CFETR Superconducting Magnet system and its R&D Works

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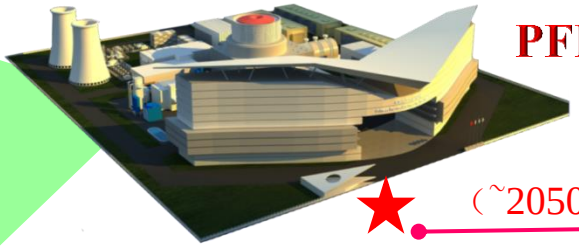
Contests

Background-roadmap



PFPP

（~2050）

1GWe, Power Plant Validation

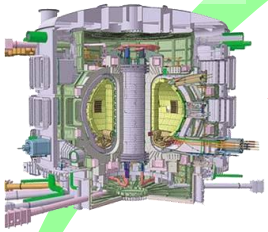
CFETR

（2030s start operation）

II: DEMO validation, Q>10, CW, 1GW, >50dpa

I: Q=1-5, steady state, TBR>1, >200MW, <10dpa

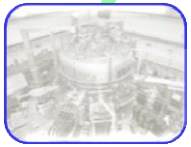
ITER



（~2021）

Phase I 1: Q=5, 3000s, 350MW, steady-state burning plasma

Phase I : Q=10, 400s, 500MW, Hybrid burning plasma



EAST Advance PFC, steady-state advanced operation

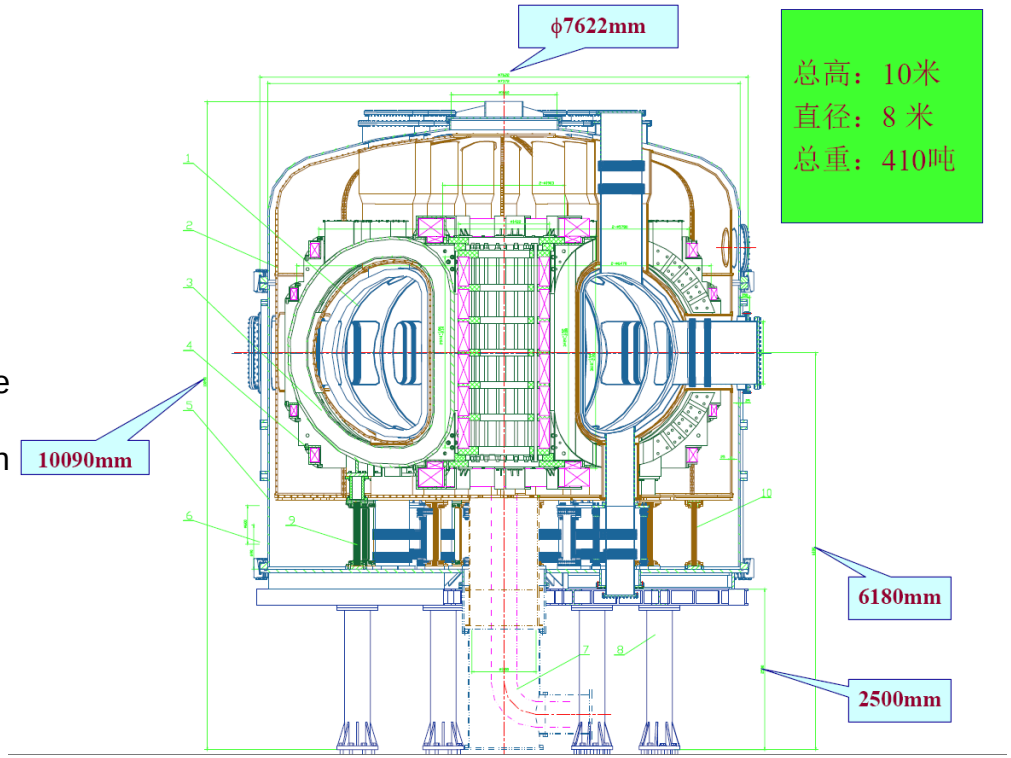
HL-2M Advanced divertor, high power H&CD, diagnostics

J-TEXT Disruption mitigation, basic plasma

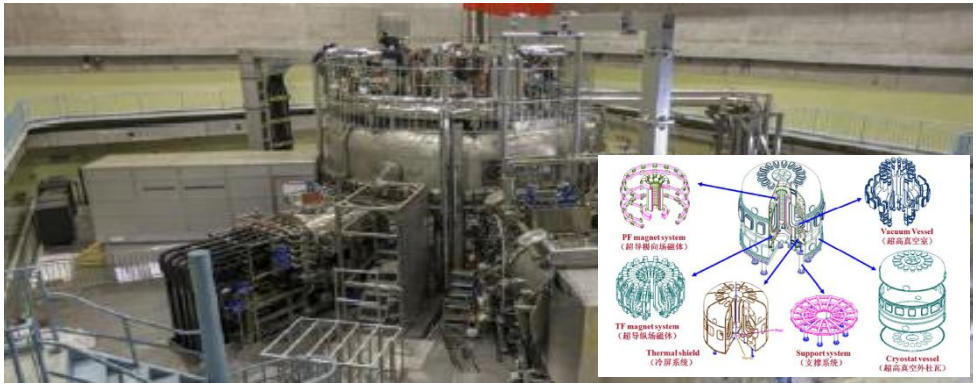
2015 2020 2025 2030 2035 2040 2045 2050 2055 2060

Background-EAST

✓The EAST is an Experimental Advanced Superconducting Tokamak.
✓The mission of the EAST Project is to bring out scientific issues on the continuous non-burning plasma scenario of steady-state operation, engineering issues on establishing the basis of technology for superconducting tokamak.
✓Superconducting magnets were chosen for all poloidal field (PF) and toroidal field (TF) systems since the engineering mission is to establish the technology basis of full superconducting Tokamak for future fusion reactors.

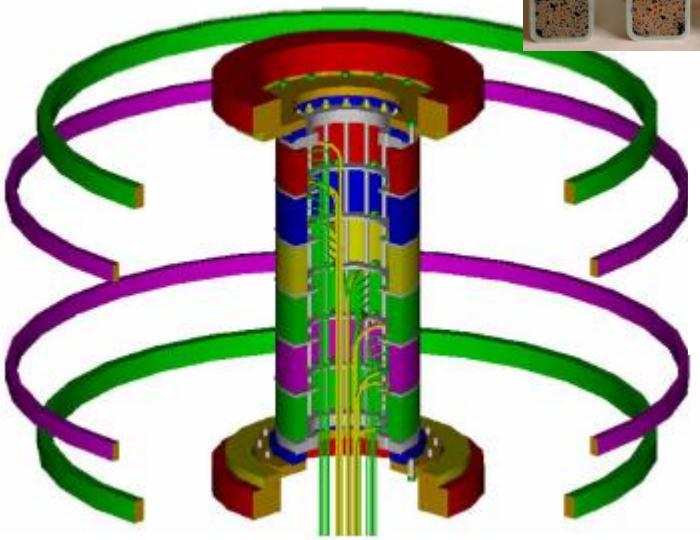


Major Radius, R_0	1.7 ~ 1.96 m	
Minor Radius, a	0.4 ~ 0.55 m	
Plasma Current, I_P	1 MA	
Elongation, K_x	1.6 ~ 2	
Triangularity, δ_x	0.6	
Toroidal Field, B_t	3.5 T	
Plasma Duration	~ 1000 s	
Configuration:		
	Pump limiter Double null Single null	
Heating and Driving:		
	LHCD	3.5~8 MW
	ICRH	3~6 MW
	ECRH	0.5~1.5 MW
	NBI	6~8 MW

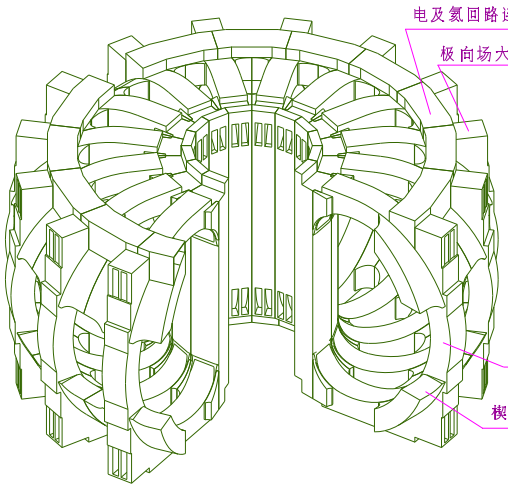


Background-EAST magnets system

Major radius (R_0) (m)	1.7
Minor radius (a) (m)	0.4
Magnetic field at the plasma center (B_t) (T)	3.5 (4.0)
Maximum field at the coil (B_{max}) (T)	5.8 (6.5)
Number of TF coils	16
Total number of Ampere-turns (MAT)	30 (34)
Operating current (I_{op}) (KA)	14.3 (16.4)
Total stored energy (MJ)	300 (390)
Total length of CICC of the TF system (Km)	19.2
Total weight of the TF system (ton)	160



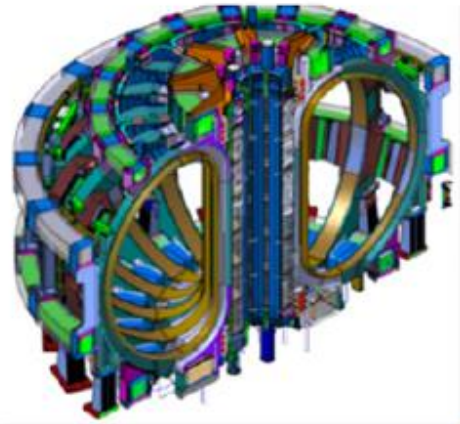
11000 米
28.8 吨
14.5 KA
4.5 T
20 KA/S
7 T/S



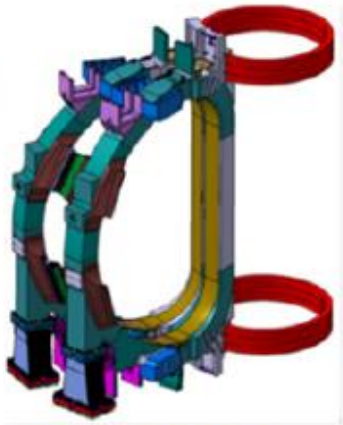
绕组单并重	4.0 吨
绕组单并	130 匝
CICC长度	1200 米
每并单重	10 吨
最高磁场强度	5.8 T
单并向心力	990 吨
单并倾覆力矩	332 吨-米

Number of PF coils	14
Maximum field (B_{max}) (T)	4.5
dB/dt (T/s)	< 7
Maximum operating current ($I_{op(max)}$) (KA)	14.5
Length of cooling channel (m)	124 to 171
Mass flow rate (g/s)	≥ 2

Background-ITER

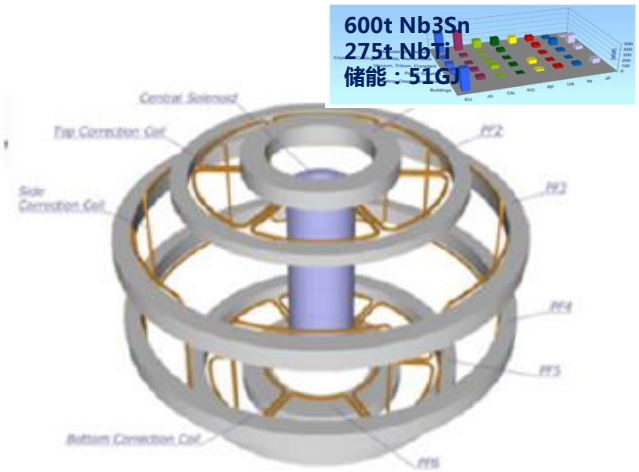


ITER Magnet System



Pair of TF Coils

CS Coil



PF Coil and CCs

(PF1) (PF2-6)

procurement allocation among the ITER partner-magnet system

Items	CH	EU	KO	JA	RU	US
TF conductor	7%	20%	20%	25%	20%	8%
TF coil	-	10		9	-	-
TF coil case	-	-	-	100%	-	-
CS conductor	-	-	-	100%	-	-
CS	-	-	-	-	-	-
PF conductor	65%	21%	-	-	14%	-
PF coil	-	5	-	-	1	-
CC	18	-	-	-	-	-
Feeder	100%	-	-	-	-	-

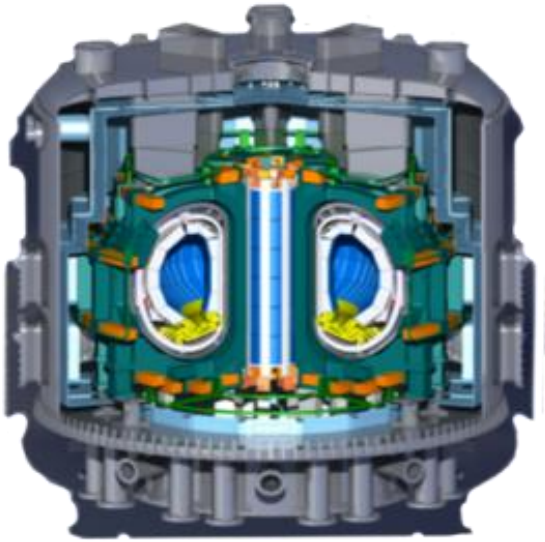
- ✓ **The conductor package**
- ✓ **The ITER CC package**
- ✓ **The Feeder package**

Contests

Introduction

Mission: Bridge gaps between ITER and DEMO, realization of fusion energy application in China

- A good complementarities with ITER
- Demonstration of full cycle of fusion energy with P_f = 200MW
- Demonstration of full cycle of T self-sustained with TBR ≥ 1.0
- Long pulse or steady-state operation with duty cycle time ≥ 0.3 ~ 0.5



I：Q=1-5, steady state, TBR>1, >200MW, <10dpa

II：DEMO validation, Q>10, CW, 1GW, >50dpa

Contests

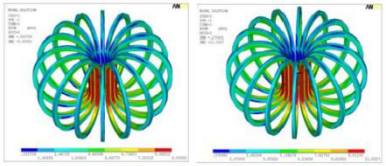
Magnet-phase I

Parameter	CFETR	EAST	ITER
Plasma current I_p (MA)	8–10	1	15
Major radius of plasma R (m)	5.7	1.78	6.2
Minor radius of plasma a (m)	1.6	0.4	2.0
Central magnetic field B_t (T)	4.5–5.0	3.5	5.3
Elongation ratio κ	1.8–2.0	1.6–2	1.70/1.85
Triangle deformation δ	0.4	0.6–0.8	0.33/0.48
Magnetic field ripple in the out-board mid-plane region of plasma	<0.5%	<0.6%	–
Number of TF coils (N)	16	16	18

(1) ITER-like; complementary with ITER;
(2) Fusion power 50–200 MW;
(3) Duty cycle time (or burning time)~(30–50%);
(4) Tritium should be self-sufficiency by blanket.

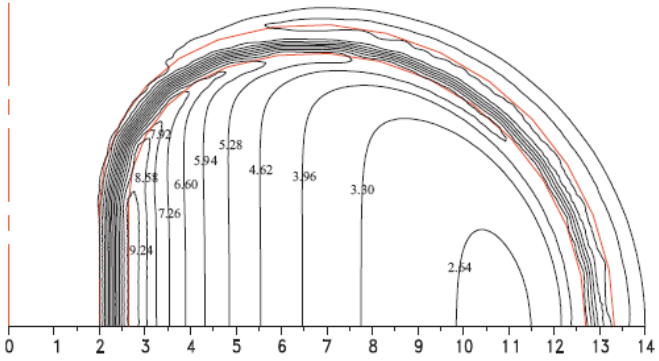
Magnet-phase I

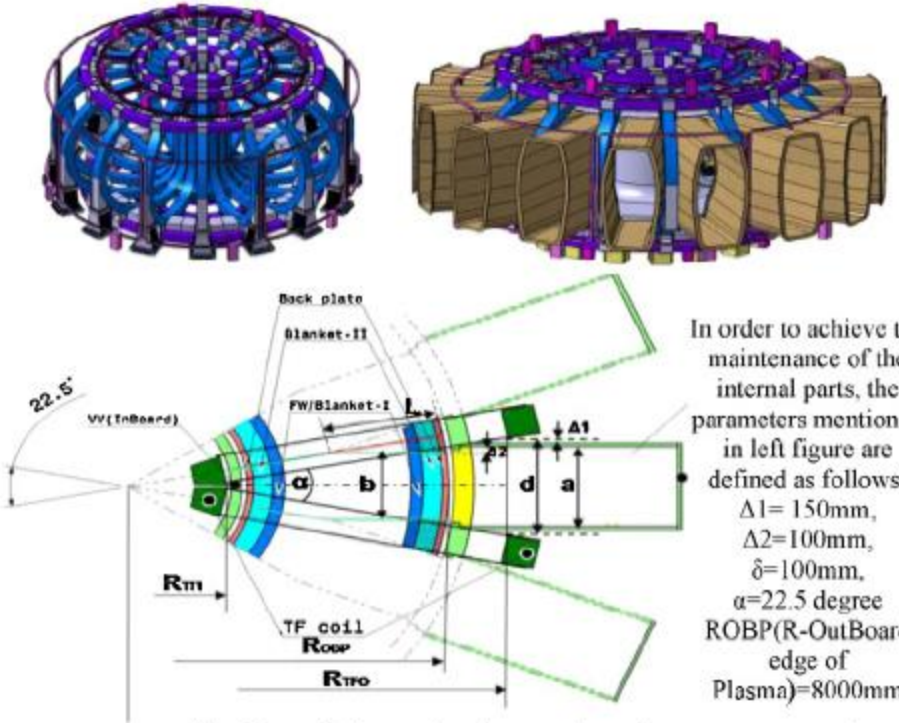
Parameter	Case 1	Case 2	Case 3	ITER			
Center field (T)	4.5	5.0	4.5	5.0	4.5	5.0	5.3
Maximum ripple in plasma area (%)	<0.1	<0.2	<0.1	<0.2	<0.1	<0.2	–
Total turns of each TF coil	132	132	132	132	132	132	134
Maximum magnetic field of TF (T)	9.94	11.00	10.0	11.09	10.1	11.193	11.8
Energy storage (GJ)	31.52	38.86	29.2	36.02	29.2	36.02	40
Overturning moment of TF coil (MN m)	383.2	382.56	190.6	180.36	181.4	180.90	–
Centripetal force (MN)	319.24	354.48	335.2	372.23	335.2	372.23	403



(a) B_{center}=4.5 T (b) B_{center}=5.0 T

Item	Requirement
Superconductor type	Nb_3Sn
Minimum piece length	1000 m
Un-reacted, Cr-plated strand diameter	0.820 ± 0.005 mm
Twist pitch	15 ± 2 mm
Twist direction	Right hand twist
Cr plating thickness	2.0 + 0–1 μm
Un-reacted, Cr-plated strand Cu-to-non-Cu volume ratio	1.0 ± 0.1
Residual resistivity ratio of Cr-plated strand (between 273 and 20 K)	>100 (after heat treatment)
Minimum critical current at 4.22 K and 12 T (as measured on ITER barrel)	190 A
Resistive transition index at 4.22 K and 12 T (as measured on ITER barrel)	>20 in the 0.1–1 μV/cm range
Maximum hysteresis loss per strand unit volume at 4.22 K over $\alpha \pm 3$ T cycle (for a sample greater than 100 mm)	500 mJ/cm^3





In order to achieve the maintenance of the internal parts, the parameters mentioned in left figure are defined as follows: Δ1= 150mm, Δ2=100mm, δ=100mm, α=22.5 degree ROBP(R-OutBoard edge of Plasma)=8000mm

(a) Case1 (large horizontal maintenance ports)

Magnet-phase I

Coil	Option	R(m)	Z(m)	ΔR(m)	ΔZ(m)	Turns
PF1U	Case1	3.4301	7.1093	1.382	1.111	616
	Case2	3.109	7.642	1.382	1.111	616
	Case3	3.109	7.642	1.382	1.111	616
PF2U	Case1	6.18505	7.42925	0.839	0.807	272
	Case2	6.18505	7.70904	0.839	0.807	272
	Case3	8.45774	6.9434	0.839	0.807	272
PF3U	Case1	10.650	6.54488	0.8856	0.909	324
	Case2	11.042	3.962	0.8856	0.909	324
	Case3	11.042	3.962	0.8856	0.909	324
PF3L	Case1	10.650	−6.54488	0.8856	0.909	324
	Case2	11.042	−3.962	0.8856	0.909	324
	Case3	11.042	−3.962	0.8856	0.909	324
PF2L	Case1	6.18505	−7.42925	0.839	0.807	272
	Case2	6.18505	−7.70904	0.839	0.807	272
	Case3	8.45774	−6.9434	0.839	0.807	272
PF1L	Case1	3.4301	−7.1093	1.382	1.111	616
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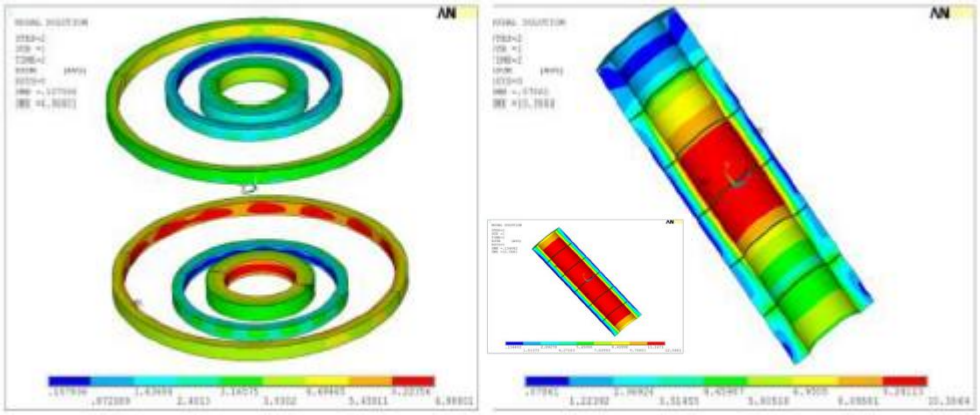
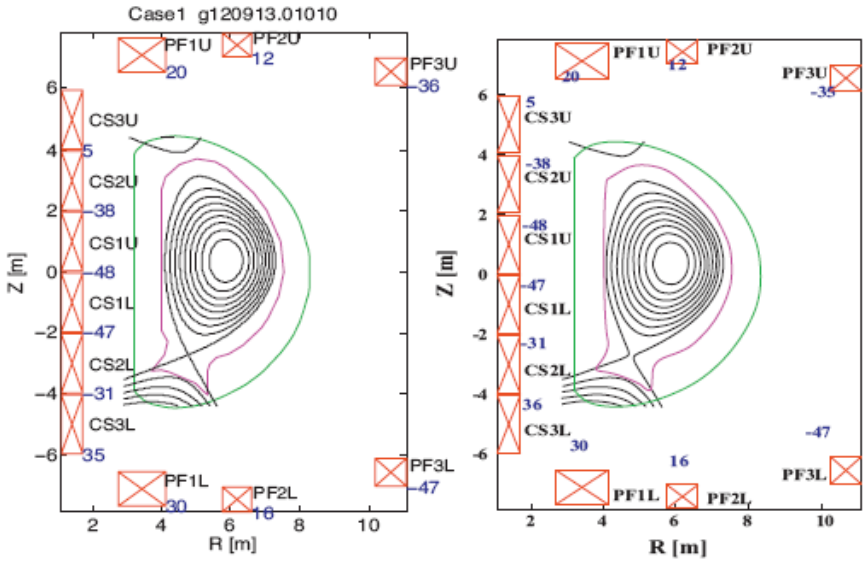
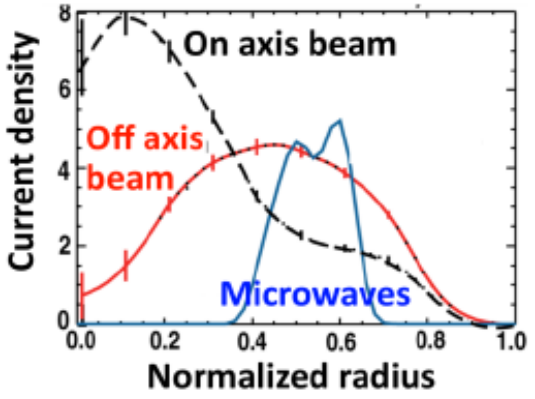


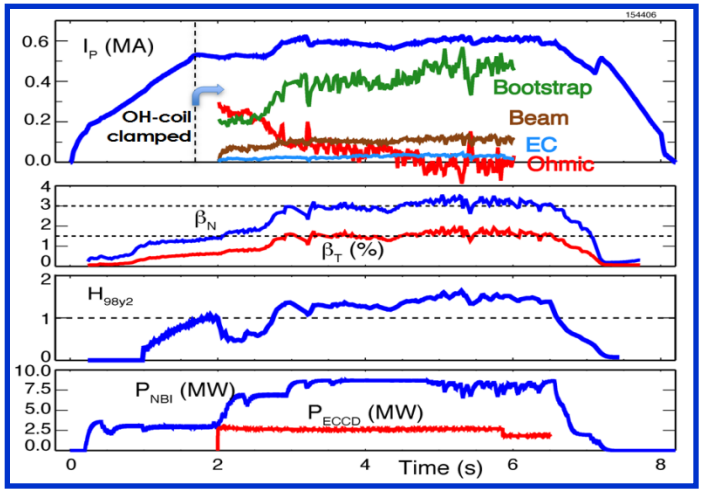
Coil	R(m)	Z(m)	ΔR(m)	ΔZ(m)	Turns
CS1U	1.415	0.999	0.630	1.938	374
CS2U	1.415	2.997	0.630	1.938	374
CS3U	1.415	4.995	0.630	1.938	374
CS3L	1.415	−4.995	0.630	1.938	374
CS2L	1.415	−2.997	0.630	1.938	374
CS1L	1.415	−0.999	0.630	1.938	374



Magnet-phase II

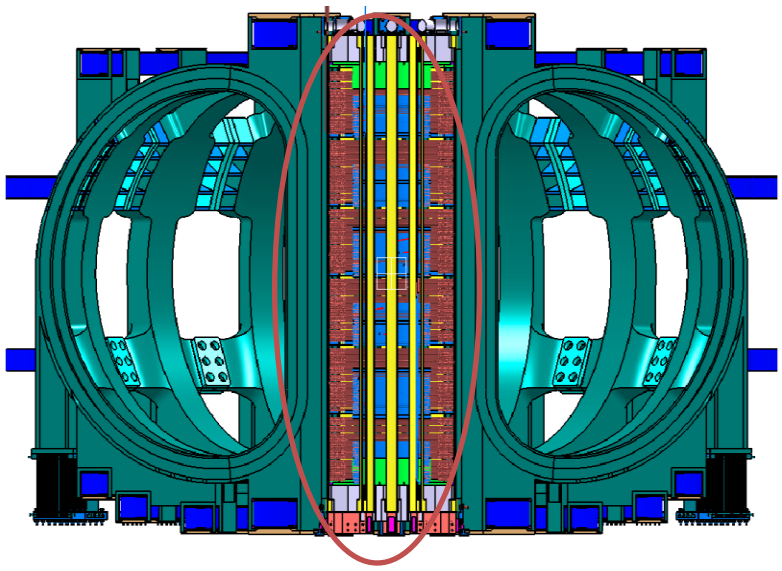
- Phase 2: AT H-mode (DT-2, 10y)
- Ip=11-15MA； Bt=7.5T, BetaN=3.0
- R=6.0m, a=2.0m, K=2.0, Advanced TMB
- Advanced diagnostics (DEMO-relevant)
- Extension DIII-D AT(10s) to EAST(1000s)
- Explore possibility for Ini =1.0
- DEMO relevant H&CD
- Explore possibility for EC (H&CD) only

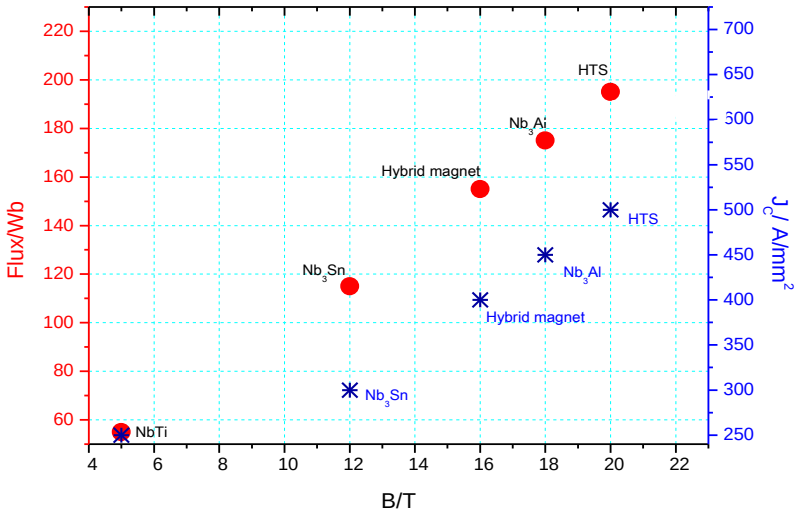


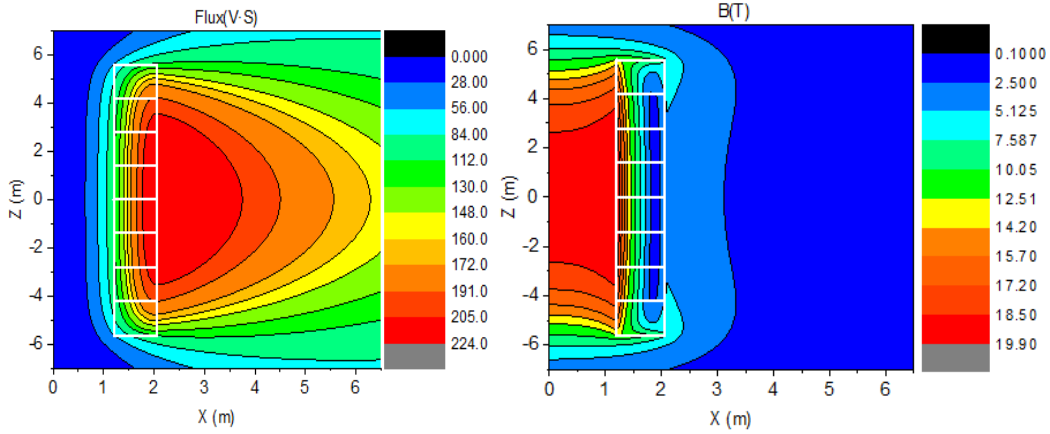


Joint DIII-D /EAST efforts
at β_N ~ 3.5, f_{NI} ~ 1, ne_{GW}~0.8

Magnet-phase II







TF coil

B_t=6-7T

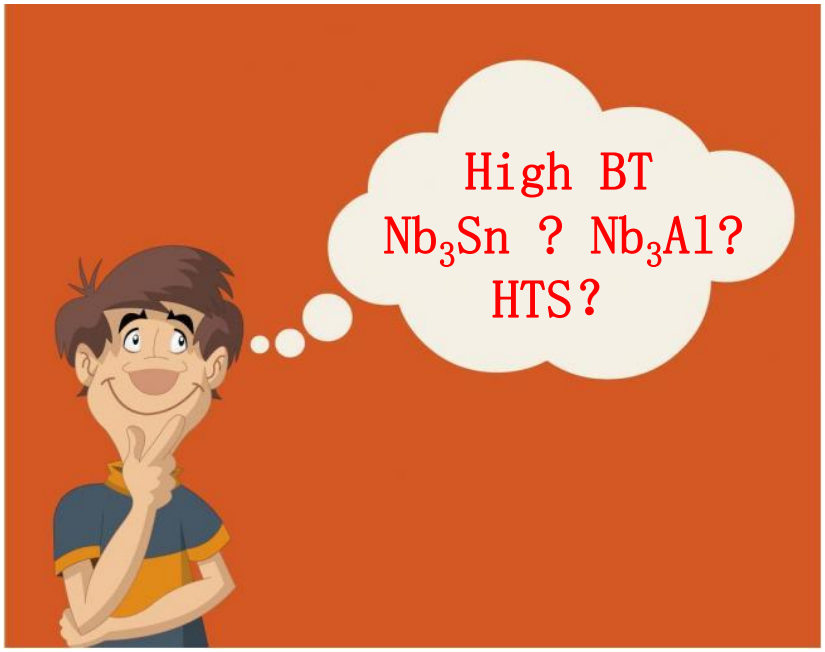
B_{max}=15-16T

CS coil

B_{max}=15-20T

Contests

Core technology



- Superconducting wire or tape
- Large current conductor
- Magnet manufacturing technique
- …

>15T

NbTi

+

Nb_3Sn

? ?

Nb3Al

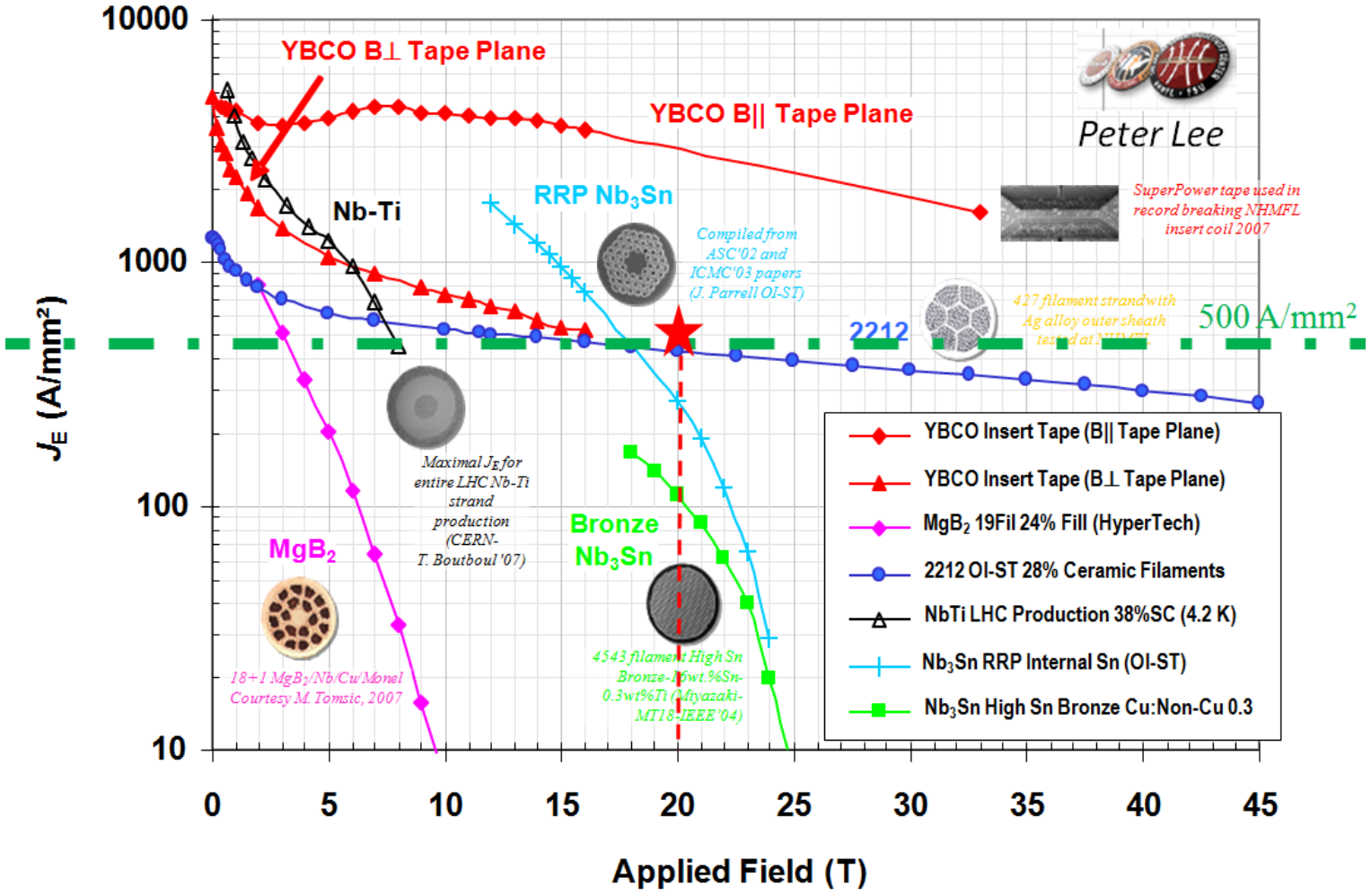
YBCO

Bi-2212

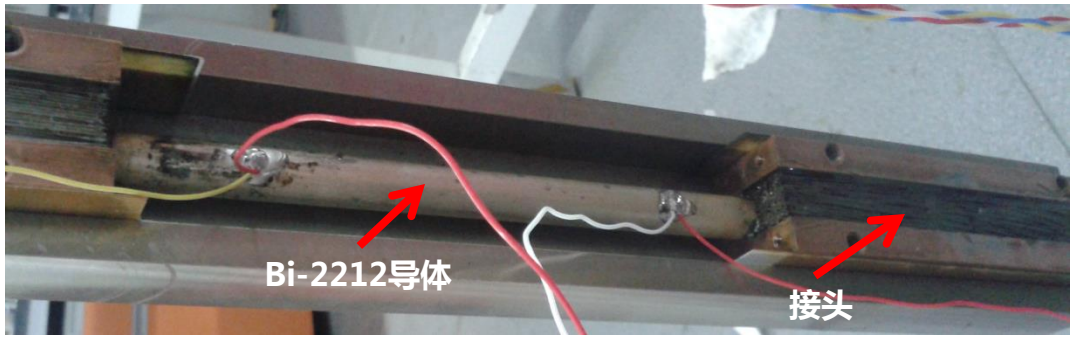
Or …

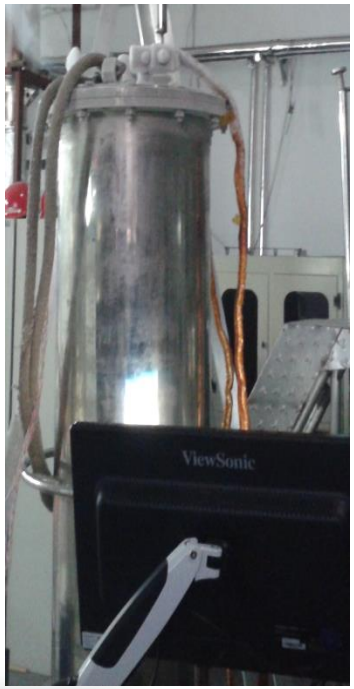
? ?

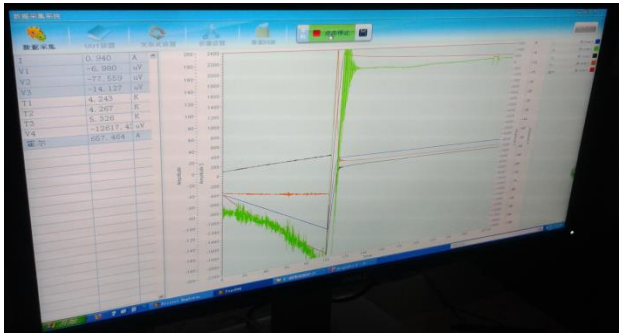
Core technology

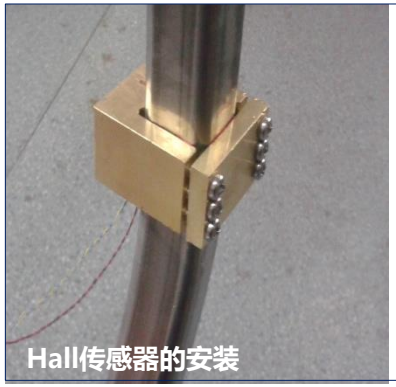


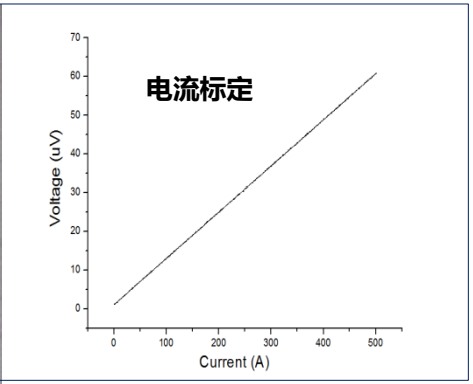
Core technology-Bi-2212



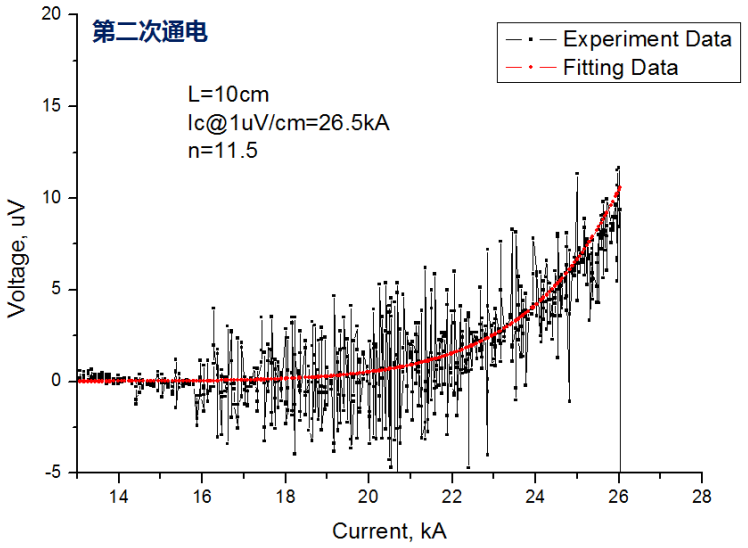


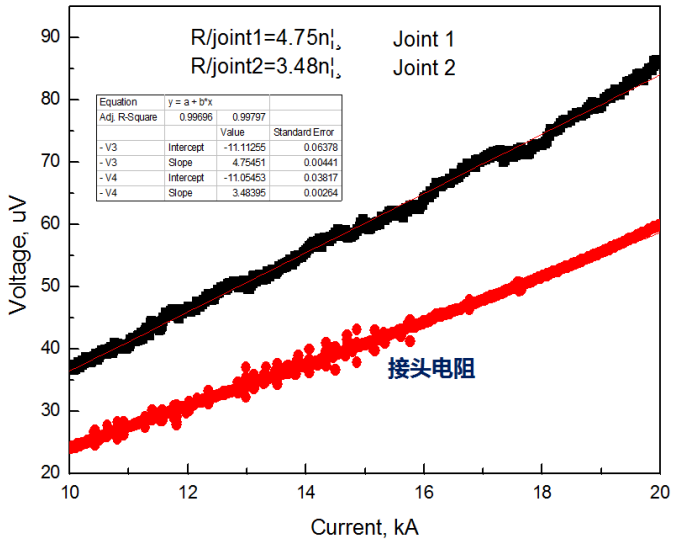


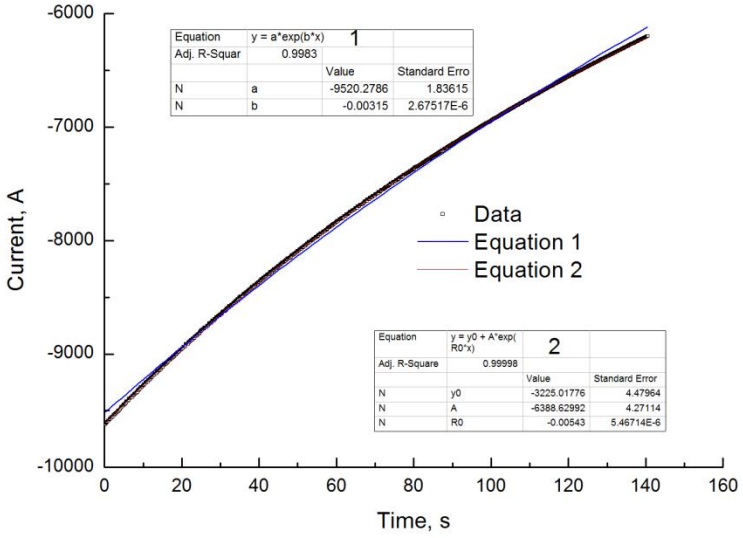




Core technology-Bi-2212





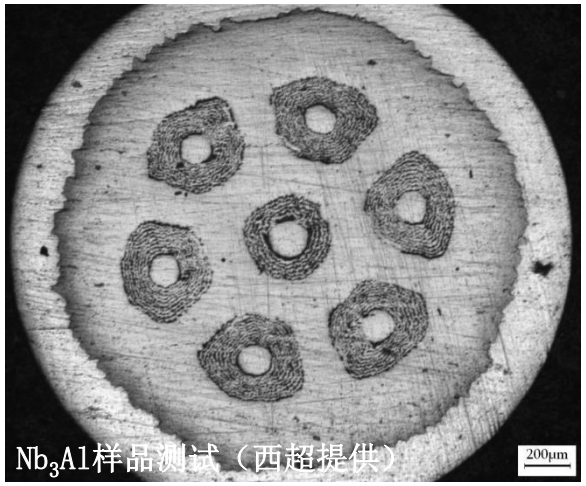


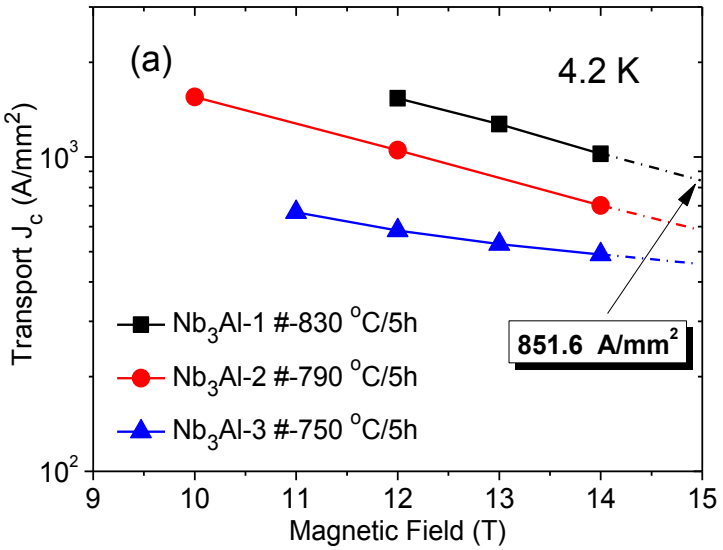
- ✓ Ic@4.2K, 26kA
- ✓ Joint resistance is about 4 nOhm

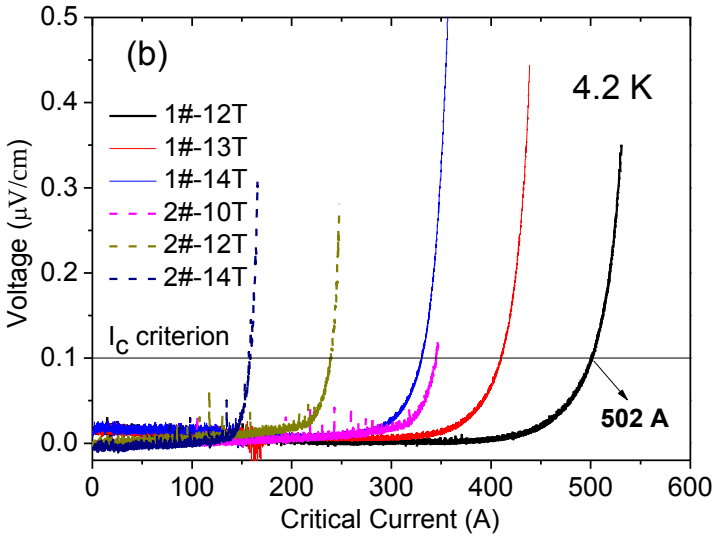
下一步实验

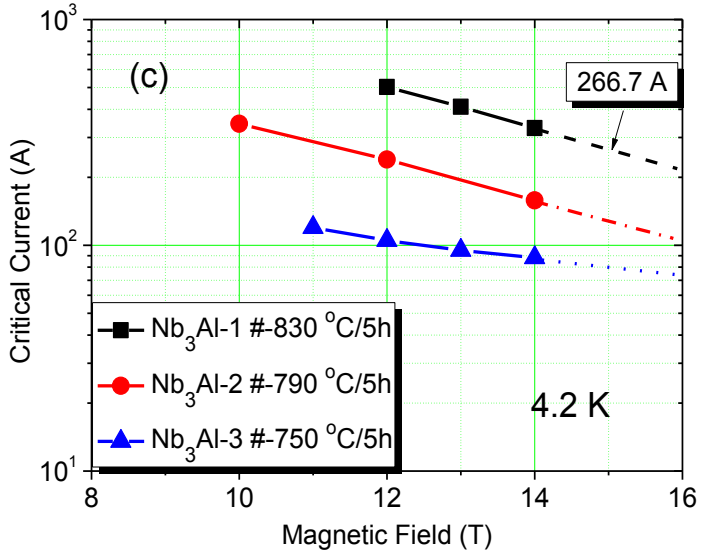
1. Test under magnetic field
2. Research on the quench propagation

Core technology-Nb3Al

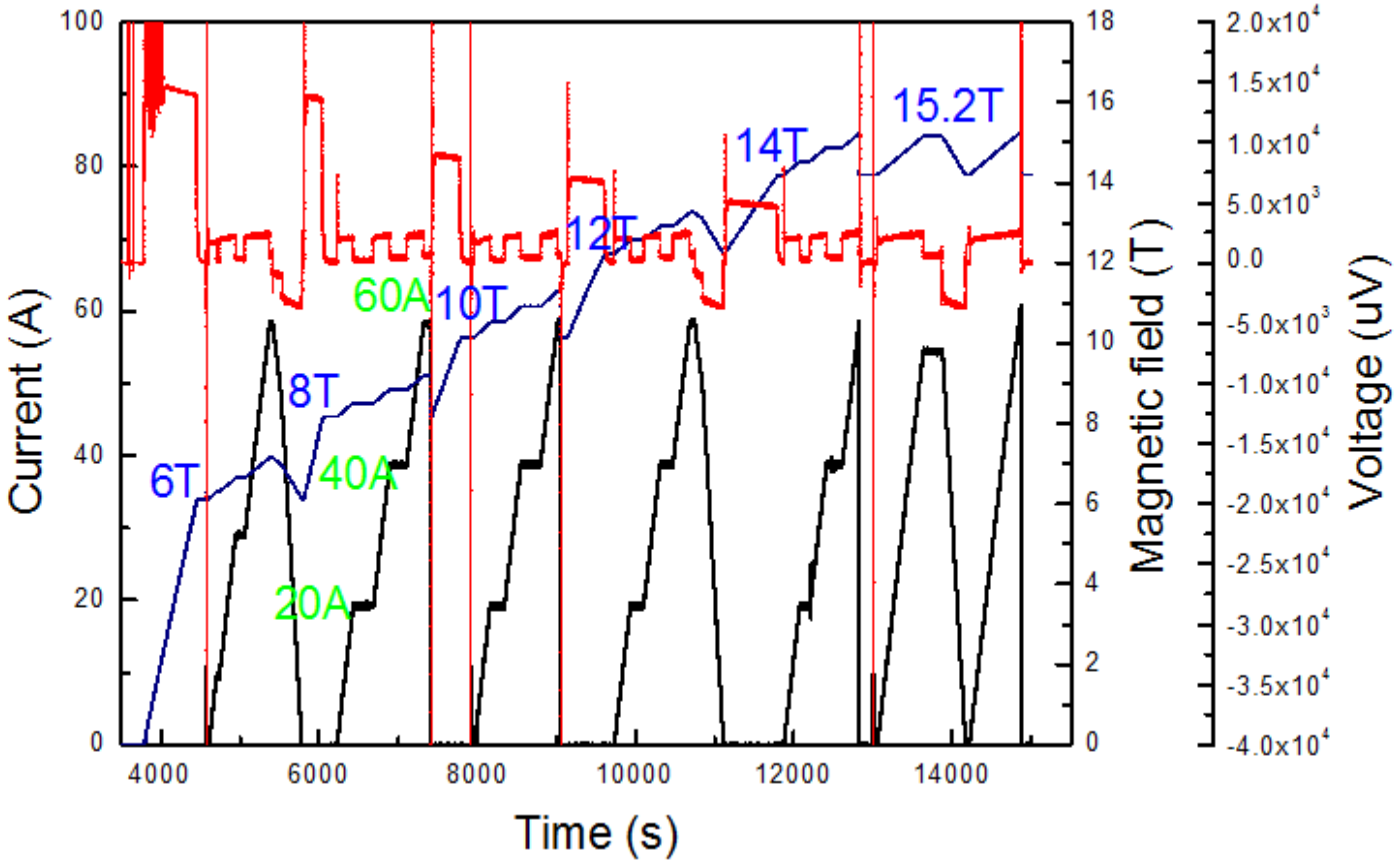




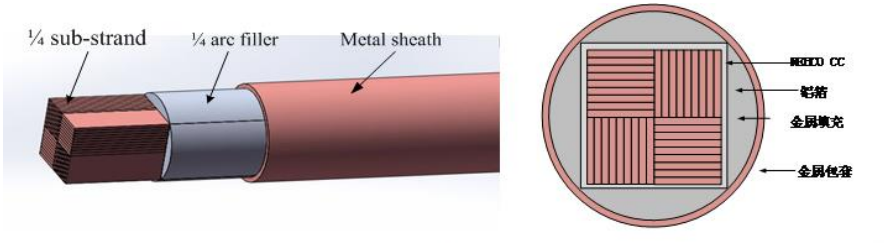




Core technology-Nb3Al



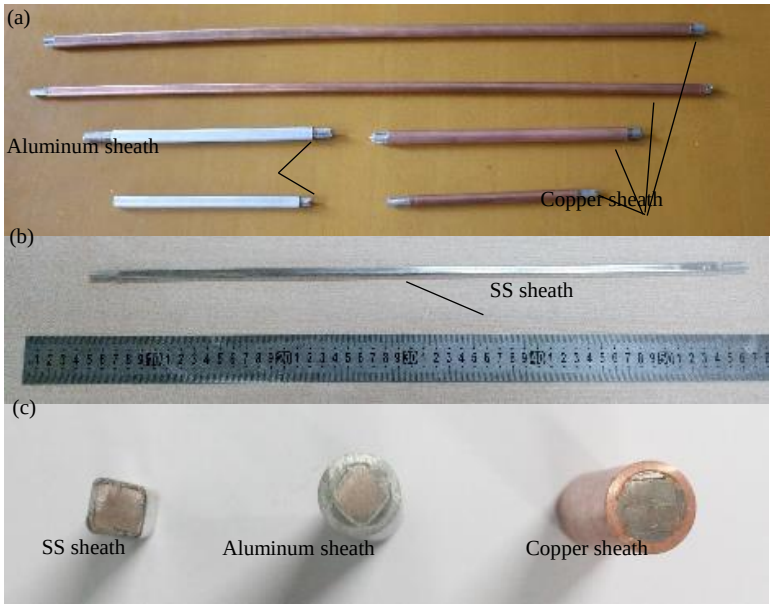
Core technology-YBCO



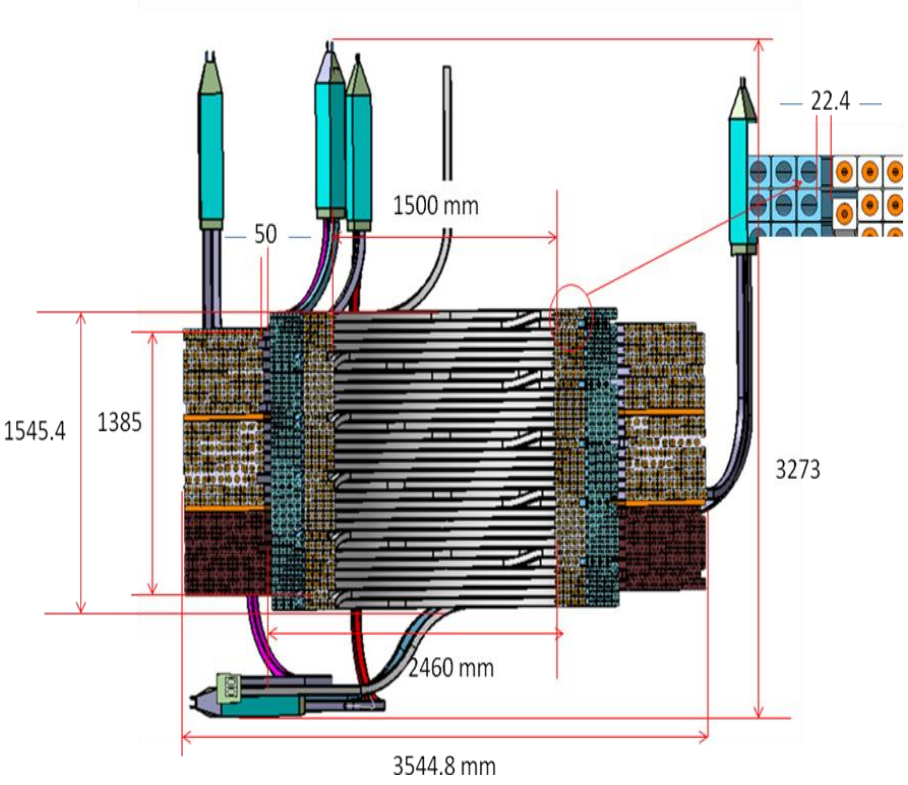
(a) 圆截面

(b)方截面

North China Electric Power University



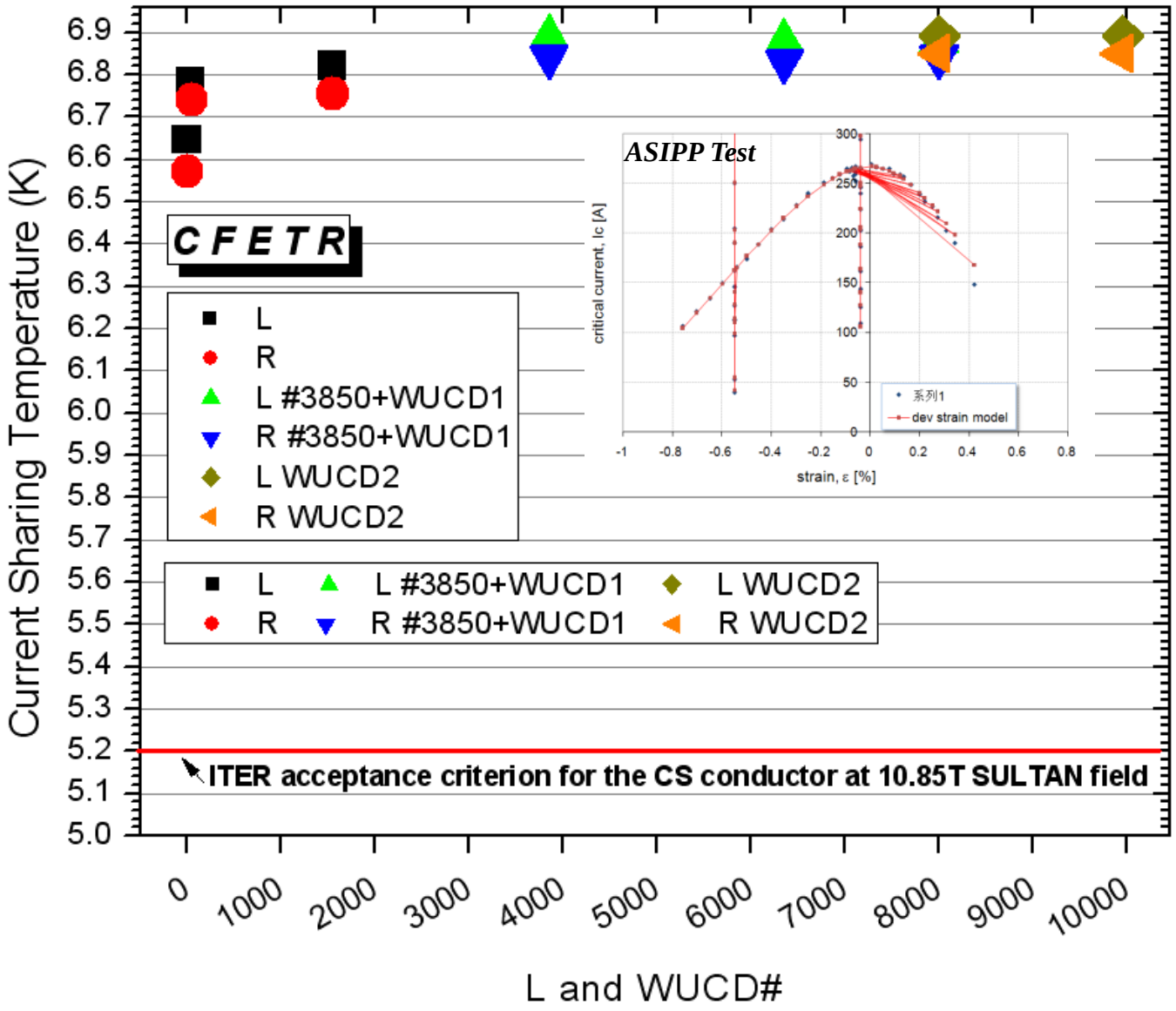
Core technology-CS coil



CFETR CS model coil

	Nb_3Sn Coil		NbTi Coil		
	Inner	Outer	Upper	Middle	Lower
Conductor outer size, square(mm)	49×49	49×49	51.9× 51.9		
Cable diameter(mm)	32.6	32.6	35.3		
Turn/layer insulation thickness (mm)	2.6/2.6	2.6/2.6	2.6/2.6		
Ground Insulation thickness (mm)	3.1	3.1	3.1		
Radial turns	4	4	10		
Axial turns	30	30	8		
Total turns	120	120	80		
Inner radius(mm)	750	976.2	1230		
Outer radius(mm)	953.8	1180	1772.4		
Height (mm)	1545.4	1545.4	433.4		
Conductor length(m)	619.4	782	746	746	739
Conductor weight(kg)	9291	11730	14174	14174	14041
Current (kA)	47.65	47.65	47.65		
B_{max} (T)	12.00	8.42	6.10	5.20	6.10
Total Inductance (H)	359 E-03				

Core technology-CS coil



Contests

Test facility

Superconducting wire testing

Background magnet

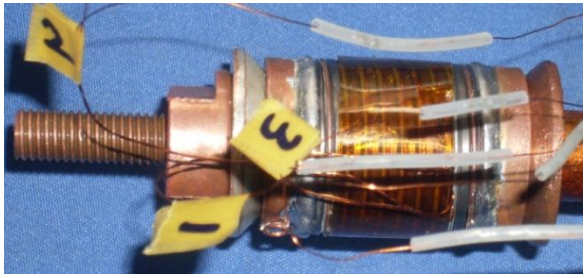
1. Magnetic field : 0-16T
2. diameter : 70cm

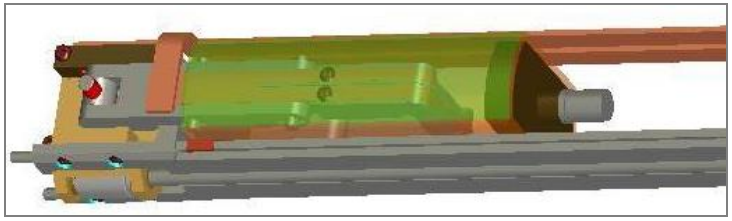
Main testing

1. Ic test at 4.2K -80K
2. Ic test under strain
3. Quencn propagation
4. RRR testing

Superconductor

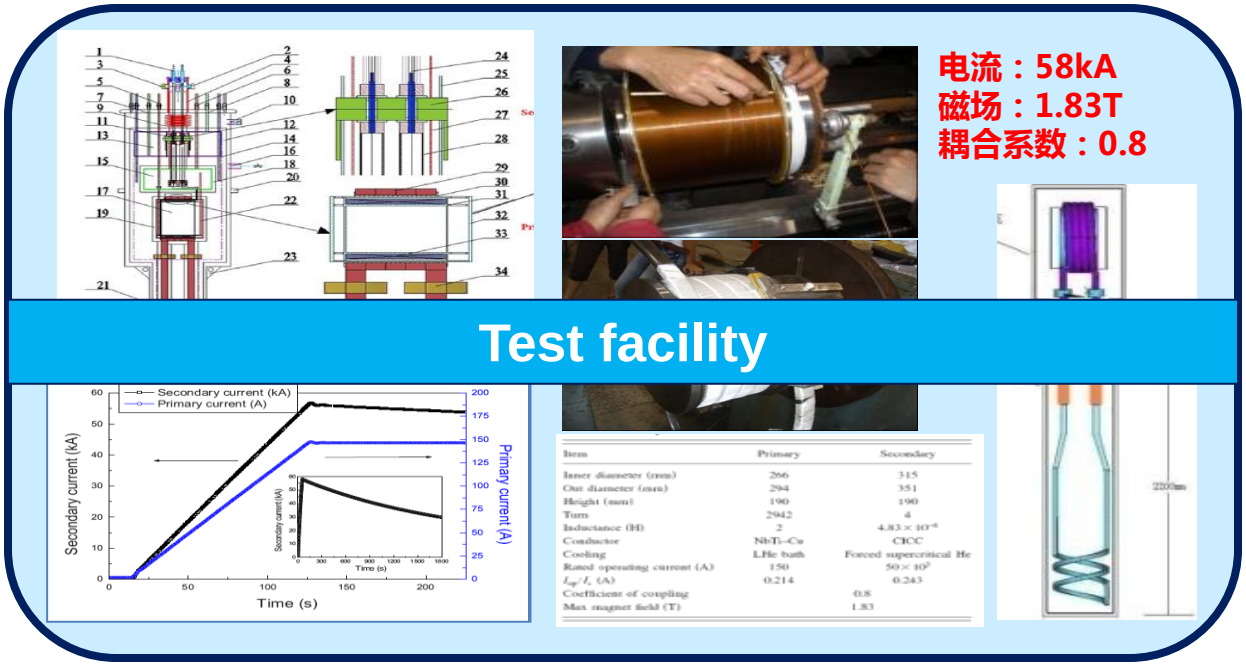
1. NbTi
2. Nb_3Sn
3. Nb3Al
4. MgB2
5. YBCO
6. Bi-2212
7. Fe-based





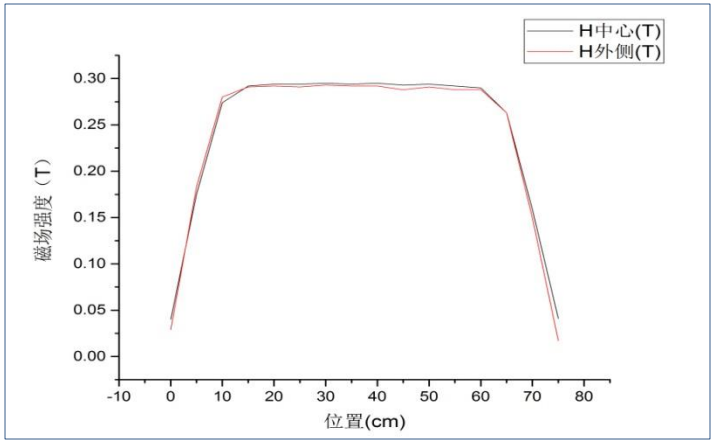
Test facility

Superconducting conductor

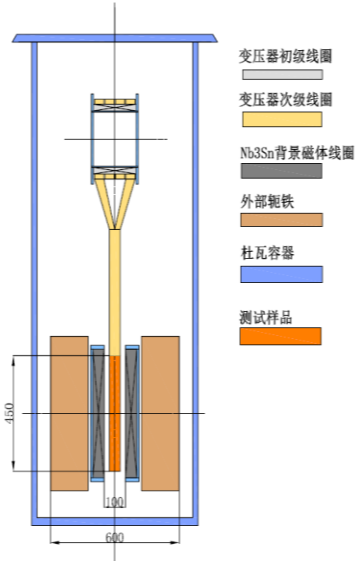


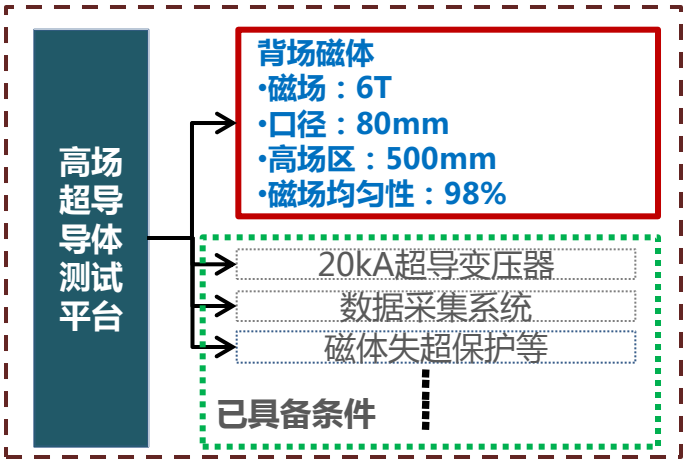
Test facility

Superconducting conductor



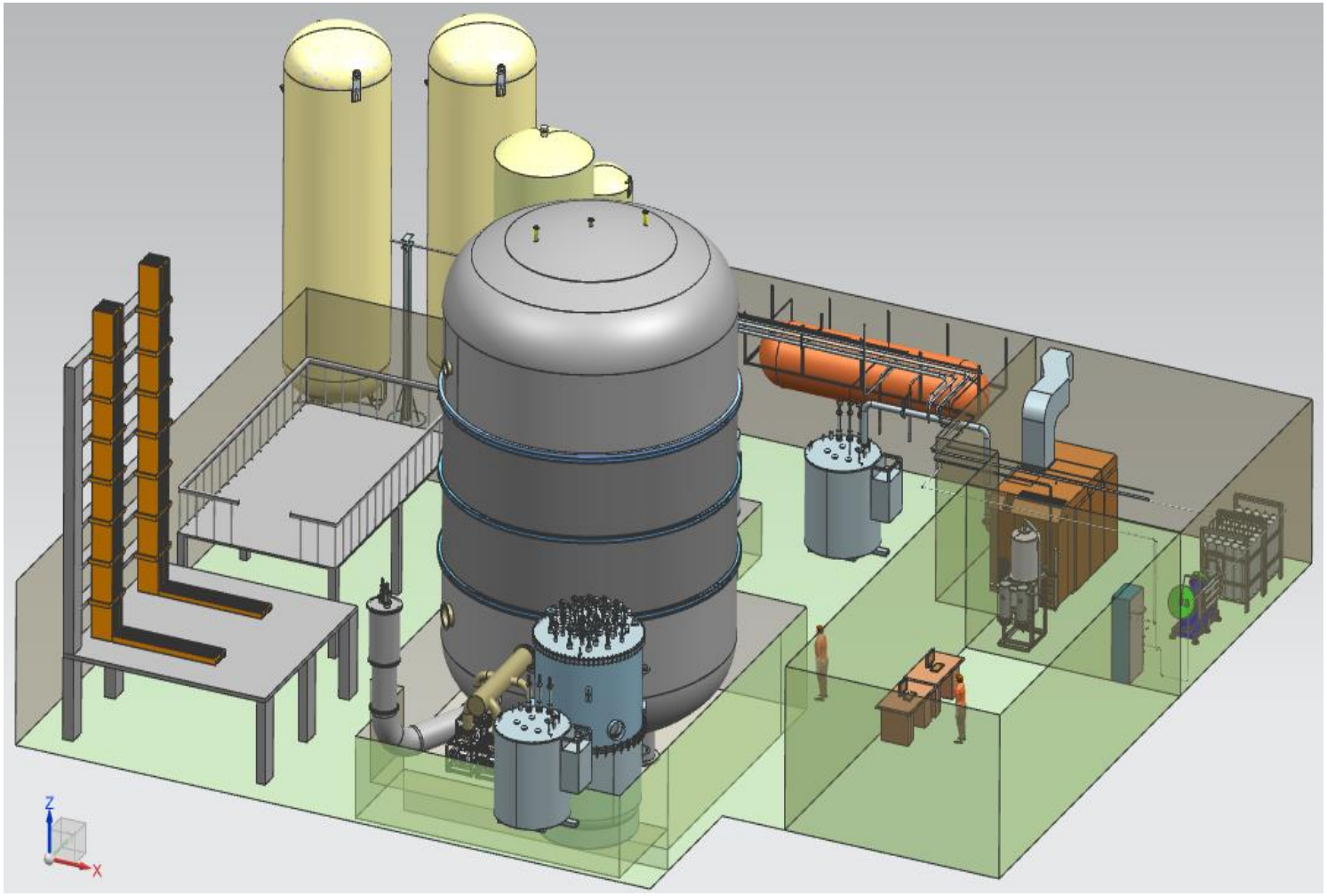
200~600mm磁场均匀度为98.31%，
在150~650mm磁场均匀度为89.15%.





Test facility

Superconducting magnet



谢　　谢！