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High Field Magnets



S. Gourlay

Director, Magnet Technology Division



U.S. DEPARTMENT
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DPF/DNP Community Meeting



A Historical Perspective to Track the Evolution of “High Field”

The highest achievable field is always determined by the conductor and our ability to utilize it effectively.

- Nb-Ti – 8T
- Nb₃Sn – 14T
- Bi-2212 – 36T – NMR configuration
- ReBCO - > 40T?

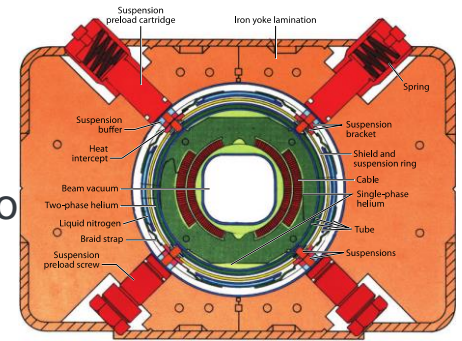
Other conductors with interesting properties, but not competitive

- MgB₂ (not so HT HTS)
- Sr/BaFe₂As₂:K (Iron-Based)

- All magnets operate with “margin,” typically at about 80% of the conductor limit.
 - So, an 8T magnet would in principle reach 10T (LHC example)
 - For an ensemble of magnets, margin is required due to manufacturing tolerances, variations in operating environment, etc.

Nb-Ti

- **1960's – 1970's: Early development and proof of principle**
 - Some prototypes built
 - 1968 BNL Summer Study (200 physicists and engineers for 6 weeks)
 - Major steps toward practical application
 - Discussion of doubling the energy of the NAL accelerator using Superconducting magnets
 - Panel discussion at the 1971 Particle Accelerator Conference was the kick-off of superco magnets in accelerators
 - Paper on compact, fully transposed cable produced by Rutherford lab



- **1980's: Tevatron – First large-scale deployment (4.5T @ 4.5K)**
 - Many innovations developed then are still in use today - set the standard for future accelerators.
 - Provided a basis for a conductor industry that benefited all subsequent projects.

Practical limit for Nb-Ti thought to be 5 – 6T



Considerable parallel effort in developing Nb₃Sn due to potential for higher field. Significant field boost for Nb-Ti in superfluid but cryo considered too expensive and risky at that time.

Nb-Ti Performance Plateau achieved ~ 4 Decades

- **1990's – 2000's: Maturation and Industrialization**
 - Became world-wide workhorse for accelerators.
- **2000's – Present: LHC – Practical limit of Nb-Ti**
 - Low-profile R&D started in the 1980's
 - Much was based on SSC and ISABELLE tech
 - Collars, Cold Iron Yoke, two-in-one design
 - **High quality Nb-Ti alloy – US Conductor Development Program**
 - LHC innovations
 - Large-scale industrialization
 - Operation at 1.9K

ISABELLE – BNL
ISR Quads - CERN

Other projects around
the same time as the
FNAL Energy-Doubler
ESCAR – LBL
TRISTAN - KEK
UNK - USSR

Tevatron

HERA

SSC

RHIC

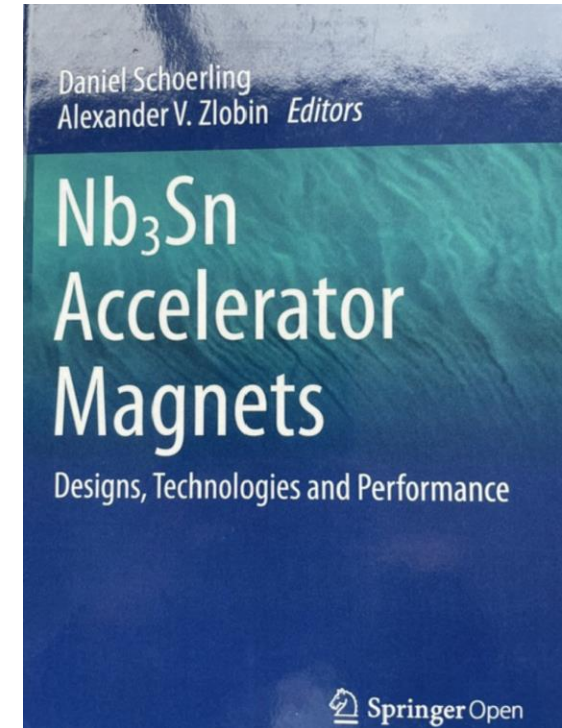
LHC

~X2 Conductor
Improvement

	Tevatron	HERA	SSC	RHIC	LHC
First Beam	Jul-83	Apr-91	N/A	Jun-00	Sep-08
Dipole Field (Tesla)	4.3	5.3	6.6	3.5	8.3
Length (m)	6.1	8.8	15	9.45	14.3
Operating Temp	4.6	4.5	4.3	4.3-4.6	1.9

Nb₃Sn

- **1960's – 1980's**
 - First Nb₃Sn accelerator magnets were built at BNL
 - Several other efforts during this time period
 - CERN (Asner) – 10T achieved
 - CEA Saclay
 - LBL D10 – 9T @ 1.8K
 - KEK
- **At the time SSC decisions were made:**
 - Nb-Ti – mature, ductile, industrialized, proven in accelerators
 - Nb₃Sn – higher potential field, but brittle, poor reproducibility at scale, not production ready.



Industrialization of superfluid cryogenics now deemed easier to achieve,
less expensive and less risky than Nb₃Sn magnets.

But, in the background, SSC R&D provided the environment for the
development of modern Nb₃Sn accelerator magnets.

Breakthrough in Nb₃Sn Magnet Technology

- 1990's – 2010's
 - First accelerator-style dipoles
 - U. Twente – 11T
 - LBNL D20 – 13T

Evolved into a series of high field demonstrations at LBNL D20 → HD1 (16T) → HD Series

- LHC Accelerator Research Program (LARP) established 2003 – develop Nb₃Sn quads for LHC Hi-Lumi upgrade (BNL, FNAL, LBNL)
- US Magnet Development Program created in 2015 (BNL, FNAL, LBNL, FSU/NHMFL)
- In 2016 LARP transitioned to US Accelerator Upgrade Project – Completion in FY28





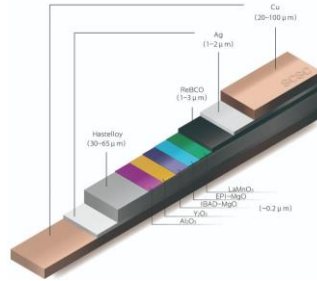
On to a New Frontier

High Temperature, High Field Superconductors

ReBCO (Rare-earth barium copper oxide)

Pros

- Very high field capability >20T
- Very high current density
- Reasonable mechanical strength (some issues)
- No reaction after winding
- **Can operate at 20K**
- **Growing industrial capacity – availability/lower cost**



Cons

- Flat tape 2 – 12 mm - Difficult to cable
- Anisotropic
- Quench detection
- Expensive

Bi-2212 (Bismuth strontium calcium copper oxide)

Pros

- Round, Multifilament wire – Rutherford Cable
- 20T achieved
- High current density
- Isotropic – better field quality, uniform current distribution



Cons

- Mechanically weak (silver matrix)
- Heat treatment at 890°C/ 50 bar O₂
- Limited to low temperatures
- Very limited industrial capacity
- Expensive

Moving Forward – Reality Check

Creating a world-leading US magnet R&D program in the current environment

Funding and completion of current project commitments dictate priorities.

- **Proposed Strategy**

- Focus on ReBCO – huge potential for growth to support future DOE facilities, societal applications
- Expand into fusion magnet technology (symbiotic relationship)
- Solutions to many of the challenges can be explored via small-scale experiments
- Exploit new facilities – e. g. MAGNES (high current cable and magnet test facility funded by HEP/FES)
- Bi-2212 has some advantages for certain applications – but very limited commercial interest



- Nb_3Sn outserts for testing HTS coils in high background field
- ReBCO prototype achieved 6T
- Technology development: design, fabrication methods, instrumentation, quench detection, magnet protection
- Conductor development and characterization



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