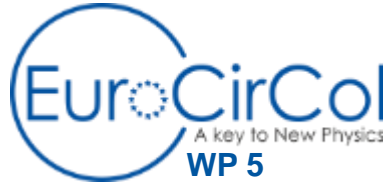




Magnets and Conductor – Highlights and Summary

Daniel Schoerling
with the conveners of the magnet sessions
28th of June 2019

The sessions



EuroCirCol WP5 16 T Magnets (2 sessions, 8 talks)



Conductor Nb₃Sn wire (and other conductor) development (2 sessions, 14 talks)

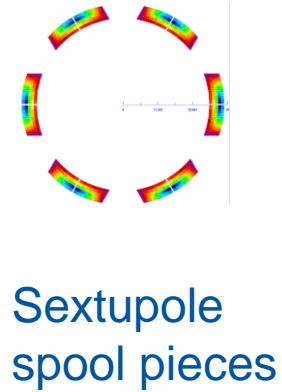
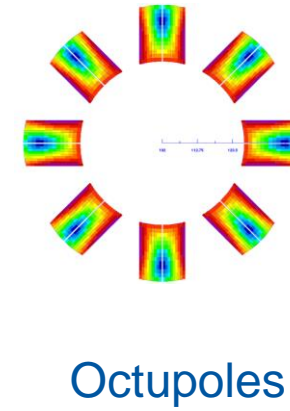
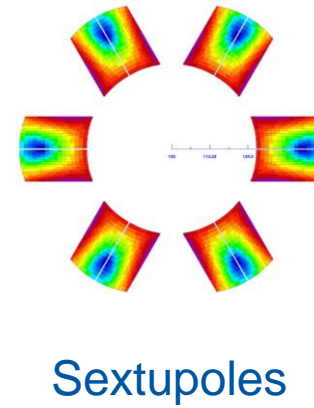
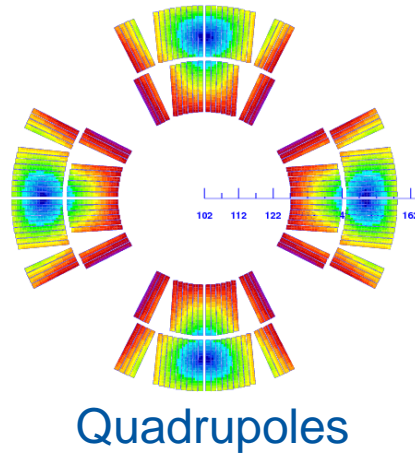
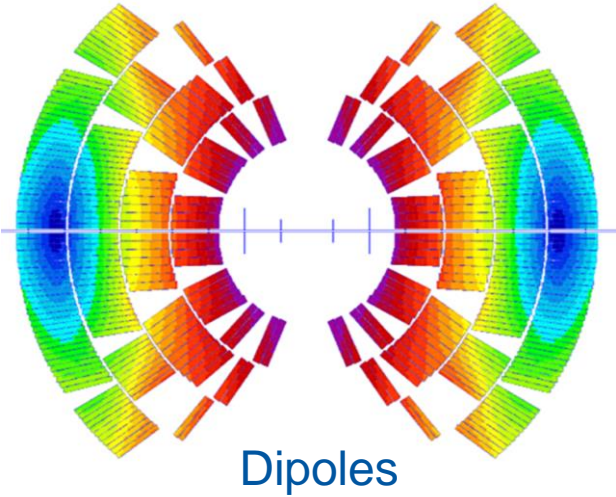


High Field Magnet R&D (1 session, 5 talks)

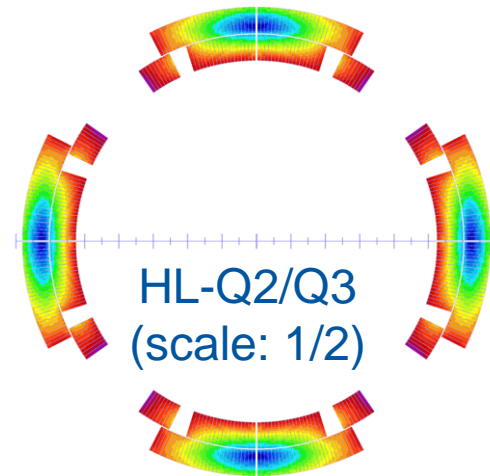
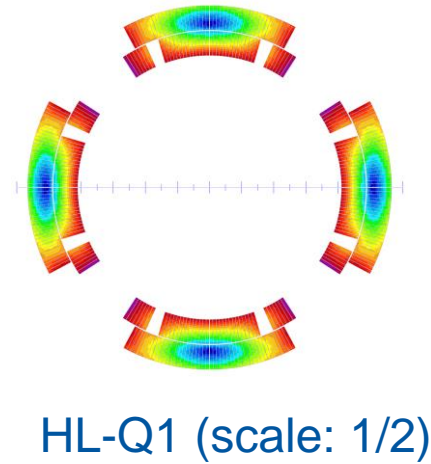
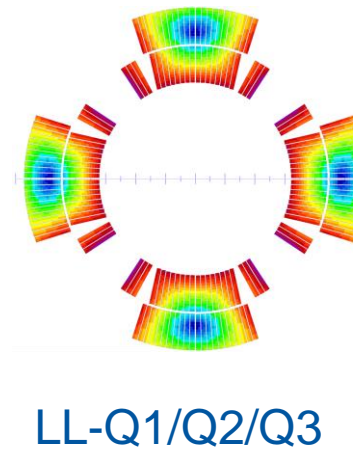
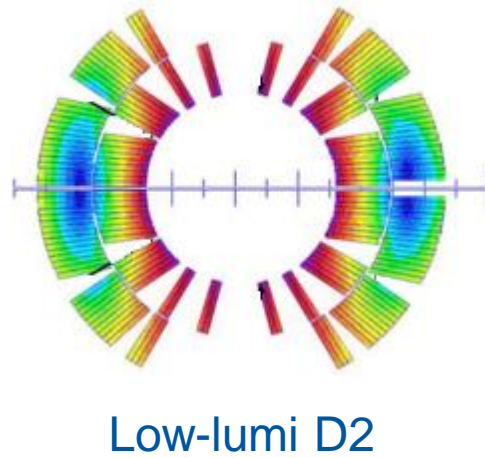
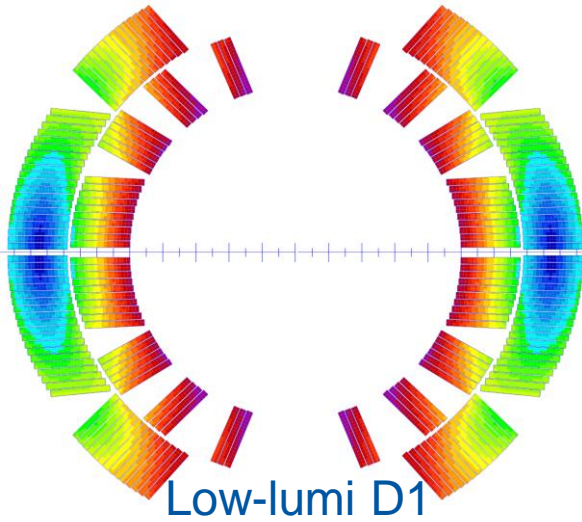


Magnets in the CDR (baseline)

Arcs



Interaction Regions



All deliverables of EuroCirCol are submitted

4.1 Overview

This chapter presents details of these technical infrastructure systems for which substantial research and development is required. It is known that it will be possible to scale up many systems from LHC for use in FCC and these systems are not presented here. Various major systems such as superconducting magnets, RF, beam transfer and transfer are described but with only a brief outline of their general principles. Finally there is a description of the radiation environment in which they will have to perform. Details for all technical systems will be given and a later stage in the design process the system which require particular attention at this conceptual design stage have been identified and are presented here.

4.2 Main Magnet System

4.2.1 Introduction

The magnetic system of the FCC will grow greatly from the experience gained with the LHC, which has demonstrated the feasibility and advantages of operating a large number of superconducting magnets controlled by using superconducting at 1.9 K. There will be about four times more magnets in FCC than in LHC and the total magnet production by the arc will be increased by about a factor of two, while maintaining a similar beam aperture and beam configuration. The field increase will be enabled by using Nb₃Sn superconducting instead of the Nb-Ti used in the LHC magnets. With respect to the conductor properties, the FCC dipole magnets will require a similar conductor than the LHC magnets with LHC magnets on the low field end and at about 80% of the maximum super critical field H_{c2} . It is believed that, within superconducting magnet properties, and of the magnets will need some design changes. The magnets will be distributed across the tunnel length of the FCC with limited magnet spacing. The technology, though not yet used in particle colliders, is being implemented for design and production of the HL-LHC project, where they will be operating at peak fields of between 11 and 12.5 T. The use of this technology will be studied to make sure production of 10 T magnets within a decade from the introduction of a first prototype.

4.2.2 Superconducting Main Dipole

The main dipoles (MD) of the FCC are the main superconducting magnets of the main dipole system. The main dipole system (MDS) is a system of superconducting magnets arranged in a series of arcs. A cross section of the system is presented in Figure 1.1. The MDS is the main dipole system of the FCC.

The MD for the FCC MD is a magnet, and has a total length between the two extremities of the main dipole system of 1.5 km and a maximum length of 1.5 km. The maximum length is 1.5 km.

FIGURE 1.1: Main dipole cross-section

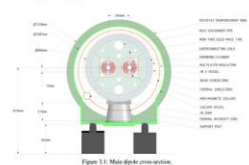


FIGURE 1.1: Main dipole cross-section

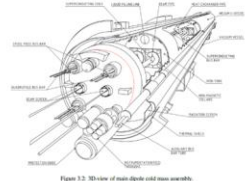


FIGURE 1.2: 3D-view of main dipole and main assembly

Installed in a cryogenic container composed of a radiation shield, a thermal shield and a vacuum vessel, it

FIGURE 1.3: Main dipole parameters

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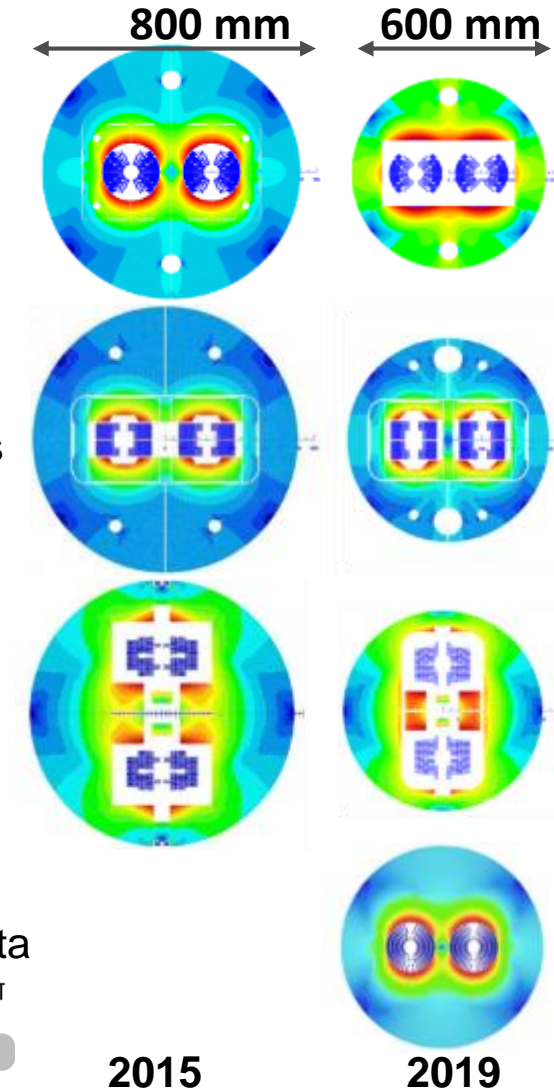
16 T dipole design options for the CDR

Main evolution in the EuroCirCol parameters:

- Coil optimization and margin 18% → 14%
- Inter-beam distance: 250 mm
- Stray-field <0.1 T at cryostat

Status:

- All designs have been documented in scientific publications
- Addenda for building prototypes have been signed



Cosine-theta (baseline)



Block-type coils



Common-coils



Canted cos-theta



ADDENDUM FCC-GOV-CC-0121 / KE3782/TE

The European Organization for Nuclear Research ("CERN"), an Intergovernmental Organization having its seat at Geneva, Switzerland, and the Commissariat à l'énergie atomique et aux énergies alternatives ("CEA"),

This Addendum defines a contribution by a Participant under Article 6 of the Memorandum of Understanding for the FCC Study (FCC-GOV-CC-0004/17.10.2014) (MS 1390795).

Address: CEA Paris-Saclay
CEA Saclay
91191 Gif-sur-Yvette
CEA Saclay
Supplément contract: CEA-01, Address code: SC02 Budget code: 10832

SCOPE OF WORK

The development of magnets for the FCC requires the demonstration of Nb₃Sn accelerator magnets with performances far beyond the HL-LHC targets with 50 mm coil aperture. This work follows-up on the Nb₃Sn high-field development program started at CEA with the participation in the design and construction of FRESA2 dipole magnet. It covers the realization of a FCC-hh short dipole model magnet designed within the H2020 EuroCirCol design study and the conceptual design of the FCC-hh arc quadrupole magnet.

Thursday 15:30-17:00
High-field magnet R&D
The CEA dipole model for the FCC (Etienne Rochepault)

ADDENDUM FCC-GOV-CC-0130 / KE3920/TE

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (hereinafter referred to as "CERN"), an Intergovernmental Organization having its seat at Meyrin, CH-1211, Geneva 23, Switzerland, represented by Frédéric Bordry, Director for Accelerators and Technology,

THE CENTER FOR THE DEVELOPMENT OF INDUSTRIAL TECHNOLOGY, S.A. (hereinafter referred to as "CDTI"), a Spanish public entity, created by R.D.-L. 9/2008 of 30th November, established in C/ Gid n. 4, 28001 Madrid, Spain, duly represented by Ferrn Ponce Martínez, Director-General, and

THE CENTER FOR RESEARCH ON ENERGY, ENVIRONMENT AND TECHNOLOGY, O.A. M.P. (hereinafter referred to as "CIEMAT"), a Spanish public entity with registered office at Avenida Complutense, 40, 28040 Madrid, duly represented by Rafael Rodrigo Montero, President, as stipulated in Article 8, R.D. 15/2000, 1 of December, which approved the Statutes of CIEMAT, (hereafter individually referred to as "Contributor" and jointly as the "Contributors").

Just signed

ADDENDUM No. KE4102/FCC

to
FCC Memorandum of Understanding (FCC-GOV-CC-0004/17.10.2014)

THE EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

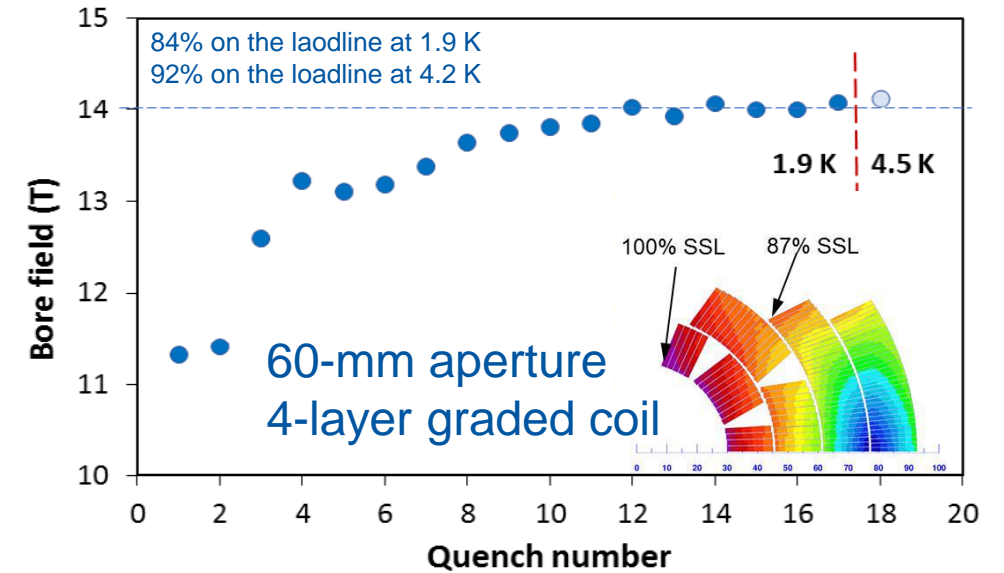
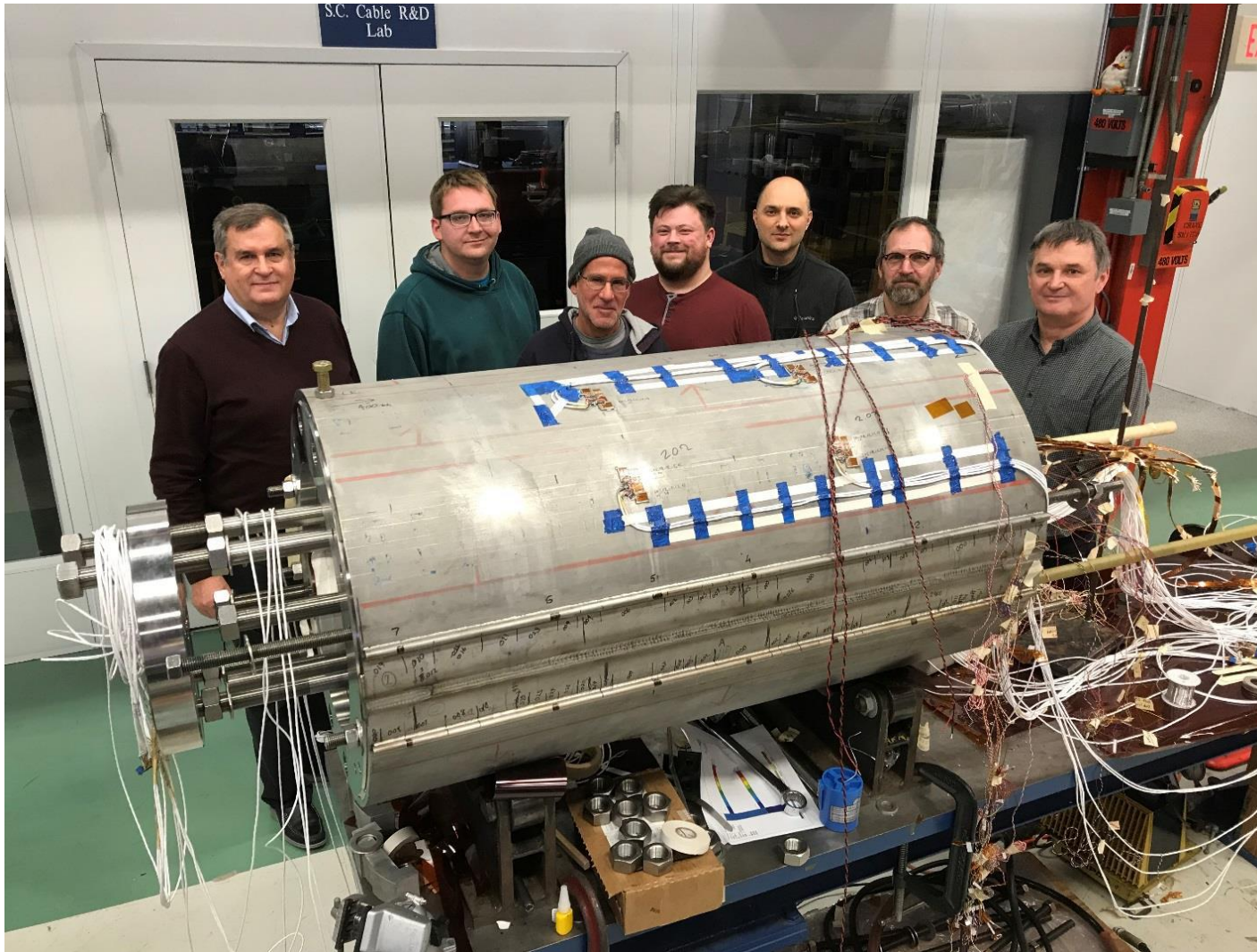
and
THE ISTITUTO NAZIONALE DI FISICA NUCLEARE ("INFN")

concerning

Collaboration on 16 T - Nb₃Sn Short Model Magnet Production
in the framework of the FCC Study hosted by CERN

Thursday 15:30-17:00
High-field magnet R&D
The INFN dipole model for the FCC (Riccardo Valente)

14 T magnet tested at FNAL!

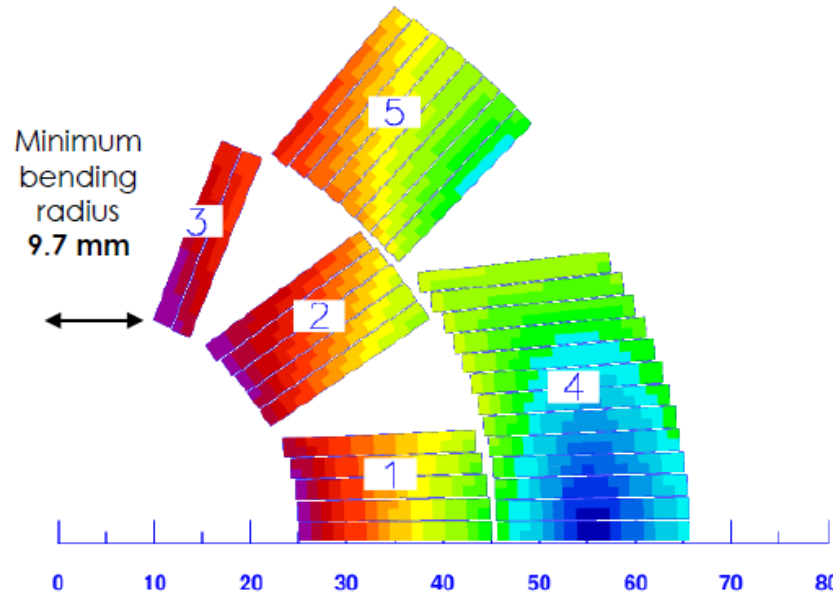


- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test foreseen in fall 2019 with additional pre-stress for 15 T

Magnet development: Magnet models



INFN: 14 T magnet with 14 % margin (FCC spec), 9.5% with current wire spec



F2D2 or



CEA: 15.5 T magnet with 14% load line with current wire spec

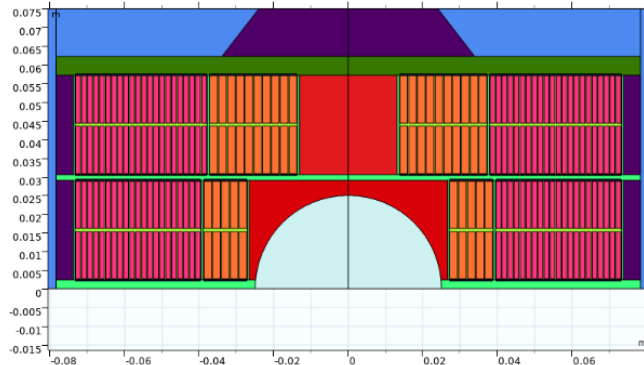
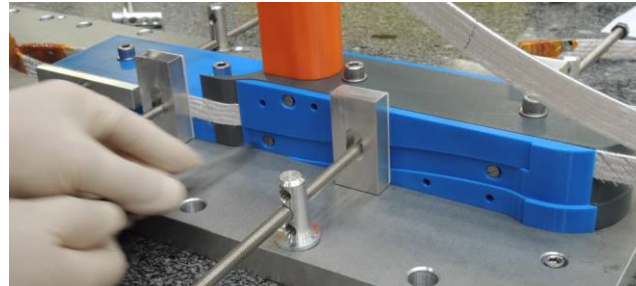
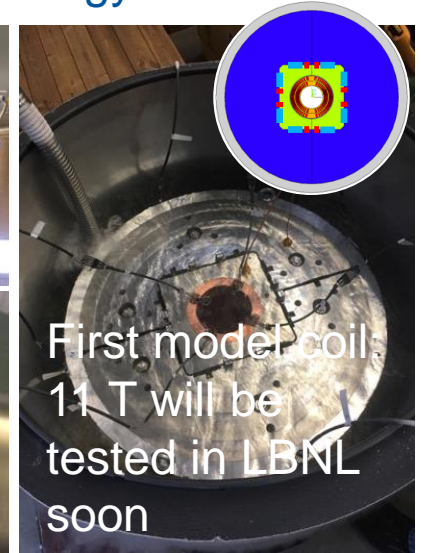
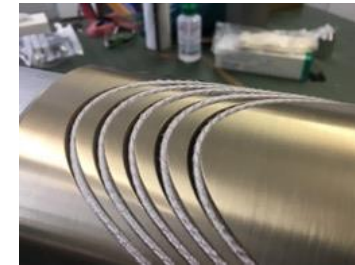
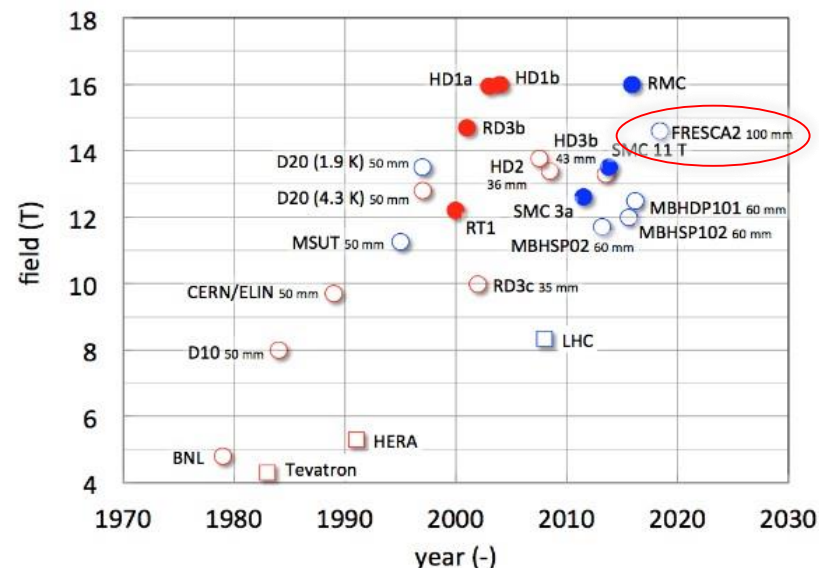


CHART2 – Swiss Accelerator Research and Technology

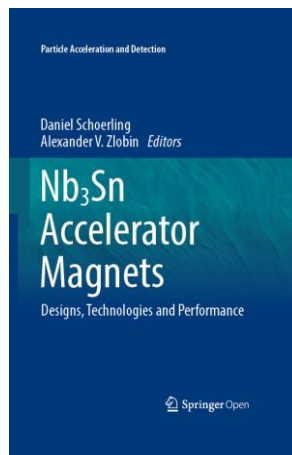


What about the field level?

- Past experience with Nb₃Sn high field magnets (13 programs), and the very recent success of FNAL shows the great potential of Nb₃Sn high-field magnet technology for a next collider in the ~14 T range
- With the aim to reduce the cost and complexity, a ~40 TeV FCC-hh with 6 T may be considered (see M. Benedikt's talk)
- What about 12 T to 14 T which would also considerably reduce the magnet cost and complexity for a collider in the next decades?



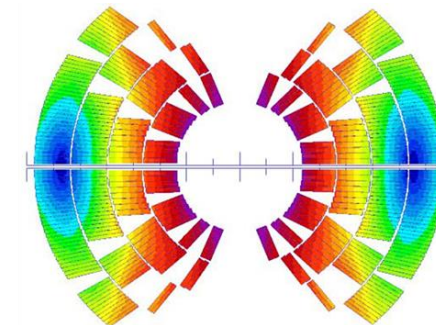
Fresca2: 14.6 T
at 1.9 K



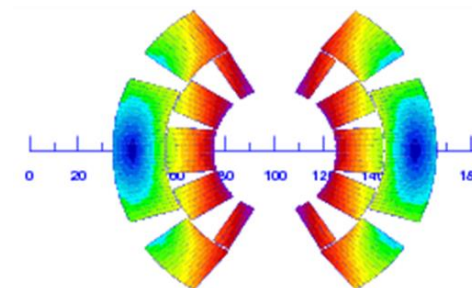
ESG request for parameters of a lower-energy hadron collider

parameter	FCC-hh	FCC-hh-6T	HE-LHC	HL-LHC	LHC
collision energy cms [TeV]	100	37.5	27	14	14
dipole field [T]	16	6	16	8.33	8.33
beam current [A]	0.5	0.6	1.1	1.1	0.58
synchr. rad. power/ring [kW]	2400	57	101	7.3	3.6
peak luminosity [10^{34} cm ⁻² s ⁻¹]	5	30	10 (lev.)	16	5 (lev.)
events/bunch crossing	170	1000	~300	460	132
stored energy/beam [GJ]	8.4	3.75	1.4	0.7	0.36

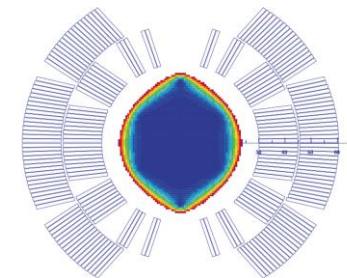
- **NbTi technology from LHC, magnet with single-layer coil providing 6 T at 1.9 K:**
 - Corresponding beam energy 18.75 TeV or 37.5 TeV c.m.
 - Significant reduction of synchrotron radiation wrt FCC-hh (factor 50) and corresponding cryogenic system requirements.
- **Luminosity goal 10 ab^{-1} over 20 years or 0.5 ab^{-1} annual luminosity:**
 - Beam current 0.6 A or 20% higher than for FCC-hh, 1.2 E^{11} ppb (FCC-hh: 1.0 ppb).
 - Stored beam energy 3.75 GJ vs 8.4 GJ for FCC-hh.
- **Analysis of physics potential, technology requirements and cost ongoing.**



16 T (FCC spec)



14 T (FCC spec)

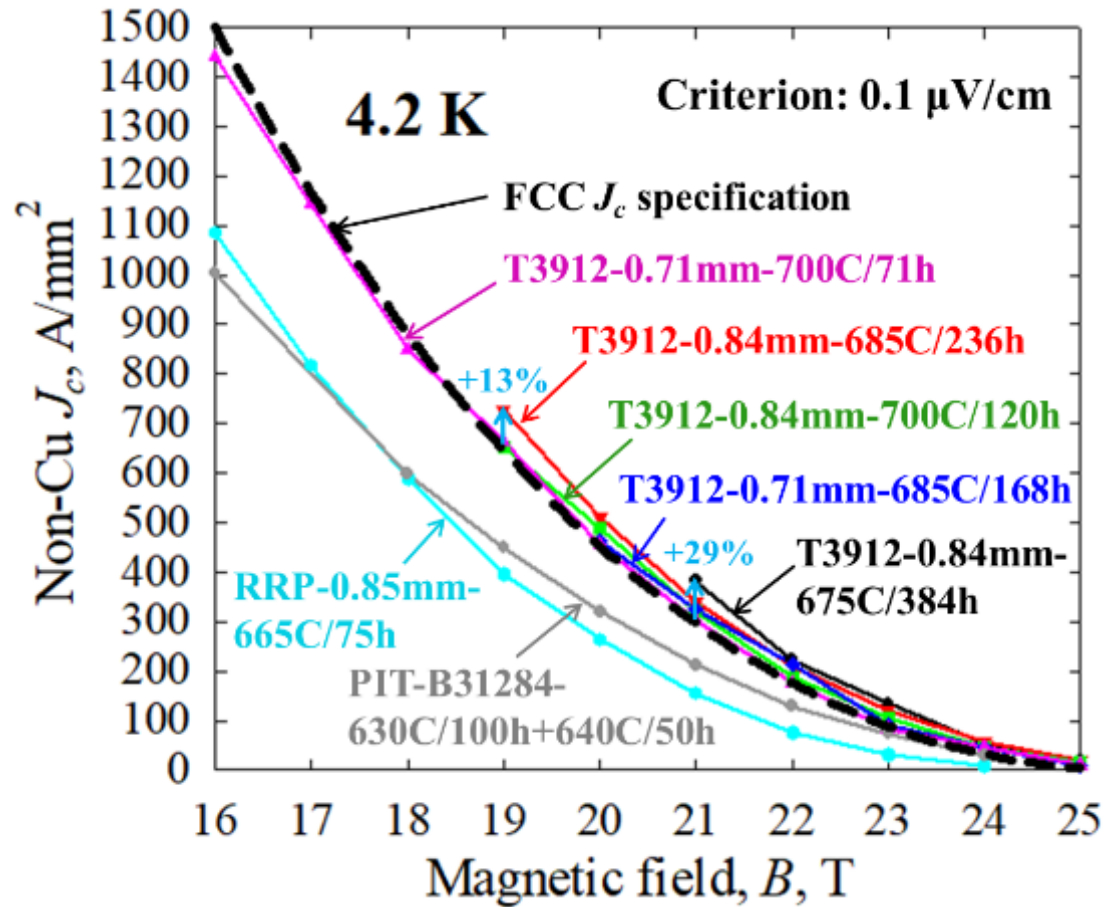


11 T (HL-LHC spec)

Conductor: Large international collaboration

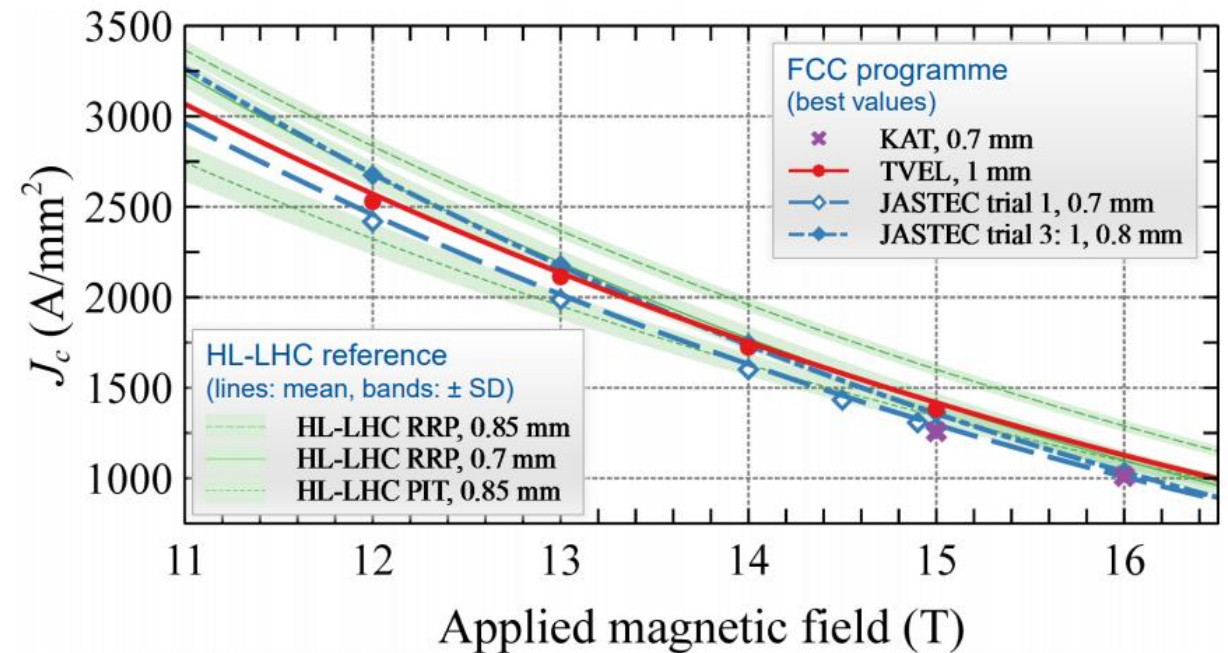


Conductor: Fantastic results



Courtesy X. Xu et al. 1. <https://arxiv.org/abs/1903.08121>

- Wire with APC has reached FCC target J_c
- Other suppliers reach now the HL-LHC specification (broadening of supplier base)
- High B_{c2} (28.8 T at 4.2 K) has been reached



Summary of non-Cu $J_c(B)$ achieved so far, with HL-LHC wires for comparison
Points: measurements at 4.2–4.3 K Lines: fits scaled to 4.22 K

Conductor: Exciting activities

KOBELCO
KOBELCO STEEL GROUP

JASTEC
SUPERCONDUCTOR

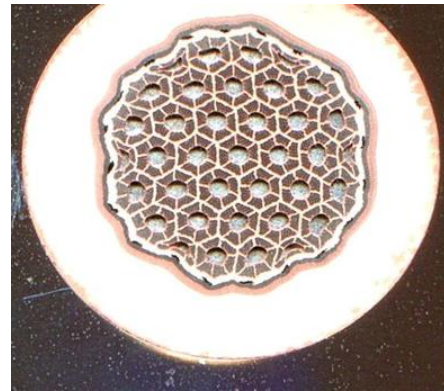
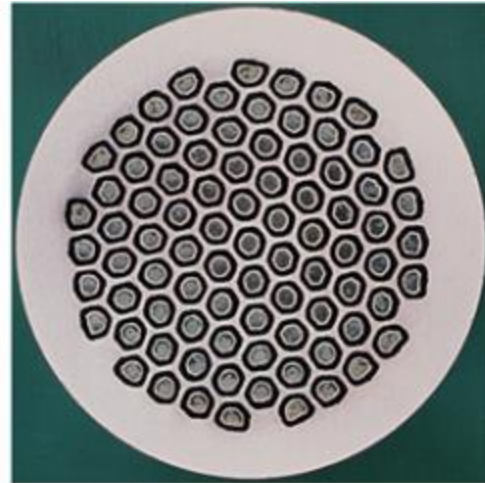
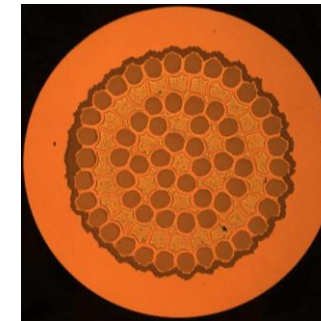
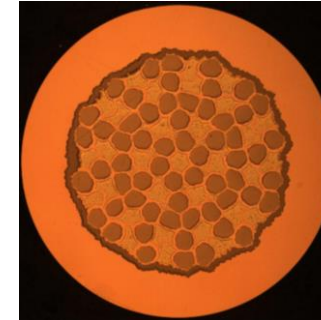
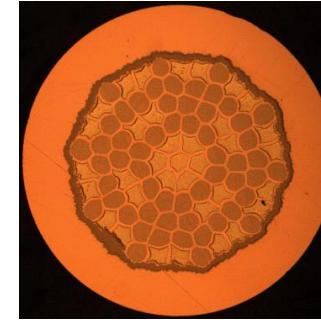
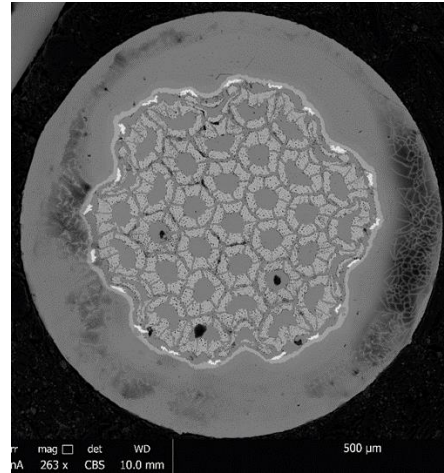
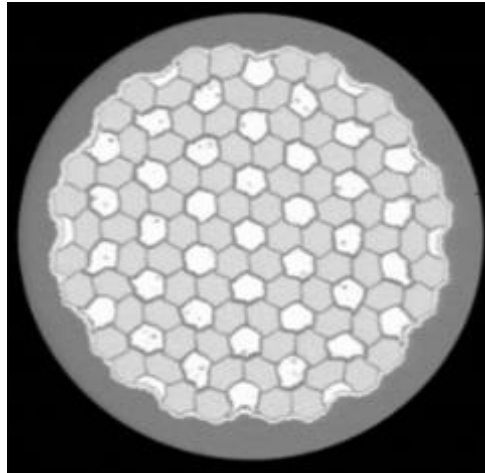
FURUKAWA
ELECTRIC

ROSATOM
NATIONAL NUCLEAR CORPORATION "ROSATOM"

TVEL
FUEL COMPANY OF ROSATOM

**BOCHVAR INSTITUTE OF
INORGANIC MATERIALS
JSC VNIIM**

Kiswire



Conductor: Electro-mechanical characterization

- **Irreversible** degradation: EuroCirCol assumption (peak stress: 150 MPa at warm and 200 MPa at cold)
- **Reversible** degradation: Strong influence of conductor technology, sample preparation and operation field: → Important input for magnet design: disentangle high-field and high-stress areas!
- The present designs attempt to place high-stress in the low-field regions
- As done for the HL-LHC magnets, to further reduce the peak stress, the pre-load can be set to a lower value than the one required for nominal field for having no pole detachment.
- The same approach was also used for the LHC magnets, which unload below ~7 T

Main Results on Cable tests

Same Results in Twente's set Up? What about the RRP conductor?
What is irreversible limit?

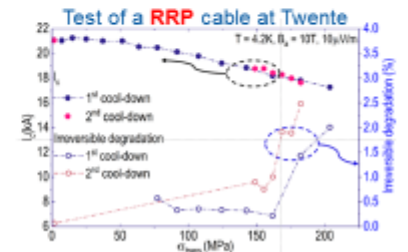
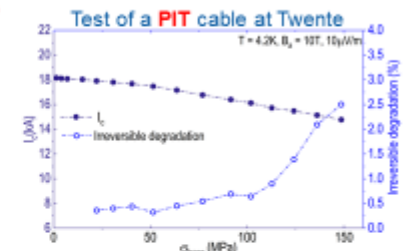
- Measurements carried out at Twente, confirmed the results found by CERN
- The **RRP** cable has still the same behavior of the **PIT** cable but it is **less sensitive** to transverse load

➤ Onset **permanent** I_c reduction

1. **PIT**: ~130 MPa
2. **RRP**: ~170 MPa

➤ **Total** I_c reduction at 11.6 T and **150 MPa**

1. **PIT**: ~ 20 %
2. **RRP**: ~ 15 %



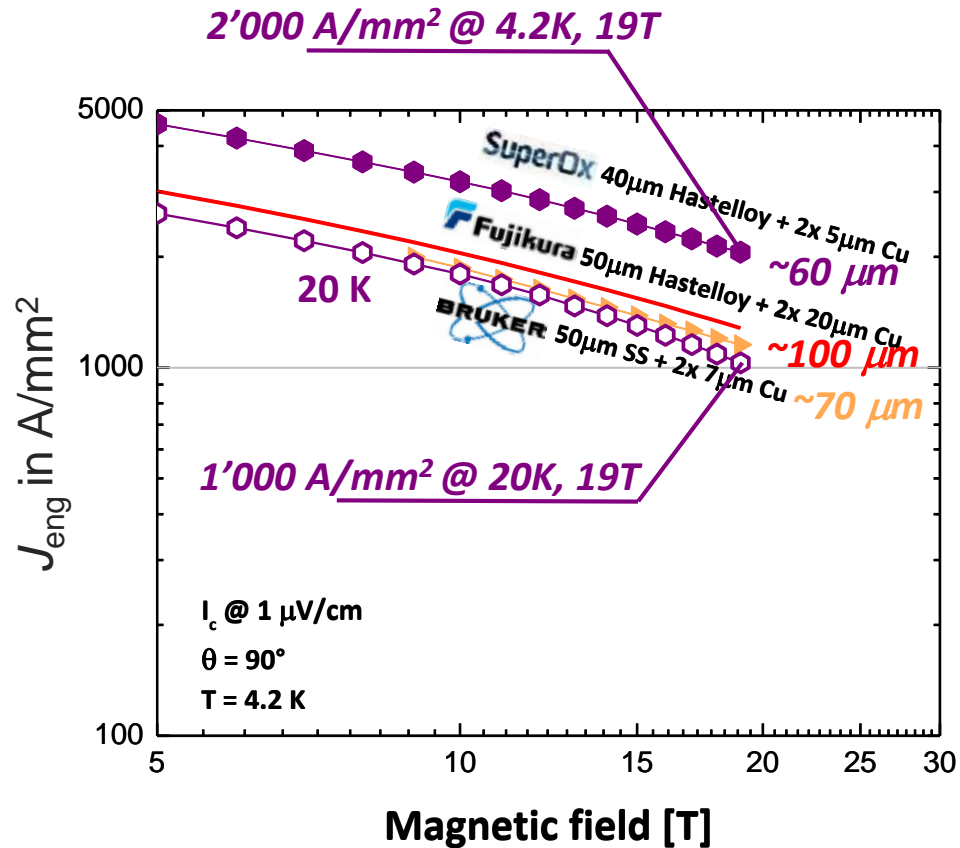
Courtesy of M. Dhalé

Options towards ~20+T dipoles

Bi-2212

- Promising performance parameters: J_c far exceeds the FCC specification, but stress sensitive
- Expensive production process (silver & over-pressure reaction) → 7-15 times the Nb_3Sn (volumetric) cost

REBCO



- Industrialization and cost reduction yet to come (~10 times more expensive than Nb_3Sn)
- Possibility to operate in the ~10 K range
- Magnet design and operation is challenging
- 3 T insert was tested and 5 T insert will be tested soon

Conclusion

- Past experience with Nb₃Sn high field magnets (13 programs), and in particular the very recent success of FNAL shows the great potential of Nb₃Sn high-field magnet technology for a next collider. A model magnet (15 T) has been tested (staged process) and smoothly reached 14 T (as planned for the first stage)
- The difference between a 14 T and a 16 T magnet is very large, in terms of quantity of conductor needed, number of coils, and complexity of the construction. Though, on paper, a 16 T magnet is possible and is costing about twice the cost of a LHC magnet for twice the field. Achieving such a construction on a large series may be extremely difficult. A two layer design with a target field in the range of 12 T to 14 T is considered by the magnet community present during the FCC week as 'consensus' for a collider in the next decades
- The design work has shown that all the considered options have a potential for FCC. This has motivated the decision of exploring experimentally all options to answer the outstanding questions of which design meets best the requirements, which margin field level (~12-14 T) should be selected
- In the last three years, the FCC Conductor Development Program coordinated by CERN has succeeded in engaging the Japanese (Jastec and Furukawa via the KEK coordination), the Russian (TVEL) and the Korean (KAT) companies in developing for the first time very high-performance Nb₃Sn wire. Critical current densities of up to about 1250 A/mm² at 16 T have been achieved, and kilometers length of wire have been produced in industry and delivered to CERN for first cabling trials
- In the US, the FCC current density target (1500 A/mm² at 16 T) has been achieved! Industrialization and cost reduction has yet to come