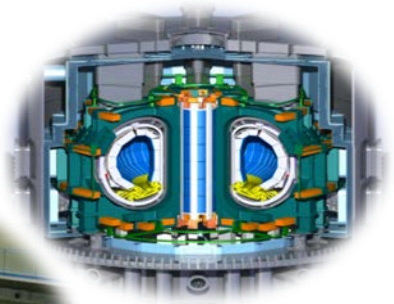
中国科学院等离子体物理研究所
Institute of Plasma Physics, CAS



Research status on superconducting Magnet system of CFETR project in ASIPP

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Introduction of ASIPP

Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) was founded in Sep. 1978 in Hefei, Anhui Province for the purpose of the peaceful utilization of the fusion energy by the magnetic confinement technology based on the tokamak approach.

Main Research Activities:

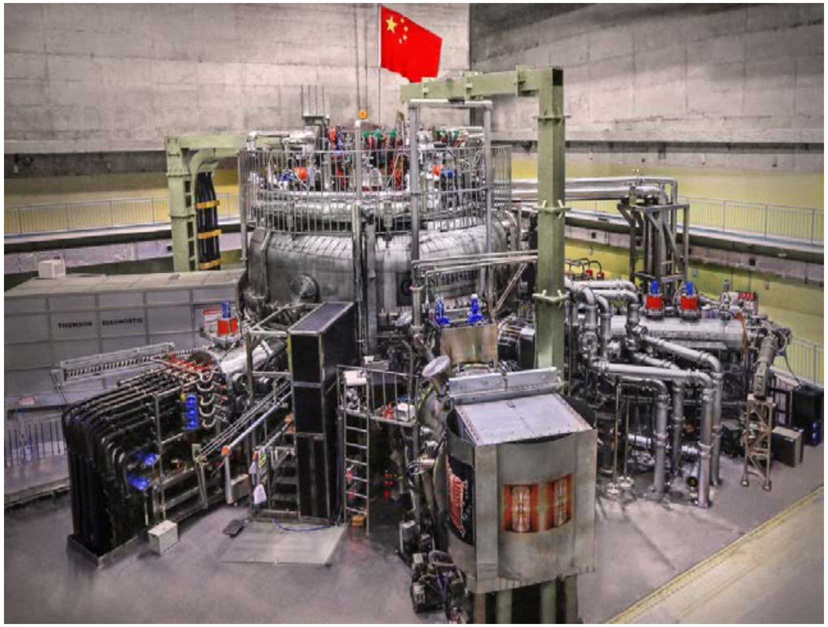
- Magnetic confinement fusion and high temperature plasma physics
- Fusion engineering and technologies
- Reactor design
- High magnetic field
- Low temperature plasma and application
- Superconductor and cryogenic engineering

There are 700 staff members in ASIPP, distributed in 13 divisions ,one technical center and two R&D companies to undertake various important national research projects, which make itself one of the most important laboratories in China and in the World.

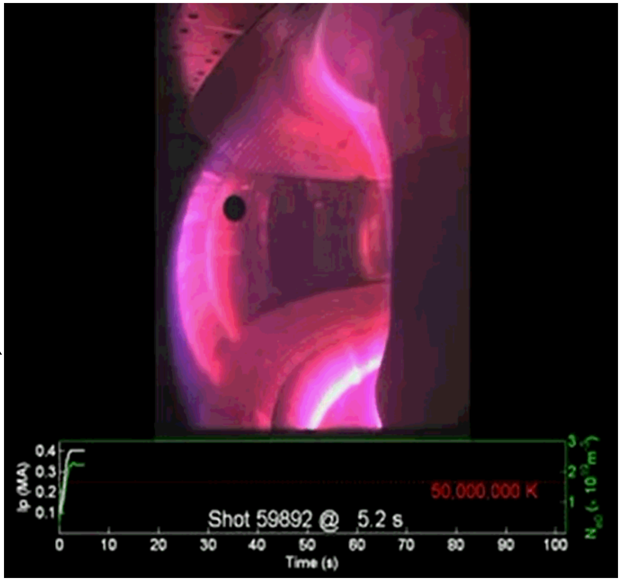
Research and Process of ASIPP

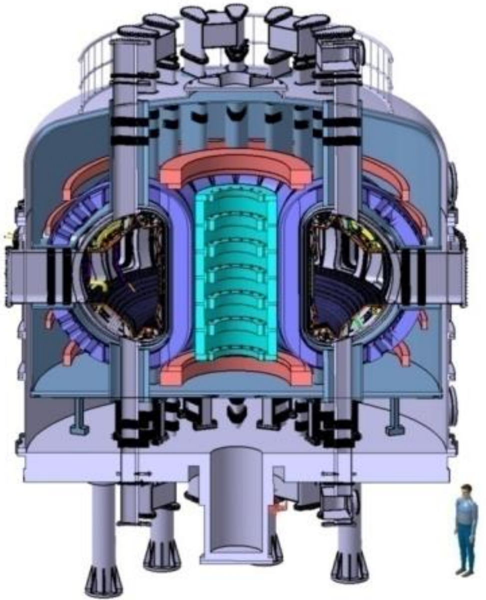
Since the establishment of the ASIPP in 1978, it has built Tokamak device of HT-6B, HT-6M, HT-7, the world's first superconducting tokamak device-EAST Tokamak.

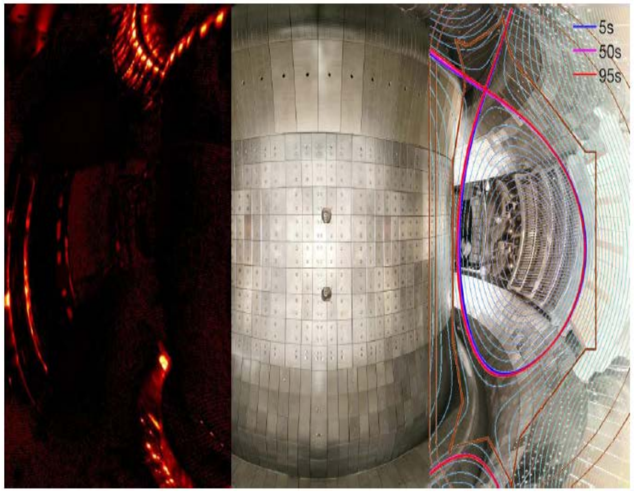
Background of fusion project in ASIPP



50,000,000 degree long pulse plasma of EAST in 2016



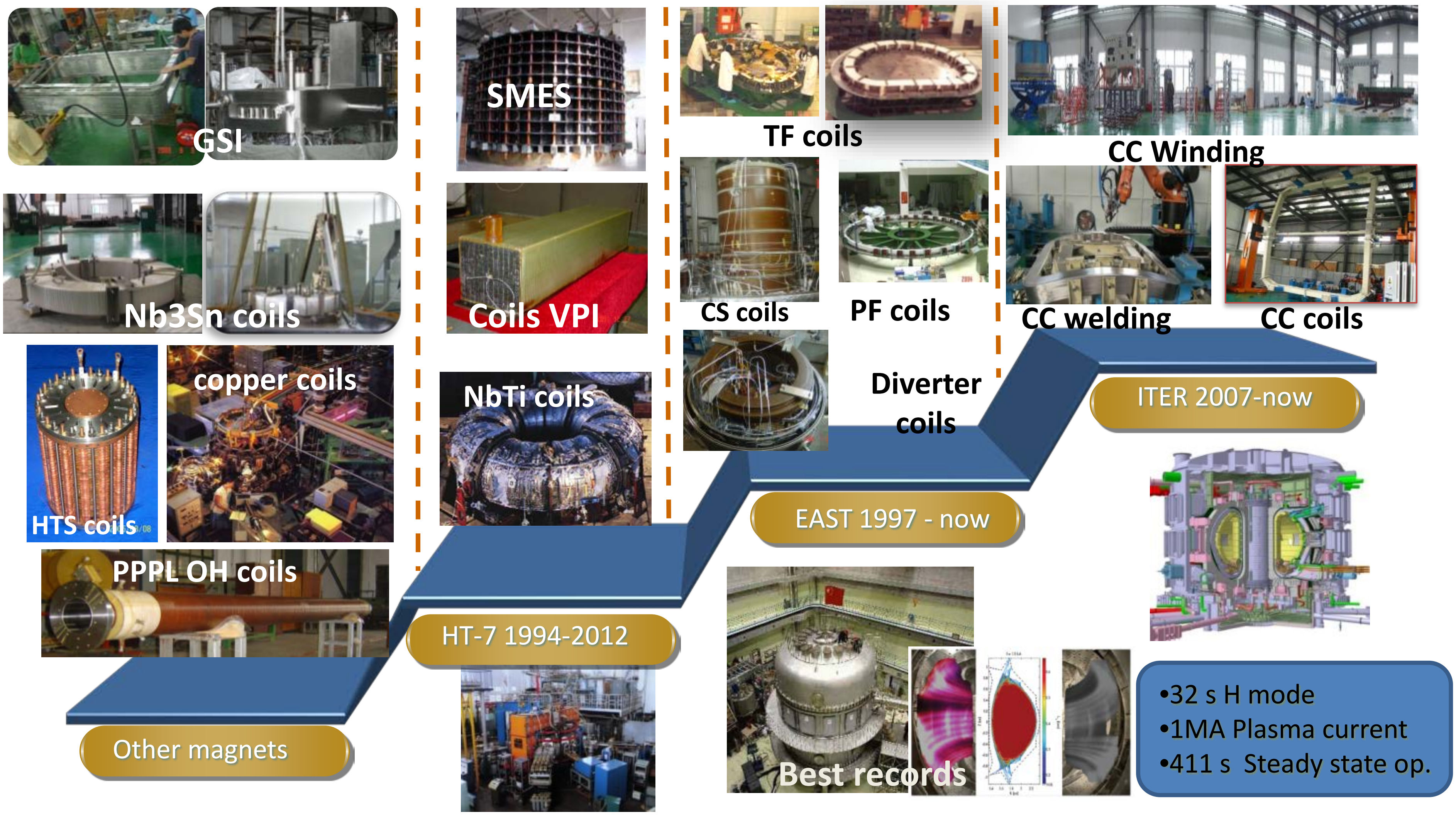




101.2 second high mode plasma of EAST in 2017

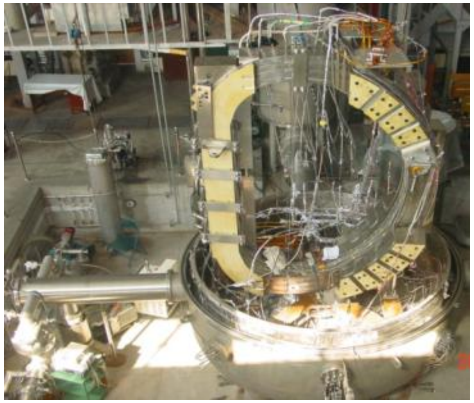
Ip=0.4MA, Bt=2.5T, P_{RF}=3.0MW, ne=3.0x10^{19}/m^3, Te=4.0KeV, H_{98y2}=1.1, USN）

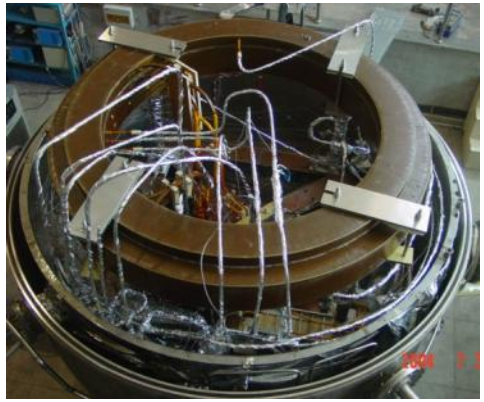
Introduction – Magnet development at ASIPP



ASIPP experience on a large scale of magnet fabrication and testing for more than 30 yrs.

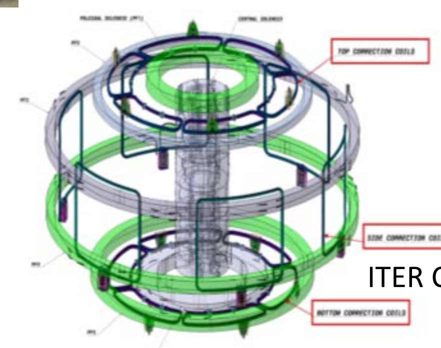
Introduction – Magnet development at ASIPP


EAST TF coils


EAST Divertor Coils

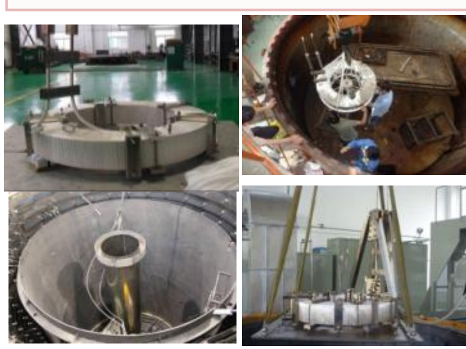

EAST CS Coils


EAST PF Coils(Max OD 7.2m)


ITER CC

ASIPP superconducting magnet development:

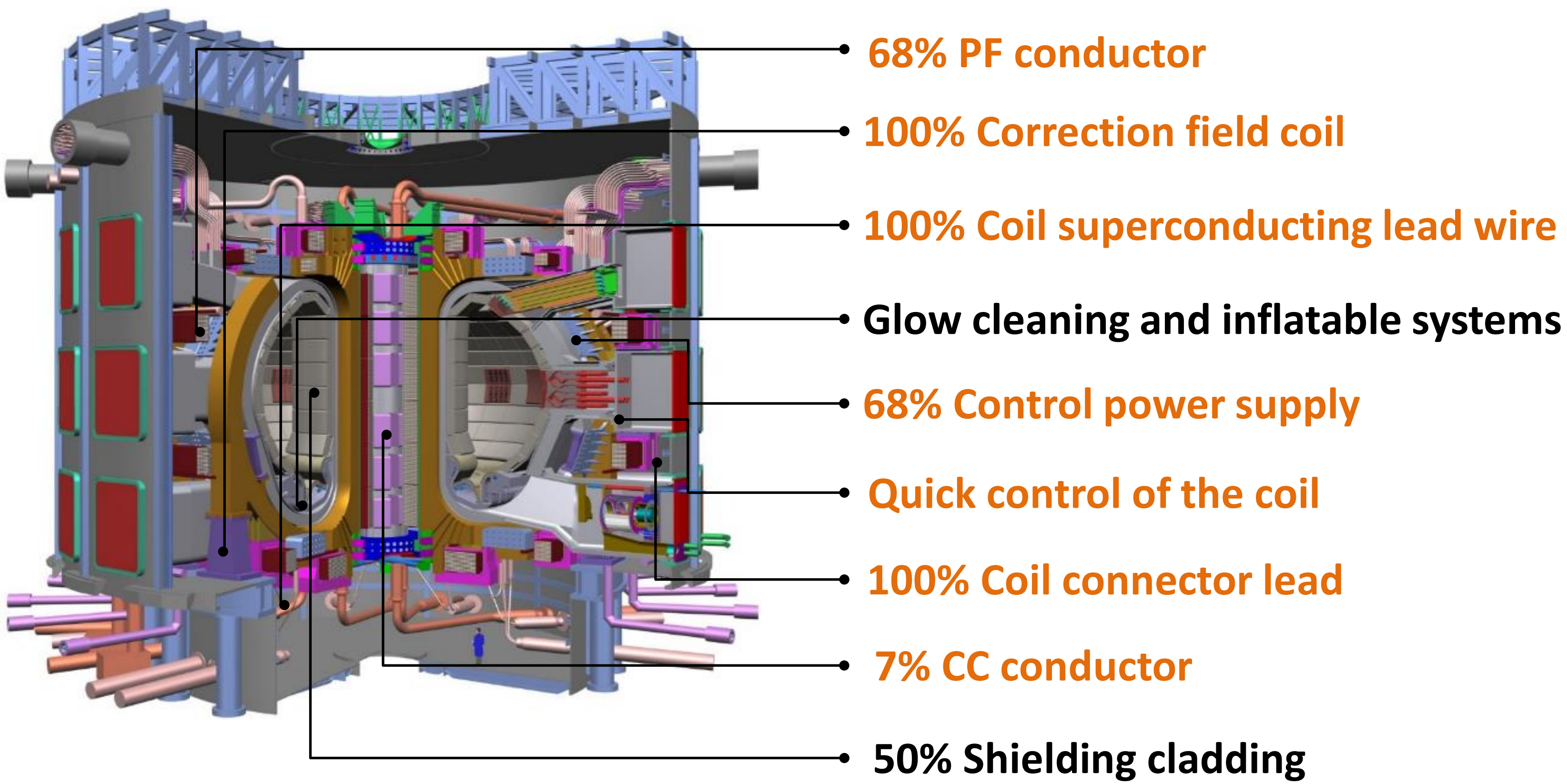
- successful experiences on a large scale of NbTi coils fabrication and test
- developed technology on Nb3Sn fabrication and test
- R&D work on HTS coils for fusion TOKAMAK.


12 T Nb_3Sn coils


GSI Dipole Coil Prototype

Contents

ITER Cooperation work



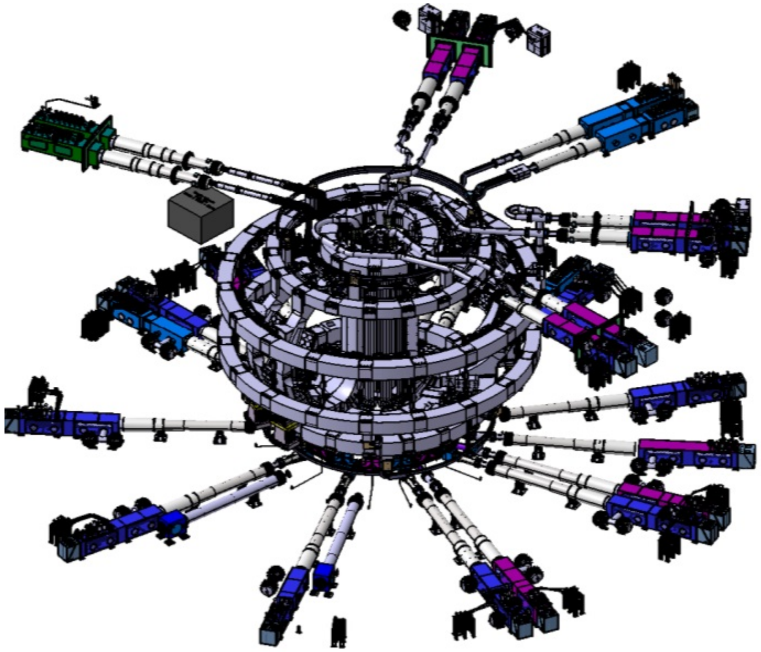
7% of the ITER design was modified according to the team's recommendations

The team presided over more than 70% of China's Purchase Package

Study on ITER Feeder system

100% ITER feeder package is carrying out by ASIPP

- 31 Feeder systems. No two pieces are identical.
- >1000 tons, >tens thousands of different parts.



Overview of Feeder system in ITER

- ASIPP has developed 68 kA/52kA/10kA HTS current lead trials, especially 68kA current lead has operated at 85kA for 65 minutes and 90 kA for 4 minutes.
- Many key components qualification have been completed.

Study on ITER Feeder system

The multi-component shunt

	Single-component Shunt	Multi-component Shunt
Material	Oxygen free copper	Stainless steel + bronze + superconductor
4.5 K Heat Load(W)	35 W	13.4 W
Current Capacity	Thousand-Ampere-Class	Ten-Thousand-Ampere-Class
Safety overheat time	7s	22s
Safety time after loss of cooling	300s	411s
Mechanical Properties	Low	High

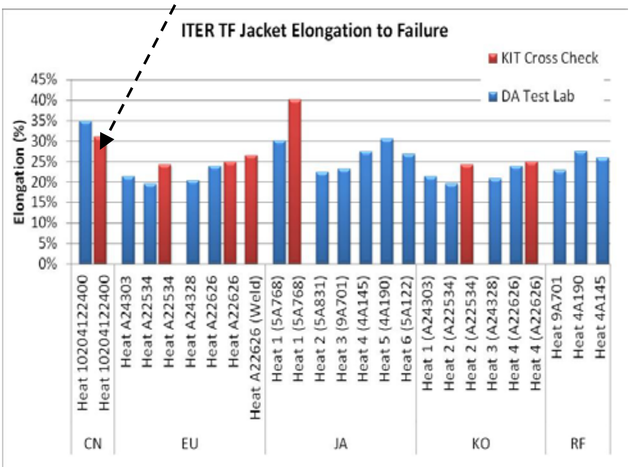
Successfully delivered a large-scale superconducting feeder system to the U.S. GA ITER CS test system

Develop the first superconducting magnet feeder system component for ITER project

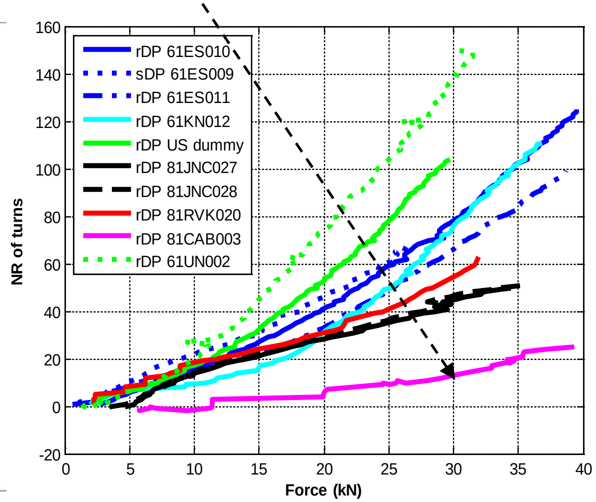
Study on ITER Superconducting Conductors

- Build 3 world's longest 1000 meters long cable winding production lines;
- All samples have passed the test at the first try, 100% of qualified rate ; Jacket fracture elongation is the best one.
- Back twist coefficient of CICC conductor is lowest compared all the ITER partners;

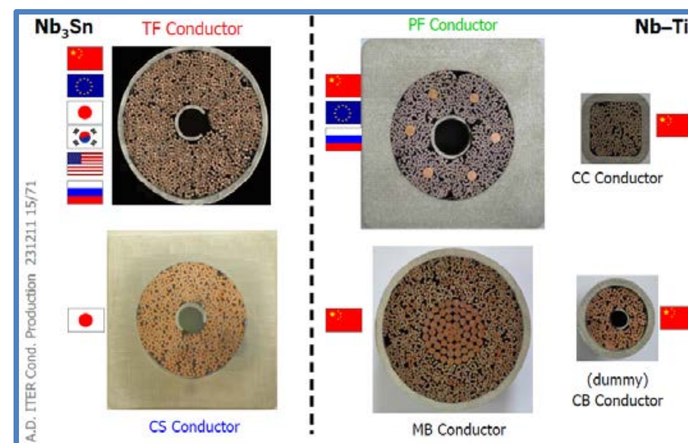
1000 meters' winding production lines



Jacket fracture elongation



Back twist coefficient of CICC conductor



Nb3Sn superconductor

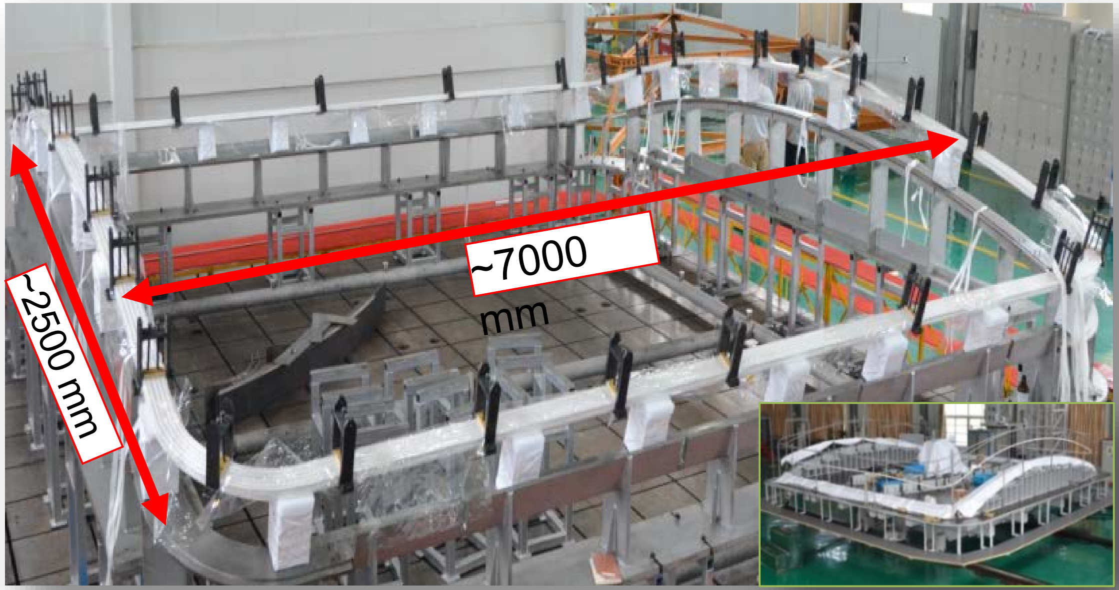
11 TF conductors （7.5%） , 60 PF conductors （69%） , all CC conductors, and all Feeder conductors' production and acceptance test have been completed. 23 conductors have been accepted by ITER and delivered.

ITER CC superconducting coils

- ITER CC coils: composed of 18 coils, made from <u>NbTi superconducting cable</u>. The series production of coil has been started from 2016.

- Manufacturing Process Qualification

1.	Winding procedure qualification	Finished
2.	Insulation system and VPI procedure qualification	Finished
3.	Helium inlet/outlets welding qualification	Finished
4.	Terminal joint qualification	Finished
5.	Filler material (between WP and Case) qualification	Finished
6.	BCC Case section manufacturing qualification	Finished

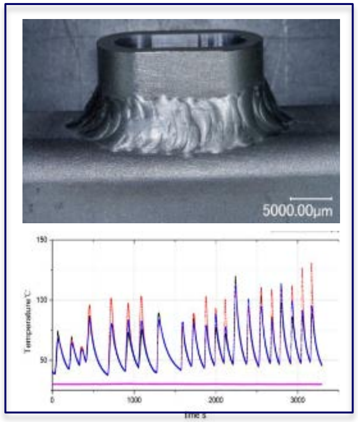


ITER CC superconducting coils

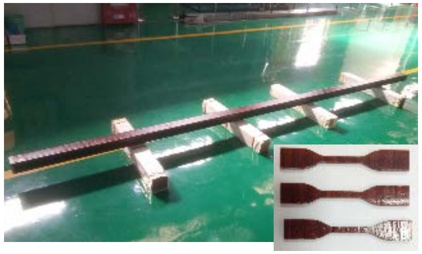
- The series production of coil has been started from 2016. The winding process of BCC1 is finished, and next is the VPI. The coil case is under the NC machining. The whole coil is expected to be cold tested in the middle of 2018.
- BCC5 and BCC6 will be delivered to ITER site at the beginning of 2019.

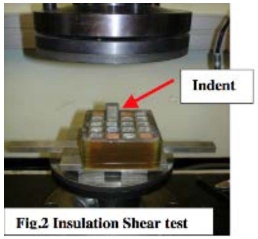
BCC1 winding pack

BCC coil case



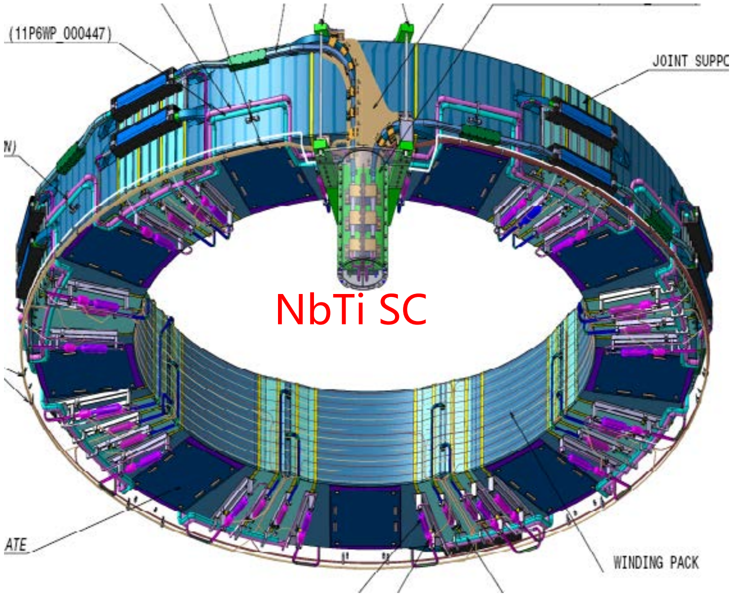
Terminal joint



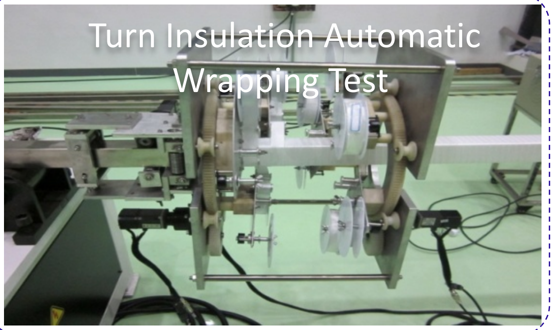


The insulation system and VPI process

R&D work for ITER PF6 superconducting coil



Main parameters: weight 396 ton, outer diameter 10.278 m and cross section 1.584 m×1.131 m.

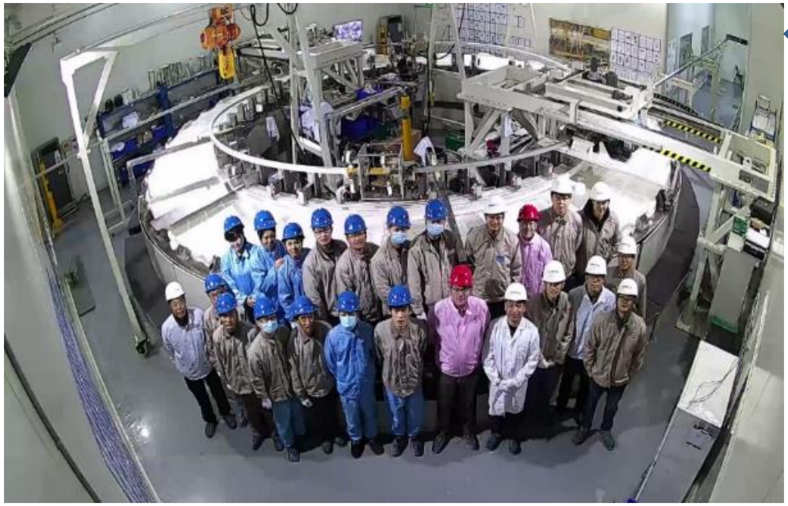


It is one of the largest and most difficult superconducting magnet under construction in the world. Its energy storage is 60 times compared with the largest poloidal field magnets of EAST.

Complex structure → Technical difficulties

- ✓ High stability requirement ;
- ✓ High precision magnetic field;
- ✓ High requirement of Joint resistance, AC loss and insulation system.

ITER PF6 superconducting coil



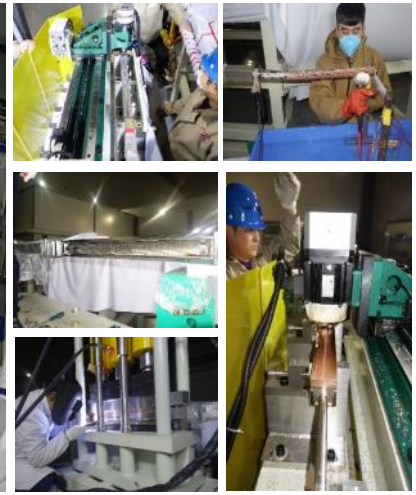
Dummy DP winding was started in Oct 2016 and completed in two months.

The first DP winding was finished within one month by 24th Apr, which demonstrated better efficiency thanks to the upgrade of the clamping system and stable operation of the winding system.

DP8 winding was started and is foreseen to be finished soon.

ITER PF6 superconducting coil

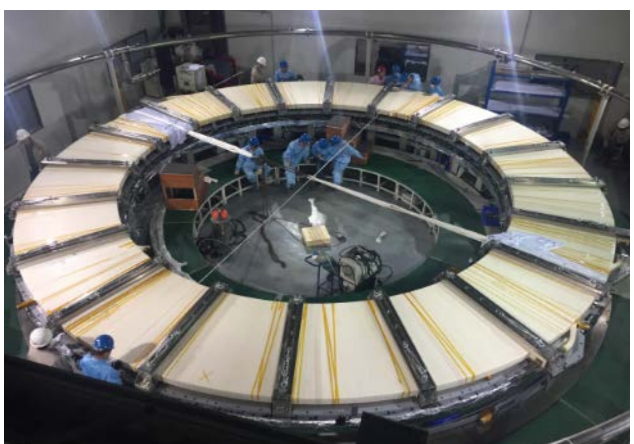
- DP terminations fabrication



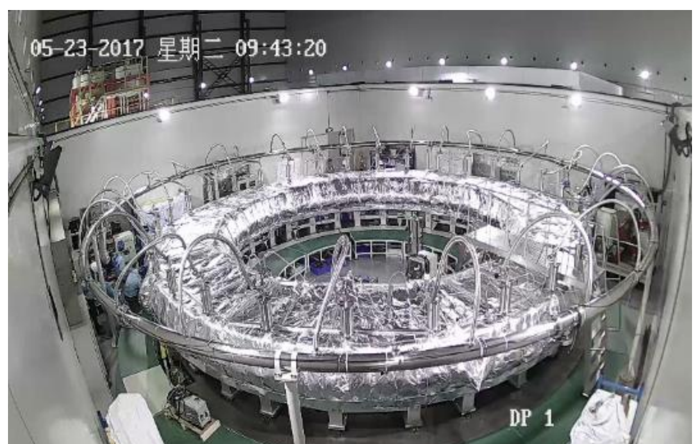
DP terminations were fabricated on a rack station which reproduced the procedures applied on Dummy joint qualification; Two terminations in-parallel production practice was proven working.

Dummy DP was enclosed in the VPI mold and the heating system commissioning was carried out.

- DP VPI



Resin envelop welding and hard mold assembly

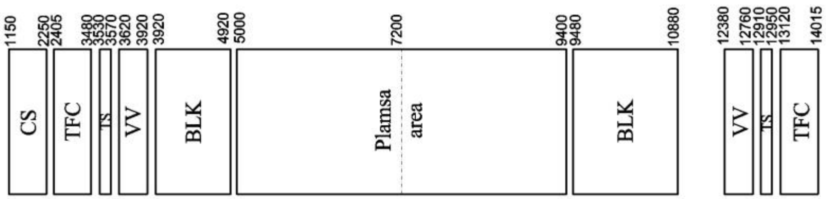


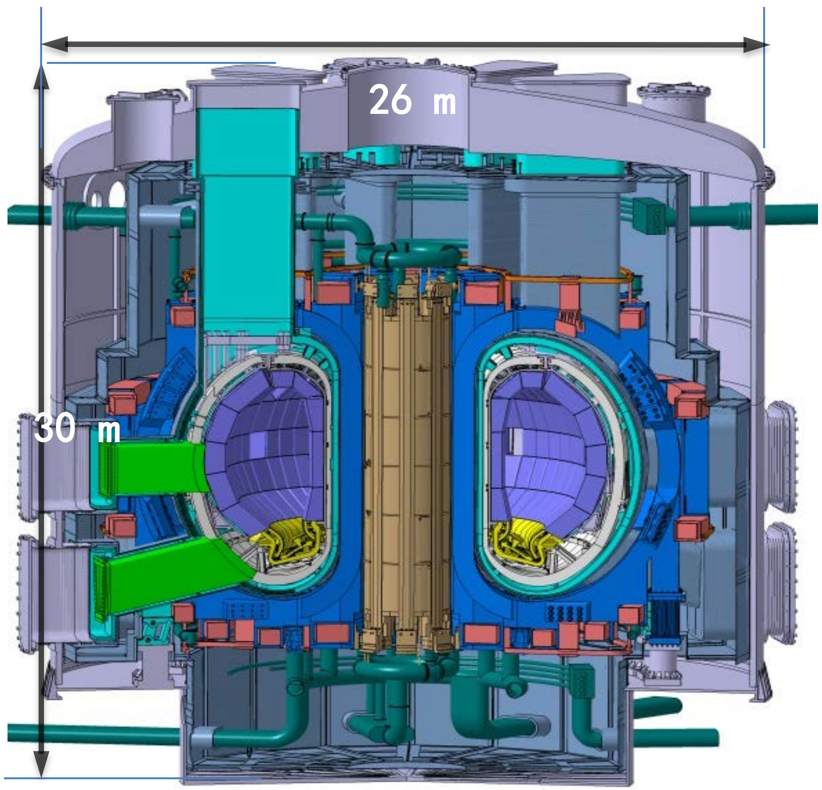
Heating system Commissioning

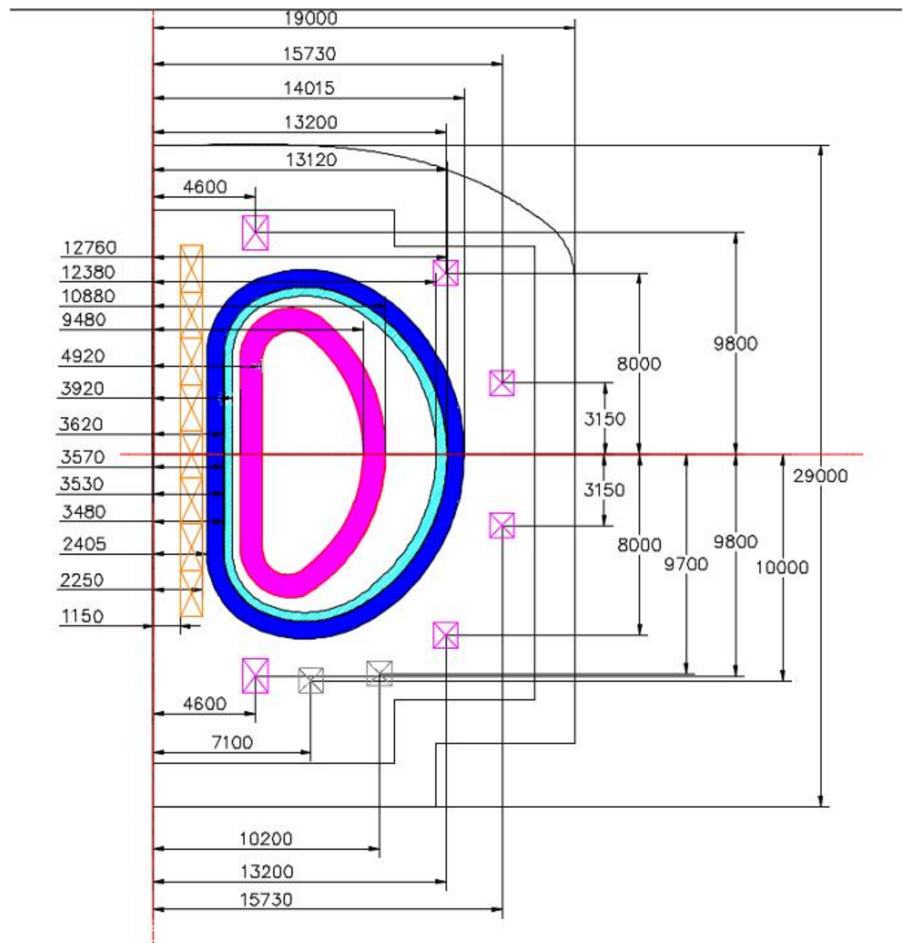
Contents

Key issues for CFETR

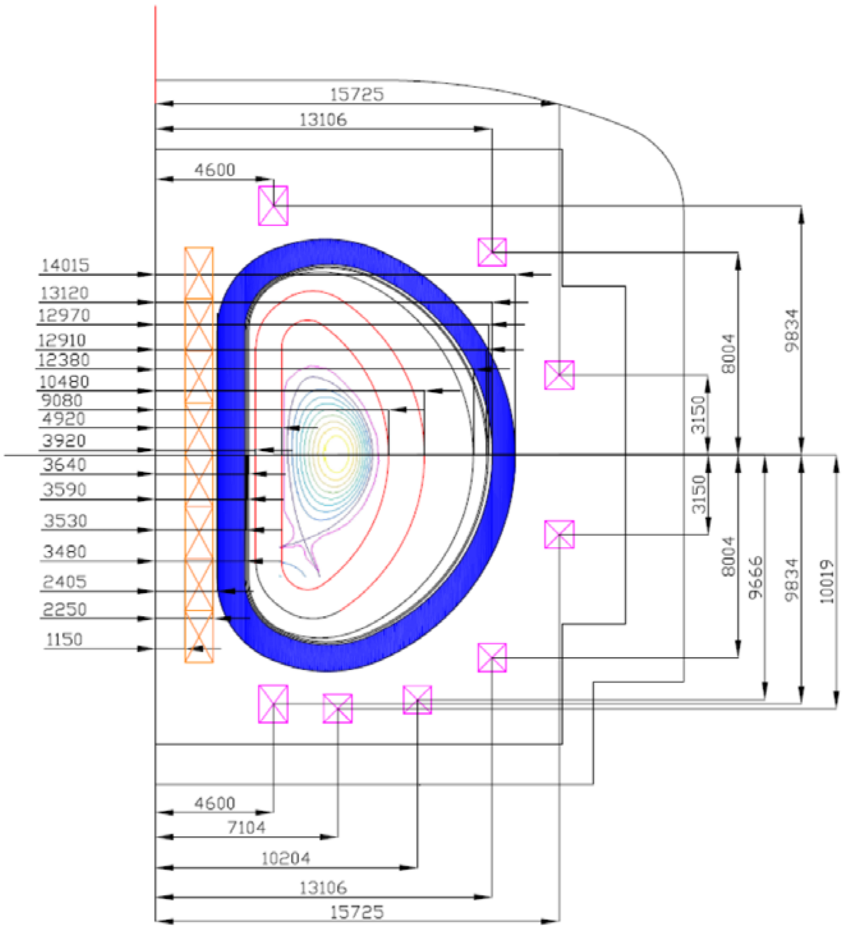
- ☐ Larger size: R= 7.2 m, a=2.2m
- ☐ High B_T : 6.5-7T
- ☐ Low Ip: 10-15MA
- ☐ Advanced CS magnet: ≥ 480 VS
- ☐ More reliable Plasma targets



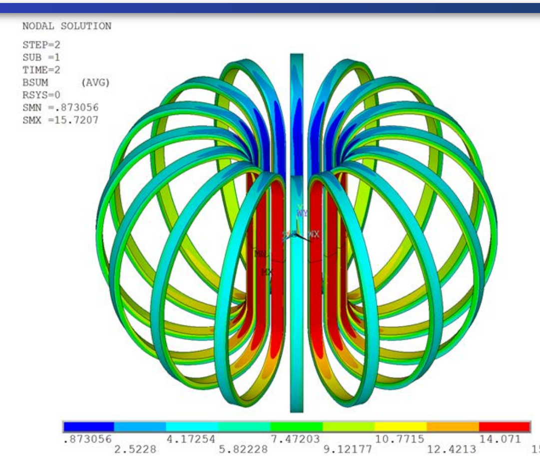


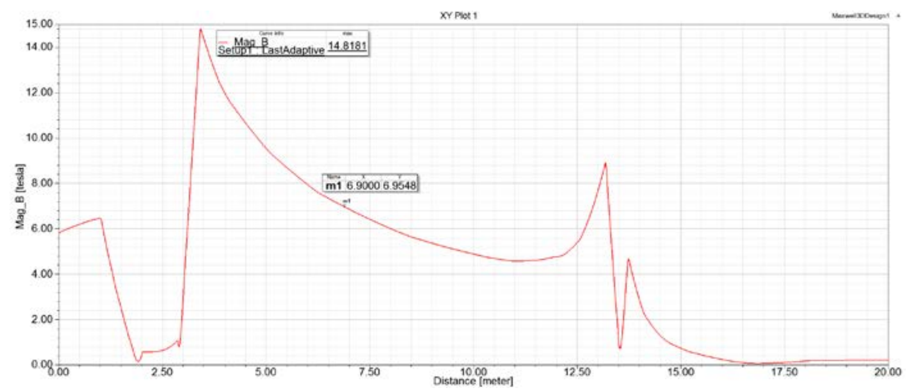


Superconducting magnet system of CFETR



DC1 and DC2 is just kept to be additional option in near future.
NOTE: DC2 is canceled in now stage





Type	Parameter
Type of conductor	Nb_3Sn
Number of turns	168
Operation current(kA)	87.6
Maximum field(T)	14.3
B_0(R=7.2m)	6.5
Ripple in plasma region(r=2.2m)	＜1%

key parameters of TF coils

	ITER TF	EU-DEMO[2015]	CFETR TF /τ=20 s
Number	18	18	16
Operating current	68 kA	81.7 kA	87.6 kA
Inductance	17.34 H	32.68 H	34.93 H
Total stored energy	40.1 GJ	109.08 GJ	134.02 GJ
Stored energy (single coil)	2.227 GJ	6.06 GJ	8.376 GJ
Discharge time constant	11 s	23s	20 s
Quench protection Resistor	-	-	109.1mΩ
Max voltage	5954 V	6450 V	9562 V

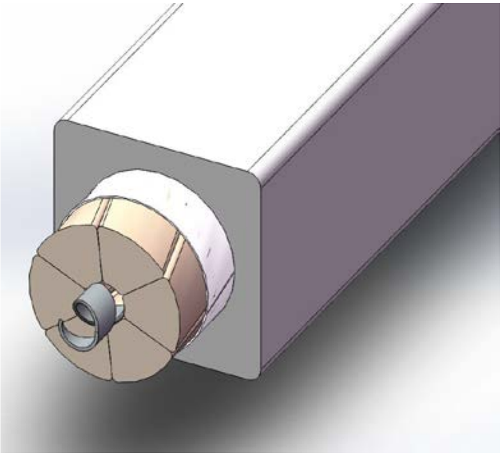
key parameters of TF coils

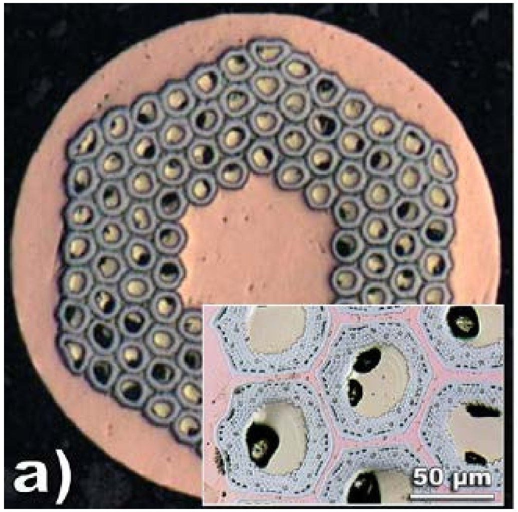
- **Main Parameters:**

Operating Parameters:
Maximum Field: 14.3 Tesla
Operating Current: 87.6 kA

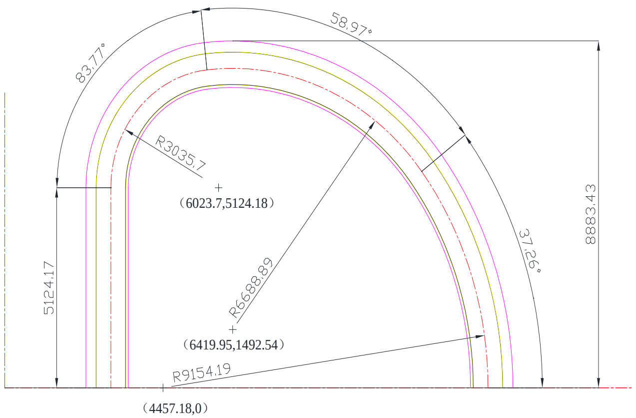
Conductor Parameters:
SC strand No.: 900
Cu strand No.: 522

SC Strand Performance
Strand diameter: 1.0 mm
J_c @ 12 T, 4.2 K: ~ 2200 A/mm^2

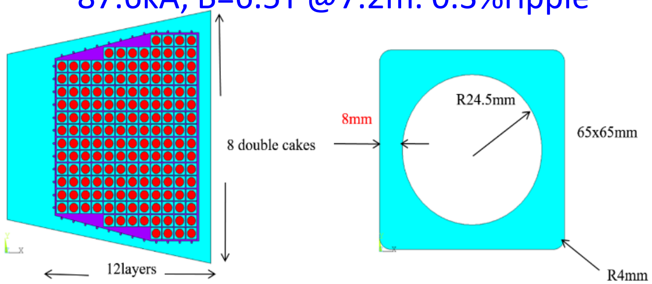




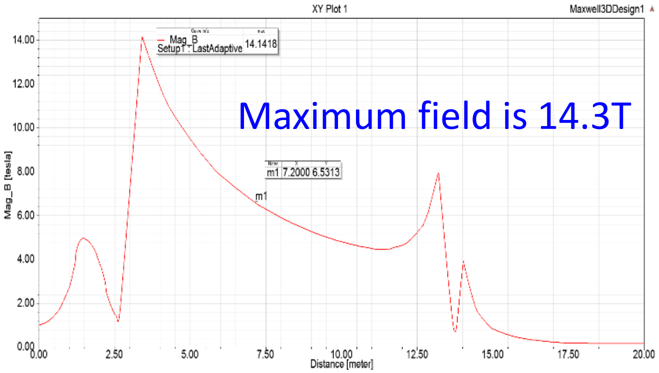
TF SC coils for CFETR



Total turns of 168 , operation current 87.6kA, B=6.5T @7.2m. 0.3%ripple

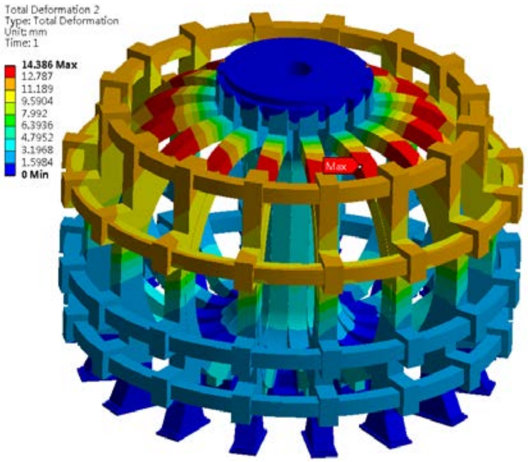


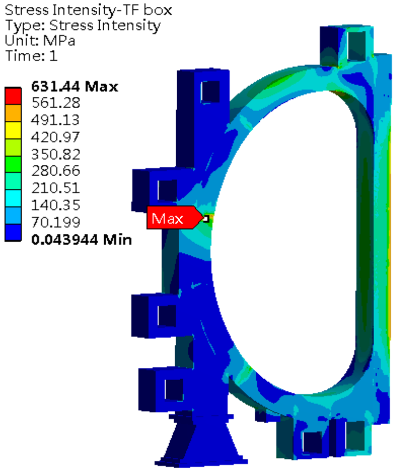
Double pancakes in middle region is 1100m , side double pancake:500m

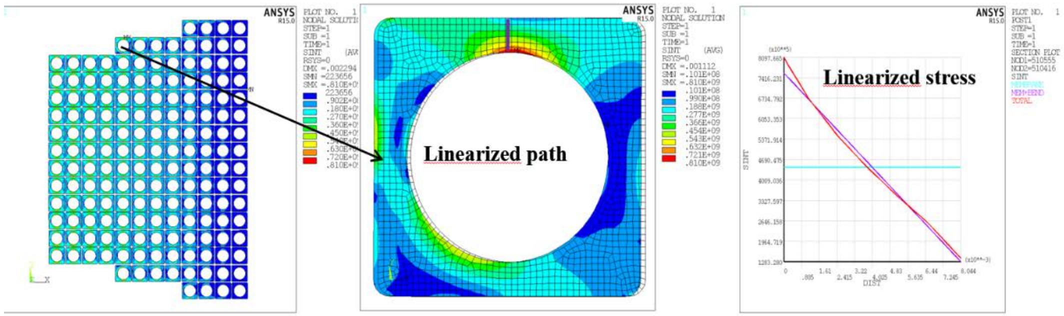


Maximum field is 14.3T

- Maximum membrane stress of the conductor jacket Pm=443MPa<533MPa, membrane stress + bending stress **Pm+Pb=758MPa<800MPa**
- **Mises stress is 570 MPa** maximally, which is lower than the value of S_y(SS316LN of the ITER magnet at 4K is Sy=800MPa).



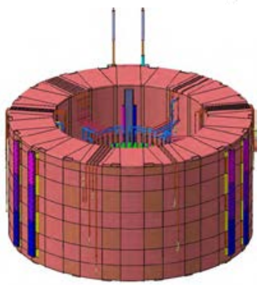


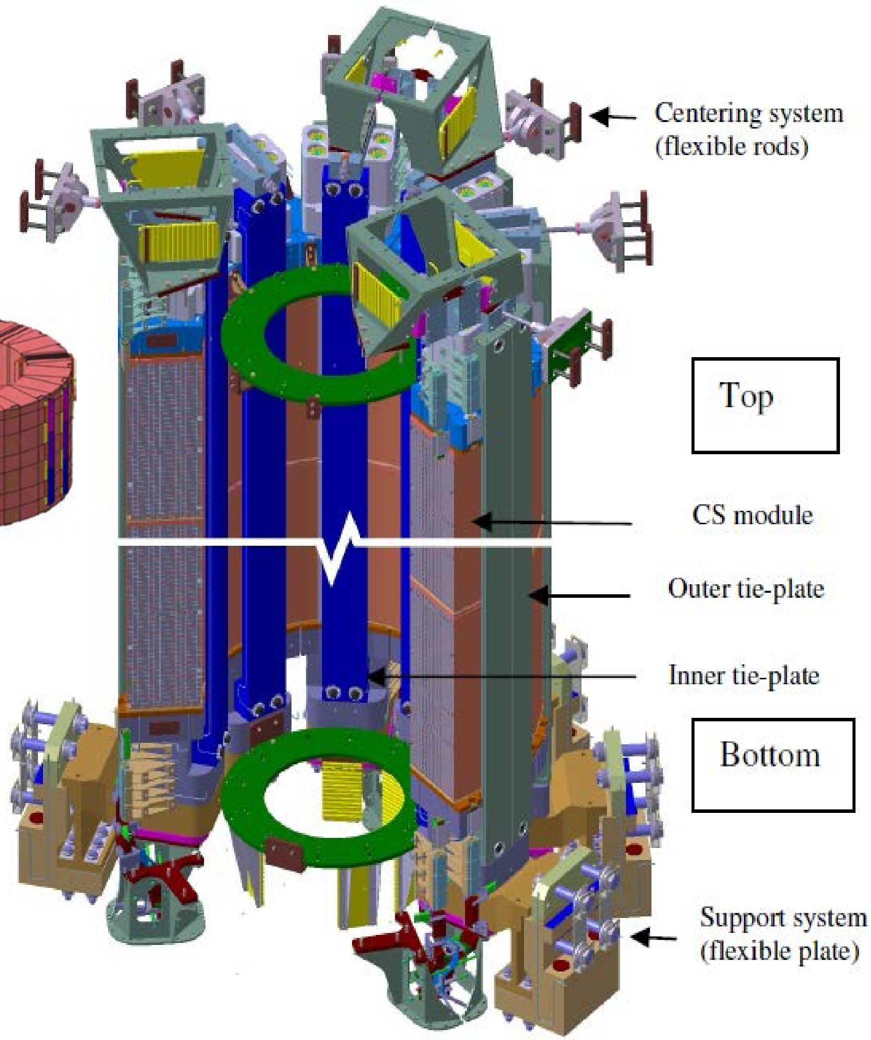


Linearized stress:(1)Pm=443MPa<533MPa;(2)Pm+Pb=758MPa<800MPa

CS Coil for CFETR

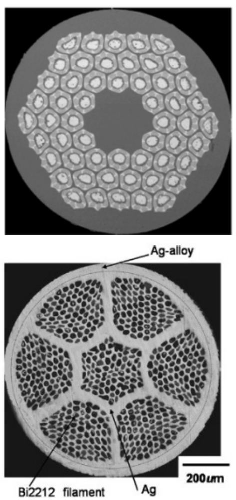
COILS	△R(m)	△Z(m)	TURNS
CS1U	1.0	2.05	738
CS2U	1.0	2.05	738
CS3U	1.0	2.05	738
CS4U	1.0	2.05	738
CS4L	1.0	2.05	738
CS3L	1.0	2.05	738
CS2L	1.0	2.05	738
CS1L	1.0	2.05	738

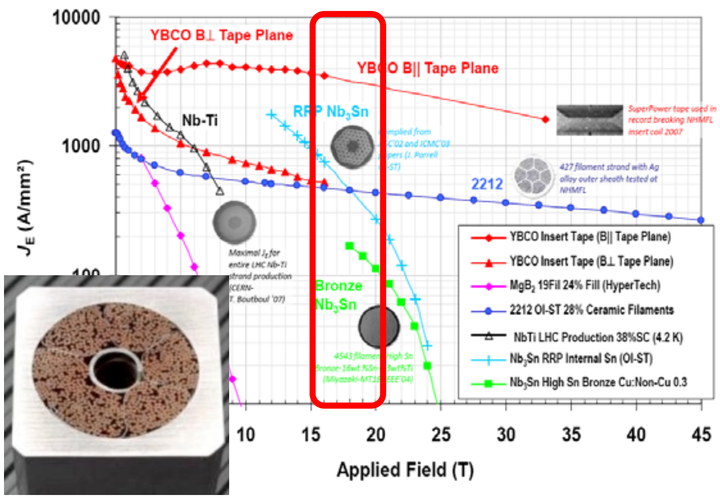




CS Conductor

- **material**： High Jc Nb_3Sn or Bi-2212
- **Conductor**： Cable-in-Conduit Conductor(CICC

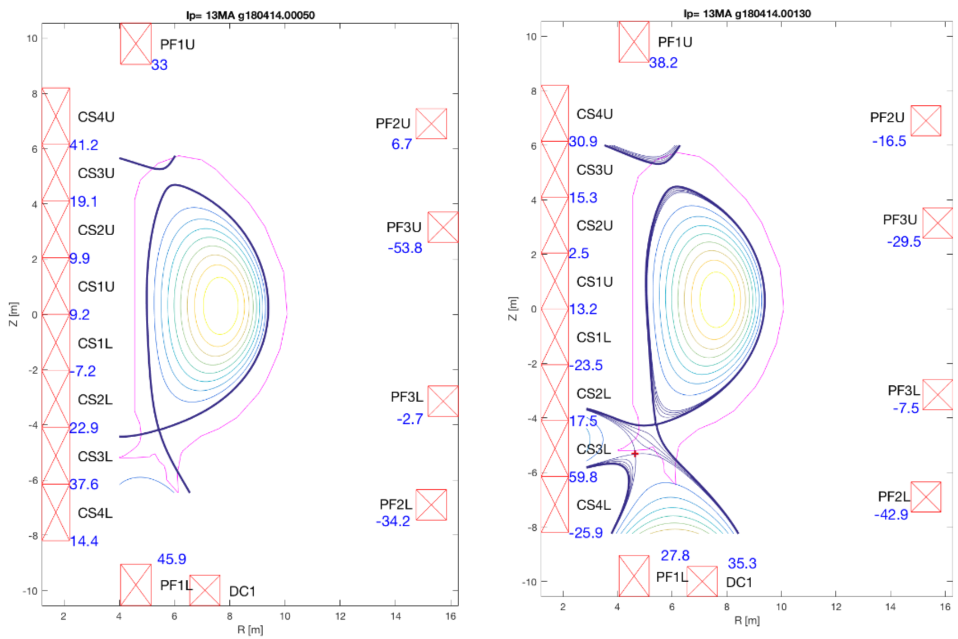




Plasma equilibrium configuration for CFETR

Coil	SN	SF+
	Maximum filed/T	
PF1U	5.2318	4.9051
PF2U	0.84155	0.85487
PF3U	3.8982	4.3090
PF1L	5.5761	4.4089
PF2L	1.4326	4.2372
PF3L	2.4204	0.6777
DC1	1.4498	4.4638

Maximum field is about 5.6T

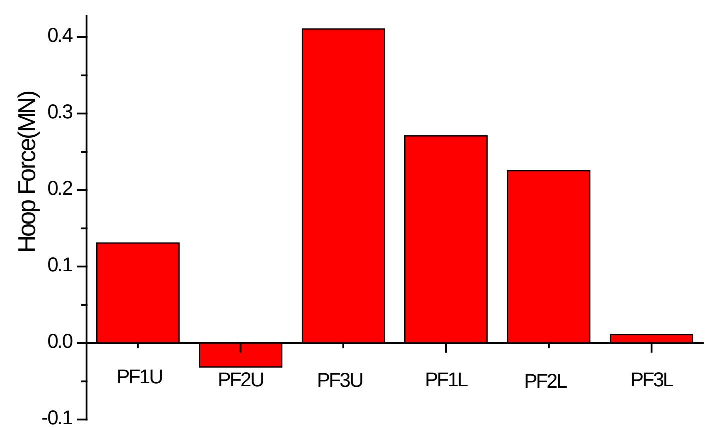


Different equilibrium shape

Inductance between PF coils

	PF1U	PF2U	PF3U	PF1L	PF2L	PF3L	DC1
PF1U	2.81						
PF2U	0.269	3.69					
PF3U	0.211	1.51	3.82				
PF1L	0.02	0.08	0.12	2.81			
PF2L	0.08	0.44	0.67	0.27	3.69		
PF3L	0.12	0.67	1.07	0.21	1.51	3.82	
DC1	0.02	0.09	0.14	0.72	0.33	0.24	1.36

Totally energy is about 10GJ



Maximum hoop force is about 0.4MN

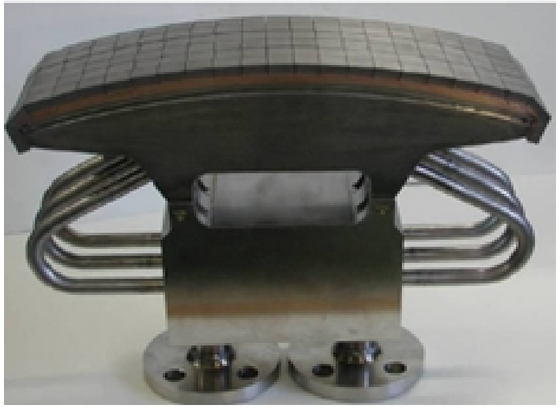
R&D research work of key components of CFETR

Main research work for the key technologies of superconducting magnet, VV, divertor, blanket, RH system and other key components, which will play important role in the development of the fusion reactor.


Superconducting Magnet

1/8 Vacuum Vessel

Blanket R&D Components

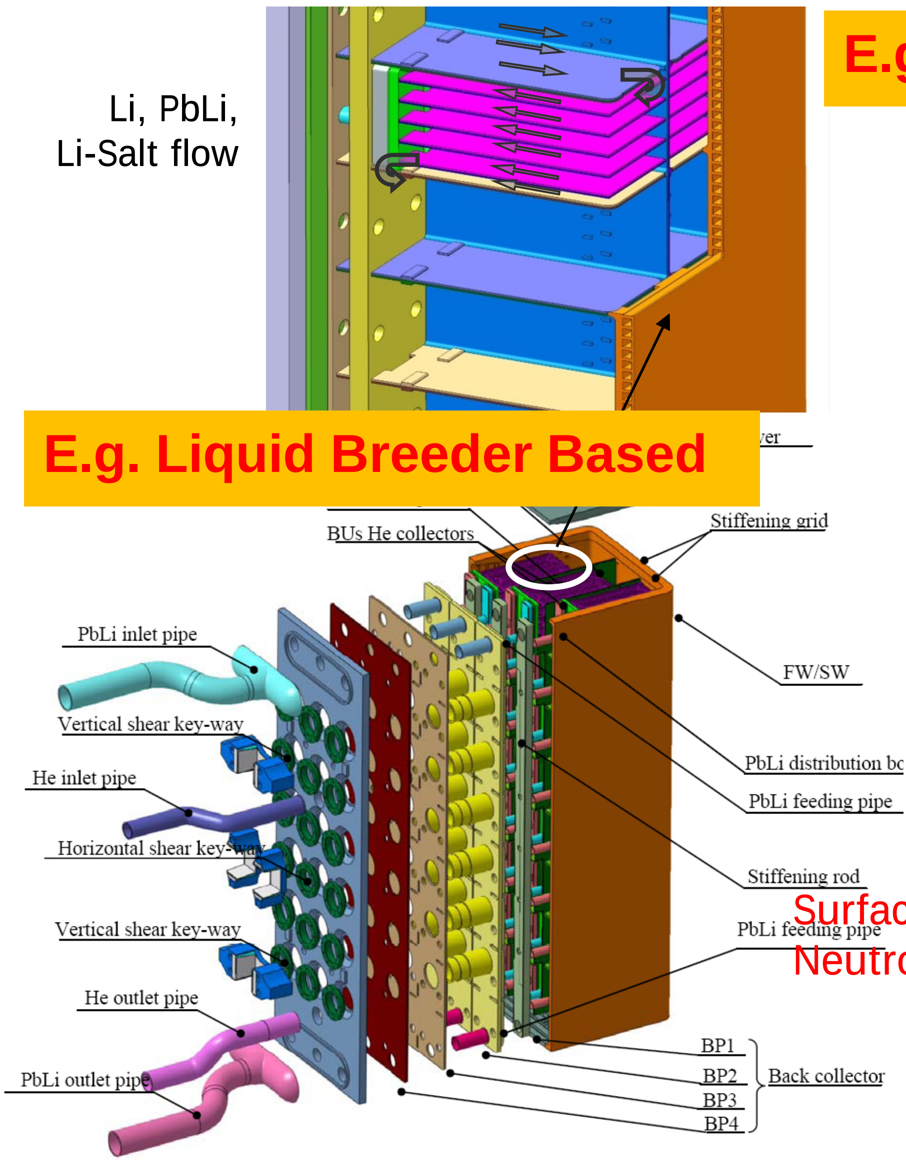


Divertor monoblock mockup

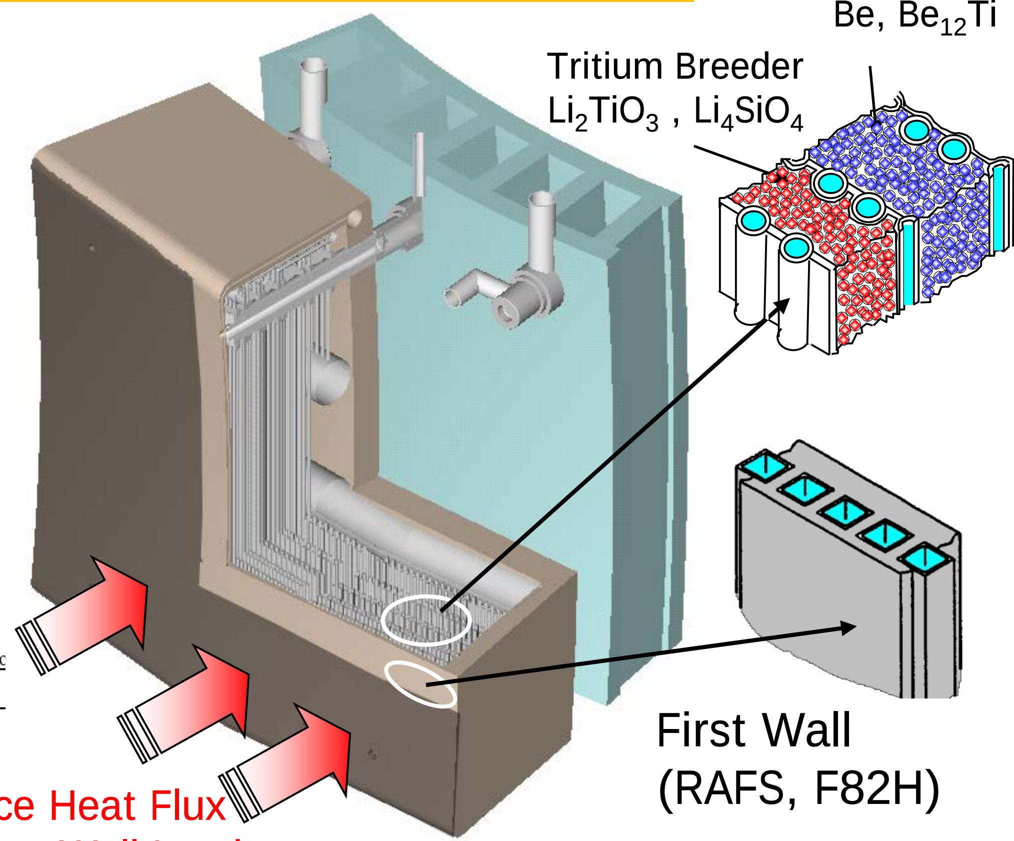
Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

Li, PbLi, Li-Salt flow

E.g. Liquid Breeder Based



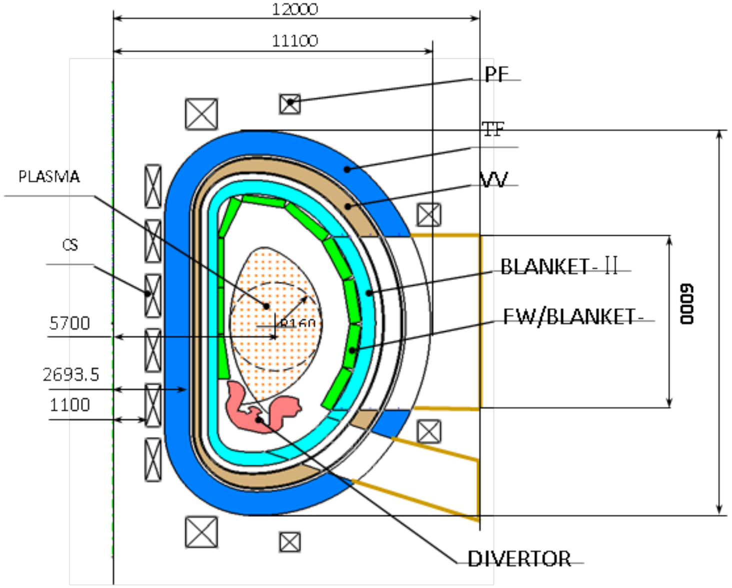
E.g. Ceramic Breeder Based

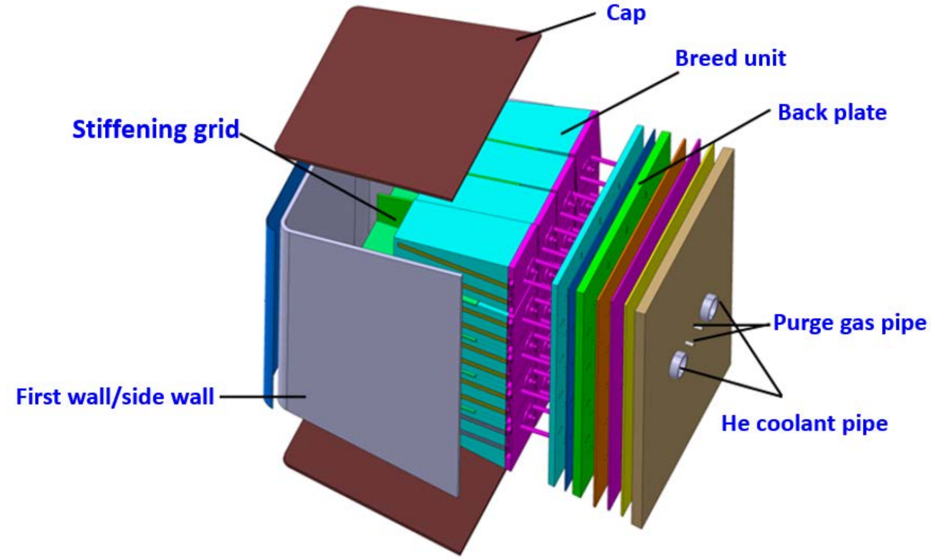


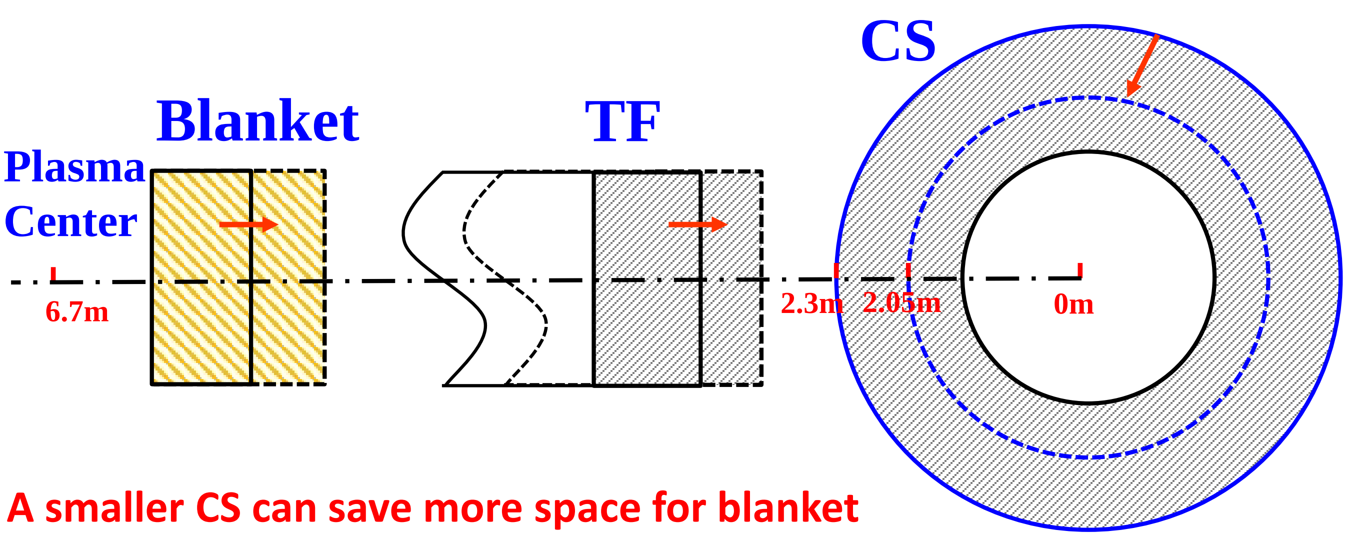
Surface Heat Flux
Neutron Wall Load

Coolants: He, H_2O, or liquid metal or salt

HTS for CFETR







Outer radius:
2.3m→2.05m

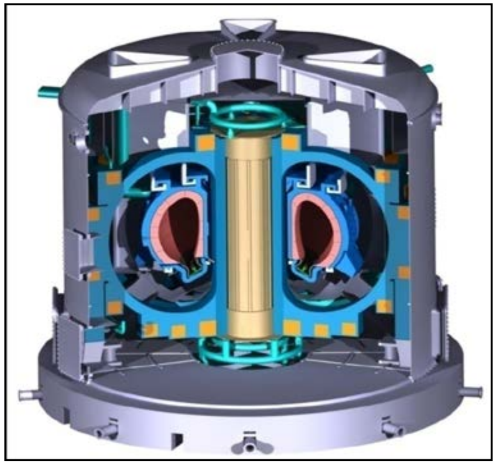
Voltage Second:
480V·s→400V·s

Extra 0.25m for blanket

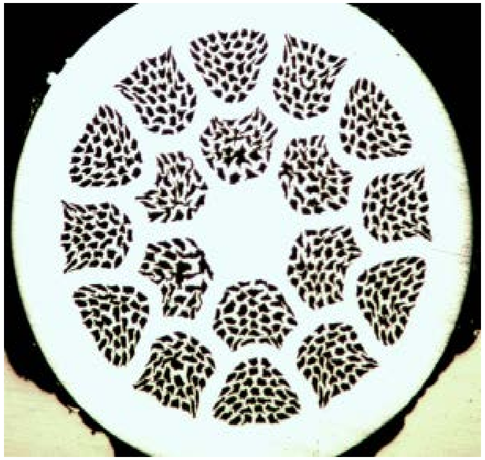
A smaller CS can save more space for blanket

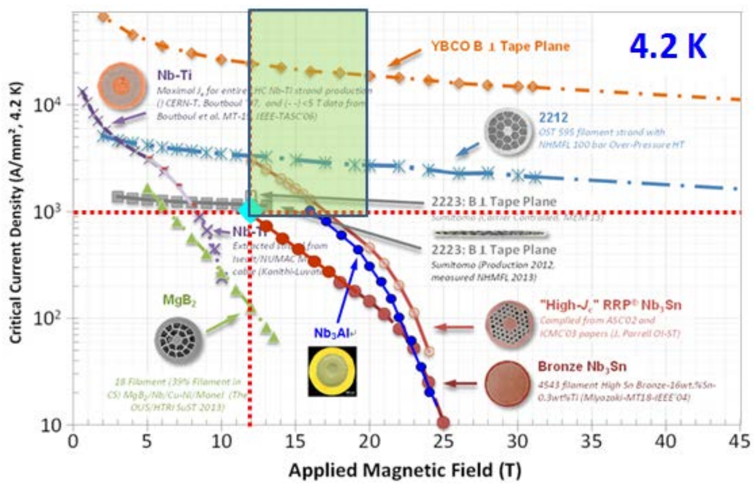
HTS for CFETR

The optimized design is in process, but the maximum magnet field will be higher than 15T.



- ✓ Plasma Ip=8-15MA， R=7.2 m， B_t=6.5T;
- ✓ B_{max}＞15T;
- ✓ Advanced Divertor Plasma Balanced Position Type: Snowflake, SuperX and ITER-like.





Superconducting materials properties

Bi-2212 Advantage:

- ☐ High performance:
- ☐ Similar loss to ITER Nb_3Sn
- ☐ Round, suitable for CICC development
- ☐ Conductor technology is mature at present scale.

Bi-2212 Disadvantage:

- ☐ Wire is brittle, easily to be damaged during cabling and conductor manufacturing;
- ☐ special heat treatment- with O_2, high temperature, and high pressure.

R&D plan for CFETR

Ultimate target:
develop the full size Bi2212 CICCs and YBCO conductor, which could meet the CFETR requirements- I_{op}>60kA, B_{max}~15T, similar scale to ITER conductor。

1: verify the feasibility of Bi2212 CICC、YBCO

2: develop the small sub-size conductor (stage 3)

3: develop the sub-size conductor (stage 4)

4: develop the full-size conductor

The research will be supported by CAS and MOST.

R&D plan for CFETR

Goal:
Develop the **full size** HTS conductor, which could meet the CFETR requirements- **I_{op}>60kA, B_{max}~15T**, similar scale to ITER conductor

Step 1

Verify the feasibility of Bi-2212/YBCO conductor

Bi2212 CICC

2016.01.29

I_c=13.1kA
@4.2K, self field

I_c=26.6kA
@4.2K, self field

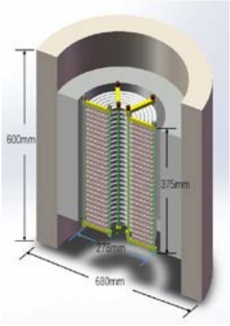
2016.11.23

Step 2

Small sub-size

Insert coil:
B_{max}>12T
Back fi

2018~2019



Step 3

Sub-size

Insert coil: B_{max}>15T
Back field: 12T

2019~2020

Step 4

Full size

I_{op}=60~80kA
B_{max}~15T

2021~2022

Develop the Bi2212/YBCO CS model coil

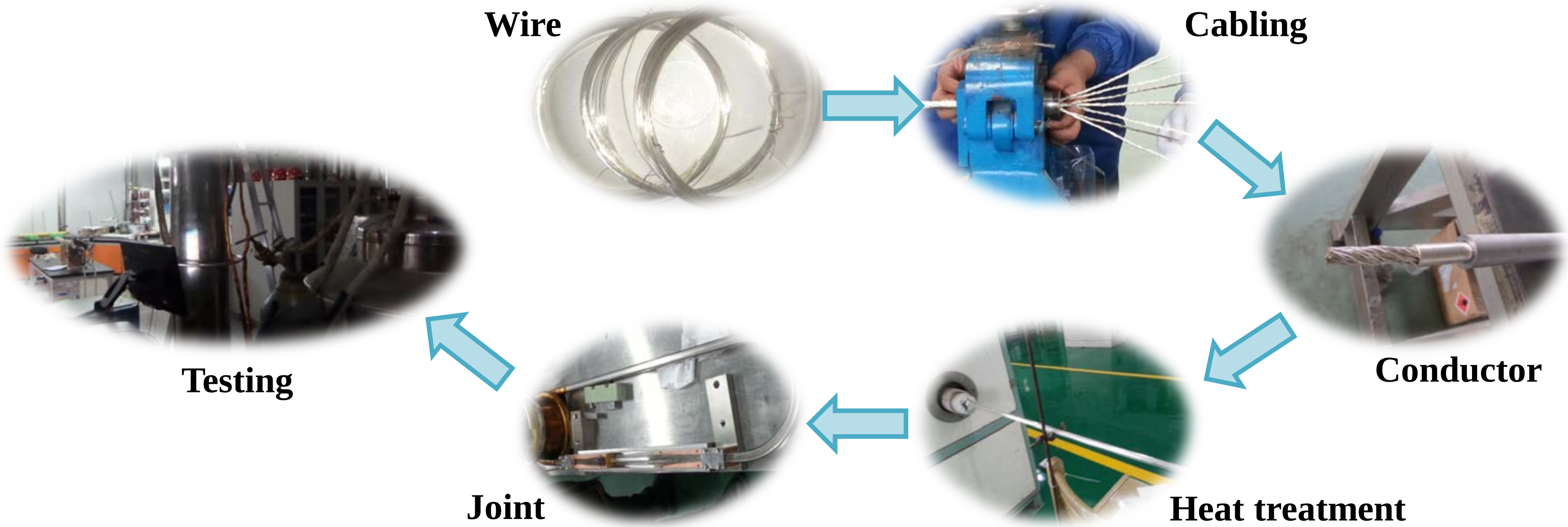
Bi-2212 for CICC

Verify the principal question

Whether Bi2212 is suitable for CICC development

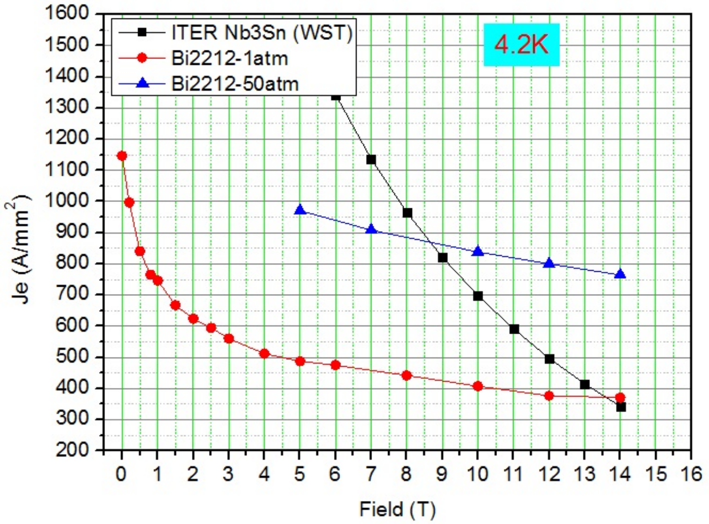
- Cabling
- Heat treatment (normal pressure to high pressure)

Process

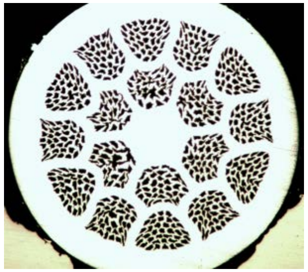


Bi-2212 for CICC

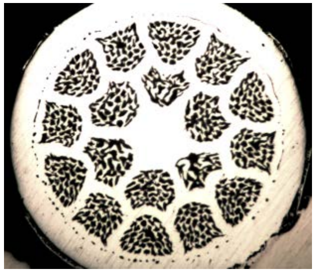
Wire



Material	Ag - 0.2wt% Mg sheathed Bi-2212
Diameter	1.0 mm
Filament configuration	19 × 18
Ag/Mg:Ag:Bi2212	1.8:1:0.9

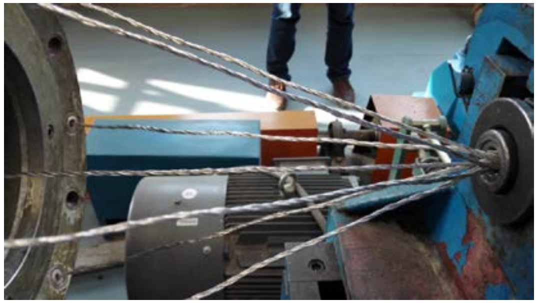


Unreacted



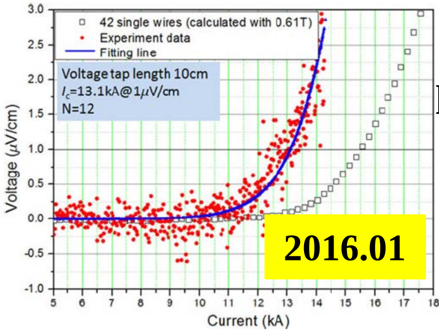
Reacted

Cable

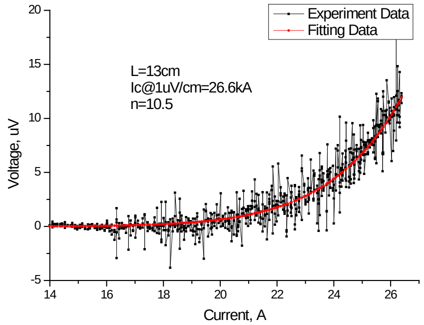


Bi-2212	1.0 mm
Cable layout	2×3×7 (42)
Pitch (STP)	20.7×50×87mm
diameter	10.0mm

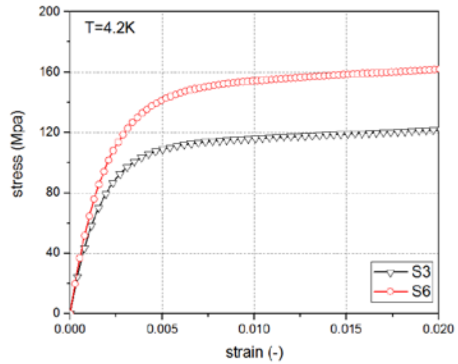
Testing result of heat treatment



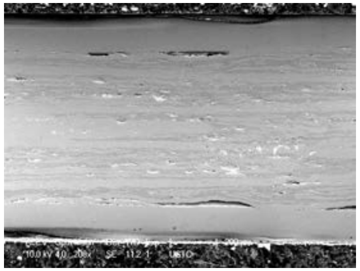
Normal pressure

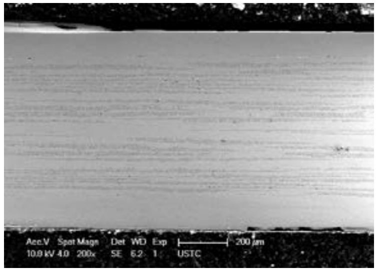


High pressure



Wire strength





Name	I_c	n value	Joint resistance	Pressure
Bi-2212-01	13.1 kA	12	19 nΩ	1 atm
Bi-2212-02		10.5	3.48 , 4.75 nΩ	50 atm

	state	Tem /K	YS /MPa	UTS /MPa	YM /GPa
Bi-2212	No-aging	300	**143**	151	68
	1 atm	300	**94**	107	40.2
		4.2	**104**	175	56.1
	50 atm	300	**121**	134	60.3
		4.2	**133**	223	69.7
Nb_3Sn	No-aging	300	**380**	513	85
	Aging	300	**160**	230	98
		4.2	**250**	325	189

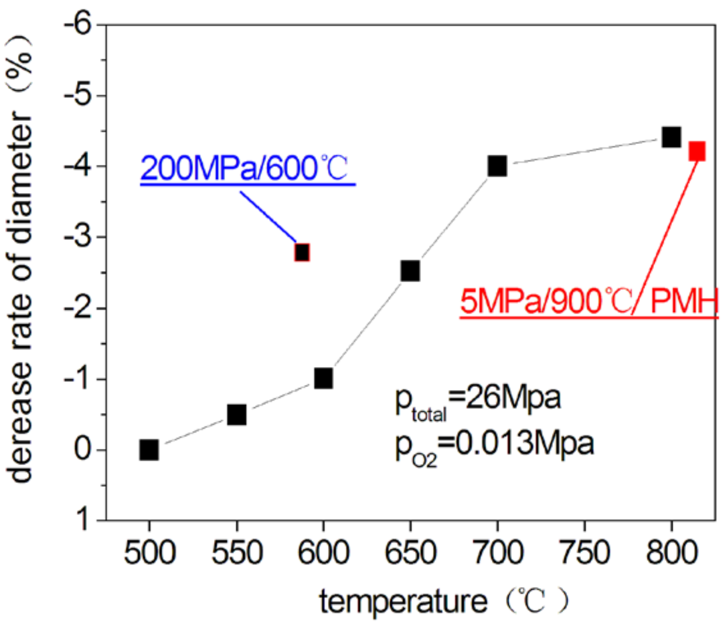
- The Bi-2212 has **potential** to develop CICC;
- The **high pressure** heat treatment (50atm) for conductor could improve the performance obviously, which is twice higher than normal pressure.

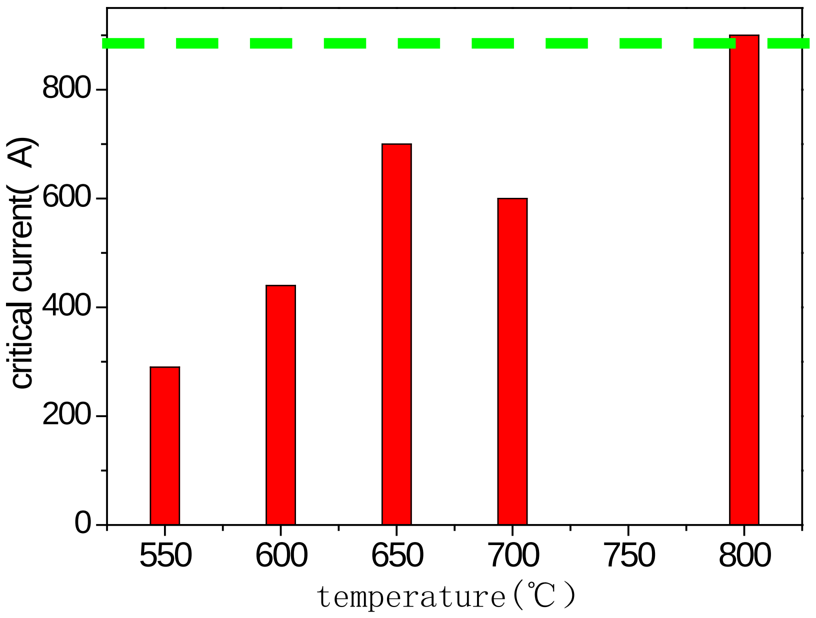
We think Bi-2212 is deserved to develop for high filed applications.

Testing result of heat treatment

- The O_2 was input from the inner of conductor during the normal pressure heat treatment.
- For high pressure heat treatment, all jacket was removed because of small inner bore.

Testing result of heat treatment





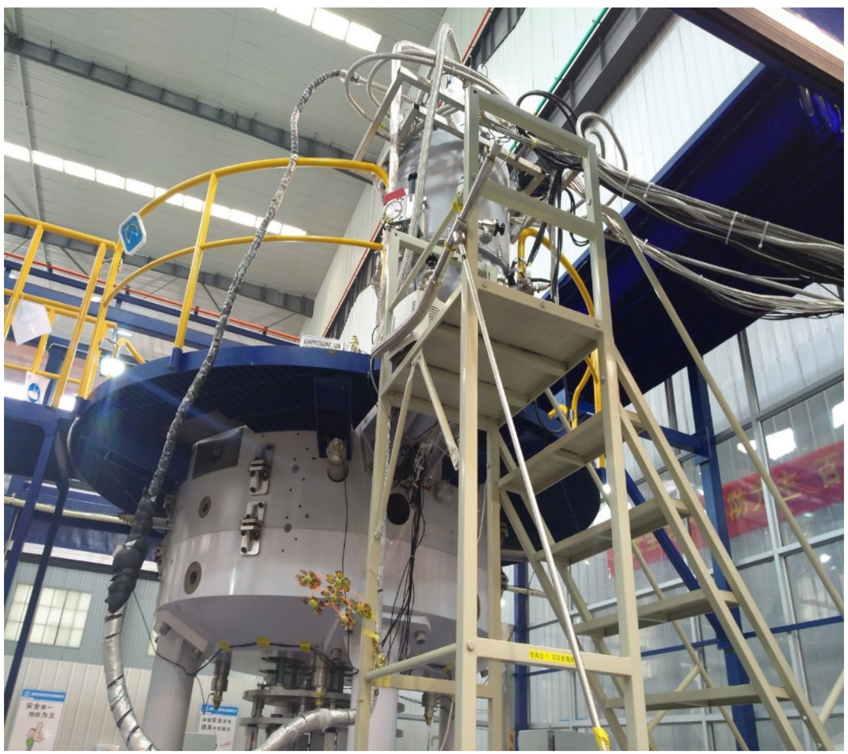
- **at 800℃, d reduced by 4.5%，which is close to 50atm aging。**

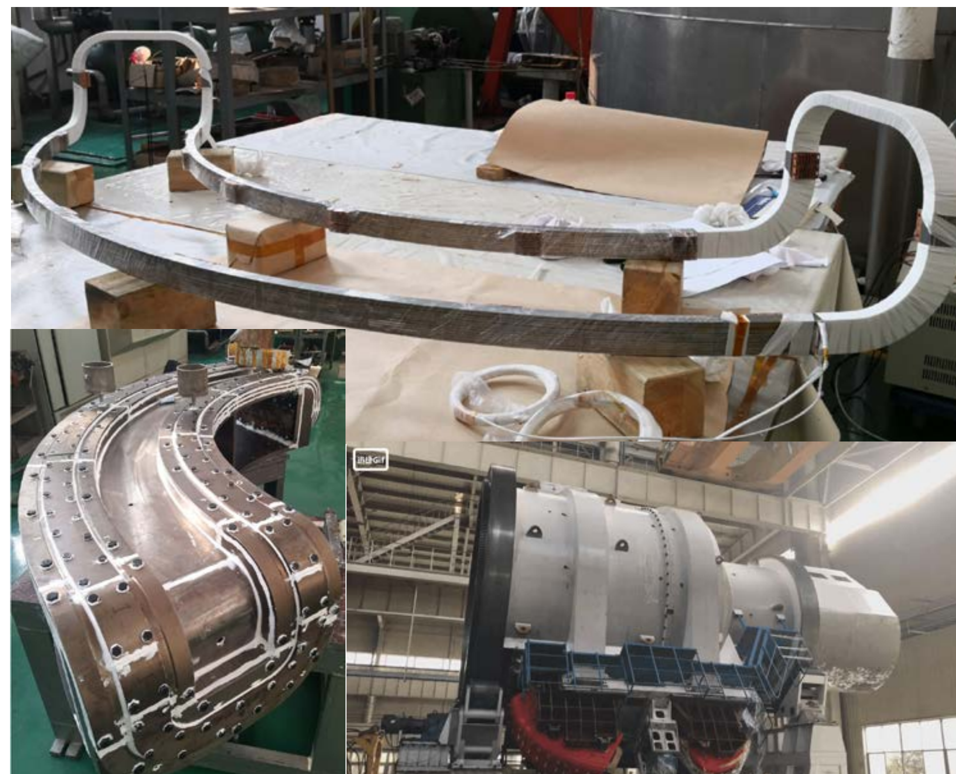
- **the wire performance reach to the required value.**

The pre-high heat treatment is basic feasible solution, but it needs more investigations.

Summary

- CFETR is under-research in ASIPP. Key technologies of High field SC magnet and conductor should be developed in next three years.
- ASIPP looking for more international cooperation on fusion SC topics and Proton therapy topics including SC dipole magnet, Accelerator SC coil and so on. We are also now developing SC200 proton therapy system in ASIPP





Thank you!

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