Status of design and strategy for CFETR

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26 -28 March 2013
Kyoto Japan

Content

- Introduction
  - background
  - opinion and consideration
- Progress on the concept design of CFETR
- Summary

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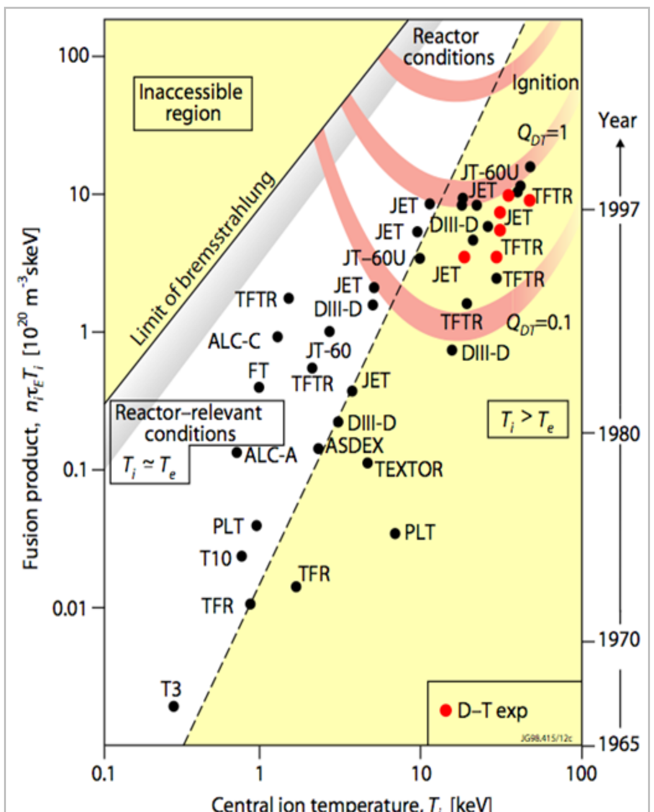
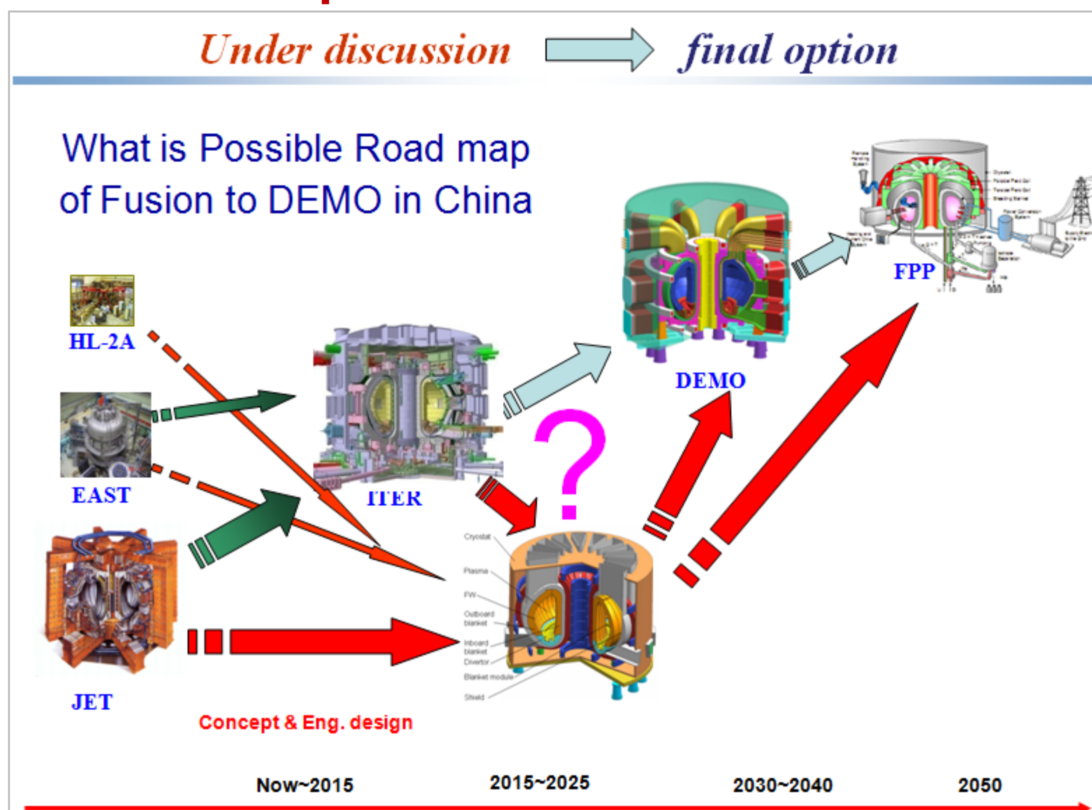
Background

- Significant progress of fusion research has been achieved within last 50 years;
- International Thermonuclear Experimental Reactor (ITER) has been approved for construction by 7 partners.
- In China many important progresses on tokamaks (e.g. EAST, HL-2A) have been achieved during last 20 years;

What should be the next step for MFR in China ?





Background

- China is facing serious energy problem (energy shortage and environment pollution). Which will be even more serious in the near future;
- Chinese government made the decision to join in ITER. The purpose is to promote the development of the fusion energy for ultimate use as early as possible;
- Therefore the National Integration Design group for Magnetic Confinement Fusion Reactor has been founded in 2011
- The design activities of the Chinese Fusion Engineering Test Reactor (CFETR) as the next step are under way by the group.

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National design group

Vice heads

Head: Wan Yuanxi

Li,Jiangang

Liu Yong,

Wang, Xiaolin

Wan,Yuanxi	USTC, ASIPP
Li, Jiangang	ASIPP, USTC
Liu, Yong	SWIP
Wang, Xiaolin	CAEP
Ye, Minyou	USTC
Wan, Baonan	ASIPP
Duan, Xuerun	SWIP
Yu, Qin quang	Germany
Zhuang, Ge	HUST
Yang, Qinwei	SWIP

Wu, Songtao	ITER
Li, Qiang	SWIP
Weng, Pede	ASIPP
Guo, Huoyang	USA
Feng, Kaiming	SWIP
Wan, Farong	BUST
Fu, Pen	ASIPP
Wu,Yican	USTC
Gong, Jun	INS

Headquarter： SNST-USTC

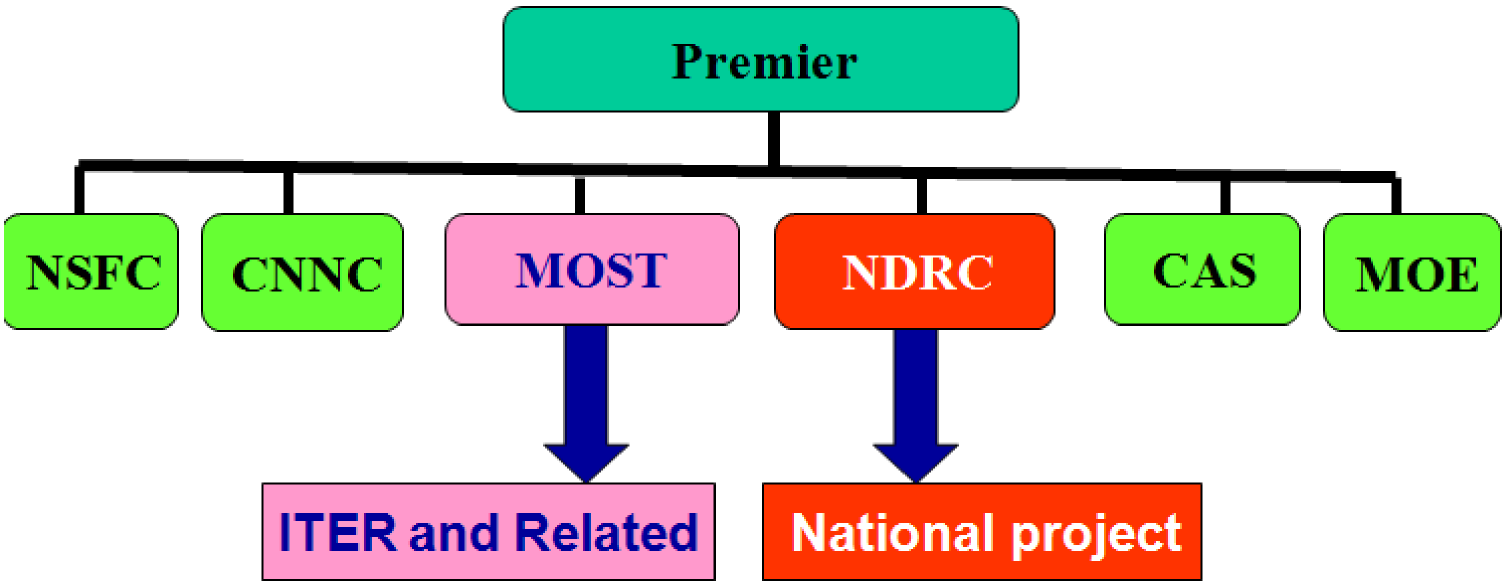
Working task and schedule

2011- 2014: provide **two** options of engineering concept design of CFETR which should include in:

- Missions
- Type
- Main physics basis
- Main techniques basis to be taken
- **The concept engineering design for all sub-systems**
- Budget & Schedule
- Location
- Management system
- List of the key R&D items
- The plan for 200 PhD students / year

- **2015:** will make the proposal to government to try to get permission for CFETR construction;

Support system for fusion research in China



Fusion supported by

- National Development and Reform Commission – NDRC
- Ministry of Science and Technology – MOST
- Ministry of Education – MOE
- Chinese Academy of Sciences – CAS ;
- China National Nuclear Corporation – CNNC
- Natural Science Foundation of China – NSFC

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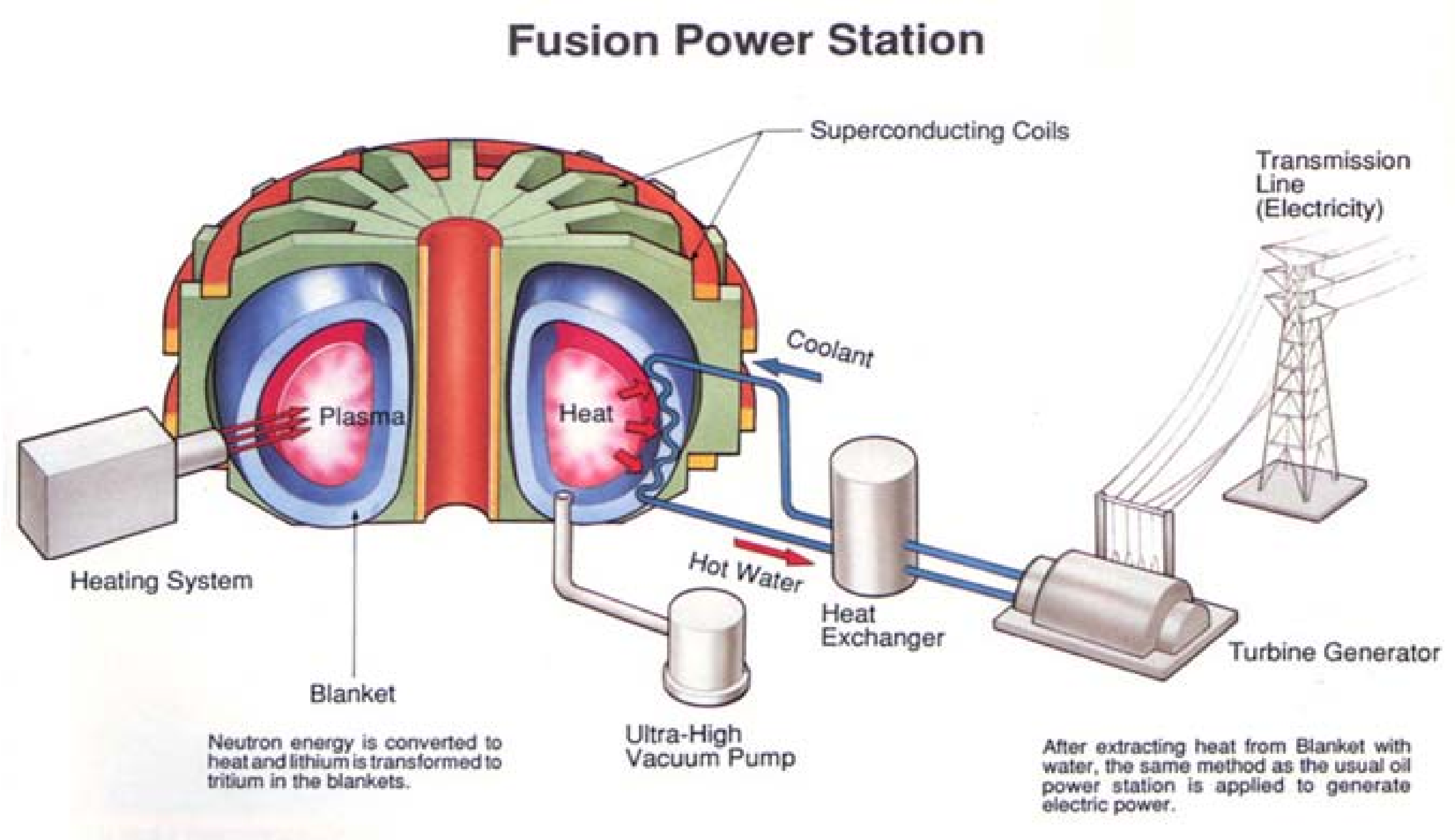
Final goal is to obtain realistic FE (FPP)



D-T burning plasma with the SSO or high duty

The steps for going to fusion energy (FPP)

If the fusion energy is goal the necessary steps should be :

1.achieve the burning plasma :

high density n ;
high temperature T_i ;
high energy and particle confinement τ_E ;

2. sustain the burning plasma to be SSO or long pulse with high duty cycle :

CW heating : α particles or external heating such as NBI, RF?
CW CD: bootstrap CD ? or external inductive or no-inductive ?
"continual" fueling
CW exhausting the ash of burning by divertor
CW extracting the particle's energy by divertor
CW extracting the fusion neutron energy by blanket via first wall

3.Tritium must be self–sustainable by blanket ;

4. The materials of first wall and blanket have suitable live time ;

Before ITER

The most important issue for fusion research is to improve the confinement

$$\tau_{E,p}$$

The most important issue for fusion energy is to sustain the burning time

$$t_{burning}$$

Practical energy resources should be SSO !!

$$P_{fusion} \propto n * T * \tau_E > 10^{21}\ m^{-3} * s * kev$$

$$E_{fusion} \propto (n \times T \times \tau_E) \times t_{burning}$$

Steady-State Operation (SSO)

The long burning time for FE is a basic requirement

$$t_{burning}$$

- Are there good physic and technology basis for SS burning plasma operation ? Answer is no !!
- **And how to achieve ?**

- How to achieve the T- self-sustain by Blanket ?
- What will be happened for key in-vessel components and related materials under high flux irradiation by 14 MeV neutrons ?

The scientific goals of ITER

ITER is the burning plasma device and its **scientific goals** are:

- to produce a plasma dominated by α-particle heating
- produce a significant **fusion power amplification** factor (Q ≥10) in long-pulse operation (300 - 500s)
- aim to achieve steady-state operation of a tokamak (Q=5)
- retain the **possibility** of exploring controlled ignition (Q≥30)
- demonstrate integrated operation of technologies for a fusion power plant
- **test** components required for a fusion power plant
- test **concepts** for a tritium breeding module

Gaps between ITER and FPP

Even if ITER can make great contribution to long pulse or SSO burning plasma but it is mainly on physics and not on real fusion energy because of the real burning time during 14 year D-T operation is only about 4 %, which results in :

1. **There is no enough fusion energy produced for utilization.**
2. **As the consequent the total neutron flux is not enough to demonstrate the real tritium breeding for tritium self sustainable by blanket.**
3. **No enough neutrons to do the material tests in high flux fusion neutron radioactive environments.**
4. **Therefore there only are shielding blankets for ITER.**
5. **Even if adding the TBM with addition budget but it is only concept testing for tritium breeding and not real self sustainable blanket and related material tests**

Conclusion: the engineering test reactor is necessary to be constructed parallel with or after ITER and before the fusion power plant (FPP).

For this purpose the China Fusion Engineering Test Reactor (CFETR) is under discussion seriously for design and construction.

Common understanding (1)

The CFETR must be built before the FPP in China

- ITER can be a good basis for CFETR both on SSO burning plasma physics and some technologies;
- The goals of CFETR should be different with ITER and aim to the problems related with fusion energy
- Both physic and technical basis of the CFETR should be more realistic when it is designed.
- CFETR should not make over-promise, it just is a important engineering test reactor for future DEMO or FPP for FE

Common understanding (1)

So mission must be realistic and sequence must be right !!

- **The cost for fusion energy , the multi application of blanket could be lower priority in compare with T selves- sustainable and heat conversion and extracted;**
- **The divertor will be another key component for the success of future FPP- it will be the most important components related with the basic requirements for SSO both on physics and technologies.**

Content

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The mission and design goal of CFETR

1. A good complement to ITER；
2. Relay on the existing ITER physical and technical bases ;
3. Fusion power P_f = 50～200MW；
4. Steady-state or long pulse operation (duty cycle ≥ 0.3- 0.5)；
5. Demonstration of full cycle of T self-sustained with TBR ≥ 1.2;
6. Exploring options for DEMO blanket & divertor with an easily changeable capability by RH.

CFETR will be the important facility to bridge from ITER to DEMO in China, which is necessary step to go to DEMO and then the fusion power plant.

Preliminary design consideration

1. Physics consideration
2. Integrated design consideration of the device with RH
3. Blanket considerations
4. Divertor considerations
5. Tritium consideration

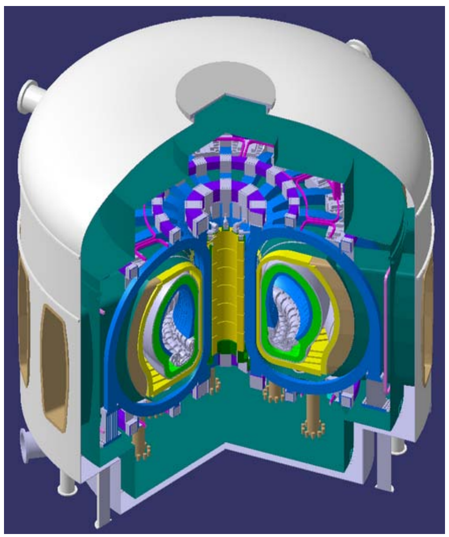
Physics consideration

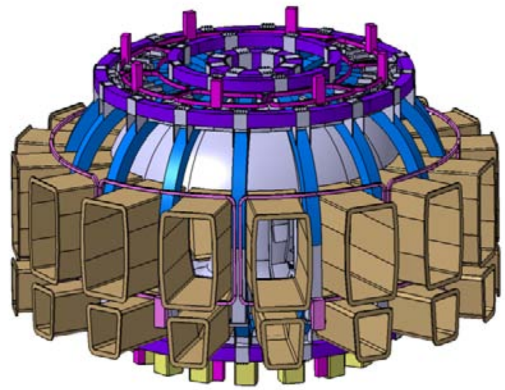
• CFETR as a test reactor to achieve the fusion energy at reasonable fusion power level should have high reliability and availability. So the core plasma designs are based on relatively conservative physics and technology assumptions, such as operation far away from the stability limits and readily achievable performance；

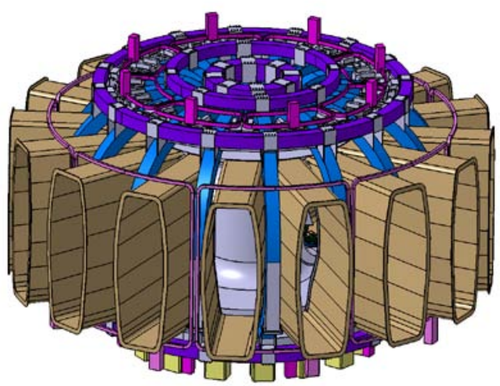
• A device of R=5.7m, a=1.65m in size with Bt=5T and total H&CD source power of 80MW (assumed efficiency 0.8) with SN configuration could be projected based on a zero-dimensional system study using extrapolations of current physics, which are from the multi-iteration and optimization among plasma performance, blanket module and superconducting magnet requirements, etc.

• Analysis of vertical stability control indicates that the basis configuration with an elongation kx=2.0 can be reliably controlled using in-vessel coil similar to that used in EAST.

key parameters and
several design versions of CFETR are under comparison







	CFETR
Major radius (m)	5.7
Minor radius (m)	1.65
Elongation	1.8 – 2.0
Plasma current (MA)	8-10
Toroidal field (T)	5.0/4.5
Elonation	1.8-2.0
Triangularity	0.4
Heating Power (MW)	80/100
Fusion power (MW)	50~200
Plasma volume (m^3)	612
Flux(Vs)	160

Simple scaling for Parameter investigation

R(m)=5.7, a(m)=1.65, B(T)=5； κ=2.0, δ=0.4； α_n=1, α_T=1； Vp(m^3)=612；

Ip=10MA， q_{95}=4.17, Z_{eff}~1.76， Power deposition 80%， g_{CD} = 0.16~0.26 (ITER target 0.4)

Paux(MW)	50	50	80	80	80	80	80
E(MJ)	168	191	1701	209	270	302	237
P_Fus(MW)	215	280	209	332	498	583	333
Q	5.38	7.01	3.26	5.19	7.78	9.1	5.21
Ti0	15.3	14.3	18.1	15.7	20.2	22.6	25.1
nel	0.82	1	0.7	1	1	1	0.7
nGR	0.7	0.85	0.6	0.85	0.85	0.85	0.6
betaN	1.52	1.73	1.54	1. 9	2.44	2.73	2.14
betaP	0.79	0.89	0.79	0.98	1.26	1.41	1.1
fbs	31.67	35.9	32.05	39.46	50.8	56.76	44.48
taoE98Y2	2.25	2.21	1.79	1.79	1.53	1.43	1.55
Pn/Awall	0.37	0.48	0.36	0.57	0.86	1	0.58
Res	7.77E-09	8.63E-09	6.06E-09	7.49E-09	5.13E-09	4.34E-09	3.71E-09
Pthre	64.9	74.6	58.1	74.6	74.6	74.6	58.1
ICD(MA)	1.43	1.1	3.16	1.93	2.49	2.78	4.38
H98	1	1	1	1	1.2	1.3	1.3
T_burn(s)	715	656	1377	972	2500	4500	7093

B.N. Wan et al.,

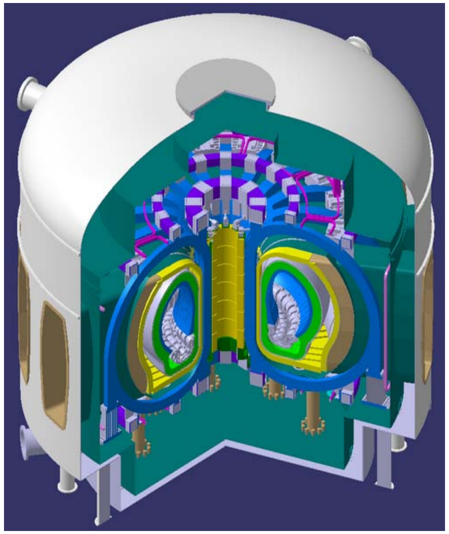
Conclusion·：

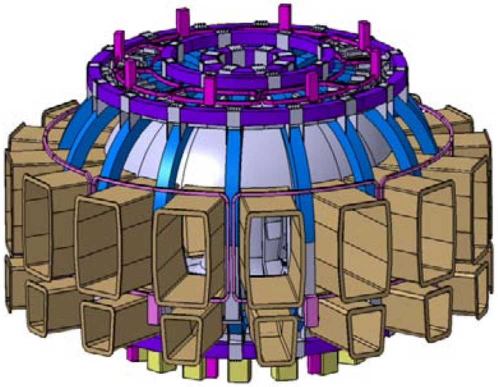
- Scenario analysis based on "ITER physics design guidelines" show that CFETR can achieve 200MW fusion power at Ip~10MA in H-mode for over 1000s；
- 8.5MA in "improved H-mode" (H98~1.2) for several hours or at Ip~7.5MA for steady-state in advanced regime with a moderate factor of H98~1.3 and beta_N <2.8.

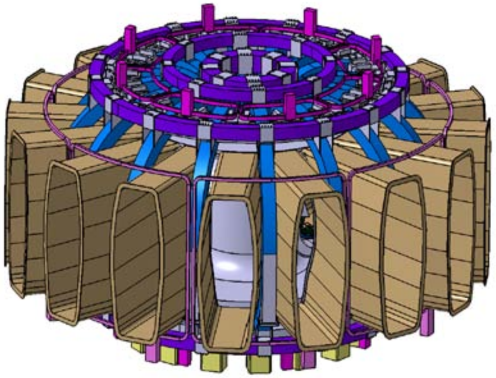
I_p~8MA， Bt=5T， q_{95}=5.2， Z_{eff}~1.76， P~80*0.8MW， γ_{CD} = 0.15~0.22 (ITER target 0.4)

E(MJ)	141	159	178	196	206	183
P_Fus(MW)	155	193	234	276	298	226
Q	2.4	3.0	3.7	4.	4.6	3.53
Ti0	13.2	14.8	16.6	18.4	19.3	20.8
nel	0.79	0.79	0.79	0.79	0.79	0.65
nGR	0.85	0.85	0.85	0.85	0.85	0.7
betaN	1.59	1.79	2.00	2.22	2.33	2.07
betaP	1.03	1.16	1.29	1.43	1.50	1.33
fbs	41.4	46.7	52.2	57.8	60.7	54
taoE98Y2	1.65	1.56	1.48	1.41	1.38	1.38
Pn/Awall	0.27	0.33	0.40	0.47	0.51	0.39
Res	9.72E-09	8.13E-09	6.89E-09	5.90E-09	5.49E-09	4.88E-09
Pthre	63.6	63.6	63.6	63.6	63.6	55.3
ICD(MA)	2.03	2.29	2.56	2.83	2.97	3.9
H98	1	1.1	1.2	1.3	1.35	1.35
T_burn(s)	1933	3075	5714	15693	margin ss	ss

key parameters and several design versions of CFETR are under comparison







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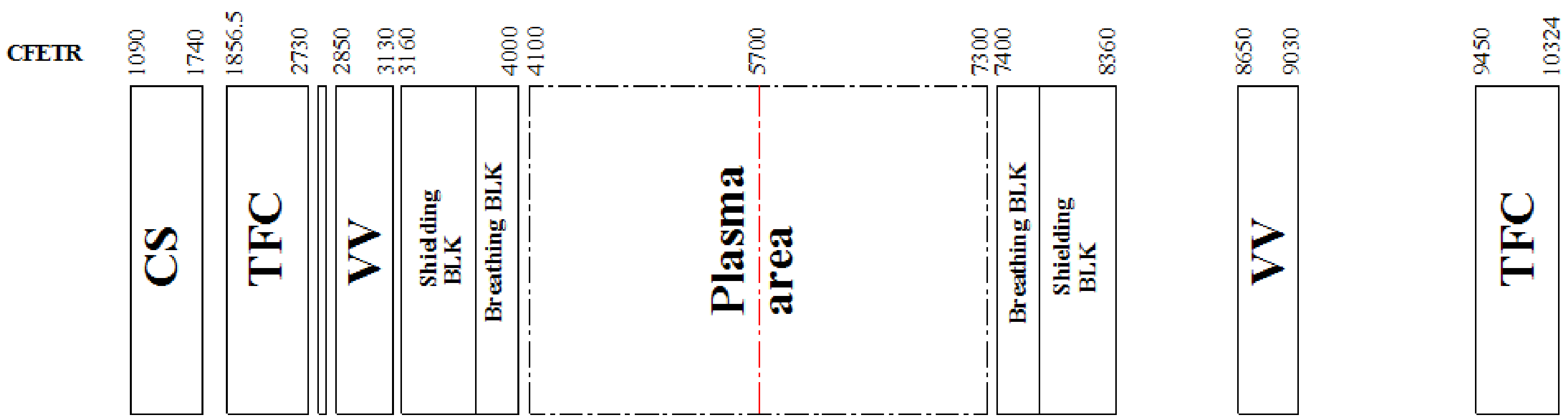
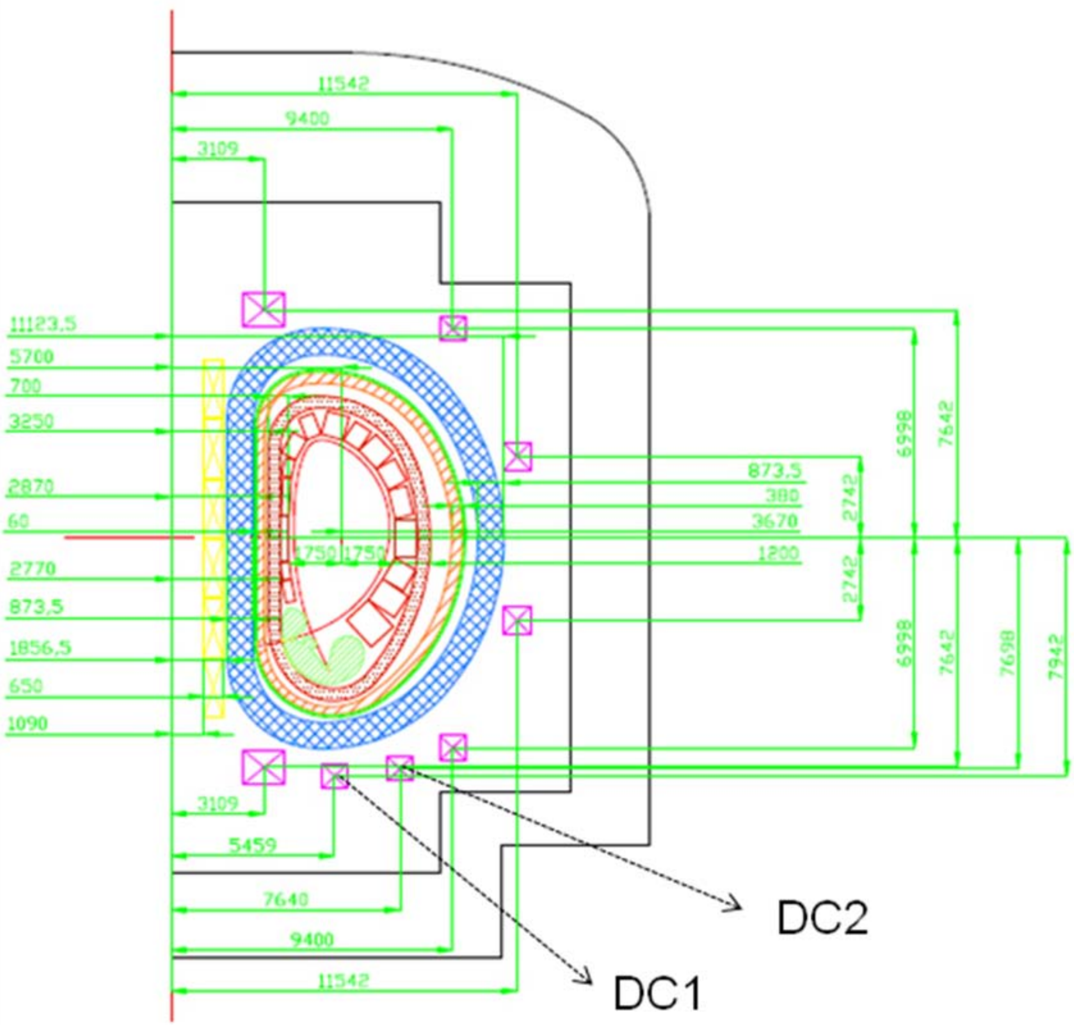


图一：　CFETR 主机重要部件分布及尺寸分配-1


11542
9400
3109
11123,5
5700
700
3250
2870
60
2770
873,5
1856,5
650
1090
873,5
380
3670
1200
2742
2742
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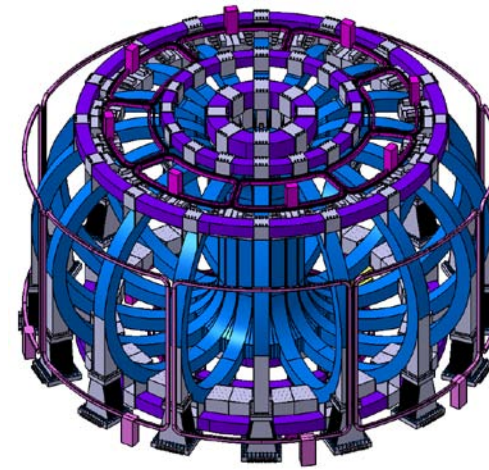
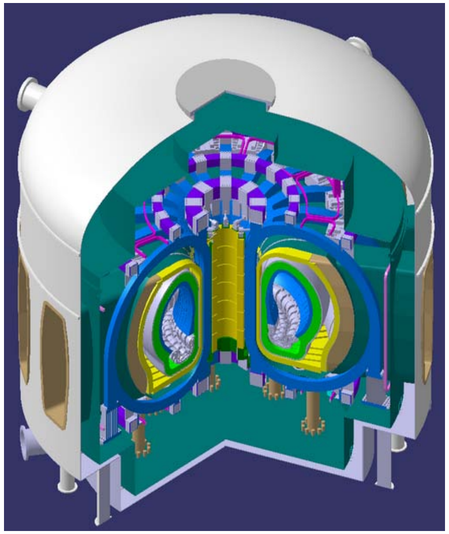
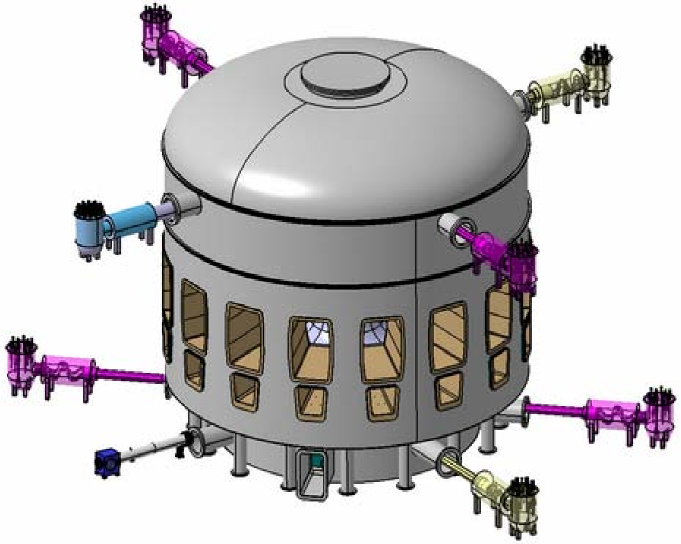
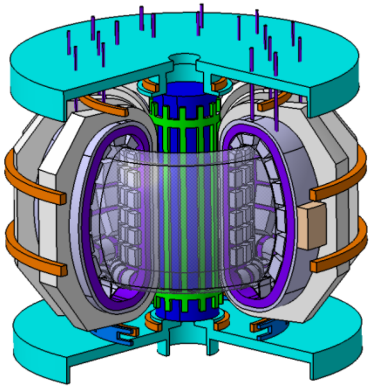
9400
11542
DC2
DC1

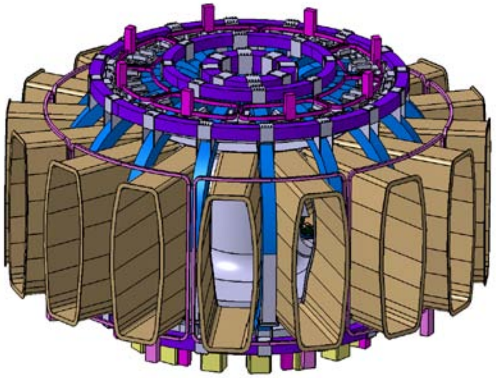


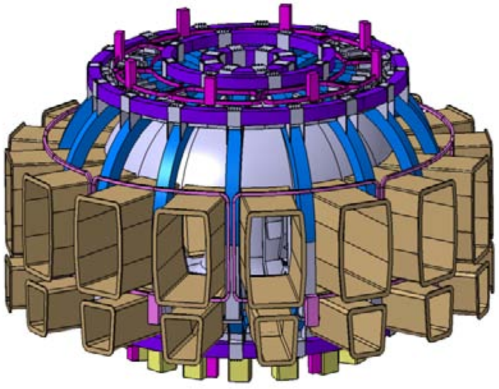
Range of key parameters and several design versions of CFETR are under comparison











Preliminary design consideration

1. Physics consideration
2. Integration consideration of the tokamak device with RH
3. Blanket considerations
4. Divertor considerations
5. Tritium consideration

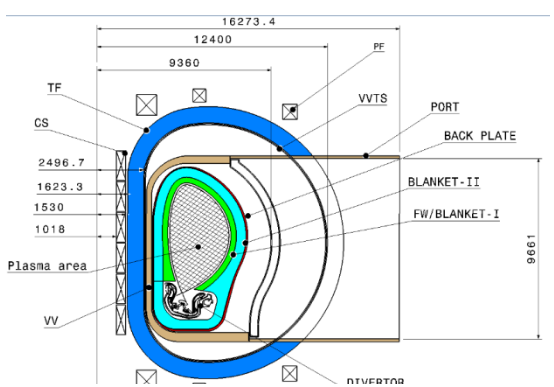
The duty cycle of CFTER will be impacted

by the principle of RH significantly

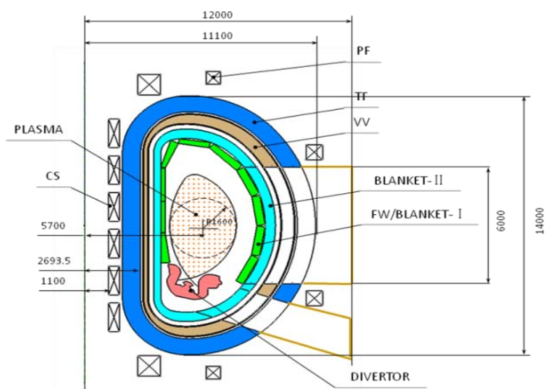
Main parameter for option 2 of CFETR (Major radius is 5.7 m, 4.5/5.0 T)

Case1 is the main machine with a big level maintenance window ; Case2 is the main machine with a mid level maintenance window ; Case3 is the main machine with a top maintenance window ;

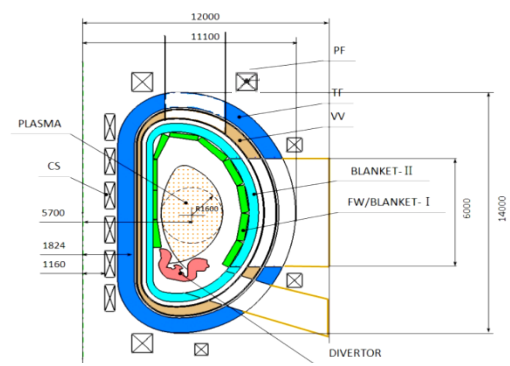
Parameter	Option 2						ITER
	Case 1		Case 2		Case 3		
Center field(T)	4.5	5.0	4.5	5.0	4.5	5.0	5.3
Total turns of each TF coil	132	132	132	132	132	132	134
Enlongation	1.83	1.82	1.83	1.82	1.82	1.82	1.70/1.85
Triangularity	0.38/0.58	0.38/0.58	0.33/0.57	0.27/0.57	0.32/0.58	0.32/0.57	0.33/0.48
Maximum Magnetic field of TF	9.93491T	11.0072T	10.0355T	11.0919T	10.1335 T	11.1934T	11.8 T
Maximum Magnetic field of CS（T）	10.3864	10.3903	10.6339	10.44	10.1535	10.1542	12
Maximum Magnetic field of PF（T）	6.98801	7.01	6.93114	6.97336	12.1278	12.1368	6.8
Energy storage（GJ）	31.52	38.863	29.218	36.024	29.218	36.024	40
Centripetal force（MN）	319.24	354.475	335.19	372.227	335.192	372.23	403



The structure of Case 1 for CFETR



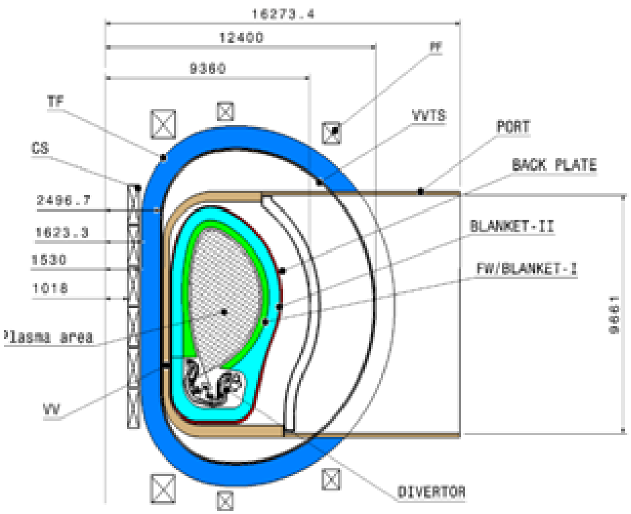
The structure of Case 2 for CFETR

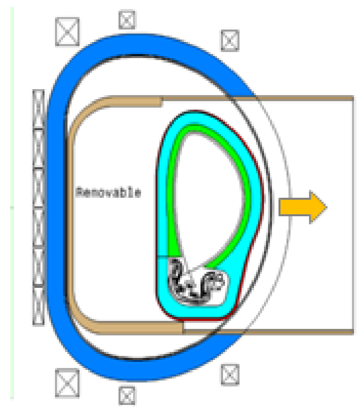


The structure of Case 3 for CFETR

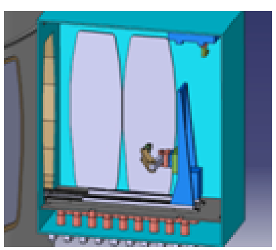
RH conceptual design for big window style strategy

All of the in-vessel components can be moved out in one time.

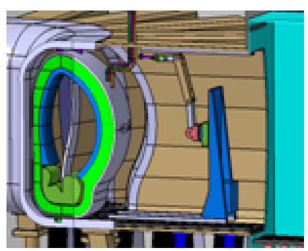




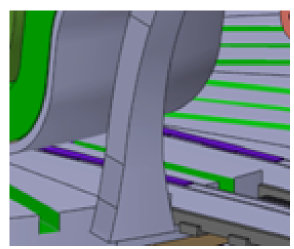
Maintenance process:



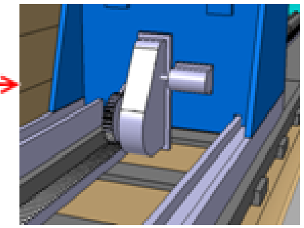
1. Dismantle the window's flange



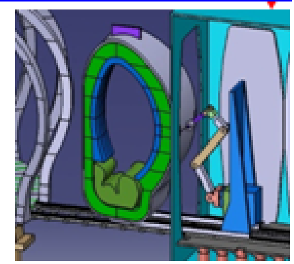
2. Cut the cooling pipe and other connection things by remote handing



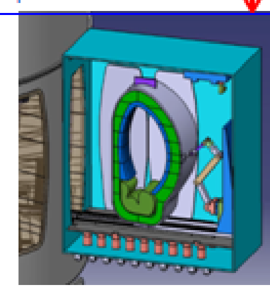
3. Inset wheels assemble under the blanket and lifting the blanket



4.Move back the wheels with the blanket, by gear system

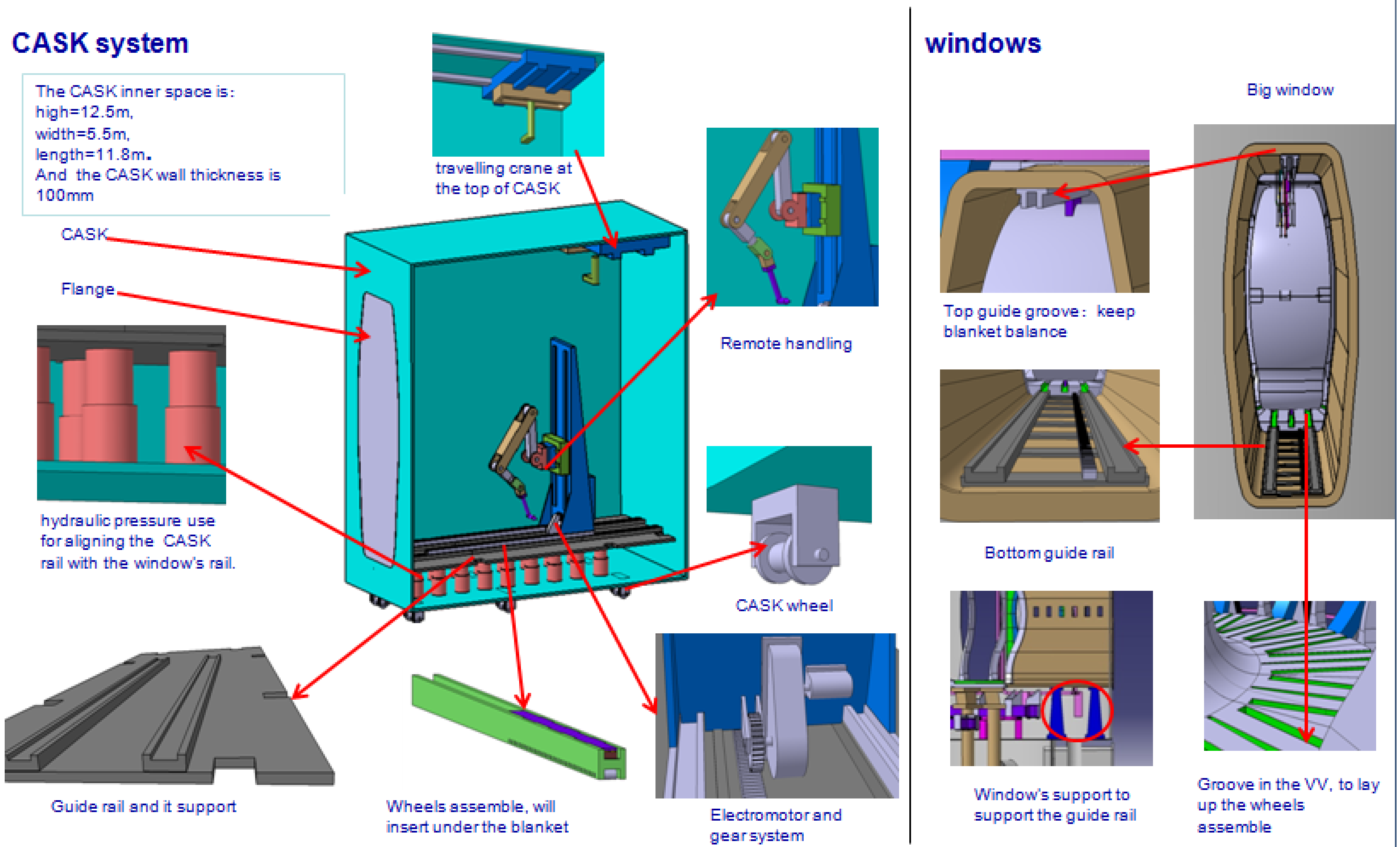


5. Use remote handing and guide rail to keep the blanket balance



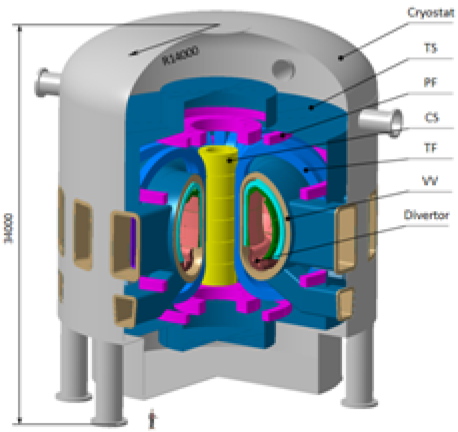
6.Close the window's flange and move the CASK to hot cell for repair

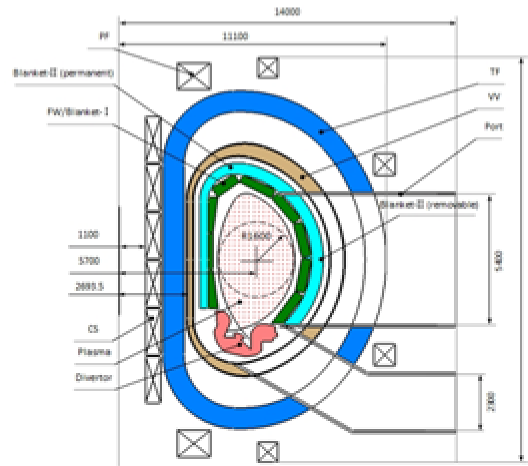
RH conceptual design for big window style strategy

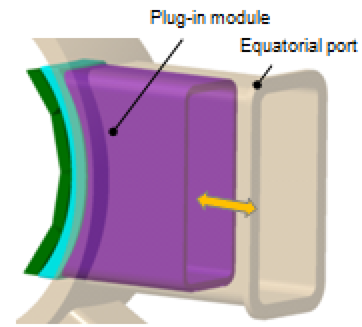


RH conceptual design for medium window style strategy

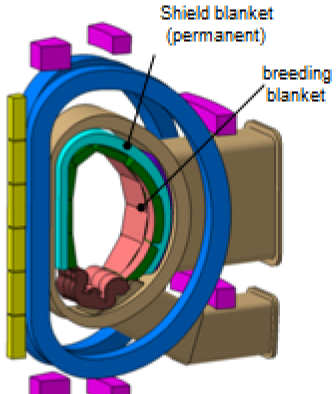
Every equatorial port shall be used as maintenance port for blanket Remote Handling (RH) system.
4 lower port shall be used for divertor RH system. (TBD)



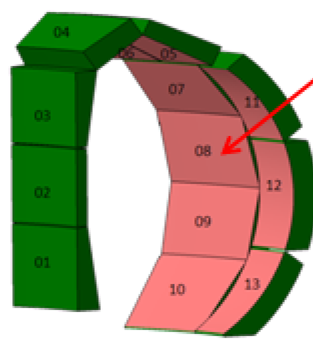




Plug-in module: move 07~10 segments out in one time

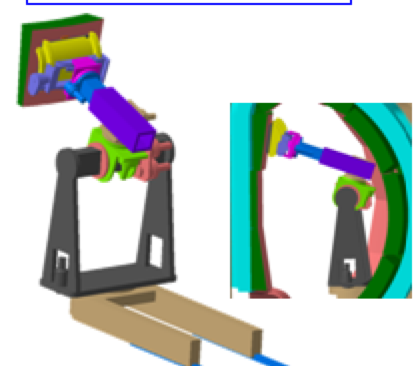


Single section (with lower port)



Maximum dead weight: 9-ton.

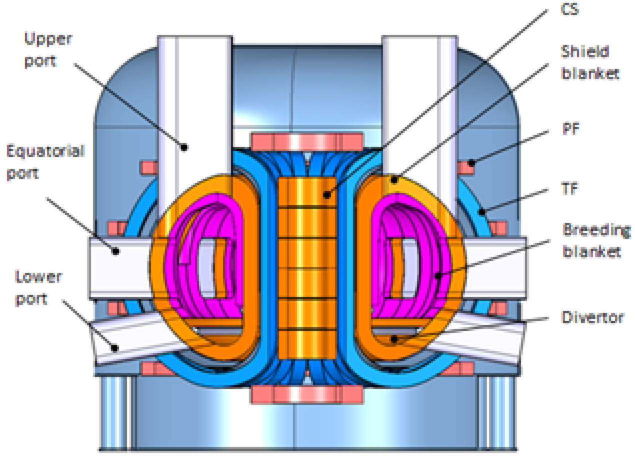
13 breeding blanket segments

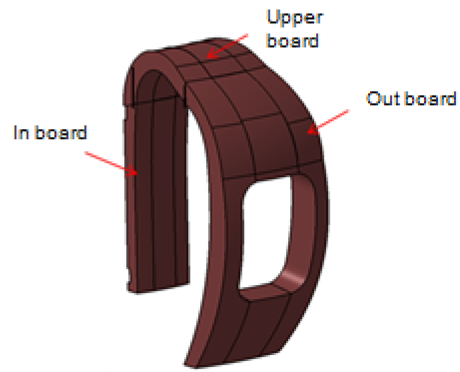


The rest segments (01~06, 11~13) are handled by a manipulator

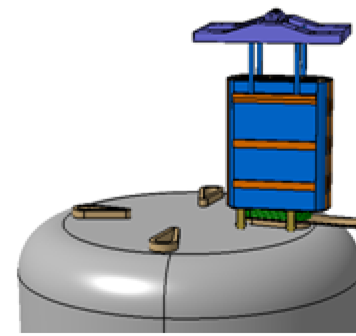
RH conceptual design for Upper port strategy

The reactor has 16 sections with 8 equatorial ports ,4 lower ports and 4 upper ports.
The shield blanket modules are permanent and the breeding blanket modules are removable.

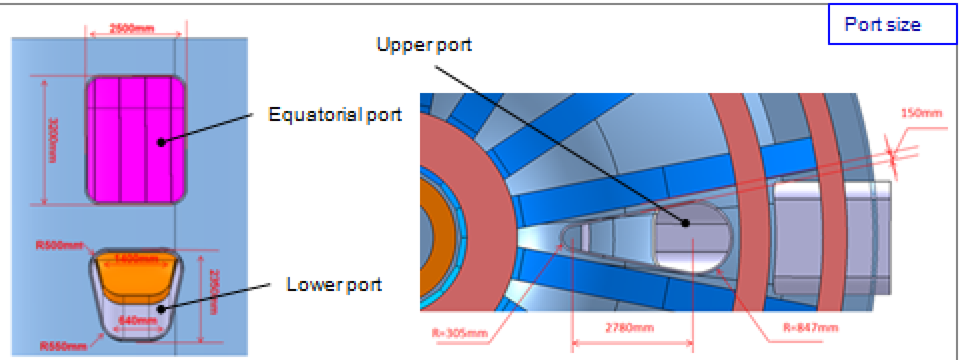




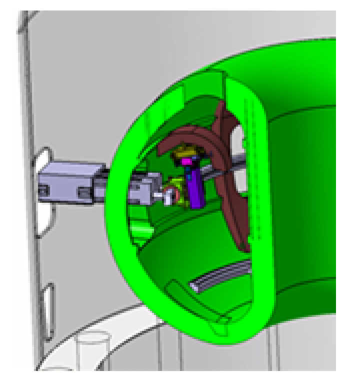
3 breeding blanket segments for one section



The Lift cask upon the upper port



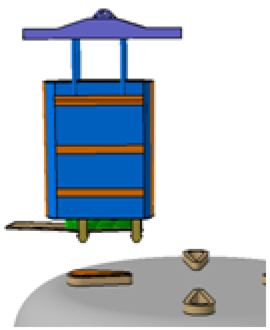
Port size



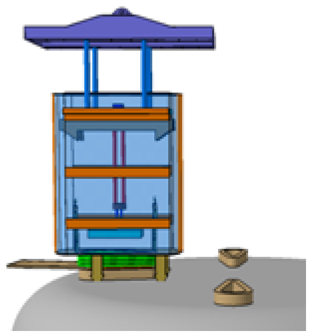
Manipulator (from equatorial port) for module segments toroidal movement

RH conceptual design for Upper port strategy

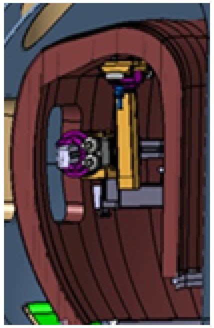
Maintenance process:



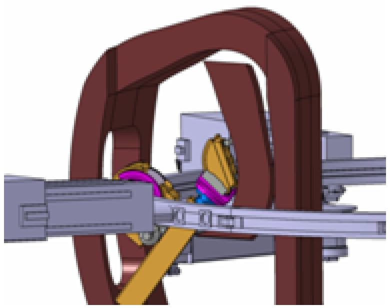
1. Move cask to the upper port



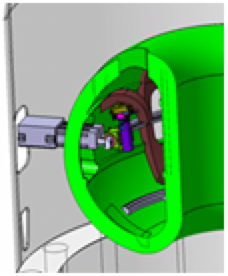
2. Connection, open the sealed door



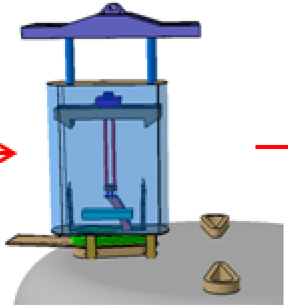
3. Manipulator enter VV



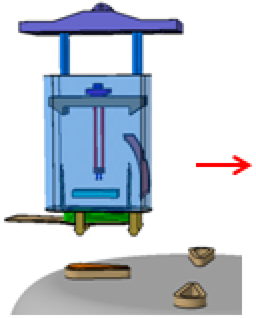
4. Manipulator grab the blanket module.



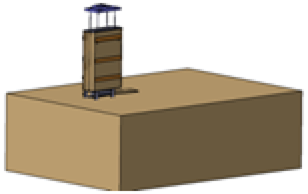
5. Transfer the module to lifting position(under upper port)



6. Lift the module



7. Close the sealed door and disconnect

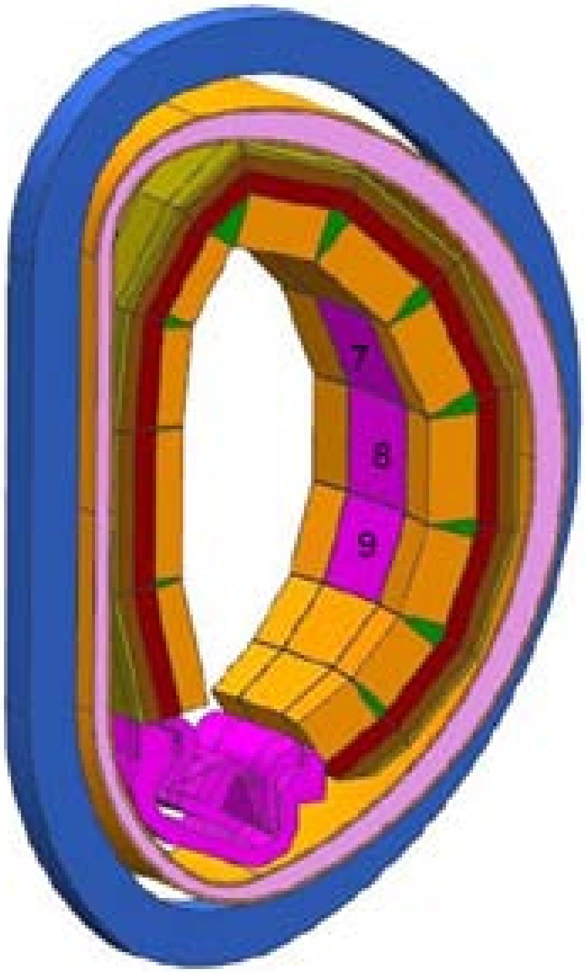


8.Move to Hot cell

Preliminary design consideration

1. Physics consideration
2. Integration consideration of the tokamak device with RH
3. Blanket considerations
4. Divertor considerations
5. Tritium consideration

Three groups are working on the concept design of CFETR blanket



Group I:

1) HC (8MPa, 300/500 ^{0}C), Li_4SiO_4 (Li_2TiO_3), Be , RAFM

Group II :

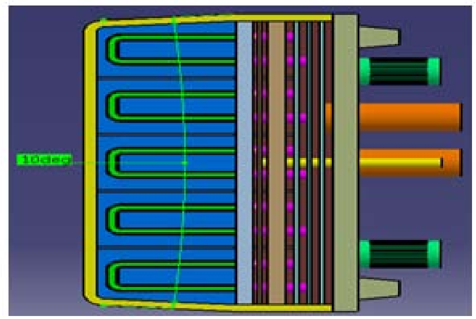
1) SLL (~150 ^{0} C) , CLAM
2) DLL(~700 ^{0}C), CLAM

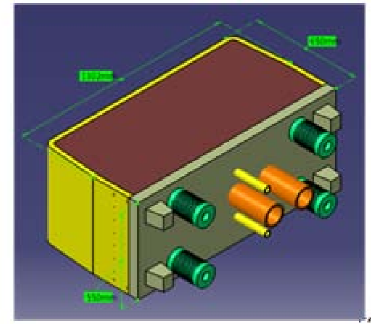
Group III :

1) HC, Li_4SiO_4 , Be , RAFM
2) WC, Li_2TiO_3, $Be_{12}Ti$, RAFM

Group I:

HC (8MPa, 300/500^{0}C), Li_4SiO_4 (Li_2TiO_3), Be , RAFM

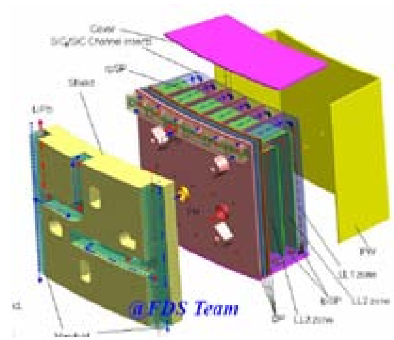




Group II:

SLL (~150 0 C) , CLAM

DLL(~700 0C), CLAM

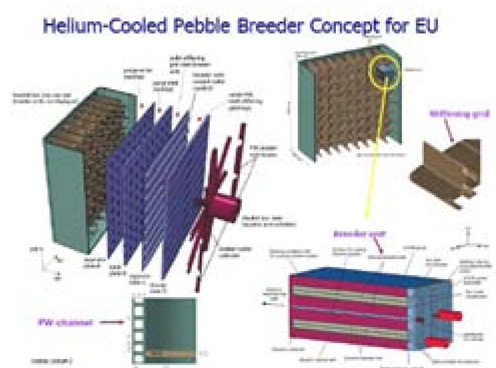


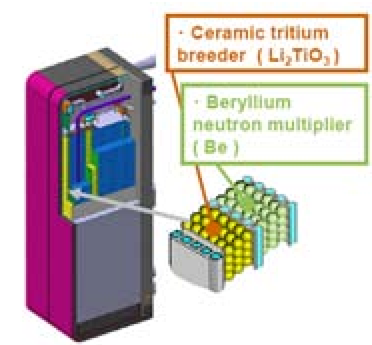
phase II and III

Group III:

1) HC, Li_4SiO_4 , Be , RAFM

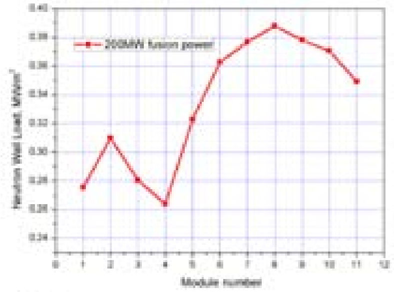
2) WC, Li_2TiO_3, $Be_{12}Ti$, RAFM

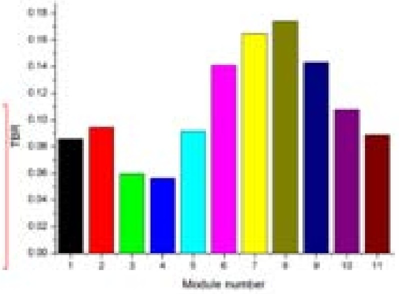




Conclusions

- NWL （average）： 0.33 MW/m²
- Inboard shielding thickness : ～ 46 cm
- Outboard shielding thickness: ～40cm
- Inboard breeder thickness: ～ 37cm
- outboard breeder thickness: ～ 67cm
- TBR can ≧ 1.2 but very sensitive by outboard windows
- TBR is impacted by first wall material and thickness;
- Difference between 1 D and 3D calculations ～ 15-20%





Preliminary design consideration

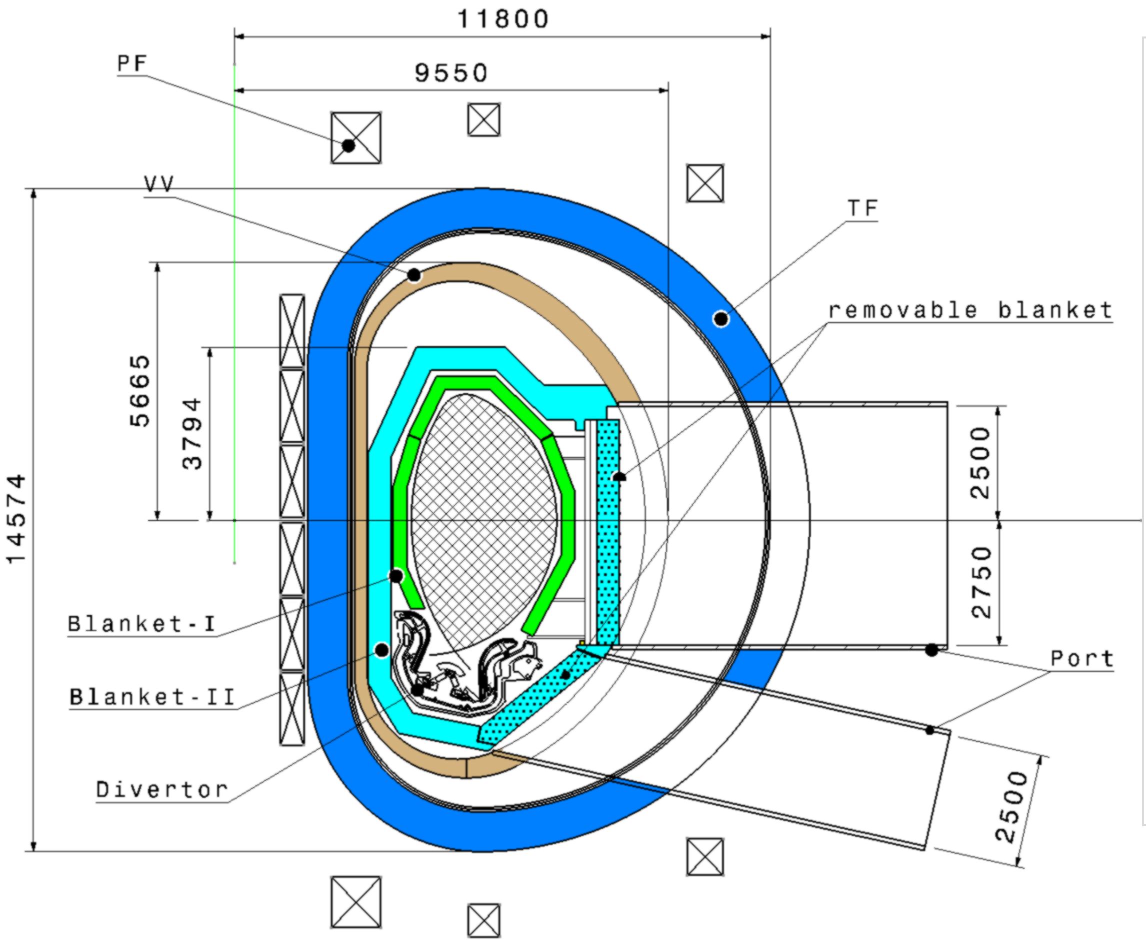
1. Physics consideration
2. Integrated design consideration

   of the device with RH
3. Blanket considerations
4. Divertor considerations
5. Tritium consideration

Main Functions of Divertor

- **Exhaust the major part of the plasma thermal power, reducing heat flux below limitation of target materials (10 MW/m^2).**
- **Remove fusion helium ash from core plasma while providing sufficient screening for impurities influxes.**
- **Maintain acceptable erosion rate in terms of reactor lifetime.**

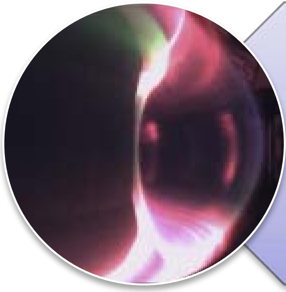
Considerations of Divertor Design of CFETR



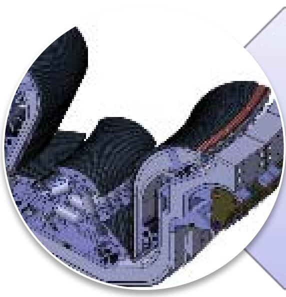
CFETR divertor configurations: bottom SN

Advantages of SN:

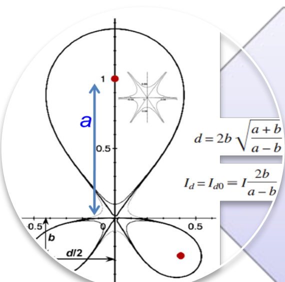
- **more simple**
- **lager volume of pl.**
- **benefit on TBR**



Key issues for divertor design

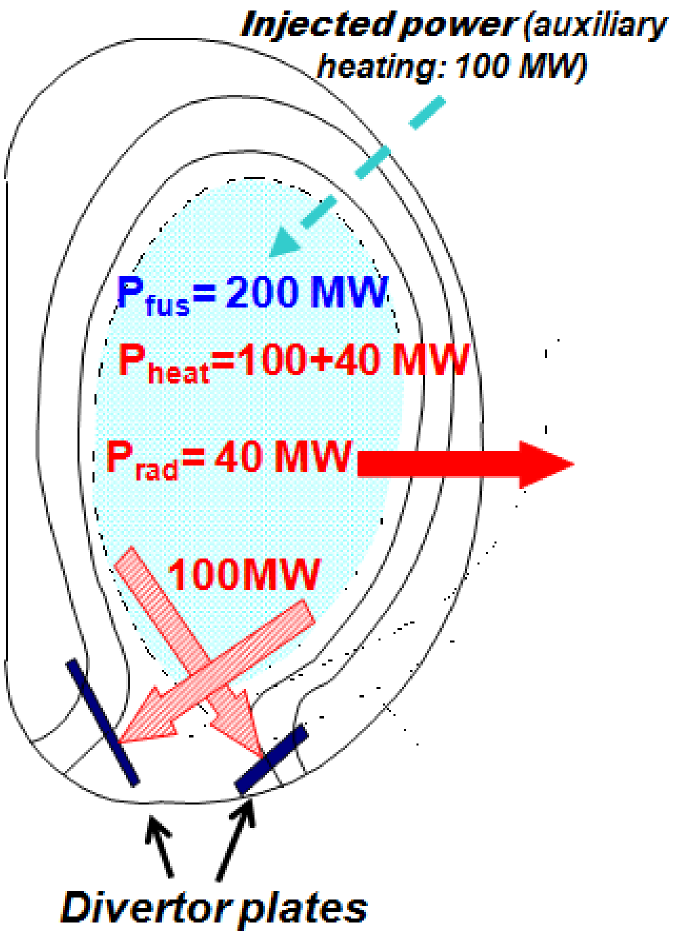


ITER-like divertor



Advanced divertor

The power exhaust (estimated for CFETR)



$P_{SOL} = P_{add} + Pa - Prad^{core}$

$= 100 + 40 - 40 = 100MW$

The plasma-wetted surface area A_w at the divertor plate $A_w = 4RW_{SOL}F_{exp}/\sin(\alpha)$

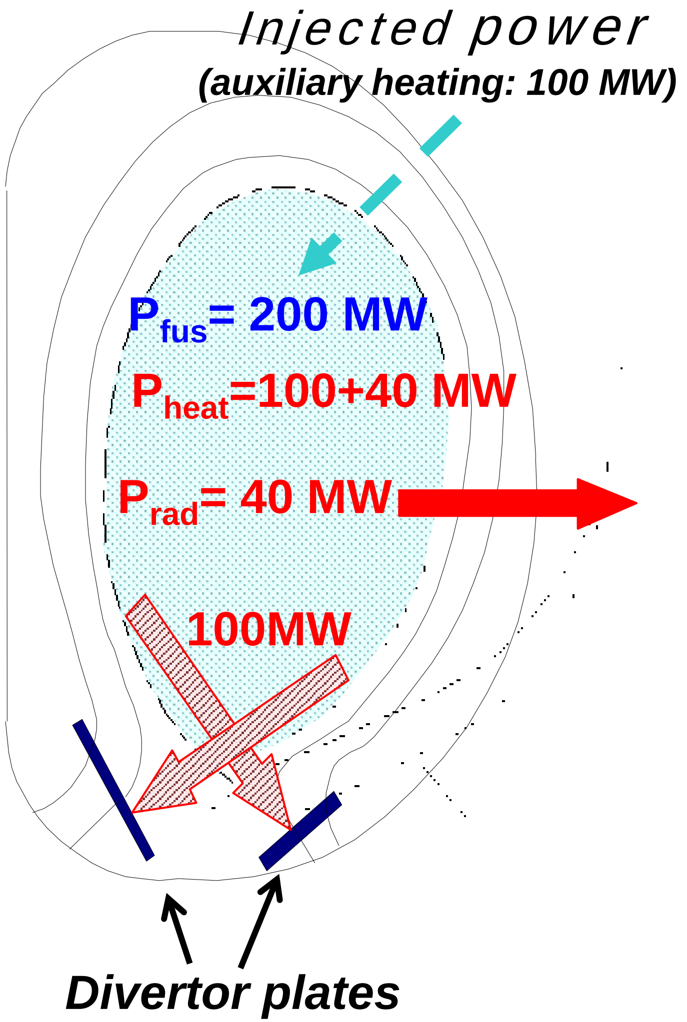
W_{SOL}=4.4mm, Fexp=4.3, α=25 degree
$A_W=3.2m^2$

For a maximum heat flux of 10 MW/m^2
(material and engineering constraints) 32MW

68MW must be radiated away before arriving at the divertor plate

Require divertor detachment to reduce heat load to < 10 MW/m2

Power handling is the most important issue for the reactor design



Power handling [MW]	
P_{fusion}	200
P_a	40
P_{aux}	100
P_{rad}^{core} (brem+sync.)	40
$P_{out} = P_a + P_{aux} – P_{rad}^{core}$	100
P_{out}/R_p [MW/m]	17
P_{div} (= $P_{out} – P_{rad}^{Div\&Edge}$) for = A_{wet} = 1 m^2.	<10
⇒ $P_{rad}^{Div\&Edge}$	>90

Advanced Divertor Configurations

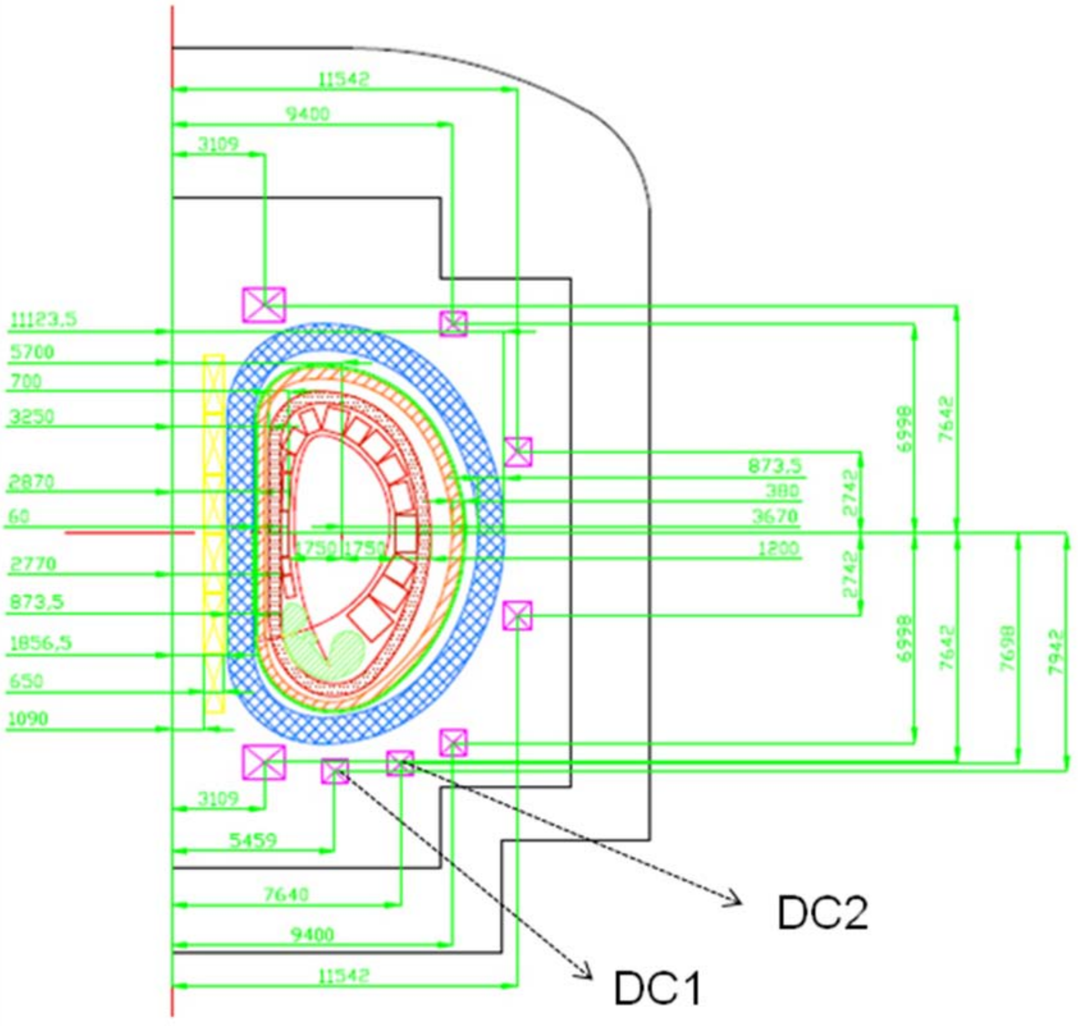
New options: Super-X, Snowflake

Advantages:

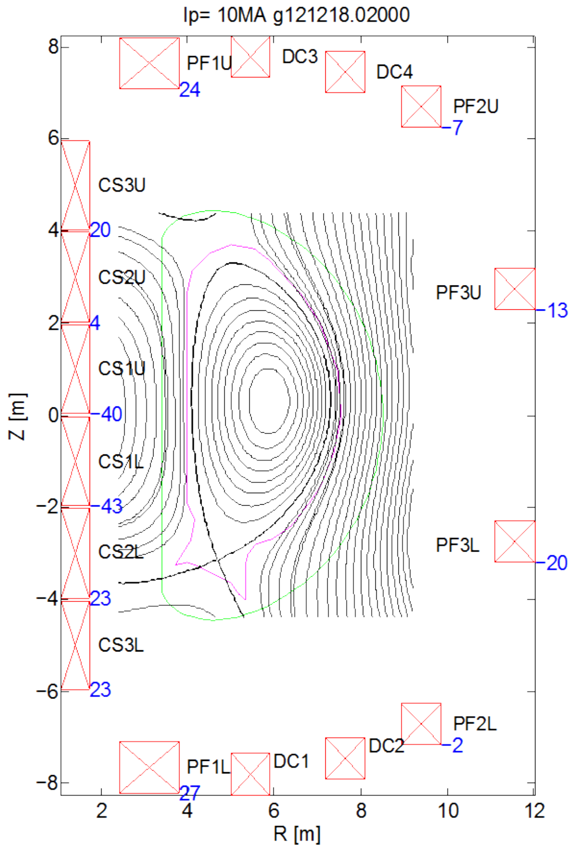
- **Increase wetted area to reduce peak heat flux**
- **Increase $L_{//}$ to facilitate radiative divertor.**

Issues to be addressed:

- **Minimum number of PF coils**
- **PF current and size**
- **Restrictions of poloidal coil location**

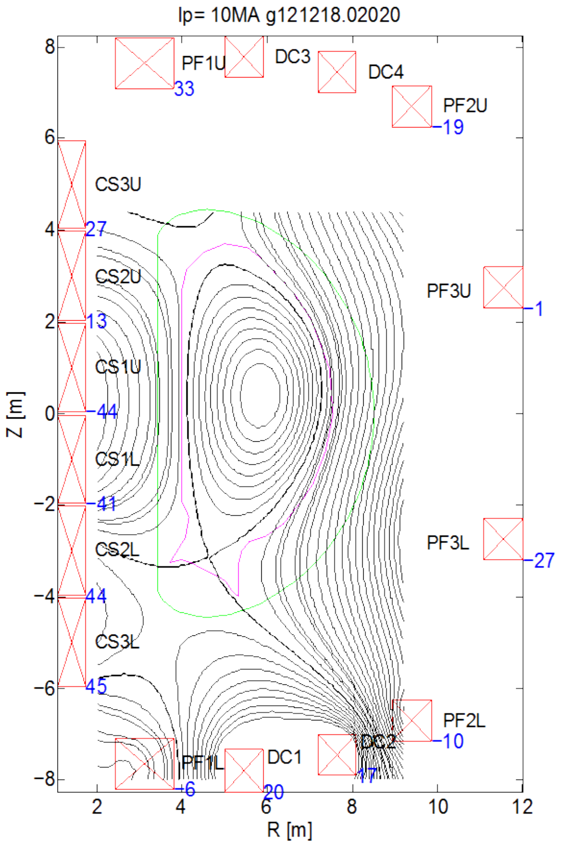

11542
9400
3109
11123,5
5700
700
3250
2870
60
2770
873,5
1856,5
650
1090
873,5
380
3670
1200
2742
2742
6998
7642
6998
7642
7698
7942
1750
1750
3109
5459
7640
9400
11542
DC2
DC1

Single null



Ip [MA]	10
R[m]	5.7
a[m]	1.6
β_p	1.01
l_i	1.09
k	2.0
δ	0.4/0.62
Rxpt [m]	4.692
Zxpt[m]	-3.134

Snowflake (LSN)



Ip [MA]	10
R[m]	5.7
a[m]	1.59
β_p	0.80
l_i	1.09
k	2.01
δ	0.45/0.67
Rxpt [m]	4.637
Zxpt[m]	-3.129

Preliminary design consideration

1. Physics consideration
2. Integrated design consideration

   of the device with RH
3. Blanket considerations
4. Divertor considerations
5. Tritium consideration

Summary of tritium inventories

(maximum instantaneous values for each system; not all simultaneous)

Type of inventory		Maximum values (g T)
In-vessel		**450**
Fuelling system	55	
Mechanical vacuum pumps (VPS)	20	
Torus exhaust processing (TEP)	30	
Isotope separation system (ISS)	220	
Storage and delivery system (SDS)	480	
Other systems (<15 g each)	28	
Estimated subtotal for FC systems		**833**
Long term storage		**2×450**
Hot cell and waste treatment		**250**
Total		**2433**

Assume : fraction of burn up 5% ; Reserve time : one day
First inventory of T: ~ 2000 g

Summary of tritium inventories

(maximum instantaneous values for each system; not all simultaneous)

Type of inventory		[g-T]
• Mobilizable in-vessel (in PFC's,		
• dust, co-deposited etc.)	330	
• Cryopumps open to VV	120	
➢ **Subtotal in-vessel**		**450**
• Fuel cycle		
• Pellet fuelling (PIS)	45	
• Gas fuelling (GIS)	10	
• Mechanical vacuum pumps (VPS)	20	
• Torus exhaust processing (TEP)	30	
• Isotope separation system (ISS)	220	
• Test blanket module tritium recovery (TBM-TRS)	~15	
• Water detritiation (WDS)	~10	
• Atmosphere detritiation (ADS)	~1	
• Gas analysis (ANS)	~2	
• **Estimated subtotal for FC systems**		**~ 353**
➢ **Subtotal of fuel cycle (project guideline)**		**450**
➢ **Long term storage**		**2* 450**
• Hot cell and waste treatment	200	
• Tritium recovery and waste storage	50	
➢ **Subtotal, hot cell and waste treatment**		**250**

Content

- **Introduction**
  - **some background information**
  - **opinion and consideration**
- **Progress on the concept design of CFETR**
- **Summary**

Summary-1

1. SSO or long operation with high duty cycle of the burning plasma is the most important issues both for the physics and related technologies for MFE development:
2. Missions required for CFETR should be more realistic and aim to the most important challenges for FE;
3. CFETR should be a good complement to ITER and it will demonstrate the fusion energy with a minim P_f = 50～200MW; long pulse or steady-state operation with duty cycle time ≥ 0.3～0.5; demonstrating the full cycle of T self-sufficiency with TBR ≥ 1.2; relay on the existing ITER physical and technical bases ; exploring options for DEMO blanket & divertor with an easy changeable core by RH.

Summary-2

4. The design choices of CFETR are still open;
5. The goal of CFETR design activities is to make a proposal at the end of 2014 to government to try to get permission for construction with the key R&D items for CFETR;

CFETR will be the important facility to bridge from ITER to DEMO in China, which is necessary step to go to DEMO and then the fusion power plant FPP.

Thanks for your attention !