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Electromagnetic design, fabrication of LPF2: a 12-T hybrid common-coil dipole magnet with inserted iron-based superconducting coil

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Report ID: Tue-Mo-Or7-05

Outline

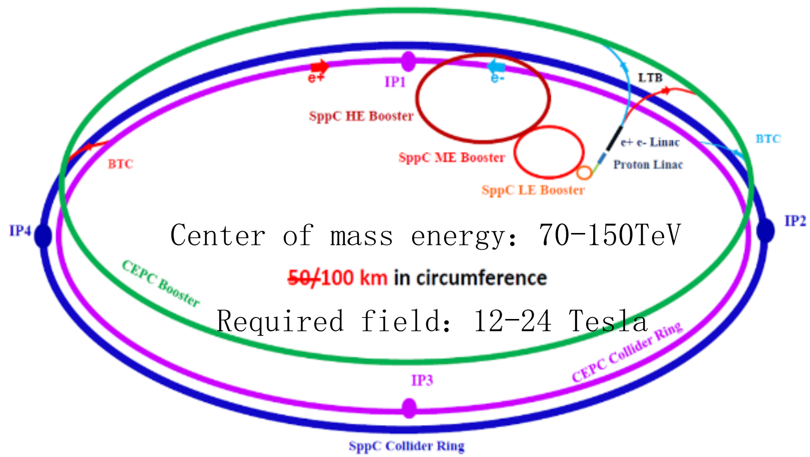
- Fabrication and test of LPF1

(A 10.2-T common-coil dipole magnet with graded coil configuration)

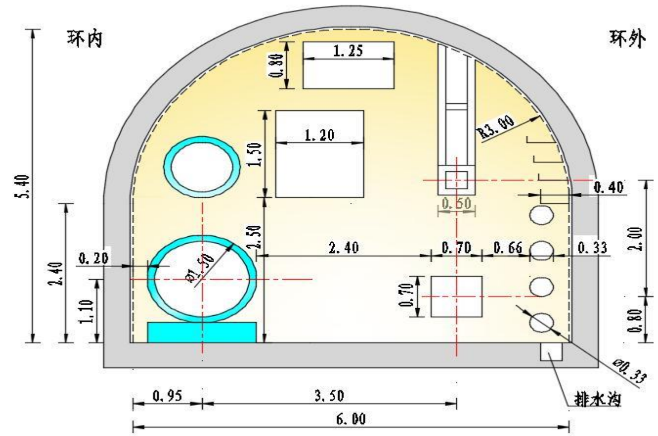
- Fabrication and test of LPF1-2
- Recent progresses in the fabrication of LPF2
- Summary

Background

High field dipole magnets are the key components of high-energy particle accelerators

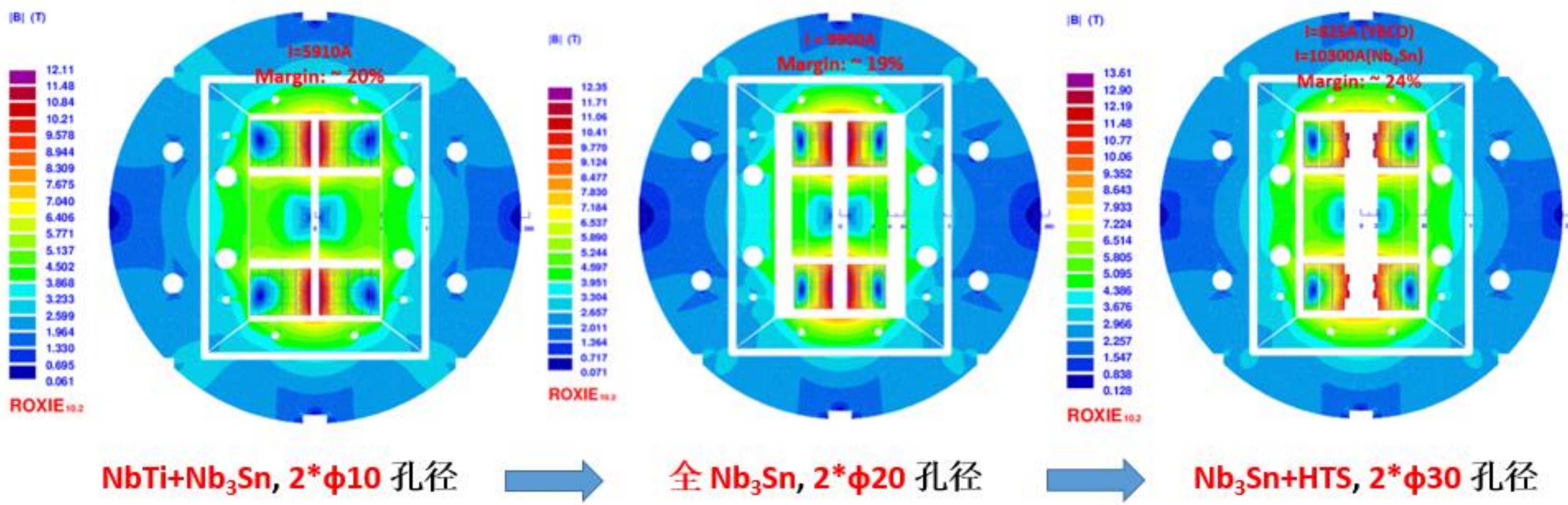


The lay-out of CEPC-SPPC



Tunnel for CEPE-SPPC

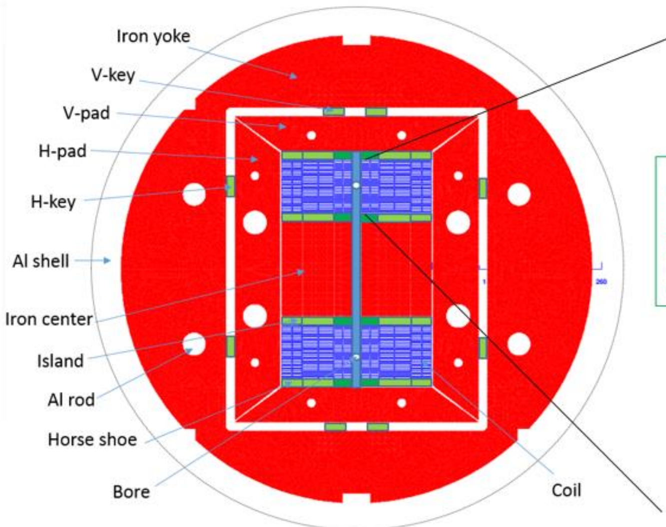
Courtesy: Qingjin Xu, FCC Week 2017. CEPC-SPPC Pre-CDR: Available at: http://cepc. ihep. ac. cn/ preCDR/ volume.html



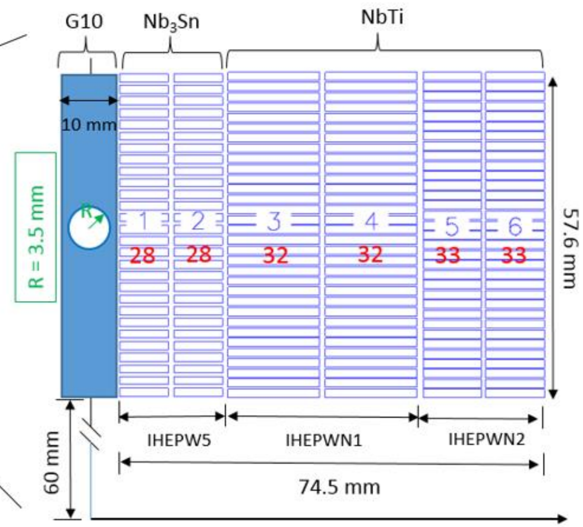
R&D plan of 12-T high field dipole magnets with common coil configuration

Electromagnetic design of LPF1

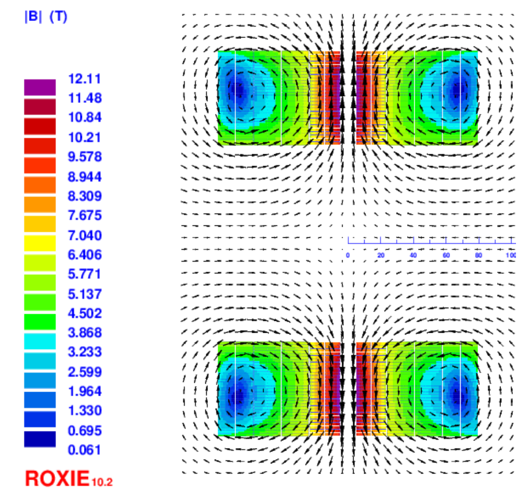
(Nb_3Sn + NbTi)



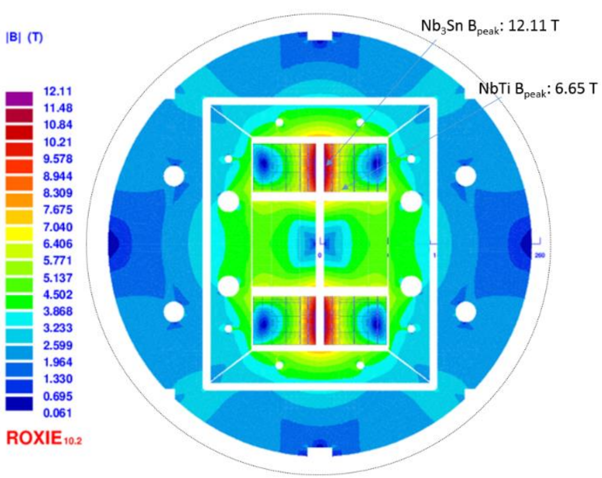
Cross-section of LPF1



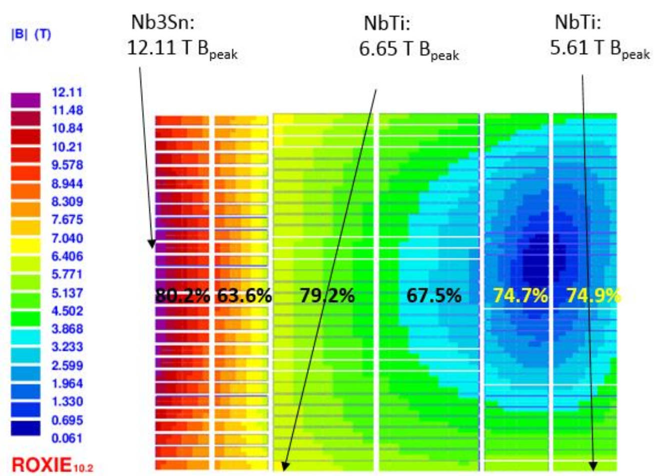
First quadrant coil layout



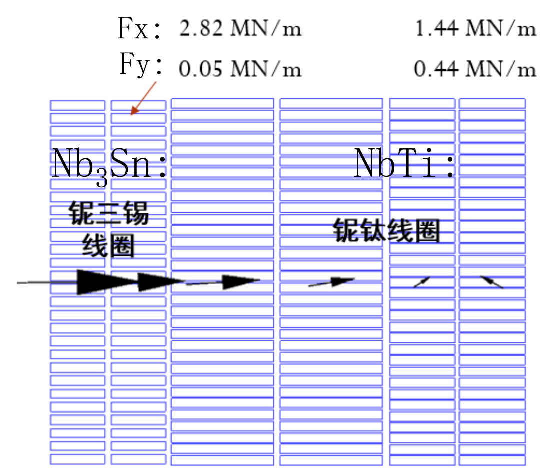
Flux distribution



Field distribution

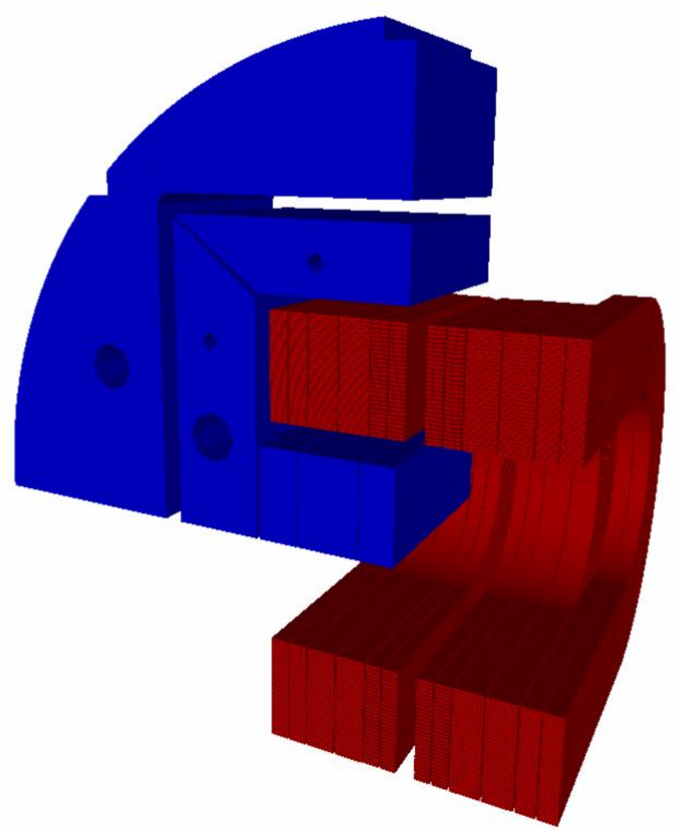


Field distribution in the first quadrant coil

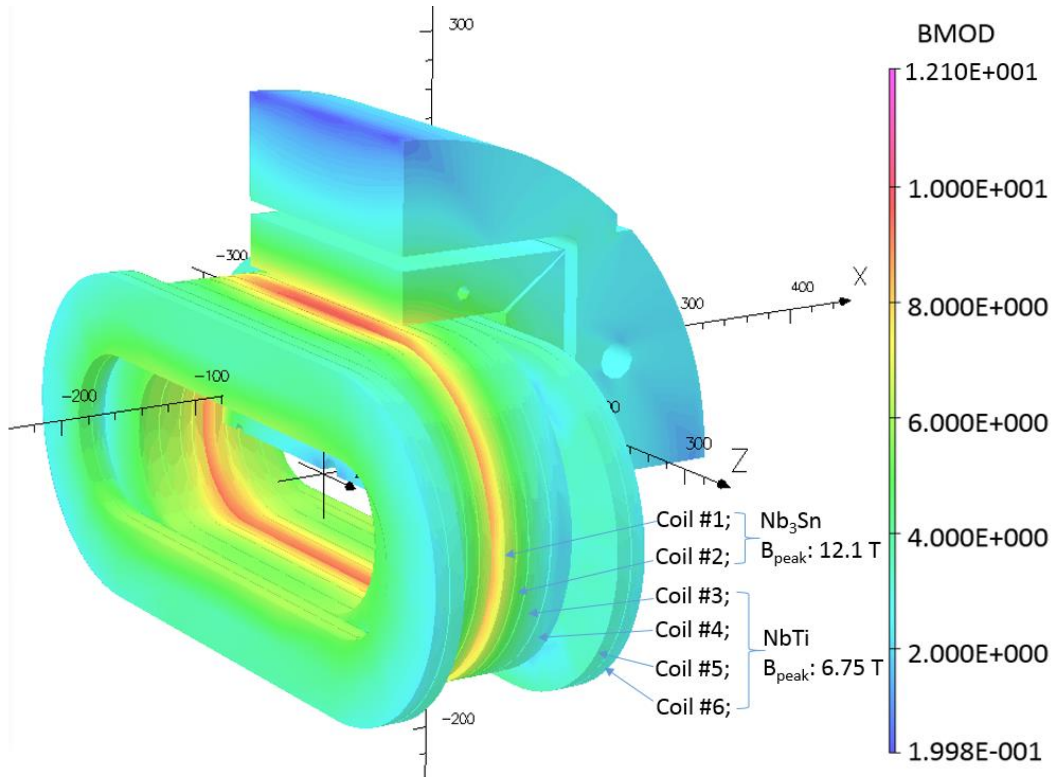


Lorentz force distribution

Characteristics of this dipole magnet- 3D simulation



Simulated with Roxie



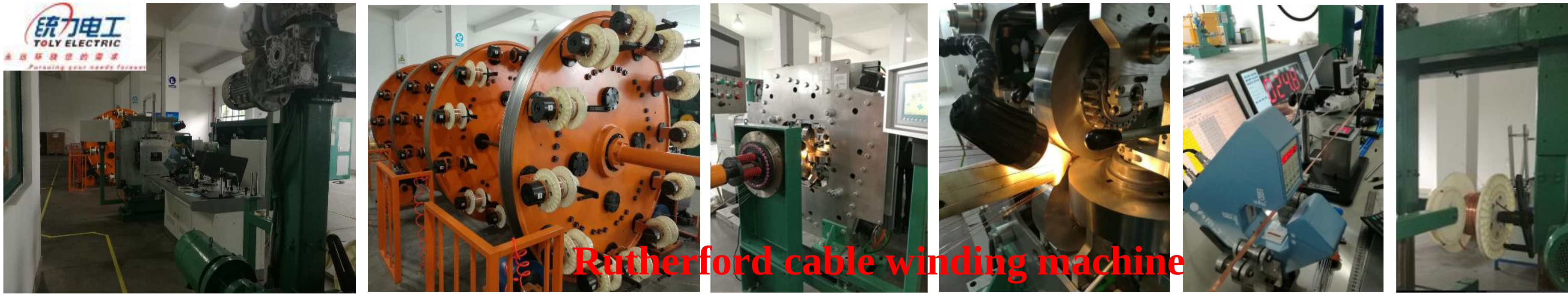
Cross check with Opera

Table 1: Main parameters of this subscale magnet

Current	MF	Block	1	2	3	4	5	6
6100	11.99	Field (T)	12.09	8.72	6.75	6.58	6.19	6.23
A	T	Loadline (%)	82.73	60.59	80.51	78.84	81.47	81.85

Fabrication of LPF1

Rutherford cable R&D



A close collaboration between IHEP, Toly Electric Works Co. Ltd (Wuxi, China) and Western Superconducting Technologies Co. Ltd (WST, Xi'an, China) has been established in making Rutherford cables since 2015.

Fabrication of LPF1

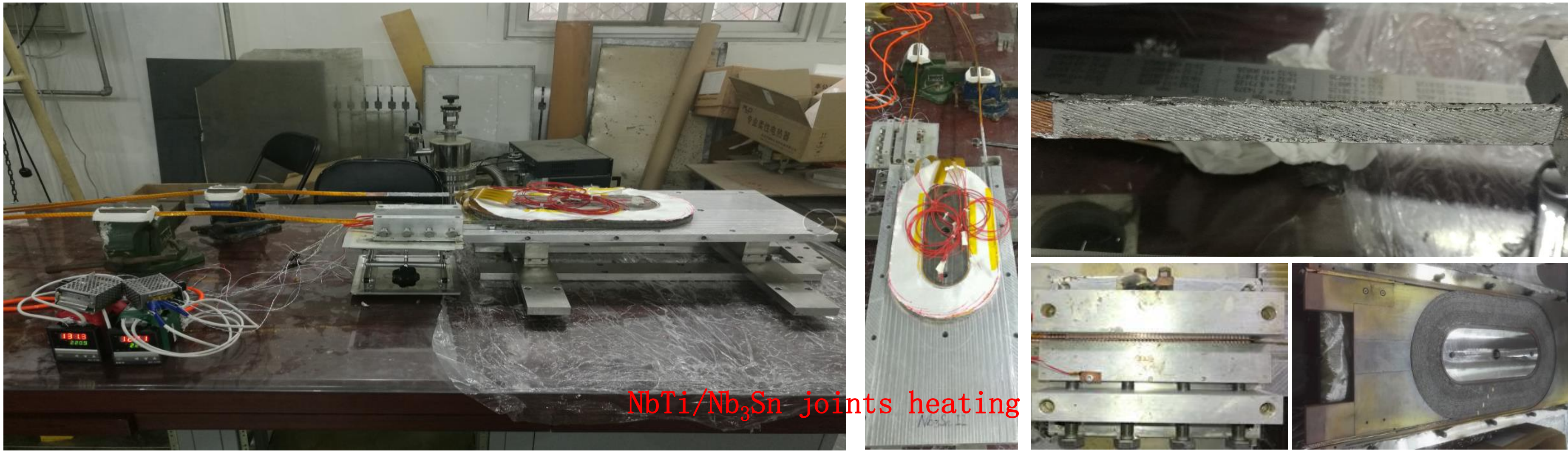
Coil winding

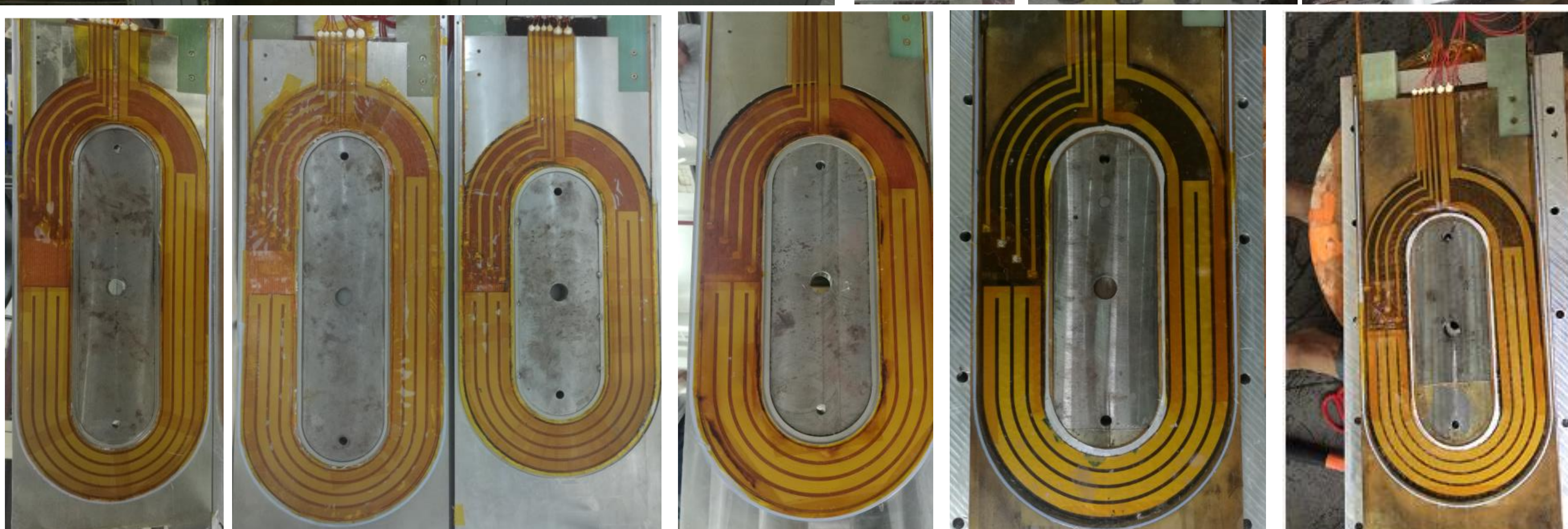
(a) (b) (c)

Pictures of the coils after winding. (a): Outer NbTi coils; (b) Middle NbTi coils; (c): Inner Nb_3Sn coils.

Fabrication of LPF1

NbTi/Nb_3Sn joints and coil VPI

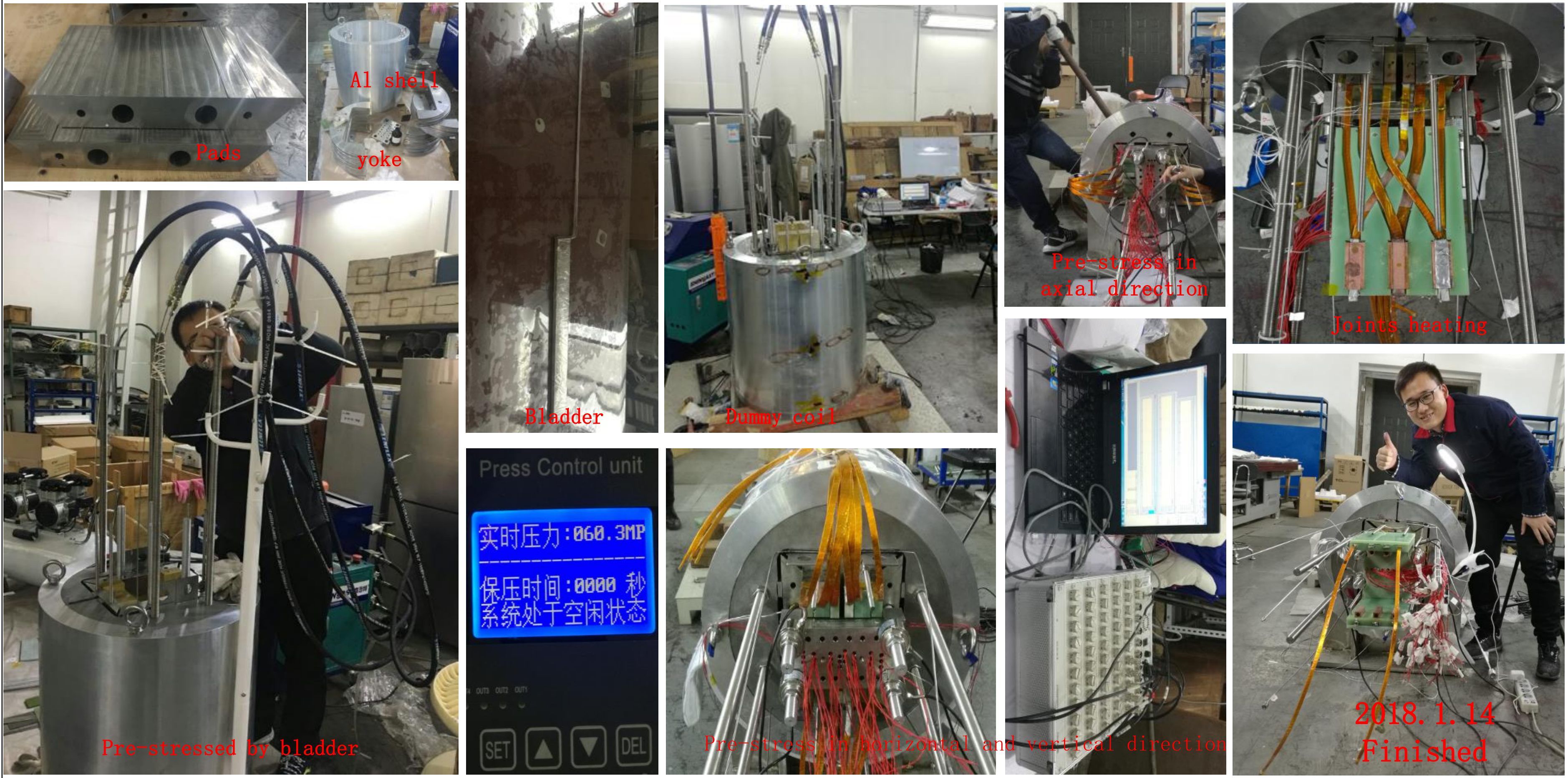




Pictures of the coils after VPI

Fabrication of LPF1

Assembly



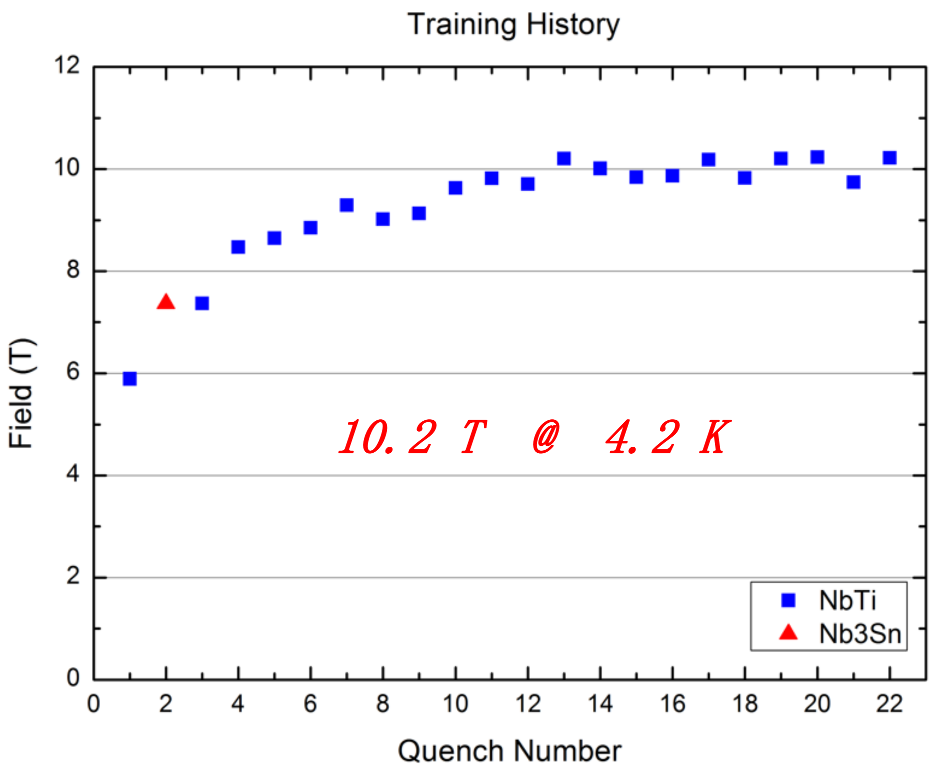
The shell-based structure was adopted in our hybrid dipole magnet design.

Coils were pre-stressed during assembly, using an external aluminum shell pre-tensioned with water -pressurized bladders mainly in horizontal and vertical directions (30 MPa).

While in the axial direction, two end plates and four aluminum tension rods were adopted for pre-loading. The force loaded in AL-7075 rods is 100 KN.

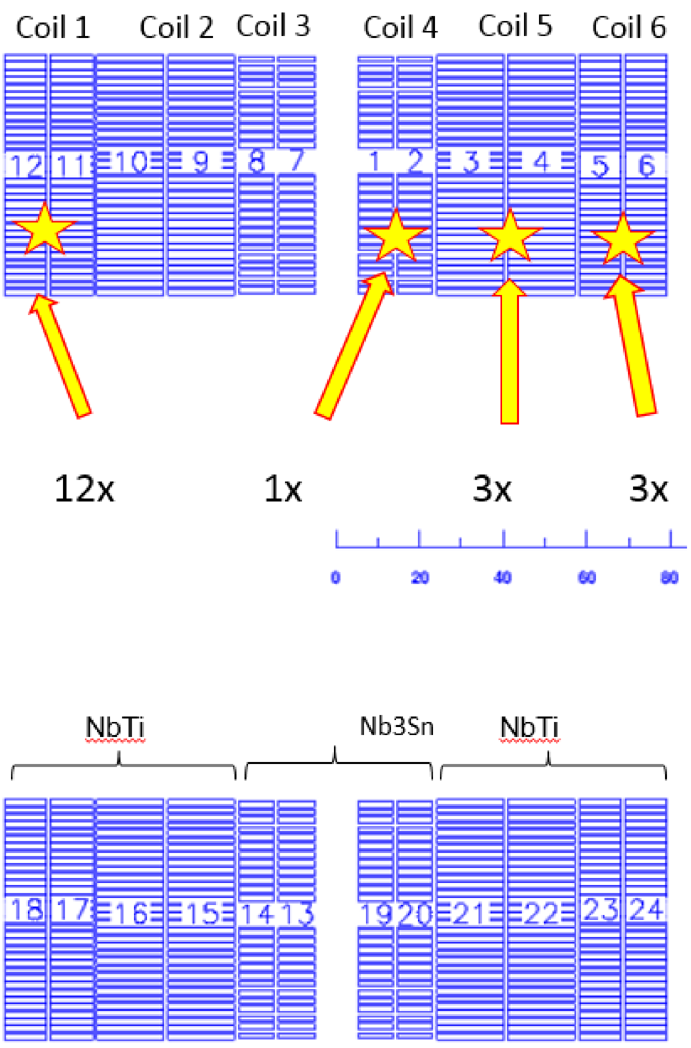
Test results-Training history

Training history	Quench current (A)	Quench field(T)	Quench location	Superconductor
1	2650	5.89	5外?	NbTi
2	3455	7.37	4外	Nb_3Sn
3	3550	7.51	5	NbTi
4	4122	8.47	1	NbTi
5	4224	8.65	1	NbTi
6	4361	8.85	5	NbTi
7	4603	9.29	1	NbTi
8	4420	9.02	?	NbTi
9	4511	9.13	6	NbTi
10	4793	9.63	1	NbTi
11	4895	9.82	1	NbTi
12	4837	9.71	1	NbTi
13	5101	10.2	6	NbTi
14	5036	10.01	5	NbTi
15	4931	9.84	1	NbTi
16	4929	9.87	5外?	NbTi
17	5094	10.18	1	NbTi
18	4902	9.83	1	NbTi
19	5105	10.2	1	NbTi
20	5122	10.23	6	NbTi
21	4855	9.74	1	NbTi
22	5109	10.22	1	NbTi

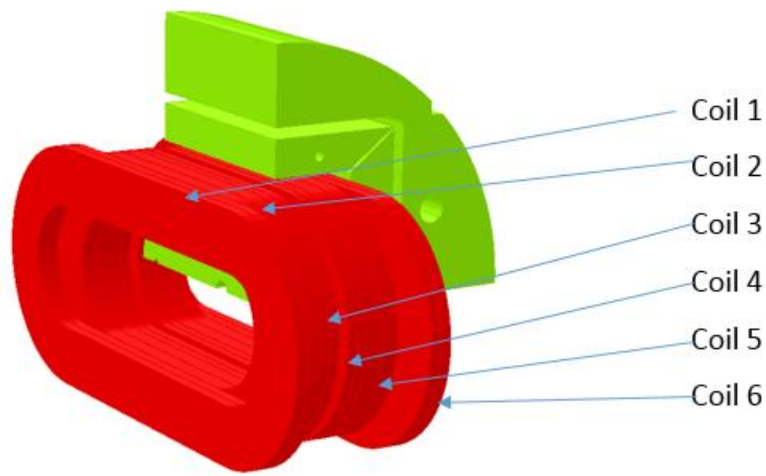


LPF1 quenched totally 22 times during the whole test process and it showed good training memory.

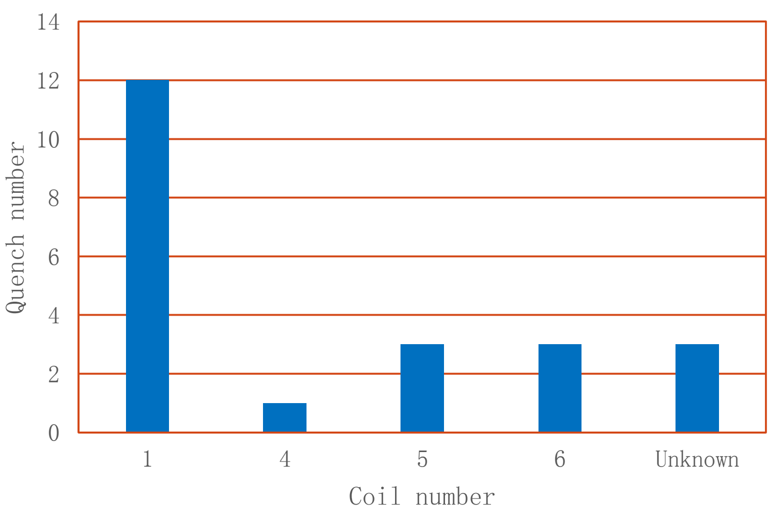
Quench location



Coil configuration (2D)



Coil layout (3D)

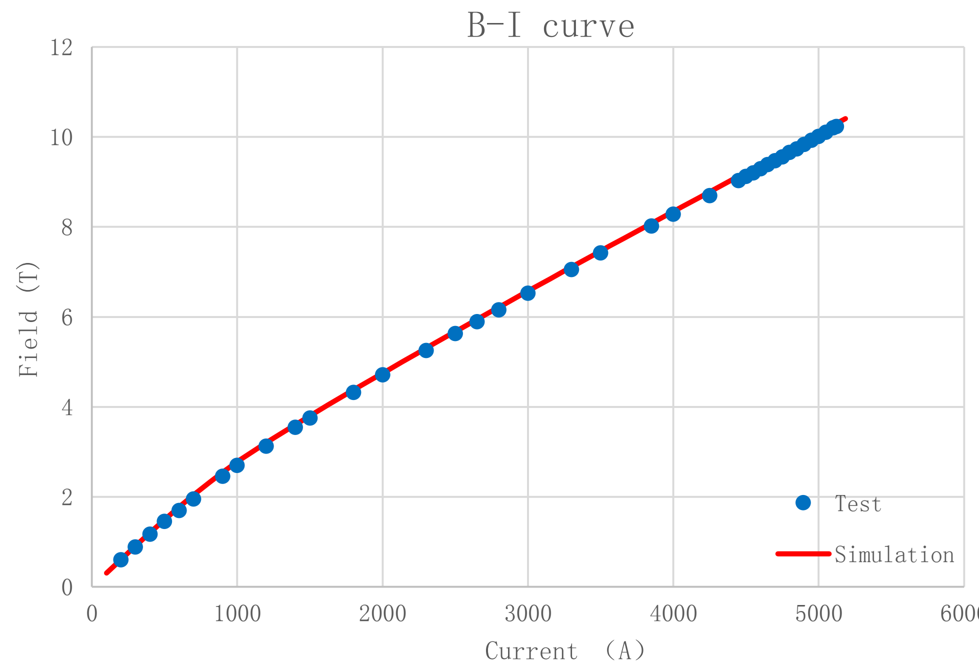


Most quenches are located in the NbTi coils, especially in coil #1

Test results： B-I curve

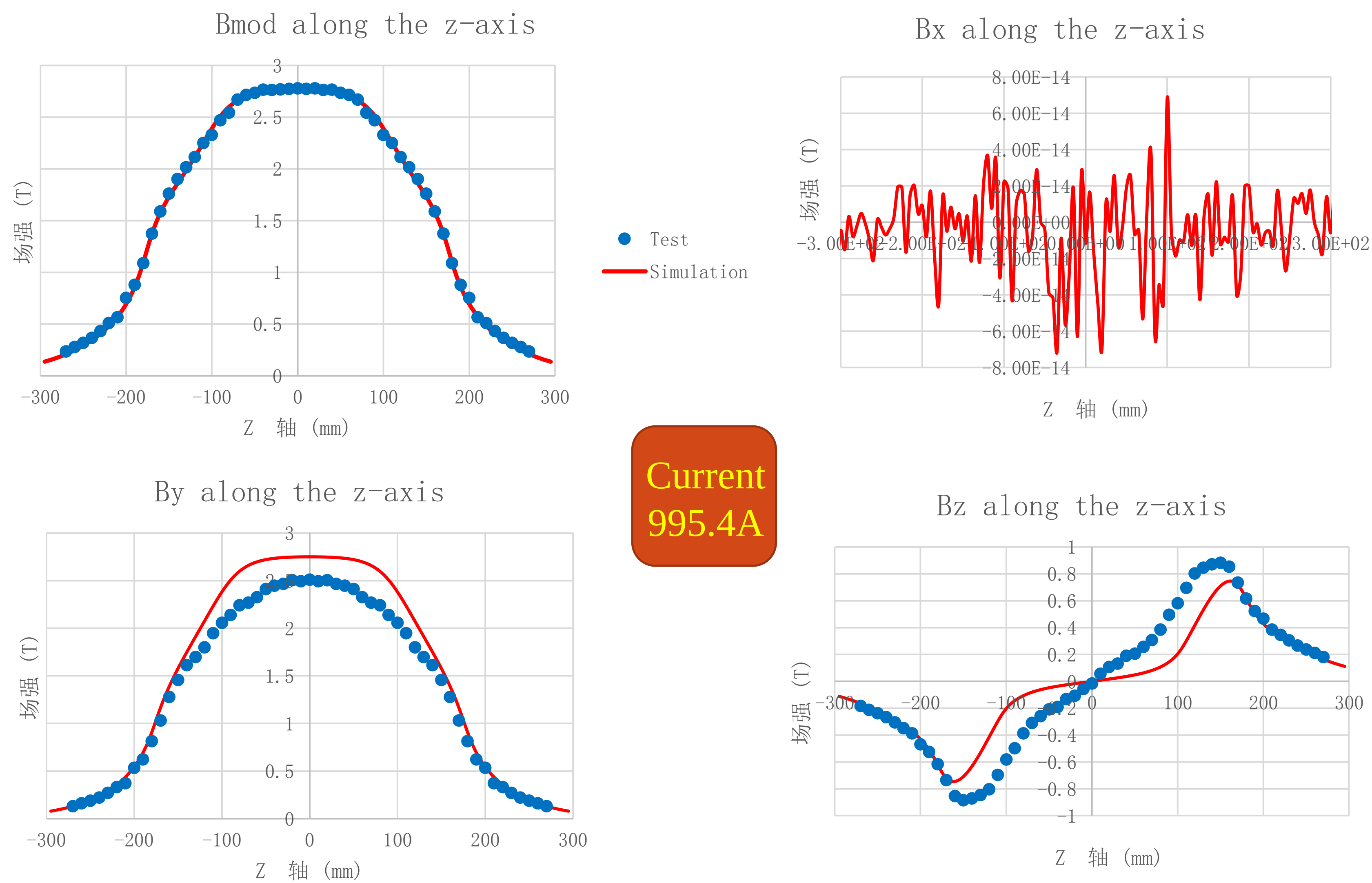
B-I (test)

Current (A)	Field (T)	Current (A)	Field (T)	Current (A)	Field (T)
200	0.6	2300	5.25	4600	9.29
300	0.8835	2500	5.63	4650	9.38
400	1.17	2650	5.89	4700	9.47
500	1.45	2800	6.15	4750	9.55
600	1.692	3000	6.52	4800	9.65
700	1.952	3300	7.05	4850	9.73
900	2.454	3500	7.42	4900	9.83
1000	2.7	3850	8.02	4950	9.92
1200	3.12	4000	8.28	5000	10.01
1400	3.54	4250	8.69	5050	10.1
1500	3.75	4450	9.03	5100	10.2
1800	4.32	4500	9.12	5122	10.23
2000	4.71	4550	9.2		



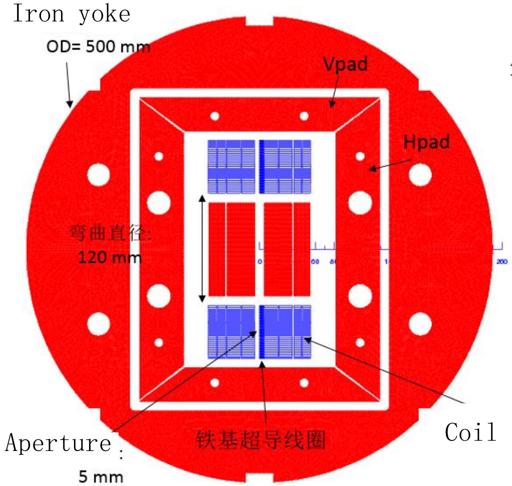
With red solid line for the simulation results and blue scatters for the test results.
Each scatter represents the average value of the measu red field strength in the 22 trainings at corresponding current. It shows very high consistency between the si mulation results and test results.

Field distribution along the z-axis

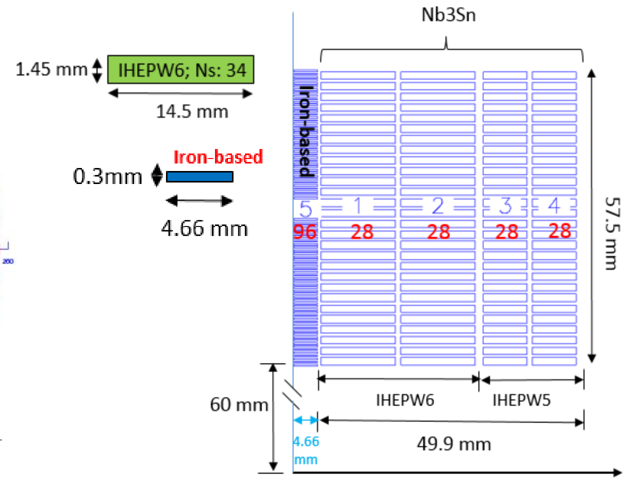


A Hall probe was fixed on a removable rod with accurate calibration which could be moved along the center axis of one aperture. The red solid line is for the simulation results and blue scatters is for the test results. Test results are also in good agreement with the simulated results.

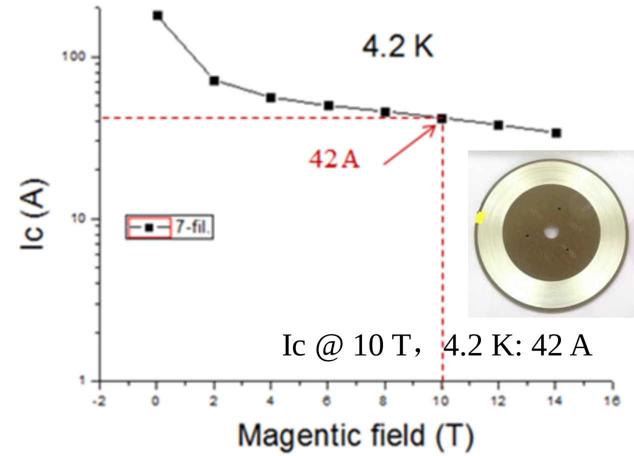
Electromagnetic design of LPF1-2



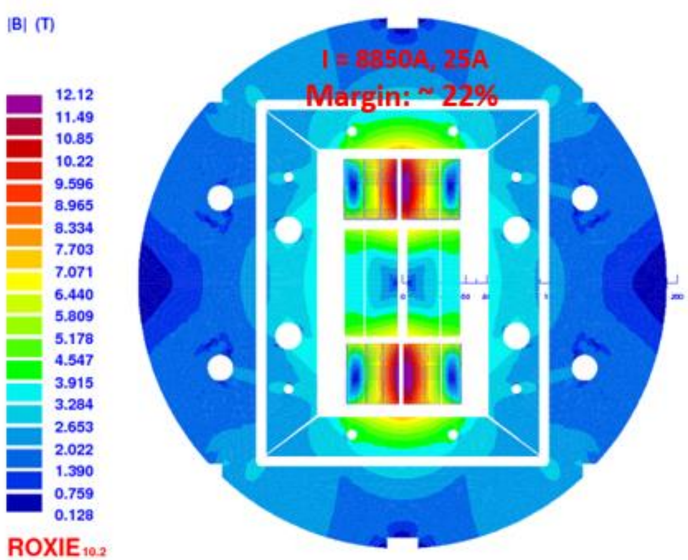
Cross-section



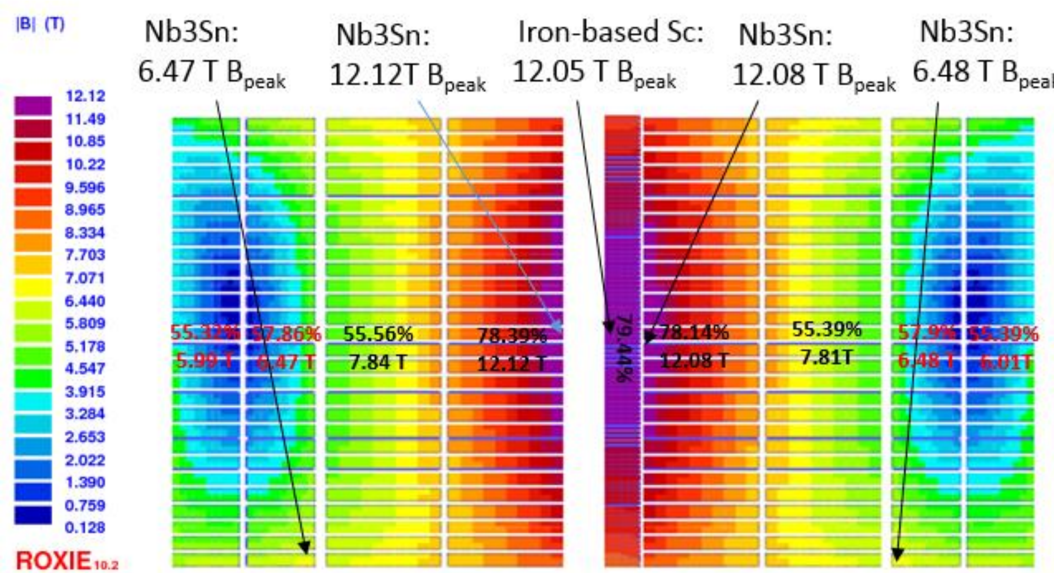
First quadrant coil layout



IBS tape



Field distribution

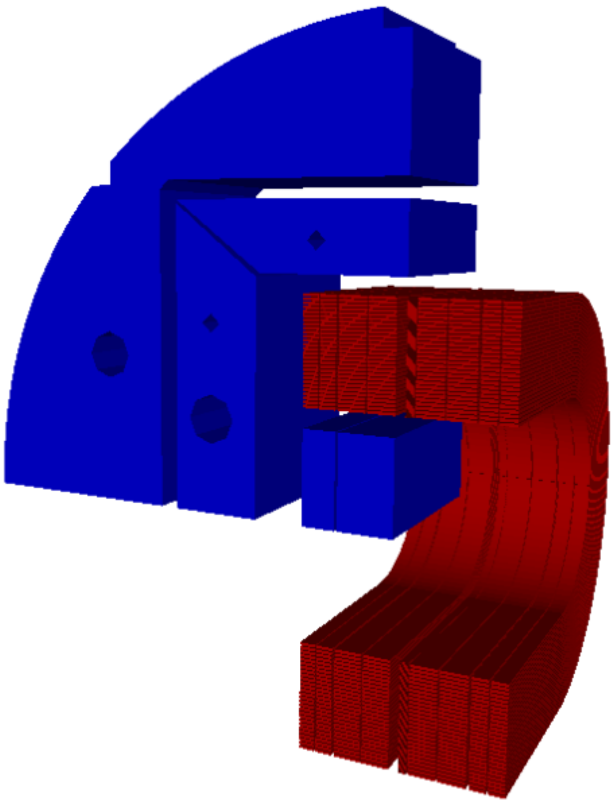


Field distribution

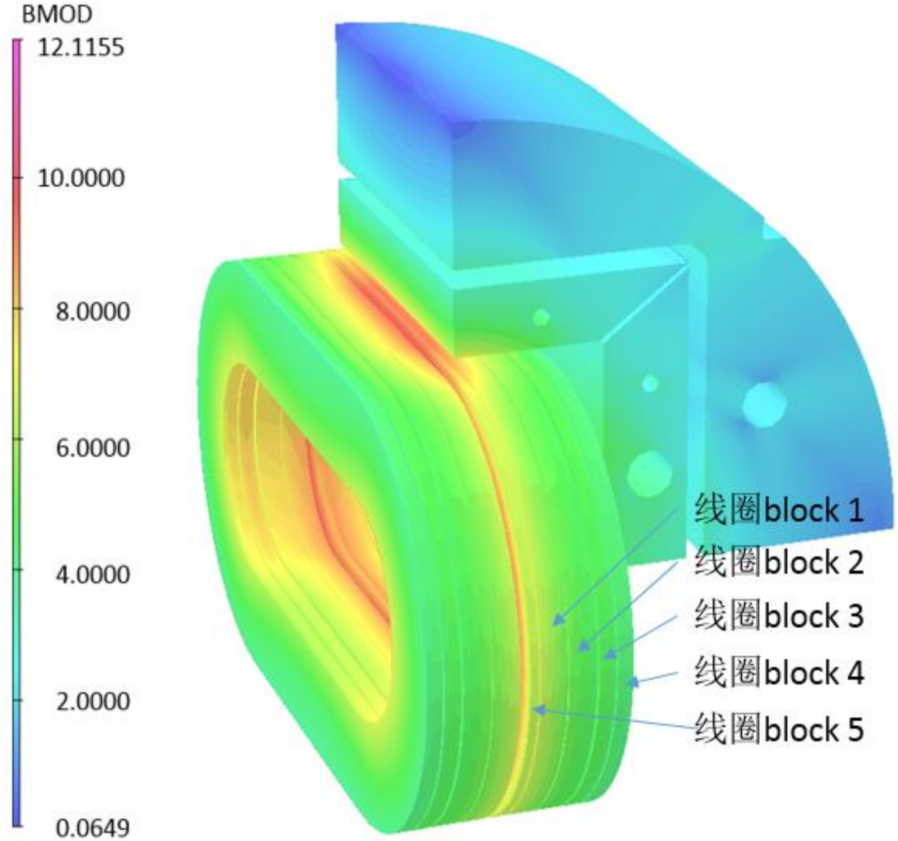
Characteristics of this dipole magnet- 3D simulation

Table 1: Main parameters of this subscale magnet

Current	MF	Inductance	Energy	Block	1	2	3	4	5
9120/25	12.02	4.97	206.83	Field (T)	12.07	8.15	8.66	8.33	12.04
A	T	mH	KJ	Load line(%)	78.5	57.6	70.3	68.4	79.4

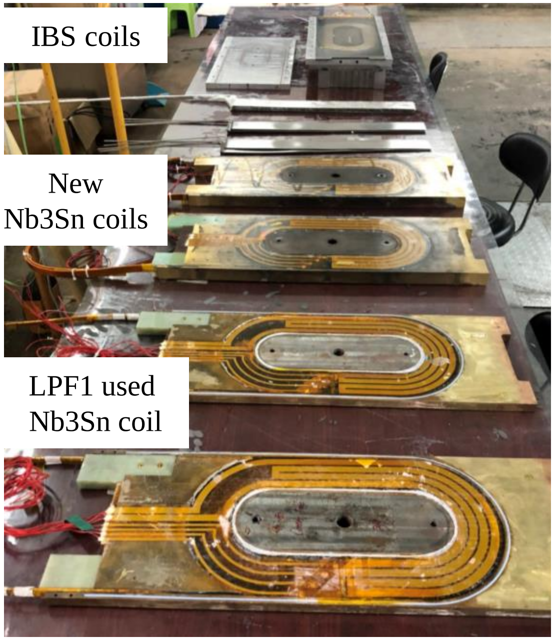


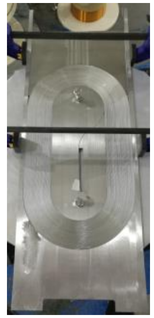
Simulated with Roxie

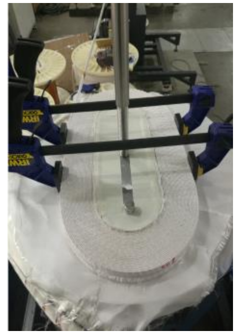


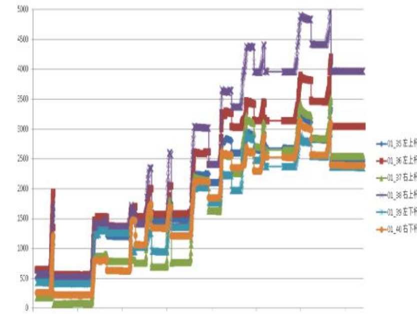
Cross check with Opera

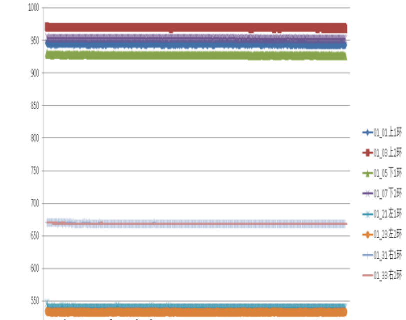
Fabrication of LPF1-2



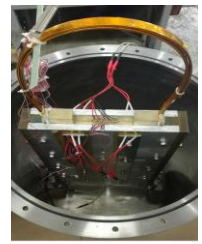


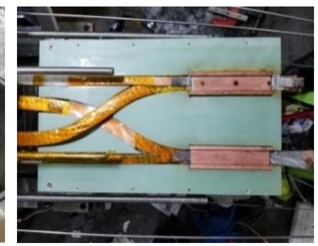


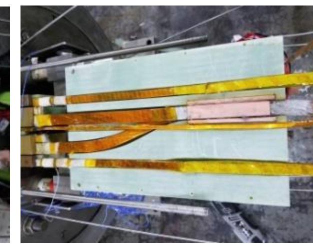


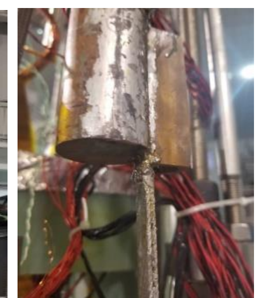


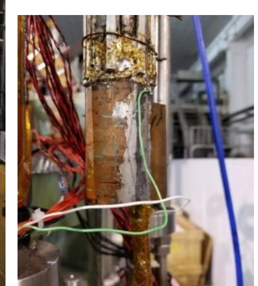
Pre-stress in axial direction>40ton; Pre-stress in horizontal and vertical direction>78.8Mpa





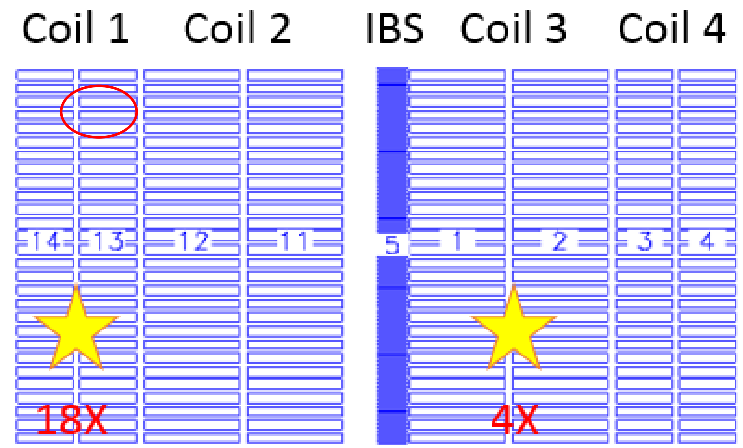




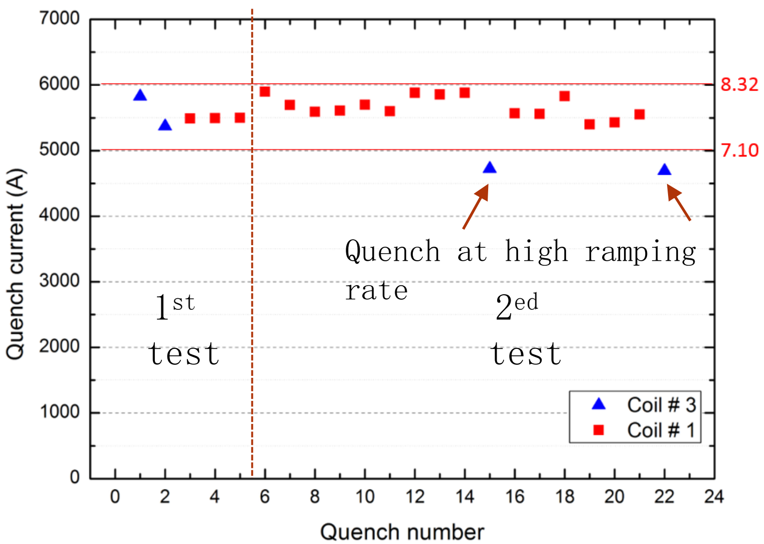


Test results of LPF1-2

	Training number	Quench current (A)	Quench field (T)	Quench location	Ramping rate
1st test	1	5825	8.11	coil #3	5A/s for 30A-1000A; 5A/s for 1000A-2000A; 5A/s for 2000A-3000A; 5A/s for 3000A-4000A; 5A/s for 4000A-5000A; 5A/s for 5000A-6000A
	2	5370	7.55	coil #3	5A/s for 30A-6000A
	3	5489	7.7	coil #1	5A/s for 30A-4000A; 5A/s for 4000A-5000A; 2A/s for 5000A-6000A
	4	5494	7.7	coil #1	5A/s for 30A-4000A; 5A/s for 4000A-5000A; 2A/s for 5000A-5500A
	5	5501	7.71	coil #1	5A/s for 30A-4000A; 5A/s for 4000A-5000A; 1A/s for 5000A-5500A; 1A/s for 5500A-6000A
2ed test	6	5899	8.19	coil #1 inside	5A/s for 30A-5000A; 1A/s for 5000A-6200A
	7	5694	7.95	coil #1 inside	5A/s for 30A-5000A; 2A/s for 5000A-6000A
	8	5592	7.82	coil #1 inside	5A/s for 30A-5000A; 2A/s for 5000A-5500A; 1A/s for 5500A-6000A
	9	5609	7.84	coil #1 inside	5A/s for 30A-5000A; 1A/s for 5000A-6500A
	10	5700	7.95	coil #1 inside	5A/s for 30A-5000A; 2A/s for 5000A-6500A
	11	5600	7.83	coil #1 inside	5A/s for 30A-5000A; 1A/s for 5000A-6500A
	12	5882	8.17	coil #1 inside	5A/s for 30A-5000A; 3A/s for 5000A-6500A
	13	5856	8.14	coil #1 inside	5A/s for 30A-5000A; 5A/s for 5000A-6500A
	14	5882	8.17	coil #1 inside	10A/s for 30A-5000A; 3A/s for 5000A-6500A
	15	4725	6.76	coil # 3	10A/s for 30A-7000A
	16	5568	7.79	coil #1 inside	10A/s for 30A-4000A; 5A/s for 5000A-6000A
	17	5560	7.78	coil #1 inside	10A/s for 30A-4500A; 5A/s for 4500A-5500A; 3A/s for 5500A-6000A
	18	5830	8.12	coil #1 inside	5A/s for 30A-5000A; 2A/s for 5000A-6500A
	19	5400	7.59	coil #1 inside	5A/s for 30A-5000A; 3A/s for 5000A-6500A
	20	5430	7.63	coil #1 inside	5A/s for 30A-5000A; 1A/s for 5000A-6500A
	21	5551	7.77	coil #1 inside	5A/s for 30A-5300A; 4A/s for 5000A-6500A
	22	4691	6.72	coil # 3	10A/s for 30A-6500A



Quench locations



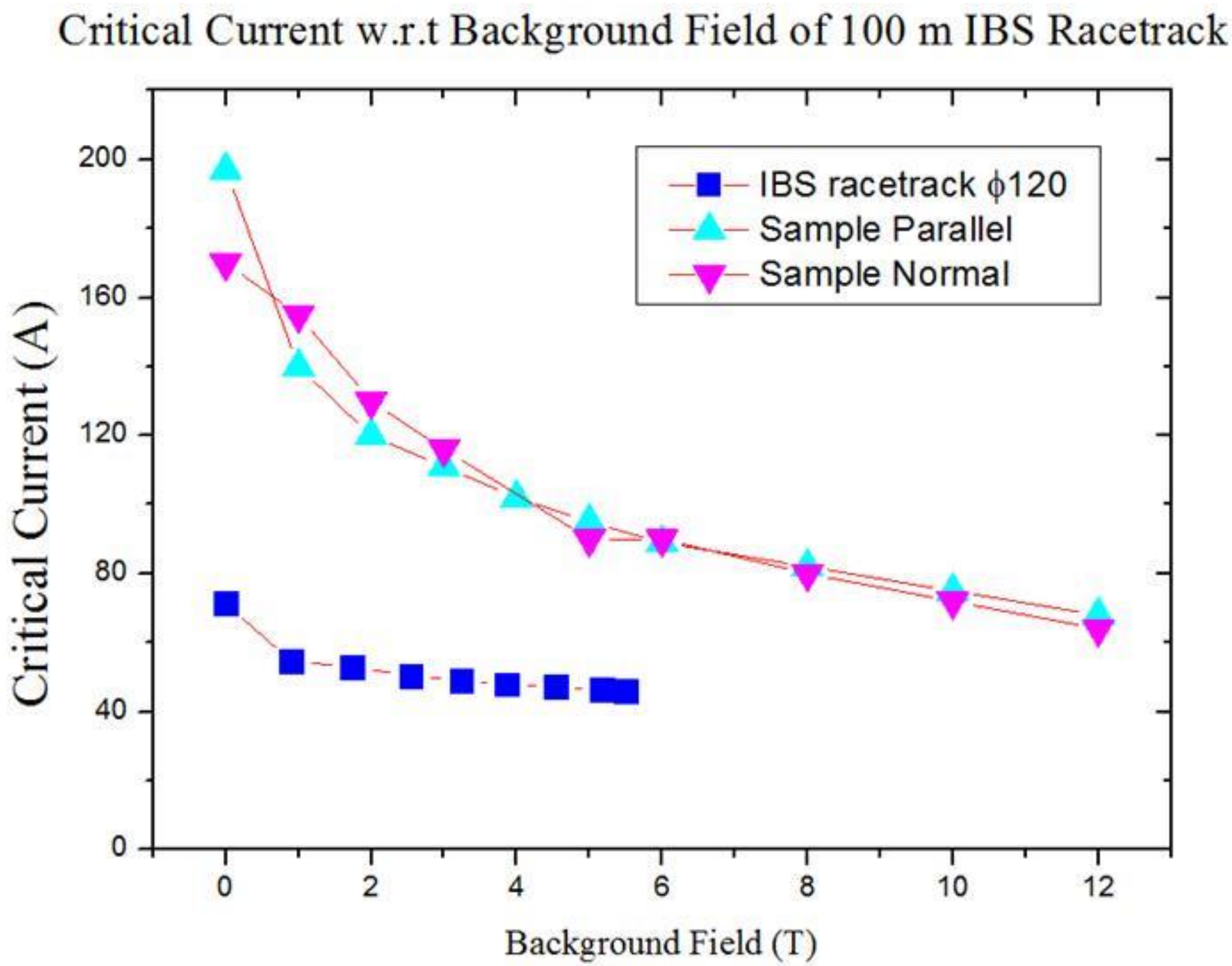
Training history of LPF1-2

The reason for these quenches was analyzed to be imperfectly welded Nb3Sn & NbTi joints.

Performance of IBS racetrack coil

Courtesy: Zhan Zhang

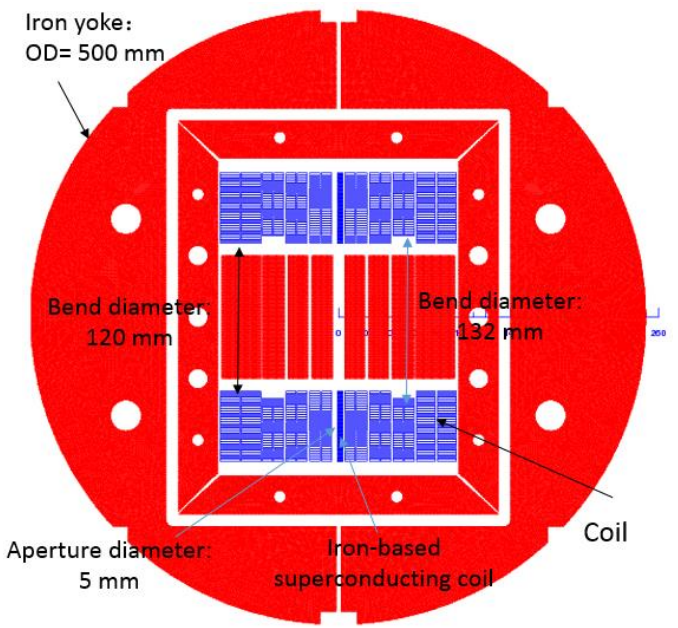
Current (A)	Field (T)	Ic (A)
0	0	71.4
650	1.003	54.7
1300	1.997	52.9
2000	3.037	50.4
2700	4.037	49.1
3400	4.984	48
4200	6.009	47.3
5000	6.992	46.4
5420	7.498	45.9



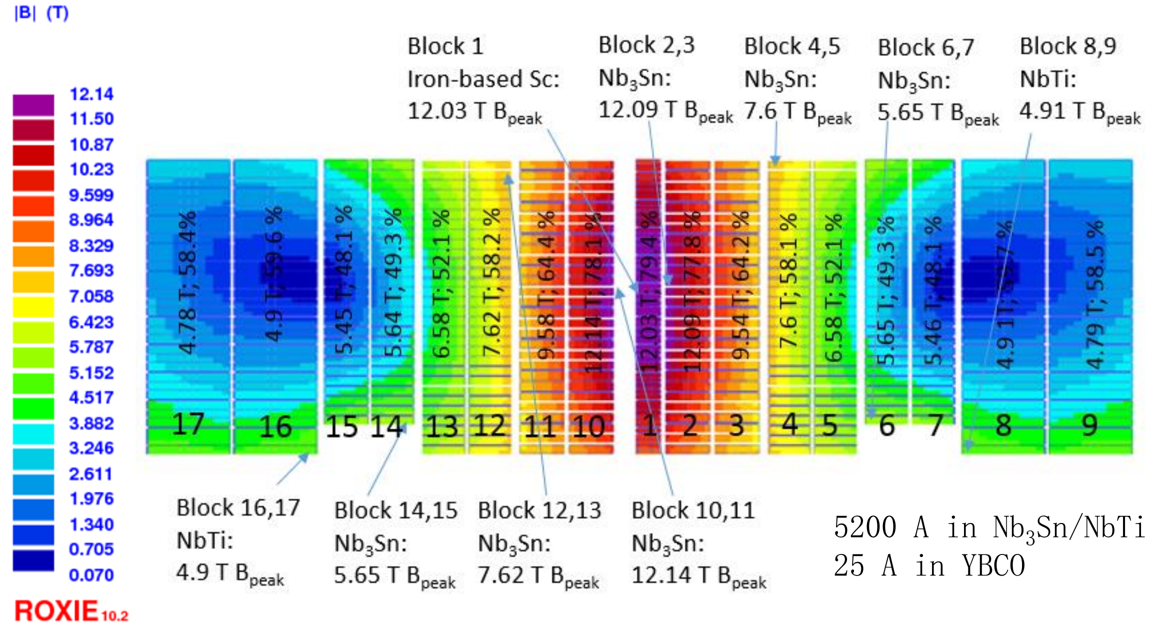
The world first 100m-IBS racetrack coil shows good performance.

Design of LPF2

（Nb_3Sn + NbTi + IBS）



Cross-section



Field distribution （2D）

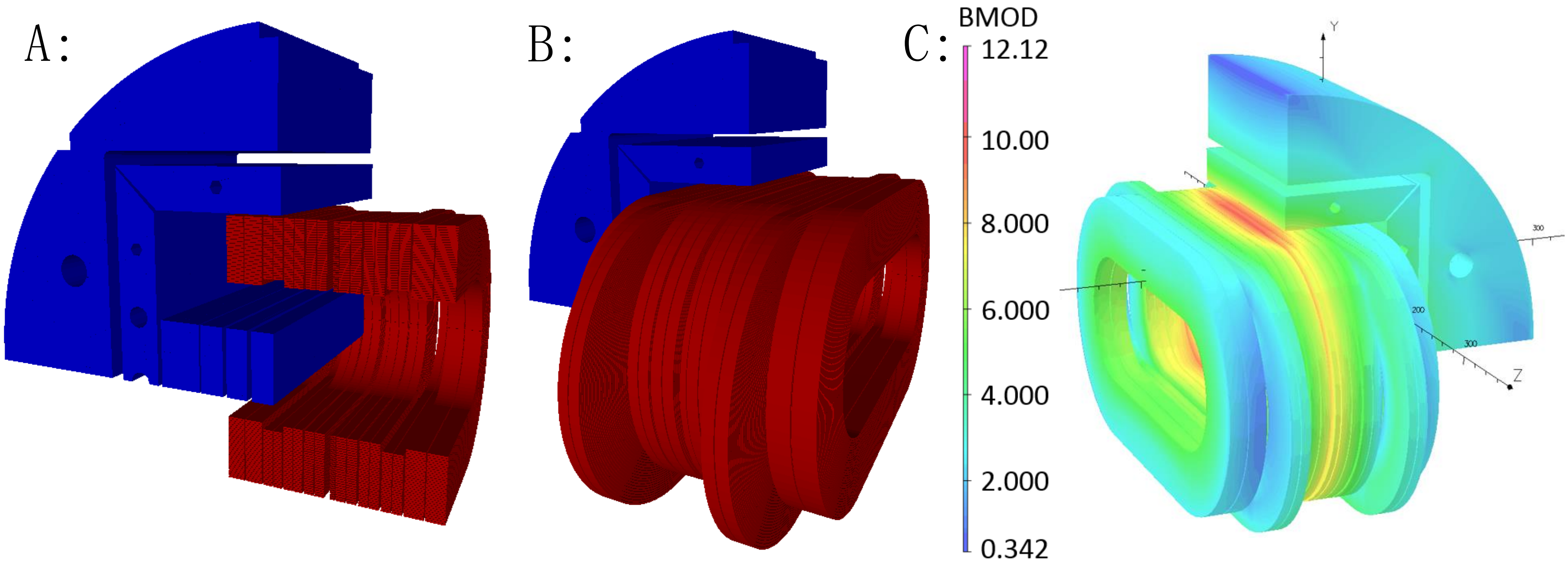
Parameters of strands

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB	Ic@ BrTr
IHEPWCJC	0.802	1	200	4.2	12	2700	400	682
IHEPNS1	0.818	1.1	100	4.2	12	2470	500	618
IHEPNS2	0.818	1.1	100	4,2	12	2000	500	500.5
IHEPNTJC	0.82	1	130	4.2	5	2613	550	690
Iron-based	-	6.7	100	4.2	12	216.5	11.4	38

Parameters of cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation Azimut	Insulation Radial	Twist angle	Filling factor
IHEPW5	8.5	1.45	1.45	20	IHEPWCJC	Nb3Sn	0.3	0.2	16.91	85.68%
IHEPNS1	8.2	1.5	1.5	18	IHEPNS1	Nb3Sn	0.21	0.2	16.91	80.38%
IHEPNS2	8.2	1.5	1.5	18	IHEPNS2	Nb3Sn	0.21	0.2	16.91	80.38%
IHEPWN1	16	1.5	1.5	38	IHEPNTJC	NbTi	0.15	0.15	16.91	87.39
Iron-based	4.5	0.3	0.3	1	Iron-based	Fe-based	0.15	0.1	-	-

Characteristics of this dipole magnet- 3D simulation



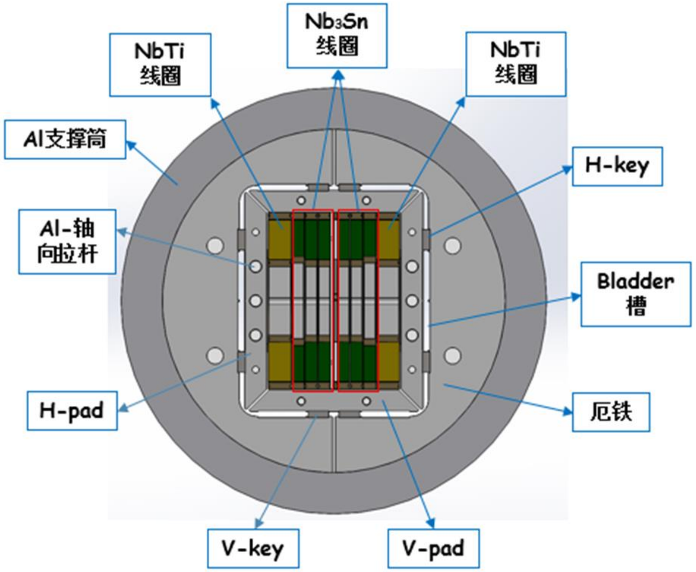
A, B: Simulated with Roxie C: Cross check with Opera.

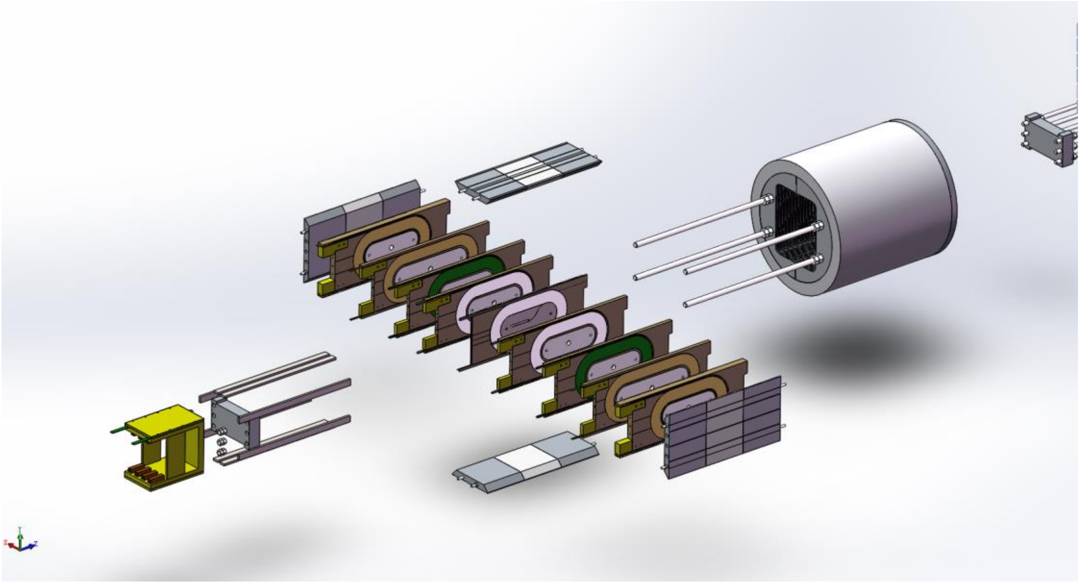
(Straight section length: IBS coil:200 mm; Inner Nb_3Sn coil: 200 mm; Middle Nb_3Sn coil :300 mm; Outer Nb_3Sn coil : 200mm)

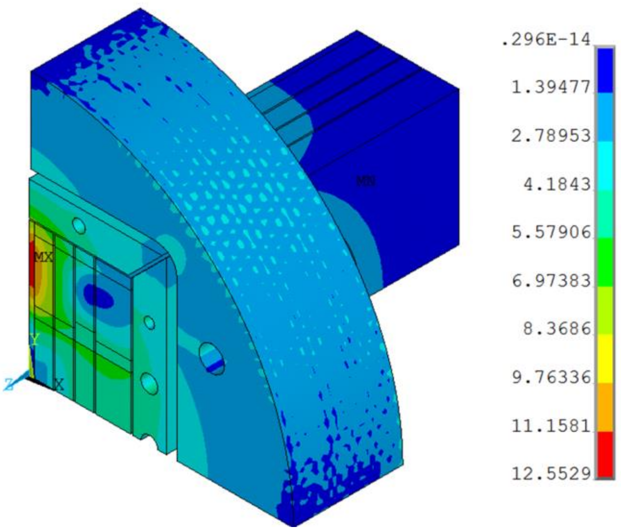
Table 1: Main parameters of this subscale magnet

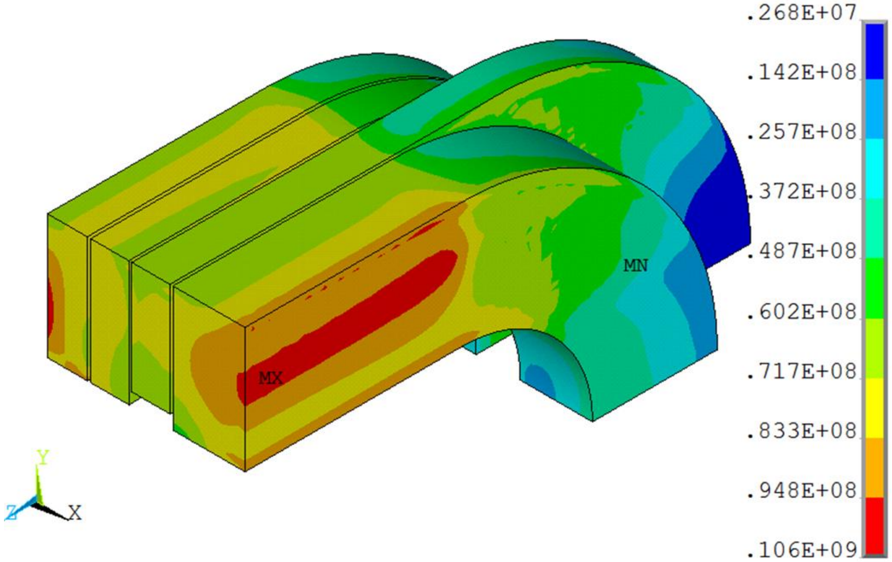
Current	MF	Block	1	2	3	4	5	6	7	8	9	10
5300/25	12	Field (T)	12.01	12.04	9.26	7.65	7.45	6.34	6.24	6.46	6.09	12.09
A	T	Loadline (%)	79	78.02	63.2	58.87	57.7	54.13	53.54	75.99	72.13	78.28

Mechanical design



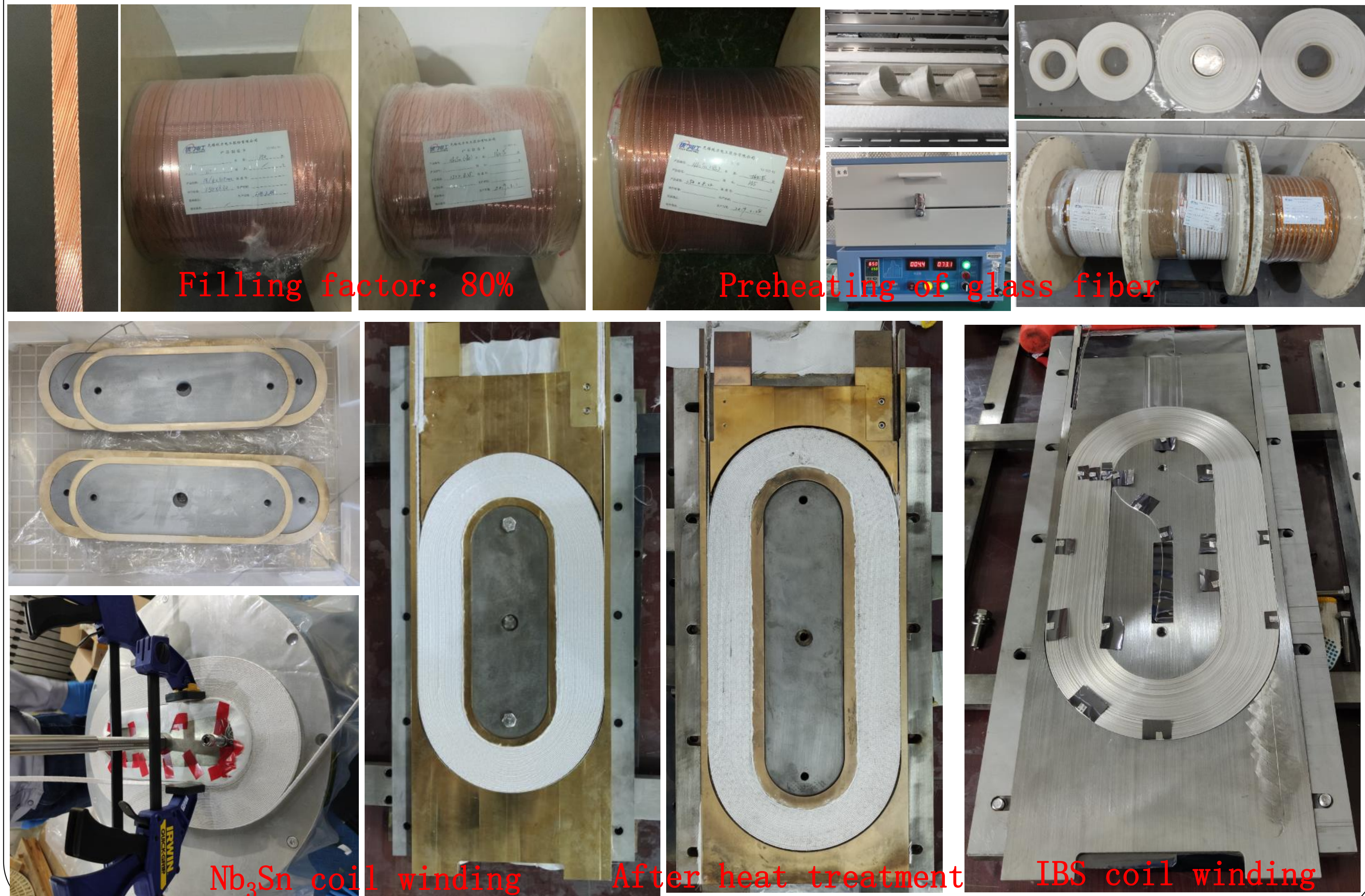






Peak stress in coils: 106 MPa

Fabrication of LPF2



Fabrication of LPF2

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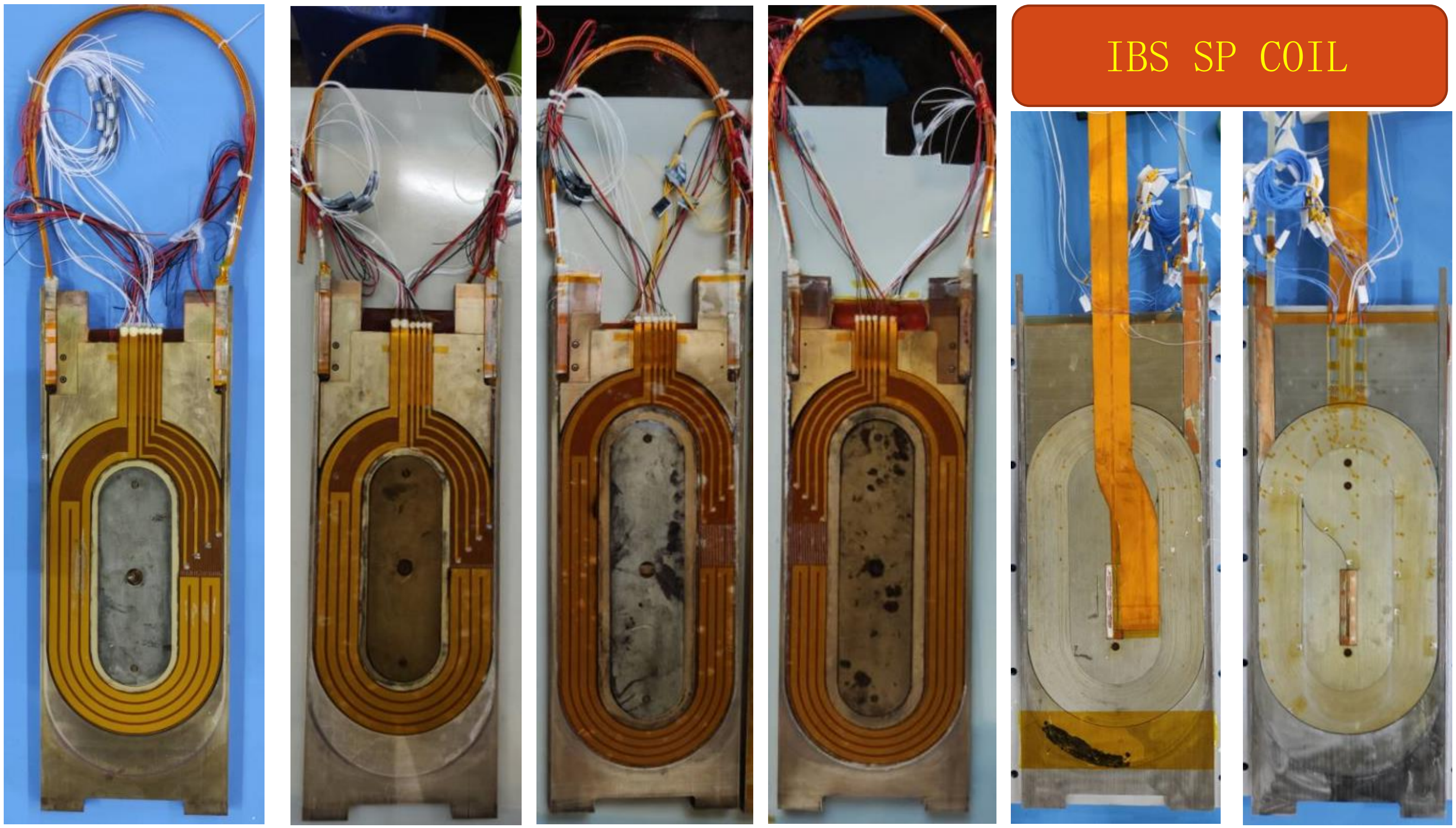

Pictures of the new fabricated Nb_3Sn and IBS coils after VPI.

Next step: Assembly of the magnet.

The magnet would be tested later. Hope for a good result!

Summary

1. As the first step, a twin-aperture hybrid dipole magnet named LPF1 has been designed, fabricated and tested. A peak field of 10.2 T has been achieved after 22 trainings.
2. Most quenches are located in the NbTi coils, especially in coil #1, which is the outmost coil. Imperfect impregnation of coil # 1 may be one of the reasons for these quenches as there are some grooves caused by the bubbles on the surface of this coil.
3. Then LPF1-2 has been fabricated with two new Nb_3Sn coils, and an IBS coil is inserted into the middle of this dipole magnet to test its property under high field and high stress. A peak field of 8.2 T has been achieved, most quenches are located in the outer Nb_3Sn coil. High resistance of the NbTi&Nb_3Sn splice may be the reason for the quenches. IBS coil showed good performance.
4. After summing up experience, we are fabricating a hybrid common coil dipole magnet named LPF2 now. Coil winding and VPI have already been finished. Assembly of the magnet would be carried out soon. The test of the magnet would be carried out later.

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Thanks!

谢谢！