Research Progresses and Challenges for CFETR Fusion Reactor

Jiansheng Hu, Kun Lu and CFETR team

hujs@ipp.ac.cn

Institute of plasma physics, HFIPP,

Chinese academy of Sciences, China

Outline

1. CFETR overview
2. Progresses and challenges
3. Technology supports
4. Summary and outlook

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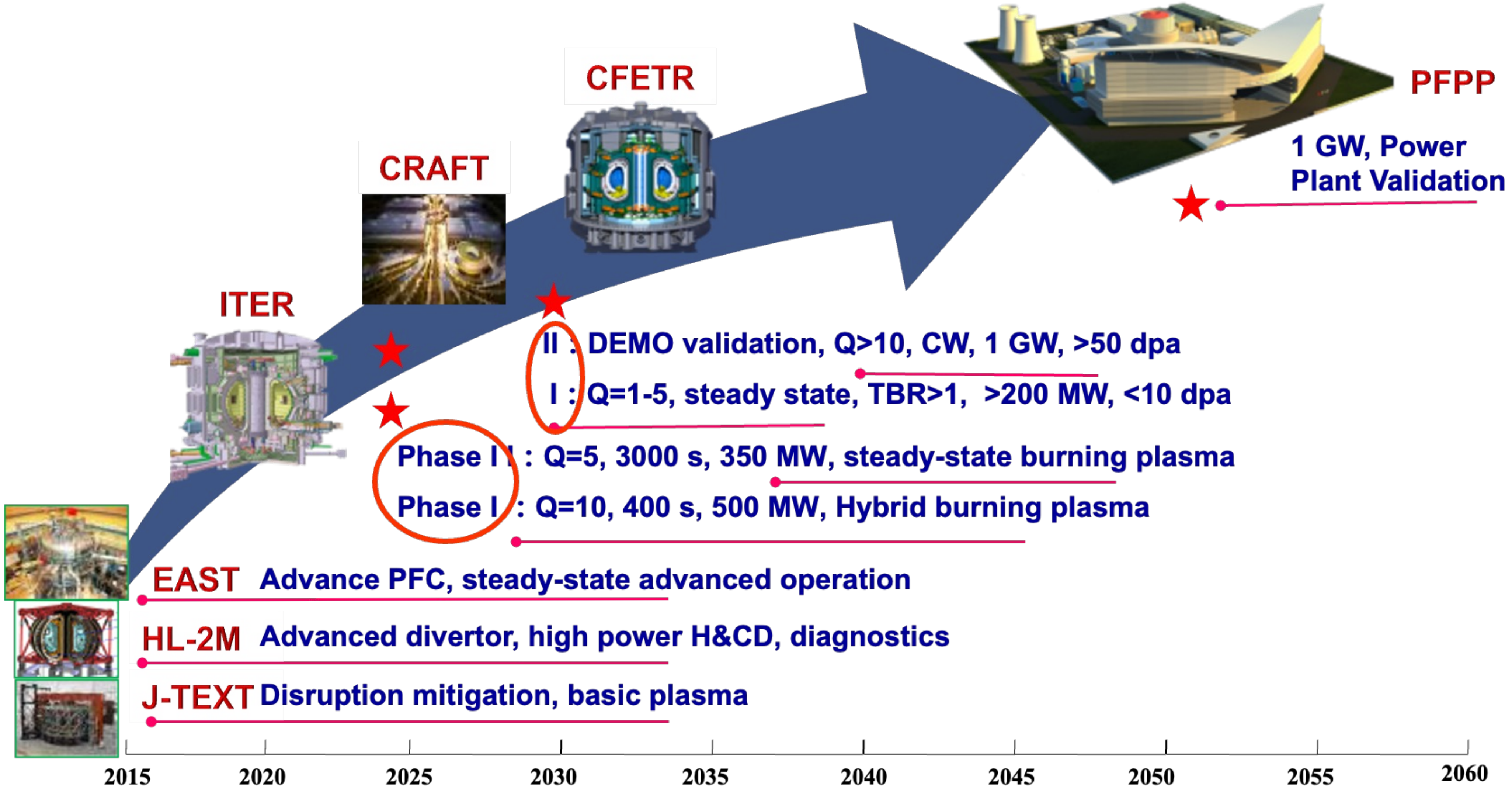
China Fusion Roadmap



CFETR missions

Obtained burning Plasma for fusion power

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

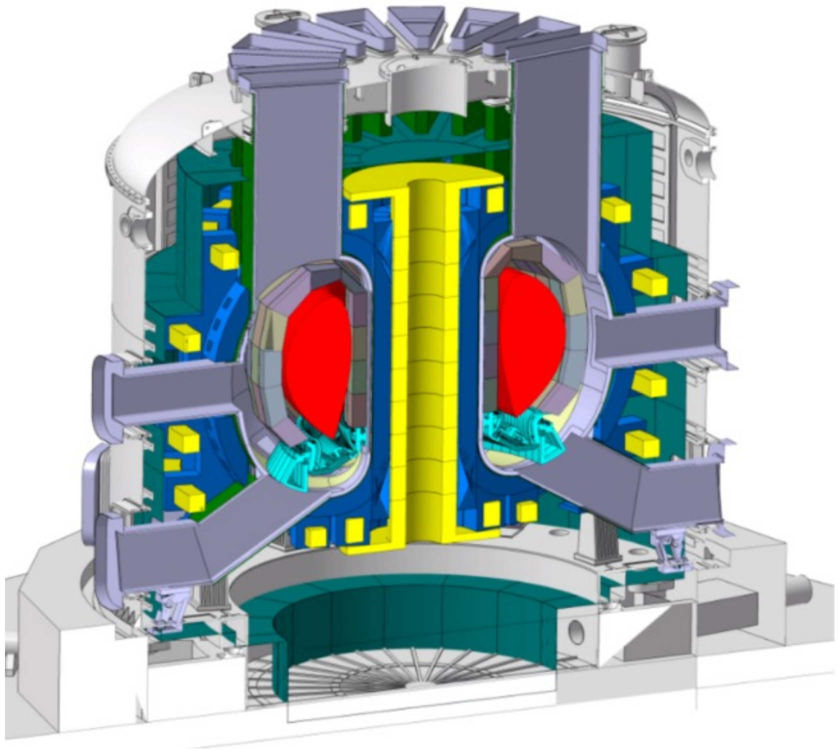
Steady-state operation for fusion energy

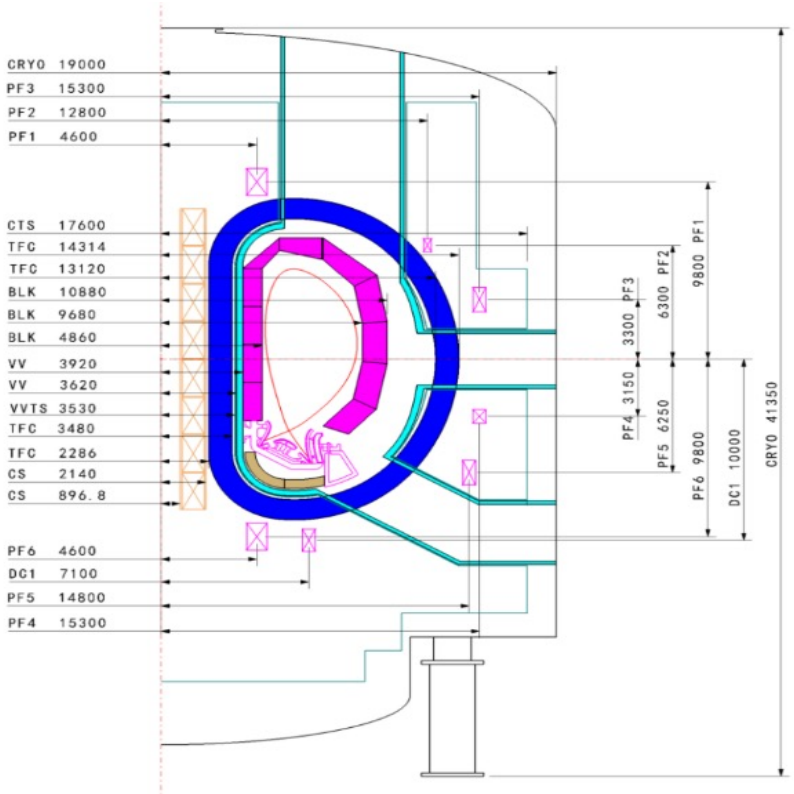
5. Hybrid OH+BS+CD
6. SSO Ext H&CD + Higher fb
7. PSI on the first wall
8. Heat & particle exhaust on Div.

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 main Parameters





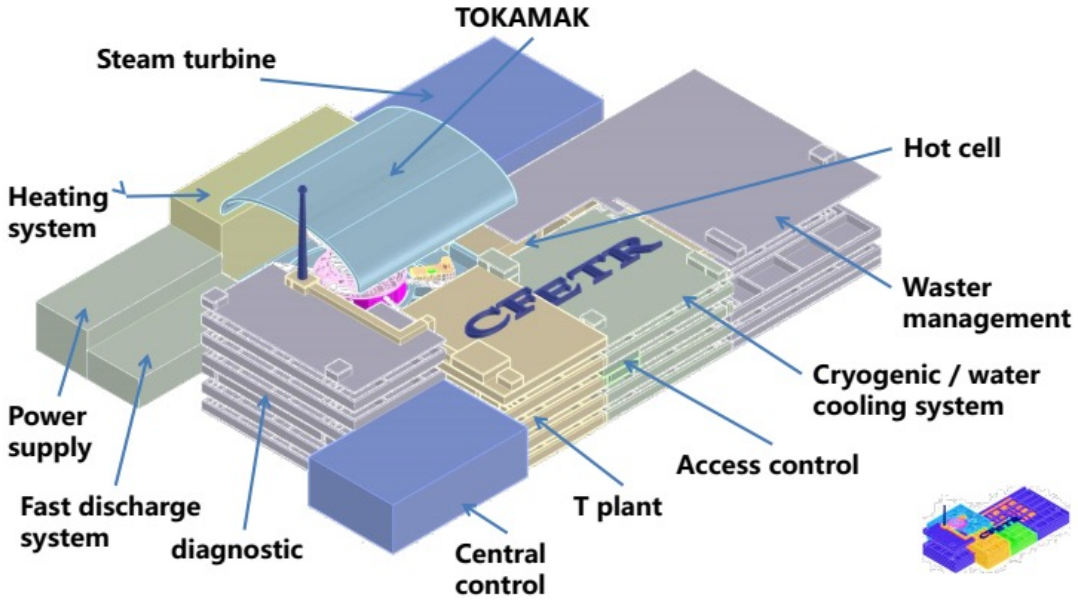
- I_p=14 MA
- B_{to} = 6.5T
- R_0 = 7.2 m ,a = 2.2 m

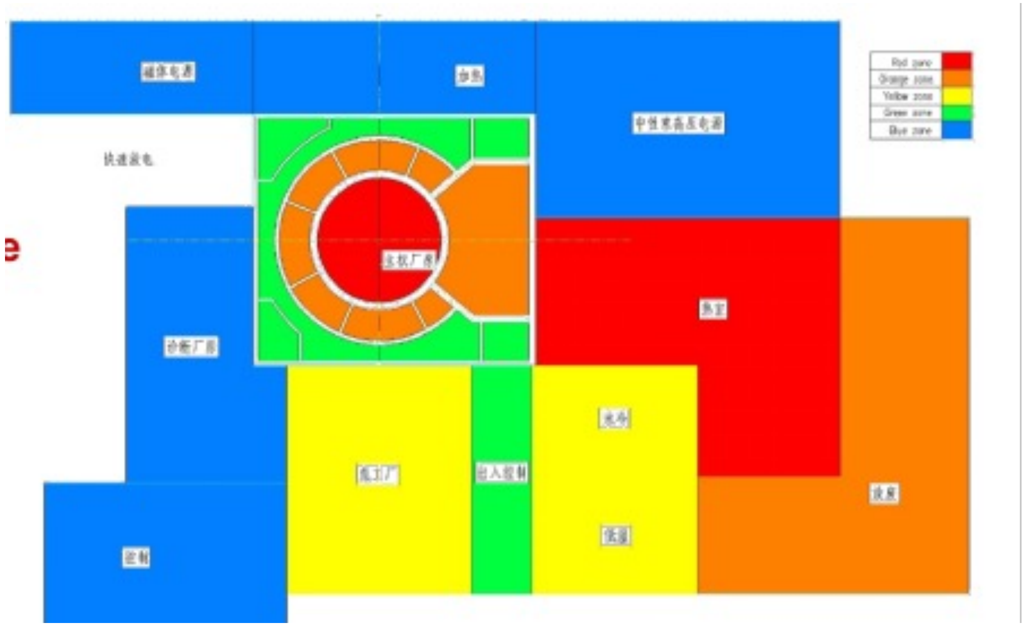
- P_{fusion} : 200-1000MW
- TBR > 1
- Duty time ≥ 0.5

CFETR operation Parameters

Parameters	ITER	EU DEMO (2hours)	JA DEMO (SSO)	CFETR (SSO)	K-DEMO (SSO)	EU-DEMO Op 2 (SSO)
R/a	6.1/2	9.0/2.9	8.5/2.42	7.2/2.2	6.8/2.1	7.5/2.5
Aspect ratio	3.1	3.1	3.5	3.3	3.2	2.7
B_{T0}	5.3	5.9	5.9	6.5	7.4	5.6
Ip q	15 3.0	18, 3.9	12.3, 4.1	12-14 5	12, 7.5	22, 3
Elongation, triangularity	1.75 0.45	1.65 0.33	1.65 0.33	2 0.5	2.0 0.625	1.8 0.5
Fusion P.(GW) Heating P.(MW)	0.5 73	2.0 50	1.5 83.4	0.1-2.0 80	1-2.0 150	3.0 150
G. output (GW)	0	0.5	0.25	0-0.8	0.4-0.7	0.9

CFETR building and radiation





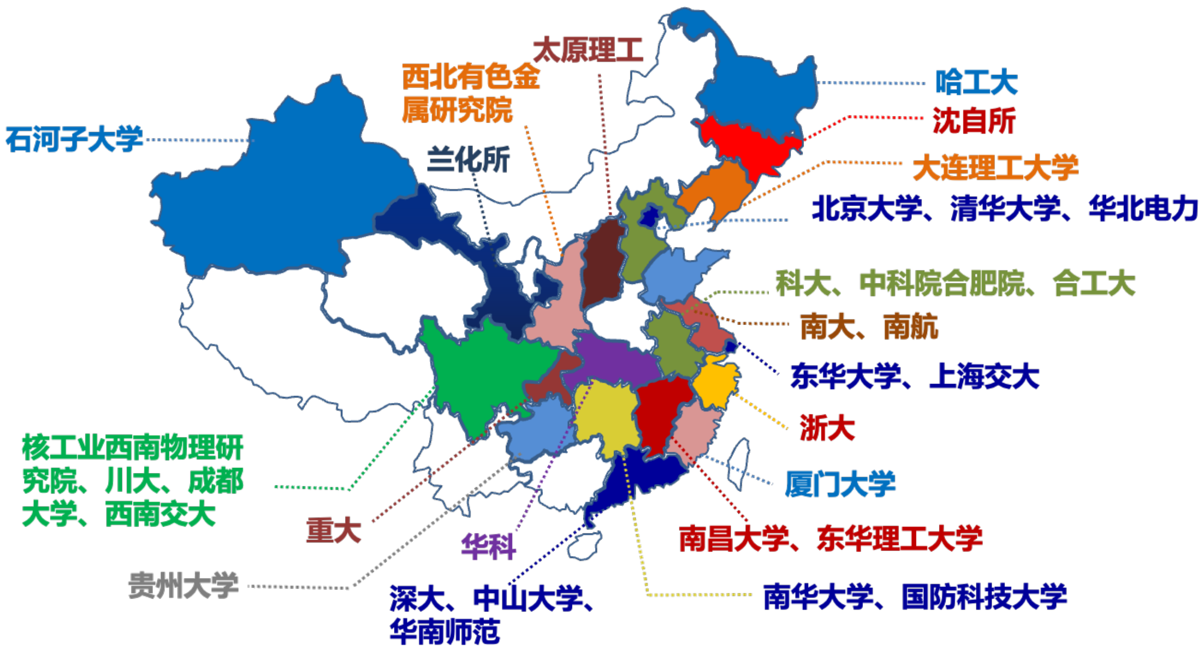
Radiation zoon definition of the

CFETR main building complex

Working places			Radiation dose	Present/Access
Non-radiation			/	/
Radiation	Monitor	Blue	≤ 2.5 μSv/h	<2000h in one year
	control	Green	≤ 10 μSv/h	Regular access, <2000h in one year
		Yellow	≤ 1 mSv/h	Access control
		Orange	≤ 10 mSv/h	Access limited
		Red	≥ 10 mSv/h	Access prohibited

CFETR design team

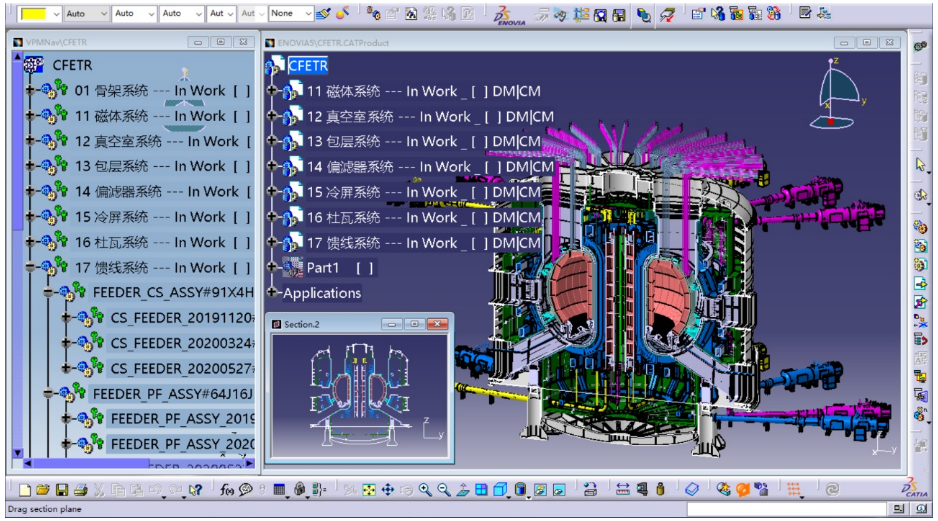
Physical design(2013-2016)、Engineering design (2017-2021)



- >800 persons in >30 Inst.&Univ.
- 87 task forces
- Important review meeting >20
- Fusion plus fission researcher

CFETR Data Management

- **Engineering data:**
  - 3D part/components, physical interface
- **Management data**
  - Project management, Document management, Design Collaboration
- **Account Data**
  - Account, Password, Access right for each account
- **Networking and Security**
  - Assure the security of data transfer and Design Collaboration
- **Design collaboration system based on data management and networking**



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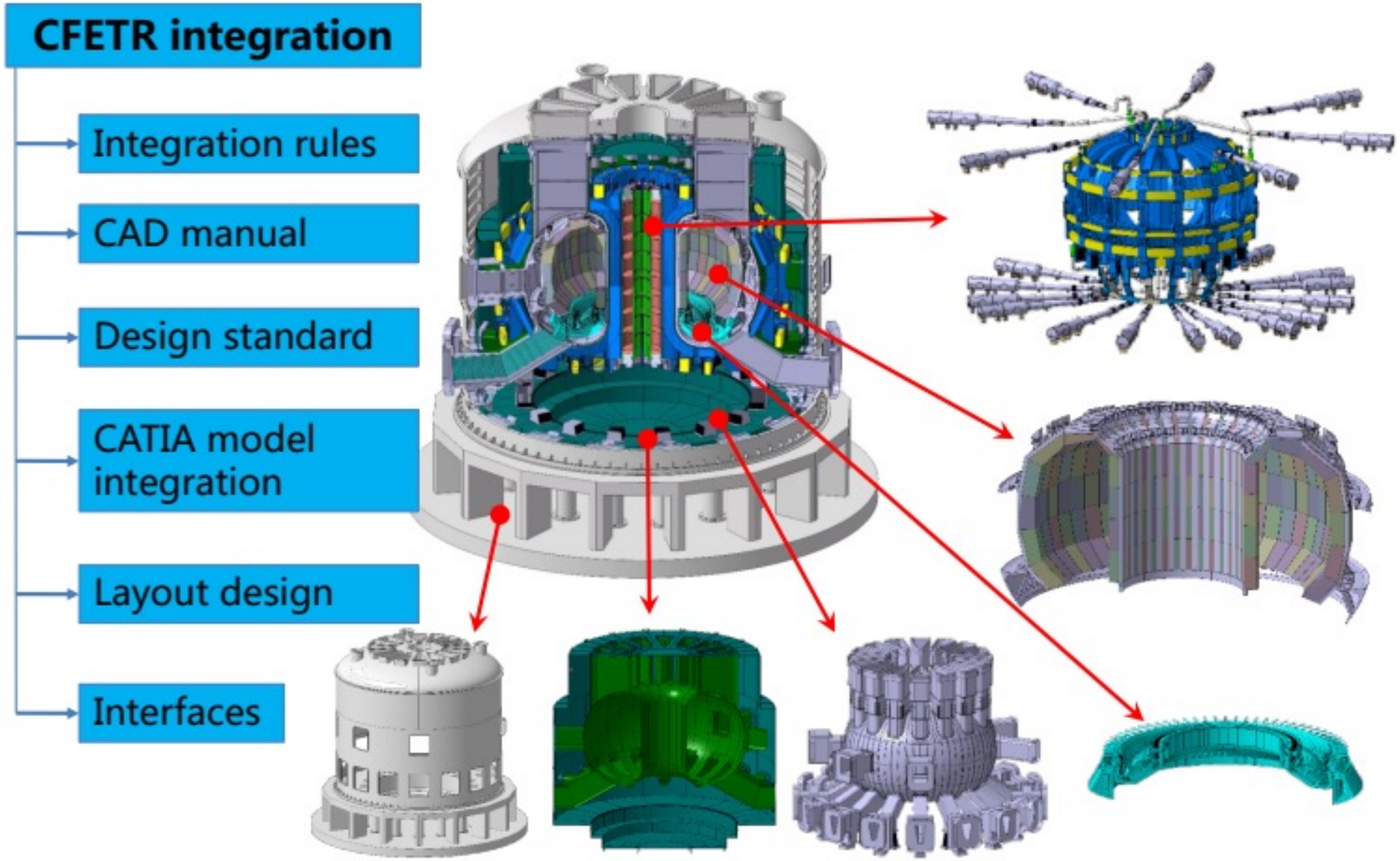
CFETR design progresses

Physical design(2013-2016)、Engineering design (2017-2021)

- ✓ Defined physical and engineering parameters and requirements
- ✓ Established design rules and standards, interfaces for most systems
- ✓ Built integration design, communication and data exchange platforms
- ✓ Completed design of main machine and most sub-systems
- ✓ Made RAMI (Reliability, Availability, Maintainability, Inspectability) analysis
- ✓ Proposed neutron radiation related material develop map
- ✓ Analyzed neutron radiation distribution, building design and construction
- ✓ Made strategy for assembly, remote handling, decommission, waste disposal
- ✓ Analyzed fusion nuclear laws, rules and safety for license application

CFETR Integration



Completed designs

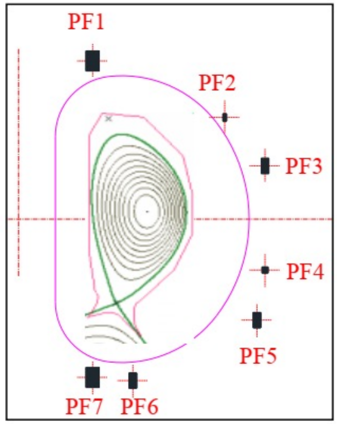
- ✓ General integration rules, CAD design manuals and standard
- ✓ VPM import, layout, interface for all 3D models
- ✓ Overall assembly process and tooling design
- ✓ Assembly benchmark net and measurement

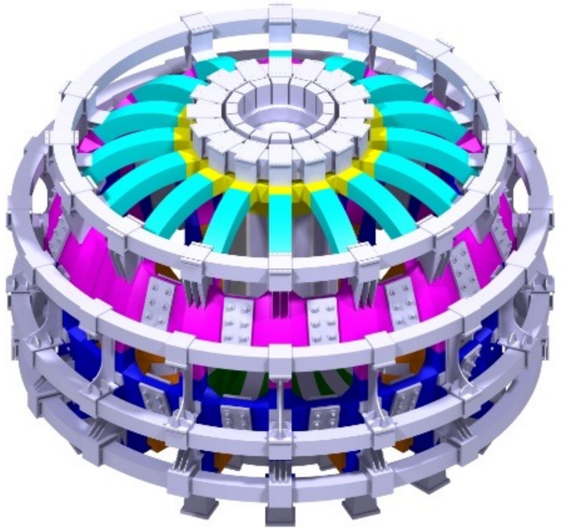
Challenges:

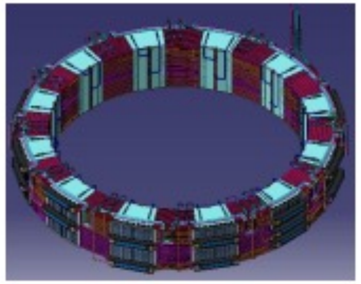
- High precision, low tolerance
- Lots interfaces with components, sub-systems

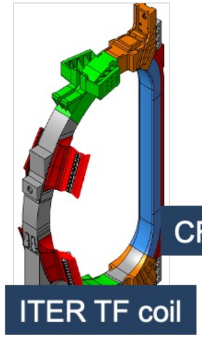
CFETR superconducting coils

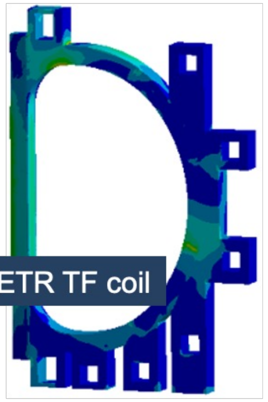
- ◆16 TF coils, 8 CS coils: 7 PF coils
- ◆High Tc Nb3Sn, NbTi/ Nb3Sn

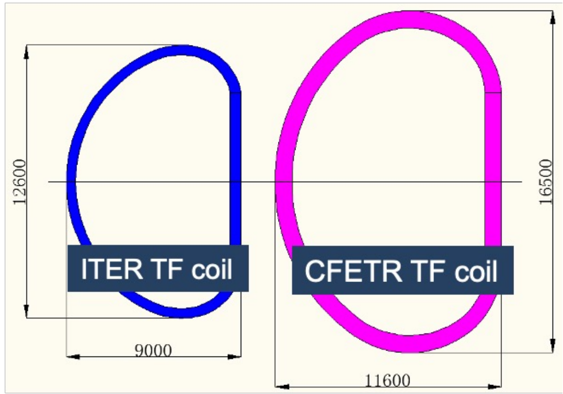




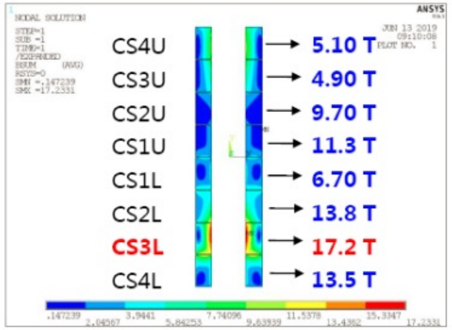


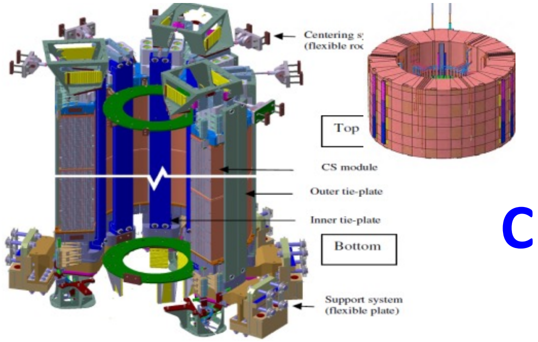






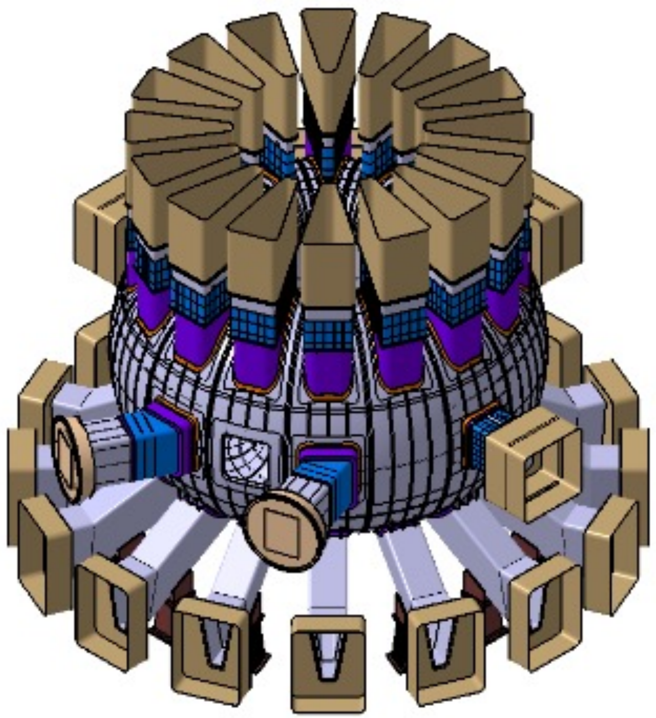
	ITER TF	EU-DEMO[2015]	CFETR TF	CFETR TF (Option 1)	CFETR TF (Option 2-2)
No. of Coil	18	18	16	16	16
Operation current	68 kA	81.7 kA	87.6 kA	96.8 kA	95.6 kA
Inductance	17.34 H	32.68 H	34.93 H	25.8H	26.742H
Total storage energy	40.1 GJ	109.08 GJ	134.02 GJ	135.3GJ	136.37GJ
storage energy(single coil)	2.227 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	-	-	109.1mΩ	----	98mΩ
Maximum voltage	5954 V	6450 V	9562 V	----	9.37 kV

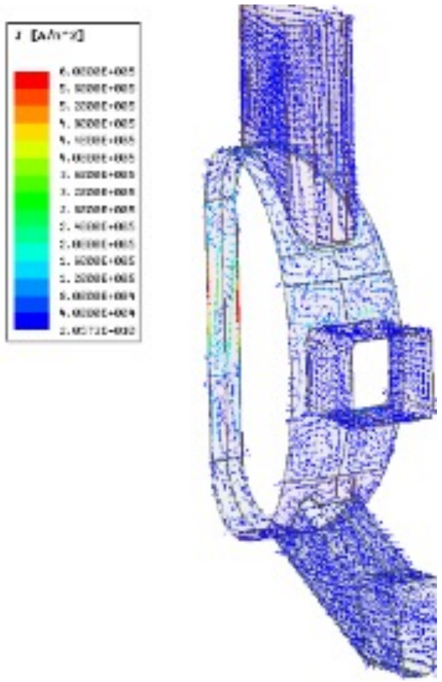


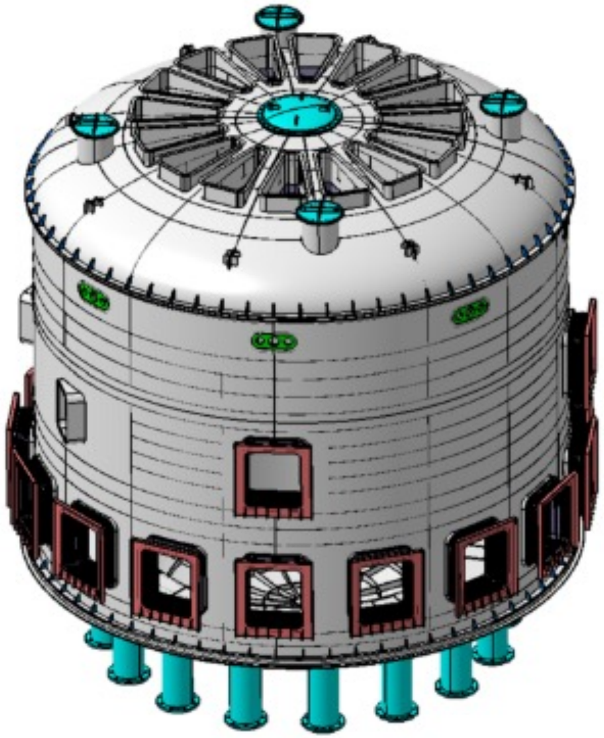


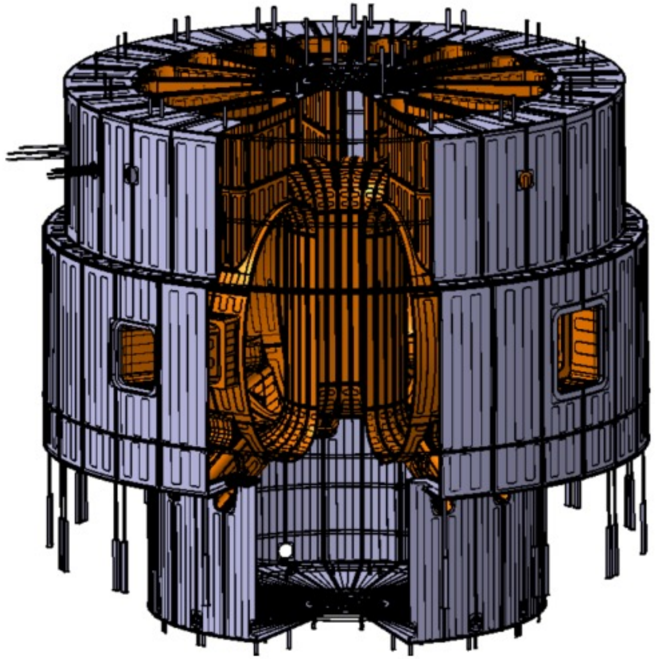
Challenges: High magnetic field, high current and voltage, high storage energy, coils joint and isolation, quench detection and protection, radiation heat load, etc.

CFETR vessel, cryostat, Shield





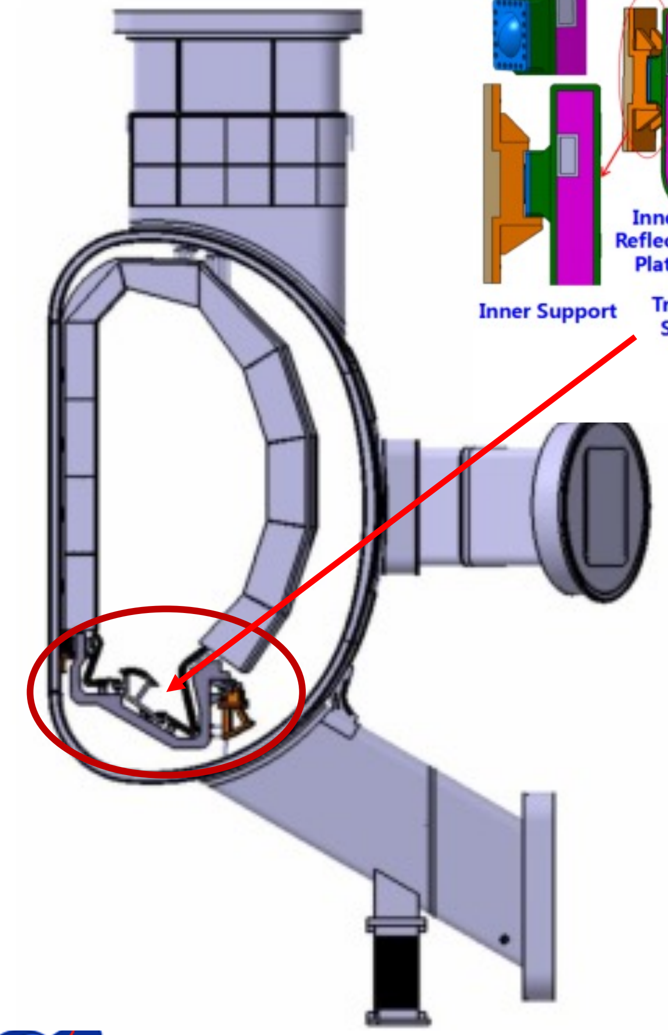


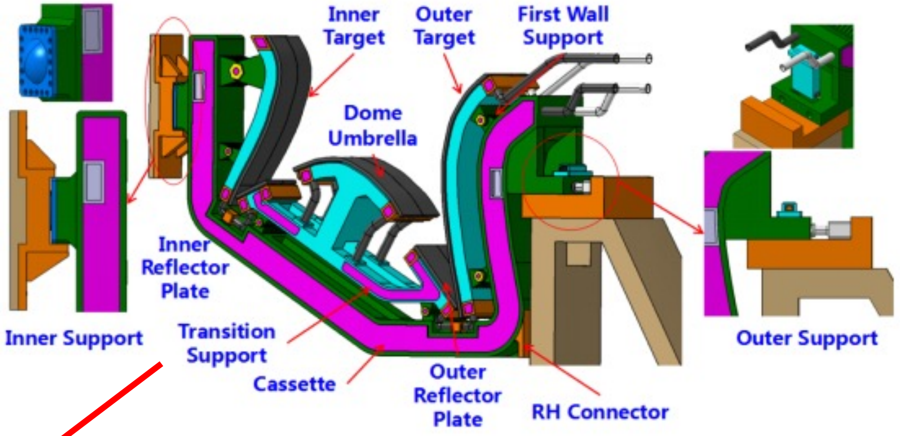


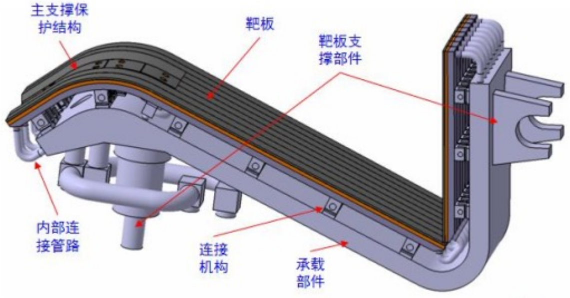
Challenges:

- **manufacture for robust vacuum or pressure large chamber**
- **lots interfaces, Iteration with physical and engineering requirements**
- **Different load and complex stresses (EM, Heat, Thermal, Radiation)**
- **High requirement for engineering Feasibility, compatibility, stability**

CFETR Divertor







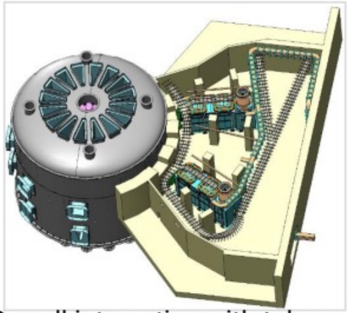
72 divertor modules, each one ~**11** tons

Phase1: $10MW/m^2$ (SSO), $20MW/m^2$ (Transient)

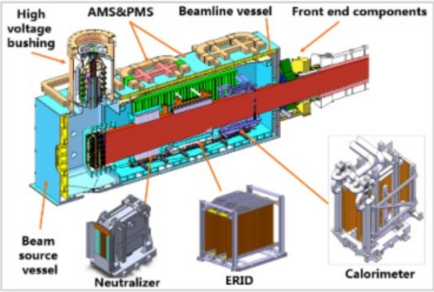
Phase2: $20MW/m^2$ (SSO), $40MW/m^2$ (Transient)

- Target and structure material directly under neutron radiation, heat flux and EM force
- Structure and Targets shaping optimization under thermal hydraulic load & EM load
- Compatibility with plasma performance, fuel cycle, particles exhaust, remote handling

CFETR auxiliary heating

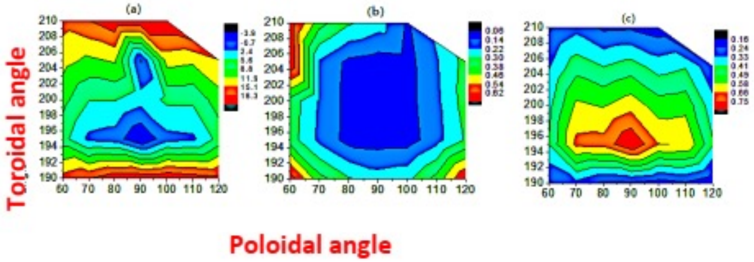


Overall integration with tokamak



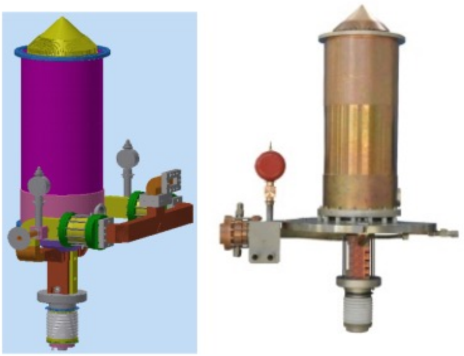
NBI structure

2 NBI with D0; Beam energy 1 MeV; Beam power: 40 MW; Duration: 4 h



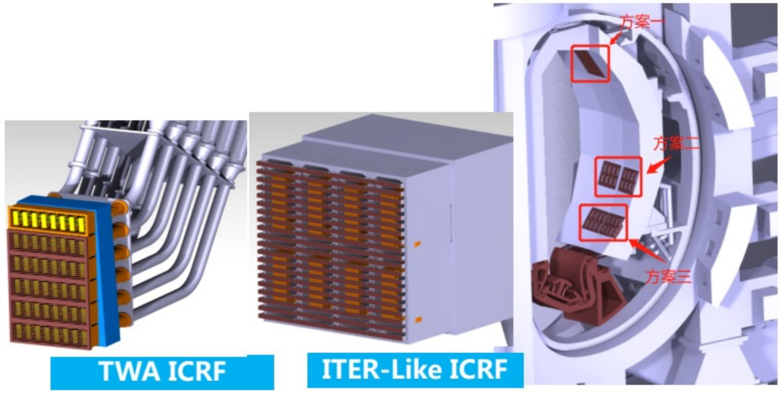
Performance of 230GHz ECCD（Za = 0 m）
(a) ECCD （kA/MW）;（b）Peak location of J_{CD};
（c）2nd Harmonic absorp. ratio（%）

ECRH 170GHz / 30MW



4.6GHz 500kW/CW Klystron model and structure

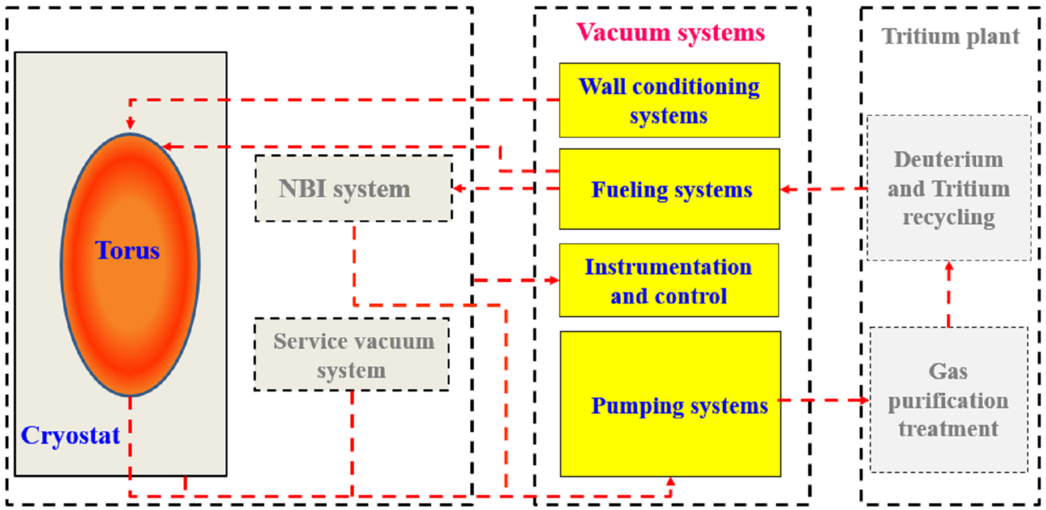
LHCD 4.6GHz, 20MW



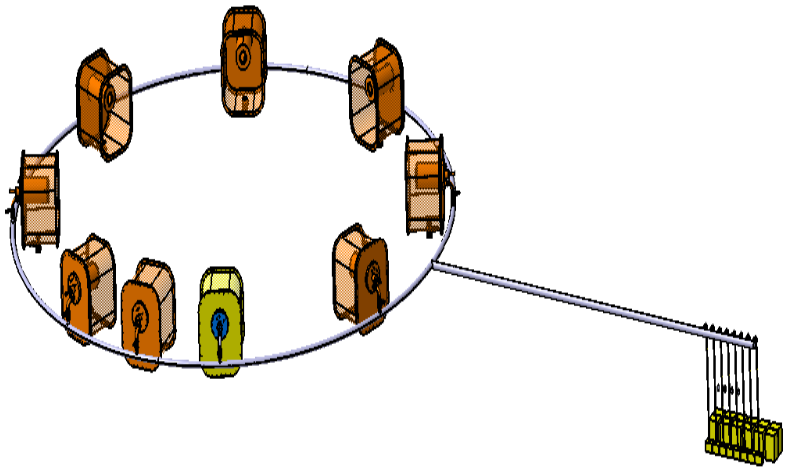
ICRF 40-80MHz, 12MW;
Three options: antenna, port

- **Total effective >80MW, Long operation, stability**
- **Compatibility with Neutron screening blanket and material**
- **Antenna with good coupling and heating, remote replace**
- **High quality wave components, High voltage power supply (1MV)**

CFETR particle exhaust and fueling

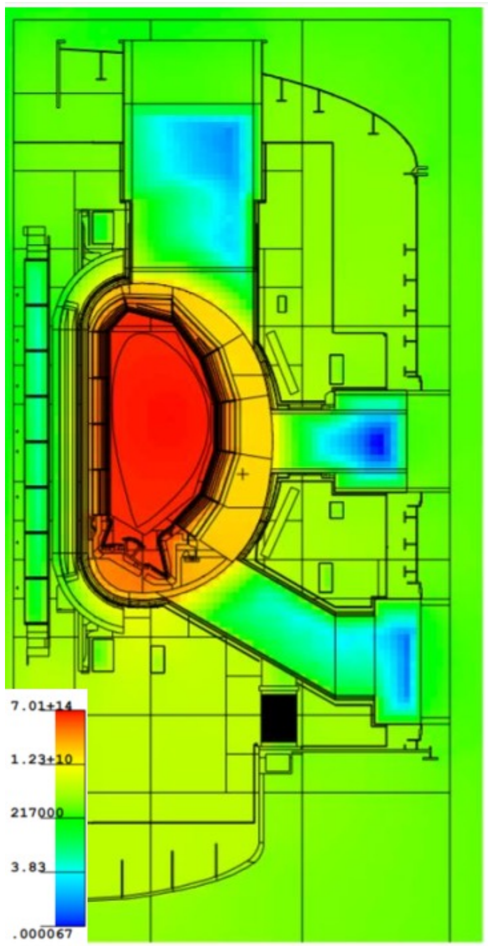


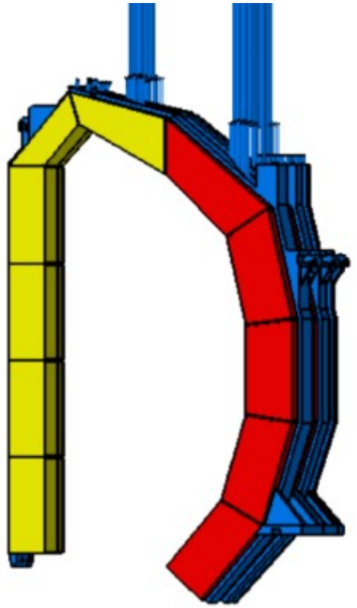
- DT steady-state operation
- torus ~2300m^3, cryostat ~34000 m^3
- D-T fueling/pumping ~290 Pa·m3/s
- 10 cryopumps (68m^3/s), shift running
- Pellet injection, SMBI, gas puffing

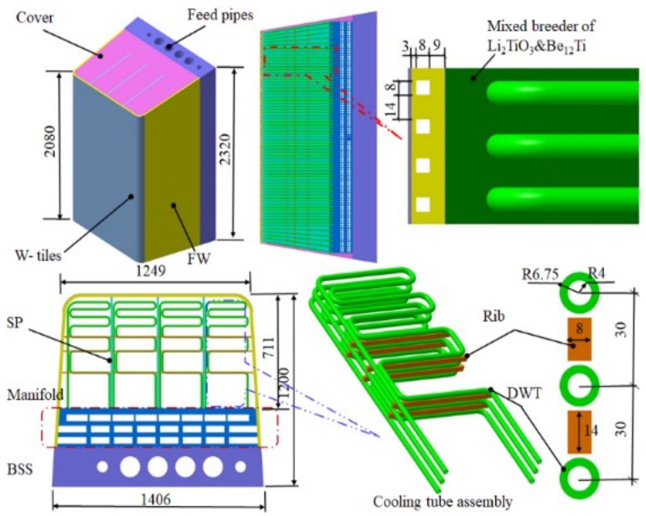


- Compatible with T (pump, valve, instrument, etc)
- Neutron radiation and remote handling
- Remote leak detecting, positioning and repairment

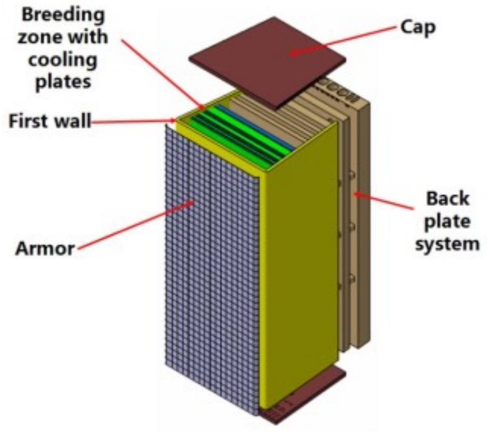
CFETR proposed Blankets







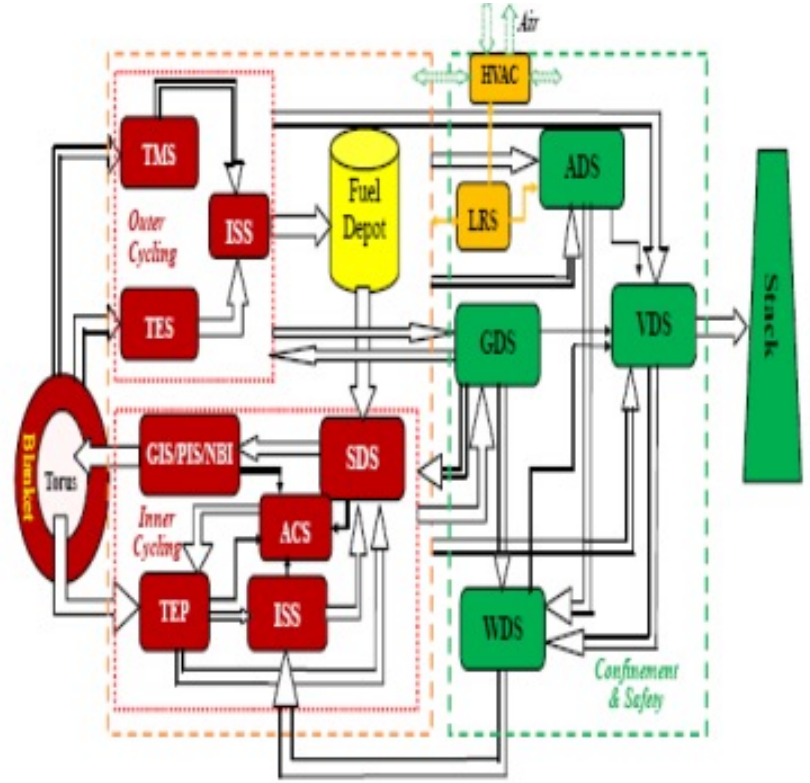
water-cooled blanket



helium-cooled blanket

- TBR ≥1.1 for fuel cycle, and its balance with power generation
- Neutron energy deposition and wall load @Fusion power = 1GW, 2GW
- Non-united Structure influenced by configuration, diagnostics, heating, etc.
- First wall and structure material under neutron radiation, heat flux and EM force
- Tubes forest with various requirement and their joint in a limited place
- Compatibility with remote handling

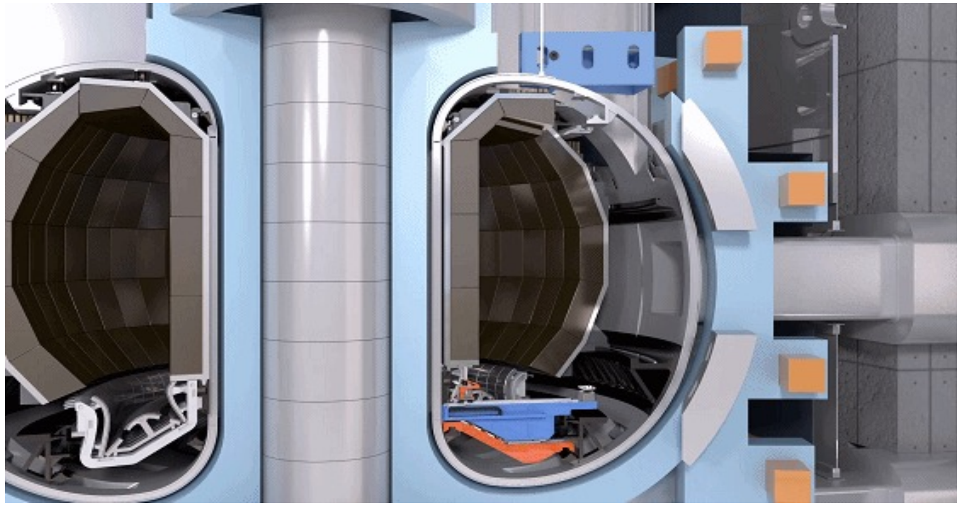
CFETR Tritium cycling systems (T-plant)

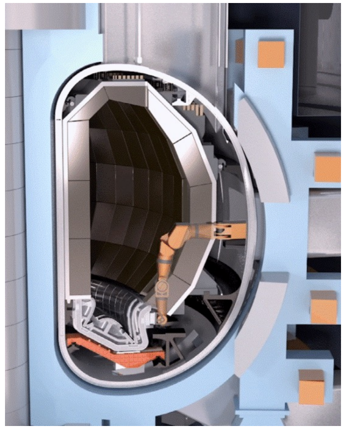


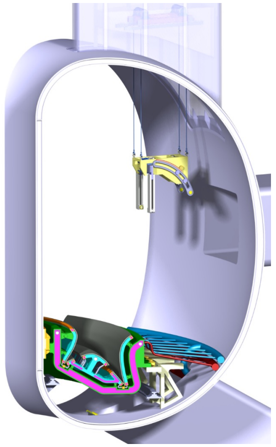
Simple block diagram of CFETR tritium plant

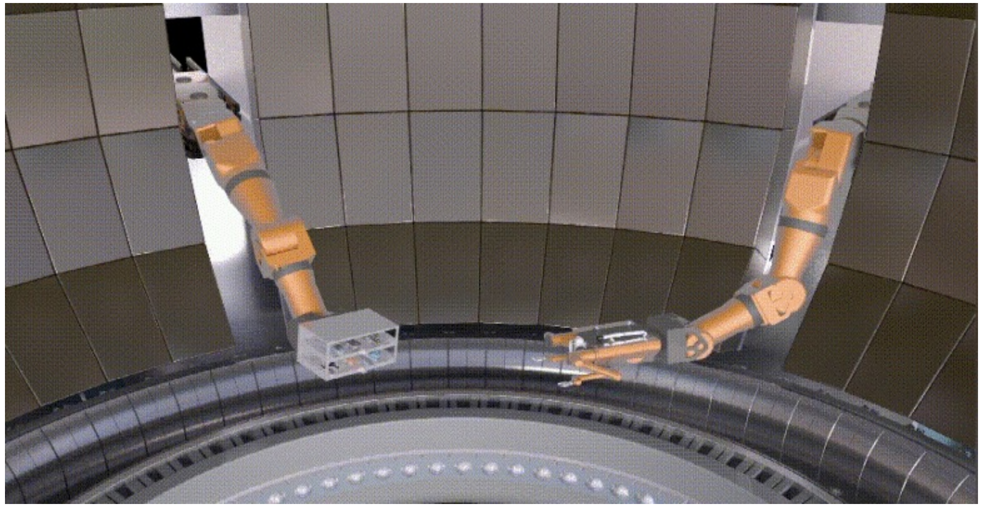
- ~2kg tritium for startup, 4500s of time span for cycling
- Inner cycling: ~357g T/shot, $2m^3(D_2,T_2)$/h for TEP and SDS, >$4m_3$/h for ISS
- Outer cycling: tritium extraction every two weeks to get more than 200g of pure tritium from the breeders.
- Tritium confinement: 3g/a of environmental tritium release at current stage, to be minimized as 0.6 g/a for the future
- Tritium recovery, isotopic separation from plasma exhaust gases and re-fueling to torus.
- Tritium extraction and measurement from in the full breeding blanket.
- Tritium confinement and effluent detritiation

CFETR remote handling



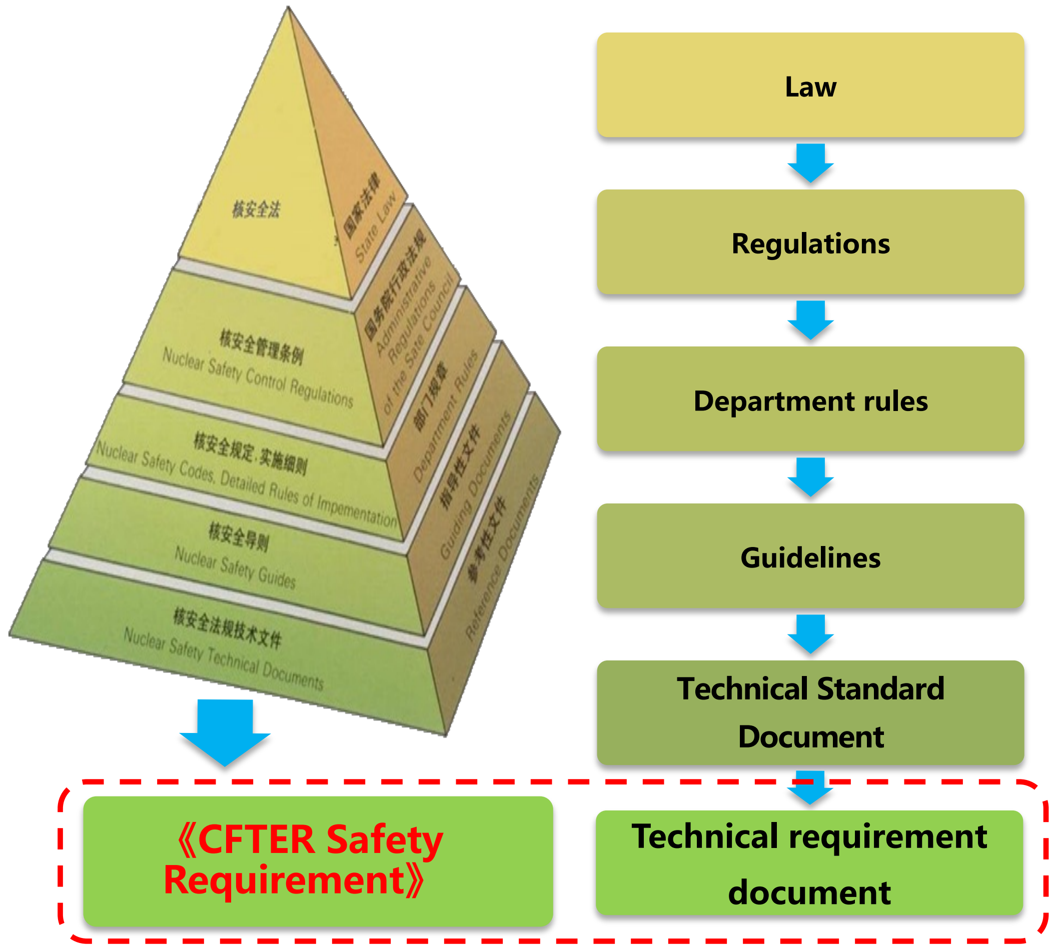






- ➢ **Strategy with high efficiency, high reliability**
  - ■ **Replace blanket and divertor module**
  - ■ **Maintenance in vessel： cut/joint, detect, installation/dismantle, positioning, etc.**
- ➢ **Multi-system synergism remote control**
- ➢ **Methods and standard in fusion reactor**

CFETR Nuclear Safety Research



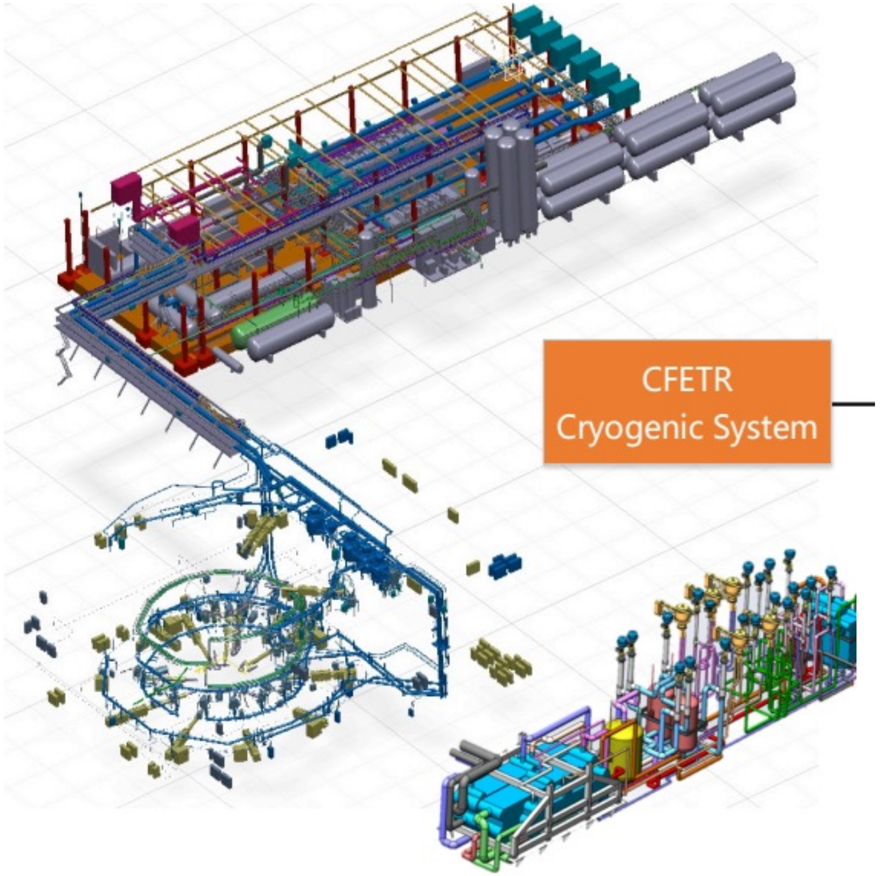
Studies on Laws, regulations, permissions, license, etc.

- **Accidence analysis**
- **Radiation protection**
- **Safety regulations**
- **Construction permission**
- **Operation permission**
- **Tritium permission**
- **Decommissioning regulations**
- **Waste disposal**

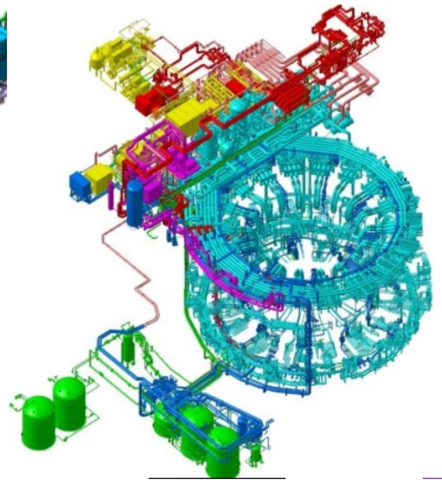
CFETR material develop map

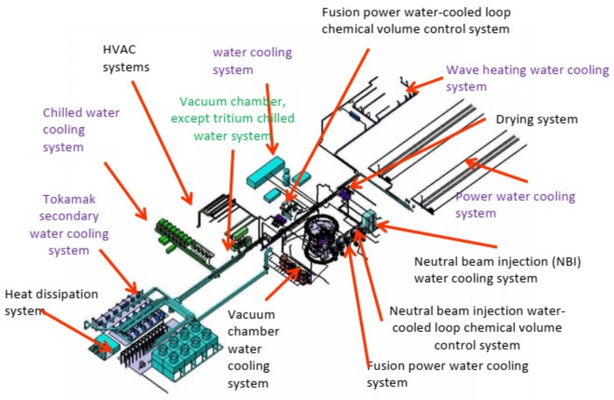
	2020	2030s	2040
FW: W， W alloy	3-5dpa	10dpa, CFETR	20dpa, CFETR
Advavced W	1E25-1E28 PSI	CFETR	CFETR
Divertor			
ODS-Cu， Cu alloy	10dpa	50dpa, CFETR	100dpa, CFETR
Structure Material			
Low active FS	5dpa, 1000T	50dpa, CFETR	100dpa, CFETR
ODS-LFS	10dpa， kg	50dpa， CFETR	100dpa， CFETR
Breeding Material			
Li_4SiO_4	specification， T level	fix， CFETR	CFETR
Li_2TiO_3	specification， T level	Fix， CFETR	CFETR
Neutron multiplier			
Be12Ti	Fission reactor	fix， CFETR	CFETR
Resistance tritium layer			
	500C， 1000	500C， 1E4， CFETR	500C， 1E5， CFETR

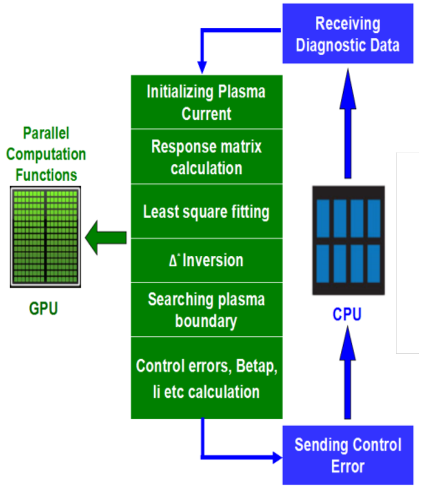
CFETR other Systems



- **Cryogenic System: 4.5K equivalent thermal load of 100kW**
- **Water cooling: Severing various system, high pressure/temp., Nuclear + non-nuclear-related cooling circulation**
- **Diagnostics: Nuclear environment, integration design, etc.**
- **Plasma control: P-EFIT/ISOFLUX etc.**
- **Power supply : magnetic coils, heating system etc.**







Water Cooling System

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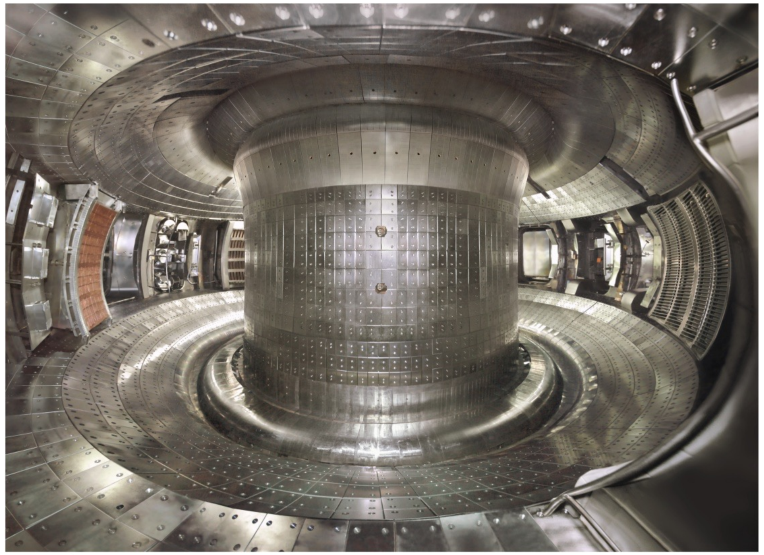
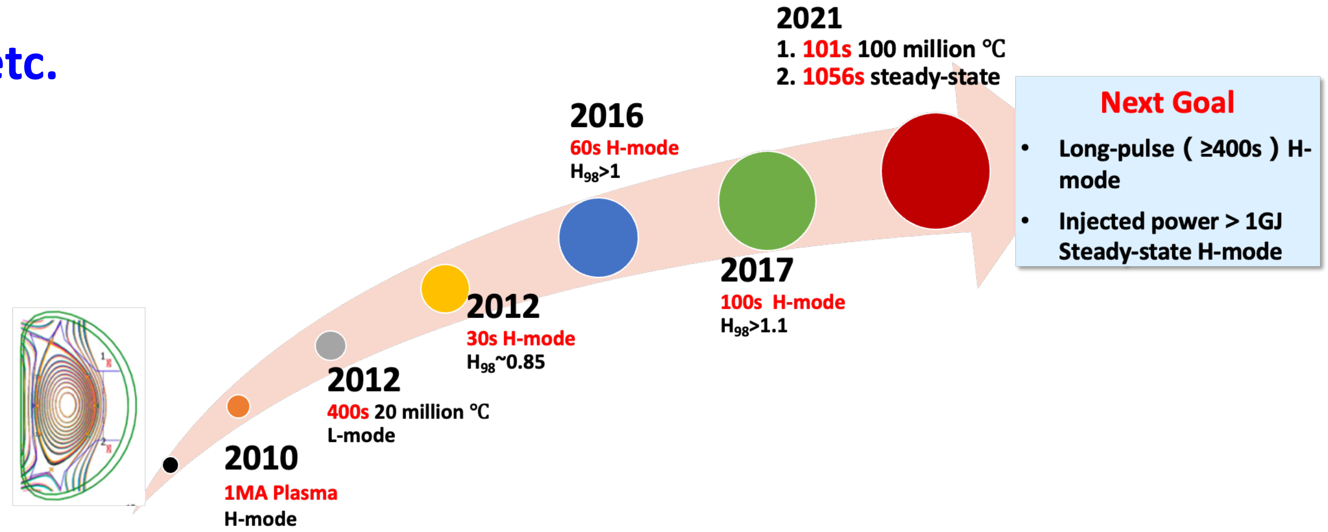
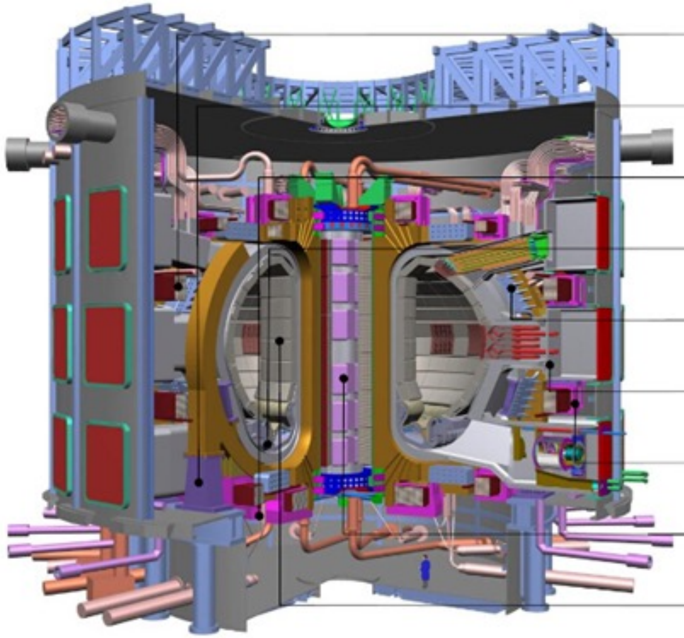
Experiences from EAST



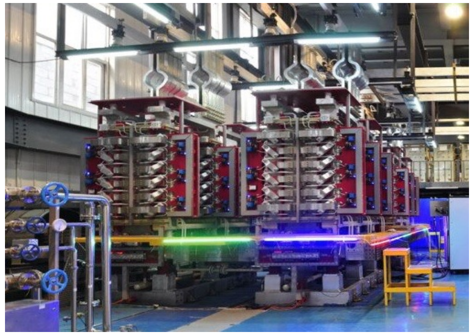
- ✓ Full superconducting coils, flexible configuration(USN, LSN, DN)
- ✓ NBI, LHCD, ICRH, ECRH auxiliary long heating system
- ✓ W/Cu divertor to exhaust 10MW/m² heat flux
- ✓ Record steady-state operations with stable systems for integrated control of configuration, plasma heating, particle/heat flux
- ✓ More than 80 diagnostics
- ✓ etc.

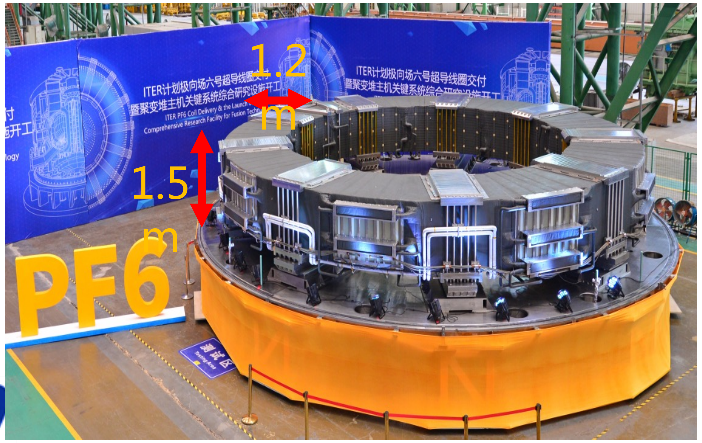


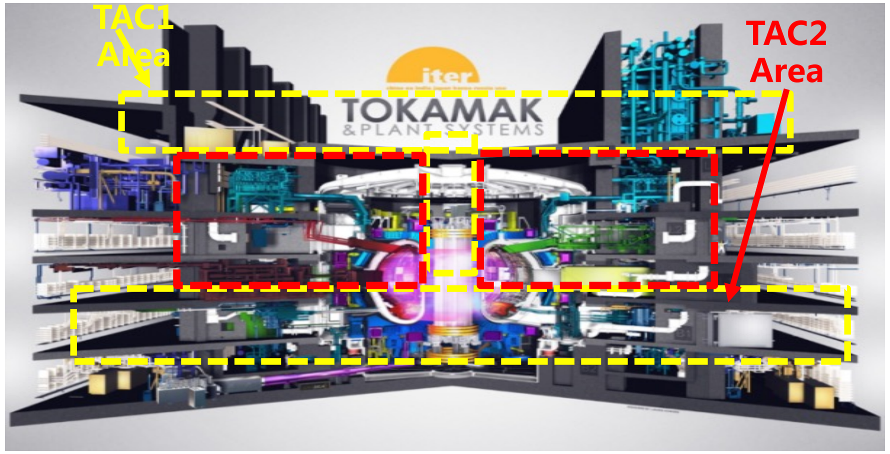
Technologies based on ITER



- 68% PF conductor
- 100% CC
- 100% current lead
- Glow Discharge Cleaning
- 68% Power supply
- ELM coil
- 100% Feeder system
- 7% CC Conductor
- 50% shield blanket



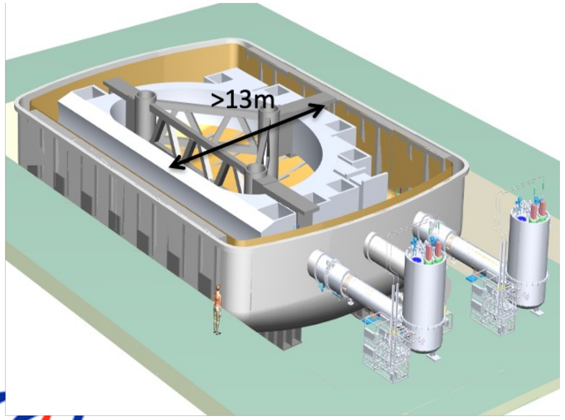


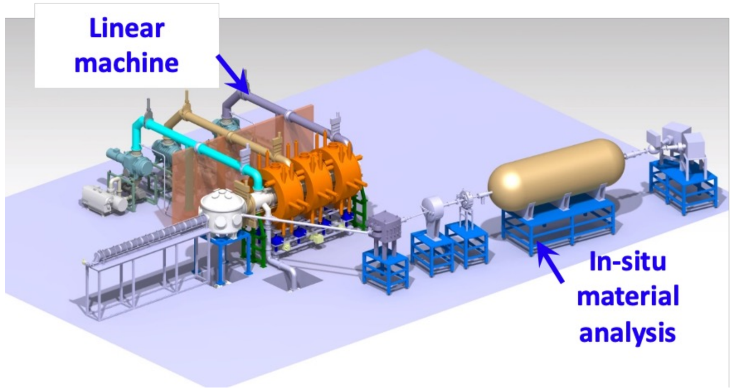


Validation and verification for key technology

CRAFT (Comprehensive Research fAcility for Fusion Technology)

- ✓ National big project launched in 2019, and will finish in 2025
- ✓ Magnet Research Platform (Diameter >13m; Max Current 100kA)
  - ——low Temp. Material, Conductor, Magnet, TF Coil, Bi2212 CS Coil, CSMC
- ✓ Divertor Material PWI Research Platform (>1000 s; >1x10^{24} m^{-2}s^{-1}, >3 T)
  - ——PFM, Divertor, 1/8 Vacuum vessel, N-NBI, ECRH, LHCD, ICRF, RH
- ✓ Auxiliary system: Central control, Power distribution, Cooling, Cryogenic, Power supply





400,000 m^2(land)
138,900 m^2(building)
~1 billion \$(total)

International and Domestic Collaborations

Fusion + Fission field
Inst. + University

Summary and Outlook

1. CFETR physical and engineering design almost finished with 45% machinable drawing.
2. Challenges need to be overcome for construction, specially on nuclear related license application, materials under neutron radiation, key technology developments.
3. Technologies of EAST, ITER and other fusion/fission devices would be scaled for most CFETR systems. Key technologies for CFETR are under R&D in the CRAFT project.
4. Collaborations strengthened in both international and domestic. Fission researches would support CFETR on nuclear data, nuclear safety, T and other nuclear material, construction/operating/dismission for nuclear facility, etc.

Thank you for attention!