

Towards 16 T Dipole Magnets for Future Circular Colliders

Accelerators for HEP

Contribution 2577786

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*With warm thanks to L. Bottura, P. Ferracin, S. Izquierdo Bermudez, F. Lackner, G. de Rijk, and D. Tommasini
who have provided most of the material included in this presentation*

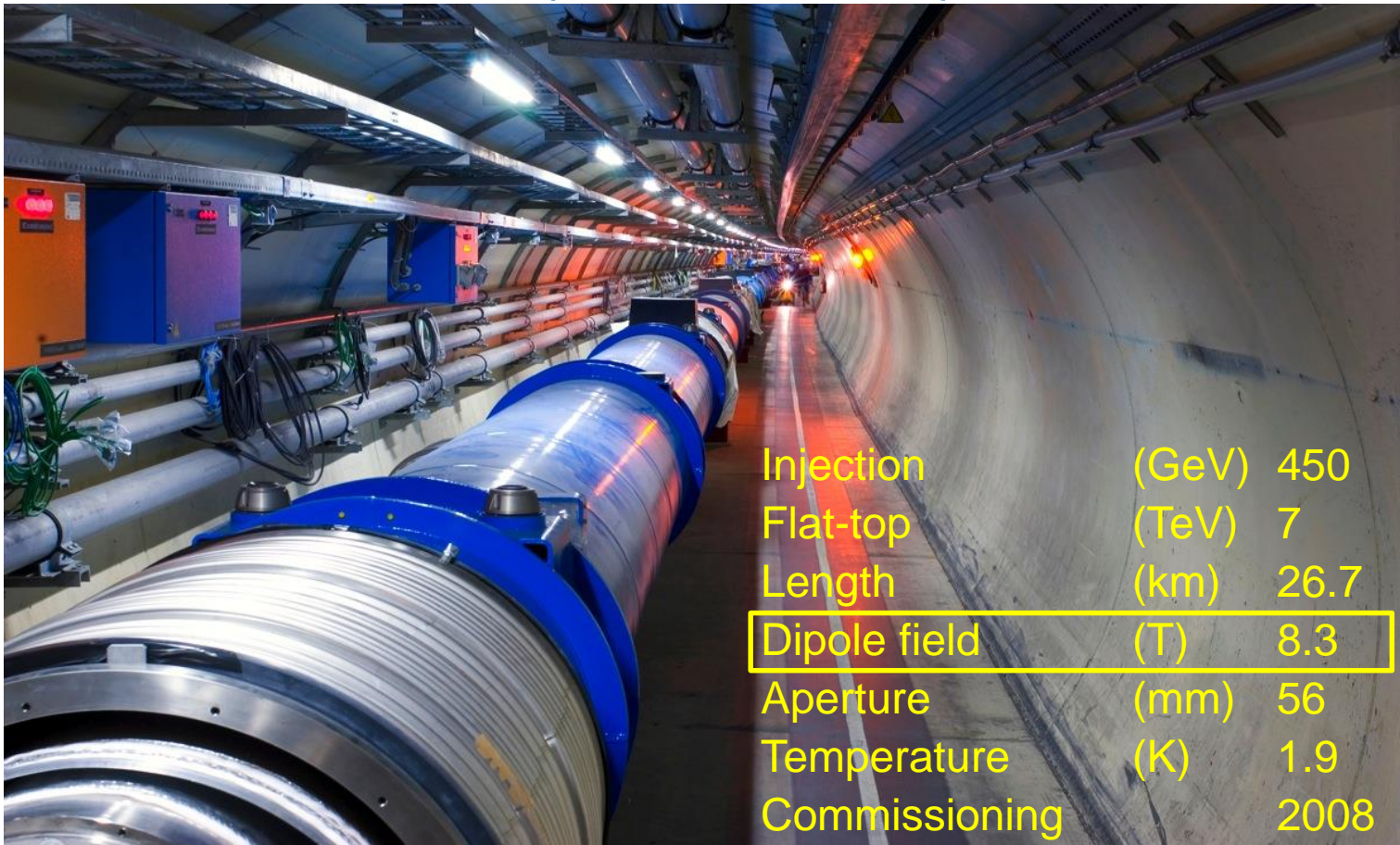
Outlook

- Introduction
- 16 T Dipole Magnet Program
- FRESCA 2 Magnet
- 11T Dipole for the Upgrade of the LHC Collimation System
- Challenges
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LHC at CERN (Geneva, CH)



Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commissioning		2008

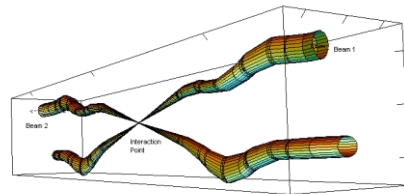
HEP Demands

- **More collision energy** will increase the “physics reach” (generate new particles)
- This corresponds to an **increase of the beam energy**

$$E[GeV] = 0.3 \sqrt{B[T]} \sqrt{r[m]}$$

Beam energy **Dipole field** Bending radius

- The **beam energy in a circular machine is directly proportional to the dipole field**



Relative beam sizes around IP1 (Atlas) in collision

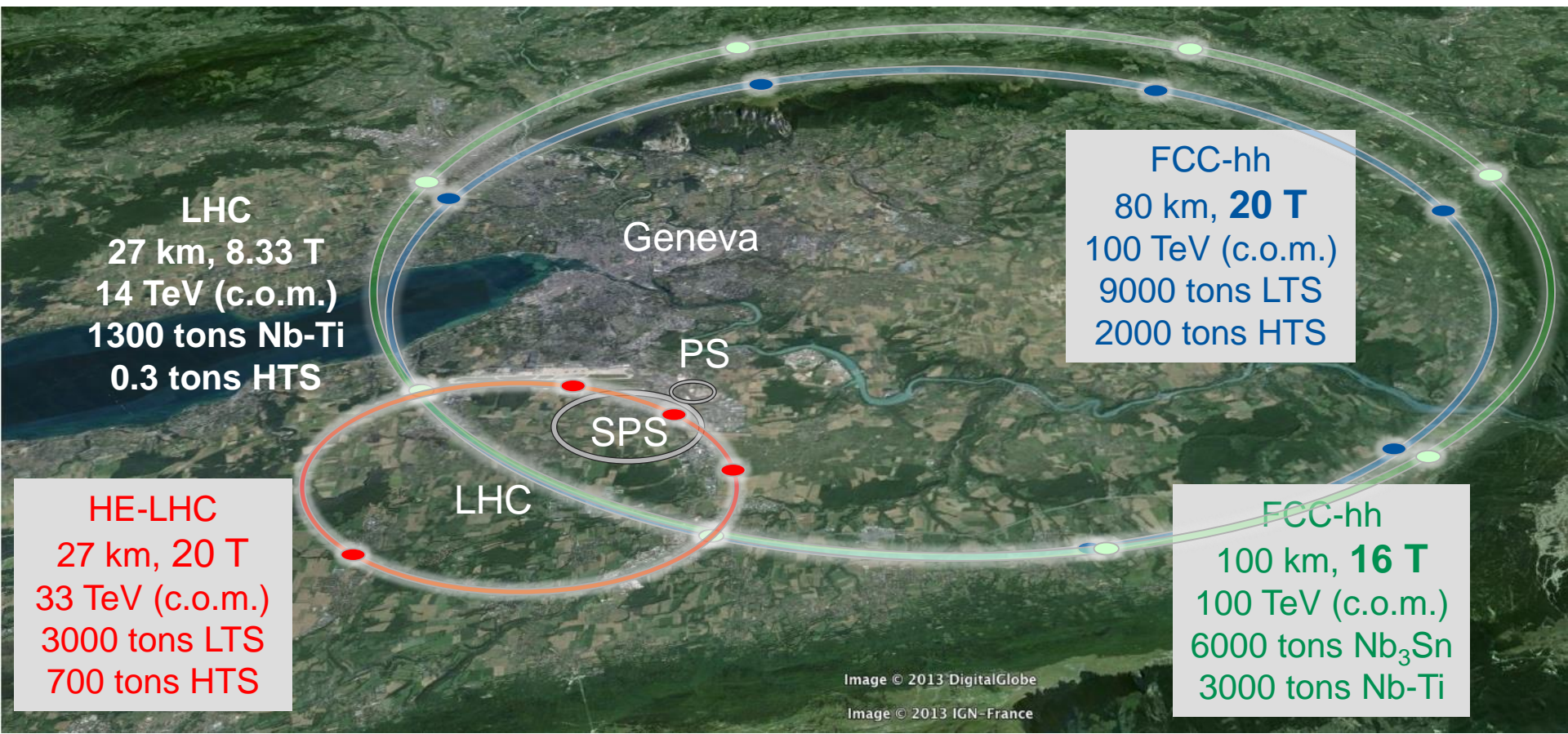
- Events are needed to increase the statistics of the measurements (**luminosity L** at the experiment)
- Increase the density of particles at the collision point, reducing the dimension of the colliding beam (β^*) by **strong focusing**

$$\text{Luminosity } L = \frac{f N^2}{4\pi b^*} \text{ Particles}$$

Emittance **Amplitude function**

- This requires quadrupoles with **large gradients and wide aperture → high field**

Ideas beyond the LHC: the FCC's



Key numbers regarding the main dipoles

- **From LHC: 27 km circumference, 7+7 TeV**
 - Filling factor (magnetic) : 66%, about 17.5 km
 - Required field integral : $\int B dl \sim 0.15 \text{ MTm}$
 - Obtained with : **1232 magnets**, 14.3 m long, **8.33 T**
- **To FCC: 100 km circumference, 50+50 TeV**
 - Filling factor (magnetic) : 66%, about 66 km
 - Required field integral : $\int B dl \sim 1.0 \text{ MTm}$
 - Obtained with : **4578 magnets**, 14.3 m long, **16.0 T**
- **16 T magnets would allow doubling the energy of the LHC machine (HE-LHC*)**

*Proceedings of the EuCARD-AccNet-EuroLumi Workshop, Oct. 2010, Republic of Malta, <http://cds.cern.ch/record/1344820>

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Questions to be addressed

- **Are 16 T accelerator magnets feasible?**
 - Can we achieve the field with **sufficient margin**?
 - Can we **protect the magnet**, once in the whole circuit?
 - Can we meet the **field quality requirements**?
- **If all “yes”, at what cost?**
 - Cost of conductor
 - Cost of construction

Development plan: 2017-2023

- **Conductor**

- Procurement of ~ 1 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), trim of other properties
- Vigorous conductor R&D, the FCC program is co-funding a 2nd production line at Bruker-EAS
- Initiatives in Russia (Bochvar/TVEL), Korea (KISWire/KAIST), Japan (KEK/Jastec/Furukawa) for conductor development towards target J_c
- Comprehensive electro-mechanical characterization

- **FCC Conceptual Design Report (end 2018)**

- Feed the CDR with a baseline, including a cost model, and a description of the possible options

- **R&D Magnets (2016-2020)**

- Design, Manufacture & Test of **ERMC** (Enhanced **R**acetrack **M**odel **C**oil) and **RMM** Magnets (**R**acetrack **M**odel **M**agnet)

- **Short Models (2018-2023)**

- Design, Manufacture & Test of Model Magnets

Implementation plan



- FCC 16 T Magnets Technologies (until 2023)
 - Conductor development & procurement (about 1 ton/year)
 - Winding characterization
 - R&D magnets : ERM/ERM, start winding in 2017
 - Model magnets at CERN, CEA, CIEMAT, INFN, PSI, start winding in 2019



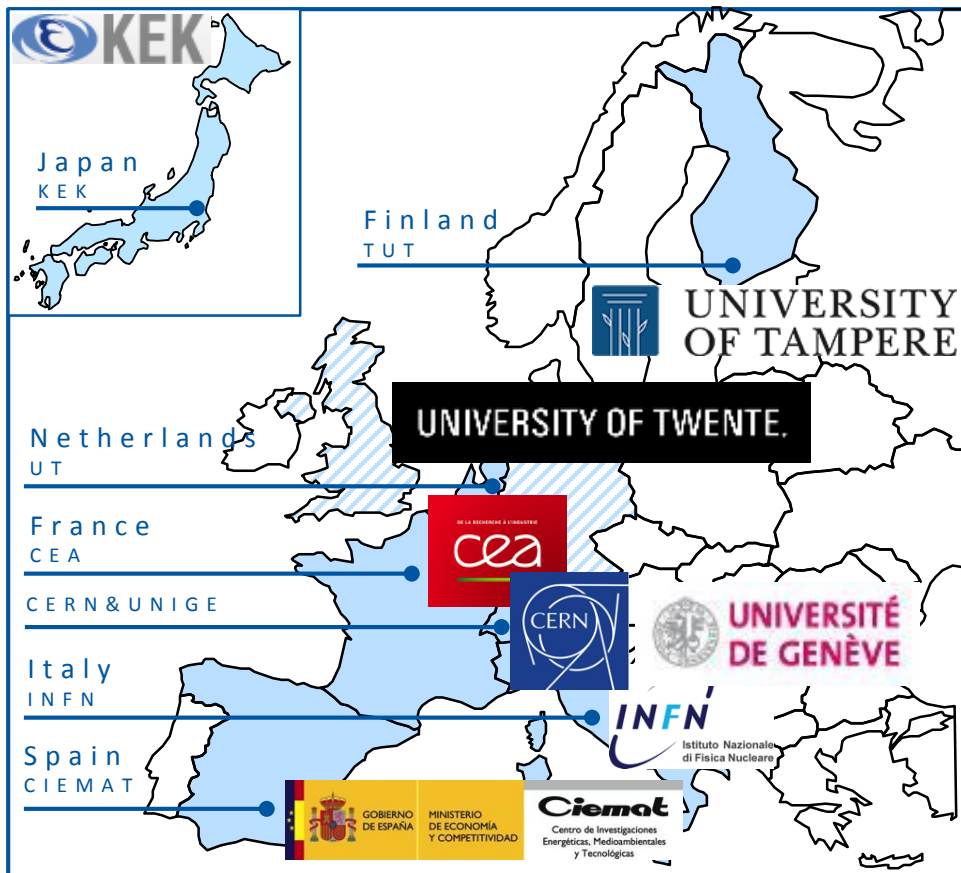
- EuroCirCol WP5 (until 2019)
 - 7 institutes involved
 - Feed the FCC CDR with a baseline design and a cost model for 16 T magnets



- US Magnet Development Program
 - Initially focused on a 14-15 T cosine-theta demonstrator (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 demonstrator quoted above



CERN/EU program for 16 T dipole



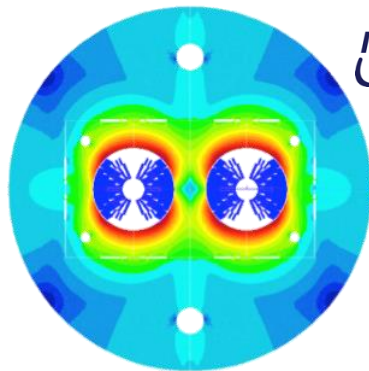
WP 5

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



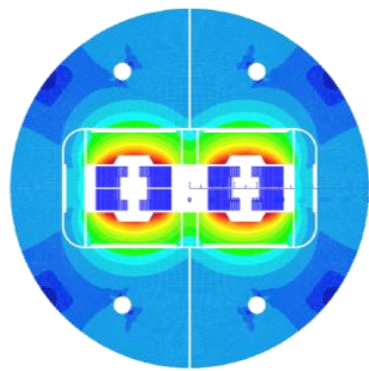
FCC: 16 T design options

Cos-theta



S. Farinon, M. Sorbi (INFN)

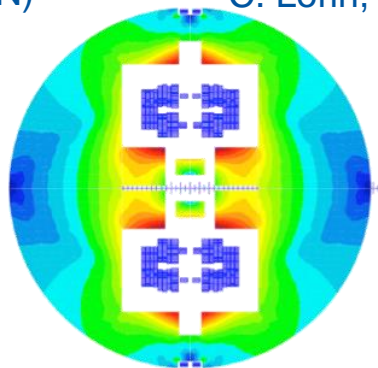
Blocks



C. Lorin, M. Durante (CEA)



Common coils



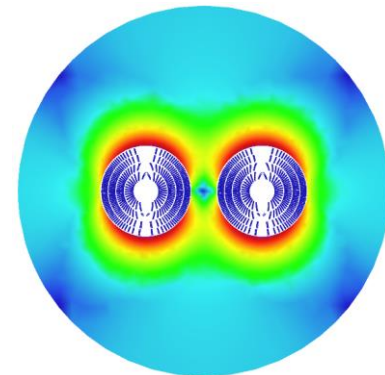
F. Toral (CIEMAT)



Wide-range study,
based on the **same**
design
assumptions



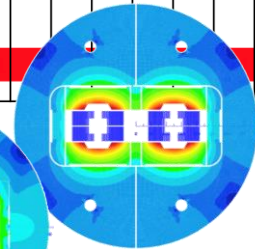
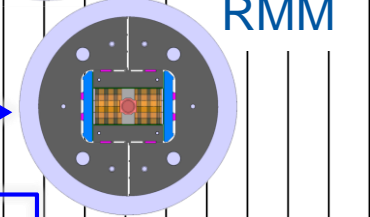
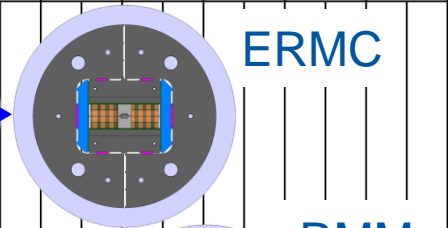
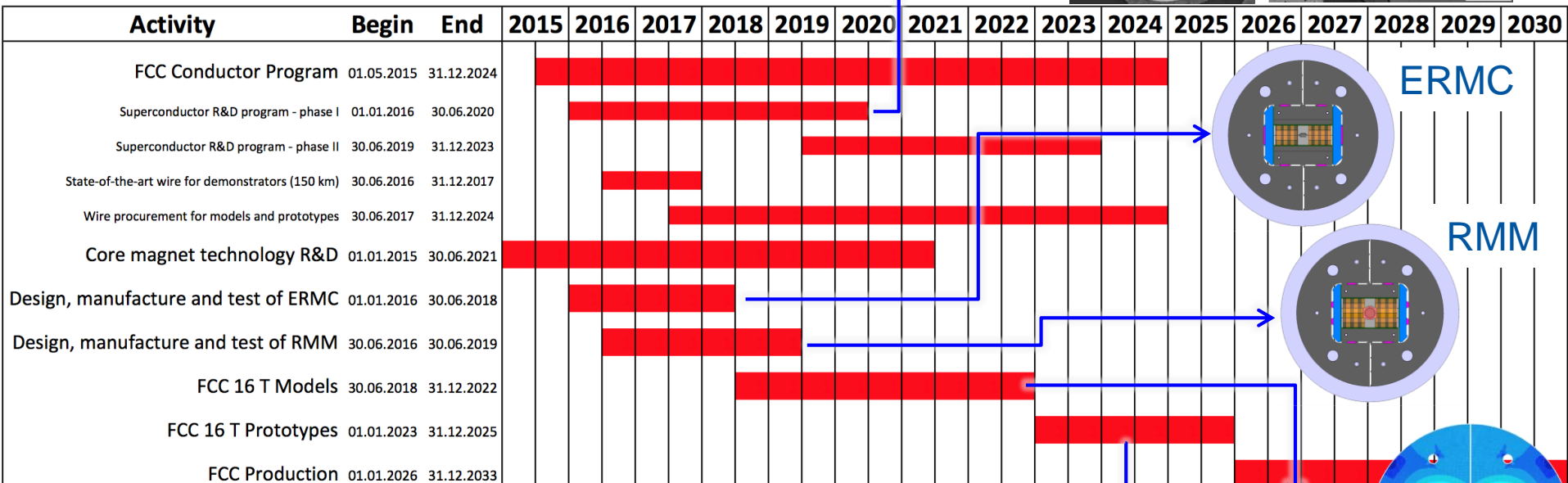
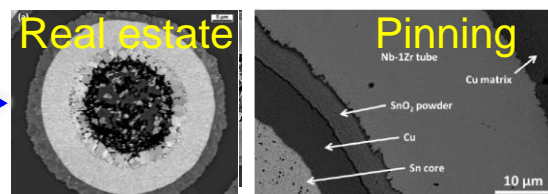
Canted Cos-theta



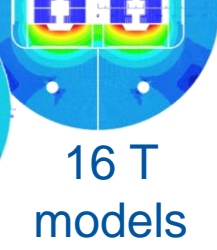
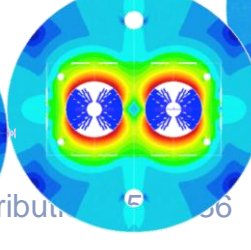
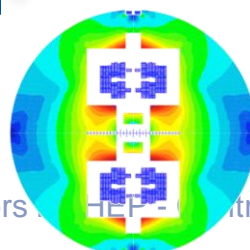
EP - B. Auchmann (CERN/PSI)

In a Gantt chart

Conductor R&D



Opportunity for full length prototypes built in industry



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HEP

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16 T models

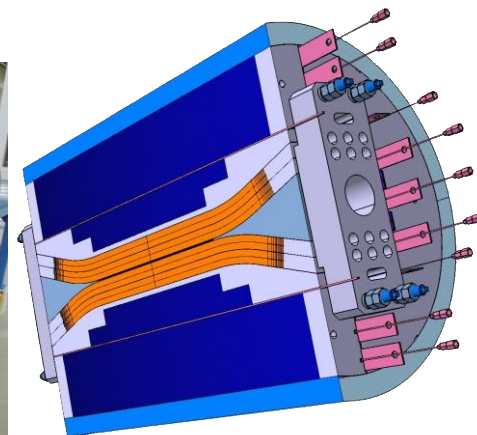
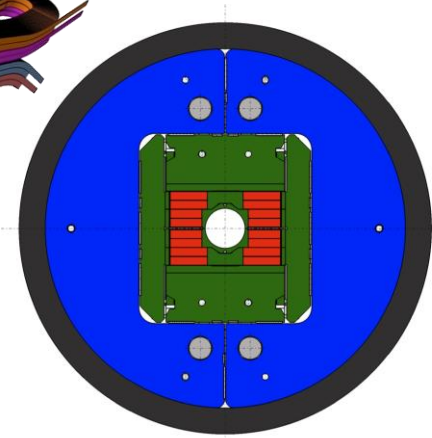
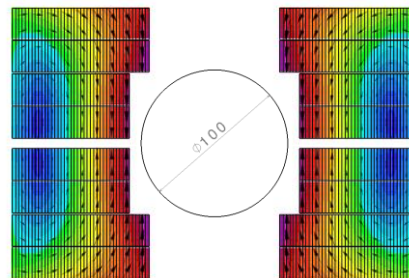
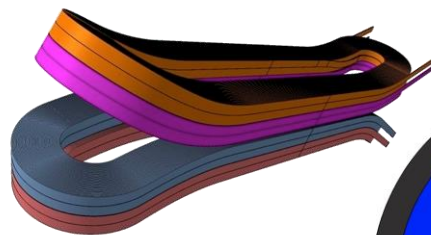
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FRESCA 2

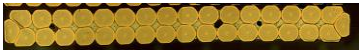
*European Coordination
for Accelerator R&D

- A CERN, CEA, EuCARD* collaboration
- A Nb_3Sn dipole magnet to upgrade the CERN cable test facility
- A high field magnet demonstrator and technology incubator
- Nominal field, B_{center} : 13 T
- Current $I_{13\text{T}}$: 10.9 kA
- Peak field, B_{peak} : 13.4 T
- Aperture diameter: 100 mm
- Load line margin: 20% @ 4.2 K
- Stored energy: 3.8 MJ/m
- L coils: 1.6 m
- L straight section: 0.7 m
- Magnet diameter: 1.03 m

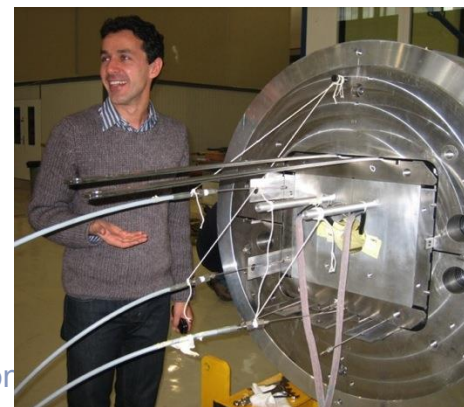
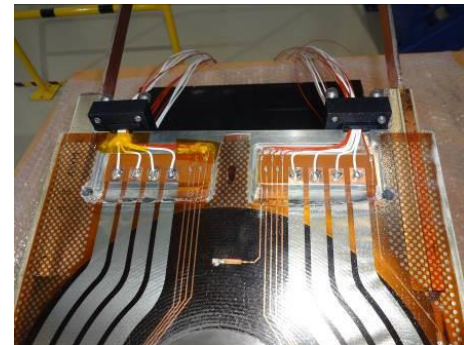
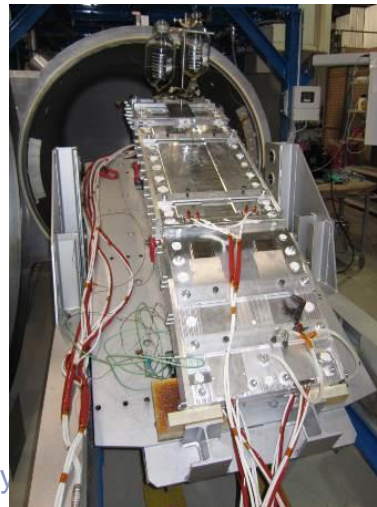


Technological aspects

- Flat cable, i.e. no key-stone angle, however rather large (20.90 x 1.82 mm), Rutherford type



- Coil packs made of two double-layer coils (coil 1 contains 2 x 36 turns, and coil 2, 2 x 42 turns)
- Flared ends are easy for winding
- No ceramic binder needed after winding
- No end spacers needed
- Cable growth during the reaction process needs to be taken into account (2% in width, and 4 % in thickness), as well as longitudinal cable thermal expansion
- Impregnation with epoxy resin CTD101K
- Bladders and keys are used for pre-stressing the coils in the outer 65-mm thick cylinder made of aluminum (grade 7075)
- Axial preload by means of 60-mm diameter rods made of aluminum
- A magnet of **unusually large diameter!**



**Reached 12.1 T, was consolidated,
and will be retested**

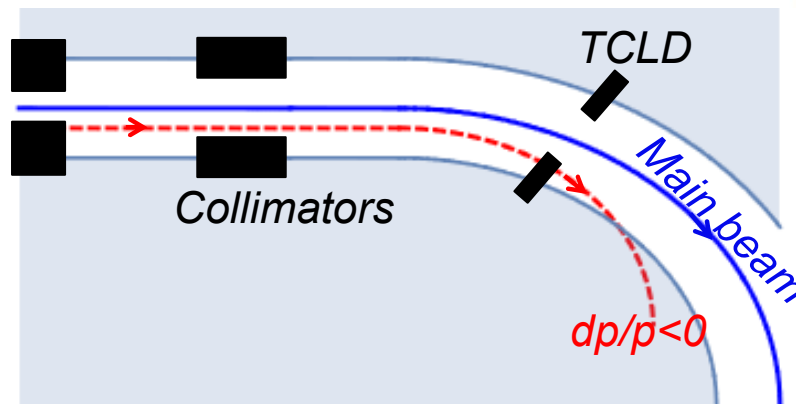
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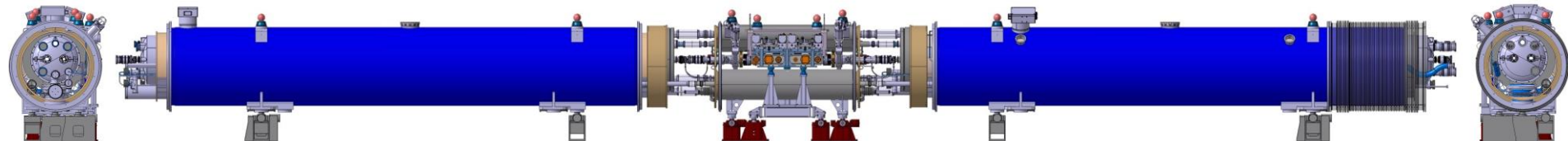
11T Dipole – HiLumi LHC @ CERN

How to improve for HL-LHC

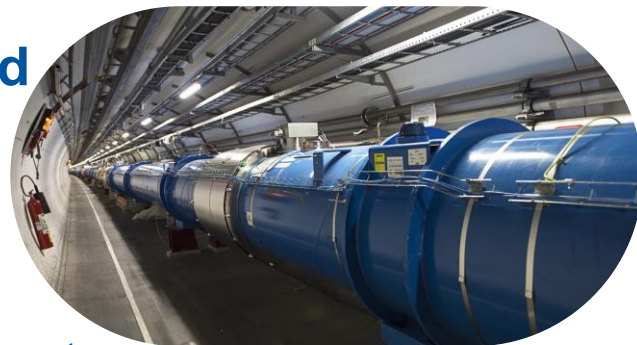
- Risk to be limited in intensity reach if nothing is done
- **IR7 DS** is the bottleneck, due to off-energy particles (or ion fragments) scattered out of primary collimator
- Solution: **introduce extra collimators, TCLDs, in dispersion suppressor**
 - Make space by replacing a standard dipoles by two shorter 11T dipole, with TCLD in between
- Present HL baseline: **install 1 IR7 TCLD per beam in LS2**
 - 2 TCLDs per side also studied (previous baseline)
 - Excluded to have more 11T units available by LS2



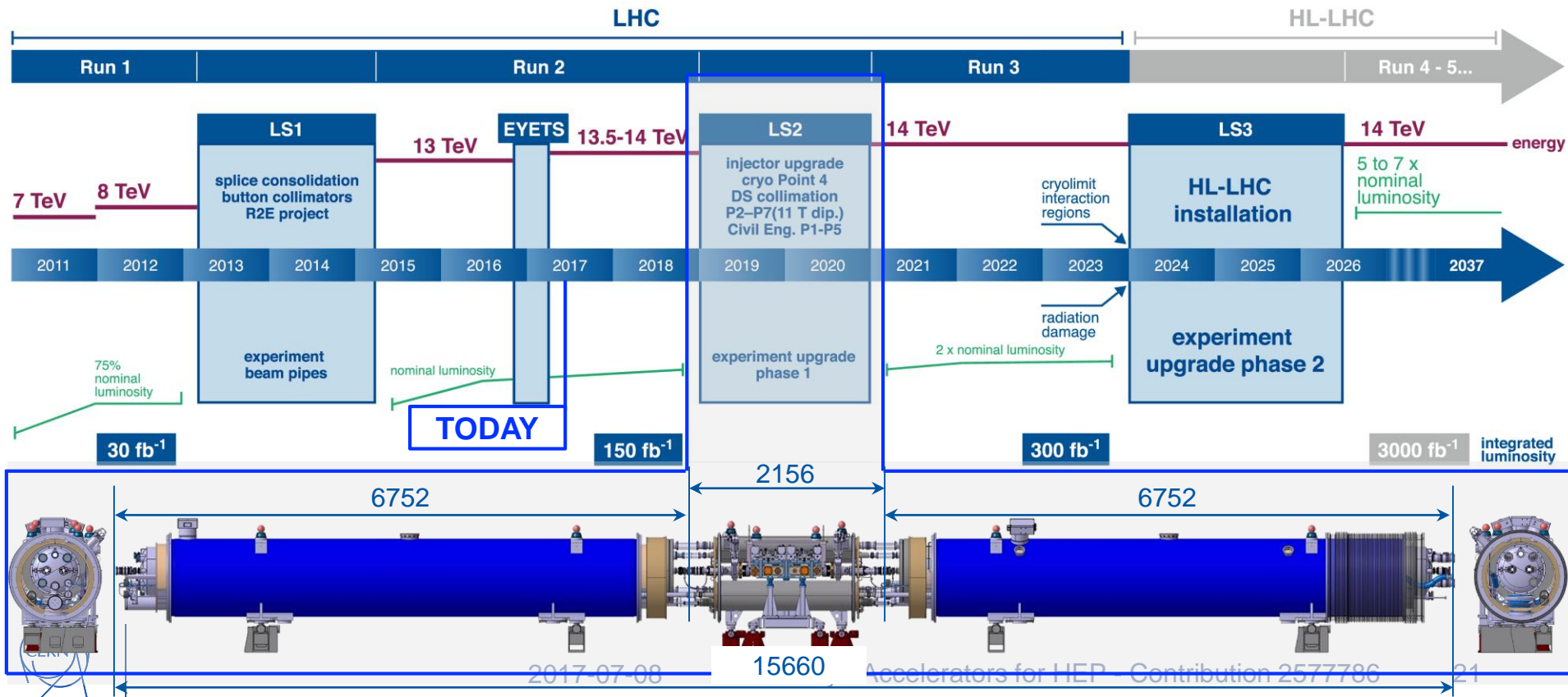
Motivations for an 11 T Dipole



- The HL-LHC Project implies beams of larger intensity ➔ **additional collimators are needed** in order to intercept and absorb higher beam losses (dynamic heat loads on cryogenics and risk to quench superconducting magnets)
- Two collimators, **one per beam, installed on either side of interaction point 7 (IP7)** for both proton and heavy-ion collimation losses, in the Dispersion Suppressor region
- **Replace a standard Main Dipole by a pair of shorter 11 T Dipoles producing the same integrated field of 119 T·m at 11.85 kA**

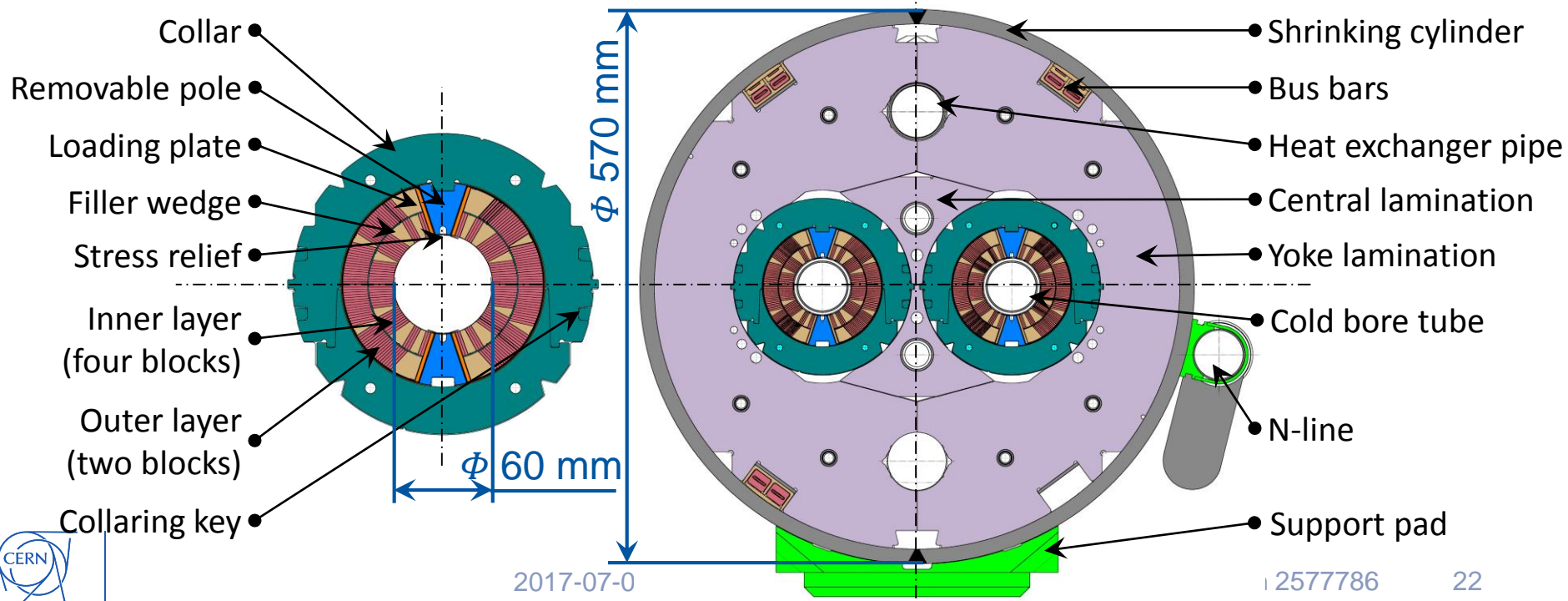


LHC / HL-LHC Plan



11T Dipole – Main design features

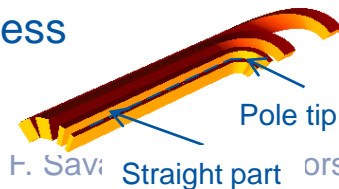
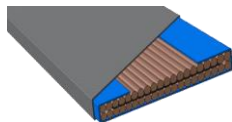
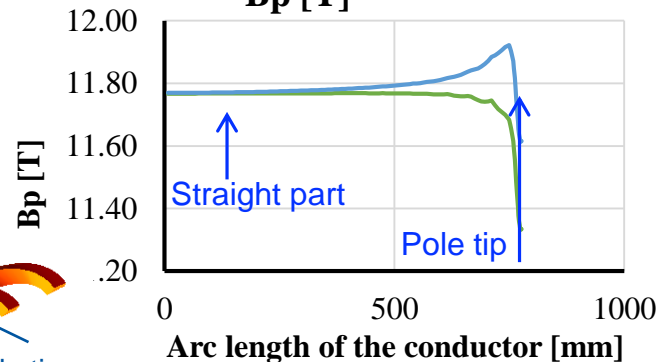
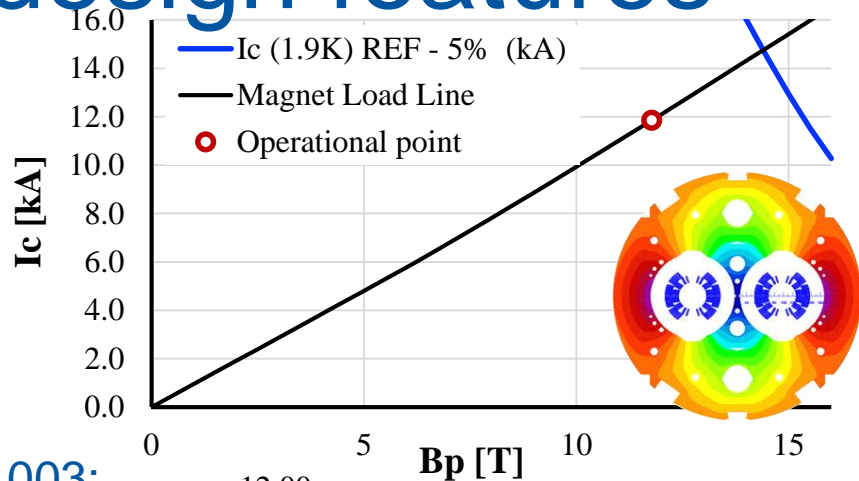
- Like the LHC main dipole, the 11 T dipole has a **two-in-one** structure
- Cold mass length: 6.252 m, weight $\cong 8$ t, magnetic length = 5.307 m



11T Dipole – Main design features

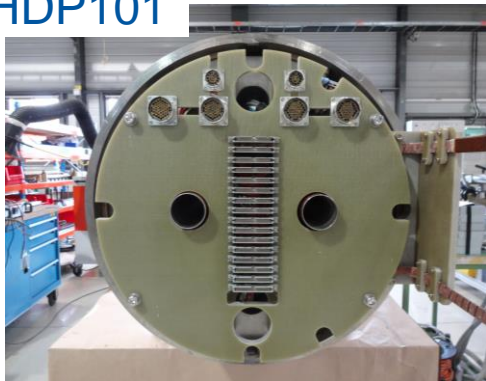
- Operational Conditions:

- $T = 1.9 \text{ K}$
- $I_{op} = 11.85 \text{ kA}$ – **$B = 11.23 \text{ T}$**
- $B_p = 11.77 \text{ T}$ (with cryostat, strand self-field, and yoke cutback)
- Load line **margin** $\cong 20 \%$ (operational point at 80.1% of I_{ss} at 1.9 K with yoke cutback)
- Conductor, **Nb_3Sn** , strand $\Phi 0.700 \pm 0.003$:
 - RRP, keystone angle 0.79°
- Cable mid-thickness **1.25 mm, 40 strands**
- Cable insulation:
 - **1 layer of Mica tape** of $80 \mu\text{m}$ thickness
 - **1 layer of S2-glass** of $75 \mu\text{m}$ thickness



Ongoing work and results

MBHDP101

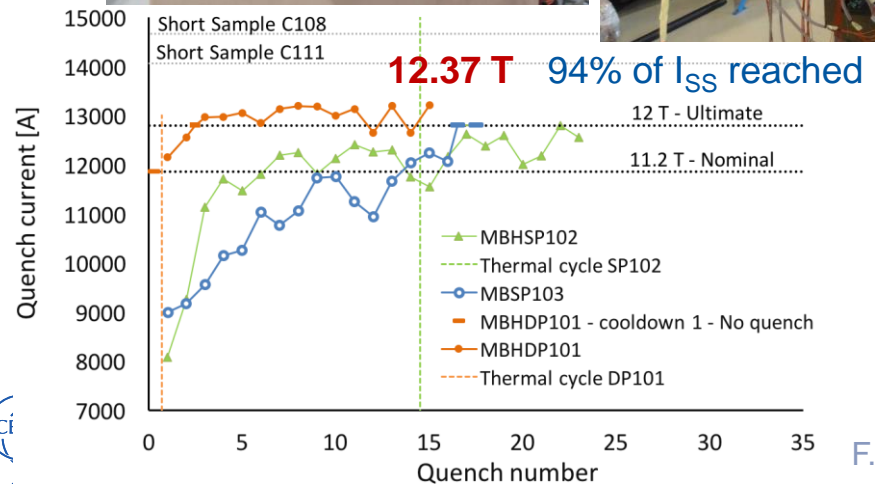


MBHDP102



5.5 m long collared coils

5.5 m long coil



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- Challenges ... a selection of ...
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Characterization of Nb₃Sn wound conductor

Irreversible degradation

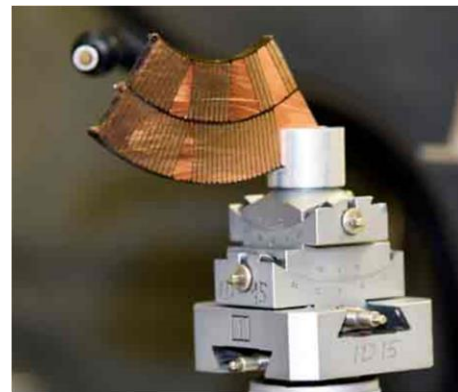
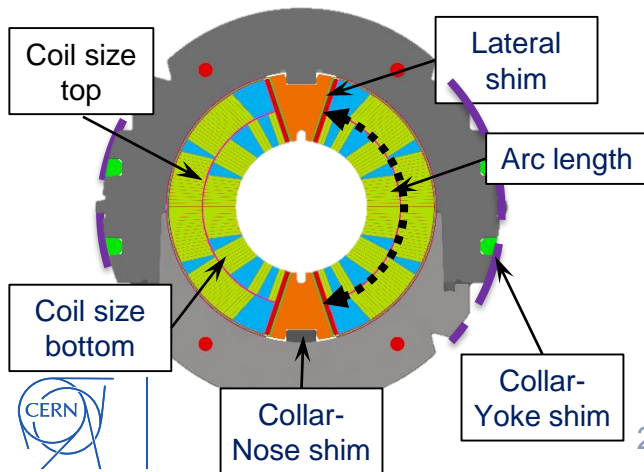
- Quantify irreversible degradation of the conductor during the magnet assembly at RT
- Develop knowledge about stress distribution on Rutherford cable stack under the transversal load

Wind-ability

- Development of **winding test setup** to define a “wind-ability factor” allowing comparison between different Rutherford cables
- Development of adequate **scanning method to quantify strand displacements** during the winding process

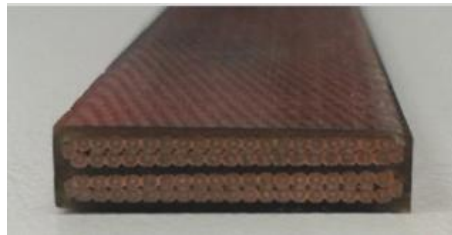
Material characterization

- Improving **knowledge of magnet material parameters** for better **accuracy of FE modelling**
- Improved FE meshing using tomographic coil characterization

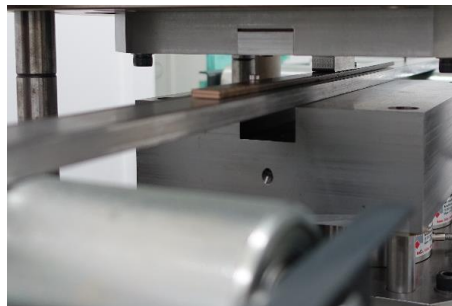


Irreversible degradation

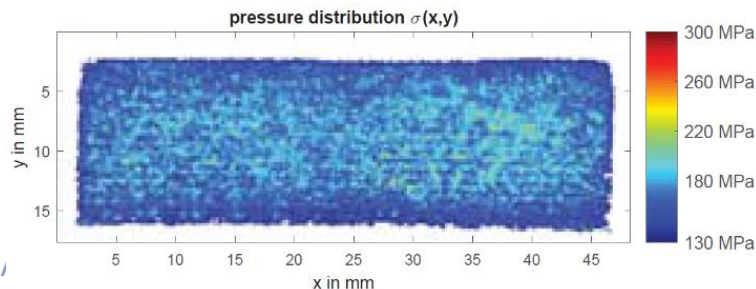
- The I_C of a reacted and impregnated sample stack made of 2 cables is measured in FRESKA (@ CERN)
- The sample is taken out from FRESKA, and compressed across thickness in a controlled manner at ambient temperature
- The sample is measured again in FRESKA to check whether, and by how much, the compression has modified the I_C
- The test setup was optimized in order ensure a known / uniform pressure distribution during the load step



FRESKA sample, RRP – Nb₃Sn 11T cable stack



Cable compression on hydraulic press

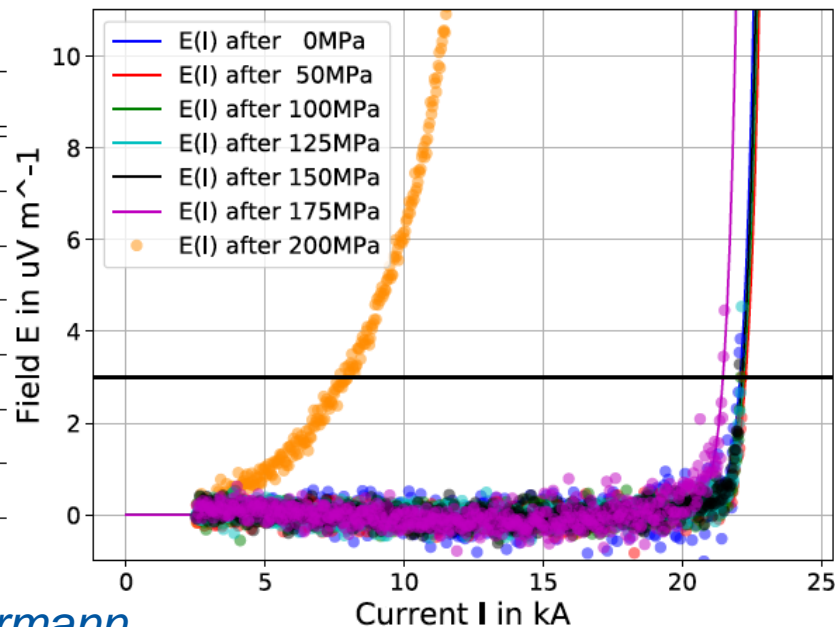


Results available to date – tests ongoing

- Comparison of fitted voltage-current curves at $B_{\text{app}} = 9.6 \text{ T}$ and $T = 4.2 \text{ K}$
- No degradation observed up to 150 MPa

σ_{desired}	$I_c _{B_{\text{app}}=9.6 \text{ T}}$	$\varepsilon_{\text{degr}}$
MPa	kA	%
0	22.1	0
50	22.2	0.4
100	22.2	0.4
125	22.2	0.4
150	22.2	0.4
175	21.45	−3.2
200	7.9	−64.0

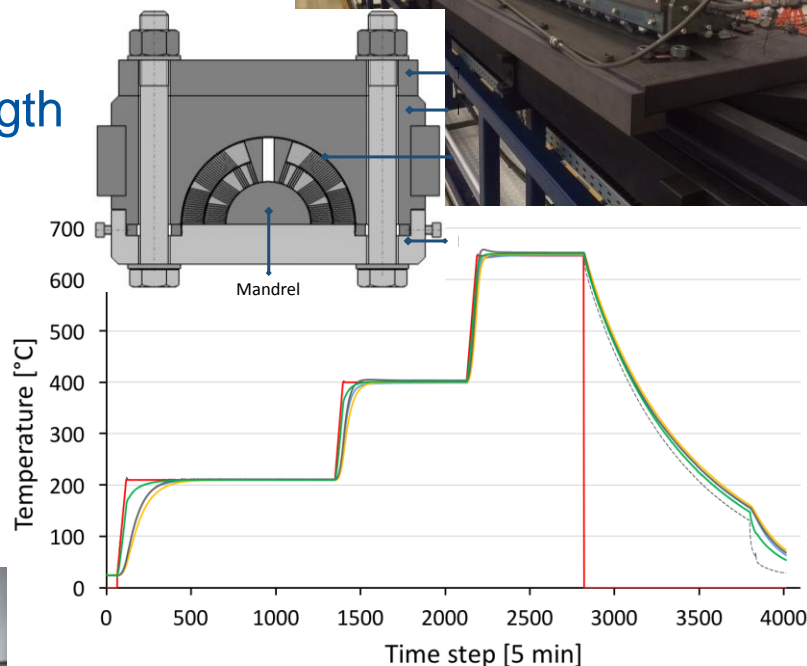
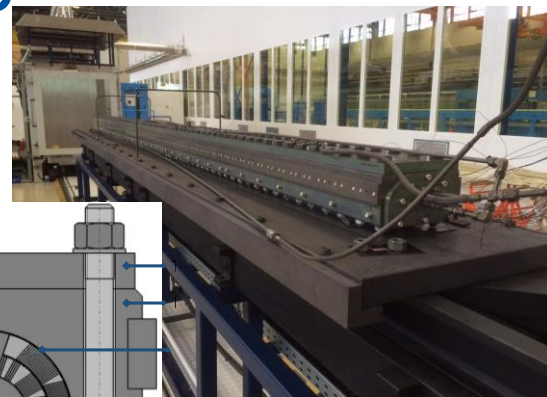
$\varepsilon_{\text{degr}}$... Degradation in % since 0 MPa



Results by courtesy of P. Ebermann

Reaction process, how on large scale?

- Coils reacted after winding/curing in order to **form the superconducting Nb_3Sn compound**
- In a mould called **reaction fixture**
- **Reaction furnace under Ar atmosphere (retort / fixture)**, for coils up to 6.5 m length
- Reaction fixture sized taking into account volumetric expansion of the cable during reaction, 1% in width (radial direction in coil) and 3% in thickness (azimuthal direction in coil)
- **Homogeneity** of temperature in the coil **shall be better than $\pm 3^\circ\text{C}$**
- Cycle: 72 h @ 210°C , 48 h @ 400°C and 50 h @ 650°C , total 170 h!



Reacted conductor is BRITTLE

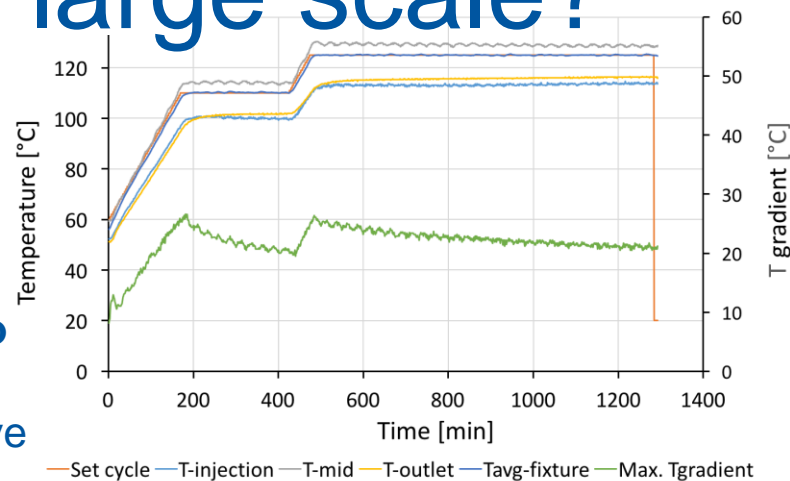
2017-07-08

F.



Impregnation, how on large scale?

- Coils impregnated after they have been reacted, with an anhydride **epoxy system CTD-101K**
- Mould is heated to 110°C and flushed with nitrogen, then cooled down to 60°C and evacuated for resin injection (4-5 h), gelling @ 110°C (5 h), and post curing @ 125 °C (16 h), **mould pressurized to ~ 3 bar** before starting gelling stage
- Coil insulation will be tested by means of a capacitive discharge at 4.7 kV corresponding to 85 V/turn on the finished coils



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Summary

- The demands from HEP were expressed and translated in terms of magnet requirements
- Key numbers for the main dipoles of a FCC were given
- The 16 T dipole magnet program currently ongoing for FCC, including via EuroCirCol and the US magnet program, was described
- Demonstrator magnets, namely FRESKA 2 for the upgrade of the cable test facility @ CERN, and the 11T dipole for the High Luminosity LHC Project, were presented. These magnets are a major step forwards in the development of the know-how and technology towards high-field magnets for future accelerators
- **A very interesting era ahead of us!**



Thank you!