16 T Magnet R&D Overview

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On behalf of EuroCirCol WP5 and the FCC-hh Magnet Development Program

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16 T dipoles, a key technology

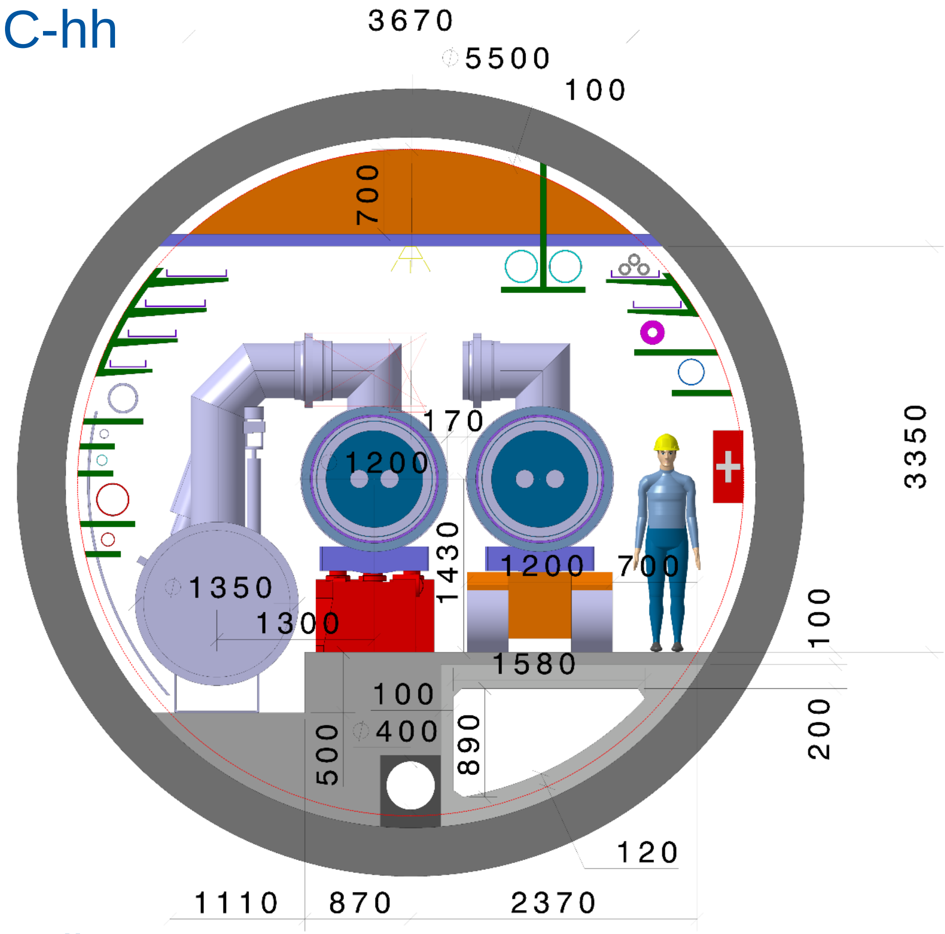
Future Circular Collider (FCC), or an energy upgrade of the LHC (HE-LHC), would require bending magnets operating at up to 16 T.

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 Nb_3Sn magnets for the High Luminosity LHC.

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

Accelerator quality

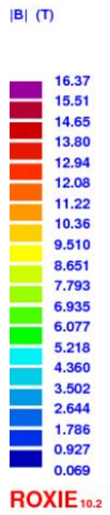
FCC-hh

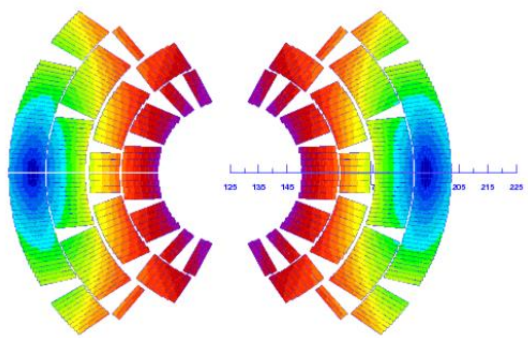


5.5 m diameter

Driving design criteria:

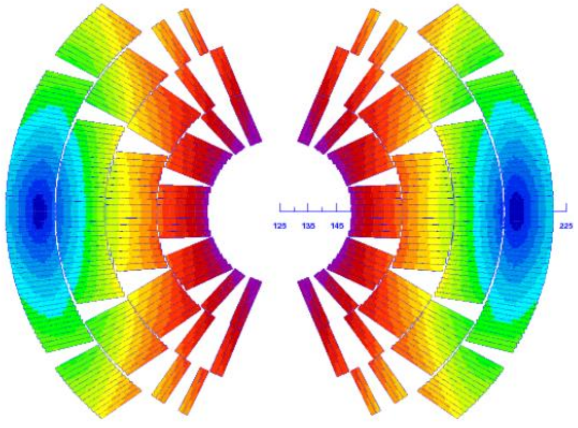
- Compact magnet with sufficient margin
  - Same magnet design for FCC-hh and HE-LHC
- Construction including alignment
- Field quality
- Protection in a circuit





FCC target strand

(J_c = 1500 A/mm^2 at 4.2 K, 16 T)



HL-LHC strand

(J_c = 1000 A/mm^2 at 4.2 K, 16 T)

Present 16 T Development Programs

WP 5

EuroCirCol WP5 (CEA, CERN, CIEMAT, Geneva UNIV, KEK, INFN, Tampere UNIV, Twente UNIV)
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

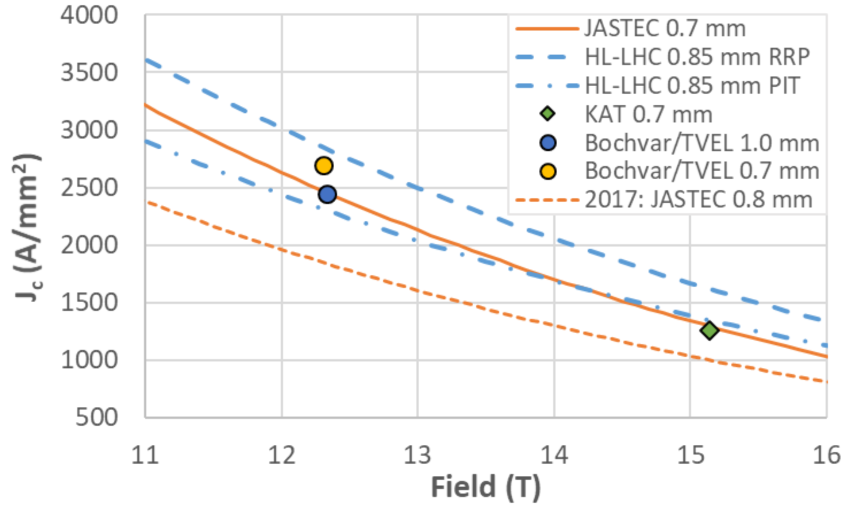
US Magnet Development Program (ASC/NHMFL, FNAL, LBNL)

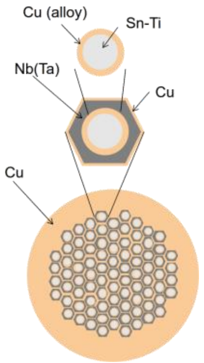
- initially focused to a 14-15 T cosine-theta magnet (2017-2018)
- also exploring a canted cosine-theta option, in a first step possibly as an insert to the outer layers of the 14-15 T magnet above

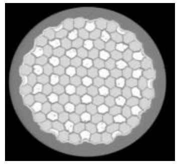
Conductor

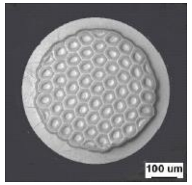
Initial effort is to achieve J_c = 1500 A/mm^2 at 4.2 K, 16 T
Until 2023, the 16 T development program requires up to 1.5 tons/year

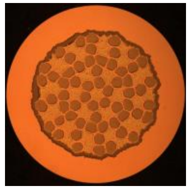
- Interesting results from collaborations
  - Korea, Japan, Russia
- Non-Cu J_c approaching HL-LHC specification at 12 and 16 T



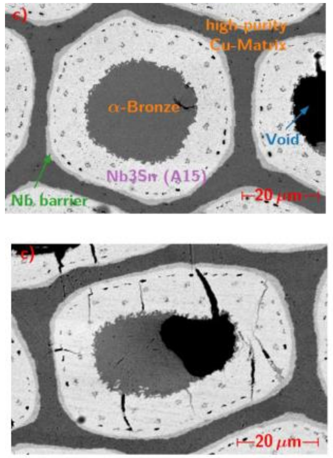


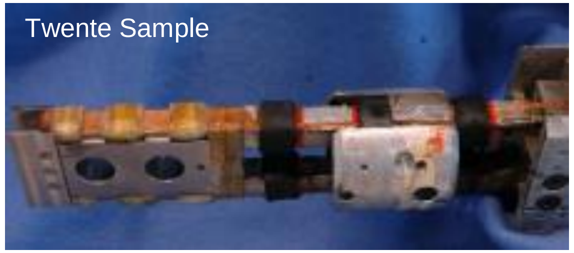






- Intensive studies on-going for the electro-mechanical characterization of the conductor.
- Irreversible degradation starts at around 170 MPa.





Sample without (top) and after (bottom) loading with 200 MPa (CERN).

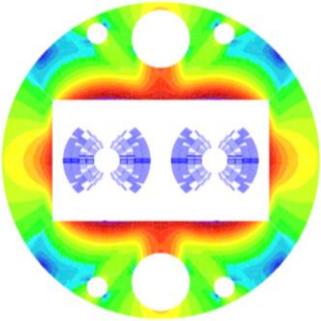
See sessions on Tuesday Morning

EuroCirCol – WP5: Design options

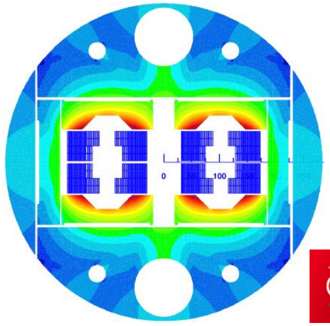
EuroCirCol shows that **more than one design option may work**

- Each of the options has stronger and weaker points than the others.
- For the FCC CDR, the cos-theta variant has been selected as the baseline option.

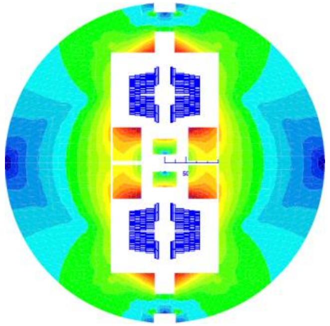
We have now an **opportunity to build up** a varied experience on Nb_3Sn magnets beyond the HiLumi specifications thanks to new initiatives:



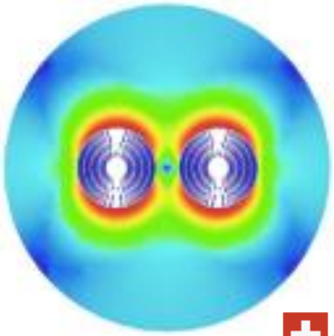
Agreement to build a model magnet at INFN under finalization



Agreement to build a model magnet at CEA signed



Agreement to build a model magnet at CIEMAT under finalization



Magnet model under construction at PSI

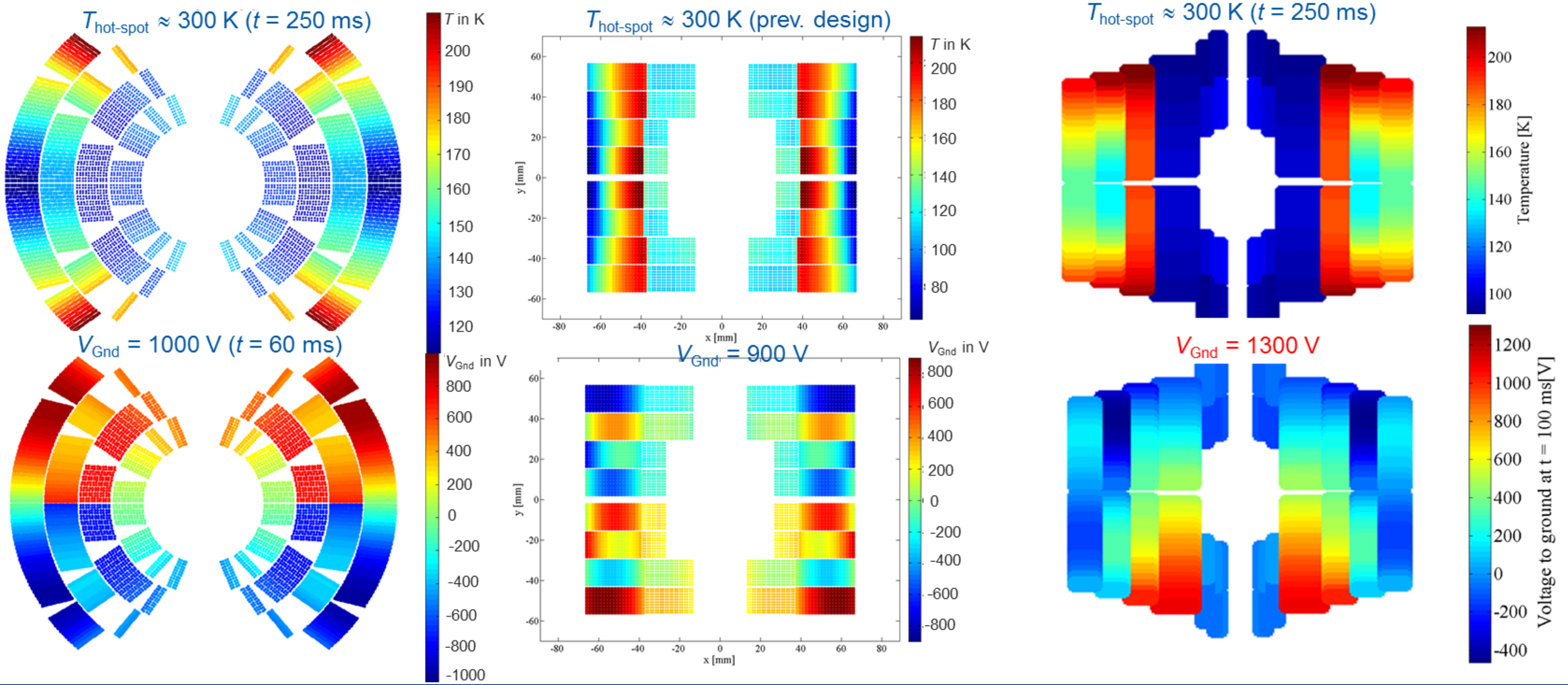
See sessions on Tuesday Afternoon & Wednesday Morning

EuroCirCol – WP5: Circuit & protection

- Quench protection was integrated into the magnet design since an early state, using the same software tools under the same assumptions.

- All designs fulfill the required targets:
  - T_{hot} < 350 K at 105 % I_{nom}
  - V_{max}< 1.2 kV at 105 % I_{nom}

- CLIQ has been selected as the baseline protection design.



See sessions on Wednesday Morning & Thursday Afternoon

EuroCirCol – WP5: Cost model

Phase 1

- Scope: Establishment of a full and cost-effective parameter set for FCC-hh dipoles to drive the design selection.
- Status: Completed and implemented into the designs

Phase 2

- Scope: Establishment of a target cost for the 16 T magnet
- Status: Concluded and ready for the CDR

Assembly cost scale up LHC magnet cost:
- Double of coils (x 2)
- Higher coil complexity (+ 20%)
- Higher assembly complexity (+20 %)

Parts cost: + 30 % above LHC

Conductor cost:	670 kEUR/magnet
Assembly cost:	600 kEUR/magnet
Parts cost:	420 kEUR/magnet
Total cost:	**1690 kEUR/magnet**

Phase 3

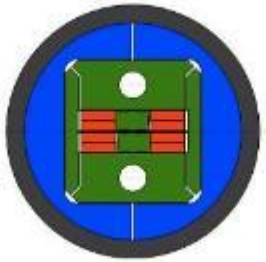
- Scope: Identify cost drivers of the assembly and magnets parts, and work with industry in the reduction of the cost.
- Status: Started

See session on Wednesday Morning

CERN R&D Model Magnets

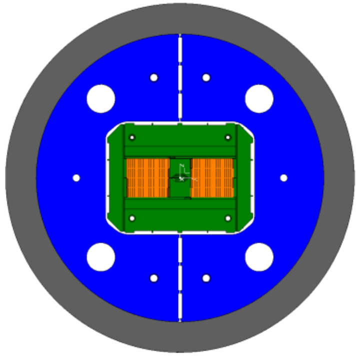
Hi-Lumi R&D

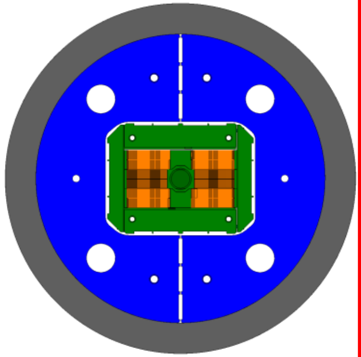
SMC	RMC
OD = 530 mm	OD = 570 mm
L = 500 mm	L = 820 mm
No Ap.	No Ap.
B_{op}= n.a.	B_{op}= n.a.
B_{ult} = 14 T	B_{ult} = 16 T



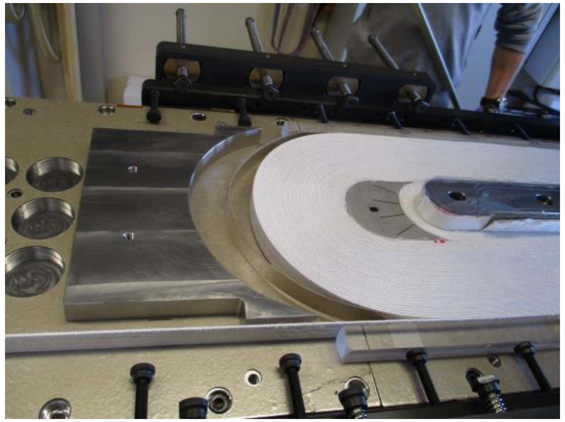
FCC R&D

ERMC	RMM
OD = 800 mm	OD = 800 mm
L = 1.2-1.4 m	L = 1.2-1.4 m
No Ap.	50 mm closed Ap.
B_{op}= 16 T	B_{op}= 16 T
B_{ult} = 18 T	B_{ult} = 18 T





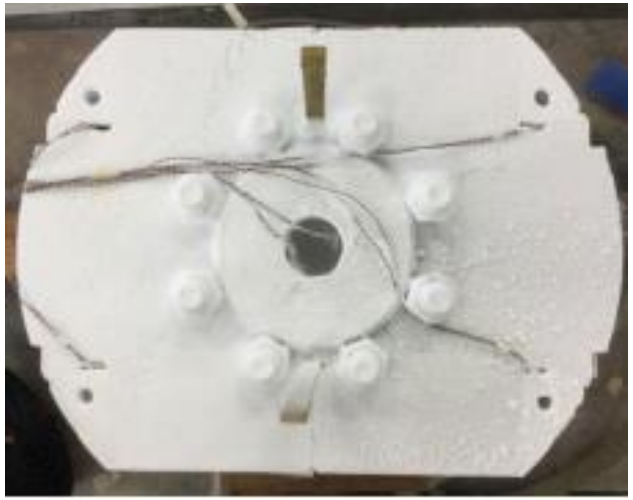
First coil has been wound



Assembly test with dummy coils on-going

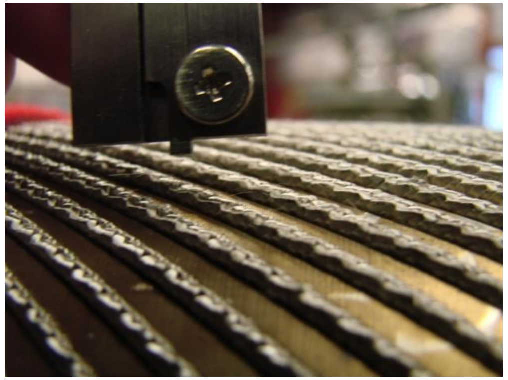
See session on Wednesday Morning

US Magnet Development Program



- Fabrication of a **15 T cos-theta** demonstrator on progress.
  - Design and procurement completed.
  - Coil fabrication on-going.
  - Mechanical structure have been tested.
- Design studies for an “utility” structure on-going

- **CCT technology** and understanding has advanced through the development of two layer models
- Issues with conductor damage have been resolved (CCT 4 reached 9.1 T (86% of SS limit)).
- Next main focus is on training reduction



See sessions on Wednesday Morning

Other initiatives

Specific initiatives to tackle key aspects

CERN-EPFL (CH) for Nb_3Sn splice R&D signed, under way.

Compact coils → Cost

See session on Wednesday Afternoon

CERN-Univ. Tampere (FI) for industrialization of large production signed

Cost

CERN-ETHZ-PSI (CH) for R&D on impregnation resins under signature

Training

CERN-Univ. Patras (Gr) for compact mechanical structures under signature

Cost & Performance

Conclusions

- Accelerator magnets in Nb_3Sn technology are becoming reality in HiLumi. Still, the distance between 11 T and 16 T is large.
- We are ready to the FCC CDR:
  - The contribution for the <concise, short> CDR volume (8 pages for magnets) is ready, and will be shared for final check by the end of April.
  - The first drafts for the contribution for <comprehensive, long> CDR volume will be ready by end of September, and the final documents will be provided by the end of November.
- HE-LHC has triggered a development towards compact magnets, which is both beneficial for FCC-hh and HE-LHC.
- The effort of EuroCirCol will be continued and we plan 3 short model 16 T magnets built by the respective institutes with CERN contributions.
- 16 T Dipole development is an international collaboration, including our European, US, Korean and Japanese partners, and now Russia is about to join our effort ☺

Thank you!

Programs:

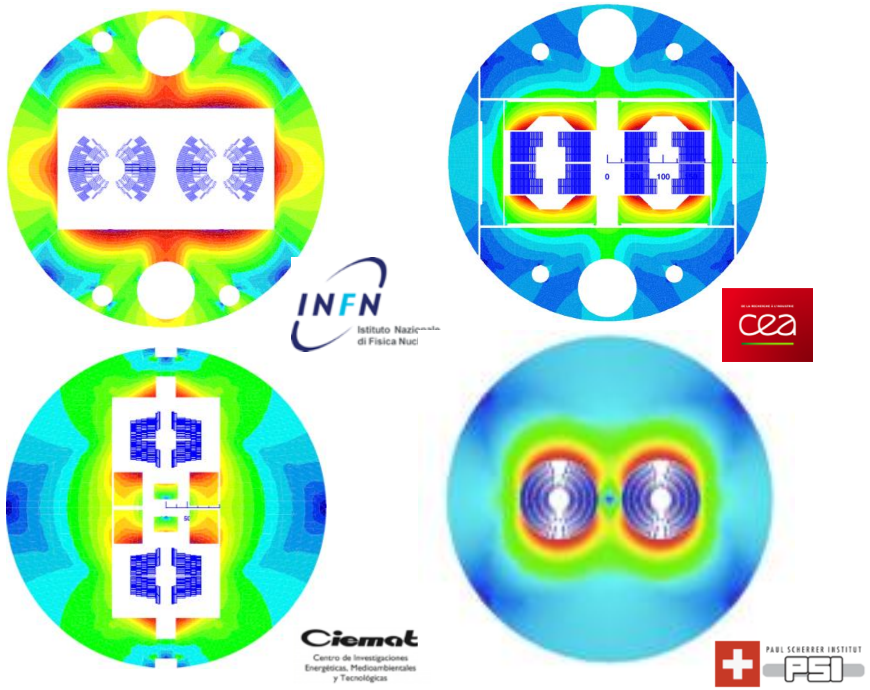
EuroCirCol – A key to New Physics – WP 5

FCC hh ee he

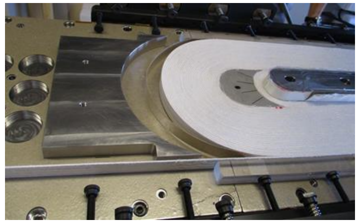
U.S. MAGNET DEVELOPMENT PROGRAM

Institutes and companies:

- Bruker, Germany/USA
- Technical University Freiberg, Germany
- Consiglio Nazionale delle Ricerche - SuPerconducting and other INnovative materials and devices institute, Italy
- Lawrence Berkeley National Laboratory, USA
- University of Twente, Netherlands
- INFN Milano, Milano, Italy
- INFN Genova, Genova, Italy
- Tampere University of Technology, Finland
- IRFU, CEA, Université Paris-Saclay, France
- CIEMAT, Spain
- PSI, Switzerland
- Columbus Superconductor, Italy
- Technical University Vienna, Austria
- University of Geneva, Switzerland
- Fermi National Accelerator Laboratory, USA
- Bochvar Institute, Russia
- TVEL, Russia
- Kiswire (KAT), Corea
- KEK, Japan
- Jastec, Japan
- Fukurawa Electric, Japan




MDP 15 T technological model


CERN’s first ERMC coil is wound

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Columbus Superconductors · UNIVERSITÉ DE GENÈVE · Fermilab 50 Years of Discovery · ВНИИНМ имени А.А. Бочвара · Kiswire · JASTEC SUPERCONDUCTOR · FURUKAWA ELECTRIC · EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

CERN

Field quality table for 3.3 TeV (LHC injection, 1.1 T)

- Better field quality would ease machine operation
- Smaller random b_3 is required to control the chromaticity, which cannot be measured in real time during beam acceleration
- Within EuroCirCol WP5 studies to mitigate in particular b_3 have been started
- b_2 can be reduced by increasing the inter-beam distance, for example to 20 units at 250 mm

	FCC Dipole field quality version 3 - 24 Jan 2018- R_{ref}=16.7 mm. 3.3 TeV Injection								
	Systematic					Uncertainty		Random	
Normal	Geometric	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field
2	-2.230	-44.610	0.000	-2.230	-46.840	0.922	0.922	0.922	0.922
3	-18.140	17.000	-38.860	-57.000	-1.140	4.000	1.351	4.000	1.351
4	-0.100	-0.930	0.100	0.000	-1.030	0.449	0.449	0.449	0.449
5	-0.690	-0.340	9.190	8.500	-1.030	1.000	0.541	1.000	0.541
6	0.000	-0.010	0.000	0.000	-0.010	0.176	0.176	0.176	0.176
7	1.610	0.140	-1.010	0.600	1.750	0.211	0.211	0.211	0.211
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071
9	1.310	0.120	2.990	4.300	1.430	0.500	0.092	0.500	0.092
10	0.000	0.000	0.000	0.000	0.000	0.027	0.027	0.027	0.027
11	0.960	0.090	-0.100	0.860	1.050	0.100	0.028	0.100	0.028
12	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.009
13	-0.170	-0.020	0.170	0.000	-0.190	0.000	0.011	0.000	0.011
14	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.000	0.003
15	0.010	0.000	-0.010	0.000	0.010	0.000	0.004	0.000	0.004
Skew									
2	0.000	0.000	0.000	0.000	0.000	1.040	1.040	1.040	1.040
3	0.000	0.000	0.000	0.000	0.000	0.678	0.678	0.678	0.678
4	0.000	0.000	0.000	0.000	0.000	0.450	0.450	0.450	0.450
5	0.000	0.000	0.000	0.000	0.000	0.317	0.317	0.317	0.317
6	0.000	0.000	0.000	0.000	0.000	0.205	0.205	0.205	0.205
7	0.000	0.000	0.000	0.000	0.000	0.116	0.116	0.116	0.116
8	0.000	0.000	0.000	0.000	0.000	0.071	0.071	0.071	0.071
9	0.000	0.000	0.000	0.000	0.000	0.041	0.041	0.041	0.041
10	0.000	0.000	0.000	0.000	0.000	0.025	0.025	0.025	0.025
11	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016
12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009
13	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.003
15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.002

Systematic:
Injection = Geometric + Persistent
High Field/Collision = Geometric + Saturation