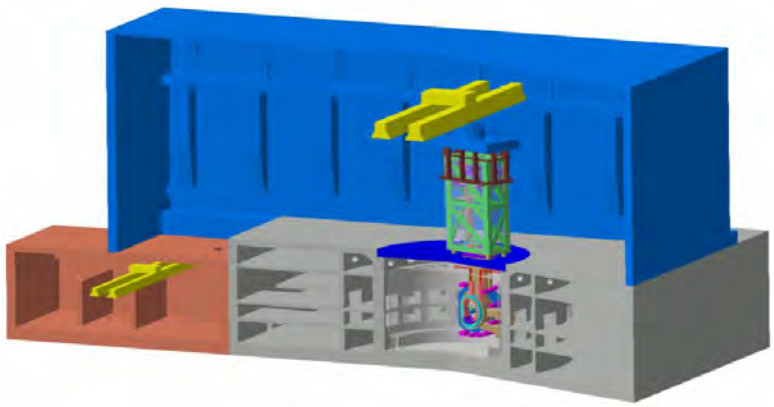
ASIPP

Japan-US Workshop on Fusion Power Plants and Related Advanced Technologies
February 26-28, 2013 at Kyoto University in Uji, JAPAN

Conceptual Design of CFETR Tokamak Machine



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Outline

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1 Introduction of CFETR

2 Limited condition for the design

3 Magnet system optimization

4 Maintenance of machine

5 Summary

Introduction of CFETR

Chinese Fusion Engineering Testing Reactor (CFETR) is built to realize the self-sufficiency of D-T reaction.

- The size of the CFETR is between JET and ITER tokamak;
- The maintenance work of CFETR is fully based on RH;
- The machine assembly and maintenance design is ongoing.

General design requirements of CFETR:

- Duty cycle time (or burning time)～(30-50%);
- Tritium must be self-sufficiency by blanket;
- Ripple at the edge of plasma should be≤0.5%;
- The leakage of tritium ≤ 1g per year;
- Necessary but minimum diagnostics;
- Main H&C methods are ECW and ICRW with LHW,NBI for flexibility, Ph&CD ≤ 100～150 MW;
- Single null diverter at the bottom (ITER-like and advanced magnetic field configuration like snowflake and super-X).

Introduction of CFETR

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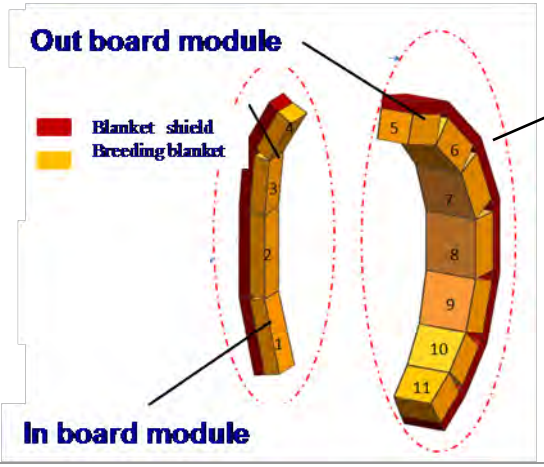
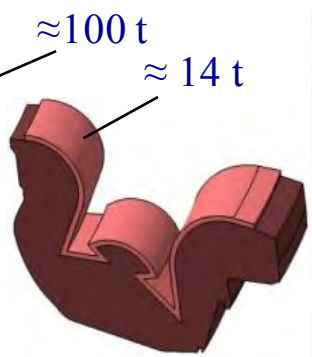
Main Parameter of CFETR

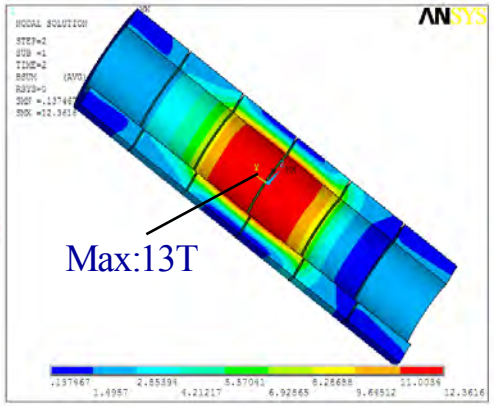
Main parameter for ITER-Like/Super-X/Snowflake of CFETR				
Parameter	ITER-Like	Super-X	Snowflake	ITER
Total number of TF coil(N)	16	16	16	18
Plasma current （MA）	10	10	10	15
Center field(T)	5.0	5.0	5.0	5.3
Maximum current of TF	67.4 kA/turn	67.4 kA/turn	67.4kA/turn	68 kA/turn
Major radius of plasma(m)	5.7	5.7	5.7	6.2
Minor radius of plasma(m)	1.6	1.6	1.48/1.58	2.0
The center radius of CS(m)	1.415	1.415	1.415	2.055
Maximum V.S	160	160	160	240-250
Elongation	1.8	1.8	2.17	1.70/1.85
Number of PF coils	6	8	8	6

Limited condition for the design

◆ Duty time : 0.3-0.5	Big modules(divertor, blanket ,etc)	High load for RH
◆Fusion power: 50-200MW	Fast heat remove of divertor （within 10MW/m^2）	New configuration and new material for divertor
◆High dosage of neutron: 2-3 orders of magnitude than ITER Tokamak	Reduce the quantity of middle port	High utilization of port (diagnostic integration, reduce maintenance port)
◆ To meet CFETR design parameters	High magnetic field intensity of CS (max:13T)	New superconducting material for magnet







Critical magnetic field at 4.2K

Super-conductor	Magnetic field(T)
NbTi	7
Nb_3Sn	13
Nb_3Al	>16

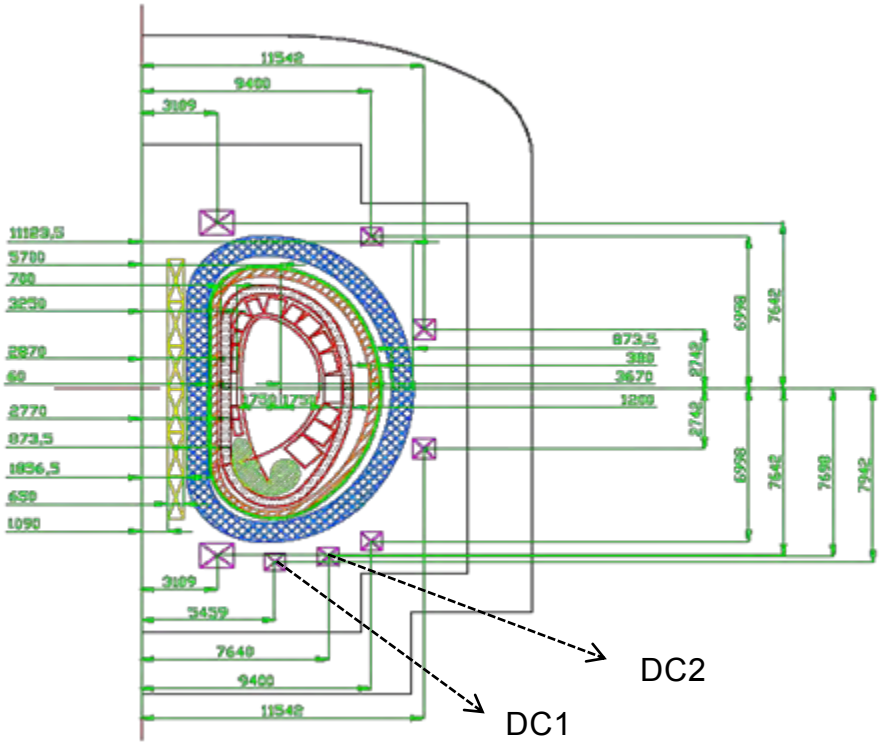
The requirements of CFETR Magnet system

- The magnet system of CFETR consists of 16 TF coils, 6 CS coils;
- PF coils divided into three types according to the type of divertor:

  ITER-like: 6 PF coils; Super-X: 8 PF coils (DC1); Snowflake: 8 PF coils (DC2);
- All of the coils have superconducting structure: the TF and CS coils intend to use Nb3Sn superconductor, while PF and CC coils are suggested to make by NbTi superconductor.

General design requirements of magnet system:

Large radius of plasma	R=5.7 m
Minor radius of plasma	r= 1.6 m
Central magnetic field	*Bt = 5.0 T*
Fusion power	50- 200 MW
Duty cycle (or burning time)	~(30-50%)
Thickness of blanket	0.8-1.0 m
Magnetic field ripple in the region of Plasma	<0.5%
Tritium must be self-sufficiency by blanket	



The structure and the layout of magnet system

Design parameter for magnet system of CFETR

System specific requirements:

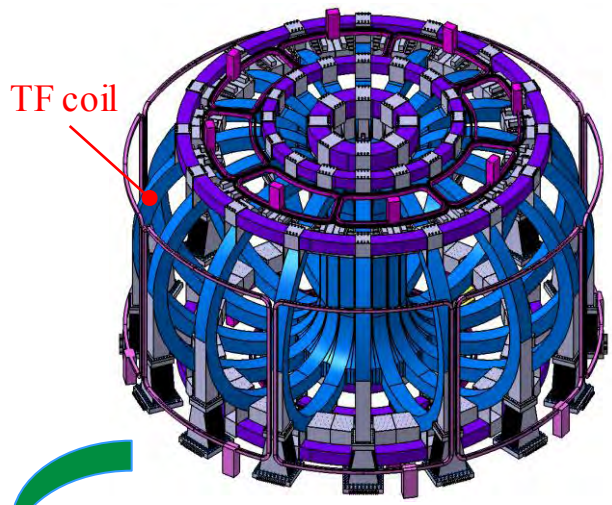
- Coils shall **not quench** during plasma operation, including plasma disruptions;
- All of magnets must be capable of **providing a long pulse capability**;
- The magnet system should be capable of continuing normal operated in **the event of plasma disruptions** (i.e. a disruption should not cause a magnet quench).

Main parameter for magnet system of CFETR

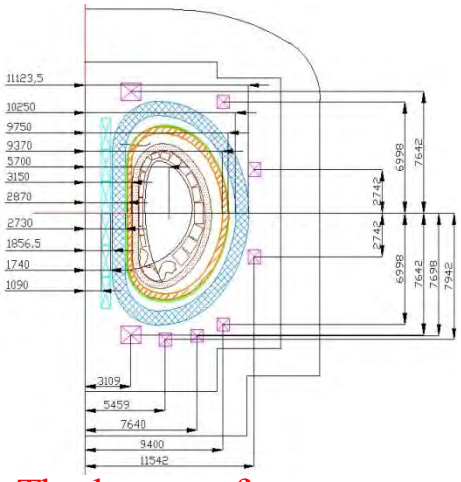
Parameter	ITER-like	Super-X	Snowflake	ITER
Total turns of each TF coil	132	132	132	134
Elongation, κ	2.00	2.01	2.01	1.70/1.85
Triangularity, δ	0.40/0.63	0.41/0.63	0.42/0.68	0.33/0.48
Maximum Magnetic field of TF （T）	10.24	10.238	10.257	11.8 T
Maximum Magnetic field of CS （T）	12.36	11.644	9.17	12
Maximum Magnetic field of PF （T）	4.47	5.411	8.04	6.8
Energy storage （GJ）	35.88	35.88	35.88	41
Centripetal force （MN）	359.69	359.69	359.676	403

The TF magnet system of CFETR

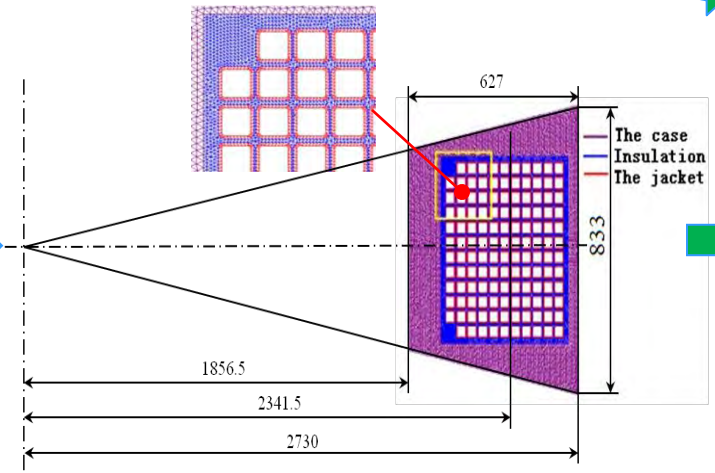
The performance of the TF superconducting material	
Item	Requirement
Superconductor type	Nb3Sn
Minimum piece length	1000 m
Un-reacted, Cr-plated strand diameter	0.820 ± 0.005 mm
Twist pitch	15 ± 2 mm
Twist direction	right hand twist
Cr plating thickness	2.0 +0 -1 μm
Un-reacted, Cr-plated strand Cu-to-non-Cu 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)	190A
Resistive transition index at 4.22 K and 12 T (as measured on ITER barrel)	> 20 in the 0.1-to-1 μV/cm range



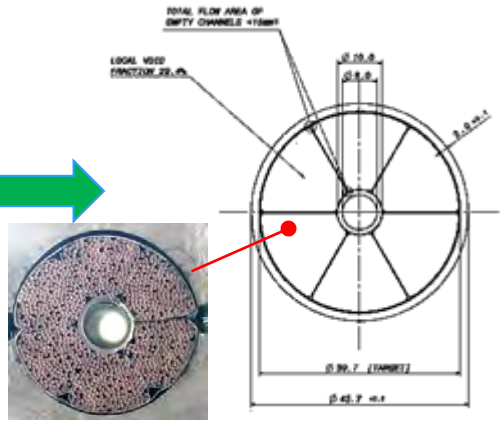
Magnet system of CFETR



The layout of magnet system

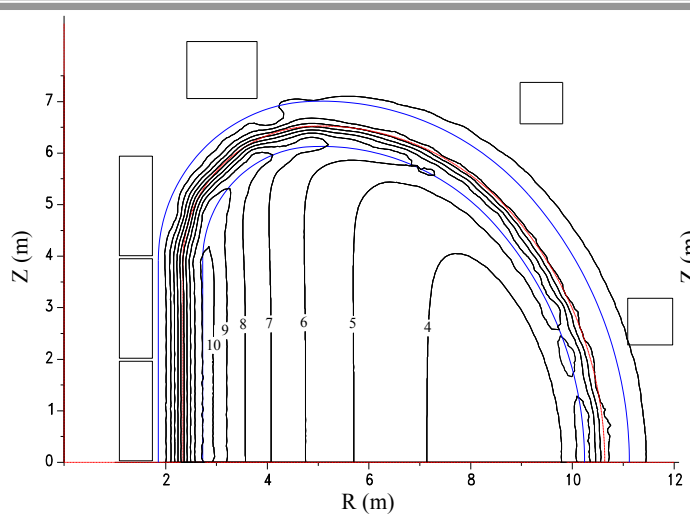


Sectional view of TF coil

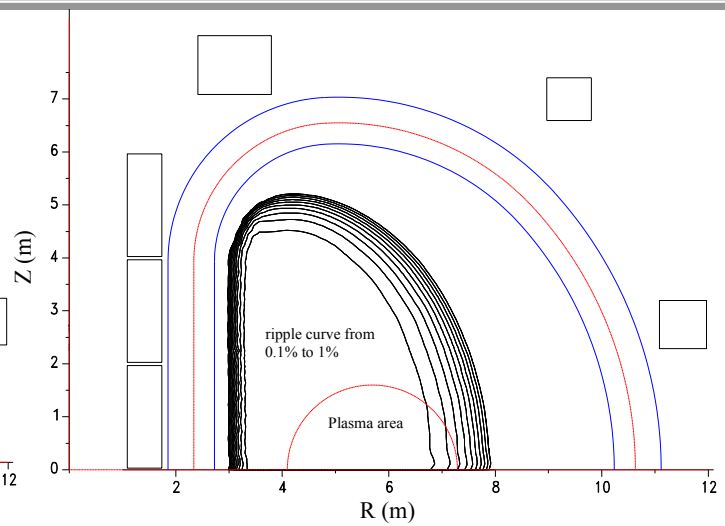


Sectional view of superconductor

The TF magnet system of CFETR



The TF magnetic field distribution



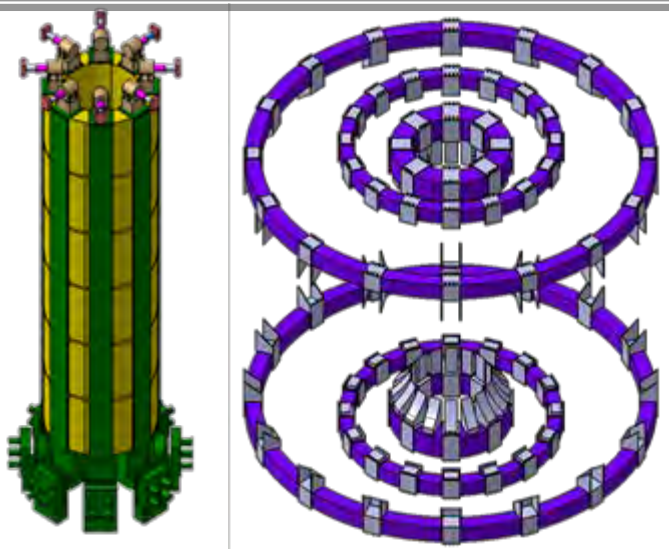
The ripple distribution

The ripple in plasma area is very tiny(less than 0.1%), which can satisfy the requirements of physical design.

TF Coil	Inductance (H)
1	0.377
2&16	0.133
3&15	0.066
4&14	0.038
5&13	0.024
6&12	0.016
7&11	0.012
8&10	0.010
9	0.009
Total Inductance	15.75

- Each TF coil has 132 turns;
- Five identical double coil (2 x 11 = 22 turns) in the middle and two double coil (8+ 3 = 11turns) on the side;
- The length of each double coil in the middle is about 880 mm, while the side one is 420 mm.

The CS and PF magnet system of CFETR



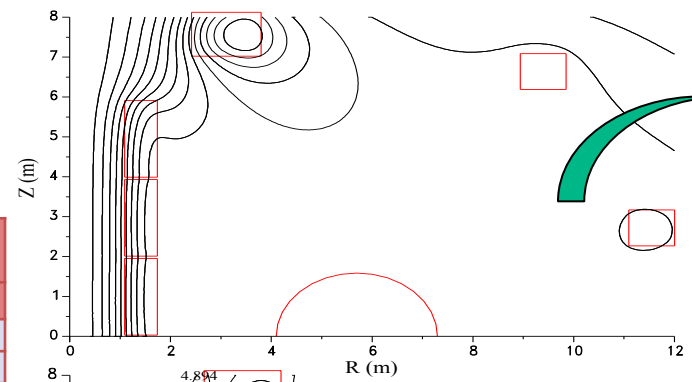
The CS conductor dimension is 50 mm × 50 mm, The corresponding inner radius of central solenoid is about 1.1m, which can provide 140Wb volt-seconds;

If the design value of volt-seconds is 160Wb, then the coil current obtained is given in following table:

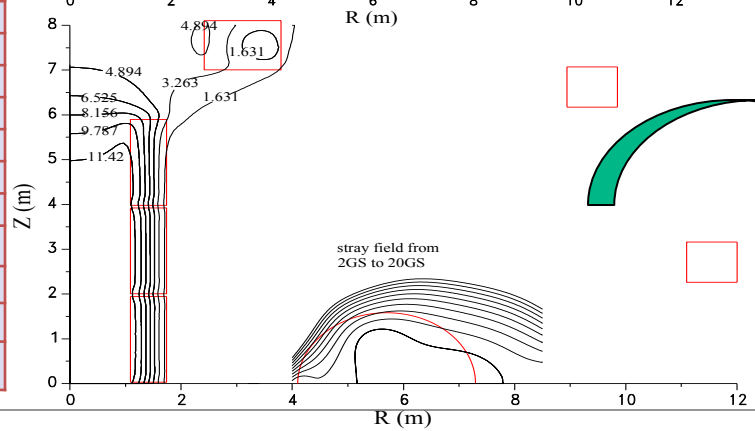
Coil	CS1U/1L	CS2U/2L	CS3U/3L	PF1U/1L	PF2U/2L	PF3U/3L
Current(kA)	55.00	55.00	55.00	19.73	1.18	0.85

The Parameters of CS and PF Coil

Coil	R (m)	Z (m)	△R (m)	△Z (m)	Turns	Current (kA/turn)	
						Case1	Case2
CS1U	1.415	0.999	0.650	1.938	374	-56	-56
CS2U	1.415	2.997	0.650	1.938	374	-13	-6
CS3U	1.415	4.995	0.650	1.938	374	13	19
CS1L	1.415	-0.999	0.650	1.938	374	-56	-55
CS2L	1.415	-2.997	0.650	1.938	374	4	11
CS3L	1.415	-4.995	0.650	1.938	374	13	20
PF1U	3.109	7.642	1.382	1.111	616	15	19
PF2U	9.400	6.698	0.909	0.909	324	-6	-5
PF3U	11.554	2.742	0.909	0.909	324	-14	-14
PF1L	3.109	-7.642	1.382	1.111	616	20	27
PF2L	9.400	-6.698	0.909	0.909	324	-1	-3
PF3L	11.554	-2.742	0.909	0.909	324	-20	-18

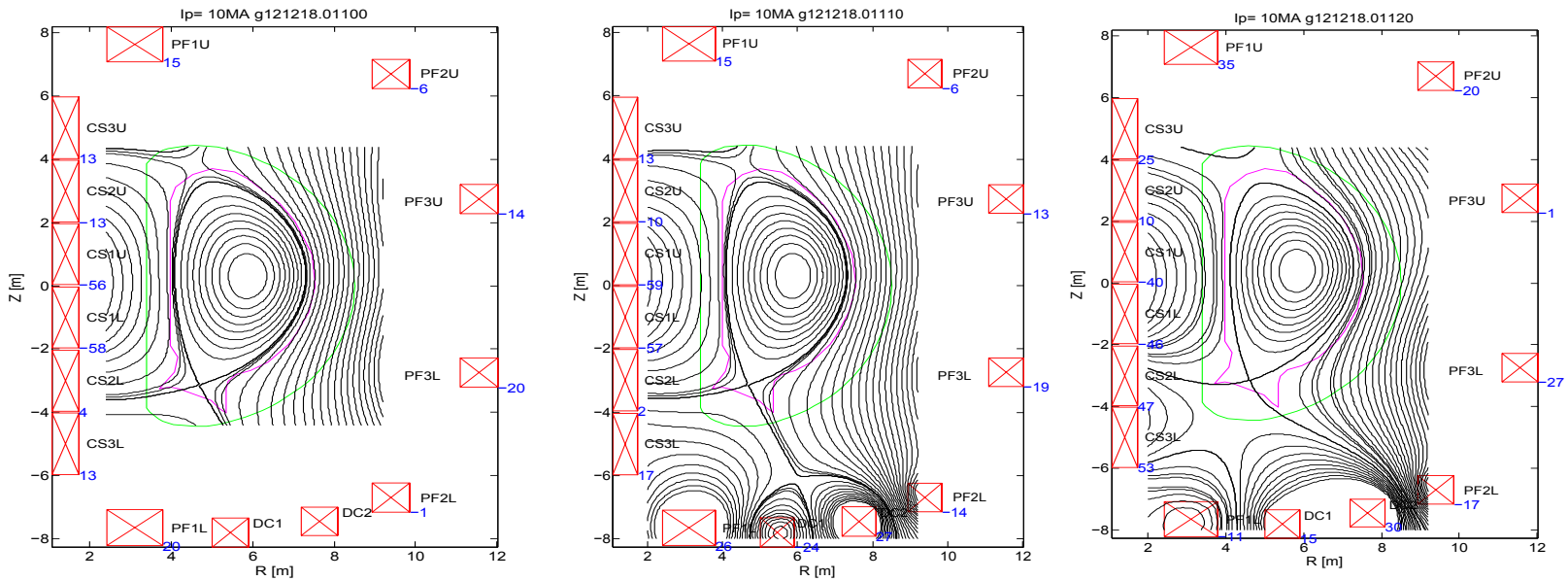


The maximum B of CS coil is about 13 T



The maximum of stray field in plasma area is about 14 GS

The equilibrium configuration



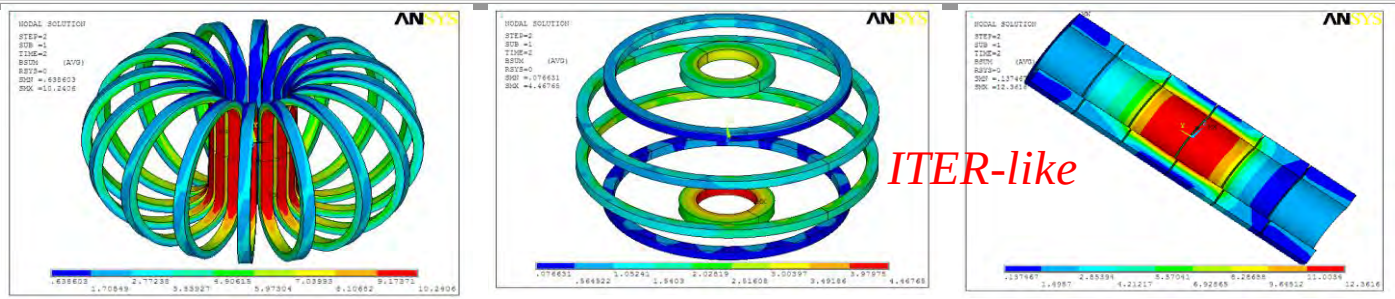
(a) ITER-like (b) Super-X (c) Snow-flake

Equilibrium configuration and coil current of 10 MA plasma

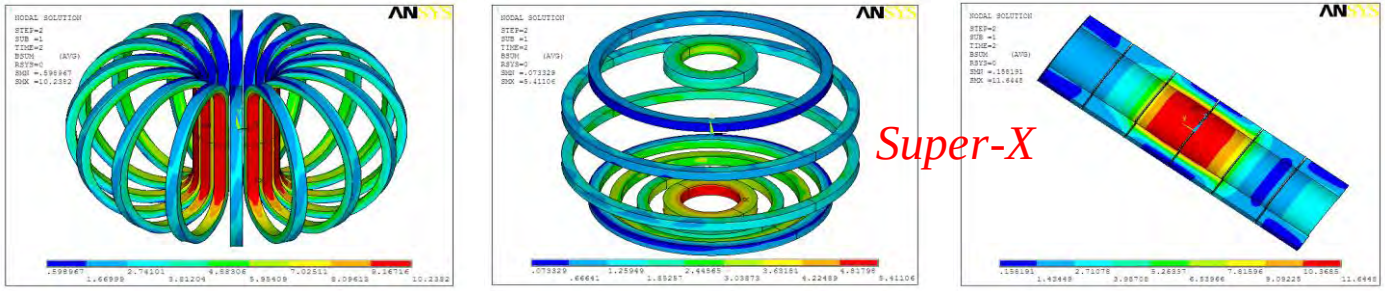
	Ip [MA]	R[m]	a[m]	β_P	Li	δ_u/δ_l	k	Rxp [m]	Zxpt[m]
ITER-like	10	5.7	1.60	1.01	1.09	0.40/0.63	2.00	4.6905	-3.1306
Super-X	10	5.7	1.60	1.01	1.09	0.41/0.63	2.01	4.6896	-3.1326
Snow-flake	10	5.7	1.58	0.80	1.09	0.42/0.68	2.01	4.6148	-3.1396

The equilibrium configuration can meet the mission and goal of CFETR. The purpose of analysis for magnet filed with equilibrium current of plasma is mainly to obtain the maximum of filed intensity and magnetic force of TF, PF and CS. The largest magnetic intensity can provide reference to the magnet coil optimization and the selection of the superconducting materials.

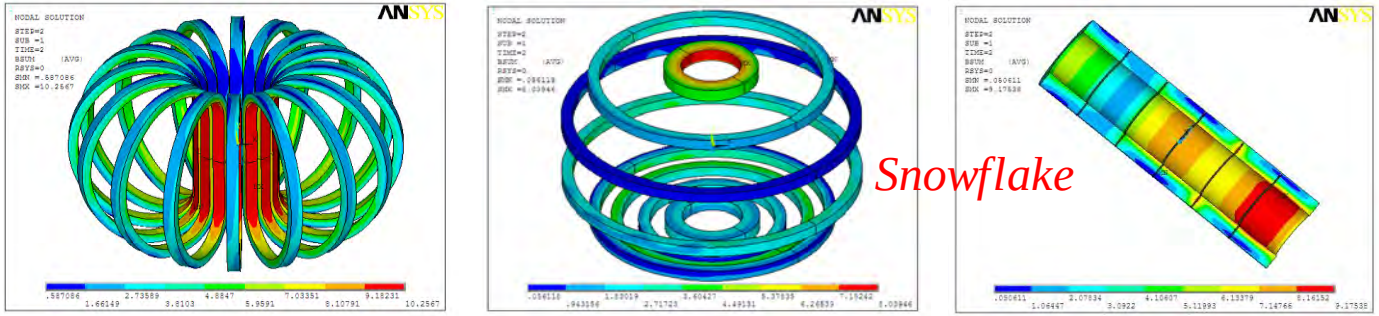
The electromagnetic analysis for magnet system



B_{max}(TF)	10.24 T
B_{max}(PF)	12.36 T
B_{max}(CS)	4.47T
Overturning moment	257.76M N.m
centripetal force	359.69 MN



B_{max}(TF)	10.238 T
B_{max}(PF)	11.644 T
B_{max}(CS)	5.411T
Overturning moment	254.52M N.m
centripetal force	359.69 MN

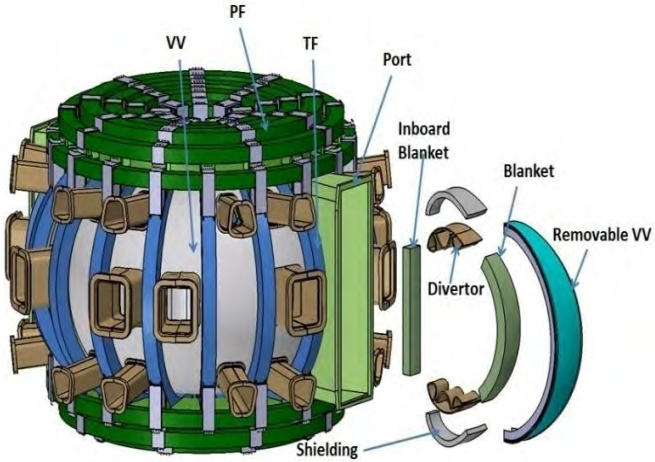


B_{max}(TF)	10.257T
B_{max}(PF)	9.17 T
B_{max}(CS)	8.04T
Overturning moment	267.24M N.m
centripetal force	359.676 MN

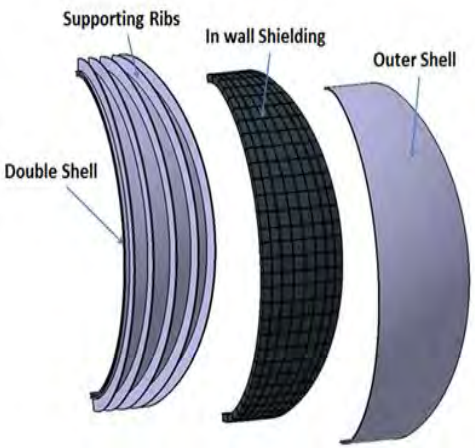
Under the plasma equilibrium current, the maximum magnetic field intensity of PF and CS is lower than 13 T. It can fulfill the requirements of Nb_3Sn superconducting materials. The overturning moment and centripetal force of TF coil similar to the results referencing from ITER TF design. The coils can meet the requirement of CFETR's mission and goal.

Conceptual design of vacuum vessel

Current design:

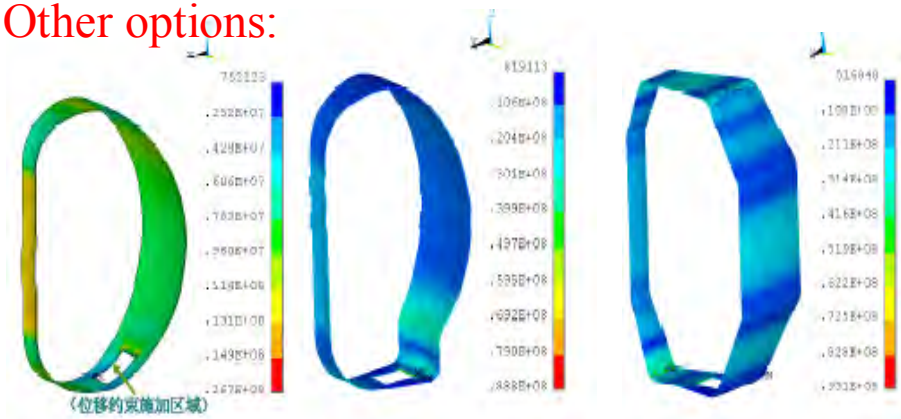


Double structure of vacuum vessel



Overall layout of VV outer board

Other options:



Size compacted	Easy to support	Easy to manufacture

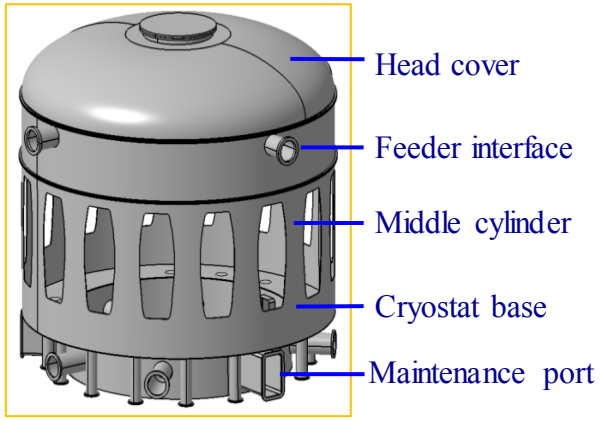
Issues considered in CFETR VV design:

- The configuration and size of VV sector: constrained by TF coils;
- Layout of VV ports: affects the plan and efficiency of RH maintenance;
- Structure strength and stability under baking and radiation;
- Add supporting ribs can strengthen VV effectively.

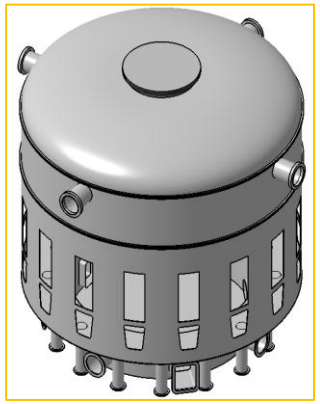
Basic design currently:

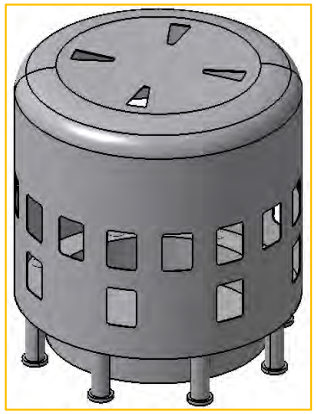
- 16 sectors, two layers (50mm each), 316L, IWS between two layers.

Conceptual design of cryostat and thermal shield



Large port

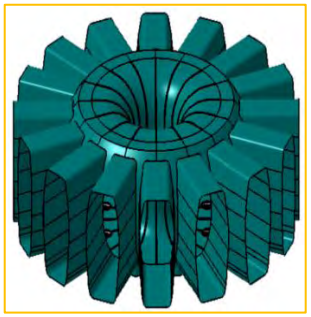


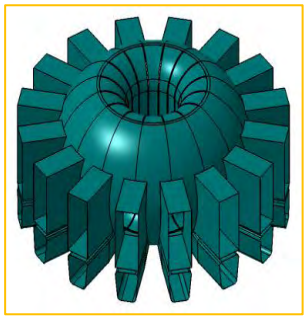


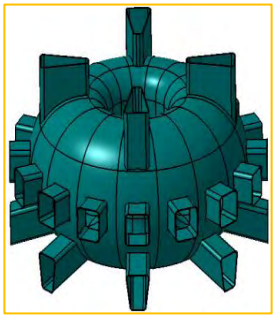
Medium port Small port

Conceptual design of cryostat

VV TS

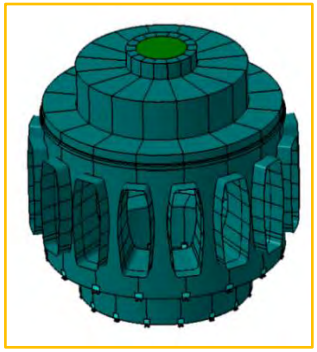


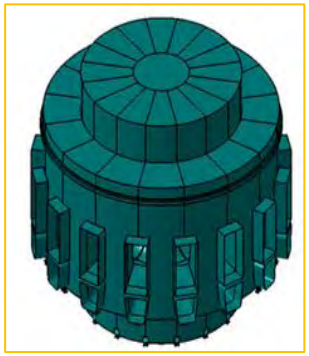


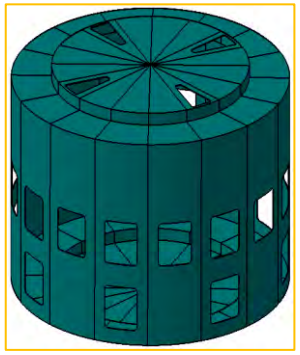


Large port Medium port Small port

CTS





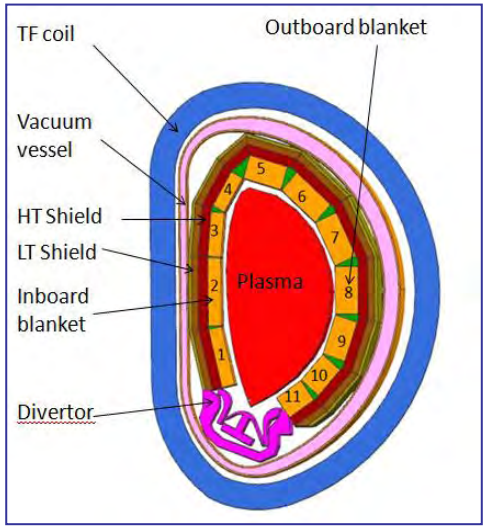


Large port Medium port Small port

Conceptual design of thermal shield (TS)

Conceptual design of blanket

Current design: Water-cooled blanket



Material Selection:

Structure:

RAFM or 316L

Tritium breeding:

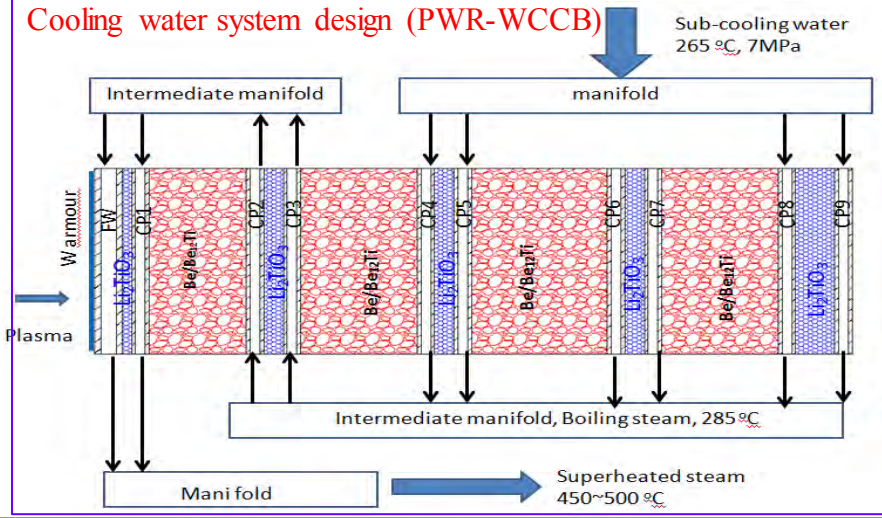
Li2TiO3

Neutron multiplication:

Be / Be12Ti

First wall: W

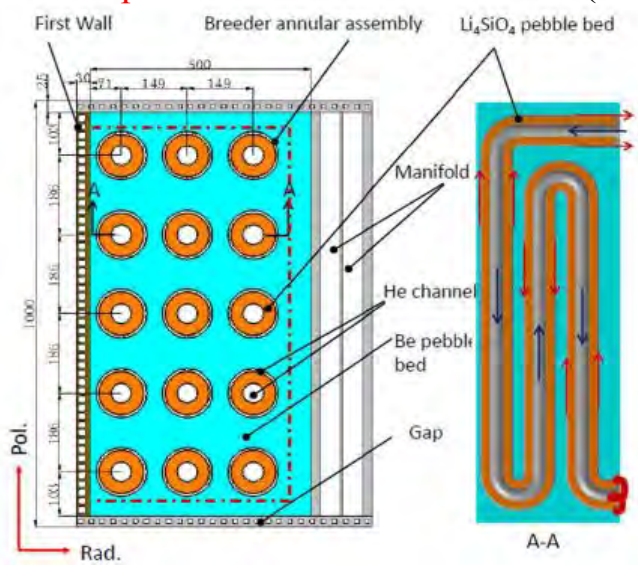
Cooling water system design (PWR-WCCB)



Design requirements of CFETR Blanket:

- Realized tritium self-sufficiency under typical parameters firstly, doubled in 2-3 years;
- Thickness of blanket: Inboard blanket ≤0.8m, outboard blanket ≤1.2m;
- Service life of CFETR key components (VV, TF, PT, etc): >20 year (under the protection of shield blanket);
- Divide breeding blanket into modules to reduce the impact of thermal stress and EM load.

Other options: Helium-cooled blanket (Breeder inside tube)



Gas pressure: 8MPa

Inlet temperature: 300℃.

Outlet temperature: 500℃.

Heat removal: 1.06MW.

Design requirements of the maintenance equipments

◆ **Maintenance time:**

- The maintenance equipments have high efficiency to meet the duty time of 0.3-0.5.

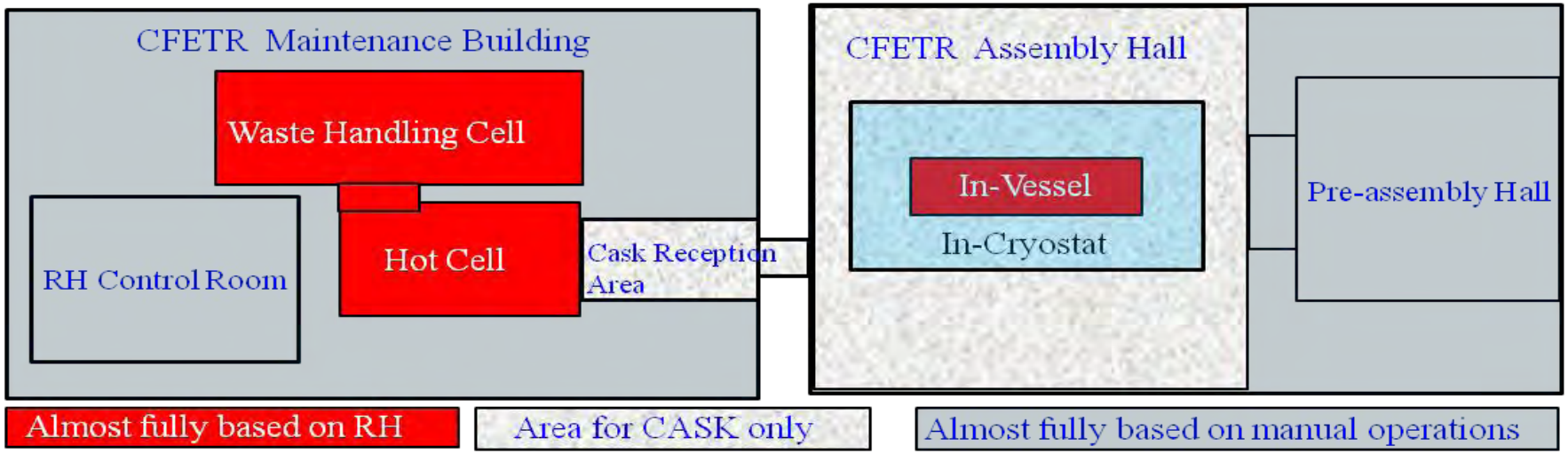
◆ **Safety to Environment:**

- The CASK should have the function of neutron shielding;
- Free of oil in the RH facilities work in In-vessel operating;
- Low out-gassing rate of the RH structure material exposed in vacuum environment.

◆ **Safety under severe working conditions:**

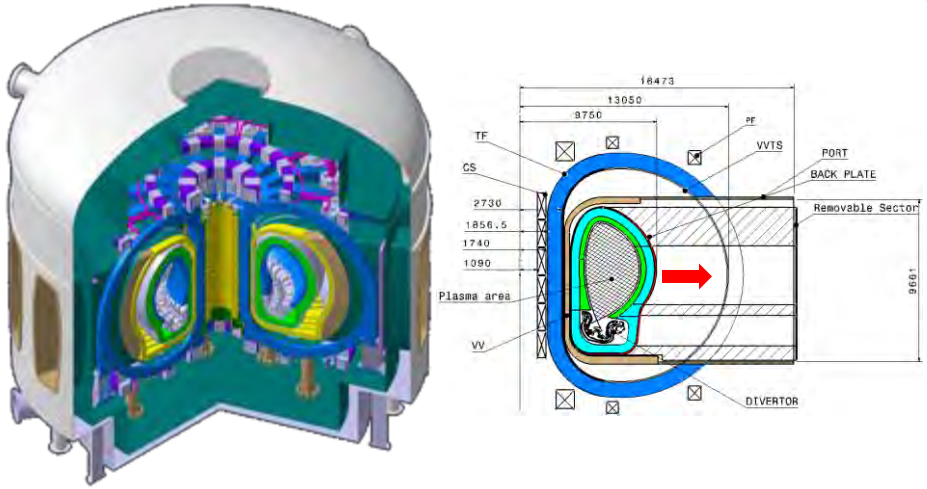
- RH (In-Vessel) can bear hours of high temperature (100℃-250℃) baking;
- RH (In-Vessel) can work regularly under radiation environment

- **Carrying capacity:**
- Security coefficient ≥1.2.

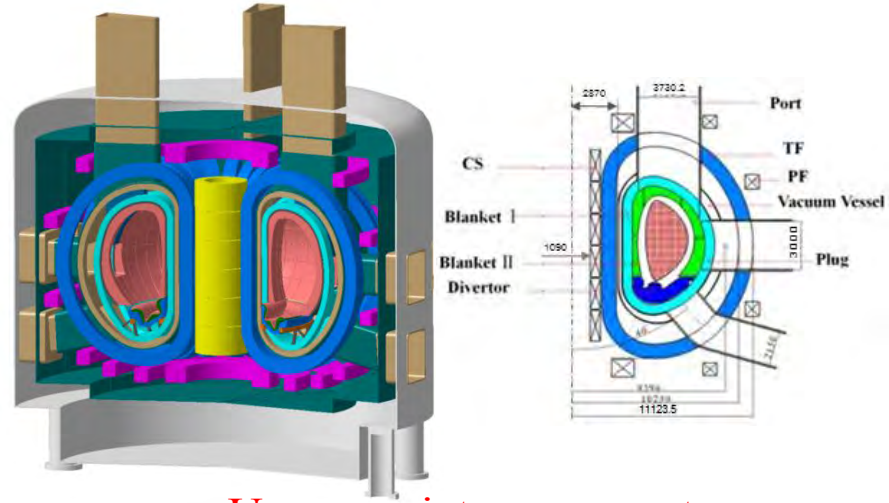


The scope of implementation of RH in CFETR assembly and maintenance process

The comparison of the maintenance port proposal



Full scale maintenance port



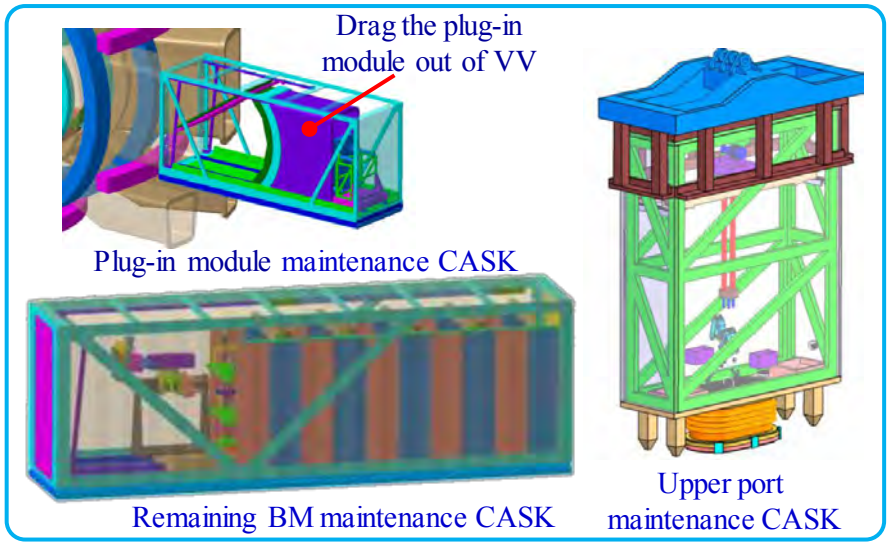
Upper maintenance port

- Convenient maintenance: Independent section remove, high maintenance efficiency ;
- Convenient RH maintenance: Only need a few RH equipments , well working condition;
- Difficulties on assembling: the weight of one section is more than 300t, the RH must have very high load capacity and accuracy;
- Need more ports: 16 full scale port will be used when maintenance.

- Convenient maintenance: Remove all the blanket from upper ports and divertor from lower ports ;
- Convenient RH maintenance: Only need a few RH equipments, easy and quick to disassembly defective parts ;
- Small equatorial port： be helpful to prevent neutron leakage.

This proposal would be a better choice!

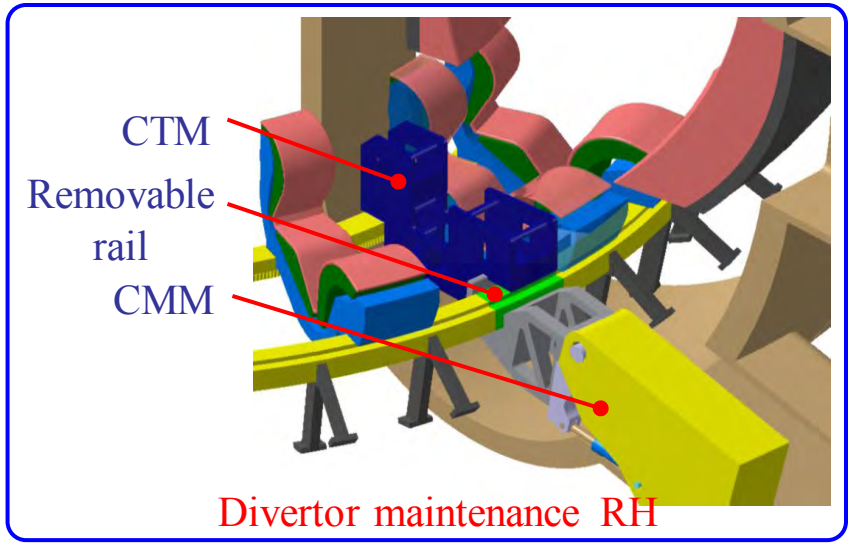
Conceptual design of maintenance equipments



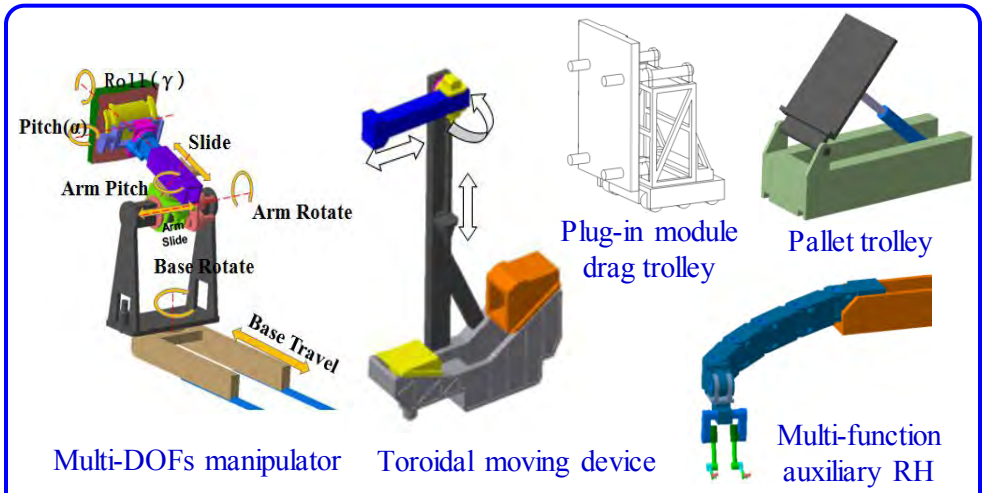
Maintenance CASK system

Main functions of the maintenance equipments:

- ◆CASK can dock with the VV port when replace the inner components and then take them to the hot cell to avoid the leakage of the of strong radiation pollution;
- ◆The divertor maintenance RH with CMM and CTM can rotate and remove the heavy divertor to the hot cell with CASK;
- ◆ The multi-DOFs manipulator and auxiliary RH can remove and carry the blanket and cut the pipes, remove the screws of the inner components, etc.



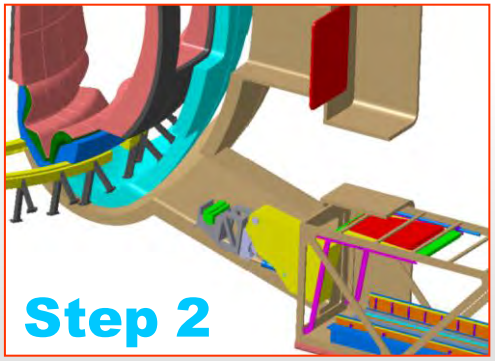
Divertor maintenance RH

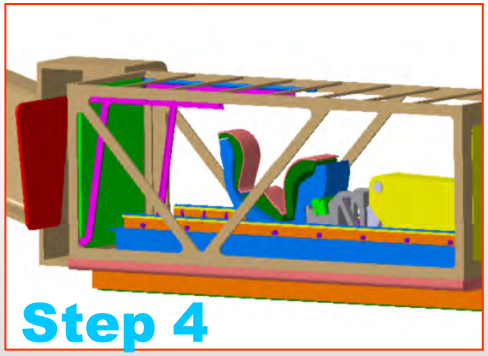


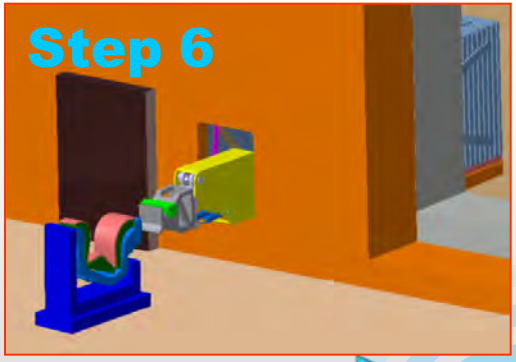
Maintenance equipments of carrier and flexible RH

Upper port proposal——maintenance of divertor

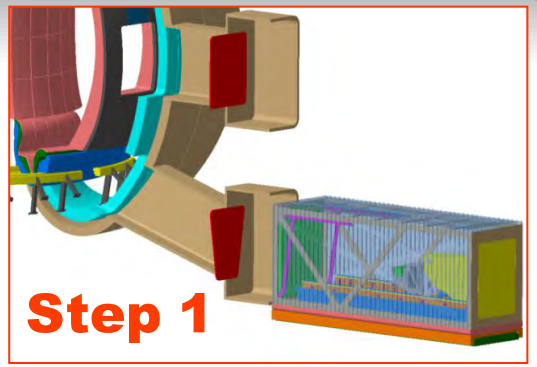
ASIPP

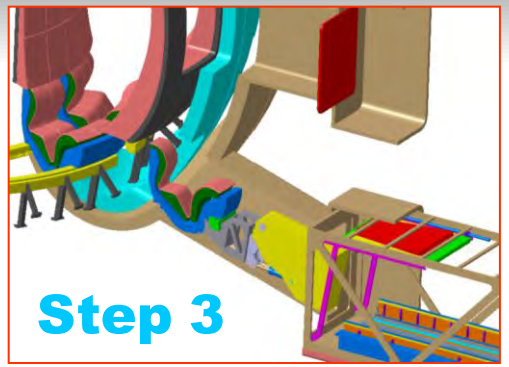


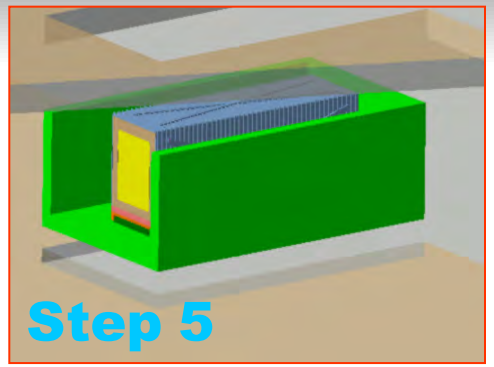




Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
CASK moves to lower port of the divertor, ready to butt	Open the double sealed door , send CMM into the port	CMM removes the divertor, and drags it back to the CASK	Close the seal door, disconnect the CASK with the lower port	Move the CASK to hot cell downstairs	The CASK docks with the hot cell and sends the divertor into the hot cell







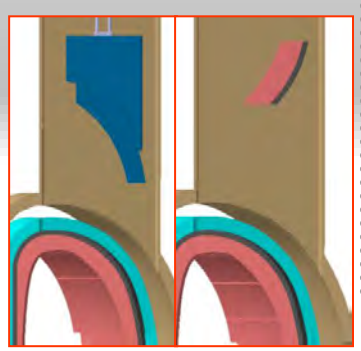
Upper port proposal——maintenance of blanket

ASIPP

The remove sequence of the blanket section: the outboard section first and then the inboard section

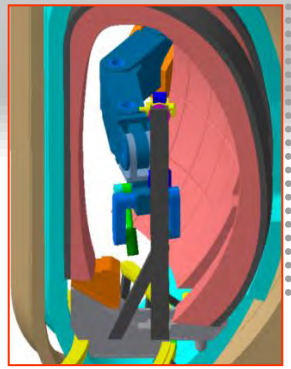
Step 1

Remove the module of plug-in and blanket below the middle port



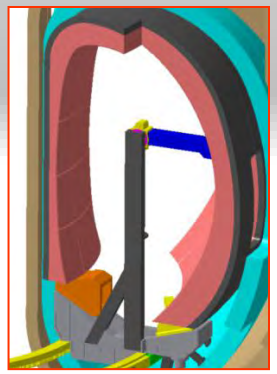
Step 2

Set the toroidal moving device and Multi-function auxiliary RH (cutting pipes and remove screw)



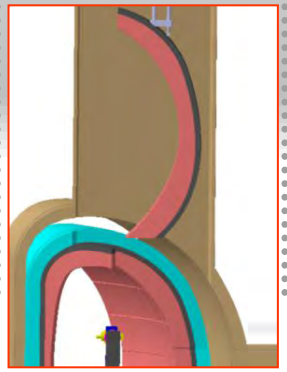
Step 3

The toroidal moving device moves the Outboard blanket below the upper port



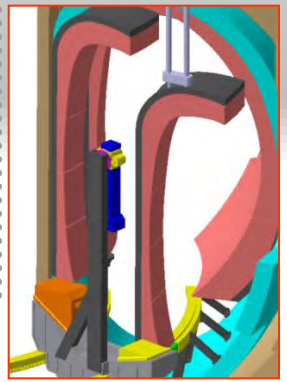
Step 4

CASK lifts the outboard blanket module to the upper port



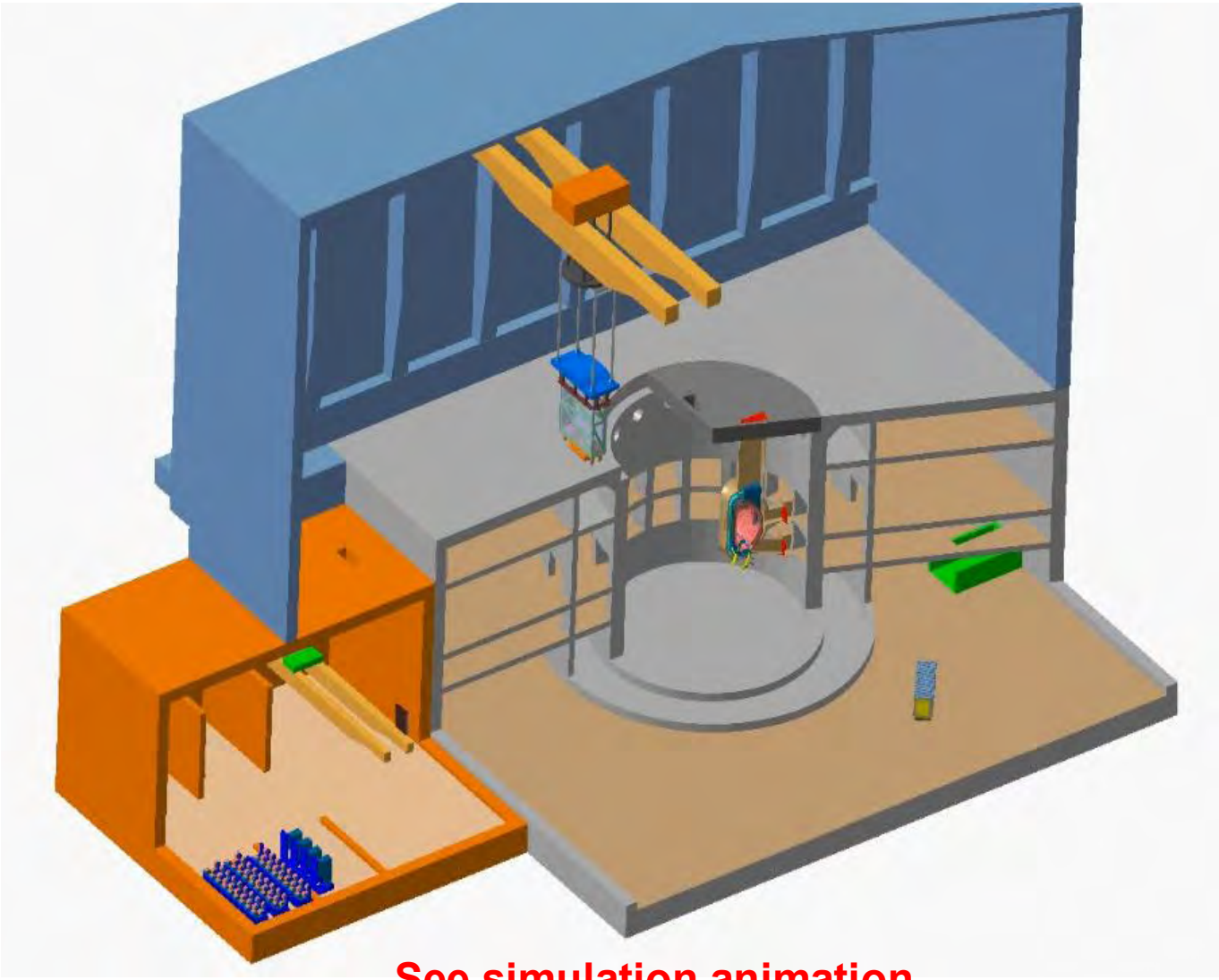
Step 5

CASK removes other outboard blanket and the inboard blanket in the same way



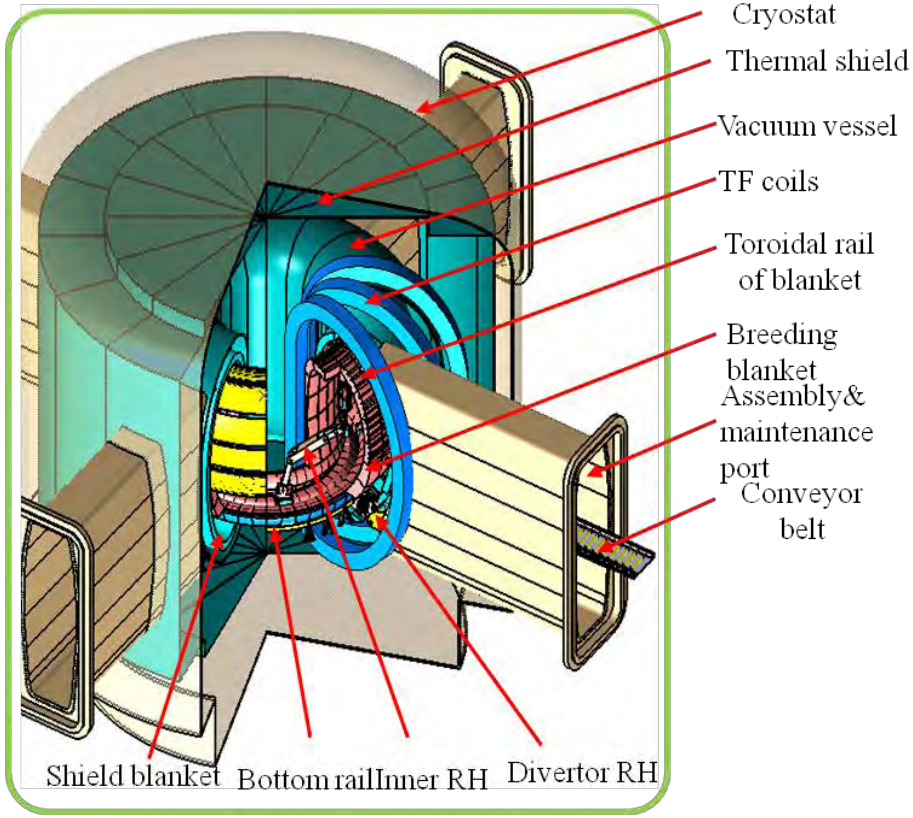
Maintenance animation demo —— integrated solutions

ASIPP



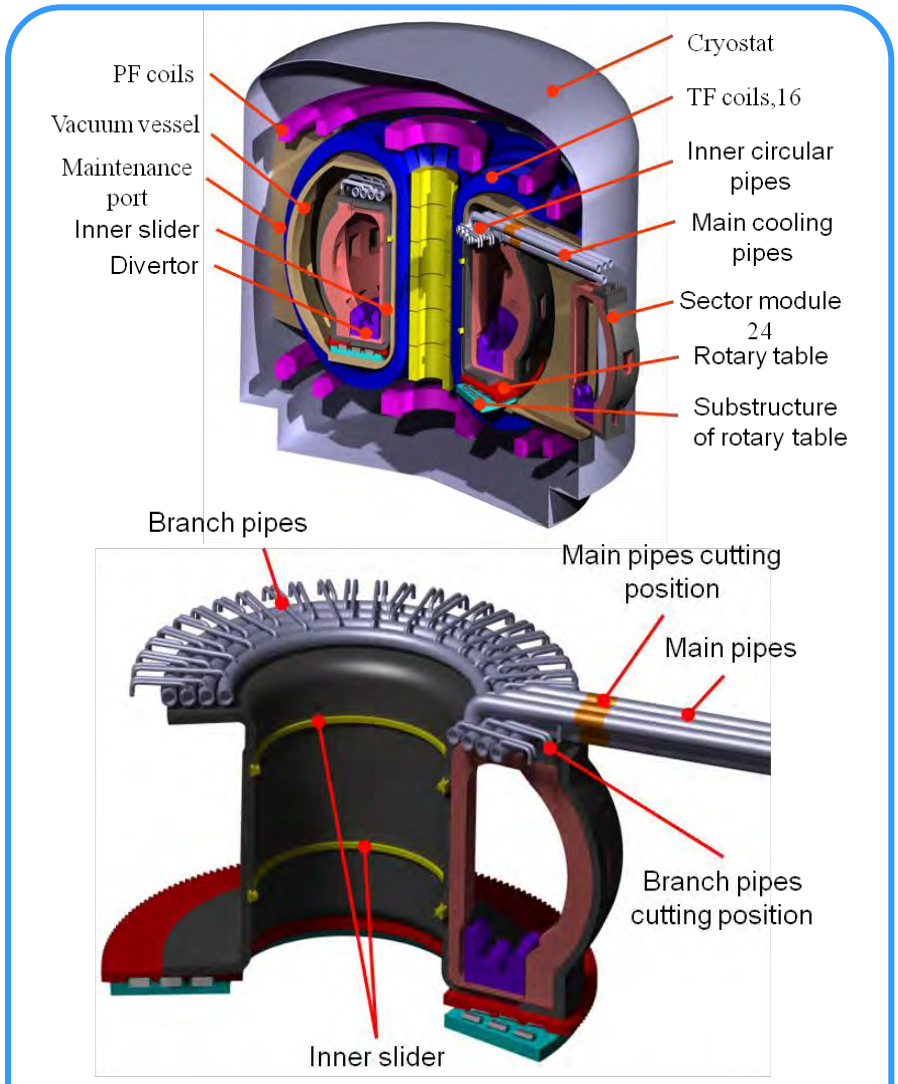
See simulation animation

Other innovative maintenance proposals



Toroidal rail assembly proposal

- The disassembly and installation of the blanket can synchronously which can greatly improve the maintenance efficiency;
- Need less maintenance ports and the blanket is easy to be disassembled.



Revolving restaurant proposal

Summary

ASIPP

- The main objective of CFETR is to develop a D-T reactor in order to provide the physical, engineering, technical and operational foundation for the DEMO and fusion reactor.
- Built a superconducting 5.7/1.6m tokomak is foreseeable within 8-10 years in China.
- The conceptual design work of CFETR is ongoing in China and the R&D process is under planning.
- New advanced fusion technologies and materials are urgently needed.
- International collaboration is important to speed up the design and construction process of CFETR project.

Thank you for your attention!