IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Tokamak Energy

HTS magnets for Spherical Tokamaks

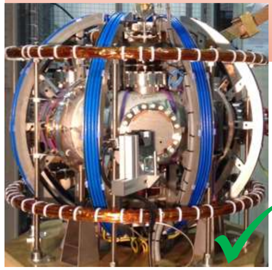
Dr Rod Bateman

5th December 2022

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

TE ST development time line

2014



ST25

ST25 Achievements
- ST Concept
- Plasma heating and current drive development

2015

ST25-HTS

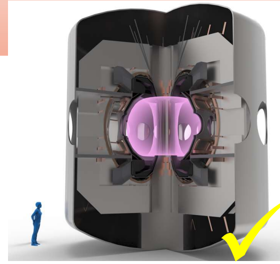
ST25-HTS Achievements
- First HTS TF coils
- H plasma held for 29 hours

2016 – on-going

ST40

ST40 Achievements
- Highest field ST worldwide at 2.1 T on-axis.
- 100M °C D-H plasma temperature
- On-going development programme

Build completion 2026



ST80-HTS

ST80-HTS Objectives
- Demonstrate long pulse operation
- Control and protection of mid-scale HTS magnets

Early 2030s

ST-E1

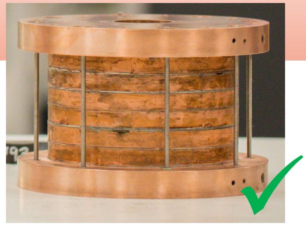
ST-E1 Objectives
- Up to 200MW of net electrical power
- Prototype energy generating ST
- Full scale HTS magnets
- Demonstrate plasma control and fault condition recovery at scale

2018

QA NI coils

QA NI Coils Achievements
- Tape QA
- Defect tolerant coils
- Robust jointing & ETI plates
- Modular magnet build

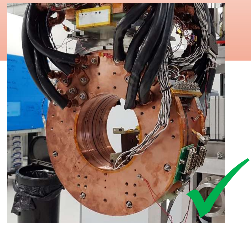
2019



Demo3

Demo3 Achievements
- First, conduction-cooled all REBCO magnet to exceed 22T (field on tape) at 20K

2020



Demo2

Demo2 Achievements
- PI development
- Validation of bespoke transient modelling tools (Racoon)
- Quench resistant
- Magnet dynamics very closely correlated to model predictions

2020 -2022

AMR WP4

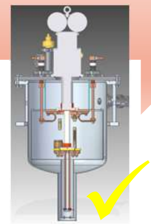
AMR Achievements
- Demonstrated cryogenic PSU technology
- Developed EFC coil design code
- Coil scale-up study
- Coil Cryogenic Compression System designed and built
- Quench modelling code developed and validated

2019 - 2023

Demo4

Demo4 Objectives
- Demonstrate PI for TF coils
- Operation of balanced set of TF coils
- Explore transient control and losses in PF coils
- Explore PF field shine on TF coils
- Quench protection and energy dumping trials

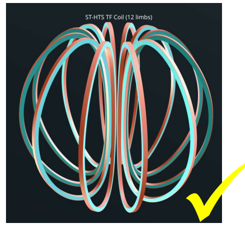
2023



Gamma

Gamma Objectives
- Irradiate small test coils wound from selected REBCO tapes
- Co60 irradiation up to 10MGy dose.
- Coils are cooled to 20K and energised to Ic
- Ic degradation measured in real time

2022 - 2026



BB01

BB01 Objectives
- Developing prototype coils for ST80
- Developing coil manufacturing processes and tooling
- Developing magnet assembly processes and tooling

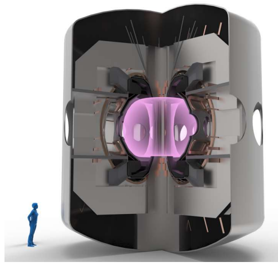
TE ST magnet systems technology development roadmap

REBCO conductors
- $I_C(B,T,\theta)$ surface FLF
- Tape construction FLF/AMR
- QC: I_C variability QA/Demo3
- Supplier capability FLF

Cable & coil design
- Current sharing / I_C dropout resilience QA/FLF
- HTS/Cu distribution AMR
- Cooling & insulation BB01
- AC loss Demo4/BB01

Coil Manufacture
- Process dev Demo4/BB01
- Tooling dev Demo4/BB01
- Jointing FLF
- Resistance / heat load contribution Demo4

Quench protection
- Current sharing / pre-quench model QA/Demo3
- Hot spot detection
- Energy dump AMR



Mechanical design AMR/BB01
- Coil geometry
- Forces / stress / strain
- Assembly sequence

HTS degradation
- Neutron damage FLF/BB01
- Gamma damage GAMMA
- Fatigue BB01

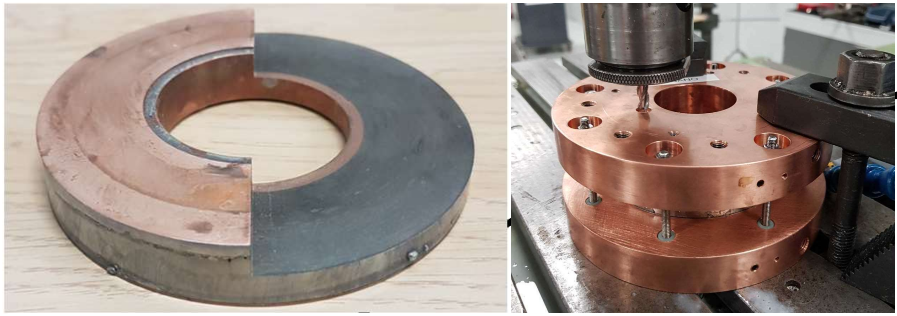
Power supplies BB01
- Current leads AMR/BB01
- Dump circuit AMR
- Cryogenic PSU

Cryogenics
- Neutron heat load Demo4
- Joint heat load FLF/Demo4
- AC loss Demo4/BB01
- Suspension ST80
- Vacuum vessel ST80

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

No-Insulation Coils Overview

Intentionally Damaged Coils

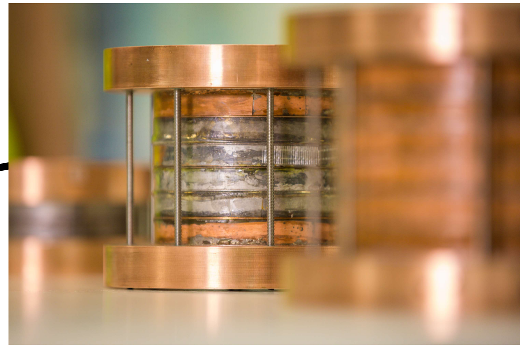


Operate stably despite gross damage

Solder Consolidated *QA* Coil

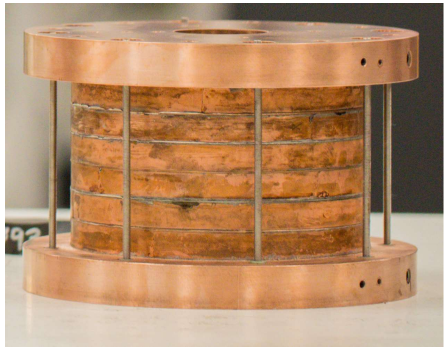
Compact, robust, modules with "ETI" Plates

Mixed supplier coil stack



>16.5 T re-mounted QA coils

***Demo3* HTS Magnet**



World First >20 T @ >20 K

Key Demonstrations

- Solder Consolidated HTS Coils
  - ✓ Proven robust and defect tolerant.
  - ✓ Enable low loss current sharing.
  - ✓ Reliable re-mountable joints.
  - ✓ Thermally stable, conduction cooled
- HTS Conductor Performance
  - ✓ Commercial tape evaluated in real coils up to B > 20 T @ 20 K.
- HTS Magnet Quench Testing
  - ✓ No spontaneous quenching.
  - ✓ Bespoke modelling tools validated.

Fusion Advancements

- Cable and Coil Design
- Coil Manufacture
- REBCO Conductors
- Quench Protection

Demo2: PI Coil Overview

Demo2 Magnet on Test

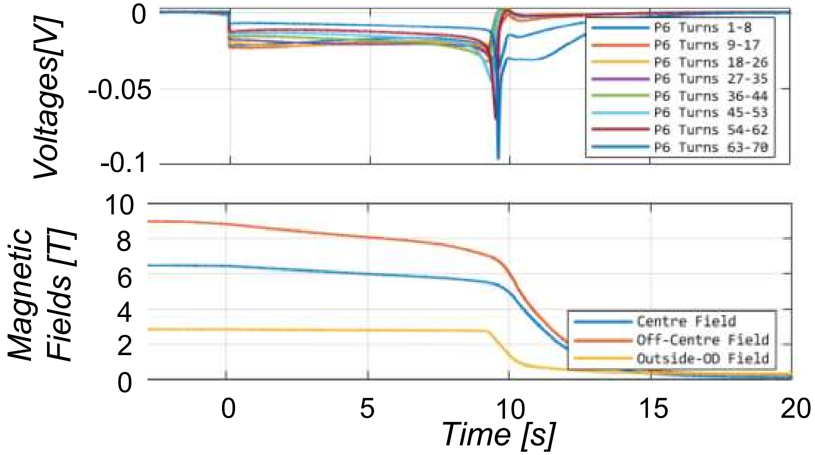
Highly Instrumented

Multi-Tape Winding

Incorporating Partial Insulation

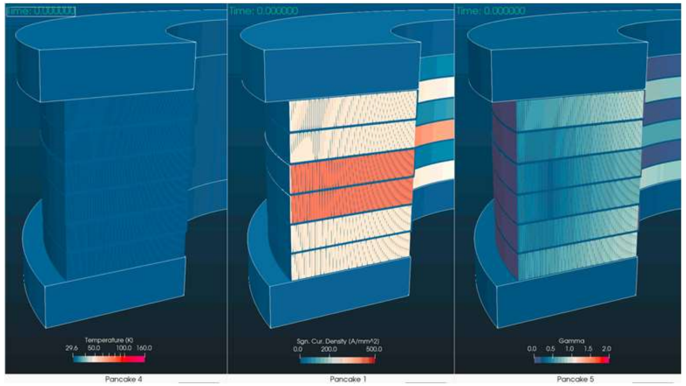
Forced Quench – Measurement Data Subset

Quench propagation captured



Forced Quench – Simulation Movie

Temperature *Current Density* *% I_c*



Real behaviour reproduced

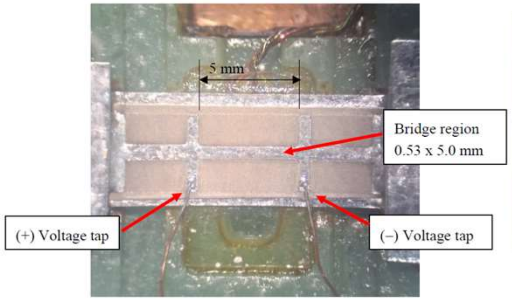
Key Demonstrations

- PI Coil Design and Fabrication
  - ✓ Designed by modelling to be quench-safe.
  - ✓ Tuneable PI implemented.
  - ✓ Modular, cond-cooled design maintained.
- Proven benefits of HTS + PI
  - ✓ No spontaneous quenching.
  - ✓ Stable against **>40 J** heat pulses.
  - ✓ No degradation from forced 200 kJ quenches.
  - ✓ Peak quench voltage limited to <0.1 V.
  - ✓ Quench models proven.

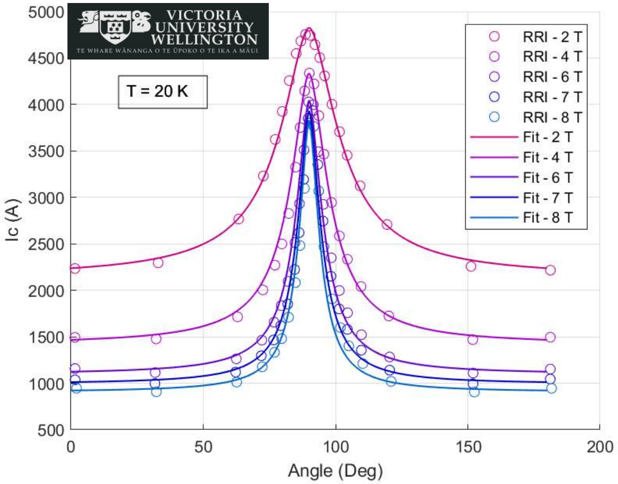
Fusion Advancements

- Cable and Coil Design
- Coil Manufacture
- Quench Protection

FLF – HTS Tape Quality

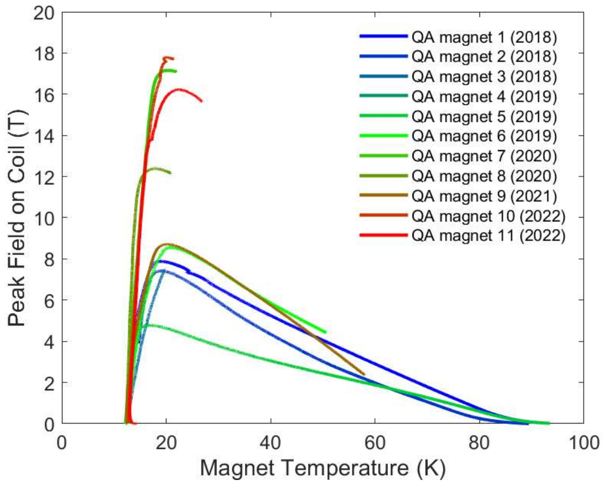


Short Sample Transport Data



I_c(B,T,θ) and fits up to 8 T from >70 km full width HTS.

QA Coils & "Saturated Mode"



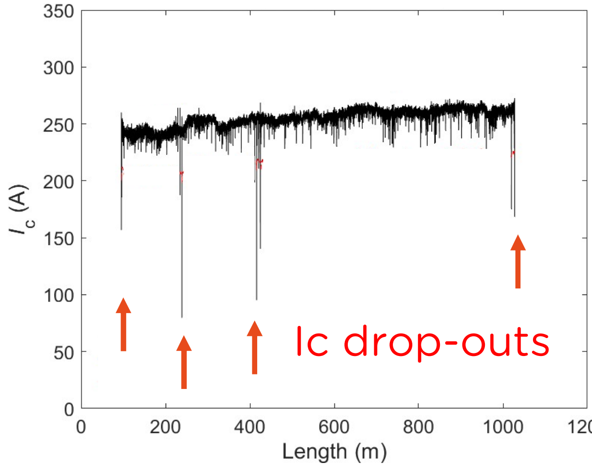
"Integral" verification of ~100m pieces.

Key Demonstrations

- ✓ Evaluation of tape from all major suppliers.
- ✓ I_c(B,T,θ) database with fits + statistics.
- ✓ Fits & extrapolation from 8 to >20 T de-risked by coil testing and simulation.
- ✓ Knowledge gained enables us to use tape containing dropouts – **Yield ↑ Price ↓**.
- ✓ ST80 specifications defined.
- ✓ **Today's HTS conductors are good enough for fusion.**

- ○ Pursue rapid and cost effective QA supporting HTS scale up.

Reducing quality demands



Defect-tolerant HTS magnets can utilise imperfect tape.

Fusion Advancements

- REBCO Conductors
- Cable and Coil Design

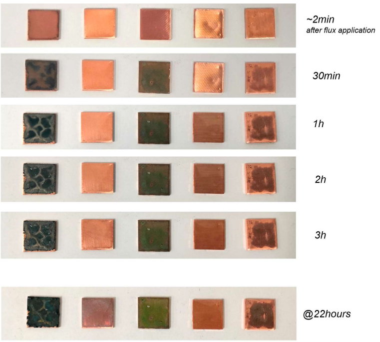
UK Research and Innovation

FLF = Future Leaders Fellowship

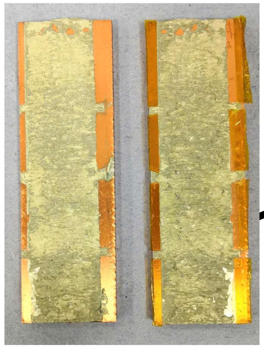
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

FLF - HTS Magnet Joints

Solder(+) Metallurgy R&D

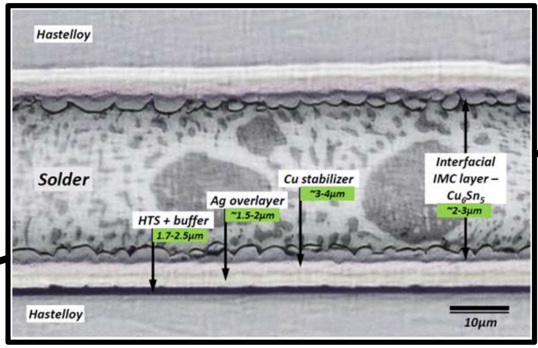


Flux Selection



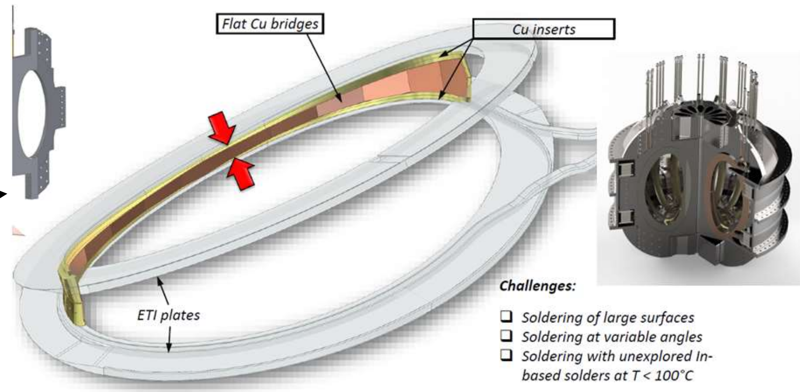
Jointing

Microscopy



Microstructural evaluation

Techniques Deployed on Magnet Builds



Must be practical, reliable, serviceable, and meet heat load requirements.

Cryo Test Rig / Tensometer

>8 K, 1 kA

Mech Robustness

Key Achievements

- ✓ Joint development facility established at Tokamak Energy.
- ✓ Successfully delivered joints for all coil builds up to Demo4.
- ✓ Developed solder potting techniques for all coil builds up to Demo4.
- ✓ Developed novel coil fabrication techniques for fusion and other applications.

- ○ Develop joints for ST-80 and ST-E1 magnet systems.

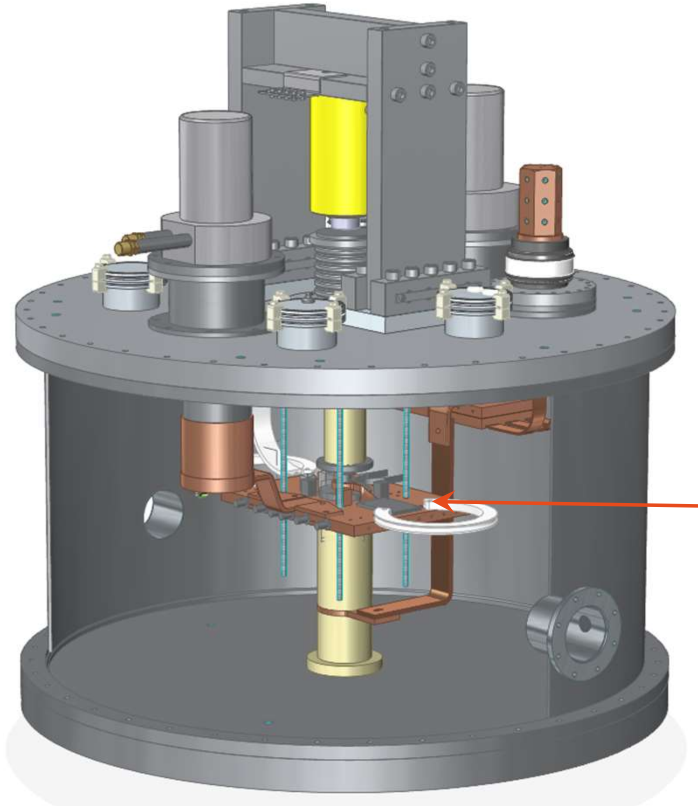
Fusion Advancements

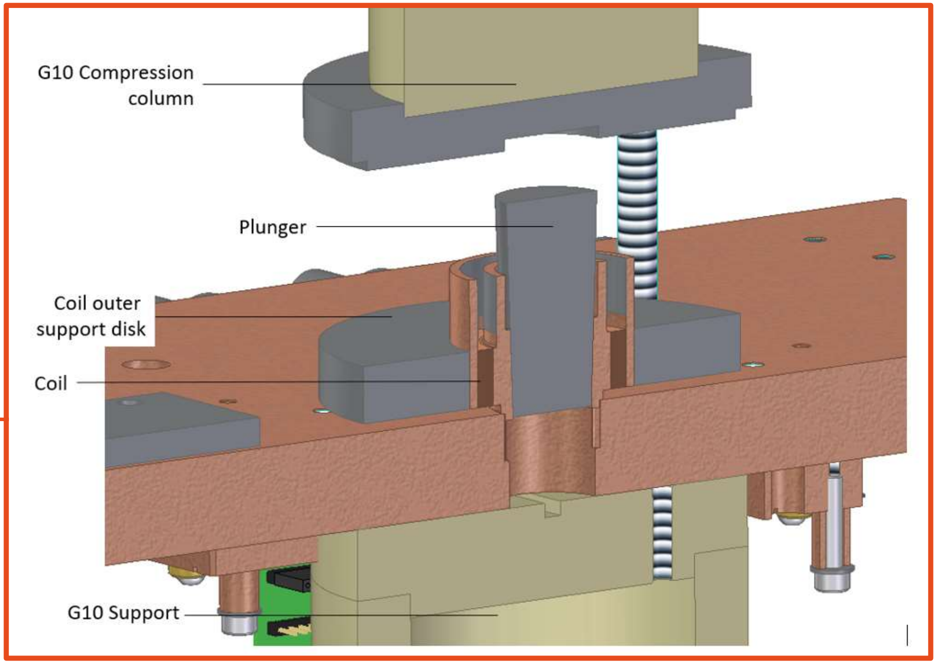
- Cable and Coil Design
- Coil Manufacture
- Cryogenics

UK Research and Innovation

FLF = Future Leaders Fellowship

AMR: WP4.4 Cryogenic coil compression system (CCCS)





CCCS platform (below)

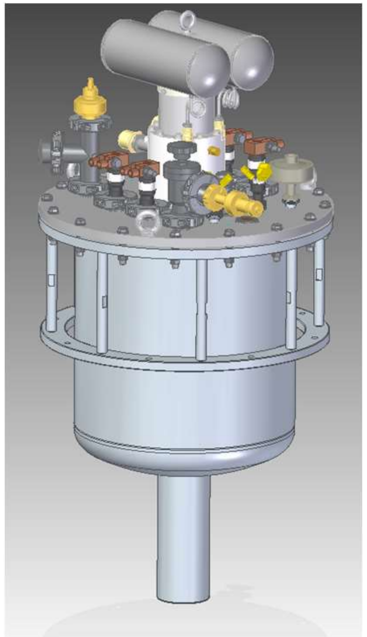
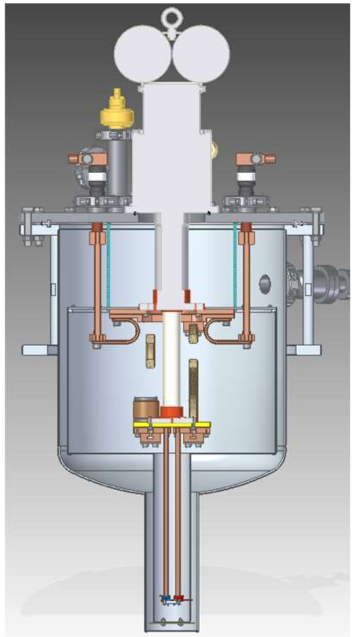
- System is complete including instrumentation rack.
- System commissioning in progress.
- Initial measurements in-progress.

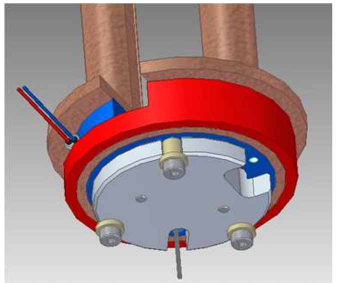
CCCS – Apply radial compression to energised REBCO test coils at 20K.

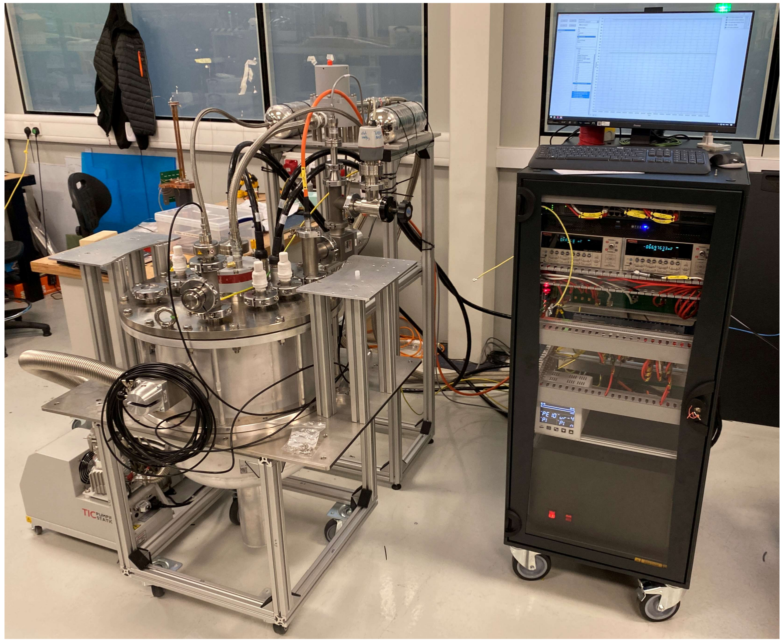
- System to apply up to 500MPa of compression onto cold and energised HTS tapes wound into small test coils. System designed and built in-house.
- Coils instrumented with strain gauges, FBG's, voltage taps and temperature sensors.
- This will show the degradation of HTS tapes under compressive stress in real time and in representative conditions.

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

GAMMA

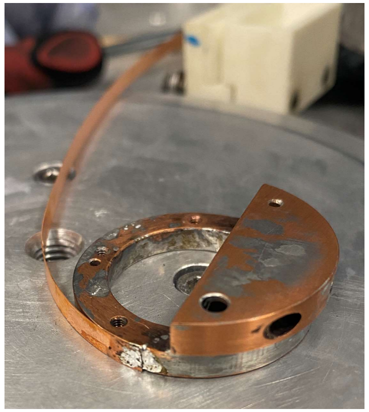




Irradiate REBCO coils using ^{60}Co sources.

- Irradiate coils at operating temperature (20 – 30 K).
- Temperature controlled via PID loop.
- Coils energised to I_c.
- Coil pack radial thickness limited to 1.6mm (12 to 24 turns depending on tape) to ensure all turns are operating at or close to I_c and Gamma radiation will penetrate the coil.

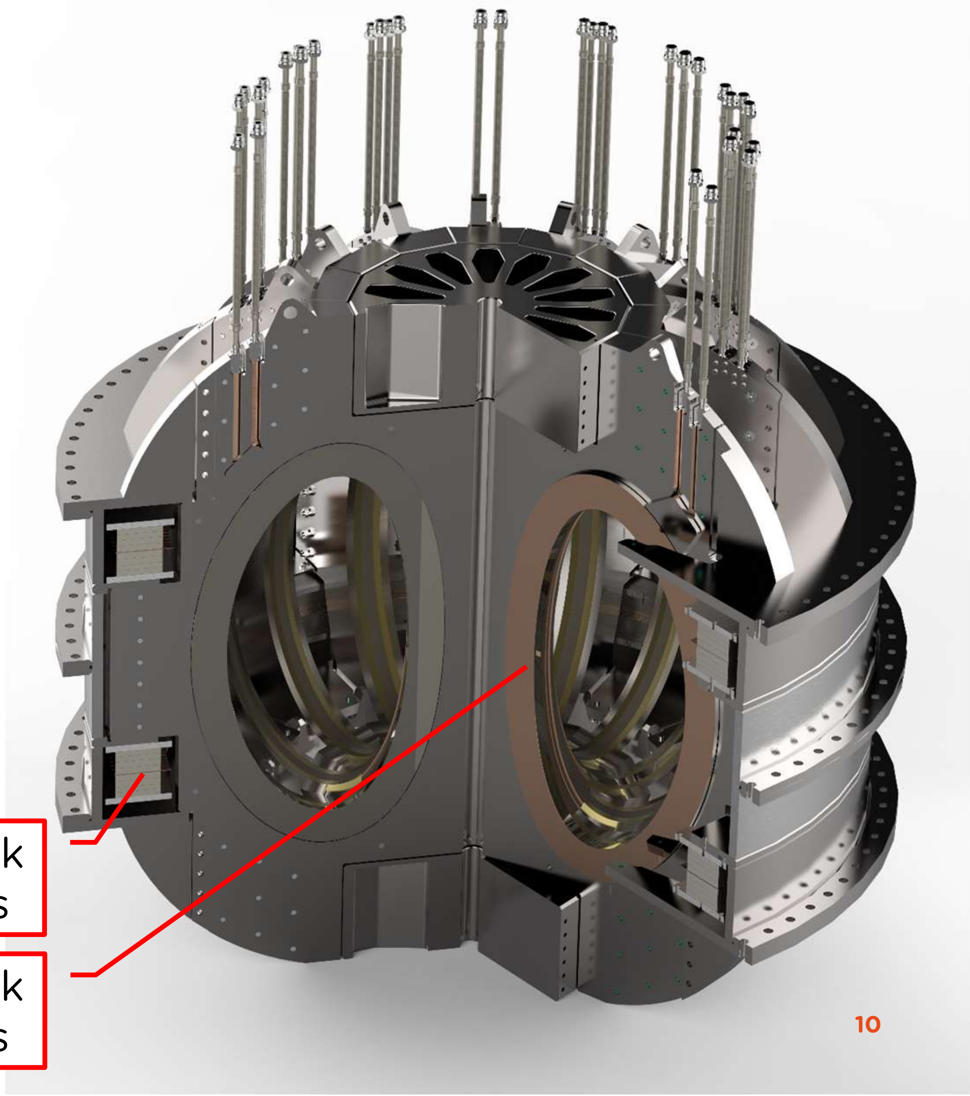
- Monitor any degradation of I_c in real-time via voltage taps during gamma irradiation up to a dose of 10 MGy.
- Feed-back loop to adjust coil current.
- Monitor B-field in real-time via Hall probes.
- Monitor coil temperature in real-time via cernox, PT-100 RTD's and thermocouples.
- Test coil (18x) fabrication in progress
- System commissioning in progress



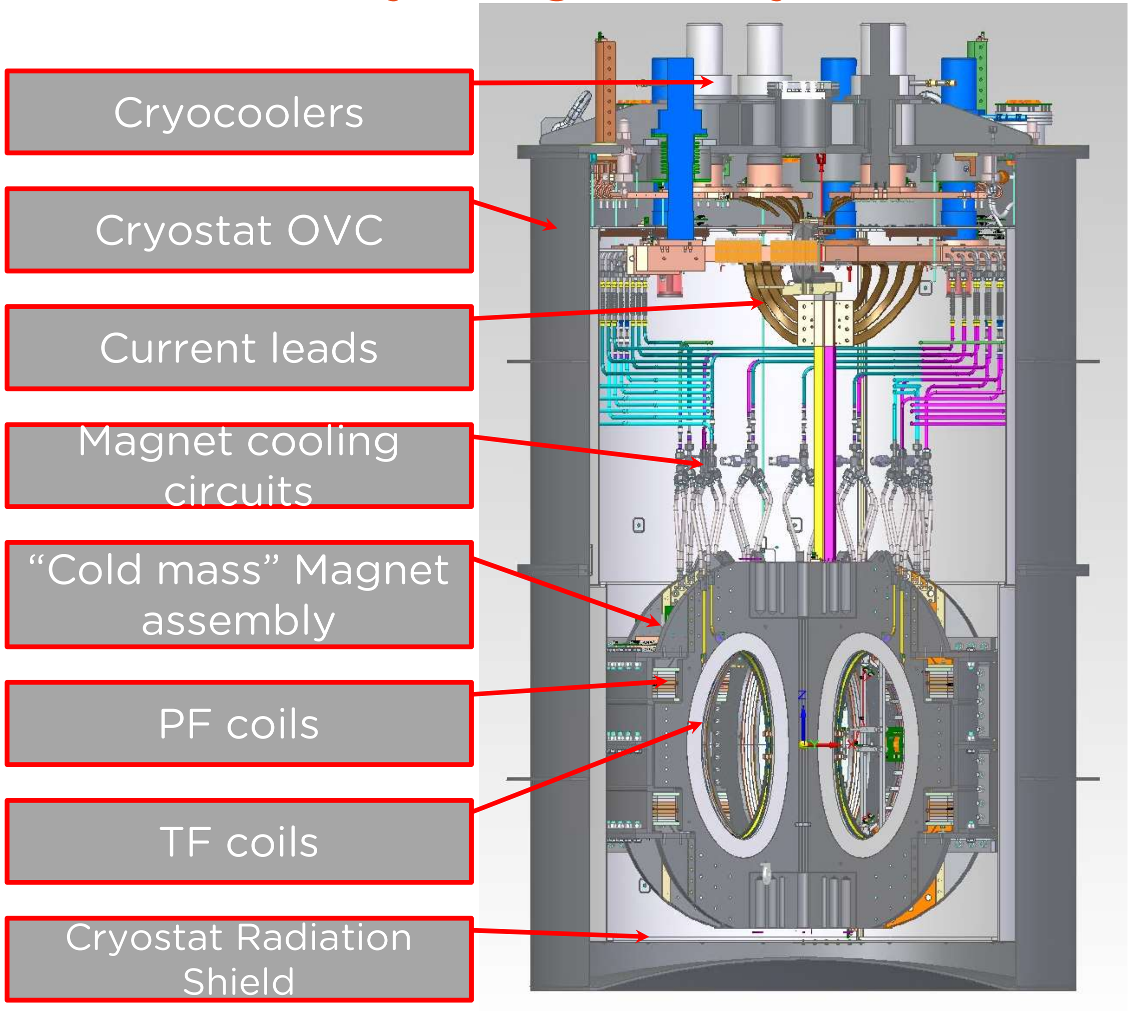
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Tokamak HTS magnet set: Demo4

- Develop ST80-HTS relevant magnet technology
- Demonstrate operation of a set of balanced TF limbs (14 limbs, 28 REBCO coils).
- Demonstrate representative compressive stress in centre column.
- Demonstrate coil protection at 16.5 MJ of stored energy.
- Demonstrate Partial Insulation system in TF coils.
- Explore the effects of PF field shine on TF coils.
- Simulate fusion pulse heat loads on the centre column.
- TF construction:-
  - Non-twisted, partially insulated stacked tape cable
  - 2 pancakes per TF limb, ETI jointing
  - 1 cooling loop per coil
- PF construction:-
  - Non-twisted, fully insulated stacked tape cable with additional Cu for stabilisation
  - 8 pancakes per PF stack, edge jointing
  - 1 cooling loop per stack

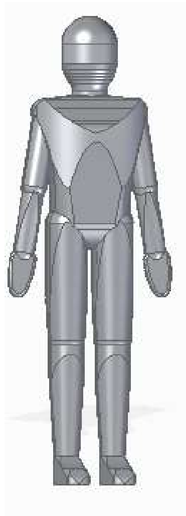


Demo4: Cryomagnetic System



Demo4 is a conduction cooled, cryogen free, HTS magnet test bed.

- System is cooled by 10 closed-cycle cryocoolers
- Magnet sets operate in vacuum
- Magnet "cold mass" is cooled by pressurised helium cooling loops driven by 3 cryofans.
- Helium circulates through coil cold plates then back to the heat exchanger.



The Demo4 TF magnet consists of:-

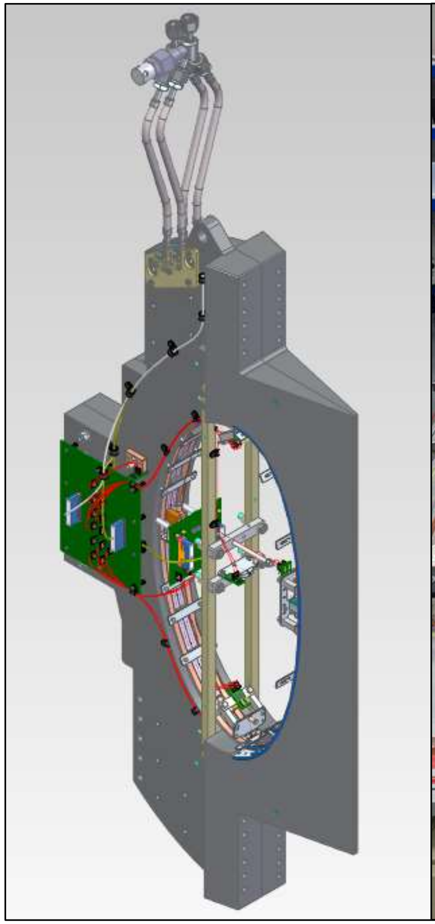
- 14 limbs – each limb contains a double pancake wound from REBCO HTS.
- TF coils use partial insulation coil pack technology

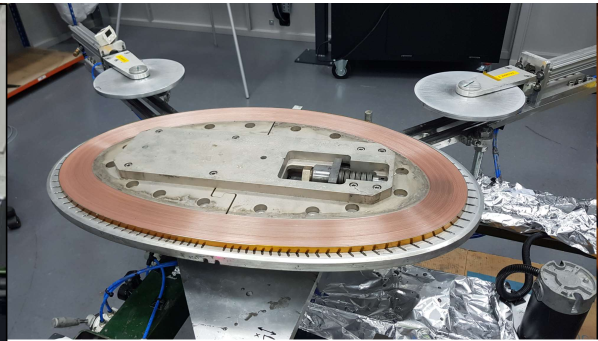
The Demo4 PF magnet consists of:-

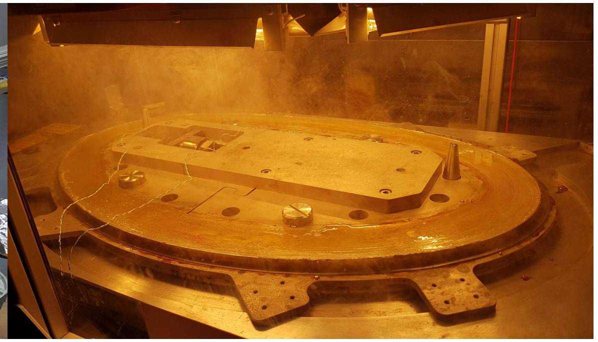
- A pair of flow cooled PF coils – each coil contains 8 pancakes wound from REBCO HTS
- PF coils are fully insulated with stabilised coil pack technology

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Demo4: Coils - Winding and Impregnation Tooling



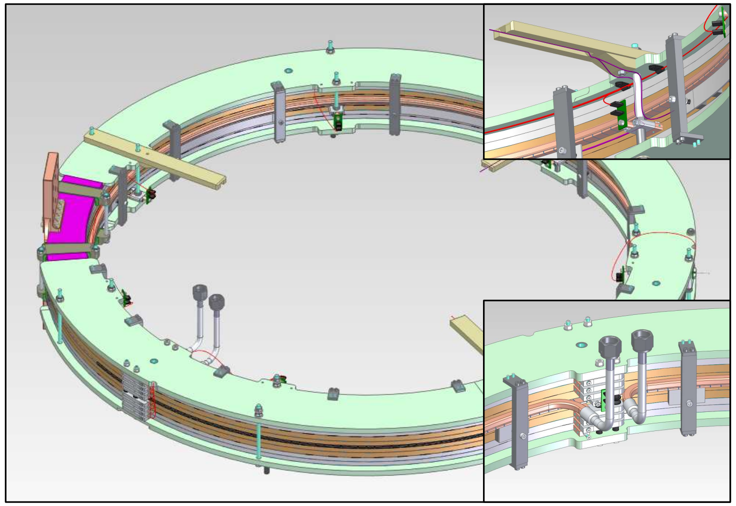


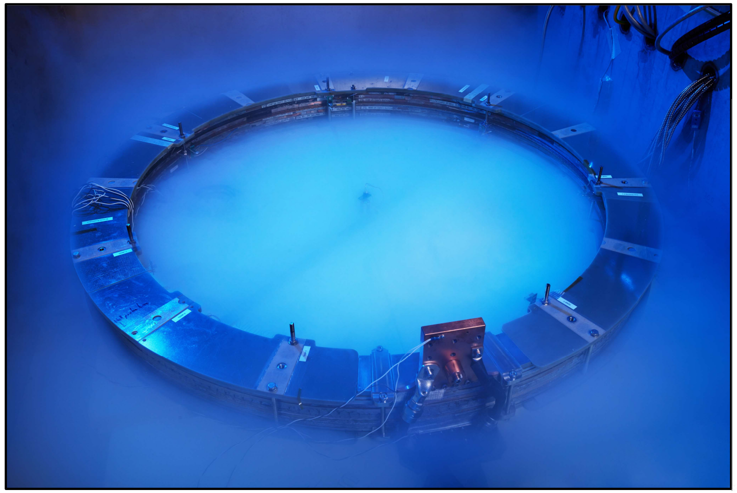


TF Coils: Winding and impregnation tooling

- Design model of assembled and instrumented TF limb. Contains 2 TF coils plus ETI plates, cooling loops and clamshells.
- The bespoke developed winding table is shown on the left. This incorporates separate tension control for each individual tape
- The winding mandrel and compression wheels are shown in the centre picture above. Angular rotation speed must be continually varied in order to provide almost linear tape speed for accurate tension control.
- Coil impregnation in progress within the glass cabinet topped with a fume extractor.
- Coil production: More than 50% of TF coils manufactured.

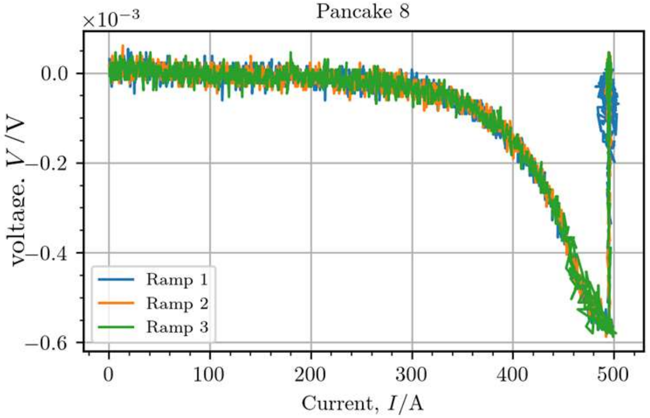
Demo4: PF coils

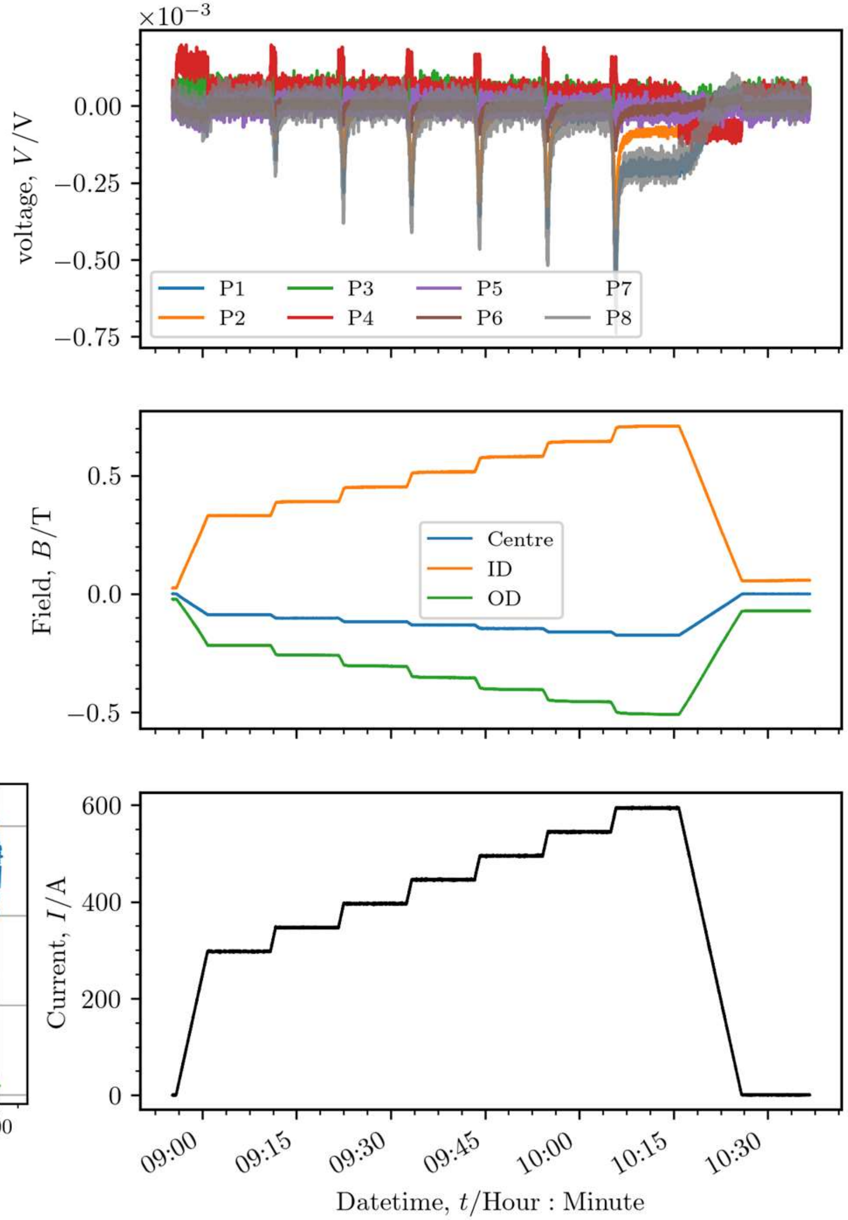




Demo4 PF concept design (top left).
PF Coil stack#1 on test in LN2 bath (bottom left).
Plots showing Coil voltages, Magnetic field, PSU current (right).

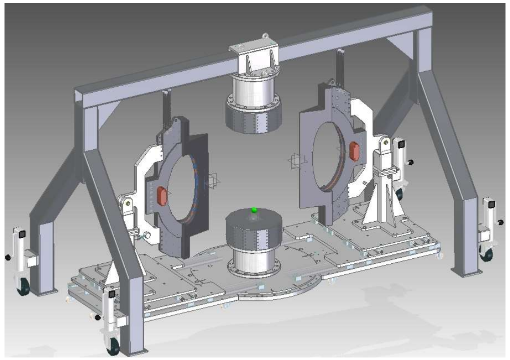
- Demo4 PF stack – 1.2m diameter, 8 coils, 1.1 MAt.
- Insulated coil wound with additional Cu for AC loss dissipation absorption and quench protection.
- Coils wound with backing wire for ramp voltage offset.
- ✓ LN2 tests indicate HTS is not degraded by coil manufacture.





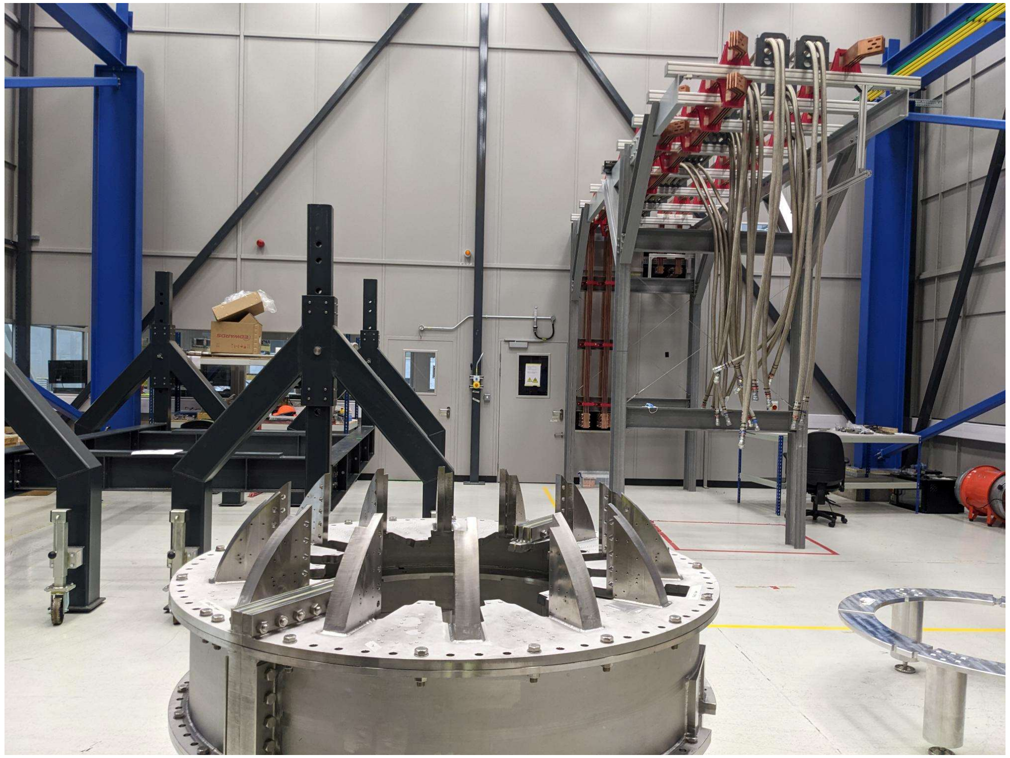
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

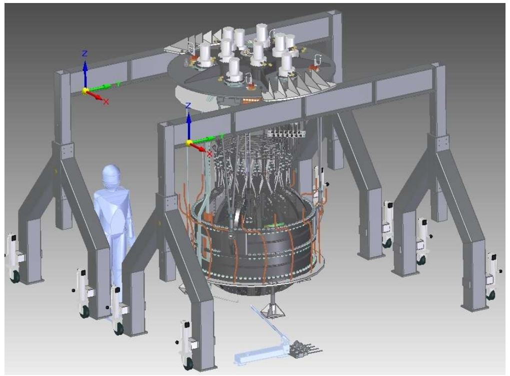
Demo4: Assembly Tooling - Test lab progress

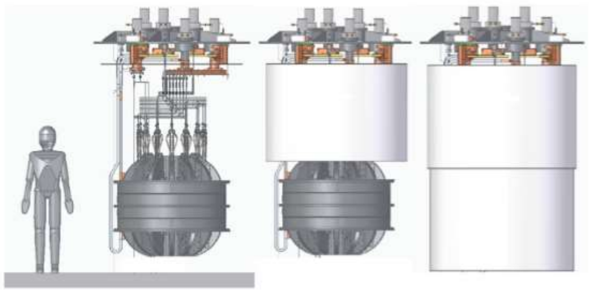


TF limb assembly tooling

- TF limbs precision assembly jig enables rotation of the limb jacks to place limbs in opposing pairs around the spider structure (top left)
- Top plate support stands enable assembly of the cold mass on its suspension structure (bottom left).
- Assembly sequence of the radiation shield (bottom centre)
- Plant room housing the PF power supply modules and the cold head compressors (top right)
- Demo4 "tokamak" hall showing the cold mass chassis, busbars, high-pressure lines and the assembly tooling (bottom right).







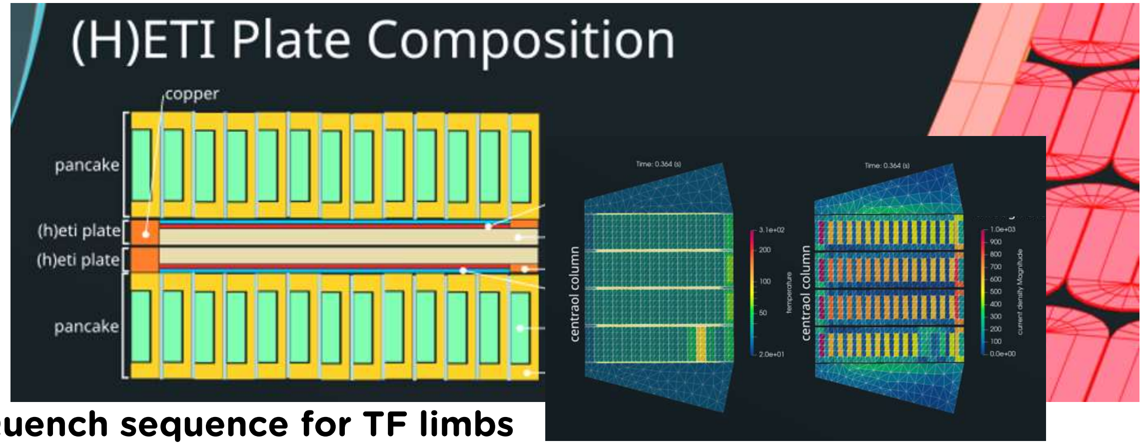
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

AMR – BB01: Quench Analysis of large HTS TF magnets - Raccoon

Little Beast engineering

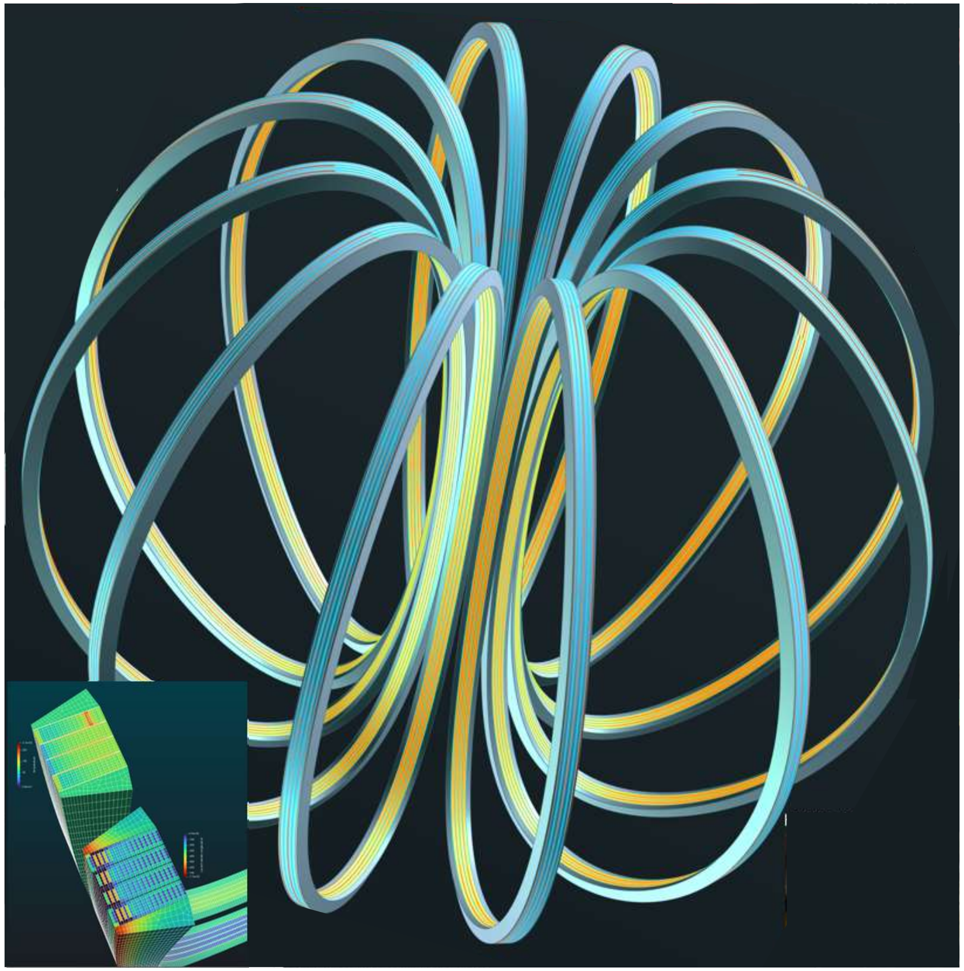
Tape in Cu channel

- Coil structure developed further from Demo2 and Demo4 TF concept.
- Higher stored energy of ST80-HTS (and ST-E1) coils requires more thermal mass in the coil pack.
- Cu U-channel structure enhances current sharing between multiple tapes to maintain coil robustness.



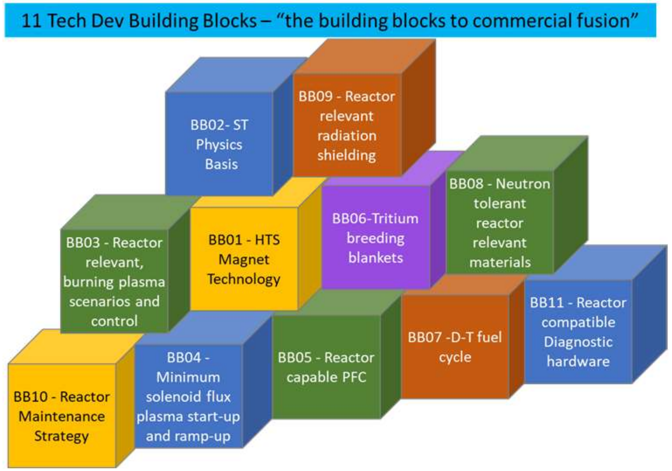
Quench sequence for TF limbs

- In the analysis, a quench heater is fired in one coil in the centre column of one limb.
- The quench is detected at 100mV after approximately 100ms. The circuit breaker is opened forcing the current radially through the PI, which is in intimate thermal contact with the HTS coil.
- The PI (heater) uniformly heats the limbs driving the transport current from the HTS into the Cu U-channel.
- The magnet energy is converted to heat with the coil temperature peaking at 250K and evenly distributed.
- The limb voltage doesn't exceed 250V, so the 12-limb TF set of ST80-HTS does not exceed 3kV S-E voltage.



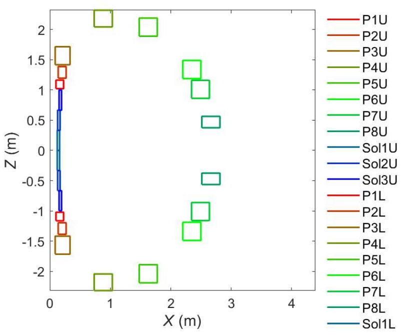
ST80-HTS TF limbs, 4m coils, 12mm tape.
4 coils +2 Cu wedge plates per limb

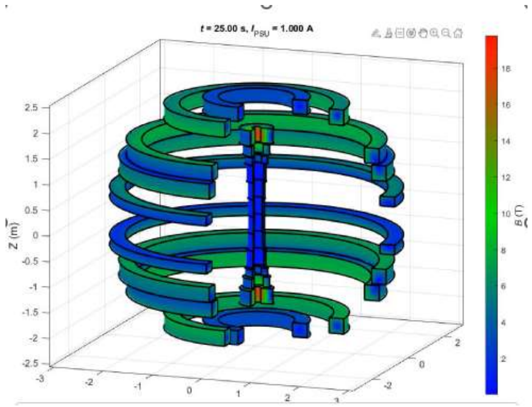
Building Blocks – BB##

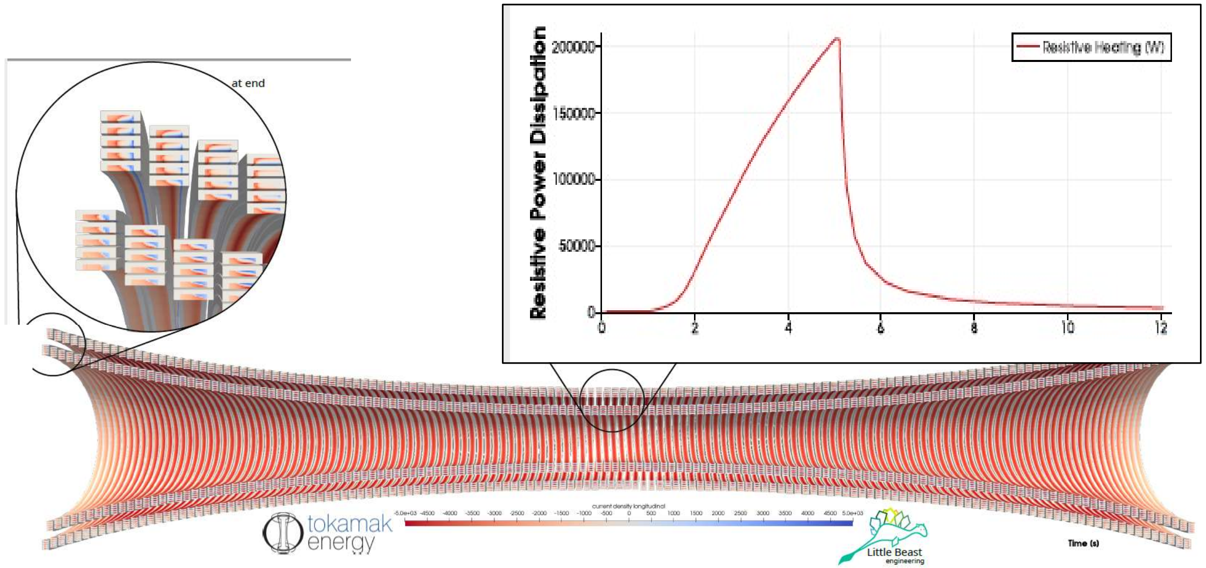


BB01 – Magnet Development

- Developing TE HTS magnet technology to support ST80-HTS and beyond.
- Prototyping ST80-HTS coil structures and manufacturing tooling for:-
  - TF coils.
  - CS coils.
  - PF P1-3 coils.
  - PF P4-5 coils.
- Developing magnet control and protection systems for the ST coil types







IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

ST80 Building Blocks supporting each coil type…

What have previous projects delivered to ST80 coils?

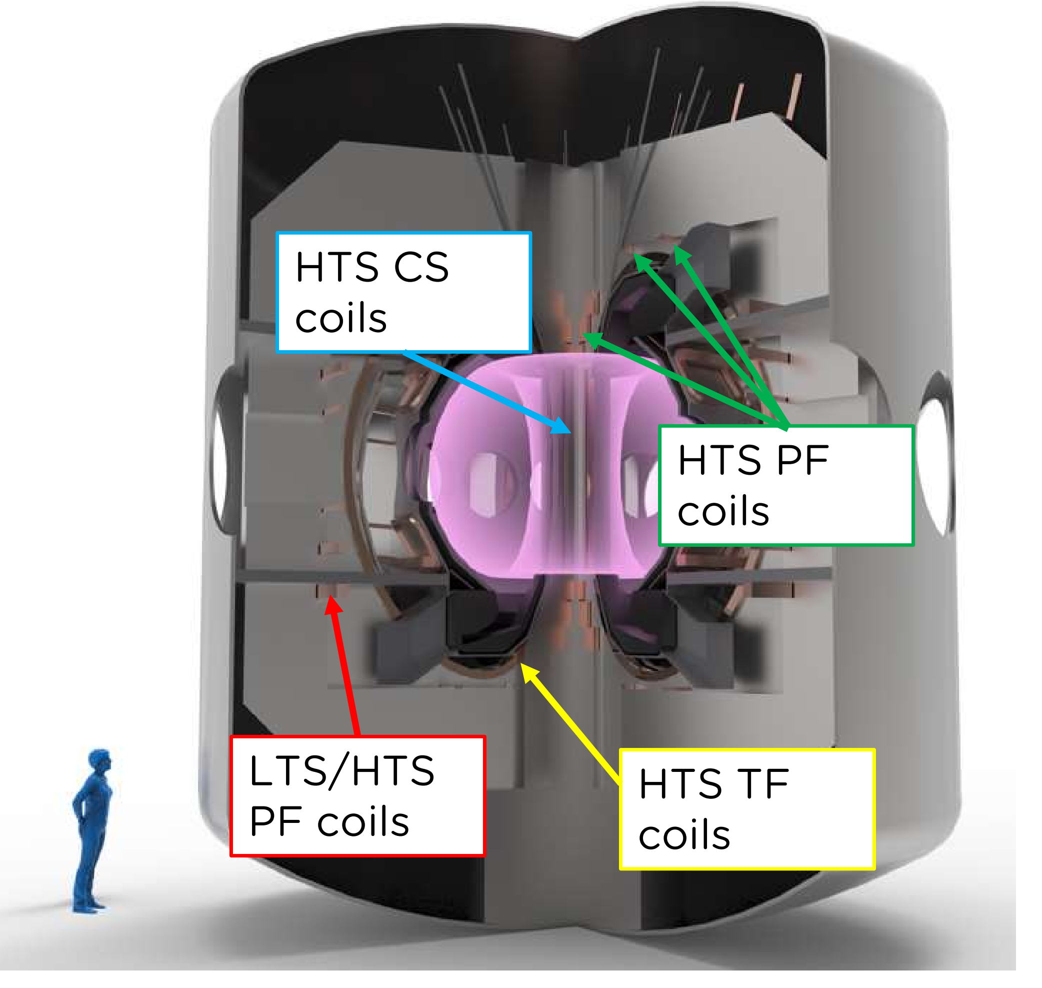
- NI - coil structures, current sharing, defect tolerance
- Demo3 – REBCO performance in high-field at 20K
- Demo2 - PI Passive protection within coil pack structure
- FLF – Tape characterisation, definition of a quality standard
- LBE RACCOON - Quench modelling coil structures

What will current projects deliver to ST80 coils?

- FLF – Optimised low-resistance jointing
- Demo4 – Operating and protecting a balanced set of coils and coil interaction effects
- GAMMA – real-time tape degradation when cooled and energised
- CCCS – Radial compression of coil packs up to 500MPa when cooled and energised

What will the BB01 program deliver to ST80 coils?

- Scaled-up coil manufacturing processes and tooling
- Designs for CS and PF (P1-P3) coils packs
- Designs for PF (P4 & P5) coils packs
- Designs for PF (P6-P8) coils packs
- Designs for EFC coils
- Prototypes of all coils



IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This invited presentation AP8-1 was given at the 35th Annual International Symposium on Superconductivity (ISS 2022), 29 November - 1 December 2022, Nagoya, Japan (Hybrid).

Thank You!