UNIVERSITY OF CAMBRIDGE

EUCAS 2017

ASCG APPLIED SUPERCONDUCTIVITY AND CRYOSCIENCE GROUP

Progress in trapped field magnets made from stacks of coated conductor tape

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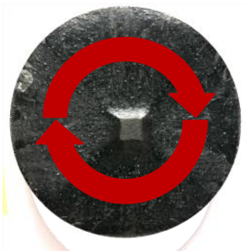
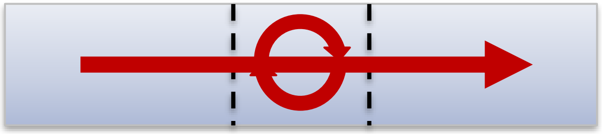
1. Introduction
Persistent currents and superconducting bulks

Bulk (RE)BCO

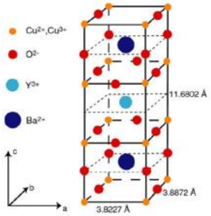


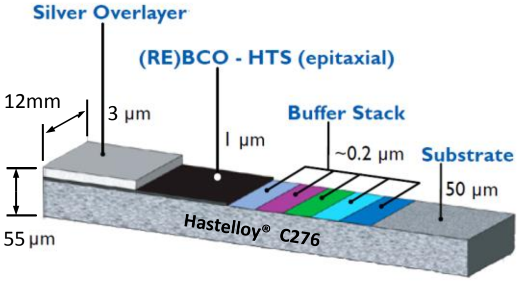
Bulk MgB_2

2nd Generation (2G) HTS tape



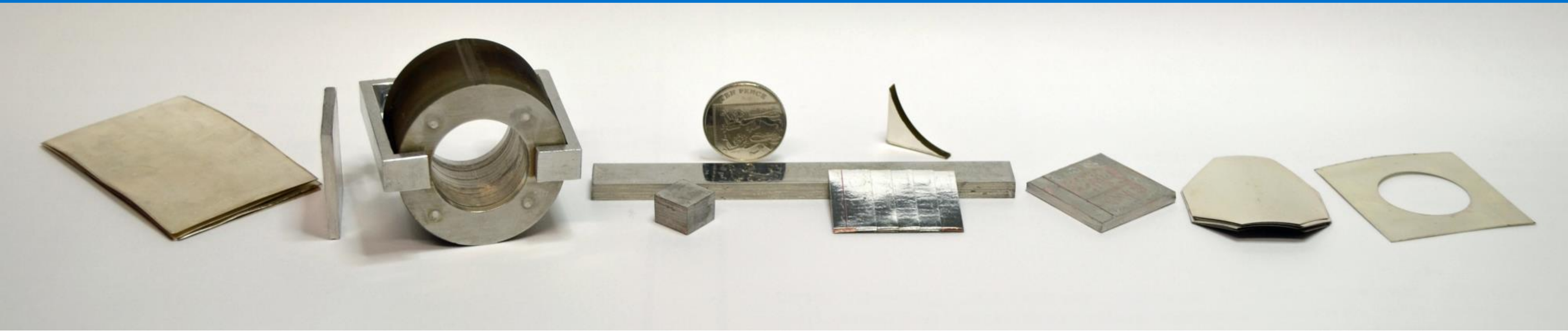
T_c = 91 K

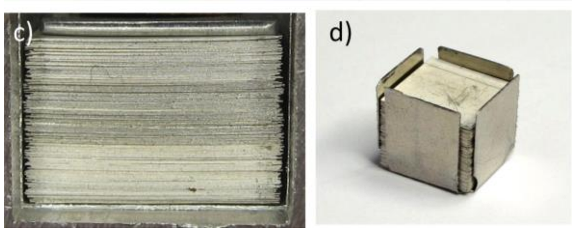




- Superconducting bulks and stacks of tape are the most compact source of high magnetic field greater than rare-earth magnets
- The ability to sustain persistent currents allows them to act as permanent magnets

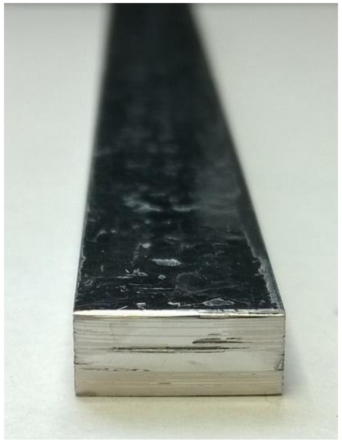
1. Introduction
Stacks of tape as composite bulks



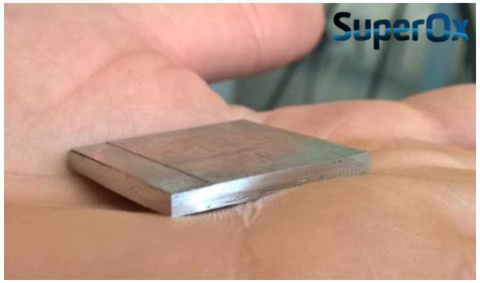


12mm wide tape is standard

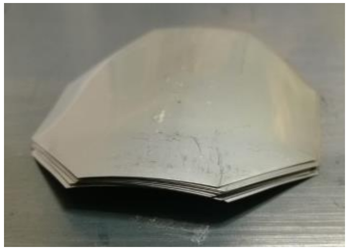
Flexible geometry and relatively predictable superconducting properties
High degree of engineerability

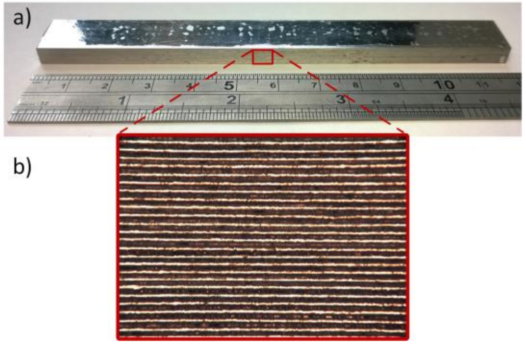


Self supporting stacks using solder plated tape

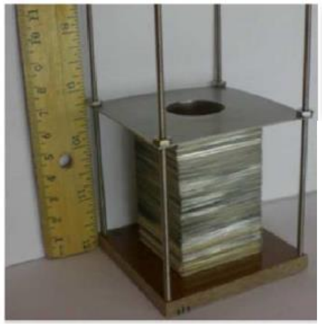


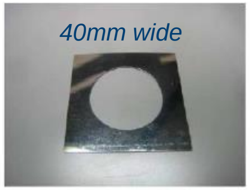
>12 mm wide tape also available





1. Introduction
Existing research areas for stacks of tape

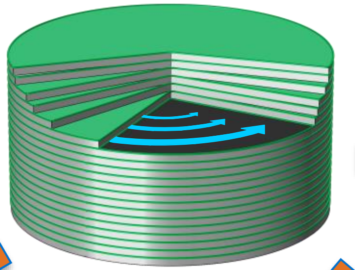




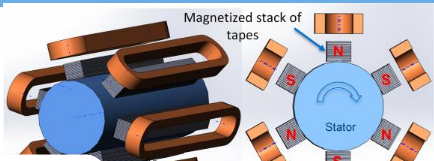
NMR magnets

Hahn S et. al. 2011 *IEEE Trans. Appl. Supercond.*, **21** 1632-1635

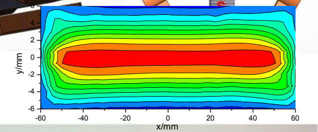
- Stable, uniform trapped fields for potential desktop NMR
- 0.7T @ 77K, ≈ 3T @ 4.2K

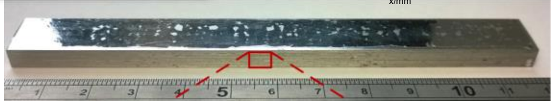


Patel A et al. 2015 *IEEE Trans. Appl. Supercond.*, **25** 5203405



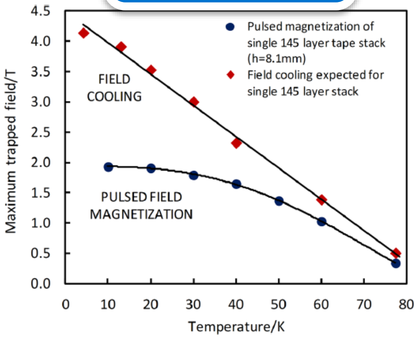
Motor field poles





- Motor field poles, flexible shapes
- EU project, 1 MW motor ASuMED

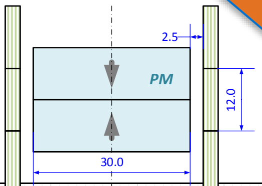
High field PMs

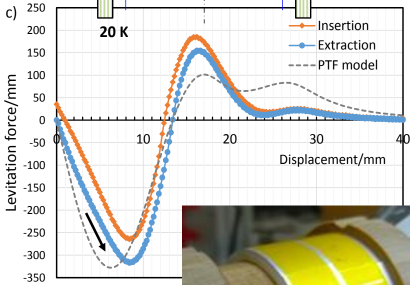


Patel A et al. 2013, *SUST*, **26** 032001

Magnetic levitation

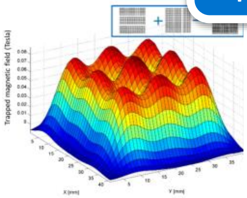
- Stable levitation
- Flexible geometries

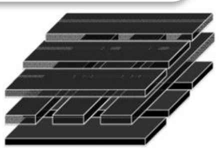




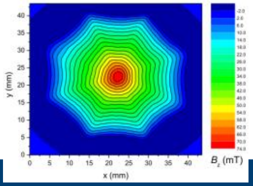
Patel A et al. 2015, *Supercond Sci Tech*, **28** 115007

Patterned field PMs



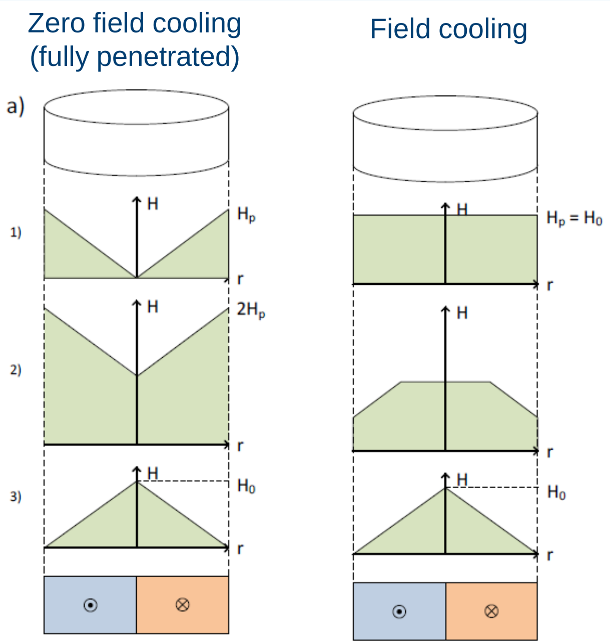


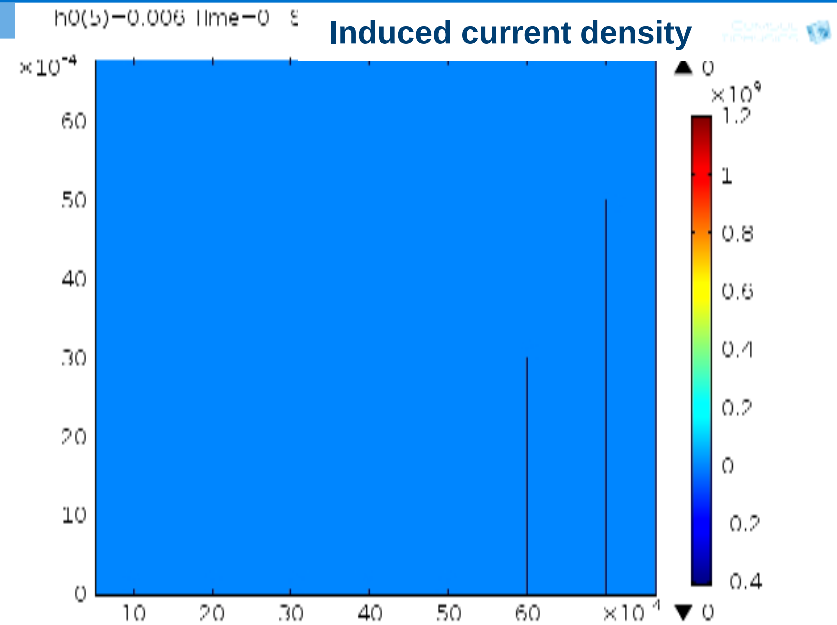
Selva K et al. 2013 *Supercond Sci Tech*, **26** 115006



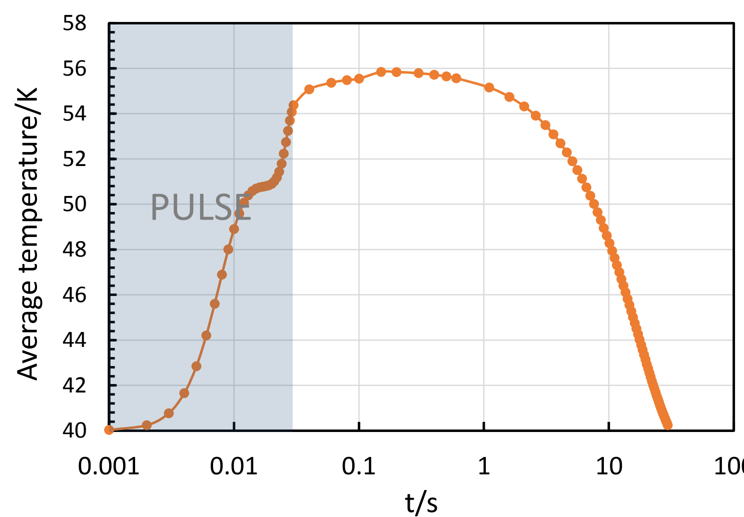
Patel A et al. 2014 *J Supercond Nov Magn*, **28** 397-401

1. Introduction
Magnetizing bulk superconductors

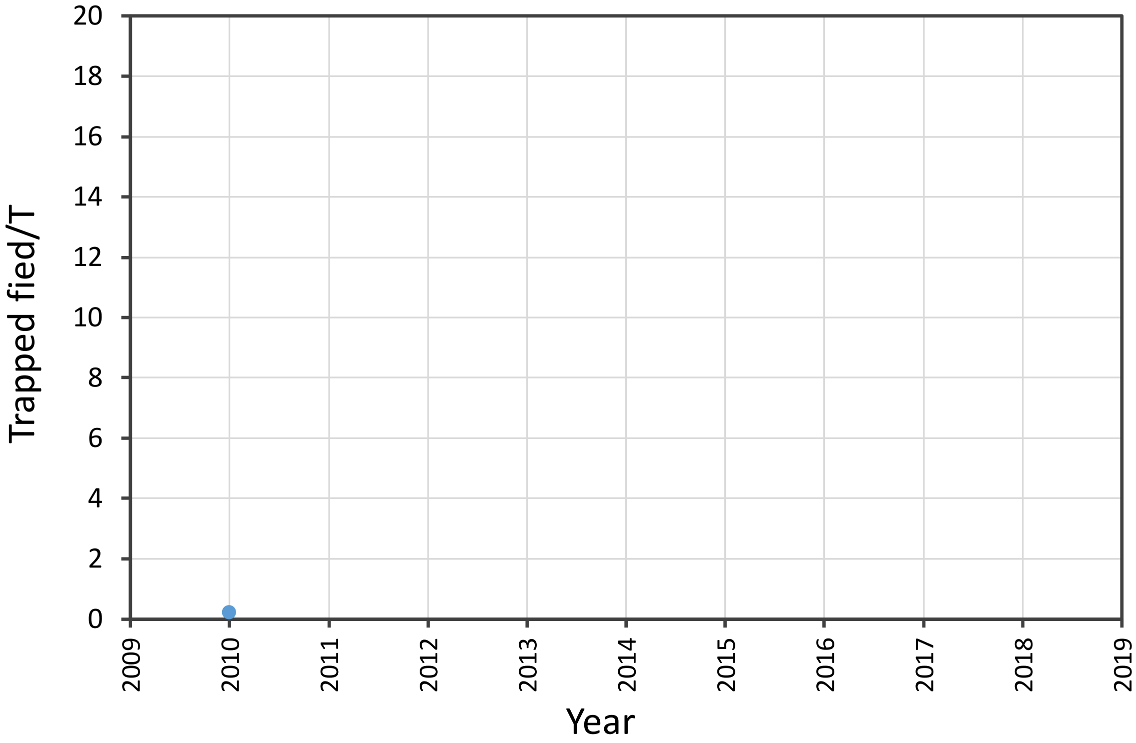




- Pulse magnetization is a type of zero field cooling
- Sufficient field needs to be applied to fully penetrate
- Field cooling does not generate significant heating in the sample like pulsed field magnetization



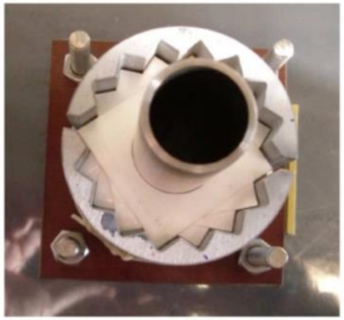
2. Previous trapped field records for stacks of HTS tape



Temperature: 77 K

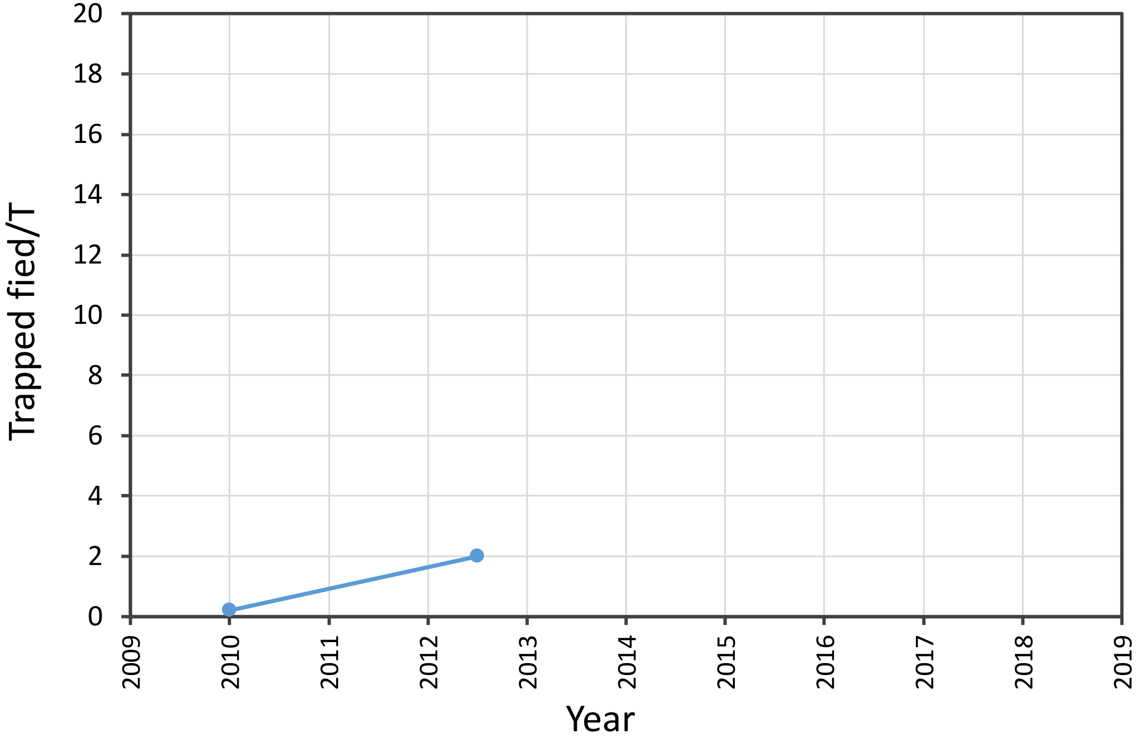
Trapped field: 0.2 T (open bore)

Tape manufacturer: AMSC



S. Hahn, S. B. Kim, M. C. Ahn, J. Voccio, J. Bascunan and Y. Iwasa, "Trapped Field Characteristics of Stacked YBCO Thin Plates for Compact NMR Magnets: Spatial Field Distribution and Temporal Stability," *IEEE Transactions on Applied Superconductivity,* vol. 20, pp. 1037-1040, Jun 2010.

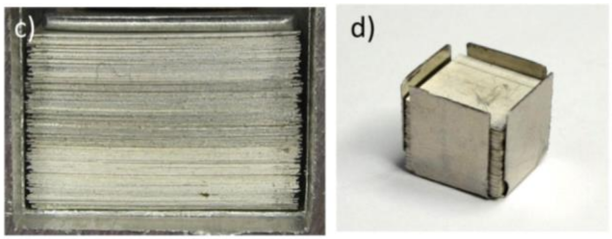
2. Previous trapped field records for stacks of HTS tape



Temperature: 10 K

Trapped field: 2 T (single stack)

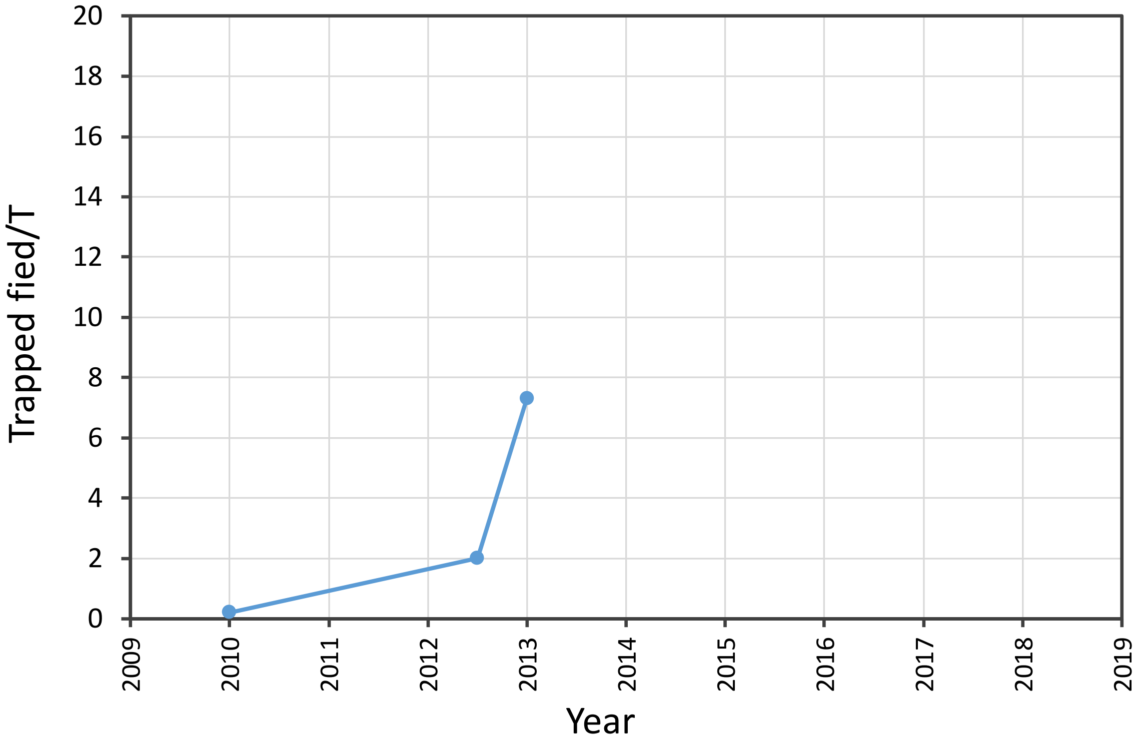
Tape manufacturer: SuperPower



pulsed field magnetization

A. Patel, S. C. Hopkins and B. A. Glowacki, "Trapped fields up to 2 T in a 12 mm square stack of commercial superconducting tape using pulsed field magnetization," *Superconductor Science and Technology,* vol. 26, p. 032001, 2013.

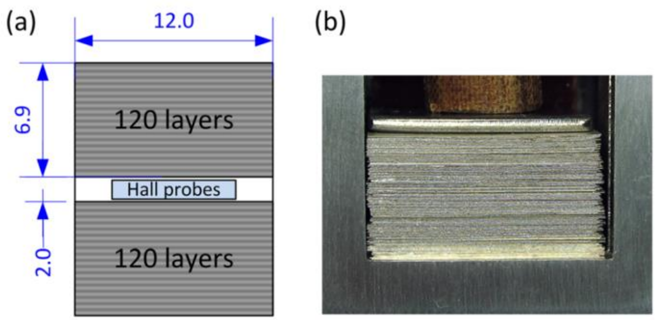
2. Previous trapped field records for stacks of HTS tape



Temperature: 5 K

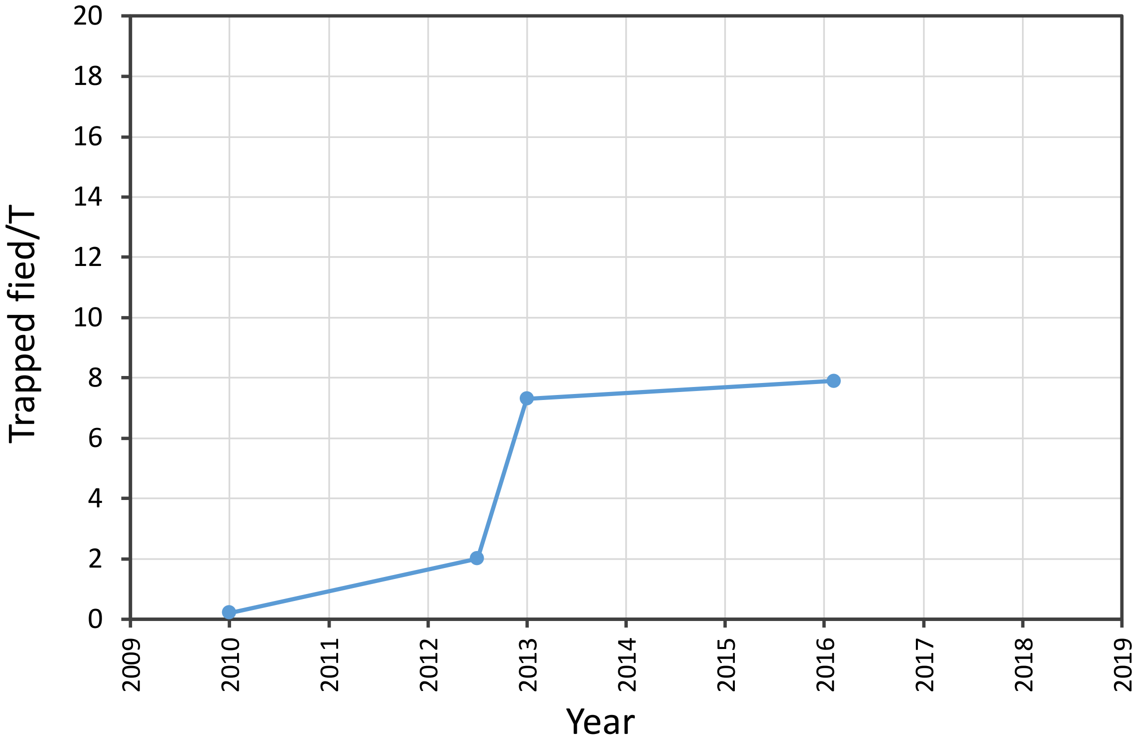
Trapped field: 7.3 T (double stack)

Tape manufacturer: SuperPower



A. Patel, K. Filar, V. I. Nizhankovskii, S. C. Hopkins and B. A. Glowacki, "Trapped fields greater than 7 T in a 12 mm square stack of commercial high-temperature superconducting tape," *Applied Physics Letters,* vol. 102, pp. 102601-5, 2013.

2. Previous trapped field records for stacks of HTS tape



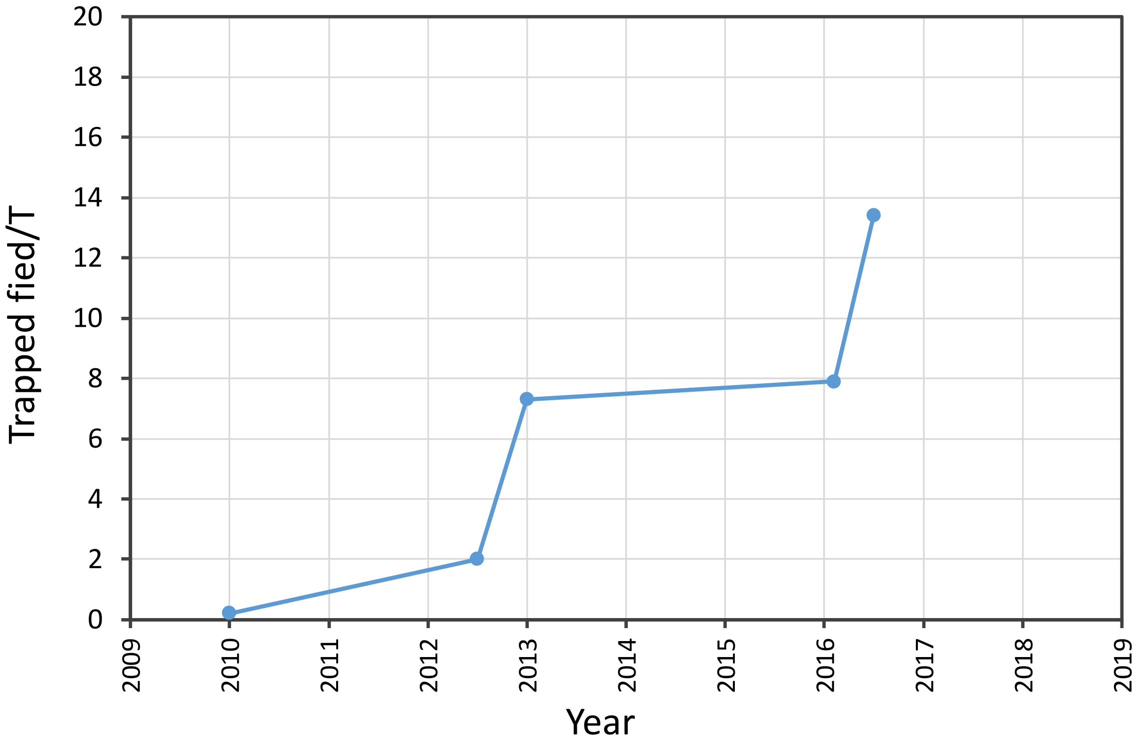
Temperature: 4.2 K

Trapped field: 7.9 T (double stack)

Tape manufacturer: Fujikura

T. Tamegai, T. Hirai, Y. Sun and S. Pyon, "Trapping a magnetic field of 7.9 T using a bulk magnet fabricated from stack of coated conductors," *Physica C: Superconductivity and its Applications*.

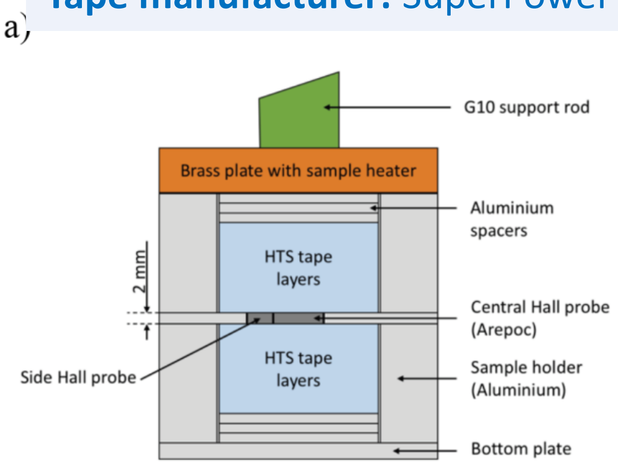
2. Previous trapped field records for stacks of HTS tape



Temperature: 5 K

Trapped field: 13.4 T (double stack)

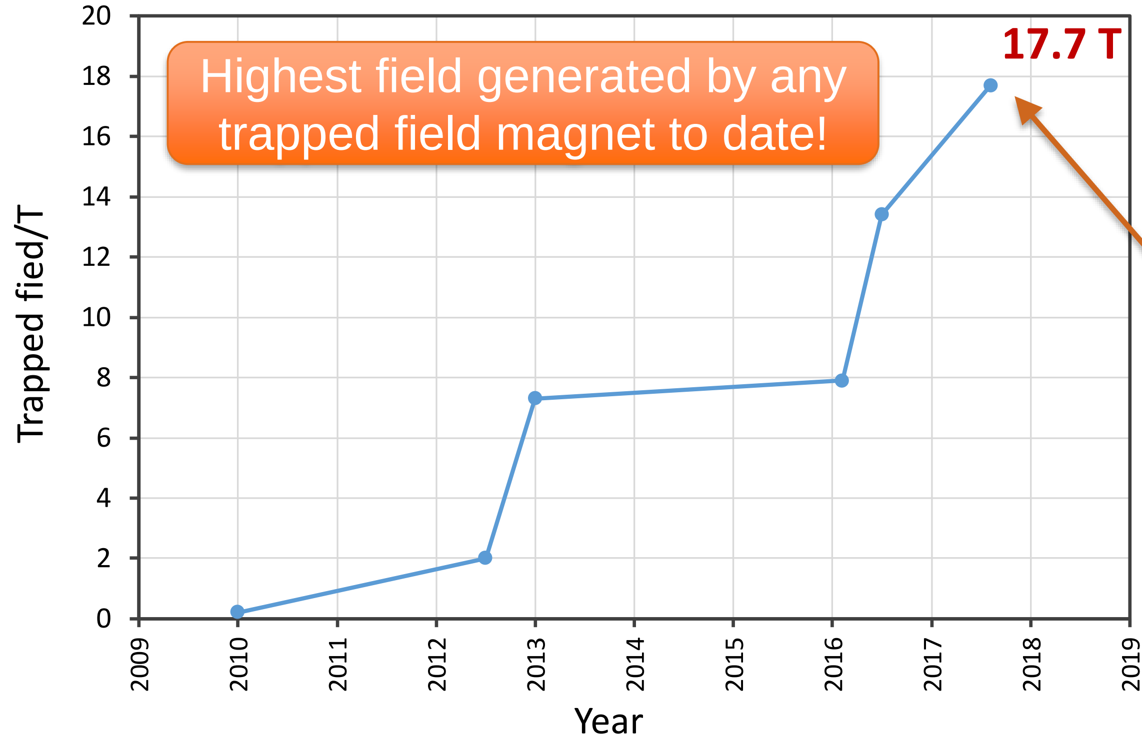
Tape manufacturer: SuperPower



30 µm substrate tape

A. Baskys, K. Filar, A. Patel and B. Glowacki, "A Trapped field of 13.4 T in a stack of HTS tapes with 30 µm substrate,", *Superconductor Science and Technology* 2017.

2. Previous trapped field records for stacks of HTS tape

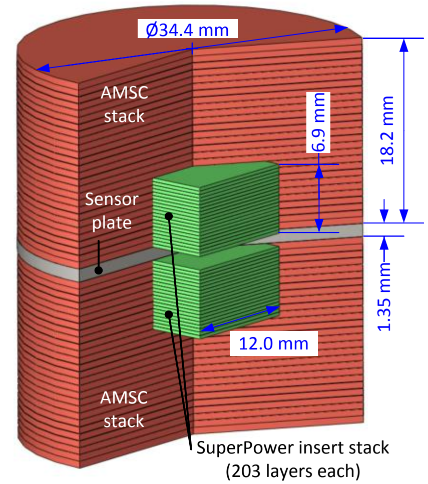


Hybrid Stack design

Temperature: 10 K

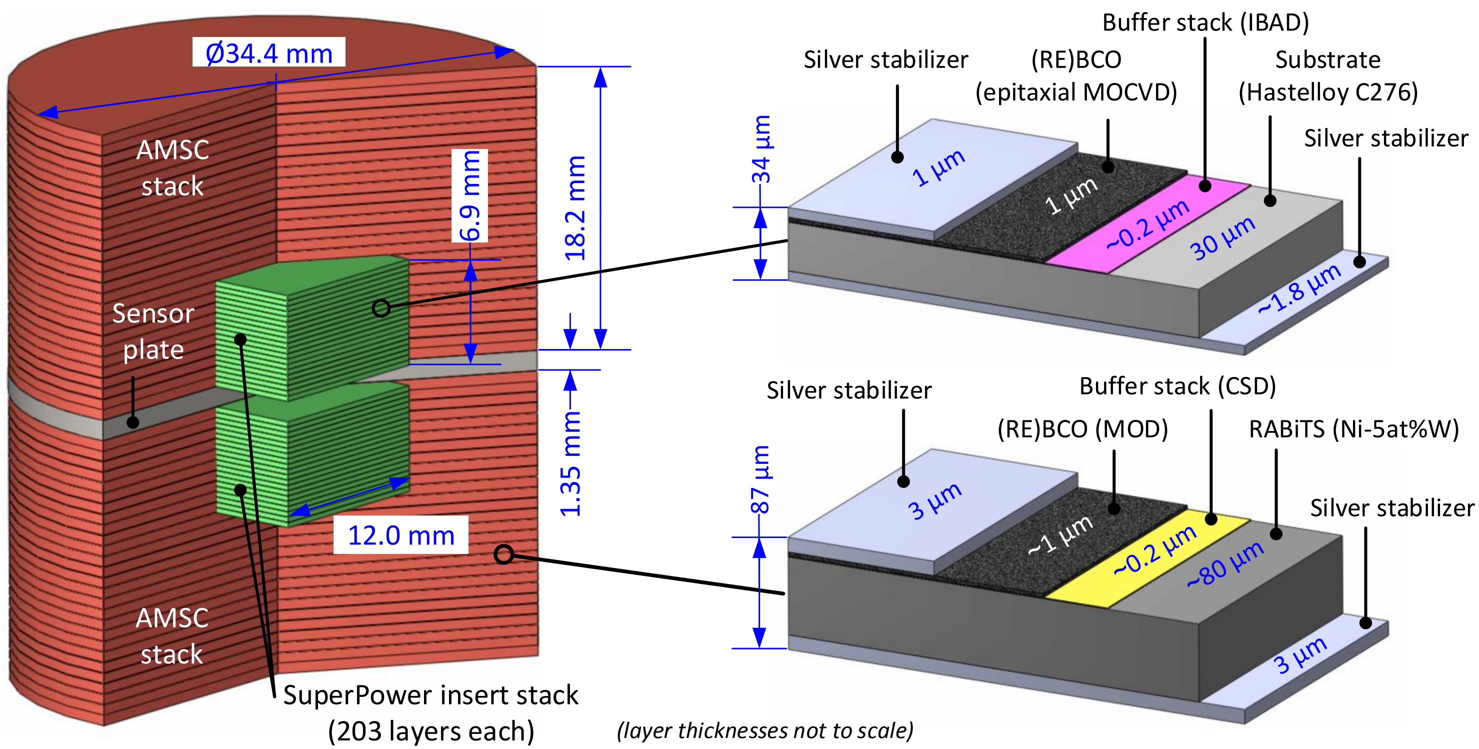
Trapped field: **17.7 T** (double stack)

Tape manufacturer: SuperPower and AMSC



A. Patel, A. Baskys, T. B. Mitchell-Williams, A. McCaul, W. Coniglio and B. A. Glowacki, "A trapped field of 17.7 T in a stack of high temperature superconducting tape " arXiv:1709.04541, 2017.

3. Hybrid stack trapped field magnet
Stack composition



SuperPower

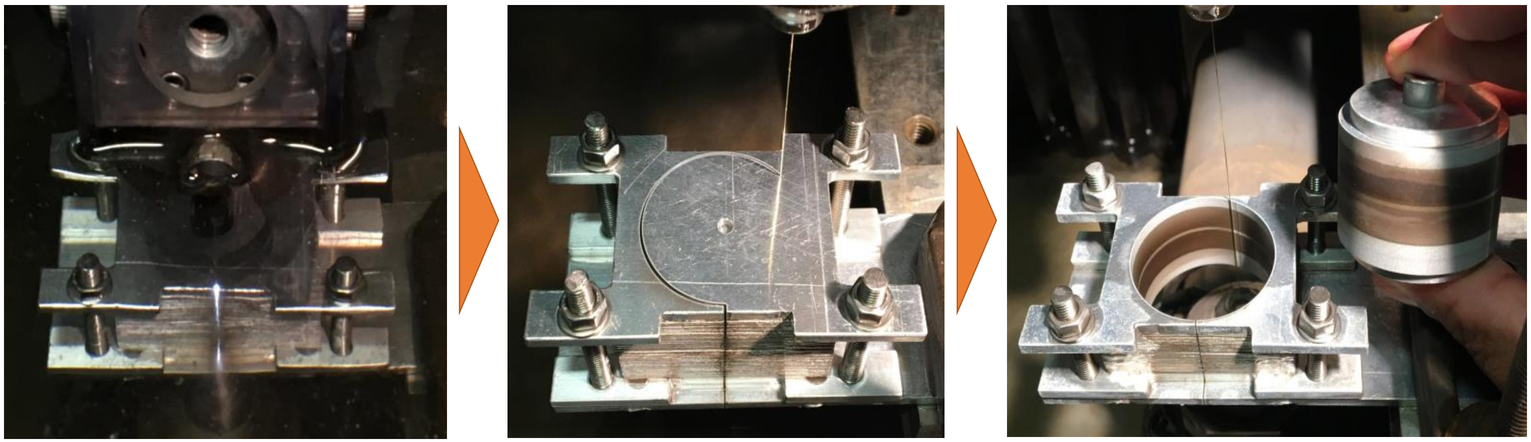
I_c = 540 A
J_e of 1.32 × 10^9 A/m^2
(77 K, self-field)

amsc

I_c of 391 A/cm-w
J_e of 4.49 × 10^8 A/m^2
(77 K, self-field)

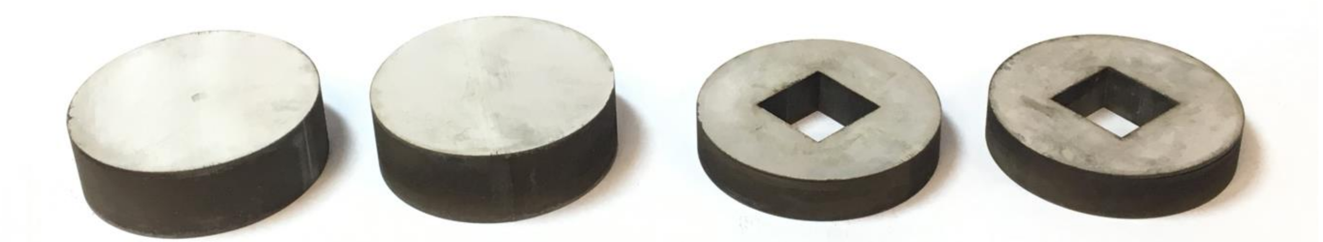
3. Hybrid stack trapped field magnet

Stack fabrication – spark erosion

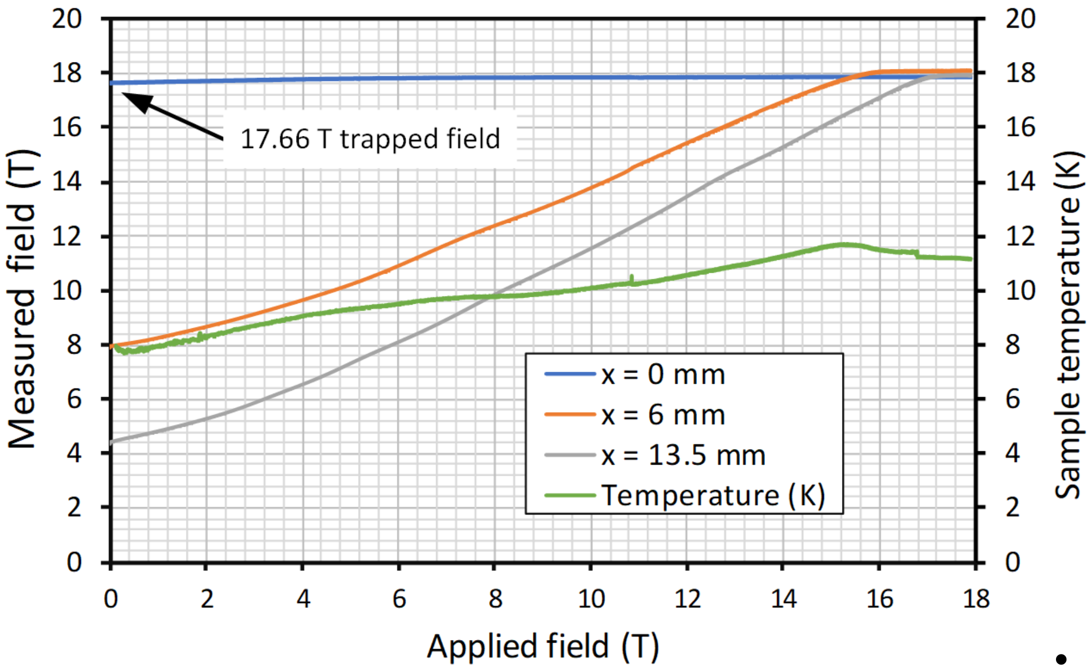


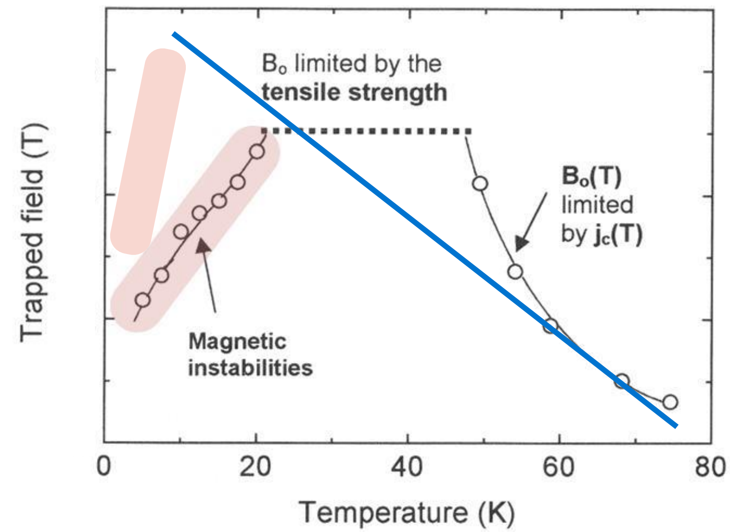
Cutting of 46 mm wide tape to 34.4 mm diameter needed to fit stack in magnet bore

- Highly precise method of machining that only works because sample is mostly metallic.
- Damage to HTS layer < 0.4 mm from cut surface
- Cut surface lightly fuses layers together aiding handling



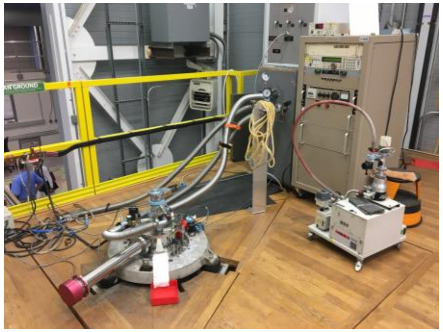
3. Hybrid stack trapped field magnet
Field cooling magnetization procedure





NATIONAL HIGH MAGNETIC FIELD LABORATORY

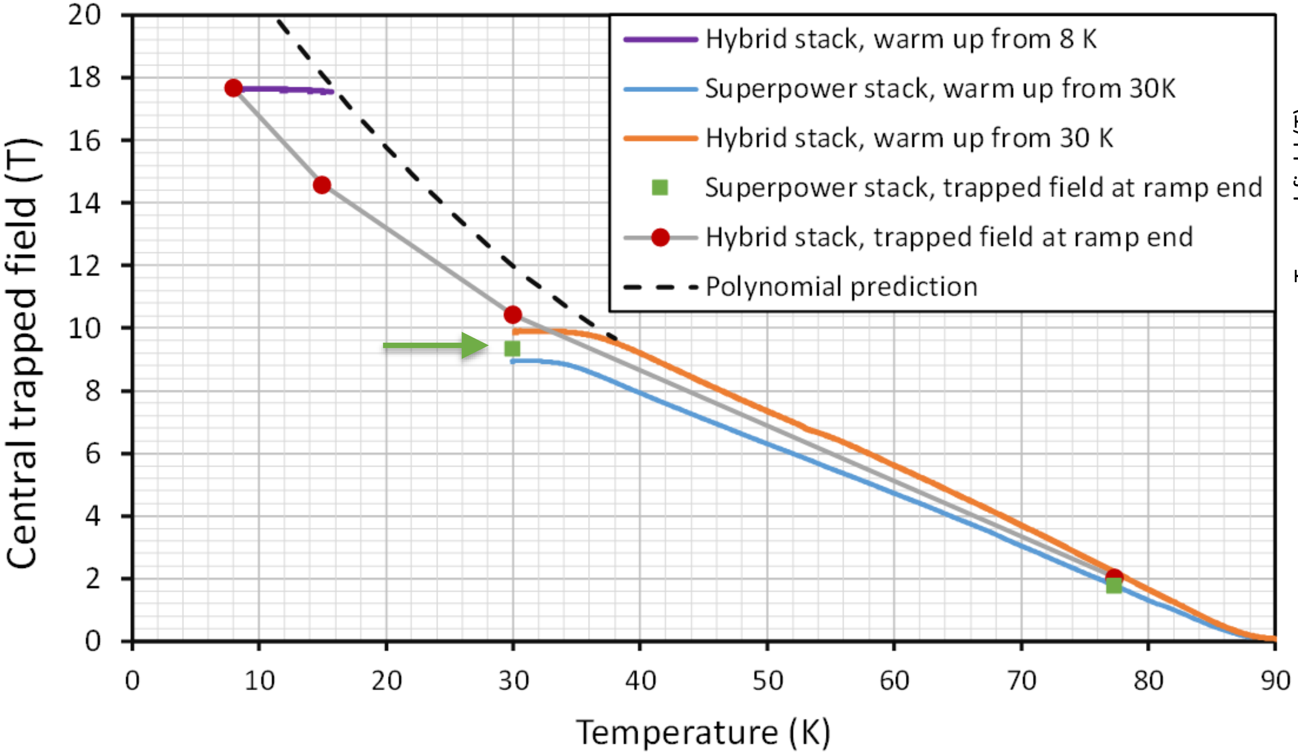
Tallahassee, Florida, USA

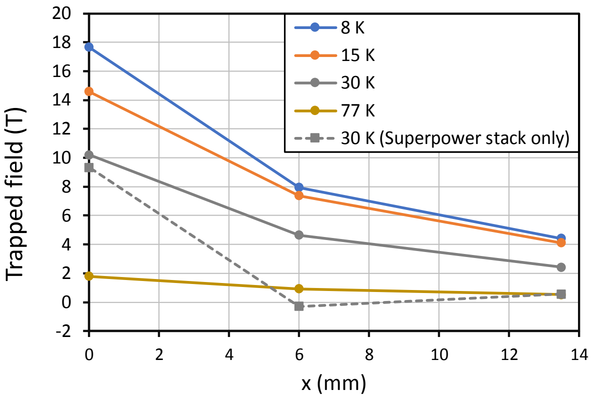


- 18 T superconducting magnet used
- Field cooling at 100 K
- Applied field was 17.9 T, ramp down at 15.5 mT/min
- Thermal instabilities can still occur but at lower temperatures than bulks

3. Hybrid stack trapped field magnet

Trapped field as a function of temperature



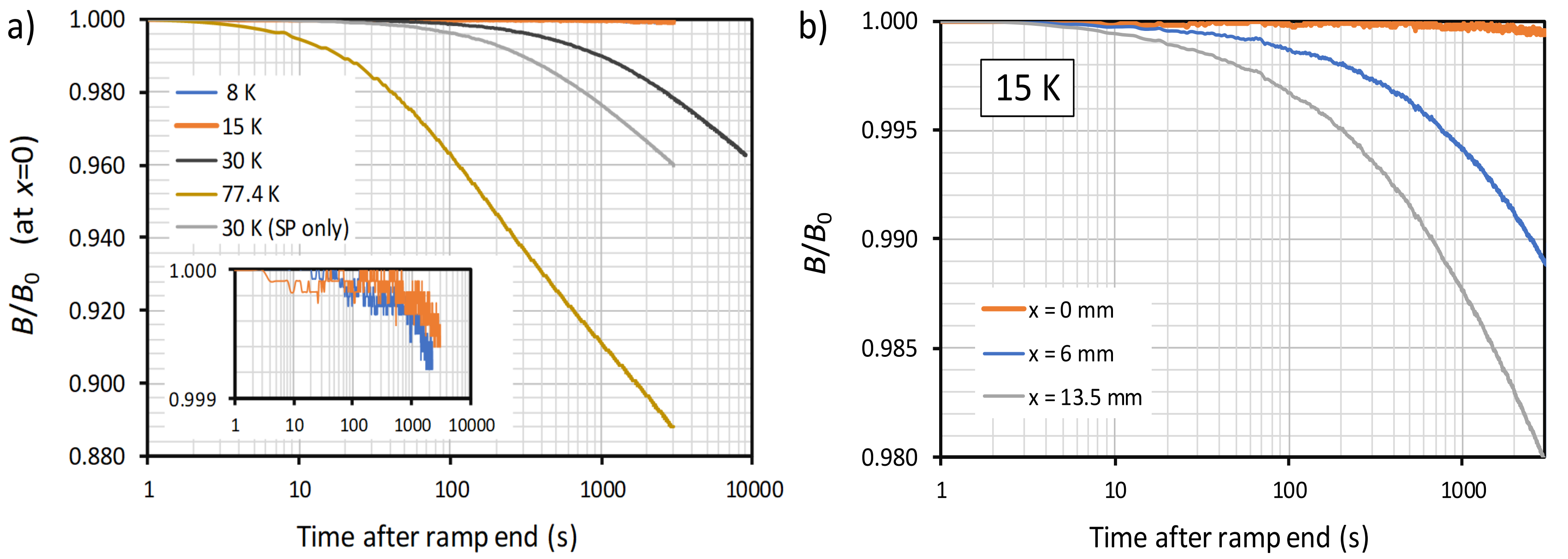


- Multiple field cooling tests performed at different temperatures
- Array of 3 Arepoc Hall probes used
- Field cooling of the SuperPower stack alone showed it is generating 90% of central field

- Warm up showed field that could be trapped at higher temperatures
- Warm up from 8 K showed **17.6 T could be sustained at 14 K**
- **Hybrid stack not saturated** – trapped fields > 18 T in sample should be possible at 10 K

3. Hybrid stack trapped field magnet

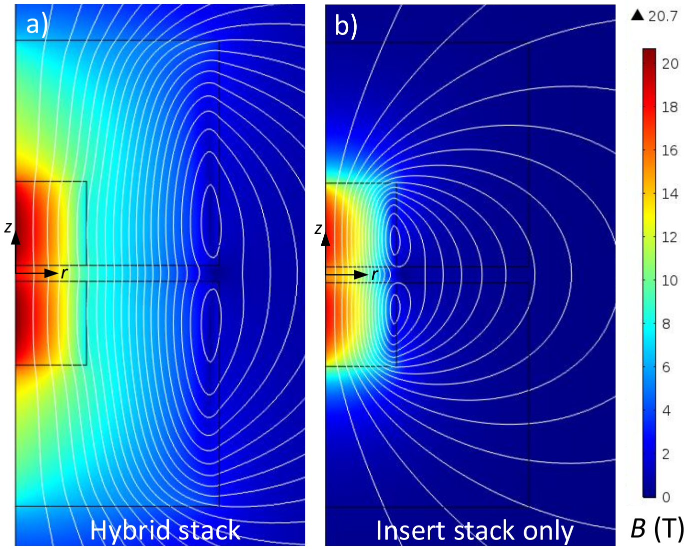
Flux creep



- Flux creep is logarithmic for field cooling magnetization after ~ 500 s
- Lower creep rates for lower temperatures. Higher creep rates near sample edges
- Lowering the temperature after magnetization by just a few kelvin practically eliminates flux creep
- Flux creep not a problem for most applications

3. Hybrid stack trapped field magnet

Mechanical stress modelling



Lorentz forces compress the layers axially and pull them outwards radially

(displacements greatly exaggerated by factor 2000, real displacements ~microns)

$$J_c(B,T) = J_e = \frac{J_{c0}(T)}{1 + B/B_0(T)}$$

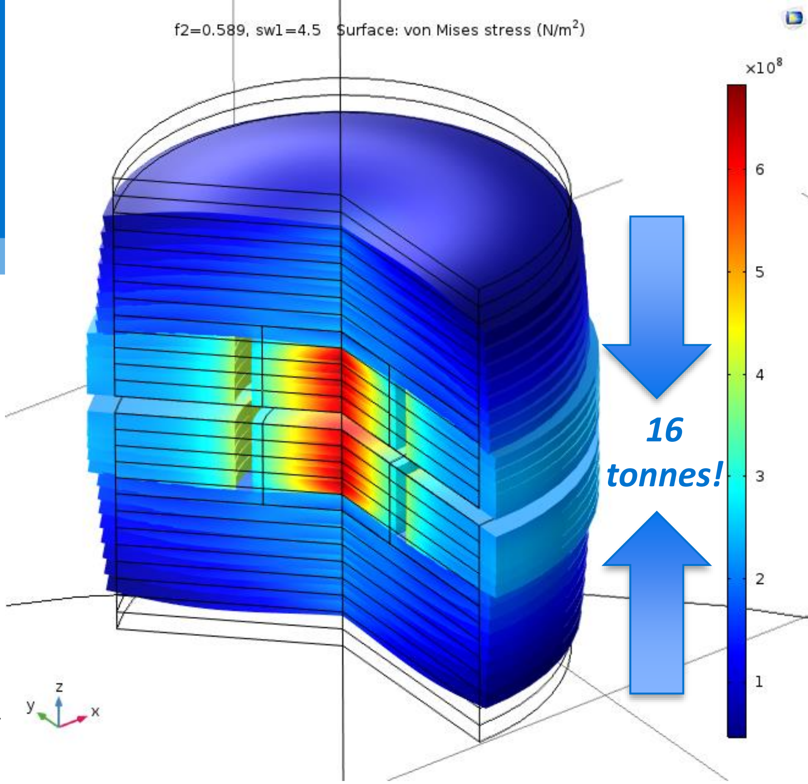
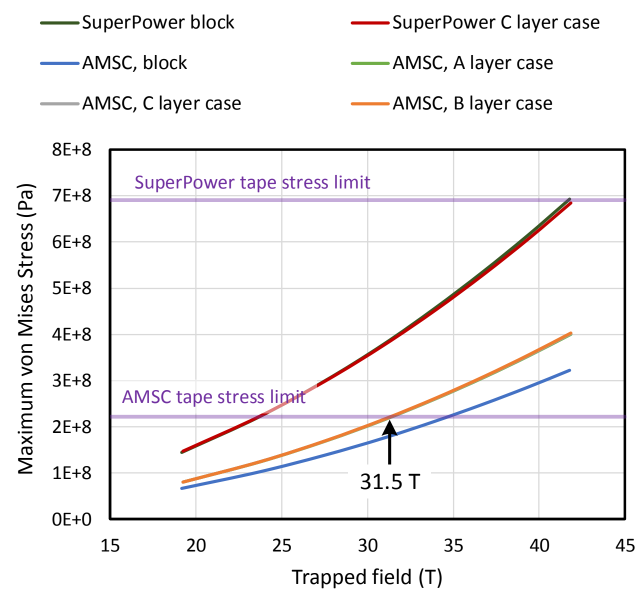


TABLE I
MECHANICAL PROPERTIES OF HASTELLOY AND NI-W SUBSTRATES

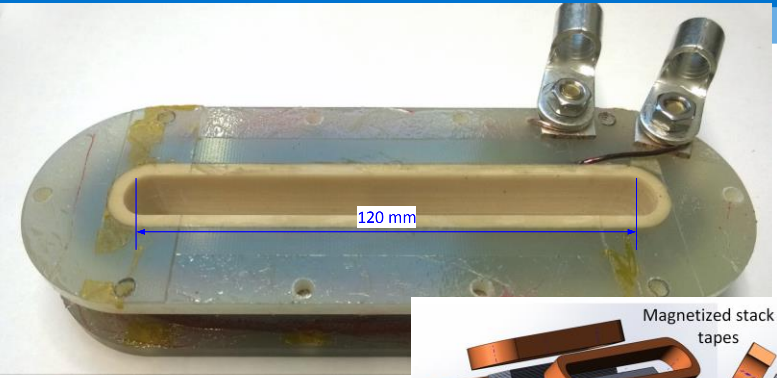
Property	Hastelloy C276		Fully coated Hastelloy	Ni-5at%W		Fully coated Ni-5at%W
Temperature (K)	4.2	77	77	4.2	77	77
Effective Youngs modulus (GPa)[a]	205	210	197	134	128	132
Tensile yield strength (0.2%)[b] (MPa)	770	700	690	283	257	222
Elastic strain limit (%)	0.37	0.31	0.35	0.21	0.20	0.16
Irreversible Ic strain (%)			0.41			0.38
5% Ic reduction strain (%)			0.43[c]			0.55[c]
Reference	[1]	[1]	[1, 2]	[1]	[1]	[1, 2]

[a]From initial slope of stress vs strain
[b]Maximum stress without permanent deformation. 0.2 % offset used.
[c]Found using graph of critical current vs strain in [2].

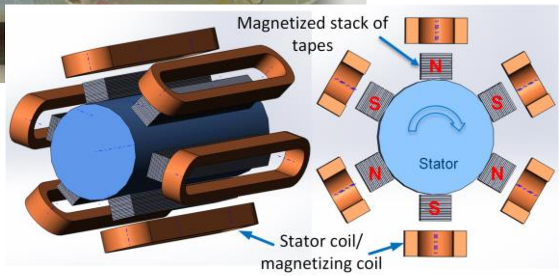
- Maximum von Mises stress considered to be tensile yield stress of substrates
- AMSC stack is limiting component due to weaker Ni-W
- **31.5 T** is theoretical max trapped field in the hybrid stack
- **Trapped field not mechanically limited in stacks**

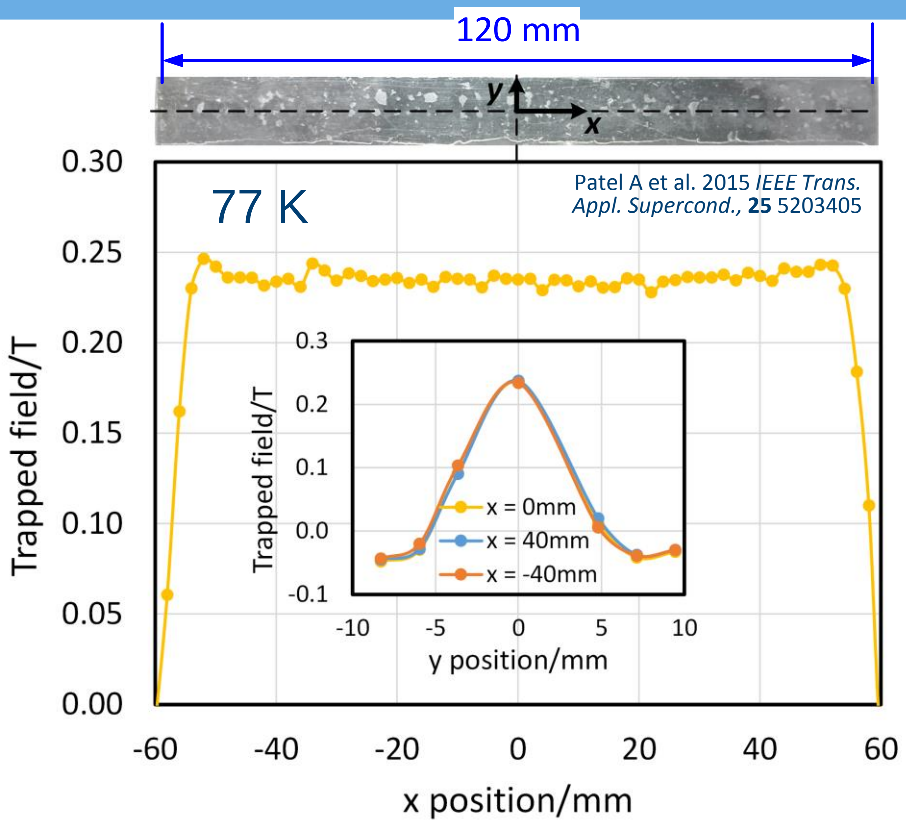


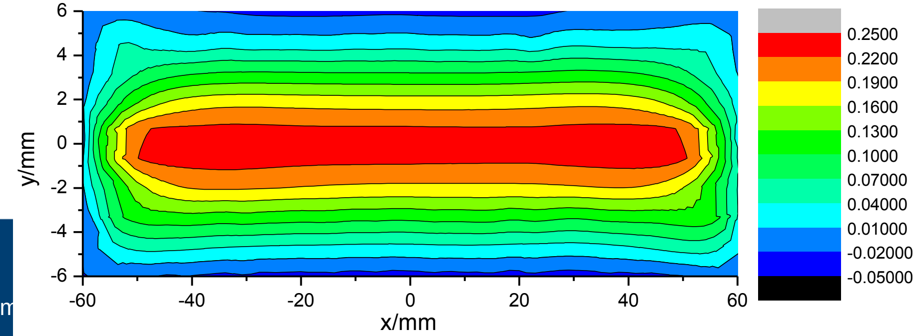
3. Applications in motors
Motors field poles



Plain copper wire pulsed field coil with internal and external glass fibre/epoxy reinforcement







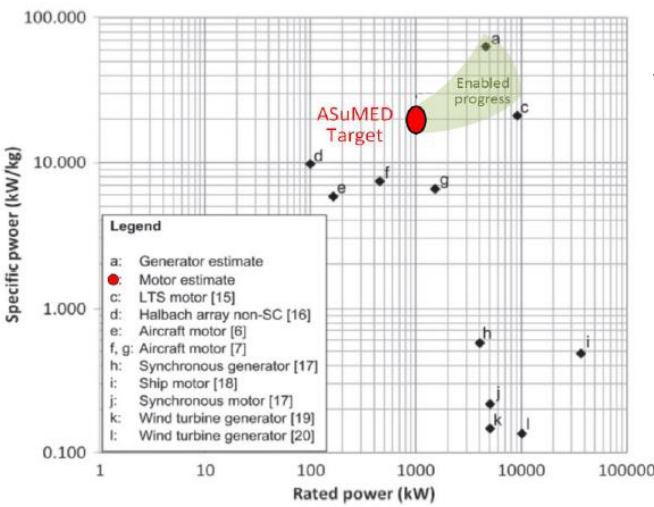
- Race-track shaped pulsed field coil constructed to deliver optimum pulsed field for a rectangle
- 120 mm long stack magnetized with a few pulses (maximum applied field ≈ 1T)
- Trapped field very symmetric and uniform
- Order of magnitude higher fields expected for < 77K
- Ideally suited to a field pole for a motor rotor

3. Applications in motors
Advanced Superconducting Motor Experimental Demonstrator

- 3 year EU H2020 project due for completion in April 2020
- Aim is to develop a 1 MW fully superconducting motor prototype with high power density for electric aircraft
- One version of the rotor will include stacks of HTS tape as permanent magnets
- Target trapped field above stack a few tesla, much less than trapped field record!

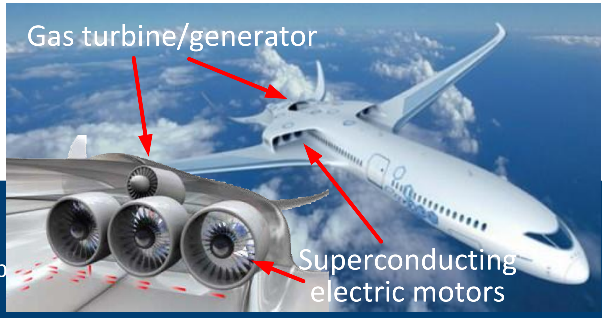
www.asumed.oswald.de

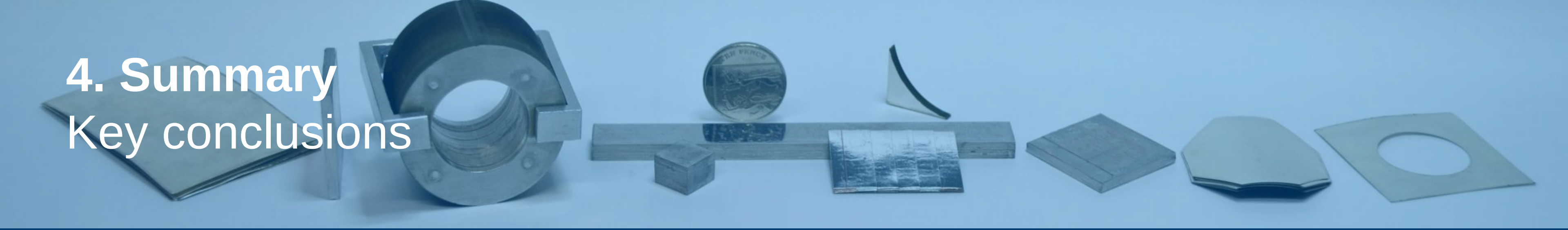
This project is funded by the European Commission
Grant No. 723119



Adapted from F. Berg, et al. IEEE TAS, ***25*** *5202705, 2015*

e from stacks of coated conductor tap





4. Summary
Key conclusions

- A trapped field of 17.7 T was achieved between using a hybrid stack of tape, the highest field generated by a trapped field magnet to date
- Greater fields can be expected as tape J_e steadily improves.
- Such stacks have potential for applications and are currently being evaluated for a 1MW fully superconducting motor

Stacks of HTS tape have 4 key selling points for permanent magnets applications

1. Their geometry is very flexible and they can be easily machined allowing many shapes
2. The superalloy substrates, which account for >85 % of the volume fraction, have very high tensile strength, which means they are not mechanically limited
3. The superconducting properties are uniform, defects in individual layers are smoothed out, different stacks made from the same batch of tape have the same performance
4. The silver stabilizer layer on top of the HTS layer provides thermal stability and supresses flux jumps