B. Auchmann CERN/PSI, J. Gao, R. Felder, G. Montenero, S. Sanfilippo, S. Sidorov PSI
L. Brouwer, S. Caspi LBNL

Superconducting Magnet R&D for Accelerators

SPS Annual Meeting, 29.8.2018
Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Overview

- Motivation
- Nb3Sn Technology Challenges
- US, China, and CERN magnet programs
- FCC-Design-Study magnet R&D
  - EuroCirCol
  - CHART – PSI/ETHZ/UniGE/EPFL
- Next steps

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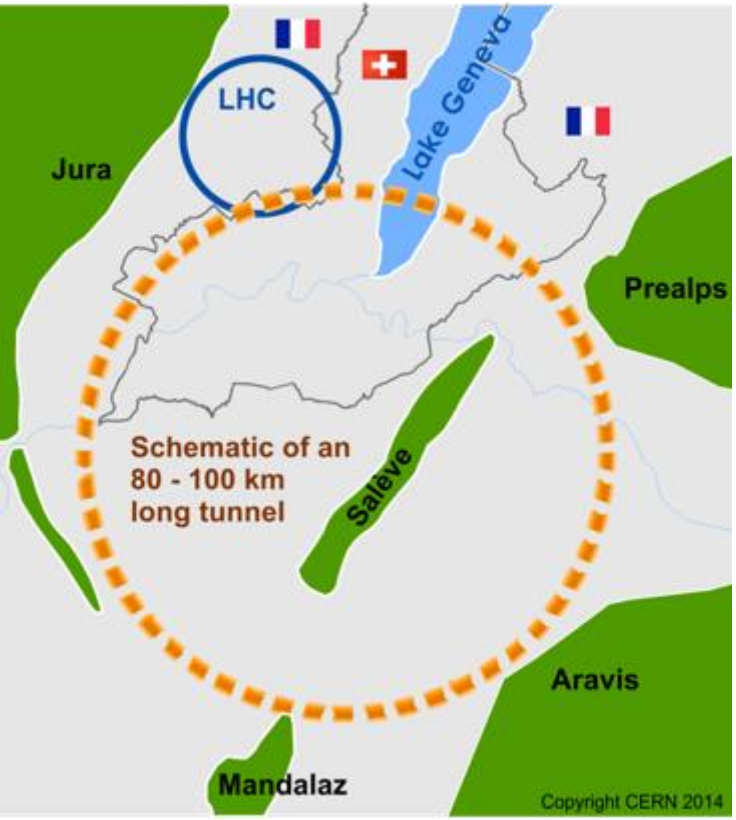
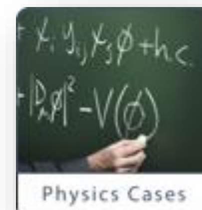
FCC Design Study

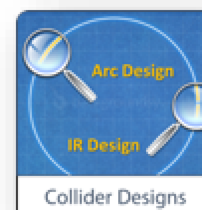
European Strategy for Particle Physics 2013:
"... *to propose an ambitious post-LHC accelerator project* ..., CERN should undertake design studies for accelerator projects in a global context, ... *with emphasis on proton-proton … high-energy frontier machines* ... *coupled to a vigorous **accelerator R&D programme, including high-field magnets*** and high-gradient accelerating structures, ..."

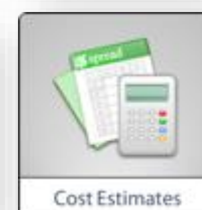


International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements
  ~16 T ⇒ 100 TeV *pp* in 100 km
- **~100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, e from ERL
- ***HE-LHC*** with *FCC-hh* technology
- **CDR for end 2018**



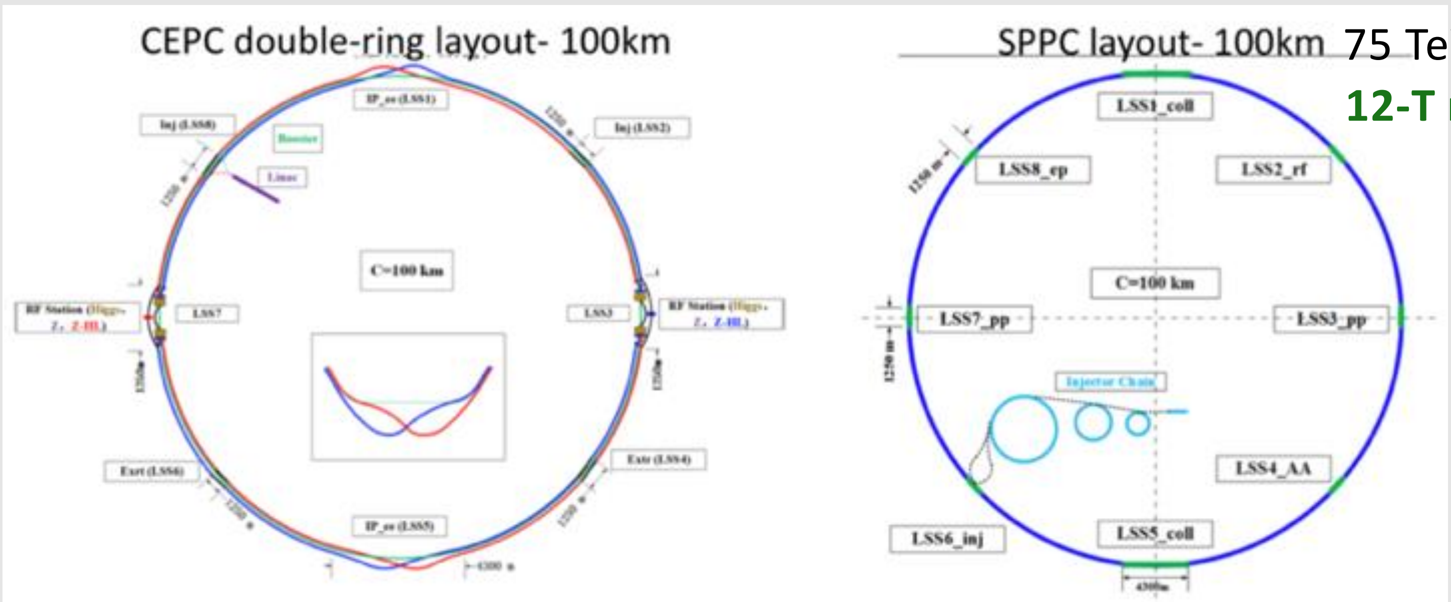




[M. Benedikt, fccw2017]

CEPC / SPPC

AsiaHEP/ACFA 2016:
"... The past few years have seen a growing interest in a large radius circular accelerator ... ultimately for *proton-proton collisions at the high-energy frontier*. *We encourage the effort lead by China in this direction*, and look forward to ... the technical design ..."



75 TeV CoM
12-T magnets

[Q. Xu., fccw2017]

ACFA .. Asia Committee for Future Accelerators
AsiaHEP .. Asia-Pacific High Energy Physics Panel

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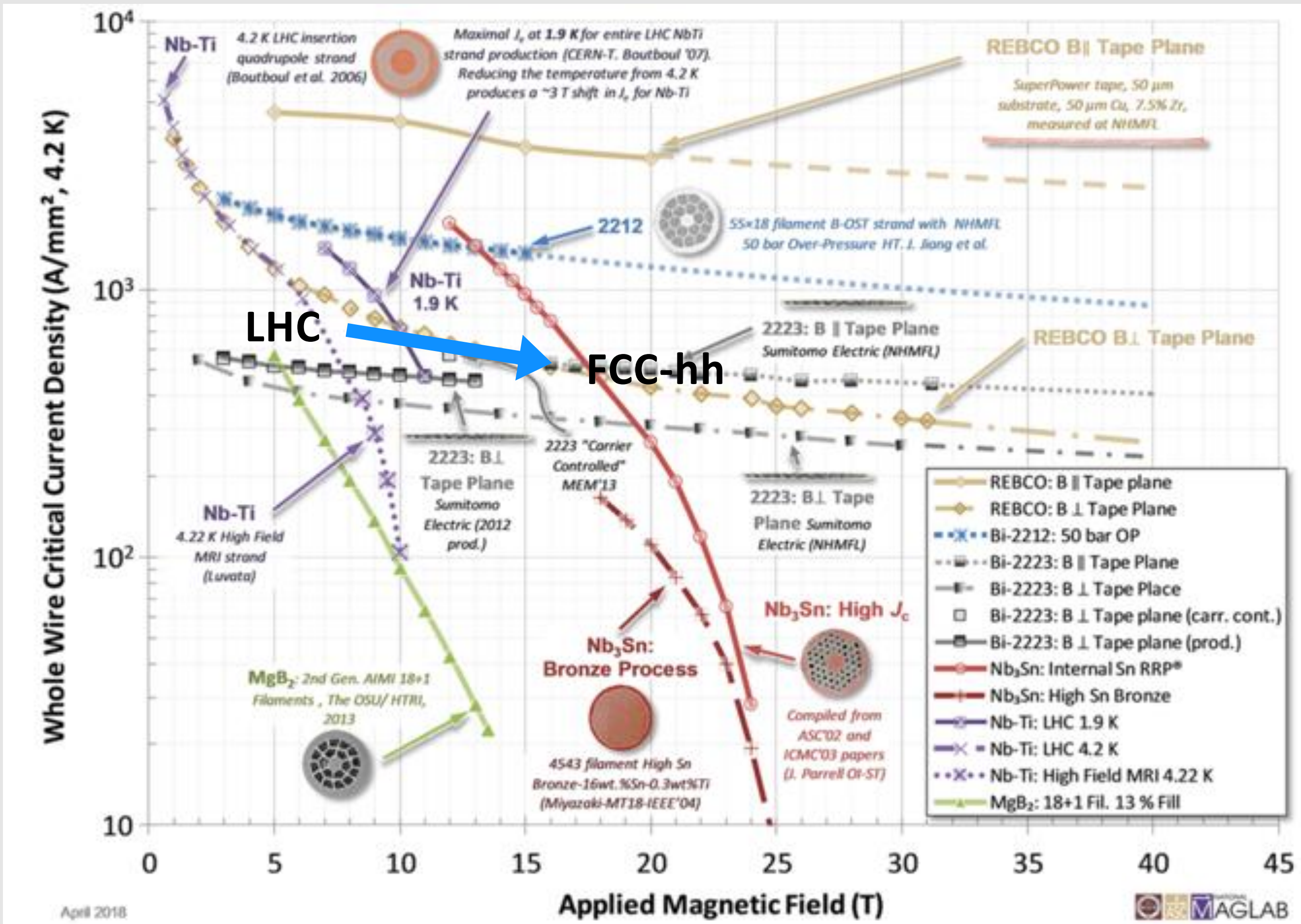
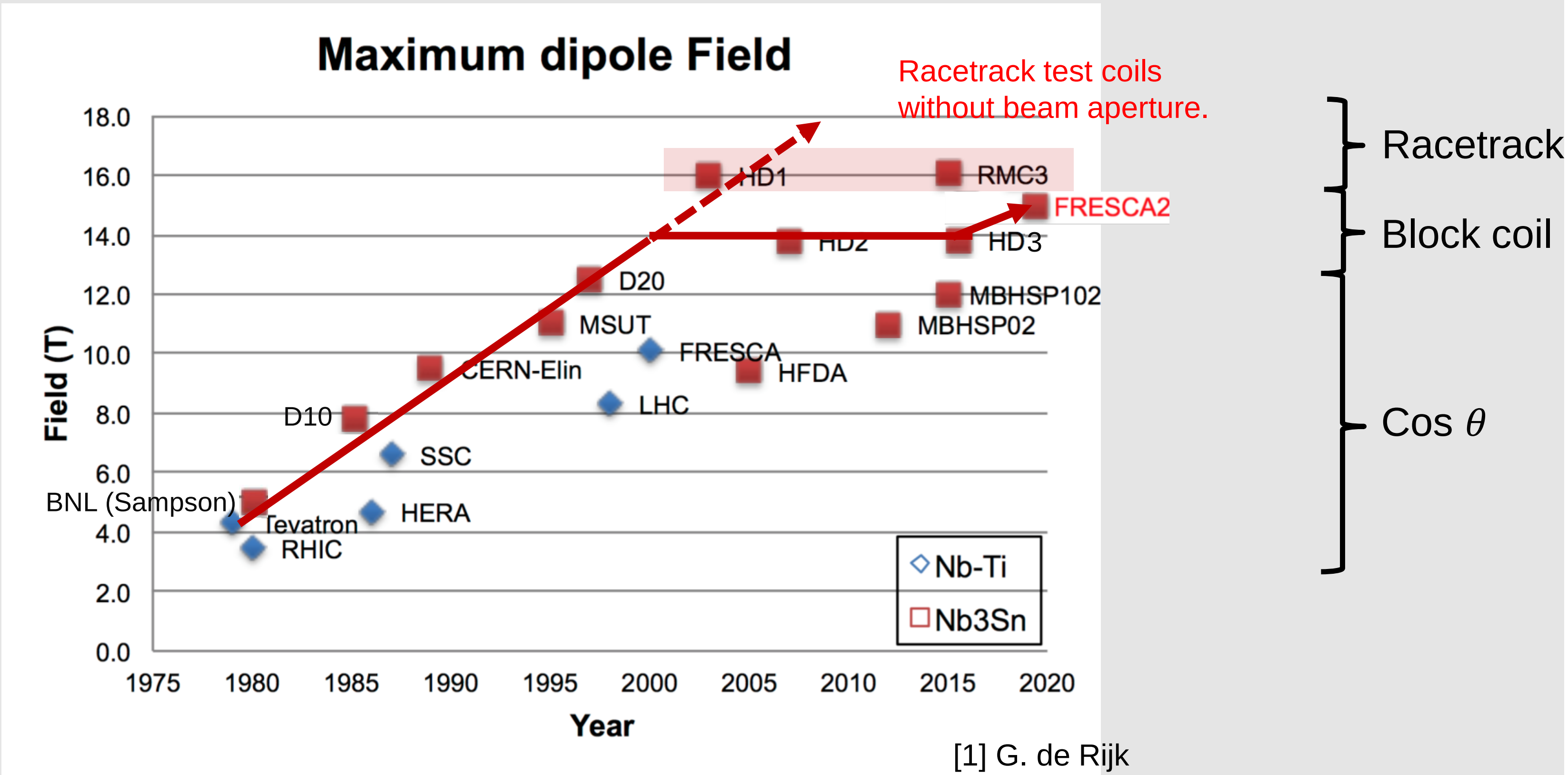
Nb_3Sn Superconductor

- The only technically mature and affordable superconductor for 9-16 T magnets.



SC Dipoles for Accelerators



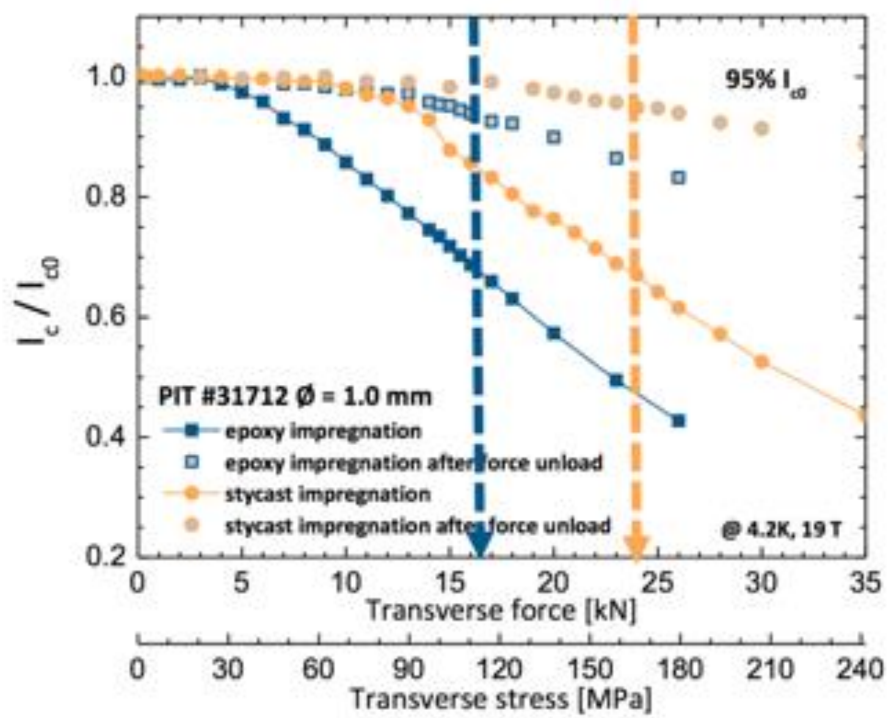
[1] G. de Rijk

Still a long and long road ahead for 14.3-m-long 16-T dipole.

(Longest Nb_3Sn magnet to date: LARP LQ quad with 3.7 m.)

Strain-Sensitivity of Nb3Sn Wires

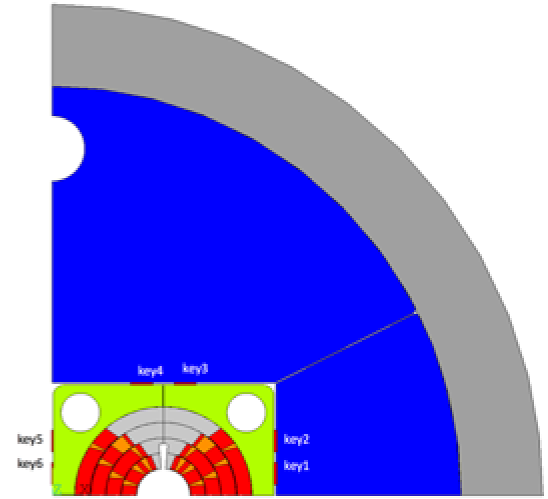
- Reversible and irreversible degradation of impregnated Nb_3Sn wires under transverse pressure.
- Epoxy impregnation helps to distribute the mechanical load.



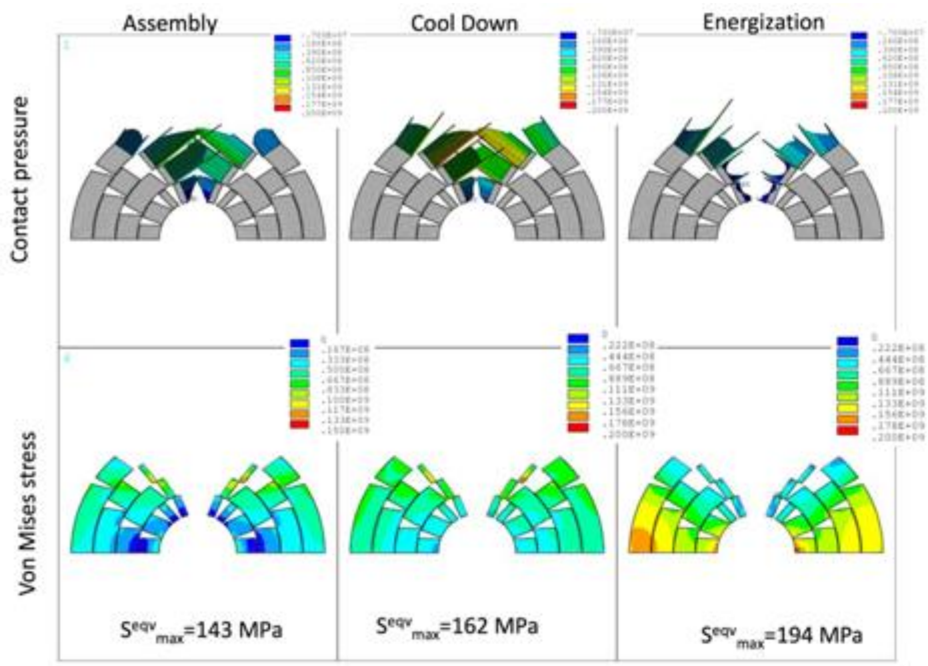
[C. Senatore et al.]

Mechanics Challenge

- Keep coils under compression at all stages of operation → avoid stick-slip motion.
  - Forces scale quadratically with field.
  - For 16 T, dipole forces of 1.5 kt/m pull coil apart.
  - 10 μm abrupt movement is enough to cause quench.
- Minimize stress on stress-sensitive Nb_3Sn.
  - Limit is of the order of 150 to 200 MPa.



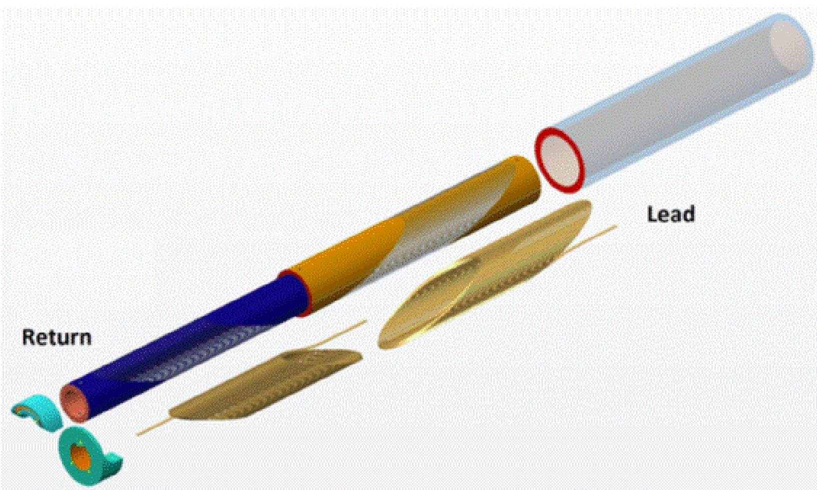
Courtesy S. Farinon, INFN

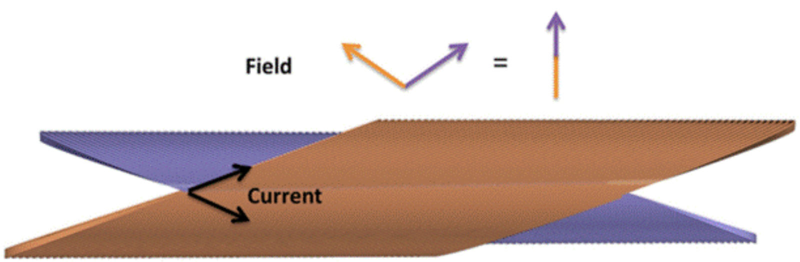


Example: Cos-theta option of 16-T FCC dipole.

Mechanics Challenge

- Canted Cosine Theta design advocated by LBNL (US).
- Individual support of turns promises a decisive reduction of coil transverse stress.





Courtesy: C. Senatore

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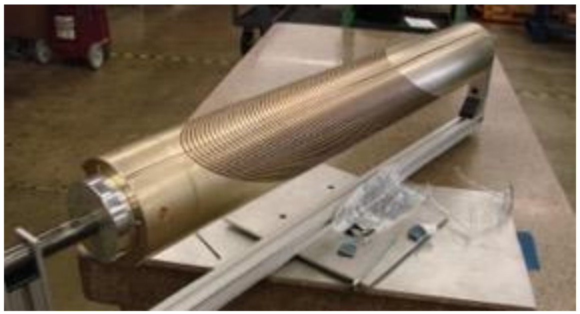
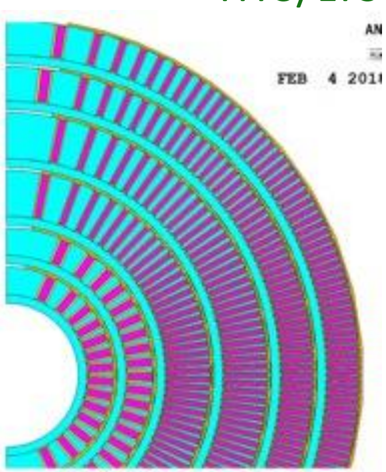
US MDP Magnet R&D Program

LBNL (Lawrence Berkeley Nat. Lab.) :

- **CCT** technology development

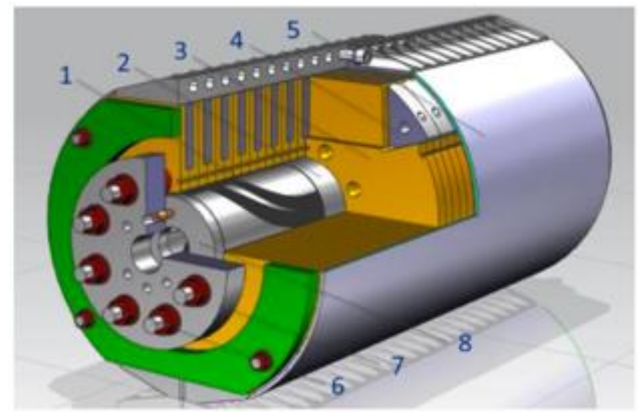


- with ultimate goal to build hybrid HTS/LTS magnet towards 20 T

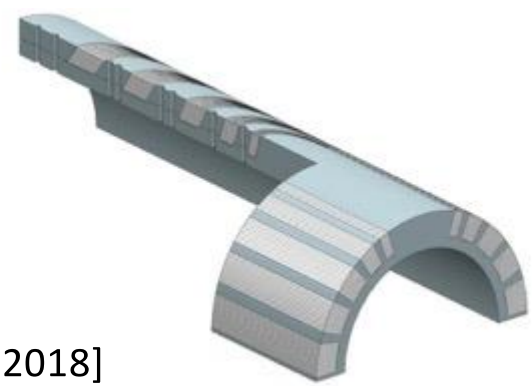


FNAL (Fermi National Lab.):

- 15-T **cos-theta** magnet in innovative mechanical structure to be tested 2018,



- followed by 16-T magnet possibly with CCT-like stress management.

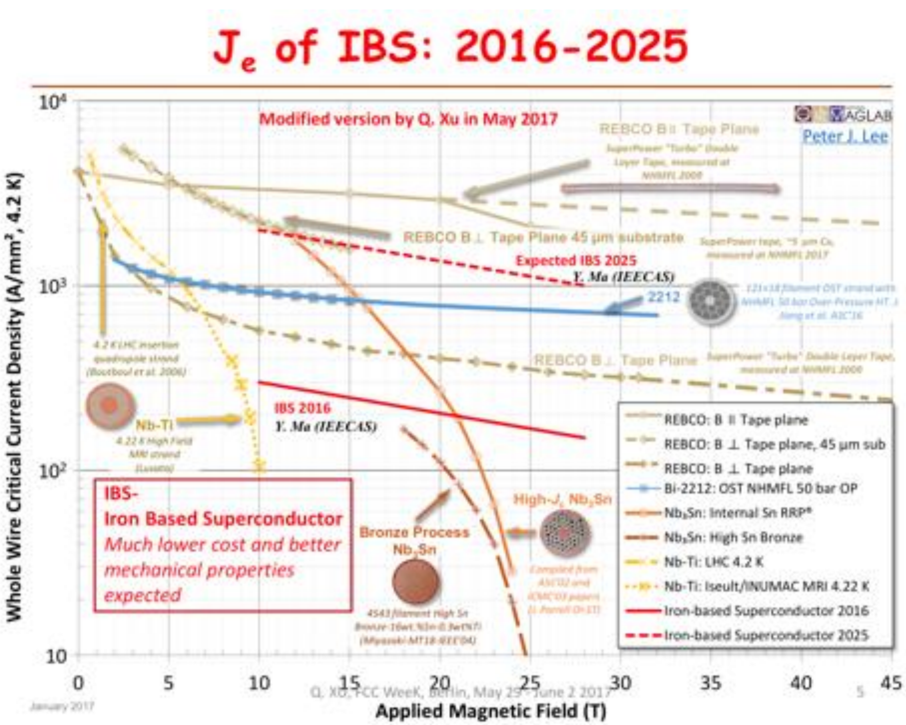


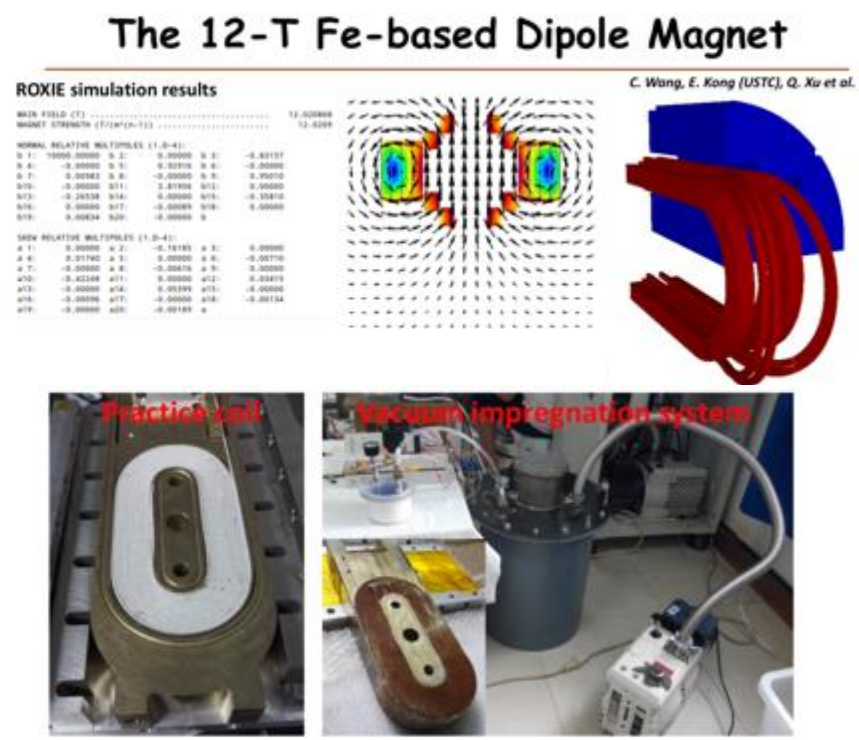
[S. Caspi and A. Zlobin, usmdp2018]

SPPC Magnet Plans

[Q. Xu, fccw2017]

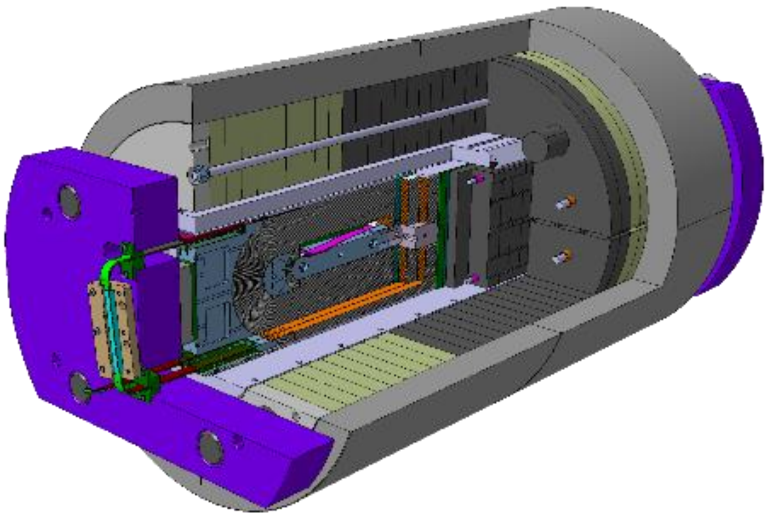
- SPPC design featuring
  - iron-based superconductor.
  - cost-saving 12-T magnets (75 TeV)
  - common-coil design
- Practical R&D for the next years is focused on building flat Nb_3Sn racetrack coils.
- (IHEP contributes Nb-Ti CCT magnets to HL-LHC, too.)



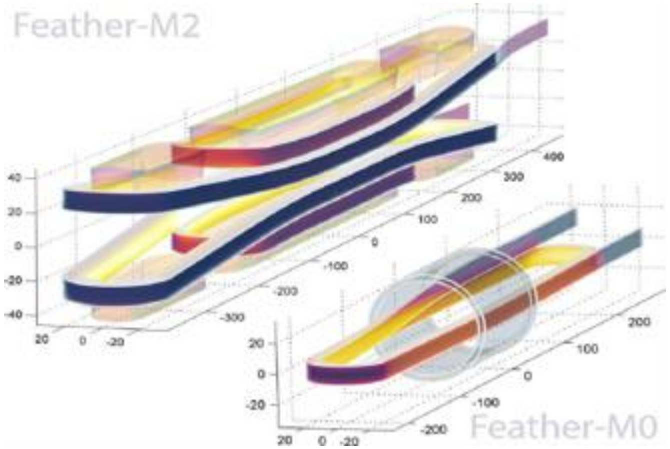


CERN 16-T R&D Program

- Main project for now: HL-LHC
- High-field Nb3Sn racetrack coils as testbeds and demonstrators for
  - conductor and cable in 16-18 T field
  - mechanical structure
  - mechanical conductor limits
  - internal splices, etc.
  - First test in 2018.
- HTS insert program had first test in 2017.
  - Thermal stability proven: no quenches!
  - Conductor price as the only obstacle.



[D. Tommasini, usmdp2018]



[J. van Nugteren, mt25 conf. 2018]

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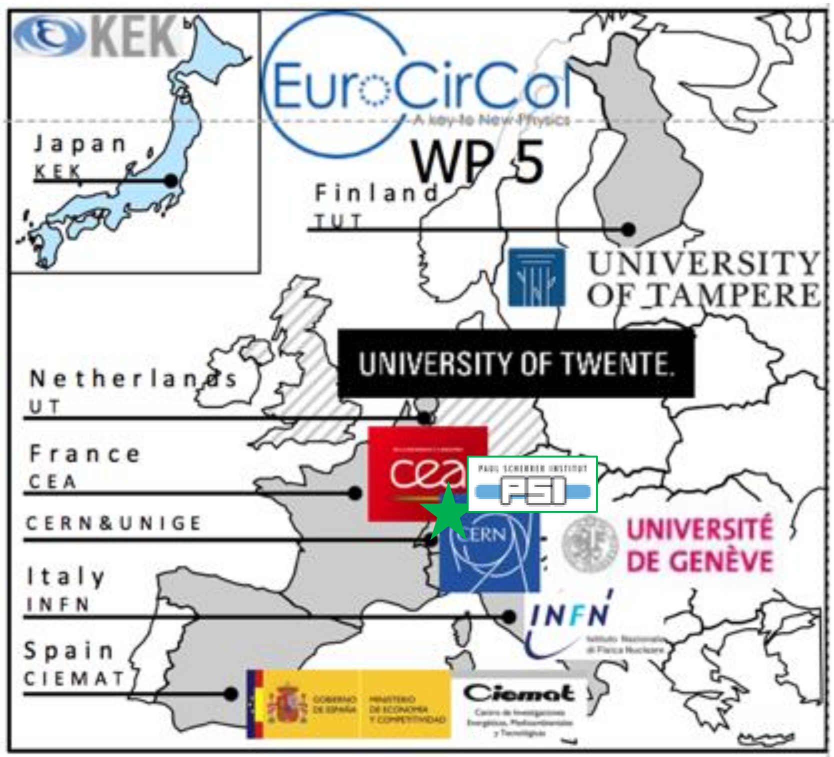
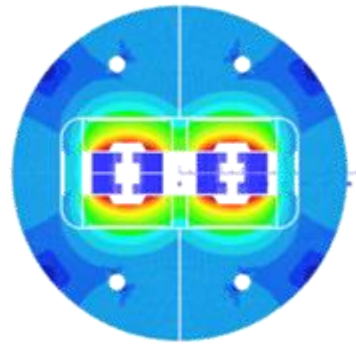
EuroCirCol WP5

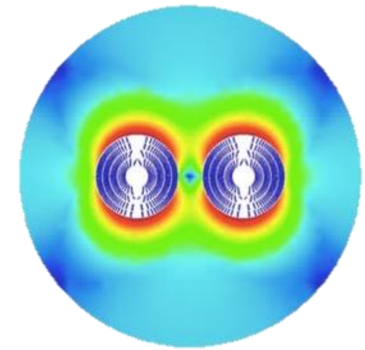
- European Circular Energy-Frontier Collider Study (started 2015)
- **Magnets fulfill specs for both, FCC-hh and HE-LHC.**



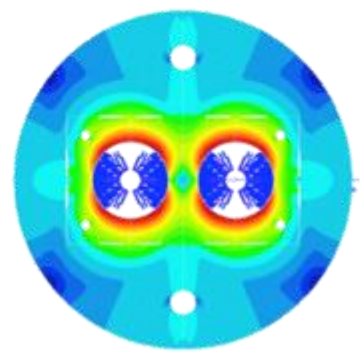
Block coil



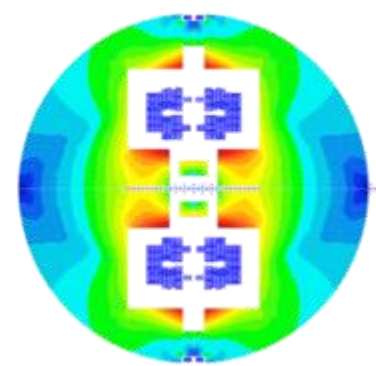
Canted Cosine Theta



Cos-theta



Common coils



[D. Tommasini, http://cern.ch/fcc/eurocircol]

CHART Accelerator Research Network – Magnet Activities

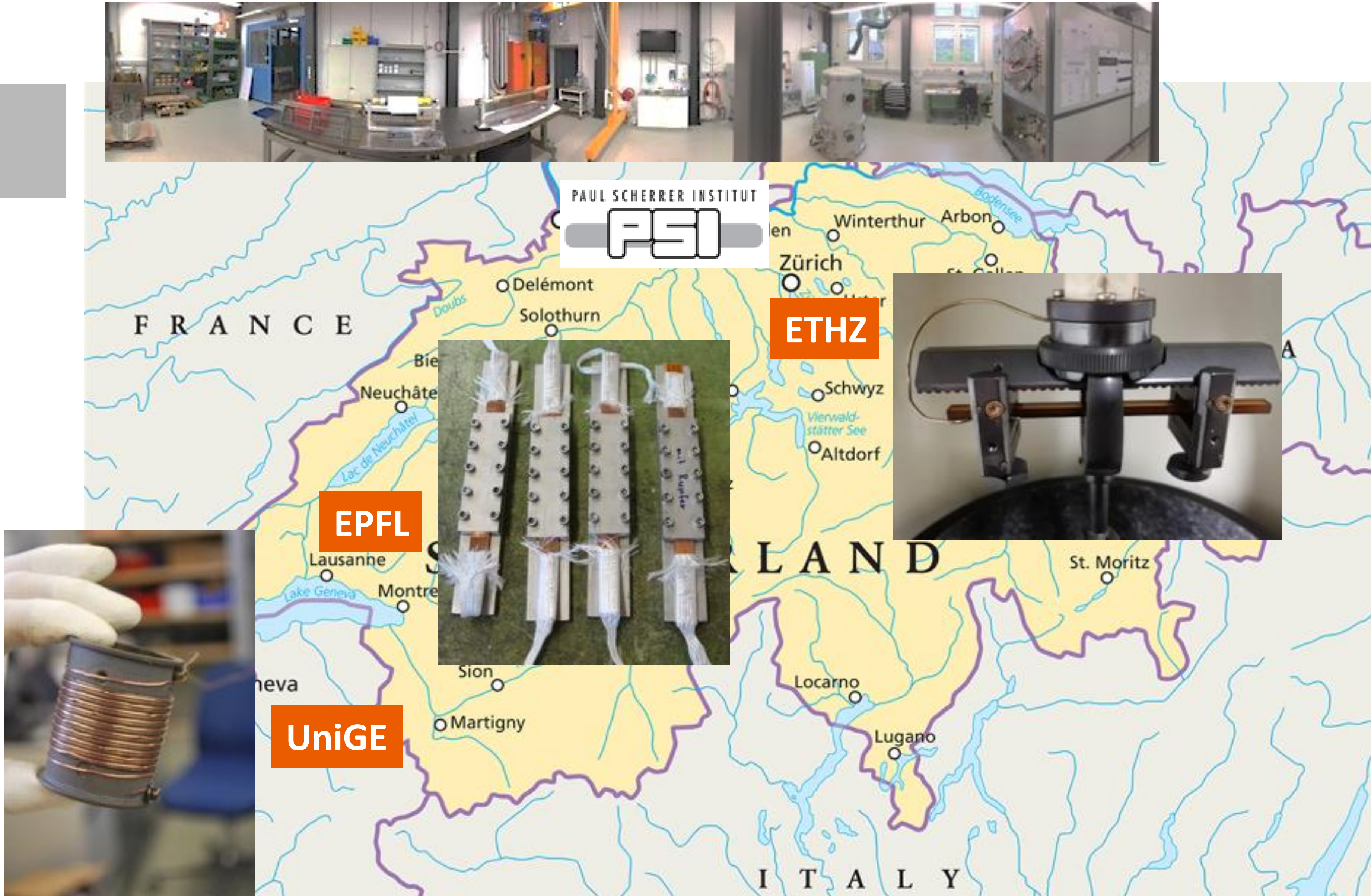
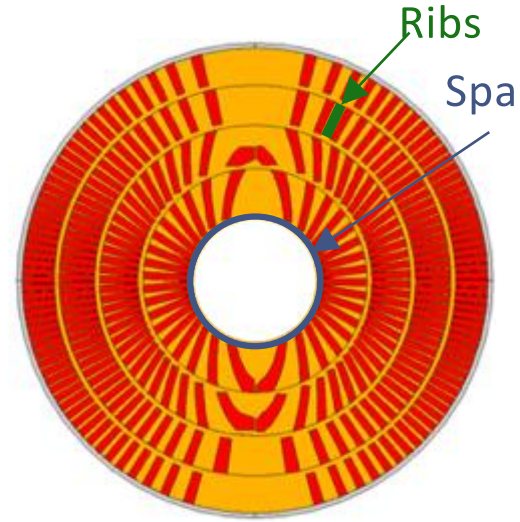


CHART-PSI Goals towards FCC Requirements

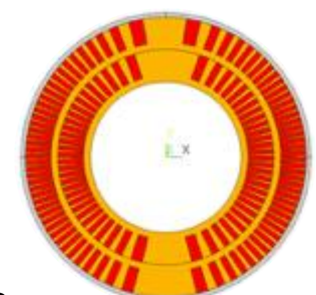


- Joint funding from CHART and the FCC design study from mid 2016
  until the end of 2019.
- Goal: Demonstrate key technological features of an **efficient** 16-T CCT in two-layer technology model magnets.

- Thin and ribs spars
- Exterior mechanical structure
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels.
- Improved impregnation procedures.

CD1 (first three items)

CD2 (all six items)



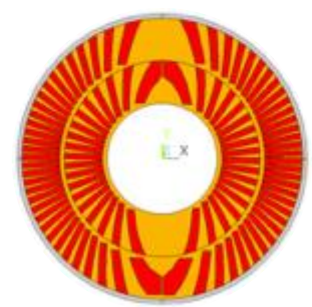
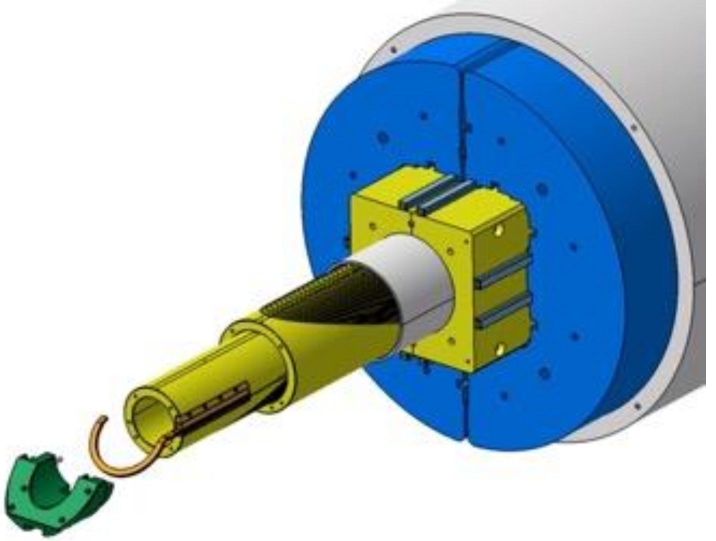


CHART-PSI Status Overview

- Within 14 months CHART-PSI has, among others:
  - Built and commissioned a lab from scratch.
  - Designed and procured all magnet components and tooling.
  - Launched epoxy-resin R&D with ETHZ.
  - Passed successfully a Production Readiness Review on Aug. 28.
- Next year we will finalize the construction of the CD1 magnet, test it, and construct a second set of coils called CD2.
- For more info on the CHART-PSI magnet program see talks by Giuseppe Montenero and Jiani Gao.



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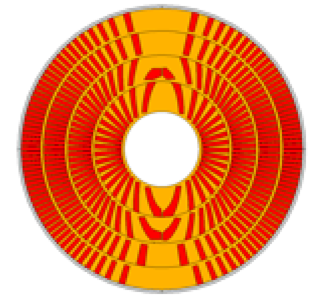
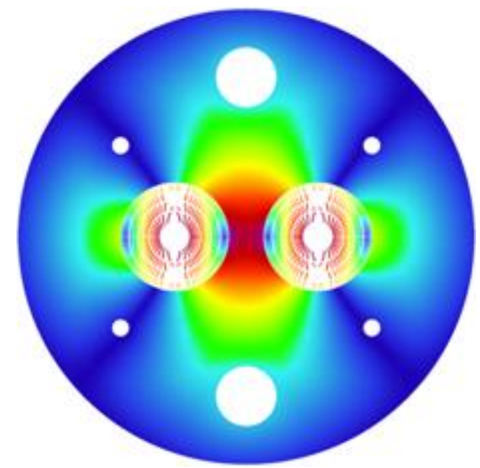
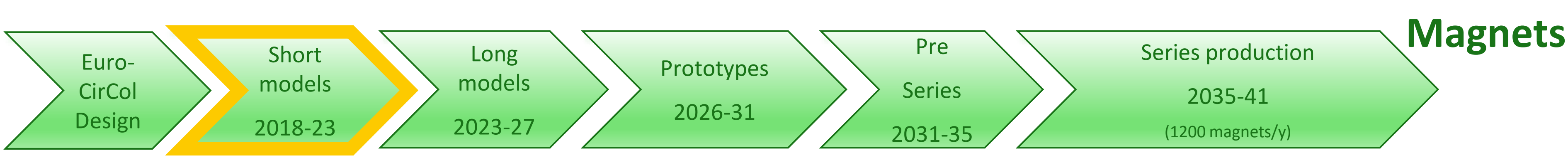
Next Steps for FCC R&D at CHART-PSI

- FCC design study recommends to build all four 16-T magnet types until 2023/24.
- CHART-PSI would build the 4-layer CCT, in collaboration with LBNL and CERN.
  - Additional infrastructure required for mounting of yokes / shell welding.
- Focus on industrialization of manufacturing and further cost reduction.
  - Advanced-manufacturing initiative for winding formers.







[M. Benedikt, fccw2017]

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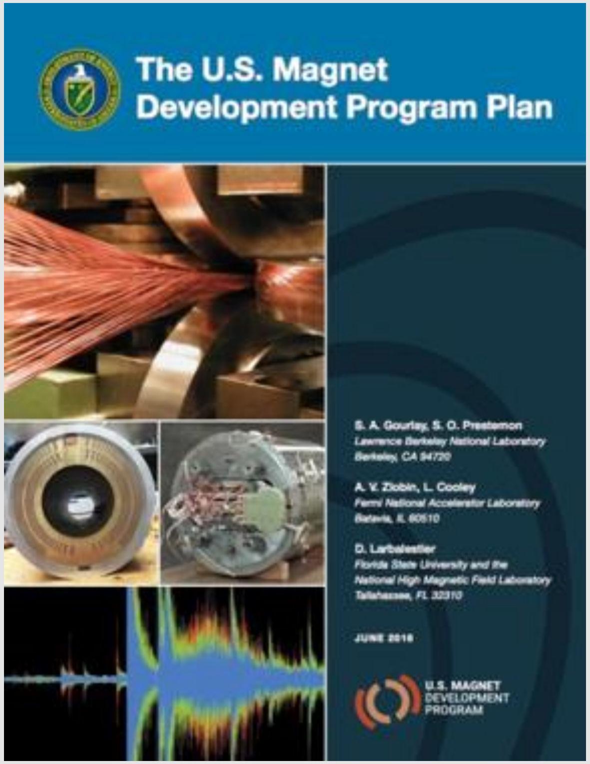
Conclusion

- High-field magnet **R&D towards FCC-hh/HE-LHC specs is gaining momentum**.
  - Agreements under preparation or already signed with four European institutes to build 16-T magnets until 2023/24.
  - The effort is more heterogeneous and dynamic than it has been for 20 years.
- US programs are increasingly contributing to FCC R&D.
  - CHART is coordinating regularly with LBNL our R&D on the CCT concept.
- Nb_3Sn conductor performance has made significant progress in the last year, rendering more credible the ambitious FCC conductor specs.
- HTS conductors are used successfully in small-scale R&D and would be most desirable if the price were lower. Will first appear in form of inserts in LTS outserts.
- **CHART is establishing itself** as actor in accelerator-magnet R&D.
- Many more opportunities ahead for collaboration under the CHART/FCC umbrella.

PAUL SCHERRER INSTITUT PSI

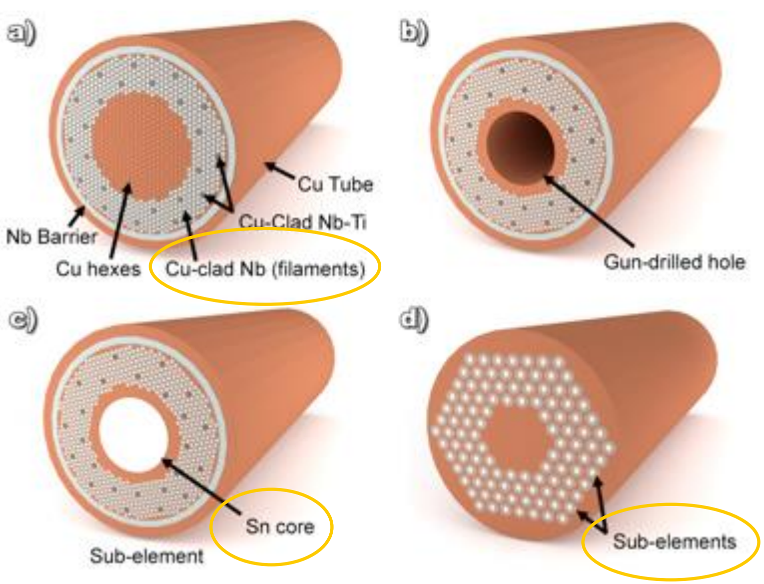
Main References

- http://cern.ch/fcc
- http://cern.ch/fccw2015
- http://cern.ch/fccw2016
- http://cern.ch/fccw2017
- http://cern.ch/fccw2018
- US-MDP collaboration meeting (link protected).
- MT-25: http://mt-25.org

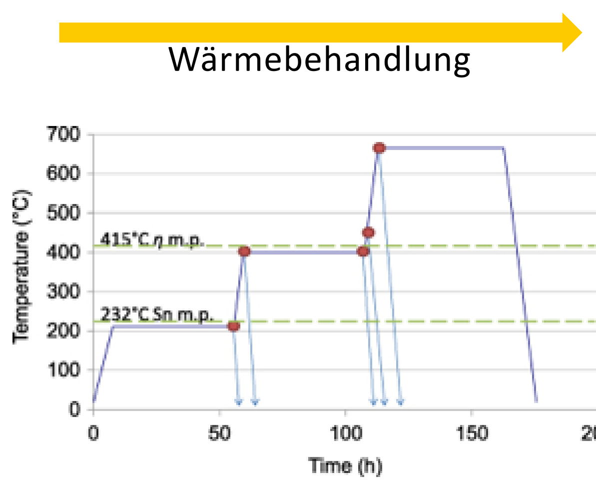


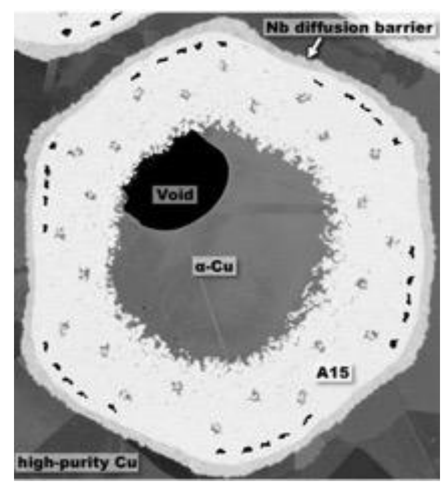
Nb_3Sn Cable

- The superconducting A15 phase is brittle and strain sensitive. Niobium and Tin are, therefore, co-extruded in the Rod-Restack Process into a strand.
- In wind-and-react processes, several 10s of strands form a Rutherford cable, that is insulated and used to wind a coil.
- The A15 phase is created during a heat treatment of 180 h at up to 660ºC.



Pictures from C. Sanabria PhD Thesis, FSU

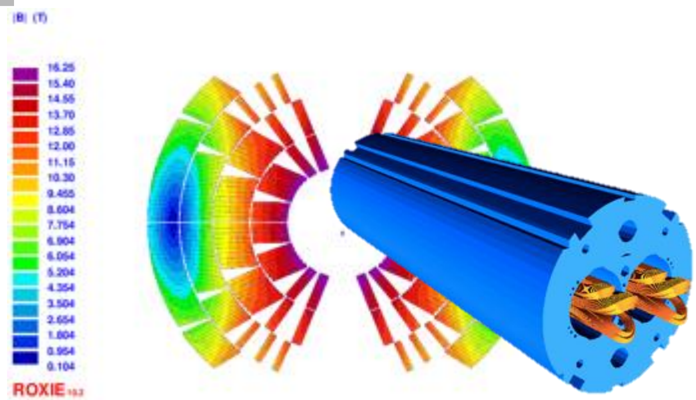




Subelement mit A15 Phase

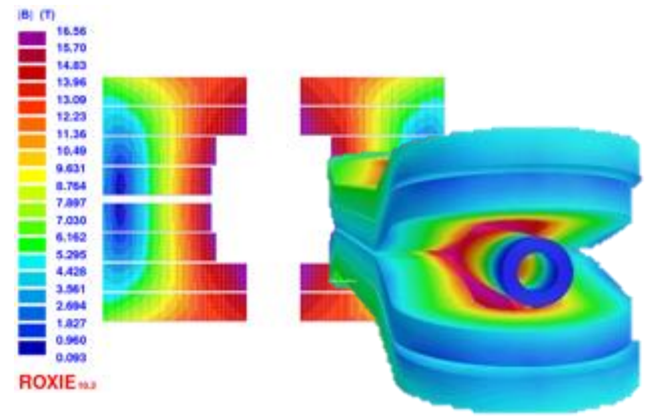
Cosine Theta Coil

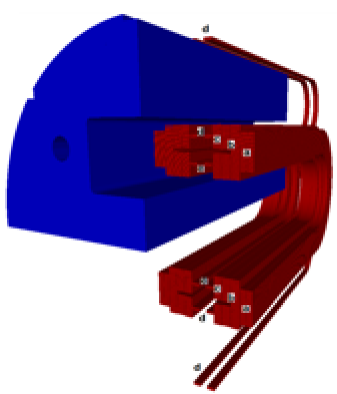
High efficiency. Difficult stress management and coil end design.



Block Coil

High efficiency. On paper, simpler end design. Peak stress in low-field region.



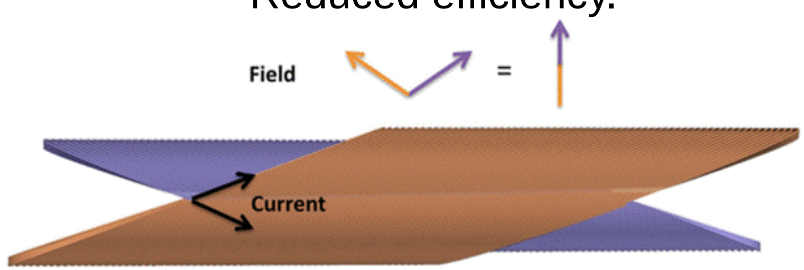


Common Coil

Simple coil ends.
Higher stored energy.
Involved mechanics.
Slightly lower efficiency.

Canted Cosine Theta (CCT)

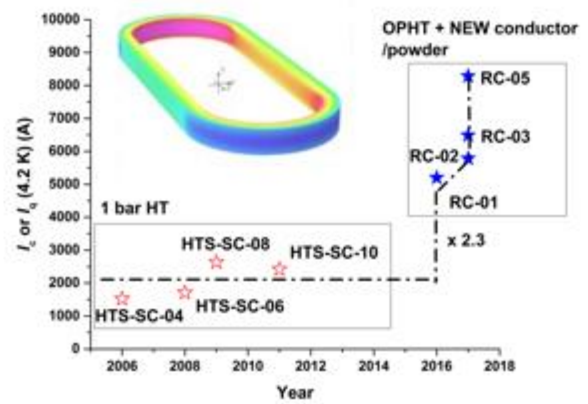
Simple manufacturing, low coil stress.
Reduced efficiency.

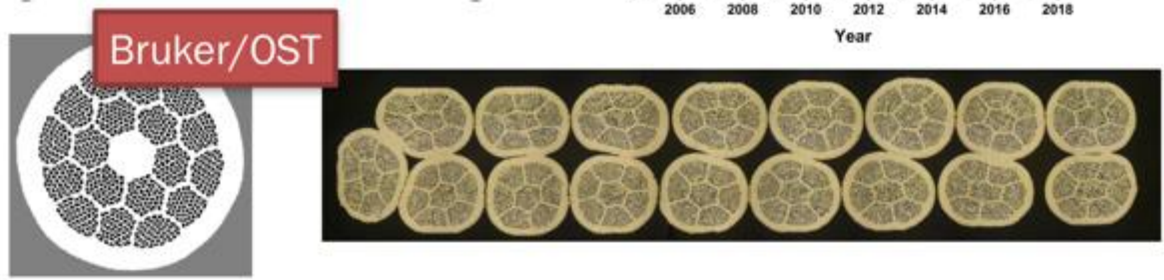


[Courtesy of L. Brouwer, S. Caspi, [2] M. Duharte, S. Farinon, C. Lorin, J. Munilla, M. Sorbi, F. Toral, Q. Xu]

US MDP HTS Program at LBNL

- **Bi2212** has made dramatic strides in J_c over last 3 years
  - Wire has been cabled and tested in racetrack configuration.
  - 50-bar heat treatment at 900ºC (FSU) is a technical challenge.
  - Stress sensitivity are to be addressed for high-field applications.
  - Roadmap being developed to integrate Bi2212 CCT in a high-field hybrid magnet design



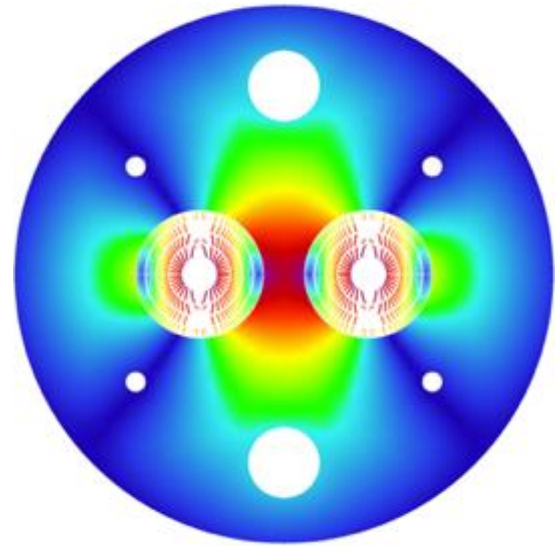


[S. Prestemon, usmdp2018]

- **REBCO CORC** is used to build CCT coils.
  - Further reduction in diameter will permit to make cable from CORC wire with high J_e.
  - Advances have been made on splicing and quench detection.
  - REBCO and CORC prices are still prohibitively high for a more vigorous magnet R&D.

CHART Magnet Design of CCT Type

- First CCT design fulfilling all EuroCirCol criteria
- Conductor needed for FCC-hh: 9.77 kt
  i.e., +30% wrt. cosine theta
- Total inductance: 19.2 mH/m
- Total energy: 3.2 MJ/m



- Keys to an efficient CCT design:
  1. Thin spars
  2. Wide cable, large strands
  3. Thin ribs
  4. Efficient protection (less copper)

  } **Increase J_e**