High Field Magnet Program for Accelerators: Status and Plan for Next Steps

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July 24th 2020

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Contents

- Fabrication of IBS racetrack coils and test at 10T
- Progress of the high field model dipoles
- Progress of the HL-LHC CCT magnets

Performance of the 1st IBS solenoid Coil

Fabrication and test of IBS solenoid coil at 24T

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Supercond. Sci. Technol. **32** (2019) 04LT01 (5pp)   https://doi.org/10.1088/1361-6668/ab09a4

Letter

First performance test of a 30 mm iron-based superconductor single pancake coil under a 24 T background field

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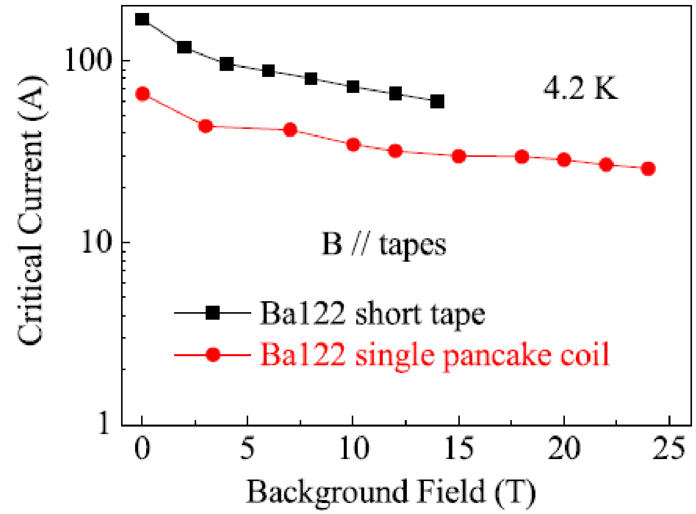

Viewpoint by NHMFL

'From a practical point of view, **IBS are ideal candidates for applications**. Indeed, some of them have quite a **high critical current density, even in strong magnetic fields**, and a low superconducting anisotropy.
Moreover, **the cost of IBS wire can be four to five times lower than that of Nb_3Sn**……

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Supercond. Sci. Technol. **32** (2019) 070501 (3pp)   https://doi.org/10.1088/1361-6668/ab1fc9

Viewpoint

CrossMark

Constructing high field magnets is a real tour de force

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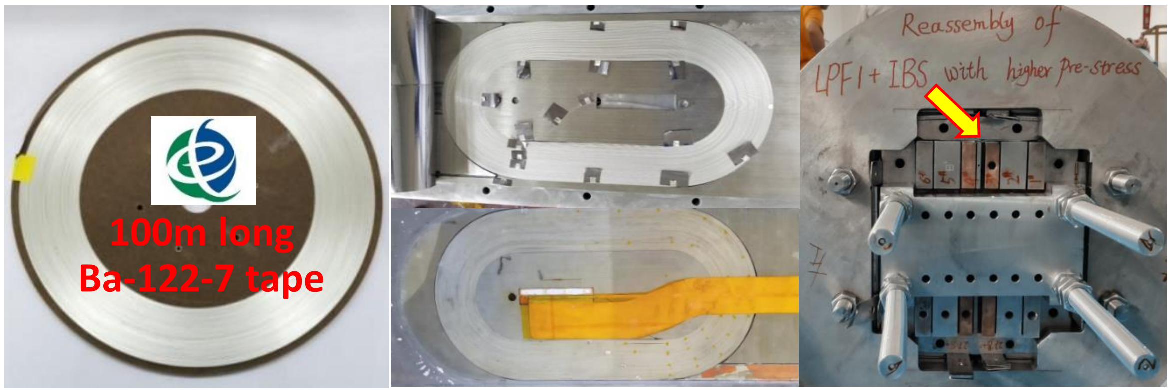
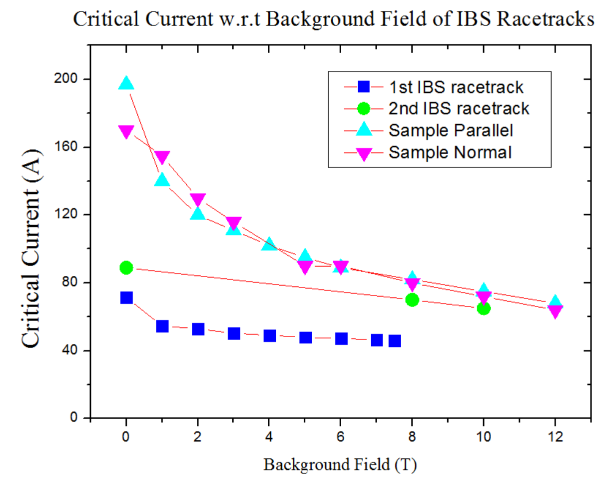
This is a viewpoint on the letter by Dongliang Wang *et al* (2019 *Supercond. Sci. Technol.* **32** 04LT01).

Following the discovery of superconductivity in 1911, Heike Kamerlingh Onnes foresaw the generation of strong magnetic fields as its possible application. He designed a 10 T electromagnet made of lead–tin wire, citing only the difficulty

Test of the 1st IBS racetrack coil at 10T

- ***Two racerack coils with 100m long IBS tapes** have been fabricated and tested at 10T background field.*
- ***The Ic in the coil reached 86.7% of the short sample at 10T.***





Comments from SUST reviewers:

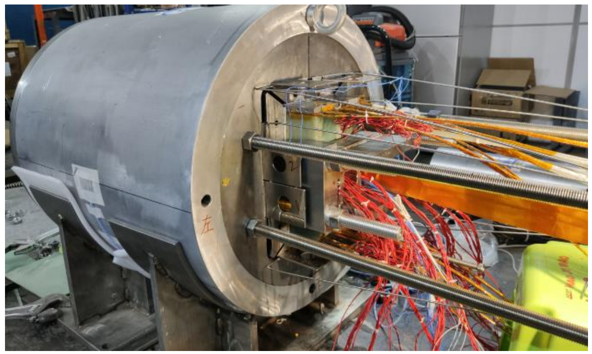
a) …the new results that can have a strong impact on the conductor and magnet community.
b) …demonstrated the great potential of Iron-Based Superconductor in the development of next-generation accelerators.
c) It is of certain significance in the path of applications of Iron-Based Superconductor…

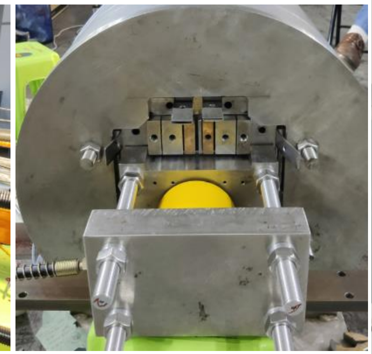
Reassembly of LPF1 with Increased Pre-stress

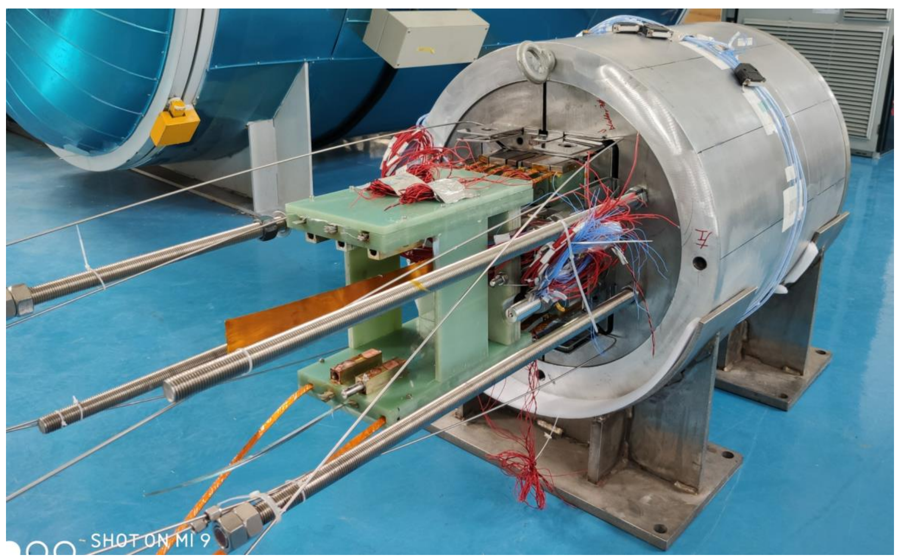
Pre-stress during room temperature assembly significantly increased.

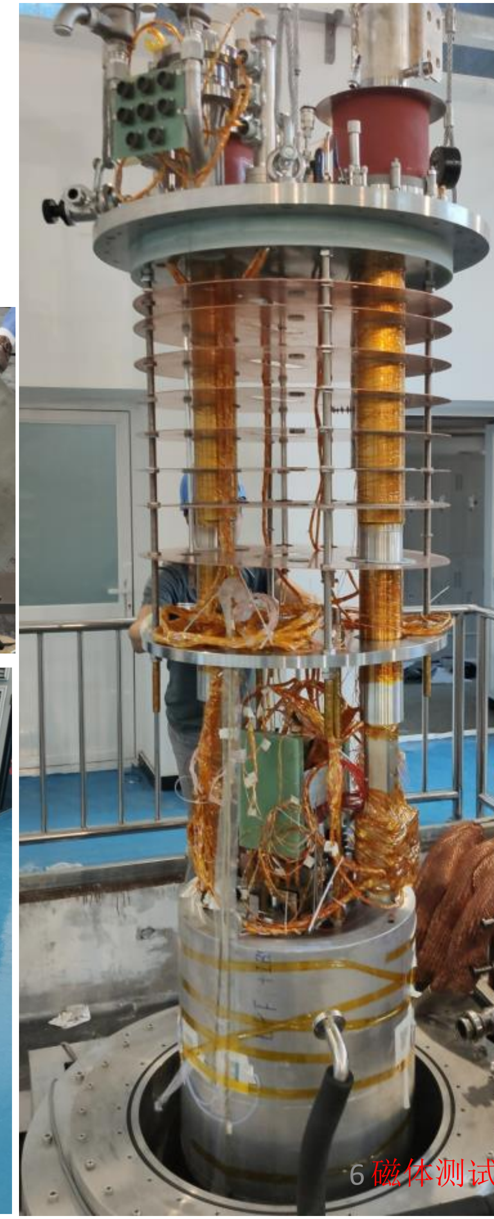
Horizontal：from previous 30 to 80 MPa;

Vertical：from 30 to 40 MPa；



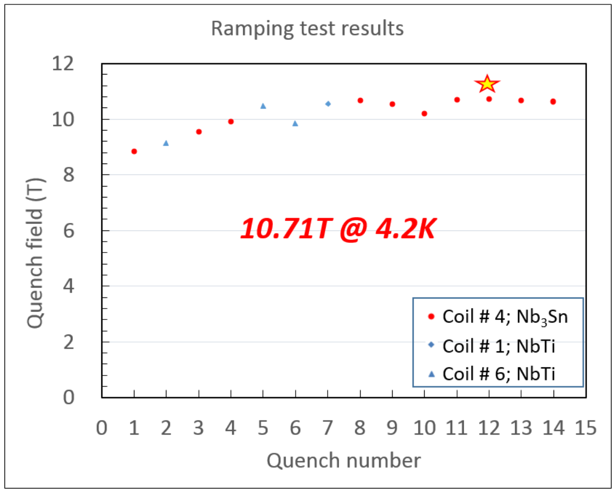


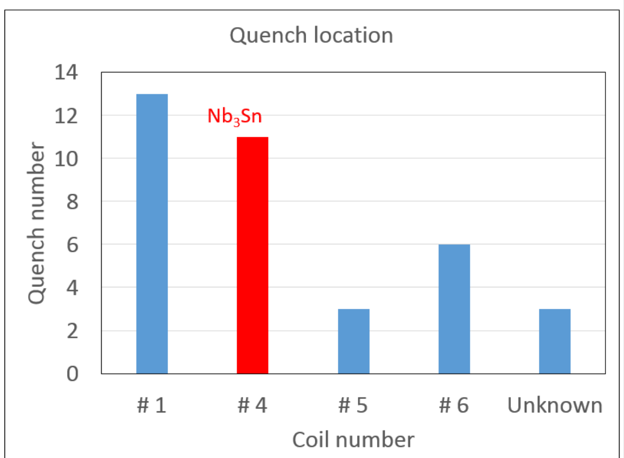


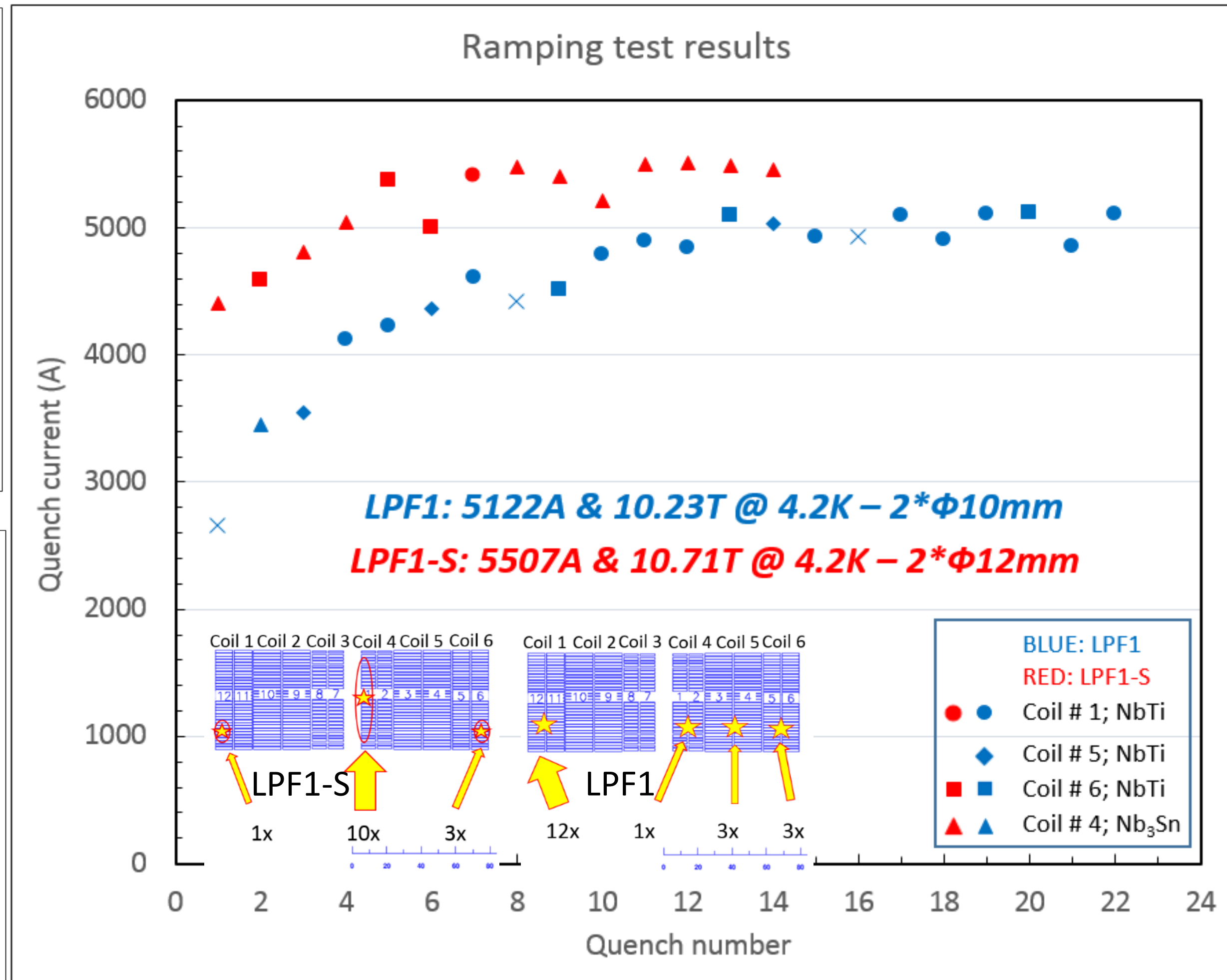


Performance with increased Pre-stress

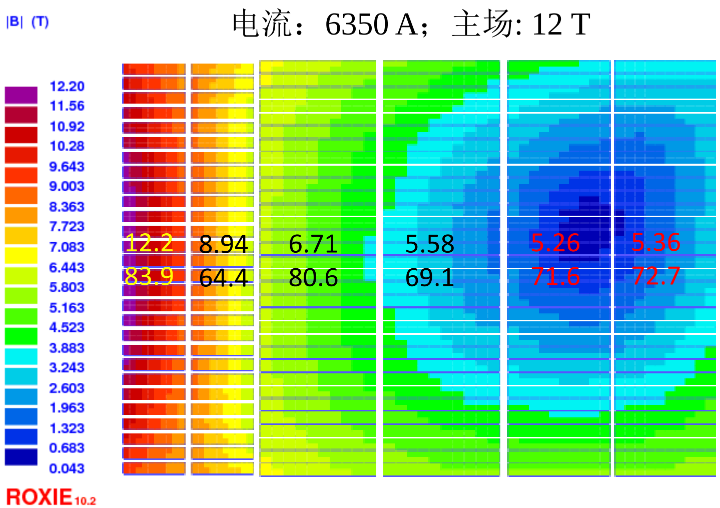
- *The dipole field increased from 10.2 T to 10.7 T with larger apertures (2*ϕ12 mm) .*
- *Performance limited by Nb_3Sn coil, possibly due to the imperfect impregnation.*
- *Next step: replace the imperfect Nb_3Sn coil and test the magnet again.*



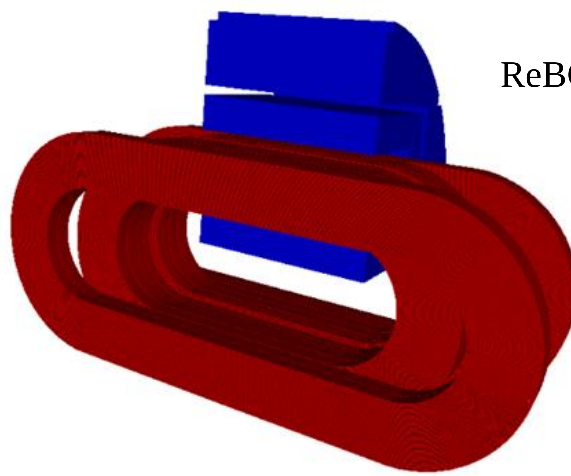




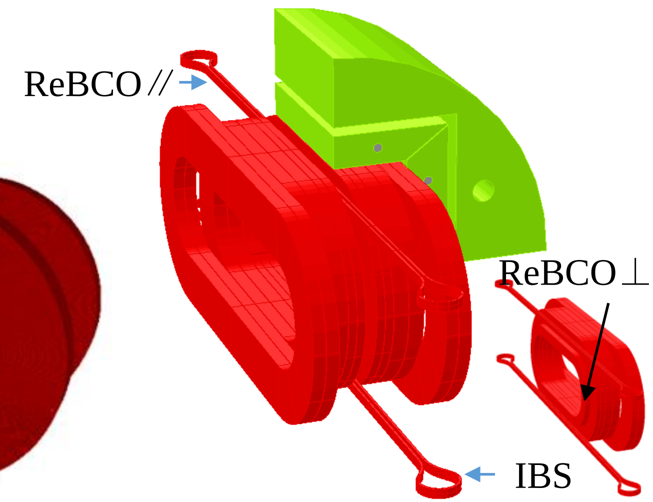
Upgrade with New Nb_3Sn and HTS Insert Coils



场强分布



线圈及轭铁布局（3D）

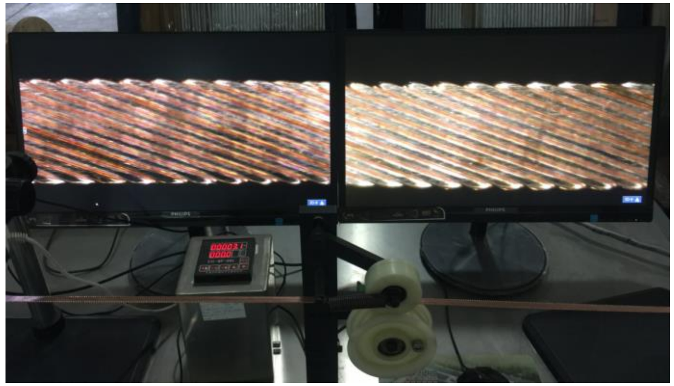


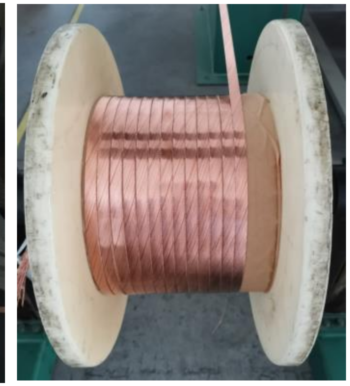
内插线圈布局

Main parameters of LPF1-U

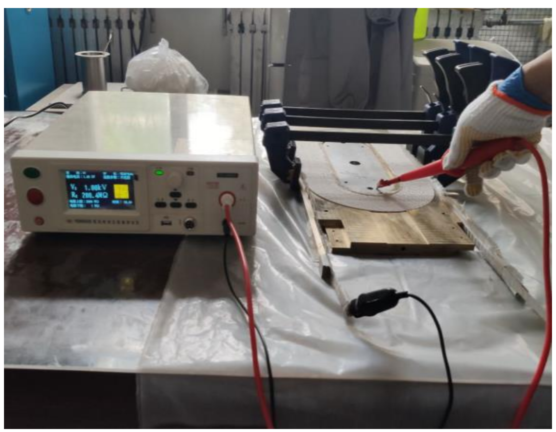
Results	Aperture (mm)	Current (A)	Main field (T)	Blocks	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	ReBCO ⊥
2D	14	6350	12	Peak field (T)	12.20	8.94	6.71	5.58	5.26	5.36	12.74
				Load line ratio	83.9	64.40	80.58	69.05	71.59	72.7	-
3D	14	6575	12	Peak field (T)	12.20	8.65	7.20	7.00	6.11	6.16	12.7
				Load line ratio	84.6	63.51	86.01	83.98	81.25	81.79	-

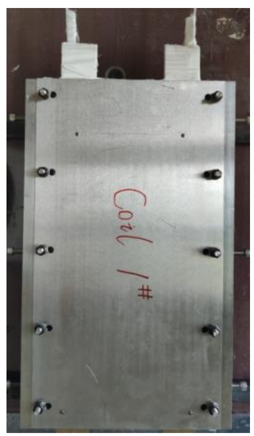
Upgrade with New Nb_3Sn and HTS Insert Coils

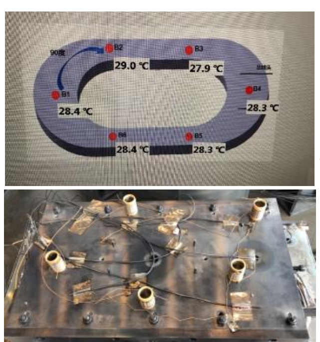


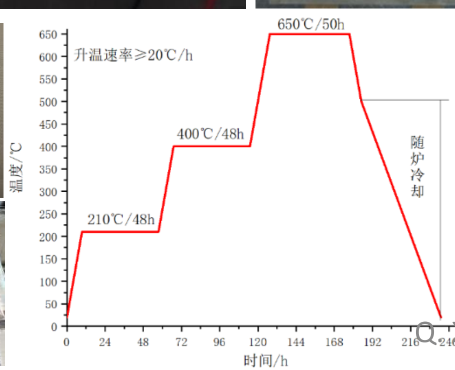


在无锡统力电工完成卢瑟福电缆的绞制,绞制20芯铌三锡缆约125米；31芯铌钛缆约205米；铜缆共约250米







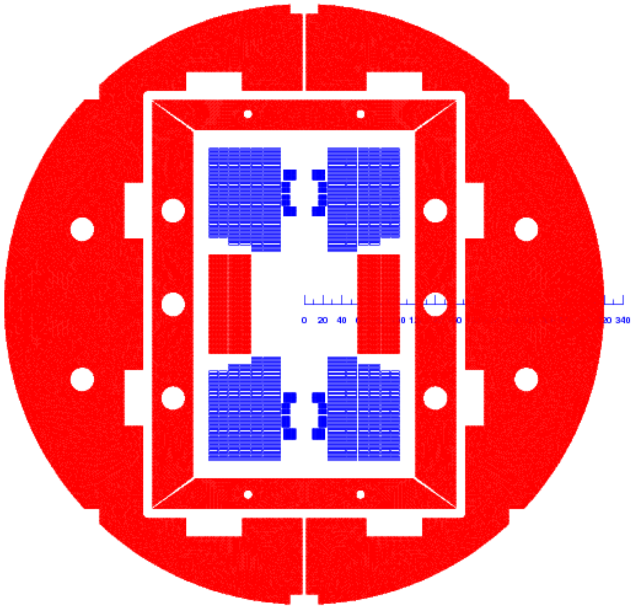


LPF 临界电流样品测试结果

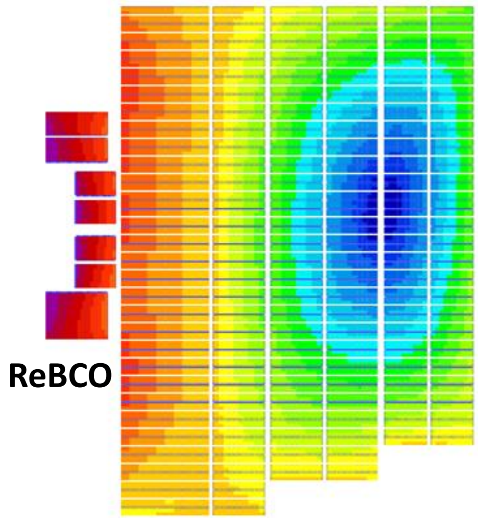
种类	样品编号	超导线编号	位置识别号	Ic（A）	n	RRR
临界电流样品	1#	2024-19021A（原始）	BS1	606A，	Quench	118
	2#	2024-19021A（截取）	BS2	644.5	39	64
	3#	2024-19017A-1（原始）	BS3	663.7	35	113
	4#	2024-19017A-1（截取）	BS4	646.7	66	74
	5#	2024-19021（截取）	BS5	541A，	Quench	68

Next:16T Dipole Magnet with Nb_3Sn+HTS

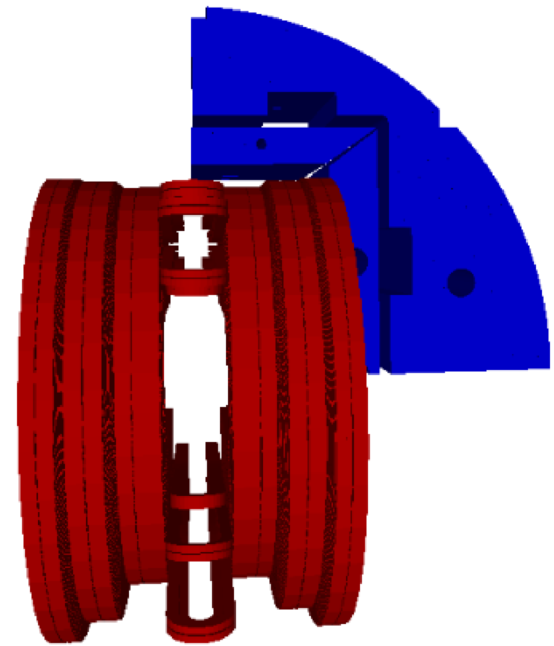
Main field 16.3 T in the two 30mm-diameter apertures



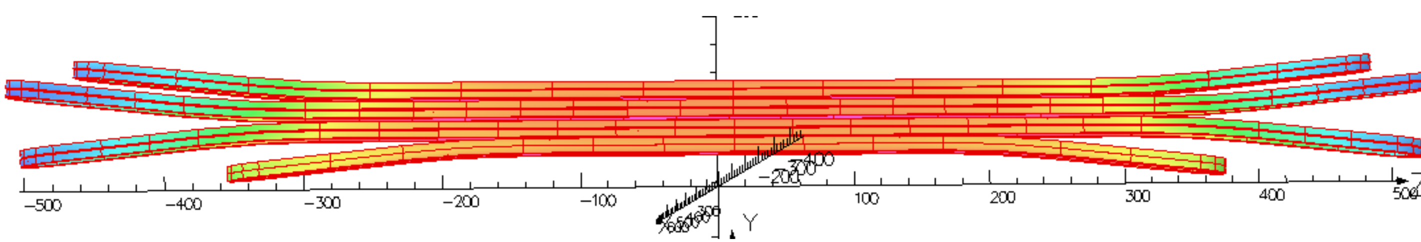
OD 640 mm   AP 2*30 mm



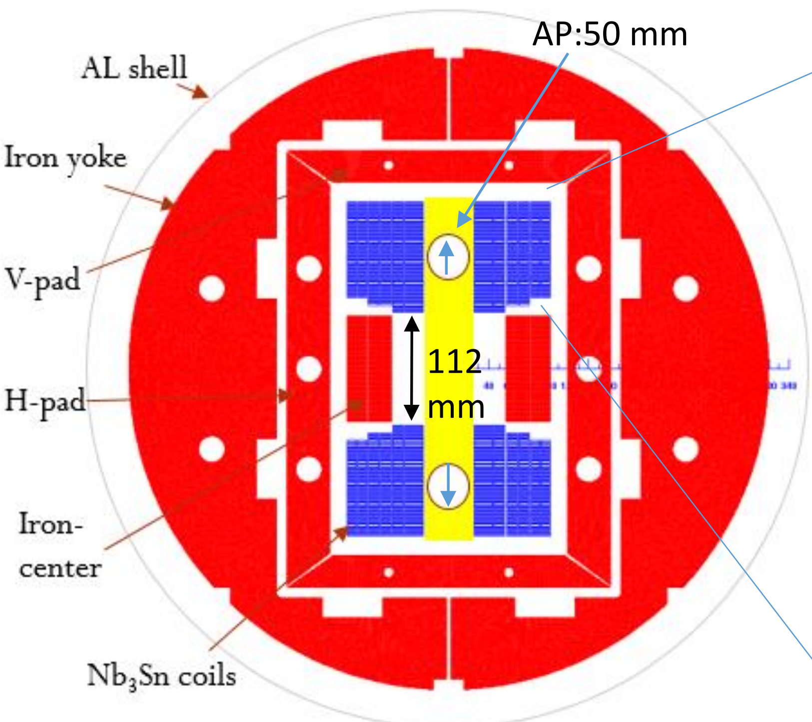
Nb_3Sn



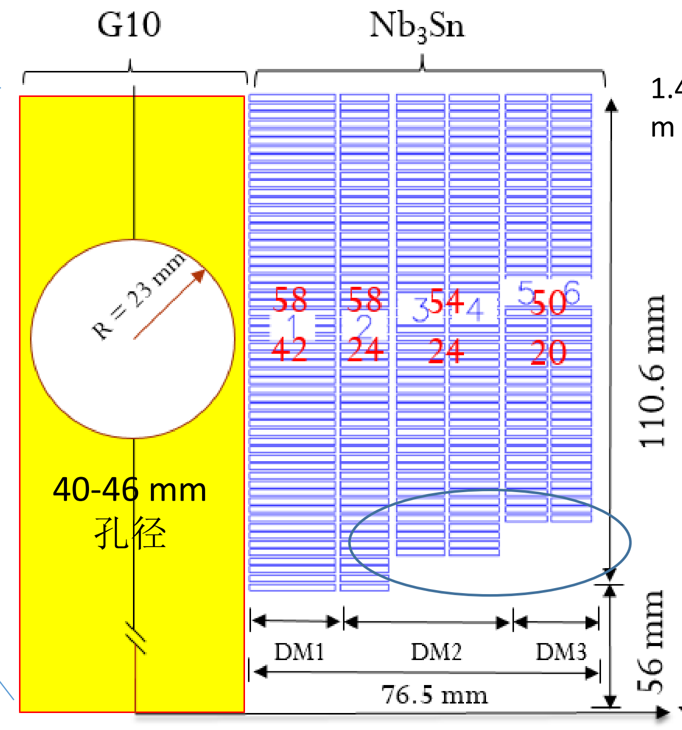
Nb_3Sn ReBCO Nb_3Sn

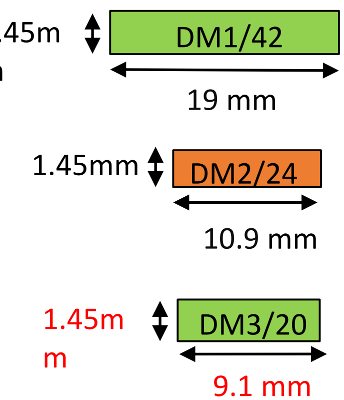


Next:16T Dipole Magnet with Nb_3Sn+HTS

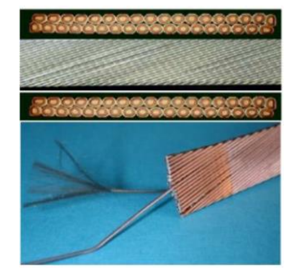


Cross section of this dipole





First quadrant coil

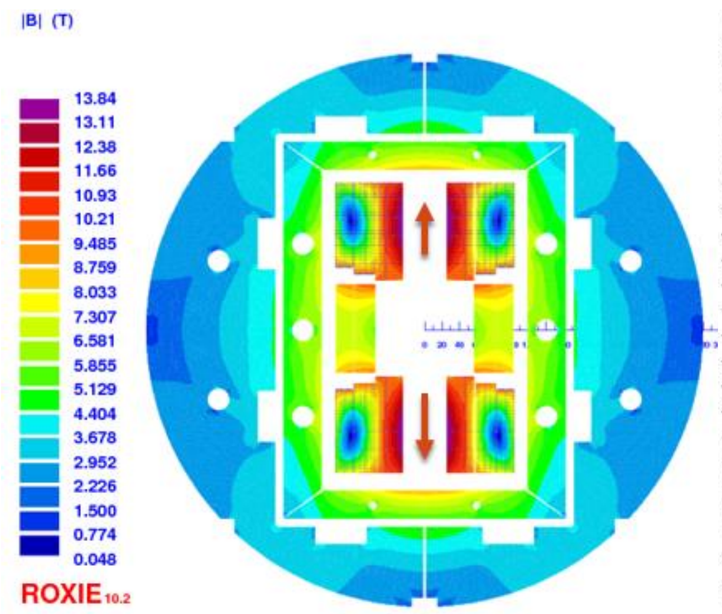


Rutherford cable

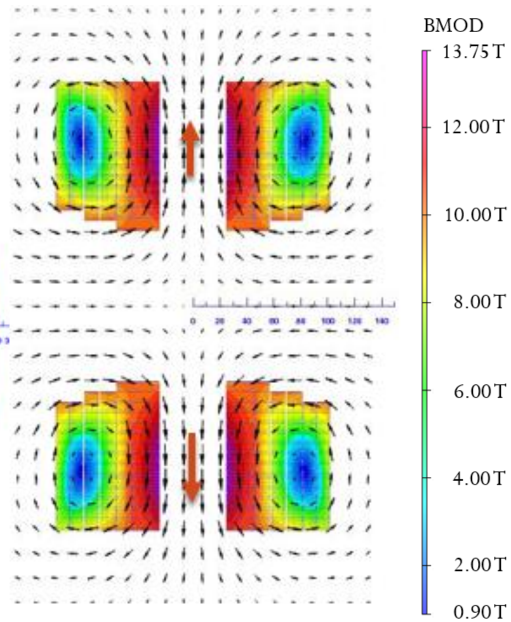
Cable parameters

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation Azimut	Insulation Radial	Twist angle	Filling factor
DM1	19	1.45	1.45	42	WSTNS1	Nb_3Sn	0.23	0.2	16.91	83.74%
DM2	10.9	1.45	1.45	24	WSTNS1	Nb_3Sn	0.23	0.2	16.91	83.41%
DM3	9.1	1.5	1.5	20	WSTNS1	Nb_3Sn	0.23	0.2	16.91	83.26%

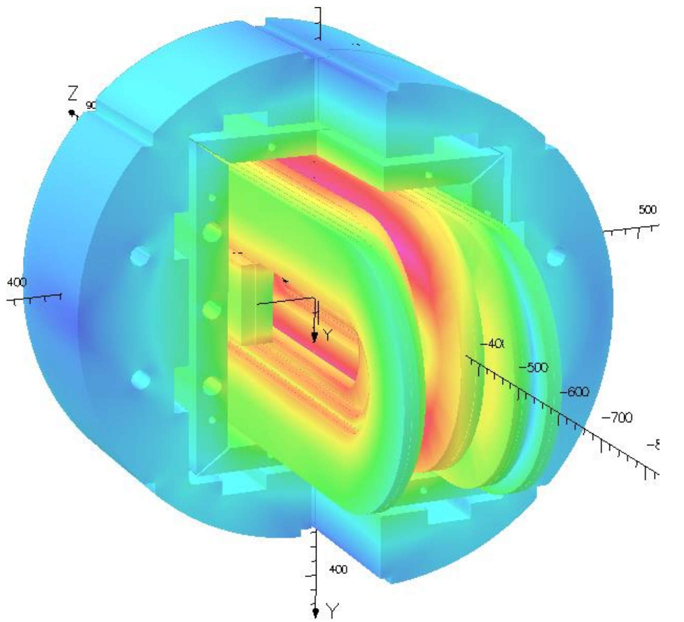
Next:16T Dipole Magnet with Nb_3Sn+HTS



Field distribution in the cross section



Flux distribution



Cross-check with Opera -3D

Main parameters

Current - 3D	7630 A		Blocks	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Main field	13.02 T		Peak field (T)	13.85	11.13	10.95	11.21	10.57	10.47
			LL ratio (%)	82.91	78.16	77.18	78.6	78.63	78.09
Integral harmonics (-150-150mm); R-10	b3: 102.76		b5: -0.08	b7: -0.01	b9: 0	a2: -48.11	a4: -0.14	a6:-0.02	a8: 0
Integral harmonics (-150-150mm); R-15	b3: 231.17		b5: -0.42	b7: -0.06	b9:0.01	a2: -72.09	a4: -0.46	a6:-0.14	a8: 0.01

R&D Roadmap for the next years

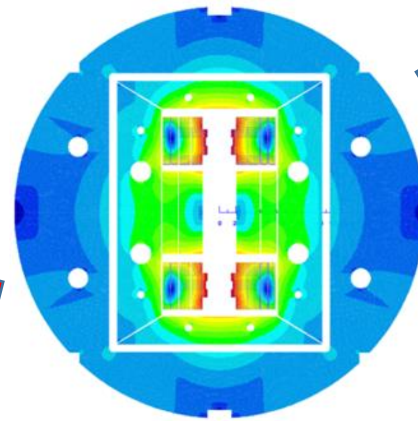
SPPC dipole field: baseline 12 T, optimum 20-24T

Field (T)

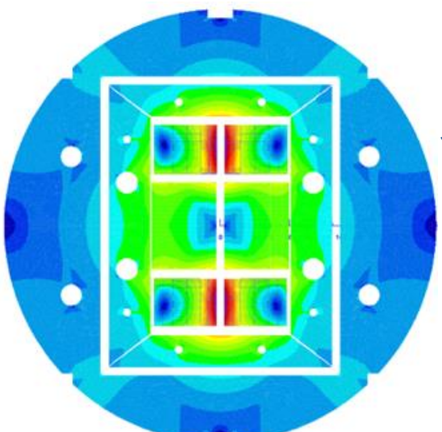
20

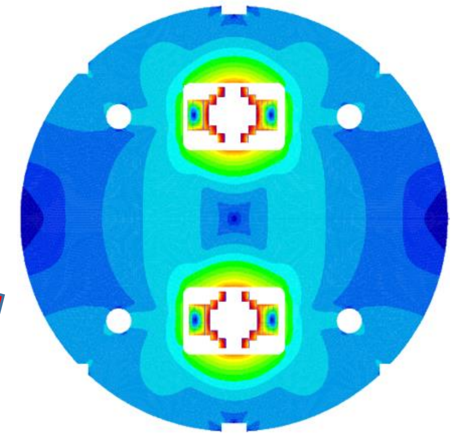
10

Nb_3Sn+HTS
2*ϕ45 aperture
15T @ 4.2K



NbTi+Nb_3Sn
2*ϕ10 aperture
10T @ 4.2K





Nb_3Sn+HTS or HTS
2*ϕ45 aperture
20T @ 4.2K
With 10^{-4} field quality

IEEE TAS 2019, 29(7), 4003807

IJMPA 2016, 31(33):1644018

IEEE TAS 2016, 26(4): 4000404

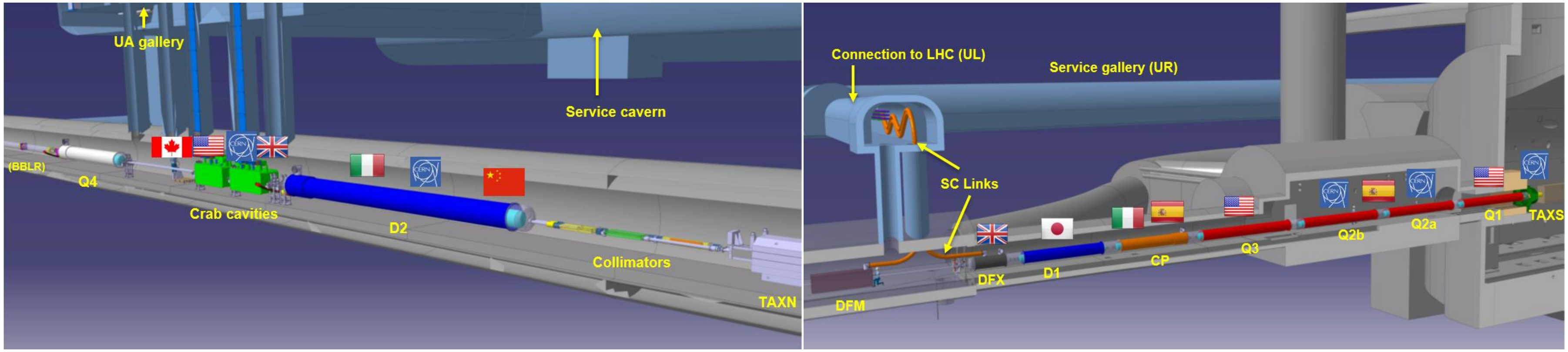
2018 *2028* *year*

CERN-China HL-LHC CCT Project

China provides 12+1 units CCT corrector magnets for HL-LHC by mid 2022

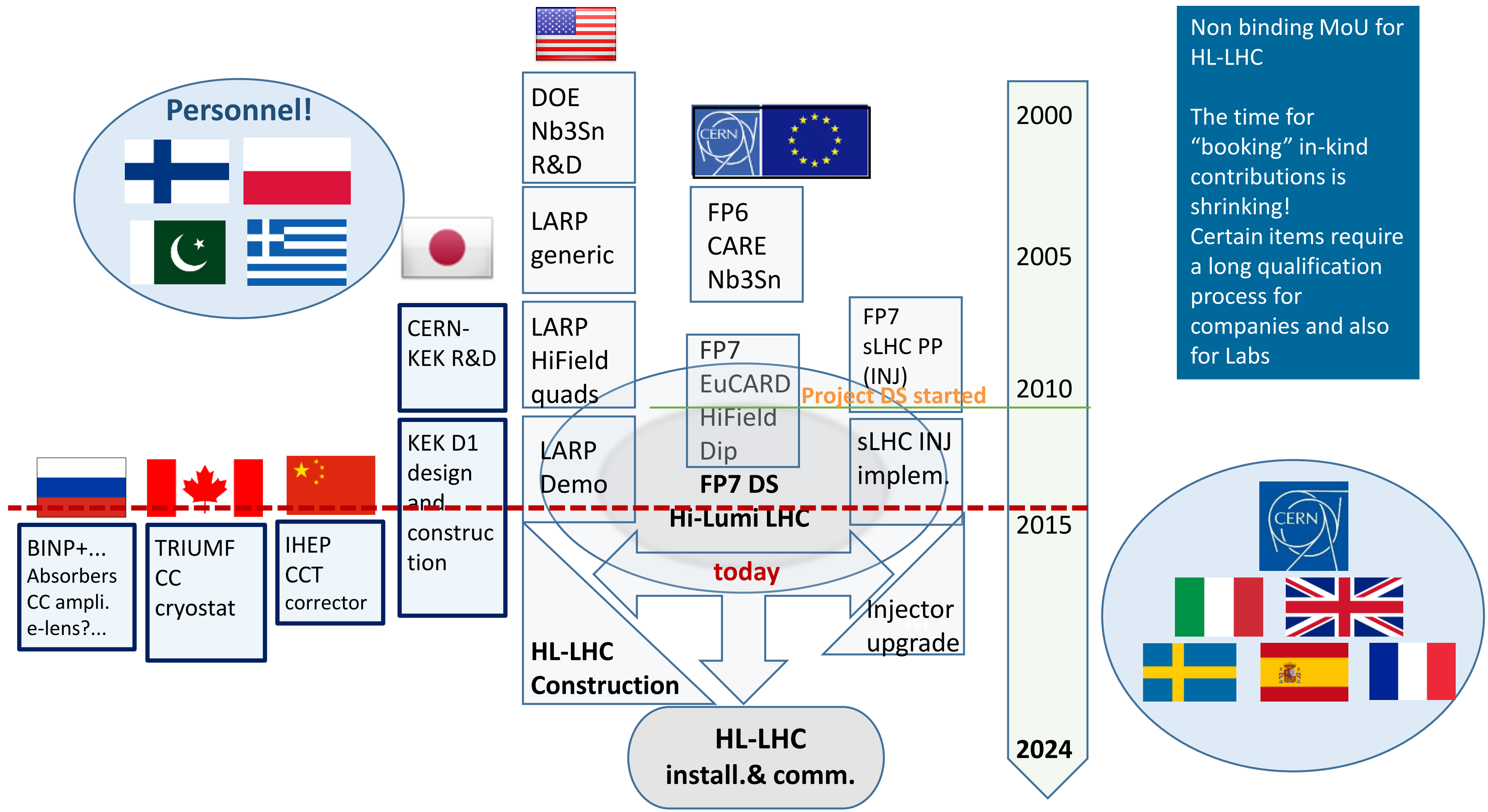
2*2.6T dipole field in the two apertures. 2.2m prototype being fabricated.

Agreement For HL-LHC CCT Magnets Signed in Sep 2018



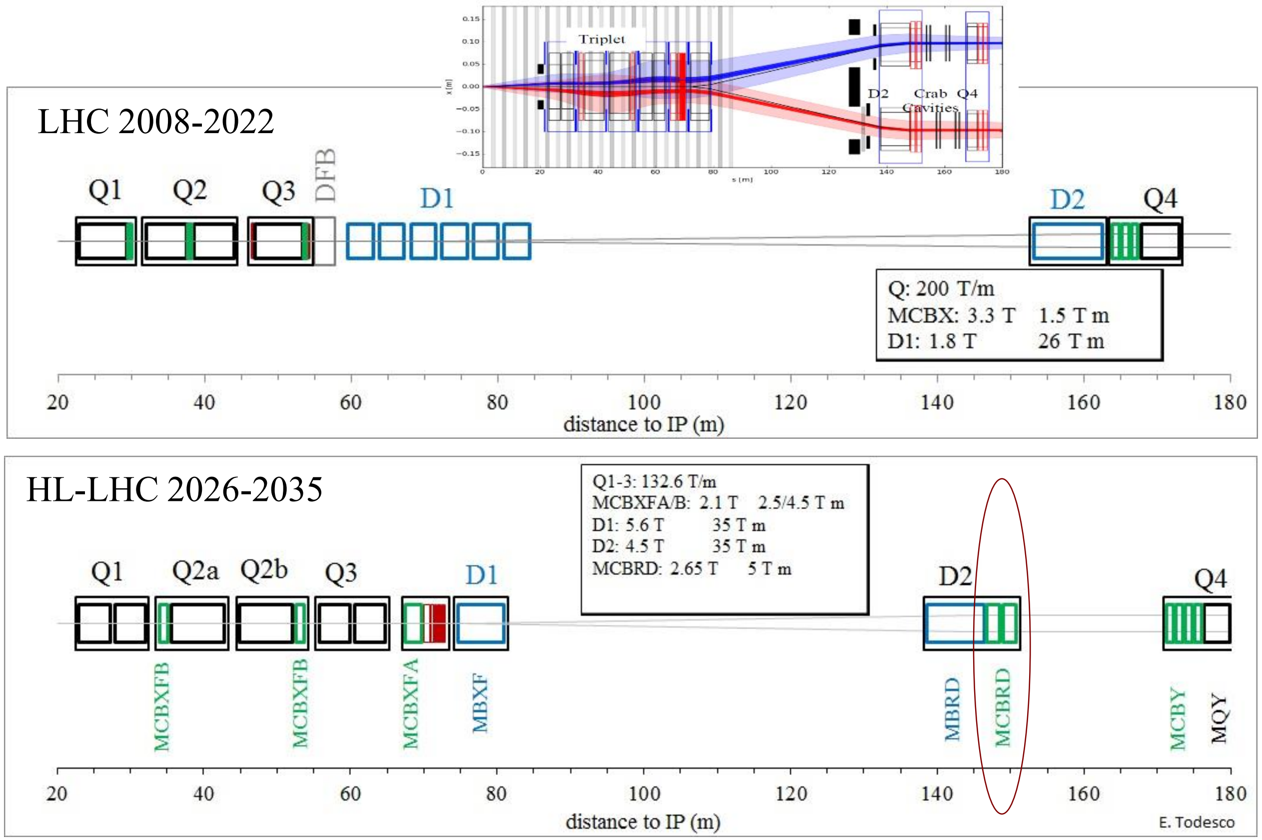
Layout of the HL-LHC Magnets and Contributors

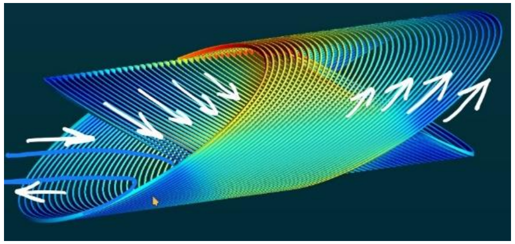
CERN-China HL-LHC CCT Project

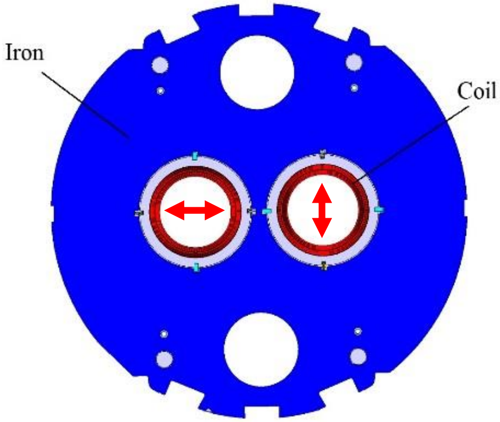


CERN-China HL-LHC CCT Project

MCBRD: the HL-LHC orbit correctors, providing a maximum 5 Tm integrated field in two apertures, vertical in one and horizontal in the other.

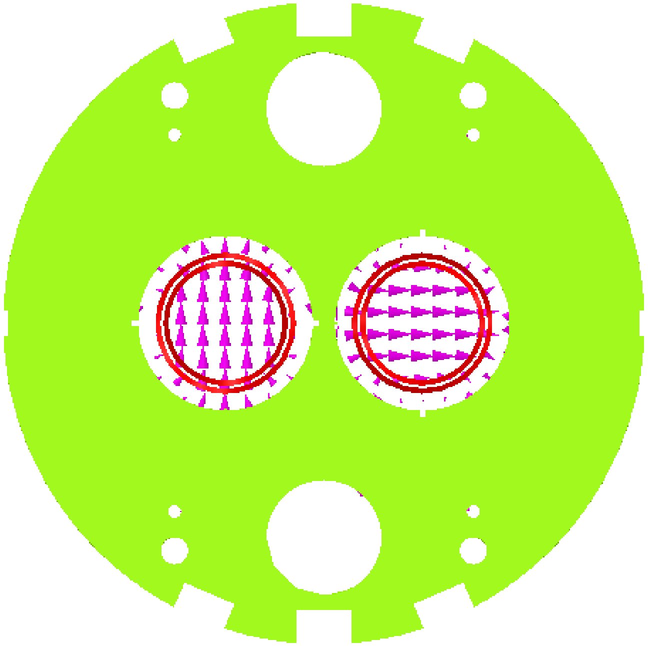


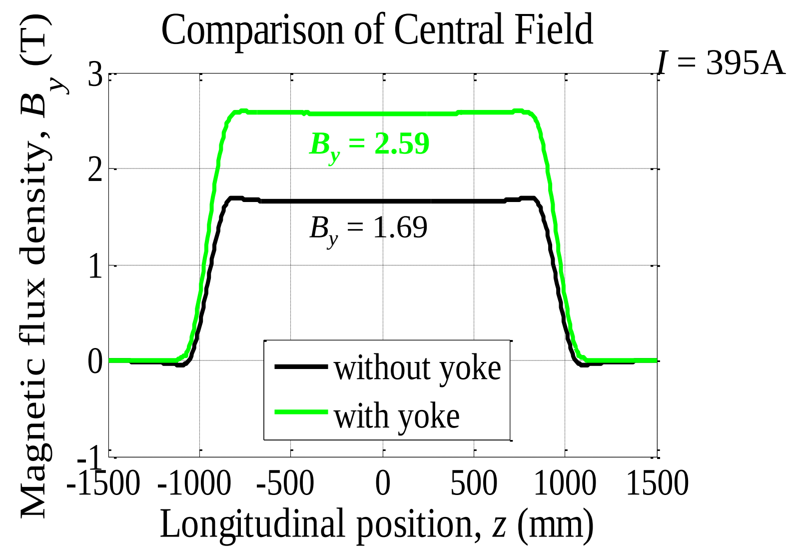


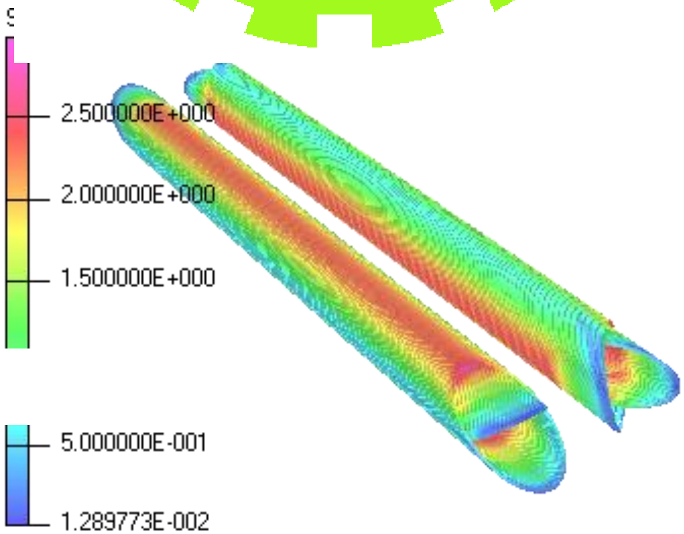


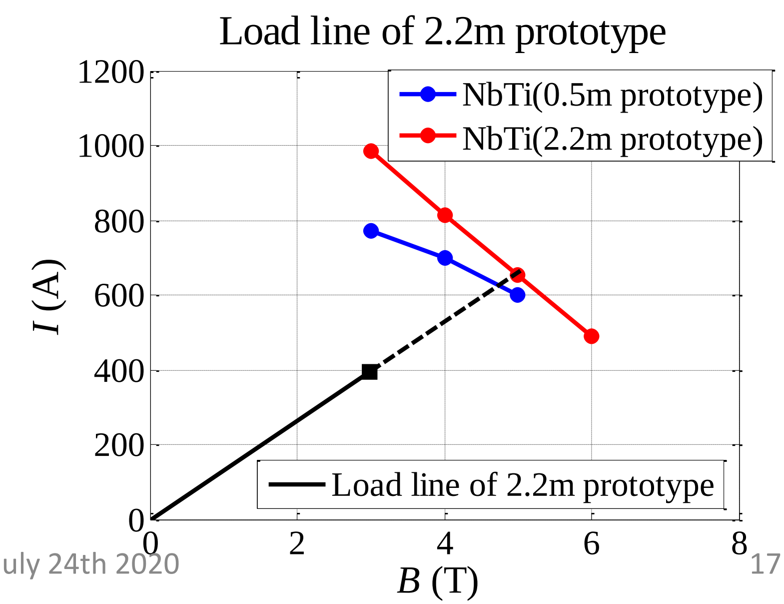
E. Todesco

CERN-China HL-LHC CCT Project





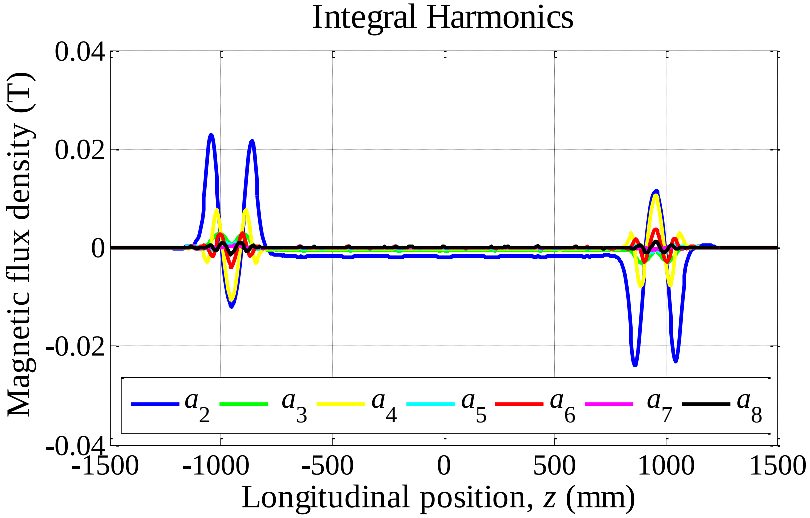


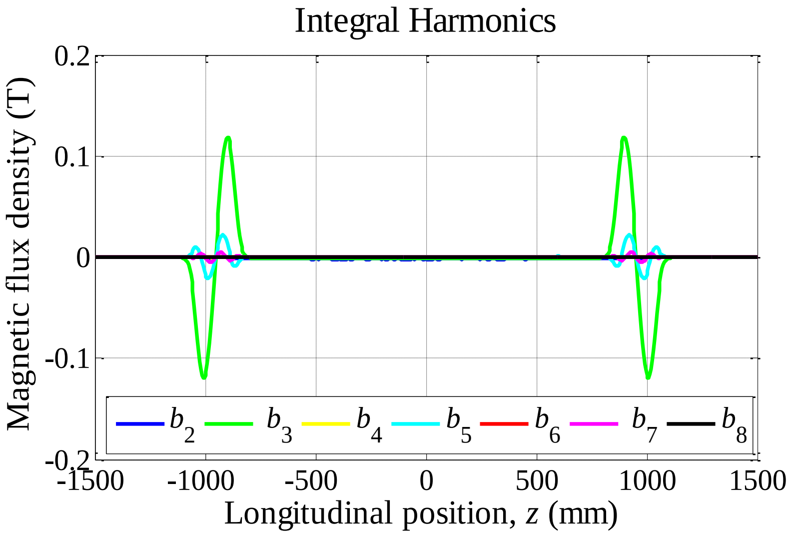


Integer harmonics for 2.2m-long CCT magnet

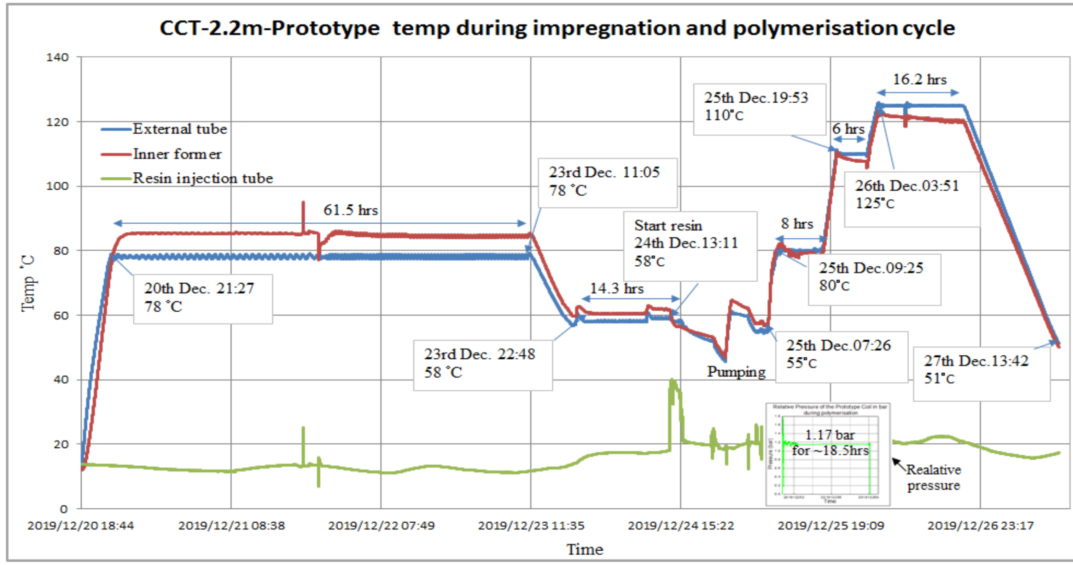
- Reference Radius r = 35mm, z = [-1500 : 1500]mm
- The integer harmonics b_3 = -6.13 unit

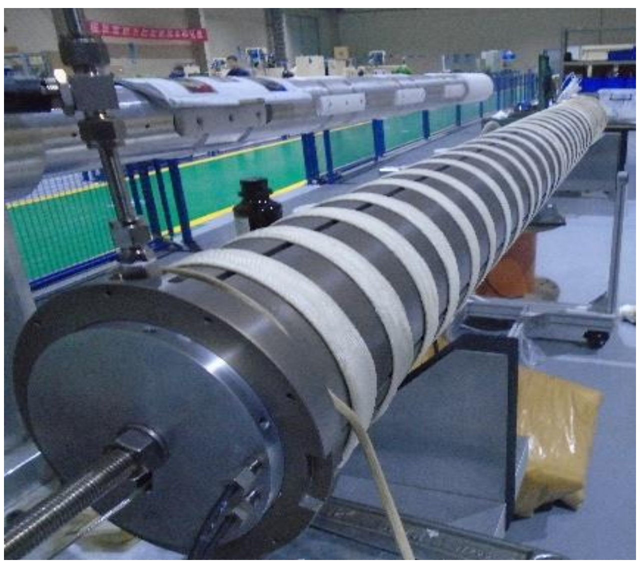
n	Integral harmonics, z=[-1500 : 1500]			
	Sin term (a_n)	Cos term (b_n)	Unit (a_n)	Unit (b_n)
0	0	9.37E-03	0	0.02
1	-7.03E+00	4.99E+03	-14.09	10000
2	-3.07E+00	-3.06E+00	-6.16	-6.13
3	-8.86E-01	-2.39E+00	-1.77	-4.79
4	-4.24E-01	-5.72E-01	-0.85	-1.15
5	-9.16E-02	1.02E+00	-0.18	2.05
6	-1.32E-02	-7.03E-02	-0.03	-0.14
7	-4.57E-03	-1.08E-01	-0.01	-0.22
8	6.59E-02	-2.06E-02	0.13	-0.04
9	3.71E-02	2.99E-02	0.07	0.06

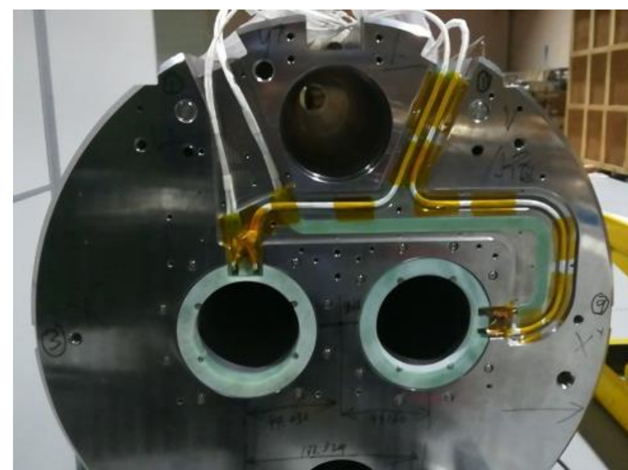




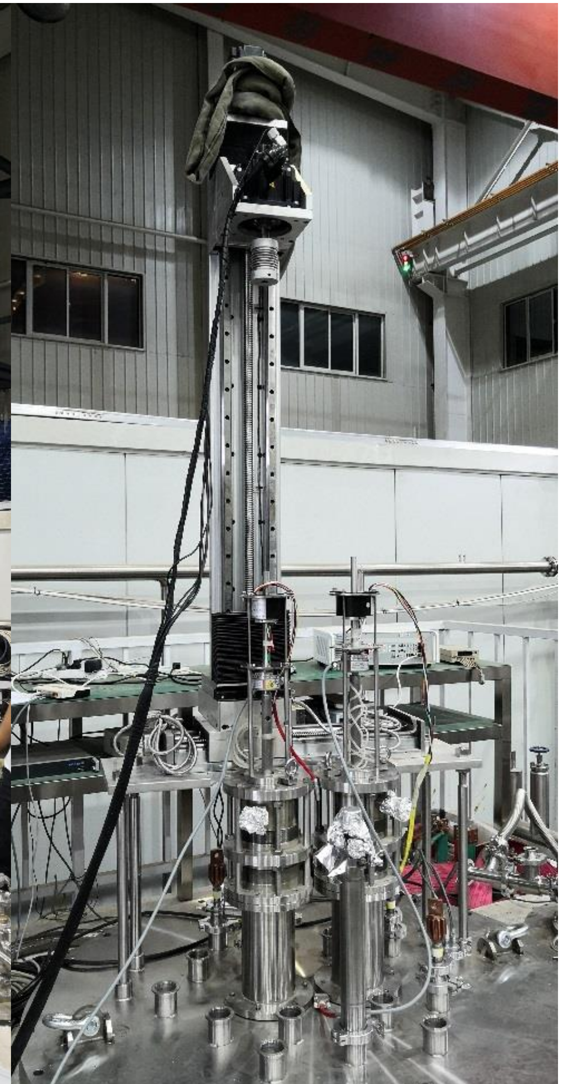
Coil fabrication and Magnet Assembly

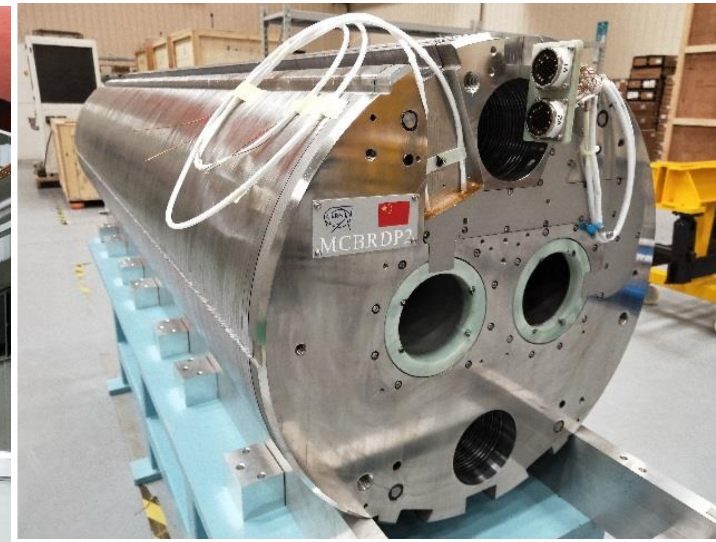






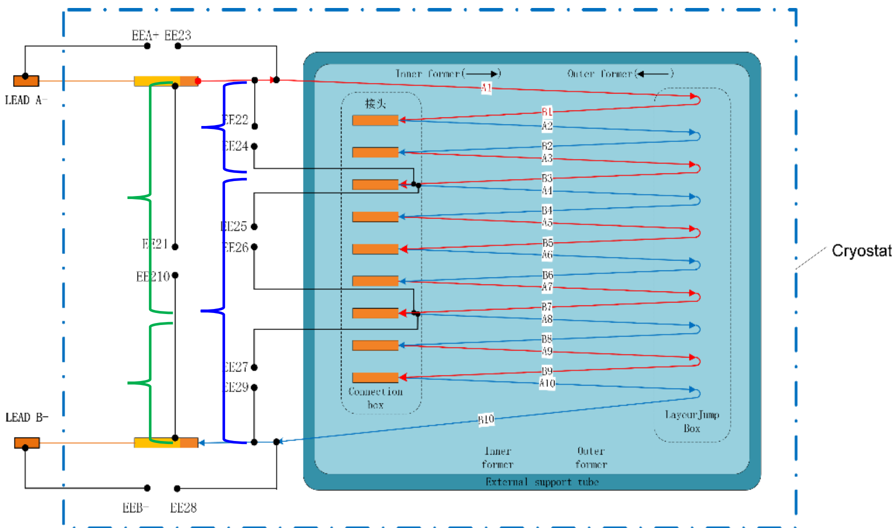
Cold test at IMP





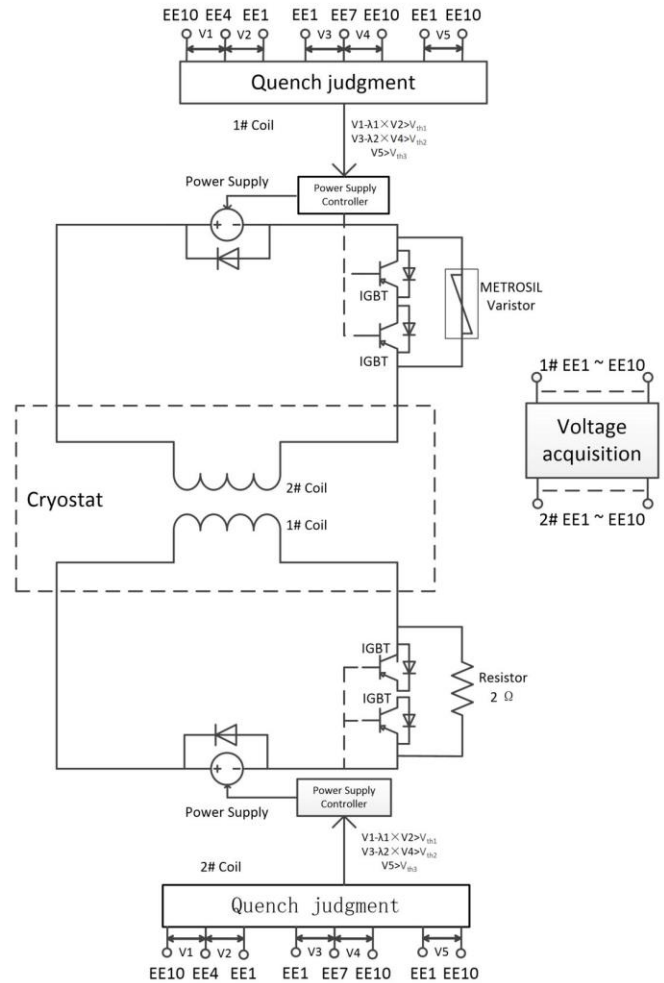
CERN-China HL-LHC CCT Project

Cold test at IMP



Quench detection

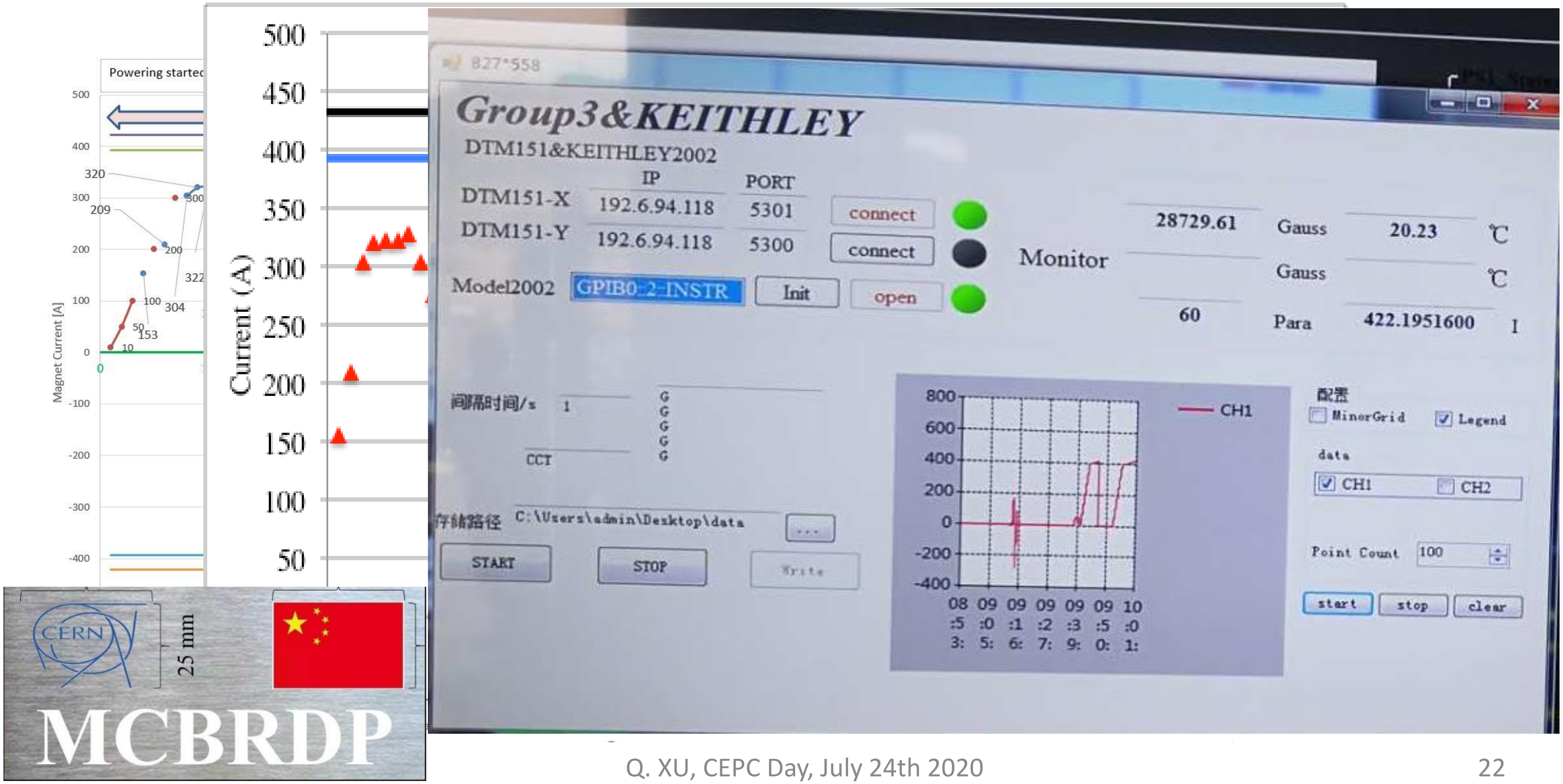
Metrosil varistor



Quench protection scheme

After ~1 month test and training at 4.2K, both apertures reached the design current 394A and ultimate current 422A. **Reached the design target!**

A good start for the next series production!



Summary

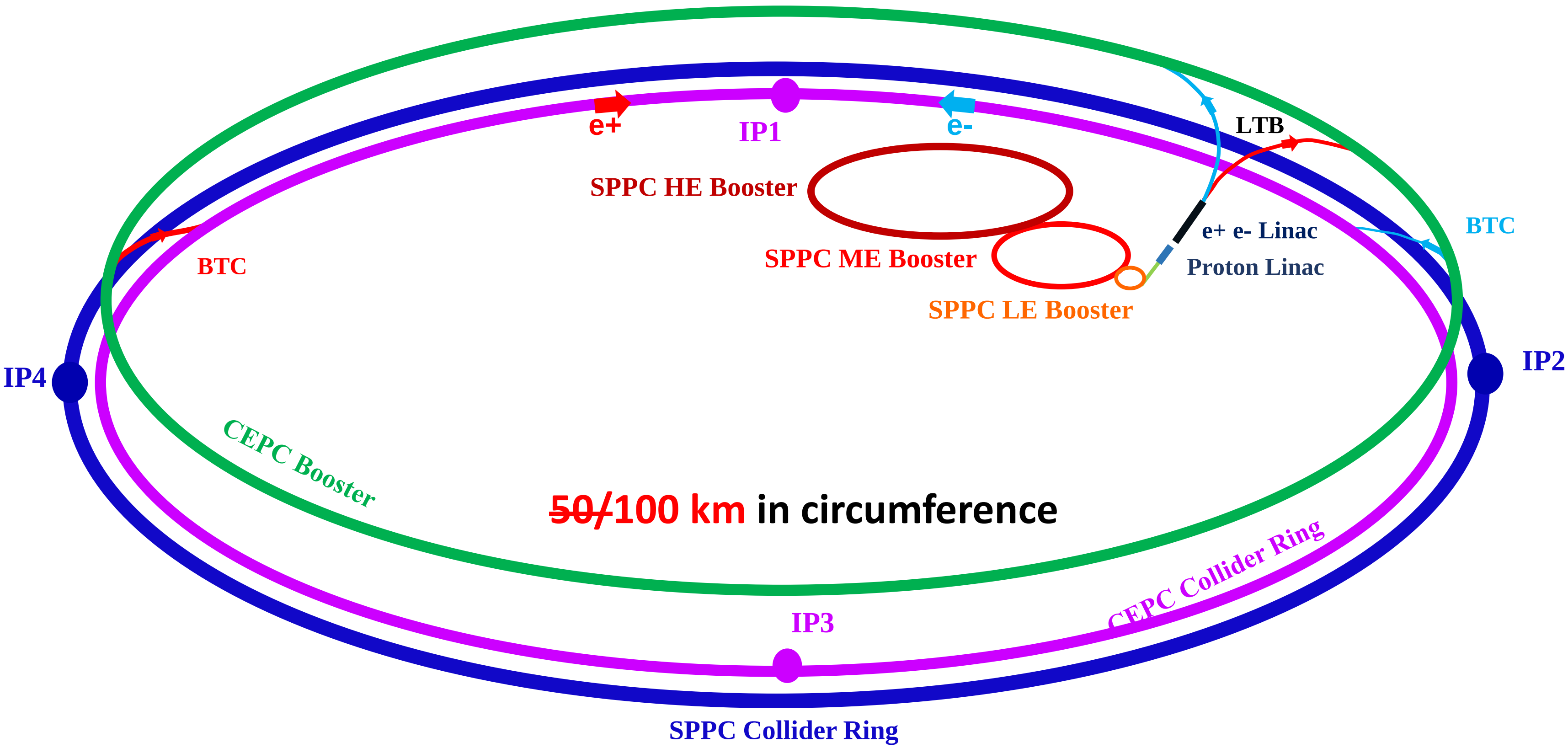
- *Advanced high field magnets are crucial components for future high energy accelerators.*
- *Strong domestic collaboration for the advanced superconductor R&D: raising performance & lowering cost.*
- *Very good performance of the 1st IBS solenoid coil tested at 24T and the 1st IBS racetrack coil tested at 10T.*
- *The 1st twin-aperture model dipole (NbTi+Nb_3Sn) reached 10.7 T @ 4.2 K; 12-16 T model dipoles being developed.*
- ***CERN & China Collaboration on accelerator technology:** test of the 2.2m prototype CCT magnet completed, reached the design target!*

Thanks for your attention

- Backup slides

CEPC-SPPC

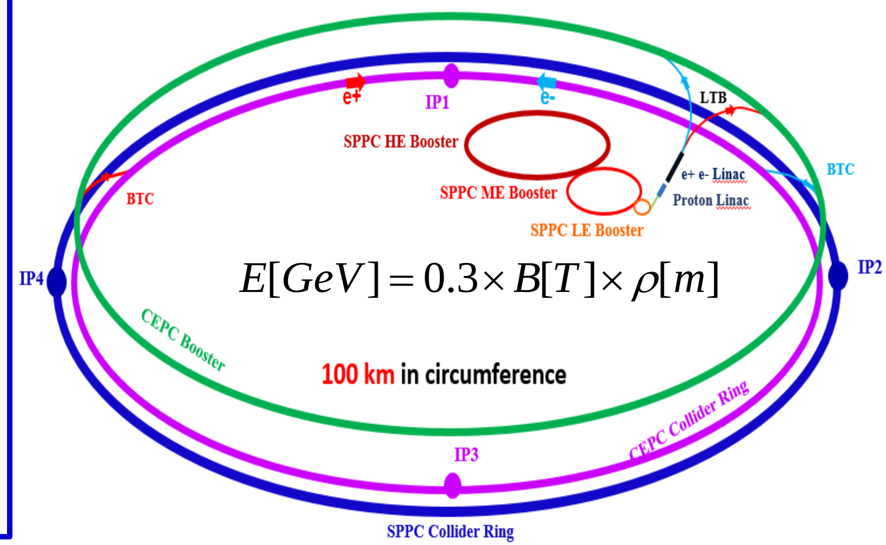
CEPC is an 240-250 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70-150 (Upgrading phase) TeV pp collider SPPC, to study the new physics beyond the Standard Model.



SPPC Magnet Design Scope

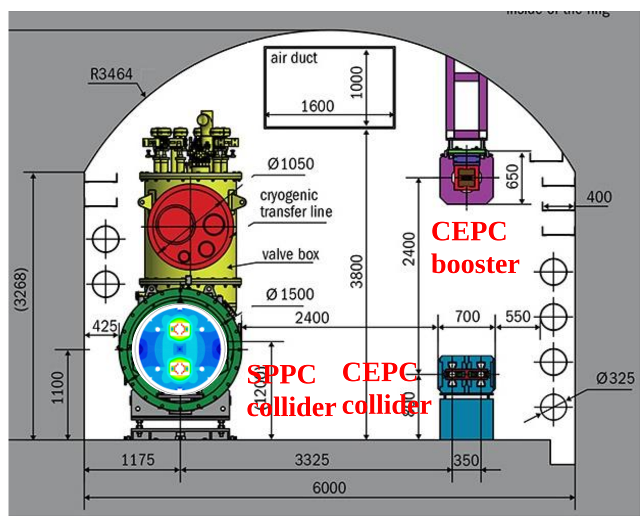
Main dipoles

- *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*

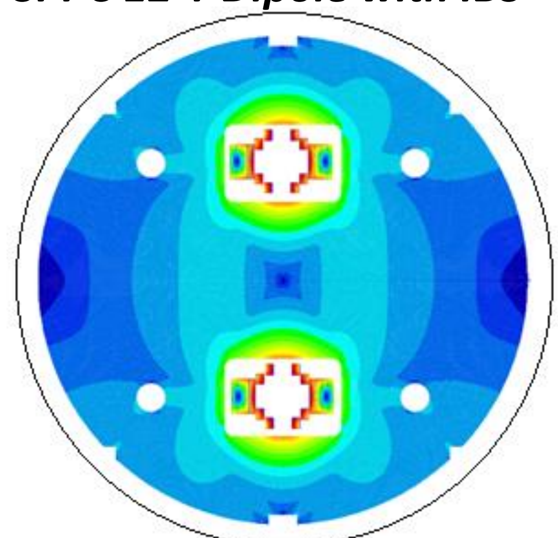


Site study of the CEPC-SPPC

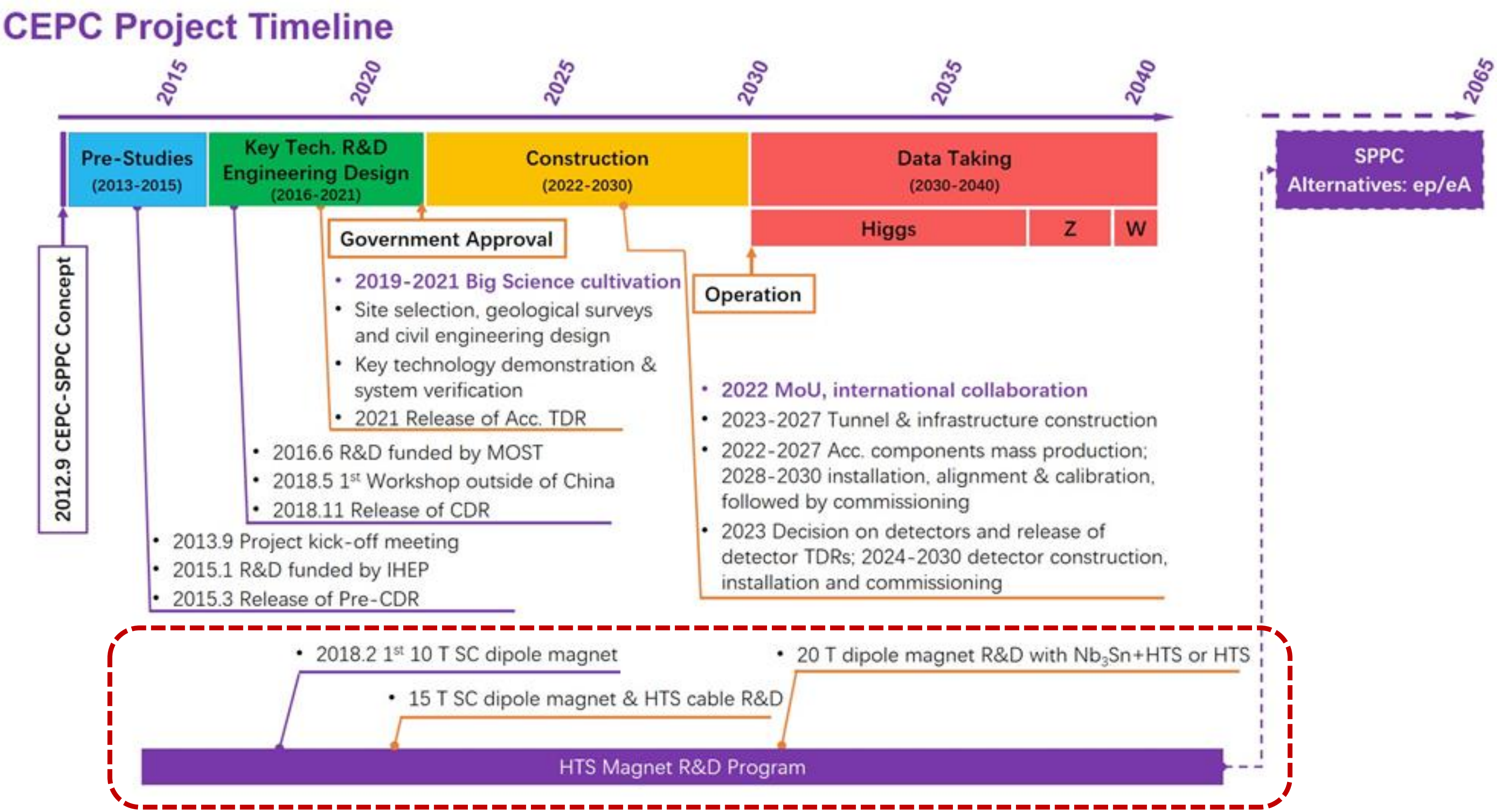
6-m width Tunnel for CEPC-SPPC



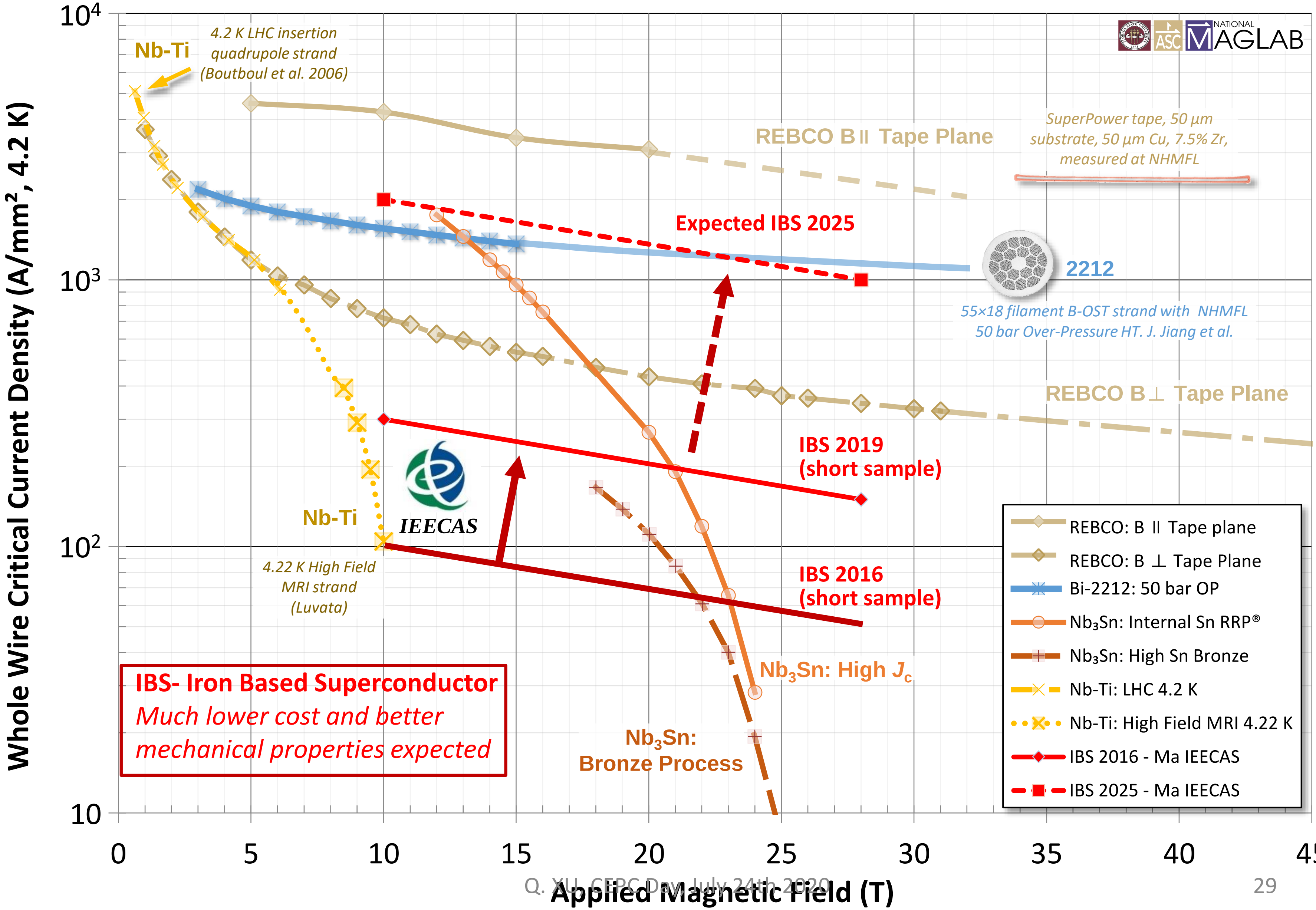
SPPC 12-T Dipole with IBS



CEPC-SPPC Project Timeline

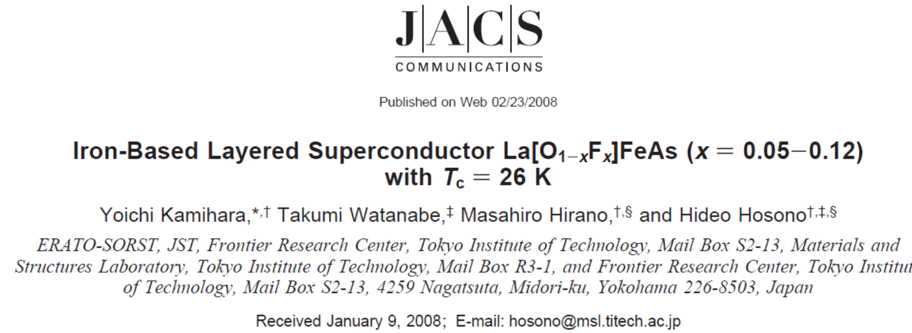


J_e of IBS: 2016-2025



Discovery of IBS Superconductor

Hideo Hosono
IBS (Tc 26K)
2008.02[1]



J|A|C|S COMMUNICATIONS

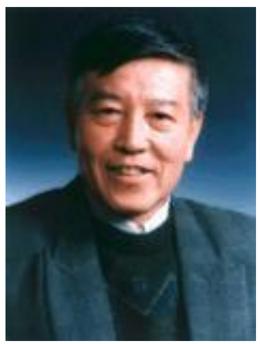
Published on Web 02/23/2008

Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs (x = 0.05−0.12) with T_c = 26 K

Yoichi Kamihara,*,† Takumi Watanabe,‡ Masahiro Hirano,†,§ and Hideo Hosono†,‡,§

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

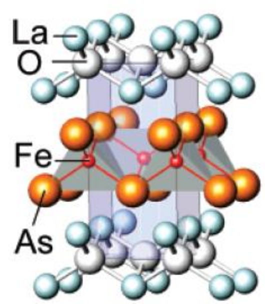
Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp



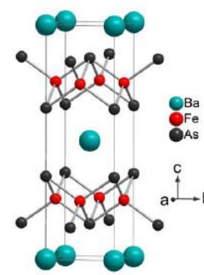
Z. Zhao
IBS (Tc 55K)
2008.04[2]

The three phases most relevant for wire applications are 1111, 122, and 11 types with a T_c of 55, 38 and 8 K, respectively.

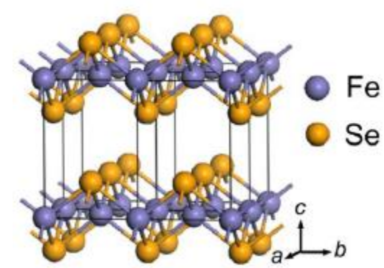
1111 Phase
LnOFeAs[2]



122 phase
AFe2As2



11 phase
FeSe[4]



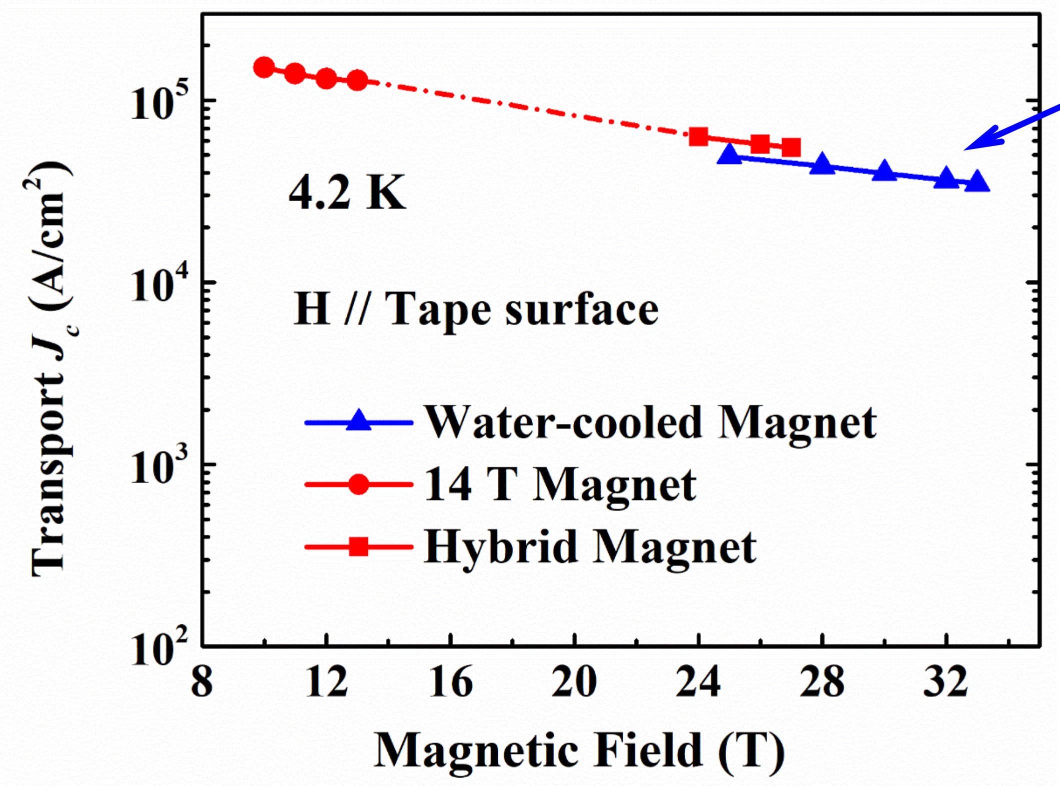
[1]Yoichi Kamihara, et al, 'Iron-Based Layered Superconductor La[O1-xFx]FeAs (x) 0.05-0.12) with Tc) 26 K', J. AM. CHEM. SOC. 2008, 130, 3296-3297
[2] Ren, Zhi-An , et al, ' Superconductivity and phase diagram in iron-based arsenic-oxides ReFeAsO1−δ (Re = rare-earth metal) without fluorine doping. EPL (Europhysics Letters). 2008, 83: 17002
[3] Marianne Rotter, et al, 'Superconductivity at 38 K in the Iron Arsenide (Ba1−xKx)Fe2As2', Phys. Rev. Lett. 101, 107006 – Published 5 September 2008
[4] Fong-Chi Hsu, et al, 'Superconductivity in the PbO-type structure α-FeSe', PNAS September 23, 2008 105 (38) 14262-14264

New record J_e 364A/mm² @ 4.2K, 10T

***Short sample** I_c: 437 A with 4-mm width and 0.3-mm thickness.*

IEECAS
Yanwei Ma

J_e = 364A/mm^2 @ 4.2K, 10T



At 30 T, J_c = 400 A/mm^2

Transport J_c of 100-m-class 7-filamentary Ba-122 IBS tapes was further improved to > 3×10^4 A/cm^2 at 10 T & 4.2 K (three times the value in 2016).

Domestic Collaboration for HTS R&D

Applied High Temperature Superconductor Collaboration (AHTSC)

- R&D from **Fundamental sciences** of superconductivity, **advanced HTS superconductors** to **Magnet & SRF technology**.
- **Regular meetings every 3 months** from Oct. 2016
- **Goal**:
- **Increasing J_c** of iron-based superconductor **by 10 times**.
- **Reducing the cost** of HTS conductors to be **similar with "NbTi conductor"**
- Industrialization of the **advanced superconductors**, **magnets and cavities**

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

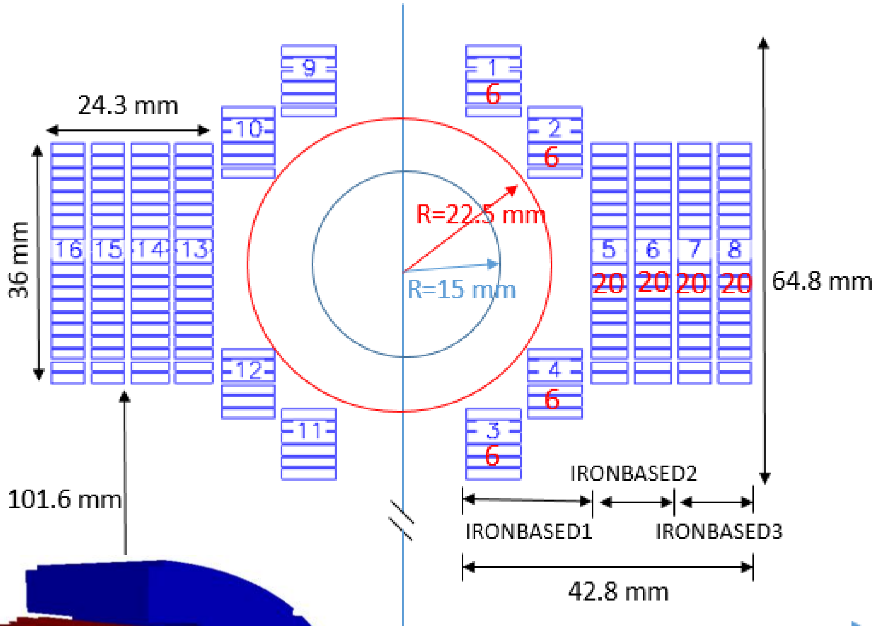
科学技术部
高技术研究发展中心

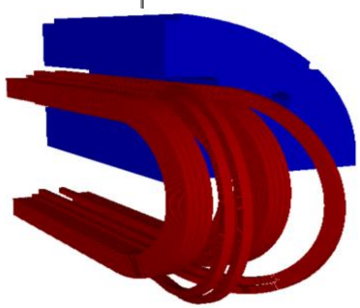
43M RMB for 2019-2024

国科高发计字〔2019〕55 号

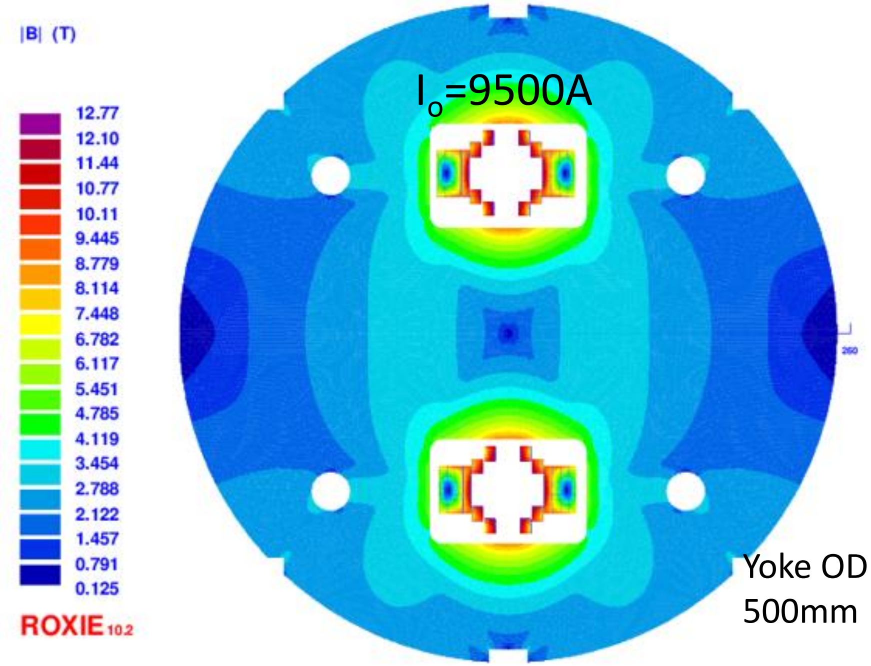
关于印发国家重点研发计划
"变革性技术关键科学问题"重点专项
2018 年度项目立项的通知

The 12-T Fe-based Dipole Magnet

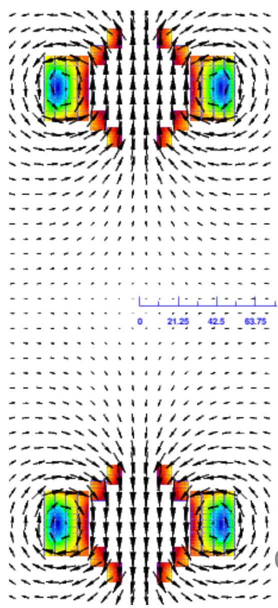




IJMPA 2019,34(13n14),1940003



Field quality	2D with R_f=13.3mm	3D with R_f= 8/13.3 mm
b3	0.45	0.79/1.91
b5	1.01	-0.65/-2.24
b7	0.46	0.08/0.67
b9	-0.27	-0.13/-0.22
a2	3.53	-1.00/-2.31
a4	0.49	-0.46/0.69
a6	0.33	0.26/2.49
a8	0.58	-0.12/0.84
a10	2.23	0.06/2.18



Conceptual design with expected J_e of IBS in 2025

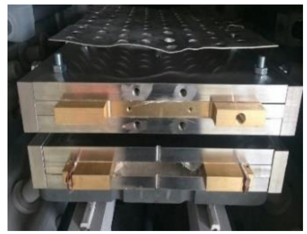
Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0.802	1	200	4.2	10	4000	111

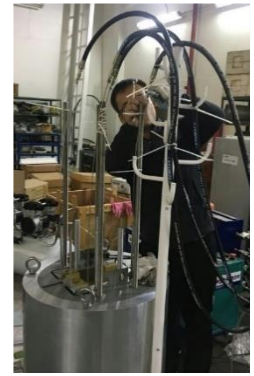
- For 100-km SPPC, needs **3000 tons of IBS**
- Target cost of IBS: **20 RMB /kAm @12 T**
- Total cost for IBS conductors: **~10B RMB**

R&D Fabrication Procedures and Challenges

Tension control, deformation
J_c and RRR degradation,
Flux jump…

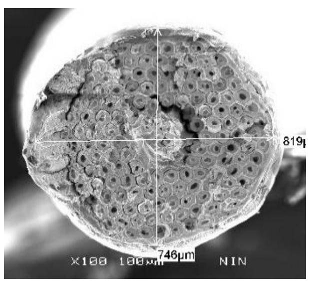
Temperature control, Thermal stress control
J_c and RRR degradation.



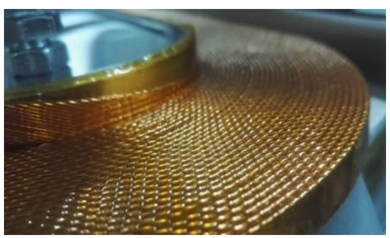


Pre-stress control
Stress of coils,
Mechanical Stability…

Cabling ➡ Coil winding ➡ HT ➡ VPI ➡ Magnet assembly ➡ Test



Material, Structure, Processing,…
J_c, RRR, Cu ratio,
Filament size…



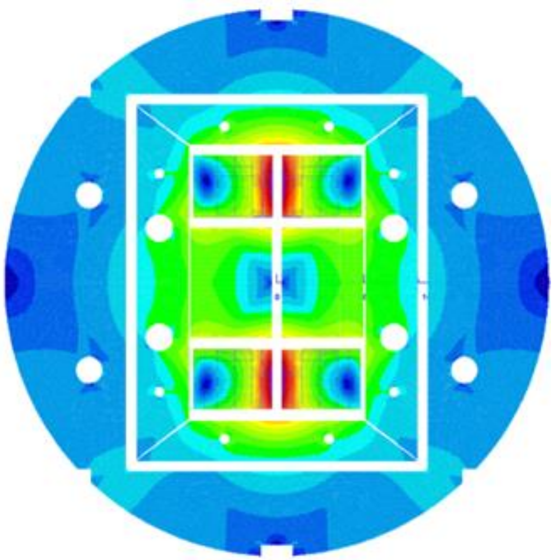
Stress control, Size control, Electrical insulation
J_c and Field quality degradation,
Electrical short…

Impregnation quality control:
type of epoxy, procedures;
Mechanical strength and stability

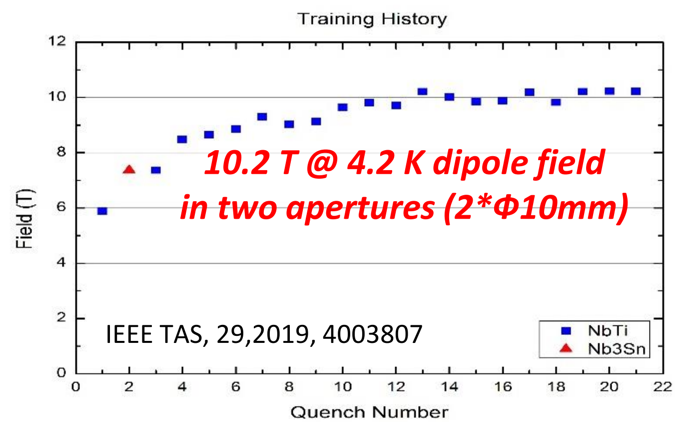
EM force, Quench protection
Training,
Strain of coils…

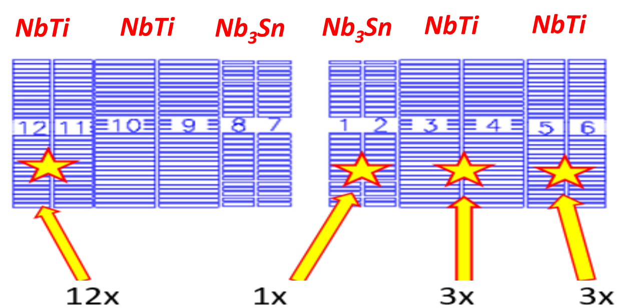
The 1st High-Field Model Dipole LPF1 in China

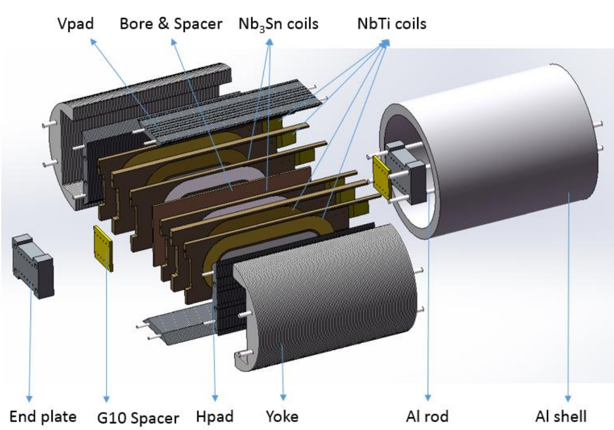
Twin aperture model dipole magnet with NbTi+Nb_3Sn



Common coil dipole magnet

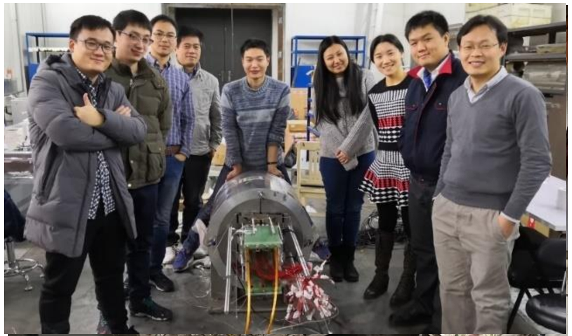


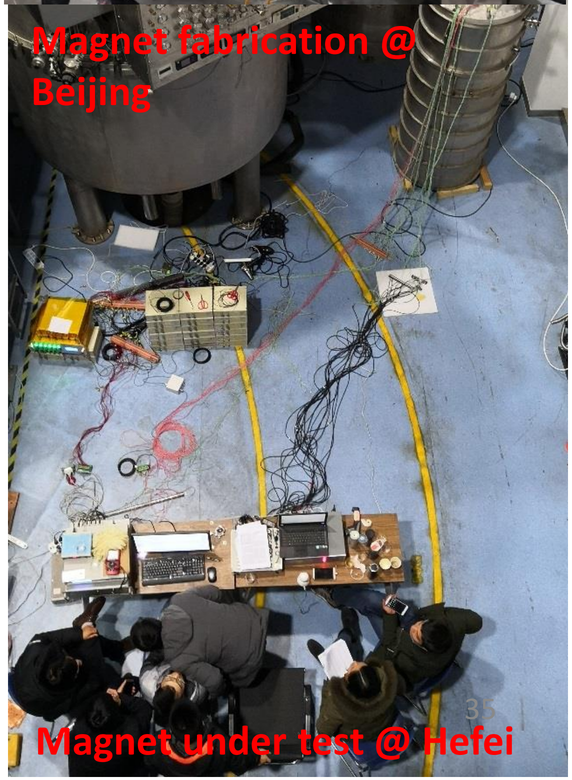




Shell-based Support structure

- *Performance **limited by the outermost NbTi coil.***
- *Very possibly due to the **less of pre-stress.***





Dipole vs. Solenoid

Dipole

$$B = \mu_o J_e \frac{t}{2}$$

J_e – Current density

t – Coil thickness

Dipole vs Solenoid

- *Different coil configurations*

  $$B_{dipole} = \frac{1}{2} B_{solenoid}$$

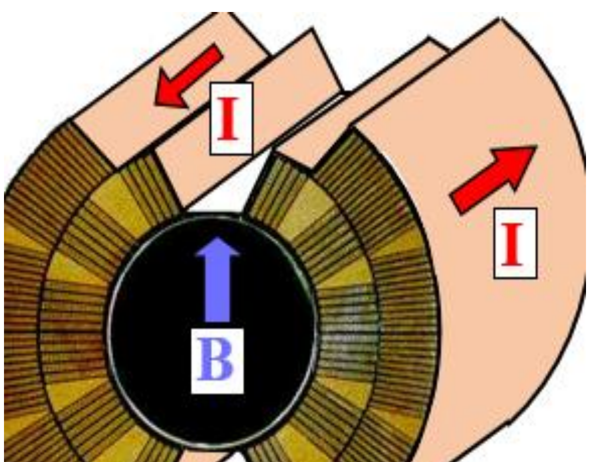
- *Limited coil width for dipole*
- *Magnetic shielding*
- *Cost*

Solenoid

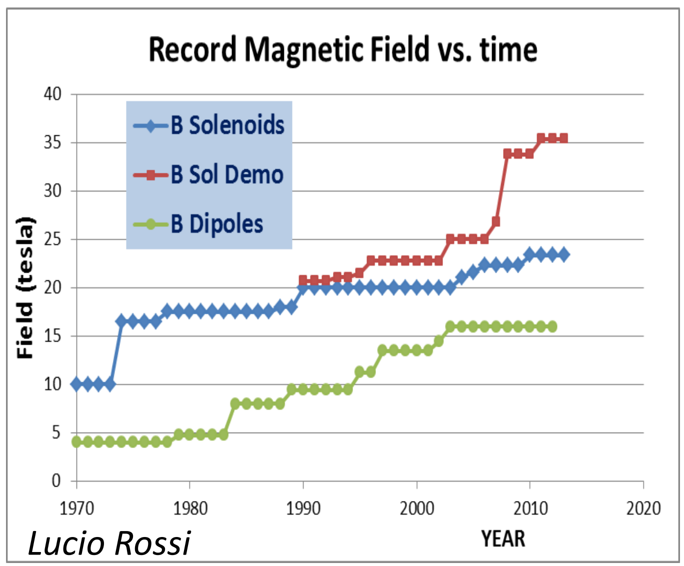
$$B = \mu_o J_e t$$

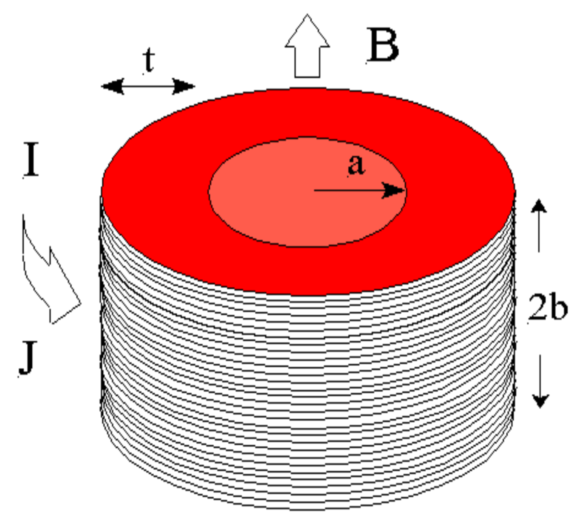
J_e – Current density

t – Coil thickness



LHC dipole





Martin Wilson