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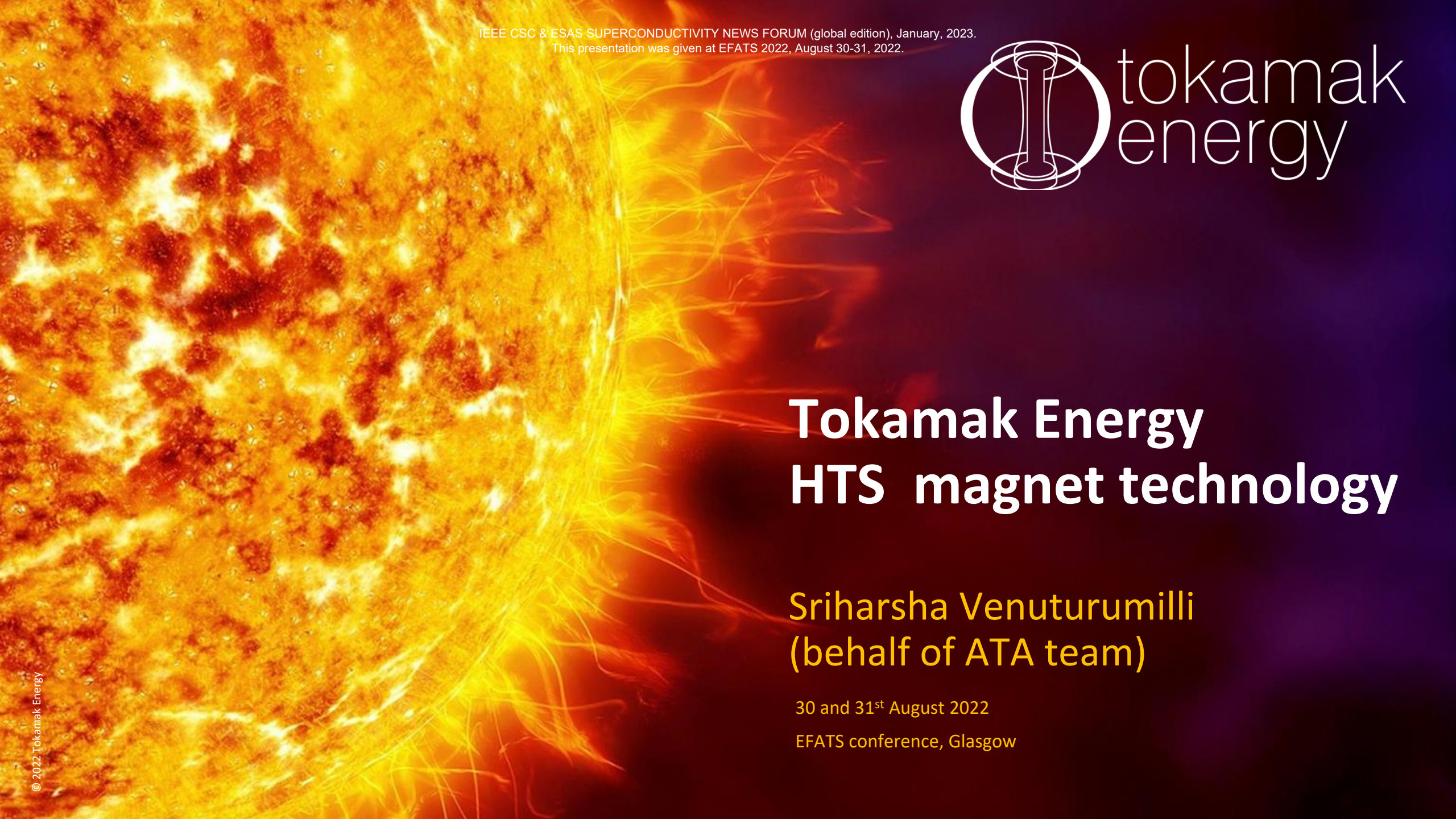

Tokamak Energy HTS magnet technology

Sriharsha Venuturumilli
(behalf of ATA team)

30 and 31st August 2022

EFATS conference, Glasgow

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Outline

- Who are Tokamak Energy ?
- Our ambitious fusion energy mission
- Our world class HTS magnet technology demonstrators
- HTS coil technologies we have developed:
  - No-insulation (**NI**) for DC applications
  - Partial-insulation (**PI**) for large scale DC
  - Buffer-layer insulation (**BLI**) for pulsed / AC
  - Cryogenic power electronics
- Alternative Technology Applications (ATA)
  - Non-fusion applications of TE technology
  - Recent projects
- Scope for TE magnet technology applications in aircraft propulsion

Spherical Tokamak – early build of ST40 (2018)
(> 2 T @ 40cm radius, copper coils)

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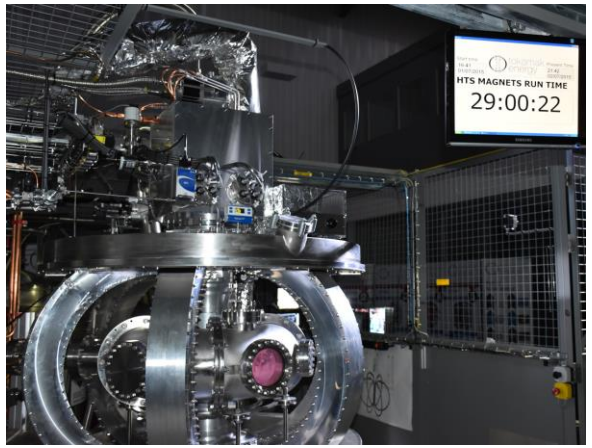
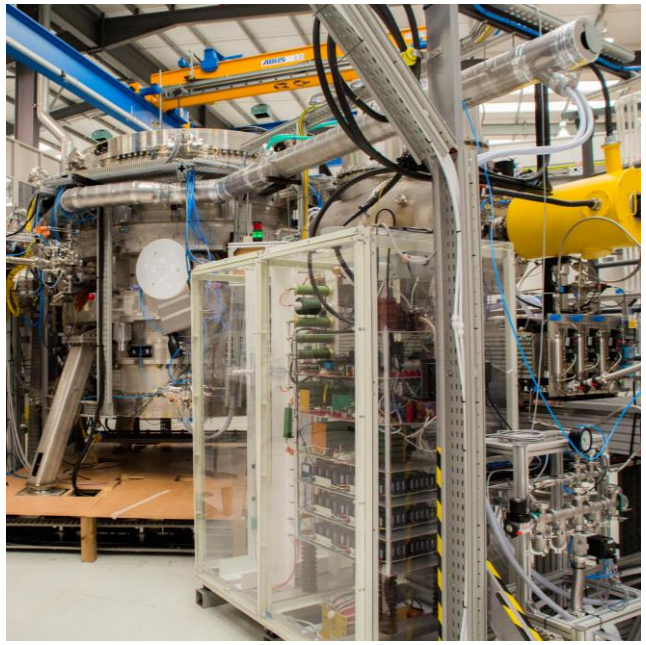
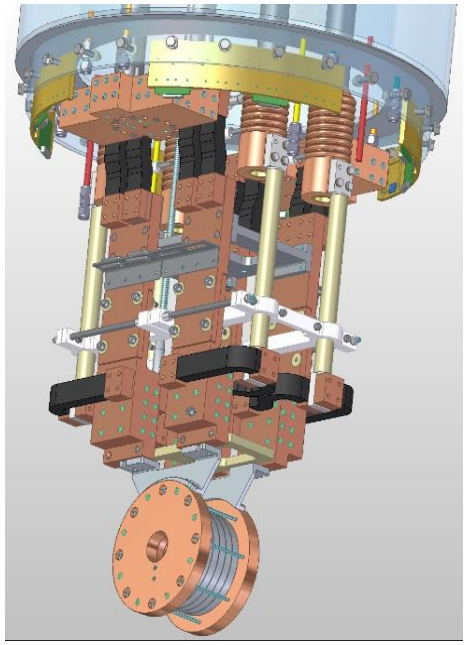
Tokamak Energy

- Established in 2009 with a mission to develop a faster way to fusion energy
- Raised $250M of investment including $50M of grants and R&D subsidy from UK and US
- Engineering centre in Milton Park, Oxfordshire
- Team of over 200 scientists, engineers and technicians (and growing fast!)
- Operating the first high field spherical tokamak, ST40 – recently achieved 100M °C milestone
- ***World leading high temperature superconducting (HTS) magnet manufacturing capability***







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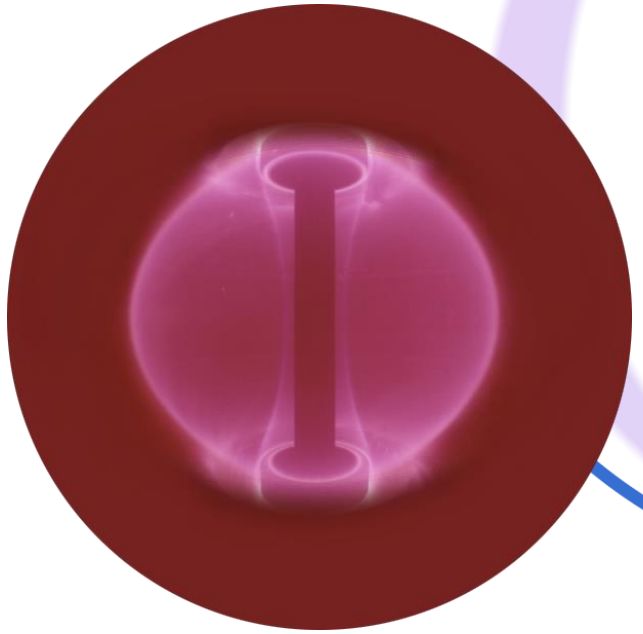
Promising physics, new technologies

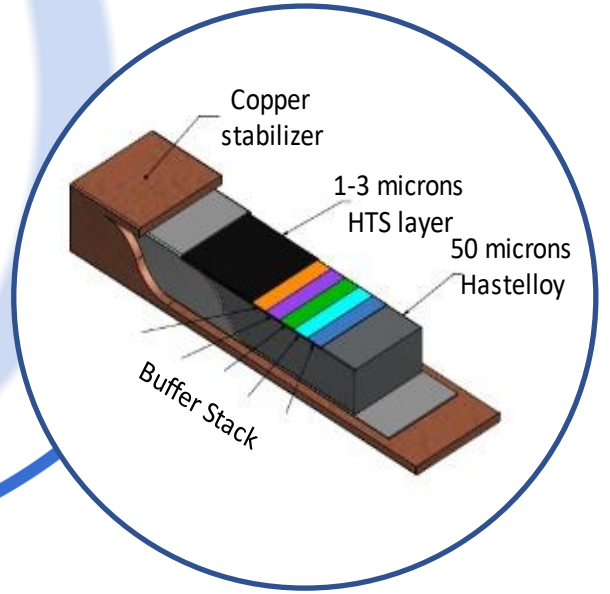
Spherical Tokamak (ST)

Improved plasma efficiency



High Temperature Superconductors (HTS)

High current at high magnetic field



FUSION POWER

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Tokamak Energy's HTS magnet technology

- Very high field HTS magnets
- Compact & robust:
  - High current density & high reliability
- Quench safe HTS magnet technology
- DC or fast ramping / AC capability
- Flexible HTS current leads
- Cryogenic power electronics integration
- World leading HTS magnet team
  - ~24 T / 20 K all-HTS non-insulated magnet
  - First large scale partial insulated magnet (fast ramping & high quench stability)

Advanced Technology Applications (ATA) team formed in 2020:

- Cryogenic, electromagnetic & power electronics expertise
- Complete system integration capability

Our dedicated ATA engineers are available to solve your superconductivity and cryogenics challenges !

4 September 2019

Tokamak Energy exceeds target of 20 tesla with HTS M...

The last 12 months have seen very rapid developments in magnet technology at Tokamak Energy. ...

+ LEARN MORE

22 September 2021

Next generation magnet technology paves the way to c...

22 September 2021, Oxford, UK – Tokamak Energy has demonstrated a transformative magnet ...

+ LEARN MORE

16 December 2021

Breakthrough in efficient powering of HTS magnets

Tests using new cryogenic power electronics show double the efficiency of previous systems

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TE's magnet technology demonstrators

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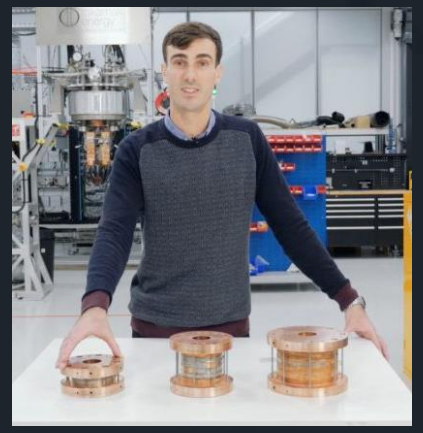
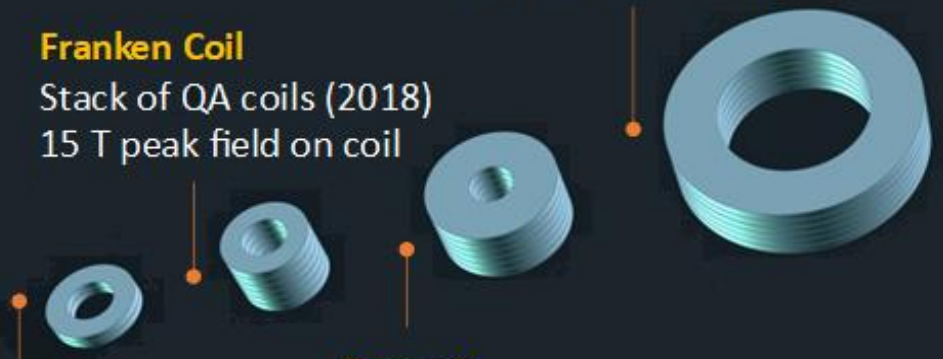


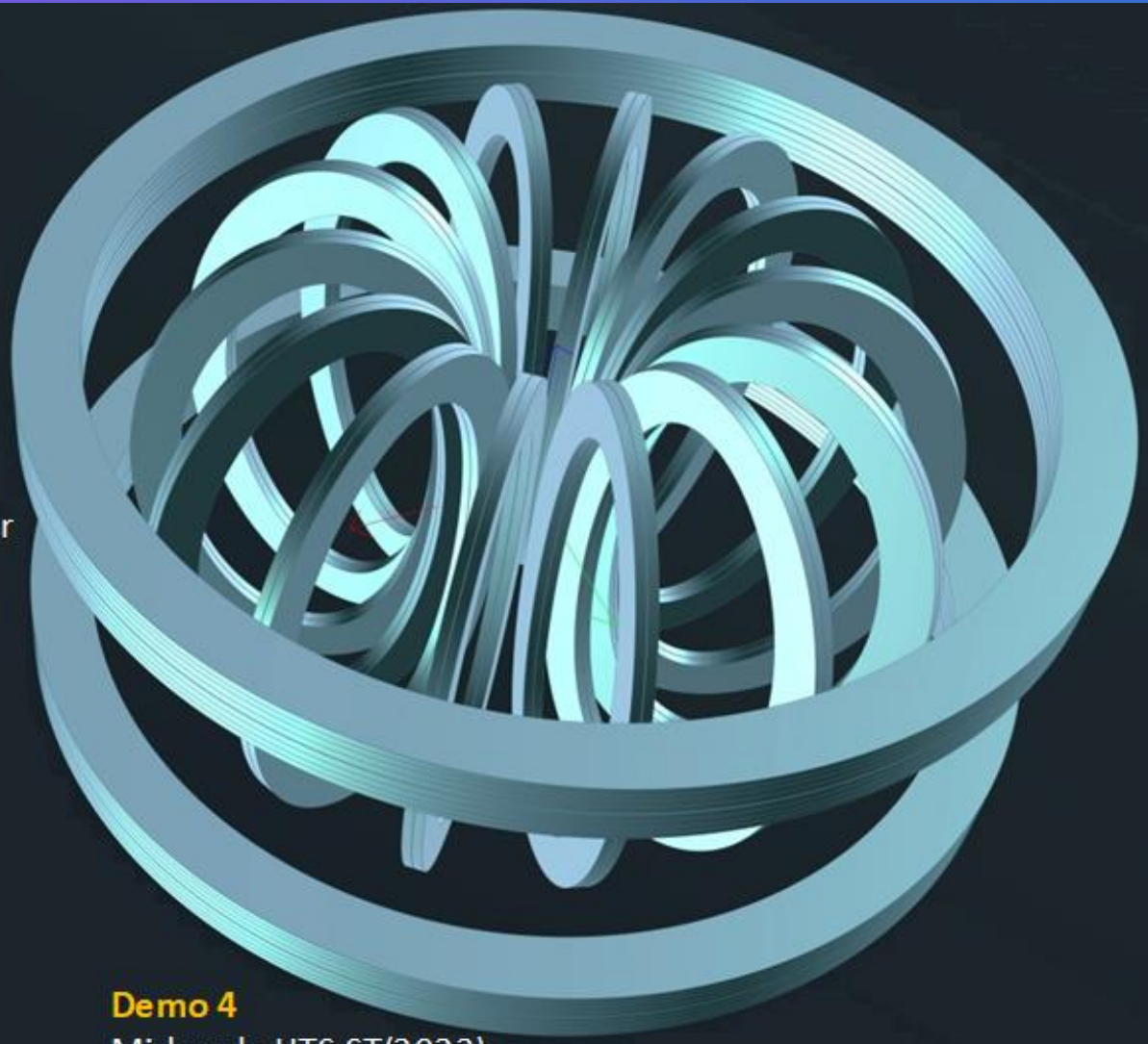
Demo 2
Mid-scale PI HTS magnet (2020)
Unique and novel quench behaviour

Franken Coil
Stack of QA coils (2018)
15 T peak field on coil



QA First small HTS test coils (2018)

Demo 3
Small high field NI HTS magnet (2019)
24 T peak field on coil



Demo 4
Mid-scale HTS ST(2023)
Demonstrate reactor-relevant HTS performance

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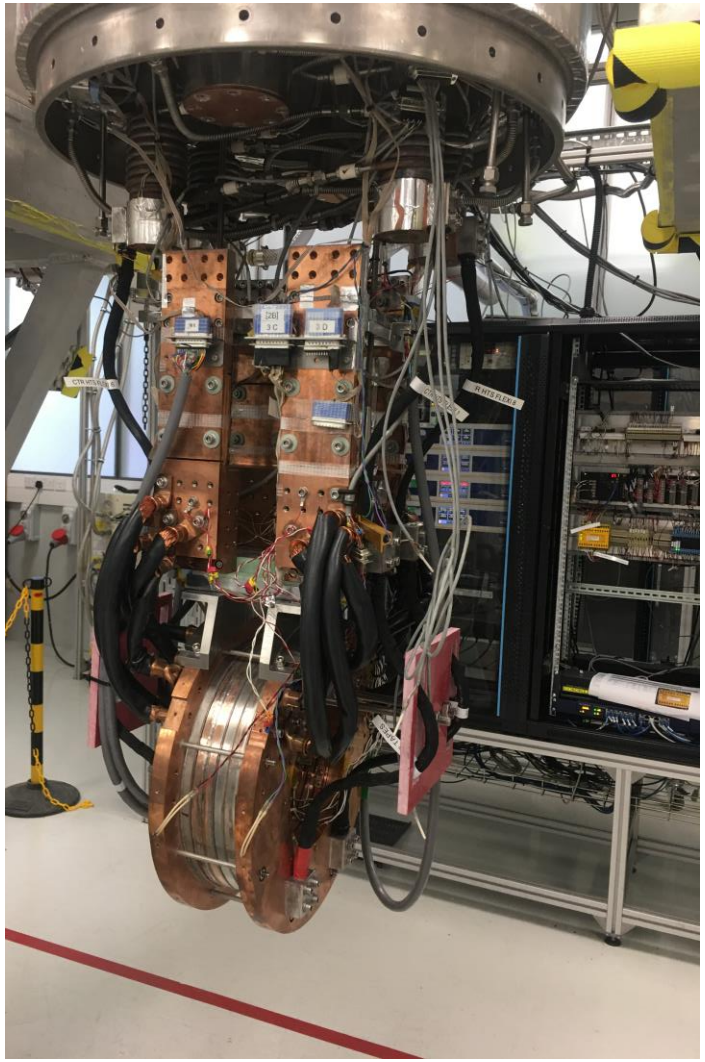
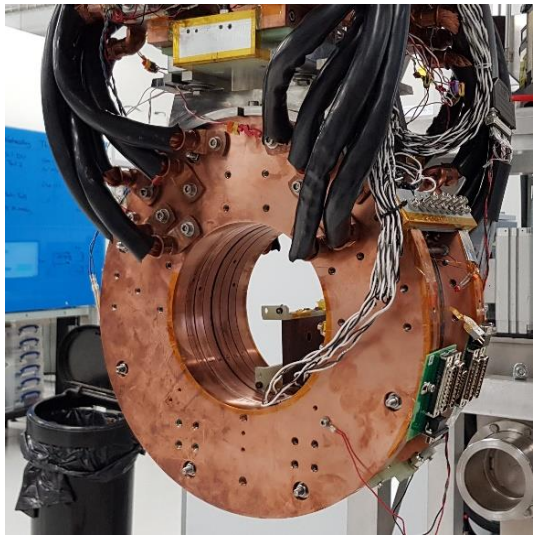
TE magnet laboratory





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2018: Quality assessment (QA) no insulation (NI) coils

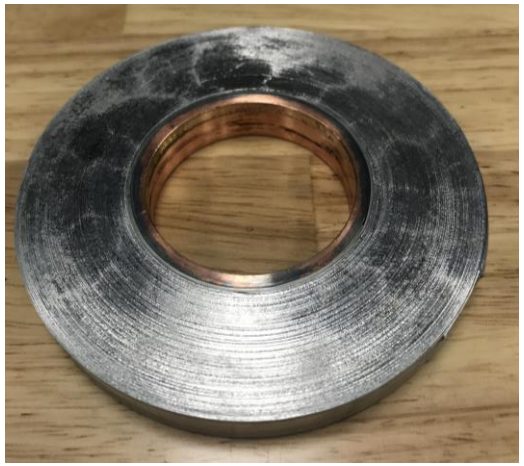
Mission: Assess quality of commercial HTS tapes from multiple suppliers in a real NI coil

- Non-insulated (NI) double pancake coils
- 50 mm ID 96 mm OD ~100 m of 10/12 mm tape in DP
- Fully solder impregnated
  - Highly defect tolerant
  - High turn-turn electric/thermal conductivity
- Conduction cooled (~12 K), current up to 3 kA

Novel stacked pancake magnet construction

- Electro-thermal interface (ETI) plates
- Ring joints at coil ID/OD
- Simple thermal & electrical interface plates
- Modular, stacked coil construction
- De/re-mountable 3 kA coil-coil joints

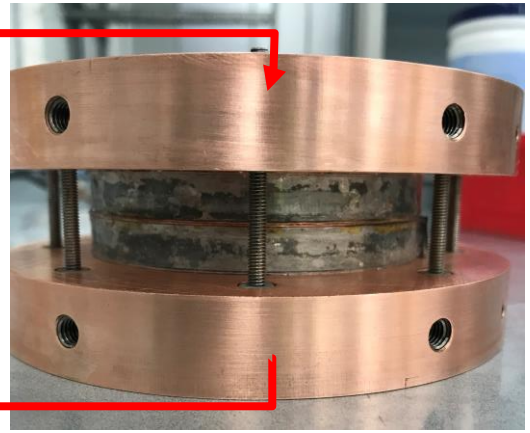
Solder encapsulated coil



ETI plates attached to faces

Stack two pancakes and current lead plates

Current in



Current out

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Demonstrating the robust nature of "QA" NI coils

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Perforated QA Coil

Coil re-tested with 50 turns severed.

Operates completely stably

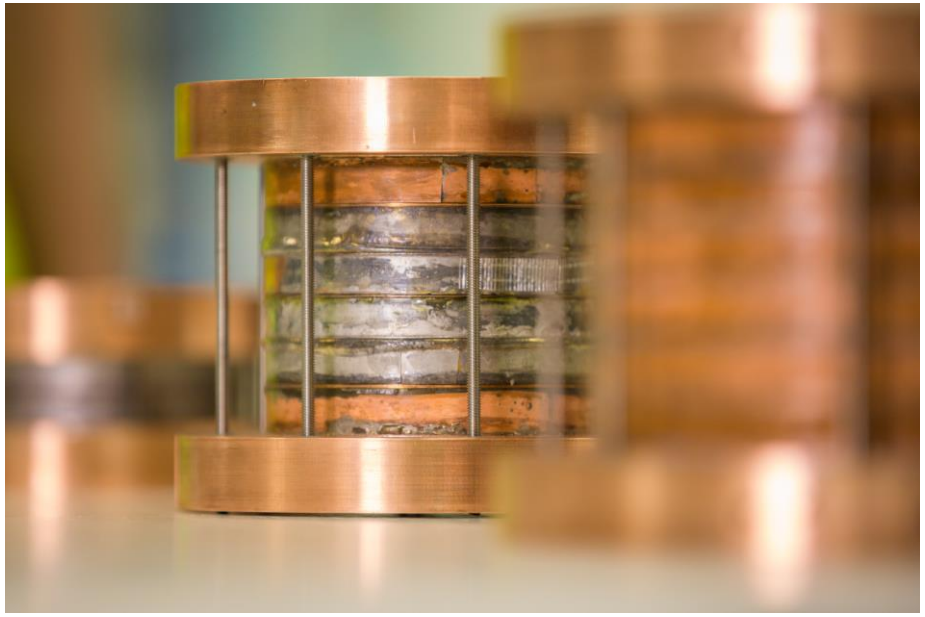
Spark Eroded QA Coil

Coil retested with quadrant removed

Operates completely stably

Mixed QA Coil Stack

(Franken Coil)



Best 3 QA coils were dismantled, re-stacked and re-tested

Operates completely stably at 16.5 T

The QA coils demonstrated that coils wound from REBCO tape can be extremely **robust** if the appropriate novel coil structure is developed. Current sharing between tapes and turns makes them **defect tolerant**. As a result we can build coils from short tape lengths, from multiple suppliers.

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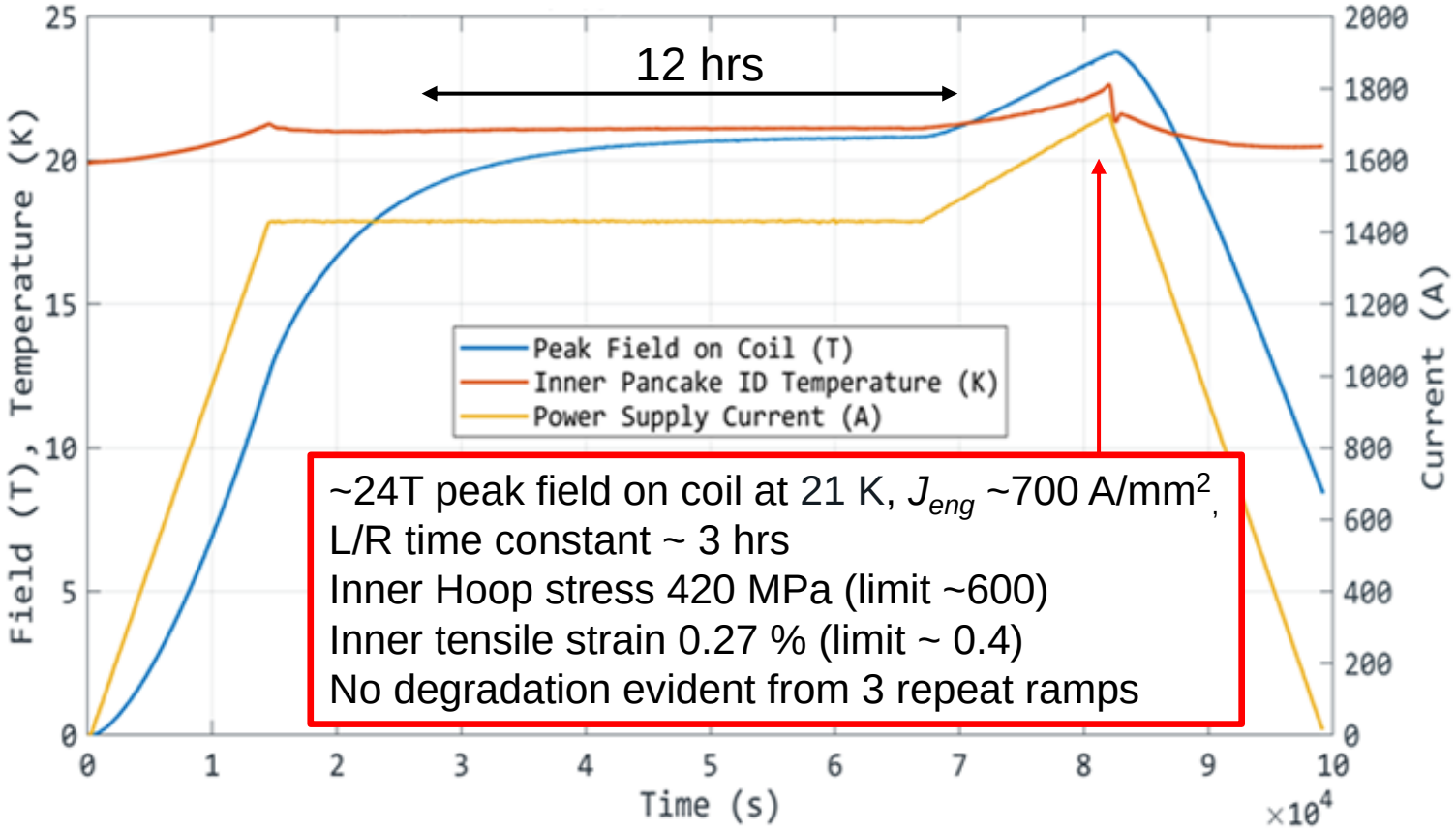
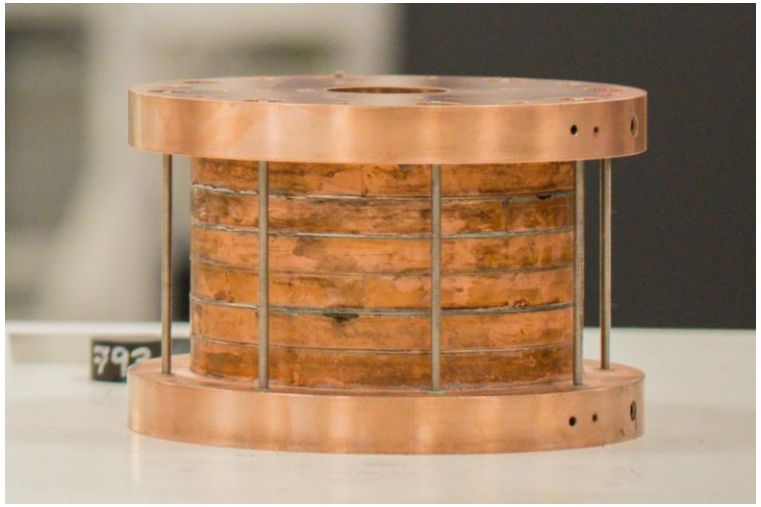
2019: Demo3 – over 20 T NI HTS magnet

Mission: demonstrate field > 20 T on tape (a fusion tokamak requirement)

- 6 pancake stack wound with two 12 mm tapes, solder potted, no over-bind
- ID 50 mm, OD 140 mm, total tape length only 738 m
- Long ramp time constant, but extremely quench stable



~24T peak field on coil at 21 K, J_{eng} ~700 A/mm^2,
L/R time constant ~ 3 hrs
Inner Hoop stress 420 MPa (limit ~600)
Inner tensile strain 0.27 % (limit ~ 0.4)
No degradation evident from 3 repeat ramps



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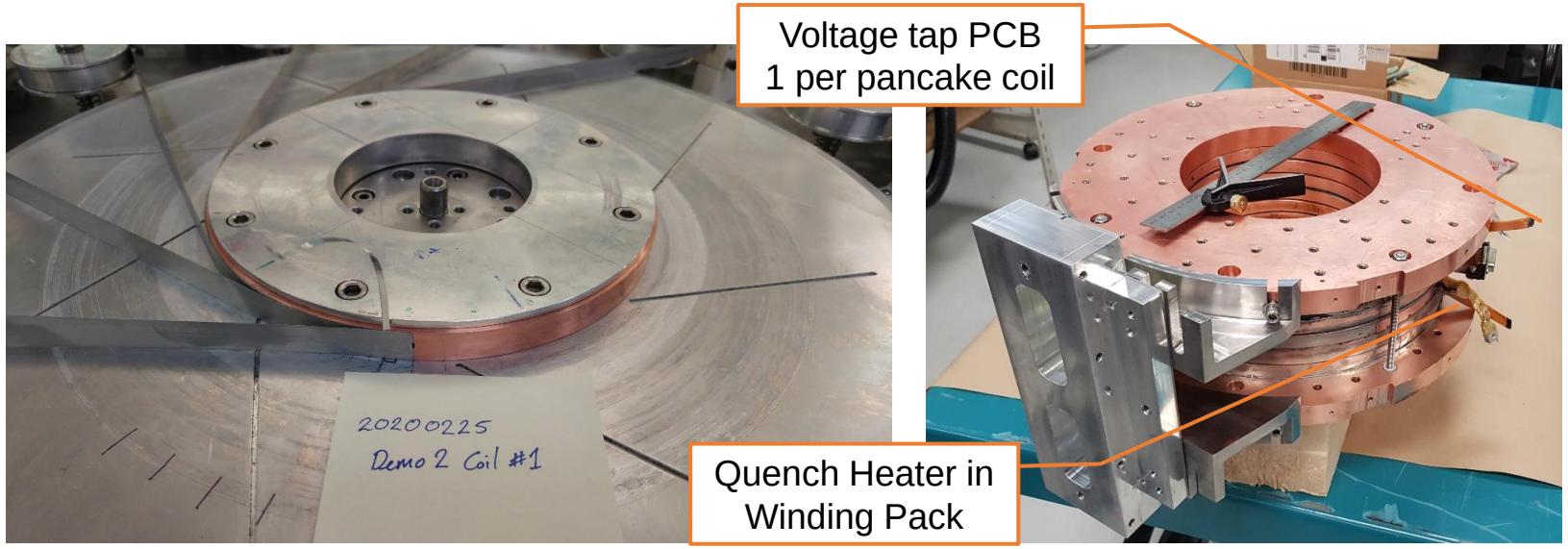
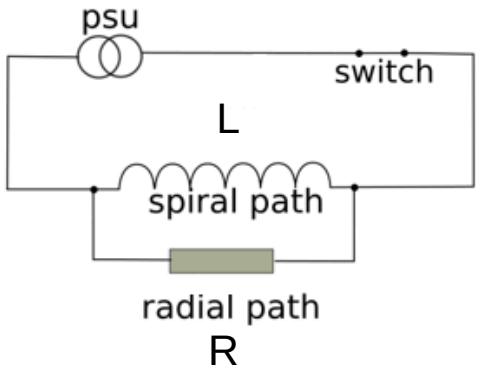
2020: Demo2 - scaling up using partial insulation (PI)

Mission: demonstrate capability to fast ramp a large no-insulation coil



- Scaling up NI coils results in a very slow ramp time due to high L/R time constant
- Putting ***novel partial insulation (PI)*** between turns allows desired, higher, turn-to-turn resistance (R)
- L/R ramp time constant can be reduced to suit coil size and application
- PI allows fast ramping of large coils, but retains the excellent quench stability & defect tolerance demonstrated in our solder potted NI coils



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2021: Buffer Layer Insulated (BLI) coils

An HTS coil in which the turns are insulated by the buffer layers within the HTS tapes

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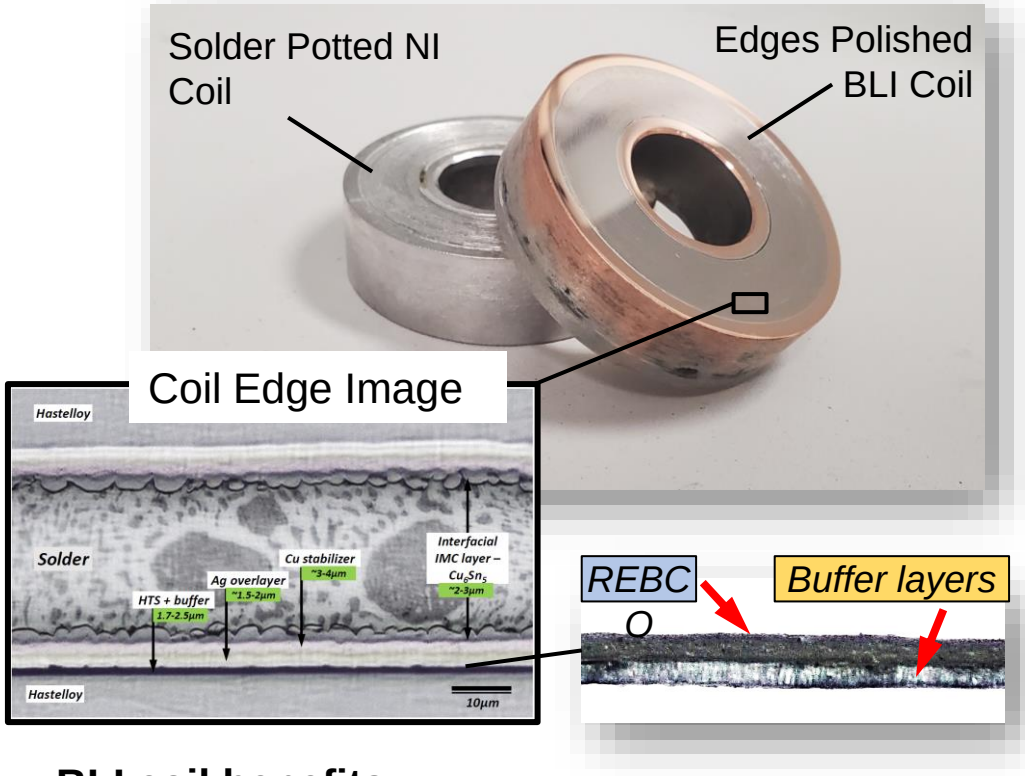
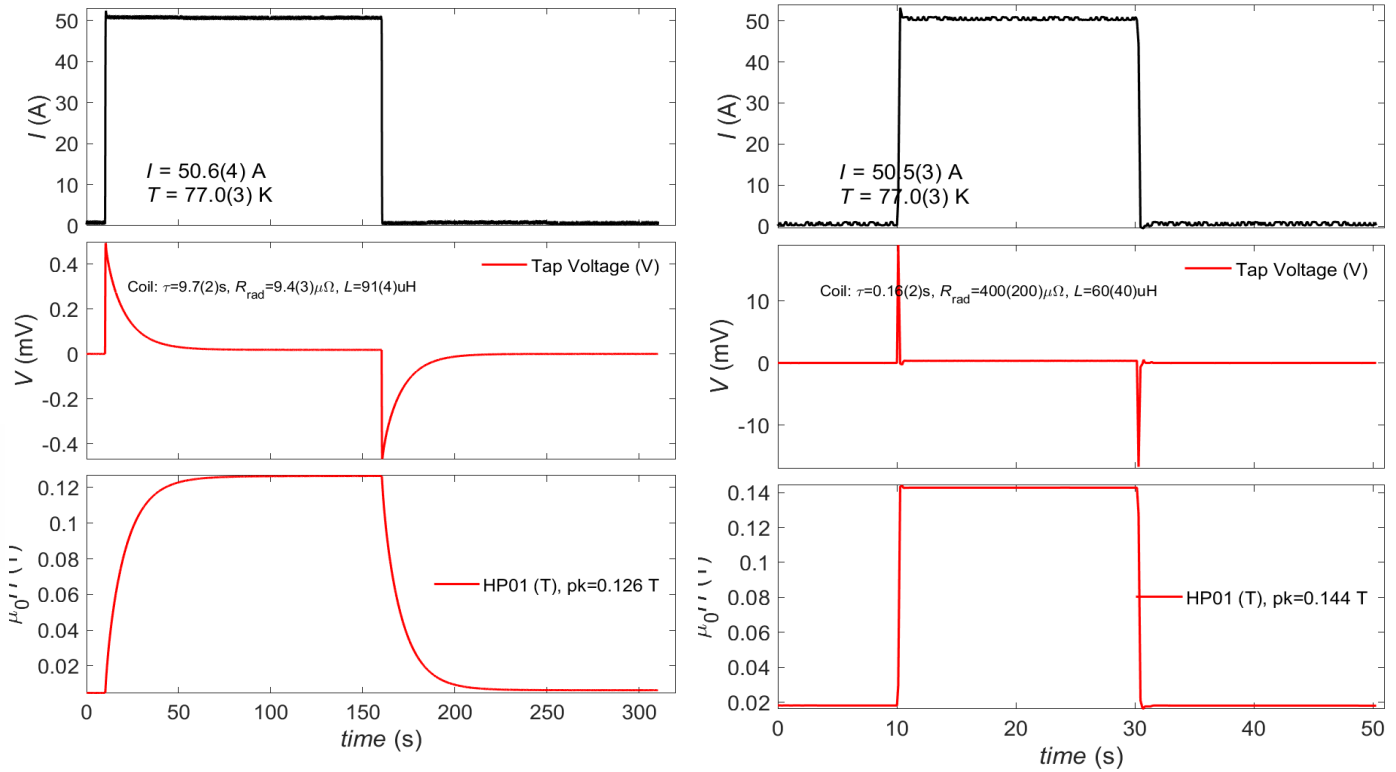


Mission: demonstrate high current density, robust pulsed / AC coils

Step Current Response



Classic NI Behaviour

τ ~ 10s / ρ_{tt} 11.7 nΩ.m

Highly Responsive

τ < 160 ms / ρ_{tt} > 730 nΩ.m

Fully insulated or very high R

BLI coil benefits:

- Fully dense HTS windings – no space used by insulation
- High Young's modulus
- Solder consolidated
- Fully insulated for very short time constant
- Less quench robust than NI / PI

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2021: Cryogenic power electronics

Mission: Develop a compact cryogenic power supply to energise superconducting magnets with improved thermal efficiency

- Power electronics at cryogenic temperature fully integrated with HTS magnet
- Reduced overall losses
- Potential to reduce system operating costs significantly
- 1000 A continuous and 2000 A pulse current operation demonstrated
- Capability to transfer power across a gap by transformer action (eg: charge HTS coils on a rotating component)

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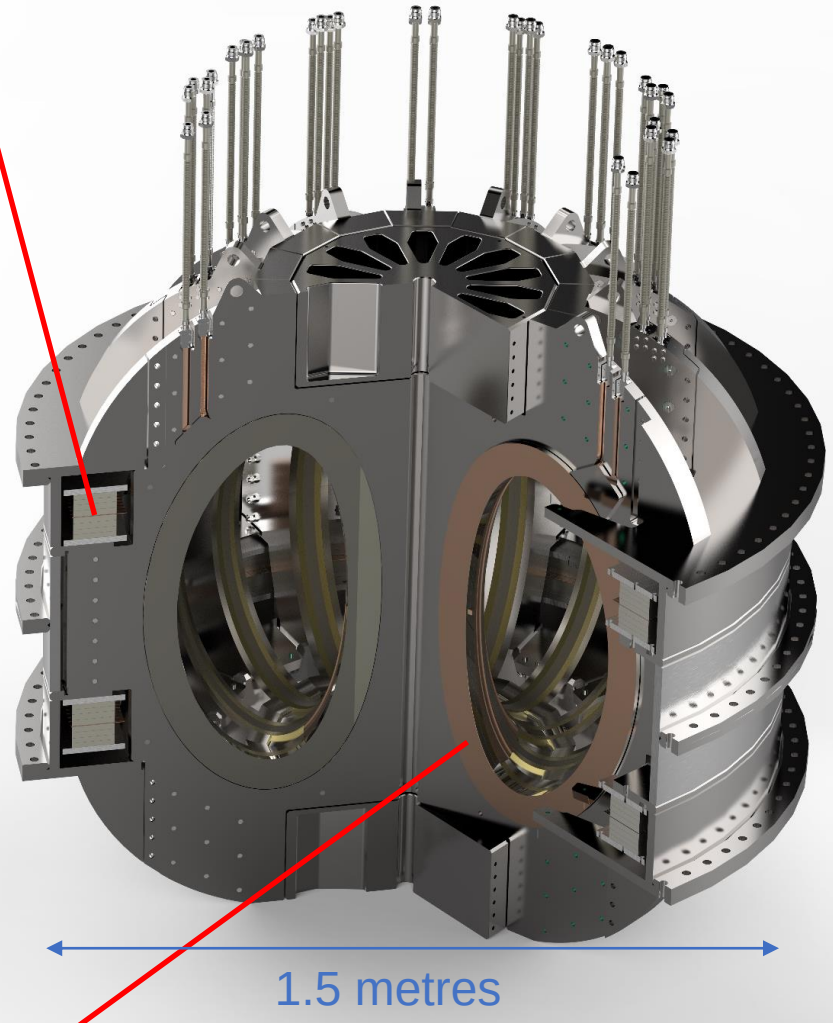
2022: Demo4 - full tokamak HTS magnet set

Mission

- Full toroid HTS **PI** magnet set
- Pair of HTS poloidal field (PF) coils (insulated)
- Generate 10 T static field @ 0.25 m radius
- 18+ T on centre column
- Exceed 250 MPa compressive stress on tape
- Operate @ ~20 K
- ~20 MJ stored energy
- Demonstrate **PI** quench protection of DC TF coils
- Demonstrate mechanical performance of TF coils up to 250 MPa
- Investigate the effects of PF field-shine on TF coil operation
- Measure AC losses in PF coils
- Investigate the effects of modulating PF coils on TF coil operation
- Develop REBCO coil manufacturing processes and tooling for full size tokamak coils
- Validate our advanced electromagnetic simulation tools



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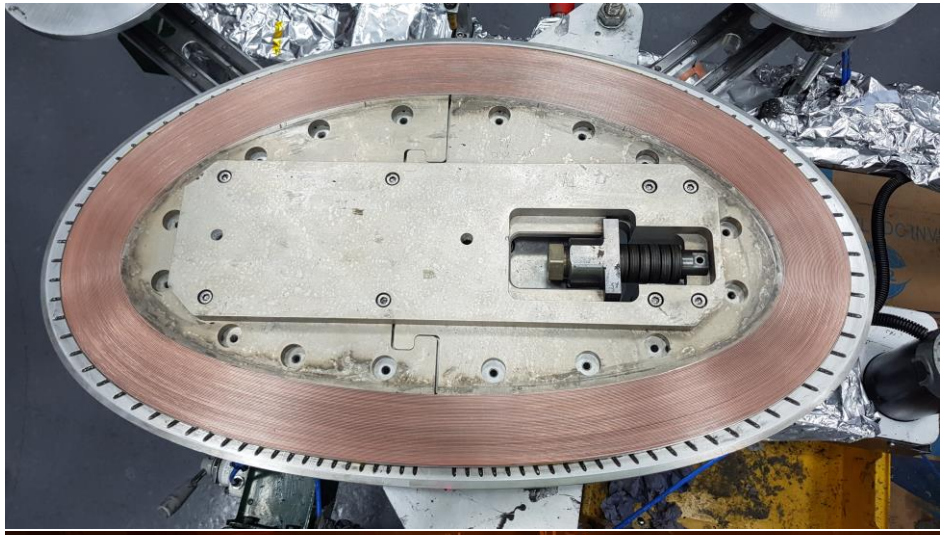
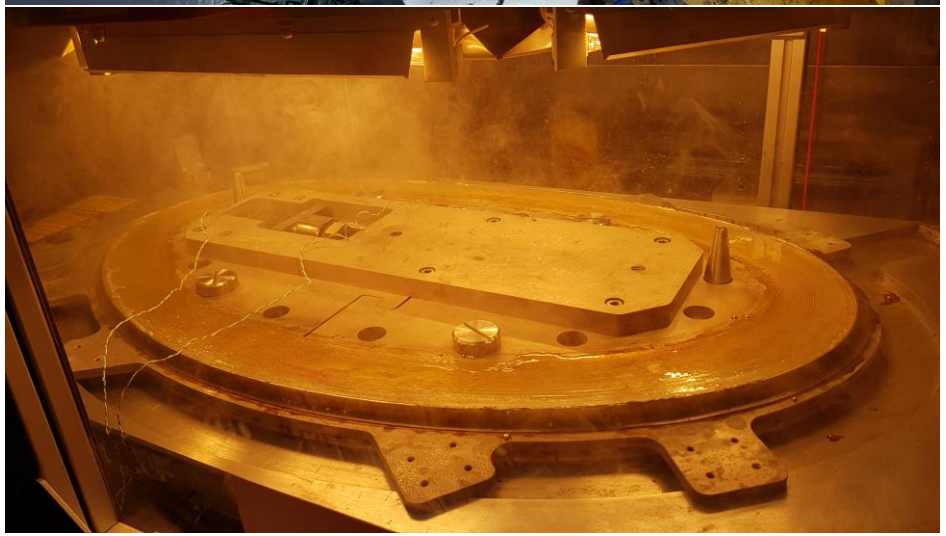
Demo4 manufacturing: HTS TF coil





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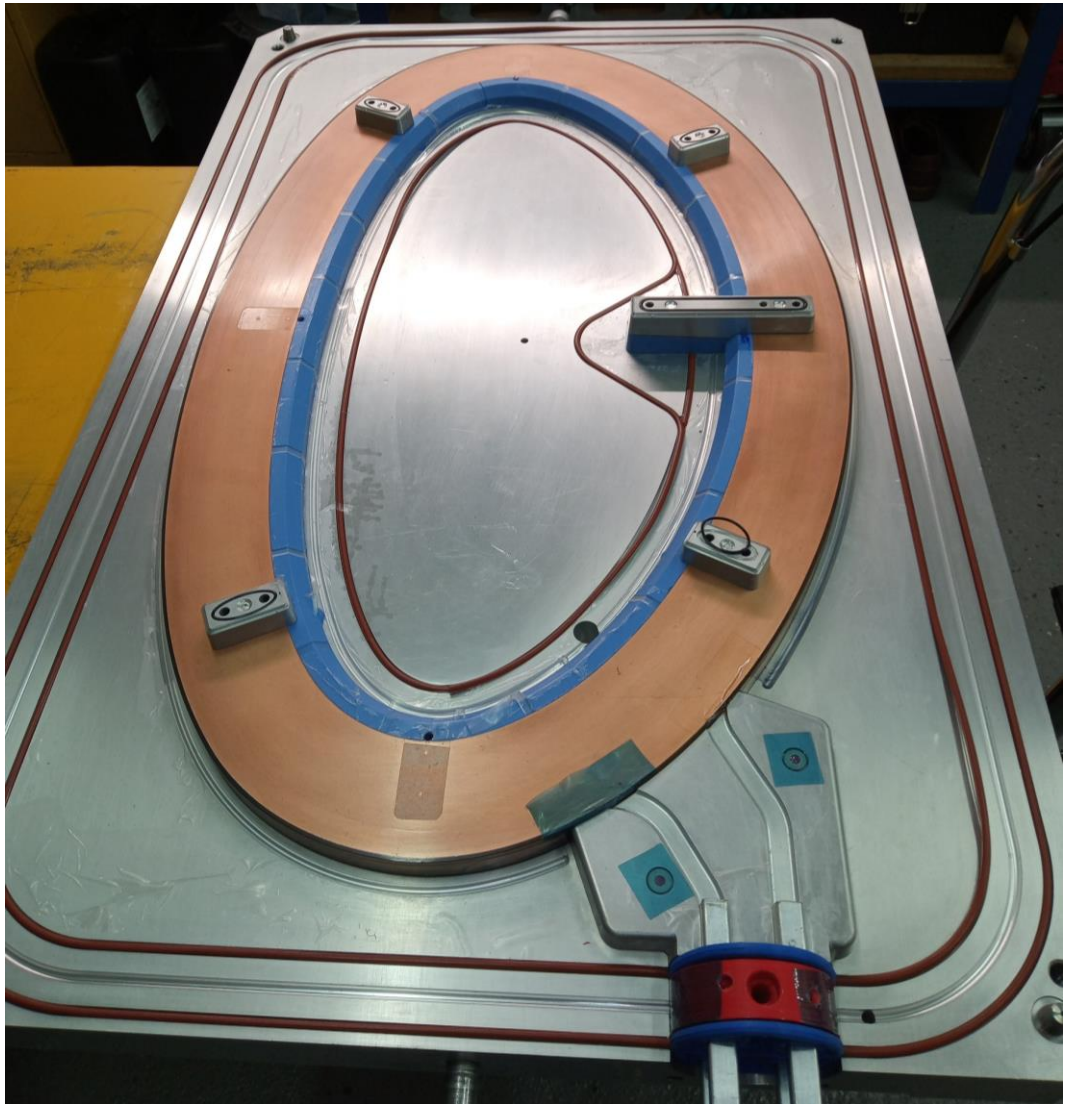
Demo4 manufacturing: TF coil tooling



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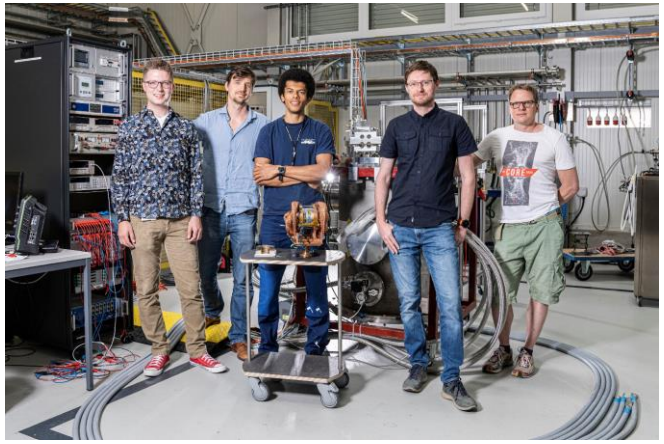
Advanced Technology Applications (ATA) projects

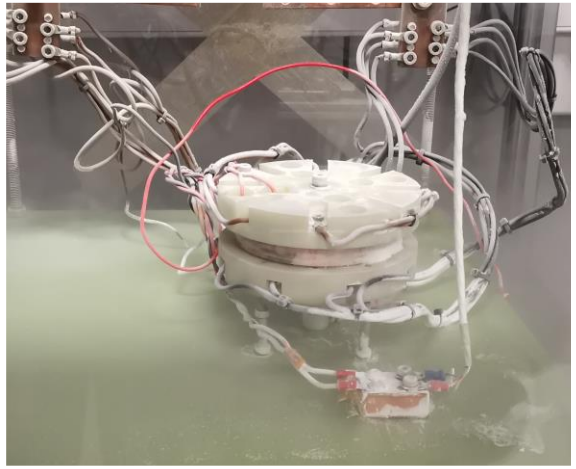
Technology demonstrator for an Adiabatic Matching Device (AMD) - Paul Scherrer Institute (2021 – 2022)

- License agreement with Paul Scherrer Institute for TE magnet technology transfer
- To be used in accelerator magnets
- AMD achieved 18 T in bore



Satellite propulsion thruster – Magdrive (2021 - 2022)

- Preliminarily tested TE HTS QA coils under space rated conditions (vibration and thermal cycle)
- Plan to develop a satellite plasma thruster



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TE technology for electric propulsion

We believe the tools/technology developed within TE for realising fusion power can help solve the technological challenges of electric aircraft propulsion

TE's HTS magnet technology

- Compact, high current density
- High field
- 20 K to 77 K operation
- NI/PI coils for DC operation
- BLI coils for pulsed / AC operation
- Mechanically & electromagnetically robust
- Easy to manufacture and assemble

→

- **Light weight**
- **High power**
- **LH_2 or LN_2 cooling**
- **PM replacement**
- **HTS field coils**
- **Inherent safety**
- **Low cost & DFM**

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