High Field Superconducting Magnet Programs in the US and Worldwide: Goals, Challenges, Plans

Steve Gourlay

Director

U.S. Magnet Development Program

Outline

- World-wide context for high field accelerator magnet R&D
- Overall Goals for magnet technology development
- Current status of the technology
- Challenges
- Overview of magnet R&D programs and roadmaps

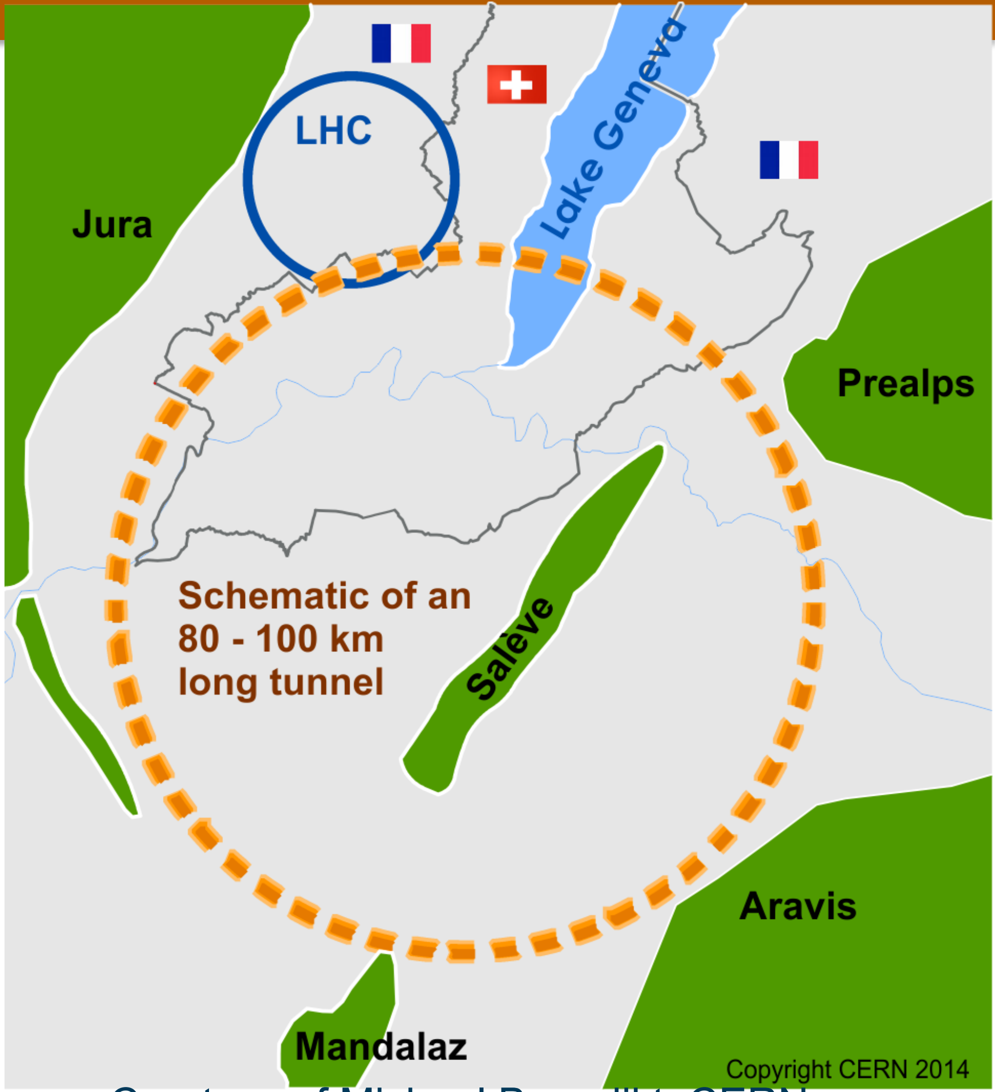
Future Circular Collider Study
GOAL: CDR and cost review for the next EuS (2019)

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

- **80-100 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, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology

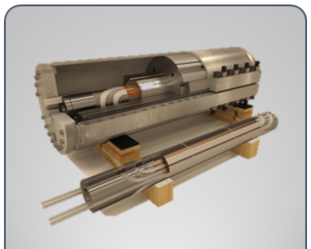


Courtesy of Michael Benedikt, CERN

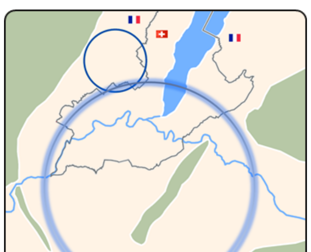
FCC Scope: Accelerator and Infrastructure

Collider Designs

FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
HE-LHC: **based on FCC-hh technology**


R&D Programs

Launch R&D on key enabling technologies
in dedicated R&D programmes, e.g.
16 Tesla magnet program, cryogenics,
SRF technologies and RF power sources

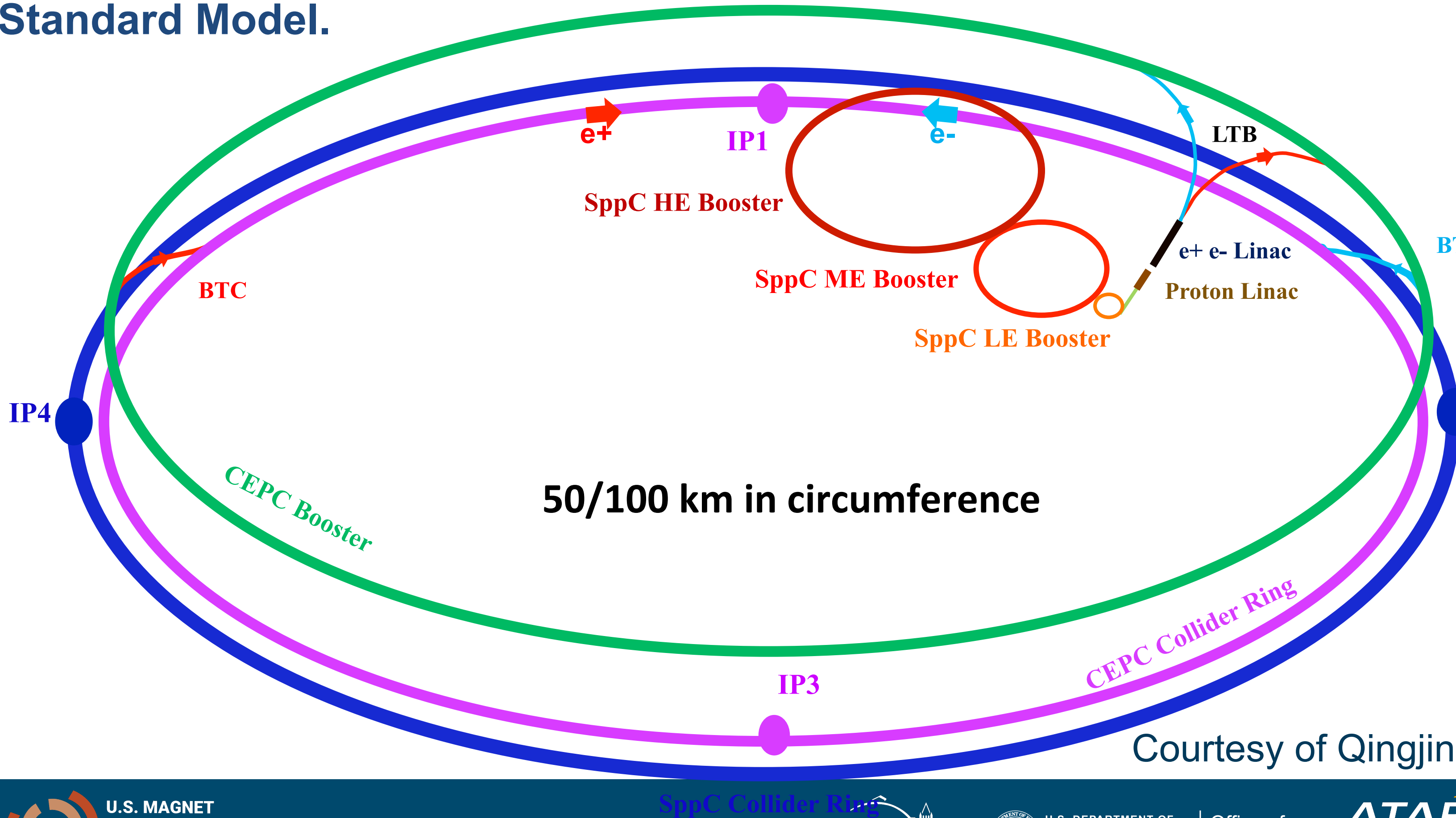

Infrastructures

Tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European strategy

Courtesy of Michael Benedikt, CERN

In China: CEPC-SPPC

CEPC is an 240-250 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider SPPC, to study the new physics beyond the Standard Model.



Courtesy of Qingjin Xu, IHEP

SPPC Magnet Specifications

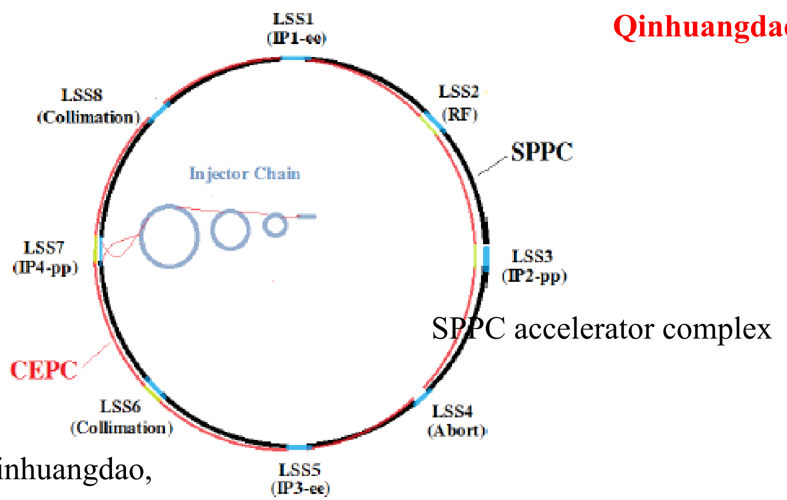
SPPC

- *50/100 km in circumference*
- *C.M. energy 70 TeV or higher*
- *Timeline*

Pre-study:	*2013-2020*
R&D:	*2020-2030*
Eng. Design:	*2030-2035*
Construction:	***2035-2042***

Main dipoles

- *Field strength: 20 Tesla*
- *Aperture diameter: 40~50 mm*
- *Field quality: 10^{-4} at the 2/3 aperture radius*
- *Outer diameter: 900 mm in a 1.5 m cryostat*
- *Tunnel cross section: 6 m wide and 5.4 m high*



The CEPC-SPPC ring sited in Qinhuangdao, 50 km and 100 km options .

Qinhuangdao

Courtesy of Qingjin Xu, IHEP

Refer to CEPC-SPPC Pre-CDR, Mar. 2015: http://cepc.ihep.ac.cn/preCDR/volume.html

U.S. Energy Frontier Strategy – Particle Physics Project Prioritization Panel (P5) Report*

- "The **future of particle physics depends critically on transformational accelerator R&D** to enable new capabilities and to advance existing technologies at lower cost. "

- "The program is driven by the physics goals, but **future physics opportunities will be determined by what is made possible.**"

- "Going much further, however, **requires changing the capability-cost curve of accelerators**, which **can only happen with an aggressive, sustained, and imaginative R&D program**."

- "Primary goal, ... **build the future-generation accelerators at dramatically lower cost**. For, example, the primary enabling technology for pp colliders is high-field accelerator magnets, . . ."

- "Strengthen national laboratory-university R&D partnerships, leveraging their diverse expertise and facilities."

*"Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context," P5 Report, http://science.energy.gov/~/media/hep/hepap/pdf/May%20 2014/FINAL_P5_Report_053014.pdf

Accelerator R&D Subpanel reinforced the P5 recommendations*

- **Participate in international design studies for a very high-energy proton-proton collider . . .**

  Vigorously pursue major cost reductions . . . targeting potential breakthroughs in cost-performance.

- **Support accelerator design and simulation activities that guide and are informed by the superconducting magnet R&D**

- **Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies . . .**

The over-arching goal is a large improvement in cost-performance.

*Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S. (HEPAP Accelerator R&D Subpanel Report, April 2015); http://science.energy.gov/hep/hepap/reports

Accelerator R&D Subpanel recommendations

- **Aggressively pursue the development of Nb_3Sn magnets . . .**
- **Establish and execute a high-temperature superconducting (HTS) material and magnet development plan . . .**
- **Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.**
- **Significantly increase funding for superconducting accelerator magnet R&D . . .**

Magnet Goals are similar around the world

- High field (16 – 20T)
  - 16T is a practical limit for Nb_3Sn
  - 20T requires use of High Temperature Superconductors (HTS)

Both Nb_3Sn and HTS are new to accelerator technology

- Bore diameter (40 – 50mm)

- All at reduced cost per T-m
  - Materials
  - Labor
  - Reliability
  - Margin

Must consider overall system cost

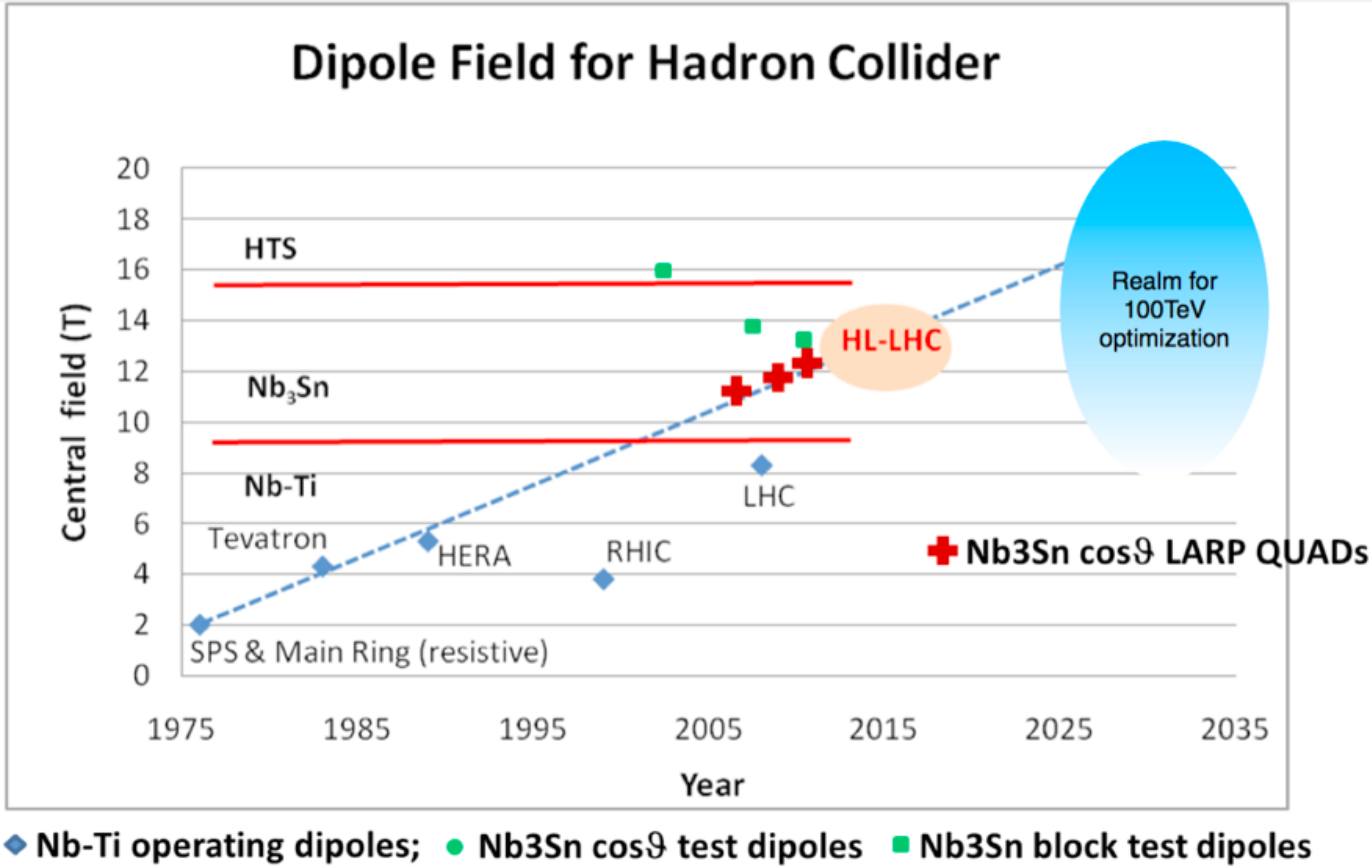
Goals require technology well beyond State-of-the-Art

Snap shot of the current status of magnet technology

- **27 km of NbTi magnets running at 1.9K and 7 - 8T**
- **More than half a century after discovery, Nb_3Sn is ready for major implementation in an operating accelerator. HL-LHC**
- **Some significant improvements in HTS conductors, but much left to do.**
- **High field accelerator magnet development has reached 14 – 15T. Getting close to the Nb_3Sn limit.**
- **Training is still a problem**
- **A relevant historical note:**

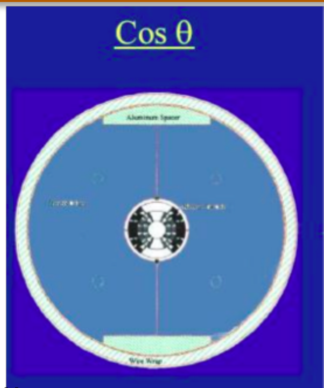
The program that developed the technology for a critical upgrade of the LHC was started at LBNL more than 20 years before the LHC turned on and while the SSC was still the flagship project of US HEP

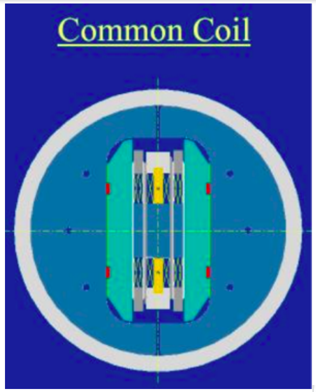
Some progress towards higher field accelerator magnets

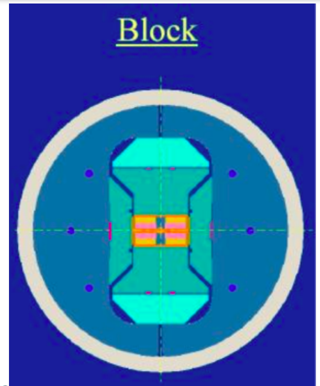


S. Prestemon, LBNL

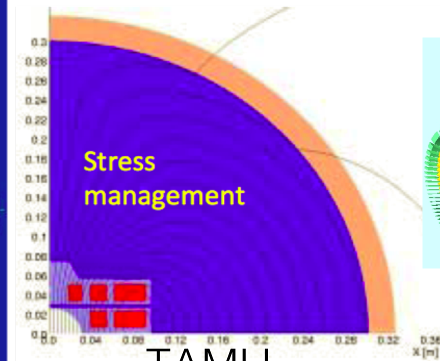
Starting point for magnet technology



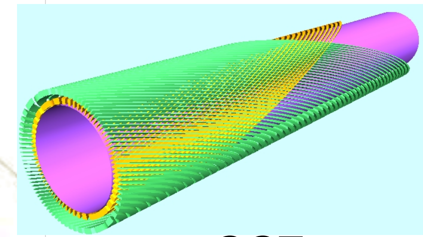




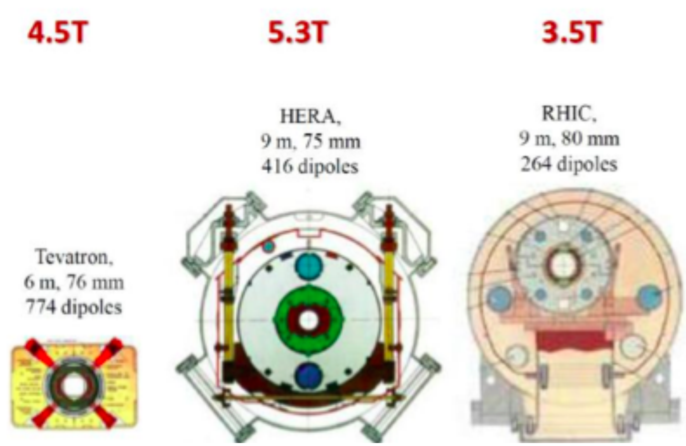
LBNL



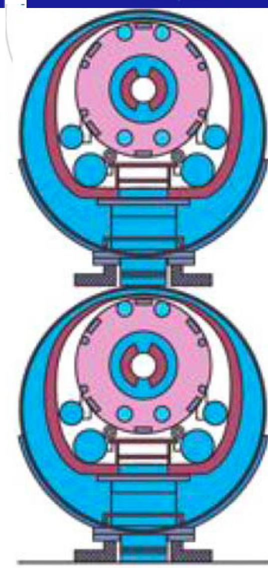
TAMU



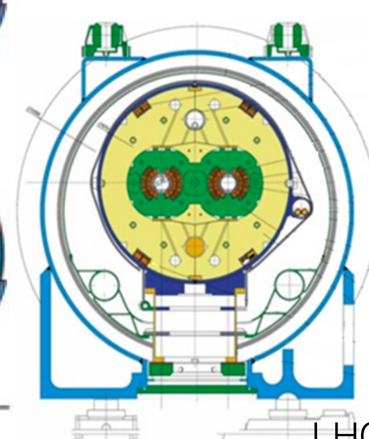
CCT



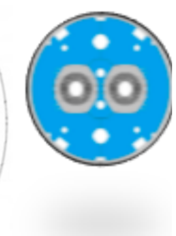
Shiltsev/Zlobin, (FNAL)



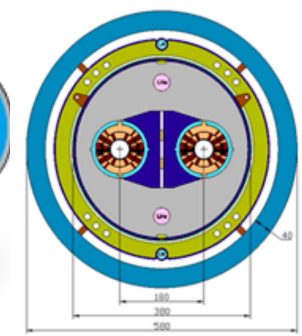
SSC, 50mm
6.6T, 4.3K



LHC, 56mm
8.3T, 1.9K

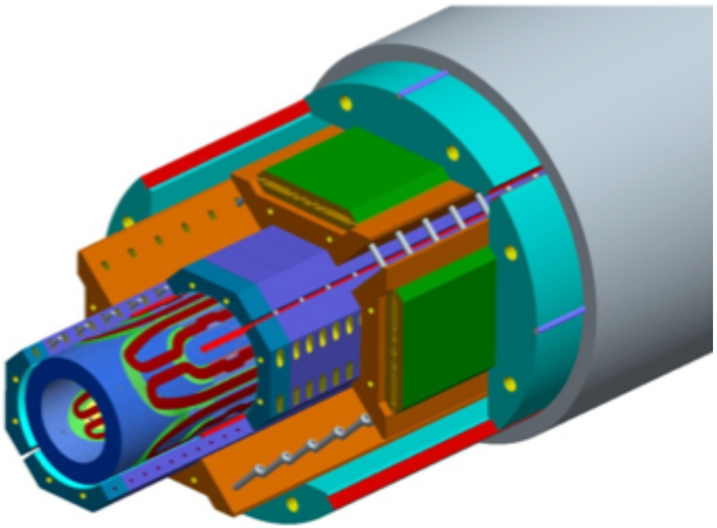


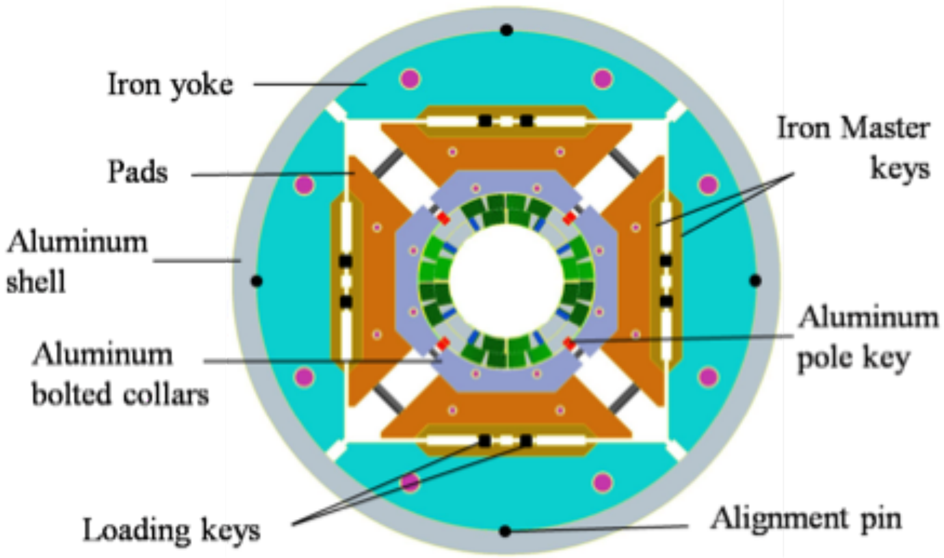
LHC, 60mm
11T,1.9K
FNAL/CERN

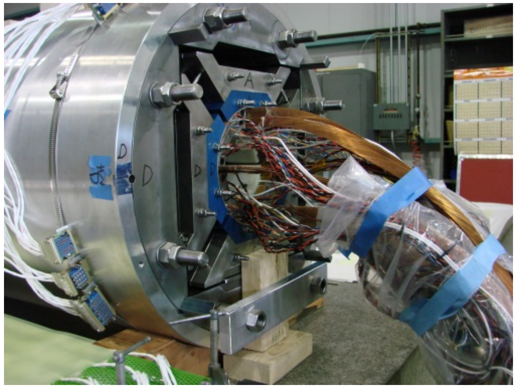


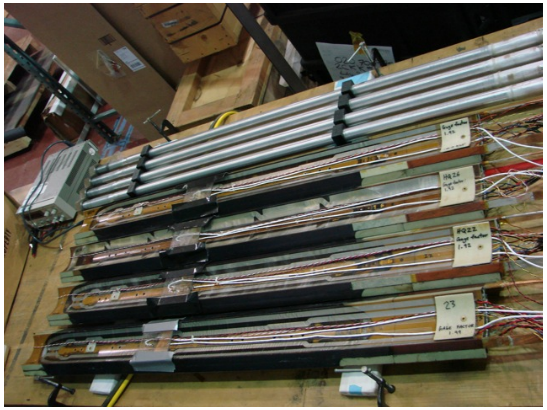
VLHC, 43mm
10T, 4.5K

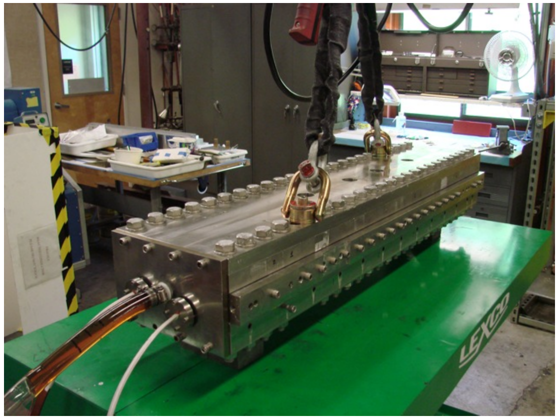
Nb_3Sn technology is being readied by LARP: FNAL, BNL, LBNL HQ ➠QXF ➠ Hi-Lumi upgrade











High field magnets require high field conductors

Material	NbTi	Nb_3Sn (Nb_3Al)	Bi-2212	YBCO
Max Field	**10-11 T**	**16-17 T**	**Stress limited**	**Stress limited**
Reaction	**Ductile**	**~675^{0}C in Ar/ Vacuum**	**~890^{0}C in O_2 (±2^{0}C)**	**None**
Wire axial compression	**N/A**	**Reversible**	**Irreversible?**	**Reversible**
Transverse stress	**N/A**	**< 200 MPa**	**60 MPa?**	**≥ 150 MPa[1]**
Insulation	**All**	**S/E Glass**	**Ceramic**	**All**
Construction	**G-10, stainless…**	**Bronze/Titanium, Stainless**	**Super alloy**	**All**
Quench propagation	**>20m/s**	**~20 m/s**	**~0.05 m/s? (4.2 K, 8 T) [2]**	**~0.01 m/s? (4.2 K, self-field) [3]**

1. Cheggour *et al.*, IEEE TAS (2007) 17(2), pp. 3063 – 3066.
2. Trociewitz *et al.*, SuST 21 (2008) 025015.
3. Song and Schwartz, IEEE TAS (2009) 19(5), pp. 3735 – 3743.

Achieving Aggressive Goals Requires a Paradigm Shift

- **Old Paradigm:** Need ~ 20% operating margin
- So, for 16T operating field we would need a 20T magnet
- This exceeds the limit for Nb_3Sn and requires HTS
- Significantly higher cost than NbTi. The last 2 – 3T is expensive!

- **New Paradigm:** Increase fraction of operating field. Could potentially save billions for a collider.

Note on conductor cost. (highest quality material available)

NbTi ~ "1"
Nb_3Sn ~ 10 X NbTi
Bi-2212 and YBCO ~ 10 X Nb_3Sn

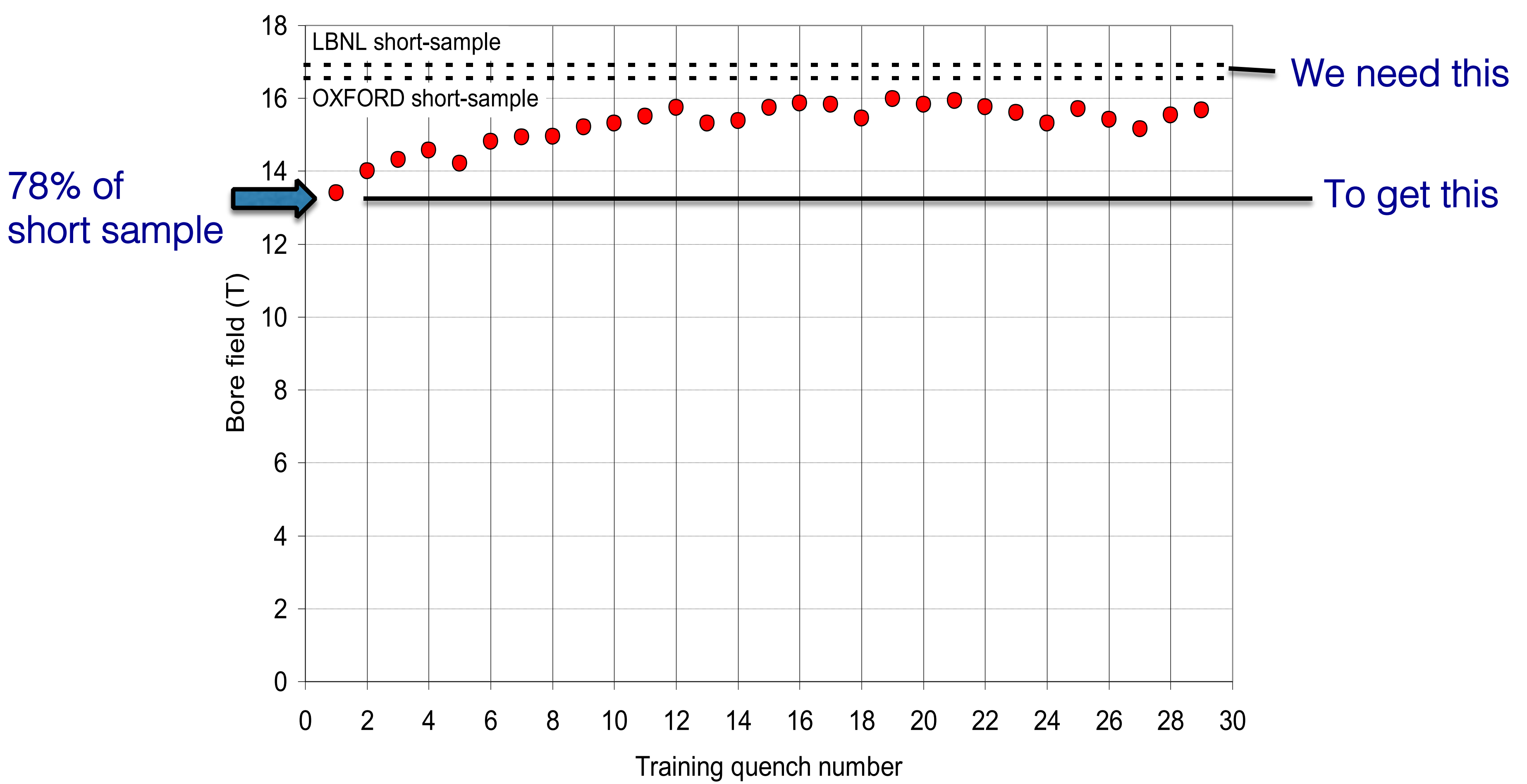
Upshot: HTS is not a candidate for ring magnets

So, an additional 2T using HTS for an insert would cost 1.5X as much as for the first 16T using Nb_3Sn

Old Paradigm: Some training and possible retraining are undesirable but expected and accepted
Conflicts with increase in fraction of operating field

New Paradigm: Understand and minimize or eliminate training (not trivial).
Linked to relaxing operating margin requirement.

HD-1 exhibited “acceptable” training performance



Achieving Aggressive Goals Requires a Paradigm Shift

- **Old Paradigm:** Need grading to minimize conductor
- Still true. Even more so with expensive conductor and more of it needed for higher fields. However, grading increases stress and Nb_3Sn is stress limited (~ 200 MPa)
- **New Paradigm:** Need a design that keeps coil stresses within limits. Grading is particularly effective for multi-layer coils required for high fields

- **Old Paradigm:** Large bore is desirable but expensive
- Still true but not as much. For high fields, bore size has relatively small impact on conductor quantity. Coil width is large compared to bore size. But, larger bores lead to higher stress.

- **New Paradigm:** Don't obsess over this parameter. Eye on stress, but other issues may dominate.

- **Old Paradigm:** Test and measure field of all magnets
- Wasn't intended for LHC but ultimately that was the case

- **New Paradigm:** Magnets have to be as simple and reproducible as possible.

Summarizing the key elements of the new paradigm

1) **Decrease operating margin**
2) **Minimize or eliminate training**
3) **Fully utilize grading**
4) **Flexible choice of bore diameter**
5) **Manufacturability (reliability and reproducibility)**

- **Take baseline technologies to higher level of performance**
- **The HD magnets are on the asymptote for Nb_3Sn so it will be difficult**
- **Combine with a strong component of high-risk, potentially high payoff disruptive technology development that can leapfrog the status quo**
- **A parallel program of supportive R&D**
- **Advanced materials R&D**
- **Explore other applications of the new technology that challenge current capabilities**

The Programs

FCC Technology program 2016-2020

FCC-ST-0001

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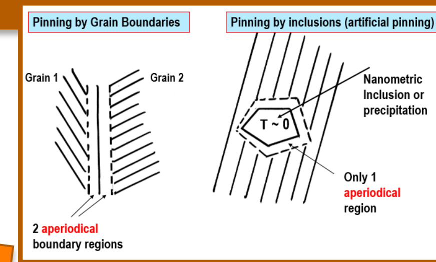
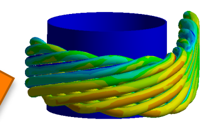
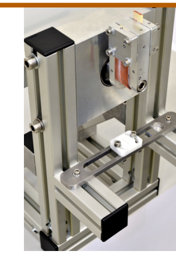
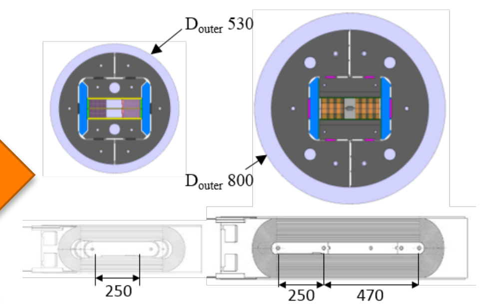
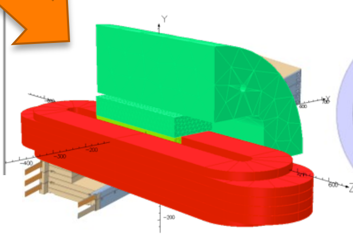
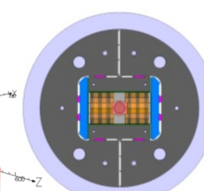








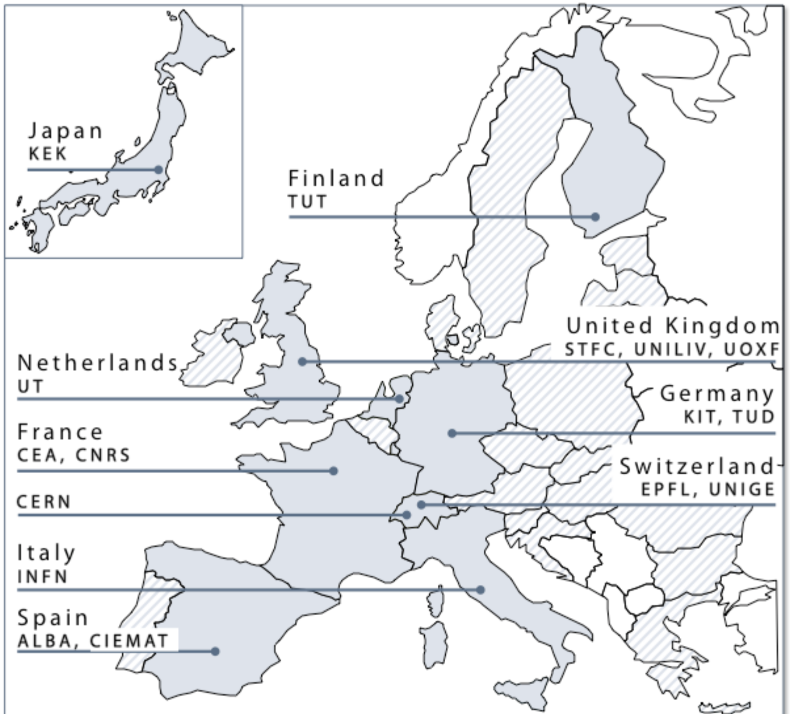




15 MCHF material over 4 years (8 MCHF on conductor R&D)

CERN-EU program: 'EuroCirCol' on 16 T dipole design

UNIVERSITY OF TWENTE. INFN TAMPERE UNIVERSITY OF TECHNOLOGY



EuroCirCol consortium, federating 16 partners, 1 from Japan and 1 IEIO

cea · cnrs dépasser les frontières · CERN · UNIVERSITY OF OXFORD · TECHNISCHE UNIVERSITÄT DARMSTADT · KIT Karlsruher Institut für Technologie · EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE · UNIVERSITY OF LIVERPOOL · UNIVERSITÉ DE GENÈVE · ALBA · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas · MANCHESTER 1824

European Union Horizon 2020 program

- Support for FCC study
- Grant agreement 654305
- 3 MEURO co-funding

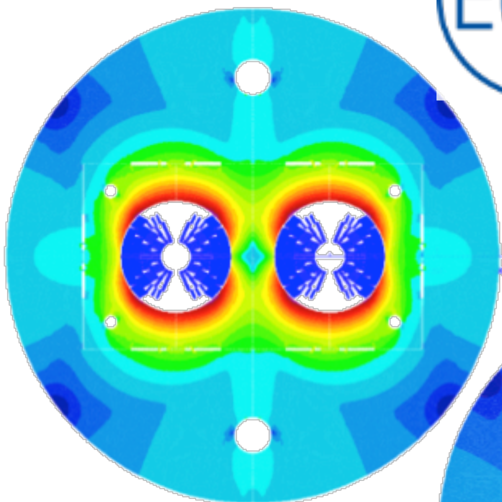
Scope:

FCC hadron collider

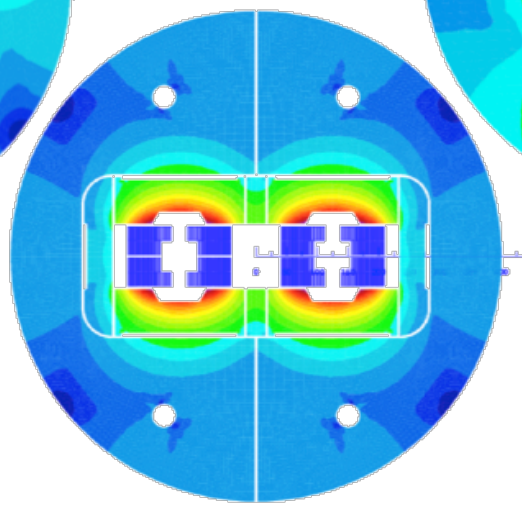
- Optics Design
- Cryo vacuum design
- 16 T dipole design, construction folder for demonstrator magnets

16 T dipole options under consideration

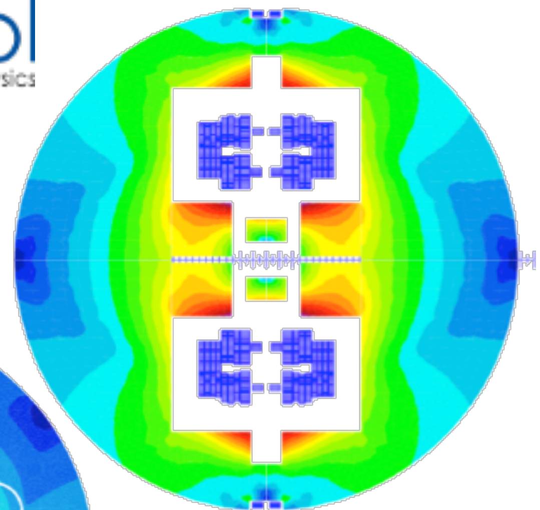
Cos-theta



Blocks

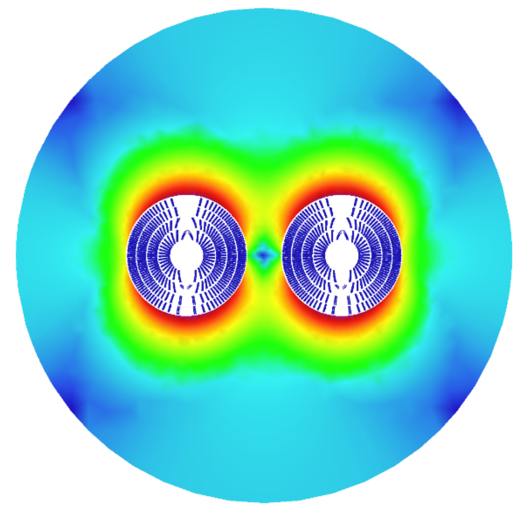


Common coil



Swiss contribution
via PSI

Canted
Cos-theta

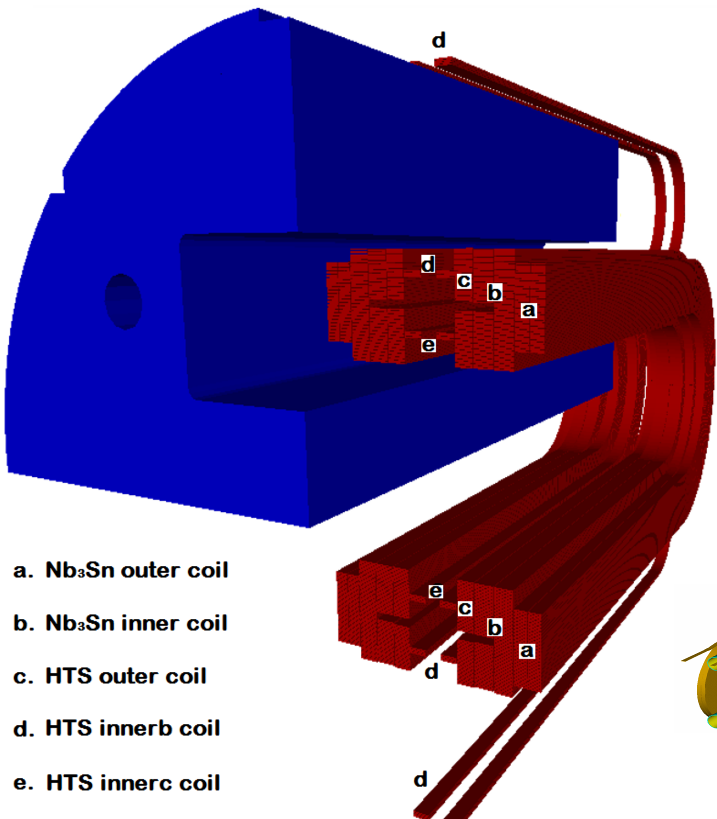


Down-selection of options end 2016 for more detailed design work

IHEP: Concept of the SPPC 20-T Dipole Magnet

Q. Xu et al.

20-T dipole magnet in common coil configuration two Φ50 mm beam pipes; load line 80% @ 1.9 K



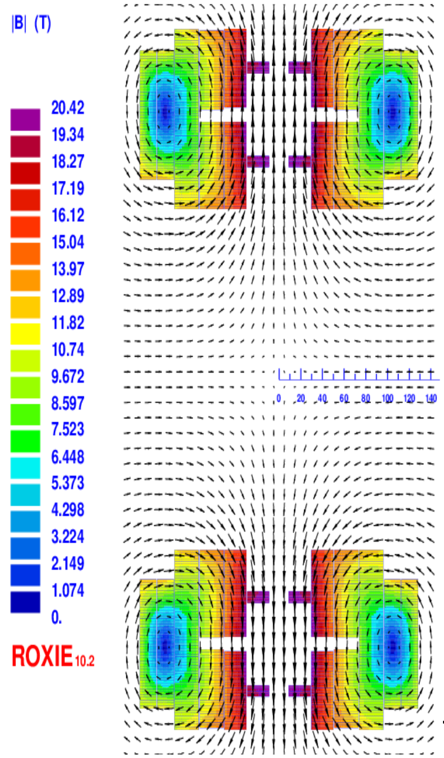
a. Nb_3Sn outer coil

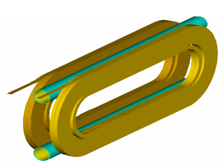
b. Nb_3Sn inner coil

c. HTS outer coil

d. HTS innerb coil

e. HTS innerc coil





Main parameters of the magnet

Number of apertures	2
Aperture diameter (mm)	50
Inter-aperture spacing (mm)	333
Operating current (A)	14700
Operating temperature (K)	4.2
Operating field (T)	20
Peak field (T)	20.4
Margin along the load line (%)	11
Stored magnetic energy (MJ/m)	7.8
Inductance (mH/m)	72.1
Yoke ID (mm)	260
Yoke OD (mm)	800
Weight per unit length (kg/m)	3200
Energy density (coil volume) (MJ/m^3)	738
Force per aperture – X / Y (MN/m)	23.5/4.4
Peak stress in coil (MPa)	240
Fringe Field @ r = 750 mm (T)	0.02

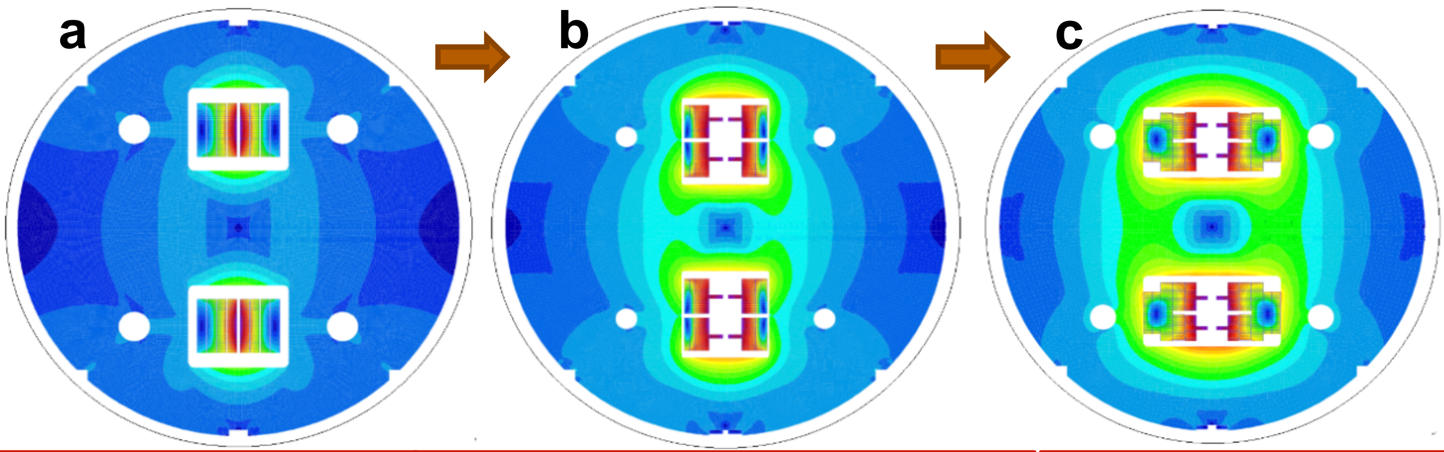
Integrated field quality

Integrated b_n & a_n	Value (10^{-4})
b3	0.14
b5	1.42
b7	-0.40
a2	-0.29
a4	-1.81
a6	0.03

Q. Xu et. al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016, 4000404

IHEP: R&D Steps towards 20-T Dipole Magnet

Q. Xu et al.



1st step
ongoing
Fabrication of 15-T Nb_3Sn and Nb_3Sn+HTS subscale magnets, to test the stress management method for Nb_3Sn & HTS coils and the quench protection method for HTS coils; By the end of 2018.

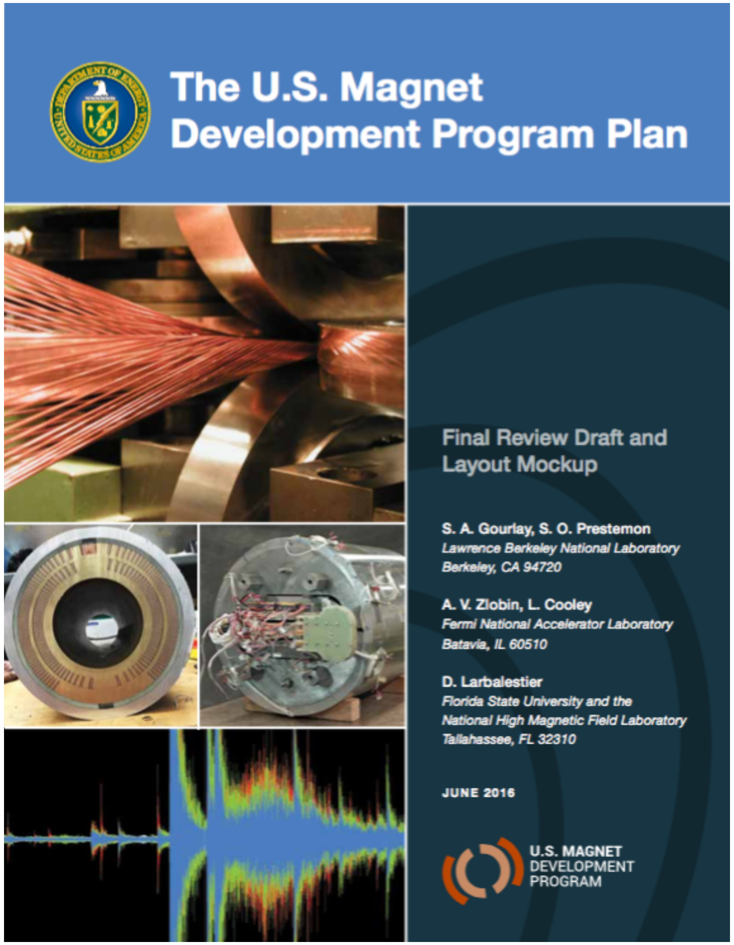
2nd step
Fabrication of 15-T Nb_3Sn and Nb_3Sn+HTS operational field dipole magnet with two Φ50 mm beam pipes and 10^{-4} field quality, to test the field optimization method for HTS coils;

To be funded.

3rd step
Fabrication of a 20-T magnet with Nb_3Sn+HTS or only one of them, if significant progress on performance of Nb_3Sn or HTS superconductors, i.e., J_c is increased 3~6 times with significant cost reduction.

Q. Xu, K. Zhang, C. Wang et. al., 20-T Dipole Magnet with Common Coil Configuration: Main Characteristics and Challenges, IEEE Trans. Appl. Supercond., VOL. 26, NO. 4, 2016, 4000404

The US Magnet Development Program has been launched (HEPAP ARD Subpanel Recommendation)


The U.S. Magnet Development Program Plan

Final Review Draft and Layout Mockup

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JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

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U.S. MAGNET DEVELOPMENT PROGRAM

Initial Participants

LBNL
FNAL
FSU/NHMFL

Goals Derived from P5 and ARD Subpanel Recommendations

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Support the above efforts by addressing fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

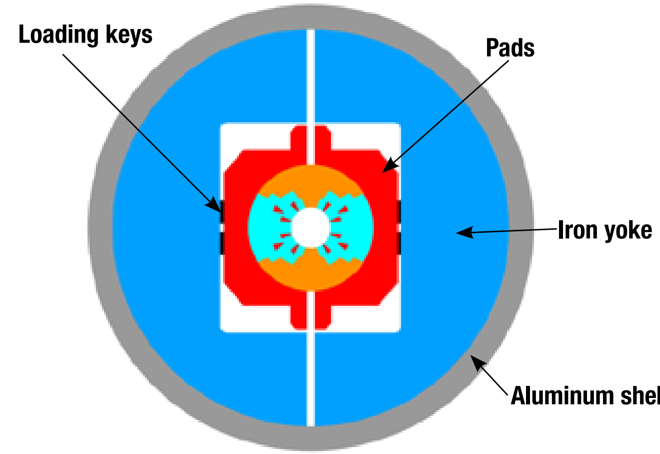
GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

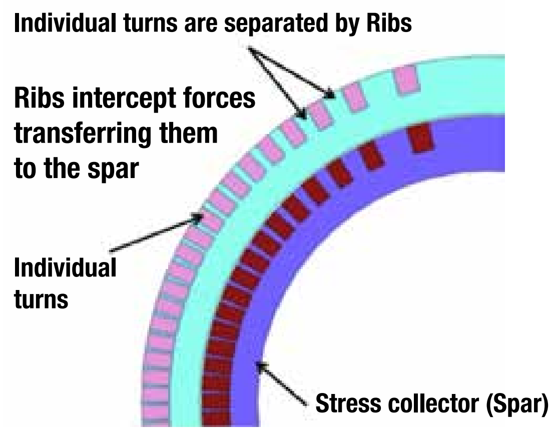
(1) High Field Dipoles to explore the limits of Nb_3Sn

Two-pronged approach

- A reference design based on cosine-theta



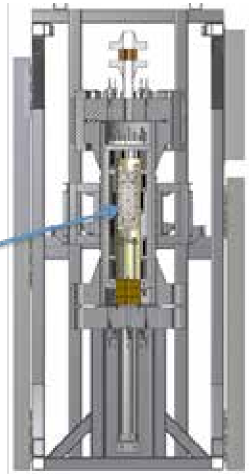
- A path to explore innovative designs – starting with the Canted Cosine-Theta (CCT)



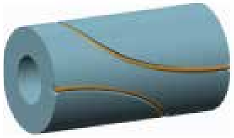
(2) High Field Dipoles to explore the limits of HTS

Two candidate HTS conductors

- Bi-2212 sub-scale magnets in racetrack and CCT configuration



- REBCO-based dipole and quadrupole magnets



(3) Backbone of the Program: Magnet Science and Developing Underpinning Technologies

Some examples:

- Training studies
- Modeling
- Diagnostics, quench detection, protection
- Develop infrastructure, e.g. insert testing
- New materials – insulation, impregnation and structural
- Design comparison and cost analysis to guide program

Improvements from the technology development program will be integrated into Nb_3Sn and HTS magnets

(4) Superconducting Materials R&D is Critical for Program Success

- Push performance limits of Nb_3Sn and HTS conductors based on magnet needs

- Understand –
  - Uniformity and reliability
  - Scalability and future cost

Closing remarks

- World-wide activity in magnet R&D is ramping up
- International cooperation is a <u>necessity</u>
- Challenges are significant but we are looking forward to it!

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