Status of the 16 T dipole development program for a future hadron collider

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Outline

- Introduction
- Overview
- Conclusion

Introduction

A Future Circular Collider (FCC), or an energy upgrade of the LHC (HE-LHC), would require bending magnets operating at up to 16 T.

This is about twice the magnetic field amplitude produced by the Nb-Ti magnets of the LHC, and about 5 T higher than the field produced by the Nb3Sn magnets for the High Luminosity LHC.

1. **Can, these magnets, be feasible in «accelerator quality»*?**
2. **If yes, at which cost?**

*** margin, construction including alignmnent, field quality, protection in a circuit**

Overview of activities 2016-2023

FCC Conceptual Design Report (to be delivered by end 2018)

Feed the CDR with one reference option, including cost model, plus a description of alternative options.

Conductor

Procurement of up to 1.5 t of conductor/year to feed models and demonstrators
Increase of J_c up to FCC target (1500 A/mm^2 @ 4.2 K, 16 T)
Comprehensive electro-mechanical characterization of the conductor.

R&D Magnets

Design, Manufacture & Test of ERMC and RMM Magnets.
Identify and implement required technological R&D (wound conductor, splices, impregnation …)

Model magnets

Design, Manufacture & Test of Model Magnets

16 T Development Programs

EuroCirCol WP5

- feed the FCC CDR with design and cost model of 16 T magnets

FCC 16 T Magnet Development, supporting:

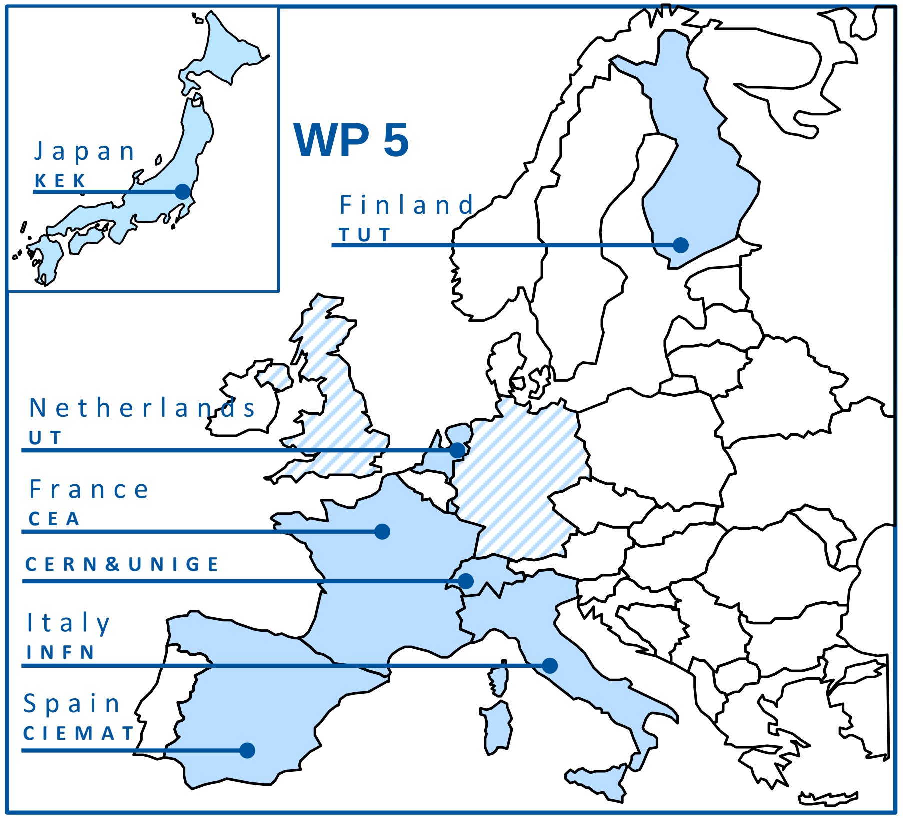
- conductor development & procurement
- R&D magnets and associated development
- model magnets

US Magnet Development Program

- initially focused to a 14-15 T cosine-theta magnet (2017-2018)
- also exploring a canted cosine-theta option, in a first step possibly as an insert to the outer layers of the 14-15 T magnet above

EuroCirCol WP5 (H2020-INFRADEV-1-2014-1)

Explore design options for a 16 T accelerator dipole
Feed the FCC-CDR with a baseline magnet, including cost



Three options* are being considered:

1. Block coils (CEA)
2. Common coils (CIEMAT)
3. Cosinetheta (INFN)

*A fourth option (canted costheta) is being considered in the frame of a Swiss contribution to the FCC

A specific feature of this program is that the different design options are being considered with the same specification and analysis tools so that they can be compared relatively to each other.

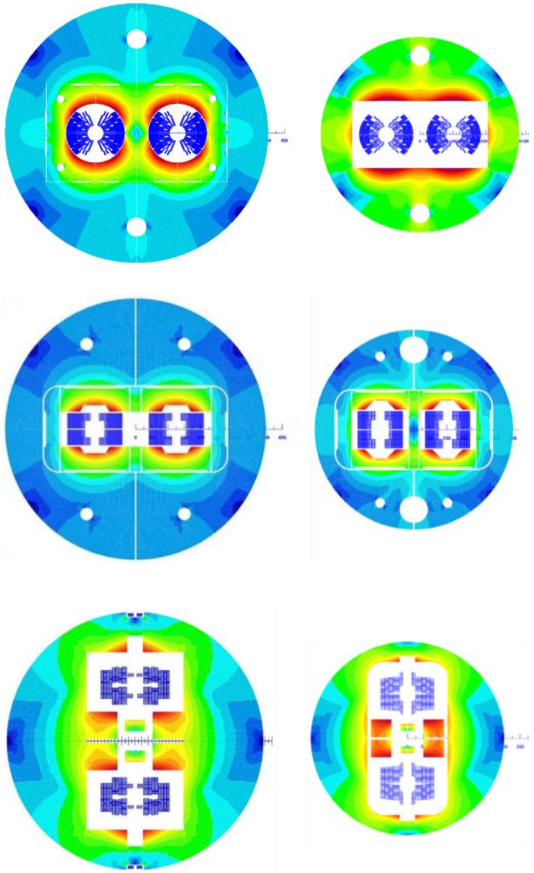
EuroCirCol WP5 : Design Options

800 mm 600 mm

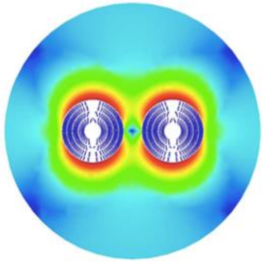
Cosinetheta
Mon-Af-Or6-04

Block-coils
Mon-Af-Or6-02

Common-coils
Mon-Af-Or6-03



2015 2017



CCT (PSI with LBNL and CERN)
Mon-Af-Or7-06

The reference parameter space has been finalized considering recommendations from the 1st WP5 EuroCirCol Review (11-13 May 2016, http://indico.cern.ch/event/516049) and follow-up of the 2017 FCC Week (http://indico.cern.ch/event/556692)

The considerable decrease of the coil size comes from a reduction of the margin on the load-line from 18% to 14%, and of the cold mass size from allowing a stray field of up to 0.2 T at the cryostat surface

Magnet length	14.3 m	
Free physical aperture	50 mm	
Field amplitude	16 T	
Margin on the load-line @ 1.9K	14 %	
Total time margin	40 ms	
Critical current density @ 1.9 K, 16T	2300 A/mm^2	
Conductor fit (Jc/B)	EuroCirCol fit	
Degradation due to cabling	3%	
Minimum Cu/nonCu	0.8	also check 0.9-1.0
Maximum strand diameter	1.2 mm	also check 1.1 mm
Maximum stress on conductor at warm	150 MPa	
Maximum stress on conductor at cold	200 MPa	
Maximum hot spot temperature (@ 105% I_{nom})	350 K	
Maximum number of strands in a cable	40	check up to 60
Maximum voltage to ground (magnet contribution)	1.2 kV	set as tentative value
Maximum TOTAL voltage to ground	2.5 kV	
Conductor cost (performance based)	5 Euro/kAm	

EuroCirCol: Quench Protection Tue-Mo-Or12-03

- **Quench protection integrated the magnet design**
- Phase 1: Fast feedback about protectability (40 ms)
- Phase 2: Technical protection designs
  - Validated the suitability of the 40 ms assumption

- Simulation tools were developed during the process
  - Aim was to use assumptions / criteria that work for the different magnet types

- **This presentation: Validation of the assumptions by comparison with experimental data**
  - **Focus on heater-based protection**

- Although not discussed here, CLIQ-based protection is a strong candidate, and shows very good results

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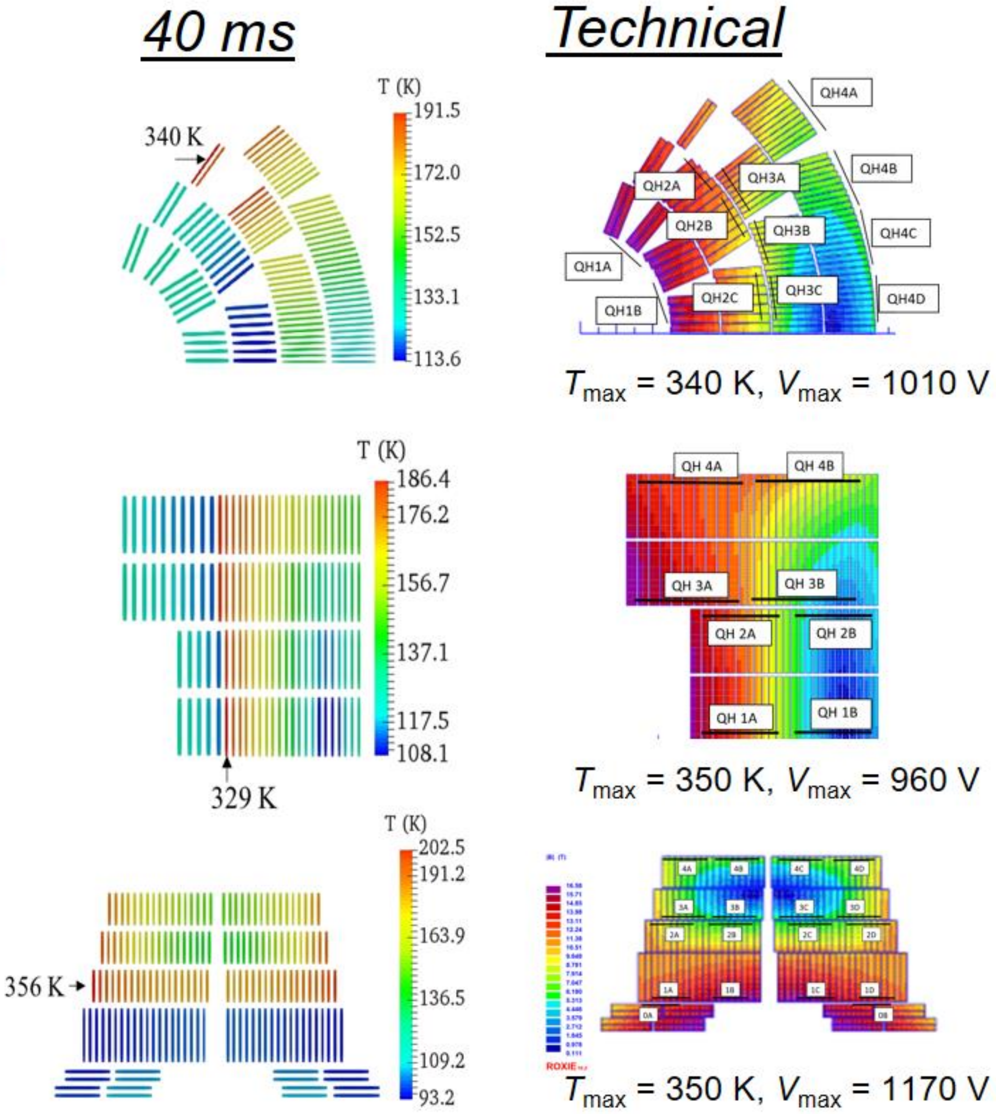


FCC 16 T Magnet Development: Conductor

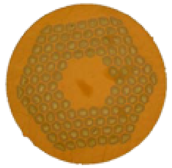
Tue-Af-Pi3-01

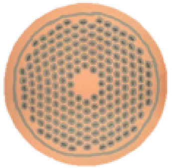
Nb_3Sn for HL-LHC

~ 20 tons of state-of-the-art high Jc conductor

Internal Tin	Powder in tube
RRP® 108/127	**PIT 192**

Bruker EAS





Bruker OST

Diameter	Layout	Sub-Element size	J_c (12 T) RMS [A/mm^2]	J_c (15 T) RMS [A/mm^2]	B_{c2}(4.3 K) RMS [T]	J_c (16 T) RMS [A/mm^2]	J_c (18 T), RMS [A/mm^2]	RRR
0.7 mm RRP	108/127	46 µm	2676 / 68	1410 / 58	24.5 / 0.39	1098 / 55	610 / 47	>150
0.85 mm RRP	108/127	55 µm	2835 / 44	1601 / 33	25.9 / 0.19	1289 / 30	785 / 25	>150
0.85 mm Bundle Barrier PIT	192	39 µm	2323 / 83	1342 / 49	26.7 / 0.1	1093 / 40	688 / 26	>150

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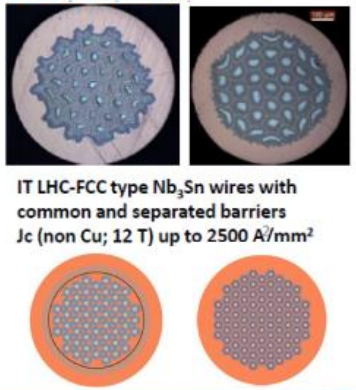
Nb_3Sn for FCC: a world-wide effort

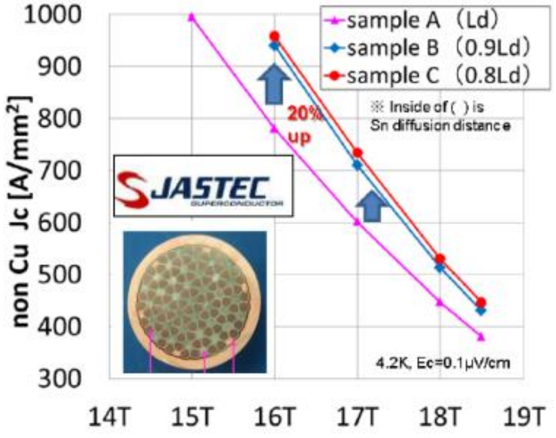
CERN-Bochvar Russia

BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM TVEL



IT LHC-FCC type Nb_3Sn wires with common and separated barriers
Jc (non Cu; 12 T) up to 2500 A/mm^2

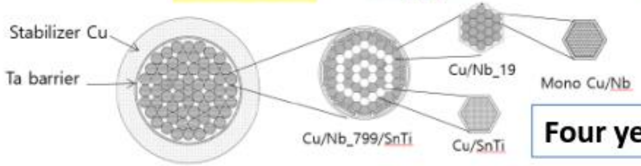
CERN-KEK Japan



CERN-KAT Korea

KISWIRE KAT

FURUKAWA ELECTRIC GROUP



FCC Week 2017, Berlin

Four years program – started in 2017

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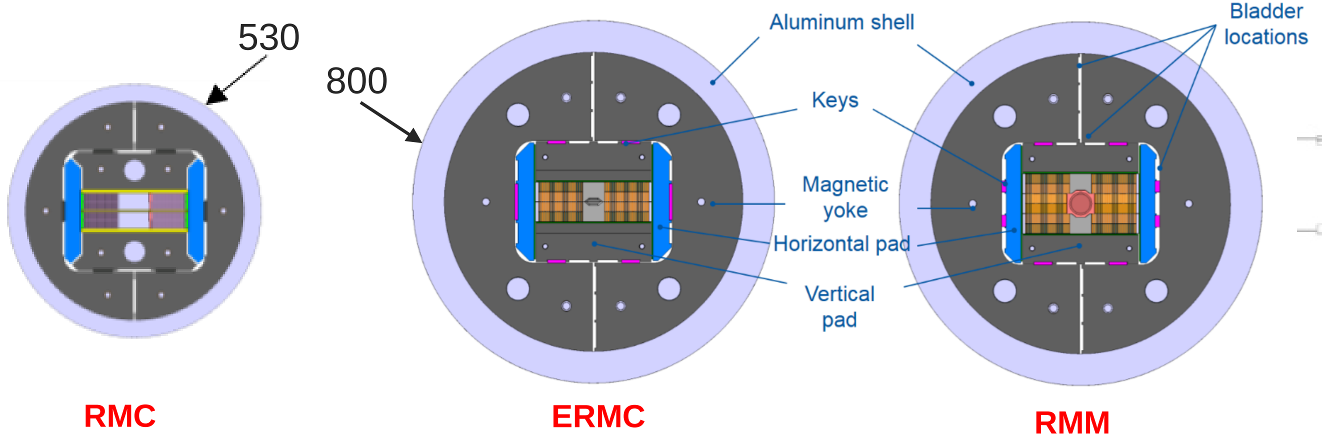
Initial effort is to achieve J_c = 1500 A/mm^2 at 4.2 K, 16 T

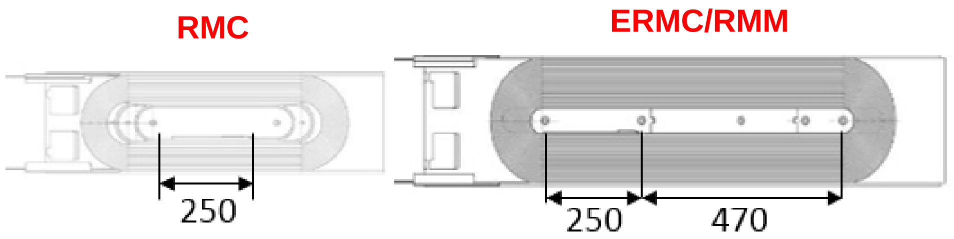
Until 2023, the 16 T development program requires up to 1.5 tons/year

FCC 16 T Magnet Development: R&D Magnets

Wed-Af-Po3-01

ERMC (Enhanced Racetrack Model Coil) and RMM (racetrack Model Magnet), non-graded and graded versions





- a real straight section
- a structure for fields up to 18-19 T
- key & bladders for ease of multiple assembly
- ERMC coils compatible with use in the RMM
- RMM equipped with harmonic field probes

- ➢ demonstrate the field level with margin and limited/no training
- ➢ measure and characterize field quality static and dynamic
- ➢ management of transitions (layer jump, ends …)
- ➢ study/optimize coil manufacture
- ➢ explore different loading configurations/strategies
- ➢ splice studies in real magnet configuration

Test of the first ERMC in 2018

FCC 16 T Magnet Development: Model Magnets

EuroCirCol shows that more than one design option may work
Each of the options has stronger and weaker points than the others
Furthermore, each of the options can be imagined in different variants

We have now an opportunity to build up a varied experience on Nb3Sn magnets beyond the HILUMI specifications thanks to new initiatives under finalization:

- Model magnet at CEA
- Model magnet at CIEMAT
- Model magnet at INFN

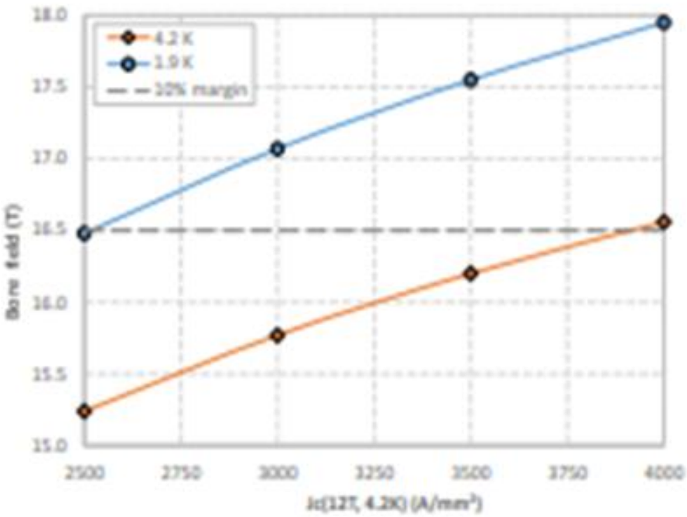
In addition to the work performed in the US, at PSI and at CERN

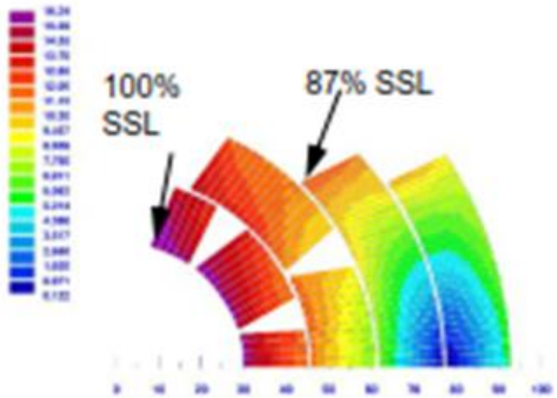
Start winding the first model magnets in 2019

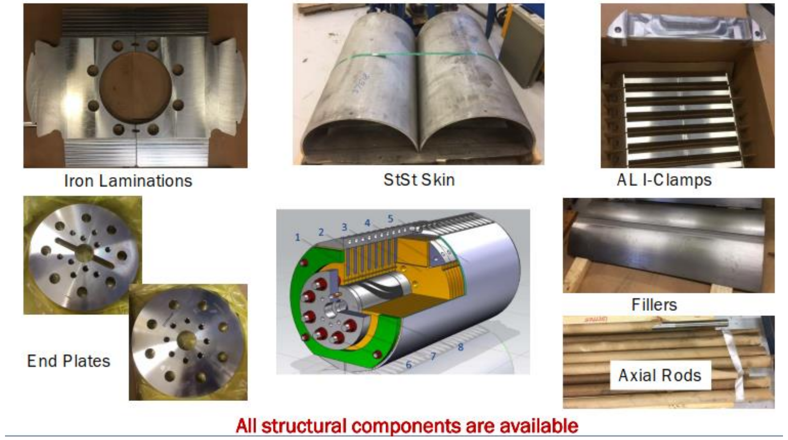
US-MDP Cosinetheta Magnet Mon-Af-Or7-04

	HFDD (MDP)
Parameter	
Test year	2018 (plan)
Max bore field [T]	15.2 (16.5*)
Max design field B_{des} [T]	15
Tested B_{max} [T]	TBD
St. energy at B_{des} [MJ/m]	1.7
Fx/quad at B_{des} [MN/m]	7.4
Fy/quad at B_{des} [MN/m]	-4.5
Coil aperture [mm]	60
Iron OD [mm]	587 (612)

- T=1.9 K







See also **Wed-Af-Po3.01** and **Thu-Mo-Or28.04**

Conclusion

- Accelerator magnets in Nb_3Sn technology are becoming reality in HILUMI.
- Still, the distance between 11 T and 16 T is large, though … **Mon-Af-P01**
- EuroCirCol is animating a both fascinating and effective global collaboration, which is now resulting in new initiatives for the development of model magnets.
- The 16 T development program allows the exploration of a wide parameter space and may enable new creative ideas. Directions may include low pre-stress assemblies, low-contraction structural materials, more effective coil fabrication (impregnation, internal and external coil interfaces), better use of the margin.
- The contribution of the US MDP is complementing the above efforts and contributing in enriching the sharing of knowledge between laboratories.

Thank you for your attention