NATIONAL HIGH MAGNETIC FIELD LABORATORY

Beyond 45 T at the MagLab and the Need for Test Facilities

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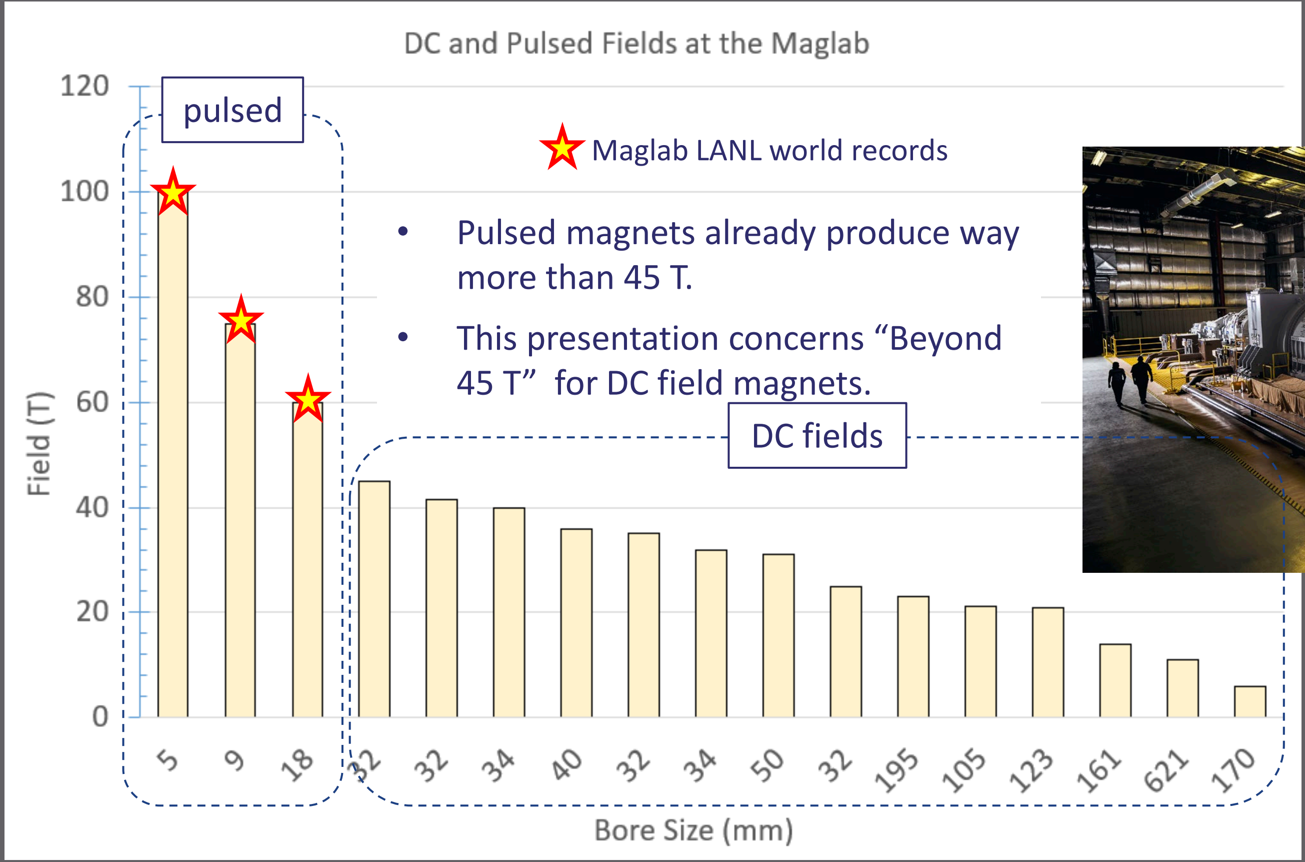
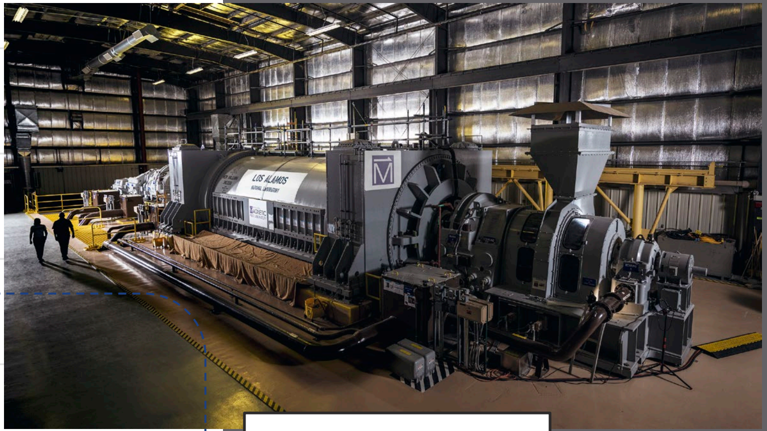
LANL Pulsed magnets are already >> 45 T

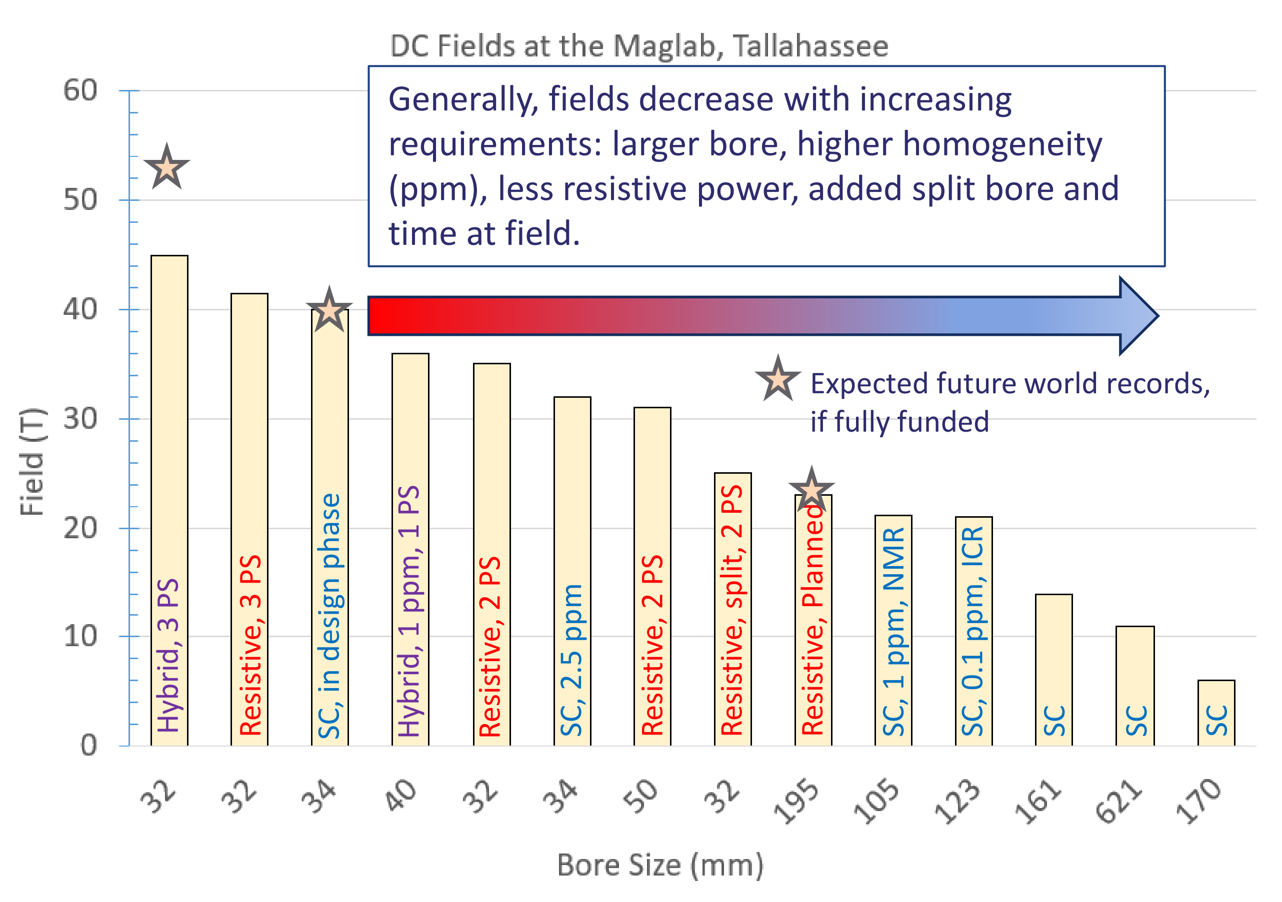


- Pulsed magnets already produce way more than 45 T.
- This presentation concerns "Beyond 45 T" for DC field magnets.



LANL Generator

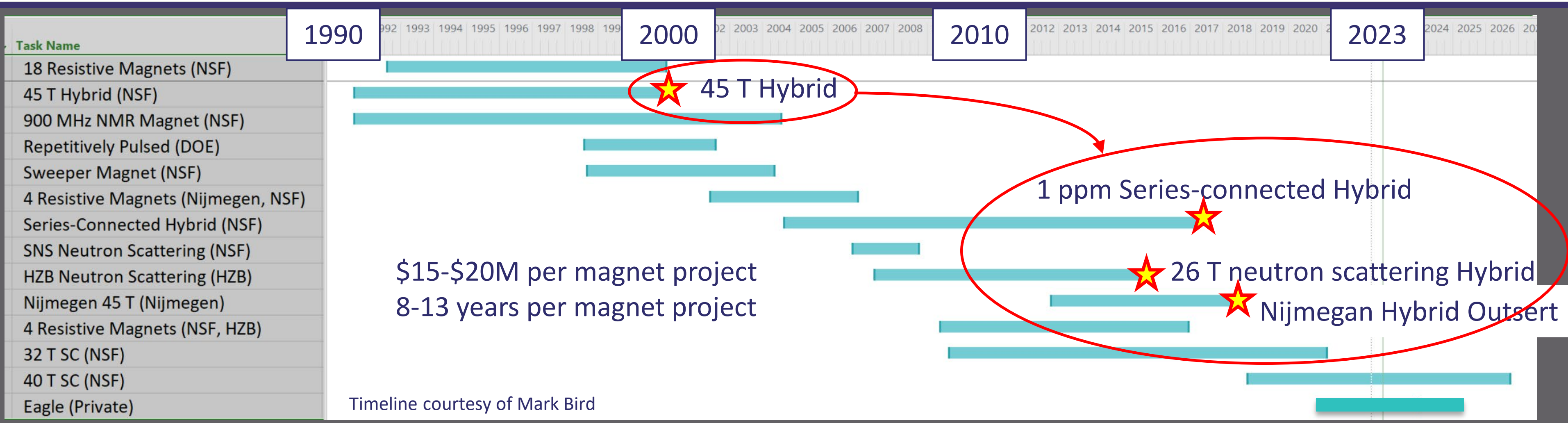
DC Fields at the Maglab



Highest field DC user magnets have always been hybrids, then technology trickles down to other magnet types with higher homogeneity, larger bores, less power, etc.

45 T Hybrid technology trickled down to three new high-field magnets

Same hybrid technology. Three new high-fields in their class. A 50-55 T Hybrid should be our next target.

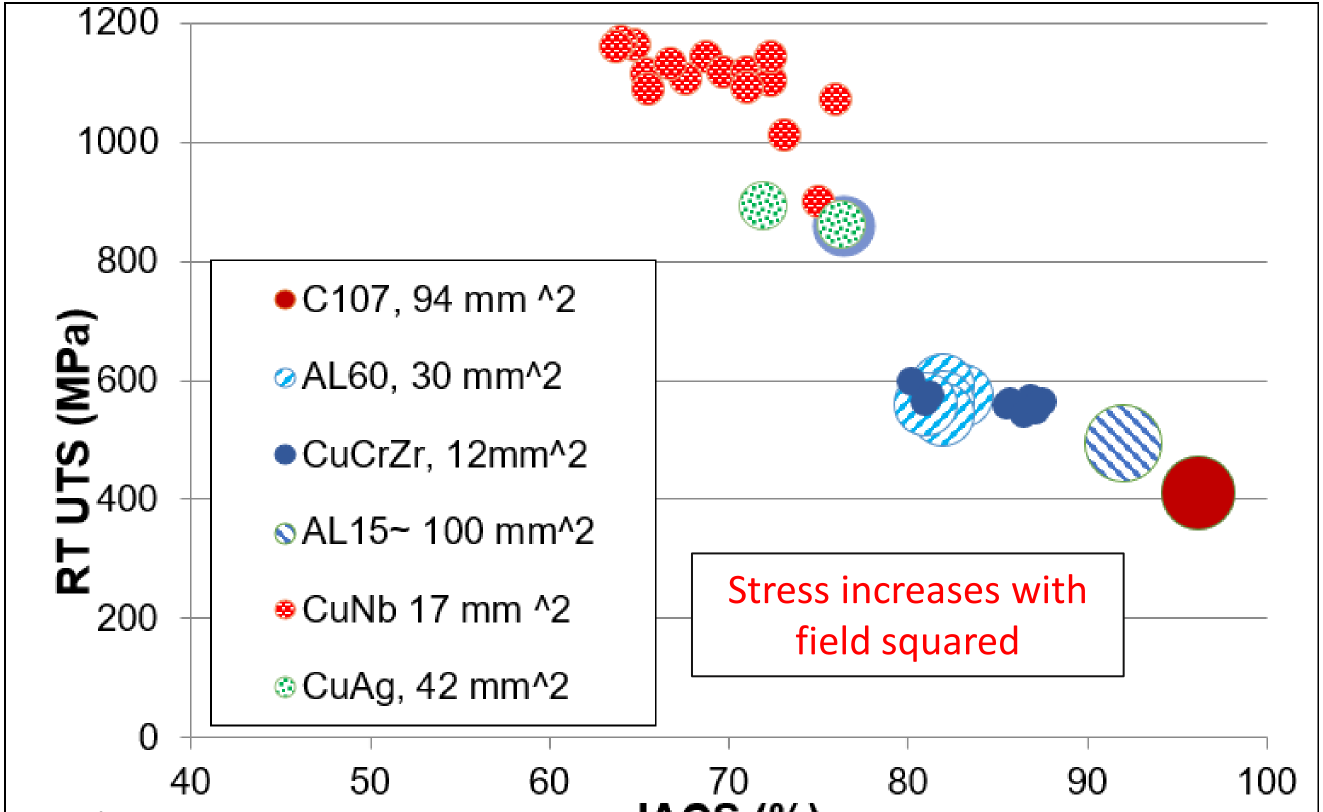


45 T Hybrid Technology:

- Developed for highest DC magnetic field possible.
- Technology used for next-higher field homogeneity, neutron scattering, and a potentially higher-field hybrid.

HSHC Materials Roadmap

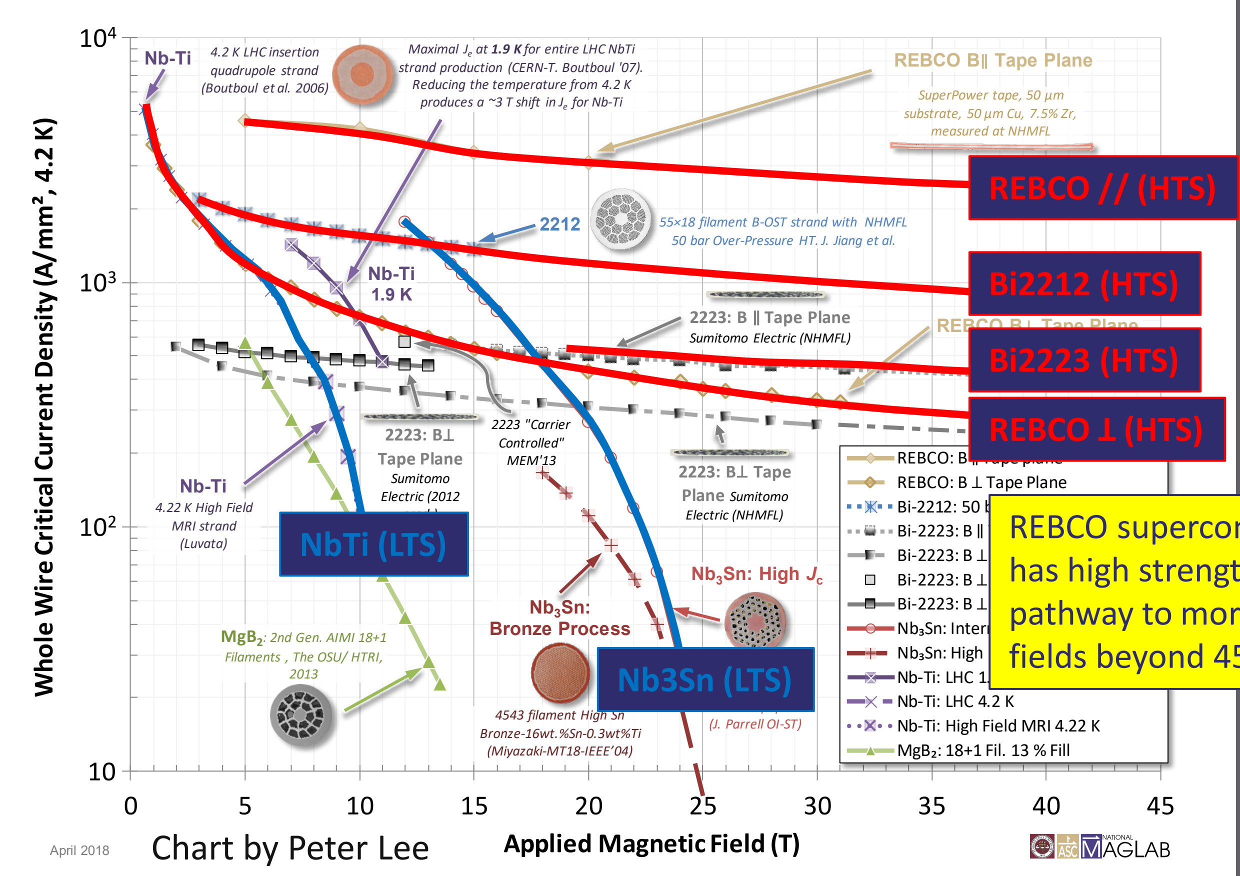
DC all-resistive magnets have potential to go to ~43 T in a 32 mm bore magnet with present conductor technology. Superconductors are required to go to higher fields.



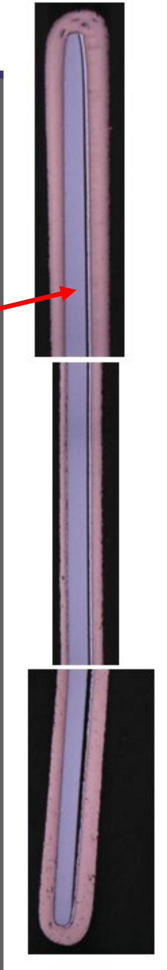
Graph courtesy Ke Han

- Pulsed and resistive magnet fields are limited by available:
  - Power supplies
  - Cooling (resmag)
  - Conductor materials

High-field, high-current, high-strength REBCO



REBCO high-strength substrate. Typically 50 µm thick.

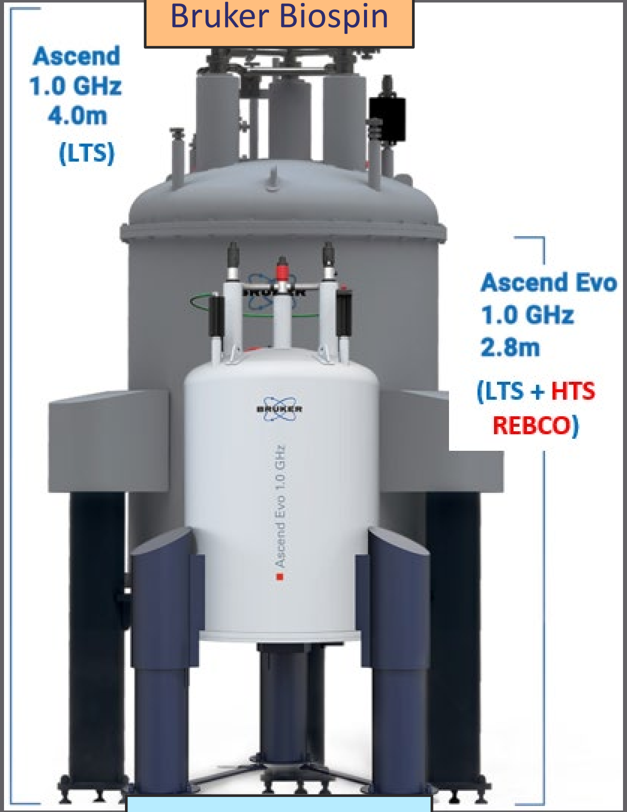


REBCO superconducts at fields > 60 T, has high strength and has opened the pathway to more compact, achievable fields beyond 45 T.

HTS REBCO Revolution

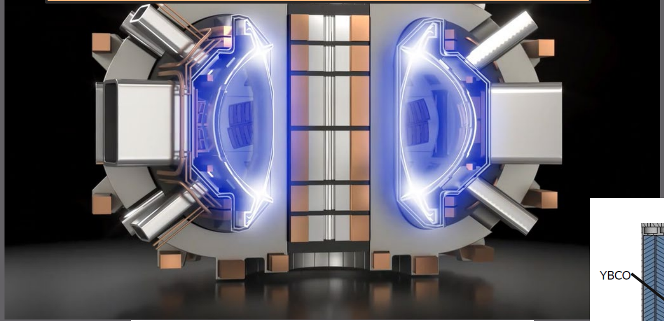
Compact NMR. Compact Fusion. Compact next-generation high-field magnets at the Maglab are within reach.

Bruker Biospin

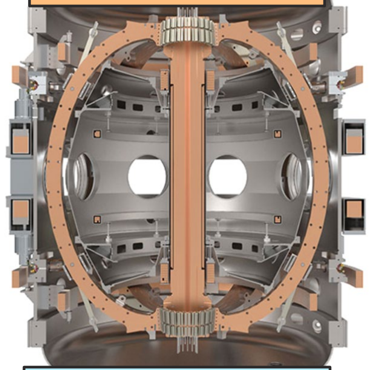


Compact NMR

Commonwealth Fusion Systems

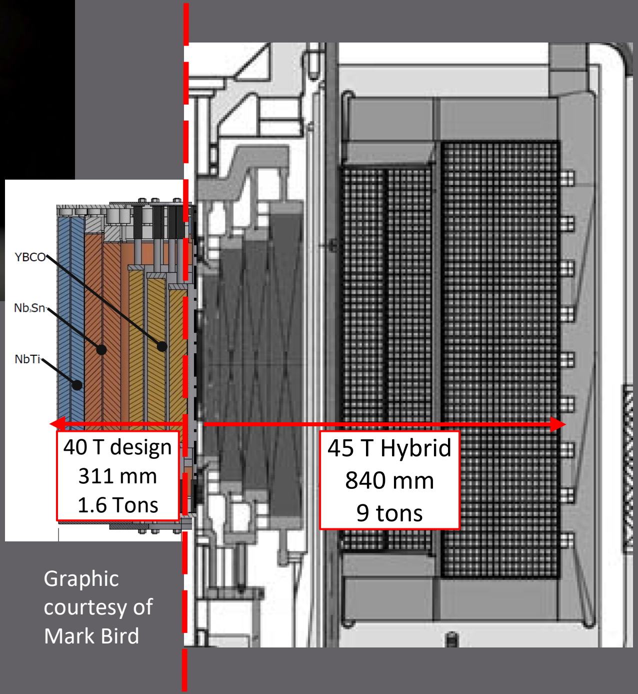


Tokamak Energy



Compact Fusion

The NHMFL

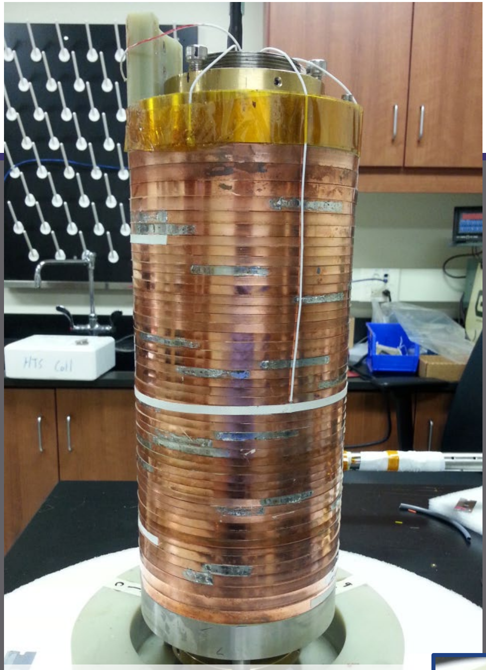


Graphic courtesy of Mark Bird

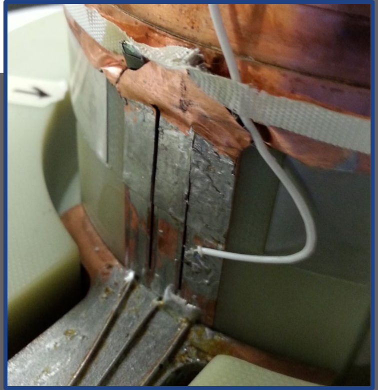
Compact Hybrids

Road to 45 T and Beyond

- Greater than 45 T technology will start with a next generation hybrid (Tribrid?) which will be some combination of resistive, LTS and HTS magnet technology.
- We don't know what the final combination will be yet and we won't know until we qualify the superconducting technology on **increasingly larger test coils and nested test-coil sets**.
- The present 40 T project design phase has already started on test coil qualification in available large bore magnets at the Maglab.



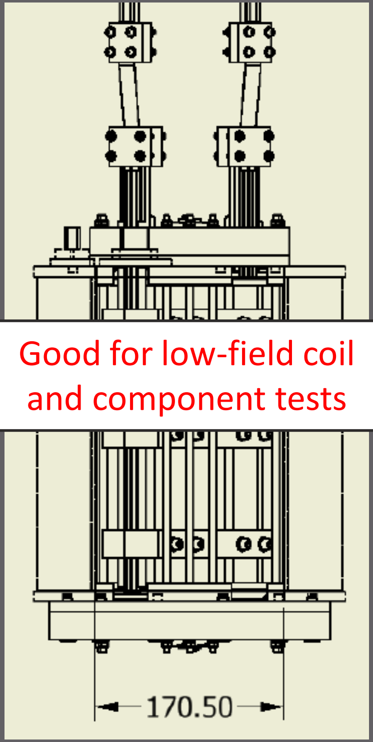
13 T NI HTS insert



In order to achieve a 50-55 T Hybrid, a higher field test bed then presently available is required to qualify test coils at these higher fields.

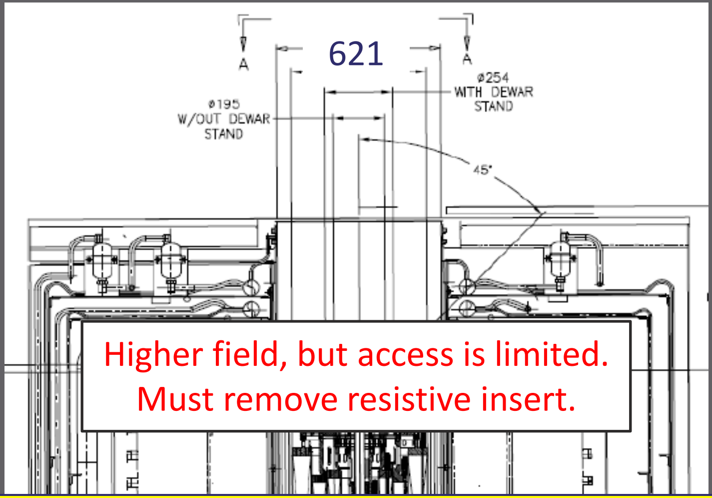
Present Large-Bore Test Coil Facilities at the Maglab

6 T, 170.5 mm bore SC



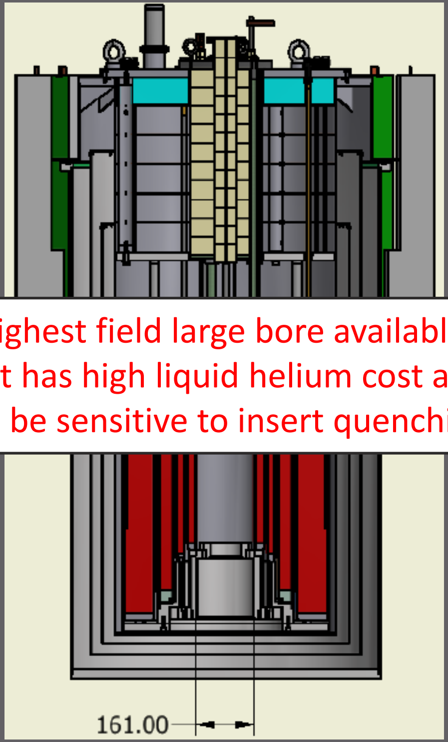
Good for low-field coil and component tests

11 T, 621 mm bore SC



Higher field, but access is limited. Must remove resistive insert.

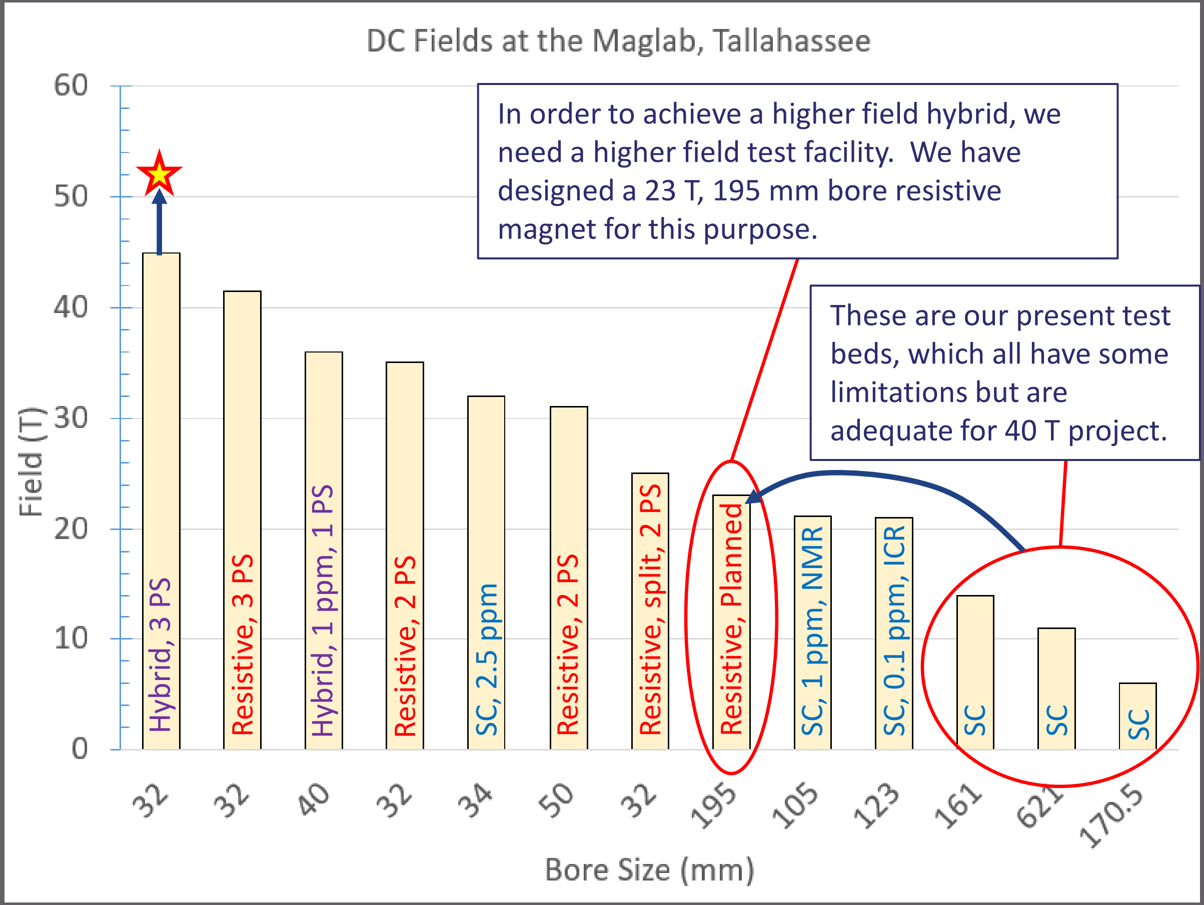
14 T, 161 mm bore SC



Highest field large bore available. But has high liquid helium cost and can be sensitive to insert quenching.

These are adequate for the 40 T all-superconducting magnet development program. But we need a higher-field, large bore resistive magnet for the next-generation magnets.

Proposed Large Bore Resistive Magnet (LBRM) Test Bed



- An LBRM is an essential first step to fields beyond 45 T at the Maglab.
- An NSF Major Research Instrumentation proposal is planned to be submitted in Nov. 2023.
- This test bed will be the highest field of its kind in the world and provide a competitive advantage to worldwide competition.

Review of superconducting high-field magnet recommendations

Report	Recommendation	Actual Achieved	Magnet Completed	Funding Comments
1991 Charge to NHMFL	45 T Hybrid	45 T	1999	• The nation increased its spending on high-field labs 3-fold from $6M/year to $18M/year. • Recommended magnets were completed.
	1 GHz NMR	900 MHz	2003	
2005 COHMAG and 2013 MagSci	60 T Hybrid	unfunded	?	• High goals were set. Little additional funding in US provided. • **German government/Bruker** funded $20M.
	1.3 – 1.6 GHz	1.2 GHz	2020	
2013 MagSci	25 – 35 T Hybrid for neutrons or X-rays	26 T for neutrons	2015	• **Helmholtz Centrum Berlin, Germany** funded 26 T for neutrons • NSF initiated mid-scale program which is funding 40 T design and may fund 40 T construction, if awarded
	Regional 32 T SC	unfunded	?	
	40 T SC	design underway	2031?	
	40 T for neutrons or X-rays	unfunded	?	
	20 T large animal/human MRI	unfunded	?	
2013 MagSci and 2017 ORNL report	40 T split for neutrons or X-rays	unfunded	?	• Recommended a minimum of 3-year R&D/Design period prior to construction for each magnet in 5 T increments. • Recommended $8M/year for up to 20 years to achieve goals.

Strictly managed projects.
No R&D allowed.

US high-field magnet design and construction capabilities exist, but they must be funded especially R&D, or US will lose its worldwide leadership.

40 T all-superconducting

REBCO HTS technology developed in the R&D and conceptual design phases set the stage for a next-generation proposal. Continual R&D is required to take advantage of the rapid, ongoing worldwide technical developments for future projects.

US/NHMFL Forecast: 40 T SC

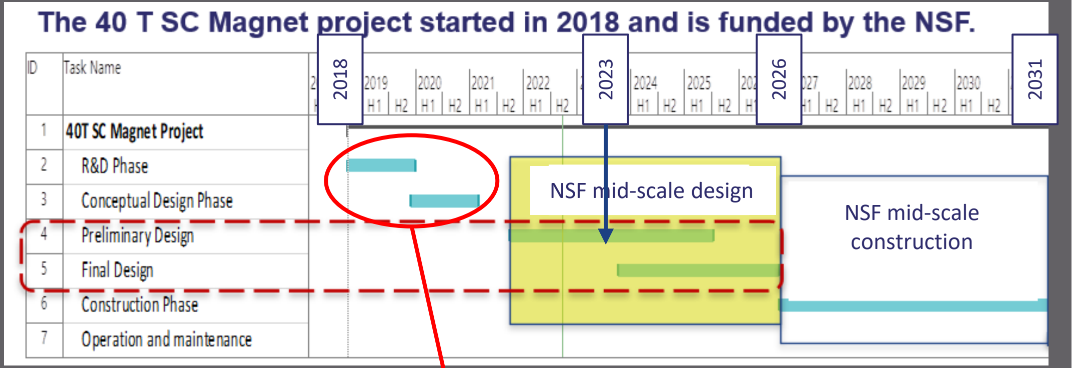
- REBCO insert, LTS outsert, 34 mm bore, 0.5 T/min ramp rate, 2.5 ppm homogeneity.
- Design: 2020 – 2025 (funded)
- Construction: 2026 – 2031 (not yet funded).
- Expected total design and construction: ~ $40M
- Record at project start: 32 T (25% increase)
- NSF RI-1 and -2 mid-scale programs are new opportunity to fund these next generation magnets.

Worldwide Competition

- Three other labs are pursuing 40 T SC but are in the early stages: Grenoble/CEA, Hefei and Sendai/Toshiba.

Past Recommendation of NRC panel

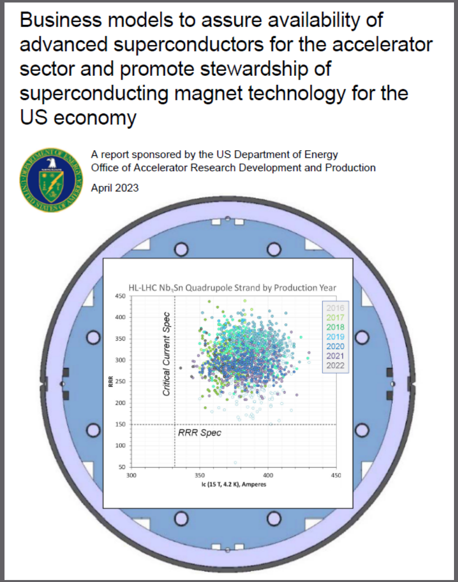
- 40 T all-superconducting



An $8M/2 year R&D and Conceptual Design phase was crucial for developing project-ready technology

R&D funding of US DOE High Energy Physics program

Accelerator Research Development and Production (ARDAP) report 2023


Business models to assure availability of advanced superconductors for the accelerator sector and promote stewardship of superconducting magnet technology for the US economy

A report sponsored by the US Department of Energy
Office of Accelerator Research Development and Production
April 2023

- *"Superconducting magnet technology and its related conductor technology are strategic and critical for global leadership…in science…magnets…energy, transportation, defense, manufacturing, health, medicine and space."*
- *"US DOE HEP has succeeded from concept to production of tunnel-ready 11 T magnets in 15 years using sustained investment of $12M/year."*
- $20M annually has been recommended to prevent stagnation/atrophy in the US program.

The success in the accelerator magnet community is an example of successful stewardship of the latest technology. $12M/year was successful in the past. $20M/year has been recommended going forward.
An analogous funding mechanism is required at the Maglab to maintain US leadership in high field magnets.

Conclusions

- Global competition is intense due to the REBCO revolution. Fields are increasing, HTS technology is rapidly improving.
- A 50-55 T next-generation hybrid magnet is our targeted next project in parallel with the 40 T all-superconducting magnet to maintain US world leadership.
- A new test facility is required for these higher fields. We have designed a 23 T, 195 mm resistive magnet test bed for this purpose. A proposal is planned to be submitted in Nov. 2023.
- This test bed will enable development of the optimal path to the next-generation hybrid by allowing test coil development in extreme magnetic field environments.
- This test bed will also serve R&D of rapidly advancing HTS technology.
- An annual funding mechanism for high-field magnet R&D is necessary for the US/NHMFL to continue to maintain world leadership in high magnetic fields.

Thank You!

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