Fusion Reactor Related Technologies Developed in ASIPP

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1, Introduction

2, Large Scale Superconducting Technologies

3, Plasma Facing Materials and Components

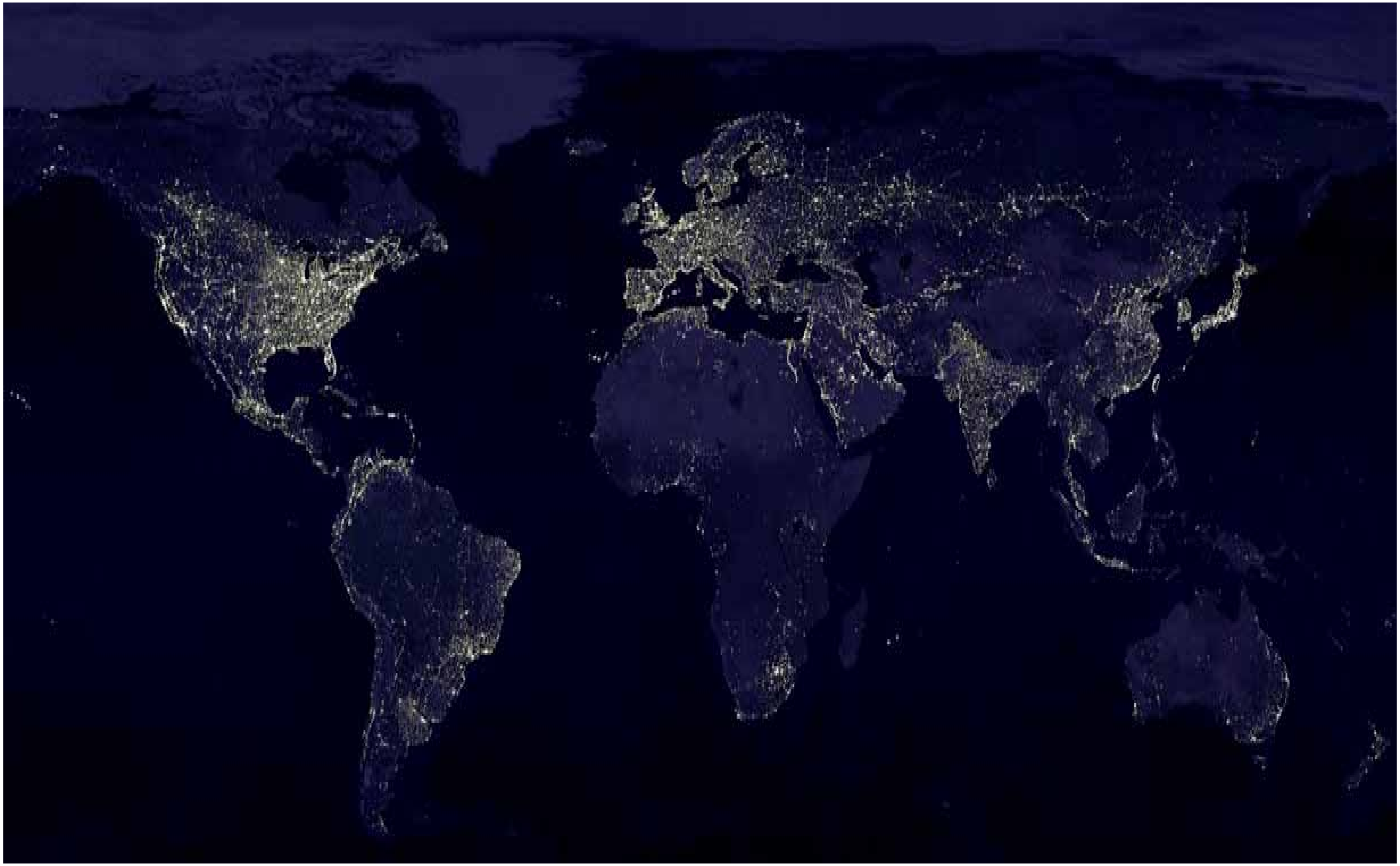
4, China Low Activation Martensitic (CLAM) Steel

5, Summary

1, Introduction

- **After fifty years research and development, fusion research nowadays in the world has been mainly focused on the fusion energy and reactor technologies.**
- **With promotion of large scale fusion devices in the world, such as ITER, fusion reactor related key technologies were developed well in the past ten to fifteen years.**
- **For its large populations and rapid economic growing, China could be the country that is the eagerest to use fusion energy in the world.**

Half of China is still in the dark



China Existing Power Ability and Electricity Produced in 2004

	Existing Ability (MW)		Power Produced (Mkwh)	
	Ability	(%)	Power	(%)
Coal&Oil	324900	73.7	1807300	82.6
Hydro	108260	24.6	328000	15.0
Nuclear	6840	1.55	50100	2.3
Total	440700	100.0	2187000	100.0

China, A Developing Country

- In 1998, a superconducting tokamak project, HT-7U, was approved by China government.
- In 2003, China government decided to joint ITER negotiation in a very short time.

In 2003, the name of HT-7U was changed to Experimental Advanced Superconducting Tokamak (EAST)

The Scientific and Engineering Missions of the EAST Project are:

- to study physical issues of the advanced steady-state operation modes
- to establish technology basis of full superconducting tokamaks for future reactors

ASIPP

SC magnets design & fabrication

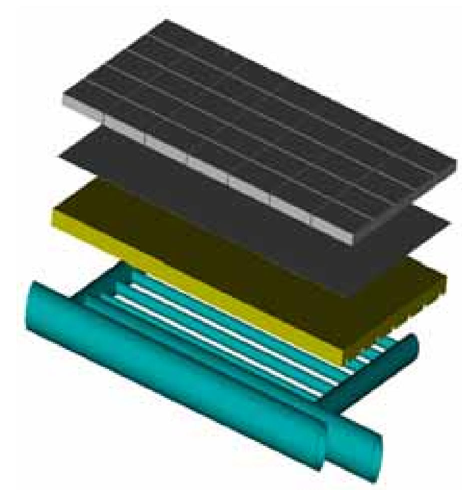
CICC design and jacketing

Plasma facing materials

Fusion Reactor Related Technologies Developed in ASIPP

SC magnet test

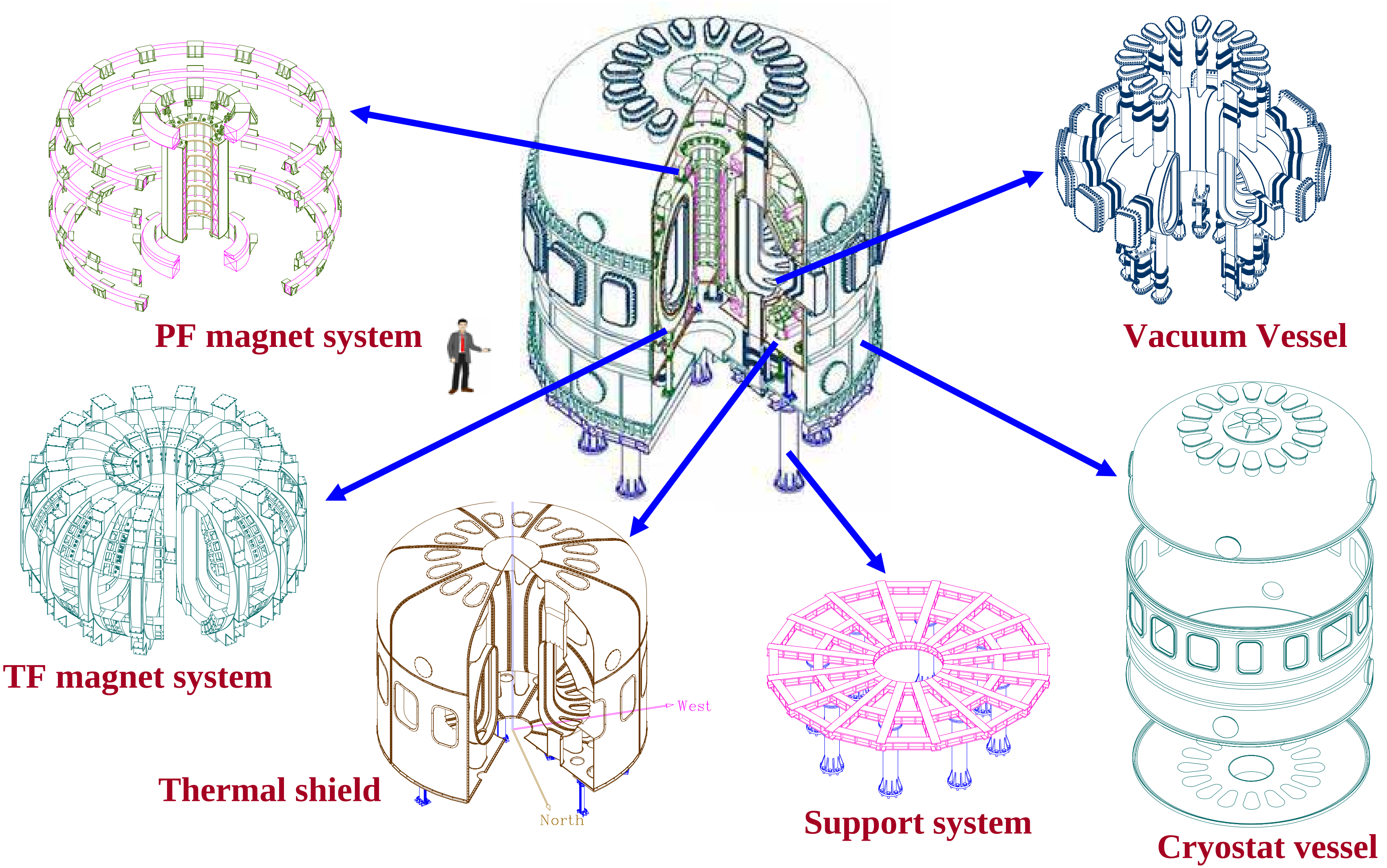
CLAM



Plasma facing components

2, Large Scale Superconducting Technologies

Main Components of the EAST Tokamak Machine



- **Because existing NbTi strands were used, the copper ratio must be optimized.**

Main Parameters of SC Strands

Strand Diameter: 0.85 mm

Ic: 500 A（at 4.5 K，5 T）

426 A（at 4.5 K，5.8 T）

Number of Filament: 8910

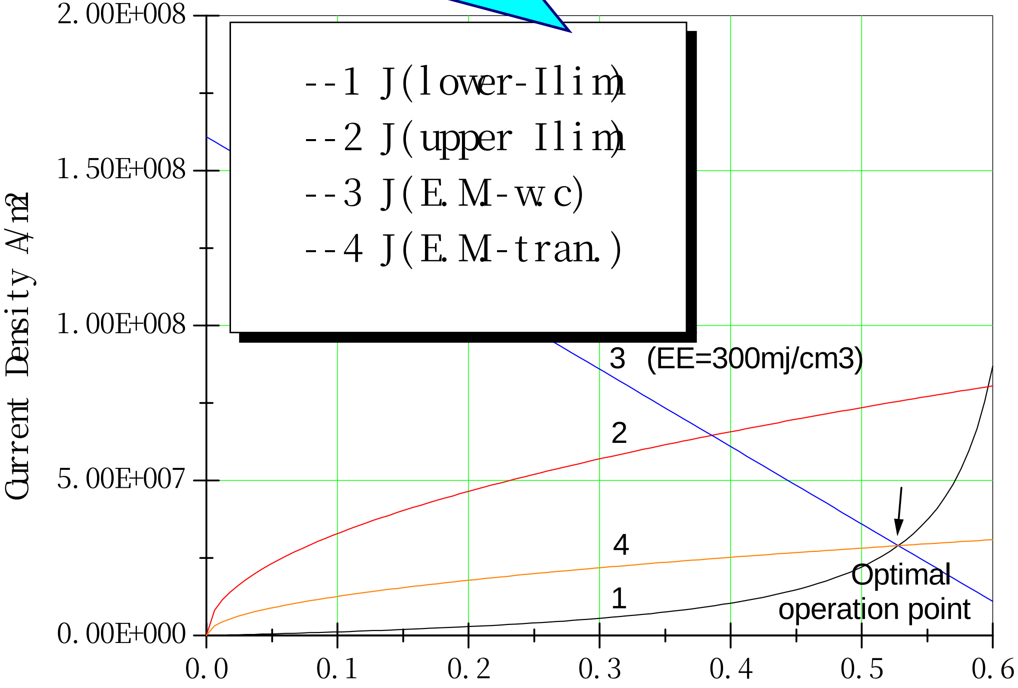
Filament Diameter: 6 μm

Twist Pitch ： 10 mm

Cu:SC 1.38：1

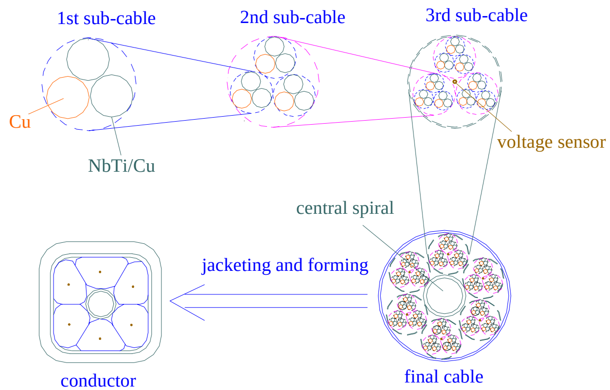
RRR： > 70

The copper fraction has been optimized to be 0.53 with specified energy margin of 300 mJ/cm^3 and the void fraction of 0.35

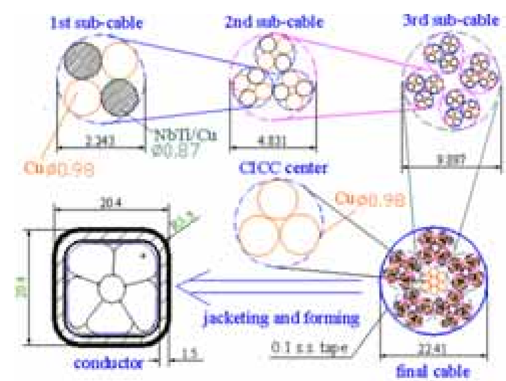


Much attention has been paid on NbTi superconductivity engineering development

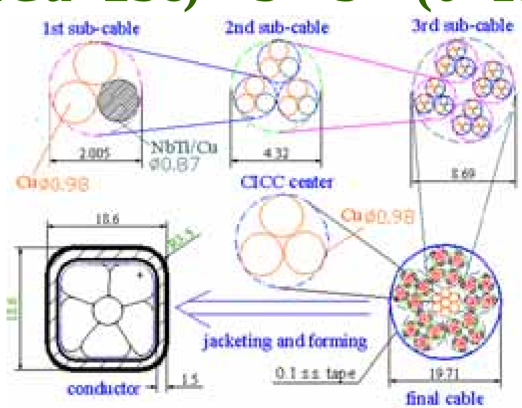
Several types of CICC were designed and analyzed.



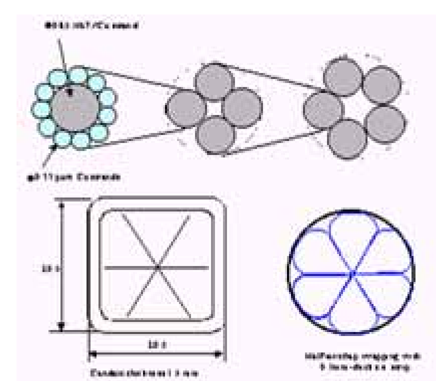
A: (1Cu+2Sc)×3×3×(6+1Spire)



B: (2Cu+2Sc)×3×4×(5+1Cu Cable)



C: (2Cu+1Sc)×3×4×(5+1Cu Cable)



D: (11Cu+1Sc)×4×5×6

To make sure how the separated copper strands and the surface treatment contribute the conductor stability, six different configuration 3rd sub-cables had been designed and tested.

No.	1	2	3	4	5	6
Configuration	(1SC+11Cu)×4×5		(2SC+2Cu) ×4×4			
Diameter of Cu	0.3		0.98		0.87	
Twist pitch	23, 45, 99		50, 86, 117			50, 85, 120
Surface handling	Coated	Coated & soldered	Bare	Coated	Bare	Coated
Dimension	8.05×8.15		9.60×9.80	9.50×9.60	9.20×9.30	9.01×9.10
Cu/Sc	4.53	4.81	4.41		3.76	
Void fraction	0.36 (design value)					
Void fraction	0.32	0.31	0.36	0.33	0.37	0.33

The test results shown sample 4 which configuration is (2SC+2Cu) ×4×4 is the best.

		Samples Sequence (from the best to the worst)					
		The best					The worst
AC losses	~ 0.15 T/s at 4.2 K	4	3	6	2	5	1
	~ 0.15 T/s at 5.7 K	4	6	3	5	-	-
	~ 9 T/s at 4.2 K	4	2	6	3	5	1
		no quench		quench			
Stability	Short (50 mm) Inductive Heater ($\tau \approx 0.3$ ms)	4	2	6	3	1	5
	Long (200 mm) Inductive Heater ($\tau \approx 0.6$ ms)	4	6	3	2	5	1

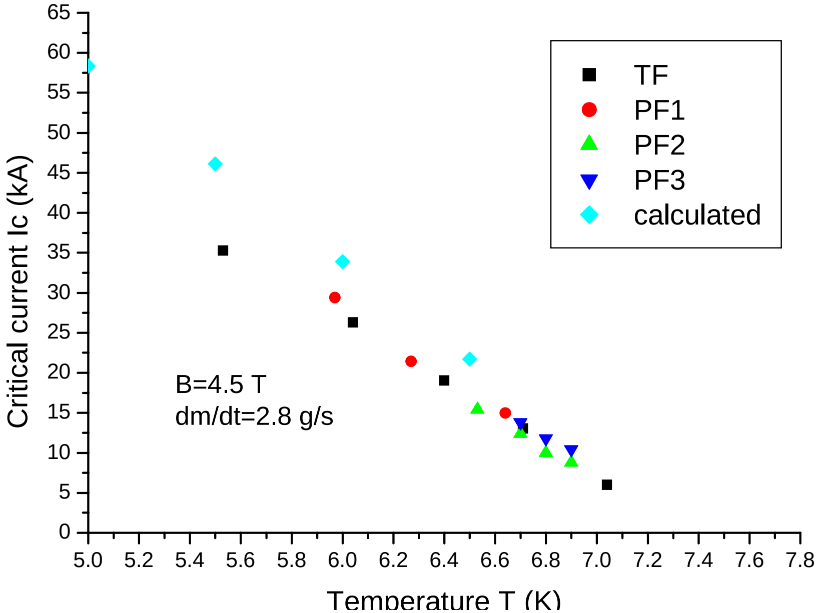
CICC Short Samples Test

Main purposes of the short samples test is to check the design of conductor and answer the following questions:

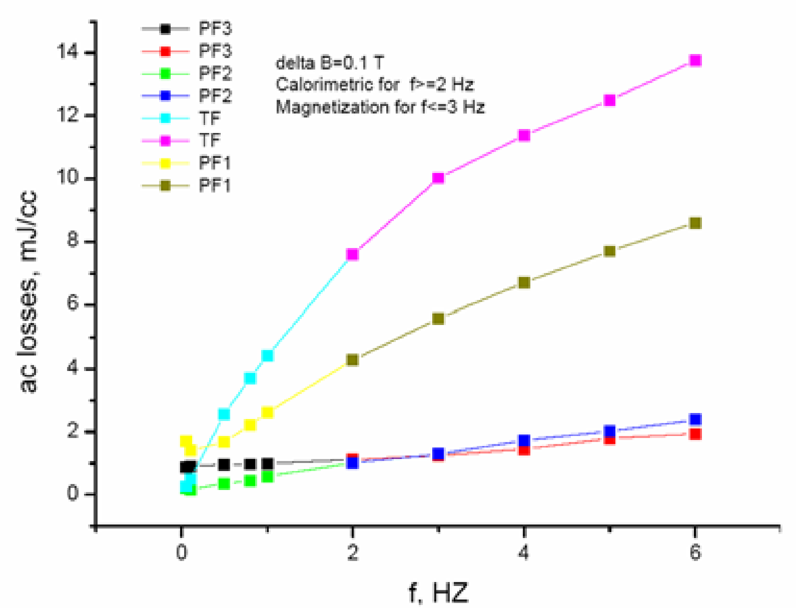
- Whether it is possible to use separated copper strands for both TF and PF conductor?
- How much margin does the conductor have? Is it stable enough to against plasma disruption?
- Which coating is more suitable for TF and PF conductor?

Short Samples Parameters

	unit	TF	PF (3 versions)		
			1	2	3
Configuration		(2SC+2Cu)×3×4×5+1 Central Cu Cable			
Surface handling		Solder coating		Ni coating	
Wrapping on the 3rd sub-cable		Without wrapping	With wrapping		Without wrapping
Conductor dimension	mm	20.4×20.4	20.8×20.8		20.47×20.47
Diameter of SC strands	mm	0.87			
Number of SC strands		120			
Diameter of Cu strands	mm	0.98			
Number of Cu strands		120+21			
Copper ration (Cu/SC)		4.91			
Void fraction (V_f)		0.341	0.355		
Peak filed (B_m)	T	5.8	4.5		
Operating current (I_{op})	kA	14.3	14.5		



AC loses measurement



The critical current of TF&PF conductors

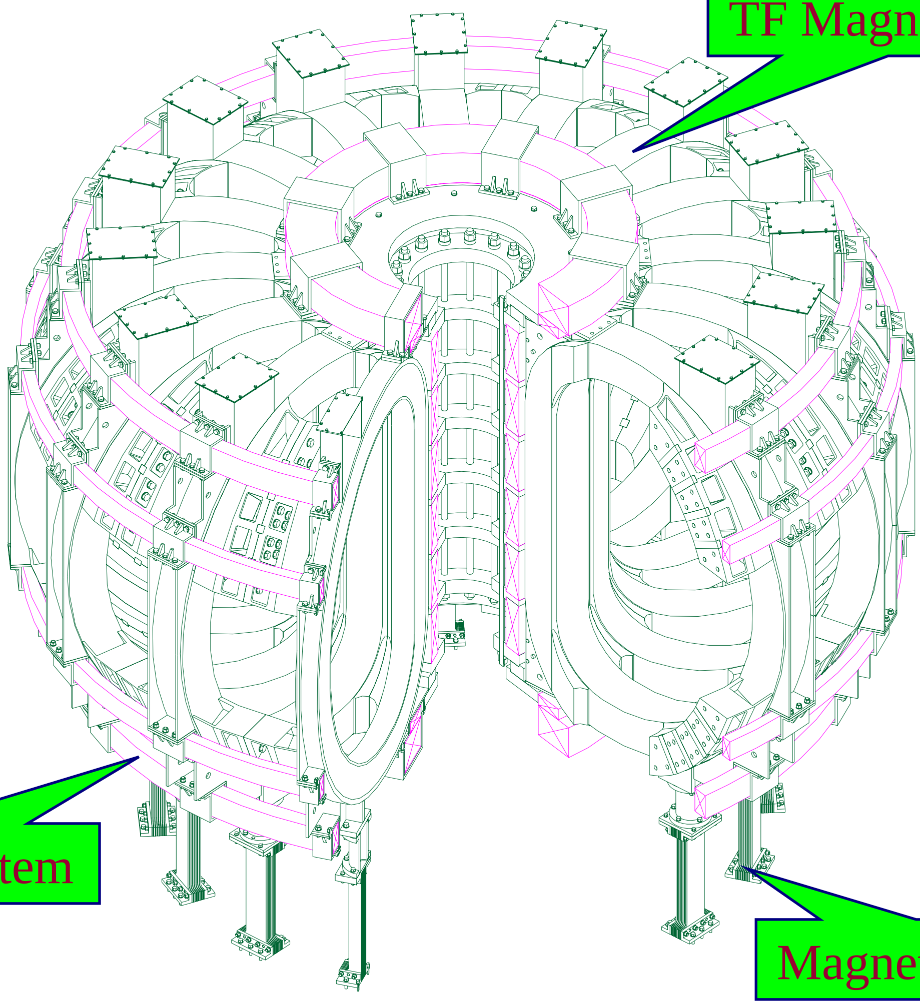
- **The critical current Ic of all samples at different fields are 10-12 % lower than strand nominal data. It could be caused by filaments broken in the strand.**
- **The current sharing temperatures Tcs are lower than calculations, which could be caused by high inter-strands transverse resistance and stainless steel wrapping on the third stage sub-cable.**
- **The AC losses test results shown the time constants of the conductors are much lower than expected.**
- **We also fond higher mass flow rate may improve transient stability.**
- **We are glad to see all conductors have enough ability against transient disturbance at the nominal operating condition.**

The main parameters of the EAST CICC

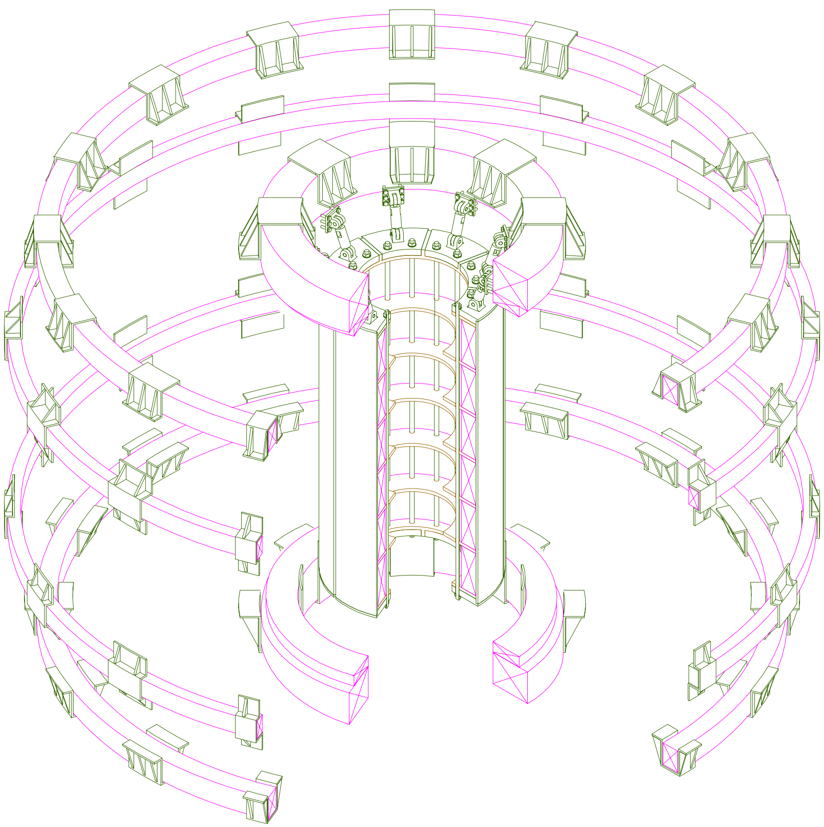
	TF	CS/Divertor	Big PF
Rated peak field	5.8 T	4.5 T	2 T
Rated operation current (I_{op})	14.3 kA	14.5 kA	
Rated operation temperature	4.2 K		
Cable configuration	(2SC+2Cu)×3×4×5+1CCC		(1SC+2Cu)×3×4×5+1CCC
Conductor dimension	20.4× 20.4 mm^2	20.3× 20.3 mm^2	18.5× 18.5 mm^2
Conduit thickness	1.5 mm		
Number of SC strand	120		60
Number of Cu strand	120+21		
Diameter of SC strands	0.85~0.87 mm		
Diameter of copper strands	0.98 mm		0.98/0.87 mm
RRR of Cu strands	> 100		
Coating materials	Pb-30Sn-2Sb	Nickel	Pb-30Sn-2Sb
Solder thickness on strands	2-3 μm	2 μm	3 μm
Cu fraction (f_{cu})	0.54		0.44
Helium fraction (f_{he})	0.34	0.35	0.359
I_{op}/ I_c	0.28	0.224	0.31
Temperature margin ($T_{cs}-T_{op}$)	1.88 K	2.54 K	2.29 K
Energy margin (ΔE)	250 mJ/cm^3	350 mJ/cm^3	400 mJ/cm^3

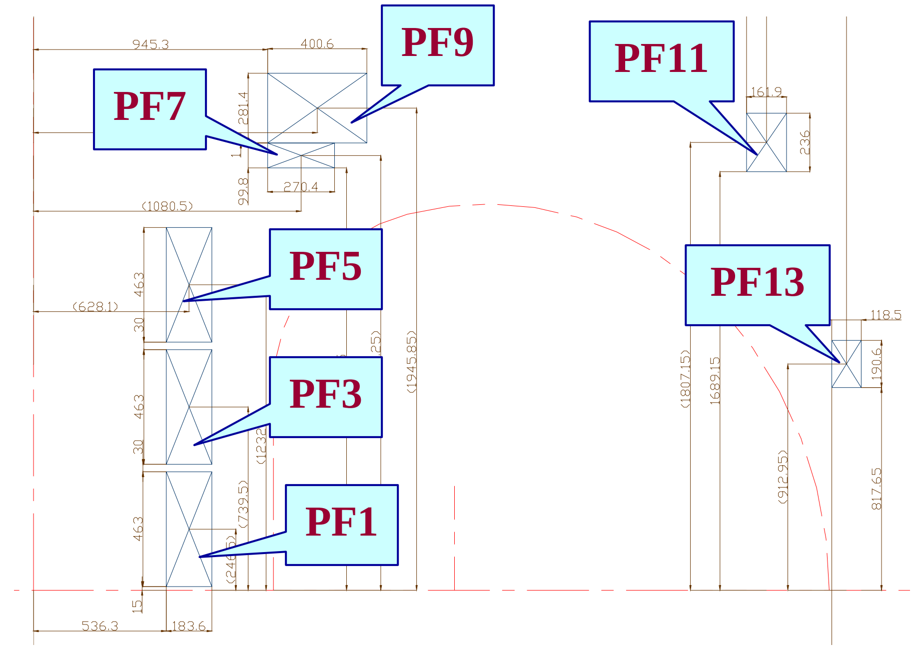
Superconducting Magnets of EAST

EAST could be the first tokamak machine with both PF and TF superconducting magnets



PF Magnets





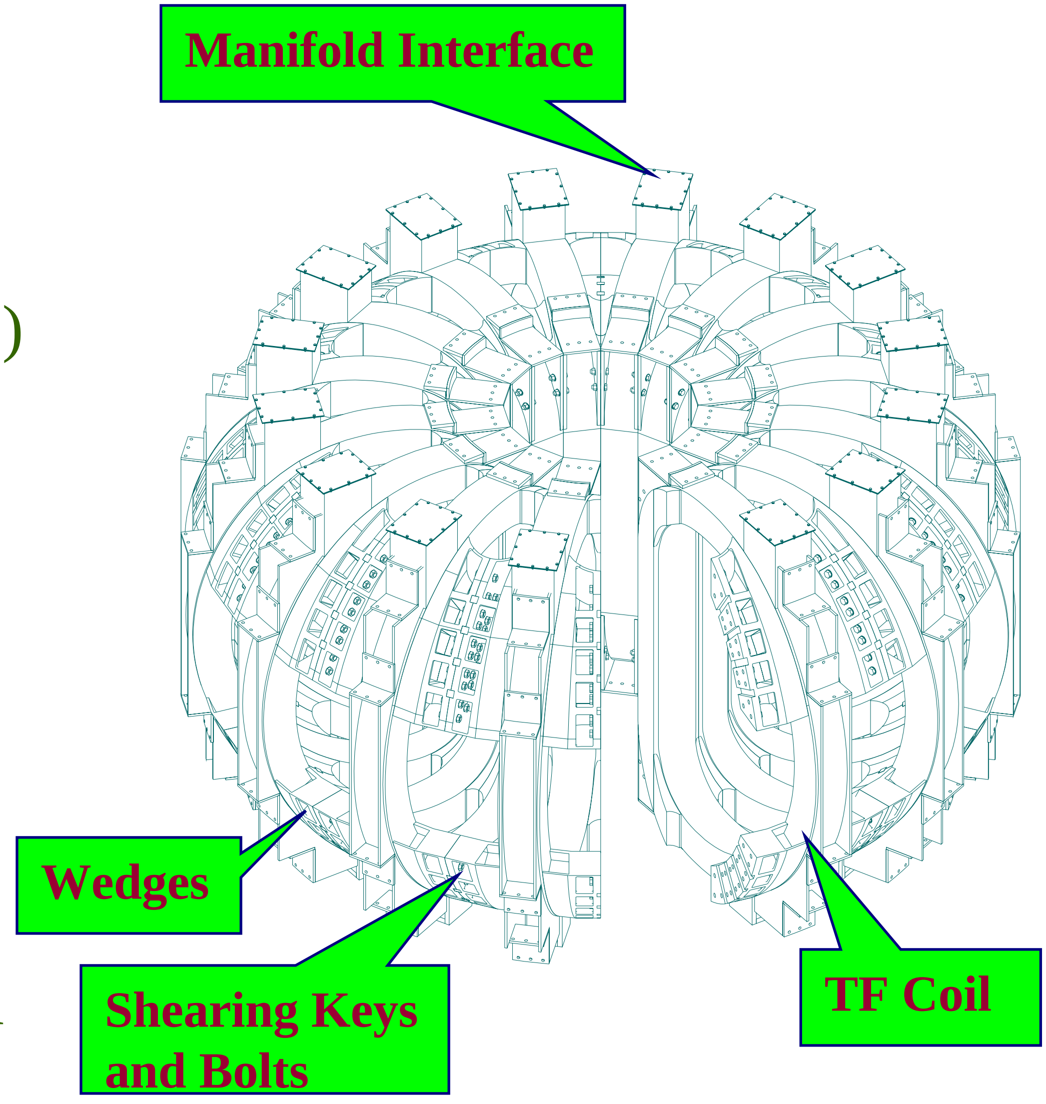
PF Parameters

Coil No.	14
I_{op}	14.5 kA
B_{max}	4.5 T
dB/dt	< 7 T/s
T_{op}	4.2 K
Mass flow	2.8 g/s
Cond.	CICC
Material	NbTi

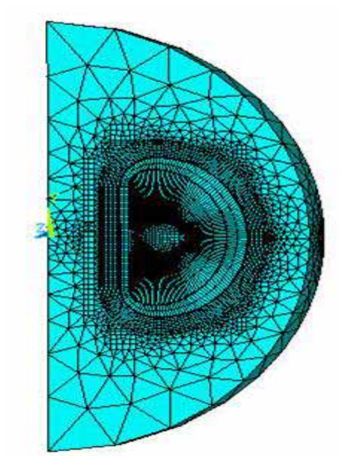
TF Magnets

TF Parameters

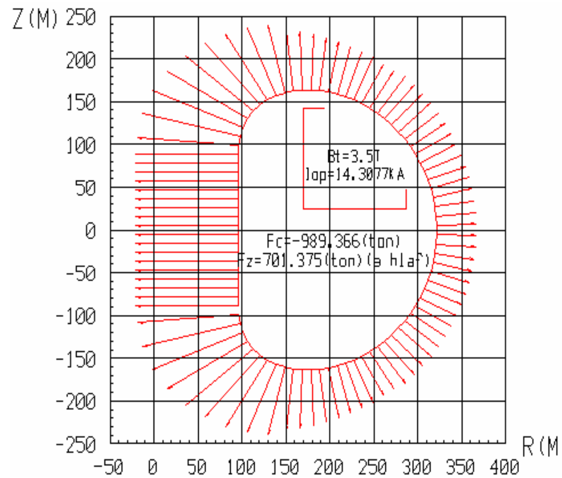
Coil Number	16
Turns	2080(16×130)
E_{stored}	300 MJ
B_{max}	5.8 T
I_{op}	14.3 kA
T_{op}	4.2 K
Mass flow	2.7g/s
Cond.	CICC
Material	NbTi
Coil Size	2.5 m ×3.5 m



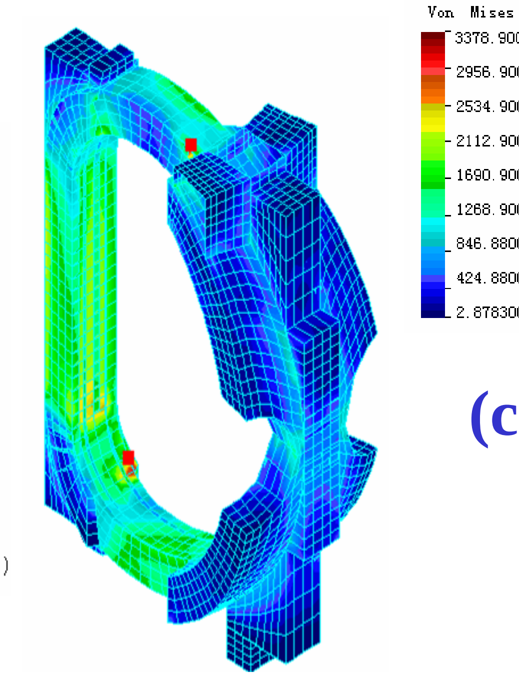
FE Analysis of TF Coil



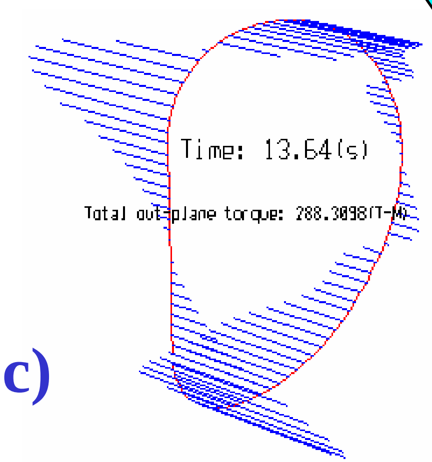
(a)



(b)



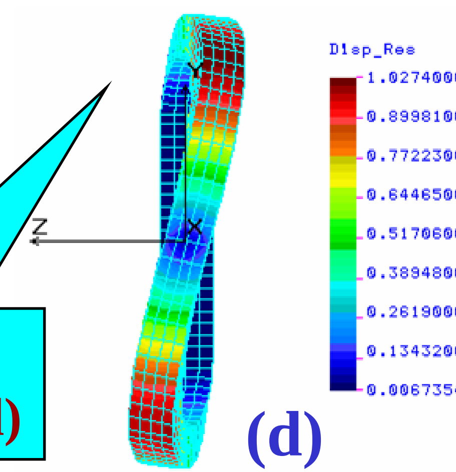
(c)



(c)

Magnet field Distribution (a), Centripetal forces (b) and torque moment (c)

Stresses (c) and deformations (d)



(d)

600 m CICC jacketing technology was developed successfully in ASIPP. 35 km qualified CICC have been produced.

Conduit Cleaning

Conduit Surface Check

Conduit Welding

Joint Test

Conductor Check

Conductor Receiving

Conductor Extruding

Cable Insert

Technologies to fabricate PF and TF coils in pre-bending and continuous winding way have been developed.

TF coil winding

TF case machining

TF magnet VPI

17 TF coils fabricated

PF coil winding on site

PF coil VPI on site

15 PF coils fabricated

To test the superconducting performances of coils before installation, a cryogenic test facility system set up in ASIPP.

Cryostat with CLs:
Diameter 3.4 m
Height 6.7 m
Vacuum 1 × 10^{-5} τ
Current leads 2 pairs
20-30 kA

Power Supply:
24 kA/0-100V(CW)
100kA/0～800V(5s)

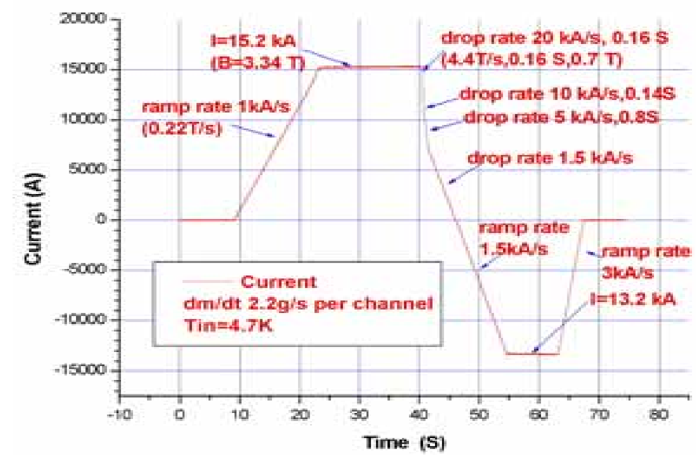
Cryogenic test facility system

Refrigerator:
500 W/4.5 k

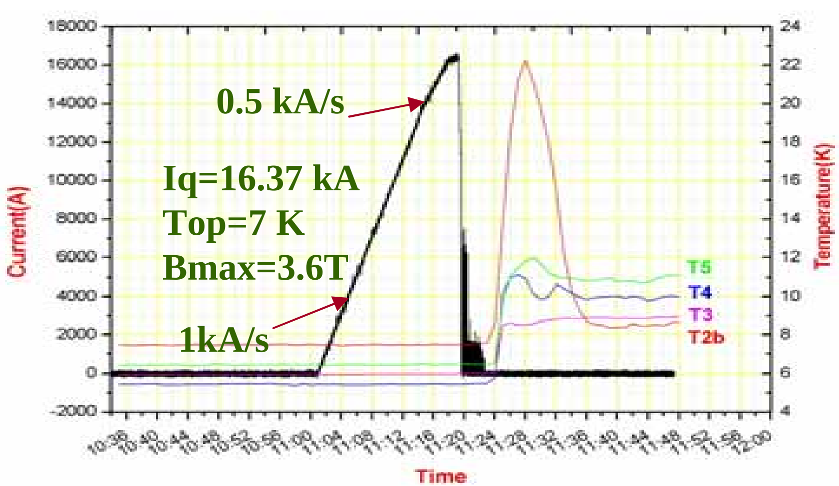
Control & Data Collection System

The tests of the CS prototype coil had shown pretty good results in 2003.

CS prototype coil inside the cryostat of the test facility

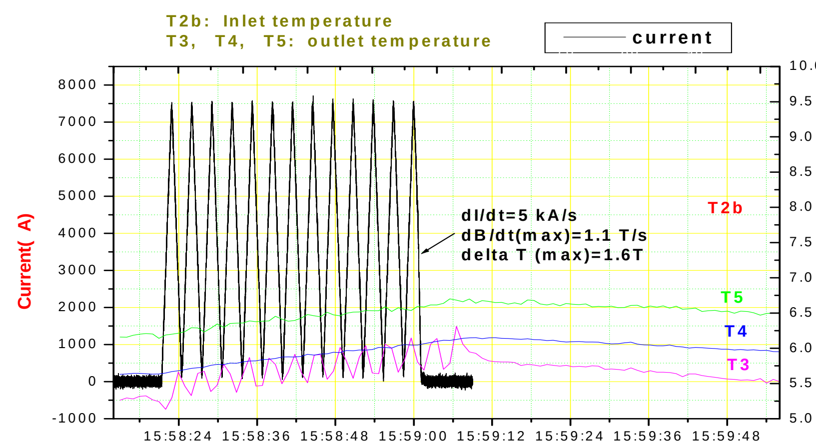


Current charge/discharge



Quench current test

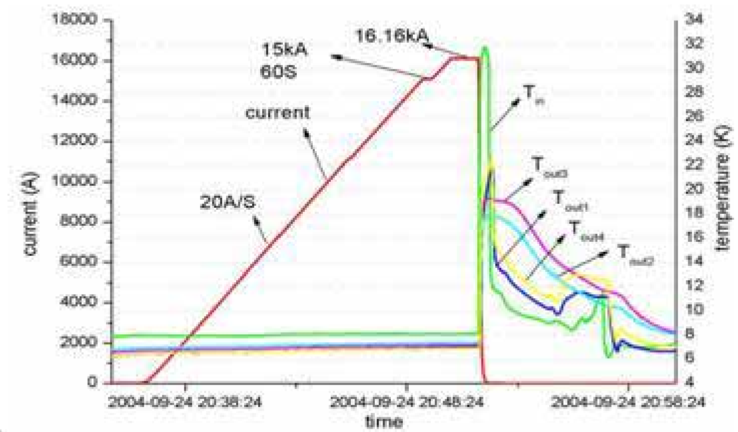
Extrapolated Iq= 54 kA (3.8 K, 4.5 T)



AC losses test

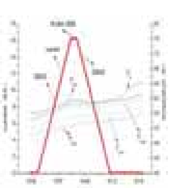
After TF prototype coil test, sixteen TF magnets have been tested successfully and shown similar performances

One TF coil inside the cryostat of the test facility

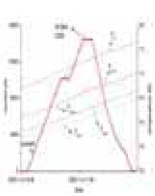


Quench current test

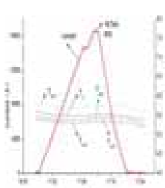
Extrapolated Iq= 58kA (3.8K, 6.72T)



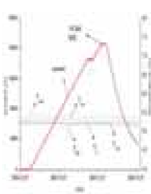
1# TF



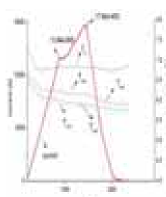
2# TF



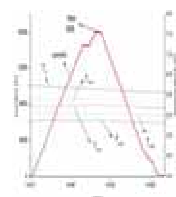
3# TF



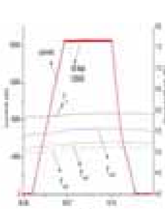
4# TF



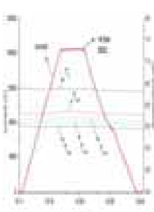
5# TF



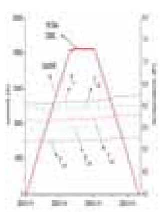
6# TF



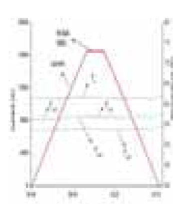
7# TF



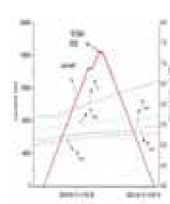
8# TF



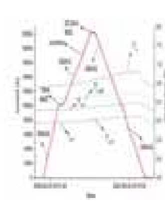
9# TF



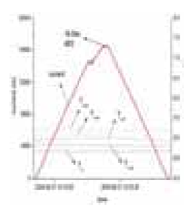
10# TF



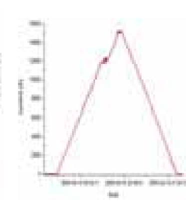
11# TF



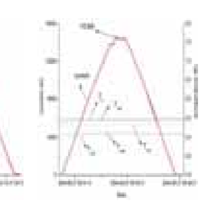
12# TF



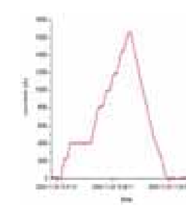
13# TF



14# TF



15# TF

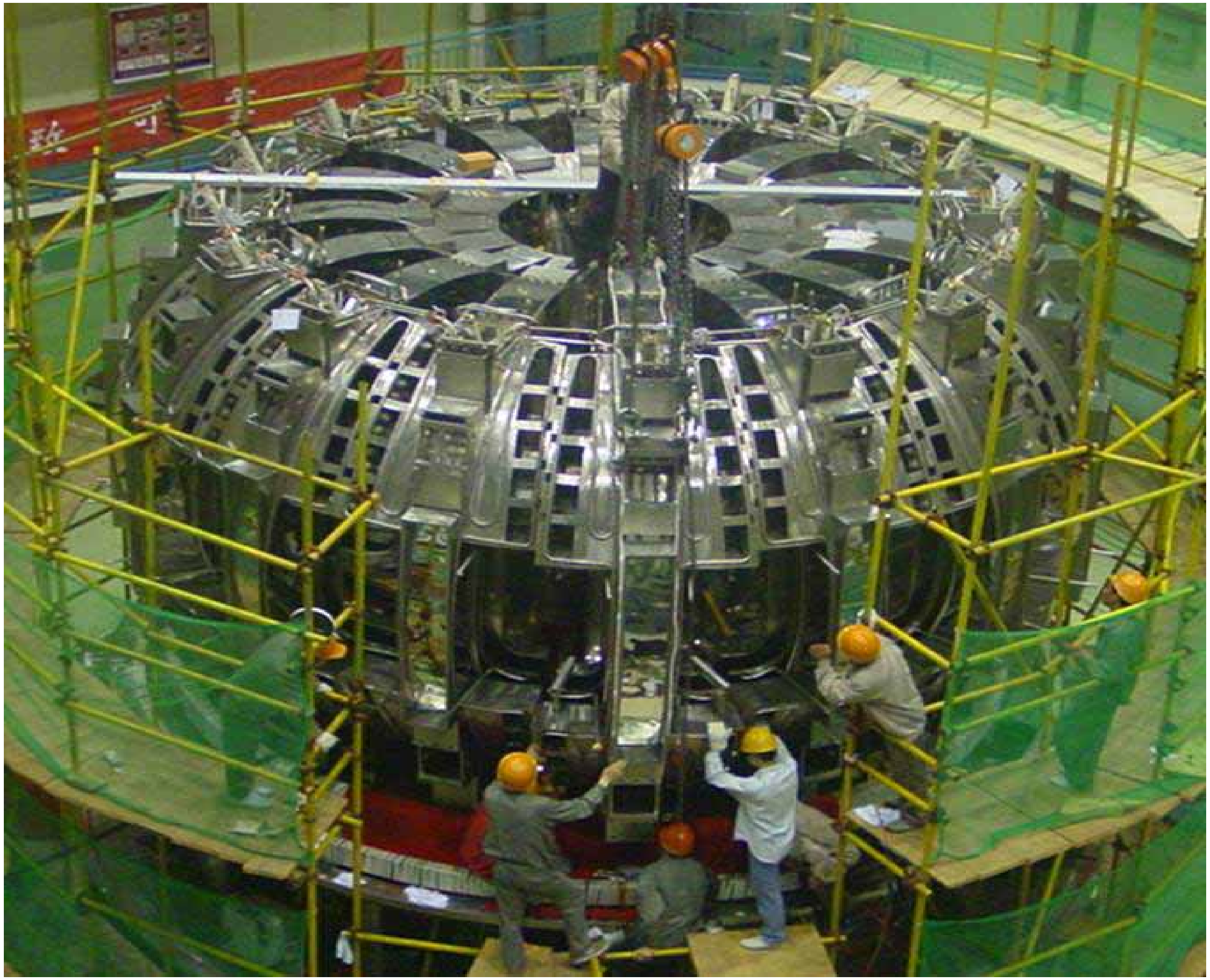


16# TF

The hints of successful CICC-SCSS

- **It is well-known that the superconducting strands are quoted as its weight no matter how much copper ratio of the strand.**
- **The fine results of CICC-SCSS (CICC with separated copper strands as stabilizer) could be useful to develop CICC with high performance-price ratio and reduce the cost of reactors.**

The assembly of toroidal field magnet system with 300 MJ stored energy has completed in the end of April.



3, Plasma Facing Materials and Components

GBST1308 Doped Graphite

- **A name of GBST1308 (1%B, 2.5%Si, 7.5%Ti) with high thermal conductivity up to 180 W/m.K (RT), has been successfully developed and used as the main belt toroidal and poloidal limiter materials of the HT-7 superconducting tokamak.**

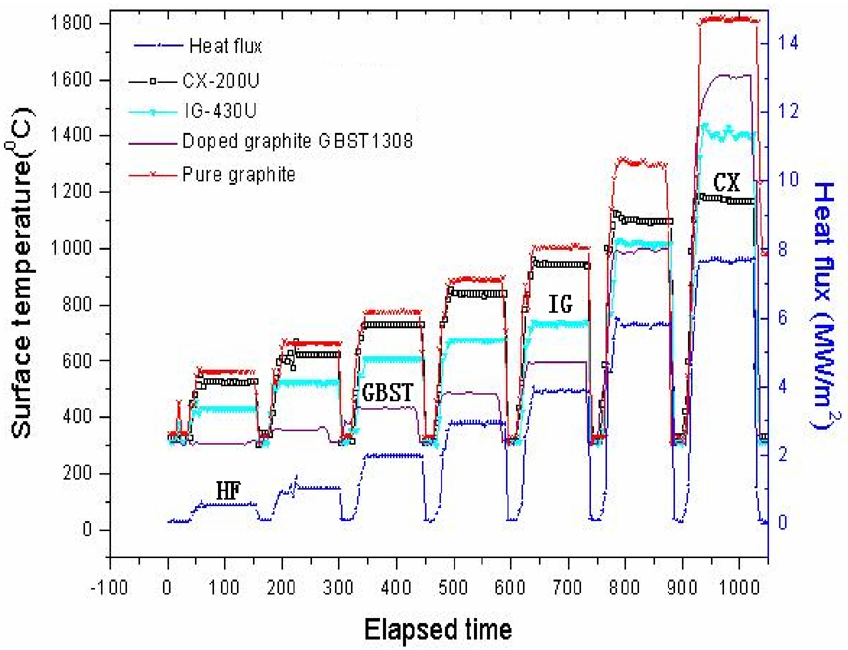
Thick SiC/B_4C gradient coatings attractive first wall material for EAST

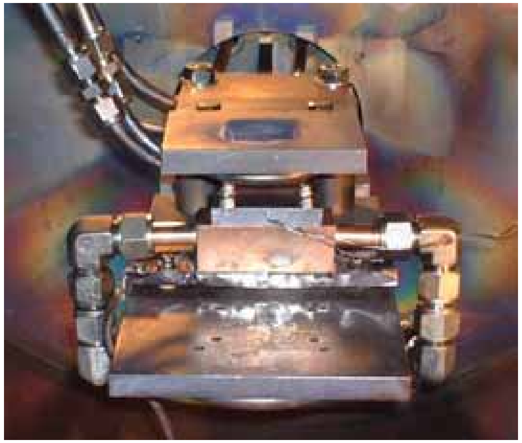
The HT-7 toroidal and poloidal limiters

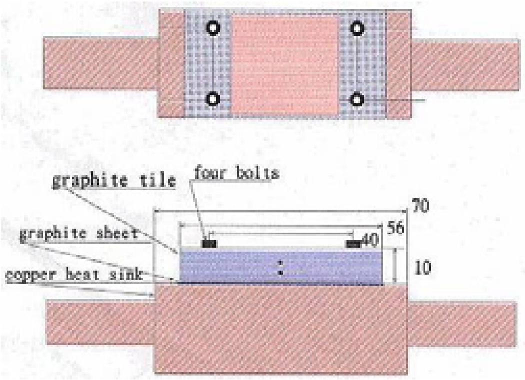
Good Performances of GBST1308

- **The bending strength of GBST1308 is higher than 46 MPa;**
- **The thermal conductivity of GBST1308 is up to 150 W/m•K at room temperature and very stable with the temperature rise.**
- **Good thermal shock resistance, which can withstand 8 MW/m^2 high heat loads for 100 s, no obvious crackle phenomena occurs;**
- **Good vacuum engineering properties with low outgassing rate favorable for reducing recycling and density control; the total outgassing rate is 5×10^{-13} Torr.L /s.cm^2 at RT, which nearly one order low than of IG-430U, an isotropic fine grain graphite;**

- The thermal performance of the material under SS-HHF was evaluated under actively cooling condition.
- The specimens were mechanically joined to copper heat sink with super carbon sheet as a compliant layer between the interface.
- Results are very encouraging that the surface temperature of GBST1308 is less than 1000 ^{o}C when HF is not more than 6 MW/m^2.

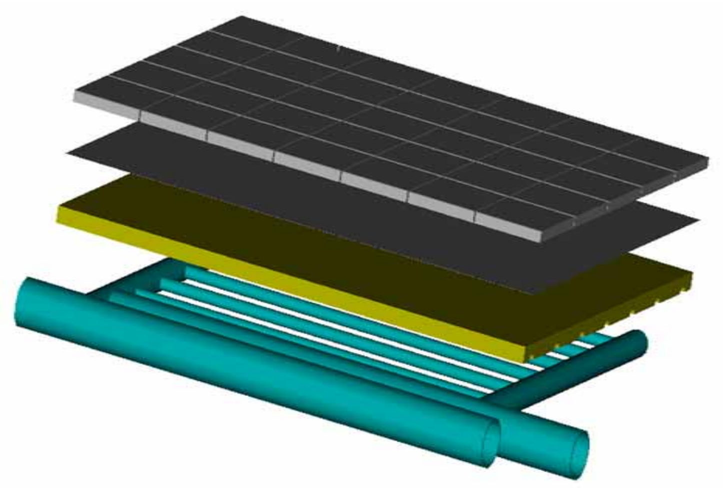


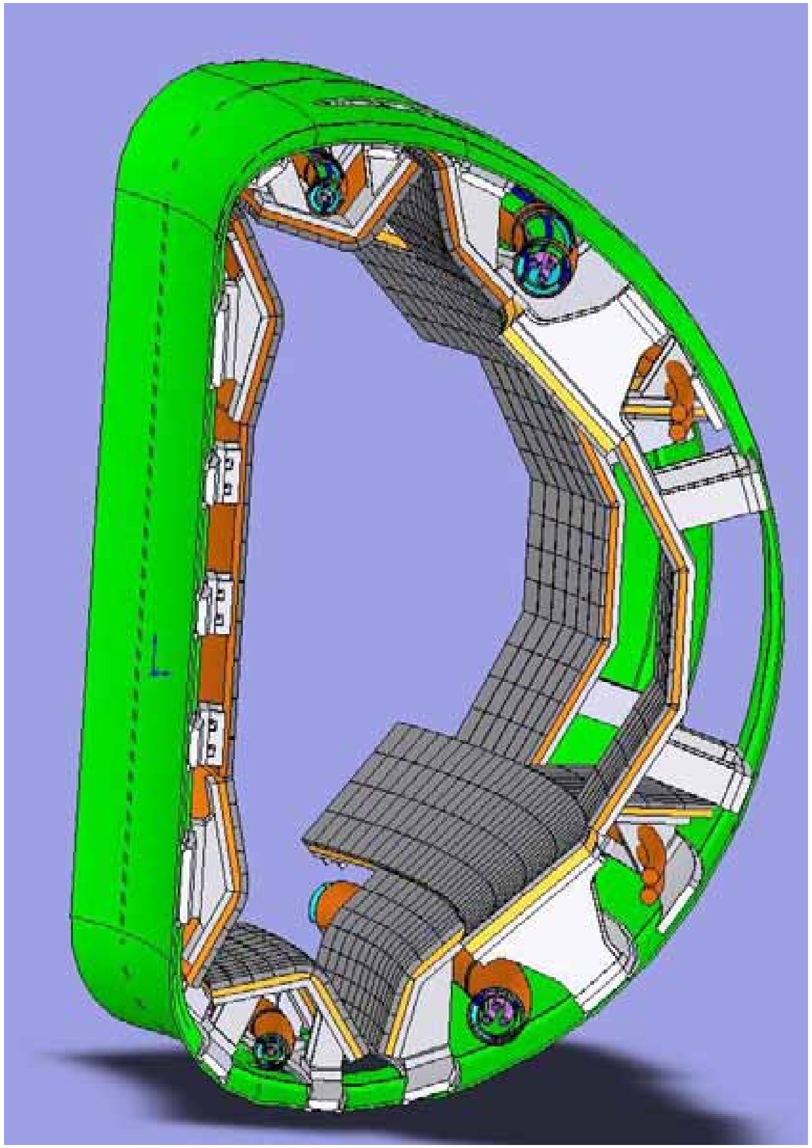




Evaluate the performance of different materials for divertor/FW

- FWM: < $1MW/m^2$, technically ready
- High-field side: SiC coating on the doped graphite, bolted heat sink;
- SiC/B_4C coating on the high performance doped graphite (inner leg), C brazed to Cu heat sink.





3, China Low Activation Martensitic (CLAM) Steel

Compositions of CLAM

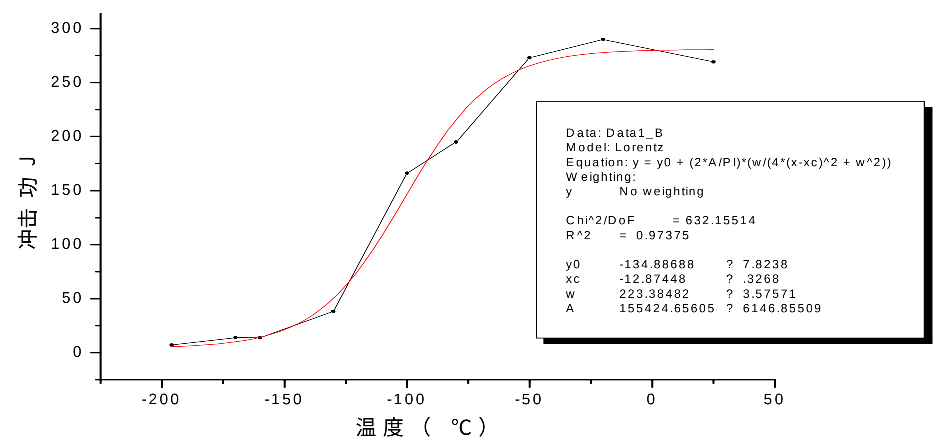
- Based on investigation of RAFMs (Reduced Activation Ferritic/Martensitic steel) in the world.
- Main considerations:
  - –Tungsten 1.5 wt%
    - **Lower than F82H (2wt%) and higher than Eurofer97 (1wt%)**
    - **to maintain the strength and reduce the possibility of Laves phase**
  - –Chromium 9 wt%
    - **To obtain the lowest DBTT**
  - –Tantalum 1.5%
    - **To fine the grains and get high creep resistance**

Heat treatment and tensile test of CLAM

- Recommended heat treatment
  - **980 °C/30 min followed by air cooling**
  - **760 °C/90 min followed by air cooling**
- Properties tests
  - **DBTT (about-100°C)**
  - **Tensile tests (results shown in table)**

Tensile tests of difference heat treatment conditions

Heat treatment	T(°C)	σ_b(MPa)	$\sigma_{0.2}$(MPa)	δ_5(%)
1040°C/air 760°C/air	RT	651.94	501	28.8
	600	336	295	27
1040°C/water 760°C/air	RT	639.69	492	28
	600	323	278	29
980°C/air 760°C/air	RT	668.65	514	24.8
	600	334	293	29
980°C/water 760°C/air	RT	654.3	509	28
	600	334	286	29



DBTT in recommended heat treatment condition

Joining techniques of CLAM

- Hot Isostatic Pressing diffusion bonding
  - **Preliminary experiments**
  - **Ongoing properties tests**
- Other joining techniques (future plan)
  - **TIG (Tungsten Inert Gas welding)**
  - **LBW (laser beam welding)**
  - **EBW (electron beam welding)**

Joints of HIP

5, Summary

- The superconducting magnet with cryogenic technologies have been developed in ASIPP quite well in the past five years.
- ASIPP has experience and effective facilities in the design, fabrication and test of different magnets.
- ASIPP would like to cooperate with institutes, universities and companies not only in China, but also in the world.

Thank You !