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High Field Magnets

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DPF/DNP Community Meeting

U.S. DEPARTMENT of ENERGY
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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.

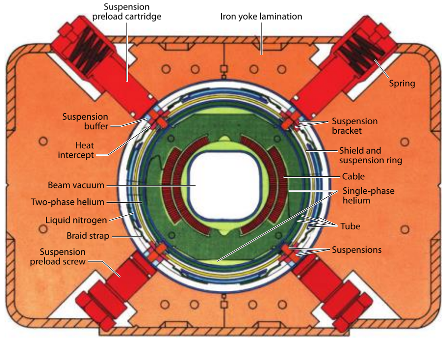
- Nb-Ti – 8T
- Nb_3Sn – 14T
- Bi-2212 – 36T – NMR configuration
- ReBCO - > 40T?

Other conductors with interesting properties, but not competitive

- MgB_2 (not so HT HTS)
- $Sr/BaFe_2As_2$: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 superconducting magnets in accelerators
    - Paper on compact, fully transposed cable produced by Rutherford lab

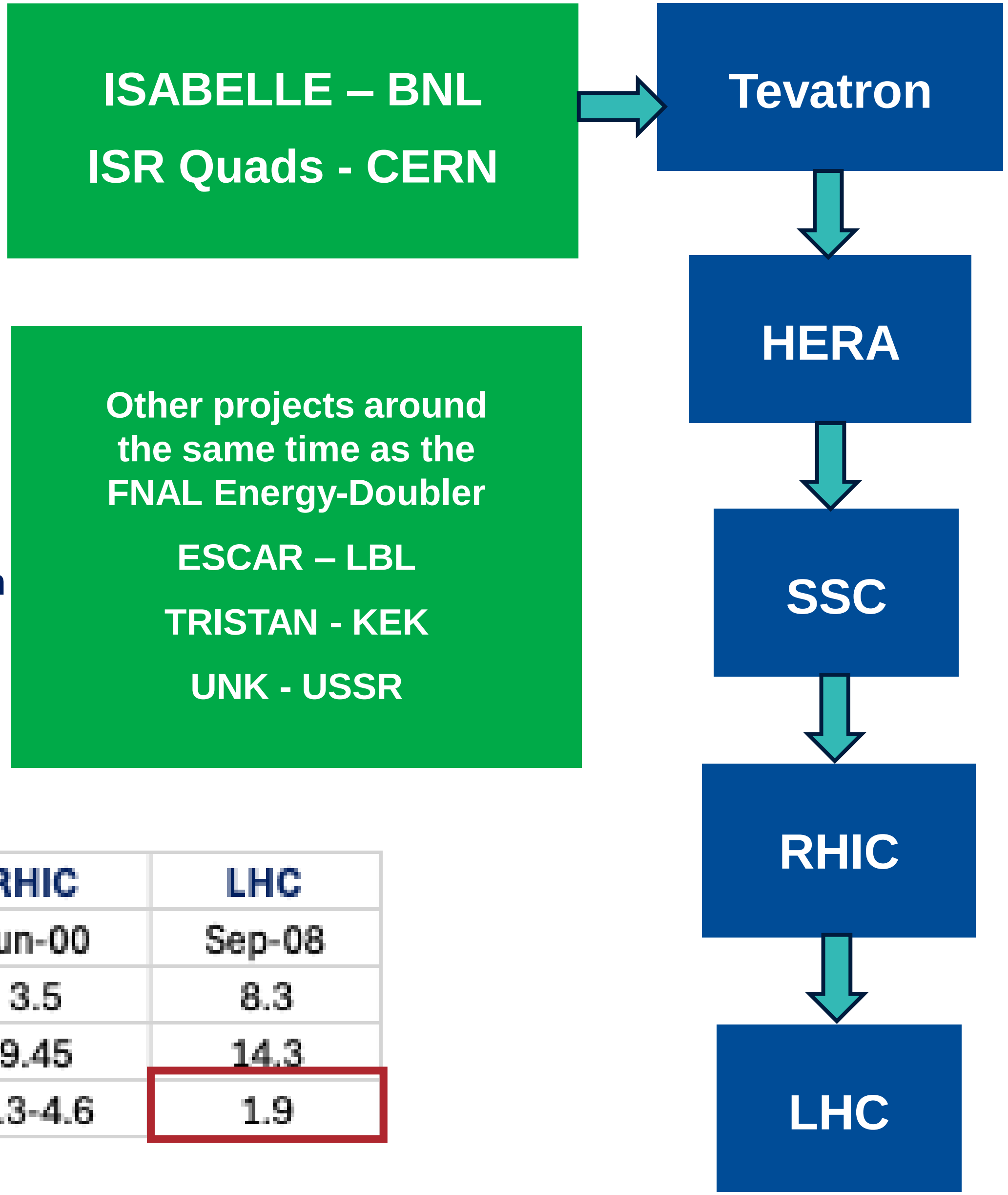
- **1980's: Tevatron – First large-scale deployment (4.5T @ 4.5K)**
  - Many innovations developed then are still in use today - set the standard for future accelerators.
  - Provided a basis for a conductor industry that benefited all subsequent projects.

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

Considerable parallel effort in developing Nb_3Sn 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

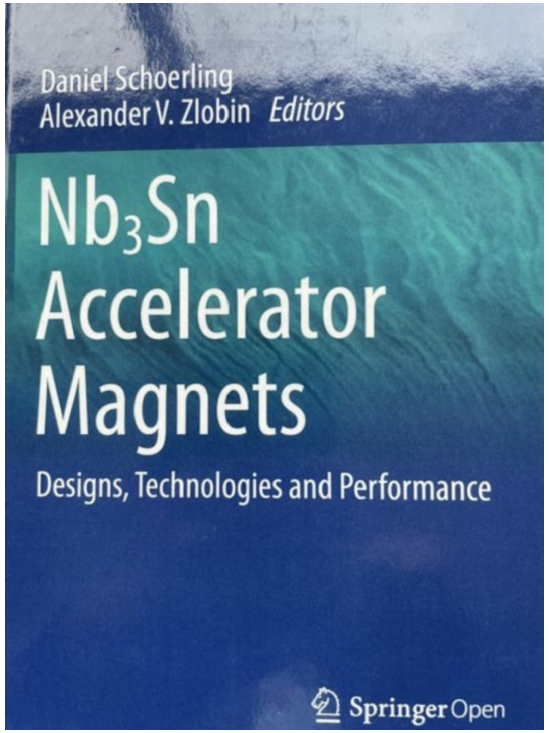


50% Conductor Improvement

	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

Nb_3Sn

- **1960's – 1980's**
  - First Nb_3Sn 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, **<u>industrialized</u>**, proven in accelerators
  - Nb_3Sn – 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 Nb_3Sn magnets.

But, in the background, SSC R&D provided the environment for the development of modern Nb_3Sn accelerator magnets.

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Breakthrough in Nb_3Sn 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 Nb_3Sn quads for LHC Hi-Lumi upgrade (BNL, FNAL, LBNL)

- US Magnet Development Program created in 2015 (BNL, FNAL, LBNL, FSU/NHMFL)

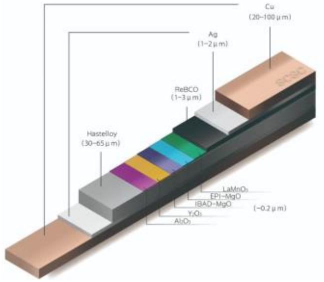
- In 2016 LARP transitioned to US Accelerator Upgrade Project – Completion in FY28

Tech X-fer to CERN

On to a New Frontier

High Temperature, High Field Superconductors

ReBCO (Rare-earth barium copper oxide)



Pros

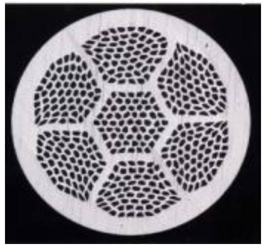
- Very high field capability >20T
- Very high current density
- Reasonable mechanical strength (some issues)
- No reaction after winding
- **Can operate at 20K**
- **<u>Growing industrial capacity</u> – availability/lower cost**

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^{0}C/ 50 bar O_2
- 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**

U.S. MAGNET DEVELOPMENT PROGRAM

- 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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