# Snowmass'21 Accelerator Frontier
# AF7 Accelerator Technology

# Magnet LoI
# Status and Plans

*LoI Authors*

*August 27, 2020*

# AF7/Magnet LoI Presentations

1. Regional program overviews
   - US (Prestemon); EU (Bottura); Japan (Ogitsu); China (Xu)
2. Detector Magnets
   - FCC-hh, FCC-ee, AMS (Mentink); J-PARC g-2/EDM, COMET-I&II, ILC (Sasaki)
3. New superconducting wire and cable development
   - Ultra thin A-15 (Kitaguchi); PIT-IBS (Ma)
4. Dipole magnet design and development
   - Cos$\theta$, CCT, Fast ramping (Fabbricatore); Block (Felice); Common coil (Gupta); REBCO (Wang); Bi-2212 Accelerators (Garcia-Fajardo); Hybrid Nb3Sn/HTS (Ferracin); Bi-2212 Solenoids (Davis);
5. Special magnets and new fabrication technologies
   - Direct wind, high field solenoids (Amm); wind-react-wind (Caspi)
6. New accelerator concepts
   - Collider in the sea (McIntyre)

# US Magnet Development Program

U.S. MAGNET DEVELOPMENT PROGRAM

## The US Magnet Development Program
## Planning for the future

Soren Prestemon
US Magnet Development Program
Lawrence Berkeley National Laboratory

**Management Team**

Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier, George Velev, Sasha Zlobin

# US Magnet Development Program

U.S. MAGNET
DEVELOPMENT
PROGRAM

## Program vision and goals

- **Vision**
  - Maintain and strengthen US Leadership in high-field accelerator magnet technology for future colliders;
  - Further develop and integrate magnet research teams across the partner laboratories and US Universities for maximum value and effectiveness to MDP;
  - Identify and nurture cross-cutting / synergistic activities with other programs (e.g. Fusion), to more rapidly advance progress towards our goals.

- **Overarching goals:**
  - ***Explore the performance limits*** of **Nb3Sn accelerator magnets**, with a sharpened focus on minimizing the required operating margin and significantly reducing or eliminating training
  - ***Develop and demonstrate an HTS accelerator magnet with a self-field of 5T*** or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16T
  - ***Investigate fundamental aspects of magnet design and technology*** that can lead to substantial performance improvements and magnet cost reduction
  - ***Pursue Nb3Sn and HTS conductor R&D*** with clear targets to increase performance, understand present performance limits, and reduce the cost of accelerator magnets

**DOE Office of HEP**
**Research & Technology Div. – G. Crawford**
**Program Manager – K. Marken**

MDP Steering Council

**Lawrence Berkeley National Laboratory**
**Associate Lab Director, Physical Sciences**
**Natalie Roe**
**ATAP Interim Division Director**
**Thomas Schenkel**

**Magnet Development Program**
**S. Prestemon, Director**
**G. Velev, Deputy**

Technical Advisory Committeee

$Nb_3Sn$ magnets

HTS magnets

Technology development

Conductor procurement and R&D

LBNL
BNL
FNAL
ASC/NHMFL

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# US Magnet Development Program

U.S. MAGNET DEVELOPMENT PROGRAM

## Major results from the previous four years

- Progress on multiple fronts
  - Cos-theta magnet MDPCT1 (FNAL) achieved 14.5T (60mm aperture)!
  - First two 2-layer $Nb_3Sn$ Canted-Cos-theta (CCT) magnets (90mm bore) tested
    - Reached 86-88% short-sample; different epoxy=> improved training;
  - Steady progress on REBCO CORC-based magnet technology
  - Significant progress on Bi2212 magnet technology
    - 4.7T common coil => no training!
  - Variety of developments and improvements in diagnostics
  - Important developments in conductor R&D (with industry)
    - Record $Nb_3Sn$ via Zr doping; strong promise from Hf alloying
    - Record Bi2212 wire performance
      - Significantly exceeds "FCC spec" at 16T
      - New Bi2212 powder producer – seeded by SBIR
  - And many others…

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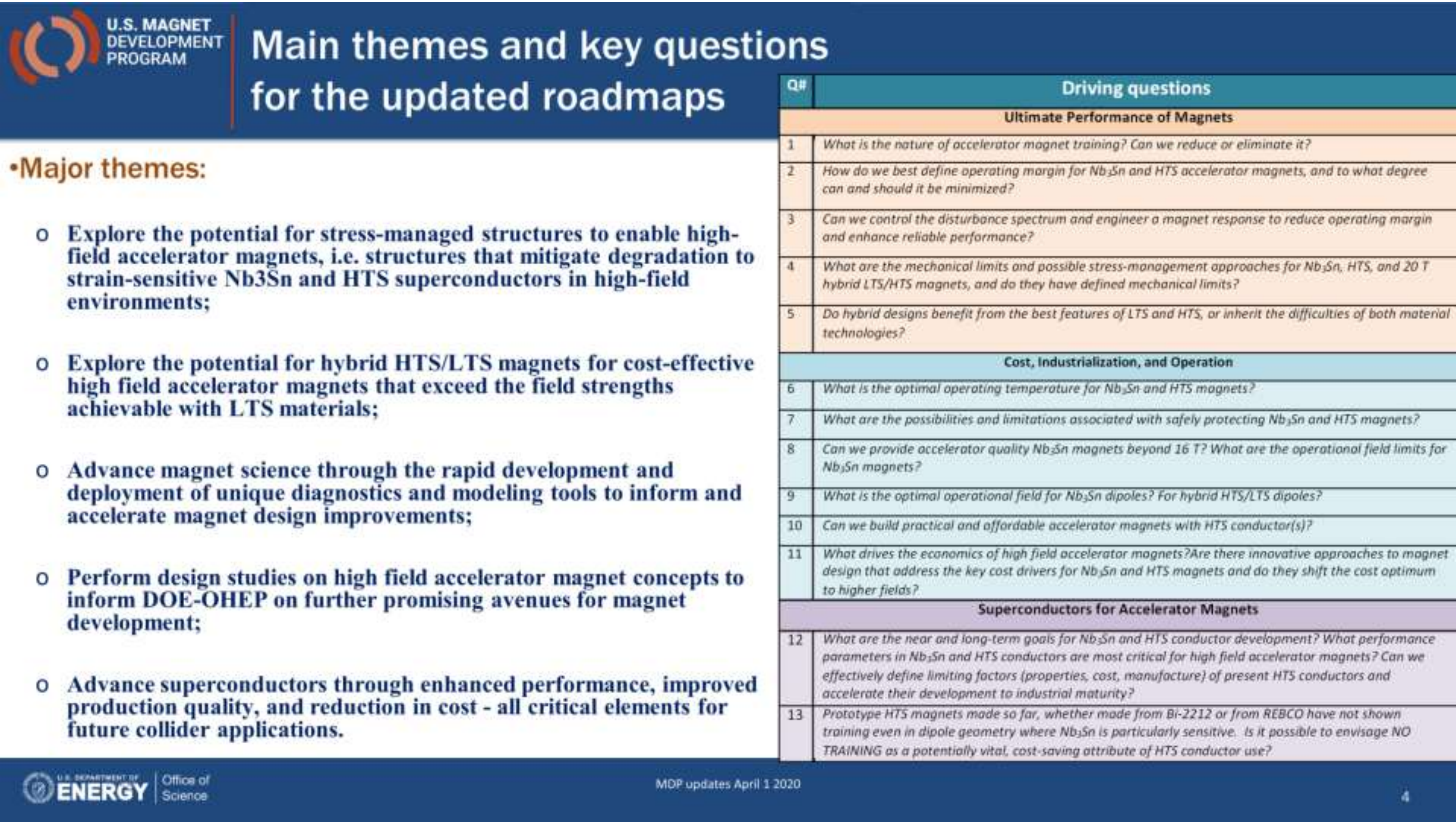
# US Magnet Development Program



U.S. MAGNET DEVELOPMENT PROGRAM

## Main themes and key questions for the updated roadmaps

•**Major themes:**

- Explore the potential for stress-managed structures to enable high-field accelerator magnets, i.e. structures that mitigate degradation to strain-sensitive Nb3Sn and HTS superconductors in high-field environments;
- Explore the potential for hybrid HTS/LTS magnets for cost-effective high field accelerator magnets that exceed the field strengths achievable with LTS materials;
- Advance magnet science through the rapid development and deployment of unique diagnostics and modeling tools to inform and accelerate magnet design improvements;
- Perform design studies on high field accelerator magnet concepts to inform DOE-OHEP on further promising avenues for magnet development;
- Advance superconductors through enhanced performance, improved production quality, and reduction in cost - all critical elements for future collider applications.

| Q# | Driving questions |
|---|---|
| | **Ultimate Performance of Magnets** |
| 1 | *What is the nature of accelerator magnet training? Can we reduce or eliminate it?* |
| 2 | *How do we best define operating margin for $Nb_3Sn$ and HTS accelerator magnets, and to what degree can and should it be minimized?* |
| 3 | *Can we control the disturbance spectrum and engineer a magnet response to reduce operating margin and enhance reliable performance?* |
| 4 | *What are the mechanical limits and possible stress-management approaches for $Nb_3Sn$, HTS, and 20 T hybrid LTS/HTS magnets, and do they have defined mechanical limits?* |
| 5 | *Do hybrid designs benefit from the best features of LTS and HTS, or inherit the difficulties of both material technologies?* |
| | **Cost, Industrialization, and Operation** |
| 6 | *What is the optimal operating temperature for $Nb_3Sn$ and HTS magnets?* |
| 7 | *What are the possibilities and limitations associated with safely protecting $Nb_3Sn$ and HTS magnets?* |
| 8 | *Can we provide accelerator quality $Nb_3Sn$ magnets beyond 16 T? What are the operational field limits for $Nb_3Sn$ magnets?* |
| 9 | *What is the optimal operational field for $Nb_3Sn$ dipoles? For hybrid HTS/LTS dipoles?* |
| 10 | *Can we build practical and affordable accelerator magnets with HTS conductor(s)?* |
| 11 | *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** |
| 12 | *What are the near and long-term goals for $Nb_3Sn$ and HTS conductor development? What performance parameters in $Nb_3Sn$ 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?* |
| 13 | *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?* |

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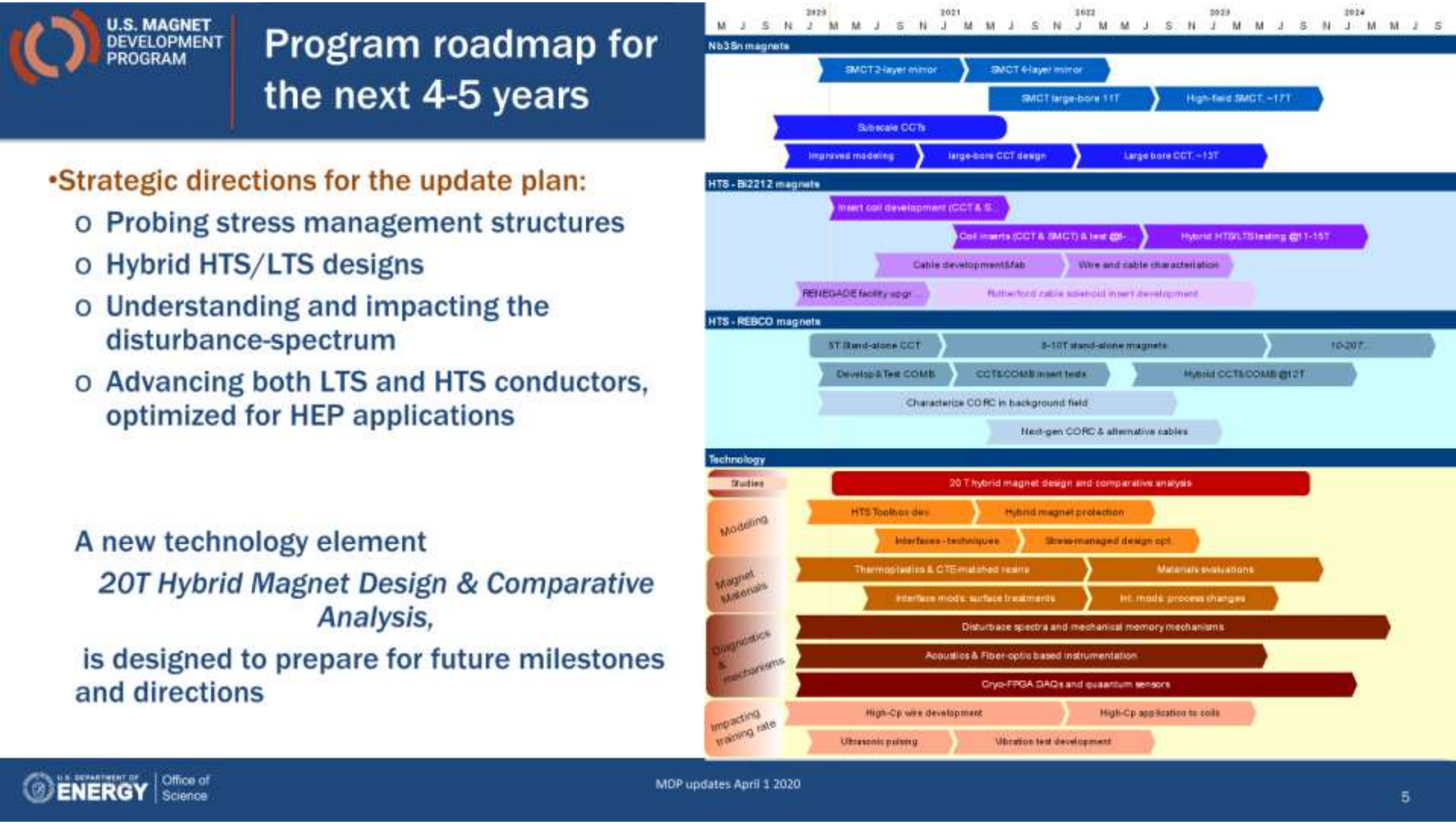
# US Magnet Development Program



U.S. MAGNET
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## Program roadmap for the next 4-5 years

- **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

A new technology element

*20T Hybrid Magnet Design & Comparative Analysis,*

is designed to prepare for future milestones and directions

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# US Magnet Development Program

**U.S. MAGNET DEVELOPMENT PROGRAM**

## Draft ten-year roadmap

- A 10-year high-level roadmap recognizes the Snowmass process and possible program adjustments

- Significant synergies with other programs
  - NHMFL development of high field solenoid technologies
  - Fusion development of high-field HTS-based Tokamaks
  - The DOE HEP and FES offices are investing now in a High Field Cable Test Facility
    - 15T, 100x150mm bore
    - Primarily for HTS Cable testing
    - Facility to be hosted at FNAL
    - LBNL responsible for magnet
      - Collaborating with CERN

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# High Field Magnet Development for HEP – A Proposal

L. Bottura (CERN), B. Auchmann (CERN), A. Ballarino (CERN), A. Devred (CERN), S. Izquierdo-Bermudez (CERN), L. Rossi (CERN), F. Savary (CERN), E. Todesco (CERN), D. Tommasini (CERN), G. De Rijk (CERN), D. Schoerling (CERN)

H. Felice (CEA), P. Vedrine (CEA)

F. Toral (CIEMAT), L. Garcia-Tabares Rodriguez (CIEMAT), J.-M. Perez (CIEMAT)

P. Fabbricatore (INFN), S. Farinon (INFN), M. Sorbi (INFN)

M. Seidel (PSI), S. Sanfilippo (PSI)

C. Senatore (UniGe)

B. Holzapfel (KIT), M. Noe (KIT), T. Arndt (KIT)

NOTE: draft author list for the moment

# The Status (August 2020)

- **The HL-LHC $Nb_3Sn$ program has set a new benchmark**: we have completed the initial model and prototype magnet development for operation in the 11-12 T field range and the next step is to capitalize on it, **use this benchmark to develop industrial, robust and efficient techniques**
- We have a few demonstrators showing that $Nb_3Sn$ has the potential to operate at fields beyond 14 T, the next step is to **confirm this potential with model magnets and prototypes**
- We have not yet had the opportunity to explore the potentials of HTS, the next step is to **develop and test demonstrators to assess this technology**

# HFM *Mission Statement* (2021-2027)

- Push $Nb_3Sn$ magnet technology to its practical limit, both in terms of maximum performance as well as production scale
  - **Demonstrate $Nb_3Sn$ full potential** in terms of ultimate performance (target 16 T)

I

  - **Develop $Nb_3Sn$ magnets for collider-scale production**, through robust design, industrial processes and cost reduction (benchmark 12 T)

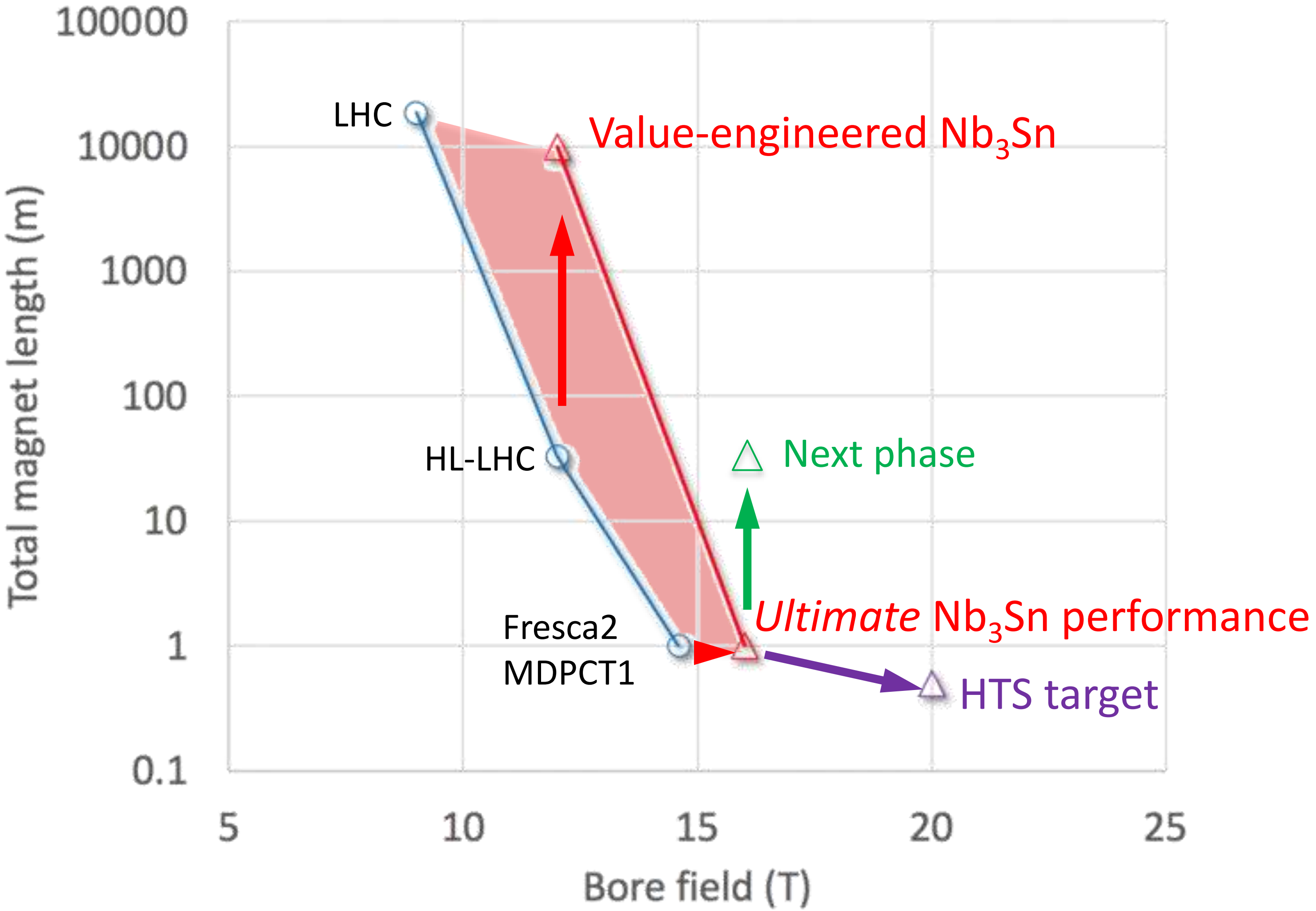
II

- **Provide a proof-of-principle for HTS magnet technology** beyond the reach of $Nb_3Sn$, and sufficient field quality for accelerator application (target in excess of 20 T)

III

OMNE TRIVM PERFECTVM

# HFM *Mission Statement* (2021-2027)



# Future plans

- A paper is in drafting phase, shared with the collaborators (description of the HFM program)
- Discussions are on-going with present and potential collaborators
- The program is intended as a collaborative effort, and will benefit from coordination and communication (worldwide)
  - How to build the structure of the program (work packages)
  - How to coordinate ands communicate
    - A governance ?

# R&D work for Superconducting Magnet for Future Accelerator Applications

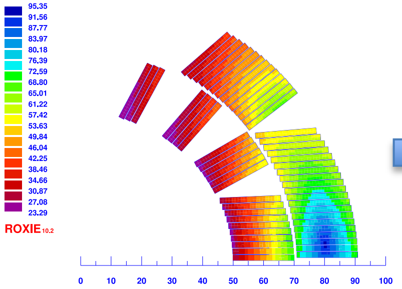
- Toru Ogitsu[1a], Tatsushi Nakamoto[1], Ken-ichi Sasaki[1], Michinaka Sugano[1], Masami Iio[1], Kento Suzuki[1], Makoto Yoshida[2], Satoshi Awaji[3b], Naoyuki Amemiya[4c], Yusuke Sogabe[4];
  - [1] KEK Cryogenics Science Center, [2] KEK Institute of Particle and Nuclear Physics,
  - [3] Tohoku University High Field Laboratory for Superconducting Materials,
  - [4] Kyoto University Graduate School of Engineering Department of Electrical Engineering
- Technical Highlights
  - High Field Superconducting Accelerator Magnet Technologies
  - Radiation Hard Superconducting Magnet Technologies

| Technology | Near Term Target | Mid Term Target | Ultimate Target |
|---|---|---|---|
| High Field | High Field High Jc Reinforced $Nb_3Sn$ | 12T Large Aperture R&D Dipole | High Field Radiation Hard SC Magnets for Future High Energy and High Intensity Accelerators (FCC, Muon Collider..) |
| Radiation Hard | Radiation Hard HTS Mag. Technologies | J-PARC MLF 2nd Target | |

# R&D work for Superconducting Magnet for Future Accelerator Applications

- High Field Superconducting Accelerator Magnet Technologies

HL-LHC D1 Development

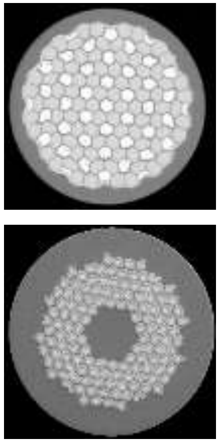


FCC D1 Design Study

12 T large aperture (100mm) $Nb_3Sn$ dipole magnet development (FCC D1 Model)

16 T dipole magnet R&D with 4 T $Nb_3Sn$ insert

20 T dipole magnet R&D with 8 T HTS insert



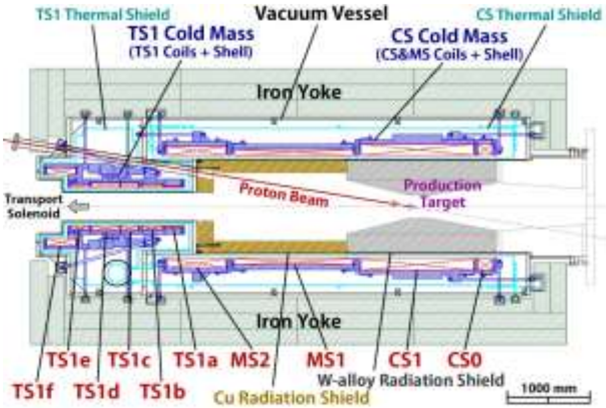
Strain-Jc Measurement Instruments

Internal Strain Measurement by Neutron Diffraction at J-PARC

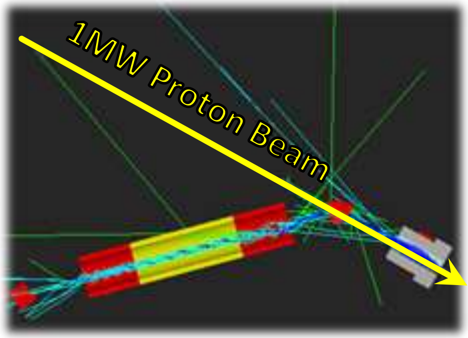
High Field High Jc $Nb_3Sn$ R&D (with Mechanical Reinforcement)

# R&D work for Superconducting Magnet for Future Accelerator Applications

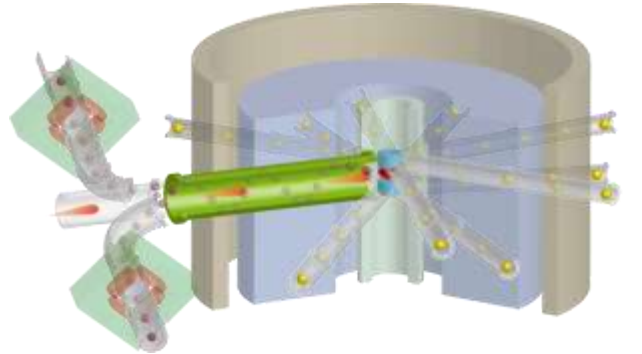
- Radiation Hard Superconducting Magnet Technologies



COMET Capture Solenoid Development



J-PARC MLF Second Target Design Study



J-PARC MLF Second Target with High Intensity Muon Source

US-JP R&Ds

Gamma Irradiation on Organic Material

Neutron Irradiation on Superconductor

**SCS4050-AP (SuperPower)**

Inorganic Insulation Study

HTS Quench Protection Study (Al Stabilizer See Sasaki's Proposal)

High Field Radiation Hard SC Magnet Technologies

FCC IRQ
Muon Collider
Etc..

# Status and Plan of the High Field Magnet R&D for Future Accelerators

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

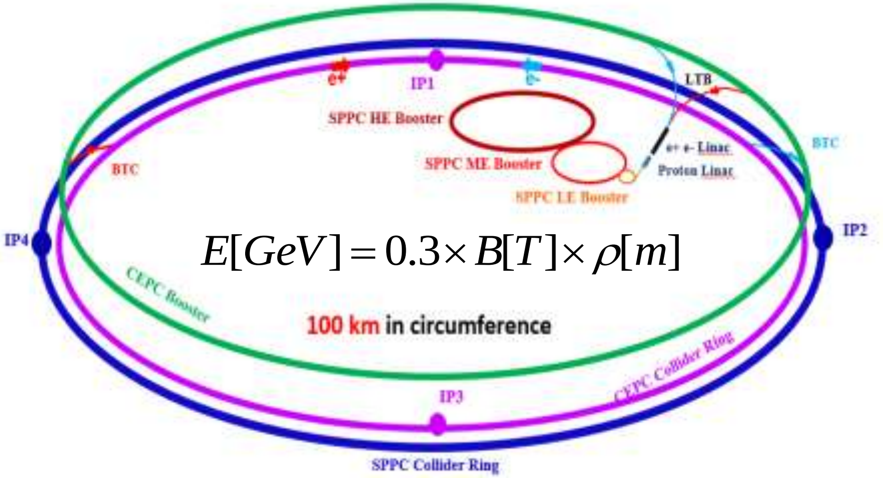
## *SPPC Magnet Design Scope*

*Field strength: 12-24 Tesla to get 75-150 TeV in a 100-km tunnel*

*Baseline Iron-Based Superconductor (IBS), $Nb_3Sn$/ReBCO etc. as options*

*Aperture diameter: 40~50 mm*

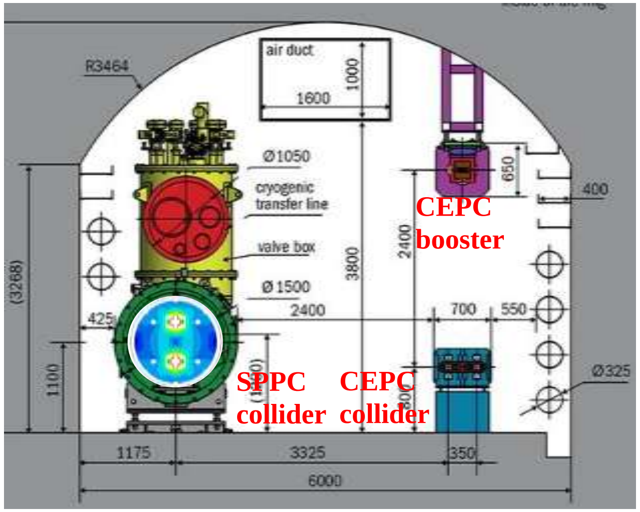
*Field quality: $10^{-4}$ at the 2/3 radius*



$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

100 km in circumference

*Site study of the CEPC-SPPC*

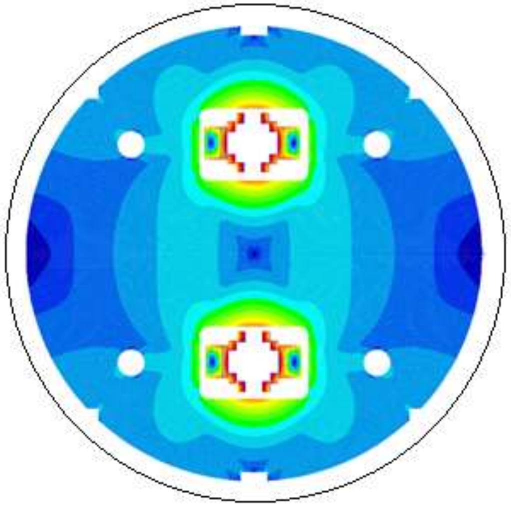


CEPC booster

SPPC collider

CEPC collider

*6-m width Tunnel for CEPC-SPPC*

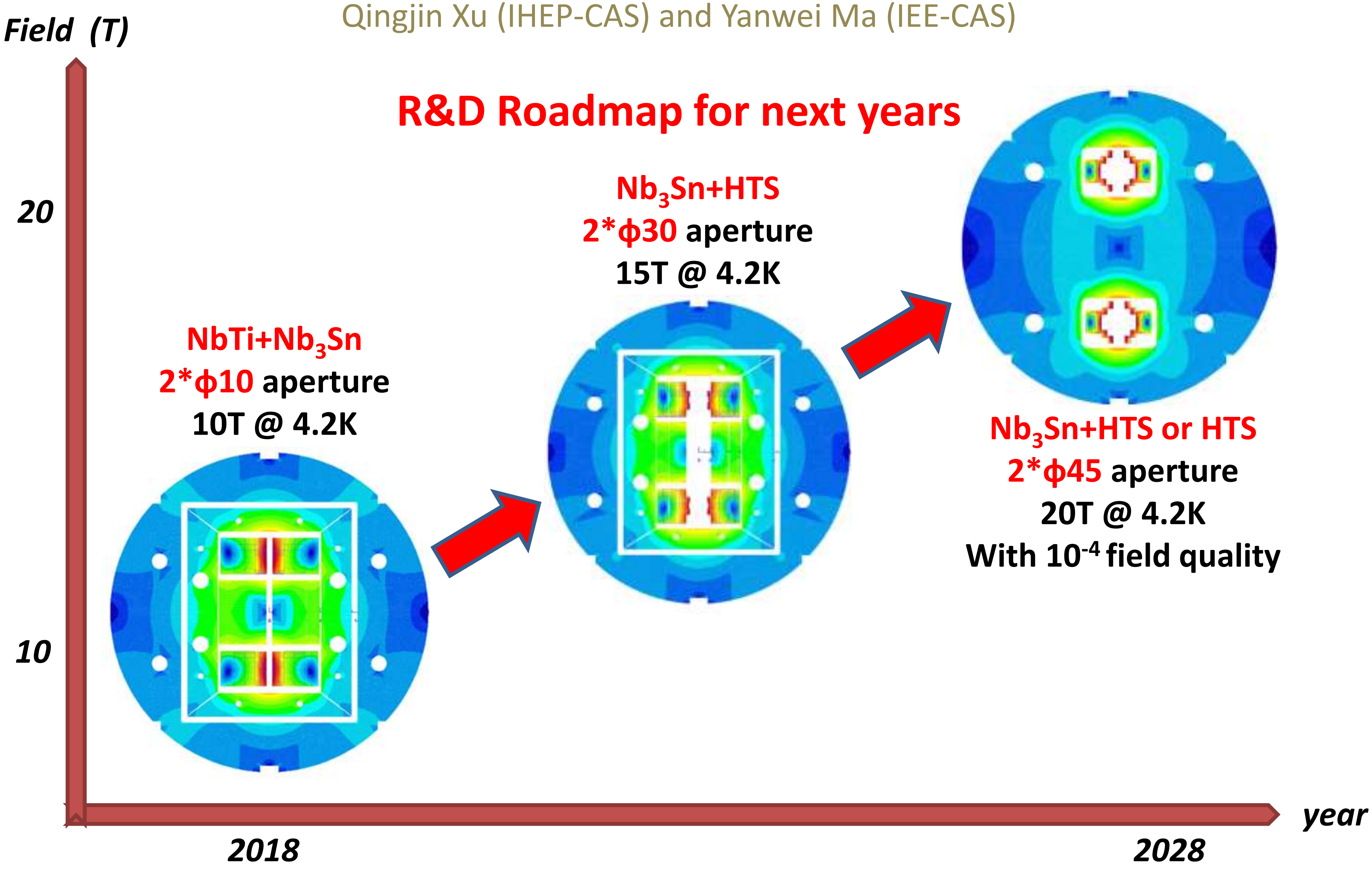


*SPPC Dipole with IBS*

# Status and Plan of the High Field Magnet R&D for Future Accelerators

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

## R&D Roadmap for next years



**NbTi+Nb$_3$Sn**
**2*ϕ10 aperture**
**10T @ 4.2K**

**Nb$_3$Sn+HTS**
**2*ϕ30 aperture**
**15T @ 4.2K**

**Nb$_3$Sn+HTS or HTS**
**2*ϕ45 aperture**
**20T @ 4.2K**
**With $10^{-4}$ field quality**

# Status and Plan of the High Field Magnet R&D for Future Accelerators

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

## Now China has two 5-Year Programs for IBS and high-field magnets, starting in 2018 and 2019, respectively.

**Proposal for**
**Strategic Priority Research Program**
**of Chinese Academy of Sciences (CAS)**
Science and Technology Frontier
Research
for High Field Applications of High
Temperature Superconductors

**Ranked No. 1 in 7 candidates**
**by Academic Committee of CAS**
**360M RMB for 2018-2023**

**The National Key Research and**
**Development Program of China**

科学技术部
高技术研究发展中心

**43M RMB for 2019-2024**

国科高发计字〔2019〕55号

**关于印发国家重点研发计划**
**“变革性技术关键科学问题”重点专项**
**2018 年度项目立项的通知**

***R&D from Fundamental research, advanced IBS conductors to Magnet & SRF technology***

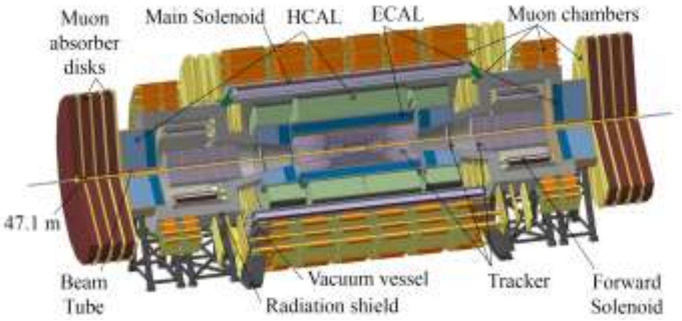
1. **Mainly *122* PIT wires & tapes**
2. ***11* coated conductors**

**(*100 m long fabrication*)**

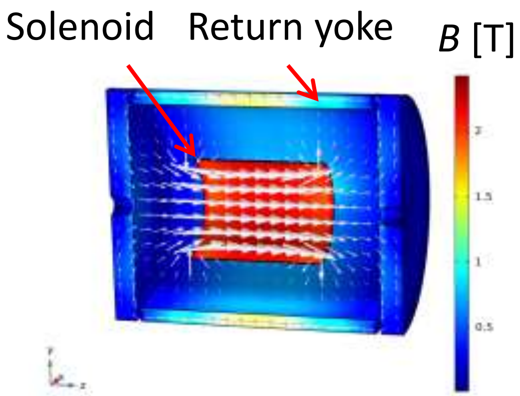
## *International collaboration are welcome!*

# Superconducting Detector Magnets for High Energy Physics

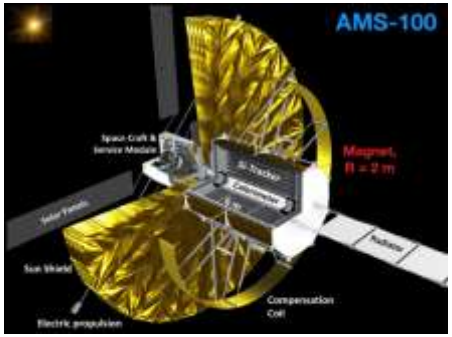
- Matthias Mentink, Helder Pais Da Silva, Tim Mulder, Alexey Dudarev, CERN
- Technical Highlights:
  - FCC-hh baseline detector design comprising superconducting solenoids utilizing aluminum-stabilized Nb-Ti conductor
  - FCC-ee “IDEA” baseline detector design, featuring ultra-transparent solenoid utilizing high-stress aluminum-stabilized Nb-Ti conductor
  - ReBCO-based ultra-transparent concentric superconducting solenoid for AMS-100 [1,2], also of interest for FCC-ee



*FCC-hh baseline design featuring superconducting Al/Nb-Ti solenoids*



*FCC-ee “IDEA”baseline design featuring ultra-transparent Al/Nb-Ti solenoid*



*AMS-100 featuring ultra-transparent ReBCO-based concentric solenoid [2]*

1. In collaboration with: University of Aachen, Paul Scherrer Institute, University of Geneva
2. S. Schael et al., https://doi.org/10.1016/j.nima.2019.162561

# Development of Large Scale Superconducting Solenoid Technologies for Future Accelerator Experiments

- Ken-ichi Sasaki[1], Mitsushi Abe[1], Makoto Yoshida[2], Masami Iio[1], Takahiro Okamura[2], Yasuhiro Makida[2], Naoyuki Sumi[1], Toru Ogitsu[1], Hiromi Iinuma[3];
  - [1] KEK Cryogenics Science Center, [2] KEK Institute of Particle and Nuclear Physics, [3] Ibaraki University Graduate School of Science and Engineering,
- Technical Highlights
  - Technology for high precision magnetic field design, control and mechanical design in 3-D and cryogenic system.
  - R&D for advanced Al stabilized superconducting cable

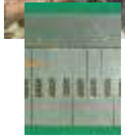
| | Near Term Target | Mid Term Target | Ultimate Target |
|---|---|---|---|
| Design technology | • J-PARC g-2/EDM<br>• COMET Phase-I | • COMET Phase-II<br>• J-PARC MLF 2nd Target | • ILD for ILC<br>• Detector for FCC<br>• Magnets for High Intensity Muon source |
| Al stabilized SC cable | Basic R&D<br>-Advanced NbTi<br>-HTS | Production | |

TOPAZ
VENUS
AMY
1980's~1990's

TOPAZ

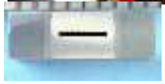
LHC ~2000's

ATLAS



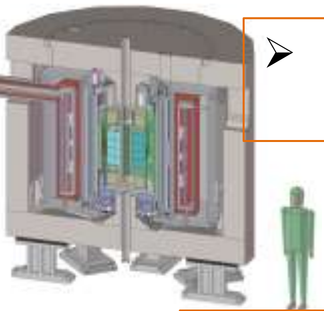
-Ni-doped Al

CMS

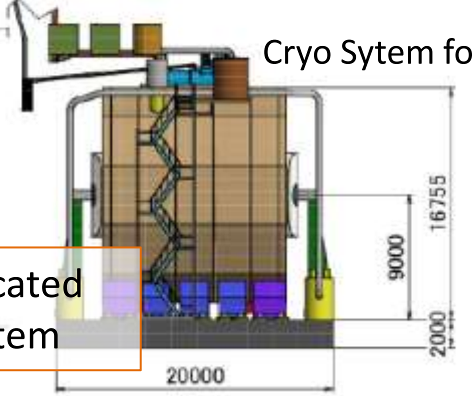


-Hybrid stabilizer

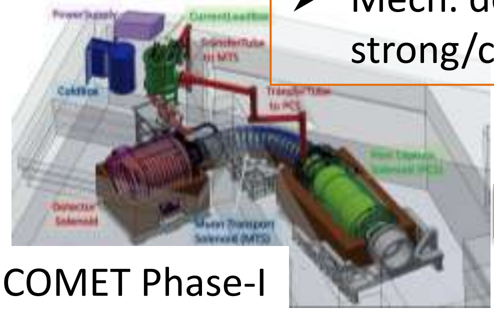
## ✓ *Design technology*



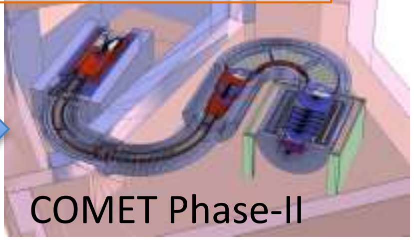
- Precision Mag. Field Design
- Sophisticated Cryo system
- Mech. design for strong/complicated mag. force



Cryo Sytem for ILD



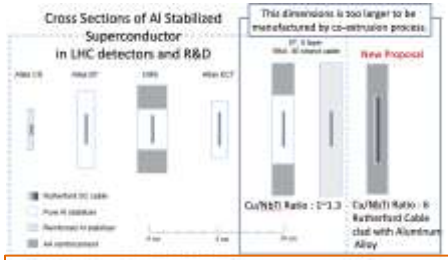
COMET Phase-I



COMET Phase-II

## ✓ *Advanced Al stabilized SC conductor*

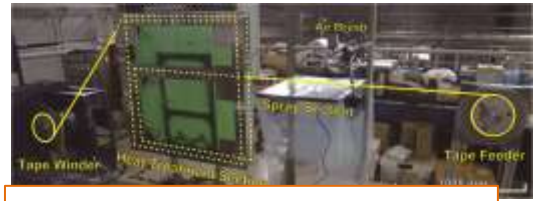
COMET CAP(2015)



Cross Sections of Al Stabilized Superconductor in LHC detectors and R&D

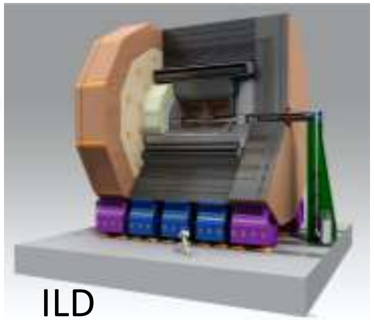
This dimensions is too larger to be manufactured by co-extrusion process

R&D of advanced cable for ILC



Basic R&D of Al stabilized HTS

- Ultimate target
  - ☐ ILD for ILC
  - ☐ Detector for FCC
  - ☐ Magnets for High Intensity Muon source

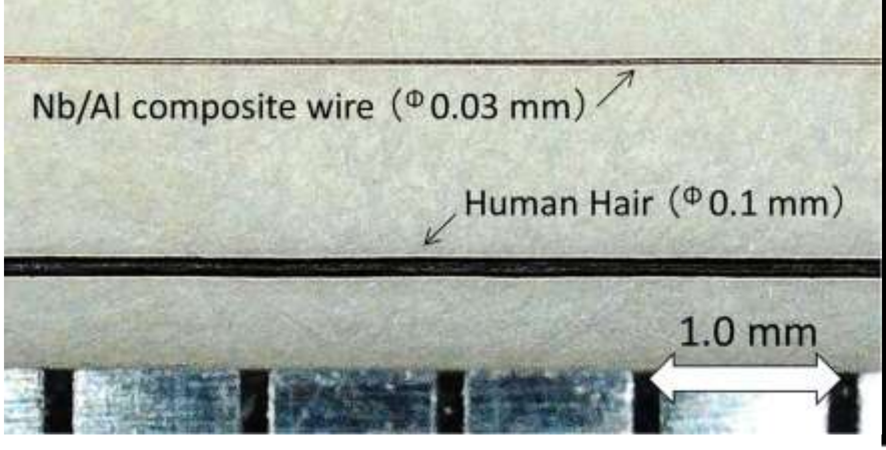


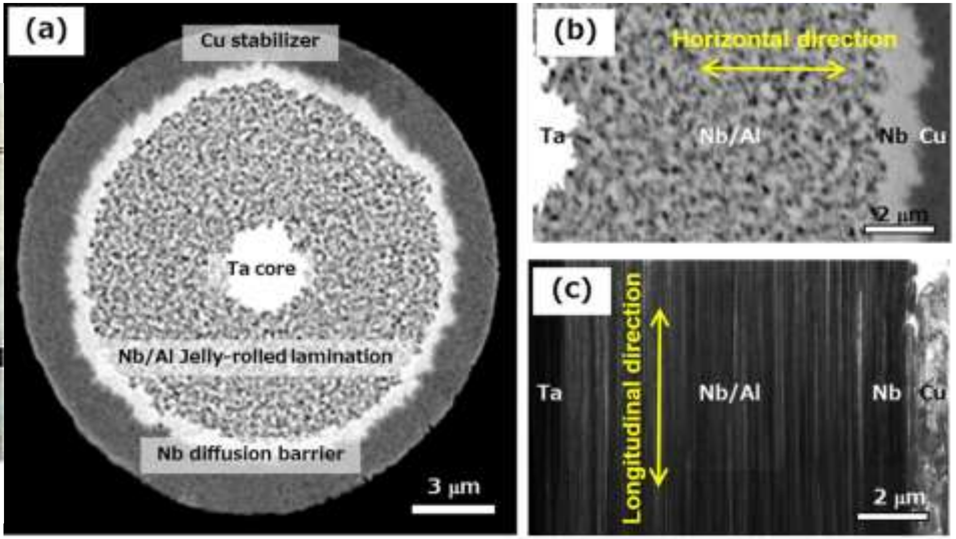
ILD

# Ultra-thin A15 SC wires for future accelerators

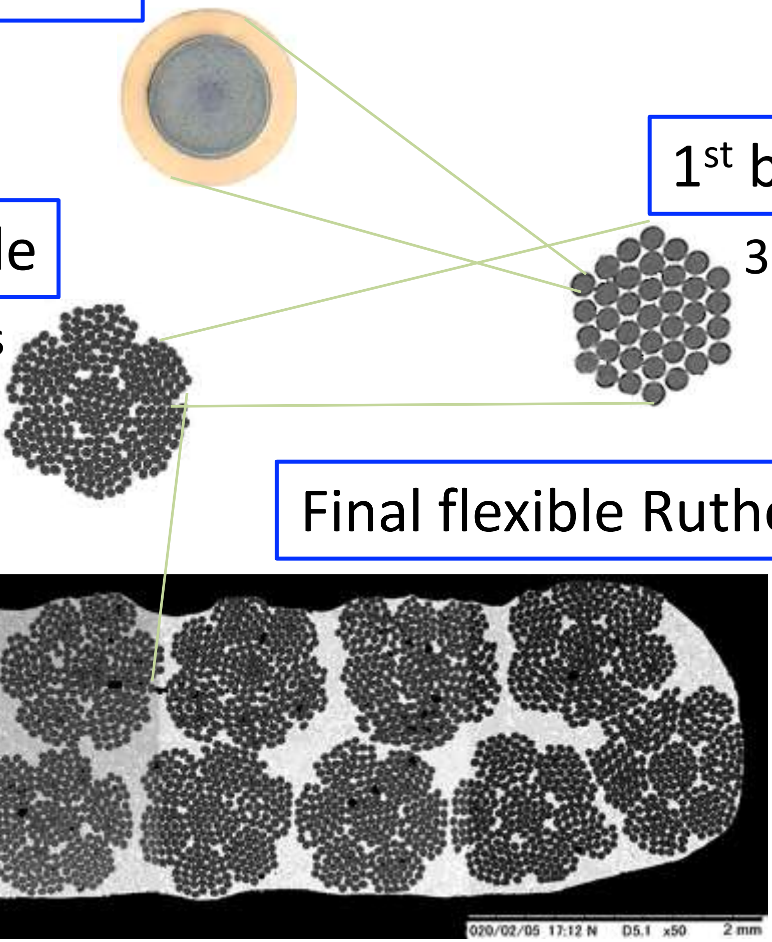
- Hitoshi KITAGUCHI and Akihiro KIKUCHI (National Institute for Materials Science, Japan)
- Technical Highlights:
  0.03-0.05mm$^{dia}$ ultra-thin A15 SC ($Nb_3Al$, $Nb_3Sn$) wires
  → "React and Wind (R&W)" coil fabrication
  Higher flexibility in cable design & tuning

***Example: 0.03mm$^{dia}$ $Nb_3Al$ wire***





- Rutherford cable for R&W magnets (under development)



Ultra-thin SC strand

1st bundle

37 ultra-thin strands

2nd bundle

37x7(259) ultra-thin strands

*(Equivalent to 1 mm$^{dia}$ monolith strand)*

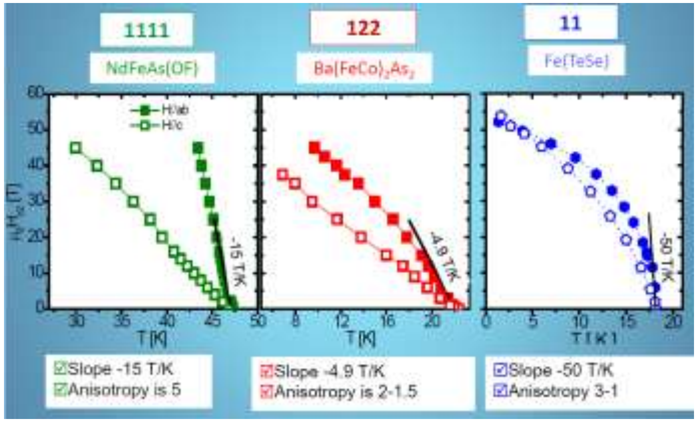
Final flexible Rutherford cable

Successful feasibility study for cabling by using 0.05mm$^{dia}$ pure copper strands

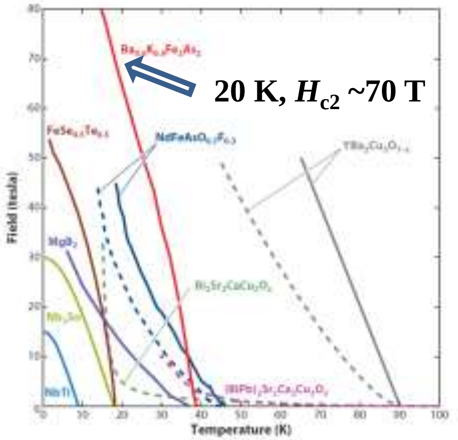
# IBS Wires Toward High-Field Applications

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

**Iron-based Superconductor (Tc = 55K) 2008**



Putti et al. ***SuST*** 23 (2010) 034003



20 K, $H_{c2}$ ~70 T

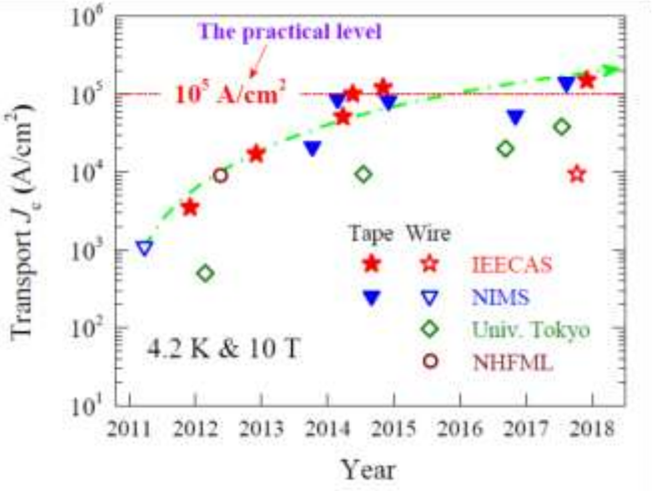
Gurevich, ***Nature Mater.*** 10 (2011) 255

## Advantages of IBS:

- **High $T_c$ (55 K), Ultra-high $H_{c2}$ (150 T) and High $J_c$.**
- **Small anisotropy, e.g., 1~2 for 122 type and Large n-value.**
- **Simple fabrication process and good Mechanical properties.**
- **No oxygen environment required, cheap metal sheath material can be used.**

# Latest Progress on PIT-IBS wires

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)



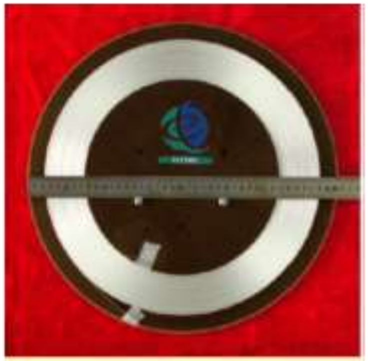
**At 30T, 4.2K:**
**$J_c$=4×10$^4$A/cm$^2$**

**Next target:**
**10$^5$A/cm$^2$**
**at 30 T**

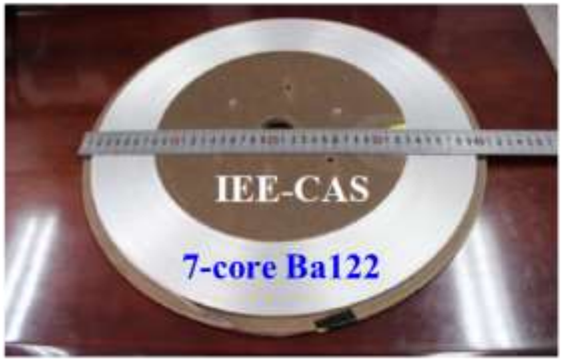
***Transport property of IBS tape (2018):***

**Short sample (~4 mm wide, 0.3 mm thick):**
**$I_c$~ 437 A ($J_c$> 1.5×10$^5$ A/cm$^2$) @4.2K, 10T**

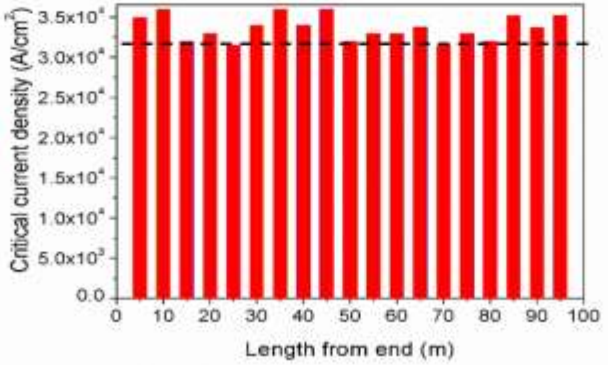
**Now 100 m long 7-filamentary tapes:**
**$J_c$ > 3×10$^4$ A/cm$^2$ @4.2 K, 10T (*3 times larger than the first one*)**



*IEEE TAS 27 (2017) 7300705*



**showing a good $I_c$ uniformity**



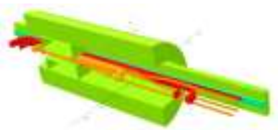
# Development of Superconducting Magnets for Future Accelerators

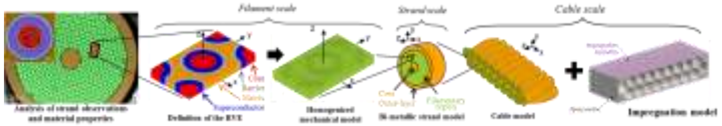
- P.Fabbricatore[1], E.De Matteis[2], S.Farinon[1], U.Gambardella[3], G.Iannone[3], F.Levi[1], S.Mariotto[2], R.Musenich[1], A.Pampaloni[1], M.Prioli[2], L.Rossi[2], M.Sorbi[2], M.Statera[1], R.U.Valente[2] (INFN Genova[1], Milano-LASA[2] and Napoli-Salerno[3])
- Technical Highlights
  - **High Field $Nb_3Sn$ dipoles**. Based on the cos-theta EuroCirCol design for a 16T dipole, in the framework of a CERN-INFN agreement a short model single aperture (Falcon_D) is under construction in collaboration with industry.
  - **HTS magnets**. First developments of canted cos-theta magnets are going on.
  - **Pulsed sc magnets**. First design of fast cycled magnets for the accelerator chain of a future Muon Collider
  - All the above developments are considered a first step toward long R&D activities with construction of many models and prototypes.
- Future plans
  - Availability to contribute to the extended write-ups.
  - Open to other labs to finding common field of interest for specific developments and/or for sharing and complementing knowledges/expertise

# Toward FCC-hh and future colliders: Exploration of high field magnet technology at CEA-Paris Saclay

- Hélène Felice, G. Dilasser, Maria Durante, Philippe Fazilleau, Thibault Lécrevisse, Clément Lorin, P. Manil, F. Nunio, Etienne Rochepault, Françoise Rondeaux, Pierre Védrine

- **Highlights**:





  - **$Nb_3Sn$** :

  Demonstrator toward FCC, Multi-scale approach modeling, PhD work on dimensional changes through digital image correlation

  - **HTS** :

  Eucard (5.4 T record), Eucard 2 cos$\theta$ (assembly stage), Metal-as-insulation double pancakes Nougat (32.5 T), studies of screening currents in REBCO tapes

- **Next steps**:
  - **Some key topics identified:** from modeling to fabrication and test
  - **Reinforced synergy** btw EU development strategy and International labs is required to achieve accelerator ready high field magnets
  - **One tool**: pursuit of topical Workshops such as:
    - Workshop on $Nb_3Sn$ technology for accelerator magnets, October 2018, Paris, https://indico.cern.ch/event/743626/

# Common Coil Dipole for High Field Magnet Design and R&D

K. Amm[1], M. Anerella[1], R. Gupta[1], P. Joshi[1], BNL
More co-authors from other institutions [2] (list still forming)

## Technical Highlights:

- Alternate design to the conventional cosine theta
- Goal is to develop a field quality design with a lower cost in a large production with improved technical performance
- Design allows a variety of cables, technologies and material

## Future Plans:

- Make a case for how this design can help future colliders based on high field dipoles and support R&D programs
- Prepare a write-up and discuss opportunities to collaborate in demonstrating a collider quality high field dipole

# Develop high-temperature superconducting REBCO magnet technology for future circular colliders

- Members from main REBCO magnet programs support the LoI
  - Bosque (ASC/NHMFL); Ben Yahia, Gupta (BNL); Kashikhin, Lombardo (FNAL); and Gourlay, Wang (LBL)
- Our message: rapidly develop REBCO magnet technology as a new tool to enable future energy frontier proton and muon colliders
  - Key advantages of REBCO: enable a dipole field of 20 T and above. Operation over a wide temperature range (2 – 50 K) and capable to tolerate higher heat loads than LTS
  - Significant room for cost reduction; synergy with HTS fusion development
  - Boost the US-Magnet Development Program and allied programs to propel REBCO R&D
- How can the REBCO R&D better meet/serve future experimental needs?
  - Provide more input to Snowmass
  - Engage physicists to understand each other and explore ideas/opportunites

REBCO tapes, SuperPower Inc.

CORC® wires, Advanced Conductor Technologies LLC

STAR™ wires, AMPeers LLC

# Very high field superconducting magnet technologies based on Bi-2212 for future proton colliders

- E. Barzi (FNAL), E. Bosque (NHMFL), D. Davis (NHMFL), L. Garcia Fajardo (LBNL), Y. Kim (NHMFL), D. Larbalestier (NHMFL), I. Novitski (FNAL), S. Prestemon (LBNL), T. Shen (LBNL), U. Trociewitz, A. Zlobin (FNAL)

- Opportunities and technical Highlights: (1) Bi-2212 – the only multifilamentary, twisted, round wire HTS conductor. (2) The conductor technology (wire $J_e$ of 1000 A/mm$^2$ achieved at 4.2 K and 27 T in 2017), experience with prototype coils, and CCT and SMCT magnet design provide an opportunity for adding a very high field, potentially quench training free accelerator dipole magnet technology (>15 T).
- Need for fabrication and test facility: RENEGADE (1 m x Ø0.25 m) OPHT furnace (being constructed@NHMFL)), hybrid magnet test facility, and high-field, large bore $Nb_3Sn$ dipole magnets.
- Collaboration opportunities: (1) Rutherford cable engineering and transverse pressure measurement. (2) Conductor development. (3) Hybrid $Nb_3Sn$/HTS magnet design and testing.
- LOI in preparation.
- Open questions: Are HTS accelerator magnets quench training free? Is the HTS magnet technology scalable?

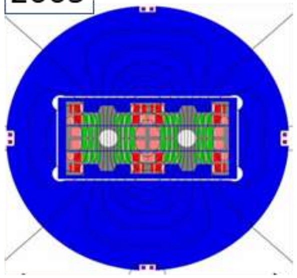
# 20 T hybrid magnets

P. Ferracin[1], G. Ambrosio[2], E. Barzi[2], L. Cooley[3], R. Gupta[4], V. Kashikhin[2], V. Marinozzi[2], I. Novitski[2], S. Prestemon[1], A. Zlobin[2]

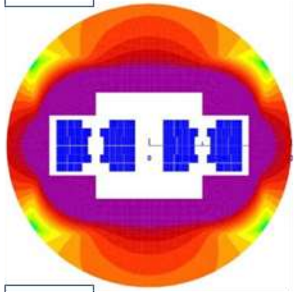
- Most effective way to achieve very high collision energies in HEP accelerators: very high field dipole magnets -> 20+ T bore field
- Beyond 16 T (limit Nb3Sn) -> HTS superconducting materials, but still significant higher cost than Nb3Sn and Nb-Ti
- Economically viable option: “hybrid” magnets
- R&D on modelling and with short model fabrication and testing to address different challenges: optimum coil and magnet design for both HTS and LTS, mechanical integration, HTS/LTS ratio, peak stresses, protection with all coils in series, testing, cost, industrialization
- Development will pave the way towards very high field magnets for the next generation of particle accelerators

Previous work

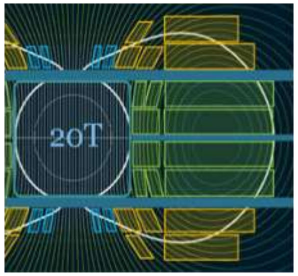
2005



2014



2018



(1) Lawrence Berkeley National Laboratory, Berkeley, CA 94720, pferracin@lbl.gov
(2) Fermi National Accelerator Laboratory, Batavia, IL 60511, barzi@fnal.gov
(3) Applied Superconductivity Center, National High Magnetic Field Laboratory, Tallahassee, FL 32310
(4) Brookhaven National Laboratory, Upton, NY 11973

# The time is right for BSCCO 30 T solenoids

E. Barzi (FNAL), E. Bosque (NHMFL), D. Davis (NHMFL), Y. Kim, D. Larbalestier (NHMFL), T. Shen (LBNL)

**LOI in preparation**

- Opportunities and technical Highlights:
  1. Bi-2212 – the only multifilamentary, twisted, round wire HTS conductor, 800-1200 m strand lengths
  2. Wire Ag matrix strengthened up to 160 MPa, composite conductor reinforced above 300 MPa, and magnet level reinforcement above 275 MPa under active development.
  3. Stable, training-free test coil operation with conventional quench management.
  4. Rutherford cable based >30 T solenoids are promising for final muon cooling.
- Facilities:
  1. *Renegade* over-pressure furnace (1 m x Ø 0.25 m now in construction @NHMFL)
  2. Large bore (>150 mm) 8-14 T LTS solenoid test beds, resistive & hybrid facilities at NHMFL
- Collaborations:
  1. Conductor development.
  2. Development of 25 T commercial user solenoids
  3. Rutherford test solenoids towards 25 T operation
  4. Proposed 28 T insert towards UHF-NMR development.
- Open question: Can we reliably react and reinforce magnets with high current densities under extreme Lorentz stresses?

# Integrated Magnet Development for HEP accelerators

- Kathleen Amm, Michael Anerella, Ramesh Gupta, Brett Parker, Piyush Joshi(BNL) Joseph Minervini, John Brisson, (MIT)
- Technical Highlights
  - Specialty magnets –
    - Direct wind(Linear e+e- colliders, electron-ion machines, proton-proton machines, muon colliders)
    - New methods for very high energy colliders
  - HTS
    - solenoids (30-50T small bore for muon collider cooling, >15T large bore for muon collider 6D cooling, >20T for HEP experiments(e.g. Axion search)
    - VHF Dipoles (20-25 T) - high energy proton-proton, muon colliders (linear luminosity dependence)
    - VHF quadrupoles and multipoles – IR regions for all high energy machines, specialty applications
  - Cross cutting applications with other SC applications – EIC, compact fusion, offshore wind. HEP can leverage efforts and expertise – more bang for the buck
- Future plans –partnerships with sister magnet teams (FNAL, LBNL, BNL, MIT NHMFL) and industry

# Snowmass 2020 - Wind-React-Wind (WRW)

Shlomo Caspi (LBNL)

SC magnet technology

Nb3Sn magnets, like NbTi magnets, have similar issues that remain unsolved

- Good progress in SC Nb3Sn magnet technology has reached a point where it is difficult to progress unless new ways are introduce to understand, explain and avoid magnet training – a critical costly problem.
- Ask yourself, in what way the R&D magnet I am building Is going to be different in solving a problem that thousand other magnets were unable to solve. If the answer is pre-stress stop and look for something new.

Future SC magnet technology

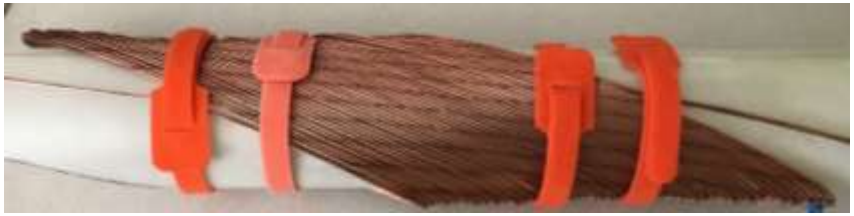
- Reduced stress in CCT coils did not solve magnet training but suggested an intrinsic mechanisms within turns to be a more likely source – sintering during reaction, the use of epoxy and mismatch between mechanical properties.
- Reacted Nb3Sn is brittle but like any other brittle material can maintain a certain degree of elasticity (e.g. fiber optics)
- The "Wind-React-Wind" method is a NEW approach for CCT coils:
  - Annealed Nb3Sn (650 C) coils retain their annealed form and maintain a degree of elasticity.
  - Reacted Nb3Sn conductor is sufficiently elastic when it is removed from a reacted CCT mandrel.
  - Placing the removed turns into a similar new unreacted mandrel should be the same.
  - Unreacted mandrel has controlled tolerances and can be made from other materials such as Aluminum.
  - Mandrels should be insulated or coated (e.g. anodizing) voiding the use of cable insulation.
  - Removing impregnation will place liquid Helium within the cable and greatly improve stability

This new R&D study has a steep learning curve on technology the potential for better understanding foundamental training issues, reduce magnet cost and improve safety

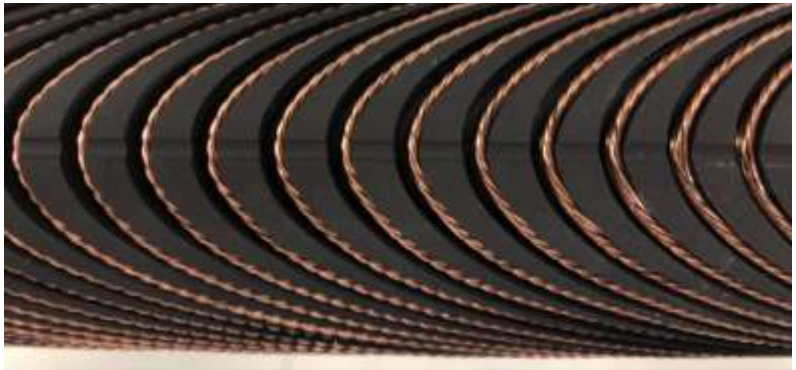
Reacted Nb3Sn cable
in a CCT bronze mandrel

Flexible Nb3Sn cable removed

Removed Nb3Sn turns

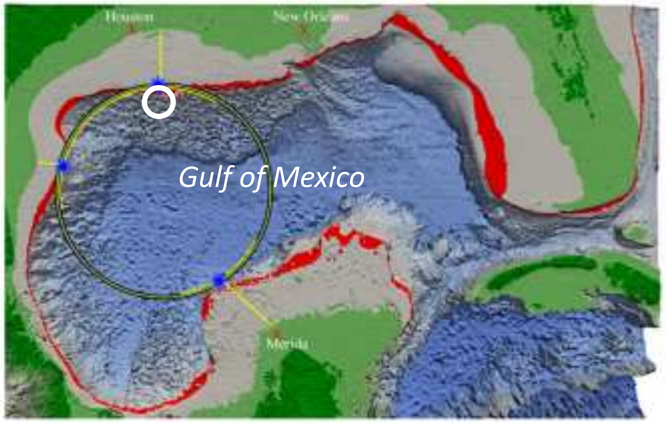


Turns replaced into a new anodized (black) Aluminum mandrel

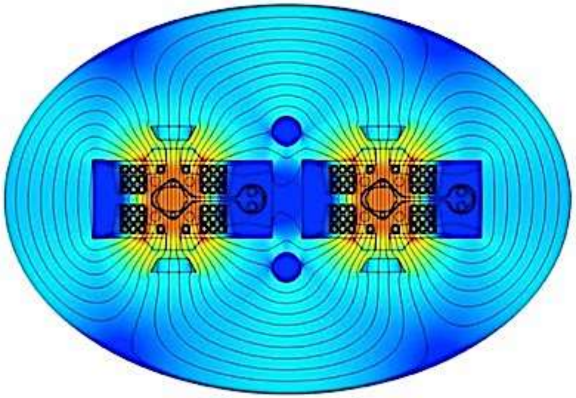


# Collider in the Sea: 500 TeV with High Luminosity

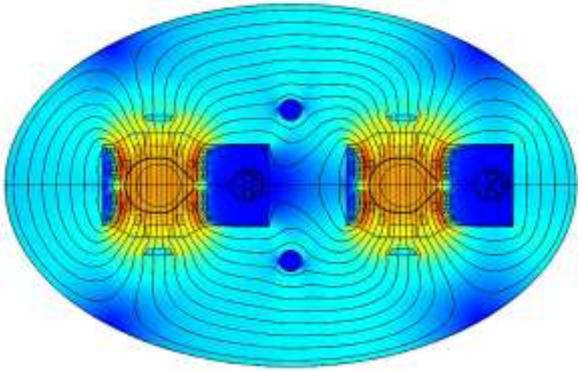
- Peter McIntyre, Texas A&M University
- Technical Highlights:
  - Magnet cost/TeV increases steeply with magnetic field.
  - Tunnel cost/TeV increases with size – faults, bad rock.
  - Solution: Choose magnetic field for minimum cost/TeV 3-4 T
  - No tunnel!: 1900 km circular pipeline at 100 m depth, neutral-buoyant
  - C-magnet w/ $LN_2$ side channel for SR: ultimate luminosity



doi:10.1109/TASC.2017.2656157
doi 10.18429/JACoW-NAPAC2016-MOB2CO03



**3.5 T NbTi Cable-in-Conduit Supercritical He 4-6 K**

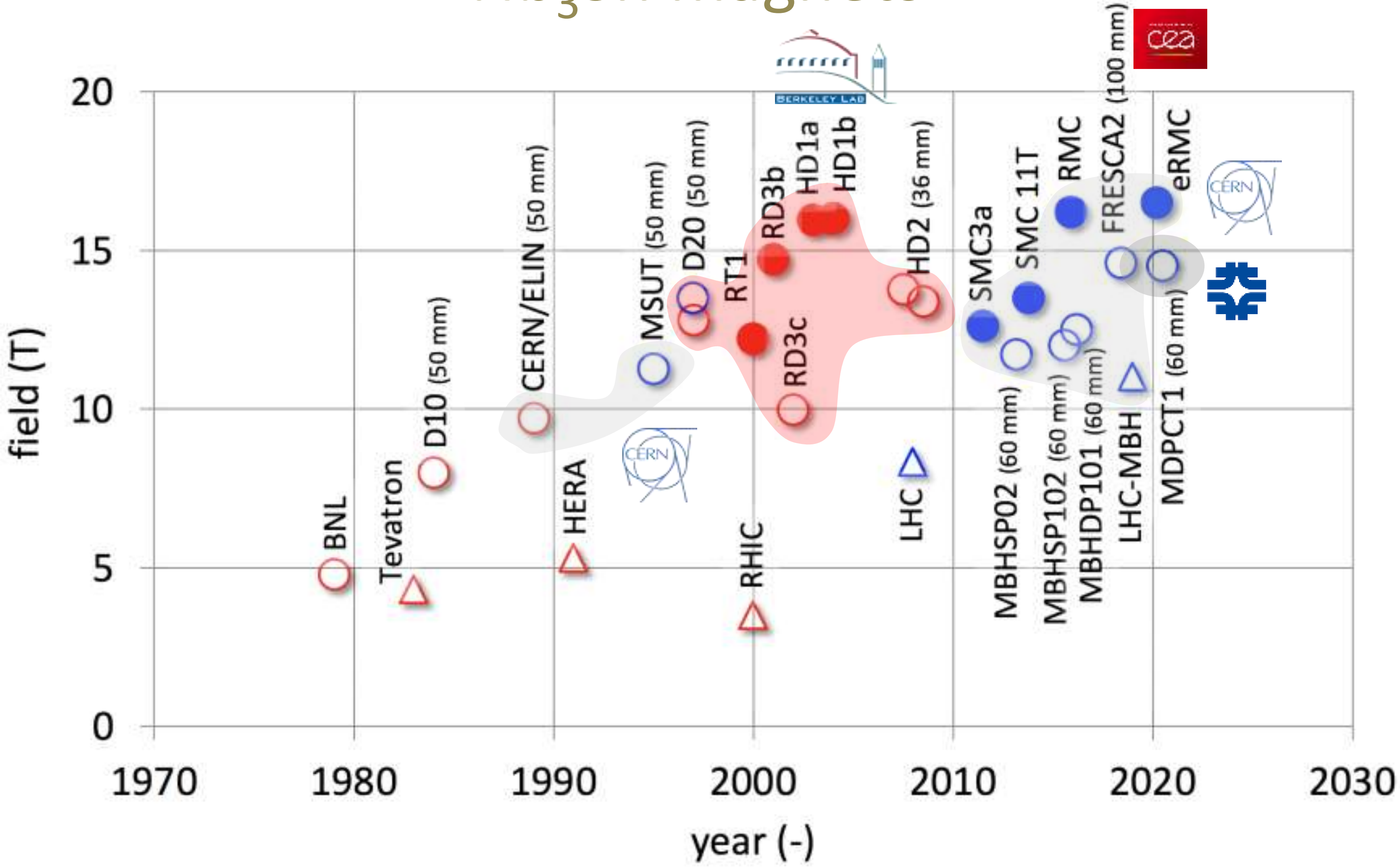


**3.5 T REBCO NI Conformal NI blocks – $LH_2$ 20-30K**

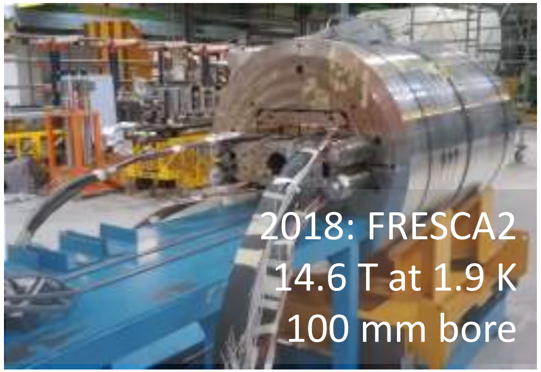
- *Working group: Collider-in-the-Sea 500 TeV* p-mcintyre@tamu.edu

# Additional/Backup Slides

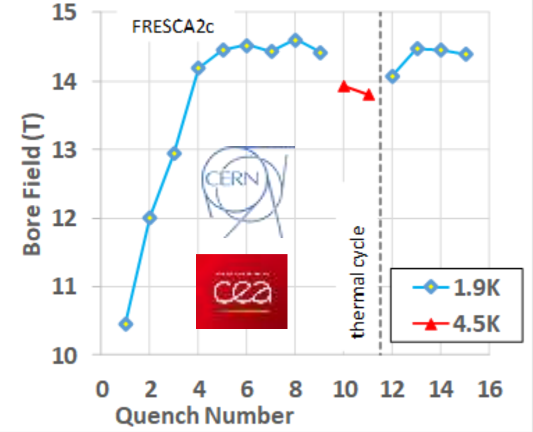
# $Nb_3Sn$ magnets

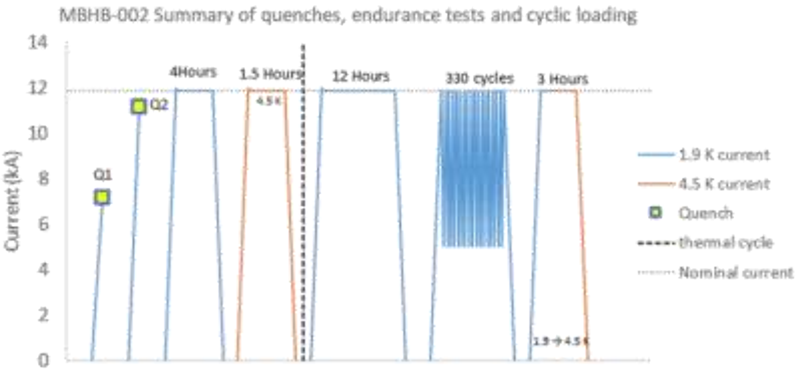


# *Best-of-breed* LTS magnets



2018: FRESCA2
14.6 T at 1.9 K
100 mm bore



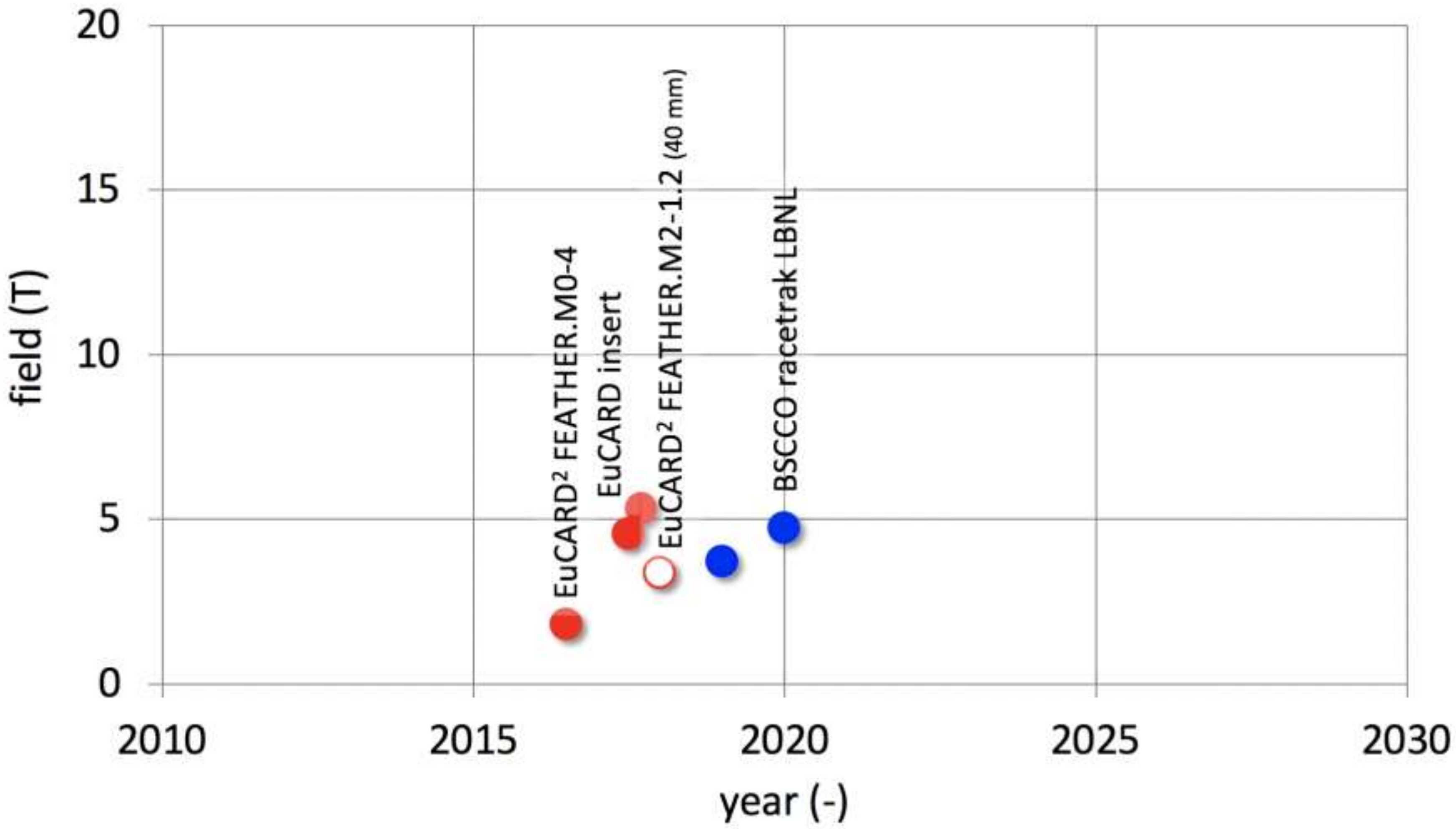


2019: MBHB002
11 T at 1.9 K
60 mm bore

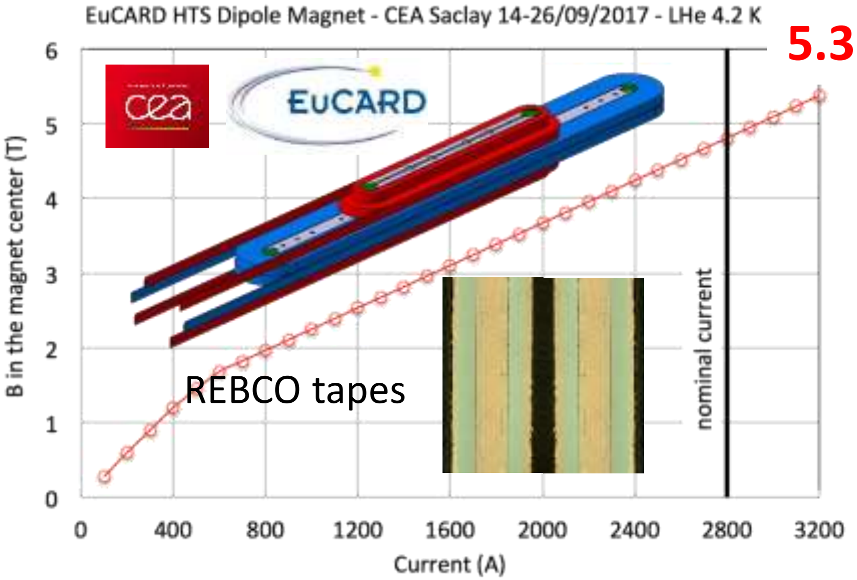
2020: eRMC
16.5 T at 1.9 K
No bore

2020: MDPCT1
14.5 T at 1.9 K
60 mm bore

# HTS magnets

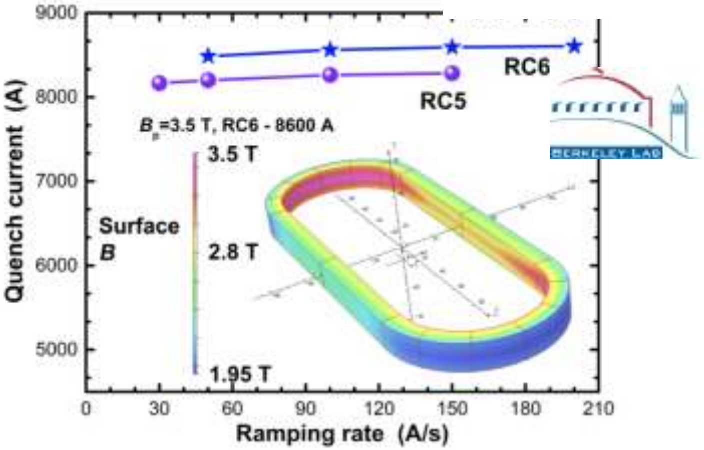

20
15
10
5
0
field (T)
2010
2015
2020
2025
2030
year (-)
EuCARD² FEATHER.M0-4
EuCARD insert
EuCARD² FEATHER.M2-1.2 (40 mm)
BSCCO racetrak LBNL

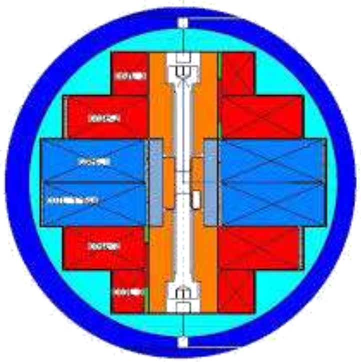
# *Best-of-breed* HTS magnets

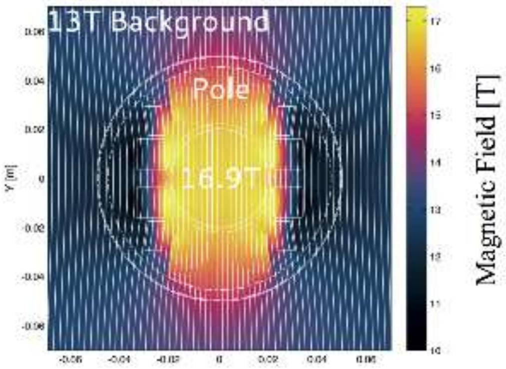


5.37 T

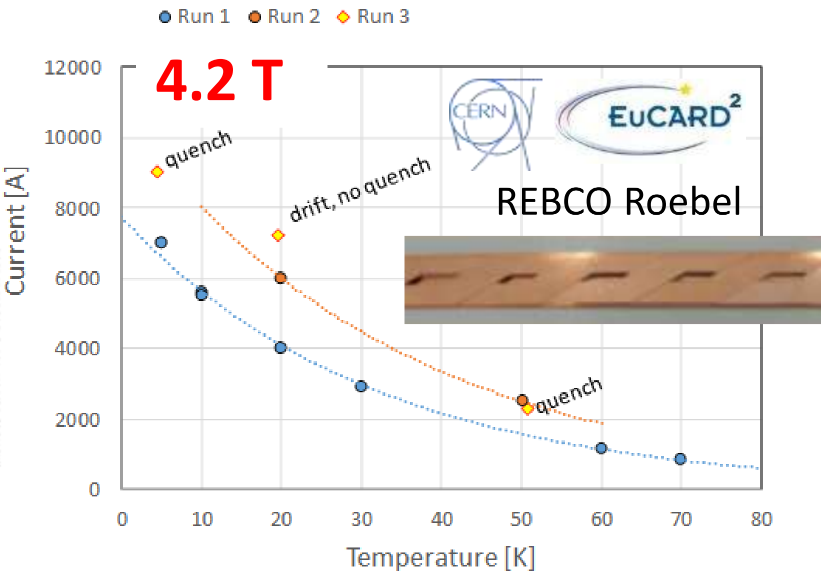
4.7 T







4.2 T

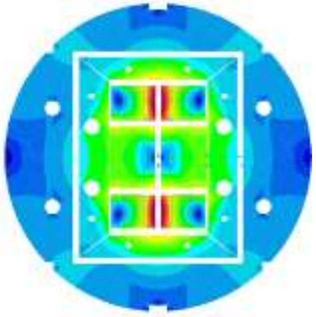


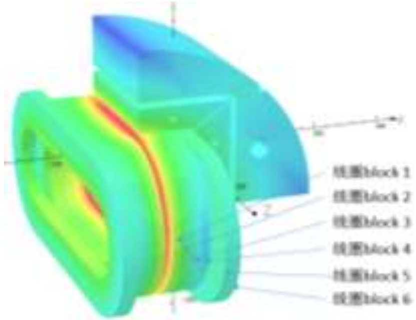
# Status and Plan of the High Field Magnet R&D for Future Accelerators

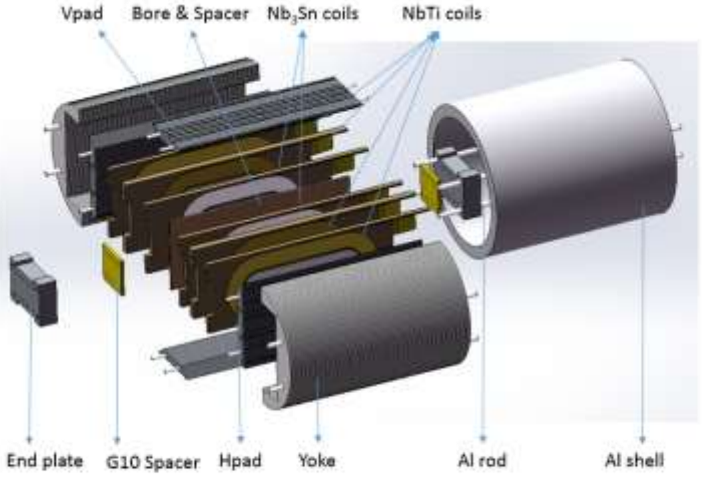
Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

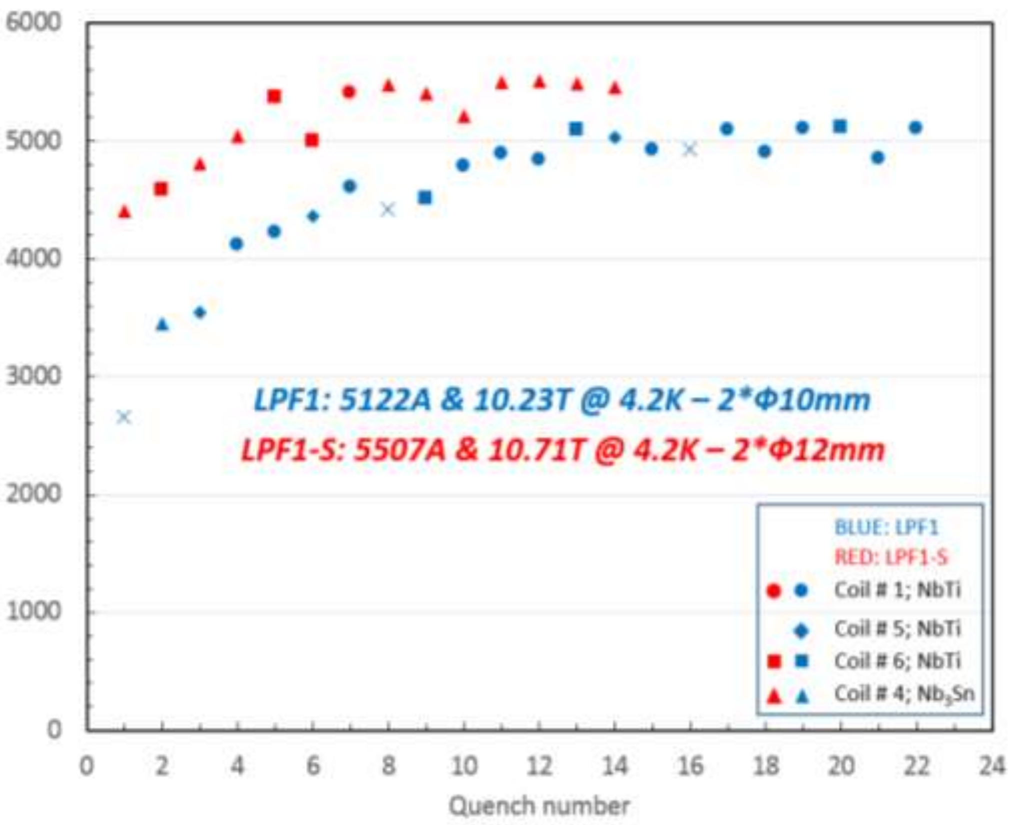
## Status of the High Field Dipole Magnet R&D

### 10.7 T NbTi+$Nb_3Sn$ Common Coil Model Dipole









# Status and Plan of the High Field Magnet R&D for Future Accelerators

Qingjin Xu (IHEP-CAS) and Yanwei Ma (IEE-CAS)

## Test of the 1st IBS solenoid coil at 24 T and the 1st IBS racetrack coil at 10 T

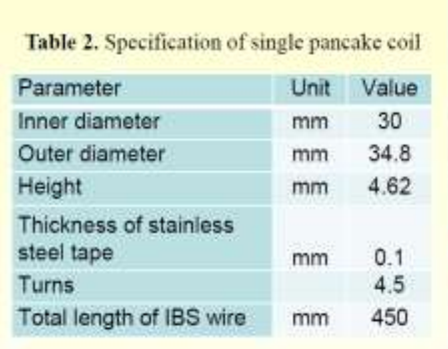
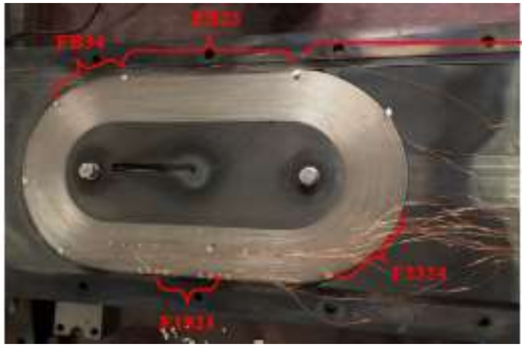


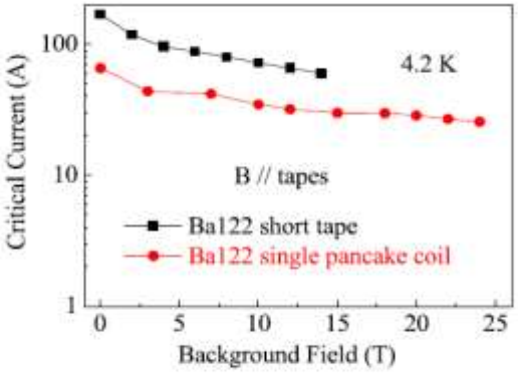
**Table 2.** Specification of single pancake coil

| Parameter | Unit | Value |
|---|---|---|
| Inner diameter | mm | 30 |
| Outer diameter | mm | 34.8 |
| Height | mm | 4.62 |
| Thickness of stainless steel tape | mm | 0.1 |
| Turns | | 4.5 |
| Total length of IBS wire | mm | 450 |

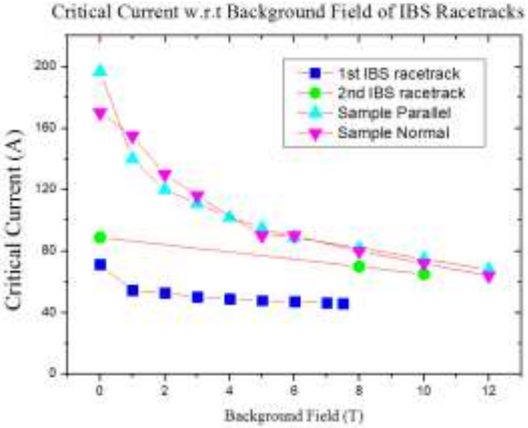
Very good performance!



25T-HM, RT bore Φ38 mm



Demonstrating that IBS are very promising for high-field magnet applications



***Supercond. Sci. Technol.*** 32 (2019) 04LT01

***Supercond. Sci. Technol.*** 2020, in press