Superconducting magnets for high field

EMFL User Meeting

University of Nottingham

11 June 2024

John Burgoyne

Head of Product Management

Key application drivers in high field superconducting magnets

High field generation for condensed matter physics – "outsert" magnets for HTS insert coils

Conductor testing (fusion and accelarator-driven)

High field + ultra low temperature physics – including STM

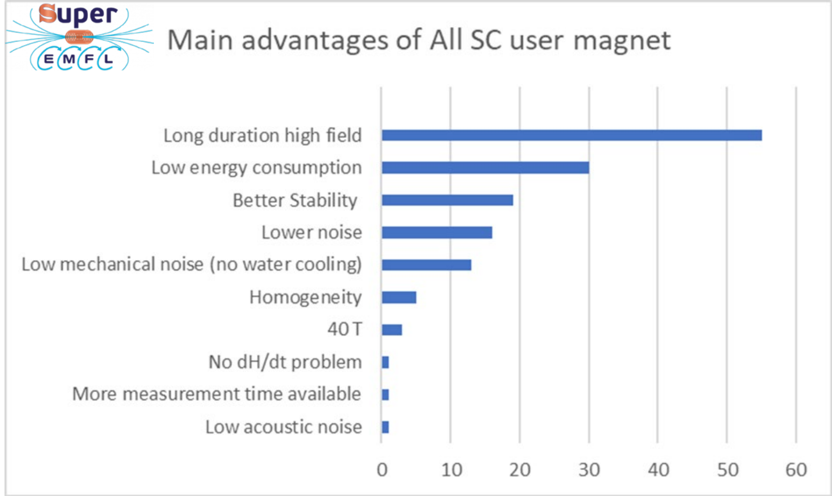
Dark matter – large bore and/or high field for axion searches

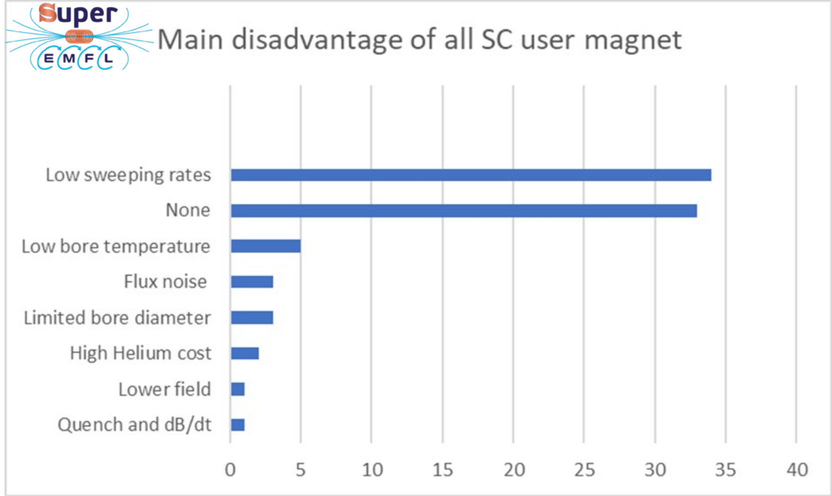
Materials processing

Beamlines – particularly neutron scattering

Why superconducting magnets?

- Experimental benefits
  - Lower noise, even assuming fully-driven mode >22 T
    - May unlock some effects at lower fields due to improved S:N
  - High homogeneity possible
  - Larger sample space sizes for e.g. DR integration
  - High uptime
    - In principle can be available 24/7
- Facility benefits
  - Compact
    - Relatively small physical footprint and easy service provision
  - Economic & sustainability balance
    - Low energy footprint balanced by liquid helium costs
    - Efficient helium recovery and reliquifier capability negates helium downside
- Downsides?





European high field installations

- University of Cambridge
  - 22 T* magnet system
  - Top-loading mK dilution refrigerator system

- UAM, Madrid
  - 22 T* magnet system
  - Dilution refrigerator capability

- HLD-HZDR, Dresden
  - 22 T* magnet system
  - 19 T, 150 mm bore magnet system

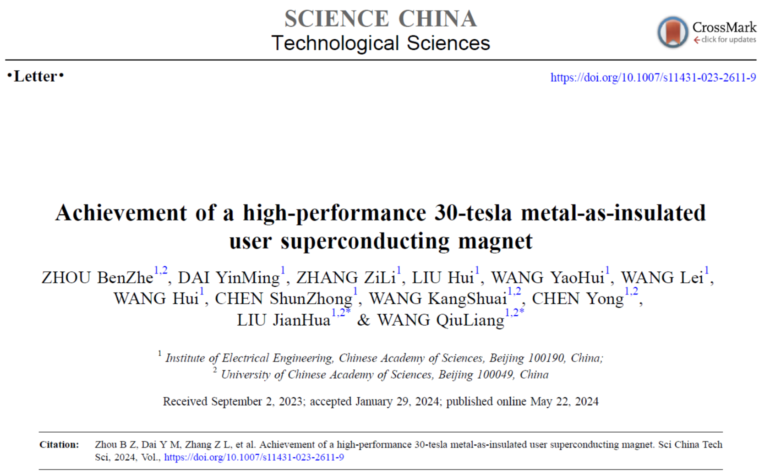
- University of Oxford
  - 21 T* magnet system

* At 2.2 K

High field all-superconducting user magnets

- National MagLab, Tallahassee, FL
  - 32 T all-superconducting magnet – world first
  - 15 T LTS + 17 T REBCO fully-insulated pancake coils
  - With top-loading mK dilution refrigerator capability
  - Typically running < 30 T as precaution for HTS coils

- Synergetic Extreme Condition User Facility (SECUF), Huairou (Beijing), China
  - Two high field systems
    - 28-30 T 15 T LTS + MI REBCO pancake coils
    - 26 T "NMR grade" 15 T LTS + BSCCO-2223 coils
  - With top-loading mK dilution refrigerator capability


SCIENCE CHINA Technological Sciences
•Letter•
https://doi.org/10.1007/s11431-023-2611-9

Achievement of a high-performance 30-tesla metal-as-insulated user superconducting magnet

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NEWS | 29 April 2024

Superconductivity hunt gets boost from China's $220 million physics 'playground'

From extreme cold to strong magnets and high pressures, the Synergetic Extreme Condition User Facility (SECUF) provides conditions for researching potential wonder materials.

By Gemma Conroy

The Synergetic Extreme Condition User Facility, just outside Beijing, can put samples through a battery of physical tests in one location. Credit: Institute of Physics, Chinese Academy of Sciences

- 2 x 22* T systems
- 2 x 20* T systems
- 20 T @ 4.2 K, 100 mm cold bore magnet system (SPM application)
- Multiple mK dilution refrigerator systems

* At 2.2 K

Superconducting high field projects for 30 T+

- Europe
  - EU Horizon project SuperEMFL, ending December 2024
    - 30 T and 40 T goals
    - Feasibility study only, 2.9 M€
    - REBCO materials
  - LNCMI "FASUM" project
    - 40 T system build for EMFL, 4.3 M€
- USA
  - National Maglab
    - 40 T feasibility study, $M15.8
    - REBCO materials
    - Targeting development program from 2025/6 subject to funding
- China
  - CAS-IEE (Beijing) and IPP (Hefei) programs, $M 100s?
- Japan?


LNCMI
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Accueil > FASUM project financed by French ANR EQUIPEX program

FASUM project financed by French ANR EQUIPEX program

15 October 2021 par Super Administrateur

FASUM – a 40 T all-superconducting magnet project (coordinating institution: Université Grenoble Alpes - with CNRS and CEA as partners) is financed by French ANR EQUIPEX program – 4.32 M€.

The FASUM (Fourty Tesla Superconducting User Magnet) project aims at keeping France as one of the leaders in experimental research in intense magnetic fields and to facilitate the use of intense field experimentation for as many researchers as possible. The project consists of building, testing and operating an all-superconducting 40 Tesla magnet based on the design study carried out as part of a European multi-partner project (SuperEMFL). This project, led by the National Laboratory of Intense Magnetic Fields (LNCMI-CNRS) which brings to it its technological knowledge unique in the world (NOUGAT technology for the internal ReBaCuO magnet), thus brings together academic and industrial partners from all over Europe.

Superconducting magnets for the European Magnetic Field Laboratory


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NSF Grant Funds New 40T Superconducting Magnet Design

Published October 03, 2021

Designing on paper
Stephen Bilenky

The world's next most powerful superconducting magnet will be designed at the National High Magnetic Field Laboratory.

More Stories

SuperEMFL project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°951714.
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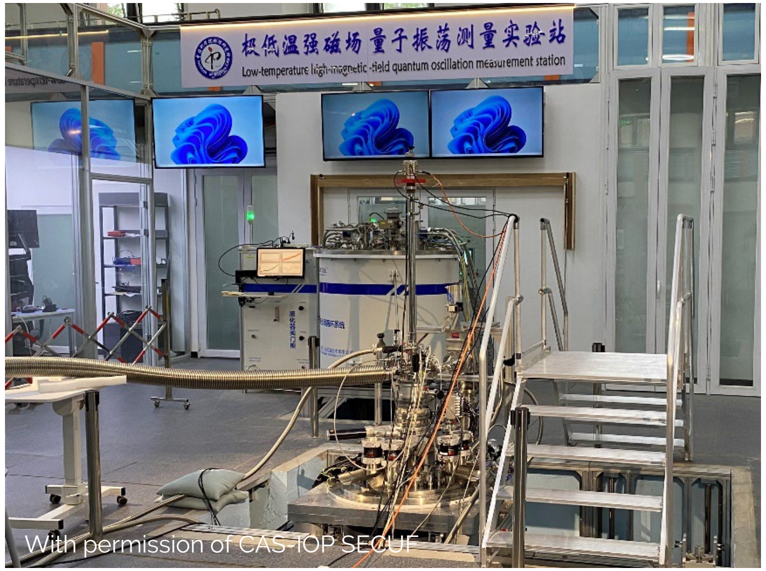
Wide-bore LTS non-persistent magnet technology

With permission of National Maglab (NHMFL)

- 15 T, 250 mm LTS "outsert" for customer HTS insert coil
- Leveraging a large installed base of compact, high energy density magnets
- Based on design, modelling and manufacturing capabilities in:
  - Coil stress management
  - Quench management
  - Coil manufacturing and process control

15 T / 250 mm
National Maglab (NHMFL), Tallahassee, FL
2014
→ 32 T

2 x 15 T / 250 mm
CAS-IOP "SECUF", Huairou, PRC
2021
→ 28-30 T and 26 T (NMR)



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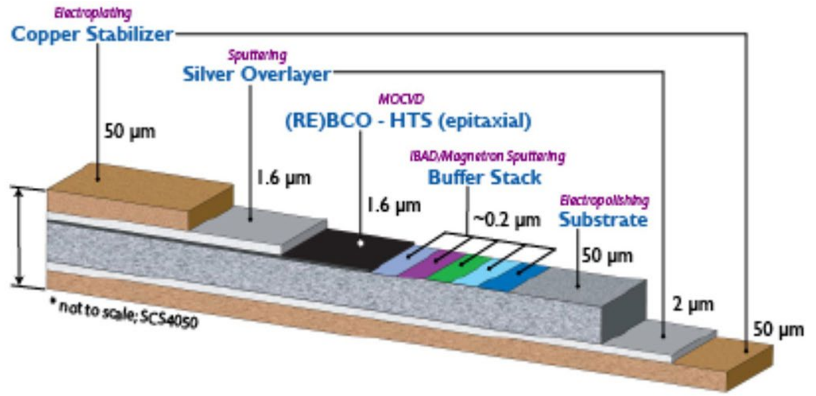
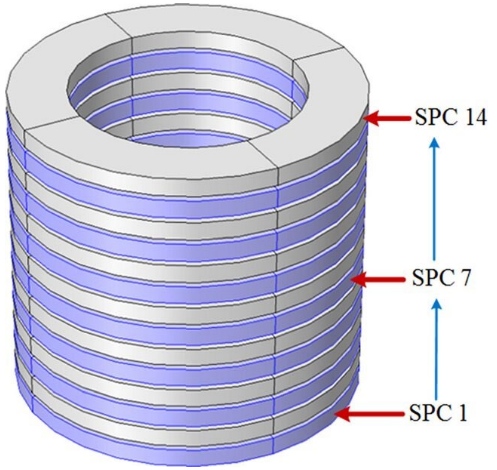
HTS conductor challenges for high field

- REBCO conductors
  - RE (= rare earth) - Ba – Cu - O
  - Coated tapes using pulsed laser deposition, sputtering, etc. – standard semiconductor/ industrial processes with in-process reaction
  - Multiple supply chain
  - Multiple insulation schemes – effectively different conductors
  - React-and-wind “pancake coils”
  - Complex quench scenarios
  - Development driven by **static field** applications
  - SuperEMFL 30 T & 40 T feasibility study



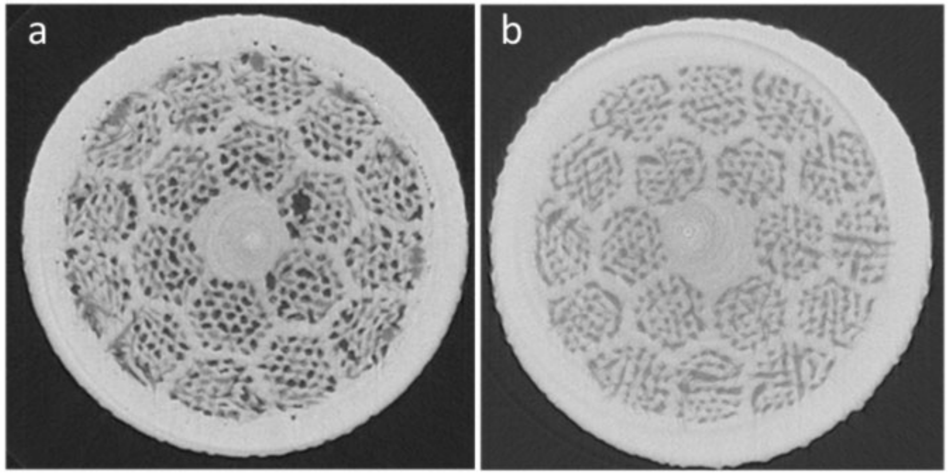
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/research/science-highlights/high-temperature-superconducting-tape/



Wang et al, (2017), *J. Appl. Phys.*, **122(5):** 053902; DOI: 10.1063/1.4997738

HTS conductor challenges for high field

- BSCCO conductors
  - Bi – Sr – Ca – Cu – O
  - Powder-in-tube manufacture in Ag matrix, conventional wire-drawing & rolling processes
  - “2223” stoichiometry – flat tapes, used mostly in HTS current leads – very limited for high field magnets (but ref. SECUF and HTS-110)
  - “2212” stoichiometry – **round wire**, mainly developing via Applied Superconductivity Center (ASC), National Maglab, Tallahassee, FL
  - Limited supply chain
  - Wind-and-react layer-wound coils
  - Simplified quench scenarios
  - Behaves much more conventionally for ramped field applications



https://nationalmaglab.org/magnet-development/applied-superconductivity-center/research-areas/bscco/

1 March 2023

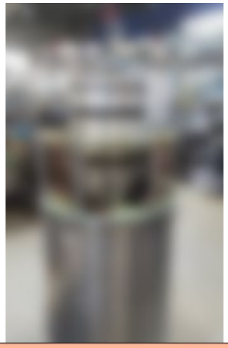
Oxford Instruments and MagLab's Applied Superconductivity Center Partner on High-Temperature-Superconducting Materials for High Field Research Magnets

https://www.oxinst.com/news/news/oxford-instruments-and-maglab-applied-superconductivity-center-partnership/

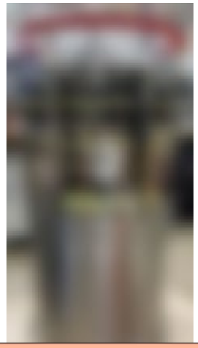
Wide-bore LTS persistent magnet technology

Central field @ 4.2 K (T)	Magnet bore size (mm)	Operation mode	Homogeneity over 10 mm DSV	Application	Country
18	150	Persistent	0.10%	STM	China
12	320	Persistent	< 0.02 %	Dark matter	S Korea
20	100	Persistent	< 0.10 %	STM	China
19.1 (1,300 T^2.m)	110	Persistent	< 0.10 %	Metallurgy	China

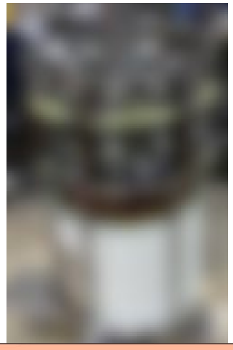
18 T / 150 mm
Persistent @ 4.2 K
2017



12 T / 320 mm
Persistent @ 4.2 K
2020



20 T / 100 mm
Persistent @ 4.2 K
2021



19 T / 110 mm / high gradient
Persistent @ 4.2 K
2022

Commercial superconducting magnets

- Significant differences between high field magnets developed in e.g. national labs, and what can be a commercial offering
  - Predictability of performance
    - Cost & time for financial return
    - Guarantees
  - Commercial contract
    - Legal agreement of supply
  - Warranties (and reputation)
    - Sustain full operation & performance in the long term
  - There is (has to be!) a profit motive
    - Otherwise no re-investment in new products
    - Duty to shareholders, pension holders, employees

The outlook for high field all-superconducting magnets

- Strong outlook for 30-40 T
- HTS materials are available and have sufficient performance
- Significant funding is needed
  - Europe is behind both US and China
  - FASUM *may* catch up?
- In-use issues have to be resolved, subject to HTS conductor selection
  - Quench
  - Ramp time
  - Repeatability of field setting

High *B/T* ratio – final thoughts

- **If** high *B/T* ratio is the critical experiments figure of merit…
- New, cryogen-free (“dry”) dilution refrigerators offer larger gains in *T* vs *B*

	B	T_{min}	T_{max}	**CP, 100 mK**	***B/T* factor**
Typical resistive	40 T	25 mK	1 K?	~400 µW	1,600
Wet	20 T (4.2 K)	15 mK	1 K	400 µW	1,333
Dry	**14 T**	**5 mK**	**30 K**	**850 µW**	**2,800**

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Thank you

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