Overview of the Present Progresses and Activities on the Chinese Fusion Engineering Test Reactor

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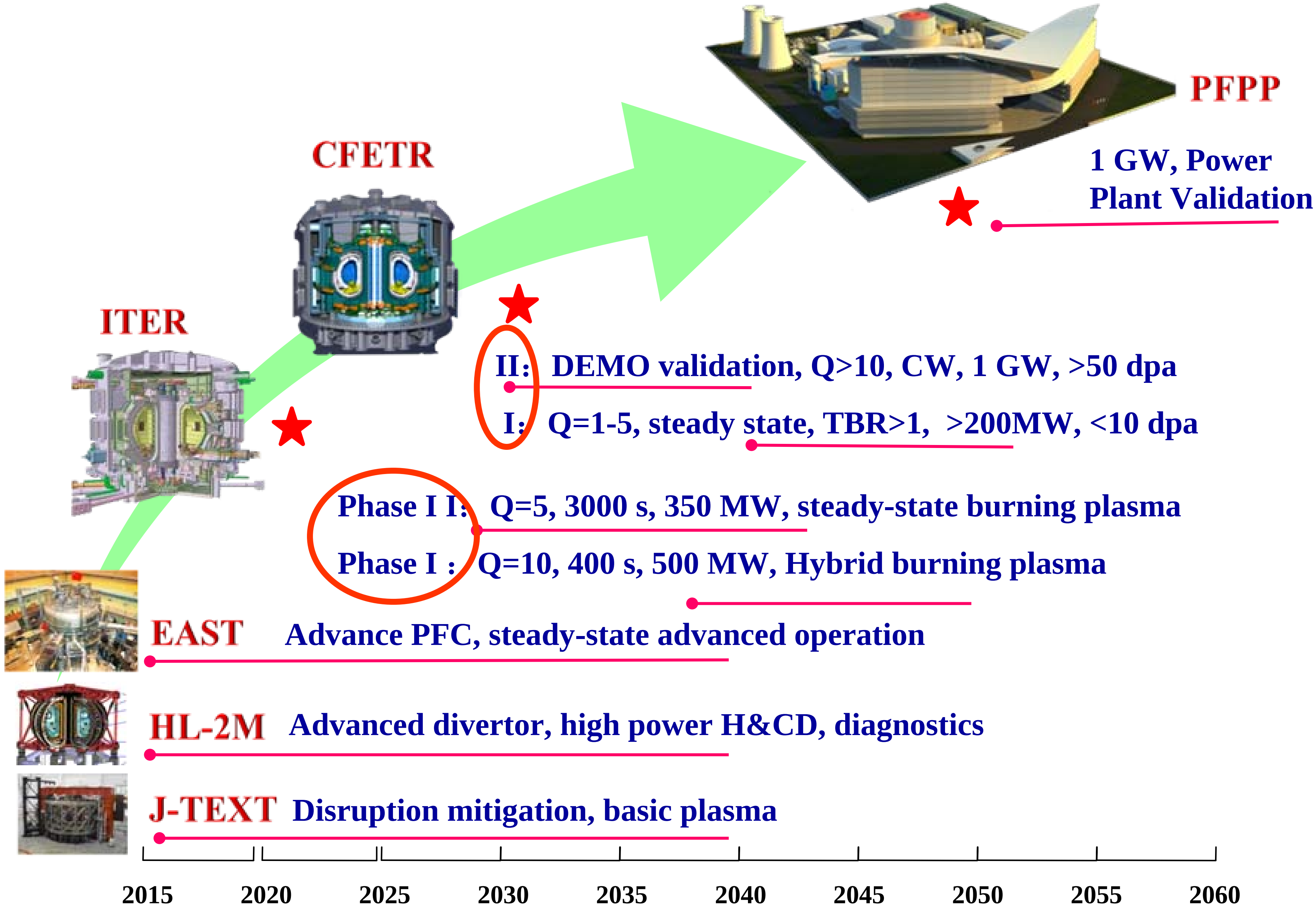
Outline

- Introduction
  - CN MCF Roadmap
  - Mission of CFETR
- Progresses and activities of CFETR
  - Previous concept design
  - New design version
    - Phase I
    - Phase II
- Key R&D activities
- Summary

CN MCF Roadmap



Mission & Objectives of CFETR

Mission: Bridge gaps between ITER and DEMO, realization of fusion energy application in China

- A good complementarities with ITER
- Rely on the existing ITER physical (k~1.8, q>3, H~1) and technical (SC magnets, diagnostic, H&CD) bases
- Demonstration of the burning plasma with P_f = 200MW~1000MW
- Demonstration Long pulse or steady-state operation of burning with duty cycle ≥ 0.3 ~ 0.5
- Demonstration of full cycle of T self-sustained with TBR over 1.0
- Exploring options for DEMO blanket & divertor with an easy changeable core by RH
- Exploring the technical solution for licensing DEMO
- With power plant potential step-by-step approach.

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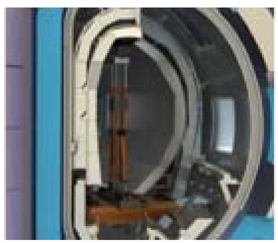
The advanced design and 3D simulation platform has been set up

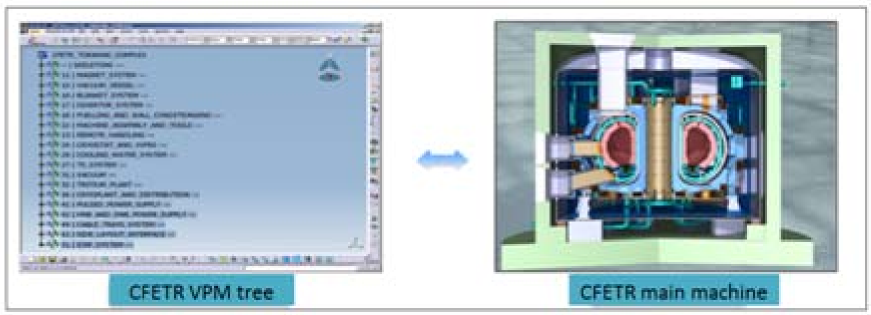
Design and management servers

Terminals of the design cloud

Virtual reality system

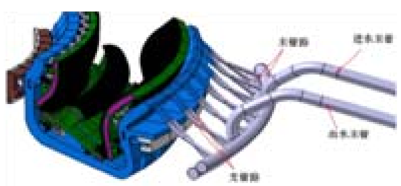


Remote handling

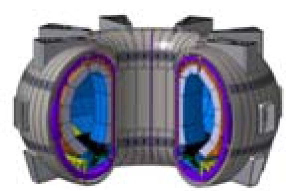


Magnet

Cryostat



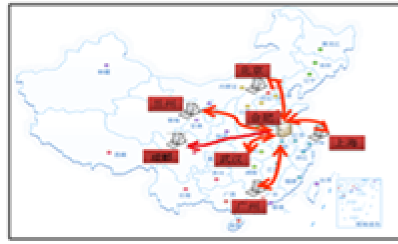
Divertor



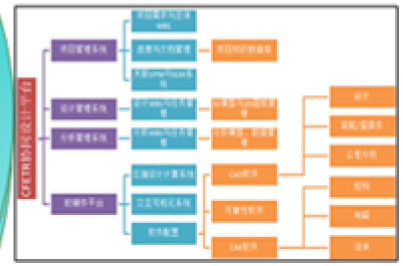
Blanket

Vacuum Vessel

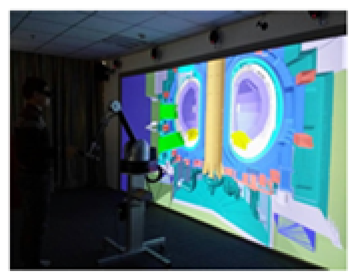
Advanced features of the design platform



- Advanced data compression technology
- Complete data sharing
- Remote design on any terminal on the internet



- Centralized data storage
- High correlation and traceability
- Safe and data tolerant



- Frequent 3D stereo review
- No need of physical mockups
- Inaccessible positions in reality become examinable

First Design version of CFETR (2011.11-2015.8)

Phase I

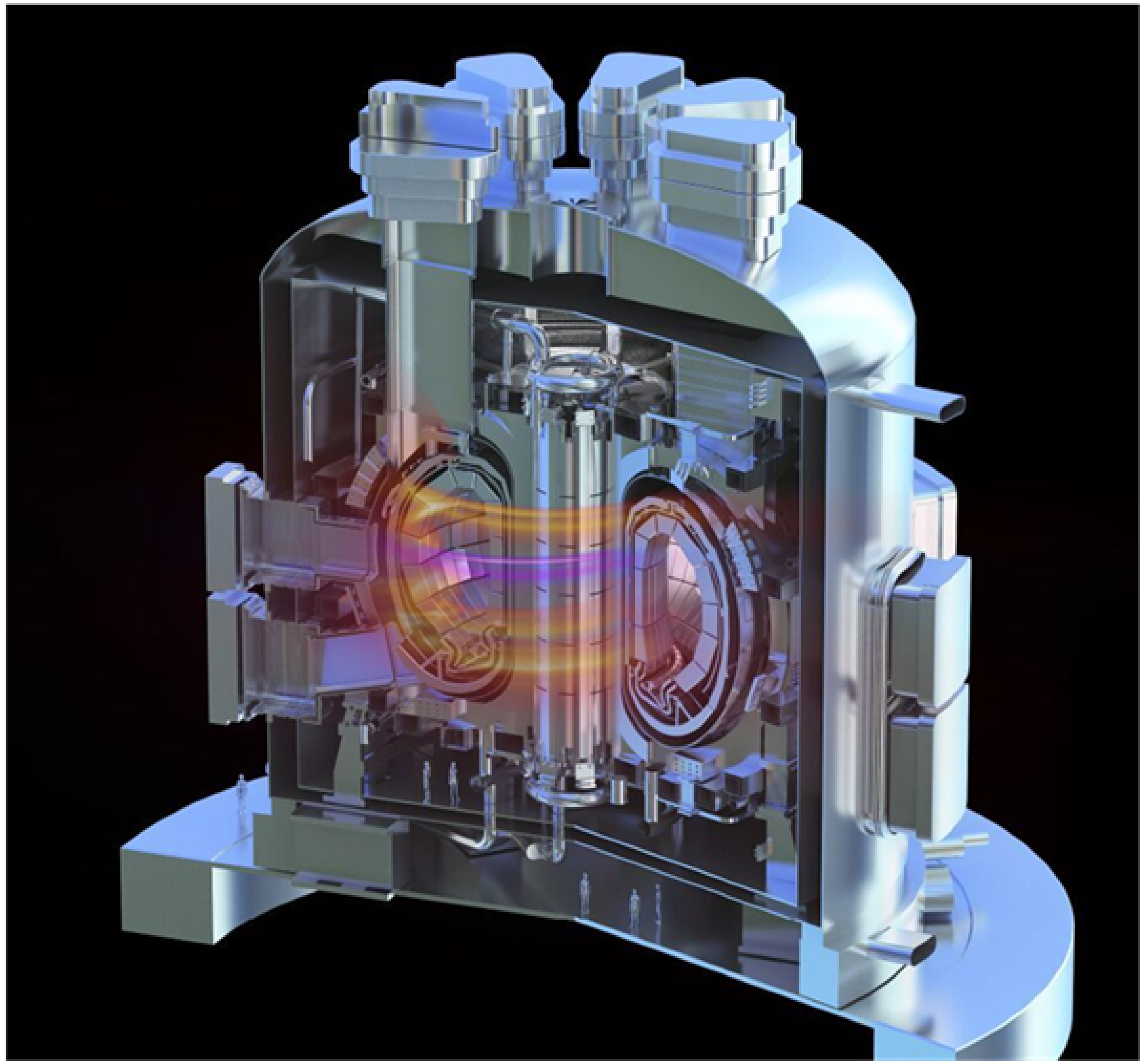
- I_p=7-10 MA
- B_{to} = 4.5-5.0T
- R_0 = 5.7 m ;
- a = 1.6 m;
- k=1.8～2.0
- $q_{95} \geq 3$;
- β_N ～2-3

P_{fusion} : 200MW

Phase II

Possible upgrade to R~5.9m, a~2.0 m, B_t= 4.8 T, I_p~15MA

P_{fusion} : 1000MW



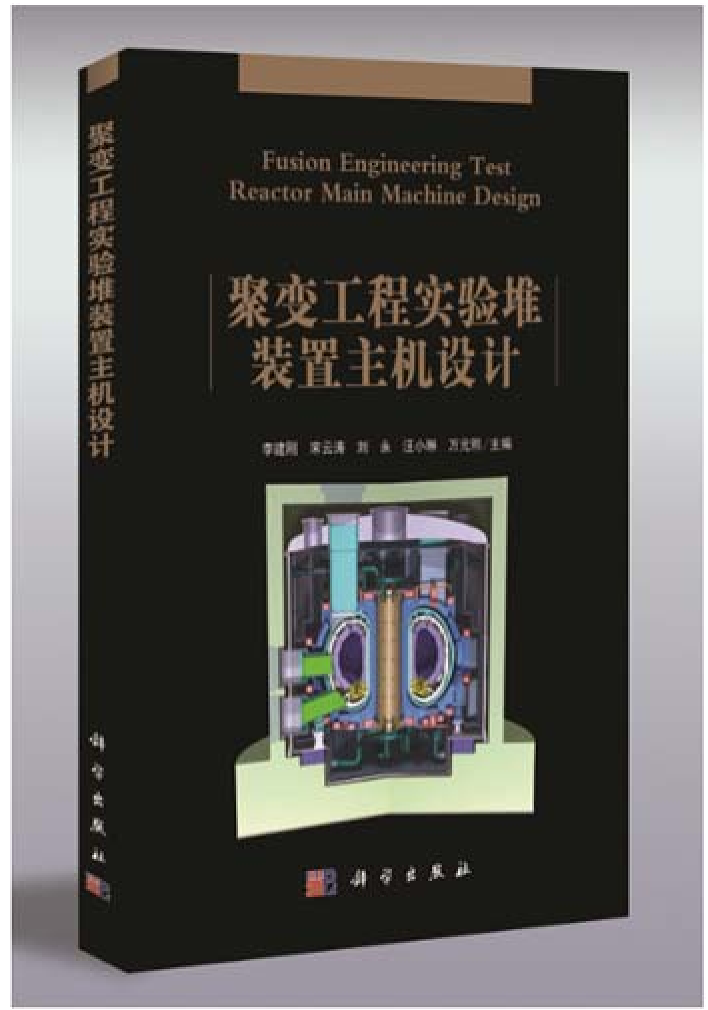
Key parameter investigation (180VS)

Operation mode	A	B	C	D	E	ITER -SS	Upgrade
I_p(MA)	10	10	10	8	8	9	15
P_{aux}(MW)	65	65	65	65~70	65	59	65
q_{95}	3.9	3.9	3.9	4.9	4.9	5.2	3.9
W(MJ)	171~174	193	270~278	171	255	287	540
P_{Fus} (MW)	197~230	209	468~553	187~210	409	356	1000
Q_{pl}	3.0~3.5	3.2	7.2~8.5	2.7~3.2	6.3	6.0	15
T_{i0}(keV)	17.8~18.5	29	19.8~20.8	20.6~21	21	19	25
$N_{el}(10^{20}/m^3)$	0.75	0.52	1.06	0.65	0.94		1
n_{GR}	0.6	0.42	0.85	0.65	0.95	0.82	0.85
β_N	1.59~1.62	1. S8	2.51~2.59	2	2.97	3.0	2.7
β_T(%)	~2.0	2.3	3.1~3.25	2	2.97	2.8	4.2
f_{bs}(%)	31.7~32.3	35.8	50~51.5	50	73.9	48	47
τ_{98Y2}(s)	1.82~1.74	1.55	1.57~1.47	1.37	1.29	1.94	1.88
$P_N/A(MW/m^2)$	0.35~0.41	0.37	0.98	0.33~0.37	0.73	0.5	1.38
I_{CD}(MA)	3.0~3.1	7.0	2.45	4.0	2.76		3.0
H_{98}	1	1.3	1.2	1.2	1.5	1.57	1.2
$T_{burning}$(S)	1250	SS	2200	SS	S		1200

B_t=4.5T; R=5.7 m; a=1.6 m; k=1.8 ~2.0

B_t=4.8T; R=5.9 m; a=2.0 m;

The first design version has been summarized



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Key issues for CFETR mission

Obtained Burning Plasma
for fusion power

1. Lager device (B_t $R_{o,}$ a K)
2. Standard H mode
3. Advanced operation scenario

Steady-state operation
for fusion energy

4. Increasing flux to sustain longer Ip
5. CW Ext H&CD (NB,EC,LH,IC)
6. Higher f_b
7. Higher energetic α heating
8. Divertor physics and tech.

Breeding Tritium
for T self-sustained

9. T-breeding by blanket
10. T-plant: extract & reprocessing
11. Materials
12. RH
13. licensing

New design version (2015.8-2016.8)

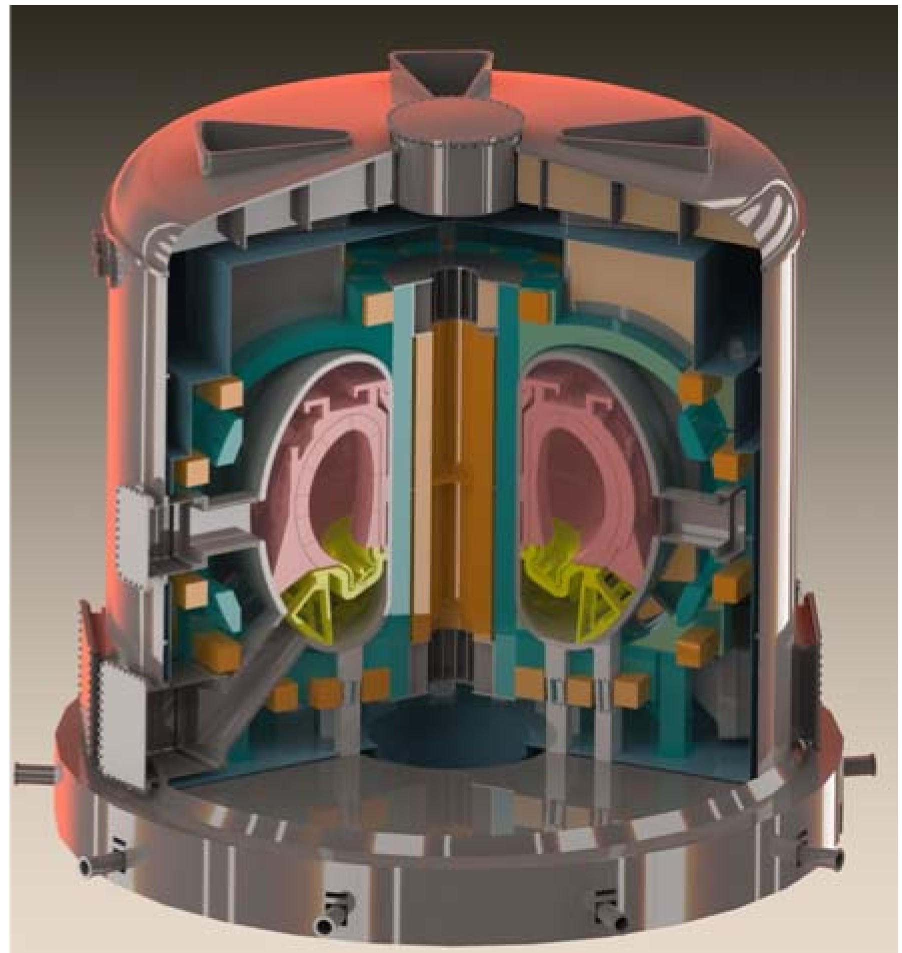
Easy transfer from Phase I to Phase II

The key points changed:

- **Larger size:**

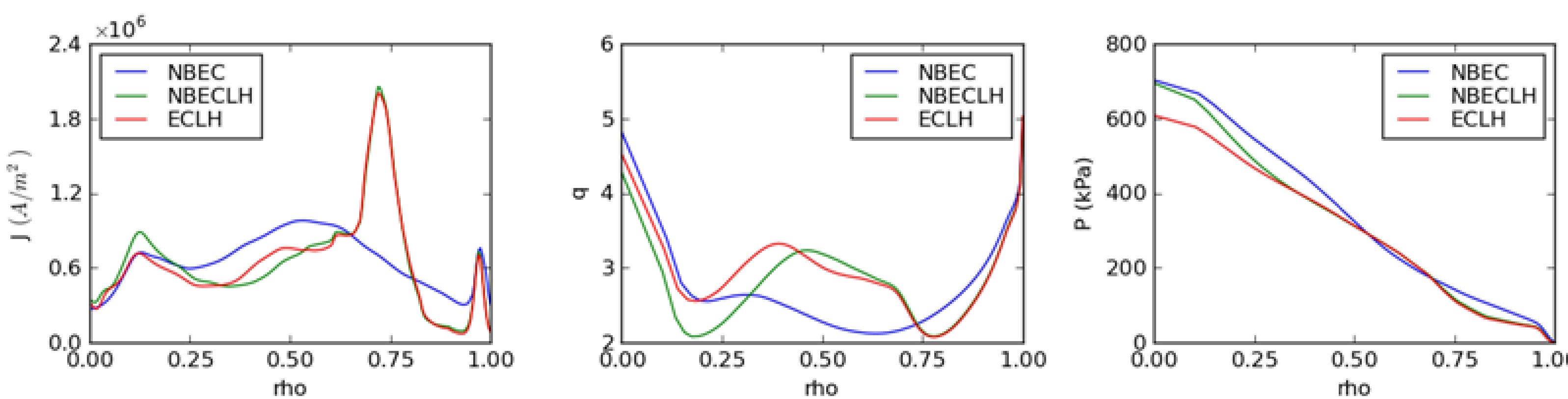
  R= 6.7m, a=1.95m

- **Higher B_T: 5.0-7.0 T**
- **Advanced CS magnet:≥ 480 VS**
- **Lower Ip: 6-12MA**
- **12 TF coils for easy RH, H&CD**
- **More reliable Plasma targets**
- **Higher confidence for STE goals**

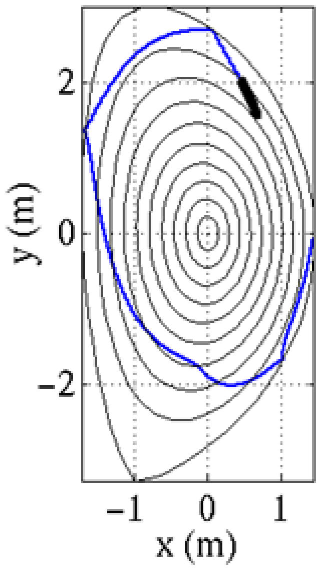


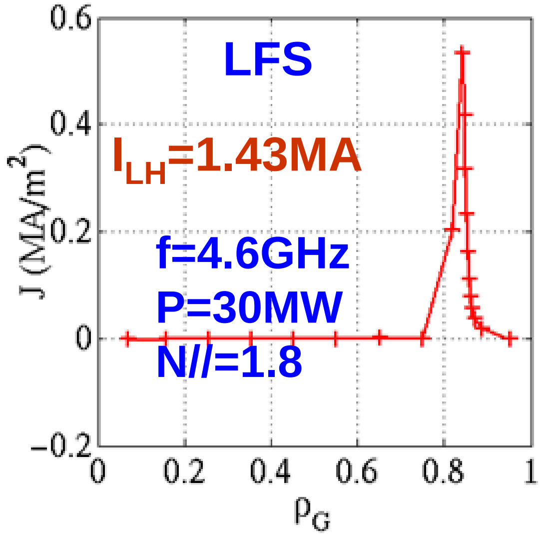
CFETR Physics design

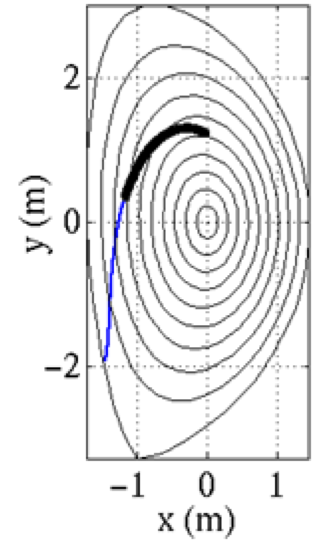
- **0D system code + 1.5D integrated modeling (OMFIT, EFT, ONETWO, GATO,TGYRO/TGLF, NEO, ELITE)**
- **Off-aix NBI + ECCD, LHCD are major H&CD tools together with bootstrap current for SSO**
- **Using 800 kV NBI(1.1MA/10MW) +190GHz ECCD for phase I operation.**

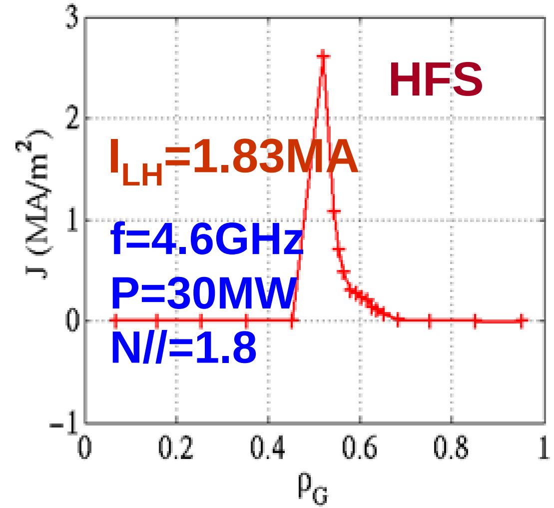


More effective current drive –HFS LHCD+Top ECCD



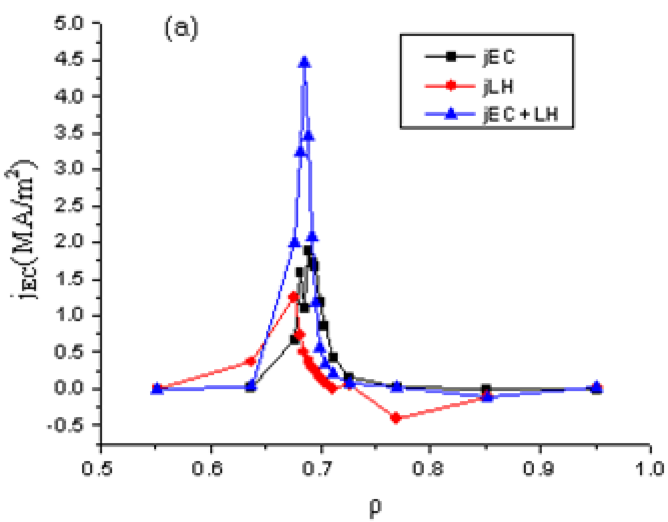




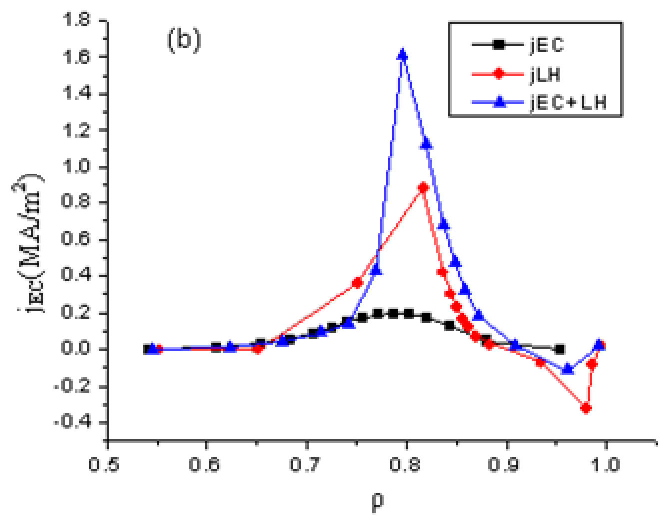


HFS LHCD
TOP ECCD
ΔI = 0.3MA
I_{CD}=4.0MA

I_{EC}=0.975MA(Φ=205°, θ=110°)
I_{LH}=2.7305MA($N_{//}$=2.04)
I_{EC+LH}=4.0062MA
$\Delta I = I_{EC+LH} - I_{EC} - I_{LH}$=0.3007MA



I_{EC}=0.698MA(Φ=250°, θ=130°)
I_{LH}=1.45MA($N_{//}$=2.04)
I_{EC+LH}=2.4923MA
$\Delta I = I_{EC+LH} - I_{EC} - I_{LH}$=0.3443MA



LFS LHCD
LFS ECCD
ΔI = 0.34MA
I_{CD}=2.49MA

Two New Fully Non-Inductive CFETR Scenarios with Larger Size Have Been Evaluated

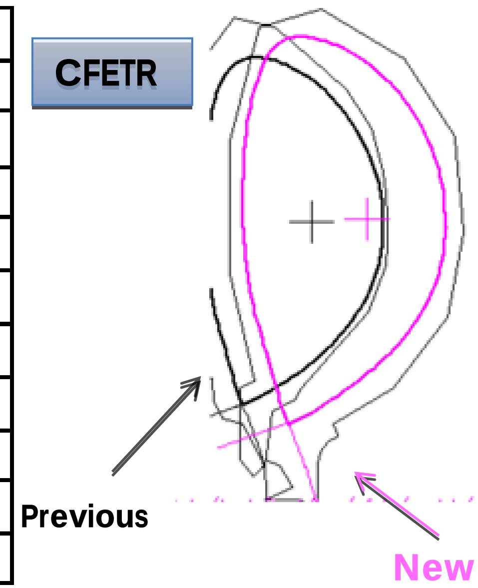
- **Computed with self-consistent core-pedetal-equilibrium model under *OMFIT***

	Previous	Phase I	0D Phase I	Phase II	0D Phase II
R_0, a (m)	5.70 / 1.60	6.60 / 1.80	6.62 / 1.79	6.60 / 1.80	6.63 / 1.79
NBI Input Power (MW)	10, 58.5	13, 22.8	132	20.0, 14.3	62
NBI Voltages (keV)	100, 400	100, 500	/	100, 500	/
NBI Absorbed Power (MW)	59.3	32.2	/	33.9	/
EC Power (MW), Freq (GHz)	8, 170	20, 230	/	20, 230	/
EC Absorbed Power (MW)	8	19.8	/	20	/
Fusion Gain Q_{FUS}	2.0	3.0	1.5	14.9	16.4
Fusion Power P_{FUS} (MW)	149.5	169	200.4	811.0	1019.2
B_T (T), I_p (MA)	5.0, 10.0	6.0, 7.6	5.8, 7.5	6.0, 10.0	5.9, 10.0
NBI CD I_{NBI} (MA)	5.5	2.0	/	0.9	/
RF CD I_{RF}(MA)	0.3	0.8	/	0.6	/
Bootstrap I_{BS} (MA), Fraction f_{BS}	4.3 (43%)	4.8 (64%)	3.8 (50.%)	8.4 (84%)	7.5 (75%)
Central T_{i0}, T_{e0} (keV)	23.5, 24.9	18.8, 25.3	12.7, 12.7	25.6, 33.5	21.7, 21.7
Central Density n_e ($10^{20}/m^3$)	0.80	0.80	1.2	1.4	1.6
Greenwald Density Ratio	49%	51%	82%	87%	81%
Z_{EFF}	2.1	2.0	2.0	2.0	2.4
β_N, H_{98y2}	1.90, 1.02	1.89, 1.32	1.60, 1.0	3.15, 1.34	2.81, 1.5
Neutron Wall Loading Γ_{NW} (MW/m²)	0.22	0.19	0.21	0.92	1.03
Diverter heat loading P_{DIV}/R_0 (MW/m)	15.7	10.4	/	25.8	/

by GA-CFETR team

New Larger CFETR Reduces Heating and Current Drive Requirements, and Lower Divertor and Wall Power Loading

	Previous	New Phase I	New Phase II
R_0, a (m)	5.7, 1.6	6.6 , 1.8	6.6, 1.8
P_{NBI}, P_{ECH} (MW)	68.5, 8.0	35.8, 20.0	33.9, 20.1
Fusion Gain Q_{FUS}	2.0	3.0	14.9
Fusion Power P_{fus} (MW)	150	169	811
B_T (T), I_p (MA)	5.0, 10.0	6.0, 7.6	6.0, 10.0
Bootstrap Fraction f_{BS}	43.3%	63.6%	84.4%
Normalized beta β_N	1.90	1.89	3.15
H_{98Y2}	1.0	1.3	1.3
Neutron Wall Loading Γ_{NW} (MW/m^2)	0.22	0.19	0.92
Diverter Loading P_{DIV}/R_0 (MW/m)	15.7	10.4	25.8



- Fully non-inductive CFETR scenarios have been developed with a self-consistent core-pedestal-equilibrium model
- New larger CFETR reduces heating and current drive requirements, lower divertor heat flux and neutron wall loading, higher bootstrap current fraction and H98y2 at similar β_N
- Higher β_N~3.2 Phase II configuration requires a close conducting wall for *n* = 1,2 ideal stability but for Phase I dont need the conducting wall

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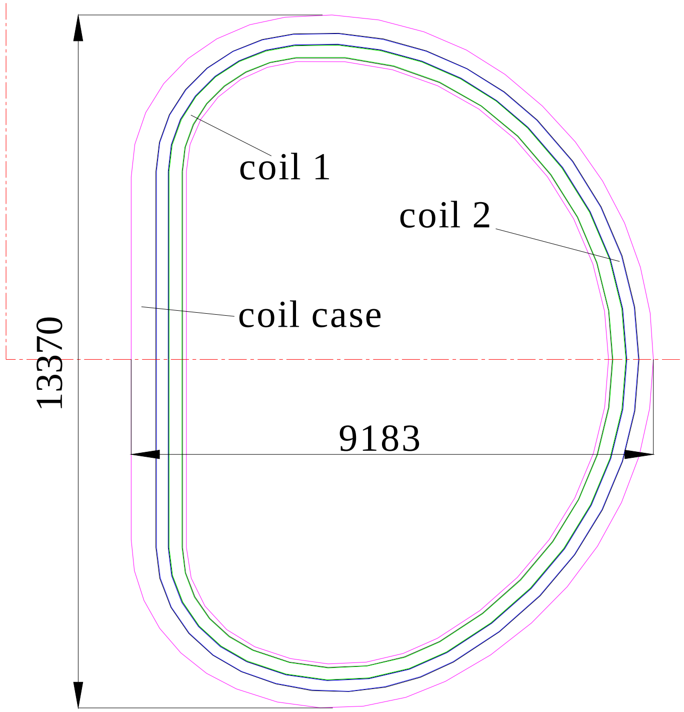
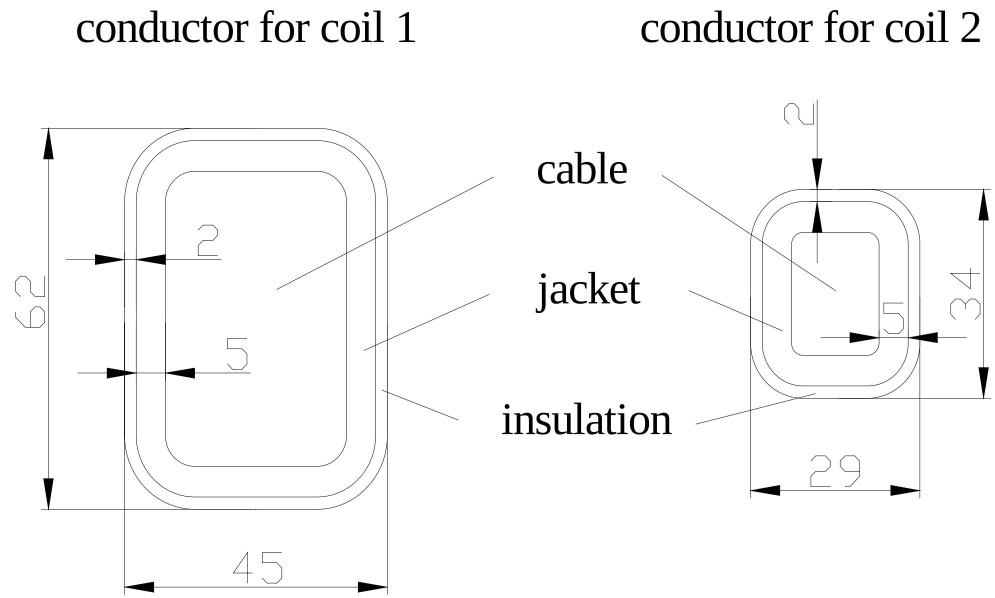
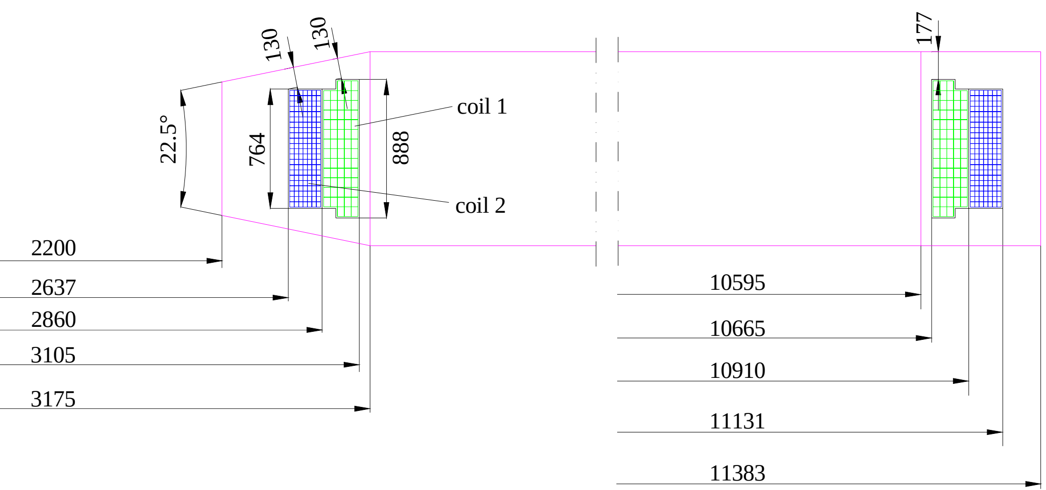
12 TF Coil design (High Performance Nb_3Sn)



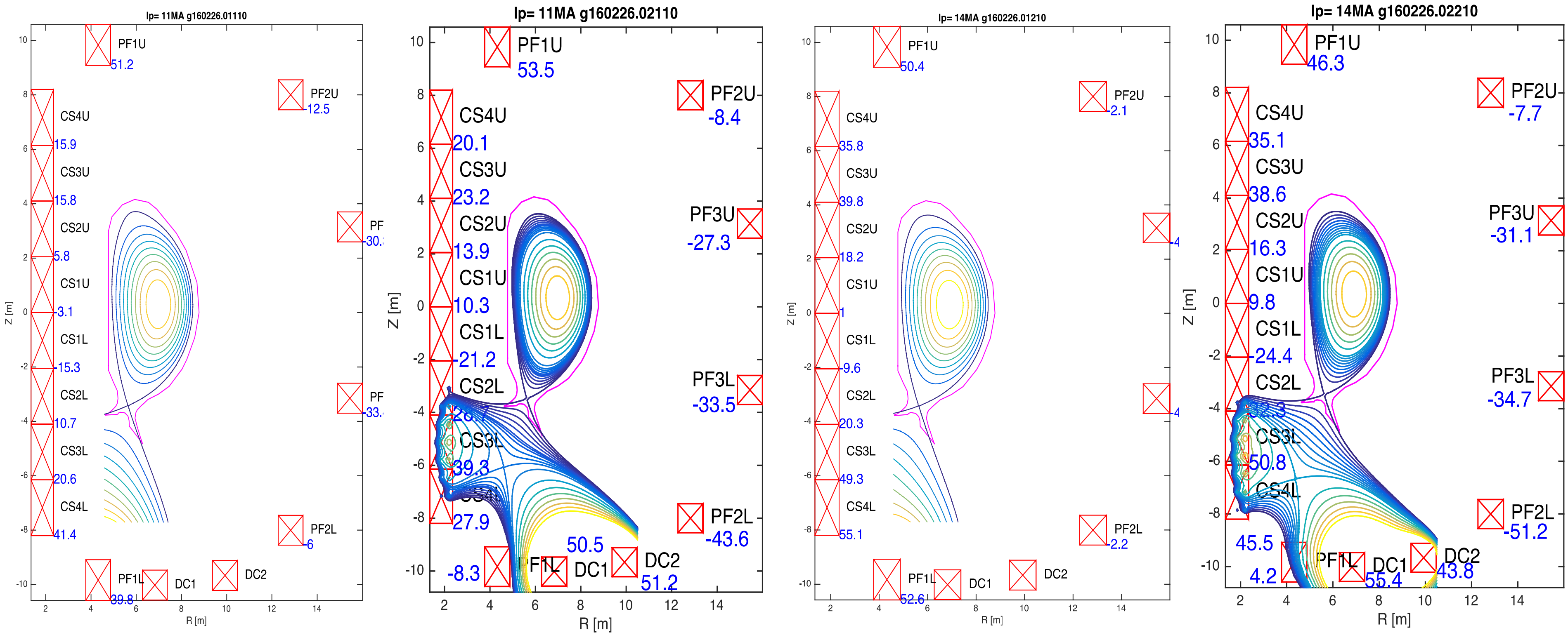




Parameters for TF magnet

Parameters	Coil 1	Coil 2
strand	high J_c(3000A/mm^2) Nb_3Sn Φ 1.0mm strand	
No. of SC strand	1350	270
Turns	66	154
Operating current for B_t=7.5T	64.3kA	
B_{max} in coil	**14.3T**	11.4T
Max Force	**643MPa**	

Advanced plasma equilibrium shape



Ip=11 MA **Ip=14 MA**

Ip [MA]	Type	R[m]	a[m]	β_p	ι_i	β_t	δ_u/δ_l	κ	q_{95}
11	Snowflake	6.72	1.76	1.59	1.02	0.025	0.33/0.63	1.99	3.9
14	Snowflake	6.72	1.75	1.1	0.95	0.024	0.33/0.63	1.99	3.3

Helium cooled ceramic breeder blanket design

Material section

- Li_4SiO_4 as tritium breeder
- Be as neutron multiplier.
- RAFM steel as structural material.
- Tungsten as armor material of the FW

Main features

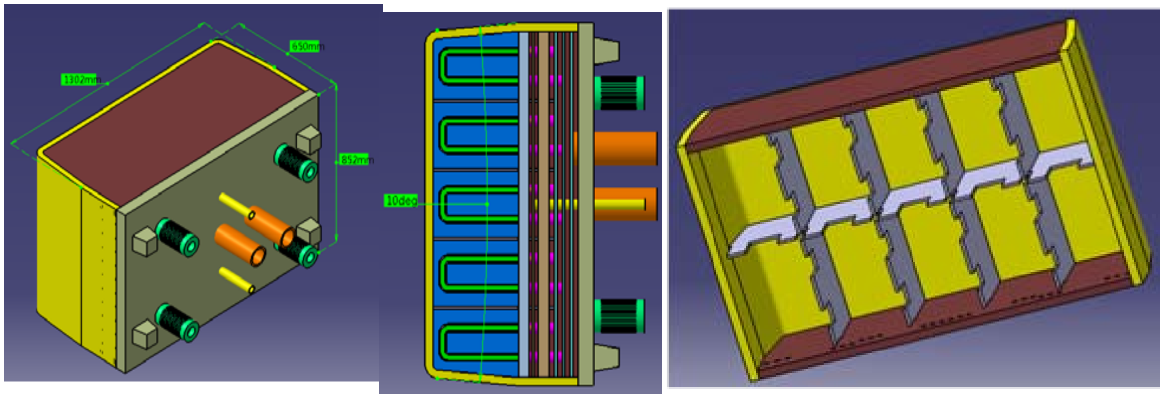
- Modularized breeding unit
- Multi-layer back plates manifold

Coolant : 8 MPa, 300 ºC inlet/500 ºC outlet

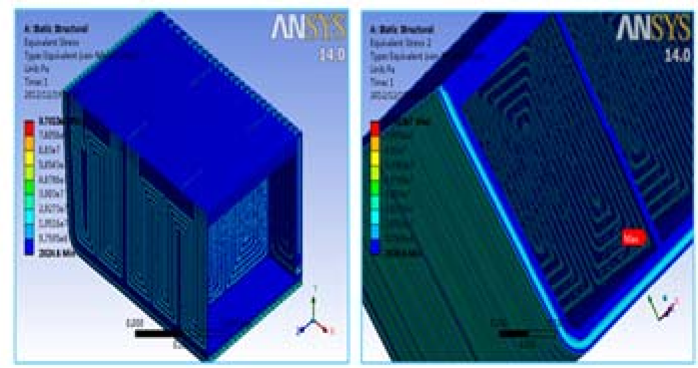
For Phase-I

5 (Tor.)×2 (Pol.) breeding unit, each has one U-shape breeder unit.

TBR: 1.213



Typical module structure

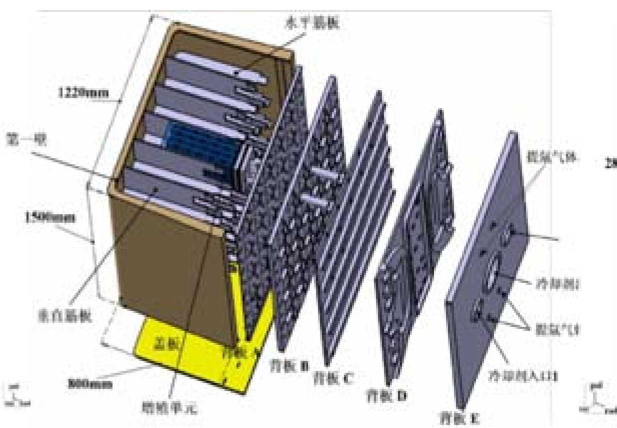


Stress analysis

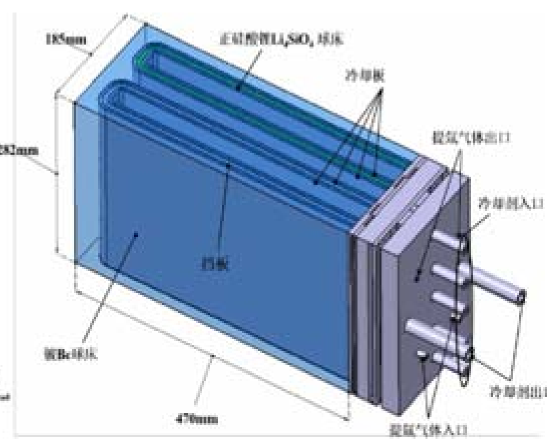
For Phase-II

6 (Tor.)×5 (Pol.) breeding unit, each has two U-shape breeder unit.

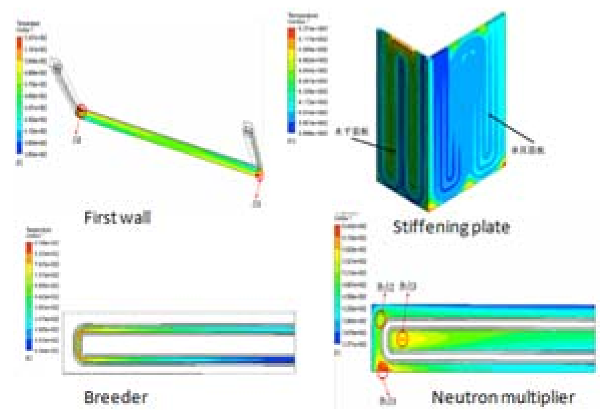
TBR: 1.15



Typical module structure



Modularized breeding unit



Temp. distribution

Water cooled ceramic breeder blanket design

Material section

- Mixed breeder of Li_2TiO_3 and $Be_{12}Ti$
- A bit of Be to improve neutrons multiplying.
- RAFM steel as structural material.
- Tungsten as armor material of the FW

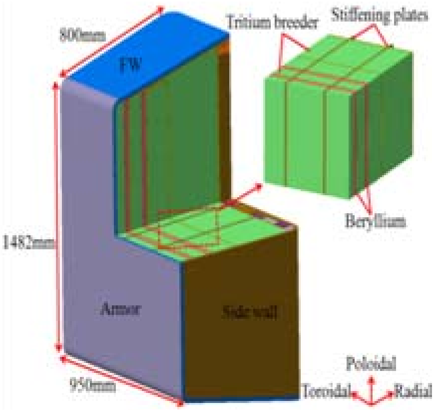
Main features

- Coolant : 15.5MPa, 285 ºC inlet/325 ºC outlet
- The cooling plates and the breeder zone parallel to the FW
- The compact coolant enlarges the breeder zone.
- Purge gas is directed in the toroidal direction to reduce its pressure drop.

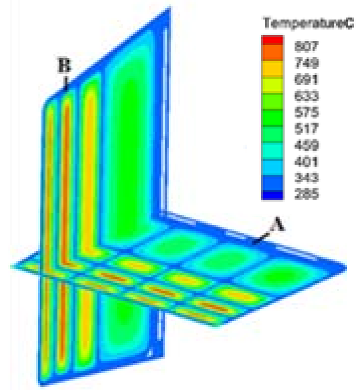
For Phase-I

4 (Rad.)×4 (Tor.) mixed breeder zones and 2 (Rad.)×4 (Tor.) thin Be layers

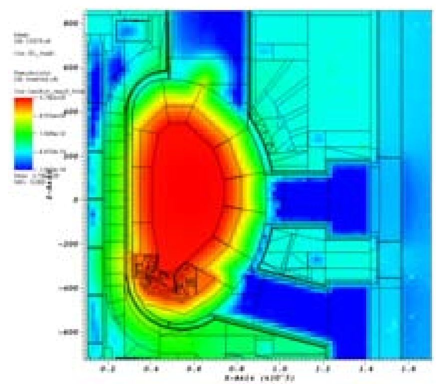
TBR: 1.21



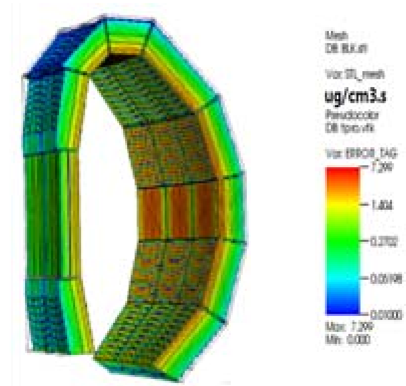
Module structure



Temp. distribution



Neutron flux distribution

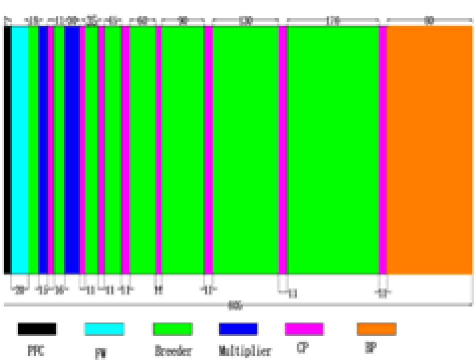


Tritium production rate
(PF0.8, ^{6}Li80% case)

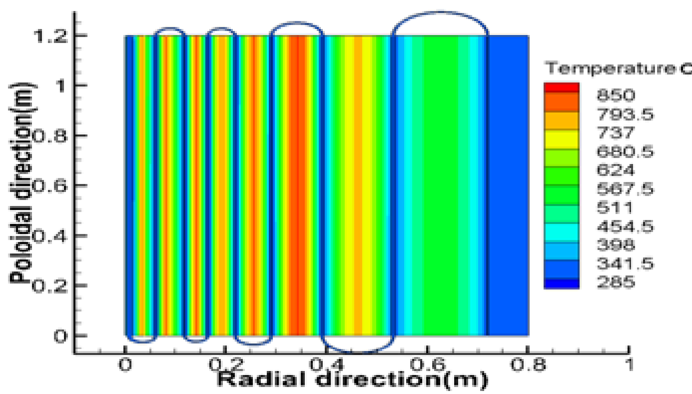
For Phase-II

8 (Rad.)×4 (Tor.) mixed breeder zones and 2 (Rad.)×4 (Tor.) thin Be layers

TBR: 1.1



Module radial building



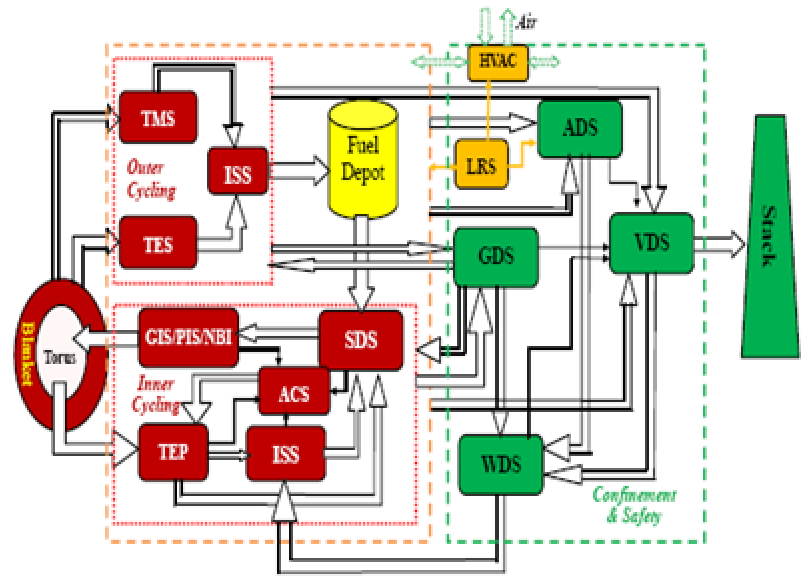
Temp. distribution along radial direction

Shielding capability for TFC

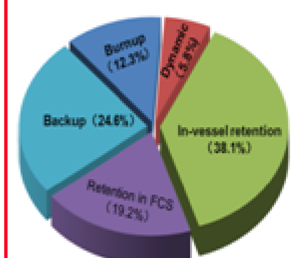
Item	Limits	value
Fast neutron (>0.1MeV) fluence in TFC conductor (n/cm^2)	1×10^{19}	3.67×10^{16}
Fast neutron (>0.1MeV) fluence inTFC insulator (n/cm^2)	5×10^{17}	1.10×10^{17}
Nuclear heating rate in TFC case(W/cm^3)	2×10^{-3}	2.19×10^{-5}
Nuclear heating rate in TFC conductor (W/cm^3)	1×10^{-3}	1.88×10^{-5}

Tritium cycling systems (T-plant)

- 3 main loops for tritium recovery:
  - Inner cycling：
    - Tritium recovery, isotopic separation from plasma exhaust gases and re-fueling to torus.
  - Outer cycling：
    - Tritium extraction and measurement from in the full breeding blanket.
  - Tritium confinement and effluent detritiation.
- Main parameters for tritium process flow (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 enviromental tritium release at current stage, to be minimized as 0.6 g/a for the future.
- Key technologies development for each sub-system are in progress



Simple block diagram of CFETR tritium plant



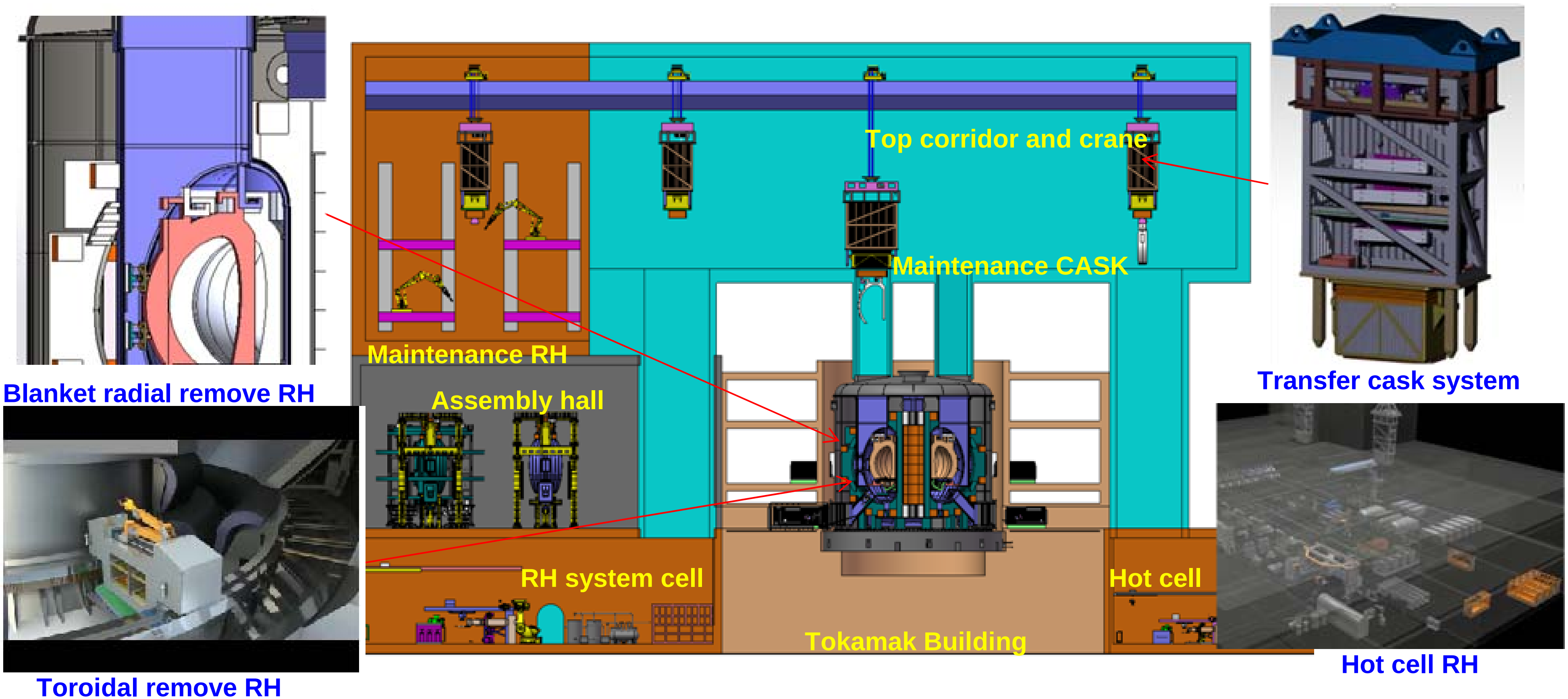
The makeup of startup tritium for CFETR.

Burnup (g)	Dynamic (g)	In-vessel retention (g)	Retention in FCS (g)	Backup (g)	Total (g)
226	107	661	353	452	1799

Totally, CFETR may need around 2 kg of tritium for startup.

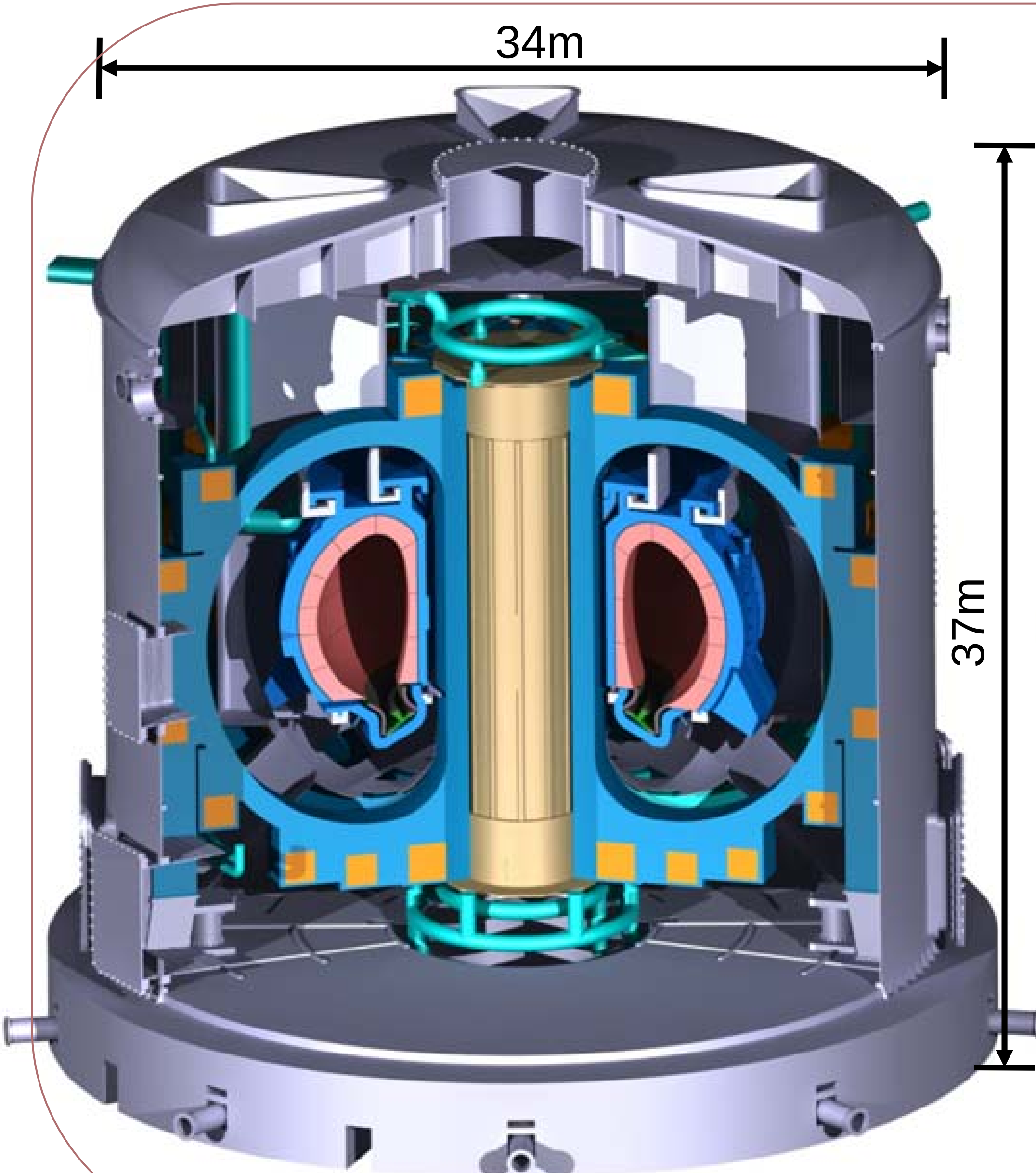
RH strategy of CFETR

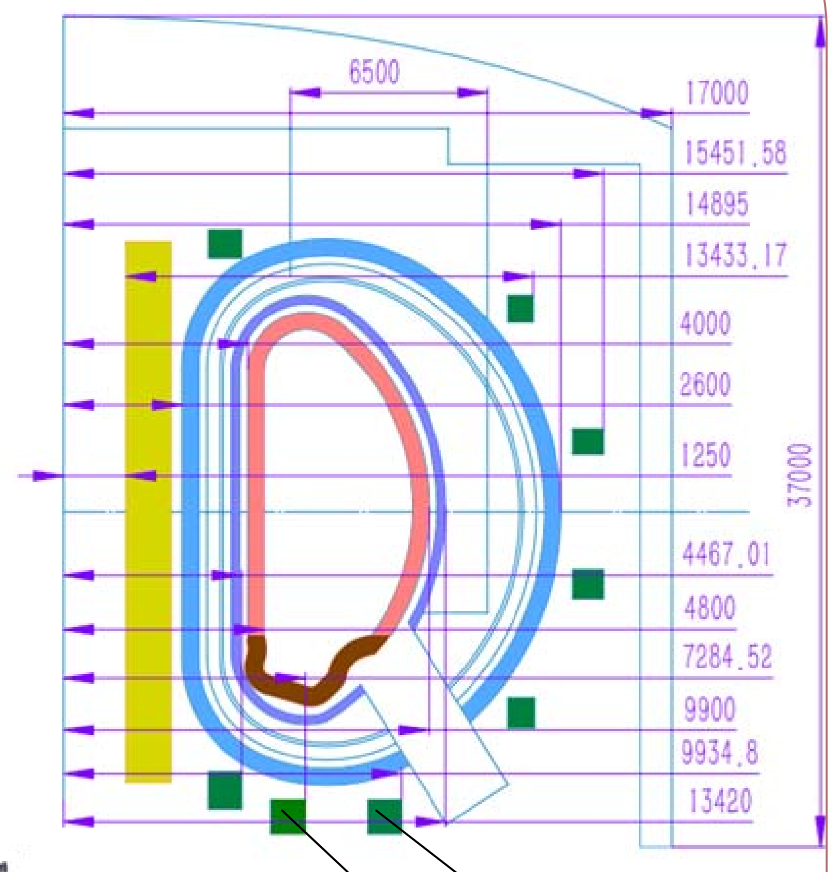
RH strategy plays the key role for the CFETR's high efficiency and reliability maintenance. The **vertical port maintenance scheme** with multi-module segment blanket and divertor was preferred for in-vessel components maintenance. It will make the RH simpler and more efficient.



The vertical port maintenance scheme for in vessel components

New Design version of CFETR



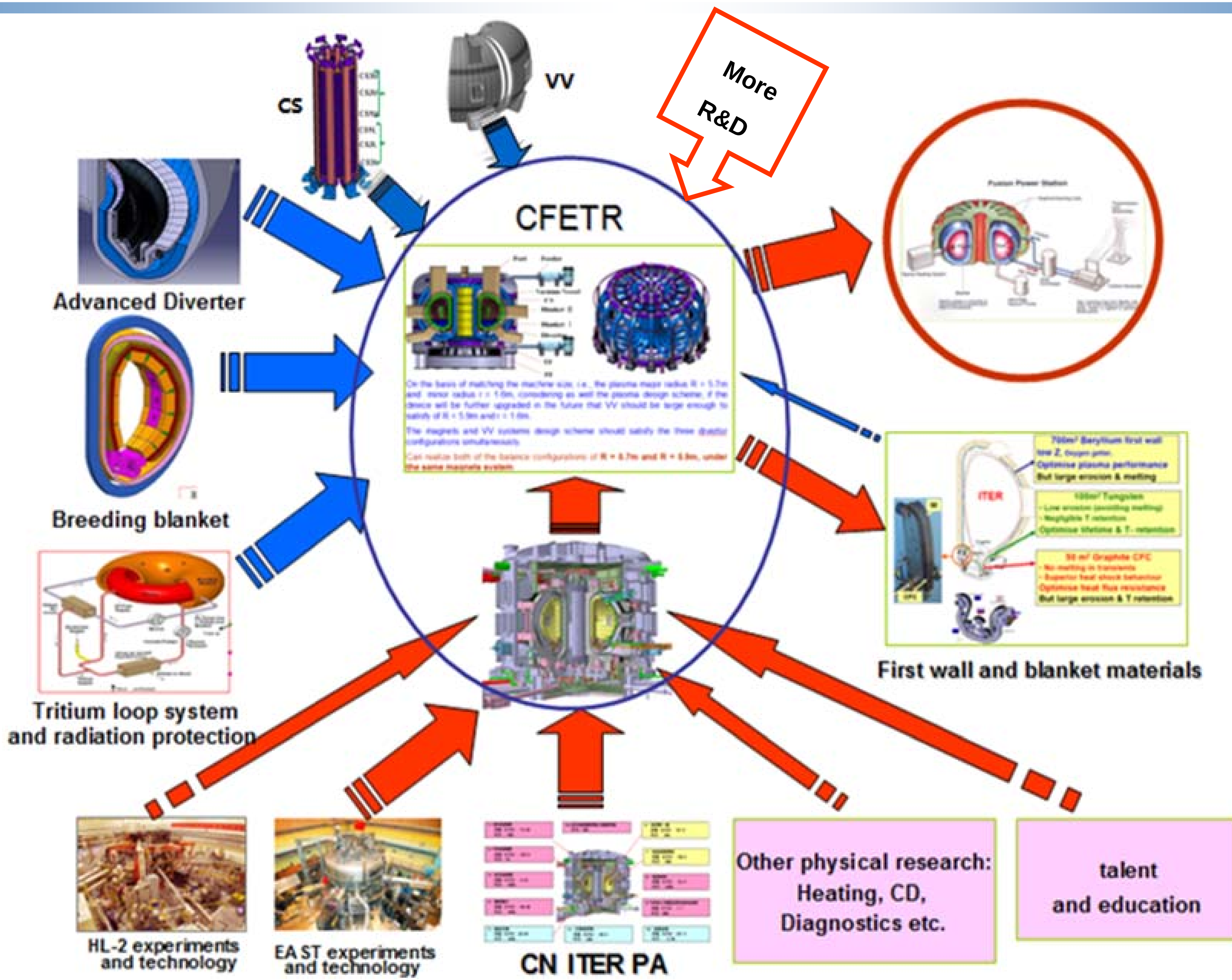


Dimensions of CFETR

Outline

- Introduction
  - CN MCF Roadmap
  - Mission of CFETR
- Progresses and activities of CFETR
  - Previous concept design
  - New design version
    - Phase I
    - Phase II
- Key R&D activities
- Summary

R&D strategy of CFETR



Other important R&D for CFETR

- **Auxiliary Heating & CD:**
  - ✓ Off-aix NBI (0.8MeV) + ECRH (top，190，230GHz)
  - ✓ LHCD (HF，4.6GHz) +ECRH (top，230GHz)
- **Advanced Superconducting Magnet**

  TF (Nb_3Sn, 7.0 T); CS (Bi 2212 CICC)
- **Advanced Divertor** (X-Divertor, >20MW/m^2)
- **Blanket** (He gas, water cooled)
- **T-Plant** (99.9% T recovery)
- **Materials** (First wall, structure)
- **RH**

R&D for RF Sources

LHW:

EAST: 2.45GHz, 200kW, CW

4.6 GHz, 0.3MW,CW

CFETR: 4.6 GHz, 0.3-0.5MW,CW

7.5GHz, 0.5MW, CW

EC:

EAST: 140GHz, 1MW, CW

170GHz, 1MW, CW

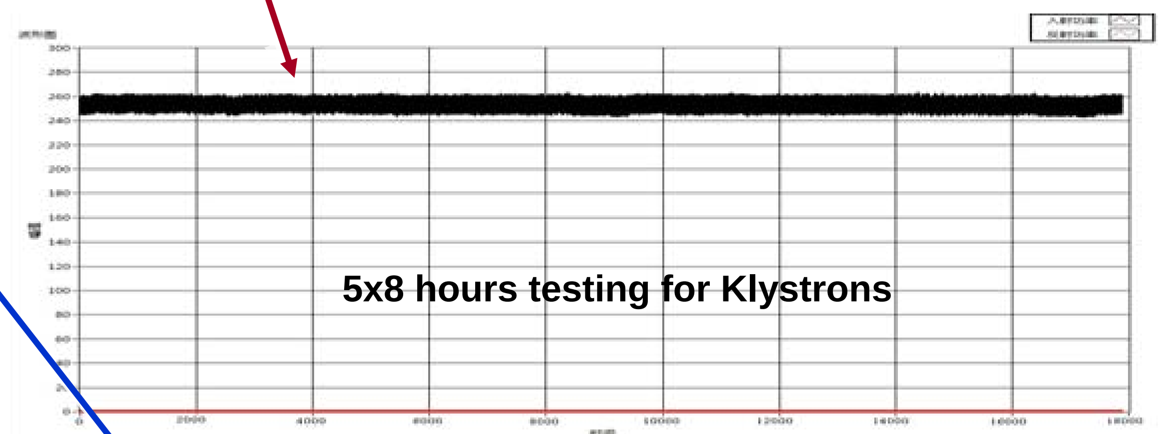
CFETR: 170GHz, 1MW, CW

230GHz, 1MW, CW

2.45GHz, 200kW

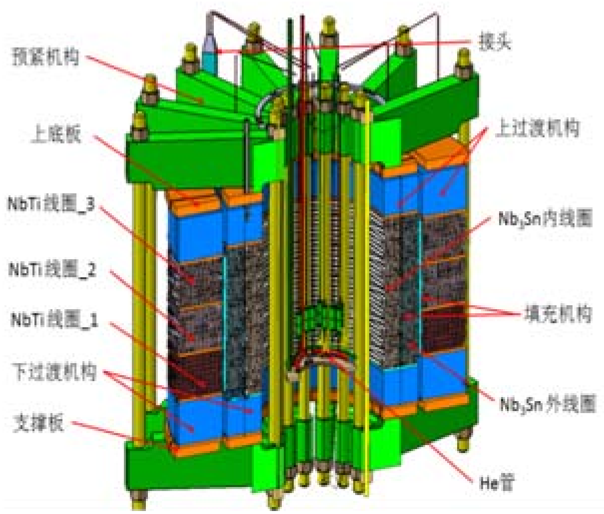
4.6 GHz, 0.3MW

140GHz, 1MW, CW



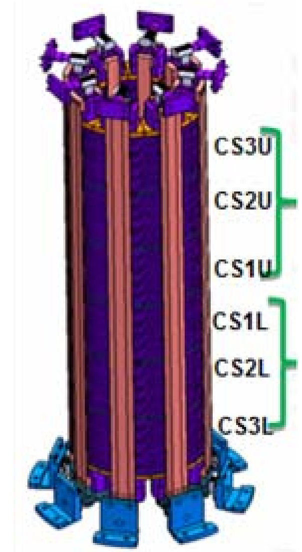
Gyrotron: Start commissioning @ 2016.12

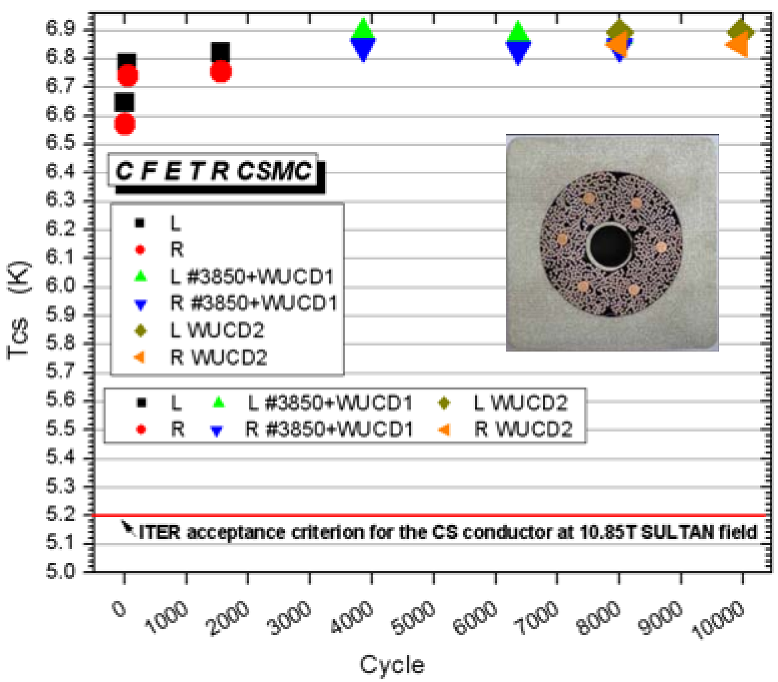
CS Model Coil –Nb_3Sn (baseline)

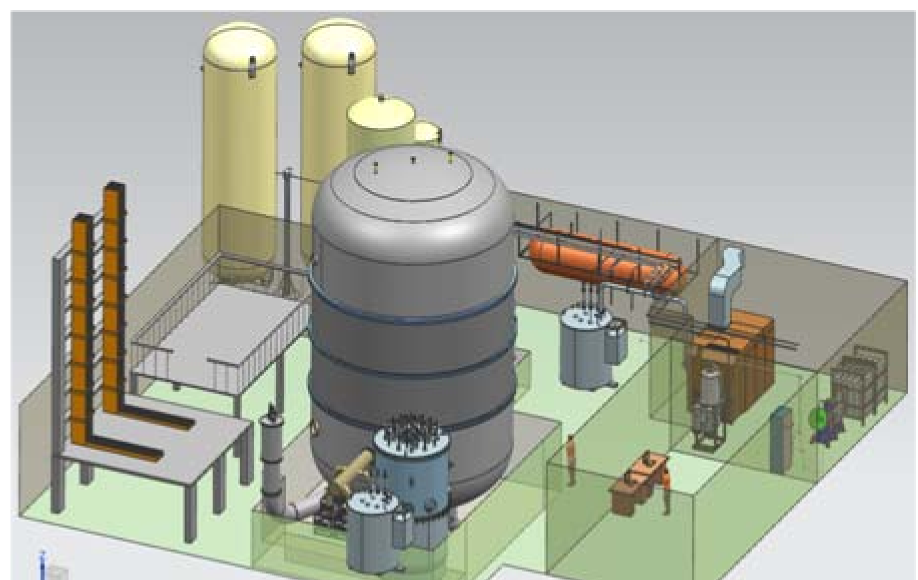


Coil Parameters

Design Parameters of CFETR CS Model Coil	
Max. field	12 T
Max. field rate	1.5 T/s
Inner radius	750 mm
Coil structure	Hybrid magnet **Inner: Nb_3Sn coil**
Conductor type	Nb_3Sn CICC

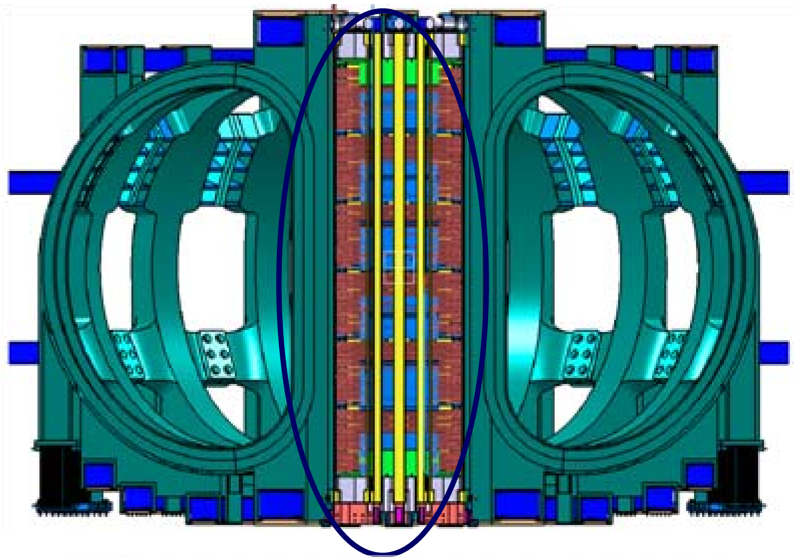


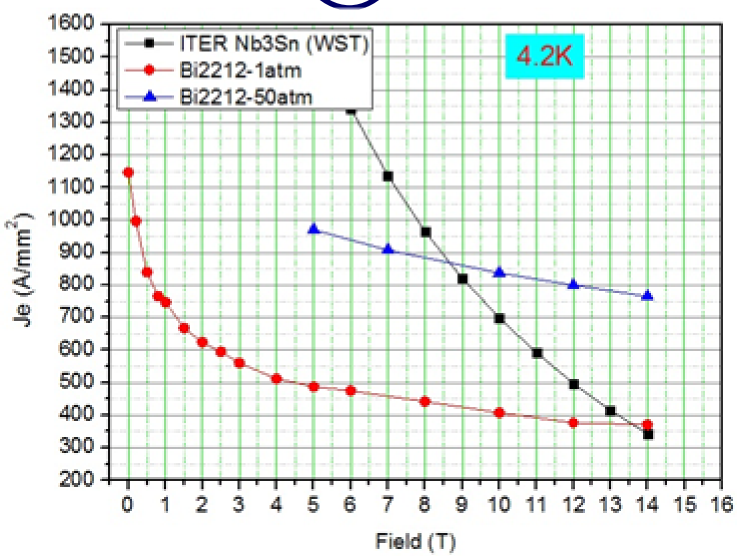




Start experiments @ 2017.12 in new ASIPP site （Huainan)

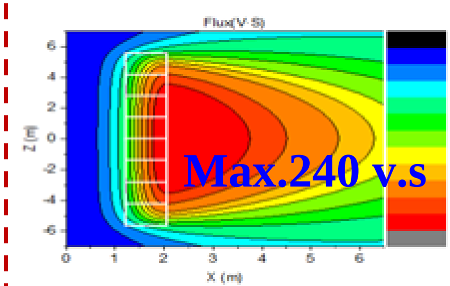
CS Model Coil (1/3 size) – 2212 CICC (Target)

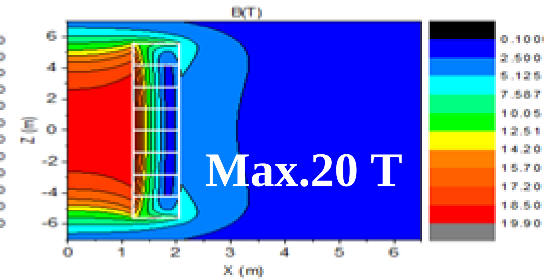




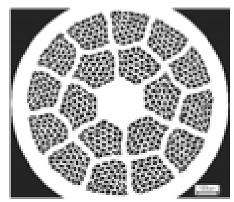
Bi2212-High temperature Superconducting Central solenoid

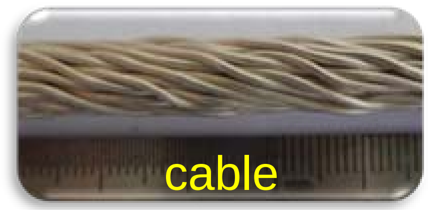
CS coils include eight Bi2212 coils. Each coil consists of 14 double pancake



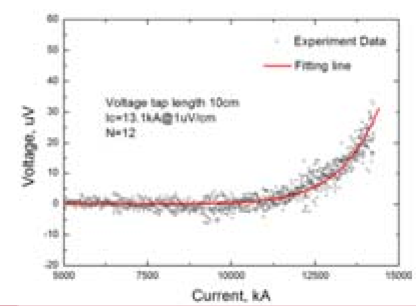


Conservative: enhanced Nb_3Sn: 360VS 4-6h
Ideal: 2212CICC, 480VS, ~8h (for Ip=10MA)

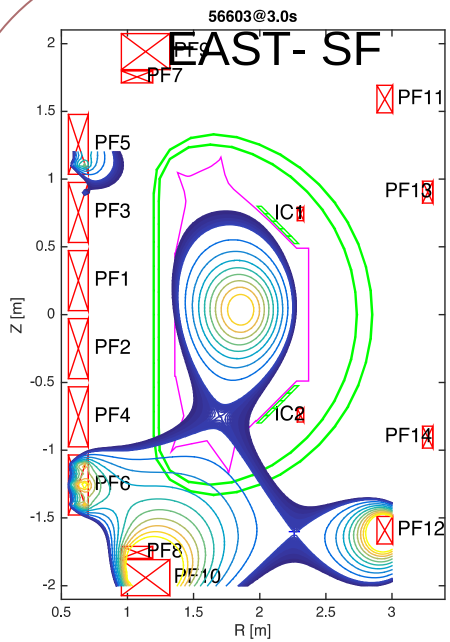


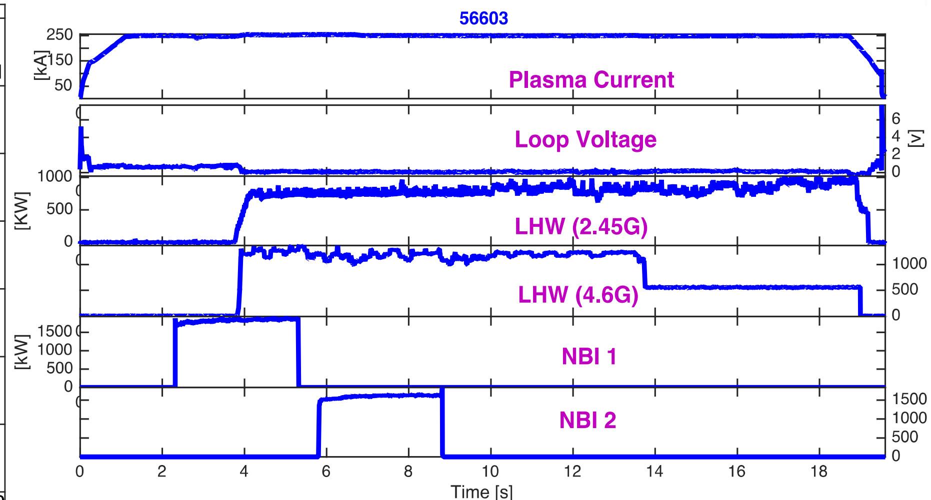


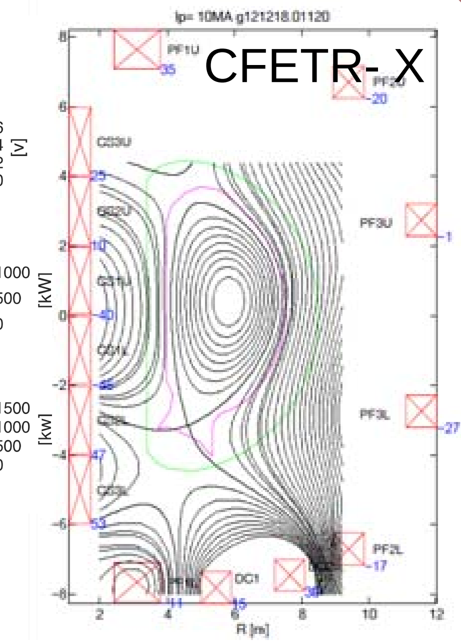
Batch production for 200-m long Φ1.0mm wires
4.2K, 14T: *J*ce > 750A/mm^2, ITER~ 320A/mm^2。
4.2K, 20T: *J*ce > 660A/mm^2, *ITER* ~ 200A/mm^2。
high pressure sintering process is on the way,
***Jc-B* property may be increased for 3 times.**



New Divertor validation







Joint Exp.with ENEA

Physics: **field expansion + radiation; Reduce the heat detail simulations (5y) + experimental validation (5-8y)**

Engineering : **design & manufacture of key components**

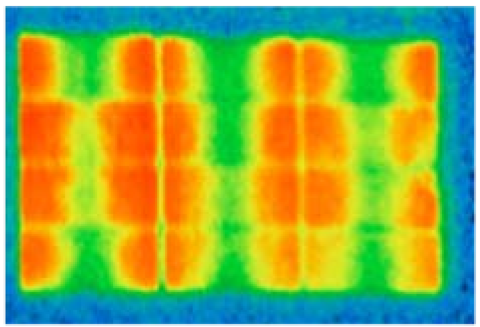
W mono-block: >20MW/m²

W-Cu mono-block : > 20MW/m² (5-10y)

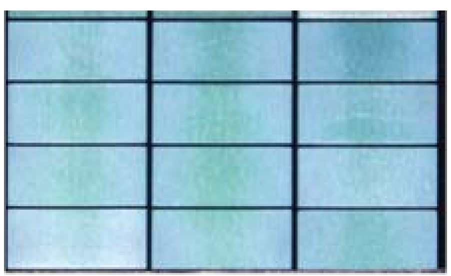
Inner+external coils optimization is underway up 15MA (12MA)

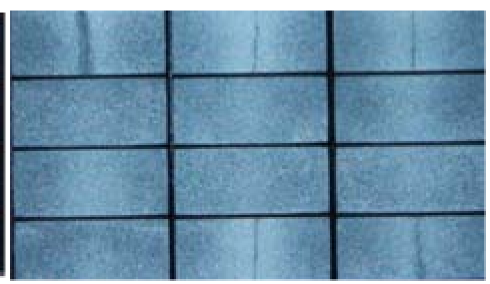
R&D for Divertor Target

Monoblock W/Cu
5000 cycles at $10MW/m^2$
300 cycles at $20MW/m^2$.



Flat tile W/Cu

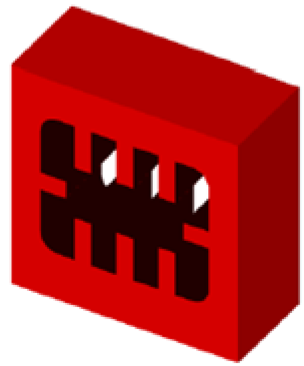


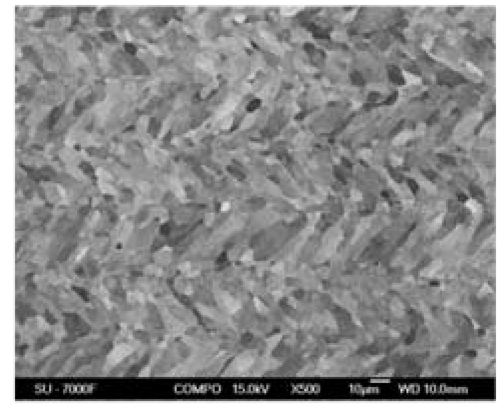


5000 cycles at $10MW/m^2$

1000 cycles at $20MW/m^2$

Efforts for $30MW/m^2$

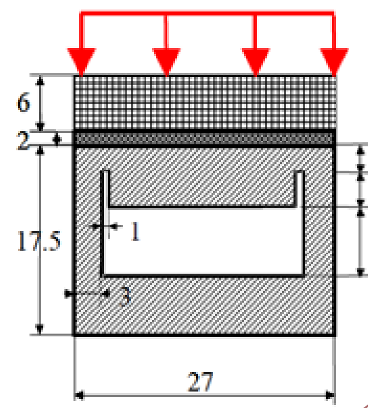




3D printing full W block: Tw=1700C

Flat tile

W/ODS-Cu
Tw = 1650C
Tcu = 520C



CFETR T-plant technologies

1 Tritium handling technologies

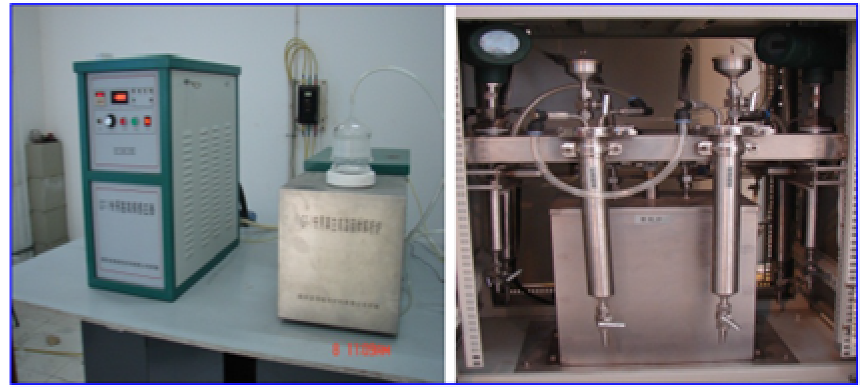
- ✓Tritium purification
- ✓Hydrogen isotope separation
- ✓Tritium removal/recovery in tritiated gases

Integrated hydrogen permeation

Cryogenic Distillation

2 Tritium Analysis and Monitoring

- ✓Tritium on line detection by gas chromatograph
- ✓Radiometric analysis



Solids contained tritium desorption and collection

TRITIUM SYSTEM

3 Tritium safety techniques

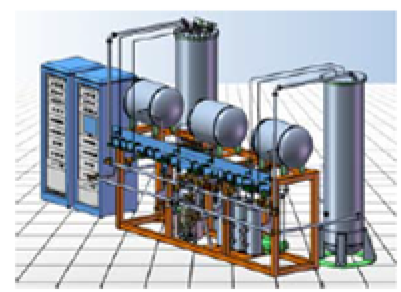
- ✓Atmospheric detritiation
- ✓Water detritiation
- ✓Tritium permeation barrier

D.S. for inert gas Metallic getter approach

4 ITER TBM tritium systems

- ✓Tritium Extraction System （TES）
- ✓Coolant purification system（CPS）
- ✓Tritium measurement system（TMS）

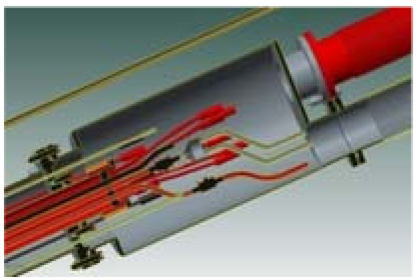
（CPS）



（TES）

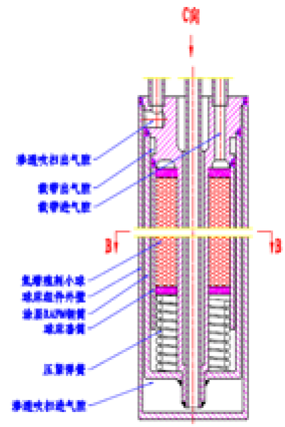
In-Pile Tritium Release and Extraction Test

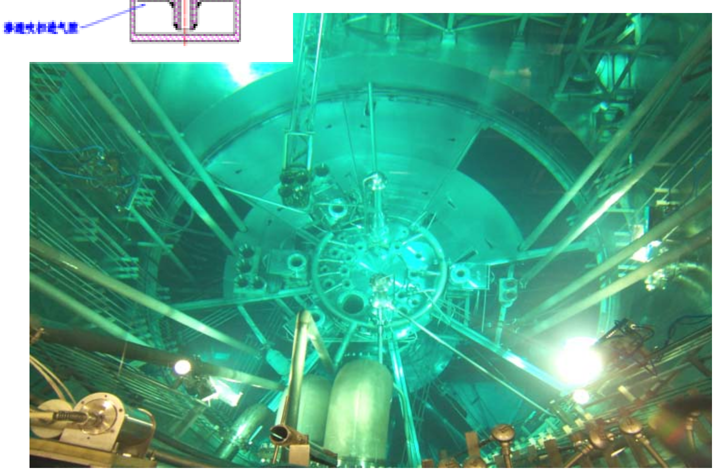
Maximum load 500 g
Tritium production1 Ci/day
Online refueling, irradiation
Irradiation temperature 300-750 ℃
Neutron flux ~5×10^{13}n cm^{-2}s^{-1}



China Mianyang Research Reactor

Maximum load 400 g
Tritium production1 Ci/day
Online thermal conductivity test
Irradiation temperature 400 ~ 850 ℃
Neutron flux ~5×10^{13}n cm^{-2}s^{-1}



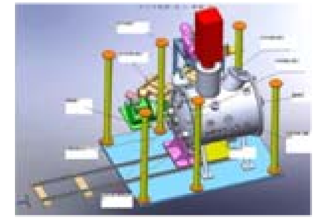
China Advanced Research Reactor

Materials Research Activities

(Simulation, manufacture, validation)

- **Low Activation Martesitic steel**
  - Nominal compositions: 9Cr1.5W0.2V0.15Ta0.45Mn0.1C
  - 5 ton smelting with good control of main compositions
- **Irradiation properties and TBM Fabrication**
  - High-dose neutron irradiation experiments
    (Spallation source ~20dpa)
    (High Fluence Engineering Test Reactor ~2dpa)
  - Fabrication of test blanket module (TBM)
    (1/3 scale P91 TBM, 1/3 scale CLAM first wall)

HIP(0.8x1.8m)



400kW EM facility

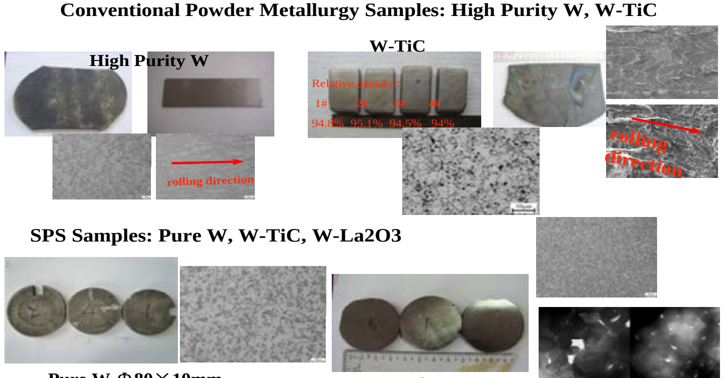
15kW laser welding (0.05mm)

- **Plasma-facing materials: W**

W material study scope: W alloy; W coating; W/Cu component

High heat-flux test facility

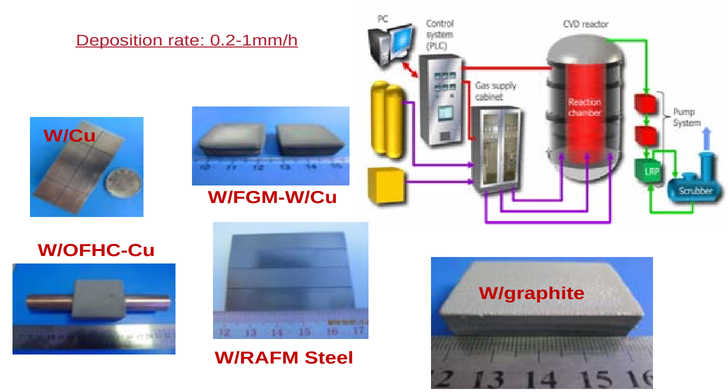
Conventional Powder Metallurgy Samples: High Purity W, W-TiC



Pure W Φ80×10mm

W-TiC Φ80×10mm

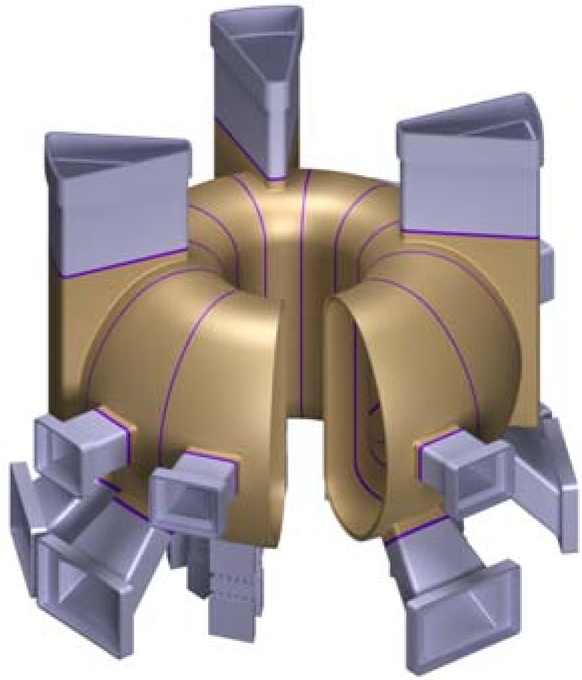
(Chemical vapor deposition) CVD-W



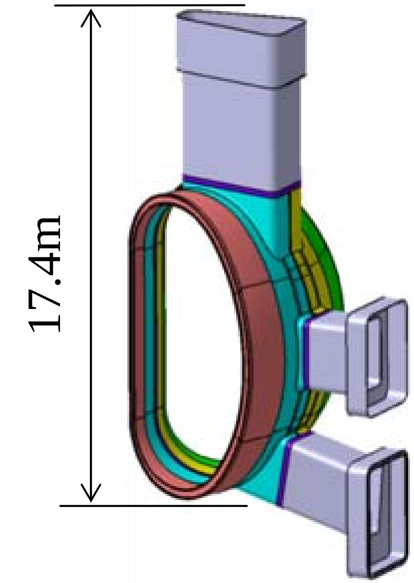
R&D on VV 1/8 mock-up

NG-TIG system

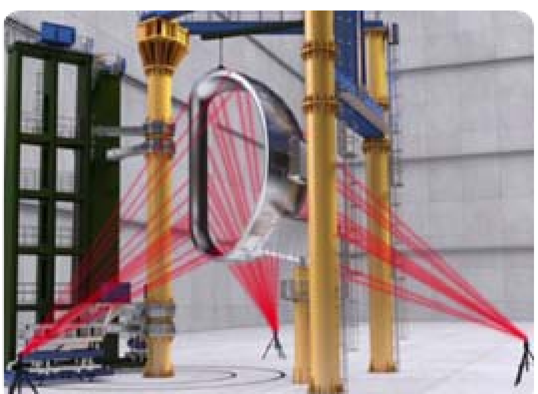
Welding samples



Overview of CFETR VV Design



Test bench for installation , replacement of VV components by RH



Laser Tracker Measurement on VV Sector

R&D of Narrow Gap TIG Welding on VV

Assembly of VV Poloidal Sectors

CFETR 5 years Plan

- Self-consistent, reliable physical design (V.Chan)
- Detailed engineering design (main machine and auxiliary systems)
- R & D for some key technologies and systems

(I): Blanket related to nuclear, thermal hydraulic processes

(II): magnets、T- factories、NBI、ECRH、RH

(III): Experimental verification, diagnosis, control, divertor, cryogenic, ICRF, radiation protection, assembly and so on.

Further working Plan of CFETR

- **Re-organize the design team by Drs. Li, Liu and Wang**

J.Li

Y.Liu

X.L.Wang

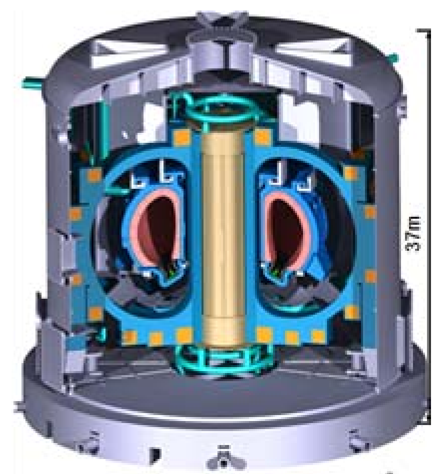
- **Promote both domestic and international collaboration more wide on design, R&D, and construction of CFETR**

J.Li

“CIC” Director

V.Chan

Division head of fusion plasma physics



International cooperation

- PPPL -CFETR team, H. Nielson, T.Bown, P.Titus, C.Kessel, A. Khodak.
- GA-CFETR team, L. Lao, R. Boivin, J. Candy, X. Chen, R. Prater, M.Christopher, A. Garofalo, O. Meneghini, M. Vanzeeland, P.B. Snyder, S.P.Smith, G.M. Staebler, E.J. Strait, and D. Zhao
- Useful discussion and suggestion from CFETR -IAC, CFETR Physics group IAC
- EU-DEMO team：（CCFE：SYScode, ENEA: Blanket, Julich: Diagnostic&Control, CCFE: RH, EPFL: H&CD, ENEA: Divertor, Julich: FM materials)

Summary

- **Integrated Design and R&D of CFETR are in progress**
- **CFETR is moving to Phase II design of the new version with emphasis for high B_T option**
- **There are gaps to CFETR readiness, especially for phase II， need new solution and technologies.**
- **Detail engineering design and large scale R&D will continue in next 5 years.**
- **It is hoped that the proposal for CFETR construction can be approved by government within next 5 years finally**

End and Thanks!