THE 2018 INTERNATIONAL WORKSHOP ON THE HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER

November 12-14, 2018

Institute of High Energy Physics, Beijing, China

Progress of High Field Magnet R&D for CEPC-SPPC

Qingjin XU

Institute of High Energy Physics (IHEP)

Chinese Academy of Sciences (CAS)

2018.11

Team Members & Collaborators

IHEP-CAS: *Chengtao Wang, Zhan Zhang, Shaoqing Wei, Lingling Gong, Da Cheng, Yingzhe Wang, Ershuai Kong, Zhen Zhang, Xiangchen Yang, Quanling Peng, Qing Qin, Yifang Wang,*

IEE-CAS: *Xianping Zhang, Dongliang Wang, Yanwei Ma*

HIPS-CAS: *Huajun Liu, Tao Zhao, Yanlan Hu,…*

IMP-CAS: *Wei Wu, Yu Liang, Wenjie Liang, Lizhen Ma,…*

WST: *Meng Li, Chao Li, Bo Wu, Yanmin Zhu, Jianwei Liu, Jianfeng Li,…*

Toly Electric: *Yu Zhao, Hean Liao, Bingxing Lu,…*

**The work is supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (CAS) Grant No. XDB25000000, the key research program of CAS Grant No. XDPB01, the Hundred Talents Program of CAS and National natural Science Foundation of China Grant No. 11675193, 11575214, 11604335, U1632276.*

Outline

- Background: SPPC Magnet Design Scope
- Domestic Collaboration Towards HTS SPPC
- Conceptual Design of the 12T IBS Dipole Magnet
- R&D of High Field Dipole Magnets
  - *Fabrication and test of the NbTi+Nb_3Sn model dipole*
  - *Fabrication and test of the Nb_3Sn model dipole with IBS coil*
  - *Fabrication of IBS solenoids*
- CERN-China HL-LHC Collaboration
- Summary

SPPC Magnet Design Scope (V201701)

SPPC

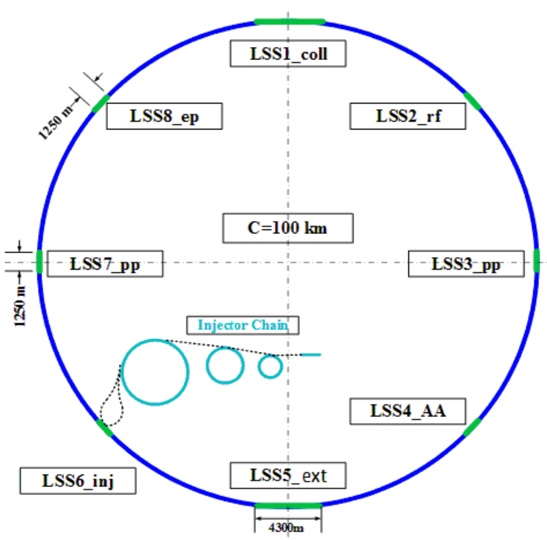
- ***100** km in circumference*
- *C.M. energy 70-150 (Upgrading) TeV*
- *Timeline*

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

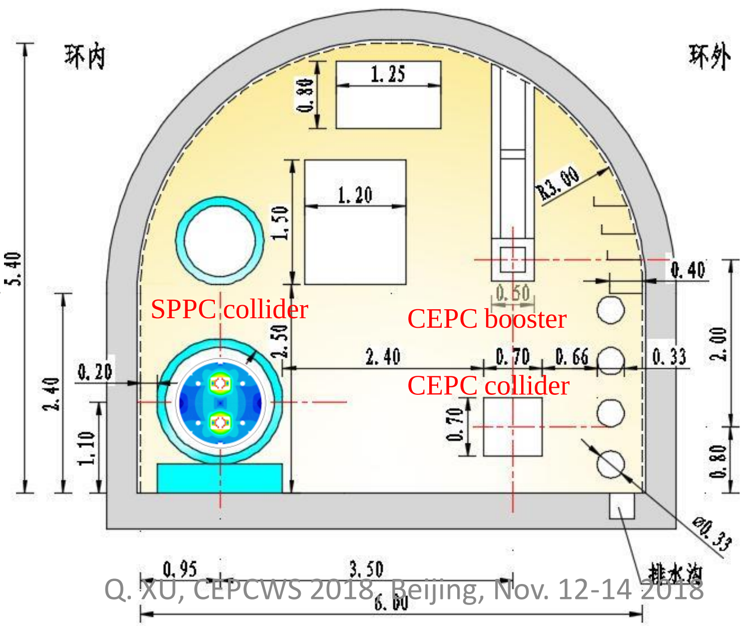
Main dipoles $E[GeV] = 0.3 \times B[T] \times \rho[m]$

- *Field strength: 12~24 (Upgrading) Tesla*
- *Aperture diameter: 40~50 mm*
- *Field quality: 10^{-4} at the 2/3 aperture radius*
- *Outer diameter: 650-900 mm in a 1.5 m cryostat*
- *Tunnel cross section: 6 m wide and 5.4 m high*

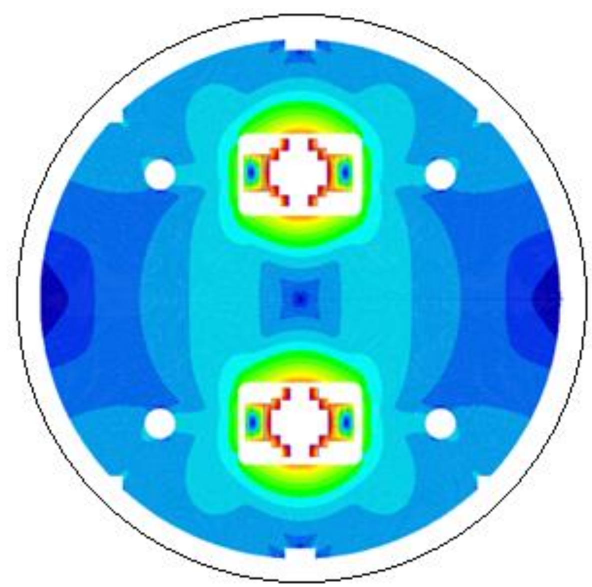
SPPC Layout



6-m Tunnel for CEPC-SPPC



Conceptual design of the SPPC 12-T magnet with IBS and common coil configuration



SPPC Magnet Design Scope

- **Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV

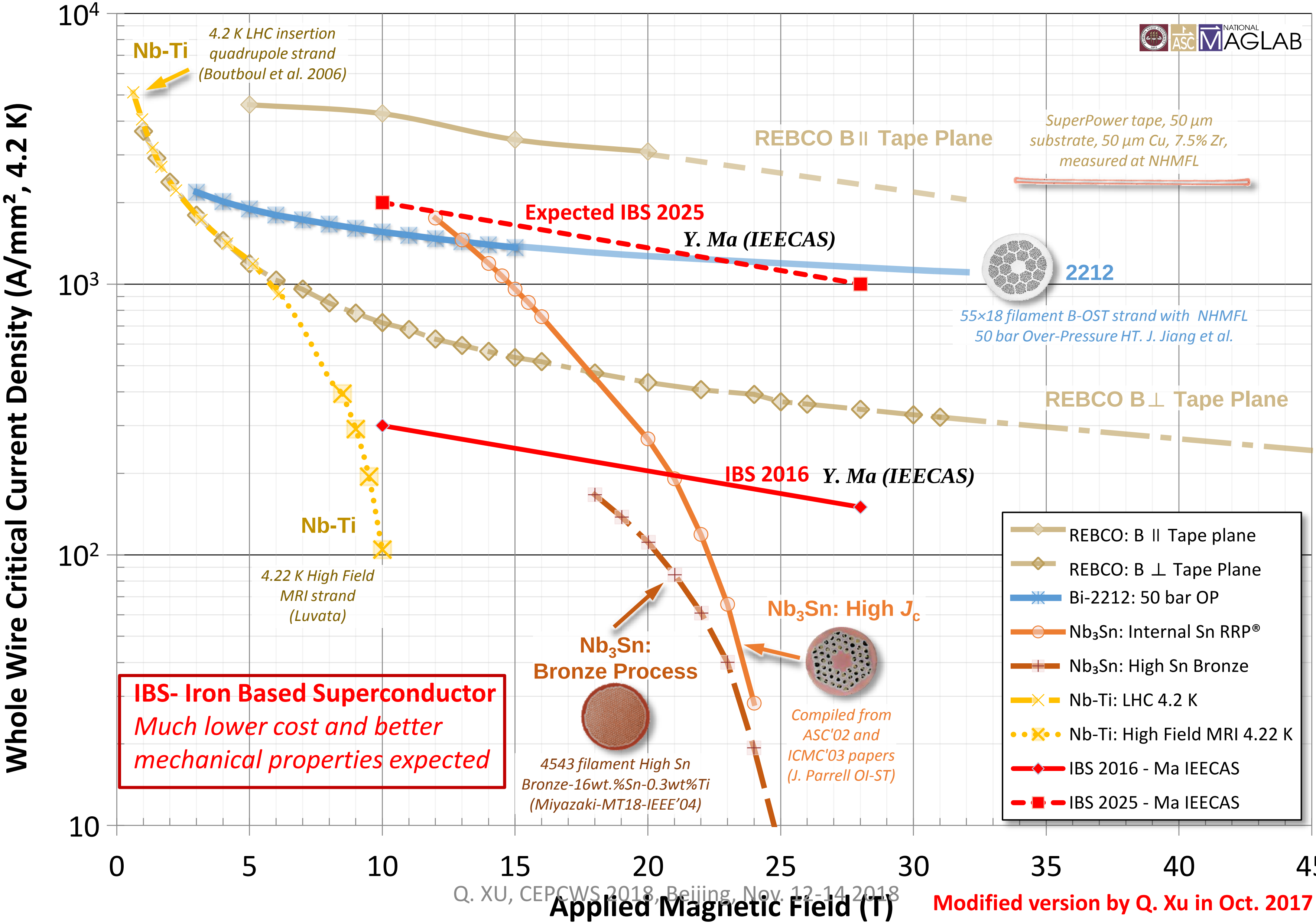
Top priority: reducing cost!
Instead of increasing field

- **Upgrading phase**
  - Dipole magnet field: 20 -24T, IBS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)

Make IBS the High-T_c and High-Field "NbTi" superconductor in 10 years!

- **Development of high-field superconducting magnet technology**
  - Starting to develop HTS magnet technology before applicable IBS wire is available
  - ReBCO & Bi-2212 and LTS wires be used for model magnet studies and as options for SPPC: stress management, quench protection, field quality control and fabrication methods

J_e of IBS: 2016-2025



Domestic Collaboration for HTS R&D

"Applied High Temperature Superconductor Collaboration (AHTSC)" formed in Oct. 2016. Including 18 institutions and companies in China. Regular meeting every 3 months.

- ***Goal :***

*a) 1) To increase the J_c of iron-based superconductor (**IBS**) by 10 times, reduce the cost to **20 Rmb/kAm @ 12T & 4.2K**, and realize the industrialization of the conductor;*

*b) 2) To reduce the cost of **ReBCO and Bi-2212** conductors to 20 Rmb/kAm @ 12T & 4.2K;*

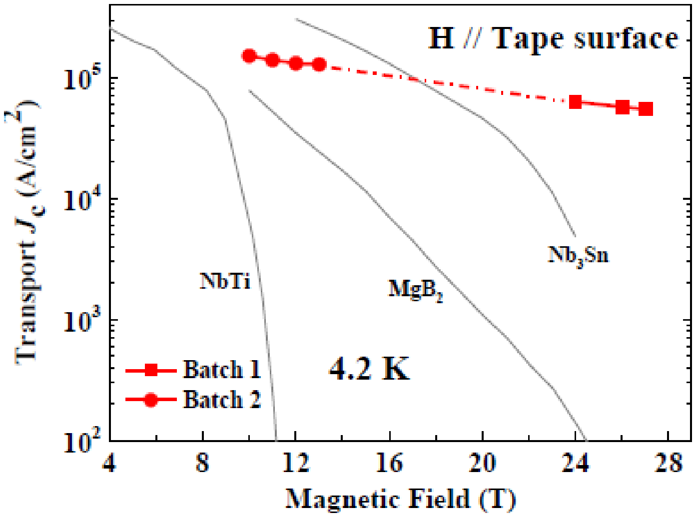
c) 3) Realization and Industrialization of IBS magnets and SRF cavities.

- ***Working groups :*** *1) **Fundamental sciences** study; 2) **IBS** conductor R&D; 3) **ReBCO** conductor R&D; 4) **Bi-2212** conductor R&D; 5) **Performance** evaluation; 6) **Magnet and SRF** technology.*

Progress on IBS wires

Supercond. Sci. Technol. 31 (2018) 015017

Y. Ma (IEECAS) et al.



Latest transport property of IBS tape (2017):

Short tape (~4 mm wide, 0.3 mm thick):

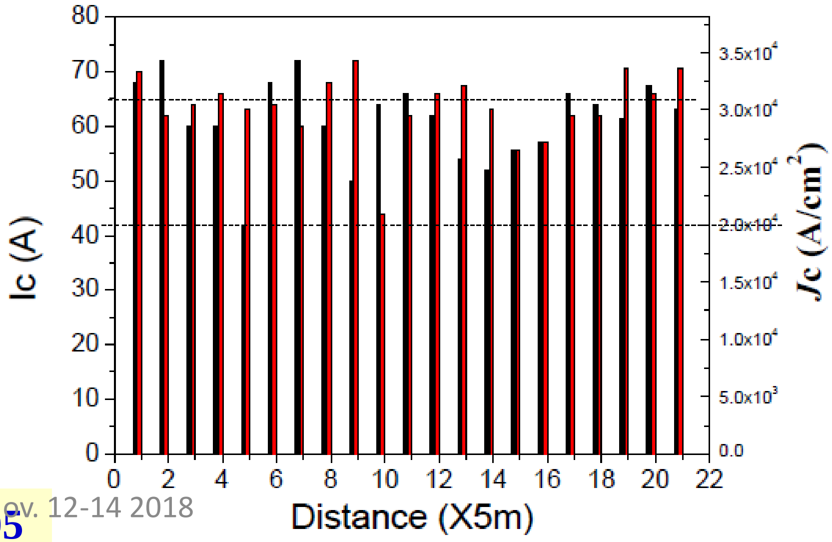
I_c~423 A (J_c>1450 A/mm^2) @ 4.2 K, 12 T

100 meter long tape:

J_c>200 A/mm^2 @ 4.2 K, 12 T

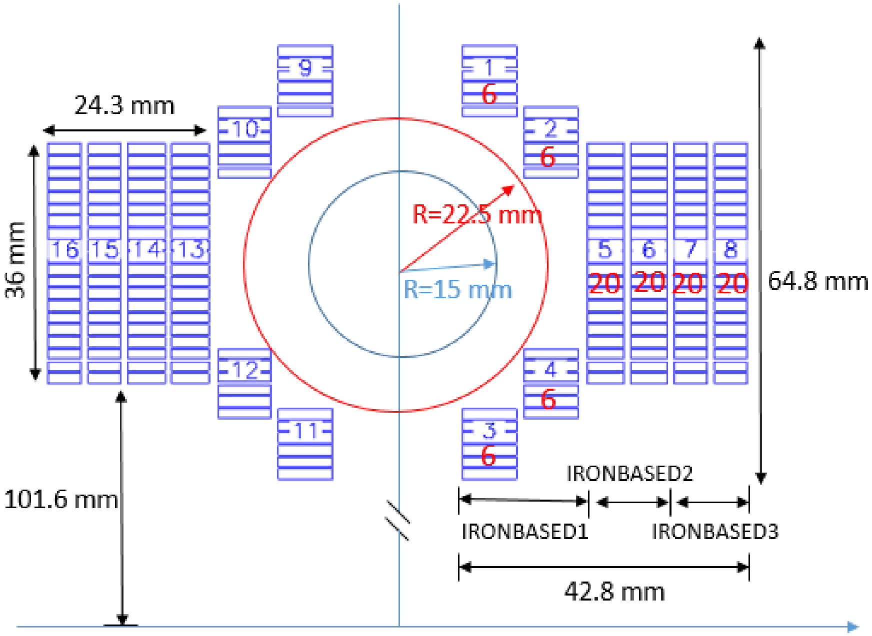
Key steps to the application

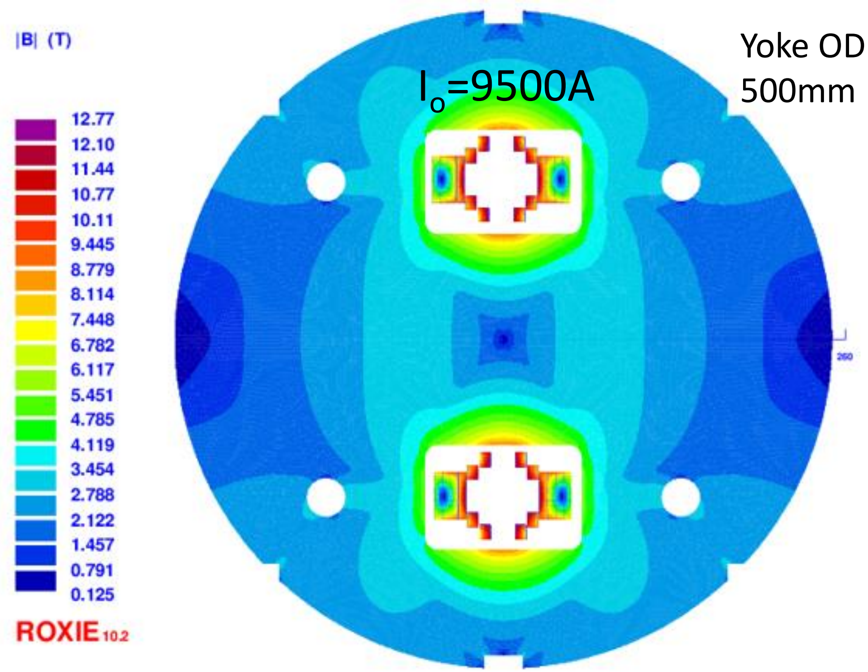
115 meter long 7-core tape

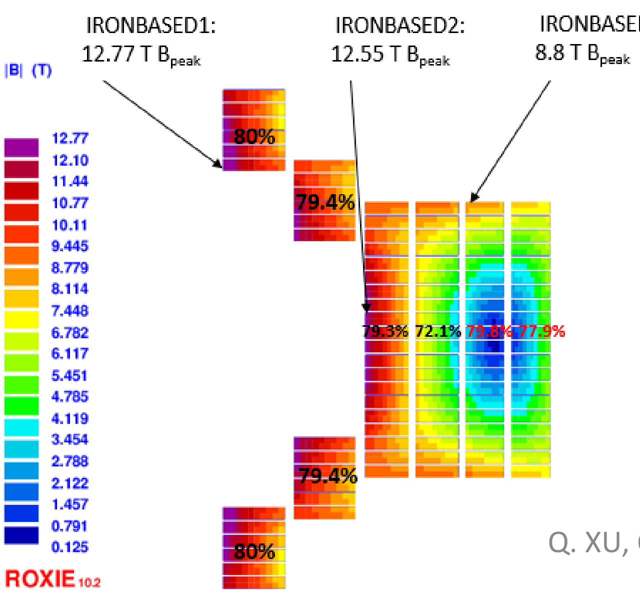


IEEE TAS 27 (2017) 7300705

The 12-T Fe-based Dipole Magnet







Design with expected J_e of IBS in 2025

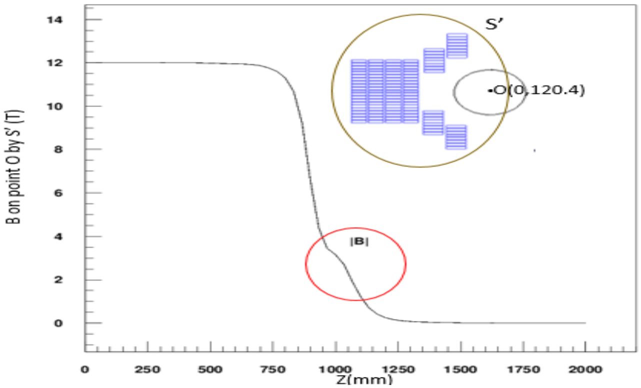
Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0.802	1	200	4.2	10	4000	111

- The required length of the 0.8 mm IBS is 6.1 Km/m
- For 100-km SPPC, 3000 tons of IBS is needed
- Target cost of IBS: 20 RMB (~2.6 Eur) /kAm @12 T

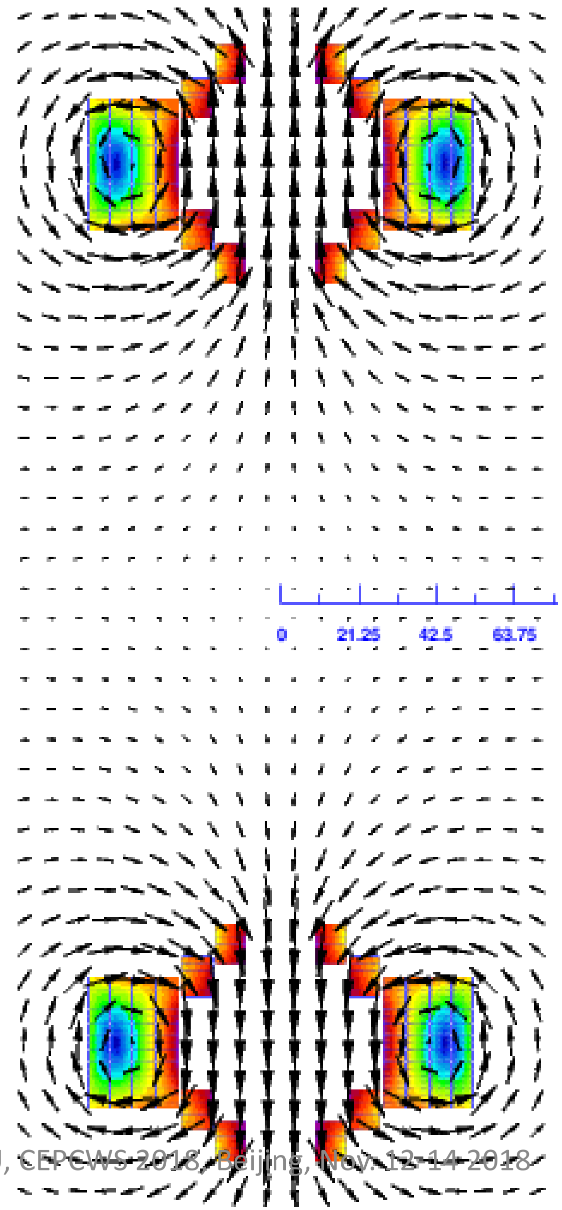
The 12-T Fe-based Dipole Magnet

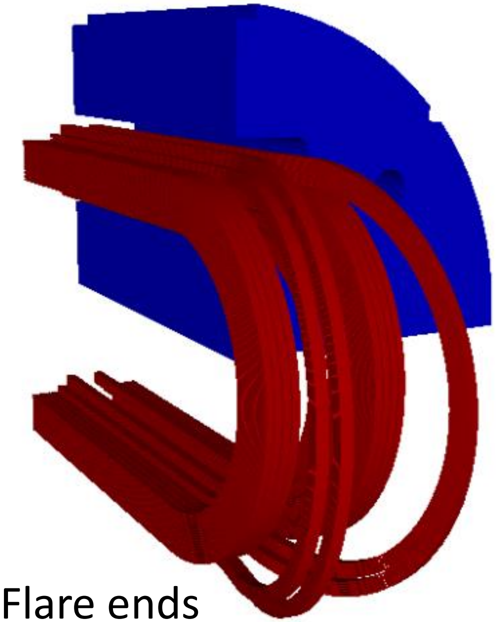
Field quality in the aperture
$<3*10^{-4}$ within 2/3 bore

(ROXIE simulation results)

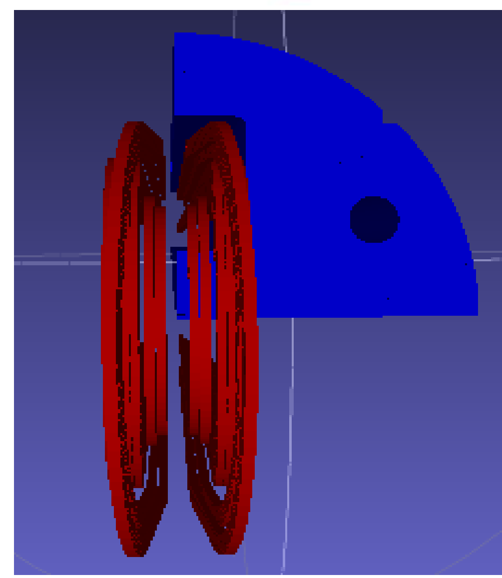


Field quality	2D with R_f= 13.3mm	3D with R_f= 8/13.3 mm
b3	0.45	0.79/1.91
b5	1.01	-0.65/-2.24
b7	0.46	0.08/0.67
b9	-0.27	-0.13/-0.22
a2	3.53	-1.00/-2.31
a4	0.49	-0.46/0.69
a6	0.33	0.26/2.49
a8	0.58	-0.12/0.84
a10	2.23	0.06/2.18





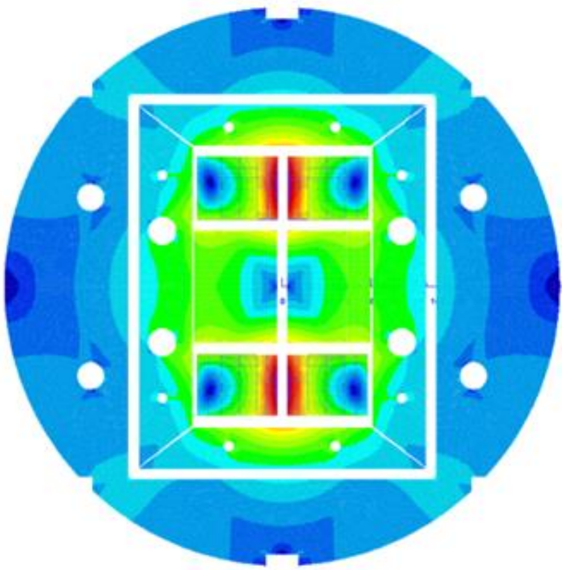
Flare ends

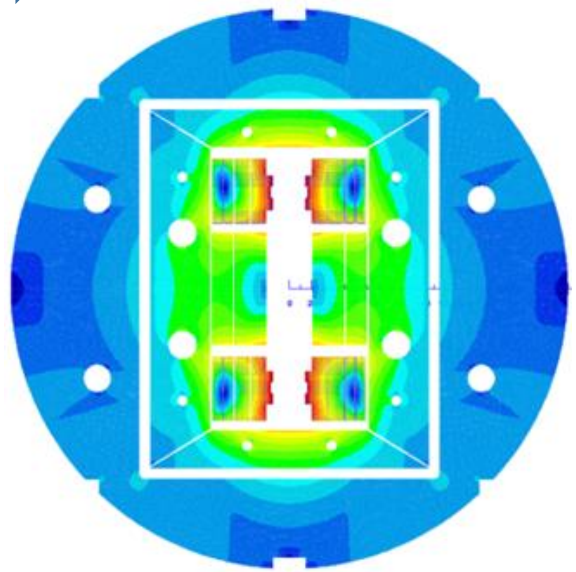


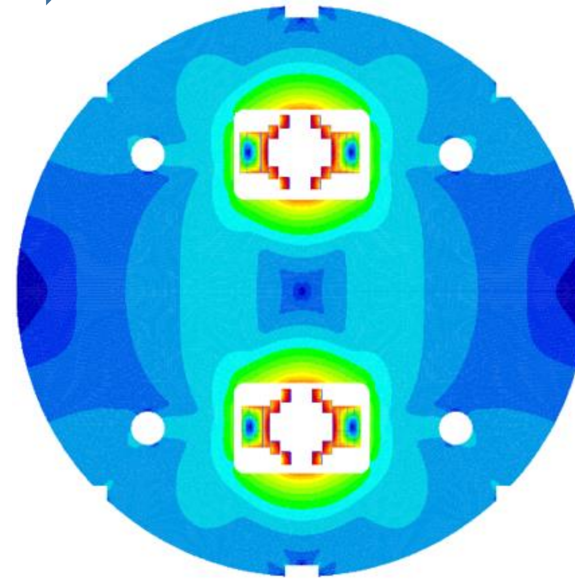
R&D of High Field Dipole Magnets

R&D Roadmap for the next 10~15 years

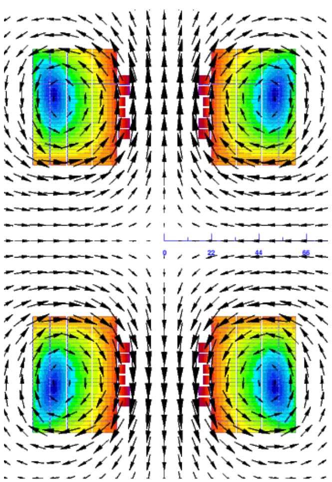
NbTi+Nb_3Sn, 2*ϕ10 aperture → **Nb_3Sn+HTS, 2*ϕ20 aperture** → **All HTS, 2*ϕ40 aperture**



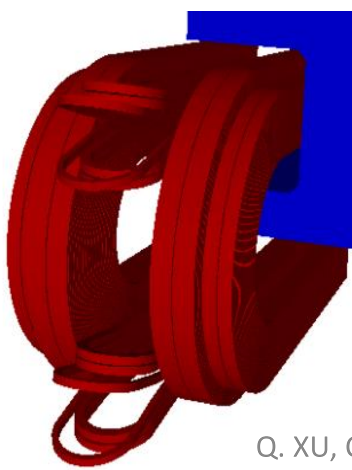




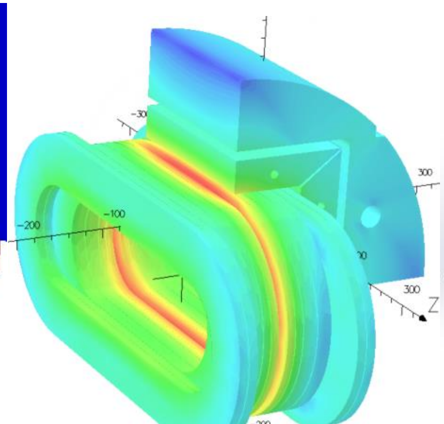
Magnetic flux distribution



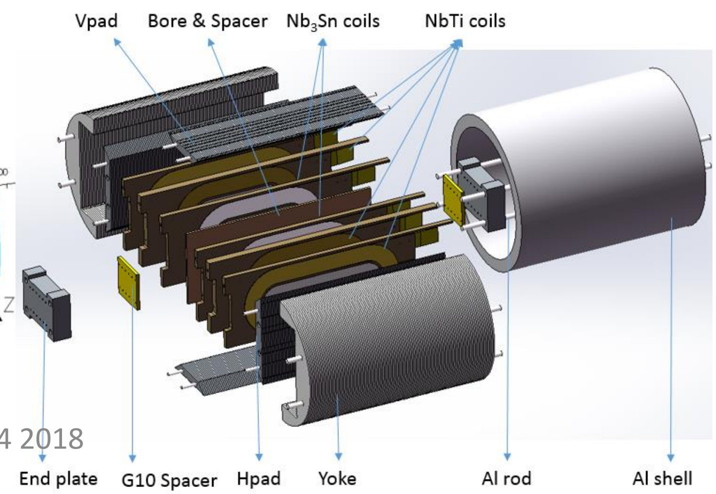
3d coil layout



3D magnetic field distribution



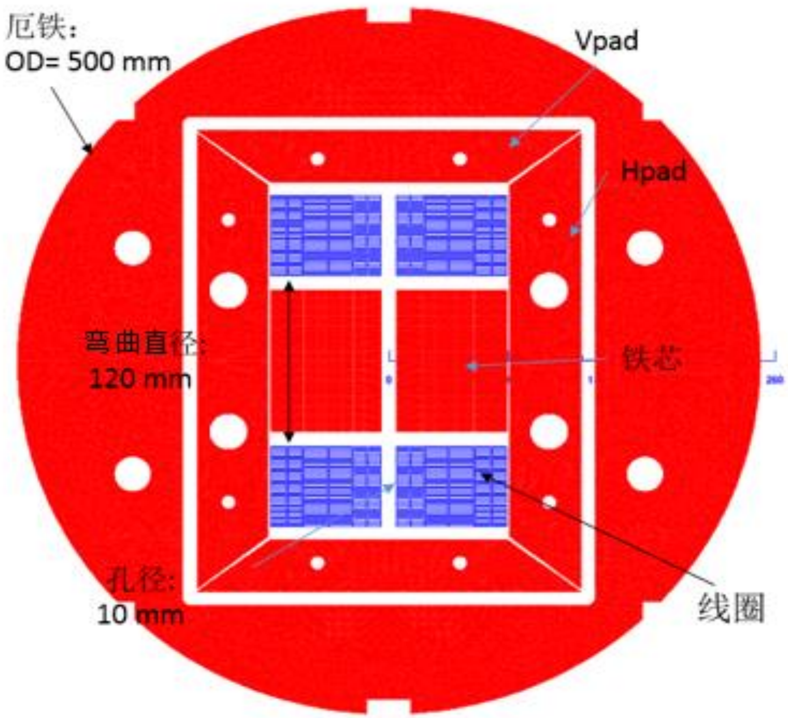
Components and assembly



R&D of High Field Dipole Magnets

The 1st High Field Dipole LPF1: NbTi+Nb_3Sn

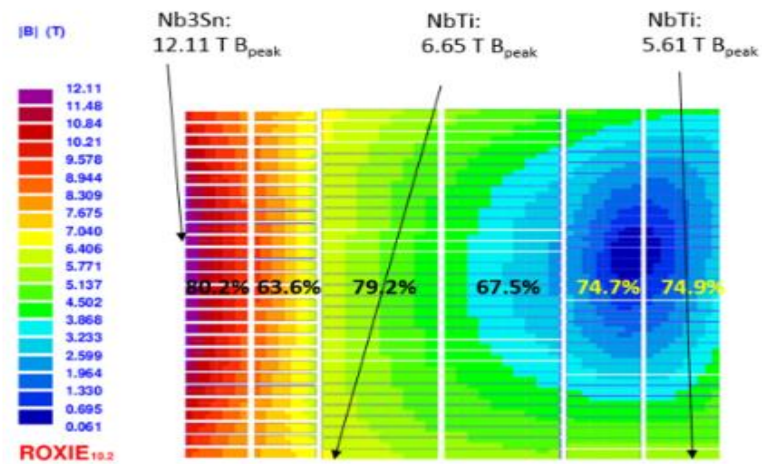
Cross section of LPF1

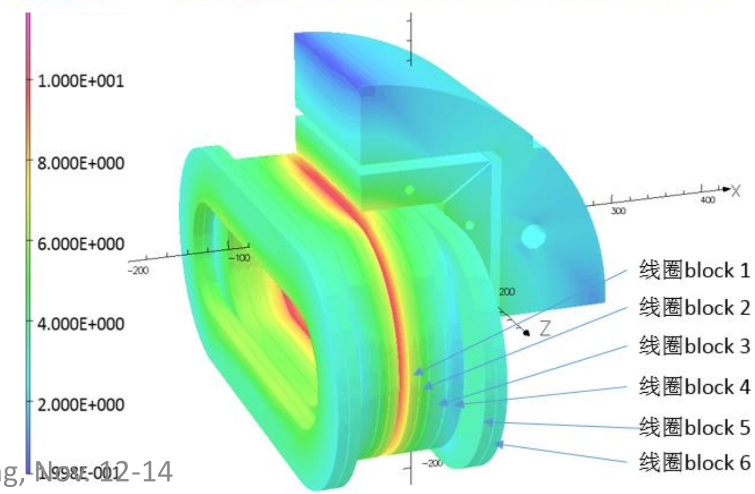


Main parameters of the strands

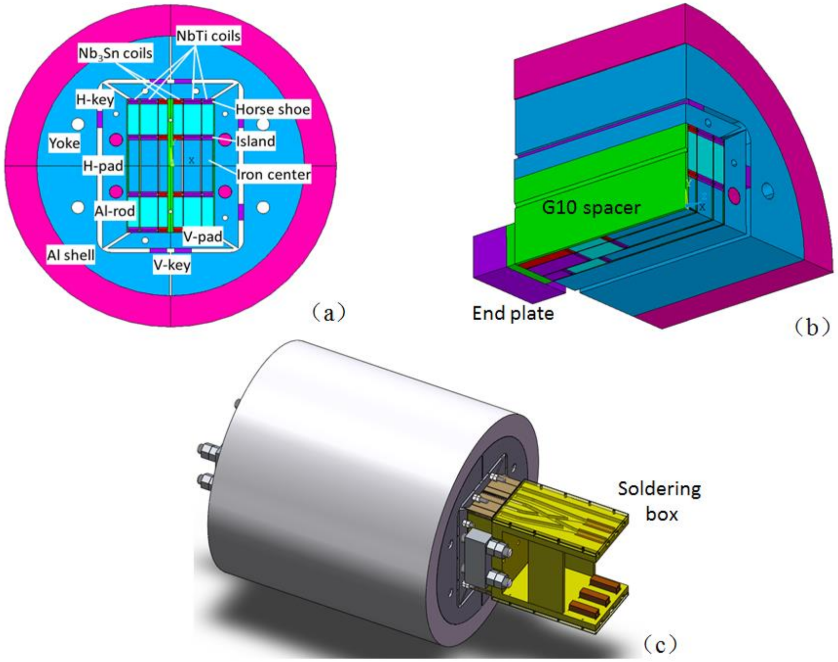
Strand	diam. (mm)	cu/sc	RRR	Tref (K)	Bref (T)	Jc@ BrTr (A/mm2)	Ic@ BrTr (A)
Nb_3Sn	0.802	1	200	4.2	12	2700	682
NbTi	0.82	1	130	4.2	5	2613	690

Magnetic field distribution

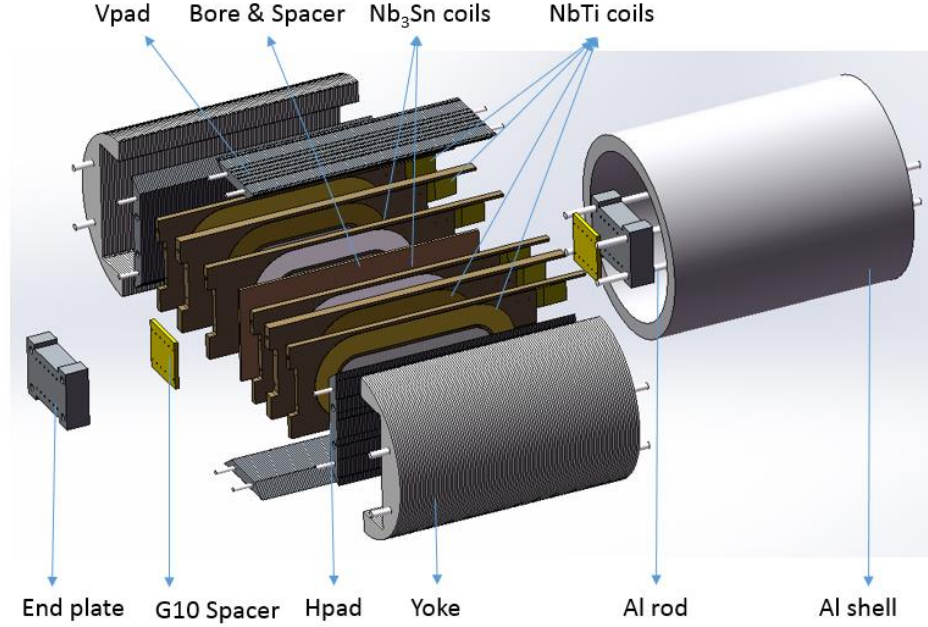




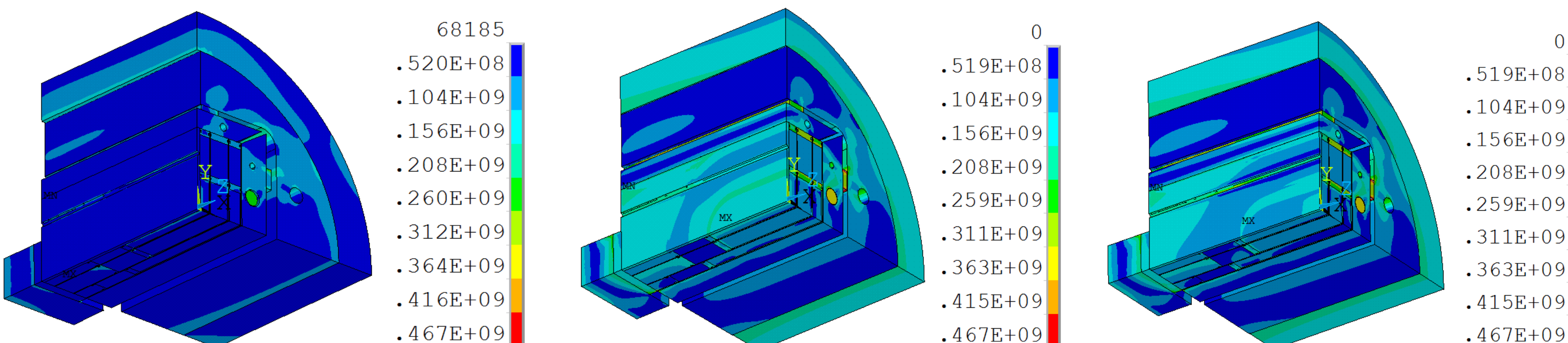
R&D of High Field Dipole Magnets



Mechanical FEA magnet model



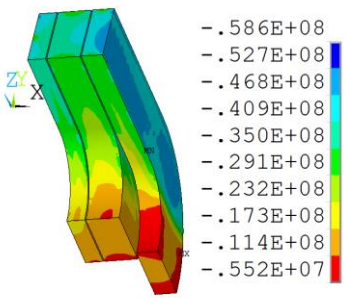
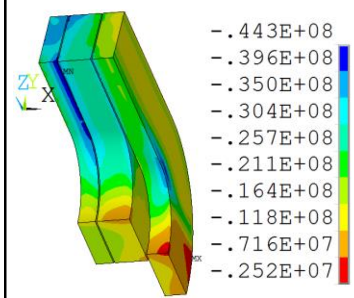
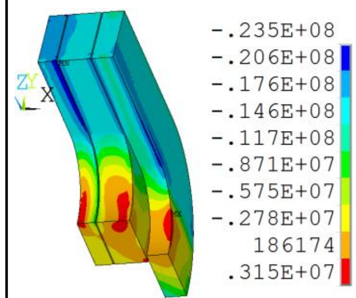
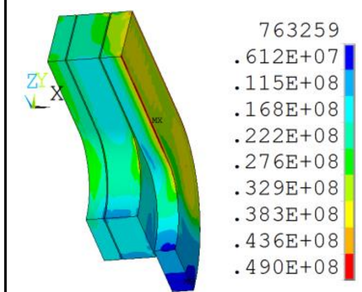
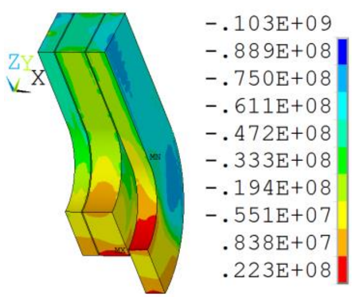
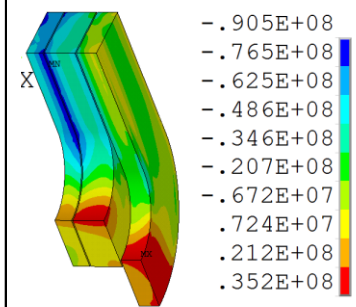
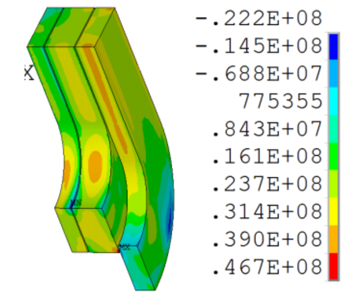
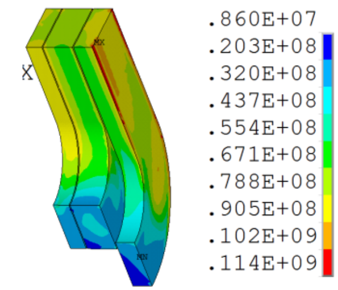
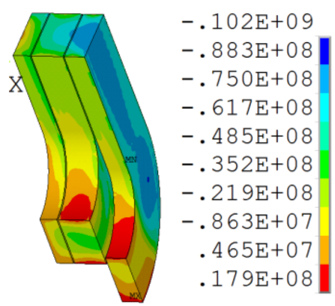
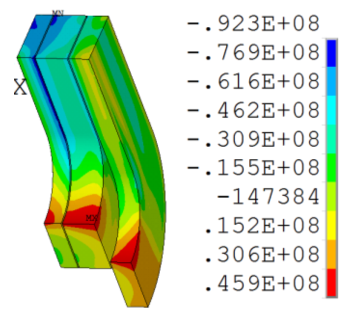
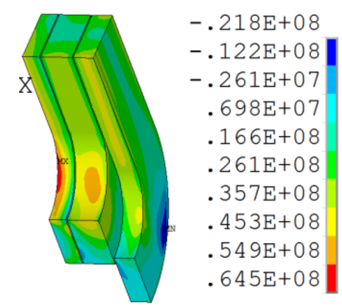
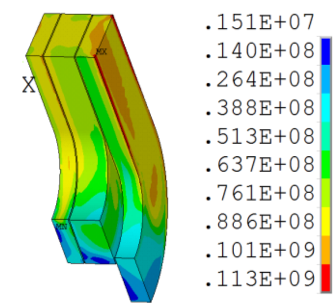
3D CAD configuration of LPF1



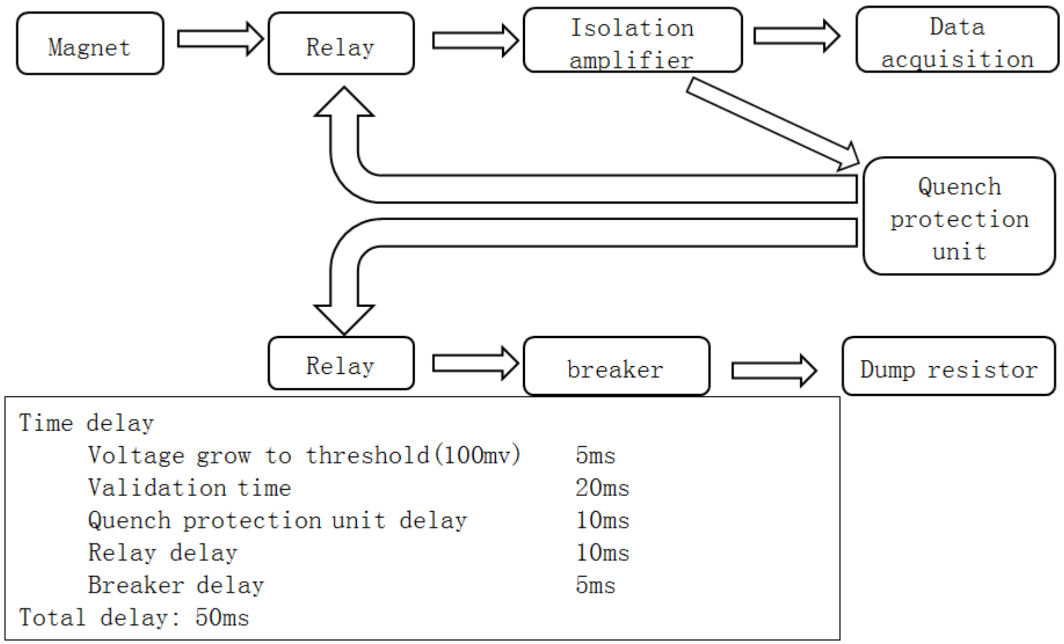
Assembly 4.2 K 5,950 A

R&D of High Field Dipole Magnets

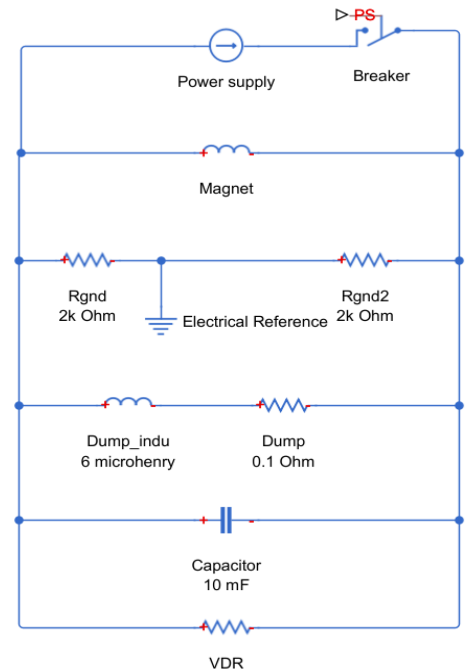
Stress analysis of the coils

<table>
<tr><th></th><th>σx</th><th>σy</th><th>σz</th><th>Mises stress</th></tr>
<tr><td>Preloading at room temperature
(Load 1)</td>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td>Cooling down
(Load 2)</td>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
<tr><td>Excitation
(Load 3)</td>
<td>
</td>
<td>
</td>
<td>
</td>
<td>
</td></tr>
</table>

R&D of High Field Dipole Magnets



Schematic of the quench protection system

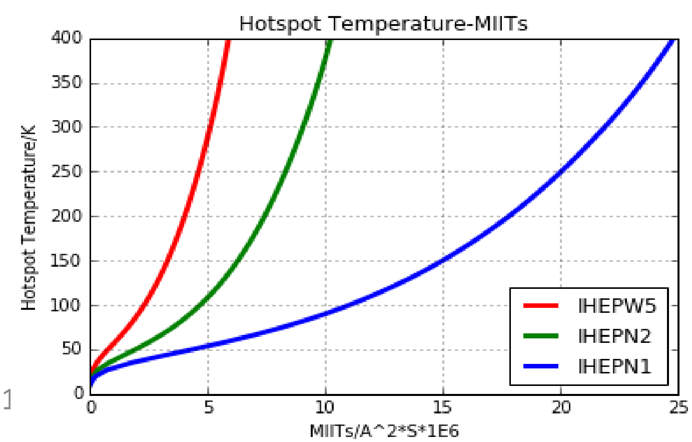


Quench protection circuit

Adiabatic analysis

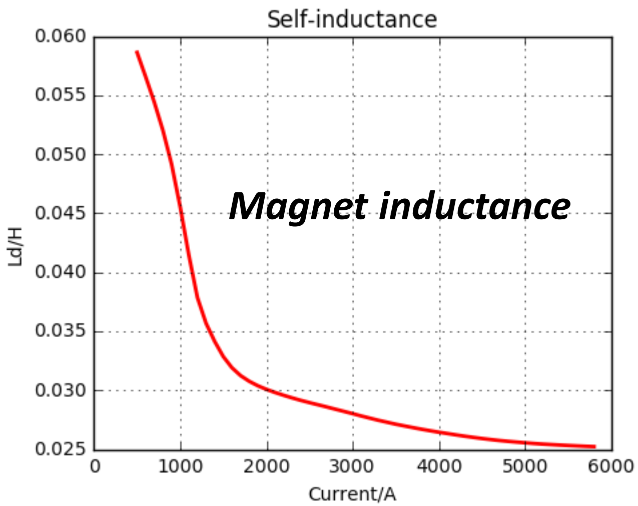
$$\int_0^\infty [I_{mag}(t)]^2 dt = \int_{T_{cs}}^{T_{max}} f_{cu} [A_{cable}]^2 \frac{(\gamma C_p(T))}{\rho_{cu}(B,T)} dT$$

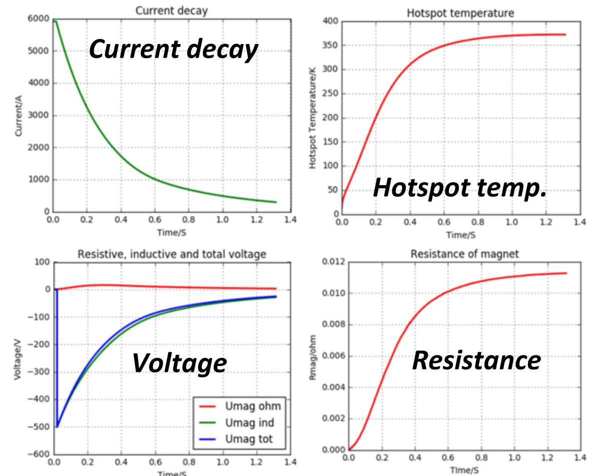
MIITs Hot spot temperature

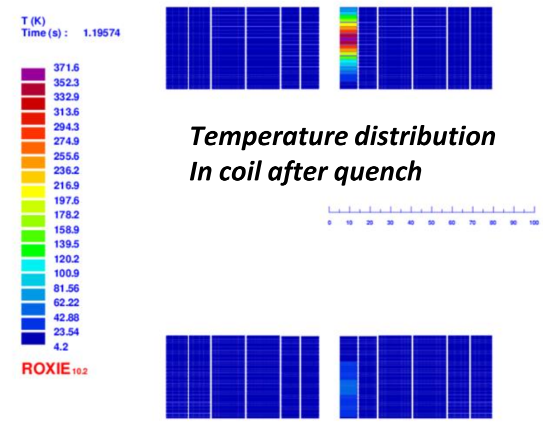


Hot spot temperature vs. MIITs for different cables

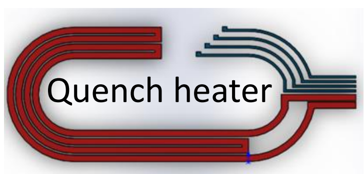
R&D of High Field Dipole Magnets



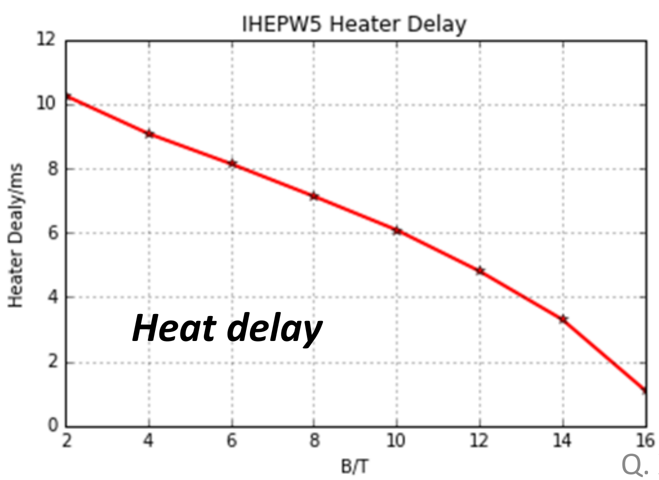


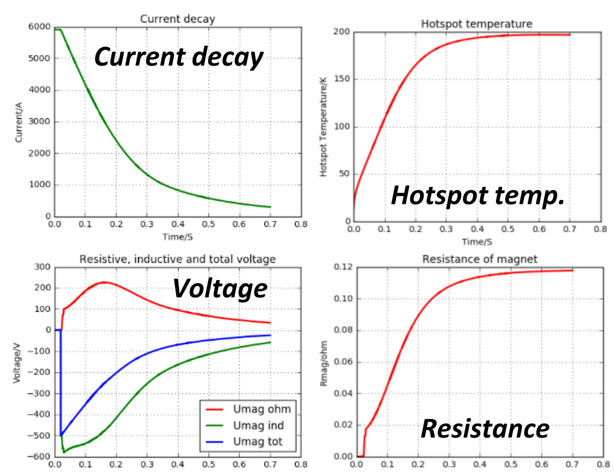


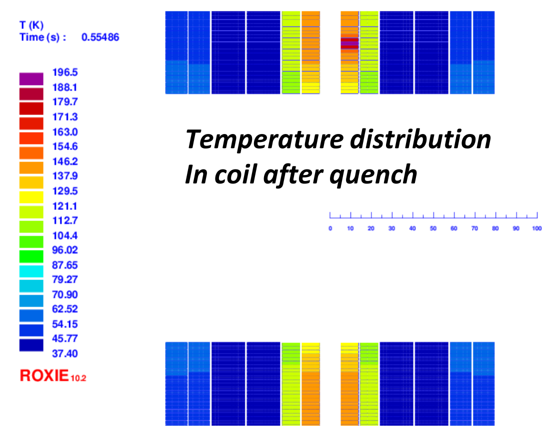
Quench simulation with dump resistor only



Thickness (μm)	Resistance （Ω）	Peak power （w/cm^2)	Charge voltage (V)	Max current (A)	Capacitance (mF)
50	3.1	100	341	110.07	9.67





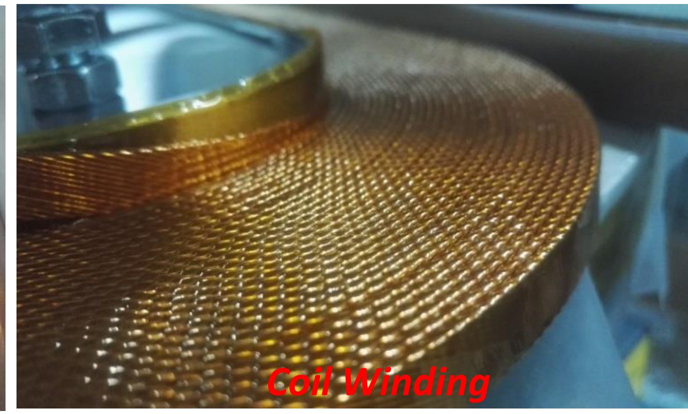


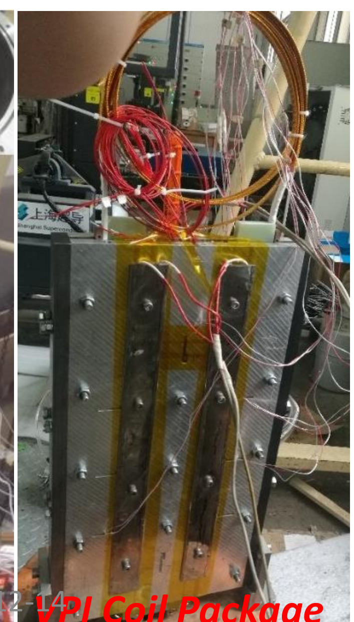
Quench simulation with dump resistor and heaters

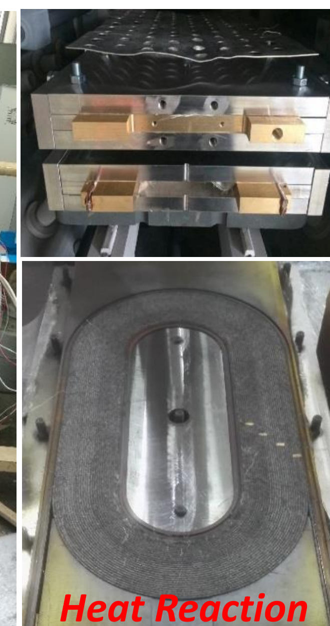
R&D of High Field Dipole Magnets

Fabrication of the 1st model dipole magnet (NbTi+Nb_3Sn)

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

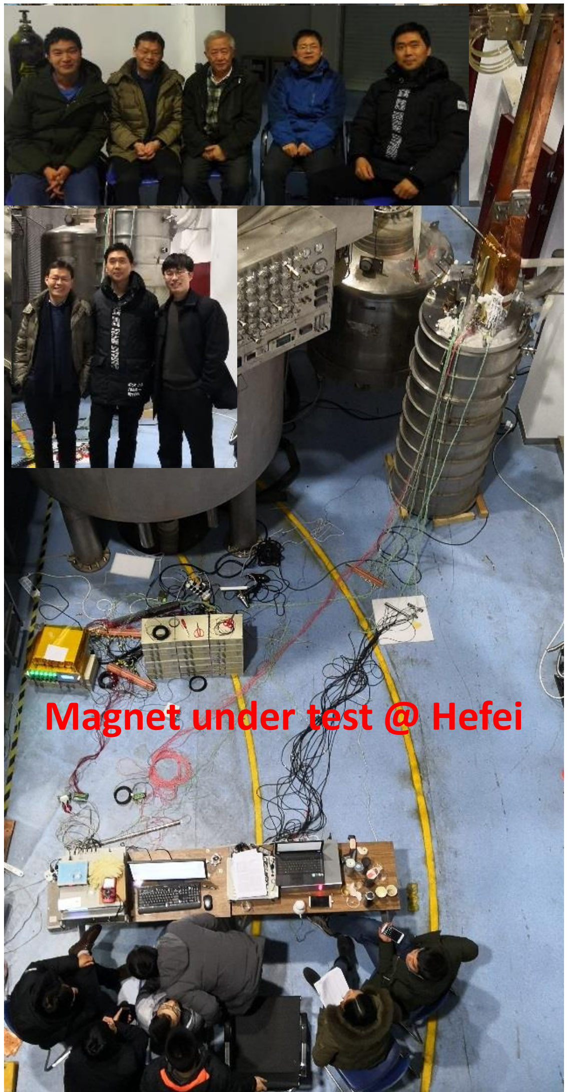


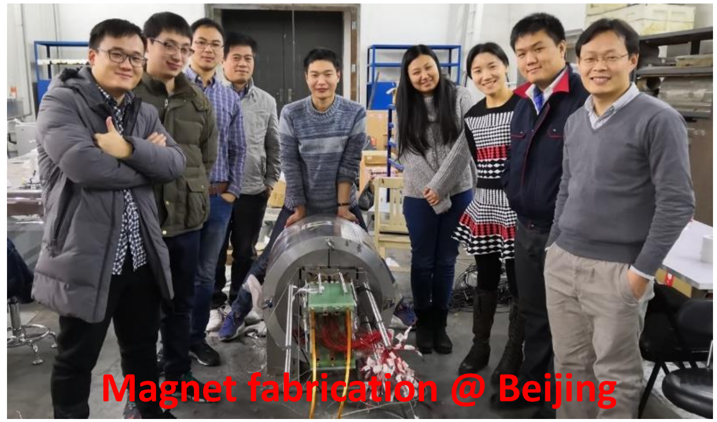


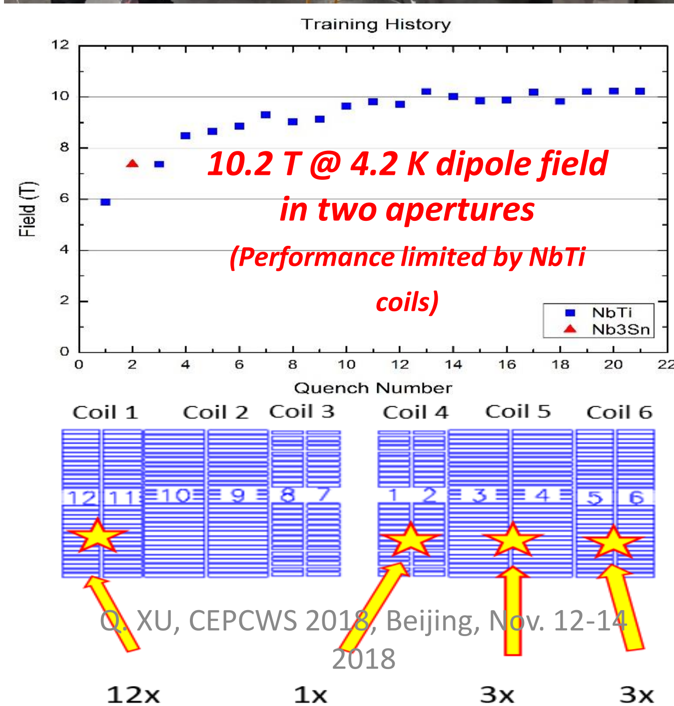


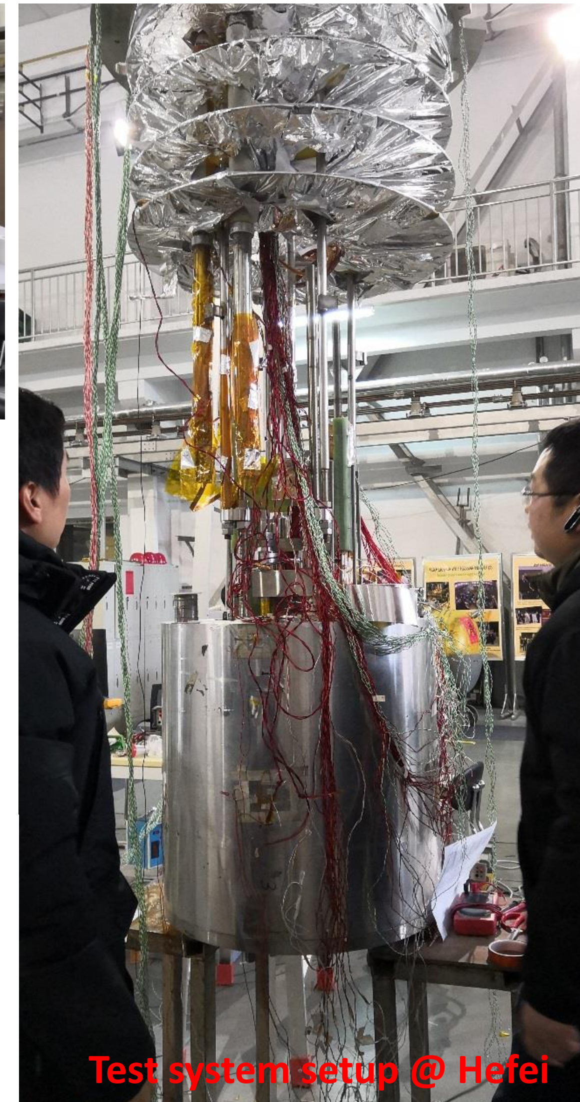
R&D of High Field Dipole Magnets

Test results of the 1st high-field dipole magnet in China Feb. 2018









R&D of High Field Dipole Magnets

The 2nd High Field Dipole LPF2: Nb_3Sn with IBS

Cross section of LPF2

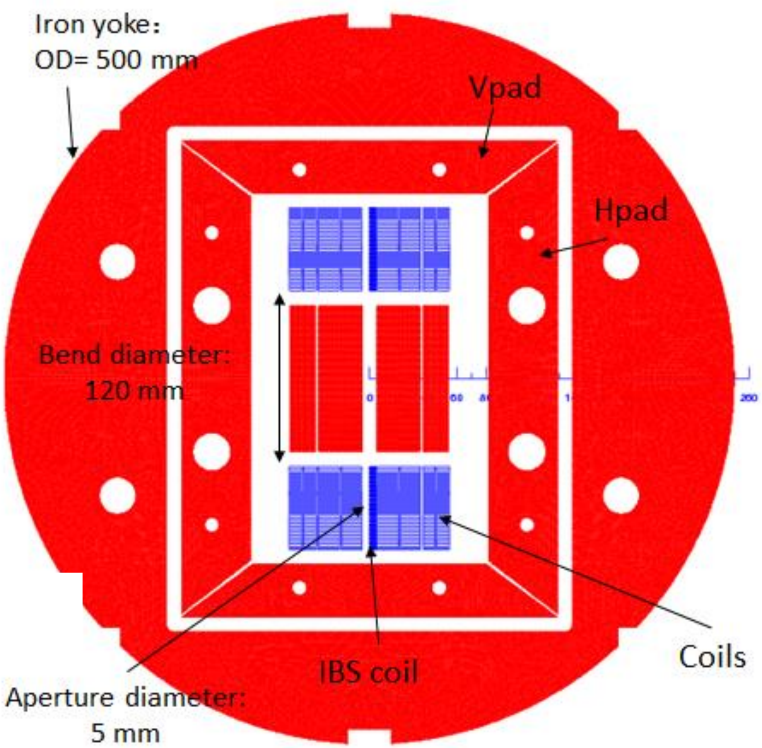
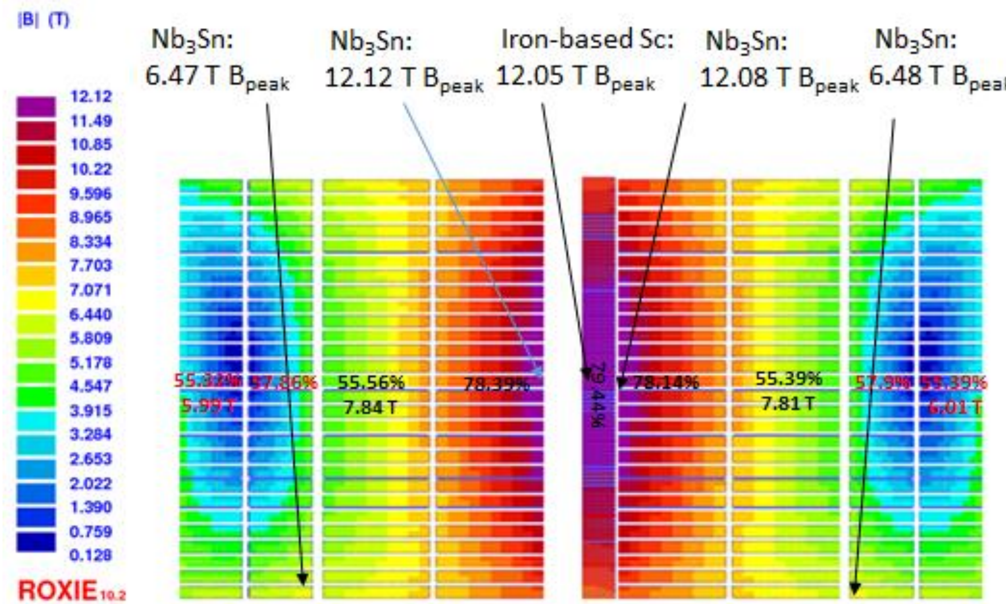


Fig. 1: The cross section of the 12-T common-coil dipole (with inserted iron-based coil)

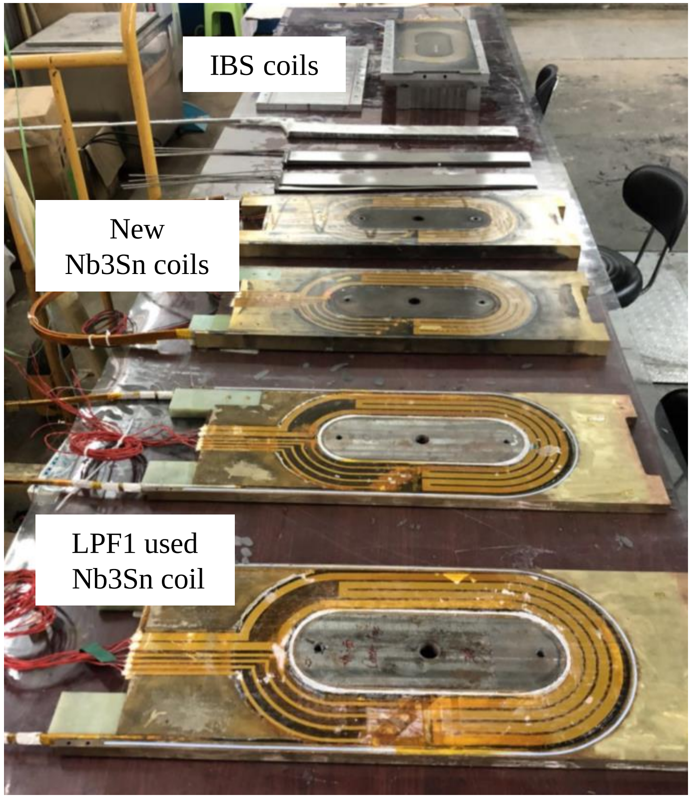
Magnetic field distribution

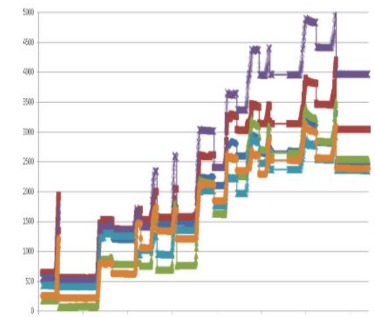


Strand	diam.	cu/sc	RRR	Tref(K)	Bref(T)	Jc@ BrTr	Ic@ BrTr(A)
IHEPW CJC	0.802	1	200	4.2	12	2700	682
Iron-based	-	6.7	100	4.2	12	216.5	38

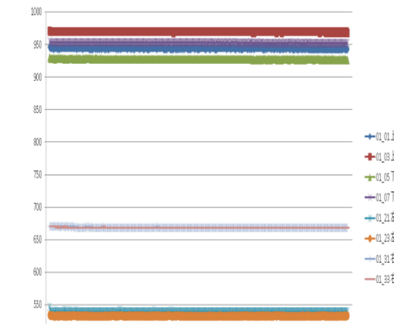
R&D of High Field Dipole Magnets

2 new Nb_3Sn coils + 1 IBS coils

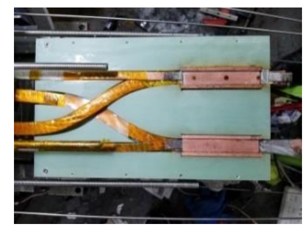


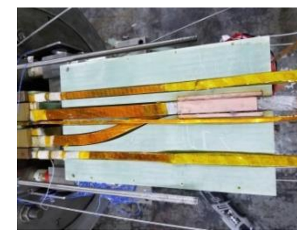


轴向预紧>40ton

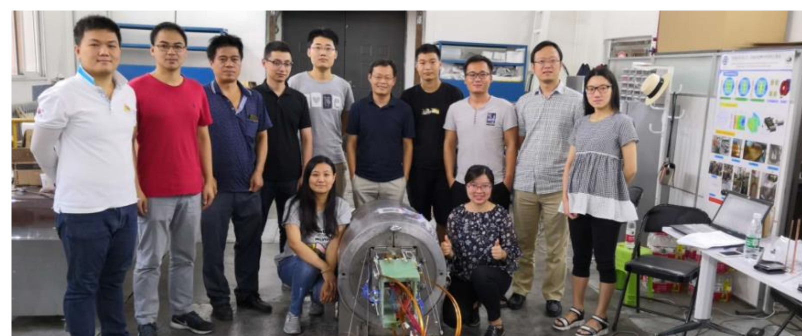


环向预紧78.8Mpa





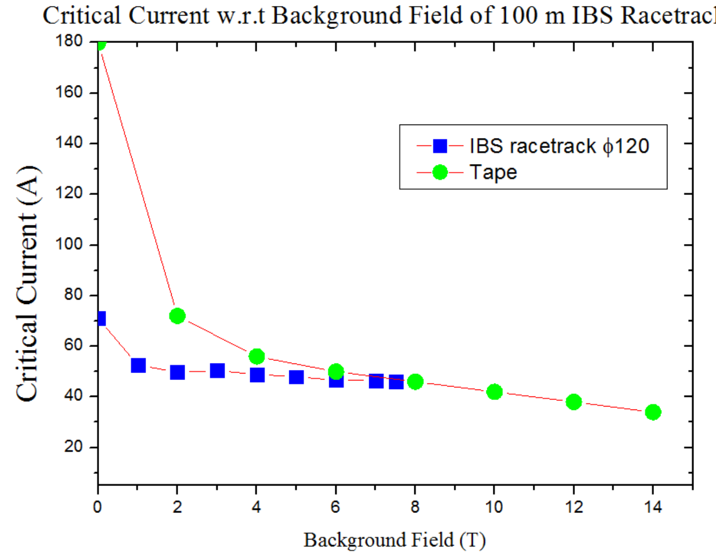
磁体制作完成 @中科院高能所

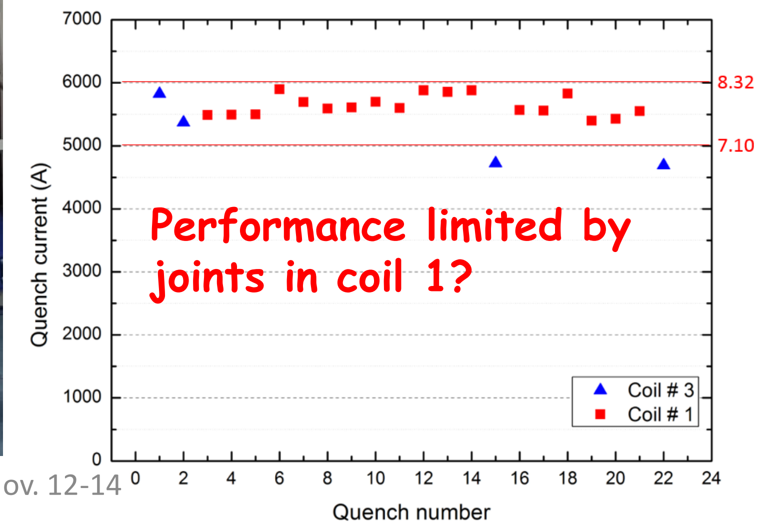


R&D of High Field Dipole Magnets

Performance of the LPF2 (Nb_3Sn with IBS)

Test stopped due to problems of joints? To be verified

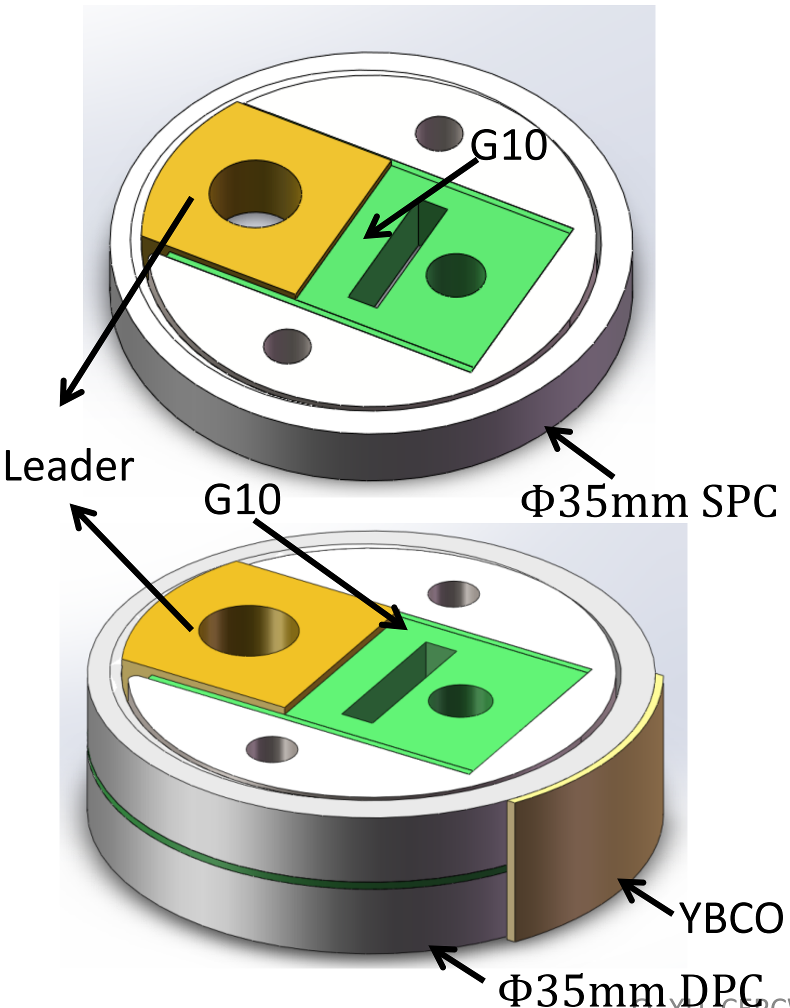




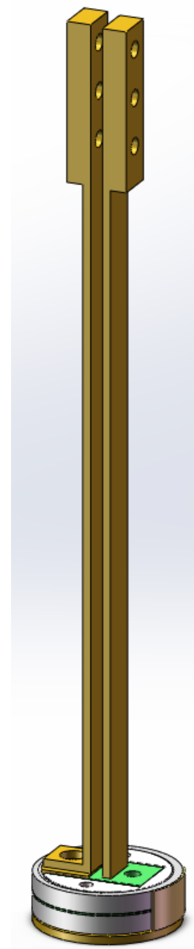
R&D of High Field Dipole Magnets

IBS solenoid for testing at 25T

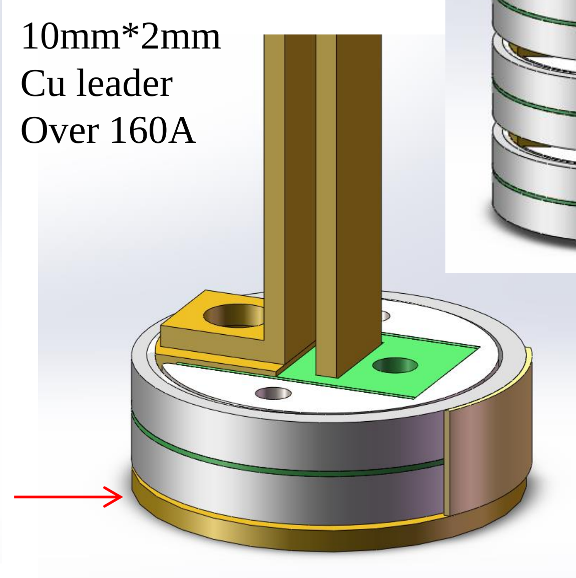
Single pancake IBS coil

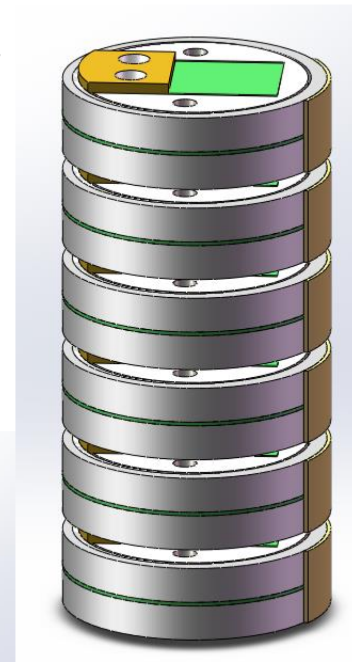


Double pancake IBS coil



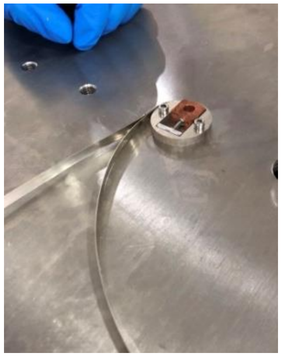
Double pancake IBS

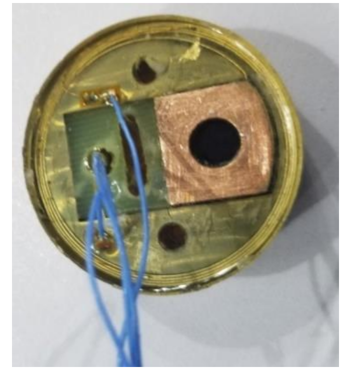




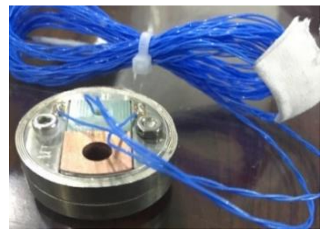
R&D of High Field Dipole Magnets

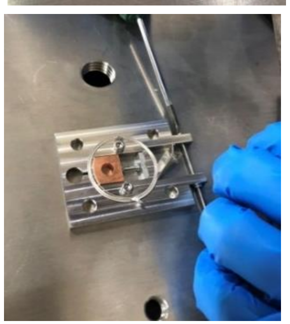
Fabrication of IBS coils.







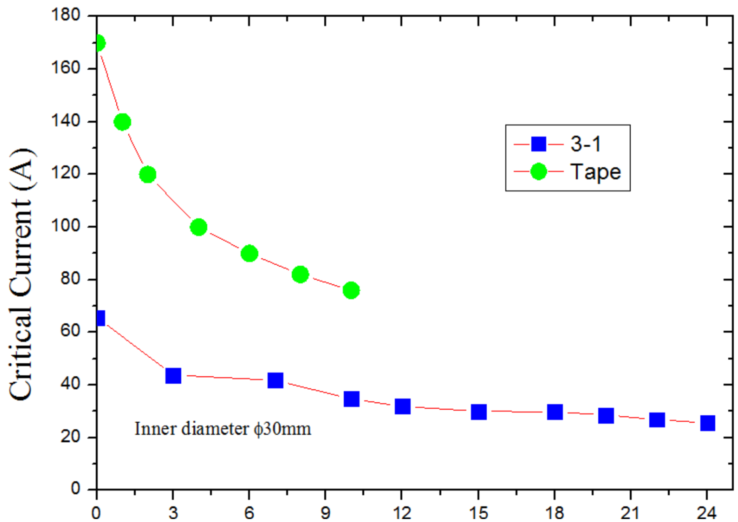


共4个SPC，6个DPC

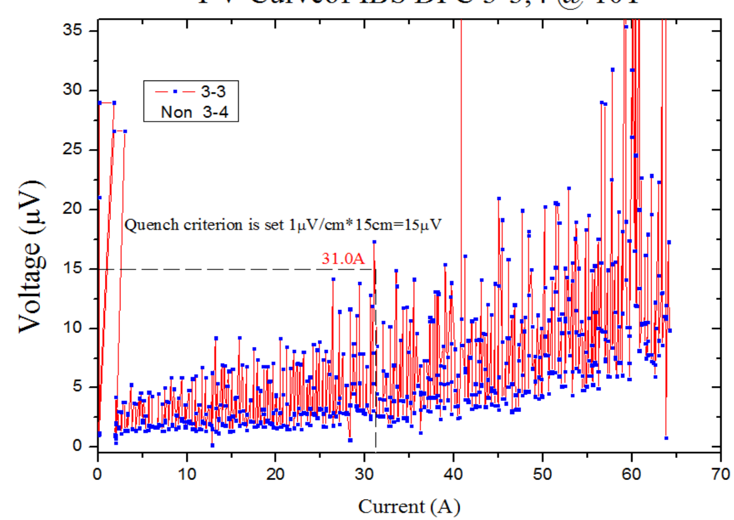
R&D of High Field Dipole Magnets

Performance test of IBS solenoid at high field

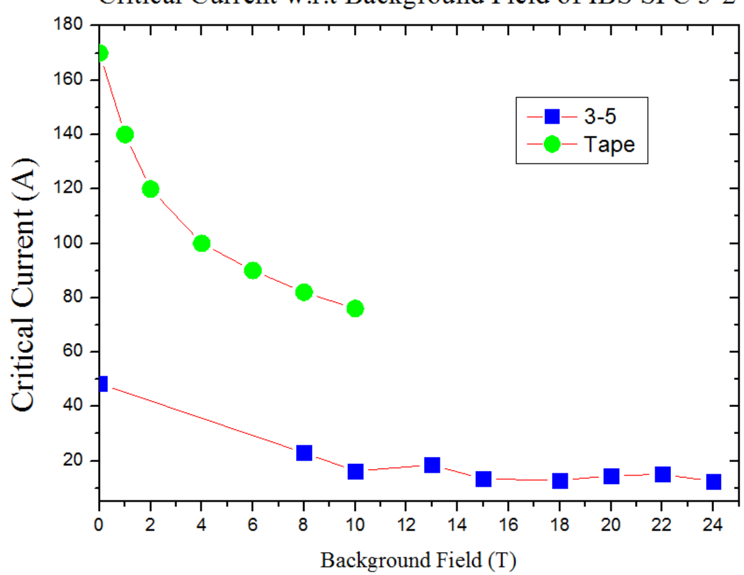
Critical Current w.r.t Background Field of IBS SPC 3-1



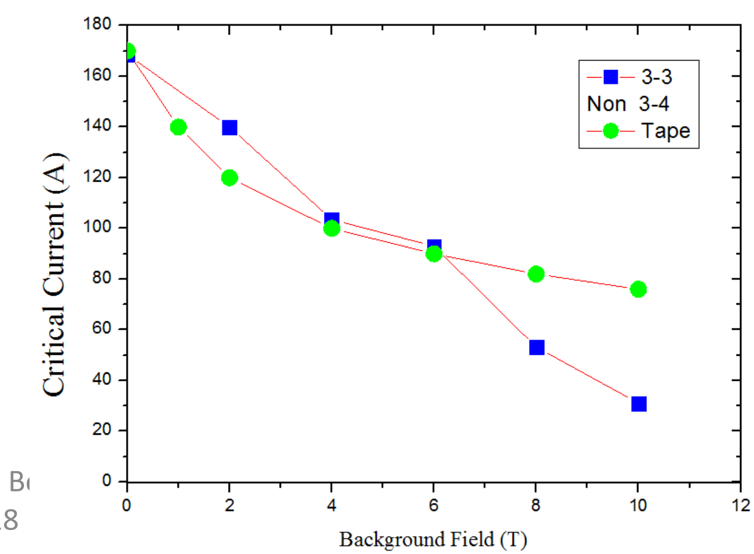
I-V Curveof IBS DPC 3-3,4 @ 10T



Critical Current w.r.t Background Field of IBS SPC 3-2

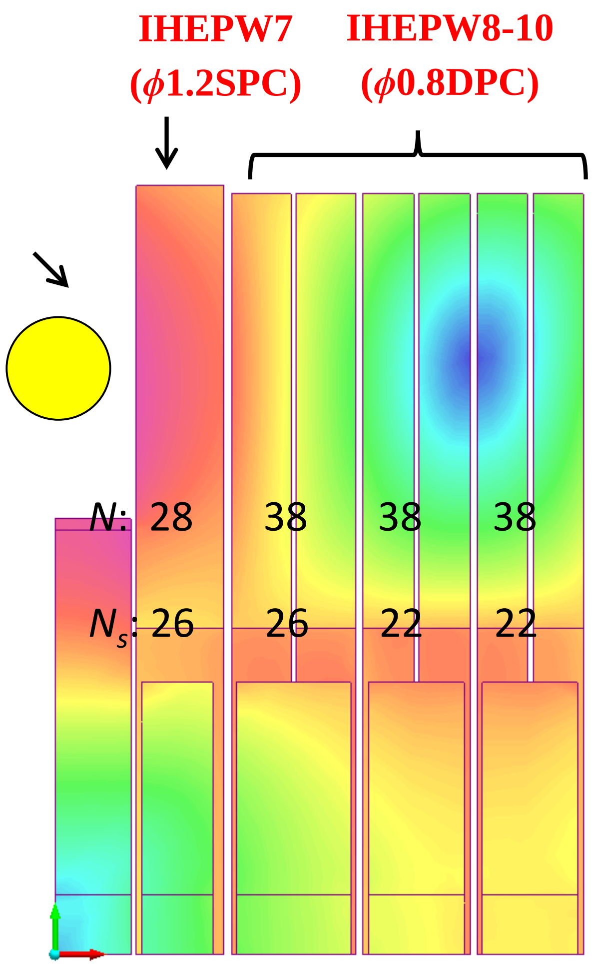


Critical Current w.r.t Background Field of IBS DPC 3-3,4



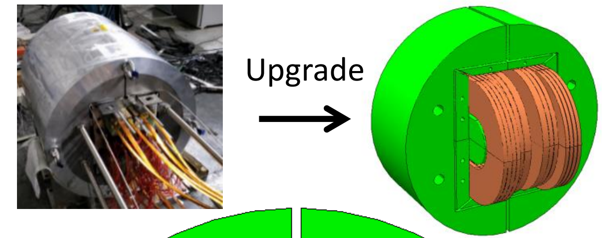
R&D of High Field Dipole Magnets

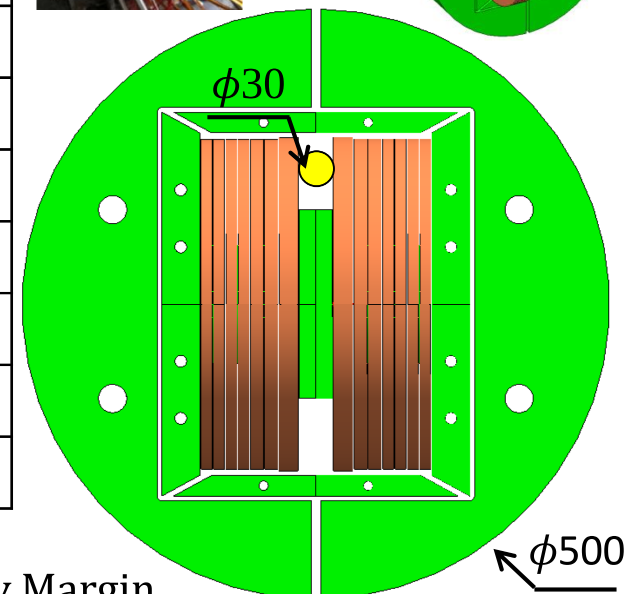
Next step 1: 15T twin-aperture dipole @ 4.2K



Coil configuration in the 1st quadrant

Windings	B_{max}(T)	Loadline(%)
IHEPW7	15.281	89.427
IHEPW8 A	13.001	88.384
IHEPW8 B	12.844	87.535
IHEPW9 A	12.444	88.666
IHEPW9 B	12.612	89.574
IHEPW10 A	12.470	88.806
IHEPW10 B	12.028	86.417



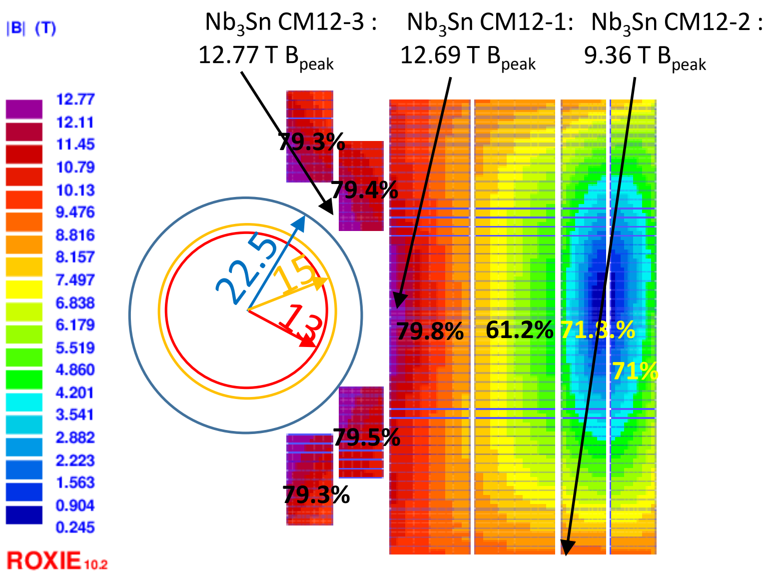


I_{op}= 8800A with 10% Safety Margin

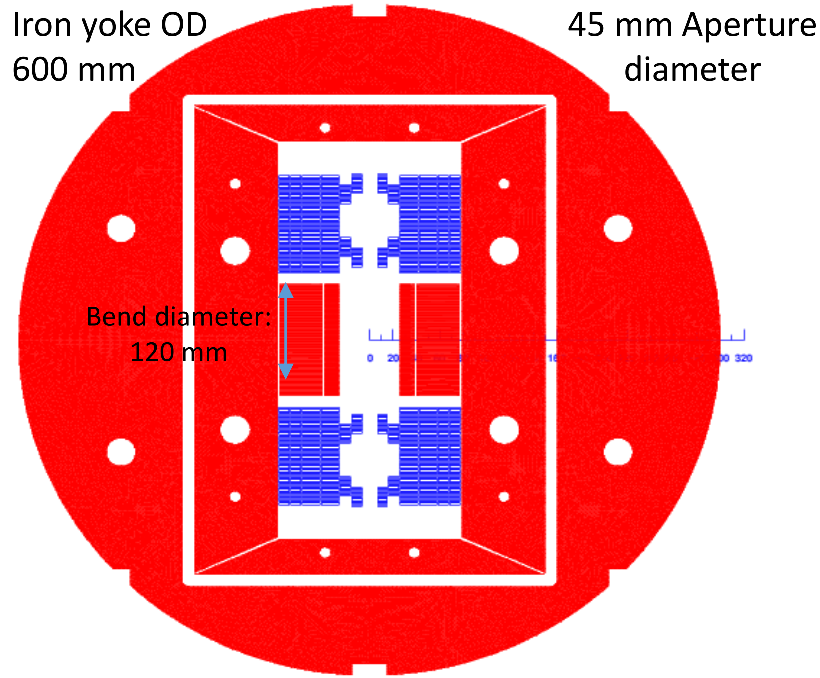
Strand	diam.	cu/sc	RRR	Tref(K)	Bref(T)	Jc@ BrTr	dJc/dB	Ic@ BrTr(A)
IHEP WCJC	0.802	1	200	4.2	14	1800	400	454.65
				4.2	15	1400	350	353.61
	1.2	1	200	4.2	14	1800	400	1017
				4.2	15	1400	350	791

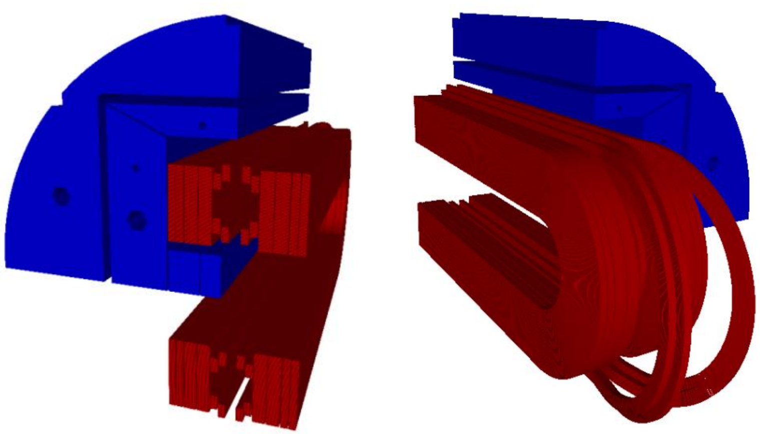
R&D of High Field Dipole Magnets

Next step 2: 12T twin-aperture dipole @ 4.2K with 10^{-4} field quality



Field distribution at 12.47T





3D model (half length of the straight section: 500 mm)

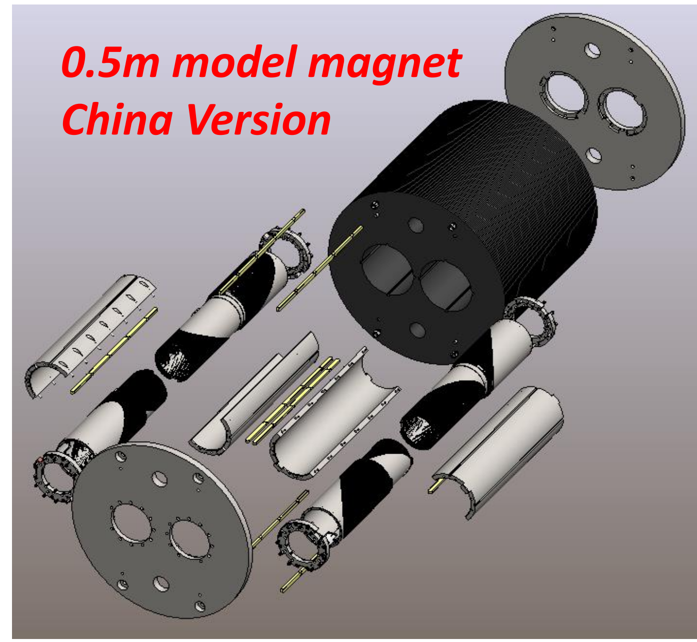
Field quality analysis

Rref	b3	b5	b7	b9	a2	a4	a6	a8
15 mm	-0.06	0.06	2.31	2.84	-0.004	0.43	1.88	2.53
13 mm	-0.05	0.03	0.98	0.9	-0.004	0.28	0.92	0.93

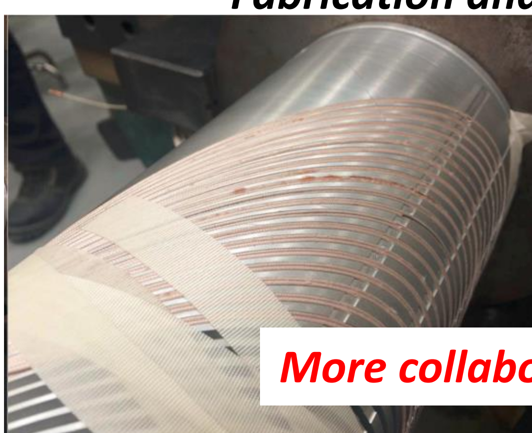
CERN & China Collaboration

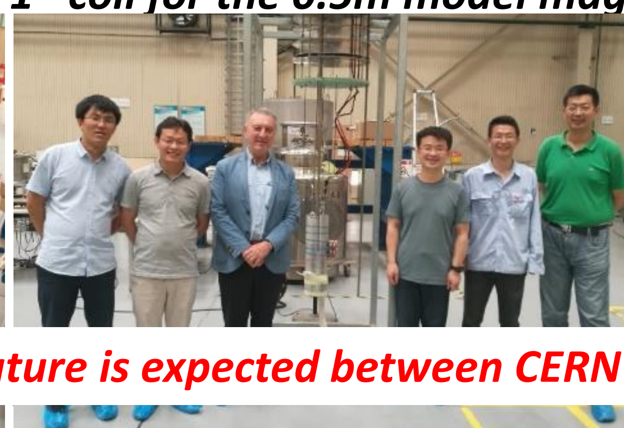
China will provide 12 units CCT corrector magnets for HL-LHC before 2022

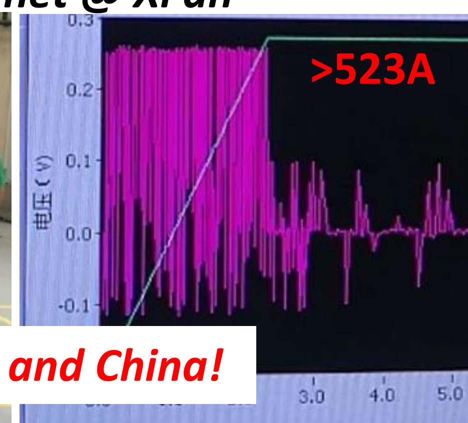
A 0.5m model and 2.2m prototype to be fabricated and tested by June 2019



Fabrication and test of the 1st coil for the 0.5m model magnet @ Xi'an



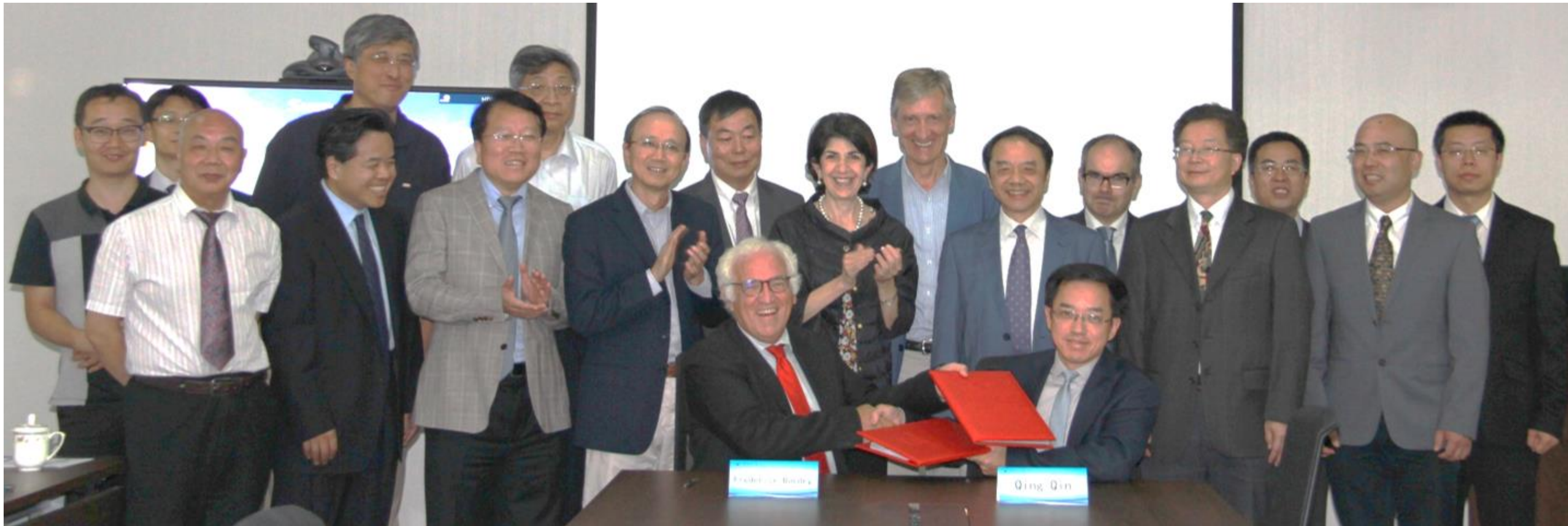


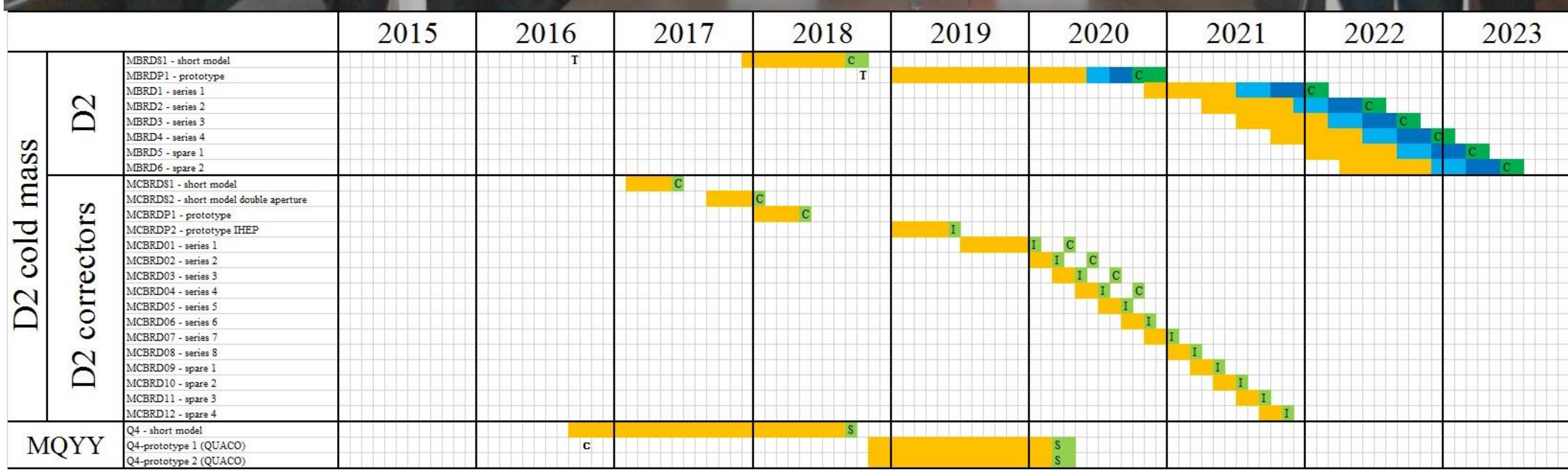


More collaboration in future is expected between CERN and China!

CERN & China Collaboration

MoU formally signed for CCT magnets in September 2018





Summary

- ***Magnet & CEPC-SPPC:*** *High field magnet technology is the key to the success of the high energy accelerators in future.*
- ***SPPC design scope:*** *12 T IBS magnets to reach 70TeV with 100 km circumference. Upgrading phase: 20~24 T IBS magnets to reach 125~150 TeV.*
- *Strong domestic collaboration for the advanced HTS conductor R&D: Make IBS the High-T_c and High-Field "NbTi" conductor in 10 years!*
- ***R&D of high field magnet technology:*** *the 1st twin-aperture model dipole (NbTi+Nb_3Sn) reached 10.2 T @ 4.2 K; the 2nd model dipole (Nb_3Sn+IBS) is being tested. 15 T twin-aperture model dipole and 12 T twin-aperture model dipole with field quality to be developed.*
- ***CERN & China Collaboration:*** *Fabricating 12 units CCT corrector magnets for HL-LHC before 2022，and expecting more in future…*

Thanks for your attention!