Very high field magnet options for ELN

Lucio Rossi – CERN
High Luminosity LHC Project Leader

Erice ISSP – 2018, June 18th
Content

- Accelerator: engines for discovers
- Accelerators & Superconductivity
- Accelerator Magnets
- LHC
- High Luminosity LHC
- FCC
- HTS and technology progress
- A 20+ tesla magnets for … ELN
60 years of experiments at accelerators have discovered the set of fundamental particles:

- Photon
- Gluon
- W, Z
- Electron
- Muon
- Neutrinos
  - Electron
  - Muon
  - Tau
- Strange
- Up - Down
- Charm
- Bottom
- Top
- Higgs
Accelerators gain us one frontier of the physics spectrum

Particle physics looks at matter in its smallest dimensions and accelerators are very fine microscope or, better, *atto-scope!*

\[ \lambda = \frac{h}{p} \]

@LHC: \( T = 1 \, \text{TeV} \Rightarrow \lambda \cong 10^{-18} \, \text{m} = 1 \, \text{am} \) (actually 30 zm)
...back to Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \approx 1/E_{\text{Gev}}^2$
- $T \approx 1 \text{ ps}$ for single particle creation
- $T \approx 1 \mu s$ for collective phenomena QGS (Quark-Gluon Soup)

But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about...

Which is a much more complex task!
Accelerators: the two frontiers

2 routes to new knowledge about the fundamental structure of the matter

High Energy Frontier

New phenomena (new particles) created when the “usable” energy > mc² [×2]

High Precision Frontier

Known phenomena studied with high precision may show inconsistencies with theory
THE MAIN COMPONENTS OF THE LHC ACCELERATOR

- Accelerating CAVITY
- Focusing MAGNET (quadrupole)
- Bending MAGNET (dipole)
- Vacuum CHAMBER

Injection → Collisions → Injection

Diagram showing the main components of the LHC accelerator, including focusing magnets, bending magnets, and injection points.
Superconductivity: an enabling technology

- **Superconducting LHC**
  - Tunnel: 27 km
  - Field: 8.3 T
  - Cryoplant power at the plug: 40 MW: *always on*
  - ~ 70 MW for LHC.

- **Normal Conducting LHC**
  - Tunnel: 120 km
  - Field: 1.8 T
  - Dissipated power at collision: ~ 2,200 MW
  - Average power (0.4 coefficient) ~ 900 MW only for 0.4 E^2 term in LHC
Accelerators progress: SC domination

![Graph showing the progress of accelerators with superconducting technology.

- Proton synchrotron
- Hadron colliders
- Lepton colliders
- Up colliders

The graph illustrates the Centre-of-mass energy (TeV) over the years from 1940 to 2050, with a focus on the superconducting technologies used in accelerators like LHC and HiLumi.](image-url)
High Luminsity: a luminous future for LHC!

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LHC


LS1
splice consolidation button collimators R2E project

13 TeV

EYETS

7 TeV | 8 TeV


LS2
INJECTOR UPGRADE
TDIS absorber
117 dipole & collimator
Civil Eng. P1-P5

14 TeV

LS3
HL-LHC installation

14 TeV

5 to 7 x nominal luminosity


experiment beam pipes

nominal luminosity

2 x nom. luminosity

2.5 x nominal luminosity


ATLAS - CMS upgrade phase 1
ALICE - LHCb upgrade

30 fb⁻¹

150 fb⁻¹

300 fb⁻¹

3000 fb⁻¹

integrated luminosity


FP7
Hi-Lumi
DESIGN STUDY

PDR PREPARATION


ASSESS & TDR


MAIN ACCELERATOR COMPONENTS
CONSTRUCTION AND TEST
INSTALLATION


TECHNICAL INFRASTRUCTURE


PHYSICS


CERN
HiLumi PROJECT
HL-LHC: Pushing the technology!

CIVIL ENGINEERING
2 new caverns and two new 300-metre service galleries, two new large shafts,
10 new technical buildings on surface in P1 and P5 (ATLAS and CMS)

CRUOGGENICS
2 new large 1.9 K helium refrigerators for HL-LHC near ATLAS and CMS

“CRAB” CAVITIES
8 superconducting “crab” cavities for each of the ATLAS and CMS experiments to lift the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

BENDING MAGNETS
2 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

SUPERCONDUCTING LINKS
Electrical transmission lines based on high-temperature superconductor to carry current to the magnets from the new service galleries to the LHC tunnel.
HiLumi LHC: An international collaboration

**US-DOE and JP-KEK** are the biggest contributor (after CERN and Member States)

Special in-kind from:
- ES – CIEMAT
- IT – INFN
- SE – Uppsala
- UK – STFC & C.I. Univ.

Canada/Triumf
China/IHEP
Russia/BINP

**DOE**
Nb3Sn R&D

**LARP**
generic

**FP6**
CARE Nb3Sn

**FP7**
EuCARD HiField
Dip

**HL-LHC install. & commissioning**

**FP7 DS**
Hi-Lumi LHC

**Construction**

**Inject**or upgrade

**2024**

**2010**

**2005**

**2000**

**CERN-KEK**
R&D

**CERN-KEK**
D1 design

**LARP**
HiField quads

**LARP**
Demo
HL-LHC magnet “zoo”

Approximately 150 single magnets and 50 cold masses for HL-LHC
MBH (11T) dipole

12.37 T

This is a tough race!

Aperture 60 (mm)
Field 10.8 (T)
Current 11850 (kA)
Peak field 11.35 (T)

RRP strand (0.7 mm, 108/127)
$J_C$: 2450 A/mm$^2$ (12 T, 4.2 K)
Cu:non-Cu: 1.15

40 strands cable
(14.7 mm x 1.27 mm)
11T production

Coil winding

Pre-collaring

Pole preparation

Collared aperture
MQXFS1 results

- Aperture: 150 (mm)
- Gradient: 132.6 (T/m)
- Current: 16.47 (kA)
- Peak field: 11.4 (T)

RRP strand (0.85 mm, 108/127)

- $J_c$: 2450 A/mm$^2$ (12 T, 4.2 K)
- Cu: non-Cu: 1.2

40 strands cable (18.15 mm x 1.52 mm)

Courtesy of G. Ambrosio, G. Chlachidze, US LAUP and CERN

$\approx 28$ kA
MQXFS5 results

PIT strand (0.85 mm, 192)
$J_C$: 2450 A/mm$^2$ (12 T, 4.2 K)
Cu:non-Cu: 1.2

40 strands cable
(18.15 mm x 1.52 mm)

$\approx$ 22 kA

Aperture 150 (mm)
Gradient 132.6 (T/m)
Current 16.47 (kA)
Peak field 11.4 (T)
LQXF production

CERN: Q2
7.15 m length

US: Q1/Q3
4.2 m length

First impregnated coil at CERN
Long mirror test at BNL

Coil winding at CERN
HiLumi LHC: preparing technology for next big steps

Dipole Field for Hadron Collider

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<td>6</td>
<td>8</td>
<td>10</td>
<td>14</td>
<td>20</td>
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<tr>
<td>SPS &amp; Main Ring (resistive)</td>
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<td>6</td>
<td>8</td>
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<td>Nb$_3$Sn</td>
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FCC
HL-LHC

HiLumi HL-LHC Project
CERN
Future Circular Collider

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<th>LHC</th>
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<tr>
<td>Circumference (km)</td>
<td>26.7</td>
<td>97.5</td>
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<tr>
<td>Dipole field (T)</td>
<td>8.33</td>
<td>16</td>
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<tr>
<td>C.o.M. energy (TeV)</td>
<td>14</td>
<td>100</td>
</tr>
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Courtesy of M. Benedikt, FCC
CERN/EU program for 16 T dipole

Is it possible? Do we have a superconductor?

We need 300-400 A/mm² of average current density $J_\text{e}$
$\Rightarrow$ 1000-1200 A/mm² of critical current density $J_\text{c}$
at the relevant field (16 T) + margin… i.e 1500 A/mm²

Design a 16 T accelerator-quality model dipole magnet by 2018

Courtesy of M. Benedikt, FCC
Nb$_3$Sn: the workhorse of the “near Future”

Solid objectives for the FCC conductor R&D

- $D_{\text{strand}}$: 0.7…1 mm
- $J_C$ (16 T, 4.2 K) > 1500 A/mm$^2$
- M (1 T, 4.2 K) <150 mT ($D_{\text{fil}} < 20 \mu$m)
- RRR > 150
- UL > 5 km
- Cost(16 T, 4.2 K) < 5 USD/kA m

The goal is ambitious but not impossible. Cost will be probably the most challenging
Conductor R&D

Specification: 1500 A/mm² @ 16T, 4.2K

- 2850 A/mm² @ 12T, 4.2K
  ≈ 1250 A/mm² @ 16T, 4.2K

- 1750 A/mm² @ 15T, 4.2K
  ≈ 1400 A/mm² @ 16T, 4.2K

- 1274 A/mm² @ 15T, 4.2K
  ≈ 1000 A/mm² @ 16T, 4.2K

Results expected later this year
FCC Magnet Designs

\[ T_{op} \approx 1.9 \text{ K} \]

\[ \frac{I_{op}}{I_C} (\text{loadline}) \approx 86 \% \]

\[ V_{\text{dump}} < 2.5 \text{ kV} \]

\[ \sigma_{\text{max}} < 200 \text{ MPa} \]

\[ T_{\text{hot}} < 350 \text{ K} \]

\[ D_{\text{out}} \approx 600 \text{ mm} \]

Current (A) | 11230 | 10000 | 16100
Inductance (mH/m) | 40 | 50 | 19.2
Stored energy (kJ/m) | 2520 | 2500 | 2490
Coil mass (tons) | 7400 | 7400 | 9200

Very efficient use of superconductor
Simplified mechanics and manufacturing?

Courtesy of D. Tommasini, CERN
CCT option
Canted CosTheta

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<td>Inductance (mH/m)</td>
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<td>Stored energy (kJ/m)</td>
<td>3200</td>
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<td>Coil mass (tons)</td>
<td>9770</td>
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135 MPa on the conductor

Courtesy of B. Auchmann, PSI and CERN
Are we stuck with 15-16 T of FCC? NO!
20 T dipole hybrid proposed in 2010 for HE-LHC

40 mm aperture
Now the standard is more 50 mm
Super proton-proton Collider in China

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<th>LHC</th>
<th>FCC</th>
<th>SppC</th>
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<tr>
<td>Circumference (km)</td>
<td>26.7</td>
<td>97.5</td>
<td>100</td>
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<tr>
<td>Dipole field (T)</td>
<td>8.33</td>
<td>16</td>
<td>12…24</td>
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<tr>
<td>C.o.M. energy (TeV)</td>
<td>14</td>
<td>100</td>
<td>70…125</td>
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</table>

Courtesy of Q. Xu, IHEP, CN
CN high-field magnet R&D

- Baseline design
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV

- Upgrade phase
  - Dipole magnet field: 20…24T, IBS technology
  - Center of Mass energy: >125 TeV

- Development of high-field superconducting magnet technology
  - Starting to develop required HTS magnet technology before applicable iron-based wires are available
  - ReBCO & Bi-2212 and LTS wires be used for model magnet studies and as an option for SppC: stress management, quench protection, field quality control and fabrication methods

- Top priority: reduce cost!
  Instead of increasing field

Conceptual design of common coil 12T dipole

Courtesy of Q. Xu, IHEP
US high-field magnet R&D

The U.S. Magnet Development Program Plan

S. A. Gourlay, S. O. Prestemon
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

A. V. Zlobin, L. Cooley
Fermi National Accelerator Laboratory
Batavia, IL 60510

D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

Courtesy of S. Gourlay, US-MDP
Cos-theta, 4 layers, 15 T dipole

L1-L2: 28 strands, 1 mm RRP 150/169
L3-L4: 40 strands, 0.7 mm RRP 108/127

Assembly and test expected in 2018

Simplify assembly, reduce cost

Courtesy of A. Zlobin, FNAL
US CCT and HTS programs

Nb$_3$Sn cable in CCT geometry

Bi-2212 cable in racetrack

REBCO CORC in CCT geometry

Courtesy of S. Prestemon, LBNL
Highest “dipole” fields

Record fields for SC magnets in “dipole” configuration

From Luca.Bottura-CERN
Current density is the dominant factor

Dipole field generated by a current distribution with constant current density \( J \) over a sector of inner radius \( R_{\text{in}} \), outer radius \( R_{\text{out}} \), coil width \( w = R_{\text{out}} - R_{\text{in}} \) and opening angle \( \phi \):

\[
B = \frac{2}{Jw \sin(\phi)}
\]

\[
A_{\text{coil}} = 2 \left( w^2 + 2R_{\text{in}}w \right) \mu \frac{1}{J^n} 
\]

\[
\mu \frac{1}{J} \approx 1 \ldots 2
\]

In the range of typical magnet designs considered \( n \approx 1.5 \)

| \( B \) (T) | 16 |
| \( J \) (A/mm\(^2\)) | 300 |
| \( w \) (mm) | 76 |
| \( A_{\text{coil}} \) (mm\(^2\)) | 20,000 |

\( A_{\text{coil}} \mu M_{\text{coil}} \mu \text{COST} \)

| 16 |
| 600 |
| 38 |
| 7000 |

Factor 2

Factor 3
Mechanics at high fields: may be anot a limitation for 20 T... (see Fresca2)

Lorentz forces in the plane of a thin coil of radius $R_{in}$ generating a dipole field $B$ (thin shell approximation), referred to a coil quarter

$$F_x = F_y \left(\frac{4}{3} \frac{B^2}{2m_0} R_{in}\right)$$

Progression of $F_x$:
- LHC MB(8.33T) $\approx$ 1.7 MN/m
- LHC MBH(11T) $\approx$ 3.2 MN/m
- FRESCA2(13T) $\approx$ 7.6 MN/m
- FCC MB(16T) $\approx$ 8 MN/m
- HE-LHC MB(20T) $\approx$ 10 MN/m

From Luca.Bottura-CERN
Protection at high fields: also not a limitation

\[ E/l = \frac{B^2 R^2_{in}}{0} \left( 1 + \frac{2}{3} \frac{w}{R_{in}} + \frac{1}{6} \frac{w^2}{R_{in}} \right) \]

Energy per unit length in a sector coil of inner radius \( R_{in} \), outer radius \( R_{out} \), coil width \( w = R_{out} - R_{in} \) producing a dipole field \( B \)

In the range of typical magnet designs considered \( n \approx 1.5 \)

\[ E/l \mu B^2 \]

\[ A_{coil} \mu J^n B^2 \]

Progression of energy density \( e \):
- LHC MB(8.33T) \( \approx 50 \text{ MJ/m}^3 \) (80 K)
- LHC MBH(11T) \( \approx 85 \text{ MJ/m}^3 \) (100 K)
- FRESCA2(13T) \( \approx 100 \text{ MJ/m}^3 \) (110 K)
- FCC MB(16T) \( \approx 200 \text{ MJ/m}^3 \) (150 K)

From Luca.Bottura-CERN
Grand challenges in HF magnets

- **Superconductor performance:**
  - High $J_C$, low cost
  - Abolish training!
  - Increase $J_{op}/J_C$ (presently $\approx 40\%$ for Nb$_3$Sn at 1.9 K)

- **Mechanics:**
  - Devise an appropriate support concepts for the coil (bladder-and-key, stress management, canted-cosinus-theta, …)
  - Cope with increasing stress on the conductor
  - Limit mechanical energy release (training)

- **Protection:**
  - Fast detection and internal dump (spread the energy)
  - Material and coil limits (hot-spot, thermal stress, voltage)
But what will gain us the 20+ T regime? Very recent results in Current density

Graph from Carmine Senatore, UniGenreva
Racetrack POPE

A 5 T, HTS based dipole Proof-Of-Principle Experiment
Racetrack POPE results

EuCARD HTS Dipole Magnet - CEA Saclay 14-26/09/2017 - LHe 4.2 K

Graph showing the relationship between current (A) and magnetic field strength (T) with a nominal current value of 5.37 T.
Short accelerator dipole demonstrator
40 mm aperture, cable (not single element)

A 5 T, 40 mm bore HTS based dipole demonstrator
Dipole demonstrator results

3.35 T

Feather-M2.1-2 (SuperOx, Sunam)
EuCARD2 // Future Magnets

Wound with low grade SC, now winding with high grade: hope for 7+ tesla!
Roebel cable (10 kA class at 4.2 K, 20 T)  Punch-and-coat sequence
First, an *executive summary*…

- The LHC High-Luminosity Upgrade is the **springboard** for new magnet technology, and provides an interesting opportunity for industry
  - Production in 2018-2022
  - First use ever of Nb\(_3\)Sn in a running accelerator
- The **next step** is the development of magnets for an “FCC”
  - Model activities are planned in EU laboratories (and US) in 2018-2022
  - Prototyping in industry (full length, ≈10 magnets), in 2022-2025
  - This is the logical sequence of the HL-LHC production, profiting from Nb\(_3\)Sn technology established in laboratories and industry
- HTS is only in its infancy, but could be the **killer technology for high-field magnet technology** of the future
  - Requires high-tech R&D, spanning from material science to electromechanical engineering, 5 years program defined
  - HTS is the high-risk/high-return investment of the future
… then, an ideal timeline

From Luca.Bottura-CERN
Can we extrapolate linearly from the past
To go BEYOND FCC? ⇒ ELN?

Dipole Field for Hadron Collider

- HTS
- Nb$_3$Sn
- Nb-Ti
- Tevatron
- HERA
- RHIC
- SPS & Main Ring (resistive)

Year


Central field (T)

20 18 16 14 12 10 8 6 4 2 0

5T HTS demos

20 T is not out of reach

ELN

HiLumi
HL-LHC PROJECT

CERN

To edit speaker name go to Insert > Header & Footer and apply to all slides except title page
We have at CERN the large infrastructure to manufacture prototypes at industrial level..

Service contracts for engineering design and prototyping of HL-LHC Nb$_3$Sn magnets, 22 FTEy

Service contract for HL-LHC 11T Nb$_3$Sn collared coils manufacturing, 35 FTEy

LS1: 250 people

LS2: 150 people
But can we take the challenge of going farther?

“Go big or go home” - Bill Barletta

- There are no insurmountable technical obstacles to realizing a high luminosity, 100 TeV-class proton collider
- Contribute to research in technologies critical for accelerator & detector
- Closely follow ongoing FCC study
  - But there are good reasons for choosing to build a much larger ring (200 - 300 km) than the CERN FCC (100 km)...
- Recognize that radiation damage can be a serious issue
- In a future phase, a 300 km circumference synchrotron might possibly reach $E_{cm} = 0.5$ PeV
  - But to ensure 1 PeV, consider 300 km diameter...

ELN as PeV collider
0.5 PeV collider: 300-330 km Needs 25 T dipoles

Is it a dream, only?

Slide form Tom Taylor talk, Saturday Morning
Towards REBCO 20 T+ Dipoles for Accelerators

J. van Nugteren, G. Kirby, J. Murtomäki, G. de Rijk, L. Rossi and A. Stenvall

Abstract—ReBCO High Temperature Superconducting (HTS) coated conductor tapes are a promising candidate for pushing the magnetic fields in accelerator magnets well beyond 20 T. They are capable of very high current densities in intense applied magnetic field, have a very high thermal stability, can withstand high transverse pressures and allow operation in 20 to 30 K helium gas flow, potentially reducing operating cost significantly. During the EuCARD2 program significant developments have been made in terms of coil design, manufacturing and testing. Now that EuCARD2 has come to an end, CERN and collaborators are initiating a new program to continue the development of HTS accelerator magnets. This paper presents our initial thoughts on the conceptual design of a 20 T+ accelerator magnet, using the results and technologies from EuCARD2 combined with some new ideas. The paper discusses the options available for the cross-sectional layout, the use of a hybrid configurations including Aligned Block, the design of the coil-ends and dual aperture configurations. Also discussed is the quench protection of the magnets. Due to the high thermal stability of the conductor and high energy densities it will be required to explore an entirely new approach.

Index Terms—Accelerator Dipoles, HTS Magnets, Quench Protection, Magnet Stability, Magnet Structure

I. INTO THE FUTURE WITH HTS

With the successful stand-alone cold powering test of the first Feather-M2.1-2 magnet in helium gas [1], (FCC) [11] tunnel and, as a possible intermediate step, beyond a considerable 30 TeV in the existing 27 km circumference LHC tunnel [12]. Due to the higher critical temperature it is possible, provided sufficient improvement of the engineering current density (see Section II), to operate HTS magnets in forced-flow helium gas at intermediate temperatures of 20 K – 30 K, greatly reducing the complexity and cost for operating them in a large accelerator. This would also allow the beam-screen, responsible for absorbing the synchrotron radiation, to be operated at a higher temperature or even become integral part of the magnet. Furthermore, in contrast to the Nb3Sn [13], REBCO coated conductor (the HTS of choice) does not require heat treatment considerably simplifying the manufacturing process.

This paper presents our initial thoughts, based on the experience gained from EuCARD2, on the conceptual design of a 20 T+ demonstrator accelerator magnet and the implications of using HTS inside a particle accelerator.

II. ANISOTROPY AND CURRENT DENSITY

The overall current density is an important parameter from a magnet design point of view, since it determines in large part the cross-sectional area of the conductor and thus the conductor volume needed for the magnet. In essence, higher current
Betting on even larger improvement of Jc
Thinking to unconventional design

Fig. 1. Critical current per tape reported by literature, plotted again.
Abandoning the concept of costheta to go to simple race track ALL HTS Operation at 10-20 K: no LHe (+ availability)

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<th>coil layout</th>
<th>property</th>
<th>value</th>
<th>unit</th>
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<tr>
<td></td>
<td></td>
<td>coil area‡</td>
<td>94 (3.8)</td>
<td>cm²</td>
<td></td>
<td></td>
<td>coil area‡</td>
<td>115 (4.6)</td>
<td>cm²</td>
</tr>
<tr>
<td>(3)</td>
<td>gap on first deck</td>
<td>field</td>
<td>20</td>
<td>T</td>
<td>(4)</td>
<td>open mid-plane</td>
<td>field</td>
<td>20</td>
<td>T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>current density†</td>
<td>700</td>
<td>A/mm²</td>
<td></td>
<td></td>
<td>current density†</td>
<td>700</td>
<td>A/mm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aperture (h×v)</td>
<td>60×60</td>
<td>mm</td>
<td></td>
<td></td>
<td>aperture (h×v)</td>
<td>40×25</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sextupole*</td>
<td>−0.01</td>
<td>units</td>
<td></td>
<td></td>
<td>sextupole*</td>
<td>+0.00</td>
<td>units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>decapole*</td>
<td>−0.00</td>
<td>units</td>
<td></td>
<td></td>
<td>decapole*</td>
<td>+0.00</td>
<td>units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tetradecapole*</td>
<td>−0.07</td>
<td>units</td>
<td></td>
<td></td>
<td>tetradecapole*</td>
<td>+0.29</td>
<td>units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>octadecapole*</td>
<td>−0.03</td>
<td>units</td>
<td></td>
<td></td>
<td>octadecapole*</td>
<td>+0.00</td>
<td>units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>coil area‡</td>
<td>117 (4.7)</td>
<td>cm²</td>
<td></td>
<td></td>
<td>coil area‡</td>
<td>127 (3.5)</td>
<td>cm²</td>
</tr>
</tbody>
</table>

* All harmonics are calculated at (2/3) of the horizontal aperture radius. † Current density is defined here as overall current density in the coil blocks. ‡ The coil area includes both sides of the coil. Also given is the ratio between the coil area and the area of the aperture.
Working on even more unconventional design of the end shape

From Jeroen van Nugteren and Glyn Kirby - CERN
Magnet R&D for the *next step for a 20+ T in view of ELN*

- Increase the effort on basic HTS materials
- Change paradigm pursuing new lines
  - FCC may be the last that can be designed with Id concept
- Develop a 25 T dipole (20 T may be the real final goal after the R&D: for LHC was 10 T and then finally worked at 8 T ...)
- May be use HE-LHC with 25 T dipole as test bed (10% of ELN, as always proposed by Prof. A. Zichichi) LHC Tripler, may be of real interest
- **Skipping FCC and going to ELN?**
  - COST ...
  - but also: what physics really needs?
The future belongs to the brave! (R. Reagan)
Thanks and…

stay tuned for our 20+ T R&D…
Old structures, new structures

mid 1970’s, FNAL: Collared coils

2002, LBNL: Bladder and keys

2014, LBNL: CCT

2017, FNAL: SM cos(θ)

1975, MIT: CICC

1998, TAMU: Stress management
Stress in high field magnets

\[ F \mu B^2 \]

\[ \frac{w \mu}{J} \frac{B}{J} \]

\[ \frac{F}{w} \mu JB \]

\[ \text{Peak stress (MPa)} \]

\[ \text{Bore field (T)} \]

Stress limited reducing J

Unconstrained scaling

QXF 11T

LHC

FCC

HE-LHC