Global plans for high-field accelerator magnet R&D

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Many thanks to
Qingjin Xu, Toru Ogitsu, Luca Bottura,
as well as the US MDP Management Team and the LDG Panel of Experts

Outline

- Motivation and Physics Strategic Planning

- Context of Magnet R&D for a future collider
    - Examples from US and Europe

- Ongoing plans in US, Europe, and Asia

- Summary comments

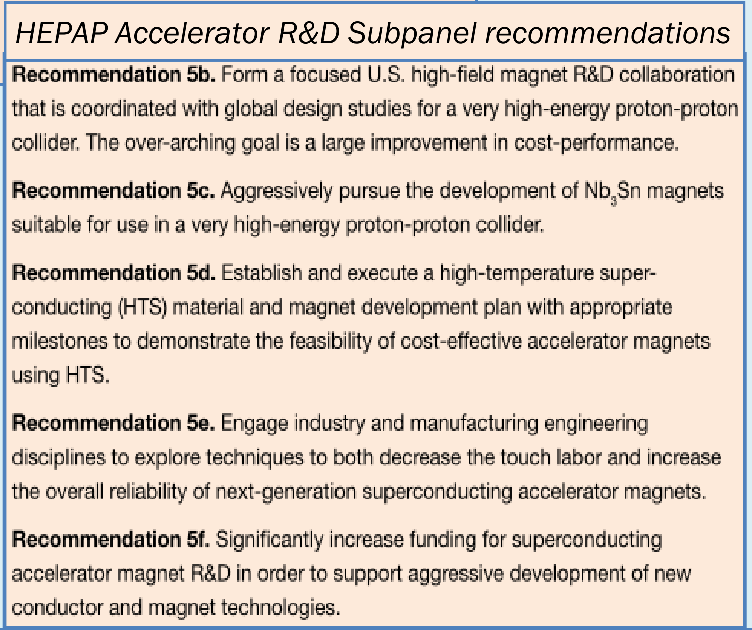
Physics motivation and strategic planning

- The physics drivers for a future hadron collider are well documented by community planning, e.g.
    - US “Snowmass” process - ***ongoing***
    - European Strategy for Particle Physics

P5 recommendation 24:

“Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs.”

Last US “P5” report ~2014



HEPAP Accelerator R&D Subpanel recommendations

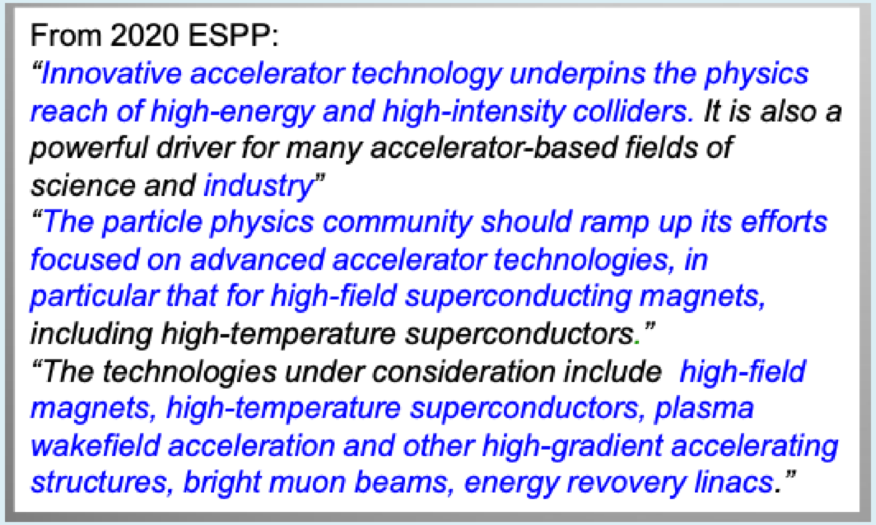
Recommendation 5b. Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

Recommendation 5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.

Recommendation 5d. Establish and execute a high-temperature super-conducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

Recommendation 5e. 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.

Recommendation 5f. Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.



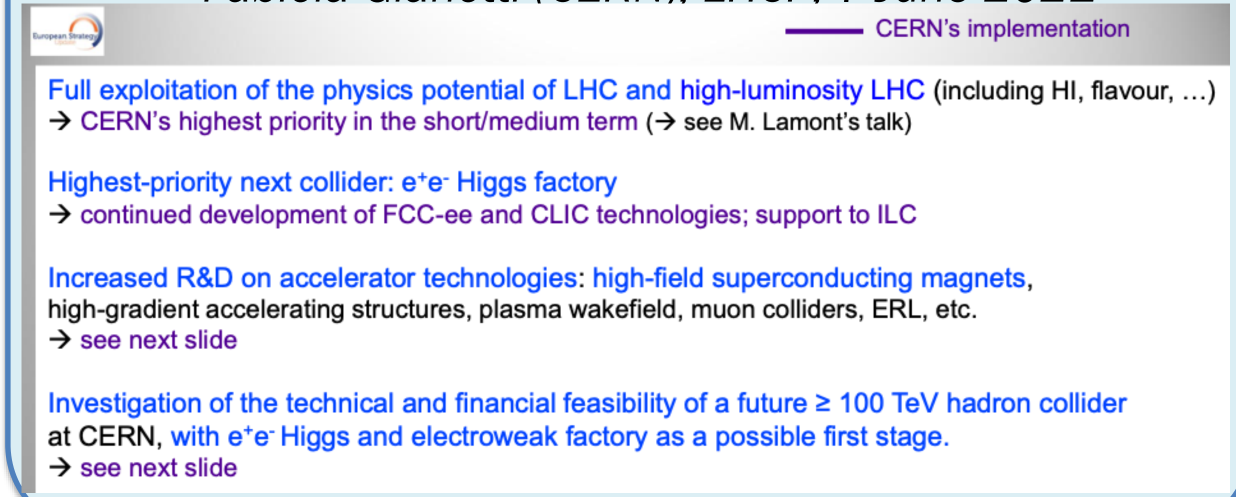
From 2020 ESPP:

“Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry”

“The particle physics community should ramp up its efforts focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors.”

“The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy revovery linacs.”

Fabiola Gianotti (CERN), LHCP, 7 June 2021



CERN’s implementation

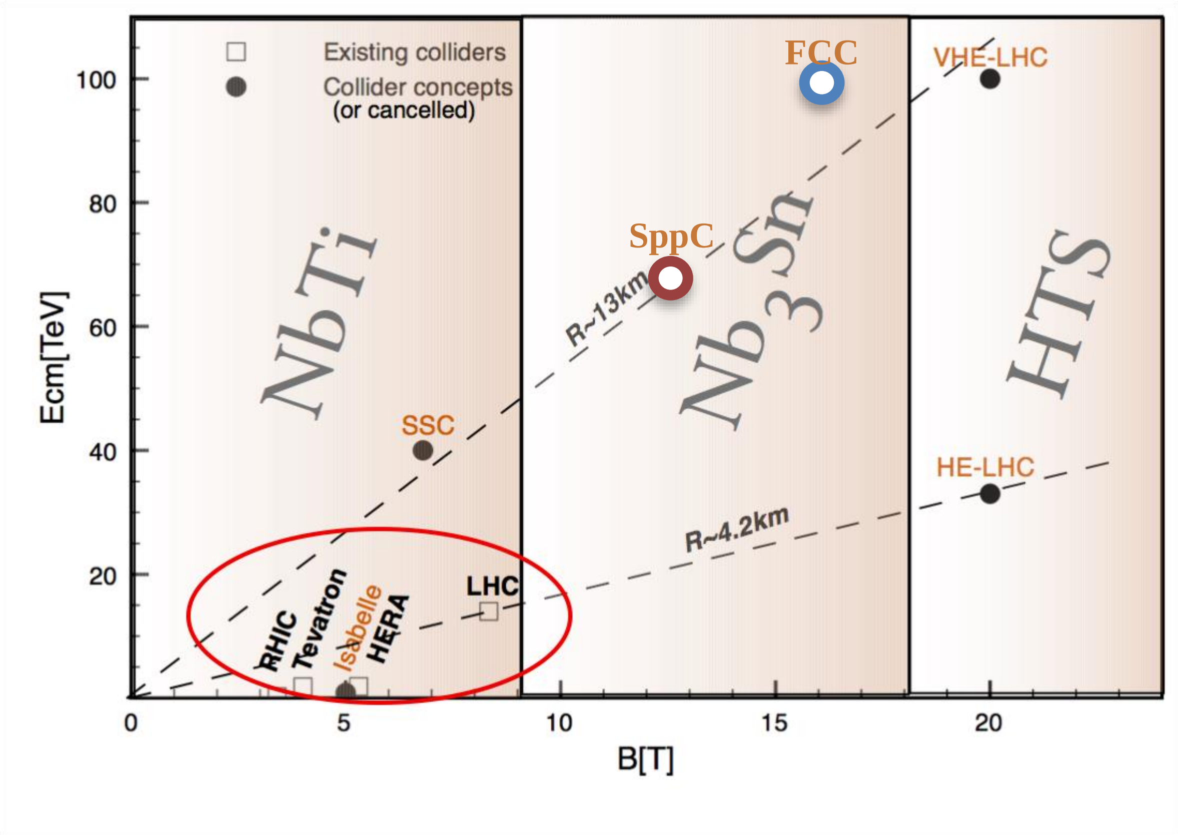
Full exploitation of the physics potential of LHC and high-luminosity LHC (including HI, flavour, …)
→ CERN’s highest priority in the short/medium term (→ see M. Lamont’s talk)

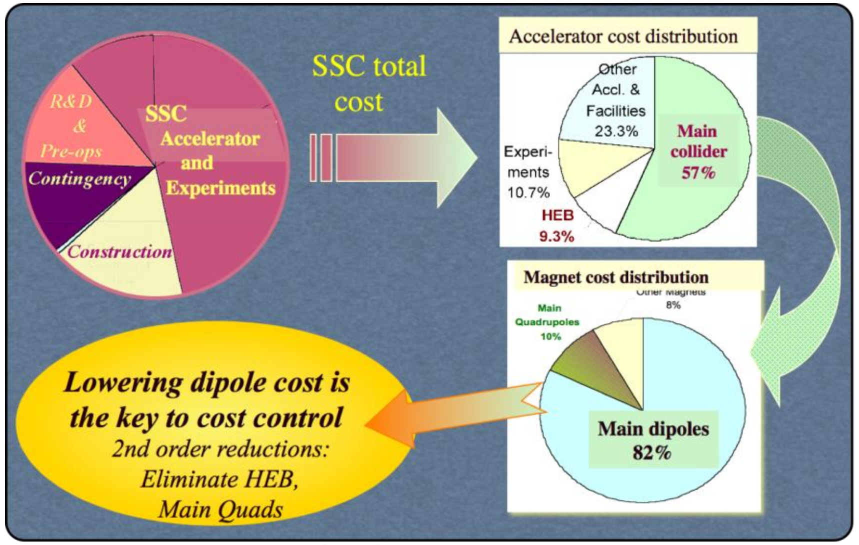
Highest-priority next collider: e^+e^- Higgs factory
→ continued development of FCC-ee and CLIC technologies; support to ILC

Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc.
→ see next slide

Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
→ see next slide

Manet technology is driving the cost and reach of a future collider





Lowering dipole cost is the key to cost control

2nd order reductions: Eliminate HEB, Main Quads

Barletta

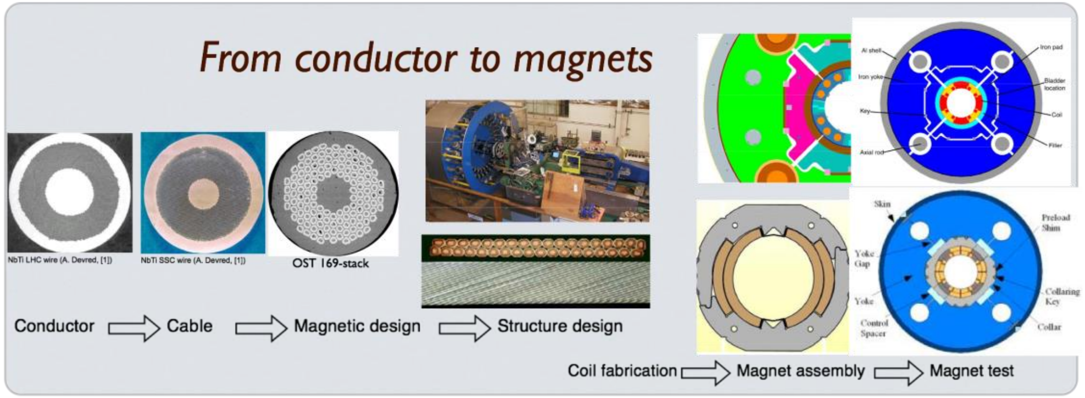
CERN cost estimates*: $\$_{magnets}/\$_{tot}$

LHC: 57%

HE-LHC:

- 70% (26TeV; Nb3Sn)
- 77% (33TeV; HTS)

*L. Rossi, "TOE" talk



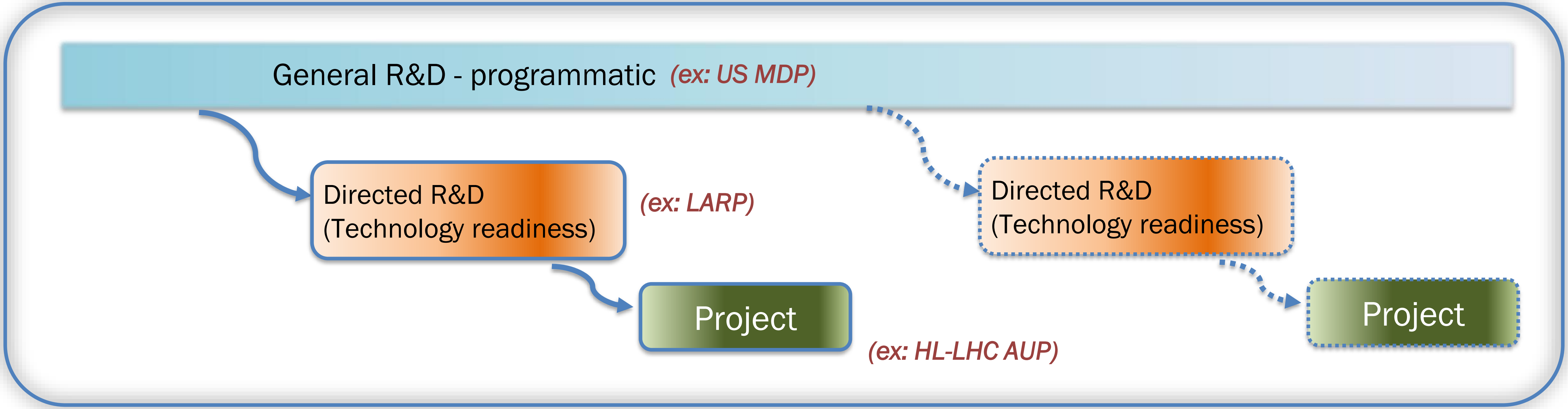
Cost/performance is the critical metric

Dominant cost drivers for a pp collider: Magnets and tunnel

R&D efforts for accelerator magnet technology are becoming more structured

- DOE created the US Magnet Development Program (MDP) in ~2016
- Europe is in the process of forming the High Field Magnet program (HFM)
  - Led by the Laboratory Director's Group (LDG)
  - Working to define roadmaps and coordinate activities by collaborating institutions

The programs strive to coordinate efforts to more rapidly advance technology development



General R&D - programmatic *(ex: US MDP)*

Directed R&D (Technology readiness) *(ex: LARP)*

Project *(ex: HL-LHC AUP)*

Directed R&D (Technology readiness)

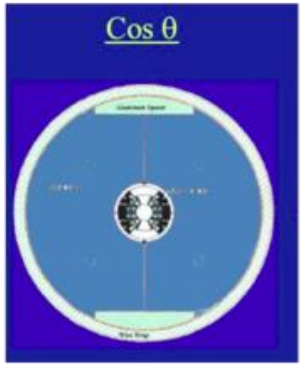
Project

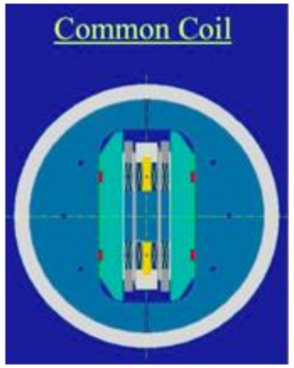
The US DOE approach balances long range R&D and project preparation

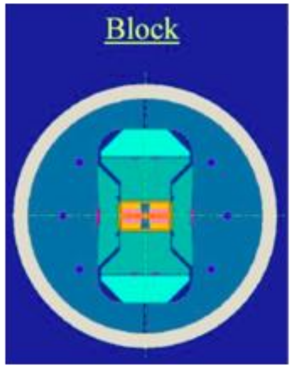
The “magnet zoo” in colliders are (to-date) all based on Cos(t) designs

- R&D magnet designs explore layouts that attempt to address issues associated with conductor strain (to avoid degradation) and reduction of conductor/coil motion (to minimize training)

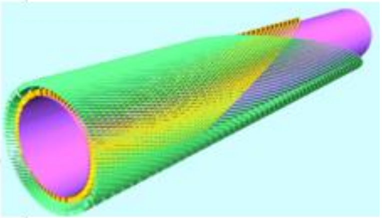
- At high field “managing” stress through judicious force interception will be required



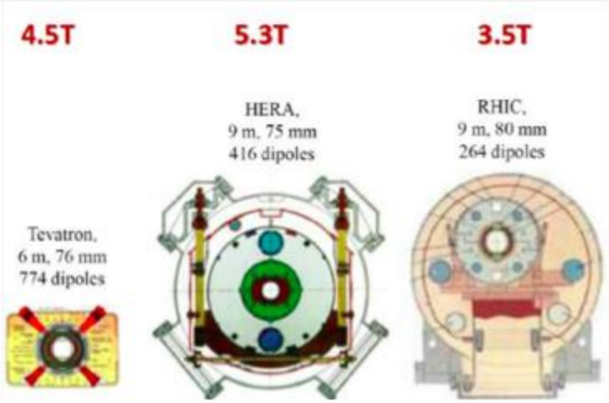




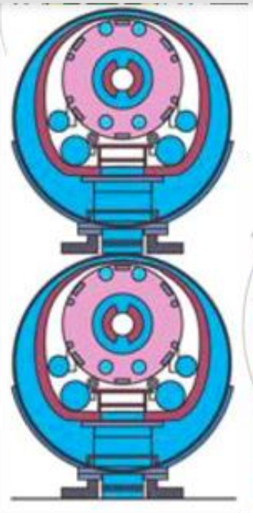
TAMU



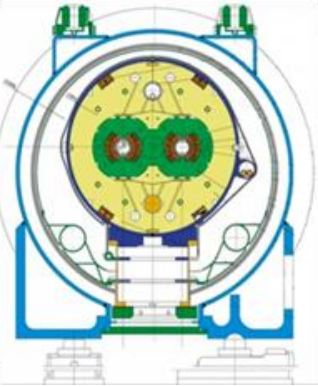
CCT



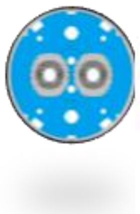
Shiltsev/Zlobin, (FNAL)



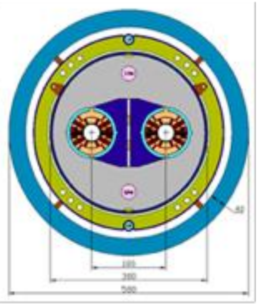
SSC, 50mm
6.6T, 4.3K



LHC, 56mm
8.3T, 1.9K



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

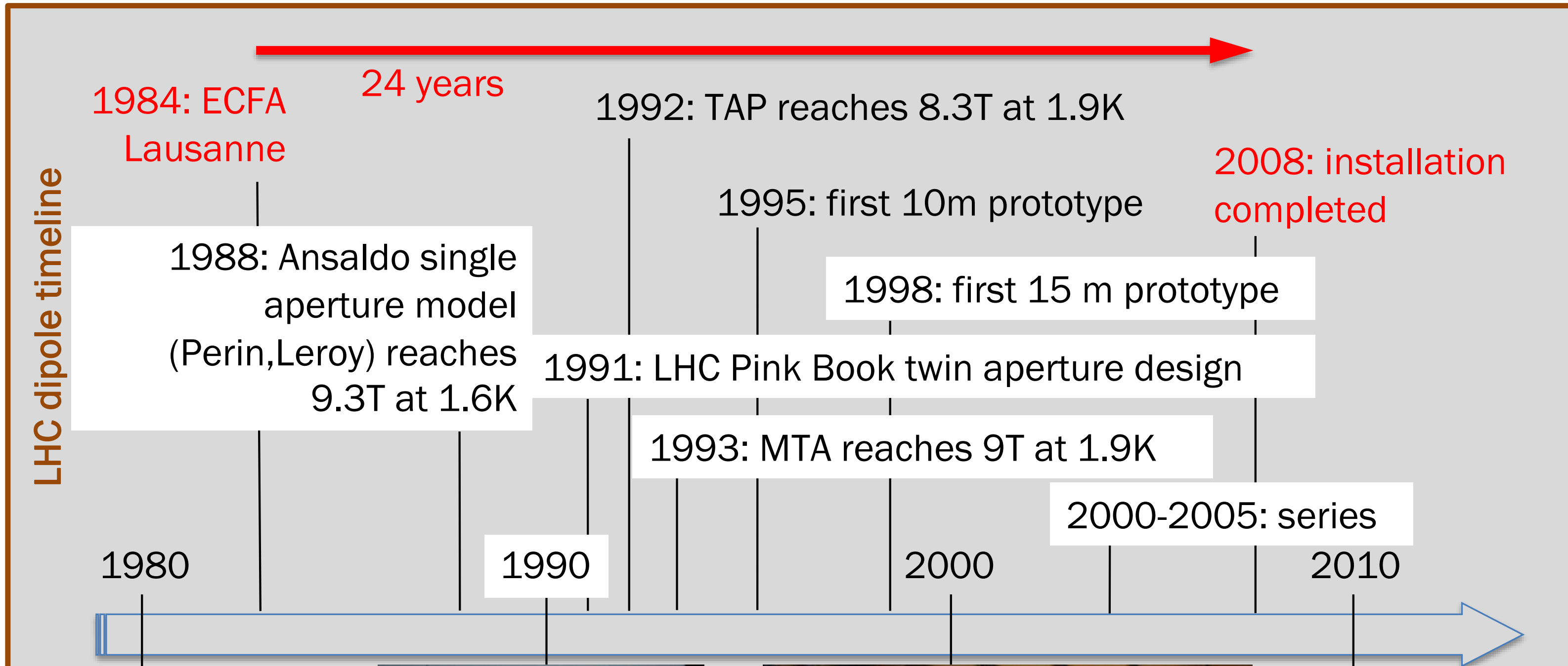


VLHC, 43mm
10T, 4.5K

A look at the timeline from the LHC

- **The path to next generation magnet technology for a collider is complex:**
  - Need R&D to probe concepts, develop and understand potential
  - Need robust industrial suppliers of conductor
  - Need to ready a given technology for a project
  - Need to develop industrial partners for magnet production
  - And finally need to produce reliable, cost effective magnets for the next collider

Requires a strong ecosystem of laboratory, University, and industrial partners


LHC dipole timeline

24 years

1984: ECFA Lausanne

1988: Ansaldo single aperture model (Perin,Leroy) reaches 9.3T at 1.6K

1991: LHC Pink Book twin aperture design

1992: TAP reaches 8.3T at 1.9K

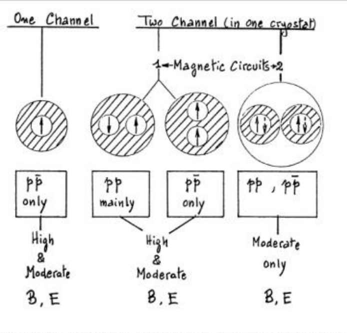
1993: MTA reaches 9T at 1.9K

1995: first 10m prototype

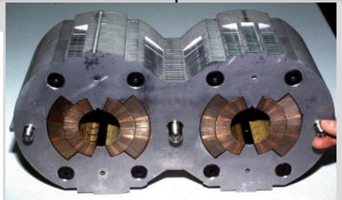
1998: first 15 m prototype

2000-2005: series

2008: installation completed



Synopsis of hadron collider options for the LEP tu



Courtesy Luca Bottura

Plans and Roadmaps are well advanced globally

- US MDP – ***well established***
- European HFM – ***in formation***
- Japan efforts at KEK - coordinated with CERN and MDP
- China efforts led by IHEP – ***progressing well***

The European HFM Roadmaps are under development

Irfu
UGA Université Grenoble Alpes
CERN
ETH zürich
PAUL SCHERRER INSTITUT PSI
EPFL
BRUKER
irig
NÉEL institut
G2Elab Grenoble Génie Electrique
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
université PARIS-SACLAY
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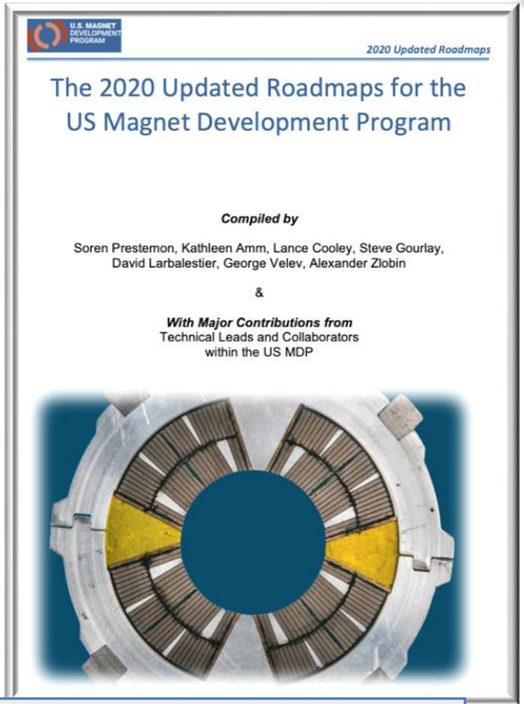


U.S. MAGNET DEVELOPMENT PROGRAM

2020 Updated Roadmaps

The 2020 Updated Roadmaps for the US Magnet Development Program

Compiled by

Soren Prestemon, Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier, George Velev, Alexander Zlobin

&

With Major Contributions from Technical Leads and Collaborators within the US MDP

Updated US MDP Roadmaps have been published
https://arxiv.org/abs/2011.09539

This is ***not*** a comprehensive list of collaborators... our community is broad and diverse!

KYOTO UNIVERSITY FOUNDED 1897
TOHOKU UNIVERSITY
KOBELCO
JASTEC SUPERCONDUCTOR
TOKAI UNIVERSITY

中国科学院电工研究所
Institute of Electrical Engineering, CAS

中国科学院高能物理研究所
Institute of High Energy Physics, CAS

Integrated programs share common themes, but unique perspectives

US Magnet Development Program (MDP) Goals:

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:

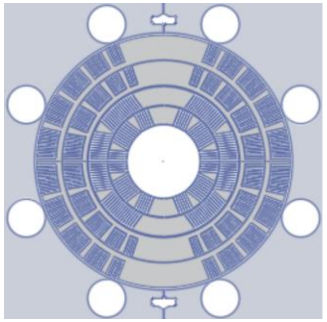
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

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

Strategic directions for the update plan:

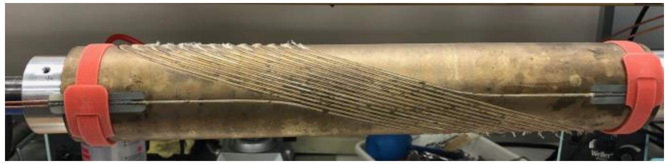
- ○ *Probing stress management structures*
- ○ *Hybrid HTS/LTS designs*
- ○ *Understanding and impacting the disturbance-spectrum*
- ○ *Advancing both LTS and HTS conductors, optimized for HEP applications*



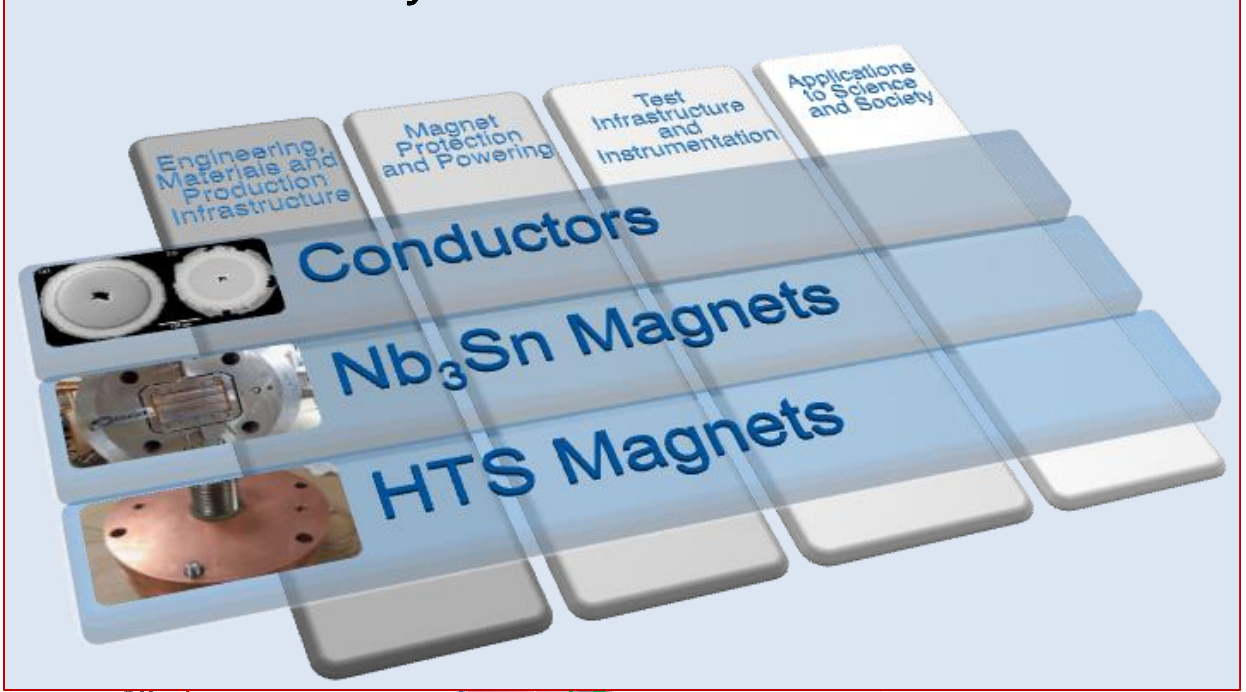
Highest priority issue: ***degradation mechanisms***; design mitigation

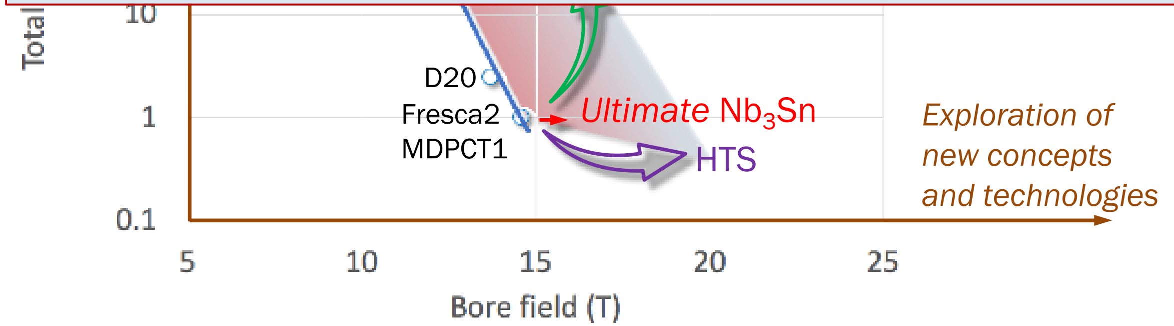
Second priority: Initial quench current and ***memory after thermal cycle***

Third priority: ***Training rate***



Preliminary HFM structure



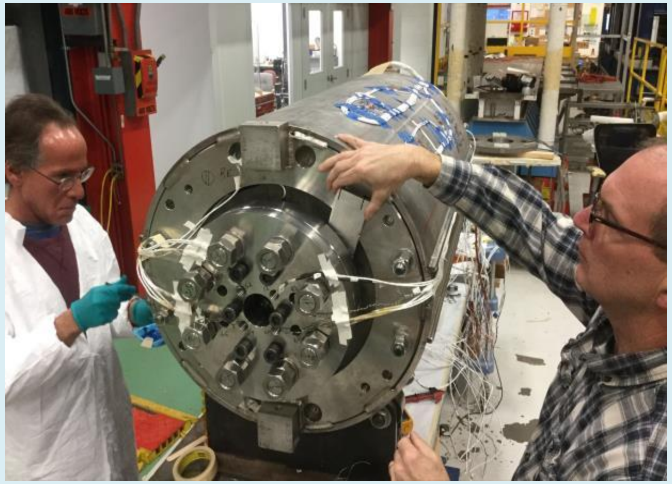


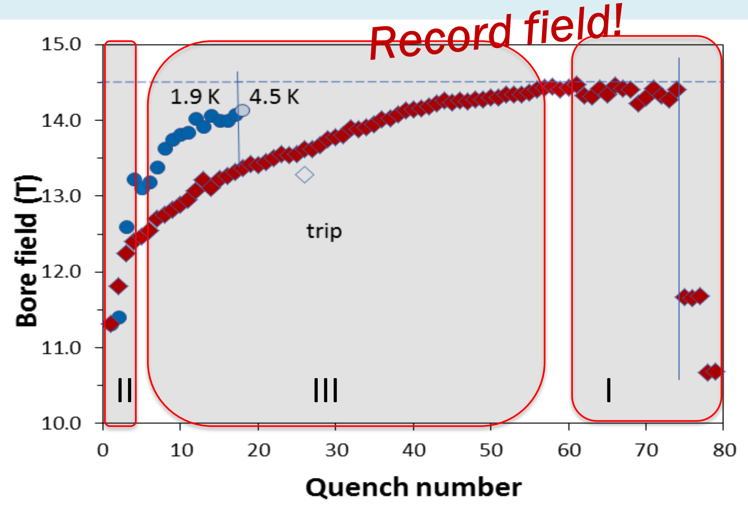
Courtesy Luca Bottura

Program strategy and goals: driving questions related to performance

- Ultimate Performance of Magnets
  - What is the nature of accelerator magnet training? Can we reduce or eliminate it?
  - How do we best define operating margin for Nb3Sn and HTS accelerator magnets, and to what degree can and should it be minimized?
  - Can we control the disturbance spectrum and engineer a magnet response to reduce operating margin and enhance reliable performance?
  - What are the mechanical limits and possible stress-management approaches for Nb3Sn, HTS, and 20 T hybrid LTS/HTS magnets, and do they have defined mechanical limits?
  - Do hybrid designs benefit from the best features of LTS and HTS, or inherit the difficulties of both material technologies?

Example: MDP 4-layer, 60mm bore cosine-theta magnet led by FNAL



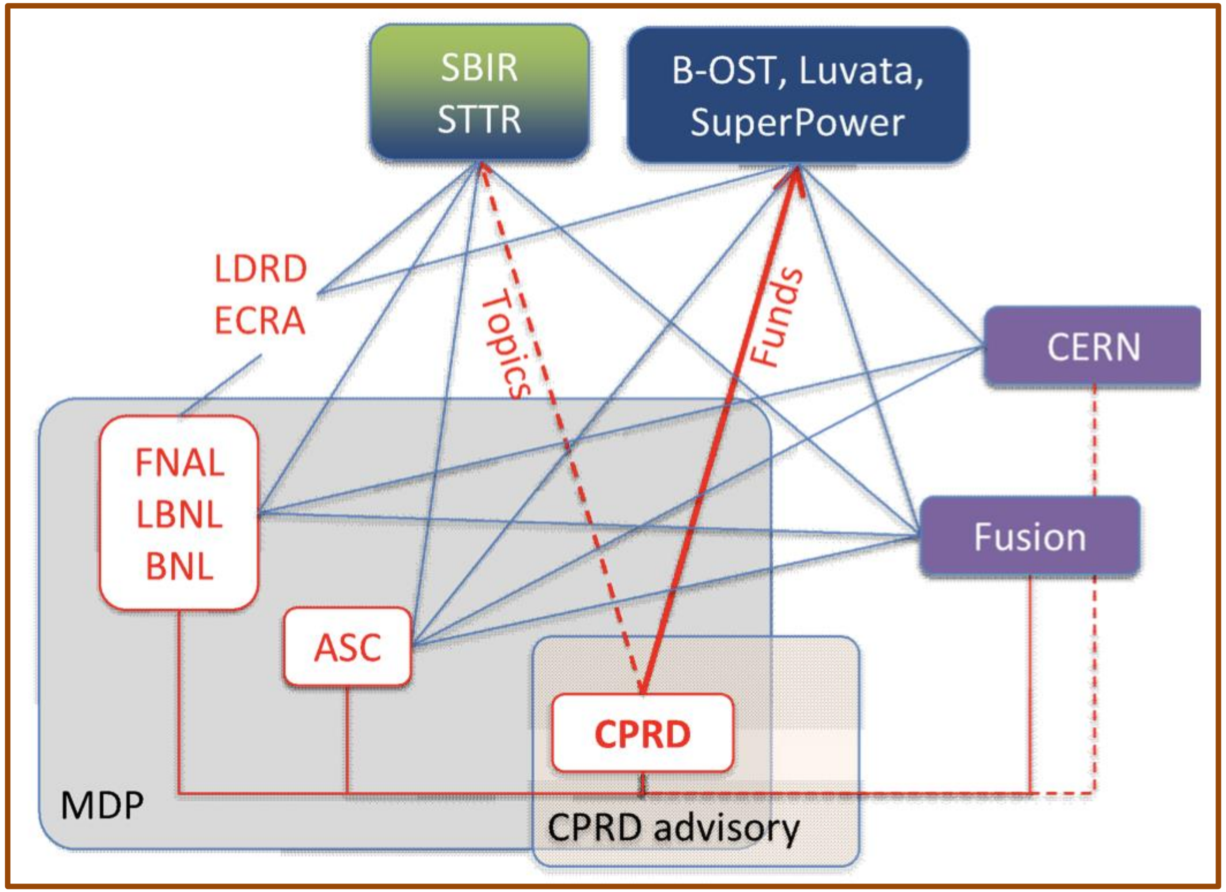


[I]: Highest priority issue: ***degradation***
Mechanisms; design mitigation
[II]: Second priority: Initial quench current
and ***memory after thermal cycle***
[III]: Third priority: ***Training rate***

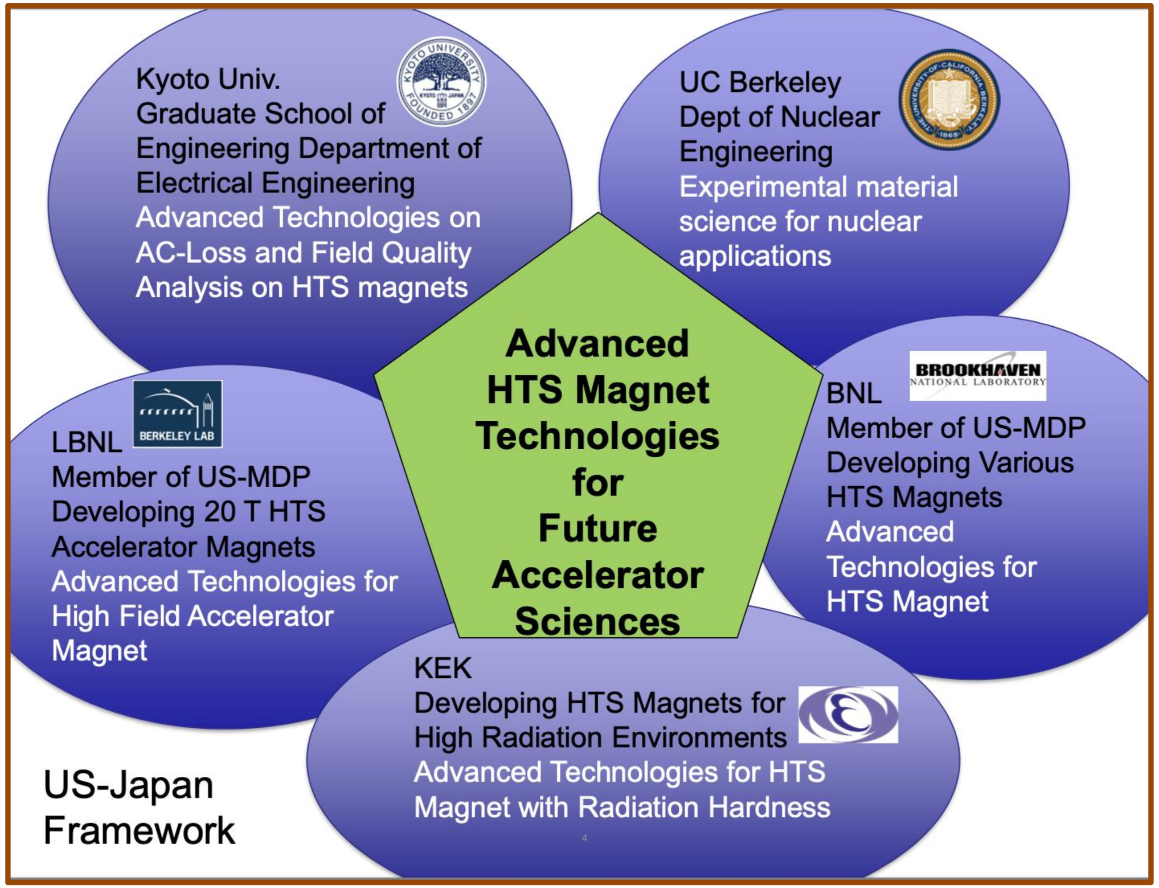
Program strategy and goals: Additional driving questions

- Cost, Industrialization, and Operation
  - What is the optimal operating temperature for Nb_3Sn and HTS magnets?
  - What are the possibilities and limitations associated with safely protecting Nb_3Sn and HTS magnets?
  - Can we provide accelerator quality Nb_3Sn magnets beyond 16 T? What are the operational field limits for Nb_3Sn magnets?
  - What is the optimal operational field for Nb_3Sn dipoles? For hybrid HTS/LTS dipoles?
  - Can we build practical and affordable accelerator magnets with HTS conductor(s)?
  - What drives the economics of high field accelerator magnets? Are there innovative approaches to magnet design that address the key cost drivers for Nb_3Sn and HTS magnets and do they shift the cost optimum to higher fields?
- Superconductors for Accelerator Magnets
  - What are the near and long-term goals for Nb_3Sn and HTS conductor development? What performance parameters in Nb3Sn and HTS conductors are most critical for high field accelerator magnets? Can we effectively define limiting factors (properties, cost, manufacture) of present HTS conductors and accelerate their development to industrial maturity?
  - Prototype HTS magnets made so far, whether made from Bi-2212 or from REBCO have not shown training even in dipole geometry where Nb_3Sn is particularly sensitive. Is it possible to envisage NO TRAINING as a potentially vital, cost-saving attribute of HTS conductor use?

Connections between the integrated magnet R&D efforts are building



Example: nexus for US conductor development



Kyoto Univ.
Graduate School of Engineering Department of Electrical Engineering
Advanced Technologies on AC-Loss and Field Quality Analysis on HTS magnets

UC Berkeley
Dept of Nuclear Engineering
Experimental material science for nuclear applications

Advanced HTS Magnet Technologies for Future Accelerator Sciences

LBNL
Member of US-MDP
Developing 20 T HTS Accelerator Magnets
Advanced Technologies for High Field Accelerator Magnet

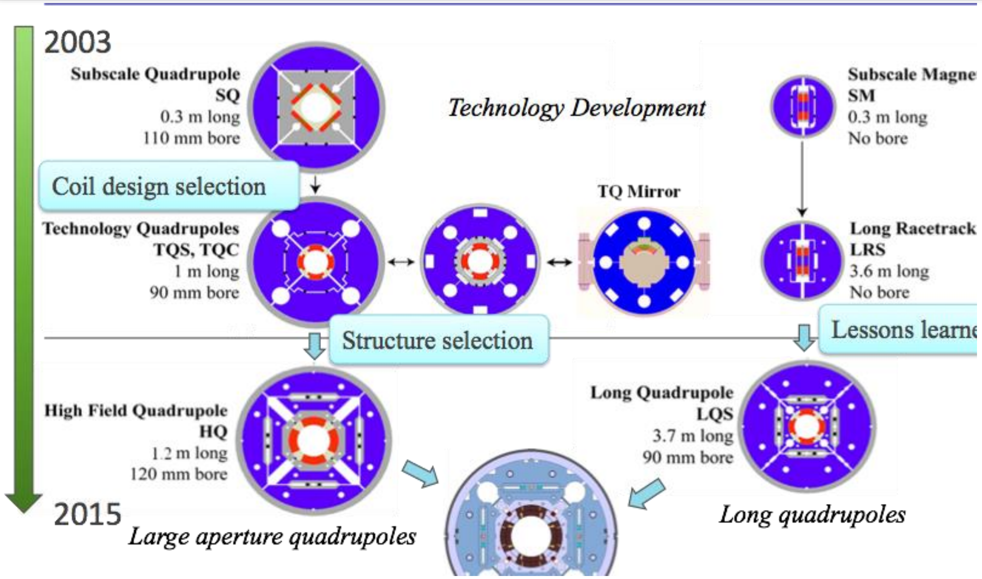
BNL
Member of US-MDP
Developing Various HTS Magnets
Advanced Technologies for HTS Magnet

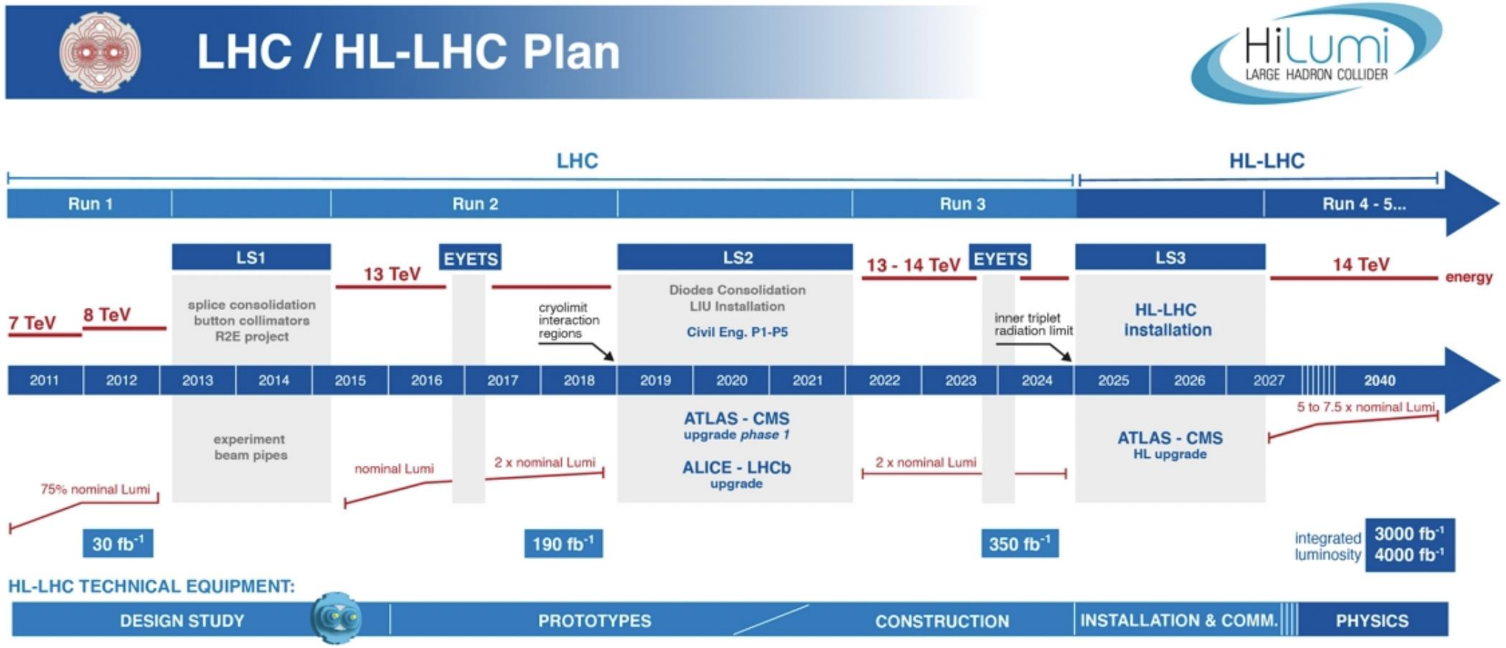
KEK
Developing HTS Magnets for High Radiation Environments
Advanced Technologies for HTS Magnet with Radiation Hardness

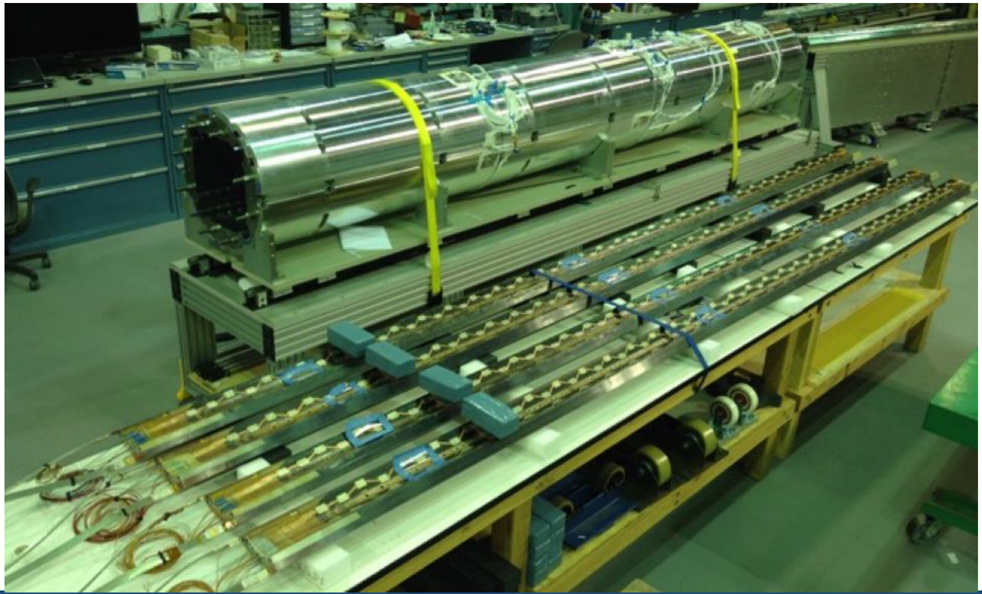
US-Japan Framework

Example: Toru Ogitsu, presentation at SoftA Workshop

Nb_3Sn accelerator magnet technology is - *for the 1^{st} time* - being installed in a collider







HiLumi production is arguably “boutique production”

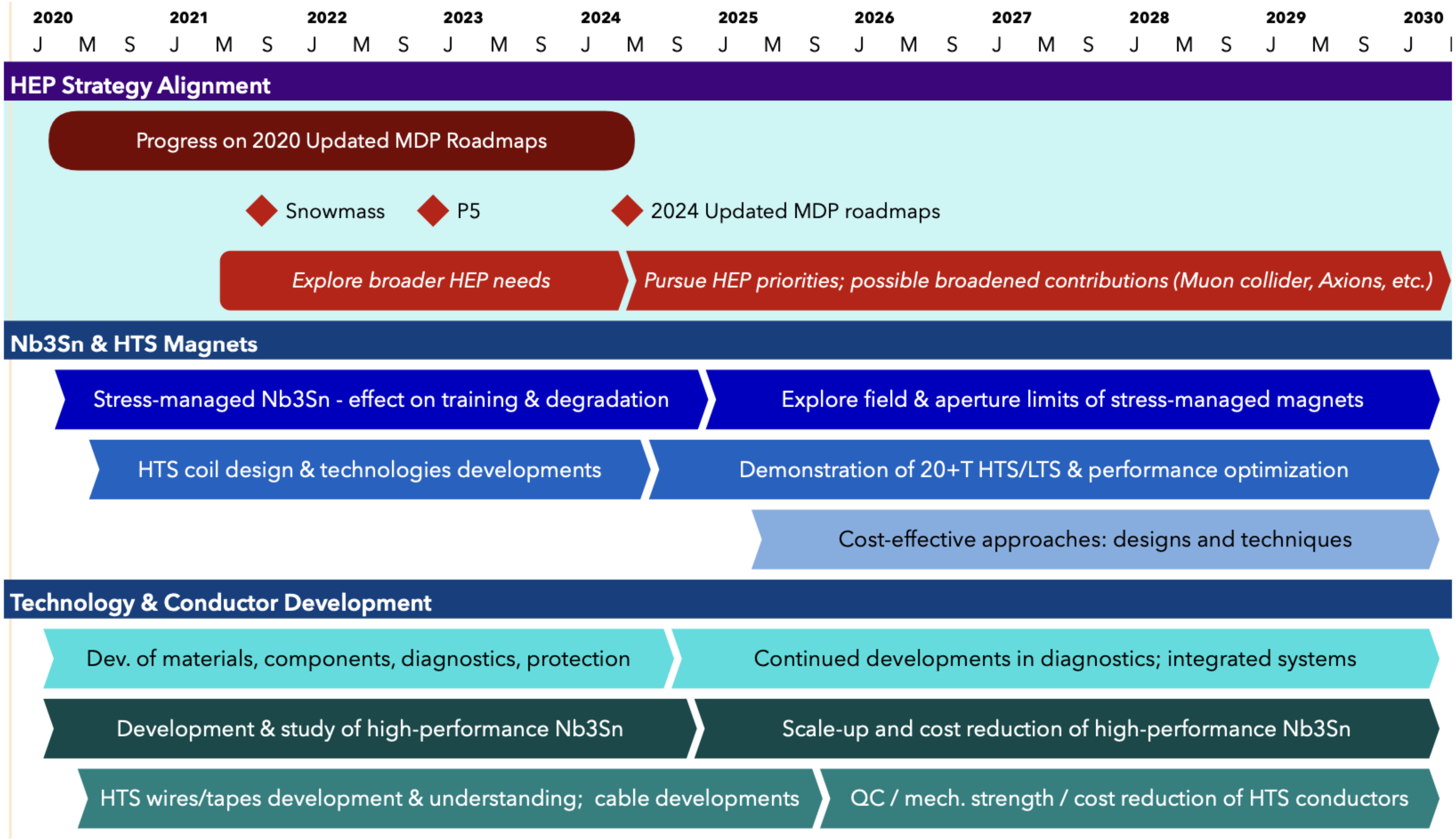
- What are the risks and benefits of full-scale industrial production of Nb_3Sn magnets?
- There is significant value-engineering that can be performed
- What elements of the design are “robust”, and what elements generate risk/performance limitations?

US MDP roadmaps

Continue alignment with physics community needs

Focus on “stress-management” as well as hybrid HTS/LTS magnet technology

Continue to invest in the “science of magnets” and in improved conductors



HEP Strategy Alignment

Progress on 2020 Updated MDP Roadmaps

Snowmass

P5

2024 Updated MDP roadmaps

Explore broader HEP needs

Pursue HEP priorities; possible broadened contributions (Muon collider, Axions, etc.)

Nb3Sn & HTS Magnets

Stress-managed Nb3Sn - effect on training & degradation

Explore field & aperture limits of stress-managed magnets

HTS coil design & technologies developments

Demonstration of 20+T HTS/LTS & performance optimization

Cost-effective approaches: designs and techniques

Technology & Conductor Development

Dev. of materials, components, diagnostics, protection

Continued developments in diagnostics; integrated systems

Development & study of high-performance Nb3Sn

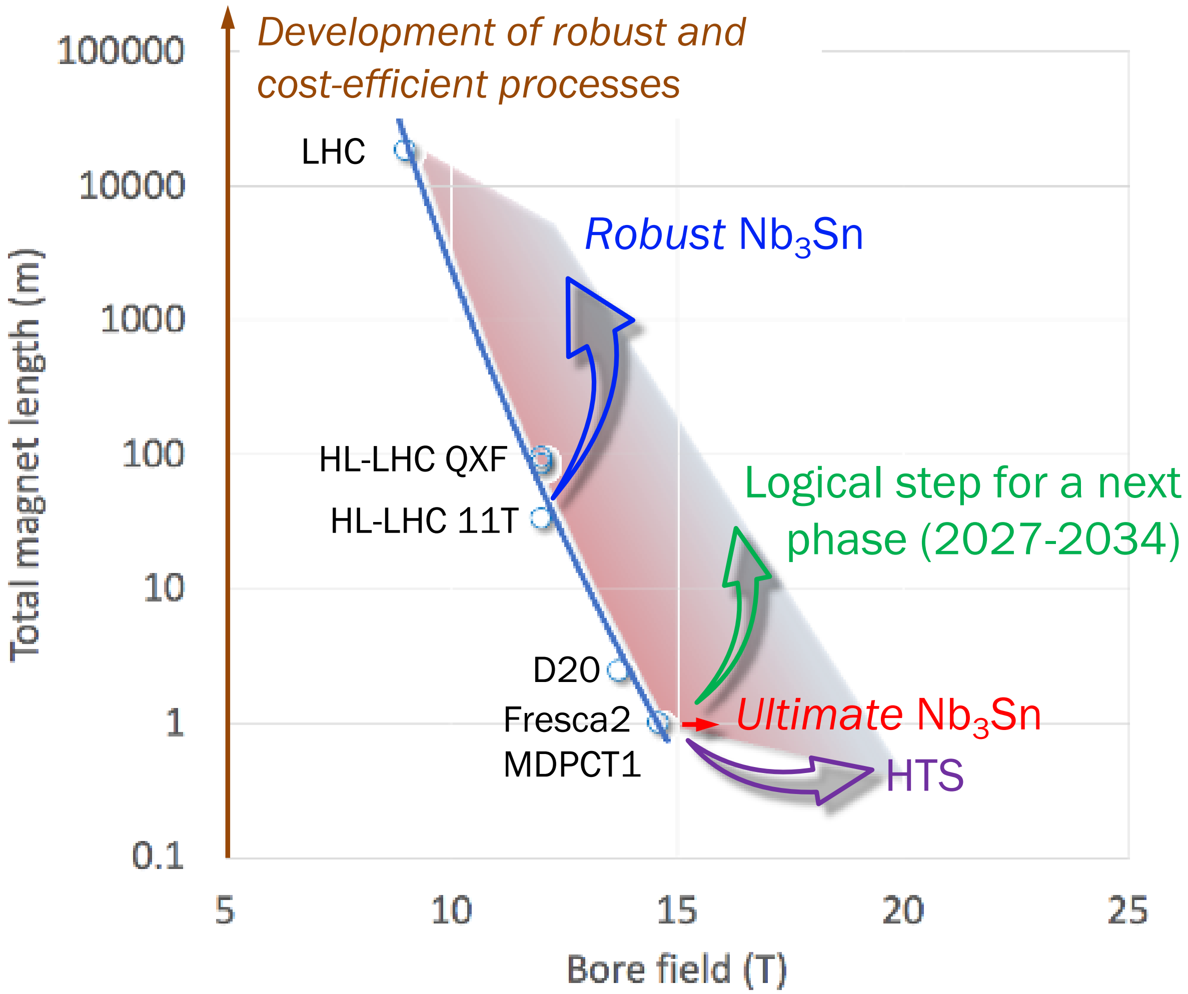
Scale-up and cost reduction of high-performance Nb3Sn

HTS wires/tapes development & understanding; cable developments

QC / mech. strength / cost reduction of HTS conductors

European HFM plans related to magnet technology

- Plans are being fleshed out, but will ***likely*** focus on:
    - Demonstrate Nb_3Sn magnet technology for large scale deployment, pushing it to its practical limits, both in terms of maximum performance as well as production scale
        - Demonstrate Nb_3Sn full potential in terms of ultimate performance (target 16 T)
        - Develop Nb_3Sn magnet technology for collider-scale production, through robust design, industrial manufacturing processes and cost reduction (benchmark 12 T)
    - Demonstrate suitability of HTS for accelerator magnet applications, providing a proof-of-principle of HTS magnet technology beyond the reach of Nb3Sn (target in excess of 20 T)
    - Implemented as a focused, innovative, mission-style R&D of collaborative nature



European HFM plans related to superconductors

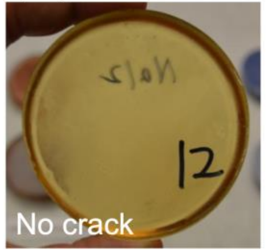
- Nb_3Sn Conductor
  - Secure **state-of-the-art** wire and cable for the magnet program at **affordable cost** (including extensive characterization measurements)
  - Pursue the FCC Conductor Development Program towards **ultimate performance** (new wire layouts and compositions, enhanced mechanical properties and reinforcements, magnetization and stability, means towards cost reduction for large scale production)
- HTS Conductor
  - Focus is on **REBCO** (exploit complementarity with US-MDP for Bi-2212)
  - Match **conductor** (tape and cable) **specifications** to accelerator magnet needs, and revisit present wisdom (EuCARD -> EuCARD2 -> ARIES-> I-FAST -> …)
  - Procure and develop **tailored conductor and cable concepts** for the magnet program
- Measurements
  - Coordinate wire, tape and cable characterization, including material studies and advanced analytical techniques

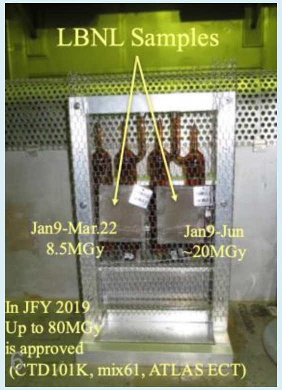
KEK plans and progress – magnet technology examples

- Task1: HTS magnet technologies for high-radiation environment
  - Gamma ray irradiation to organic materials
  - Neutron irradiation at the IMR Oarai and preform Ic test.
  - Microscopic analysis of irradiation damage.
- Task 2: Stability, quench protection, and magnet safety
  - Quench experiments of various spiral conductors.
- Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets
  - Analyses of mechanical effect of shielding current, and CCT wound with CORC wires. • Field measurement of various HTS magnets.
- Task 4: HTS/LTS high field hybrid accelerator dipole technology
  - Non-organic insulation technology R&D for HTS and Nb3Sn conductor.
  - Develop rad-hard racetrack coils that can be tested at BNL 10T test stand.
  - Prepare test stand, complete quench protection system design. Device a detailed test program including magnetization measurement.

CTD-101 k, used by US LARP, after one thermal cycle to 77 K

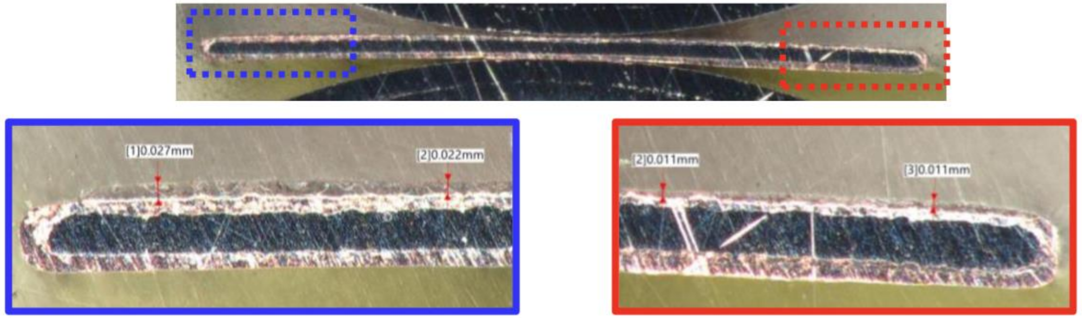
NHMFL-mix61, an amine-based epoxy after one thermal cycle to 77 K



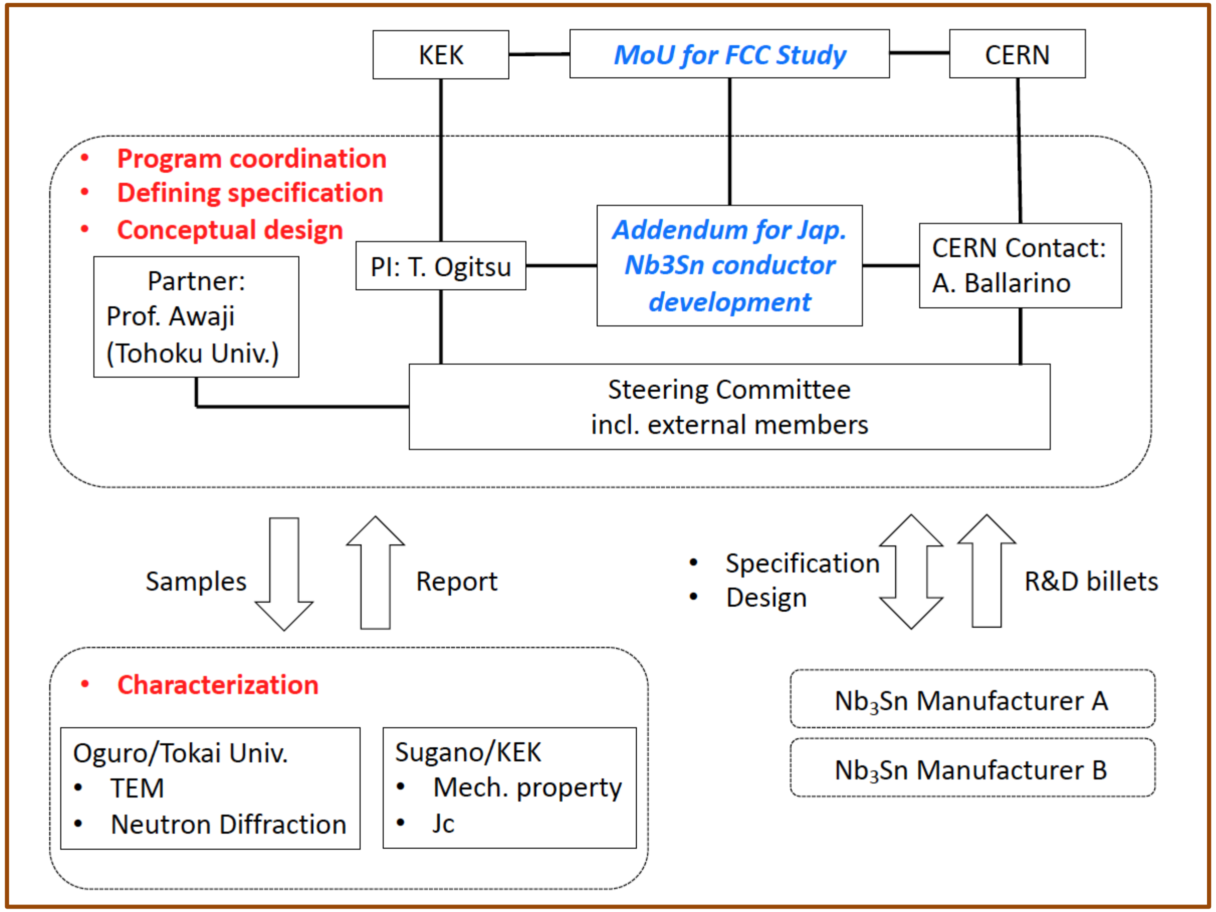


Radiation impacts on magnet materials

Development of inorganic insulation technology



KEK plans: conductors



KEK — *MoU for FCC Study* — CERN

- **Program coordination**
- **Defining specification**
- **Conceptual design**

Partner:
Prof. Awaji
(Tohoku Univ.)

PI: T. Ogitsu

Addendum for Jap. Nb3Sn conductor development

CERN Contact:
A. Ballarino

Steering Committee
incl. external members

Samples

Report

- Specification
- Design

R&D billets

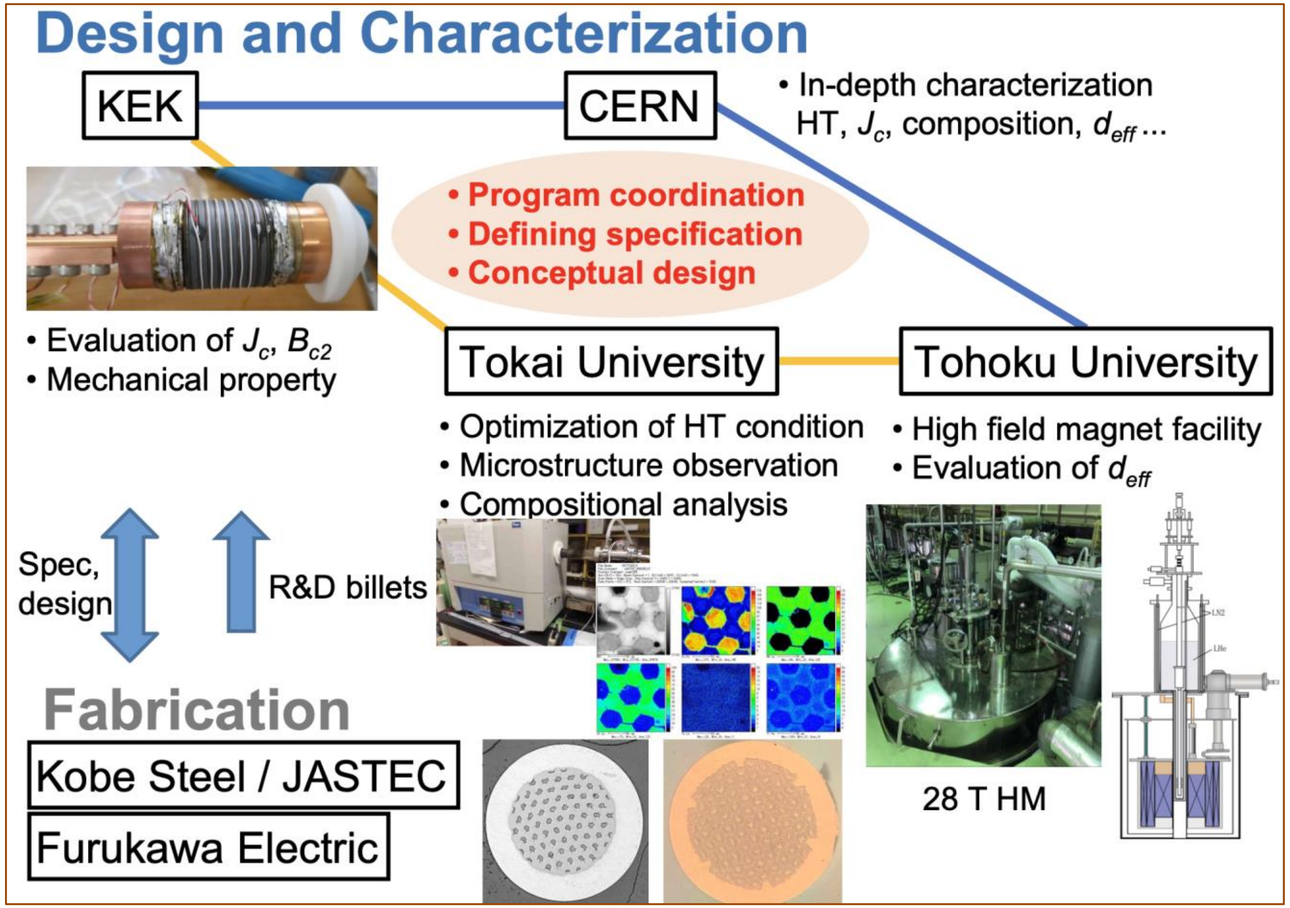
- **Characterization**

Oguro/Tokai Univ.
- TEM
- Neutron Diffraction

Sugano/KEK
- Mech. property
- Jc

Nb_3Sn Manufacturer A

Nb_3Sn Manufacturer B



Design and Characterization

KEK

CERN

- In-depth characterization HT, J_c, composition, d_{eff} ...

- **Program coordination**
- **Defining specification**
- **Conceptual design**

- Evaluation of J_c, B_{c2}
- Mechanical property

Tokai University

- Optimization of HT condition
- Microstructure observation
- Compositional analysis

Tohoku University

- High field magnet facility
- Evaluation of d_{eff}

Spec, design

R&D billets

Fabrication

Kobe Steel / JASTEC

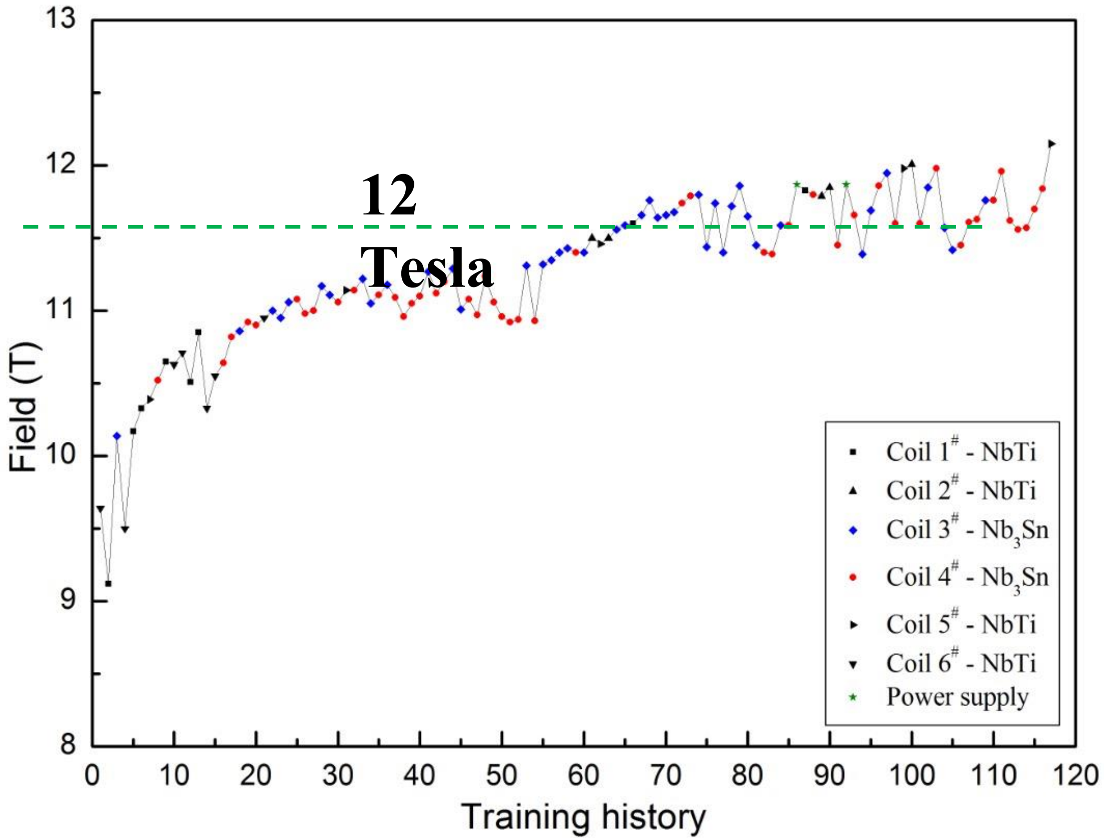
Furukawa Electric

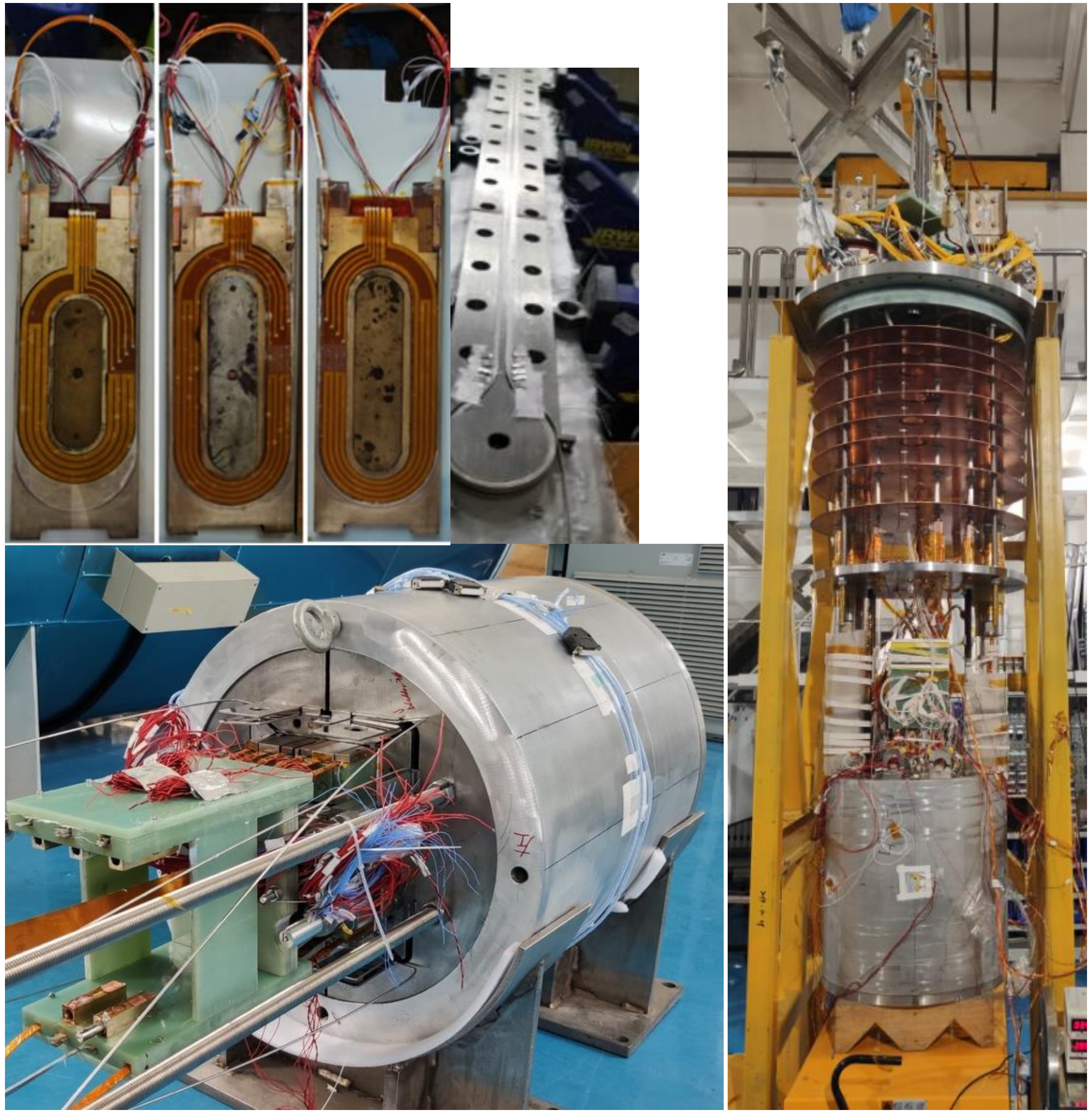
28 T HM

Toru Ogitsu, SoftA Workshop, April 2021

IHEP Progress example: R&D of the NbTi+Nb_3Sn Model Dipole Magnet

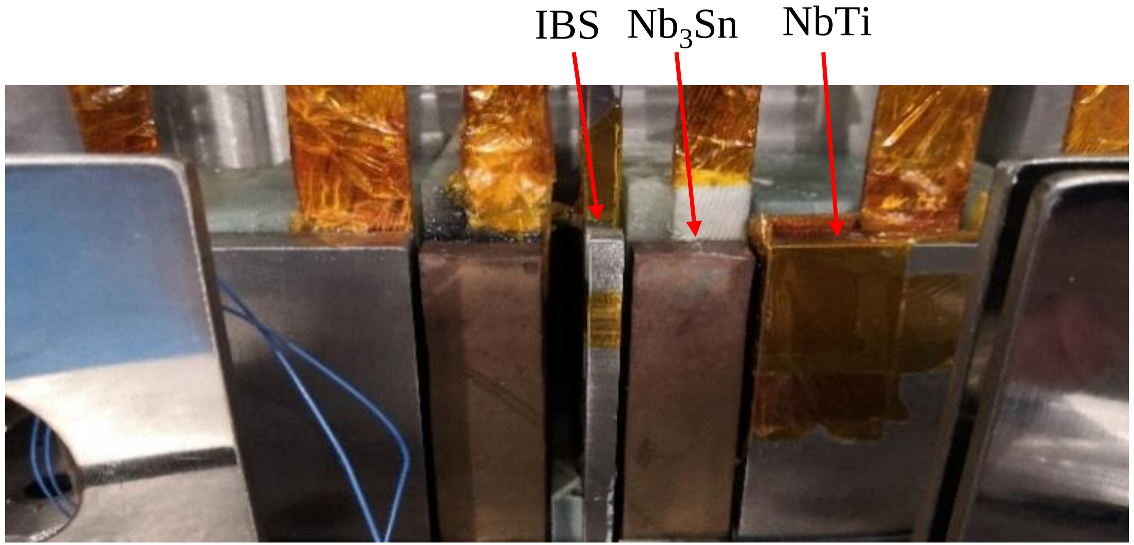
The **NbTi+Nb_3Sn dual-aperture** model dipole was developed and 1st tested in 2017-2018, reached **12 T at 4.2 K** by replacing some new coils and increasing pre-stress during assembly .



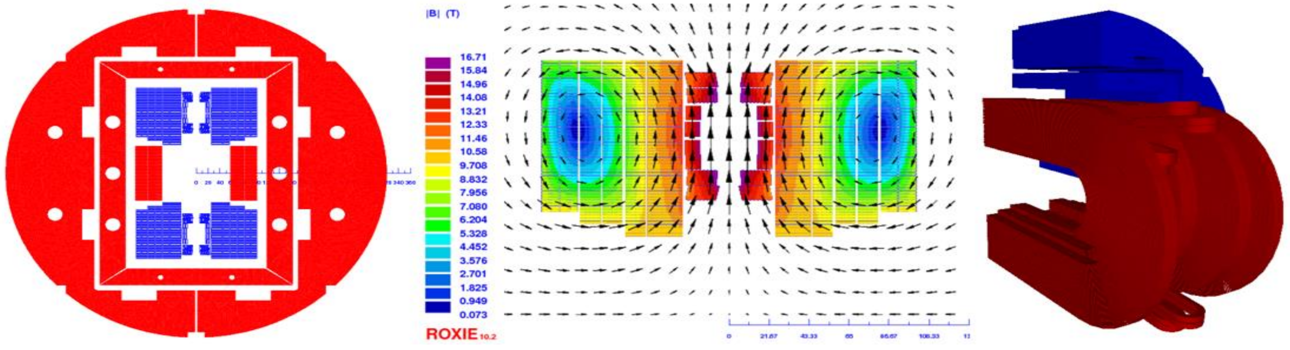


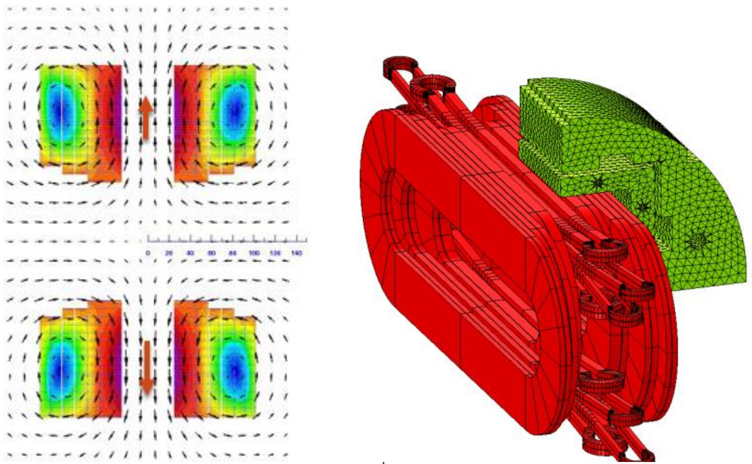
IHEP Plans: Racetrack Coils with IBS Tapes, and 16T Dipole Magnet with LTS+HTS

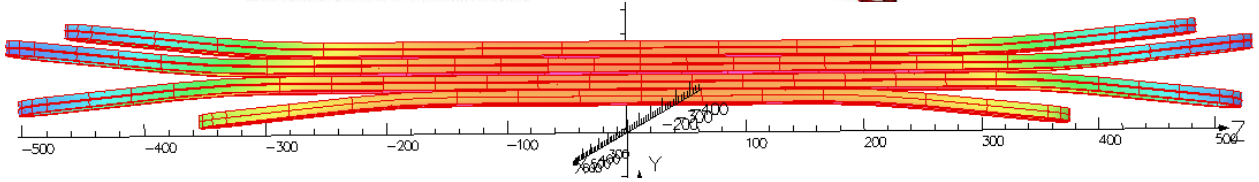
- Two racetrack coils have been made using 100-m length Iron-Based Superconducting tapes.
- The coils reached 86.7% of critical current of the short sample at 4.2 K and 10 T, and 81.25% of the quench current under self-field, with highest compressive stress of 120 MPa.



Zhang, et al., *SuST*,. 34 (2021) 035021







Summary

- The High Energy Physics community has clearly indicated the science potential associated with a future circular collider that probes significantly higher energies

=> *The onus is on the magnet community to determine what is possible and what is feasible in terms of field strength*

There is a concerted effort around the world to integrate teams of specialists and facilities to most efficiently, effectively, and rapidly advance magnet technology

There is also strong interest in collaborating internationally, where strengths and capabilities are deemed complementary

We are at a critical period, where innovation and progress in magnet technology is essential to enable the next generation of collider – we welcome the challenge while recognizing the responsibility!