

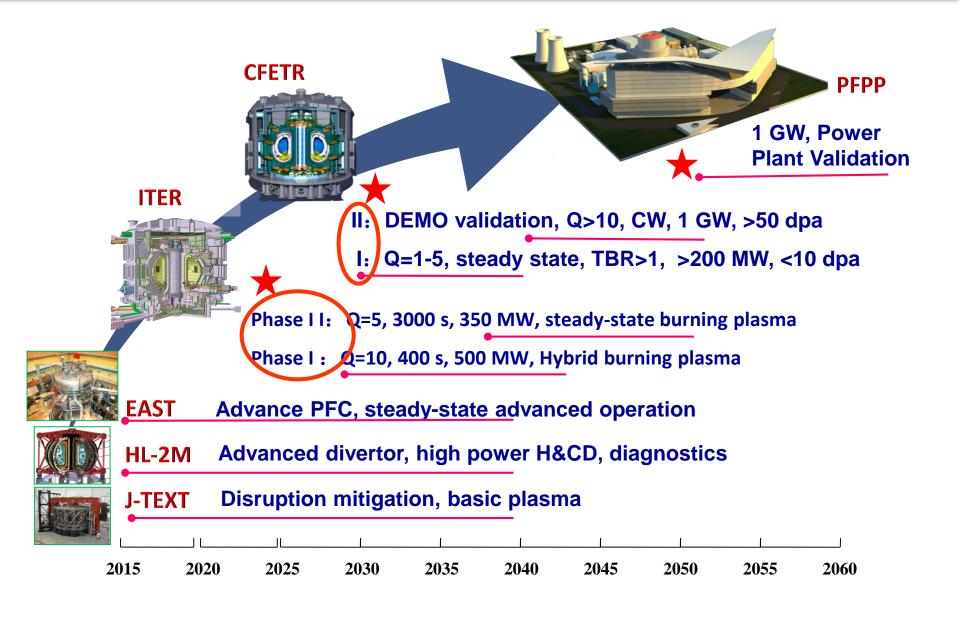
# Challenges of Superconducting Magnet System and Development of TF Prototype coil of CFETR

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2019-9-23

### China MCF Roadmap





## **Key Points of CFETR Mission**





- 1. P = 200-1500MW
- 2. Q = 1-10, SSO, hours
- 3. Q = 20-30 hours-SSO
- 4. High energetic α heating

Steady-state operation for fusion energy

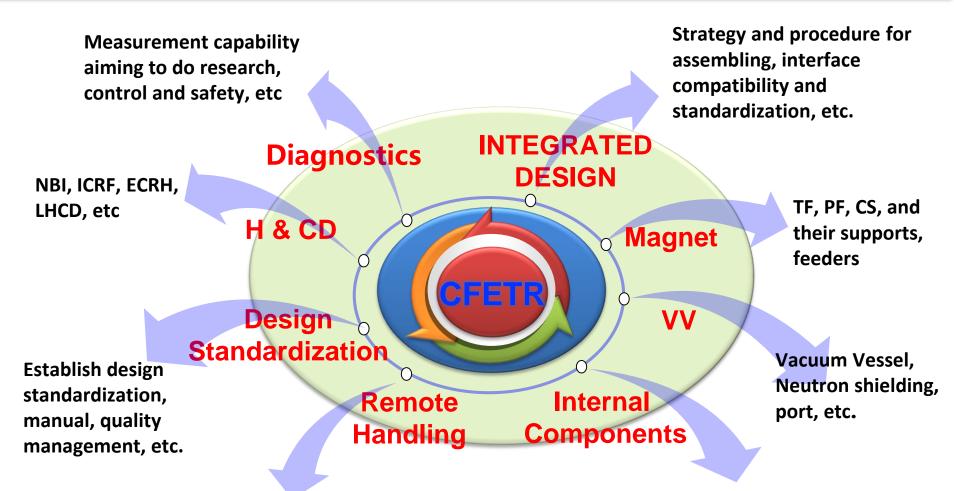
- 5. Hybrid (OH+BS+CD)
- 6. SSO (Ext H&CD + Higher f<sub>b</sub>)
- 7. PSI on the first wall
- 8. Heat & particle exhaust on Div.

Breeding tritium for T self-sustained

- 9. T-breeding by blanket
- 10. T-plant: extract & reprocessing
- 11. Materials & components
- 12. Reliable and quick RH
- 13. Licensing & safety

# **CFETR Engineering Design**





Maintenance and replacement for internal components, NBI, RF antennas, diagnostics, etc.

Blankets, interface between pipe and Blanket, Water cooled breeder blankets, Helium cooled breeder blanket, divertor, etc

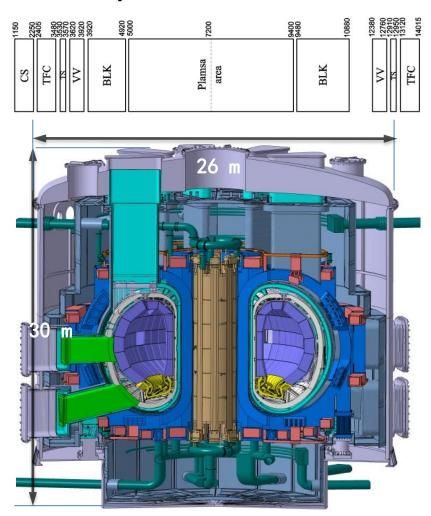
### Key issues for CFETR



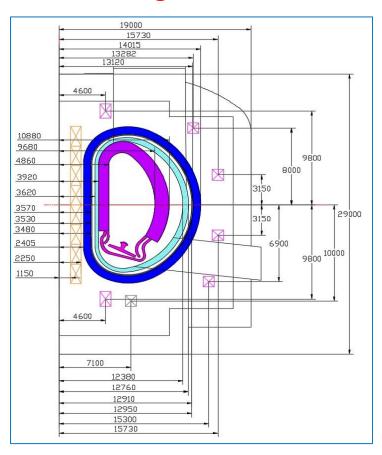
☐ Larger size: R= 7.2 m, a=2.2m

 $\square$  High  $B_T : 6.5 T$ 

☐ Low Ip: 10-15MA



- **□** Advanced CS magnet: ≥ 480 VS
- ☐ Elongation 2; Triangularity 0.8
- **□** Lower Single Null



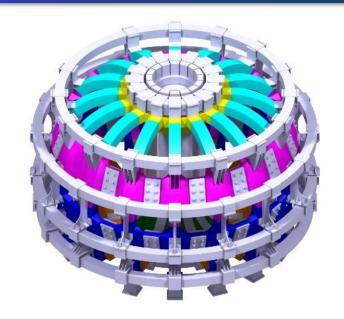
### The requirements of CFETR Magnet system

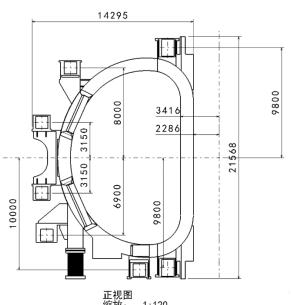


- ◆ The magnet system of CFETR consists of 16 TF coils,
   8 CS coils;
- ◆ PF coils divided into three types according to the type of divertor:ITER-like: 6 PF coils; Snowflake: 7 PF coils;
- ♦ All of the coils have superconducting structure: the TF and CS
  - coils intend to use High Tc Nb3Sn superconductor, while PF and CC coils are suggested to make by NbTi/Nb3Sn superconductor.

#### Main parameters of CFETR

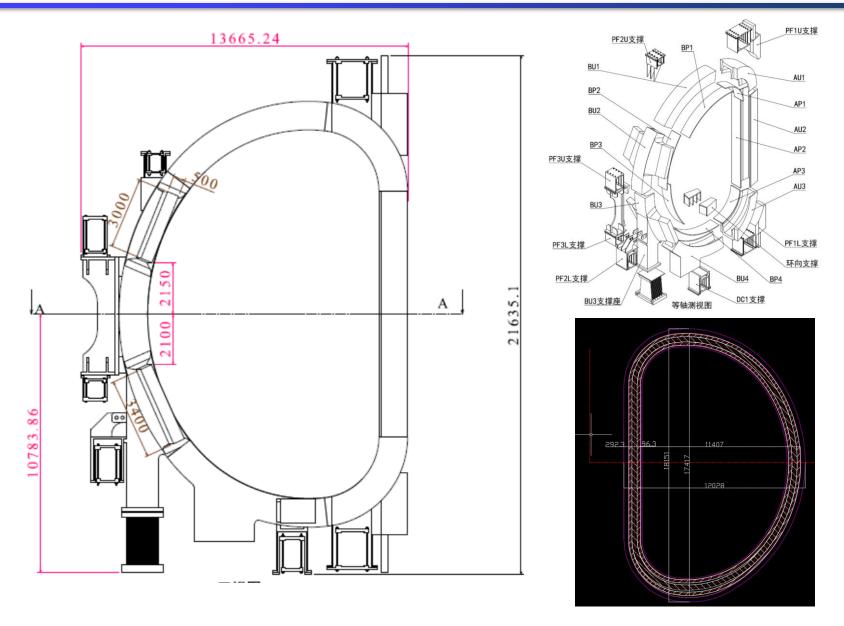
Major radius of plasma	R=7.2m				
v 1					
Minor radius of plasma	r= 2.2 m				
Central magnetic field	Bt = 6.5 T				
Duty cycle (or burning time)	~(30-50%)				
Thickness of blanket	1.0 m				
Magnetic field ripple in the region	<0.5%				
of Plasma					
Tritium must be self-sufficiency by blanket					





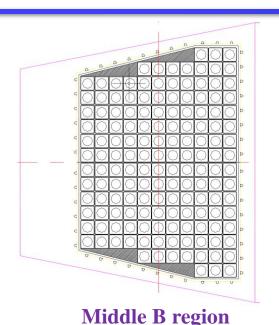
# Toroidal field SC Magnet system





### Conductor layout and jacket optimization





### **Option 1:**

#### Full same Nb<sub>3</sub>Sn conductor

Cross-section of jacket is 64x64mm, conductor R=24mm 8 double pancakes, 152 turns totally

96.8kA, 14.8 T

Just one types of Nb3Sn conductor

Advantages: easier for winding work and joint and helium

inlet/outlet

**Disadvantages:** High cost of the High-Tc Nb3Sn materials



**High B region** 

### **Option 2:**

#### **Hybrid magnets** (with same operation current/turn)

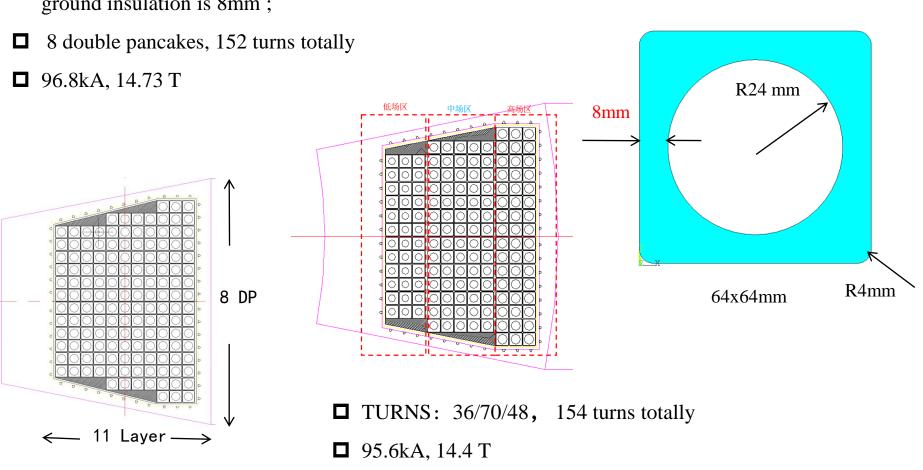
- 1. Cross-section of jacket is 64x64mm, conductor R=18mm Low B region
- 1. Cross-section of jacket is 64x64mm, conductor R=20mm Middle B region
- 2. Cross-section of jacket is 64x64mm, conductor R=24mm High B region 95.6kA, 14.43T

**Disadvantages:** Difficulty for winding work and joint and helium inlet/outlet

## Conductor layout and jacket optimization



□ The thickness of jacket is 8mm(the thinnest position), turn insulation thickness is 1.5mm (a single conductor), layer insulation is 1mm, pancake insulation is 1mm, double-pancake insulation is 3mm, ground insulation is 8mm;



# **Key Parameters**



	ITER TF	EU- DEMO <sup>[2015]</sup>	CFETR TF	CFETR TF (Option 1)	CFETR TF (Option 2-2)
No. of Coil	18	18	16	16	16
Operation current	68 kA	81.7 kA	87.6 kA	96.8 kA	95.6 kA
Inductance	17.34 H	32.68 H	34.93 H	25.8H	26.742H
Total storage energy	40.1 GJ	109.08 GJ	134.02 GJ	135.3GJ	136.37GJ
storage energy(single coil)	2.227 GJ	6.06 GJ	8.376 GJ	8.45 GJ	8.52GJ
Discharge time constant	11 s	23s	20 s		17 s
Quench protection resistance	_	-	$109.1 \mathrm{m}\Omega$		98mΩ
Maximum voltage	5954 V	6450 V	9562 V		9.37 kV

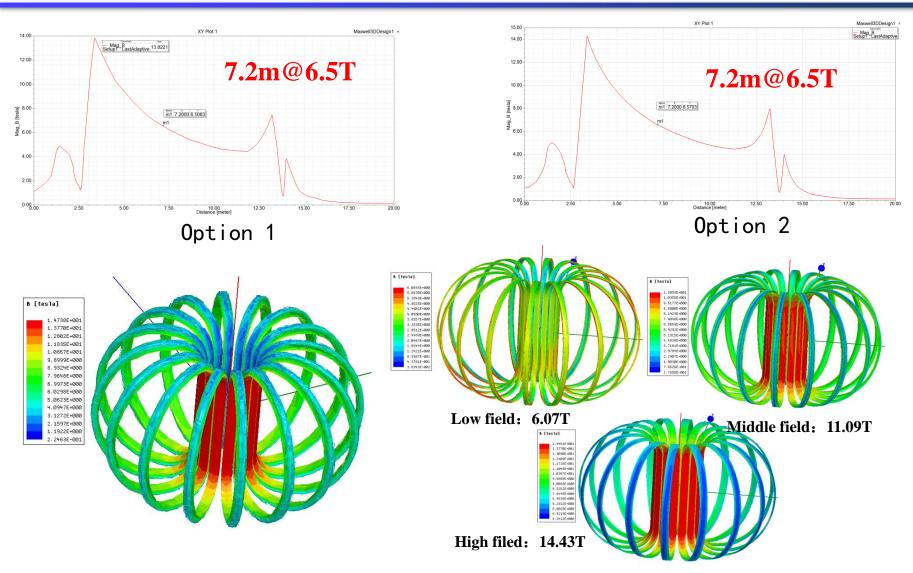
# **Key Parameters**



Parameters	Option 1	Option 2
No. of coils	16	16
Total turns	152	154
Total storage energy	135 <b>G</b> J	136. 37GJ
Operation current	96. 8kA	95. 6kA
Maximum B	14. 73T	14. 43T
Overturning moment	1081.8 MN.m	1070 MN. m
Centripetal force	1132.6 MN	1158 MN
Weight of Coil	250.5 T	249.73 T
Weight of Coil case	474.45 T	470.76 T

# **Electromagnetic analysis**





Option 1: maximum field is 14.73T (including influence from all PF coils

Option 2: maximum field is 14.43T (including influence from all PF coils

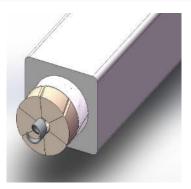
# Stability analysis of high performance Nb3Sn



#### **Conductor Parameters:**

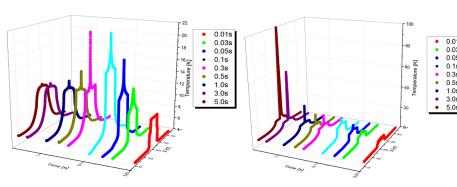
SC strand No.: 900 Cu strand No.: 522

J<sub>c</sub> @ 12 T, 4.2 K: > 2200 A/mm<sup>2</sup>, J<sub>c</sub> @ 15 T, 4.2 K: > 1000 A/mm<sup>2</sup>

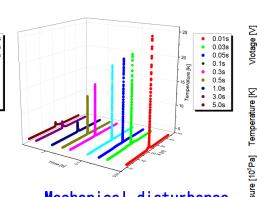


OST or WST wire near future

- total helium mass flow rate of each TF coil will be 12g/s, initial of helium pressure is 5.0 10<sup>5</sup>Pa, strain of -0.70 %
- Energy stability margin will be about 1400 mJ/cc







Mechanical disturbance (Lp=0.1m, t=1ms)



Energy stability

electromagnetic disturbance (Lp=10m, t=100ms)

Disturbance duration (c)

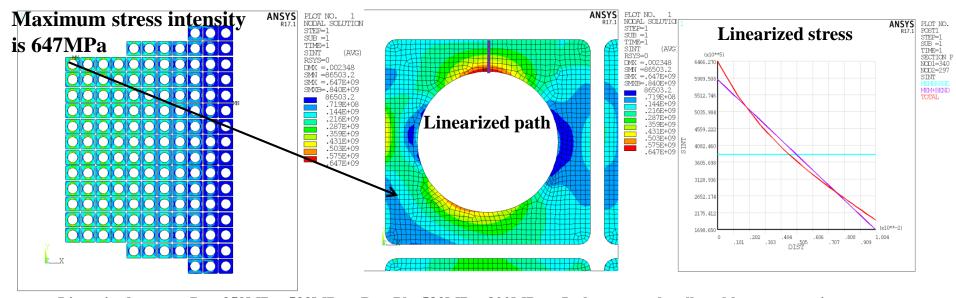
1m, t=1ms)	OutletOutlet	
	© 0.4 - Inlet Outlet	
	Mass on 0.0	
0.5	0 1 2 3 4 5	_

Energy stability					ristui Dance C	iuranon (s)		
	margin	(mJ/cc)	0.001	0.005	0.01	0.05	0.1	0.5
	D: 4 1	0.1	1702	1839	1744	1611	1539	1916
	Disturbance length (m)	1	1894	1888	1761	1523	1489	1537
	length (m)	10	1723	1785	1839	1864	1788	2264

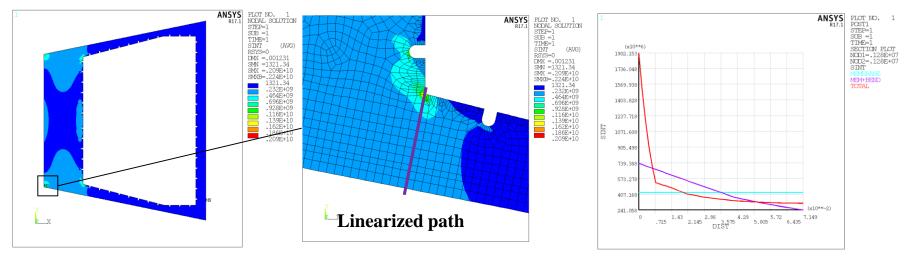
electromagnetic disturbance (Lp=10m, t=100ms

# Structure analysis of conductor jacket and case





Linearized stress: Pm=359MPa<533MPa; Pm+Pb=583MPa<800MPa, Jacket meets the allowable stress requirements.

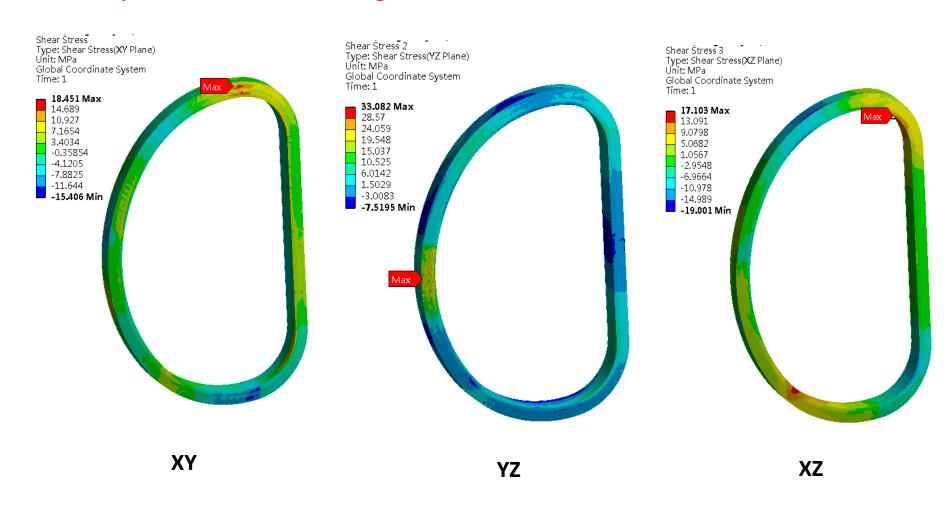


Linearized stress: Pm=415MPa<533MPa; Pm+Pb=679MPa<800MPa

# **Shear stress of ground insulation**



#### (1) Option 1-Shear stress of ground insulation

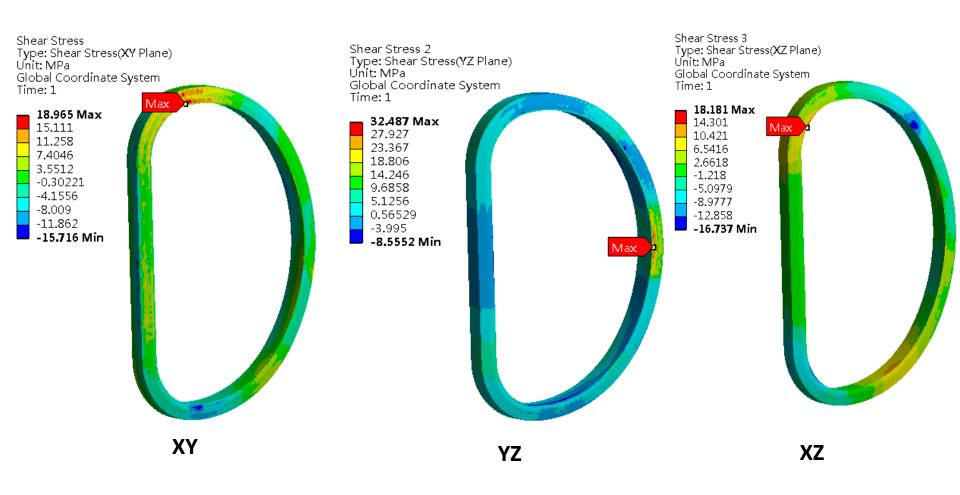


Max: 33MPa, YZ direction

# **Shear stress of ground insulation**



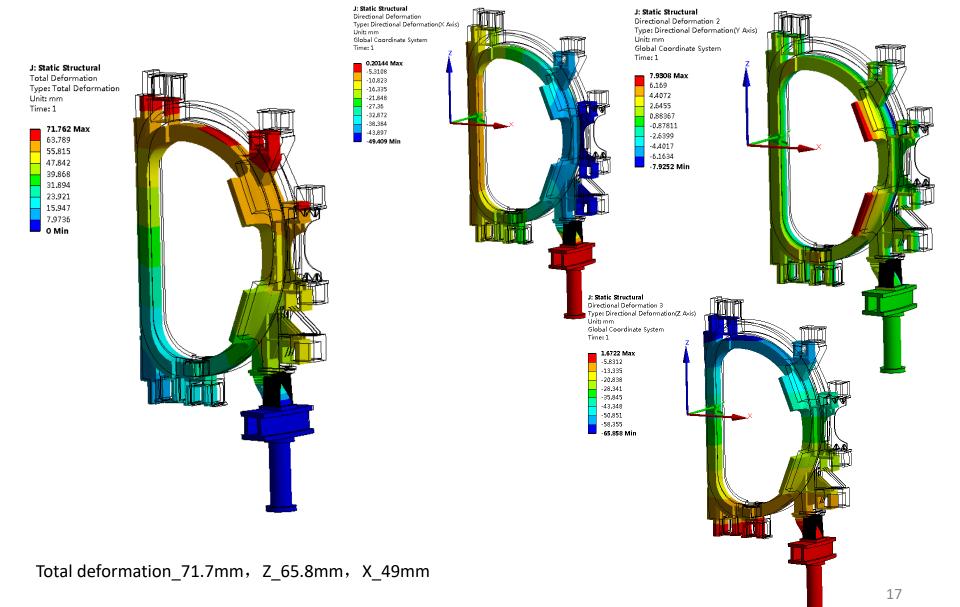
#### (2) Option 2-Shear stress of ground insulation



Max: 32.4 MPa, YZ direction

# **Cooling down deformation**

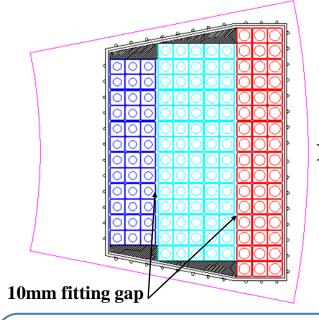




# **Fabrication Design Challenge**



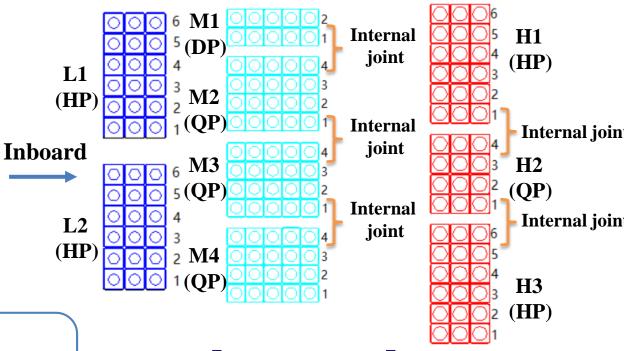




Low field WP

Medium field WP

**High field WP** 



#### Winding Characters

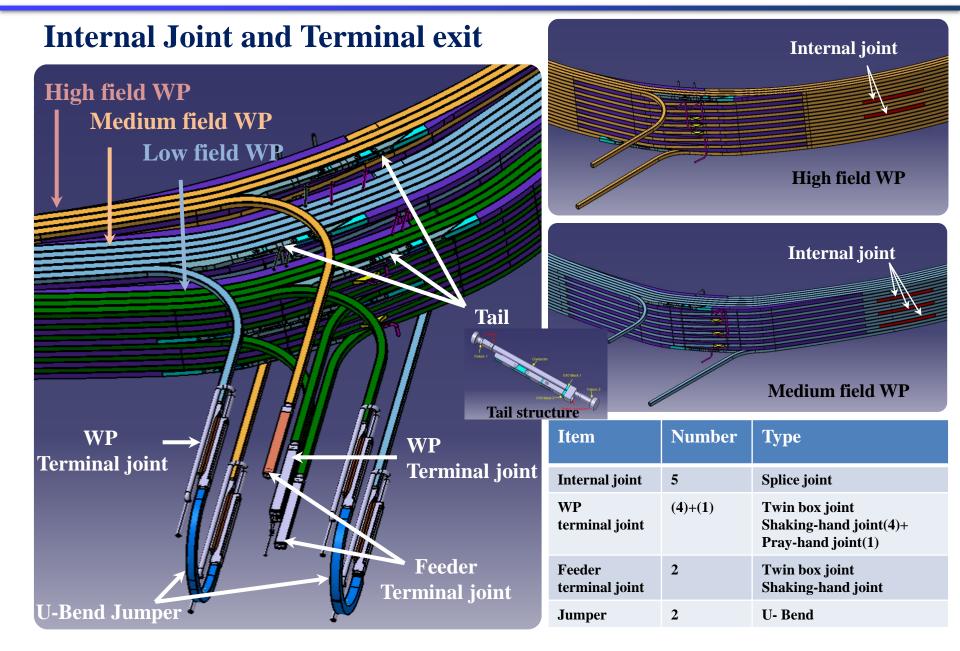
- 1. One-in-hand winding
- 2. Short unit conductor length for pattern
- 3. Counter-clockwise winding
- 4. "Wind & React" approach
- 5. Narrow gap between patterns (10mm)
- 6. Pattern connected by internal joints

Pattern A	Pattern B	4	Pattern C
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	Pattern A	Pattern B	Pattern C
Conductor Unit Length	840m	895m/450m	775m/515m
Sub-total Length	840*2= 1680m	895*3+450= 3135m	775*2+515= 2065m

### Fabrication Design Challenge

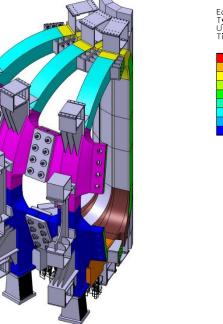


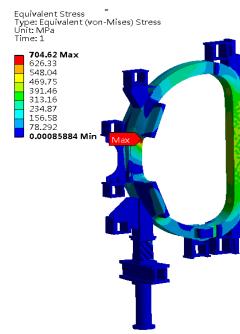


### Challenge for TF coils



ITER TF	EU- DEMO <sup>[2015]</sup>	CFETR TF	CFETR TF (Option 1)	CFETR TF (Option 2)
18	18	16	16	16
68 kA	81.7 kA	87.6 kA	96.8 kA	95.6 kA
17.34 H	32.68 H	34.93 H	25.8H	26.742H
40.1 GJ	109.08 GJ	134.02 GJ	135.3GJ	136.37GJ
2.227 GJ	6.06 GJ	8.376 GJ	8.45 GJ	8.52GJ





- **Overturning moment > 1070MN.m**
- **Centripetal force > 1130MN**
- **B**<sub>max</sub> ~14.3T~14.7 T
- Maximum stress > 700MPa
- $I_{op} > 95kA$
- **Total energy storage > 135GJ**
- Total weight > 500 t/coil

Time: 1

63.789 55.815

47.842 39.868

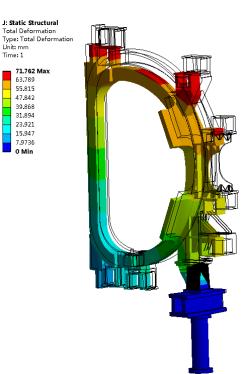
31.894

23.921

15.947

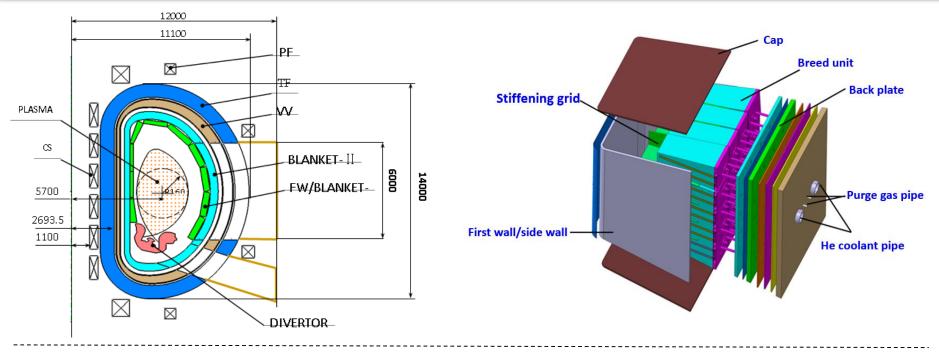
7.9736

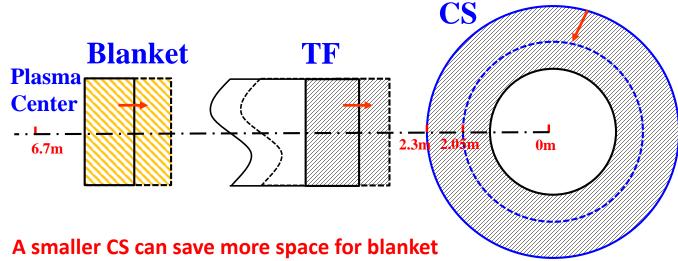
- Shear stress of insulation < 50MPa
- **Cooling down deformation > 70mm**



### Why we need a compact CS coil







Outer radius: 2.3m→2.05m

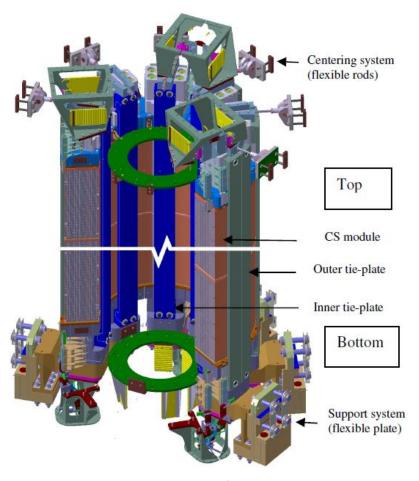
Voltage Second: 480V·s→400V·s

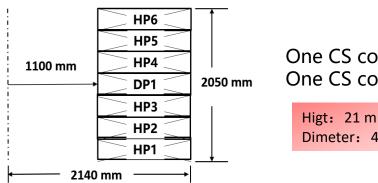
Extra 0.25m for blanket

# Magnet System (Central Solenoid)



 $\square$  CS conductor: 480V.s,  $I_{op} > 60kA$ , B<sub>max</sub>>17T, High Jc Nb<sub>3</sub>Sn or HTS





One CS coil~7.6 km One CS coil~2 GJ

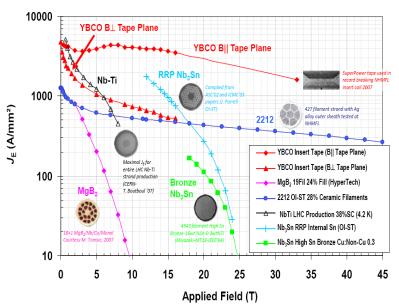
Dimeter: 4.28 m

- **High temperature superconductor** (Bi2212/YBCO) + low temperature superconductor (Nb₃Sn) → a maximum 19.9 T@ 51.25 kA/turn.
- Maximum 480 VS flux

# Magnet System (Central Solenoid)



### CS conductor ( $B_{max} > 17T$ , option 2 HTS)

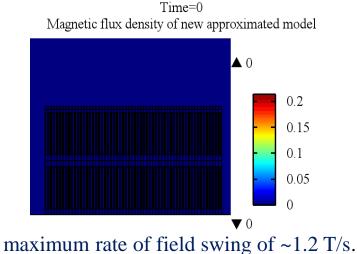


#### Bi-2212 and YBCO:

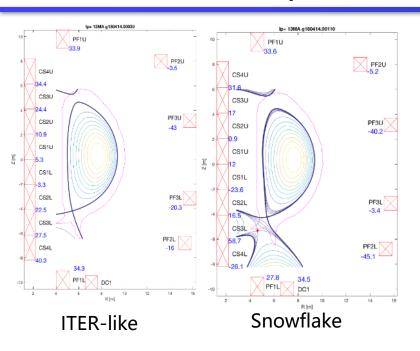
- □ brittle or not, easily to be damaged during cabling and conductor manufacturing;
- $\square$  Need or not: special heat treatment-with  $O_2$ , high temperature, and high pressure.







# Plasma equilibrium configuration for CFETR



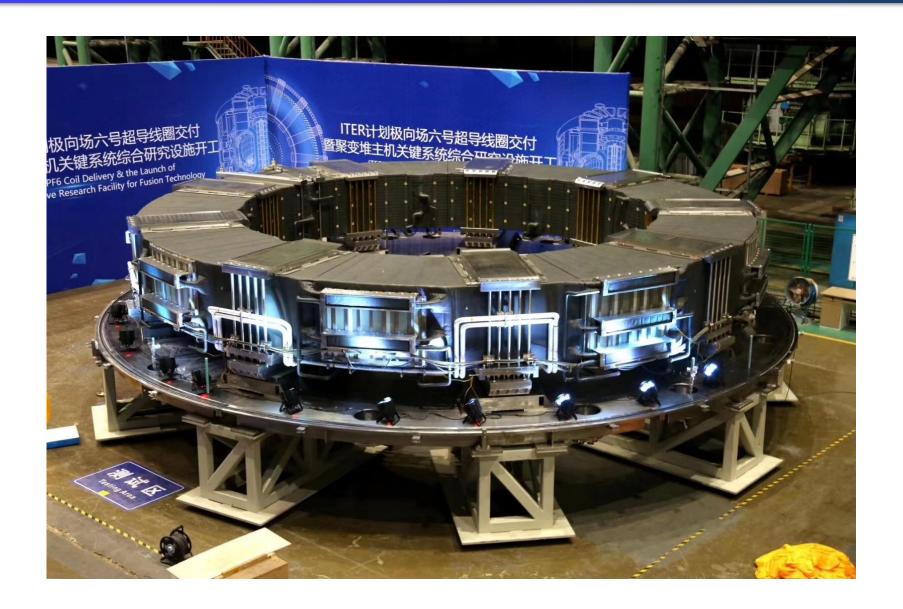
	PF1U & PF1L	PF3U	PF2U,2L,3L & DC1
Ic [A]	57.77 [6T, 6K]	125.44[5T,6K]	204.25[4T,6K]
lop [A]	41.6	74.04	111.11
Number of strands	1440	810	540
Cable Pattern	3x4x4x5x6	3x3x3x5x6	2x3x3x5x6
Ni coated strand diameter [mm]	0.73	0.73	0.73
Cu-to-Non-Cu ratio	1.6	2.3	2.3
Operating temperature K	4.5	4.5	4.5
Calculated Tcs K	6.07	6.3	6.56
Calculated Min. Temperature margin K	1.77	1.8	2.06



	I <sub>op</sub> (kA)	Quench Voltage (kV)	time constant(s)	Discharge resistance( Ω)
PF1	53.9	14	7.89	0.26
PF2	-17.9	1.2	5.67	0.07
PF3	-36.1	9	12.39	0.25
PF4	-17.2	2.4	6.32	0.14
PF5	-40.1	11	10.83	0.27
PF6	35.3	3.1	13.21	0.09
PF7	55.4	15	7.57	0.27

Coil	SN	SF+	
Con	B <sub>max</sub> /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	

### ITER PF6 coil is just finished its manufacturing in ASIPP

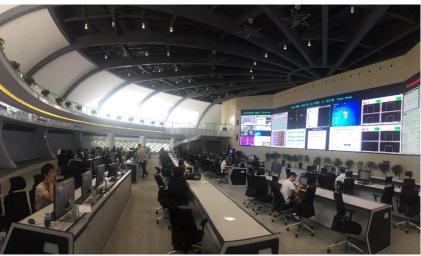


# **Summary**



- □ Integrated Design and R&D of magnet system of CFETR are in progress. CFETR is under design with emphasis for high B<sub>T</sub> option
- $\square$  There are gaps to CFETR SC magnet, especially for high B<sub>T</sub> option, need **new solution** and technologies.
- □ Detail engineering design and large scale R&D of superconducting magnet system will continue in next 5 years. We are looking forward to broad international cooperation.









We are grateful to the help and discussion from WST, OST, Tsinghua University, Shanghai Superconductor Ltd., ENEA, NIFS, QST ...

