Community Summer Study

SNOWMASS

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Next generation technology for low-cost Nb_3Sn accelerator magnets

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LBNL

In partnership with:

BERKELEY LAB Fermilab

White Paper (arXiv: 2203.07352)

Development and demonstration of next generation technology for Nb_3Sn accelerator magnets with lower cost, improved performance uniformity, and higher operating point in the 12-14 T range

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Executive summary

The scope of the proposal outlined in this white paper is the development and demonstration of the technology needed for next generation of Nb_3Sn accelerator magnets in the 12-14 T range. The main goal is to cut magnet cold-mass cost by a factor 2 or higher with respect to the Nb_3Sn magnets produced by the US Accelerator Upgrade Project (AUP) [1] for the High-Luminosity Large Hadron Collider (HL-LHC) [2]. This goal will be achieved by significant reduction of labor hours, higher operating point, and improved performance uniformity. A key factor will be automation that will be achieved through industry involvement and benefitting from the experience gained in US national laboratories through the production of the AUP magnets. This partnership will enable the development of a technology that will be easily transferable to industry for mid- and large-scale production of Nb_3Sn accelerator magnets in the 12-14 T range. This step is essential to enable next generation of colliders such as the FNAL-proposed Muon Collider, FCC and other HEP hadron colliders.

This is a "Directed" R&D where direction is given by the field range and industry involvement for high-automation and industry-ready technology. The plan includes ten milestones, to be achieved in 6-8 years at the cost of 5-7 $M/year.

From 2013 Snowmass …

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

Recommendation 24: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.

Recommendation 26: Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and longterm vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.

Accelerating Discovery

A Strategic Plan for Accelerator R&D in the U.S.

Recommendation 5. Participate in international design studies for a very high-energy proton-proton collider in order to realize this Next Step in hadron collider facilities for exploration of the Energy Frontier. Vigorously pursue major cost reductions by investing in magnet development and in the most promising superconducting materials, targeting potential breakthroughs in cost-performance.

Recommendation 5b. Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

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Not much progress in cost reduction of high-field accelerator magnets, so far … **Why?**

Because you cannot build a house starting from the roof!

How to get to Cost-Effective High-Field Acc. Magnets

In the 12+ T / 16+ T / 20 T field range

- **From this elevation point we can plan for cost-effective design & technology**
- Mini-series (6+) Production
- Full Length Prototypes (3+)
- Short Models (the more the better)
- Basic R&D (conductor, other materials, magnetic & structural design, …)

How to get to Cost-Effective High-Field Acc. Magnets

For 11-12 T magnetic field range (incomplete list):

- **In this field range (12-14 T) now we can develop cost-effective design & technology**
- AUP (7x4.2m), CERN (4x5m 2-aper.)
- LARP (3x3m), AUP (3x4m), CERN (3x7m + 1.5x5m 2-aperture)
- Large number (50+); most recently: LARP, AUP, CERN
- Lots of work at: BNL, FNAL, LBNL, TAMU, LARP, CERN, EU programs

20+ Yrs.

- **From this elevation point we can plan for cost-effective design & technology**
- Mini-series (6+) Production
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LARP = US LHC Accelerator Research Program (2003-2018)
AUP = US HL-LHC Accelerator Upgrade Project (2016 – present)

How to get to Cost-Effective High-Field Acc. Magnets

For 16 T magnetic field range (4-layers, stress management, …)

For 20 T magnetic field range (hybrid design or HTS only)

In these cases, we are 10-15 years away from starting to address cost reduction.

Now we can start if for 12-14 T range, and it will speed-up cost-reduction programs in the 16 T and 20 T (hybrid) ranges

~14.5 T

20+ Yrs.

- **From this elevation point we can plan for cost-effective design & technology**
- Mini-series (6+) Production
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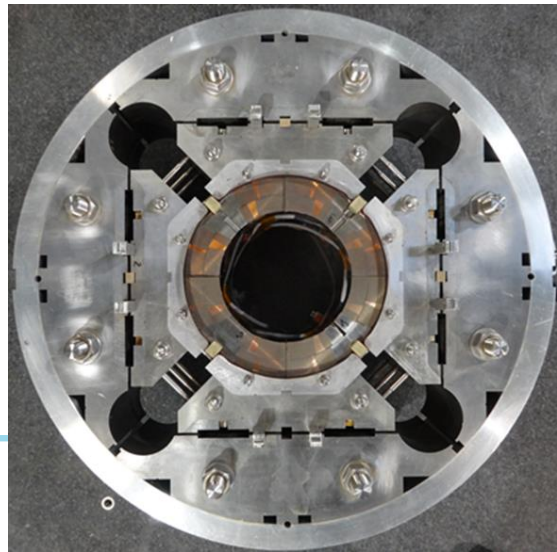
12 T range assessment (IR quads by AUP & CERN for HL-LHC)

- **Five short models** out of six exceeded ultimate current (12.1 T in the coils) at 1.9 and 4.5 K
  - More than 100 quenches in MQXFS1
  - More than 10 thermal cycles in MQXFS4
- **Four production magnets** out of 6 met requirements during vertical test
  - 5th is on track (holding acceptance current)
  - **MQXFA05 passed endurance test** (50+ quenches, 5 thermal cycles)

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.2
Nominal/Acceptance current	kA	16.23/16.53
Peak field at Nom./Accept. current	T	11.3/11.5
Stored energy at nom. curr.	MJ/m	1.15



Development and demonstration of next generation technology for Nb_3Sn accelerator magnets with lower cost, improved performance uniformity, and higher operating point in the 12-14 T range

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- Goal: **development and demonstration** of the technology needed for **next generation of Nb_3Sn accelerator magnets** in the **12-14 T range**, with **lower cost** and improved performance uniformity

- Key-points:
  - Build upon 20+ yrs development (LARP + AUP + …)
  - Bring in automation and industry
  - Strong collaboration among Labs + Universities + Industry
  - Direct R&D: direction given by focused goal

Overall Plan

- **3 Phases**
- **10 milestones**
- **6-8 years**
- **5-7 M$ / year**

MQXFA bare magnet

MQXFA Cost Analysis:

- 4.2 m magnetic length; 150 mm aperture; 11.5 T on conductor at acceptance current; bare magnet (no coldmass nor cryostat)
- "Project cost": ~ 4.7 M$ per magnet
- **4 cost drivers, each between 1.1 – 1.25 M$**
  - Cables
  - Coil fabrication
  - Structure + magnet assembly
  - Yield cost (vertical test + yield assumptions)

This plan addresses all cost drivers

Phase 1

2 Milestones

Goal: **Significant cost reduction in coil fabrication (>50%)**

- How: fabricate MQXF-like coils with **< 40% touch labor**, and allowing **higher coil yield**
- **Leveraging** AUP leftover conductor and tooling (with some modifications), plus equipment, expertise, personnel and test beds used for MQXF magnets
- **Universities and industry** will be involved from very beginning for **high automation** and **processes well fit for industrial production**
  - *Note: this is NOT industrialization; it is the development of a technology well fit for industrialization*

Phase 2

2 Milestones

Goal: **Shorter training and higher operating point with enhanced conductor and Phase-1 technology**

- How: fabricate MQXF-like coils with **enhanced conductor** (developed by other programs) and the **technology developed in Phase-1**

- **Opportunity for synergies** with other programs (MDP, CPRD, labs and universities), which will benefit from testing the enhanced conductor against a well-established benchmark (MQXF magnets); and subsequently use it to demonstrate shorter training and higher operating point.

Phase 3

6 Milestones

Goal: **development and demonstration of a low-cost high-efficiency Nb_3Sn accelerator magnet in the 12-14 T range.**

- How: use **coil fabrication technology** from phase-1; **enhanced conductor** from phase-2; together with **low-cost magnet structure**
  - magnet design will **depend on the P5 recommendations** and may be developed in collaboration with other R&D programs.
  - Design and development of this magnet will be done in parallel with Phases 1 and 2 work
- **Industry** will be involved aiming at **reducing cost of structure components**, development of **magnet assembly procedures with limited touch labor and easily transferable to industry.**

Conclusions

- High field superconducting magnets are a critical element in hadron colliders, muon colliders and other HEP machines.
- Significant cost reduction is needed to make future accelerators affordable
- US programs and projects (with international partners) have demonstrated that Nb_3Sn technology can be used for accelerator magnets in the 12+ T field range.
- This program aims at **significant cost reduction** introducing **automation** and **industry involvement**.
  - Direct outcome: low-cost accelerator magnets in 12-14 T range
  - Long-term outcome: it will enable introducing low-cost features in programs aiming at higher field ranges (16 T and 20 T hybrid)