Tokamak Energy

High-Temperature Superconducting Magnet Technology for Fusion Energy

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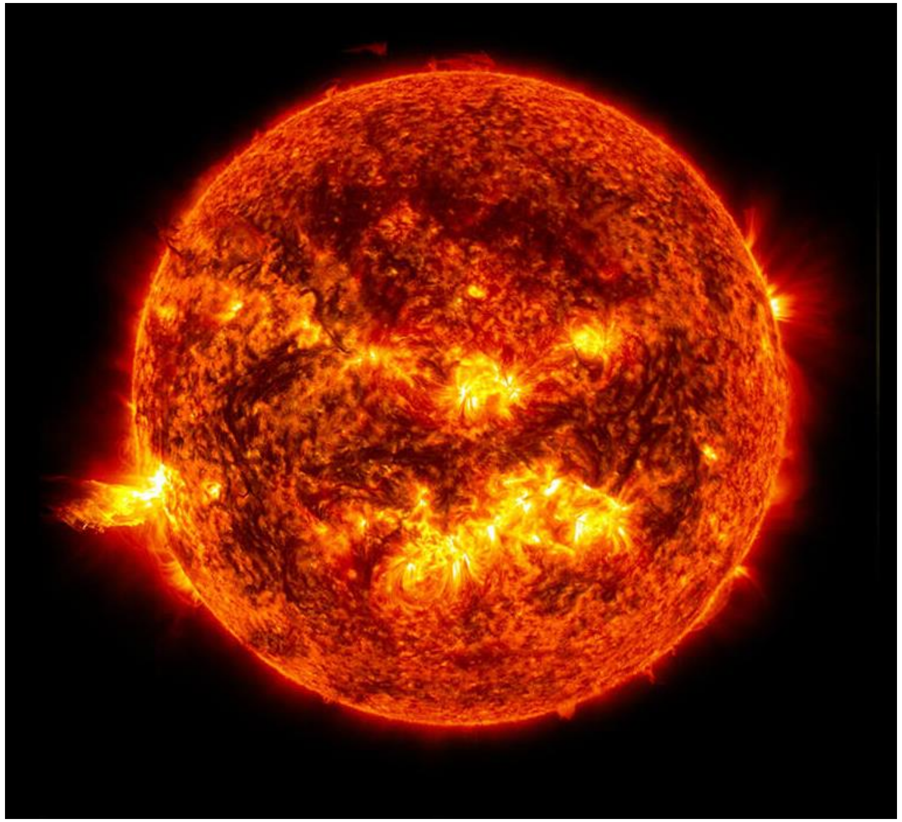
Maxwell Centre, Cambridge

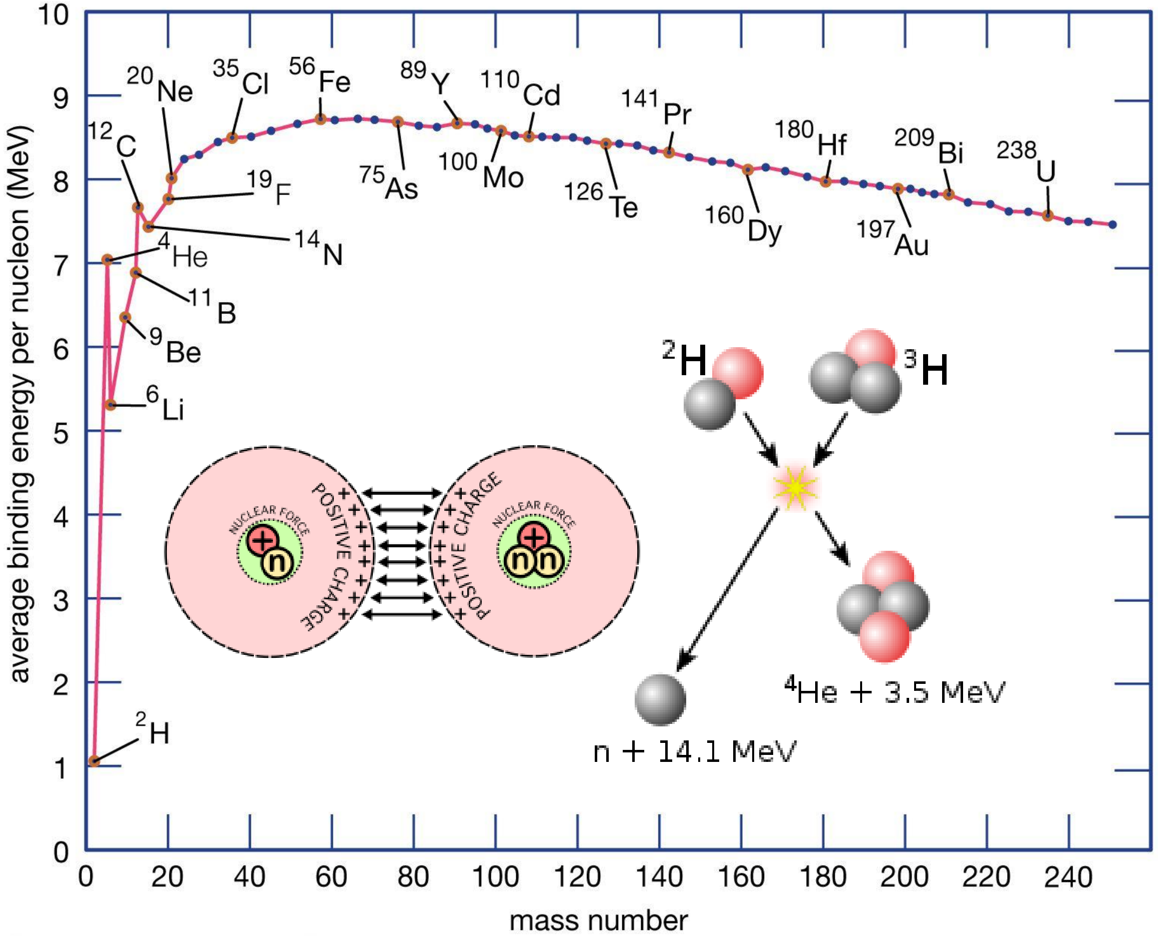
10th Nov. 2023

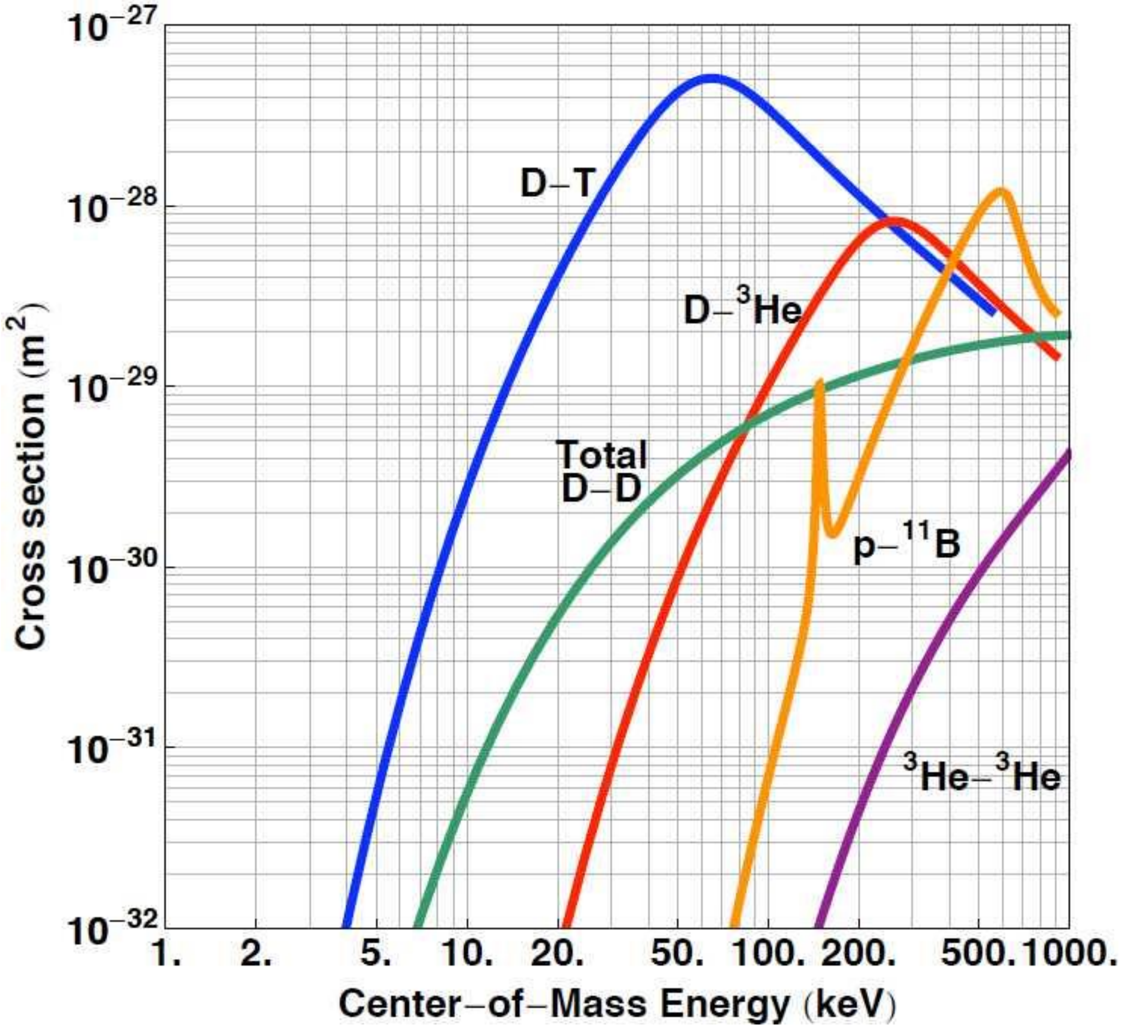
Nuclear Fusion in Cambridge



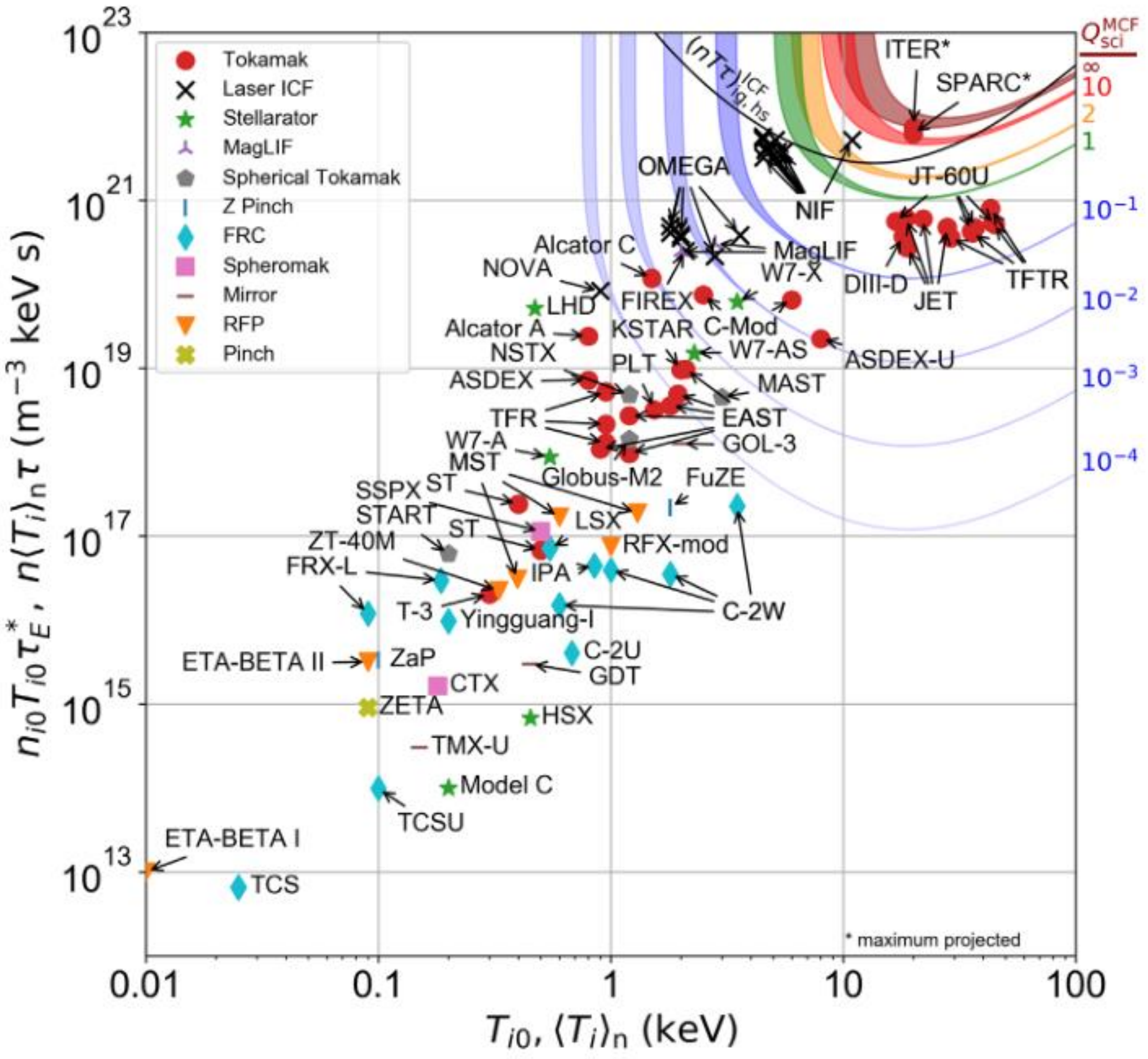
Cavendish Laboratory, 1933

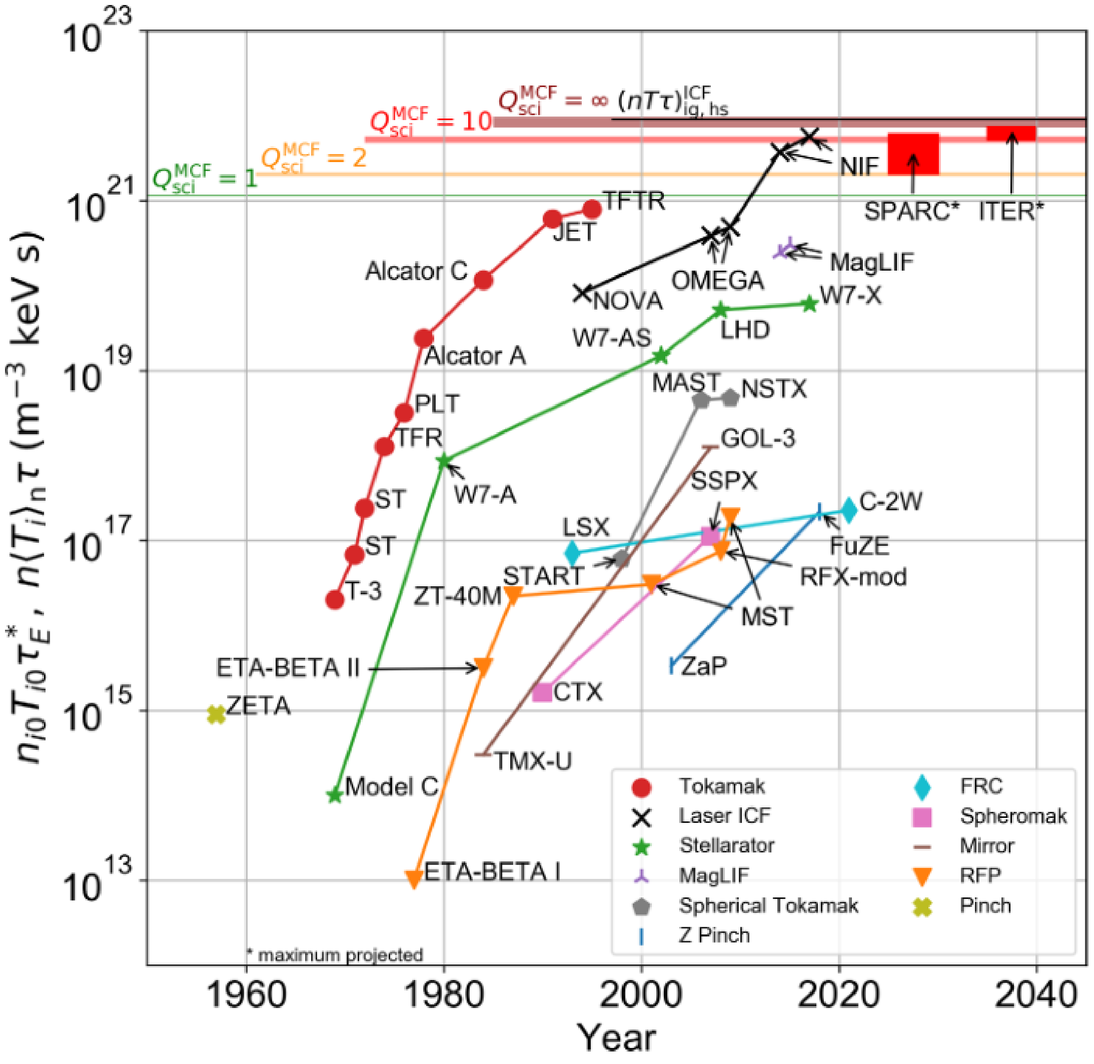
Nuclear Fusion





Engineering Fusion Devices





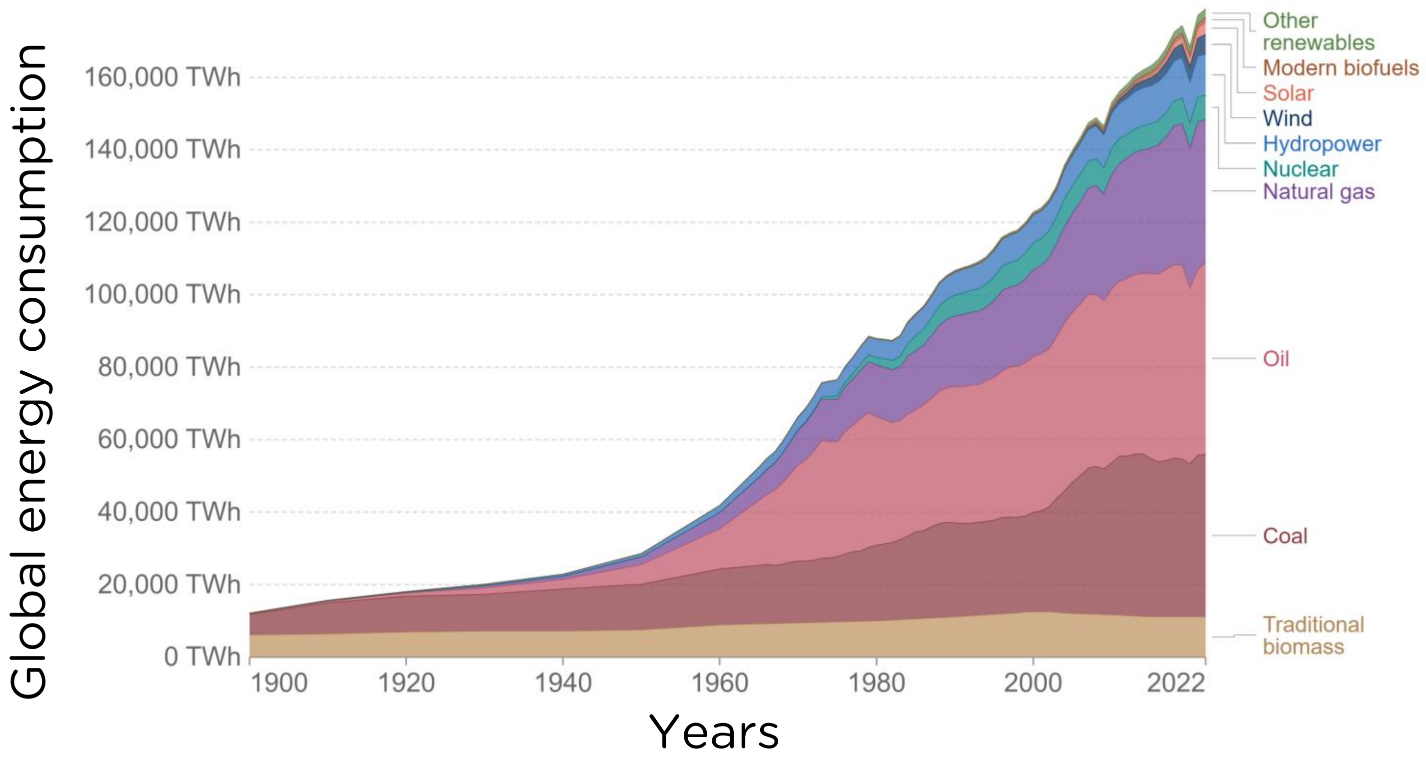
Sources: S. Wurzel, S. Hsu, Phys. Plasmas, 29, 062103 (2022)

Global Energy Challenges – the need for nuclear

By 2050, we need to deliver safe, reliable power to an extra 3.4 billion new energy customers from emerging economies, while reducing our total CO_2 emissions to zero.

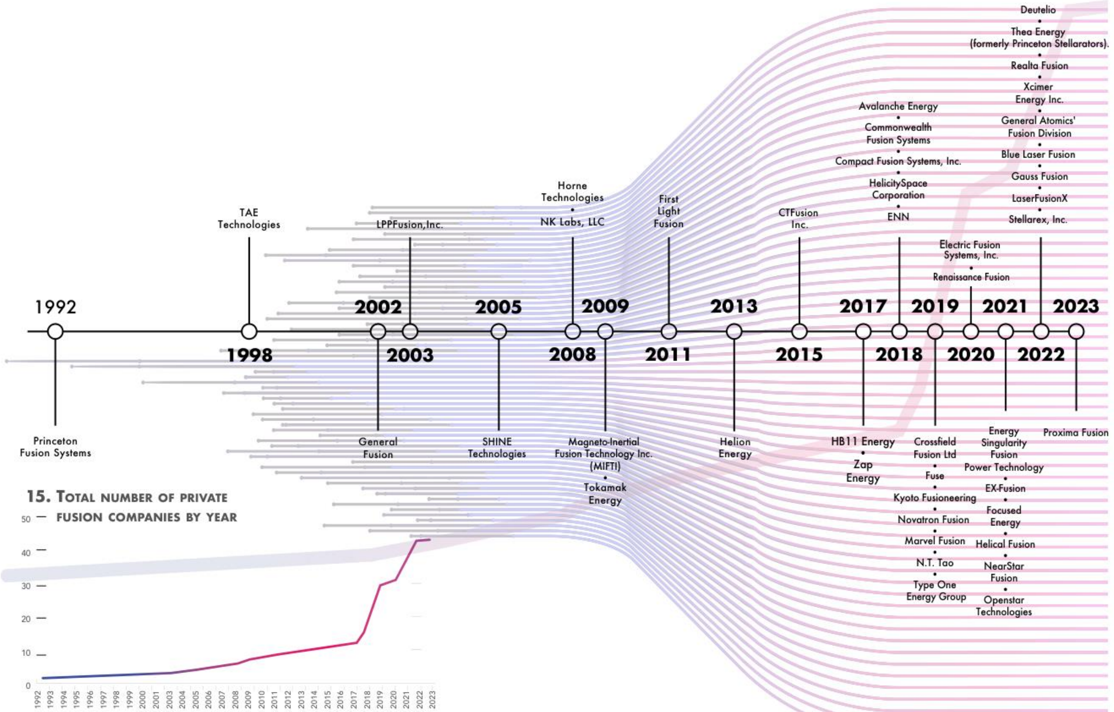
Nuclear Fusion

- Zero CO_2 generation
- High energy density fuel
- Abundant fuel source
- No long-lived nuclear waste
- Safe, controlled reaction
- Energy security
- Deployable and scalable



Sources: Energy Institute Statistical Review of World Energy (2023); Vaclav Smil (2017)

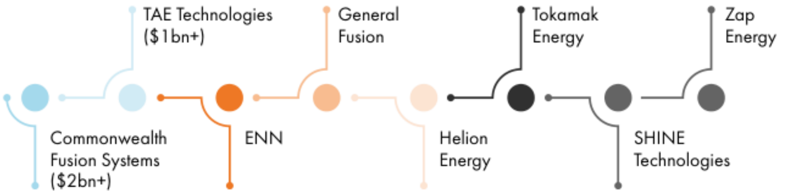
Fusion in the Private Sector



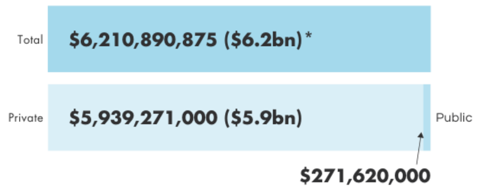
Tokamak	CFS, Tokamak Energy, ENN 新奥
Stellarator	Renaissance Fusion, Proxima Fusion, Helical Fusion, Type One Energy, Stellarex, Thea Energy
Laser fusion	HB11 Energy, Focused Energy, Marvel Fusion, EX-Fusion, Xcimer Energy Corporation
FRC	tae, Helion, Princeton Satellite Systems, Pulsar Fusion
Other MCF	Realta Fusion, Novatron, Zap Energy, Gauss Fusion
Other ICF	general fusion, first light, nearstar fusion, MIFTI, fuse
Other	Avalanche, nT-tao Compact Fusion Power, SHINE, Electric Fusion Systems, Horne Technologies

By primary HQ

Companies that have raised > $ 200M in funding:



Total funding to date:



Sources: Fusion Industry Association, Annual Report (2023)

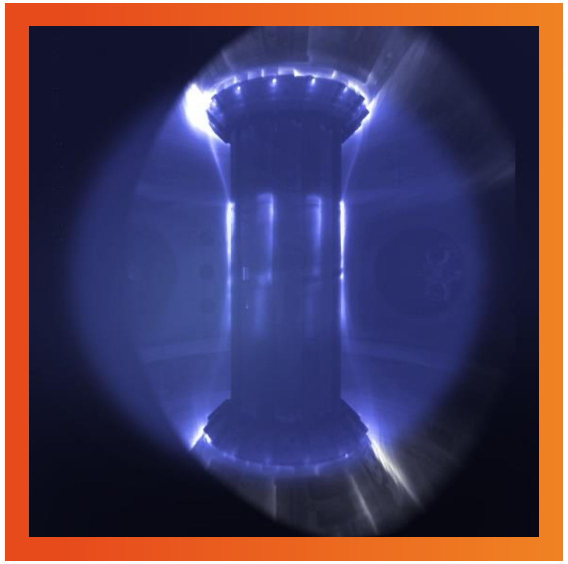
Tokamak Energy

- Founded in 2009
- Based in Oxfordshire, UK
- 300+ employees (70 PhDs, 75 MScs)
- Raised > $ 250M
- Pioneering HTS magnet technology for fusion and other applications
- Over 75 families of patents
- Only private company with operating spherical tokamak

Spherical Tokamak + HTS Magnets = Efficient Fusion

University of Oxford
Sumitomo Corporation
University of York
Sandia National Laboratories
Paul Scherrer Institut PSI
東京大学 The University of Tokyo
National High Magnetic Field Laboratory
PPPL
UNSW Sydney
University of Illinois Urbana-Champaign
CERN
Victoria University of Wellington Te Herenga Waka
Oak Ridge National Laboratory
University of Cambridge
Imperial College London
Little Beast engineering
UK Atomic Energy Authority

The Leading Global Fusion Company



2022
Highest plasma 'triple product' of any private fusion company ($6\pm2\times10^{18}\ m^{-3}keVs$).

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

2020
World-record 24 Tesla field at 20 K with patented HTS magnet technology.

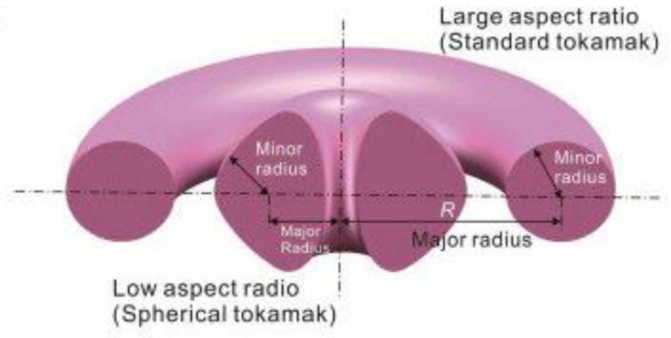
2017
Designed, built and operate the world's highest-magnetic field spherical tokamak (ST40).

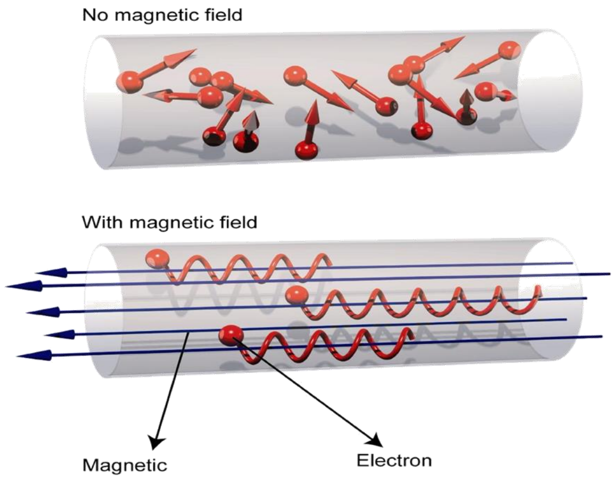
2015
First HTS tokamak sustained pulse for >24 hours (ST25 HTS).

Sources: S. A. M. McNamara *et al*, Nucl. Fusion, 63, 054002 (2023)

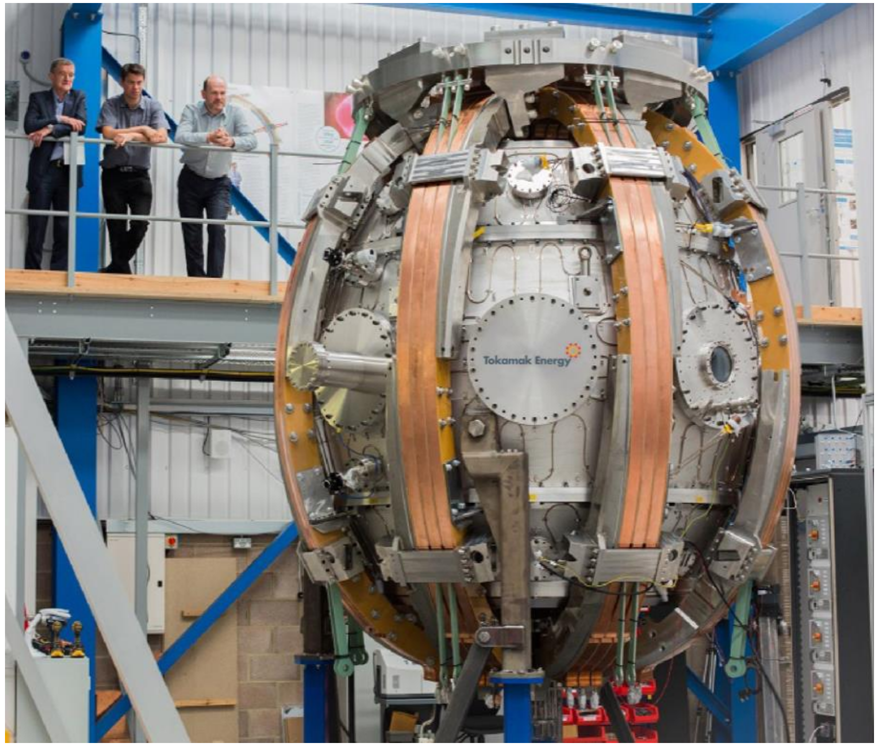
Our Operating Spherical Tokamak

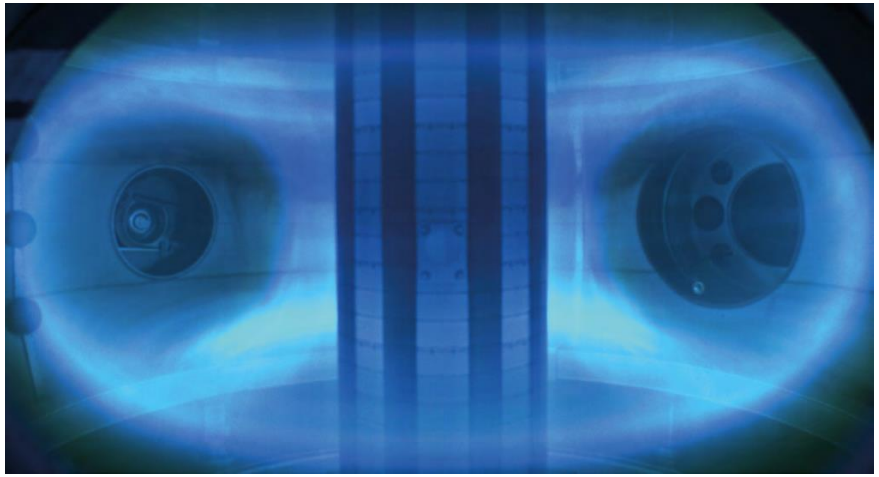
- ST40 (R = 0.4 m, B = 2.1 T)
- Uses 250 kA pulse in copper magnets
- Enable rapid validation of plasma physics and control, with simple, cheap magnets
- World-record holding 100 M °C temperatures
- Very compact, low aspect tokamak
- Total cost ~ $ 50 M
- Build time (2016-2017)





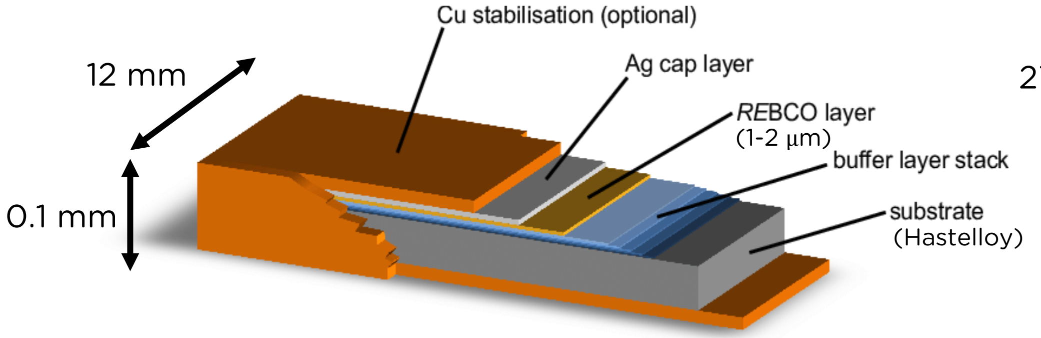
$$P_{fus} \sim B_T^4$$

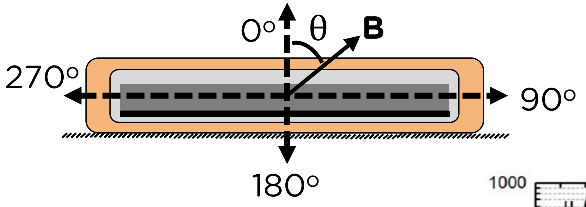


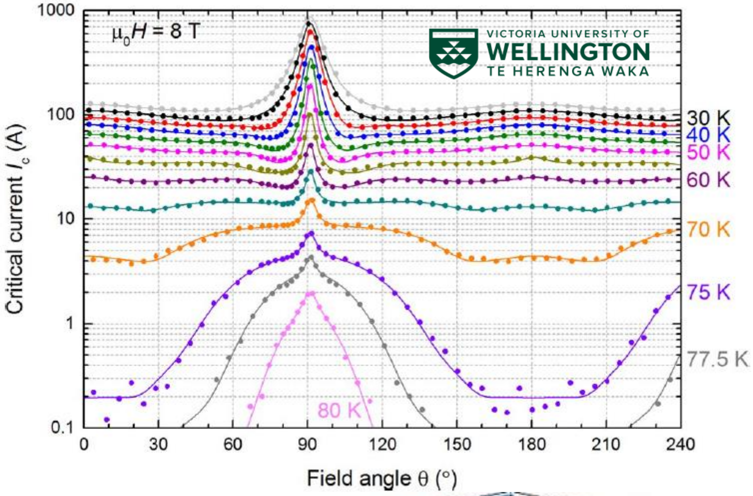


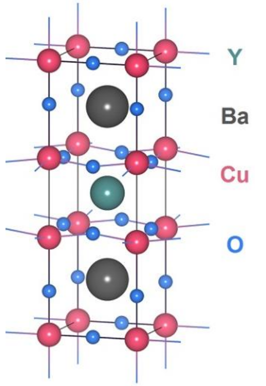
Sources: A. E. Costley *et al*, Nucl. Fusion, 55, 033001 (2015)

High-Temperature Superconducting ReBCO Tape

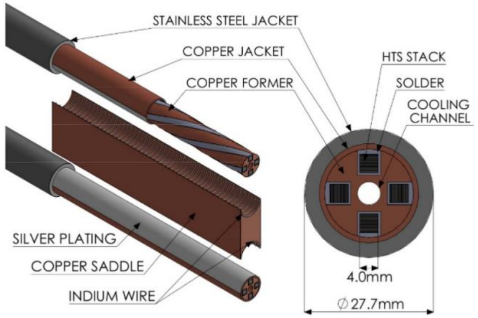






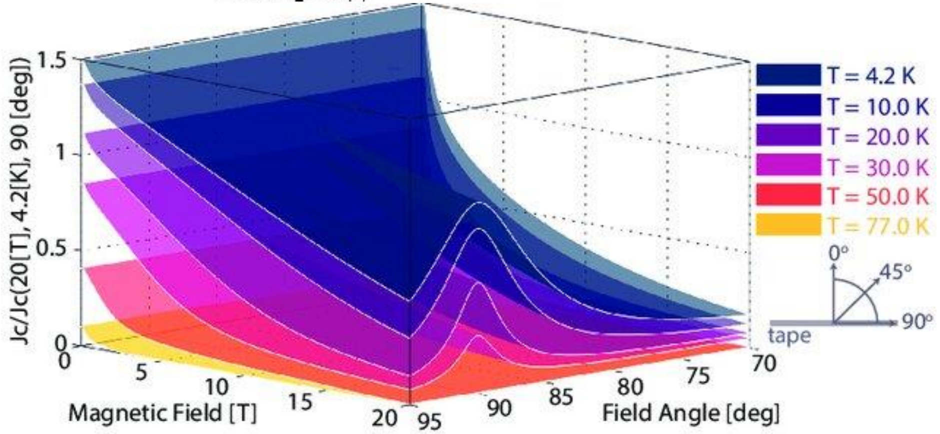


CORC® cable
Advanced Conductor Technologies LLC



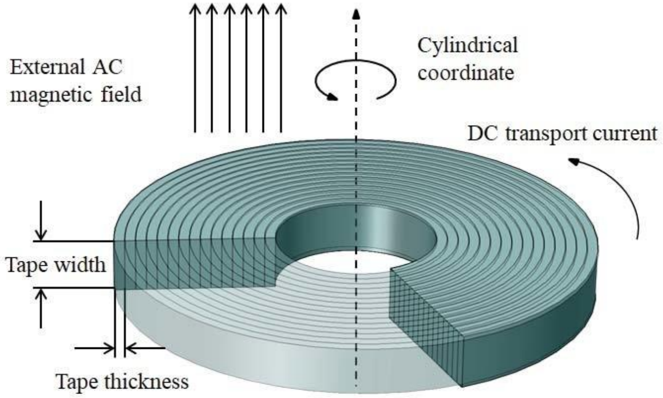
VIPER cable
Commonwealth Fusion Systems

Roebel cable
KIT and General Cable, NZ

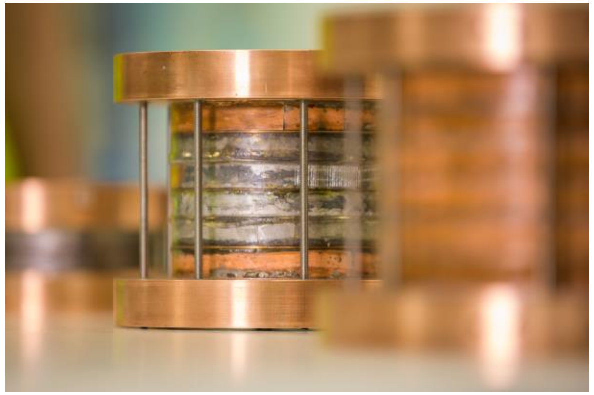


Sources: J. van Nugteren, *High-Temperature Superconducting Accelerator Magnets*, PhD Thesis (2015)

Non-Insulated HTS Magnets



Mixed supplier coil stack

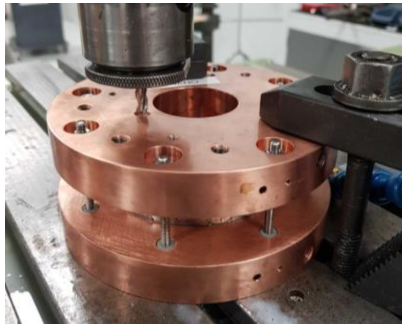


>16.5 T re-mounted QA coils

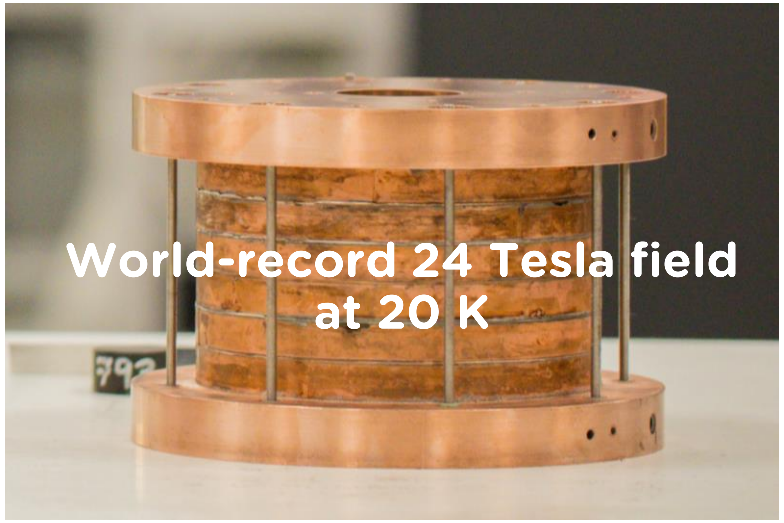
Solder Consolidated NI Coil

Compact, robust, modules with “ETI” Plates

Intentionally Damaged Coils



Operate stably despite gross damage

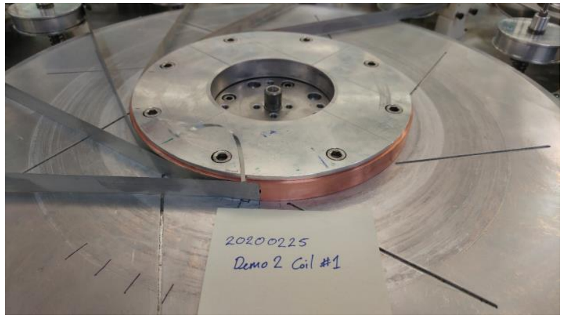


Key Demonstrations:

- 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.

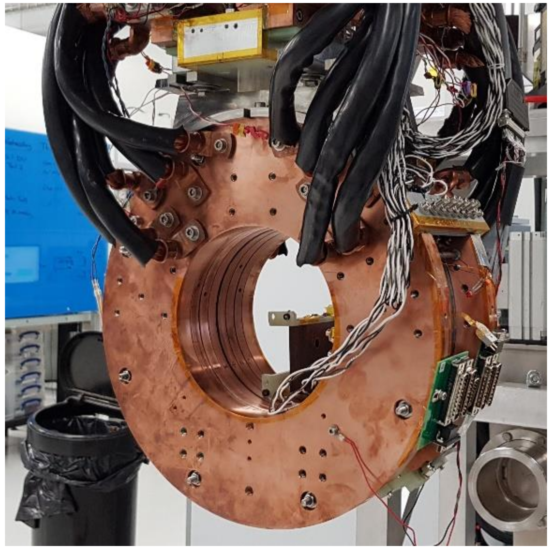
Partially-Insulated HTS Magnets

Multi-Tape Winding



Incorporating Partial Insulation

Partially Insulated Coils

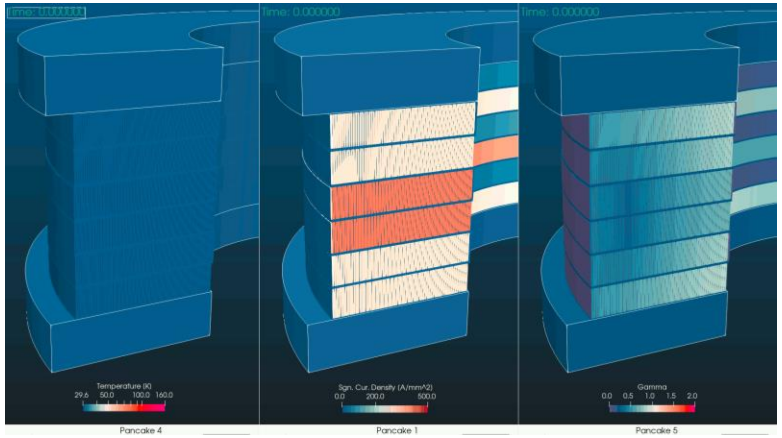


Key Demonstrations:

- PI Coil Design and Fabrication
  - ✓ Designed by modelling to be quench-safe.
  - ✓ Tuneable PI implemented.
  - ✓ Modular, conduction-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.

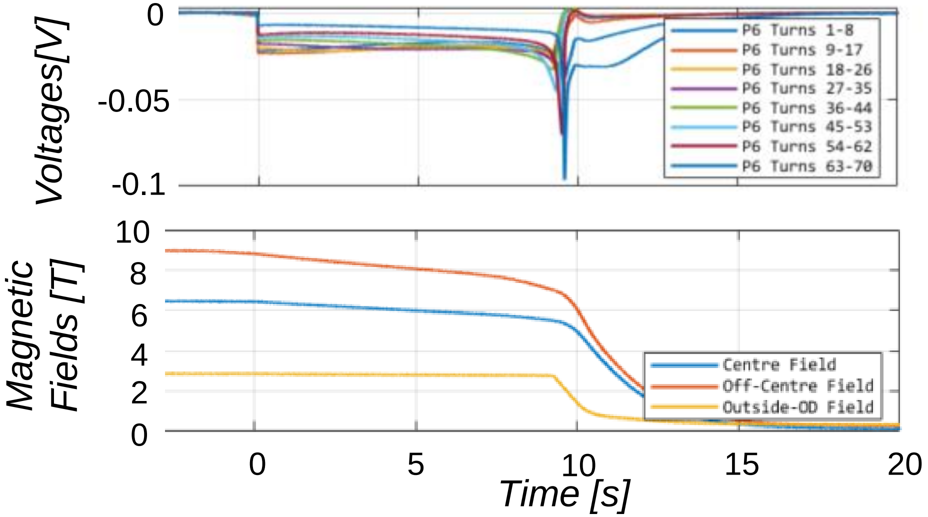
Forced Quench – Simulation Movie

Temperature *Current Density* *% I_c*



Real behaviour reproduced

Forced Quench – Measurement Data Subset

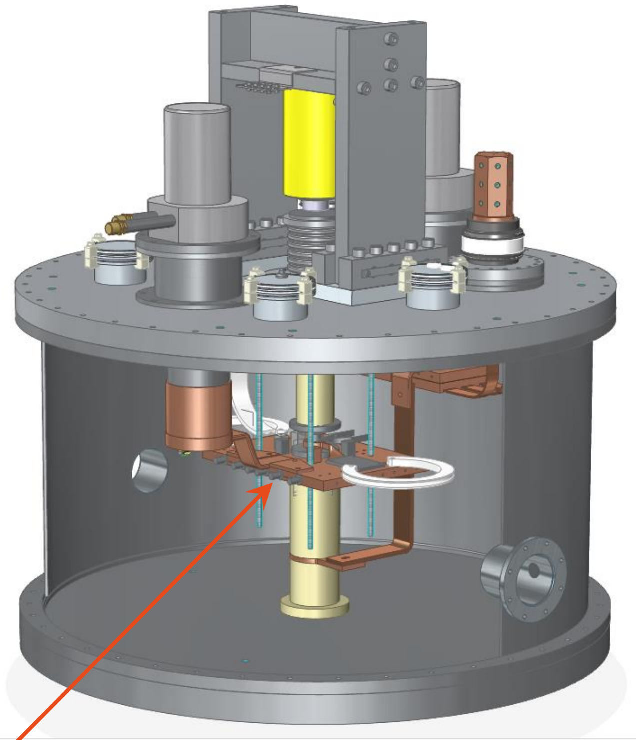


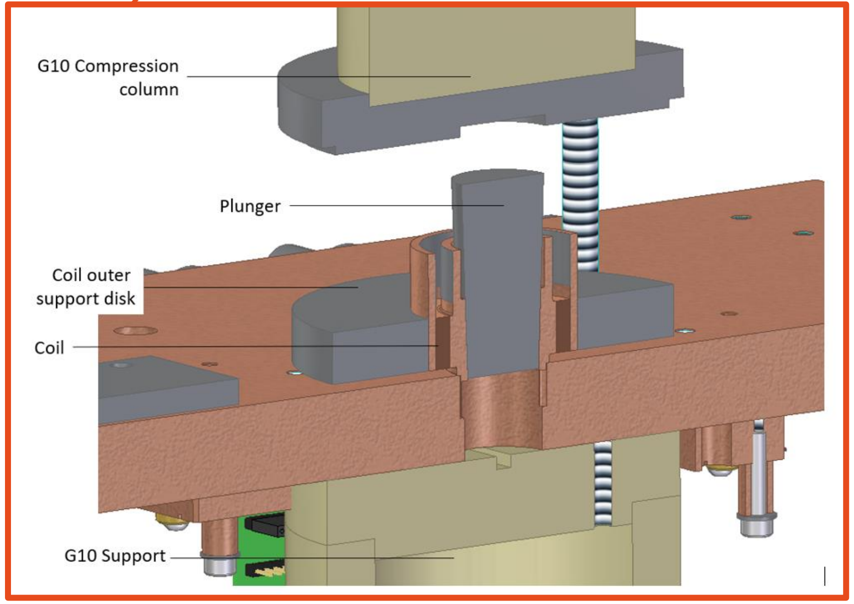
Quench propagation captured

HTS Magnets Robust to Compression

Cryogenic coil compression system (CCCS)

- Allow us to apply up to 500 MPa compressive force onto cold, energised HTS magnets
- Instrumented with voltage taps, temperature and Hall sensors, and FBGs to monitor strain
- Monitor response and degradation of HTS tape under compressive and tensile stress in real time and representative operational conditions



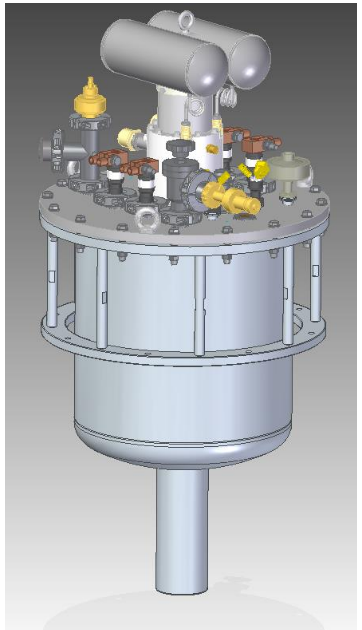


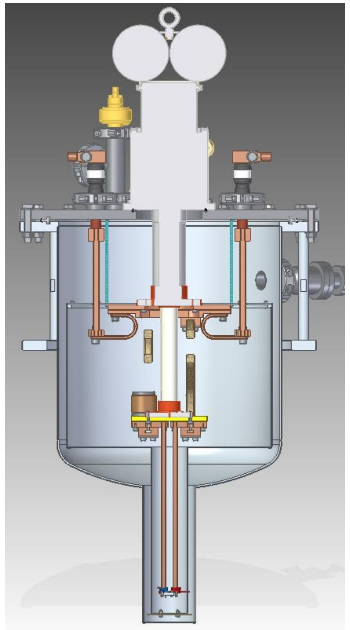
✓ System designed, built, and operated in-house

HTS Magnets Robust to Irradiation

Gamma

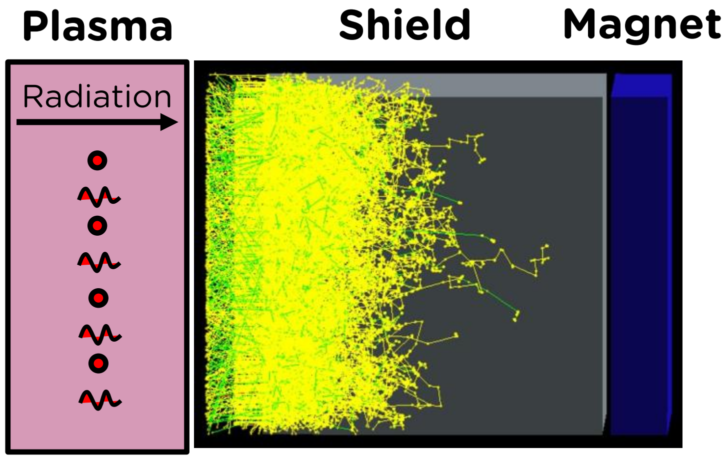
- Irradiate HTS magnets using ^{60}Co γ sources at fusion operating conditions (20 K while energised near I_c) up to 10 MGy doses
- Monitor any degradation in I_c in real-time via voltage taps, and instrumented with Hall and temperature sensors
- Outcomes guide understanding of shielding requirements for future tokamak designs (field strength on plasma vs. lifetime in service)



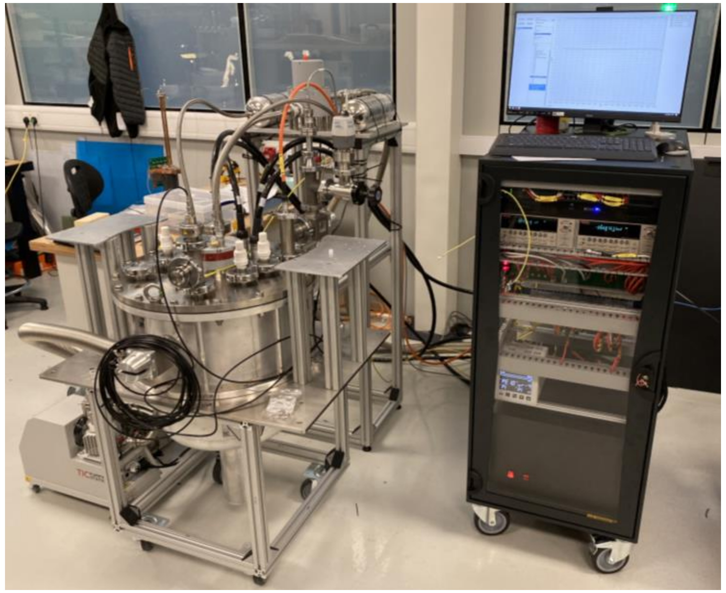


✓ System designed and built in-house
✓ Experiments ongoing in USA

Basic Shielding Schematic



Residual neutrons, and secondary gammas irradiate the HTS magnet



HTS Magnets for Fusion

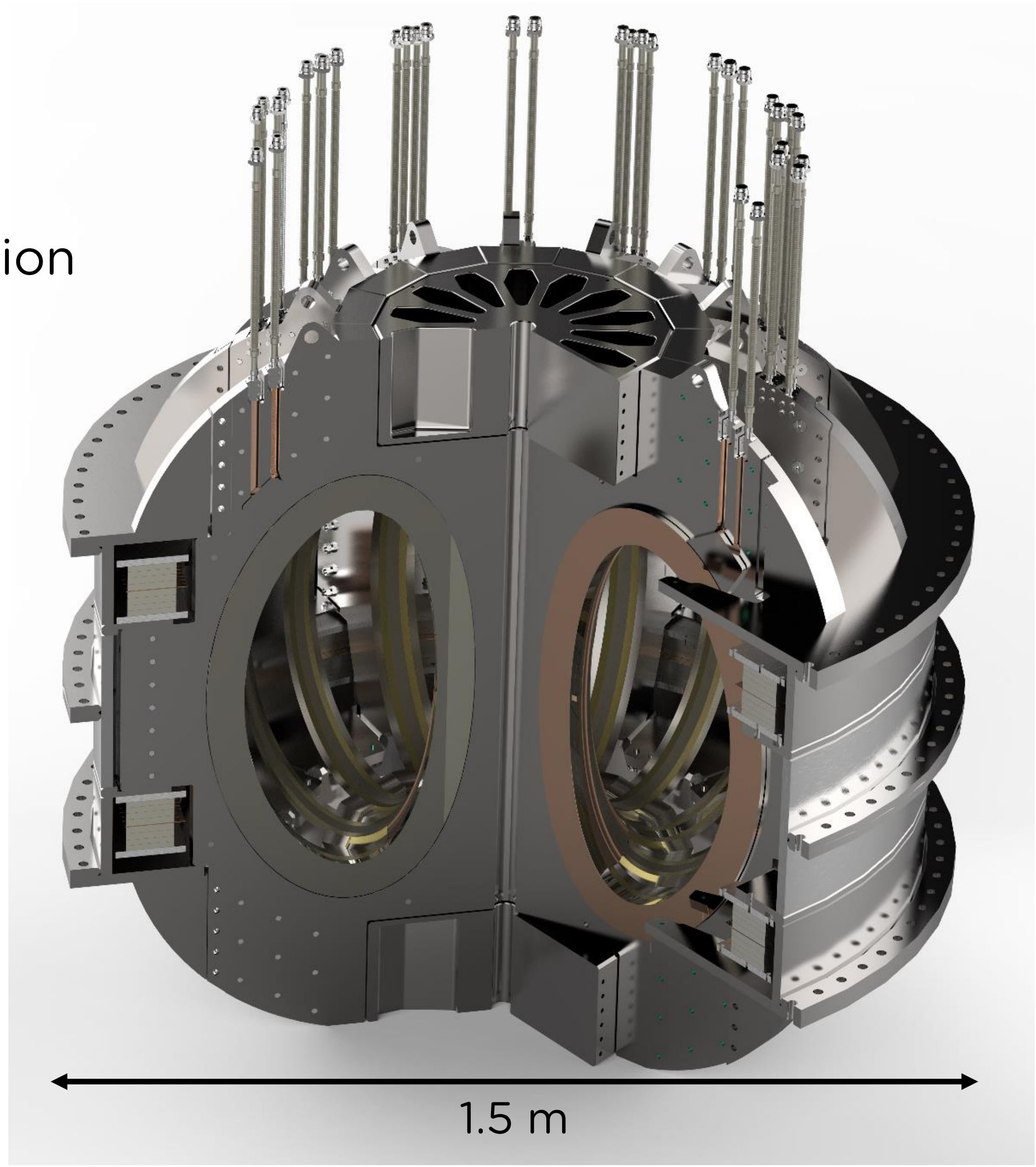
Demo4

World-first complete set of HTS magnets in a fusion configuration.

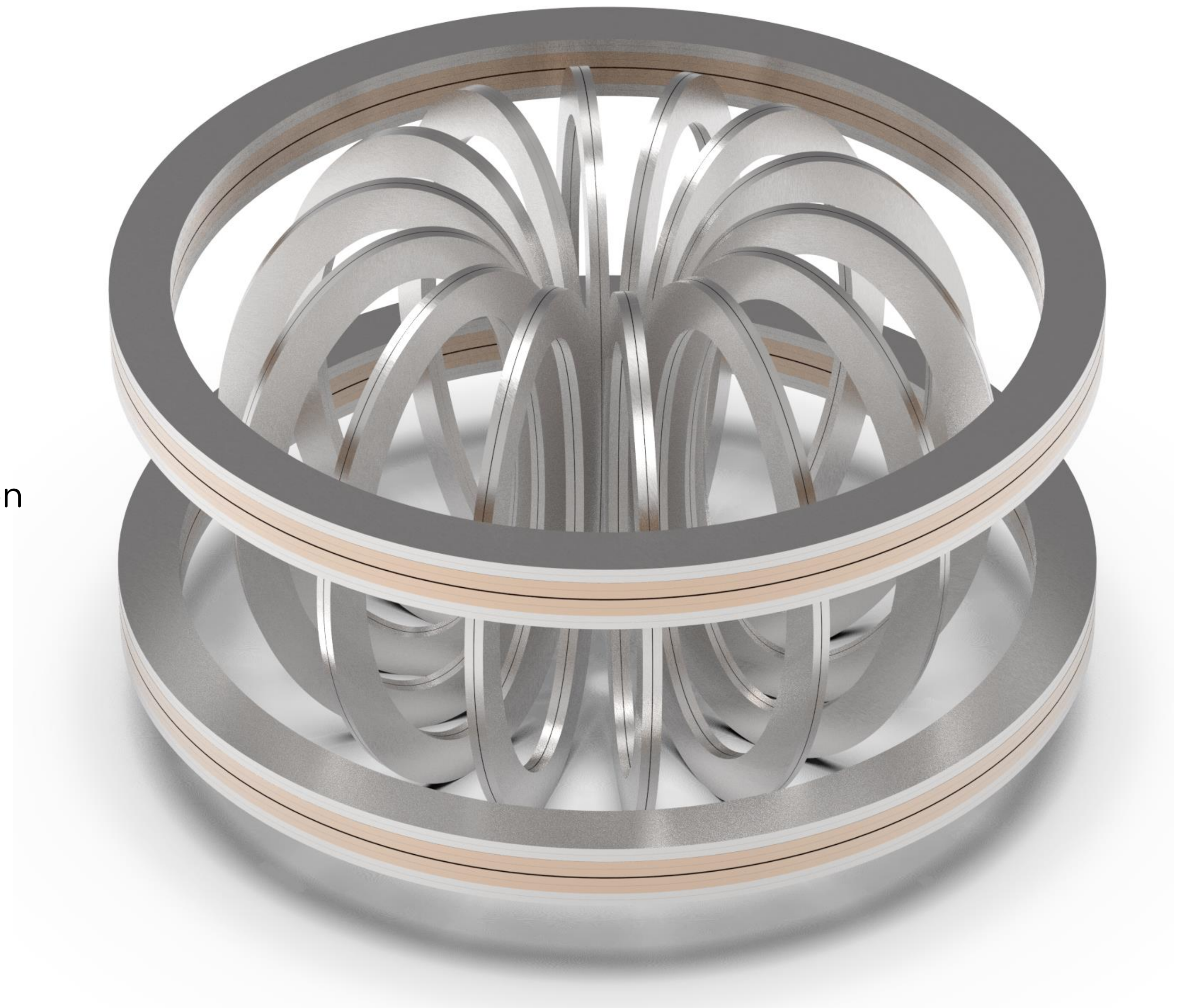
44 HTS magnets operating at 18 Tesla at 20 K

Key Objectives:

- Demonstrate operation of balanced toroidal field (28 TF coils in 14 limbs)
- Demonstrate representative compressive stress at centre column
- Demonstrate partial insulation for TF coils and quench protection at 16.5 MJ energisation
- Explore PF field shine effects on TF coils
- Explore transient control and AC losses
- Simulate plasma heating and stresses at centre column



Demo4 – HTS Magnets



Poloidal Field (PF) Coils:

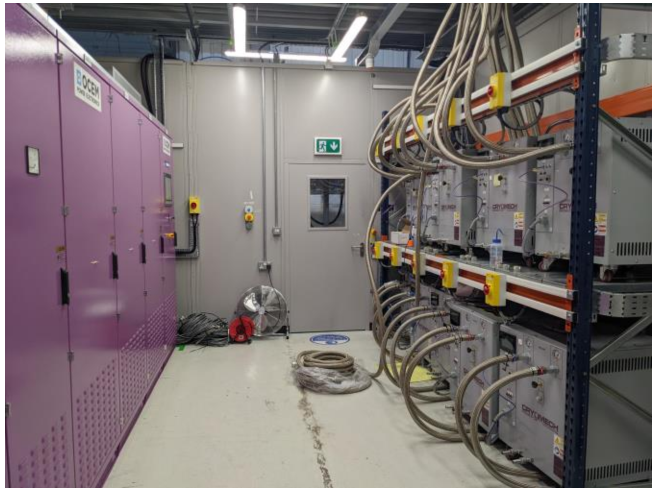
- 2 PF magnets each containing a stack of 8 PF coils
- Fully-insulated HTS magnets operating at 4 kA at 20 K
- Required fast ramp rate to modulate plasma shape in real tokamak
- Incorporates additional Cu for AC loss dissipation absorption and quench protection.

Toroidal Field (TF) Coils

- 14 TF limbs each containing 2 TF coils (28 TF coils in total)
- Partially-insulated HTS magnets operated at 8 kA at 20 K
- Required high-field steady state to confine plasma

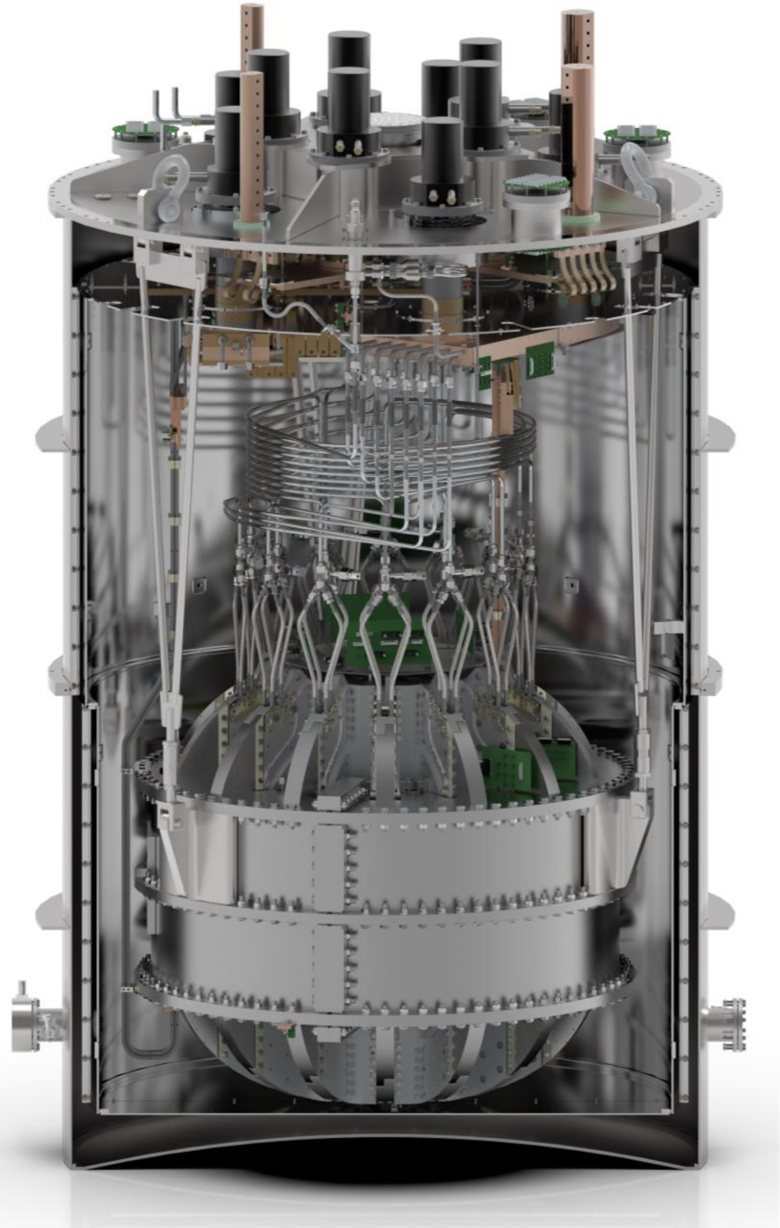
Demo4 – Cooling Power and Instrumentation

- System is conduction cooled by 10 closed-cycle cryocoolers driven by cryofans
- Pressurised ^{4}He gas circulates in parallel through magnets via heat exchangers
- 500+ instrumentation sensors (temperature, magnetic field, voltage taps, FBG strain gauges, and heaters)



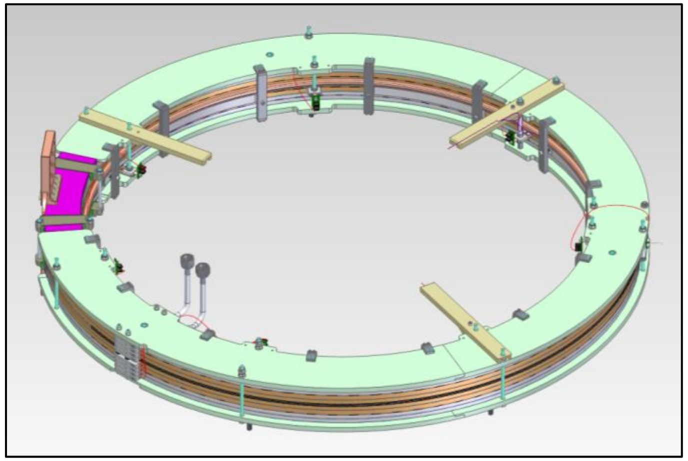
Plant Room

OVC Top Plate



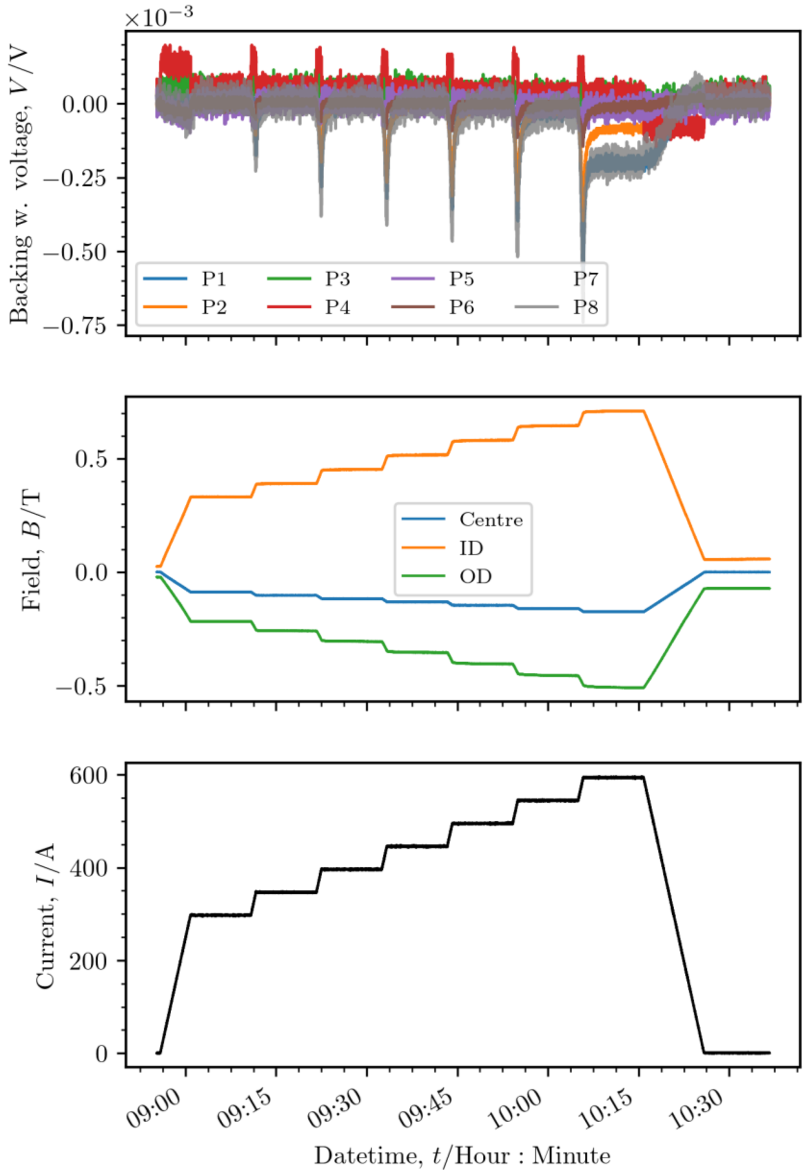
Demo4 Progress – Poloidal Field Coils

PF magnet concept design



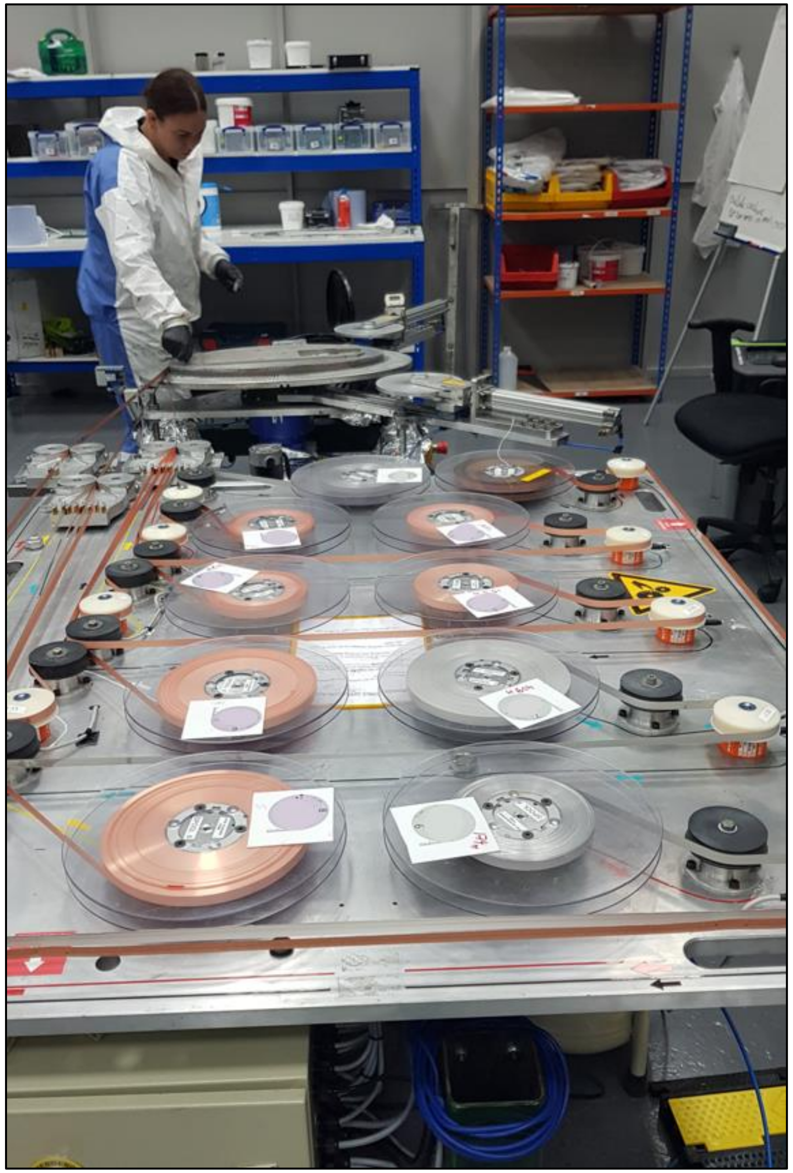
Manufactured PF magnet

Test results at 77 K



- ✓ Preliminary testing at 77 K indicate HTS tape is not degraded by manufacture
- ✓ All 16 PF coils manufactured and tested

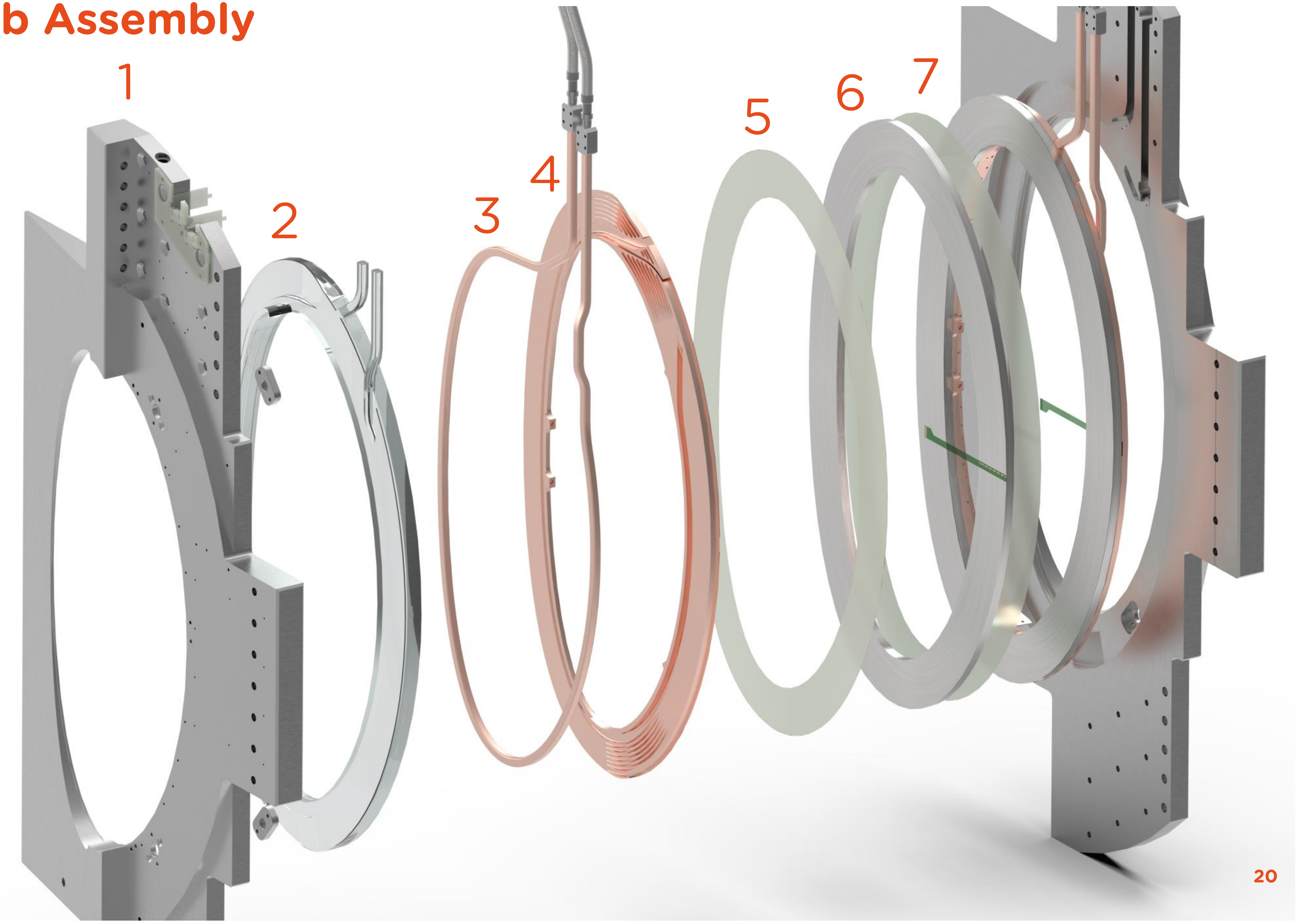
Demo4 TF Coils – All the coils are wound and impregnated



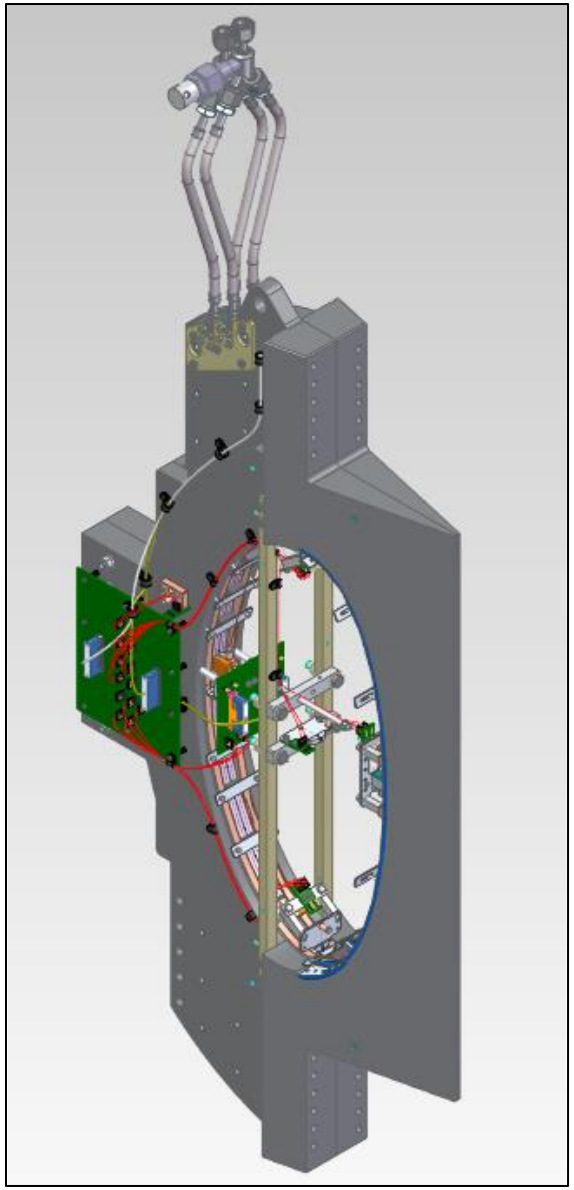
- 28 TF coils (1 pair of coils per limb, 14 limbs)
- TF coils include wound-in partial insulation
- An additional 4 TF coils (not shown) for spare limbs
- 16 PF coil pancakes
- Assembled into 2 PF coil stacks.

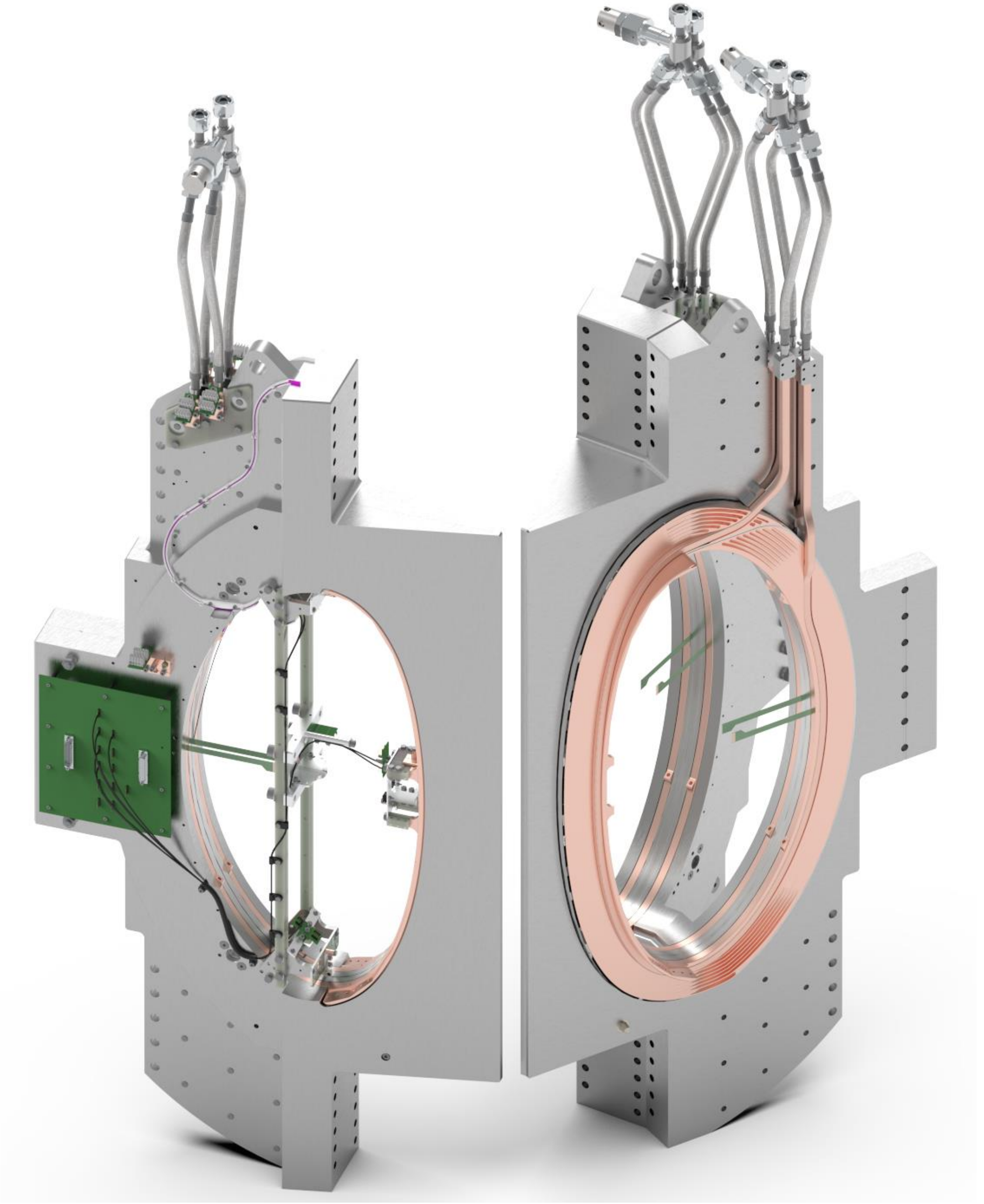
Demo4 TF Limb Assembly

1. SS clam shell
2. Resin infill
3. Cooling loop
4. ETI plate
5. Insulation
6. HTS coil
7. Insulation

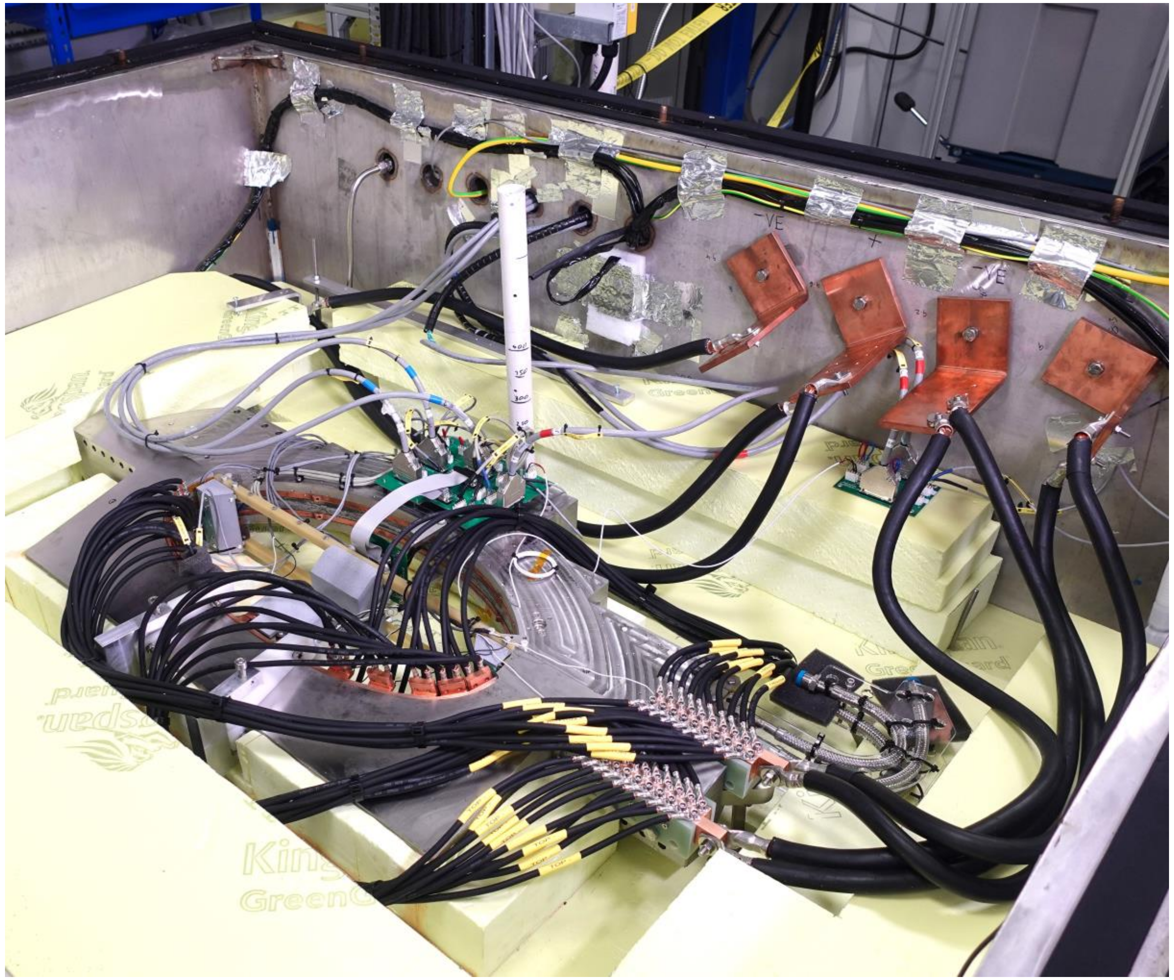


Demo4 TF Limb Instrumentation





Demo4 TF coils – Limb #1 assembled and tested at 77 K!

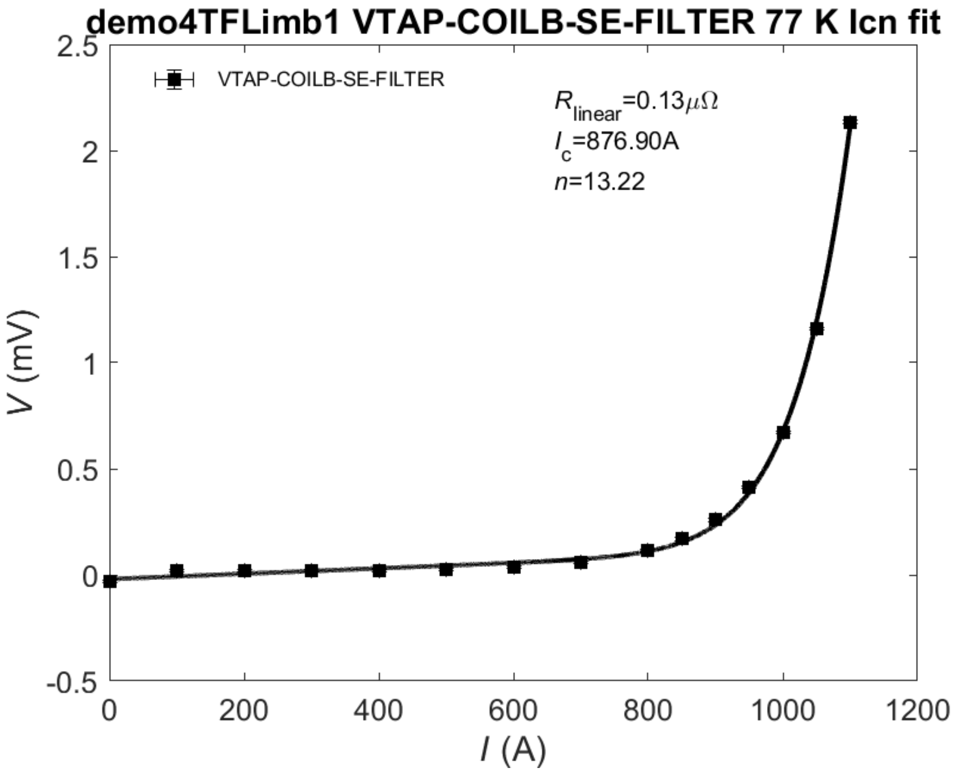


Testing in liquid nitrogen bath

Coils instrumented with voltage taps and Hall probes. Like Demo2, the Demo4 TF coils have voltage taps trough the windings.

Tests include: -

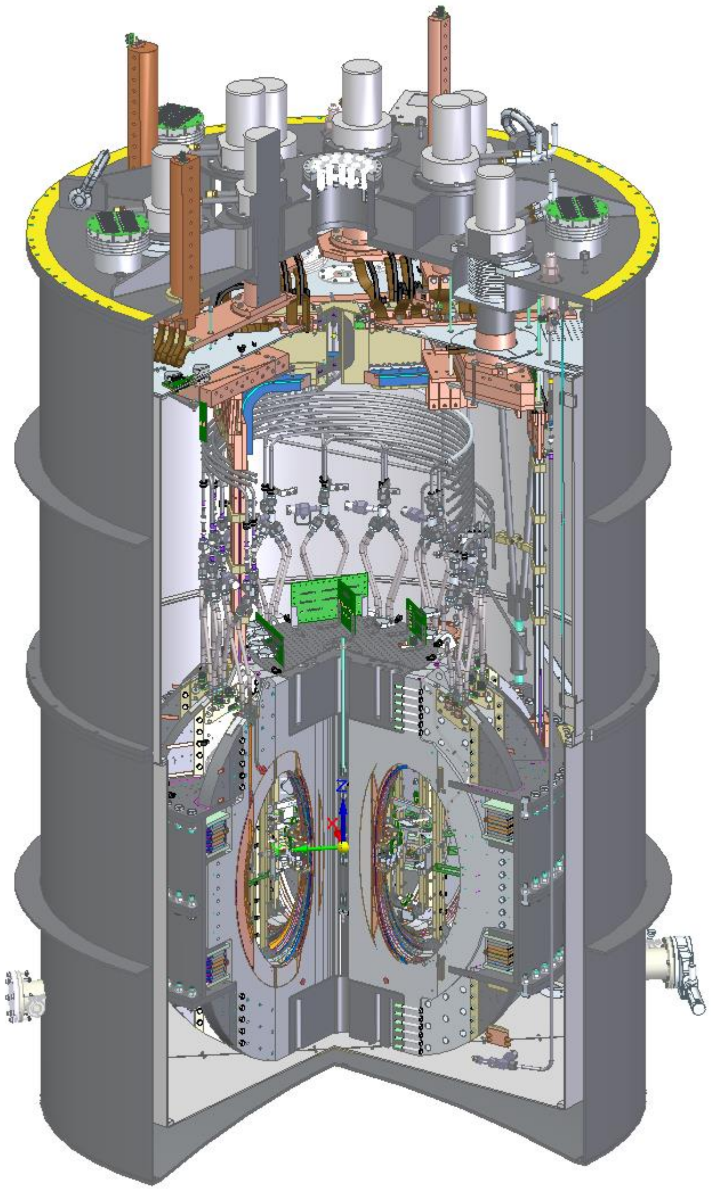
1. Slow ramp to I_c to determine the integrity of the coils (2 coils per limb including coil-to-coil joint).
2. Step and hold ramp to determine radial resistance and I_c (Determine by S-E voltage).
3. Multiple thermal and energisation cycles in progress to check for any performance degradation.



Demo4 - Looking Ahead

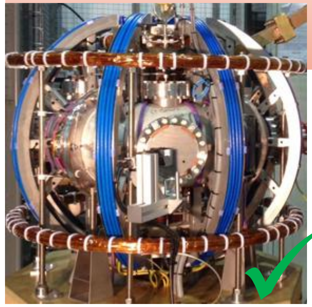
Summary:

- All 16 PF coils manufactured and tested
- All 28 TF coils manufactured and tested, and now being assembled and tested as 14 TF limbs
- Interlimb jointing and magnet assembly
- Instrumentation integration and control systems
- Final integration of cold mass, top plate, radiation shielding, and OVC with power and cooling
- Commissioning and test campaigns (Q2 2024)



Tokamak Energy Development Timeline

2014



ST25

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

2015

ST25-HTS

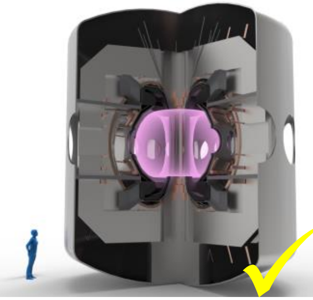
ST25-HTS Achievements
- First HTS TF coils
- H plasma held for 29 hours

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

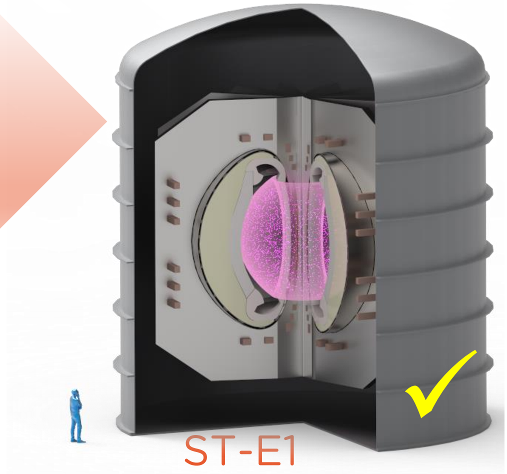
Build completion 2026



ST-X(80)

ST-X(80) Objectives
- Demonstrate long pulse operation
- Control and protection of mid-scale HTS magnets

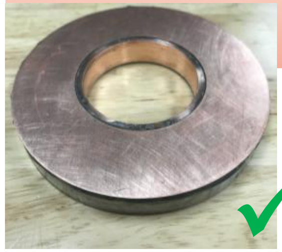
Early 2030s



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

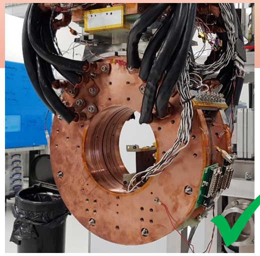
QA NI Coils Achievements
- Tape QA
- Defect tolerant coils
- Robust jointing & ETI plates
- Modular magnet build

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

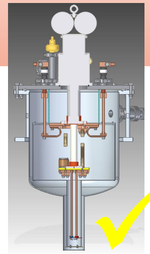
AMR Achievements
- Demonstrated cryogenic PSU technology
- Developed EFC coil design code
- Coil scale-up study
- Coil Cryogenic Compression System designed and built
- Quench modelling code developed and validated

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

2021-2023



Gamma

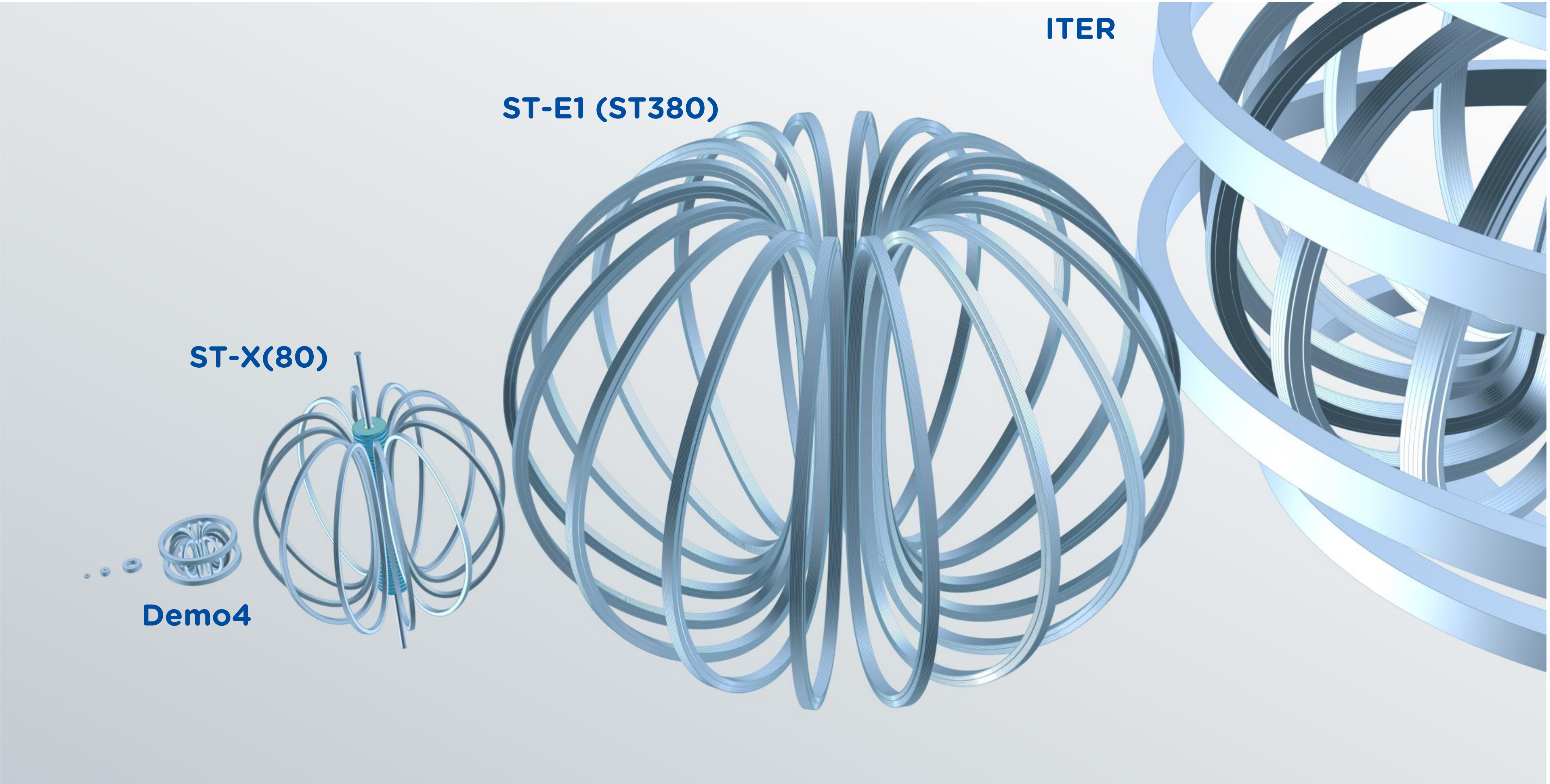
Gamma Objectives
- Irradiate small test coils wound from selected REBCO tapes
- Co60 irradiation up to 10MGy dose.
- Coils are cooled to 20K and energised to Ic
- Ic degradation measured in real time

2022 - 2026

BB01

BB01 Objectives
- Developing prototype coils for ST-X(80)
- Developing coil manufacturing processes and tooling
- Developing magnet assembly processes and tooling

Magnetic Confinement Size Comparison



Tokamak Energy

Thank you

We are hiring!

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