16T Magnets for the FCC pp

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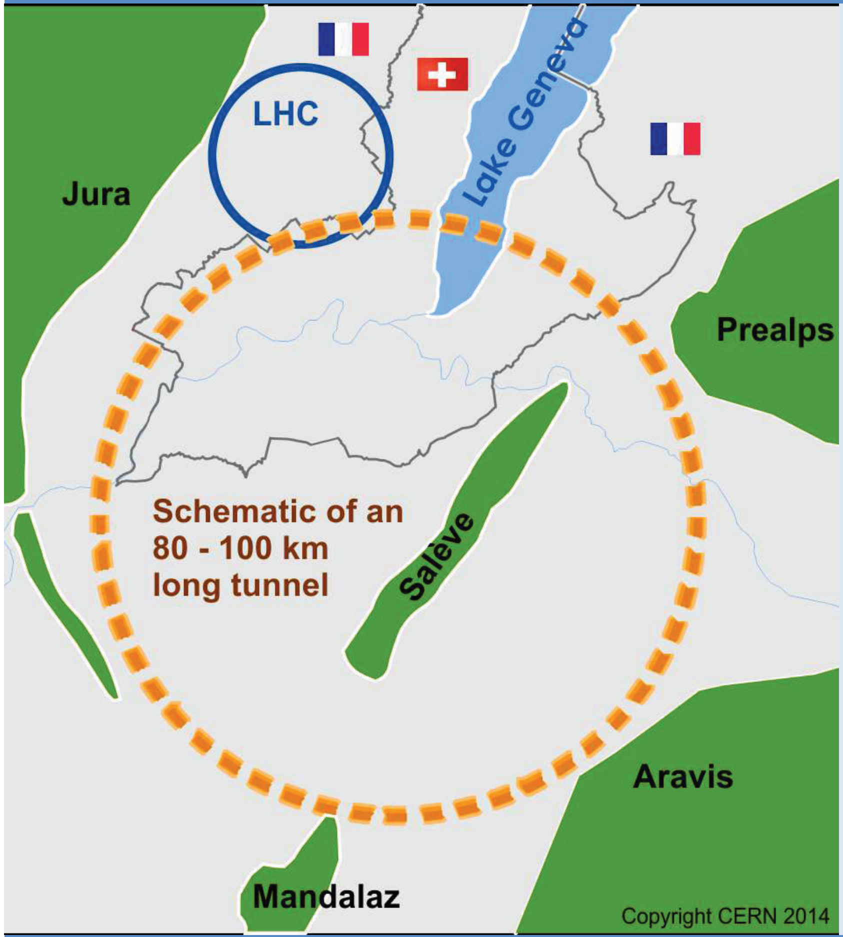
On behalf of EuroCirCol WP5 group
Information collected from *FCC*, *EuroCirCol* and *US MDP* presentations and papers
Special thanks to *D. Schoerling*, *F. Toral* and *A.V.Zlobin*

FCC hh ee he
EuroCirCol
U.S. MAGNET DEVELOPMENT PROGRAM

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

The Future Circular Collider



FCC: International Collaboration

- FCC-e^+e^-: first step?
- FCC-hh: main goal (long term)

Both using new 100 km tunnel

- (High Energy) HE-LHC

using existing LHC infrastructure

4 CDR Volumes developed (end 2018)
http://fcc-cdr.web.cern.ch/

One of them is focused in FCC-hh

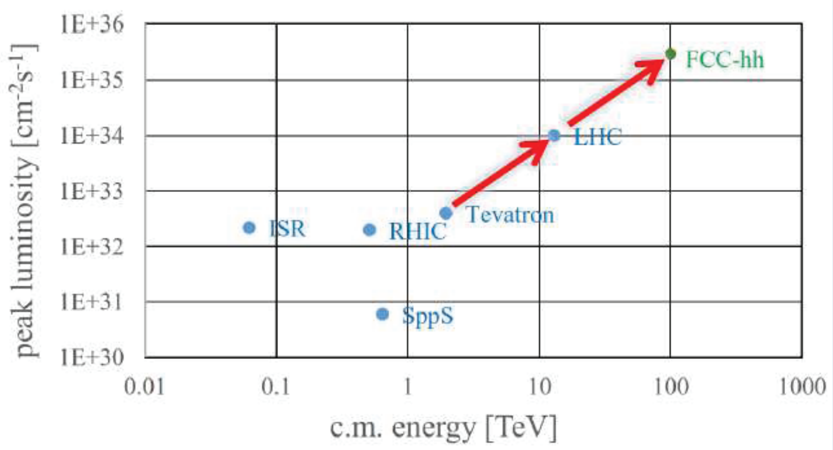
FCC: Comparison

	LHC	HL-LHC	HE-LHC	FCC-hh
Collision energy [TeV]	14	14	27	100
Dipole Field [T]	8,3	8,3/11	16	16
Peak Luminosity [10^{34} $cm^{-2}s^{-1}$]	1	8	16	30

LHC technology
8,3 T NbTi

11T Nb_3Sn

FCC Technology:
16T Nb_3Sn



High Field Magnets

- Both FCC and/or HE-LHC will require magnets at up to 16 T:
  - More than 4500/1200 of these dipoles are needed for FCC/HE-LHC options
  - 50 mm aperture
  - Particle accelerator quality (field quality, protection, alignment,…)

- Essential aspects (main challenges detected):
  - 1000 A/mm^2 and 20 EUR/kA.m @ 16T-4,2K → 1500 A/mm^2 and 5 EUR/kA.m @ 16T-4,2K
  - Cost-effective design of 16T dipoles: electromagnetic and mechanical designs
  - Improvement of dipoles training

FCC-hh	
Number of Dipoles	4668
Dipole Field [T]	16
Aperture (mm)	50
Current (kA)	<20
Temperature (K)	1,9
Magnetic length (mm)	14069

High Field Magnets

Global challenge, three main collaborations:

- FCC Magnet development
  - Conductor development & procurement
  - R&D Magnets and associated development
  - Model Magnets
- EuroCirCol WP5
  - Feed the FCC CDR with design and cost model of 16T magnets
- US MDP
  - 14T-15T cos-theta magnet
  - Design, manufacture and test of a 2-layer 10T CCT magnet
  - Novel diagnostics and advances modeling techniques

Common targets, parallel programs, same framework: facilitated sharing information

For example: US MDP participated in EuroCirCol WP5

High Field Magnets

Conductor Development
Magnet Design
Magnet Tests

- CONDUCTOR DEVELOPMENT
  - This is the key for a cost-effective design of high field magnets:
    - The superconductor in a high field magnet is the main driving cost

      NbTi was used for LHC but it reached its limit

      A different superconductor is needed, but none of them can be produced as cables
  - CERN program:
    - Increase current with respect to HL-LHC (1000 to 1500 A/mm2 @ 16T-4,2K)
    - Reduction of magnetization (at low fields)
    - Industrialization: both in length (5 km) and cost (5 EUR/kA.m @ 16T-4,2K)

    500 km of Nb_3Sn wire of different diameter procured until 2020, up to 1250 A/mm^2
  - US MDP program – Conductor Procurement and R&D (CPRD)
    - Advancing on LTS and HTS industrial conductors
    - For Nb_3Sn: exploring performance, scalability and industrialization

    For example: Artificial Pinning Center- APC (at high fields), or grain refinement

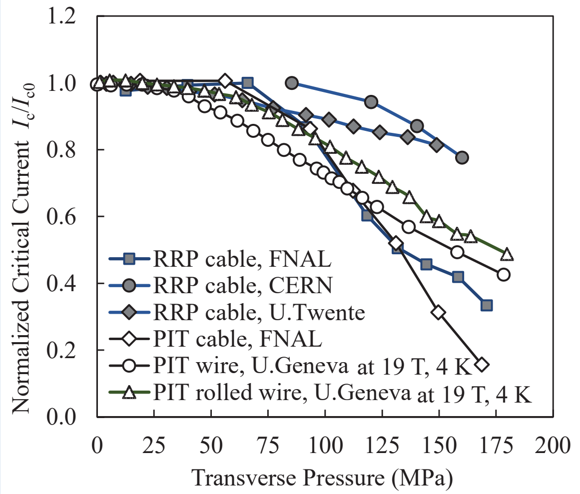
    Wire with APC has reached FCC target J_c (1500 A/mm^2 - short samples)

High Field Magnets

Conductor Development
Magnet Design
Magnet Tests

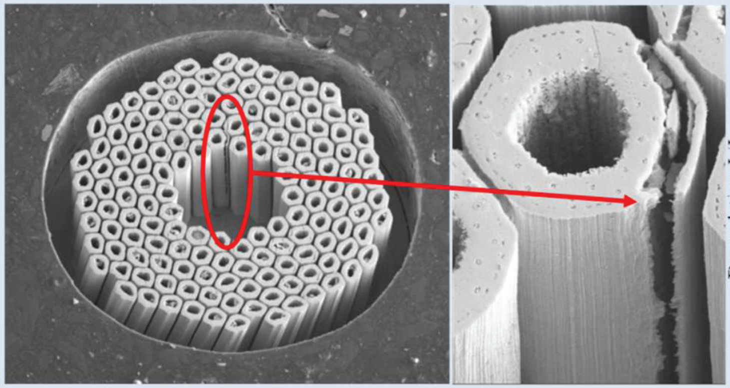
- Some challenges rely on the superconductor material
  - Brittle material
  - Irreversible degradation
  - Reversible degradation
  - Industrialization (cost and length)

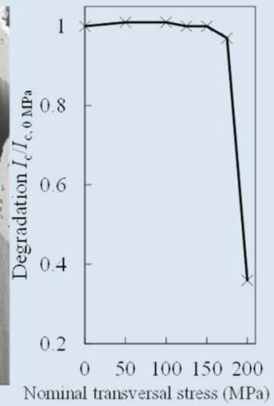
Reversible degradation at 12 T and 4.2 K



Scanning Electron Microscope (SEM) image after applying 200MPa transverse pressure on a cable

Irreversible degradation applied at warm and measured at 9.6 T and 4.2 K





High Field Magnets

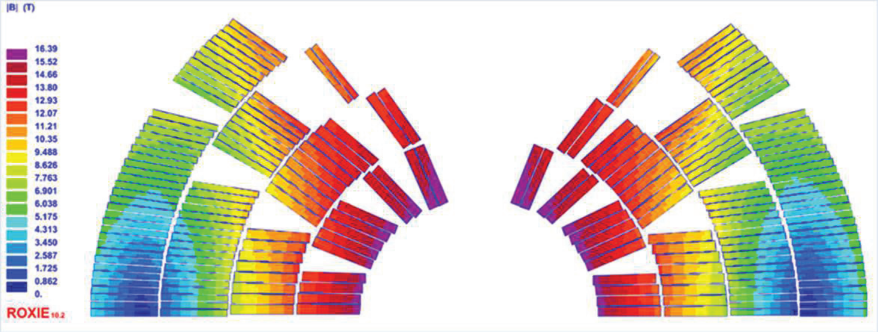
Conductor Development
Magnet Design
Magnet Tests

- MAGNET DESIGN
  - The electromagnetic approach for 16T is similar to 8.3T

    … But the mechanical design is the main challenge: large forces -> large stresses

    Also, improved protection systems are needed

- FCC Dipoles Baseline
  - Stress: below 150 Mpa during assembly (warm), below 200 Mpa at cold
  - Quench protection: hot-spot temperature below 350 K and peak voltage to ground below 2,5 kV
  - Grading: two different cables to optimize the design (High Field HF -Low Field LF)



Baseline for cables (selection)	Unit	
Critical Current	A/mm^2	1500
Strand diameter (HF/LF)	mm	1,1/0,7
Filament diameter (HF/LF)	mm	20/20
Cu/nCu (HF/LF)	-	0,8/2,1
Number of strands (HF/LF)	-	22/38

High Field Magnets

Conductor Development
Magnet Design
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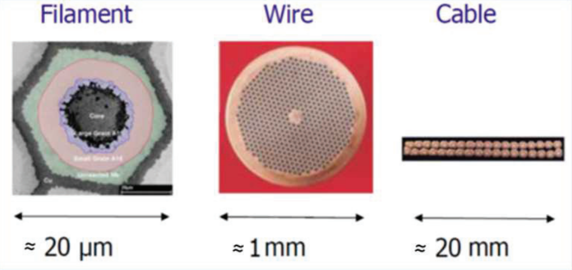
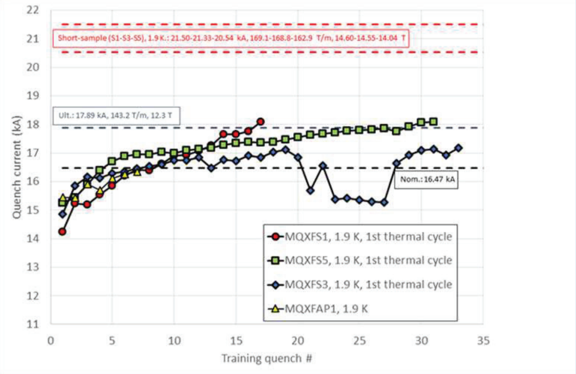
A number of studies are needed to develop the new generation of high field magnets, for example:

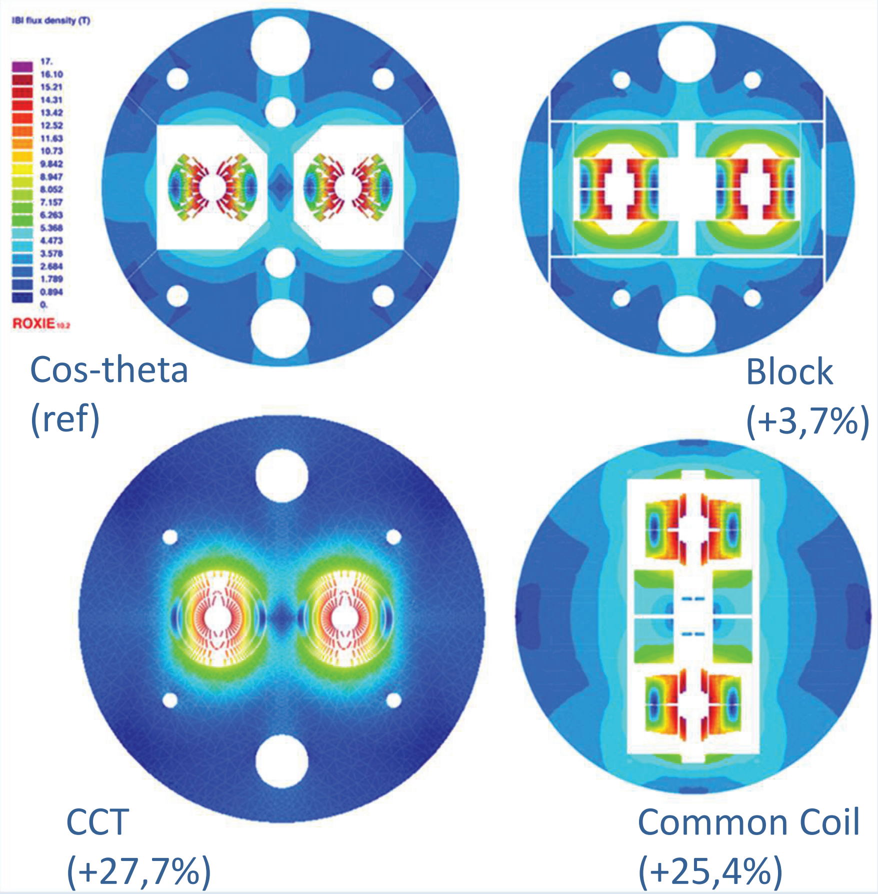
- **Material characterization of the material and the coil**
  Composite wire is the reinforcement of a composite cable which is the reinforcement of a composite coil…
  Difficult to predict the overall properties at warm, cold, magnetic and thermal loads, quenches…
- **Training**
  Learning curve of a magnet till it reaches the design current
  Linked to mechanical design
  Protection systems: CLIQ and quench heaters
- **Windability**
  Nb_3Sn vs. NbTi technology and processes
- **Impregnation**
  Effects on the training and/or overall performance?
- **Splicing**
  Effects on performance but also at geometry
- **Instrumentation**
  Measuring magnet behavior of the models for optimizing designs





High Field Magnets

Conductor Development
Magnet Design
Magnet Tests



EUROCIRCOL WP5

- Four concepts designs were developed. They are based on the same assumptions
- All of them have some strong and weak features
- Cos-theta is the most efficient in terms of amount of conductor, when the baseline and specs are the same.

(In the picture, + x% is the amount of mass of conductor compared to cos-theta option)

Model magnets to be developed:
CEA: block-type, ~10 coils
INFN: cos-theta, ~6 coils
CIEMAT: common-coil, ~6 coils
PSI: CCT

High Field Magnets

Conductor Development
Magnet Design
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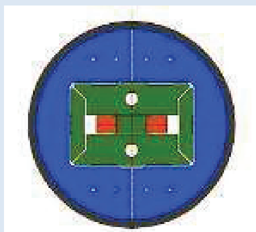
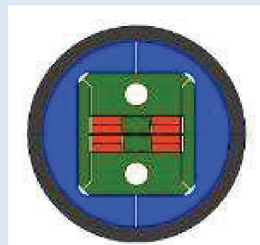
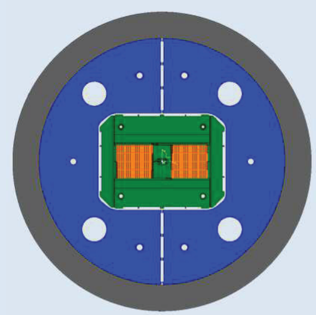
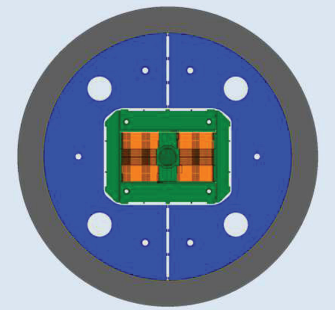
High Field Model Magnets at CERN







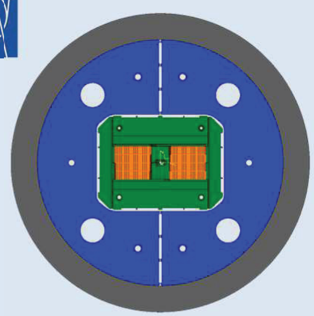


	SMC *Short Model Coil*	*RMC* *Racetrack Model Coil*	*eRMC* *Enhanced RMC*	*RMM* *Racetrack Model Magnet*
Diameter	530 mm	570 mm	800 mm	800 mm
Length	500 mm	820 mm	1,2-1,4 m	1,2-1,4 m
Aperture	No	No	No	50 mm
Ult. Field	14T	16T	18T	18T
Concept in few words	*≈ Test bench for materials, processes…*	*≈ Test bench for mechanics*	*≈ Full size test*	*≈ Real magnet test*

High Field Magnets

Conductor Development
Magnet Design
Magnet Tests

Magnet structure was assembled with aluminum dummy coils.
Two thermal cycles to characterize the mechanical behavior



eRMC

Three coils were produced

High Field Magnets

Conductor Development
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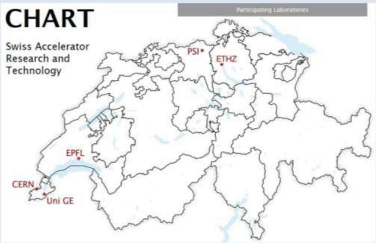
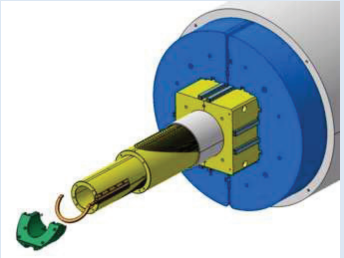
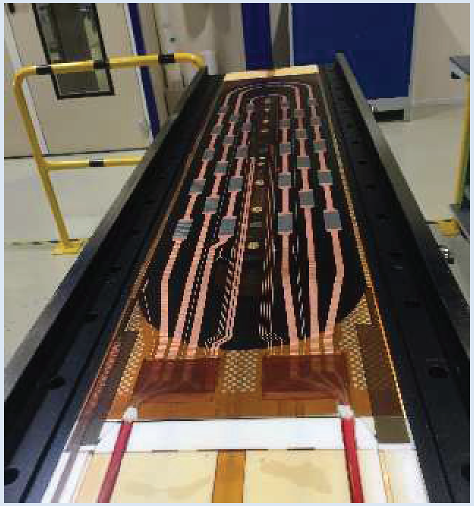


- Swiss collaboration on high field magnets for FCC
- It will explore CCT technology
- Prototypes will be produced



ERMC ($B_{ultimate}$ = 18 T)



REBCO (CORC) coil

Bi-2212 coil

CCT4 reached 9.1 T (86% of short sample

High Field Magnets

Conductor Development
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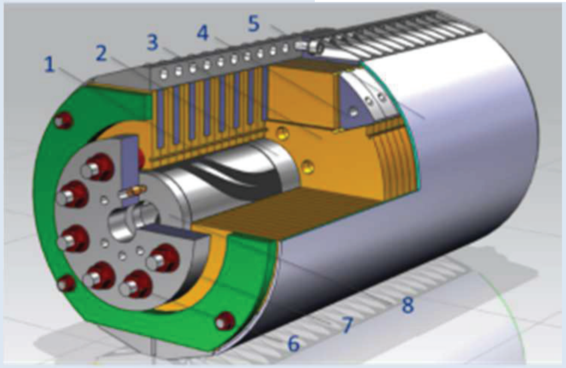
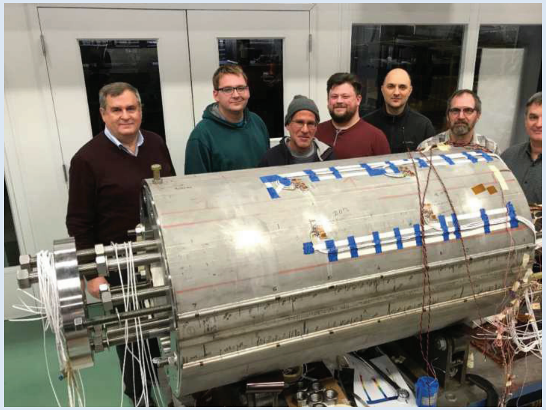
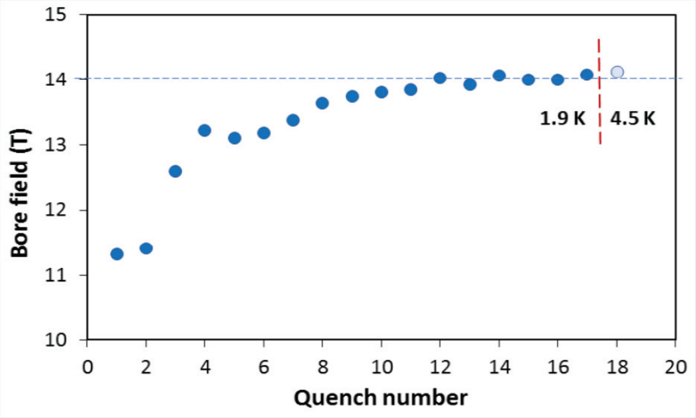




- 15 T dipole
- 60 mm aperture
- 4-layer graded coil
- First Run up to 14T: success. Next one in few months



(2019) Record measured field for 4.5 K accelerator magnet: 14,1 T

(2018) At 1,9K the record field level was established at CERN (Fresca2): 14,6 T
14,4 T for stable operation

High Field Magnets

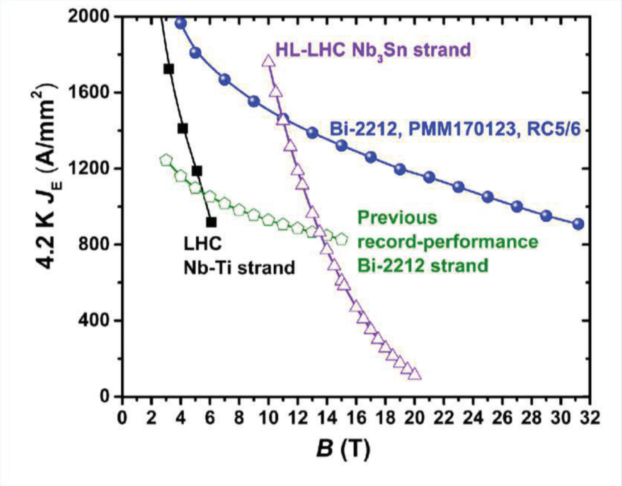
Alternatives to Nb_3Sn are being explored, for even higher fields (20+ T):

Bi-2212

Great electrical properties. Stress sensitive. Expensive
Great improvements over last years… Very promising!

REBCO

Higher temperature is possible, but expensive



U.S. MAGNET DEVELOPMENT PROGRAM

US MDP is working in this approach, model magnets are being developed with very interesting results

High Field Magnets

Conclusions

- Present accelerator high field dipoles provide 11 T, while FCC CDR is based on Nb3Sn dipole field of 16 T
  - Some other options are being explored for designs and materials
  - HL-LHC is the first step on LHC update, HE-LHC is an option for using the LHC infraestructure
  - FCC-hh is the main long-term goal
- Main challenges to develop:
  - Superconductor properties
  - Magnet design
  - Cost-effective design
- World-wide effort based on collaborations. Great improvements are being obtained, but a lot of R&D is still needed
- It is not clear which will be the best option for serial production of 16T magnets (FCC)
  - Model magnets will be needed to check every potential option. Again, world-wide collaboration is critical here

High Field Magnets

References

- FCC week 2019. Last main conference about FCC.

  This is a selection of the contributions, used for these slides:

  - Overview and status of the Future Circular Collider study. *M. Benedikt, F. Zimmermann*
  - 16T Magnet R&D overview. *D. Tommasini*
  - EuroCirCol Conductor Program. *B. Bordini*
  - Magnets and conductor – Highlights and Summary. *D. Schoerling*
  - The US Magnet Development Program and Status Updates. *S. Prestemon*
  - Assembly and First Test of the US-MDP Nb3Sn Dipole Demostrator. *A. Zlobin*

- Other references used:
  - High Field magnets. *F. Toral, (ECFA'18)*
  - The 16T Dipole Development Program for FCC and HE-LHC. *D. Schoerling et al. (ASC'18)*
  - Development and comparison of mechanical structures for FNAL 15T Nb3Sn dipole demonstrator *(ASC'16)*
  - The 16T Dipole Development Program for FCC. D. Schoerling et al. *(ASC'16)*