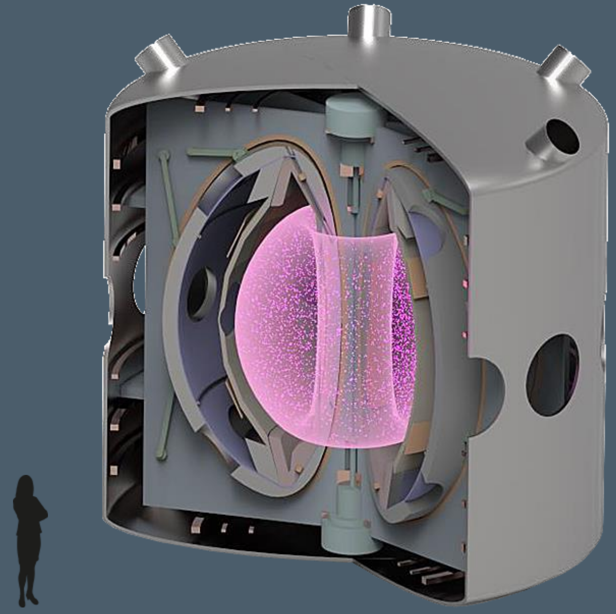
Update on two key HTS magnet projects (2023)

Demo4

Building the world's first high field HTS spherical tokamak magnet set

ST-X (80)



Designing our advanced prototype fusion device

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Key Magnets Projects Updates:

Demo4

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Demo4: Mission

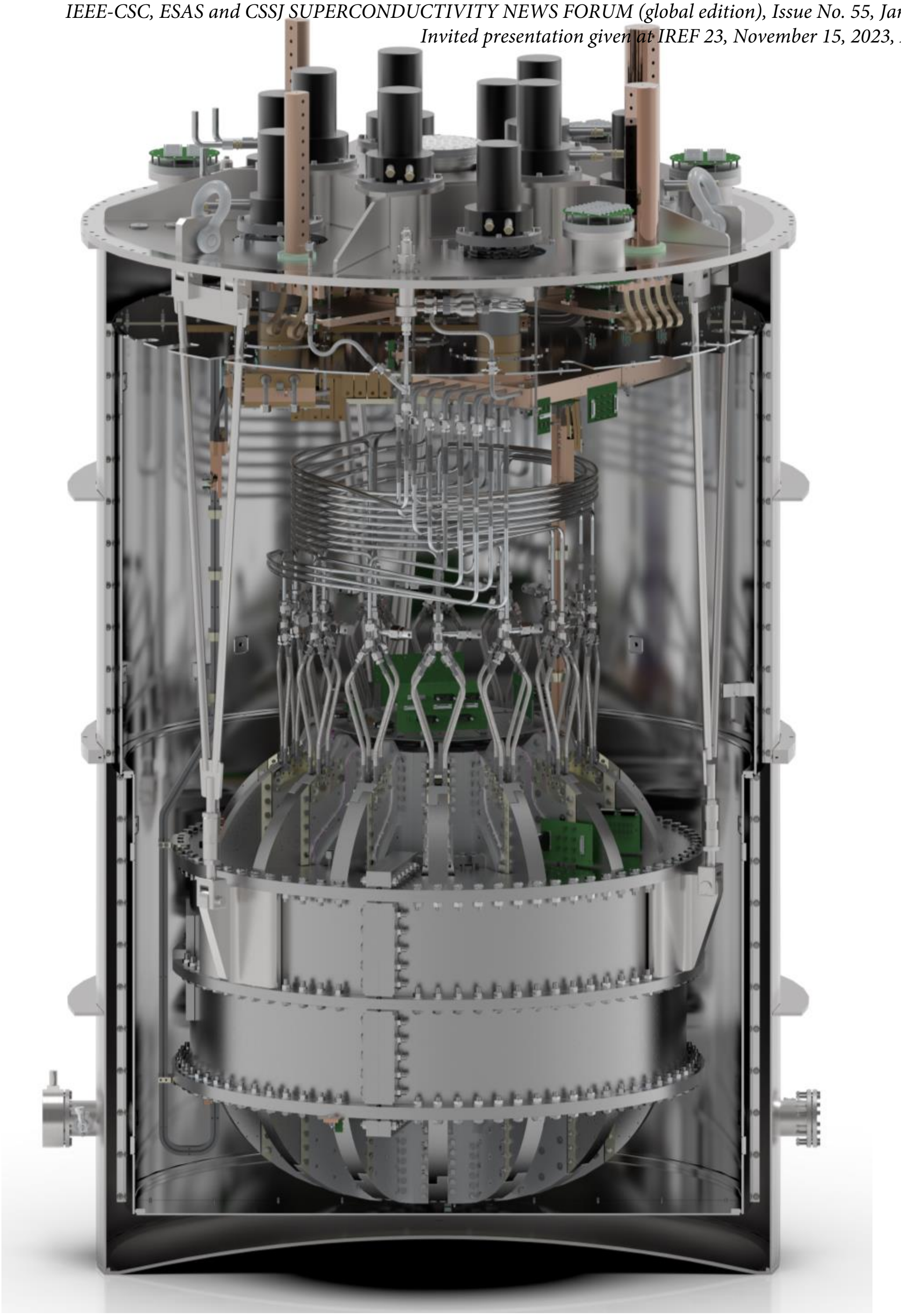
Design, build and test a full spherical tokamak magnet system, significantly increasing the technology readiness level of HTS magnets for fusion and other applications

Full-System Interactions
PF / TF coil set interactions (DC & AC), including PF AC loss measurement

Manufacturing
Demonstrate HTS coil manufacturing techniques at intermediate scale (~1.5m)

Stress
Manage high stresses in HTS coil structures (up to 250 MPa transverse compressive)

Quench Management
Demonstrate PI technology and simulation tools on a high stored energy system (~16.5 MJ). Simulate transient fusion pulse heating



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Demo4: System

Cryocoolers
10 x Cryomech AI600/630

20 K He Circuit
~170 W @ 20K

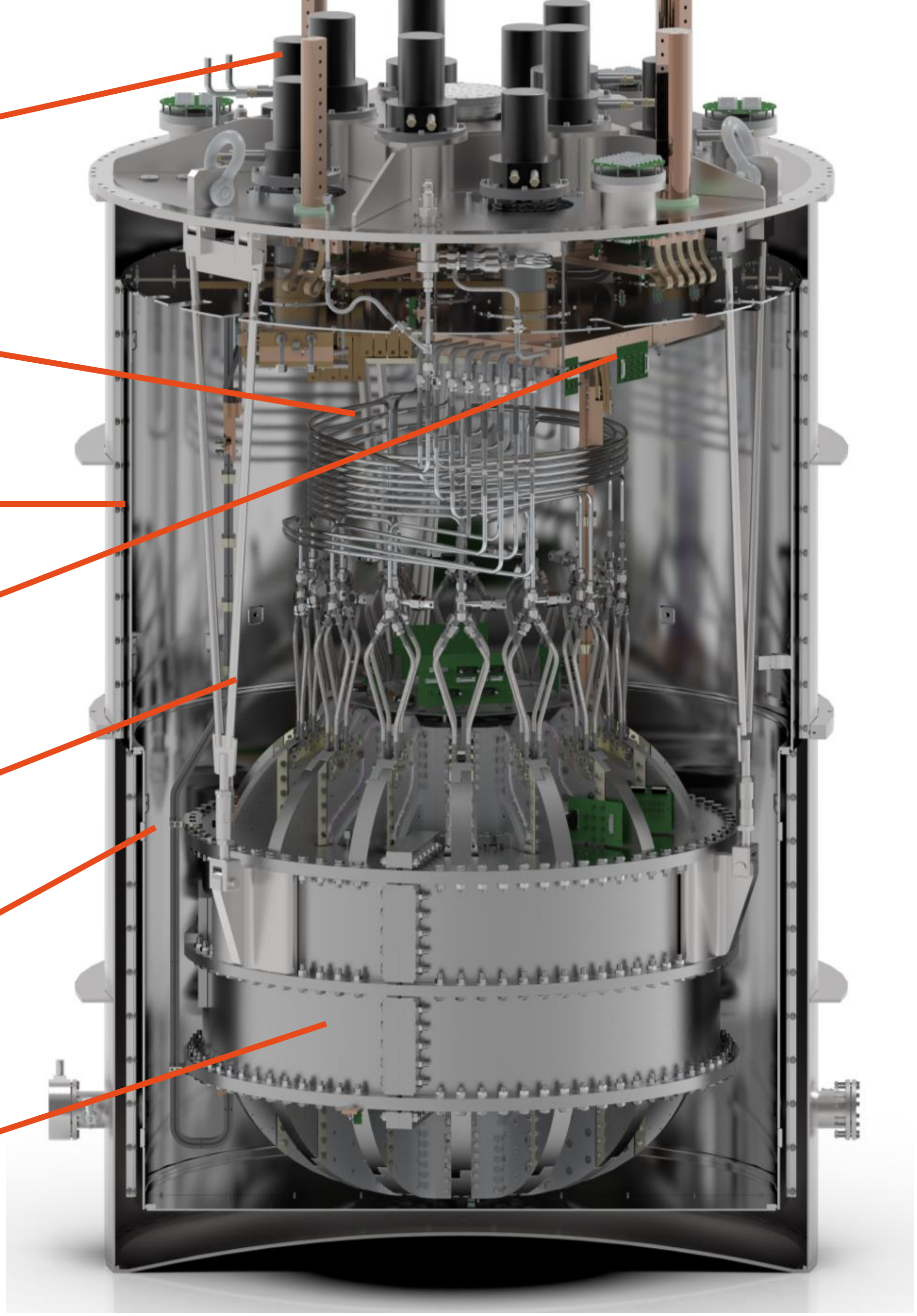
Vacuum Chamber
10^{-7} mBar

Current Leads
TF = 8 kA / PF = 4.5 kA

Suspension
Supports 10 tonne cold mass

Radiation Shield
Rejects 500 W of heat

Magnet Assembly
REBCO HTS magnet structure



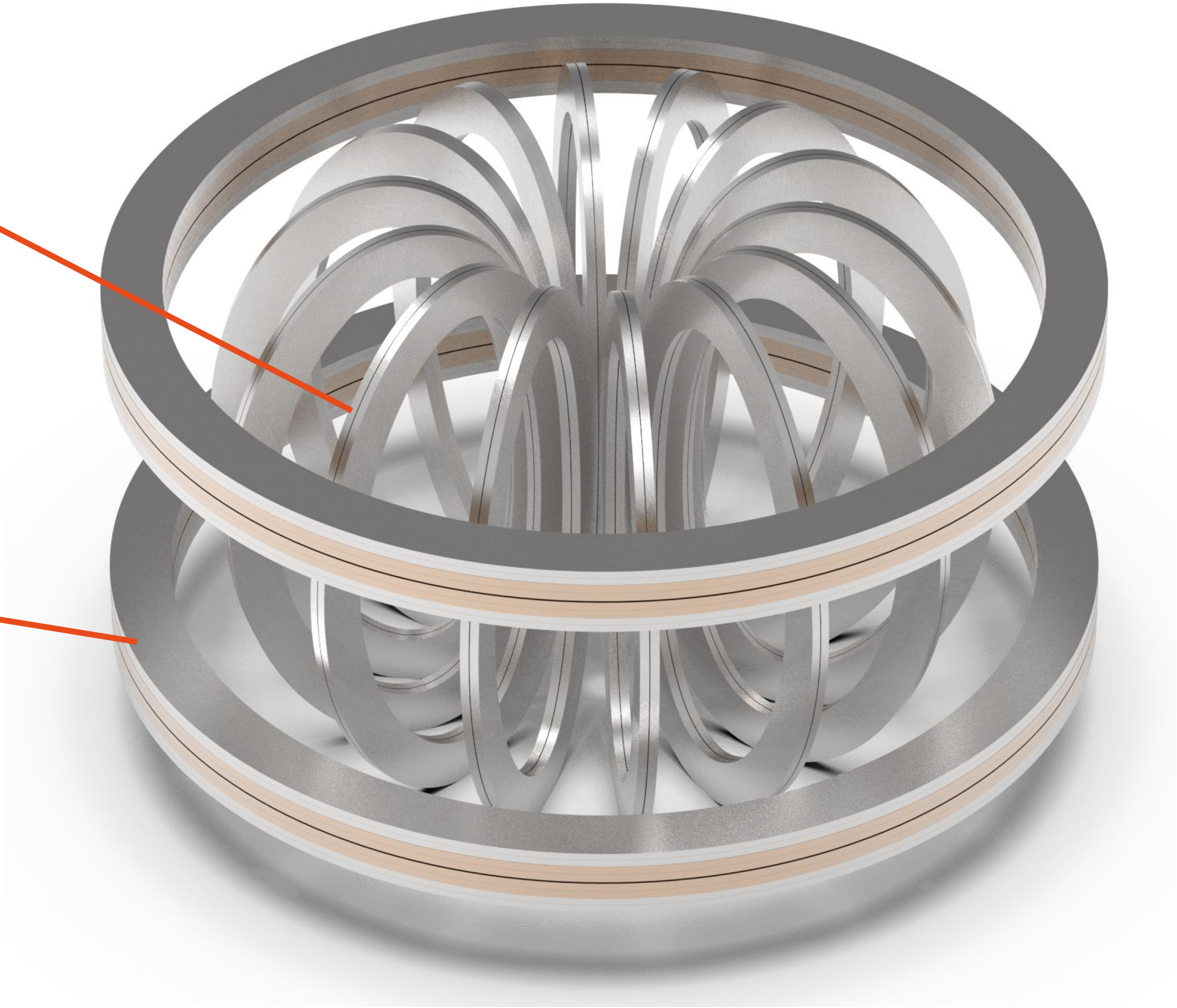
Demo4: HTS coil set

TF Coil Set

14 x double pancake limbs
0.8m major dimension
Partially insulated
No-twist stacked tape cable
18T peak design toroidal field

PF Coil Set

2 x 8-pancake stacks
1.2m major dimension
Fully insulated
0 → 3.8kA in 10 secs
No-twist stacked tape cable
~3T field shine on TF coils



- ~50 km full-width HTS tape from 4 suppliers. Thorough QA campaign

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Demo4: Coil Manufacturing

- Coils wound directly from full-width HTS tapes
- Solder consolidated
- Partial insulation (TFs) incorporated in windings

- Coil manufacturing complete
- 28 TF coils and 16 PF coils
- Ready for integration to coil assemblies

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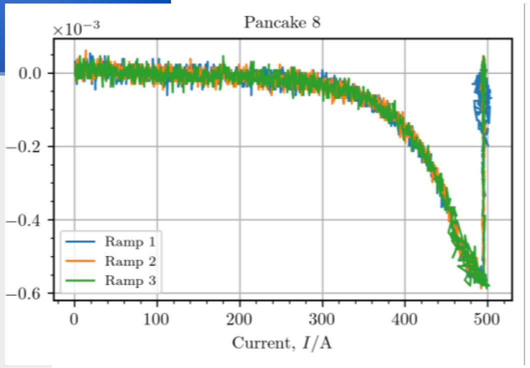
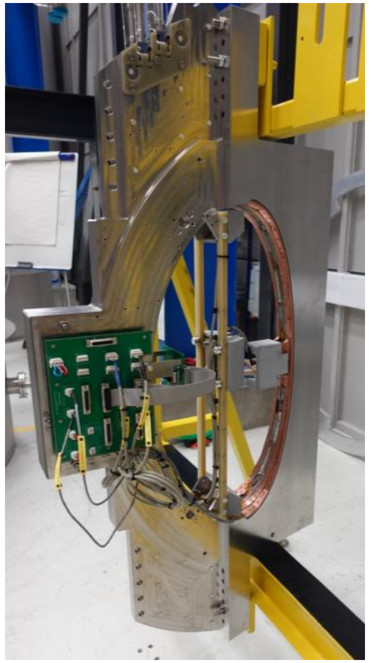
Demo4: Coil Assemblies – Build and Test Progress

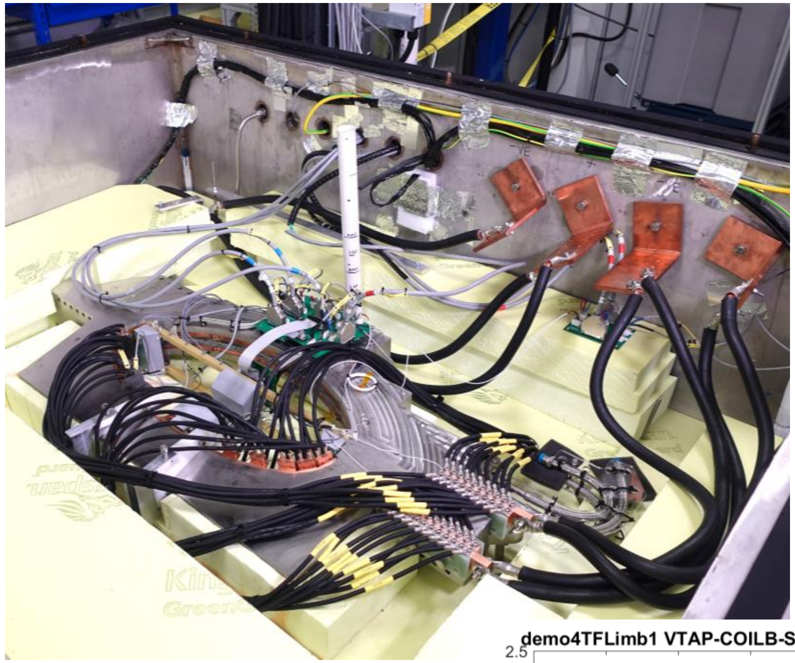
PF Coils Complete

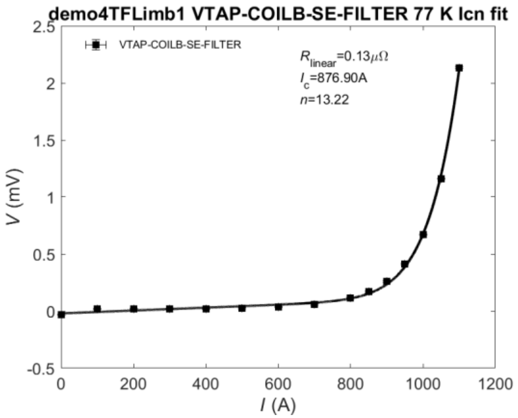


- ✓ 2 off 8-pancake stacks bonded, jointed and instrumented
- ✓ LN2 tested
- ✓ Ready for Demo4 system integration

TF Limbs Progressing Well







- ✓ 1 off 2-pancake stack bonded, jointed, resin transfer moulded and loaded into steel clamshells
- ✓ Liquid nitrogen tested
- • 13 limbs to complete for Demo4

Key Magnets Projects Updates:

STX Design

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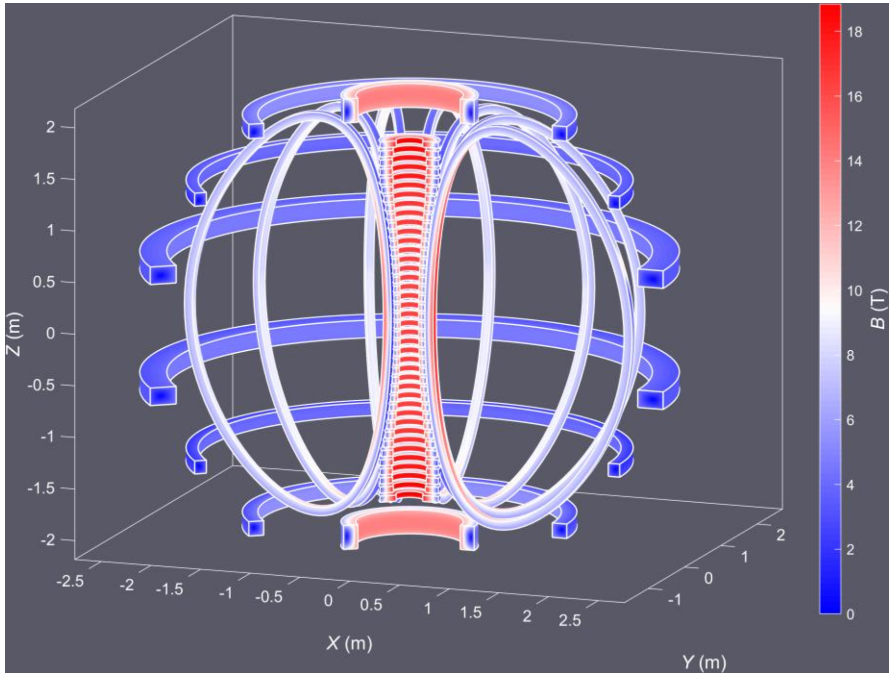
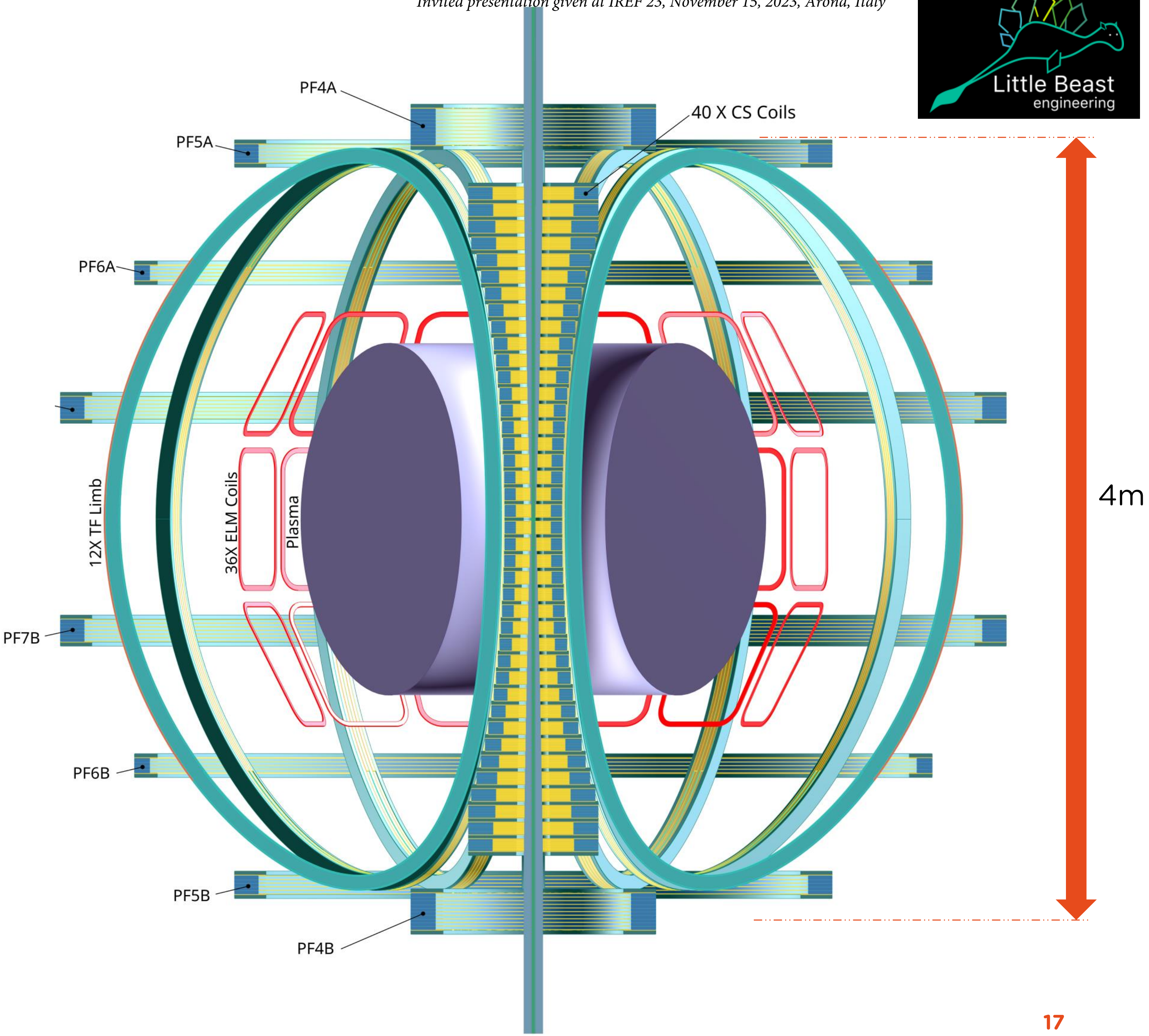
Little Beast engineering

STX: Magnet Overview

Mission:
- Demonstrate long pulse (1000s) plasma operation

HTS Coil sets:
- 12 x toroidal field (TF) limbs (80cm major radius)
- 7 x poloidal field (PF) coils
- 40-pancake central solenoid (CS)
- 36 x auxiliary (AUX) coils





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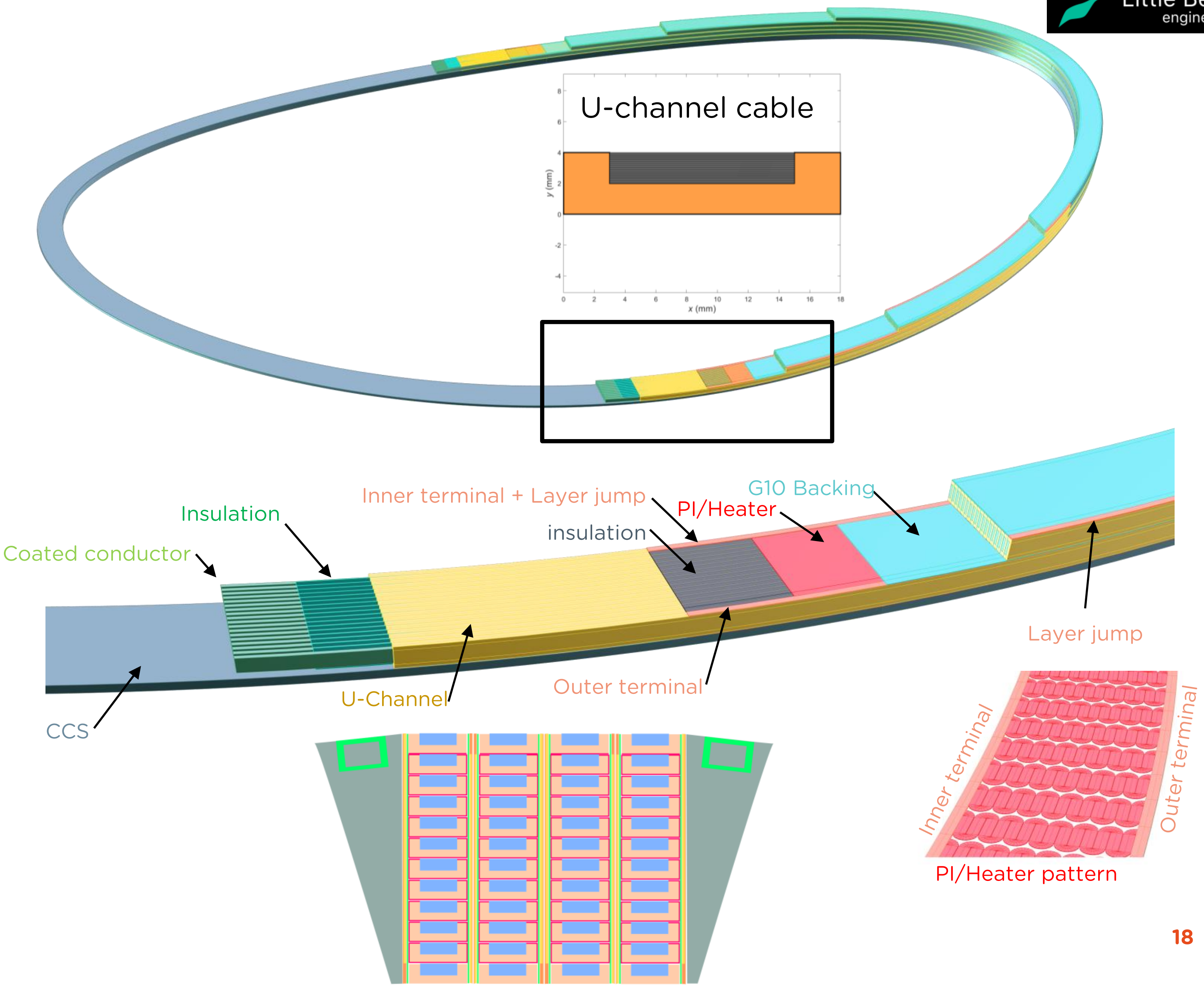
STX: TF Coil Layout

HTS "U"-Channel Cable

- >30 HTS tapes, solder consolidated, defect tolerant
- Copper "U"-channel aids with energy dump/extraction
- Utilises field-aligned tapes – no twisting or transposition

Quench Protection

- Pancake level partial-insulation (previously turn level)
- Acts as a heater and voltage limiter under rapid discharge
- Peak discharge voltage limited to 300 V per limb (3.6 kV entire TF magnet)



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Focus on Irradiation

FPP *Shielding Design*

Radiation Shield Design

Protecting the magnets from radiation-induced degradation and heating

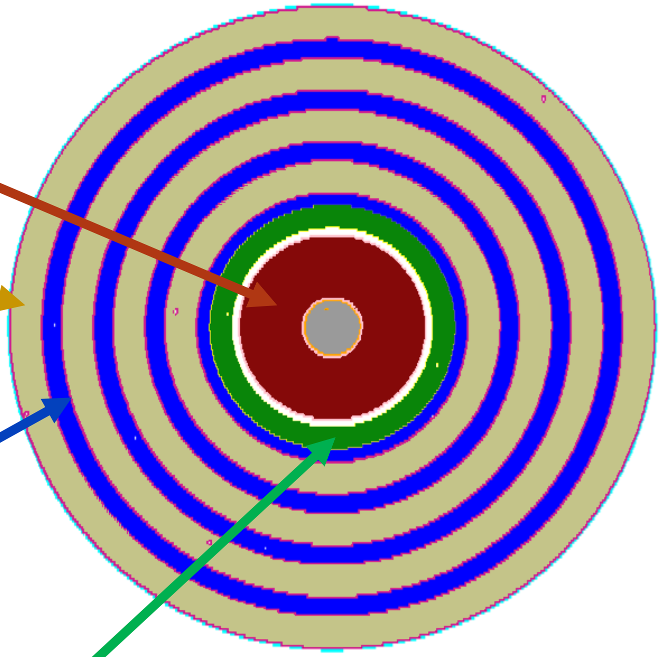
Graded Shield Architecture

Magnet Target to protect

W rich (inelastic scattering)

Combination of hydrogenous (or low Z) elastic moderators, resonance capture and further inelastic scatter

Combination of high-Z-rich (gamma attenuator) and low energy neutron absorber



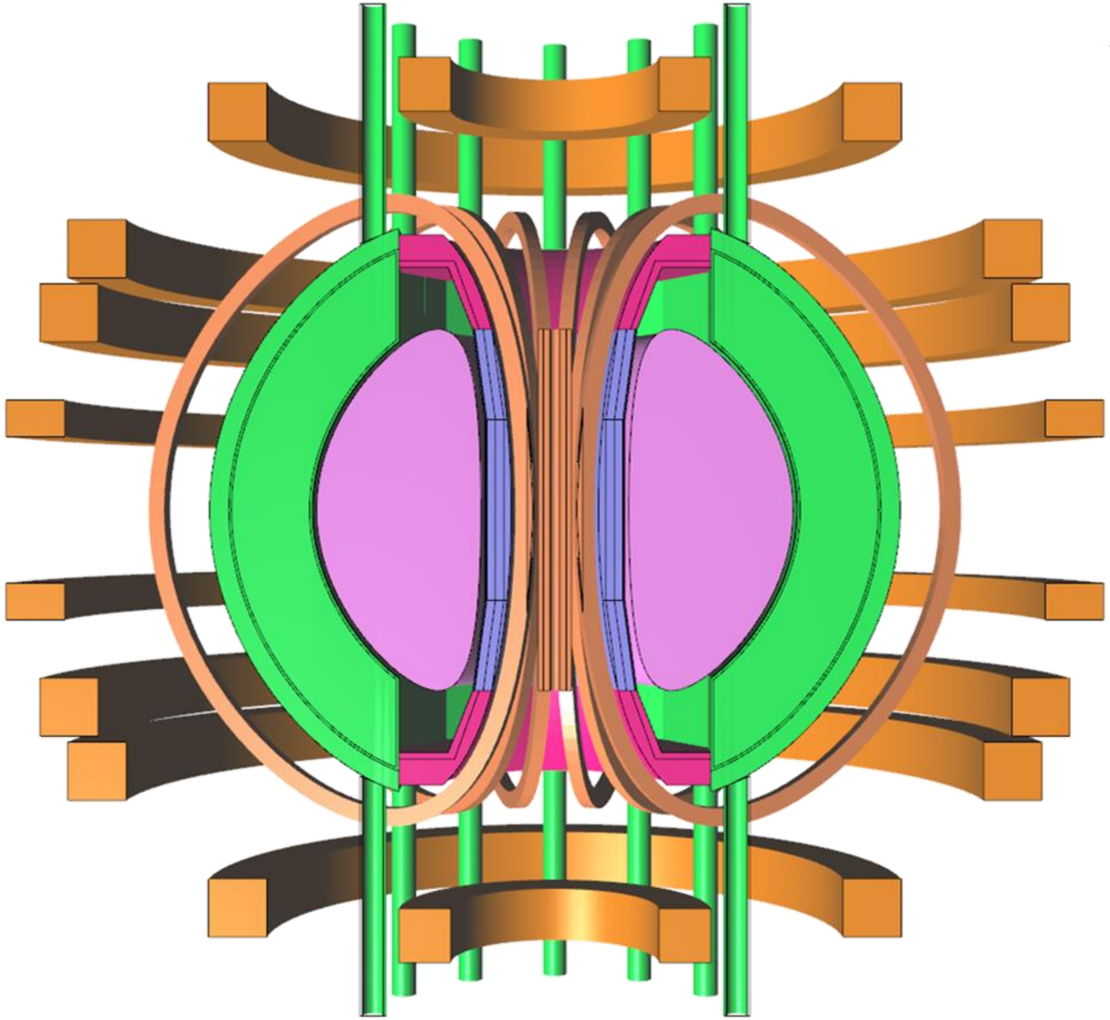
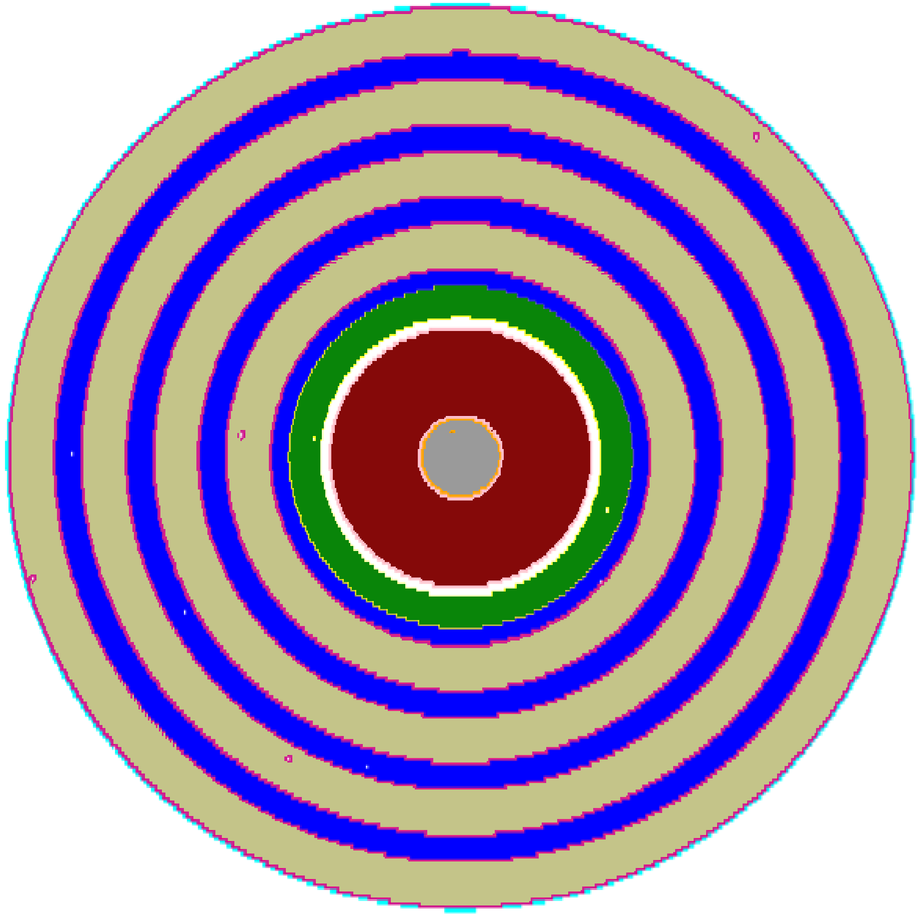


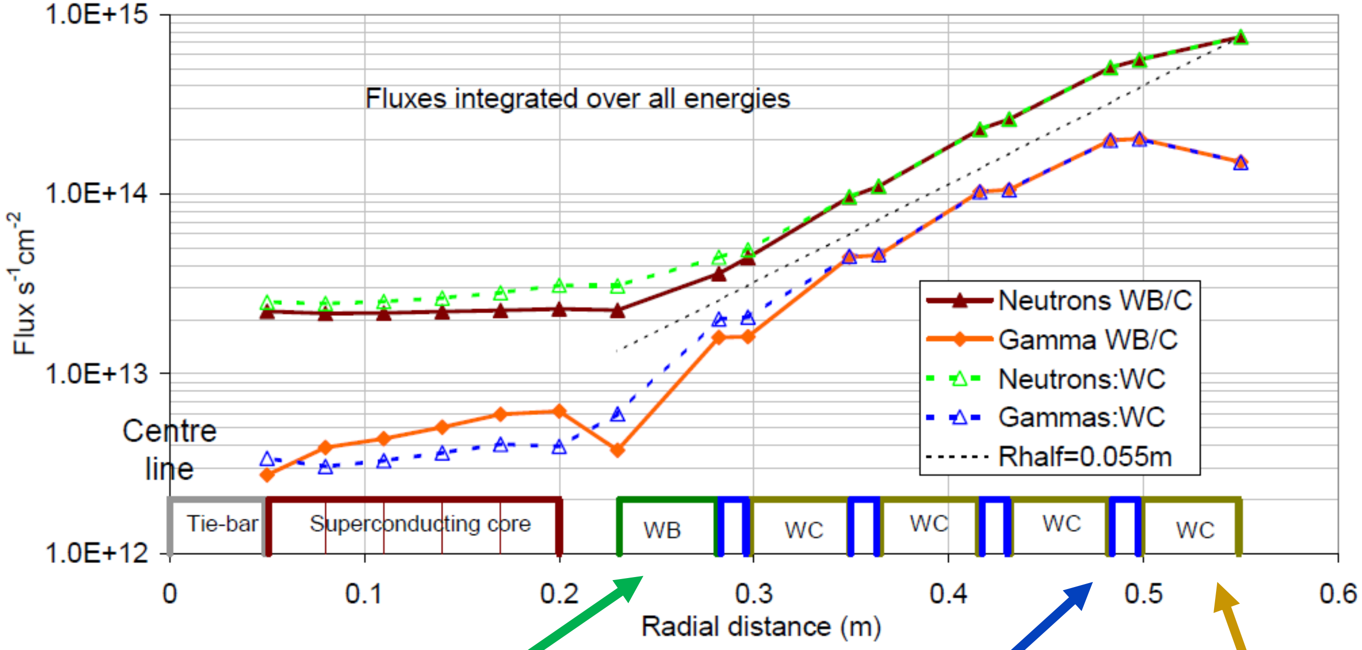
Illustration only

Radiation Shield Design

Protecting the magnets from radiation-induced degradation and heating



Example – ~100x attenuation per ~300 mm shield thickness



Combination of high Z rich (gamma attenuator) and low energy neutron absorber

Combination of hydrogenous (or low Z) elastic moderators (here H_2O), resonance capture and further inelastic scatter

W rich (inelastic scattering)

Neutron and gamma flux distributions and their implications for radiation damage in the shielded superconducting core of a fusion power plant Colin G. Windsor and J. Guy Morgan 2017 *Nucl. Fusion* **57** 116032 **DOI** 10.1088/1741-4326/aa7e3e

Focus on Irradiation

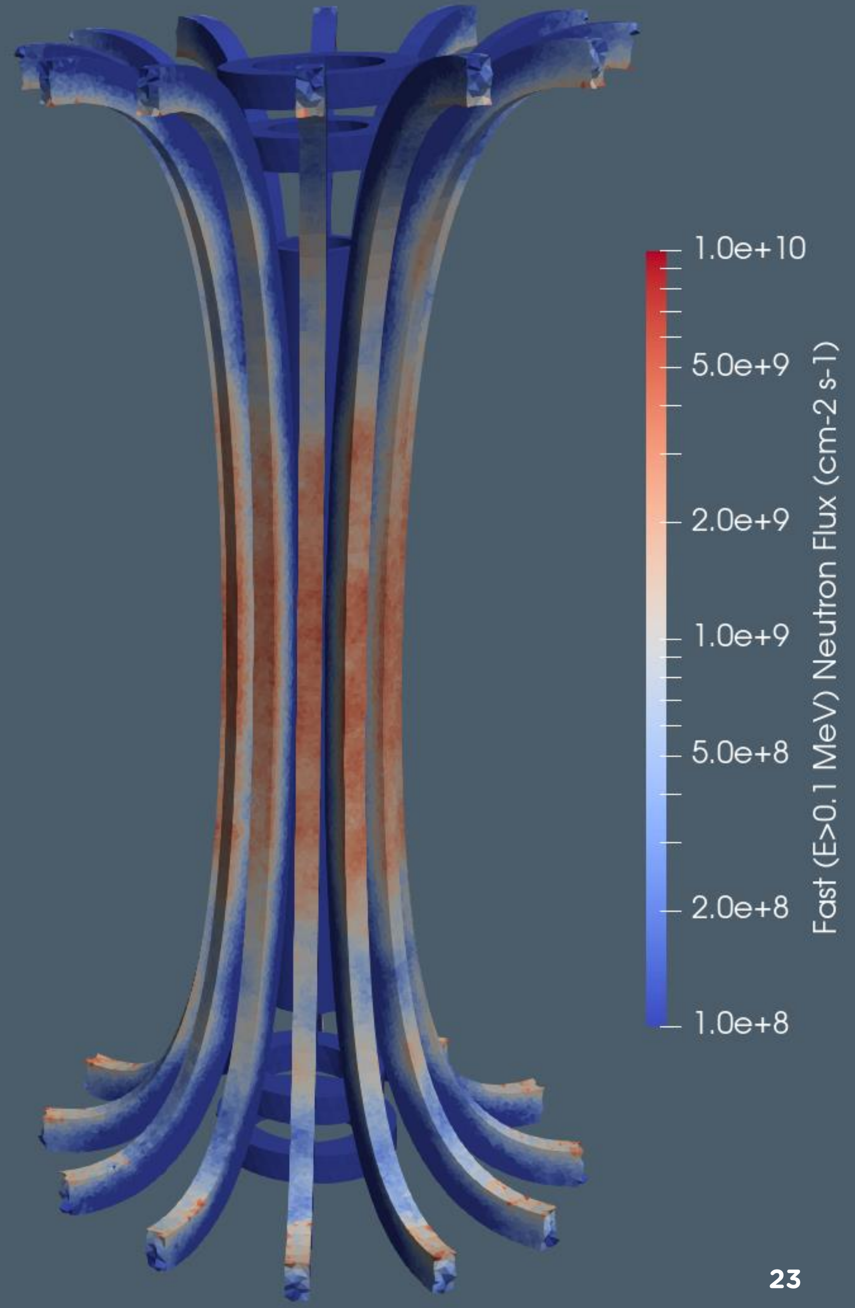
FPP *Calculated Magnet Irradiation Dose*

Neutronic Simulations

Fast Neutron Flux

- Reactor shielding studies are conducted to determine the optimum shielding solution for spherical tokamaks
- Key metric for REBCO coated superconductor is fast (E_n > 0.1 MeV) neutron fluence, which has been shown to degrade performance
- Shielding configuration aims to produce fast neutron attenuation of 1E6 in radial extent 800 – 900 mm
- Corresponds to full-power life circa 50 years for average neutron wall load of 2 MW m^{-2}

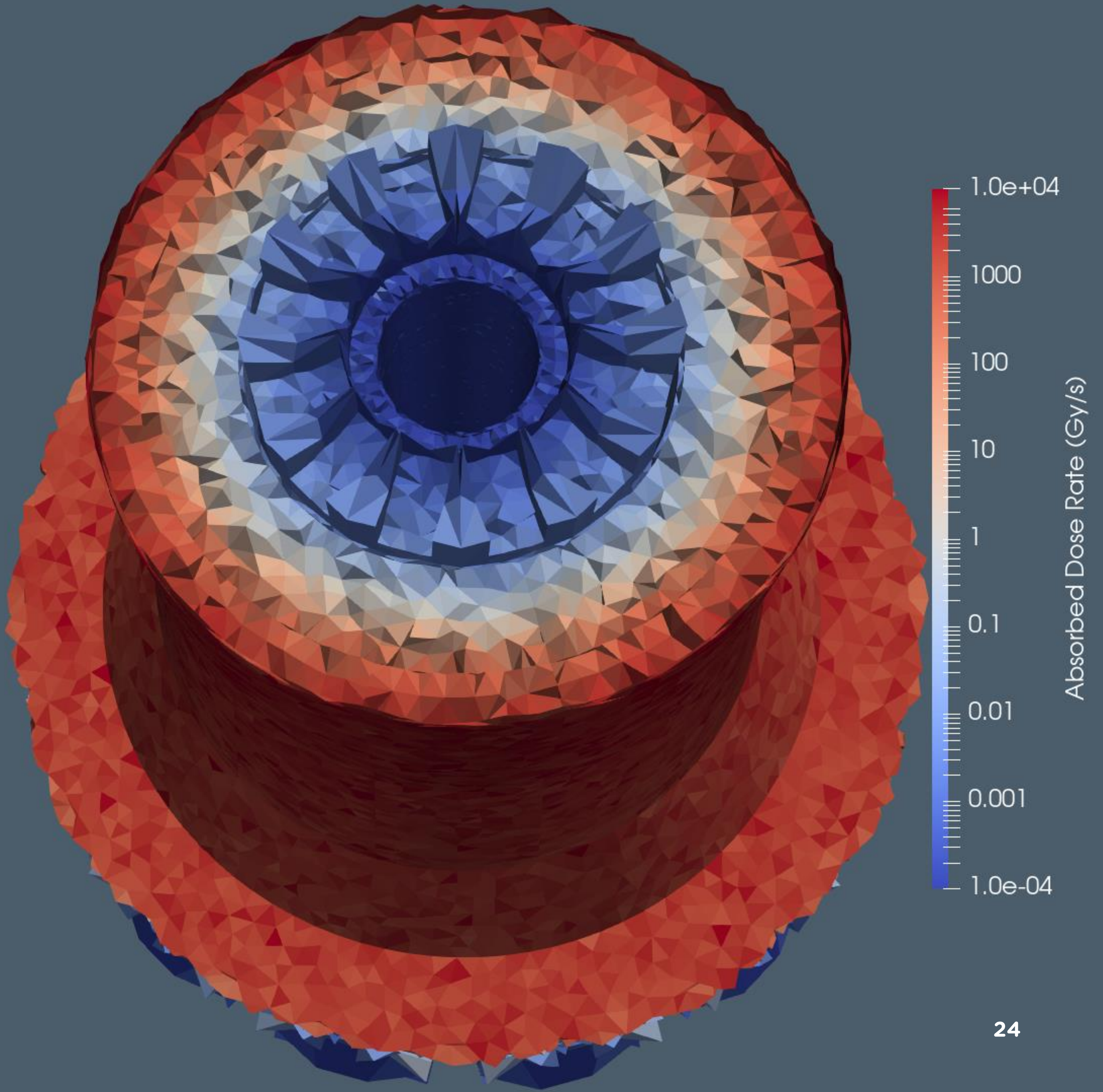
- Tokamak Energy has a bespoke application of the Geant4 toolkit for radiation simulations
  - Direct processing of unstructured mesh data
  - Automated iterative weight windows using unstructured mesh



Neutronic Simulations

Ionising Energy

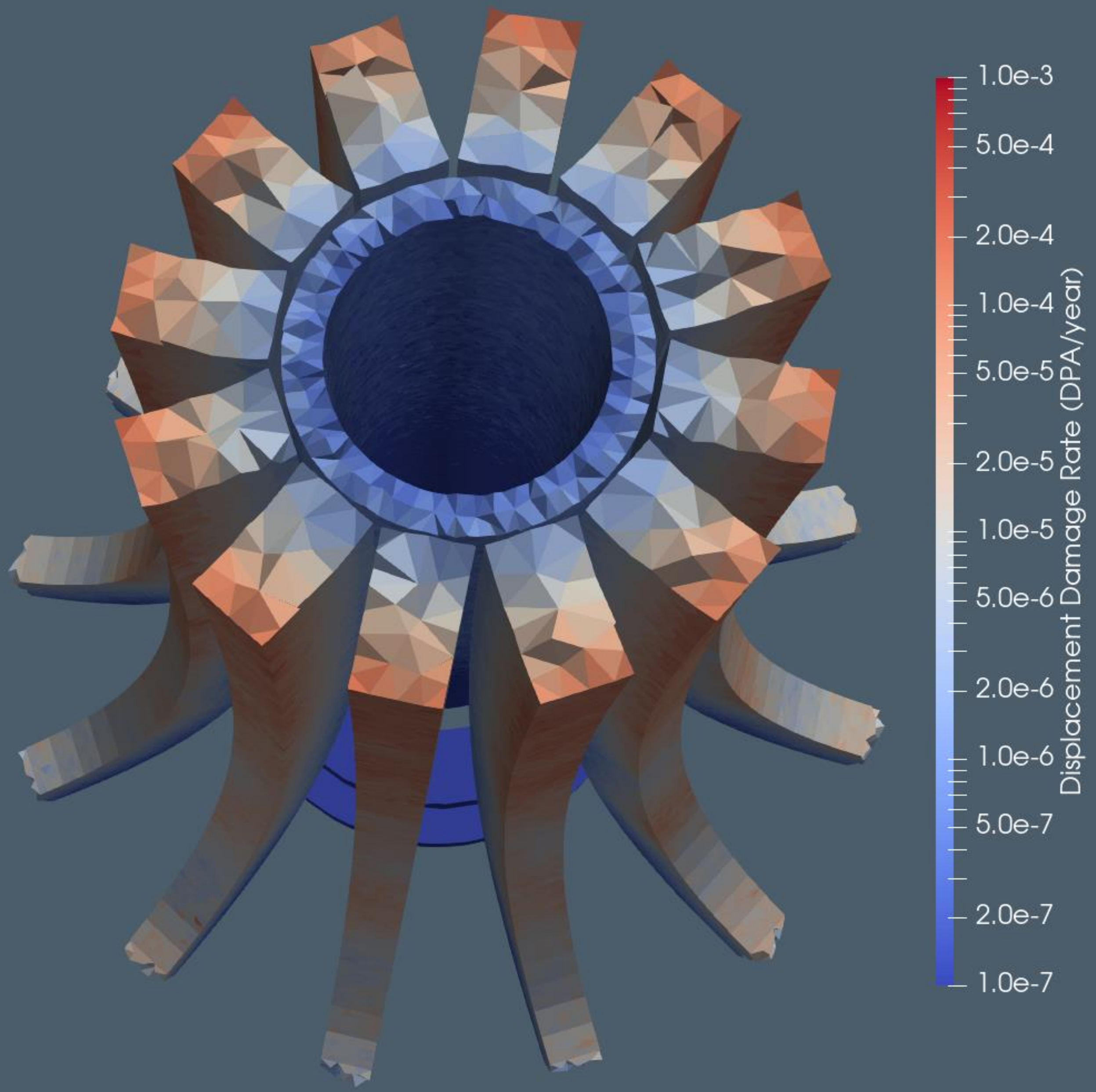
- Absorbed dose primarily caused by secondary X/gamma rays produced by neutron interactions in the core
- Absorbed dose on the midplane is in the range 5 – 10 MGy over life (limited by fast neutron fluence)
- Specialist organic insulators are expected to retain physical, electrical and thermal properties in this dose range



Neutronic Simulations

Non-Ionising Energy Loss

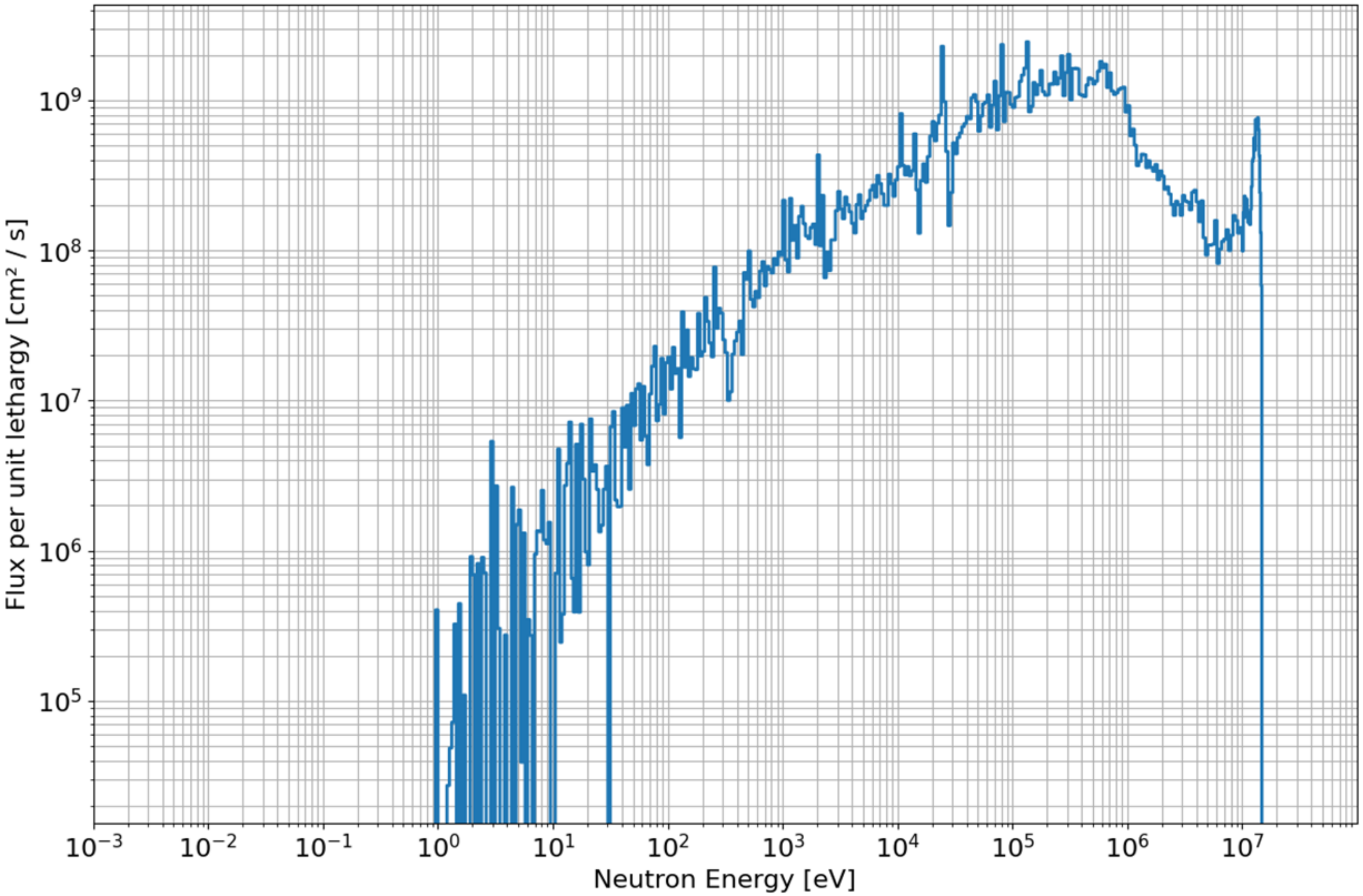
- Non-ionising energy loss estimates the atomic displacements that occur within the core
- DPA rate shown here was estimated using the NRT formula and a threshold energy of 25 eV
- Circa 5 mDPA over the lifetime of the tokamak means that degradation of structural elements of the core should not be a major concern



Neutronic Simulations

Neutron Energy Spectrum

- Neutron energy spectrum calculated in 709-group format in the interspace between the radiation shield / IVC and the toroidal-field coils
- Borided materials in the shield eliminate thermal and epi-thermal neutrons, reducing absorbed dose rate and activation in the core from thermal-neutron capture reactions



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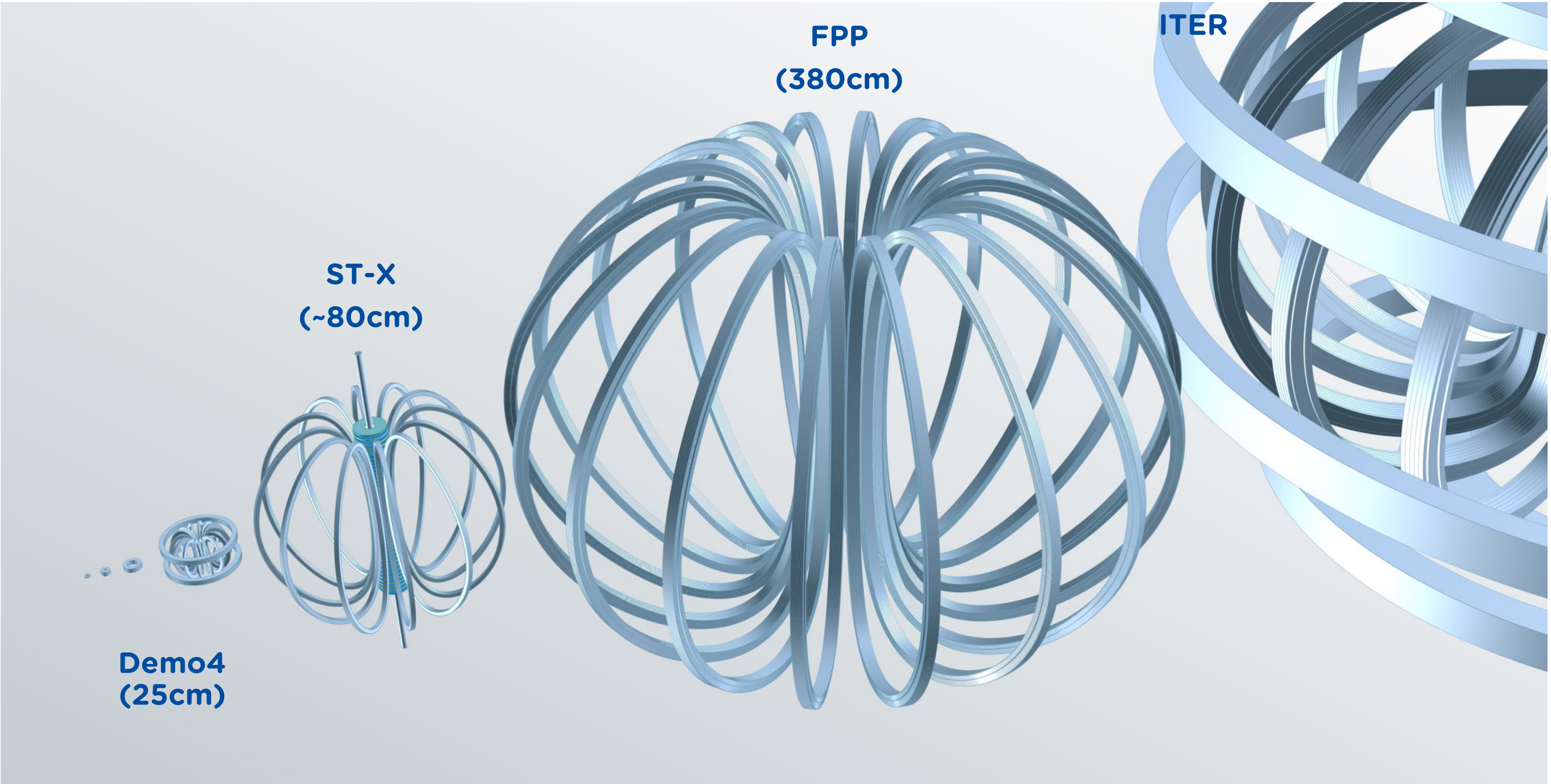
TE Magnet Sets: Size Comparison



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Focus on Irradiation

Gamma HTS Irradiation

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Gamma: Project Introduction

Project led by **Vicky Bayliss,** here with us

Motivation

- ~90% of energy imparted to REBCO in a shielded tokamak is in form of gamma rays
- Literature on gamma degradation is very limited and inconsistent
- [update 2023] UKAEA experiment (Chislett-McDonald et al) shows no effect under representative flux, up to low fluences (1-200 kGy)

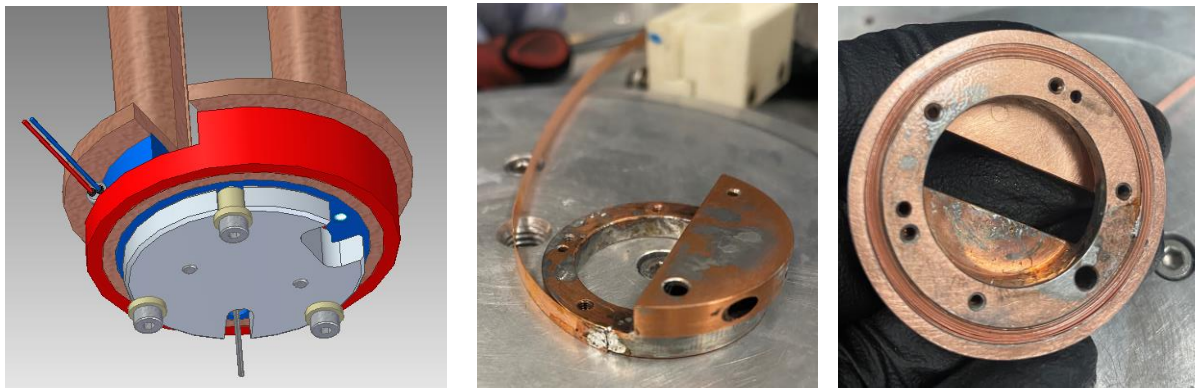
Aim

- Tokamak Energy's Gamma project measures the performance of REBCO coils, under gamma radiation up to doses of 10MGy at the Gamma Irradiation Facility at Sandia National Laboratories, USA
- 10MGy is well in excess of a 50 year lifetime dose; this is the first time HTS tape has been exposed to fusion-relevant doses of gamma radiation
- Coils to be held stable at fusion-relevant cryogenic temperature and carrying current at Ic throughout the exposure

Gamma: Experimental Setup

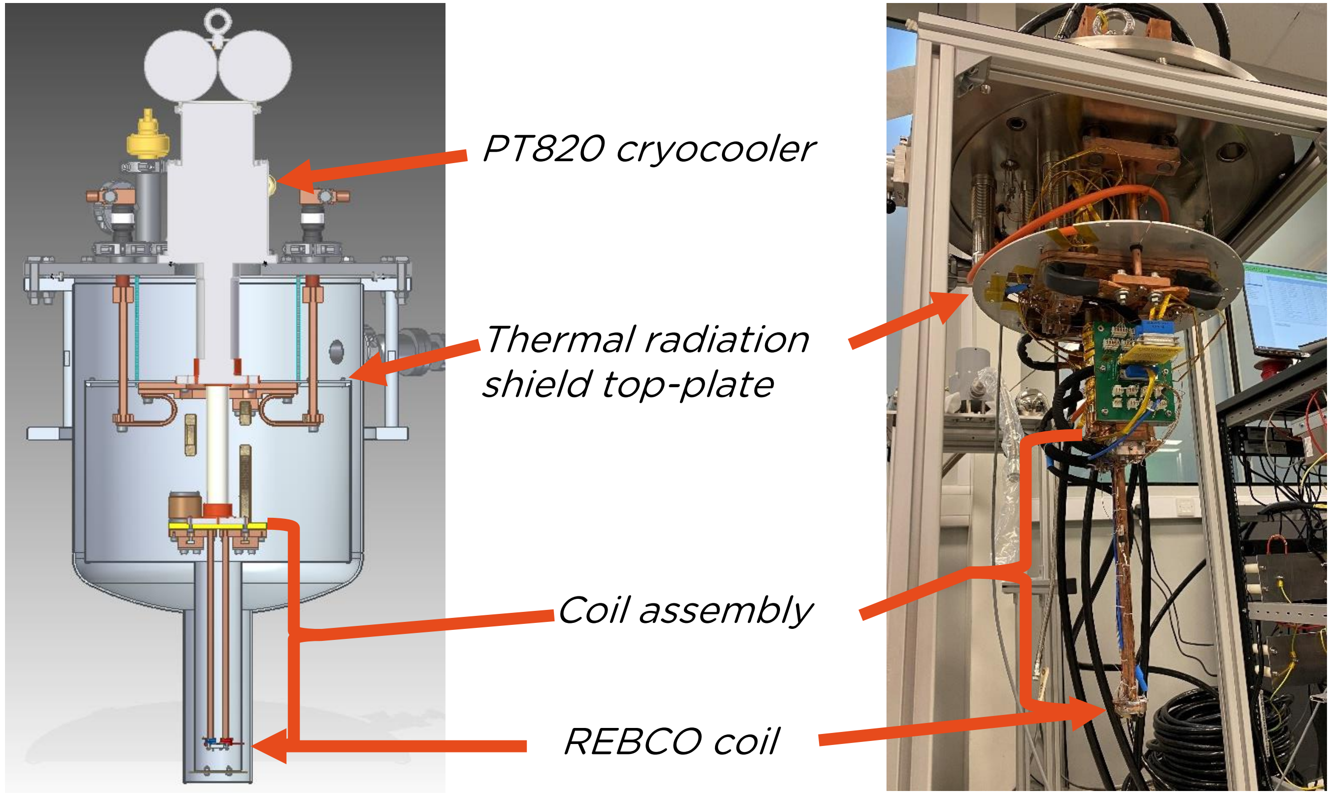
Coil Design

- 18 coils made with tape from key suppliers
- 4mmW x 1.6mm radial thickness (12-24 turns depending on tape)
- No insulation coil structure
- Ensures all turns are operating at or close to I_c and the entire coil is uniformly irradiated



Cryogenic System Design

- Cryocooled system
- 1 kA current capacity
- 20 – 50 K coil temperature (current dependent)
- Optimised current leads taking account of gamma heating along leads
- Voltage, temperature and magnetic field monitoring



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Gamma: System Commissioning at Tokamak Energy

Operating Regime

- Coil voltage monitored in real-time via voltage taps
- PID feedback loop adjusts coil current to maintain I_c
- B-field and temperature also monitored by numerous sensors

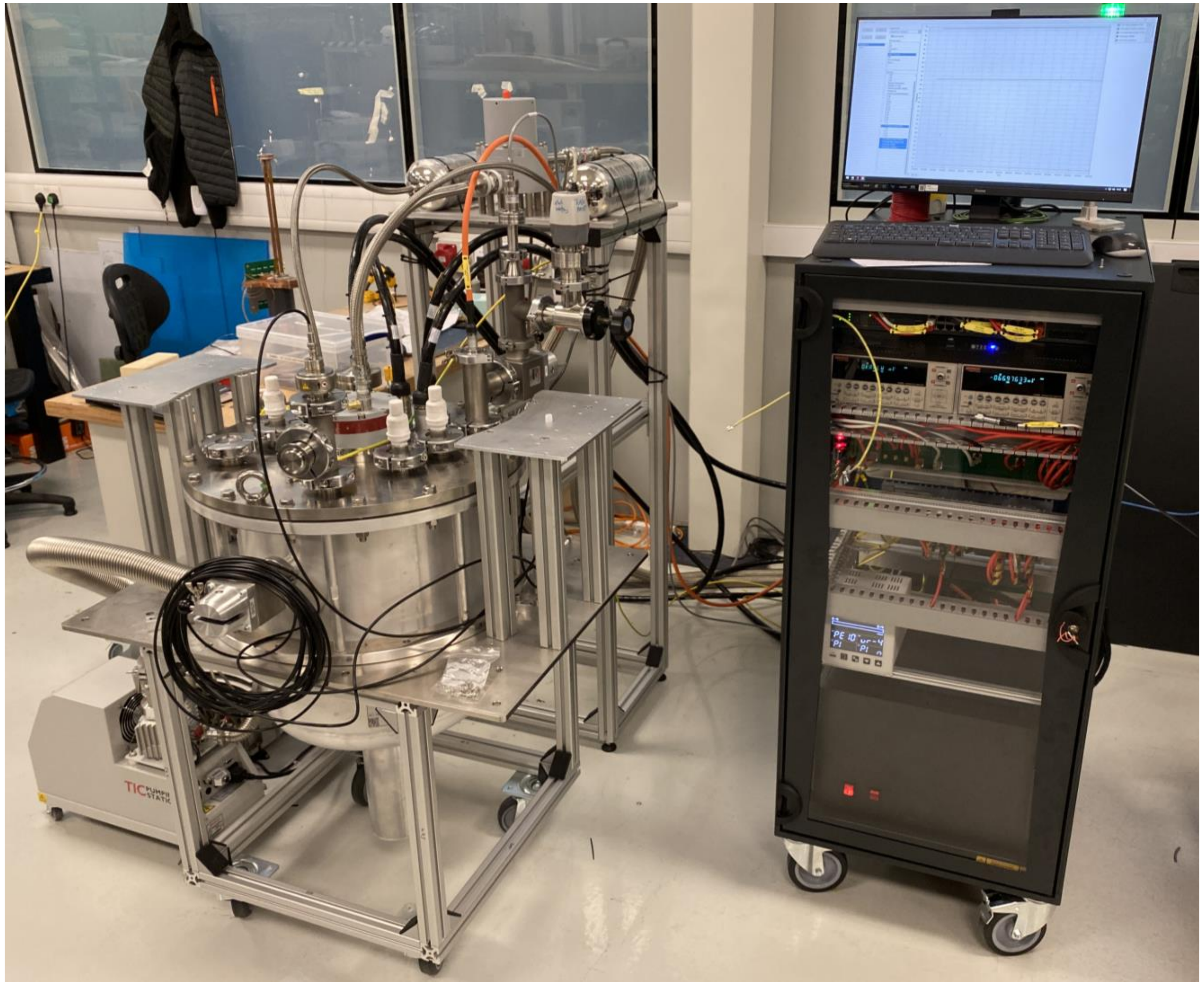
Commissioning

✓ System constructed

✓ Cryogenics and powering verified

✓ Software control proven robust

✓ Deconstructed and shipped to Sandia

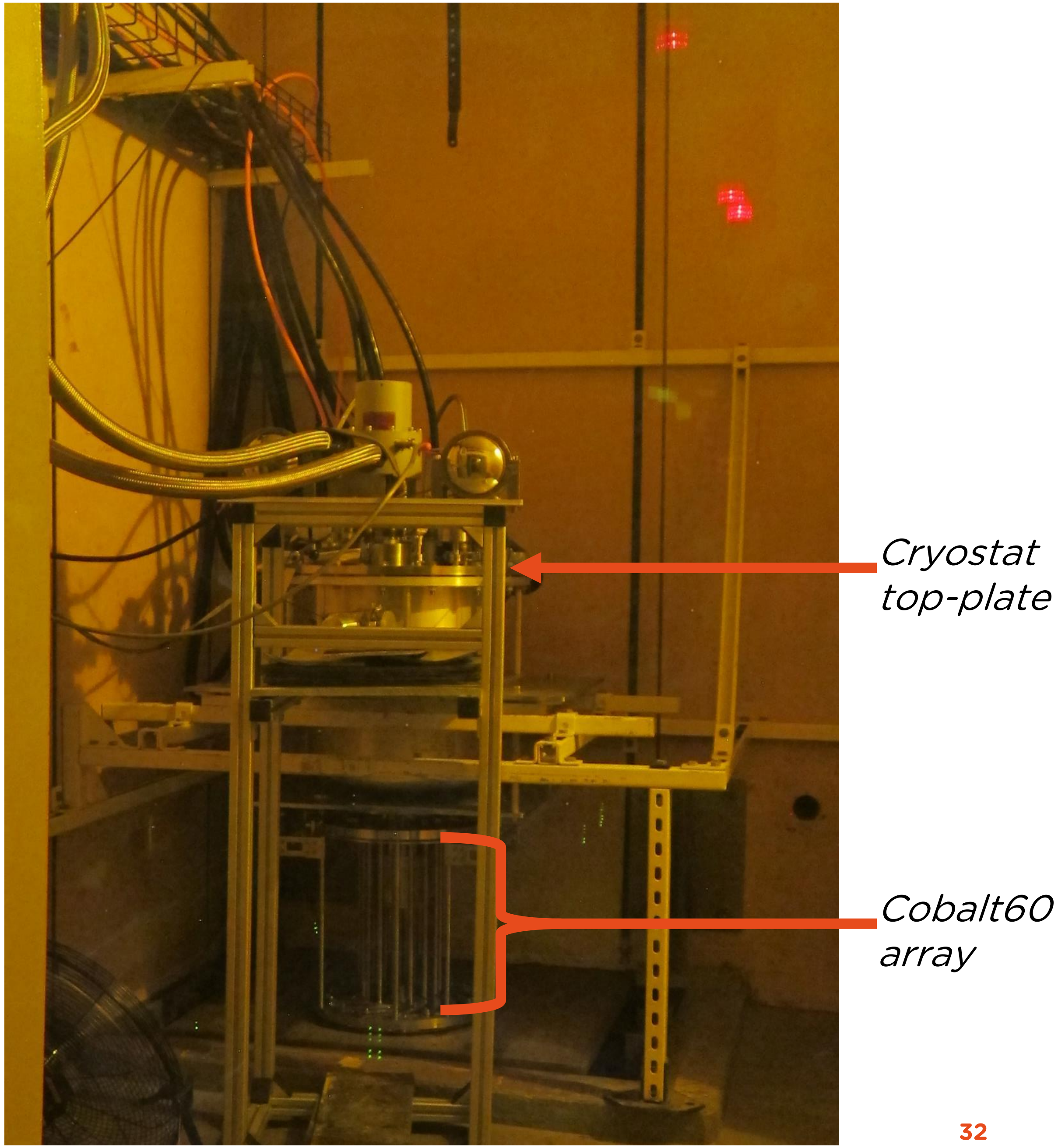


Gamma: Installation at Sandia

- ✓ System rebuilt and re-commissioned at Sandia
- ✓ Installed in hot cell

Test Protocol

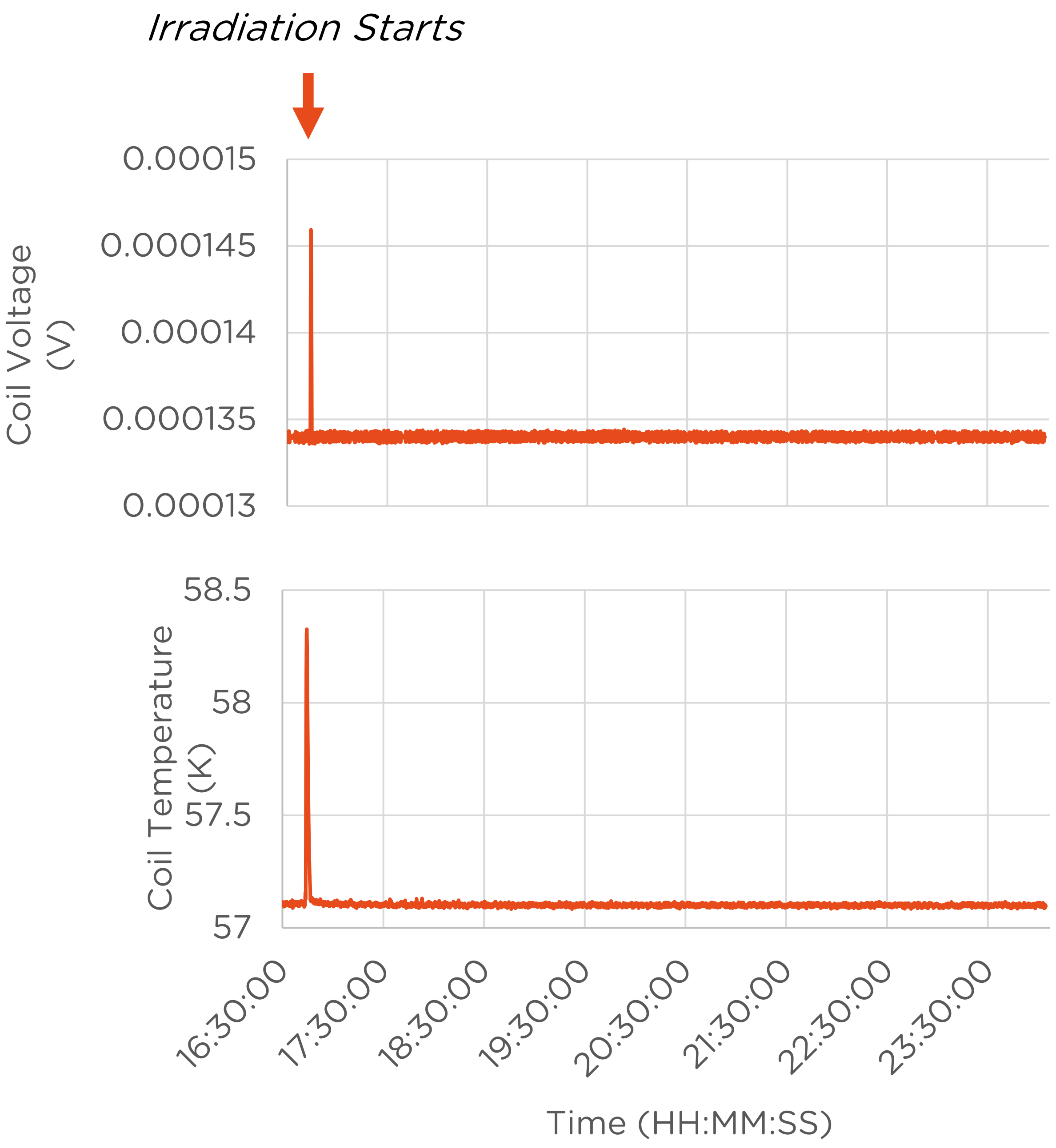
- Coil is cooled and energised
- Co60 array positioned to provide gamma dose at 7 Gy/sec
- System re-stabilises in reaction to heat load
- Irradiation continues for ~16.5 days to 10 MGy



Gamma

Experiment in progress

- ✓ System is working reliably under challenging operation conditions
- ✓ Key sensors working as expected
- ✓ Several coils irradiated to 10 MGy
- Testing continues



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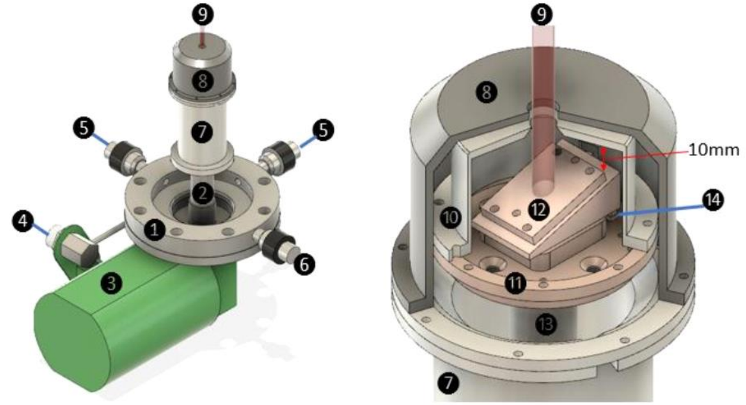
Focus on Irradiation

Supporting HTS Irradiation Science

Supporting Open Access Science on HTS Irradiation



- Supported Oxford University in developing *cryogenic* HTS irradiation and in-situ testing experimental capability
- Utilises He ions as a proxy for neutrons

- Supported Lancaster University in developing atomistic radiation damage simulations of HTS irradiation with neutrons
- Foundational principles now seeding wider work in community

Top level results indicate

- Cryogenic irradiation degradation progresses at similar rate to established ambient neutron irradiation results
- Ic recovery of ~30% is seen on warming to ambient
- A thriving field conducting very challenging experiments

W Iliffe *et al* 2021 *Supercond. Sci. Technol.* **34** 09LT01
R L Gray *et al* 2022 *Supercond. Sci. Technol.* **35** 035010

Concluding Remarks

- HTS Irradiation studies are extremely important for fusion device design
- Attaining fundamental understanding as well as engineering values is also key
- Cryogenic neutron irradiation facilities with in-situ testing capability coming online 2024/2025 may be transformational
- Don’t forget about shielding!
- Tokamak Energy are keen to continue working with this active community on this key topic

Full credit to the entire Tokamak Energy team for the engineering content of this presentation