State-of-the-art of the main objectives and challenges

ECFA
European Committee for Future Accelerators

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Plenary ECFA meeting – Open Session on Advanced Accelerator Technologies: HTS magnets
CERN 14 November 2019
Hadron Colliders are ruled by: \[ E_{\text{beam}} = 0.3 \, R \, B \, (\text{TeV; km; T}) \]

- \(< 10 \text{ y to double field: } 2 \, \text{T MR} \rightarrow 4 \, \text{T Tevatron} \)
- \( > 20 \text{ y to double again in SC: } \rightarrow 8 \, \text{T of LHC} \)

**Consideration on LHC**

- Designed for 8.33 T (14 TeV c.o.m.) with margin to go to 9 T (15 TeV c.o.m.)
- Today operating at 7.75 T (13 TeV)
- 8.33 T in 2021 possibly
- 9 T may be in 2026/2030 with HiLumi but very difficult (trade off with loss of lumi)
LHC has been the summit of > 40 y developments with SC Nb-Ti magnets. Magnet design soon converged to Cosθ

**LHC Dipole Cross section: Cosθ layout**

**DIPOLE MAGNETS**

**HERA**
B = 4.7 T  
BORE : 75 mm

**RHIC**
B = 3.5 T  
BORE : 80 mm

**TEVATRON**
B = 4.5 T  
BORE : 76 mm

**LHC**
B = 8.3 T  
BORE : 56 mm

**SSC**
B = 6.6 T  
BORE : 50-50 mm
The 25 y LHC construction time line

Striking: only 4 y to make a design «near to final». The conductor was almost there! (thanks to SSC)

Industry contracts Nb-Ti

LHC start-up

9 T - 1 m single bore
10 T-1 m Nb3Sn dipole
9 T -10 m long prototype
9 T-15 m final prototype
Last LHC dipole

The key factor: superconductor (but not the only factor!)

Developing SC is the key in SC accelerators. LHC is indebted to SSC

The perfection of LHC superconductor is such that we basically «forget» the SC effects and is the base of the repeatability and optimal performance of the collider
The superconductor space: Accelerators Magnets need $J_E > 500 \text{ A/mm}^2$ @ 20 T
Dipole Field for Hadron Collider

Year
Central field (T)

HTS
Nb₃Sn
Nb-Ti
Tevatron HERA RHIC
SPS & Main Ring (resistive)

HE-LHC
FCC-hh

Nb-Ti operating dipoles;
Nb₃Sn cos⁹ test dipoles
Nb₃Sn block test dipoles
Nb₃Sn cos⁹ HiLumi QUADs

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$\text{Nb}_3\text{Sn} \text{ DOE-CDP in USA and (less) in EU took basically 15 y of development and was key for HiLumi LHC}$
And HiLumi HF magnets magnets follows!

\[ B_p \sim 13 \text{ T no quench!} \]

IT QUAD

11T dip
After 15 y of R&D Nb$_3$Sn magnets are coming... first time in an accelerator...
Short model magnets (1.5 m lengths) to be built from 2018 – 2022
Russian 16 T magnet program launched by BINP recently.
Recent very successful 14 T magnet reached by US MDP cosØ dipole at FNAL

Key milestone: 15 T dipole

- 4 layer graded magnet, 1-m long
- 1st step: 14.1 T performance

Basically wiht HiLumi type wire. But the route is long… To operate really at 14-16 T one need sto develop very high field Nb₃Sn and demonstrate magnets at least in the 8 T range.
Is Iron-Based Superconductor good? Not yet but improving… It is the «bet» of the China National Program

Recent advances in transport $J_c$ of PIT processed 122 wires and tapes

- An scalable process is required to fabricate high performance long length tapes, e.g., Rolling (hard sheath), Hot Rolling or Hot isostatic press (HIP)…
CARE – EuCARD/EuCARD2: 15 y Nb$_3$Sn development in EU

CARE-NED 2004-2008 then CERN + CEA
Development of PIT conductor and first HF dipole design
PIT of 1300-1500 J$_c$ at 15T

Fresca2 all Nb3sn (RRP+PIT) record field dipole: 14.6 T in 100 m free bore

First attempt –in EU – to go for dipole-like coil. Stacked tapes, no transposition, with large amount Cu

Simple racetrack.

Transposition between the two sub-cables of top and bottom pole.

Cable: 0.92 mm thick

12 mm wide

M. Durante et al., CEA
YBCO (or REBCO) Conductor: the choice of

<table>
<thead>
<tr>
<th>REBCO Characteristics</th>
<th>Bi-2212 Characteristics</th>
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<tbody>
<tr>
<td>High, steadily improving</td>
<td>Critical current</td>
</tr>
<tr>
<td>Roebel cable (waste), ready to use, 50-200 m unit length</td>
<td>Cabling and general</td>
</tr>
<tr>
<td>Very bad (tape).</td>
<td>Magnetization</td>
</tr>
<tr>
<td>Excellent, better than Nb₃Sn</td>
<td>Mechanical prop.</td>
</tr>
<tr>
<td>Difficult bend in non-easy way, joints not easy, <strong>NO Heat Treatment</strong></td>
<td>Coil technology</td>
</tr>
<tr>
<td>Various suppliers and projects everywhere</td>
<td>Supply</td>
</tr>
</tbody>
</table>
CERN-Bruker complement to EuCARD2

Pulsed Laser Deposition PLD600: production equipment of Bruker

PROCESSING CHAIN OF HTS PILOT-LINE PRODUCTION

| Substrate Preparation (Sub) |
| Buffer Layer Coating (Abad) |
| HTS Layer Coating (PLD)      |
| Metal Coating (Met)          |
| Copper Plating (Pla)         |
| Final Tape Inspection (Ins)  |

Pulsed Laser Deposition PLD300: R&D line: CERN-Bruker
Roeble cable by KIT for the EuCARD2

- Large currents ~ 10 kA with good FF ~ 85% (same range Ruth. Cable)
  - Transposed (good FQ also in ramping)
- Good contact resistance despite impregnation: 10-30 µΩ (not low - not high)
Results of Eucard2: demonstrator dipole

Concept and e.m. design by J. van Nugteren, CERN
Mechanical analysis by J. Murtomaki, CERN

Design and technology innovation by G. Kirby, CERN

Quench CU bars
EuCARD 2 demonstrator test and more…

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3.35 T high ramp rate
Recent test at CERN of 2nd open race-track

Inside FRESCA2 this Eucard2 or similar insert (Eucard1, but no bore) can reach 17-18 T

FeatherM2-3.4

4.2 tesla
Tape Q065-18 (with 2x 7μm Cu) reached a very high performance of 1150 A/mm² at 4.2 K, 19 T, 90°
Result from ARIES miniproduction: repeatability not fully successful...

We need to review the process since the yield is not satisfactory (about 50%).

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LBNL: CCT with CORC™ cable (ACT LLC)

Reached 1-1.5 T
Plan to reach 3 T at 4.2 K
LBNL: Bi-2212 racetracks and CCT program

RC 7 - Twisted wires + more turns

Mechanical Assembly: Jim Swanson, Josh Herrera, Daniel Davis, Tengming Shen. Bladders used: Courtesy of Daniel Cheng
And then use B-2212 cable for CCT
Always in the 3-7 T range; to be used as insert
Historical factor 1.5-2 due to Coil «efficiency» and to force-stress.
Now factor 3 with HTS: lack of ambition?
A big leap forward by a private company… Bruker Biospin

The First 1.2 GHz (28.2 T) NMR Magnet Reached Full Field in 2019
EuCARD2/ARIES has triggered an international collaboration also beyond EU labs.

- **WAMHTS-1** in Hamburg 21-23 May 2014
  - HTS Conductor – 57 participants
- **WAMHTS-2** in Kyoto 21-23 May 2014
  - HTS Coil technology – 55 participants
- **WAMHTS-3** in Lyon 10-11 September 2015
  - HTS Magnet protection – participants
- **WAMHTS-4** in Barcelona 15-17 February 2017
  - HTS Magnet design – 87 participants
- **WAMHTS-5** in Budapest 11-13 April 2019
  - HTS Magnet applications – 66 participants
Conclusion

- Accelerator Magnets are the most challenging for superconductivity, requiring current density of \( J_E \geq 500 \text{ A/mm}^2 \) in operating condition (+ 20% margin)
- The homogeneity must be excellent and the screening currents (magnetization) sufficiently small not to hamper Field Quality (or very predictable and repeatable to be corrected with field-forward systems)
- The cost is high. Today 5 times the best Nb\(_3\)Sn. Cost decrease is being pushed by other community (Fusion).
- **But HTS can gain us the 15-25 T range at 4.2 K with training-free magnets**
  - Operating at 15 T at 10-20 K should also be explored (factor 10 energy saving wrt FCC baseline)
- The only way to make progress is a continuous and focussed program of size 2-3 times of EuCARD2: 3 M€/year in material + 15-20 FTE. The program should ~ 5+5 years (two phases), like US-LARP.
  - 5 years are needed just to complete assessment if HTS can be suitable for colliders
  - A good part of issue of HTS magnets are shared with other HF conductors (Nb\(_3\)Sn)
  - Specific disadvantage (shape) and gain (stability and NI technology) needs to be addressed.
Thanks
32 T reached in 2018!

30 T coil Non-insulated

Courtesy of M. Bird, FSU/NHMFL USA