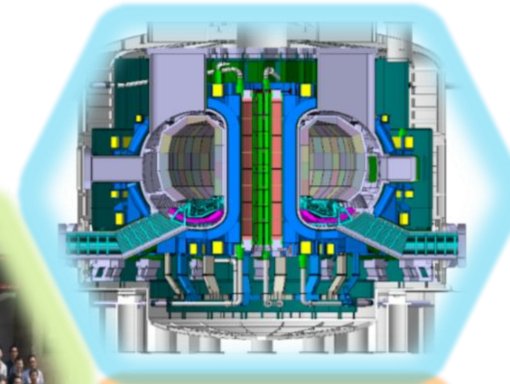
No. WED-OR3-201-02
Jinxing Zheng
jxzheng@ipp.ac.cn



Engineering Design and R&D Work for Toroidal Field Superconducting Magnet of CFETR

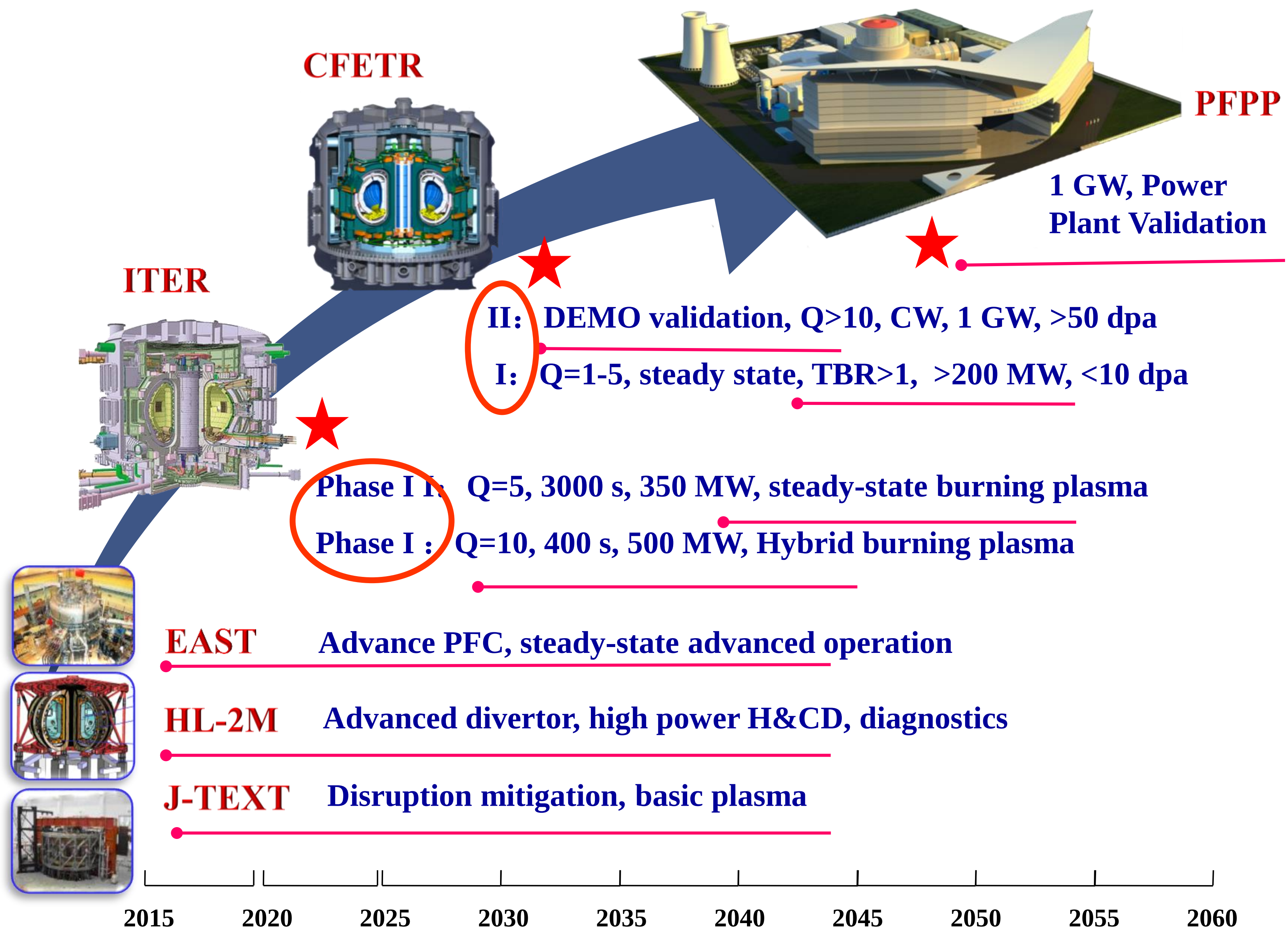
Jinxing Zheng, Xufeng Liu, Yuntao Song, Kun Lu, Guang Shen, Xiaowu Yu, Lei Zhu, Shuangsong Du, Wei Wen, Ming Li, Weiwei Xu, Wuquan Zhang, Xiongyi Huang

Institute of Plasma Physics, Chinese Academy of Sciences

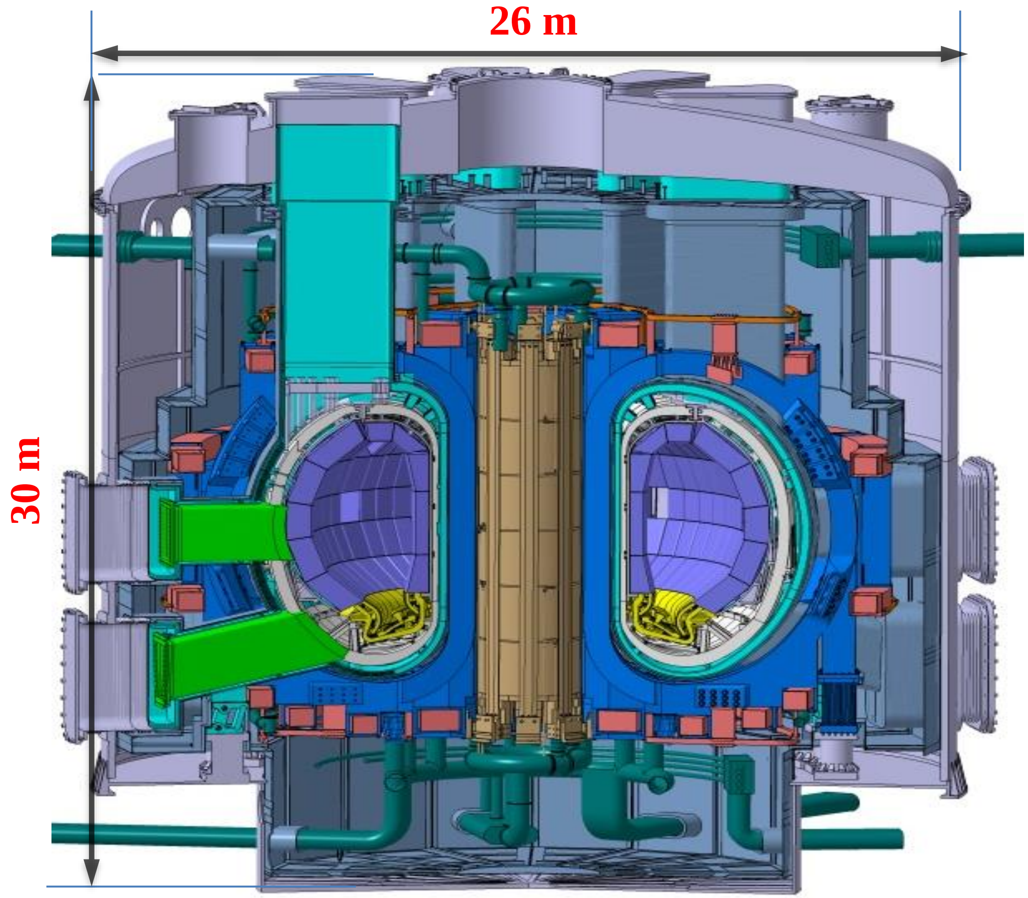
2021-11-17

Contents

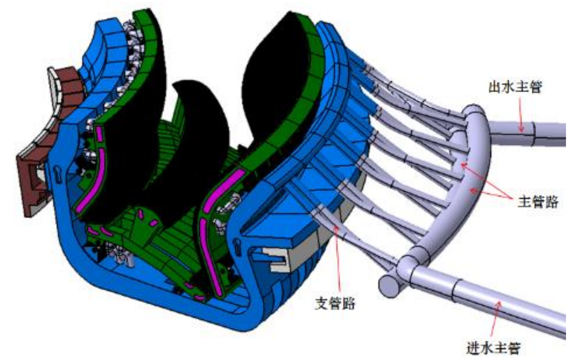
China MCF Roadmap



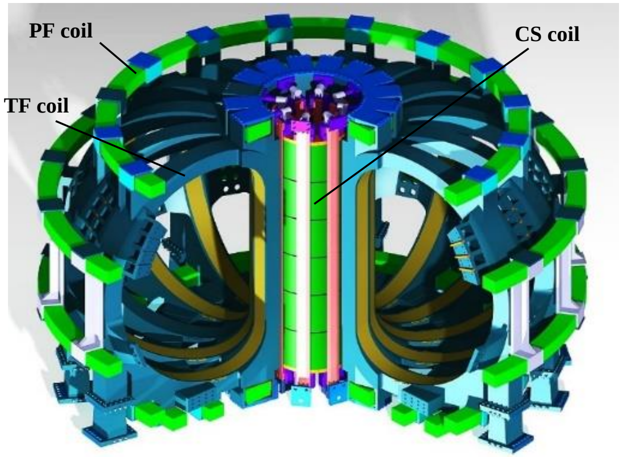
Overview of CFETR



CFETR



Divertor



SC Magnet

- ✓ Plasma Ip=11-15MA, R=7.2 m, B_t=6.5T;
- ✓ Safe and stable, realize long-pulse steady-state operation;
- ✓ Advanced divertor plasma balance type: Snowflake, Super-X and ITER-like.

CRAFT project

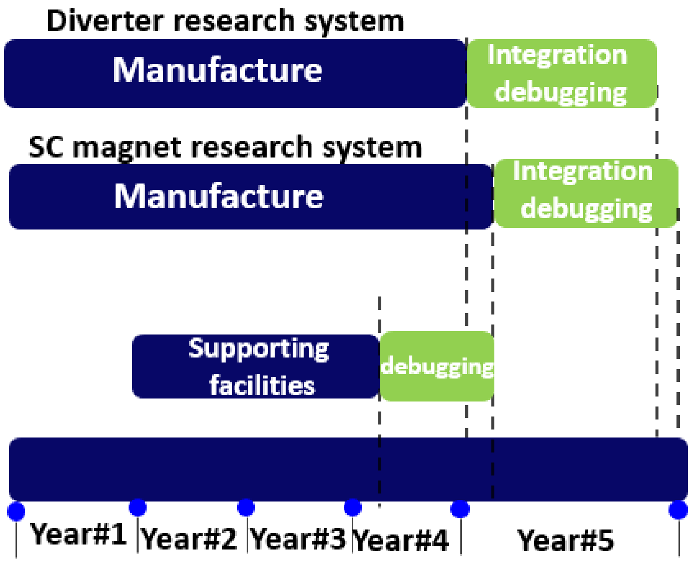
Develop precision manufacturing and testing technology for large magnets

Superconducting magnet research system:

- Magnet test size: D_{max}>13m;
- Magnet energy storage : >2.5GJ;
- Magnetic field: B_{max} =16.5T;
- Test area size: 100 × 160 × 550mm;
- Test current: : I_{max} =90kA,
- Magnetic field change rate: >5 T/s.

Diverter research system:

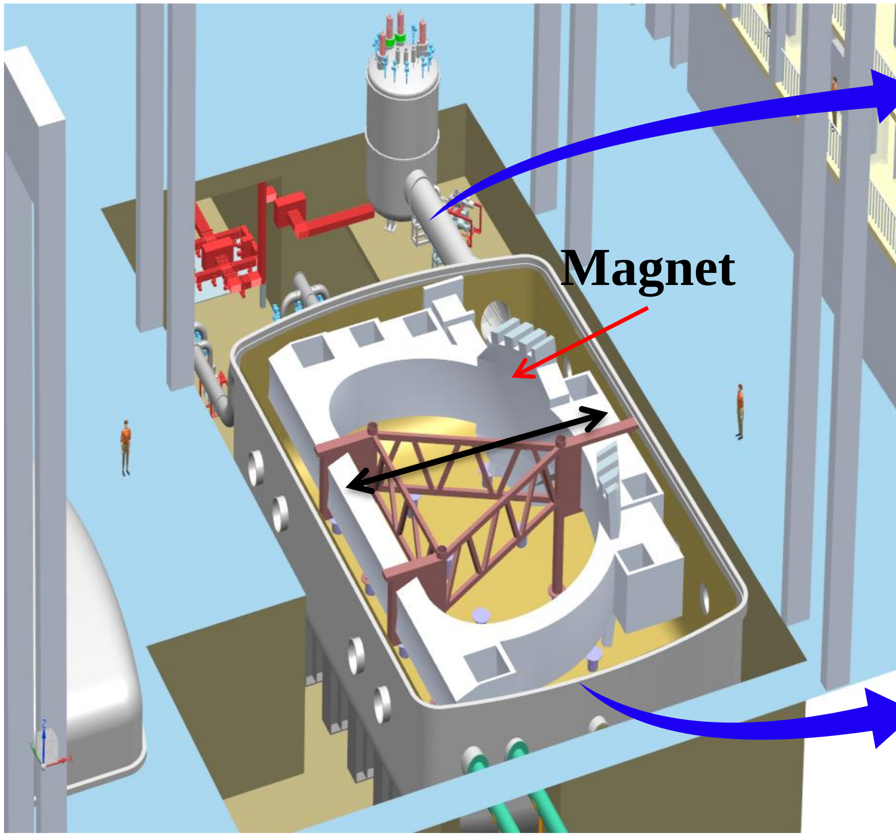
- Maximum particle flow: > $1\times10^{24}/m^2s$;
- Total heating power: 8MW;
- Steady-state heat flow: 20 MW/m^2;
- Plasma existence time: 100-1000s.



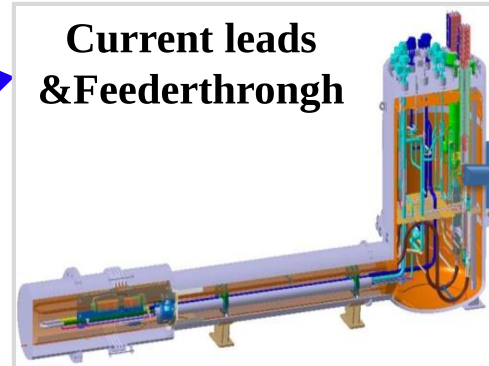
project durations: 5 years and 8 months

CRAFT project

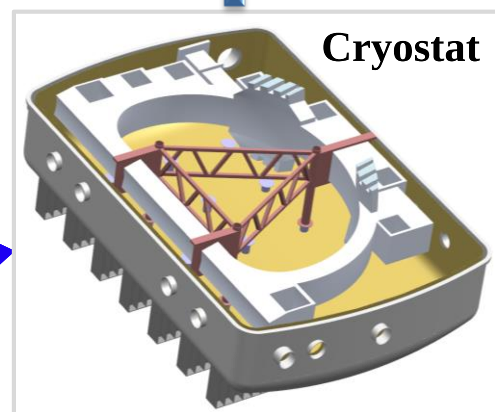
- Experimental research of large-scale superconducting magnet (mechanics, thermo-hydraulic, electromagnetics)
- Evaluation of the magnet performances (safety, stability, reliability)



Large-scale Magnet Performance Research



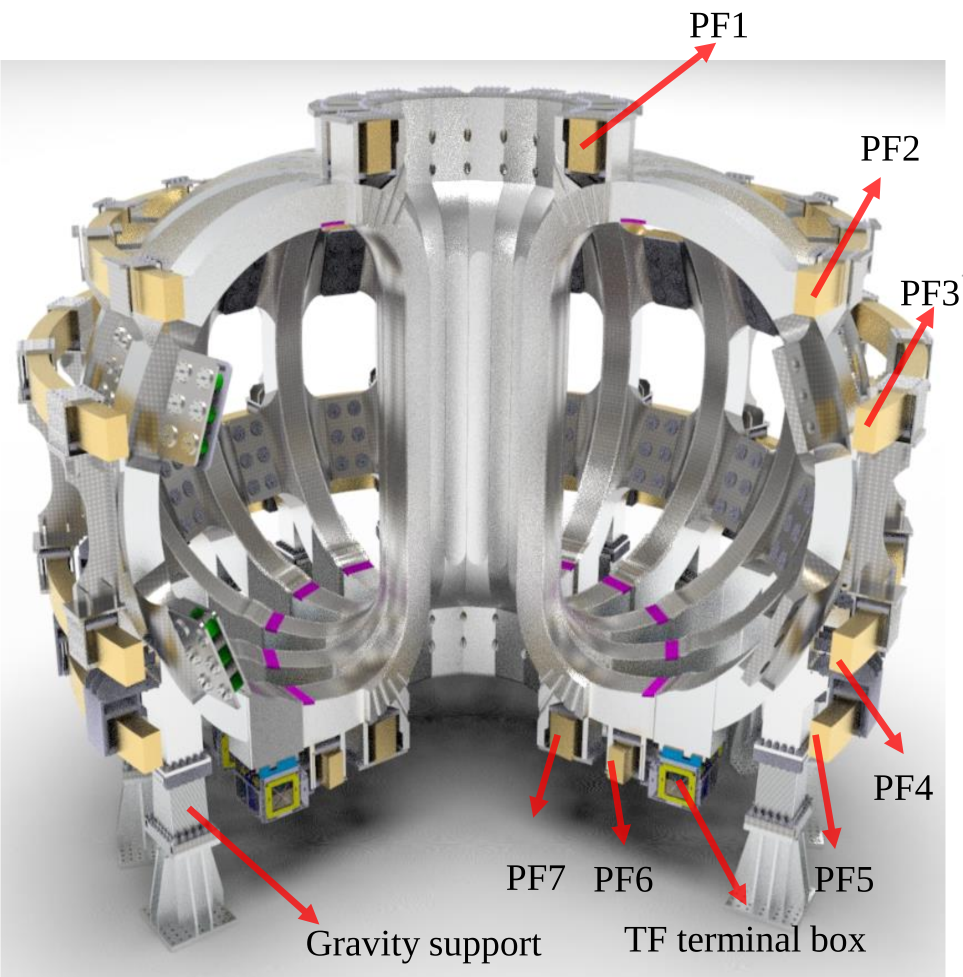
- Quench detection system
- Protection system
- Cryogenic system
- Fast discharge
- Vacuum system



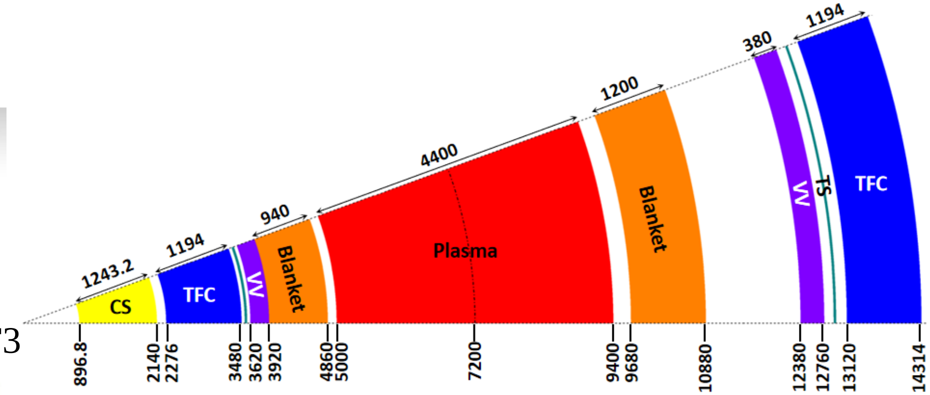
Item	Description
Cryostat main dimension	Length>18.5m Width>14m Height>3m
Operation temperature	4.5K
Current leads operation current	100kA/60kA
SHe pressure	3-6 Bar
SHe massflow	>500 g/s

Contents

Overview of CFETR Magnet system



CFETR superconducting magnet system

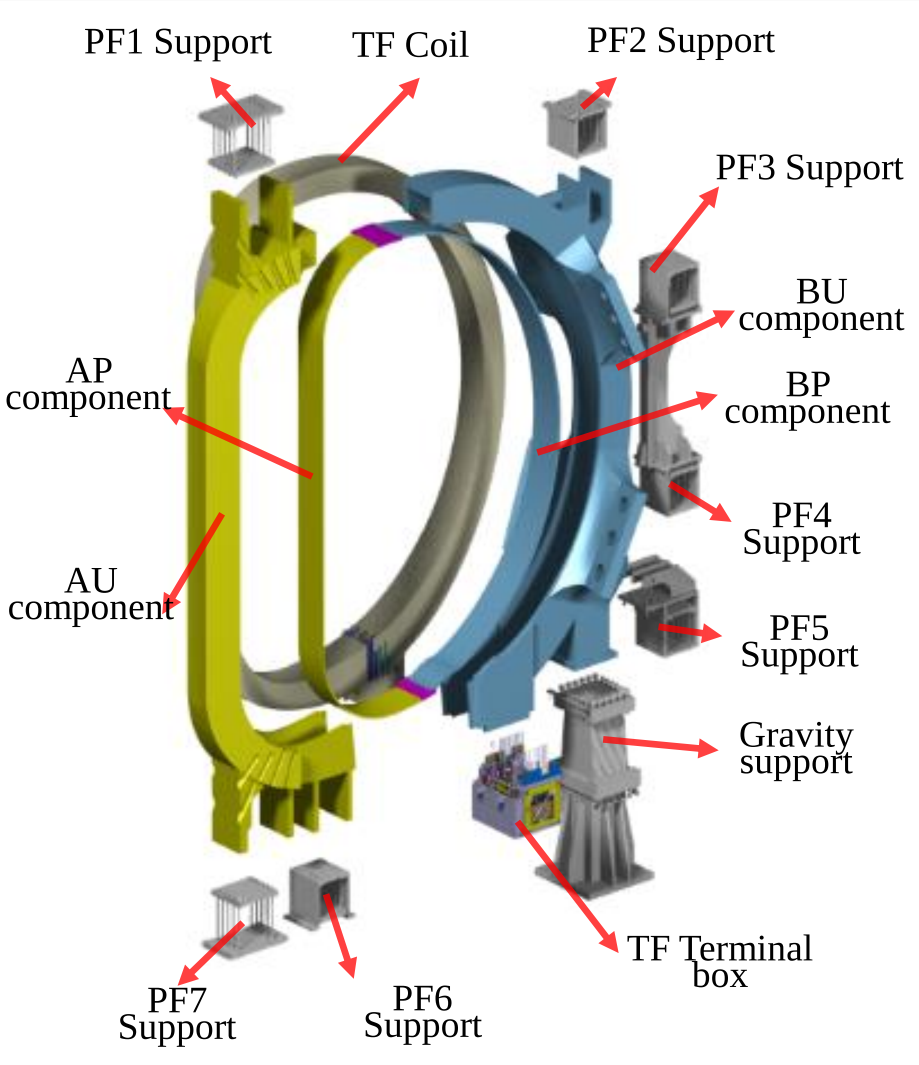


Layout of CFETR in top view

Design parameters

Project	Parameter
Major radius of plasma(m)	7.2
Minor radius of plasma(m)	2.2
Central magnetic field(T)	6.5
Magnetic field ripple in the region of Plasma	0.4%
Ip(MA)	10-15
Height of TF magnet system(m)	25
Width of TF magnet system(m)	16
Height of gravity support (m)	2.5
Botton support height (m)	3.3

Toroidal Field Magnet——Main parameter



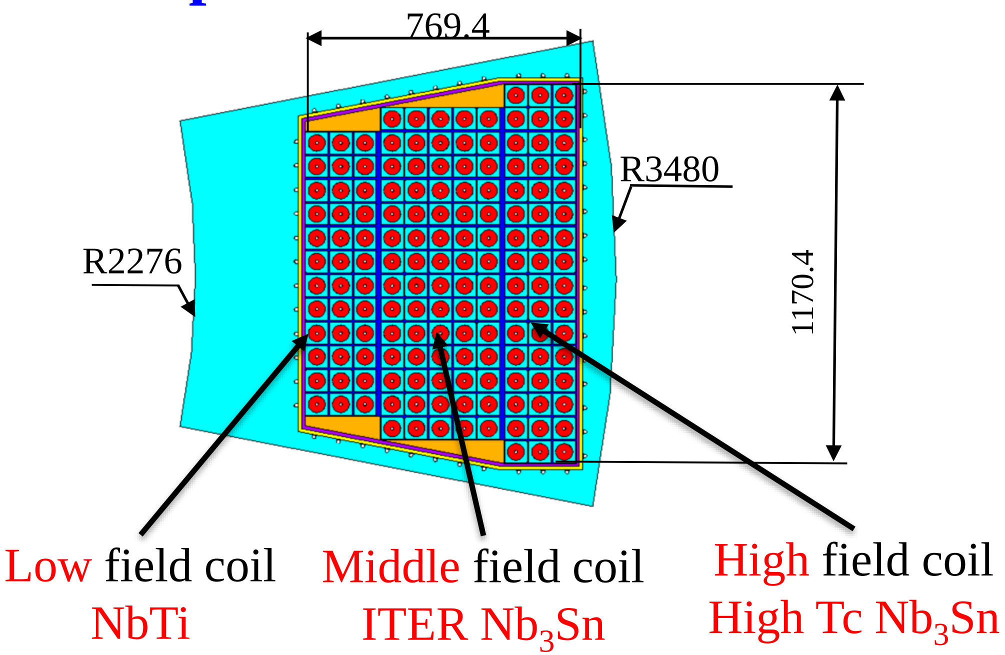
Exploded view of TF Magnet

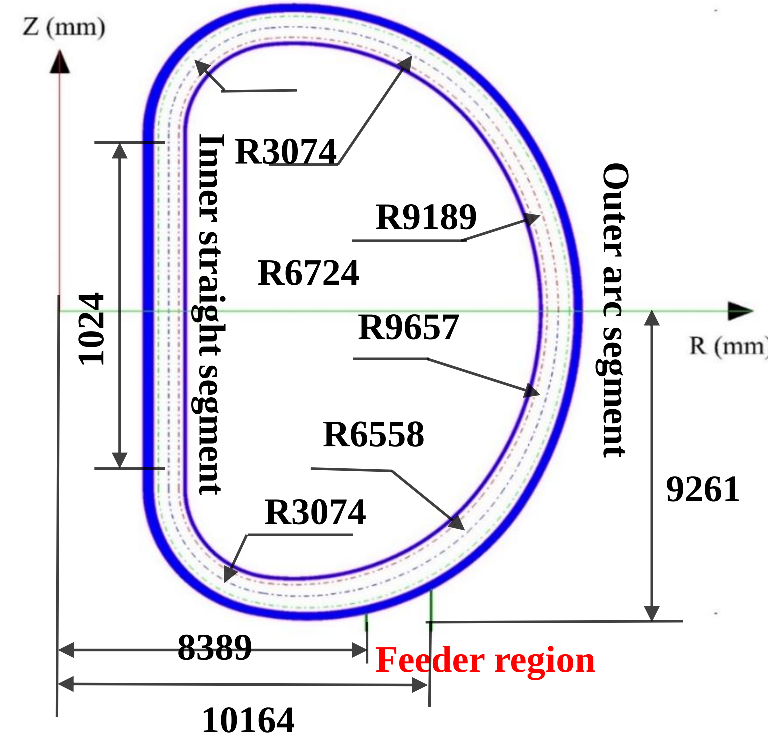
Main parameter of TF magnet

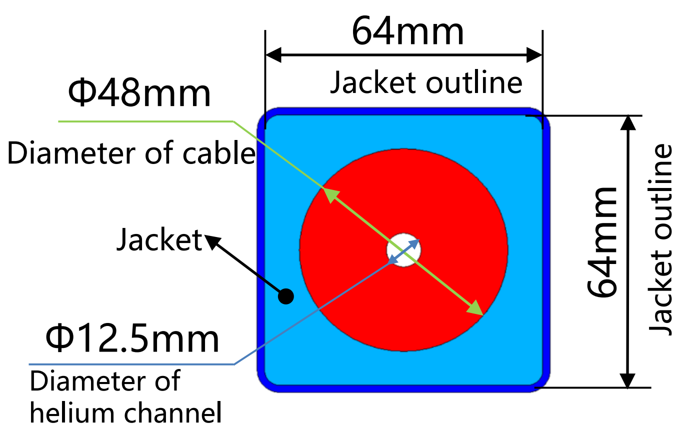
Project	Parameter
Number of TF Magnet	16
Turns of single TF coil	154
Storage energy of 16 TF coil (GJ)	122.2
Operating current (kA)	95.6
Maximum magnetic field (T)	14.5
Length of superconductor (m)	1692/3157/2069
Centripetal force (MN)	1157
Overturning Moment (MN·m))	785
Average length of sub coil in low field region (m)	47
Average length of sub coil in medium field region (m)	45.1
Average length of sub coil in high field region (m)	43.1

TF magnet structure design——Conductor

☐ The parameters of conductors







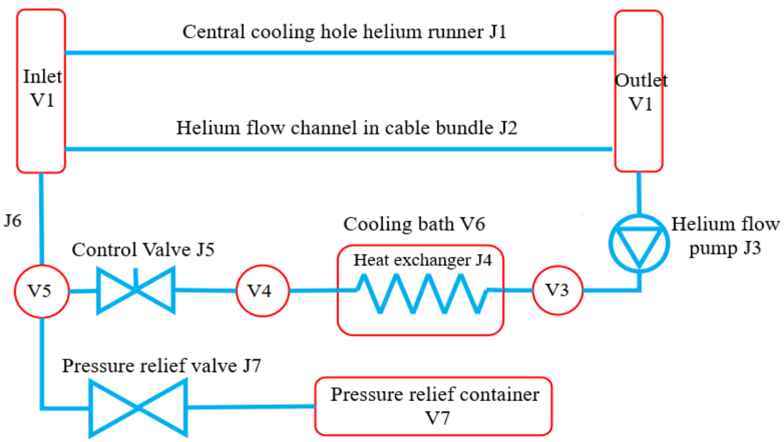
Cross-section size of superconductor

Conductor sample

- **Current: 95.6kA**
- **Low field: 204mm×827mm, 36 turns**
- **Middle field: 341mm×963mm, 70 turns**
- **High field: 204mm×1100mm, 48 turns**

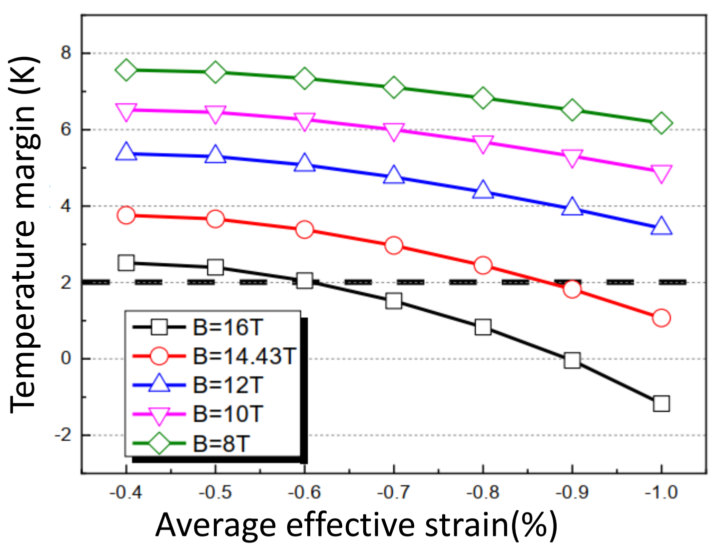
Stability analysis of TF conductor

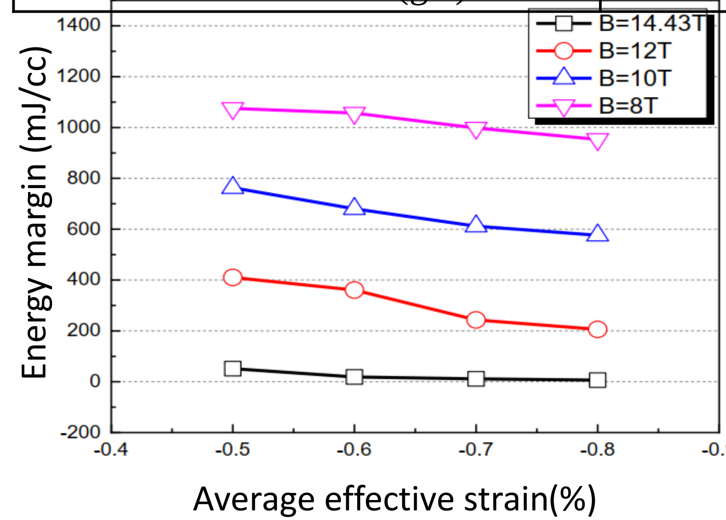
- **Minimum temperature margin is 2.96 K @ 14.43 T and ε=-0.5%~0.7% (ITER Criterion > 2K)**
- **energy margin dropped by 40.39 mJ/cc from ε=-0.5% to ε=-0.7% @14.43T**



Schematic diagram of cryogenic system loop

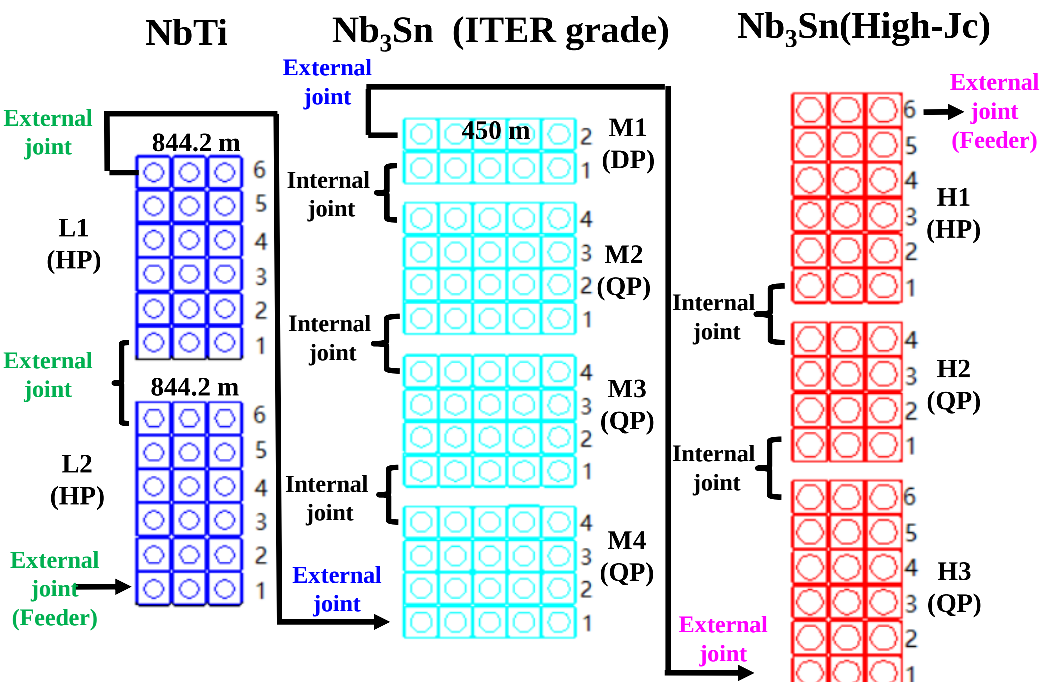
Conductor dimension(mm)	64×64
Number of Cooper strand	900
Number of Nb_3Sn strand	899
Diamater of cooper/Nb3Sn strand	0.9
Void fraction(%)	33.2
Peak magnetic field(T)	14.43
Operating current(kA)	95.6
Initial temperature(K)	4.5
Coolant mass flow rate(g/s)	12.0



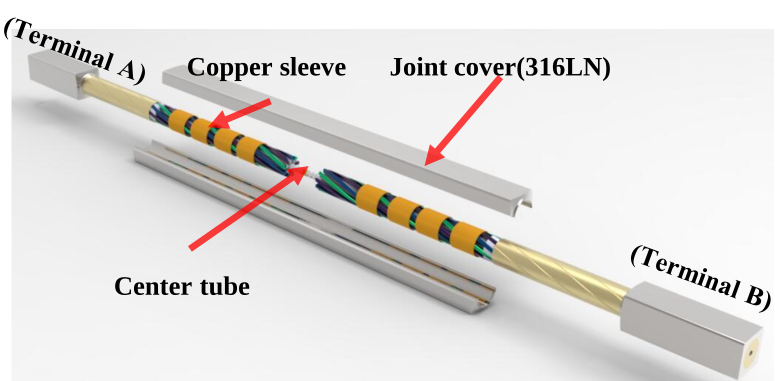


TF magnet structure design——Winding

□Internal joint design of TF coil



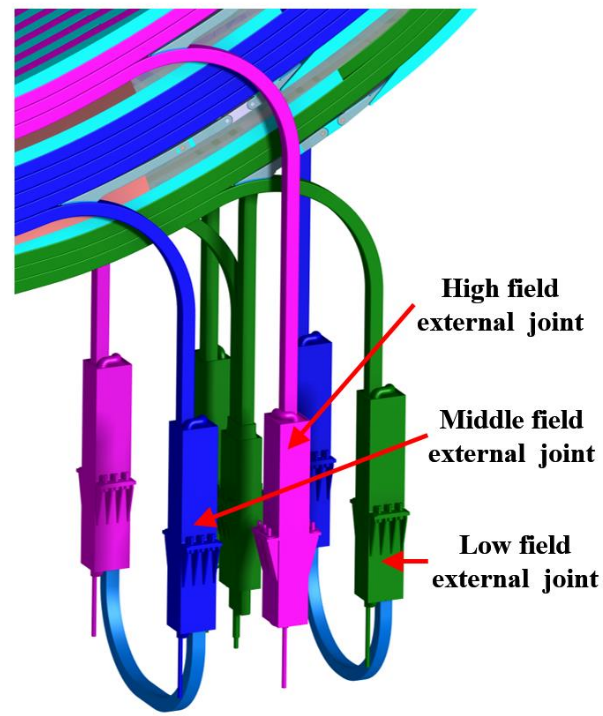
Layout of TF winding pack



Internal joint structure

Internal joints of The TF coil :

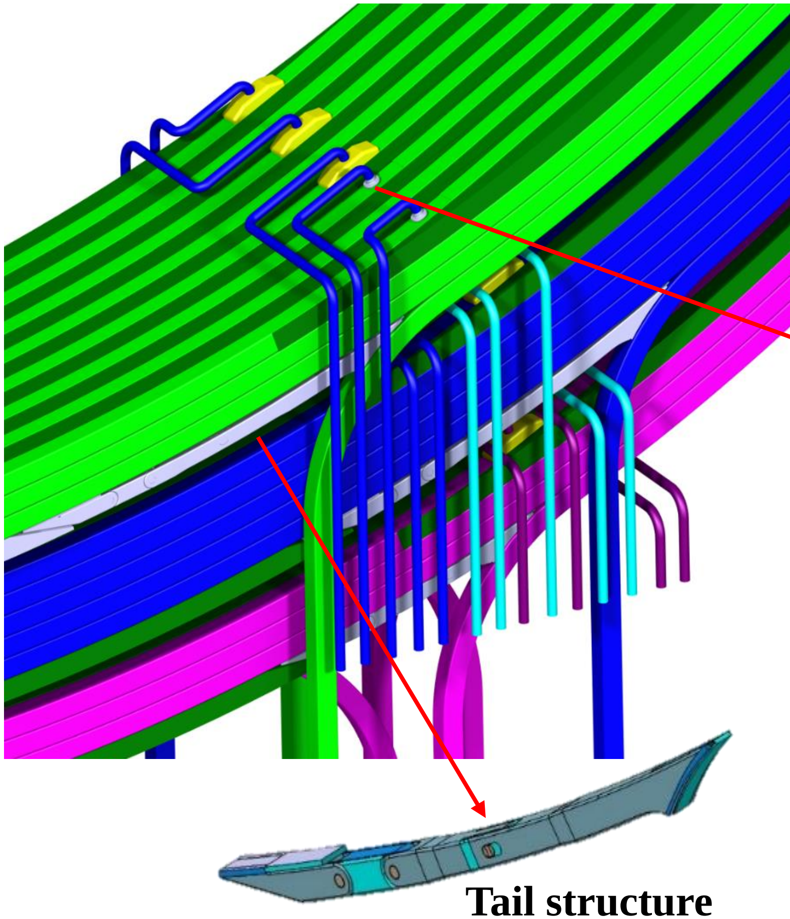
- **Middle field region: 3**
- **High field region: 2**



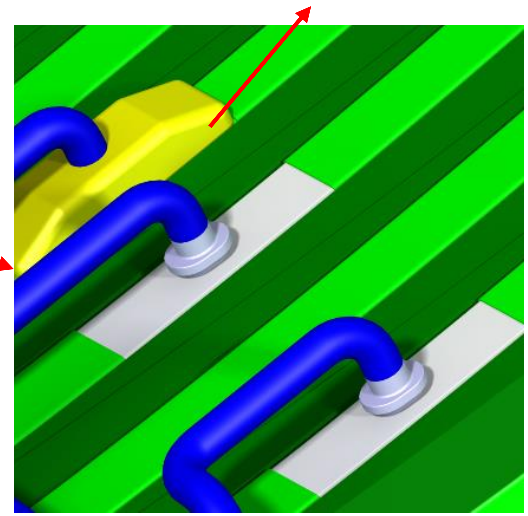
Structure design of external joint of TF coil

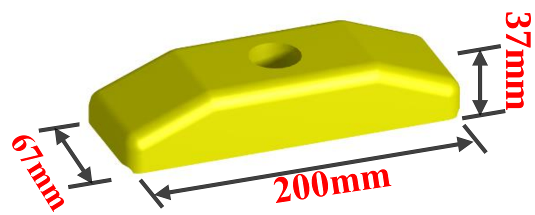
TF magnet structure design——Winding

□Structural design of TF magnet LH2 joint

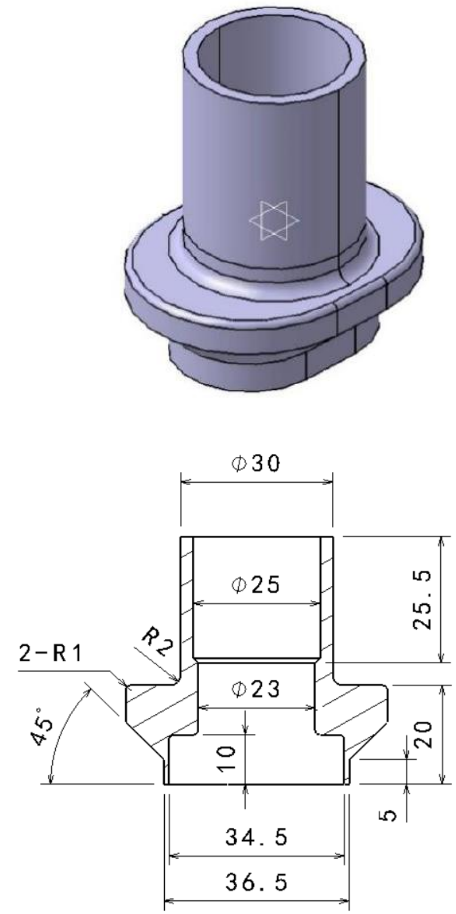


Schematic diagram of helium inlet and outlet



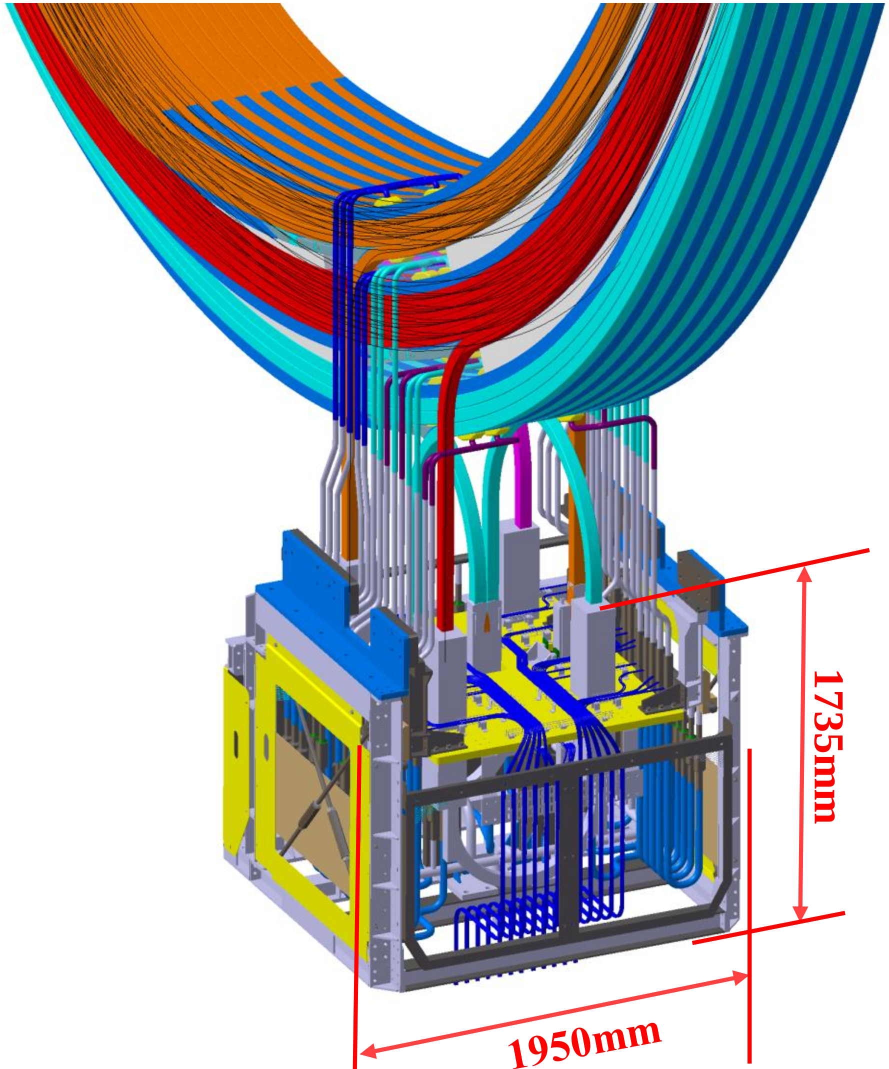


Insulation dimensions of liquid helium joints

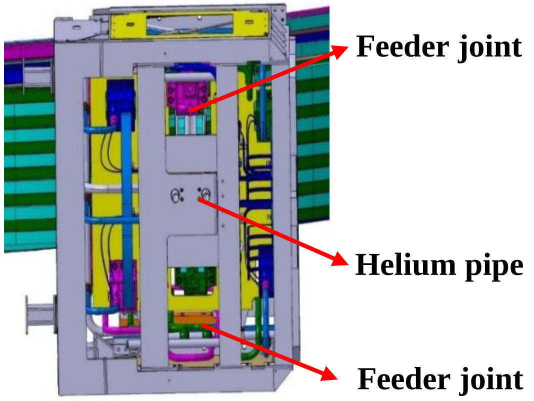


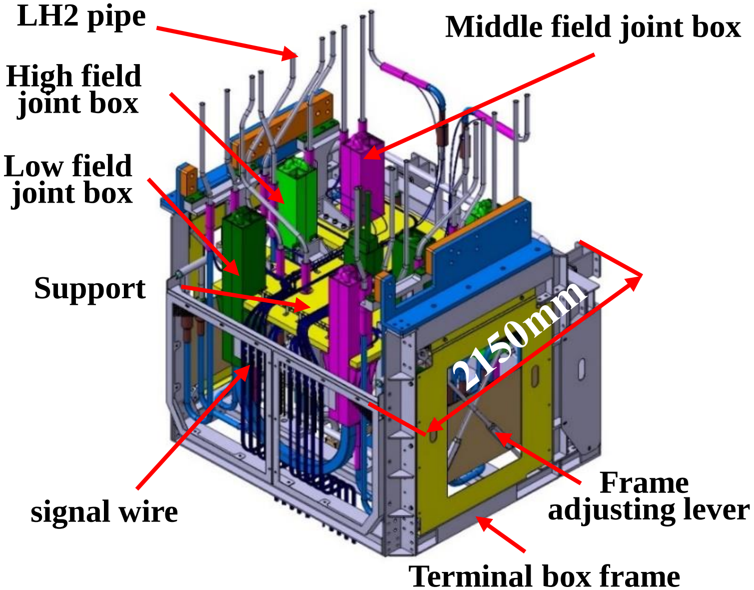
helium pipe design

Structure Design of TF Coil Terminal Box



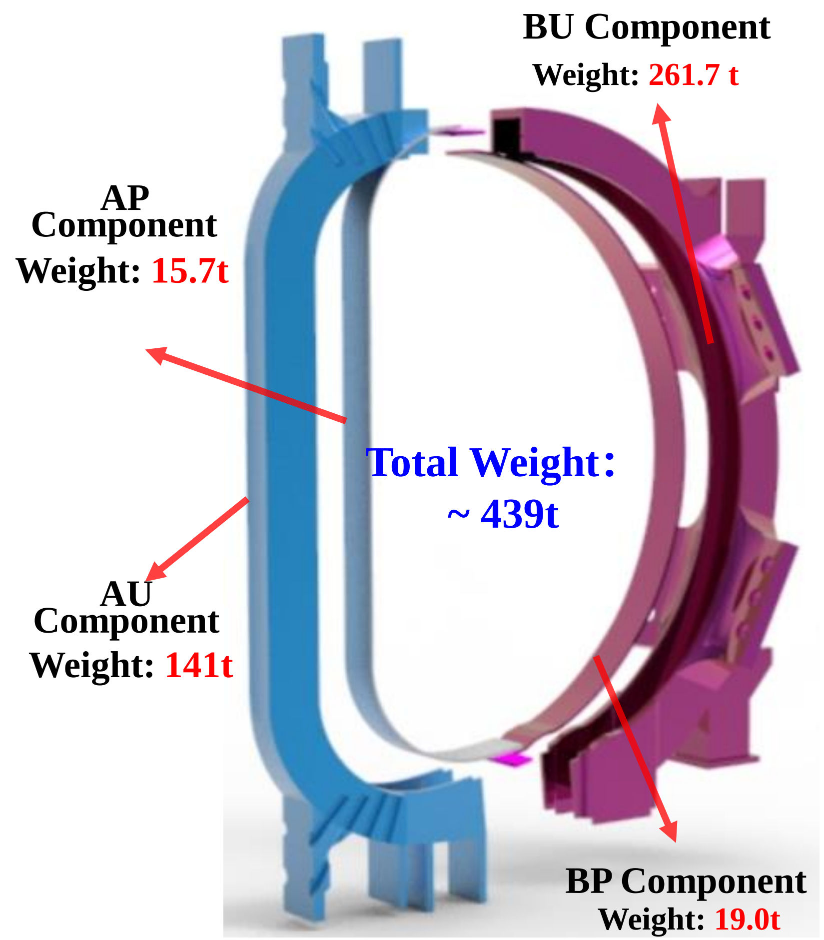
Structure design of terminal box



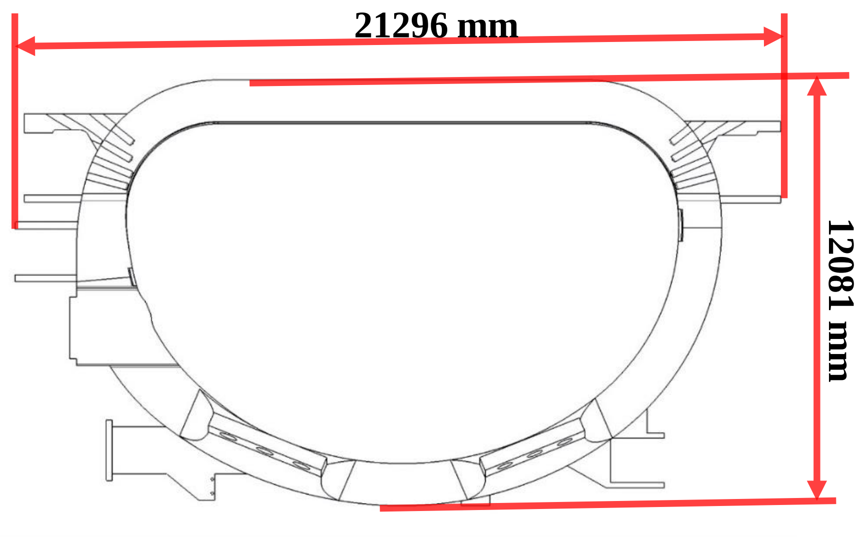


TF magnet structure design——Coil Case

Structure design of TF coil case



TF coil case structure

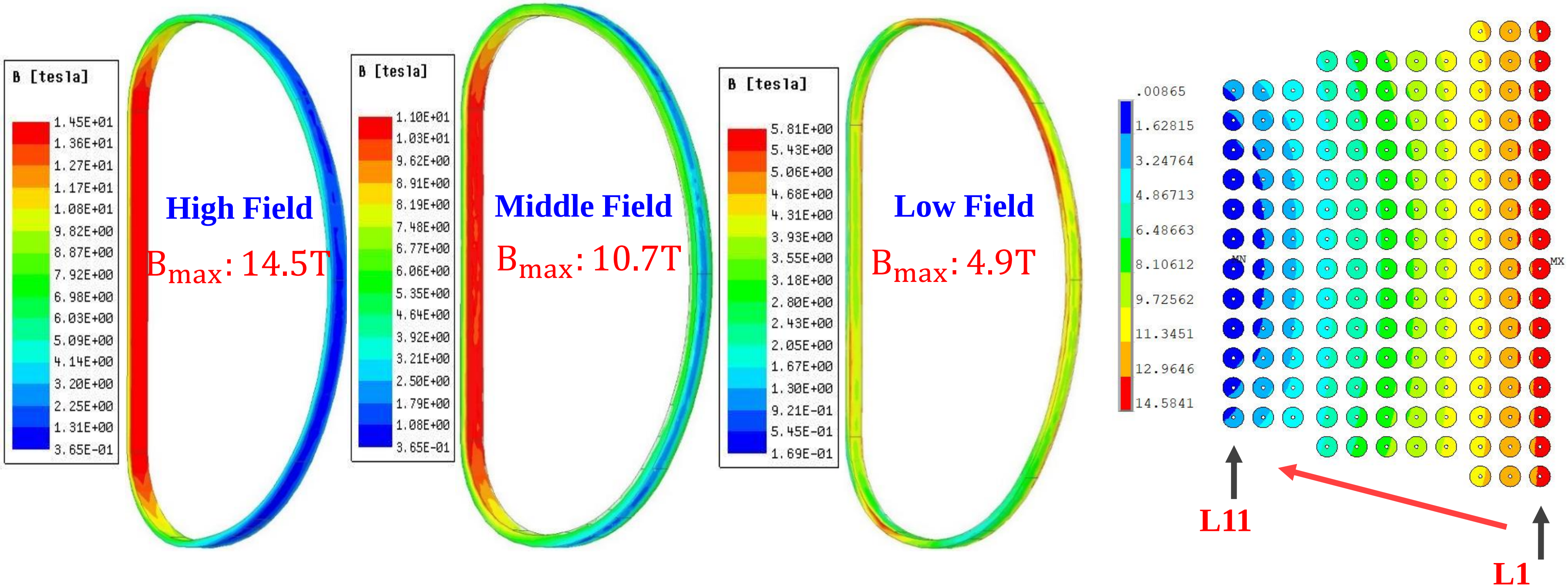


TF coil case outline size

TF material			
Component	Material	Yield strength (MPa)	Tensile Strength (MPa)
AU	316LN-Mn	>1000	>1500
AP	316LN	>900	/
BU	316L	750	1000
BP	/	>500	/

Electromagnetic Analysis of TF Magnet

☐ Electromagnetic analysis



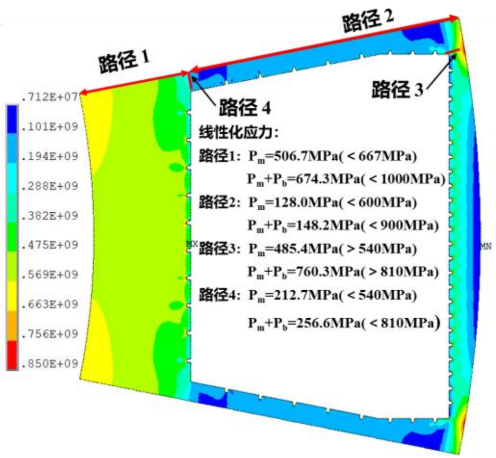
	High Field			Middle Field					Low Field		
	Nb_3Sn(ITER grade)			Nb_3Sn(High-Jc)					NbTi		
Layer	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
B_{max}(T)	14.5	13.2	11.8	10.7	9.8	8.8	7.6	6.3	4.9	3.9	2.8
Turns	16	16	16	14	14	14	14	14	12	12	12

TF magnet structure analysis——2D analysis

□Stress of Coil Case/Jacket/Insulation

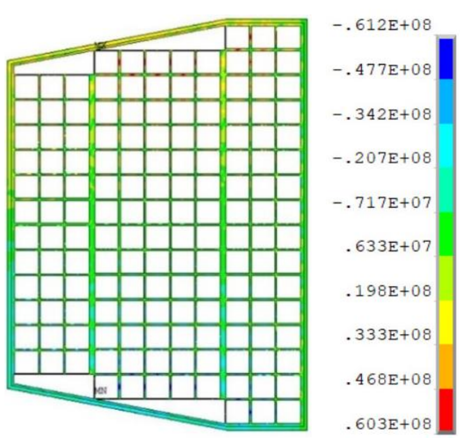
Path/Jacket(Mpa)	P_m	ITER P_m	Allowable P_m	P_m+P_b	ITER P_m+P_b	Allowable P_m +P_b
Path 1	506.7	515	667	674.3	661	1000
Path 3	485.4	468	540	760.3	663	810
Jacket	469.8	585	667	826.6	645	1000

Insulation shear stress （MPa)	Model stress	ITER Stress	Allowable stress
Packing layer	39.8	/	41.6
Ground insulation	41.2	28.6	68.6
Insulation between turns/cakes/double cakes/layers	61.2	40	68.6



Jacket stress

The coil case, jacket, and insulation stress meet the allowable stress requirements

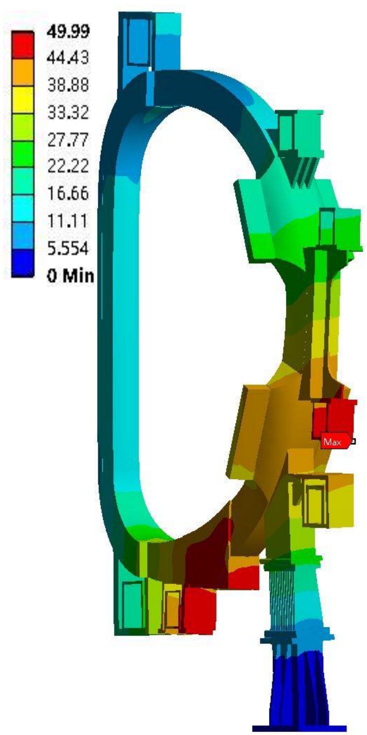


Insulation stress

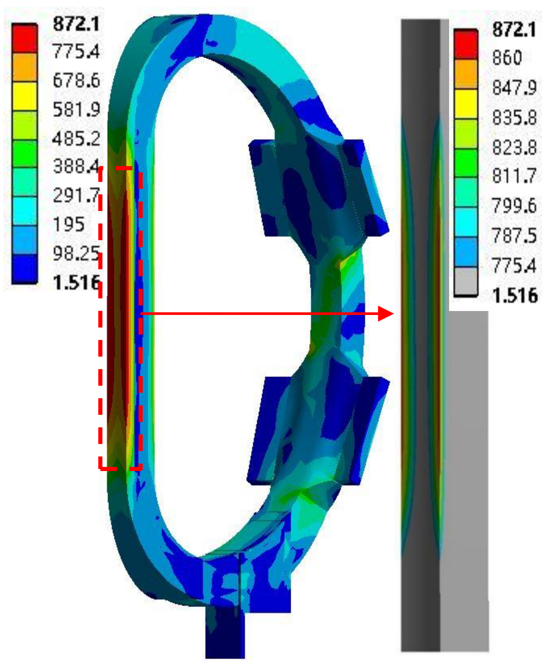
TF magnet structure analysis——3D analysis

□Structural analysis (Cooling & electromagnetic force coupling)

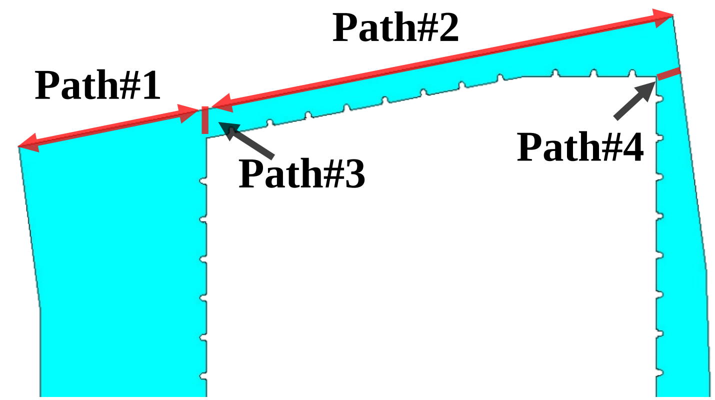
- The maximum deformation is 50 mm, the maximum stress is 872.1 MPa
- Referring to the ITER design criteria, TF magnet stress meets allowable stress requirements



Total deformation



Stress distribution
(EM force & cooling)



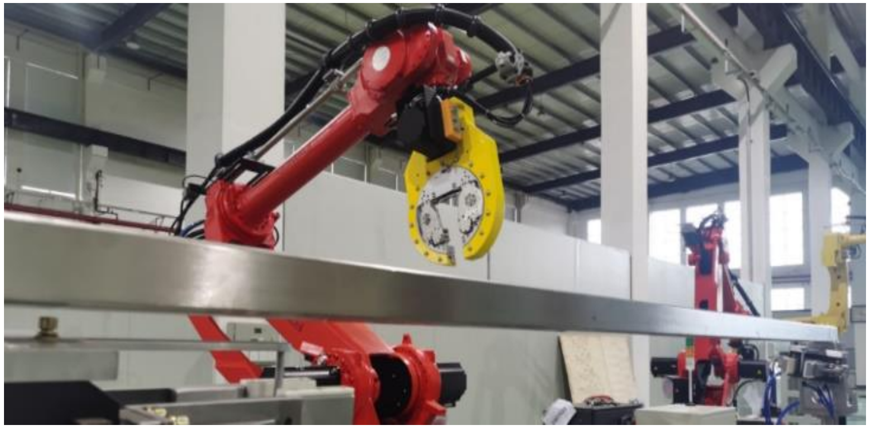
3D stress analysis results（MPa）				
Path	**P_m**	**Allowable P_m**	**P_m+P_b**	Allowable P_m +P_b
Path 1	605.2	667	870.7	1000
Path 2	387.4	600	634.0	900
Path 3	492.9	540	521.4	810
Path 4	211.5	540	232.1	810

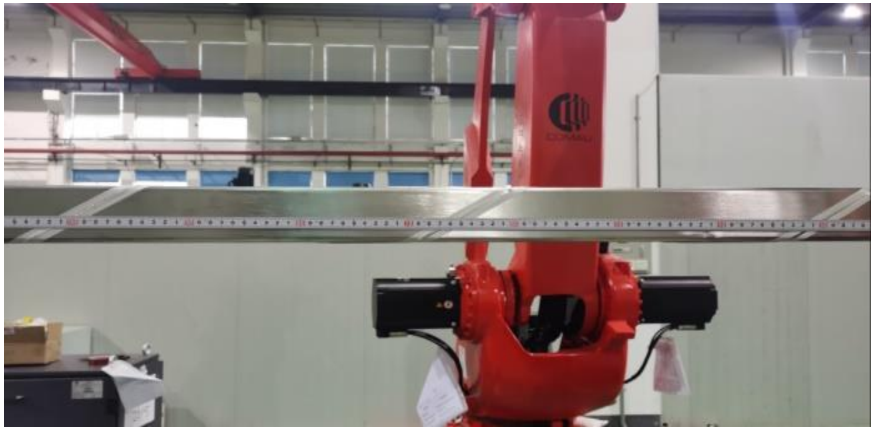
Contents

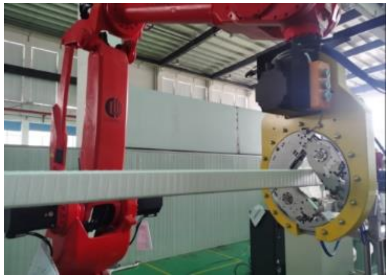
Progress of TF prototype magnet

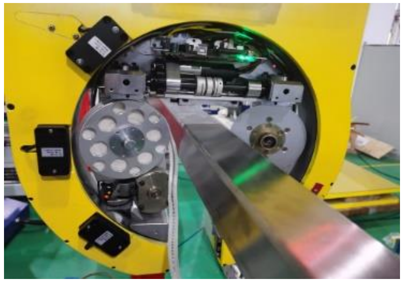
□ TF magnet inter-turn insulation wrapping test

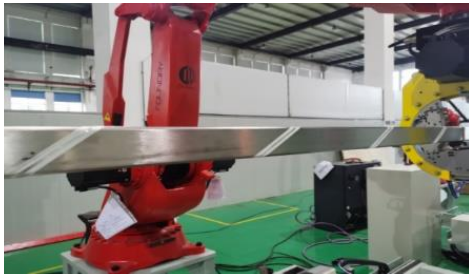
- Utilize 65×65mm stainless steel tube and robot wrapping machine to simulate glass ribbon half-stacking and quench detection belt automatic wrapping
- **Realizing uniform wrapping pitch**, which provides a test basis for the next step









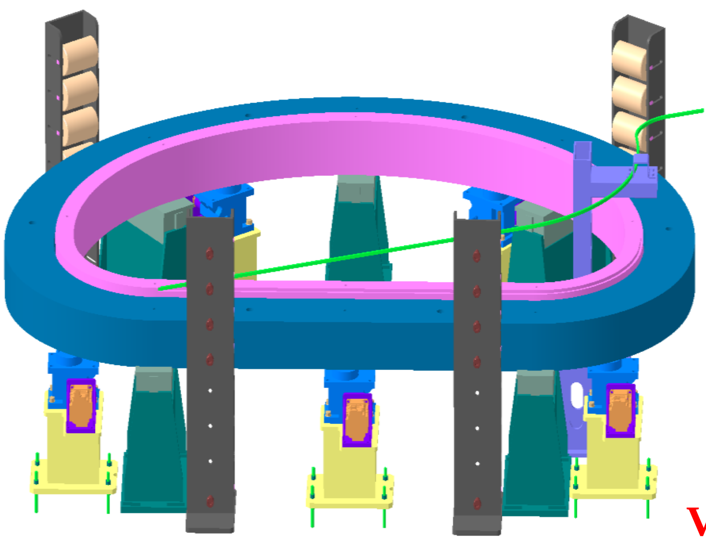


The glass ribbon and quench detection tape are evenly wrapped!

Progress of TF prototype magnet

□ TF magnet sub-coil assembly test

- **Test platform was built**: manufacture 1/4 ratio of medium & high field coil to carry out research on the process of magnet assembly;
- **Process flow of TF coil assembly was built**: the whole process test of the sub-coil assembly has been completed



Assembly system design

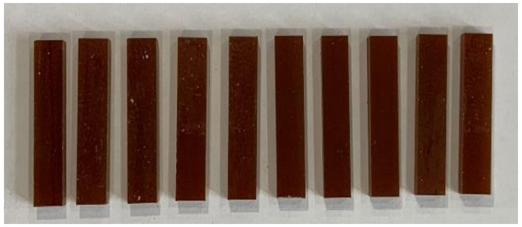
Verify the feasibility of sub-coil assembly and coil hoisting fixture design

Progress of TF prototype magnet

◻ TF Insulation material certification

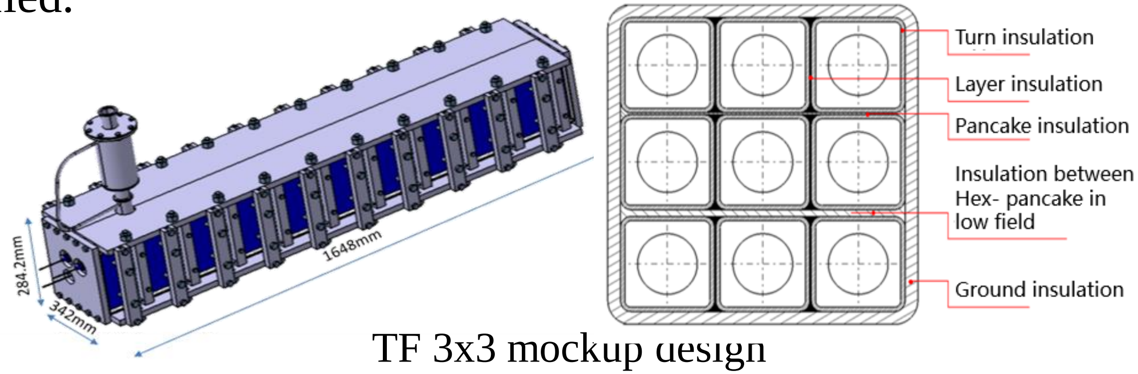
- **Turn insulation:** Polyimide tape "Kapton HN" and Fiberglass tape are used and all test results meet the design requirements
- **TF VPI process**: 3×3 mockup short sample. electrical performance of the turn insulation and the ground insulation are verified.

UTS (90/0 degree)_ASTM D 638

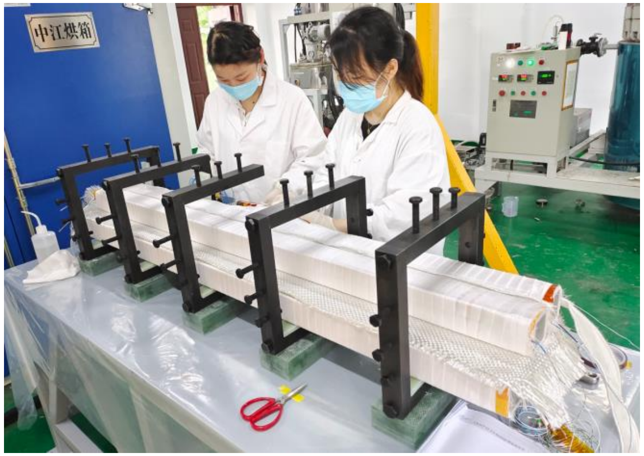


ILSS (90/0 degree) _ASTM D2344

ITEM	ITER TF (MPa)	CRAFT TF (Mpa)
UTS - 0°	750	750 （1060） *
UTS- 90°	350	350 （366） *
ILSS- 0°	80	80 （108） *
ILSS- 90°	65	65 （80） *



TF 3x3 mockup design

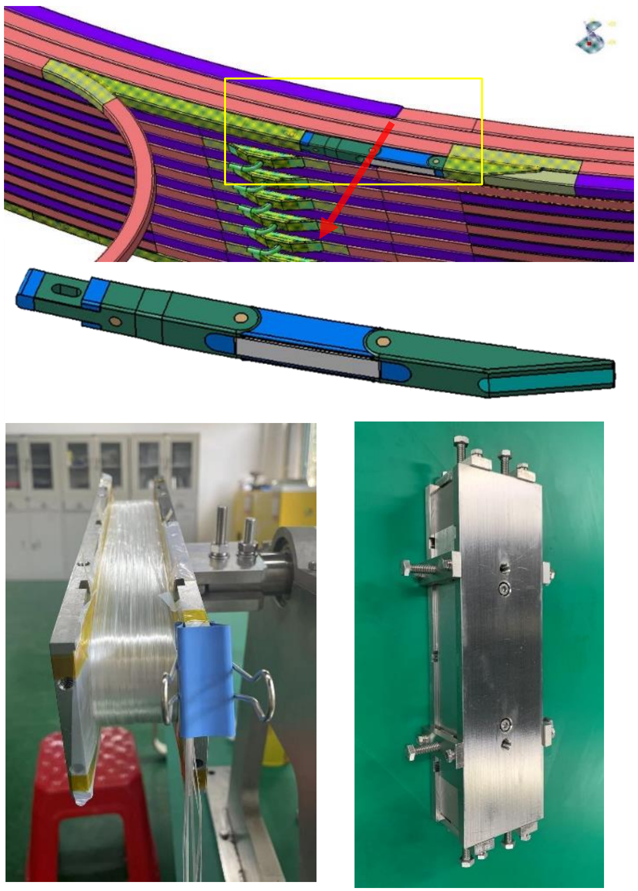


TF 3x3 mockup fabrication

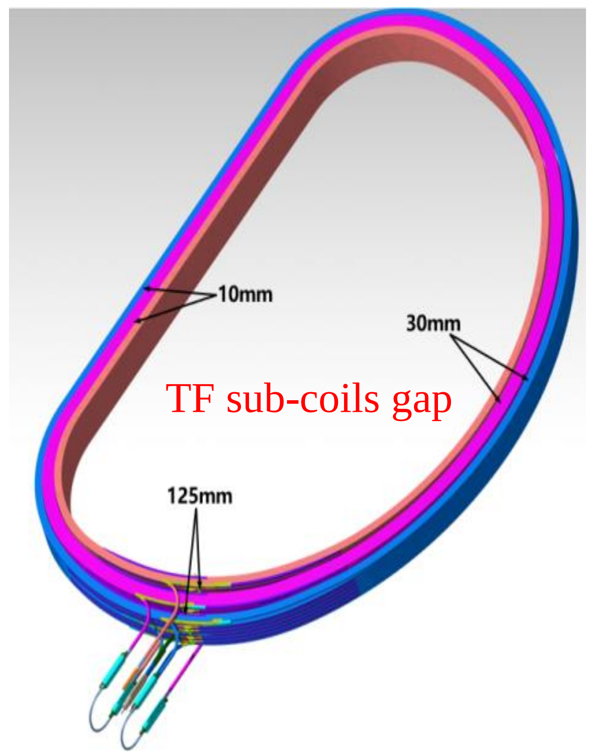
Progress of TF prototype magnet

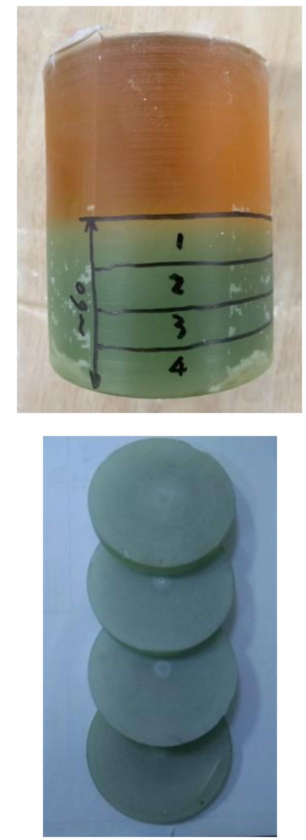
☐ TF Insulation material certification

- **TF Tail Strap:** Designed and prepared by VPI process, verify the cryogenic mechanical performance.
- **TF sub-coils gap filling materials qualification:** 10mm-125mm gap, use inorganic powder to fill the gap



TF Tail Strap





Resin/inorganic micropowder composite material samples

Progress of TF prototype magnet

☐ TF magnet internal joint

- manufacture cable joint;
- **superconducting sub-cable end welding and joint braiding process is verified**

Superconducting cable inspection

Sub-cable end welding

Center solenoid removal

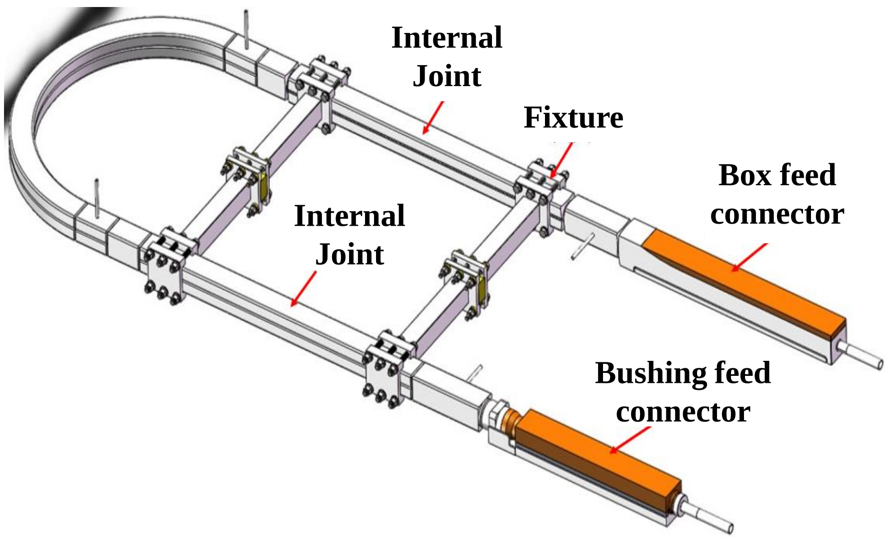
Central cooling pipe installation

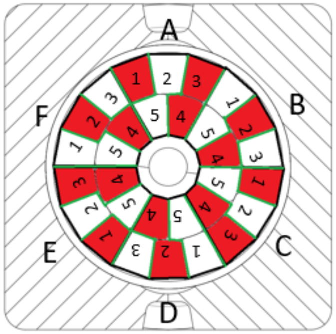
Sub-cable braiding

Progress of TF prototype magnet

□ TF magnet internal joint

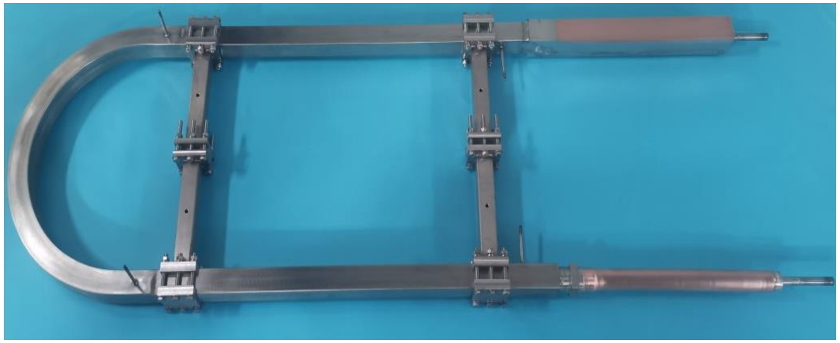
- ➢ Completed **the production of the test sample** of the internal joint of the TF conductor
- ➢ Completed **heat treatment** and low temperature **electrical performance test**.



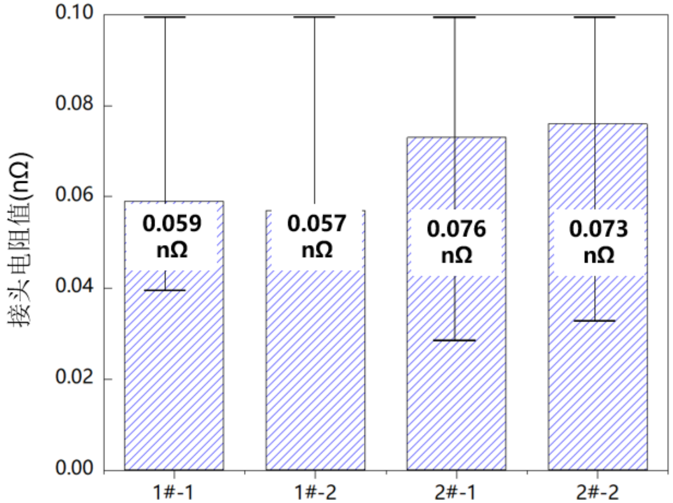


Schematic diagram of section

Section of short sample



Zero field test sample of internal joint of TF

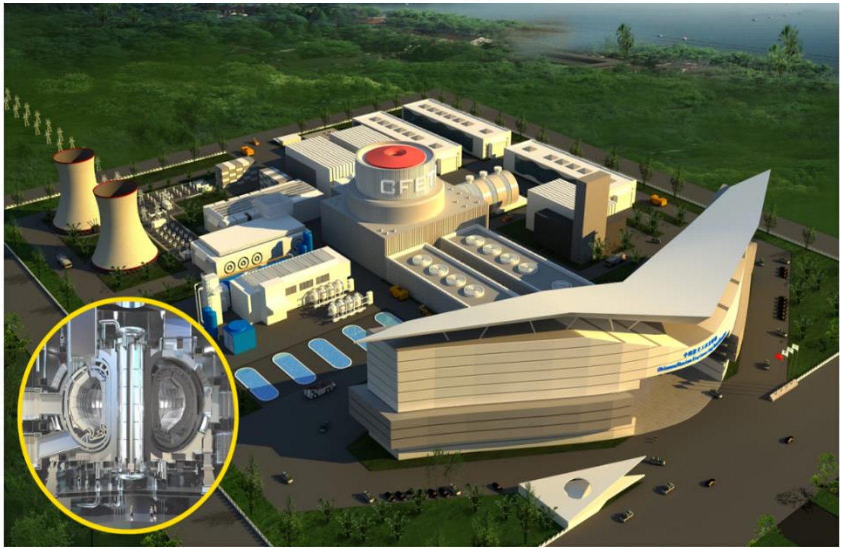


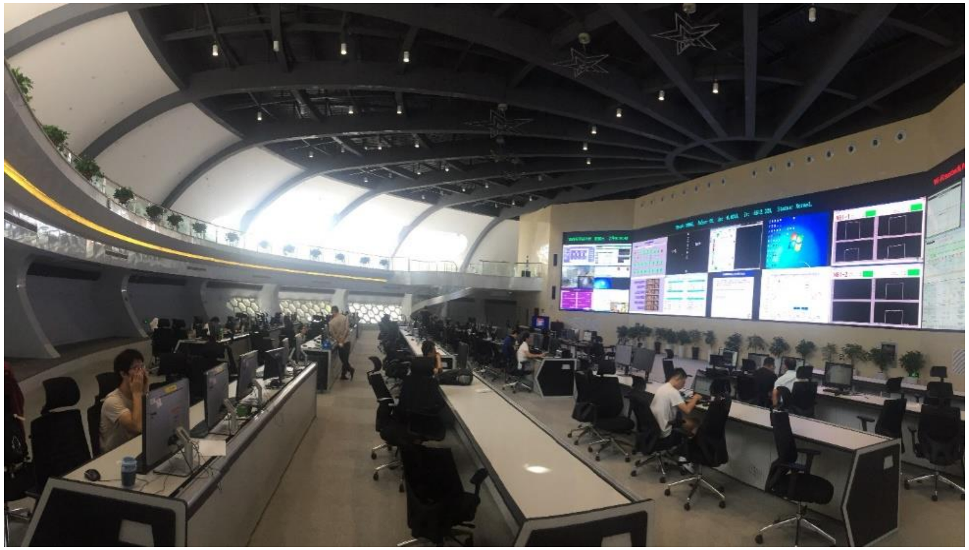
DC resistance in the interlayer joints

Contents

Conclusion

- CFETR TF adopts a hybrid magnet design (NbTi + Nb_3Sn(ITER grade) + Nb_3Sn(High-Jc)). $B_{max} = 14.5T$; $I_A = 95.6kA$; $B_{Center} = 6.5T@7.2m$;
- The engineering design of the TF magnet system (including windings, joints, coil boxes, etc.) has been completed. $\sigma_{max} = 872.1MPa$ (Under EM force & cooling).
- Completed the development of core prototypes such as insulation, sub-coil assembly, internal joints, etc.





Sincerely welcome all experts and teachers for cooperation!

Thank you!