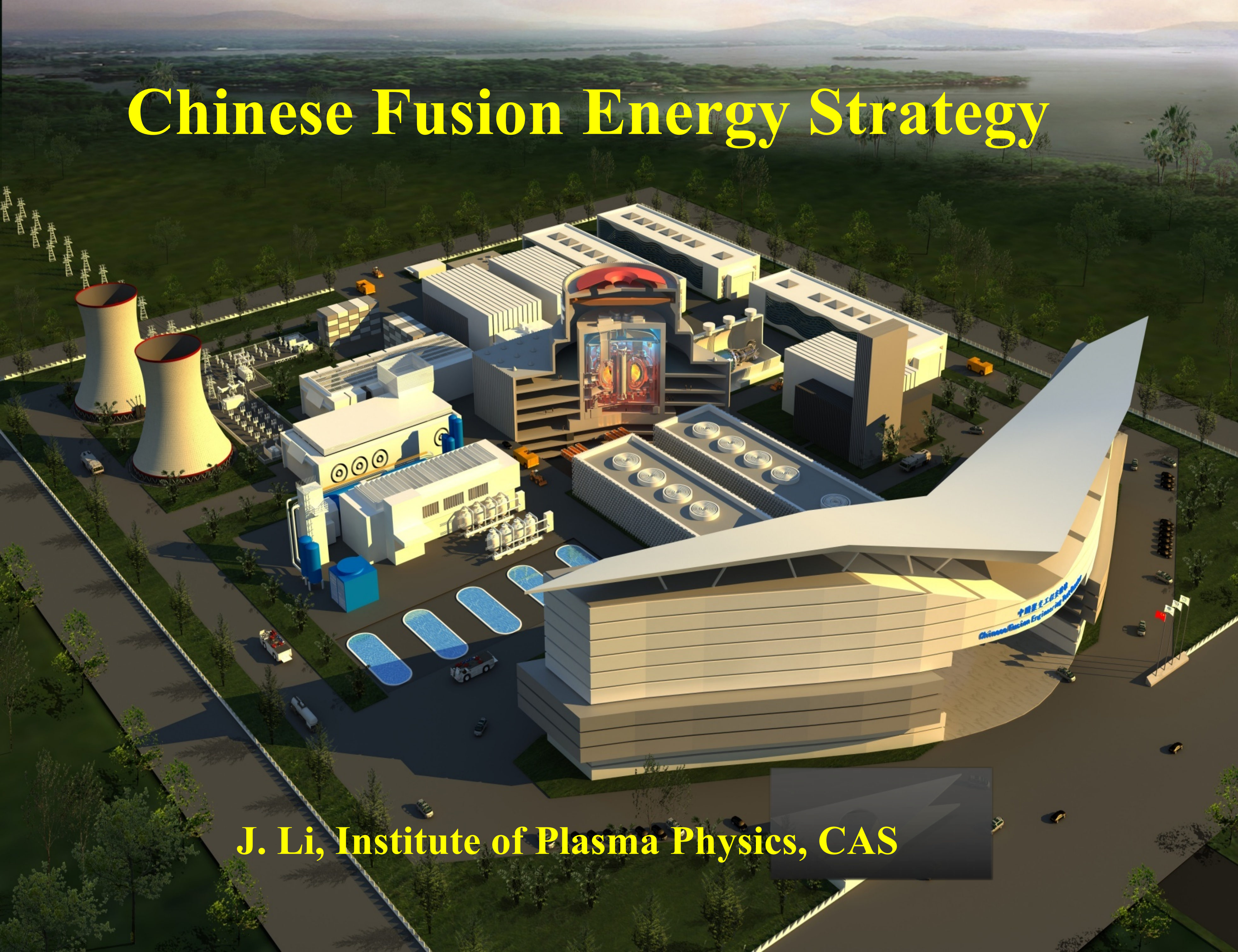
Chinese Fusion Energy Strategy



J. Li, Institute of Plasma Physics, CAS

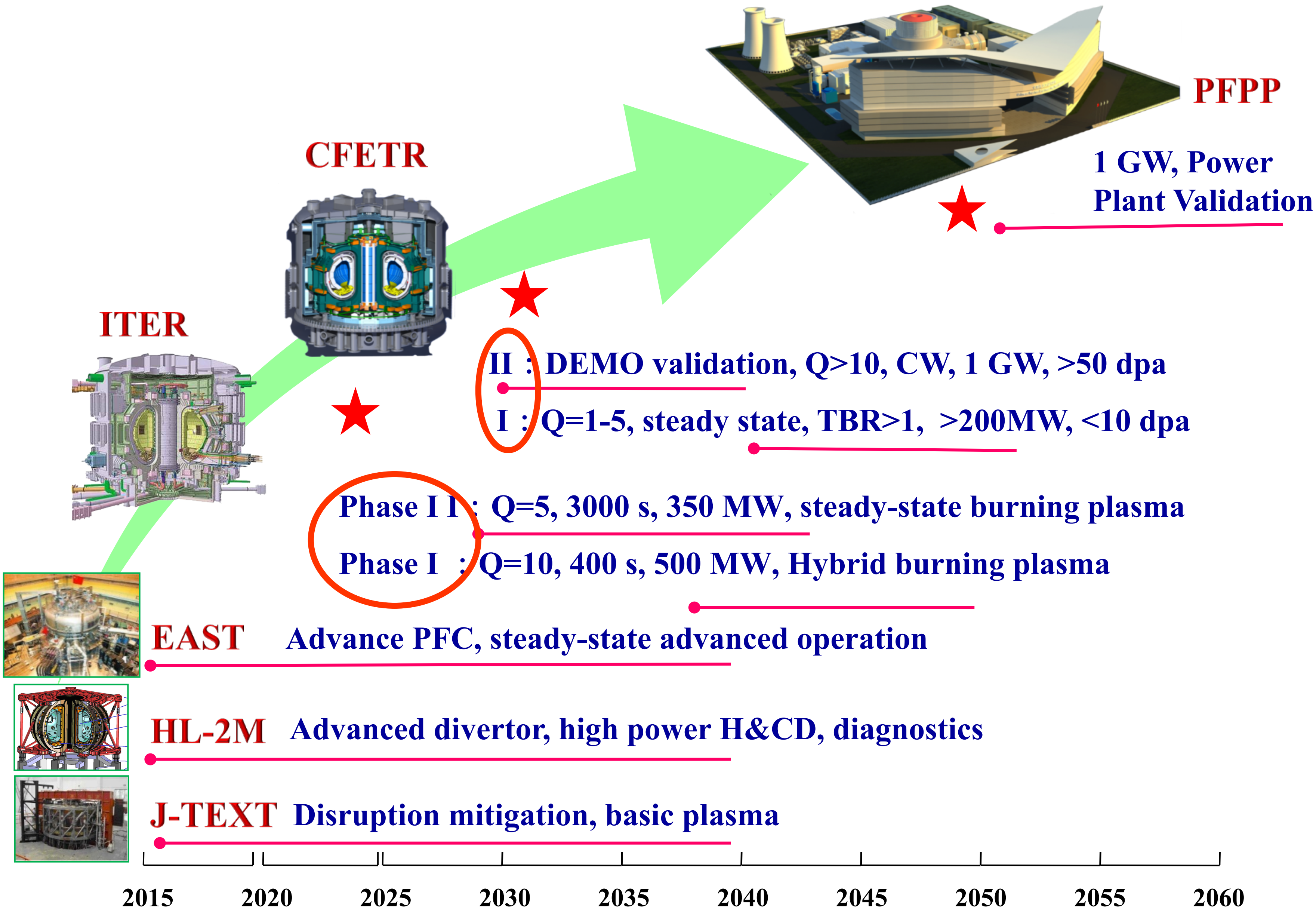
Outline

- **Introduction**
- **Progresses and activities of CFETR**
- **Future Plan**
- **Summary**

Top Priorities of CN-MCF

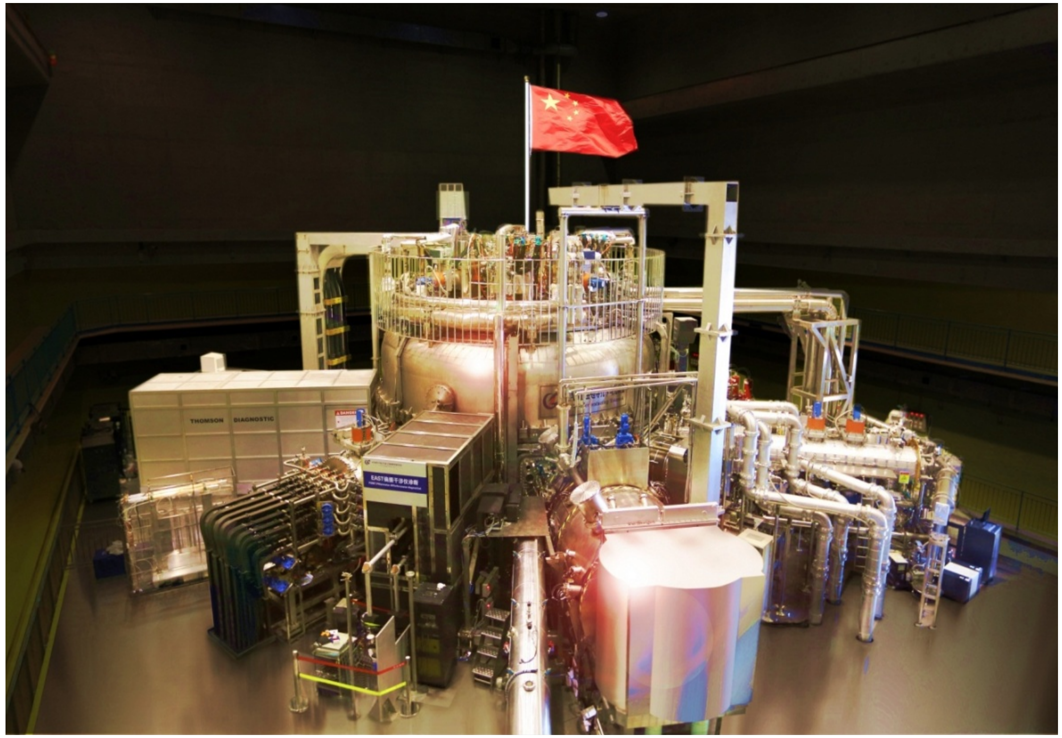
- Make ITER successful
- Promoting Domestic MCF
- Build CFETR when it is ready

CN MCF Roadmap

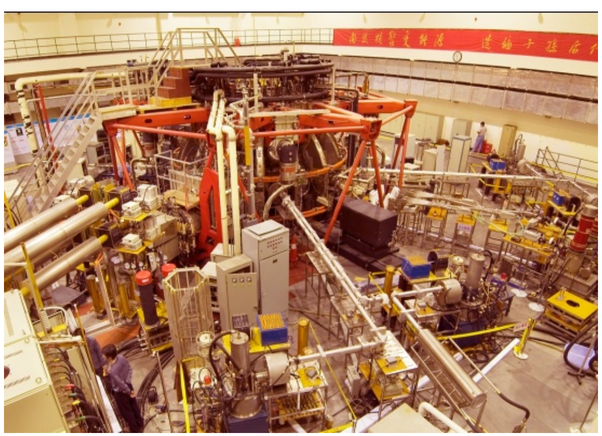


Tokamak Experiments

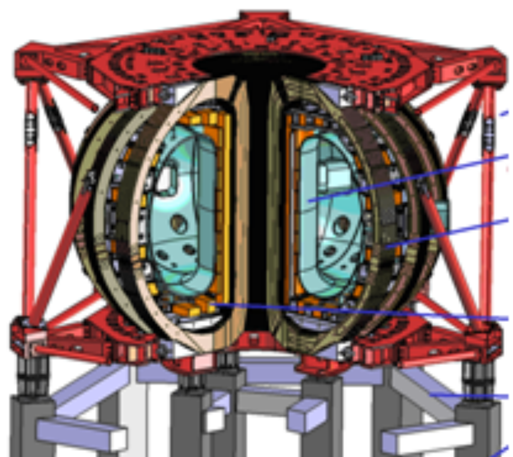
Outcome:
500 SCI papers
5 PRL
50 NF
40 Invite talks
200 PhD
300 Master



EAST
30MW H&CD
80 Diagnostics
W-divertor
10MW/m2
Long pulse
AD SSO



HL-2A 15MW, 50 diagnostics



HL-2M 25MW, 60 diagnostics

J-TEXT, 20 diagnostics

CFETR mission

Obtained Burning Plasma for fusion power

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

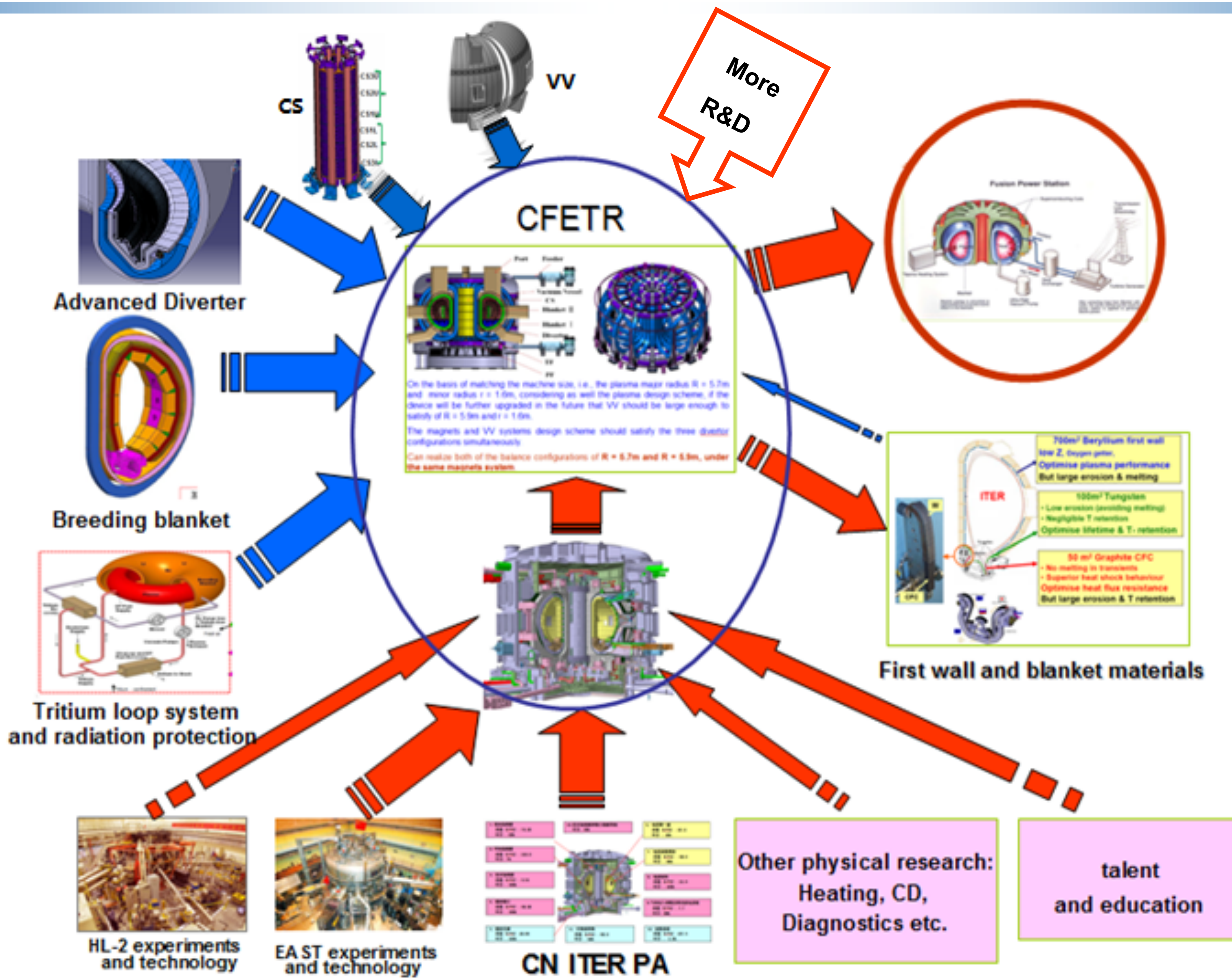
Steady-state operation for fusion energy

5. Hybrid（OH+BS+CD）
6. SSO（ Ext H&CD +Higher f_b）
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

Strategy of CFETR-centralized team



New design version

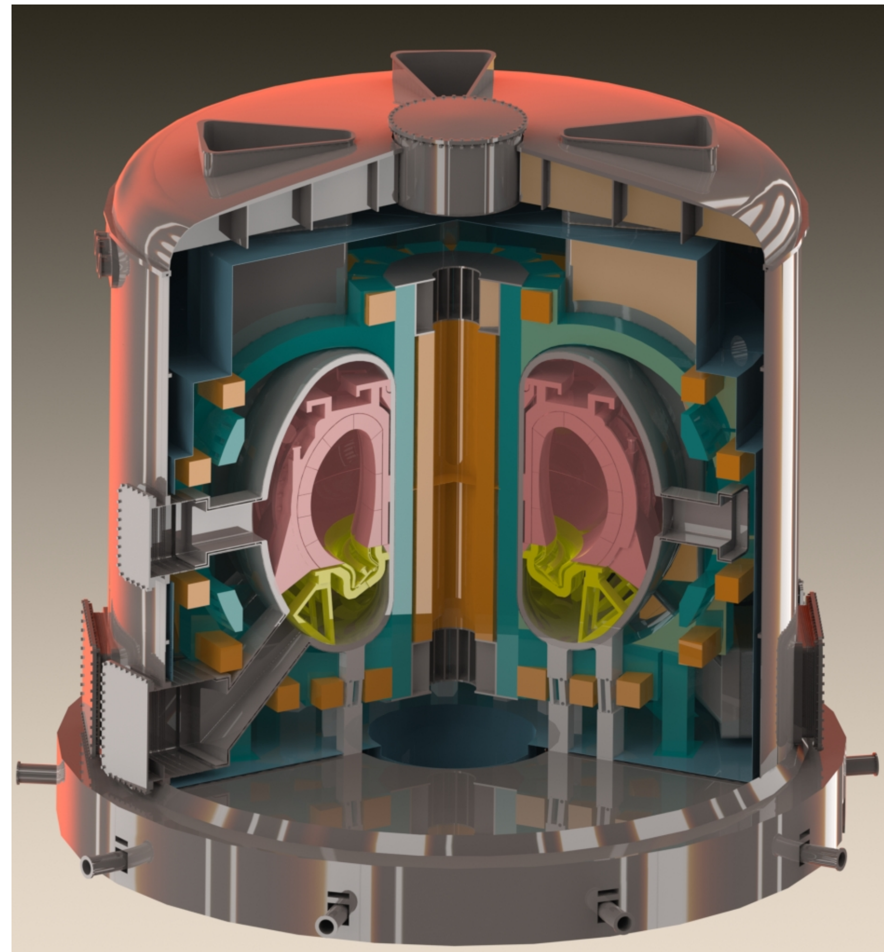
The key points changed:

- **Larger size:**

  R= 7-7.5m(5.7),

  a=2-2.5m(1.6)

- **Higher B_T: 5.0-7.0 T (5)**
- **Advanced CS magnet:≥ 480 VS**
- **Lower Ip: 6-12MA**
- **16 TF coils for easy RH, H&CD**
- **More reliable Plasma targets**
- **Higher confidence for STE goals**



New version of design(7m, 6.5-7T)

CFETR pulse mode		CaseA.1 Hybrid	CaseB.1 L-mode	Case A.2 Hybrid	Case B.2 L-mode	Case A.3 Hybrid	Case B.3 L-mode
plasma elongation	κ	2.00	2.00	2.00	2.00	2.00	2.00
fusion power	Pf	103	99	507	451	1053	932
power to run plant	Pinternal	196	174	193	196	183	104
gain for whole plant	Qplant	0.43	0.44	1.33	1.20	2.70	4.10
Pfusion/Paux	Qplasma	1.36	1.46	7.22	6.28	17.74	31.51
net electric power	Pnetelec	-113	-97	65	38	310	321
Neutron Power at Blanket	Pn/Awall	0.11	0.10	0.54	0.48	1.11	0.99
toroidal beta	BetaT	0.007	0.007	0.013	0.012	0.018	0.017
normalized beta	BetaN	1.05	1.05	1.60	1.50	2.10	1.95
bootstrap fraction	fbs	0.40	0.40	0.50	0.47	0.60	0.55
Ohmic fraction	fohm	0.30	0.40	0.30	0.40	0.30	0.40
current drive power	Pcd	76	68	70	72	59	30
plasma current	Ip	12.90	12.90	12.93	12.93	12.93	12.93
field on axis	Bo	6.00	6.0	6.54	6.54	6.54	6.54
Ion Temperature	Ti(0)	15.00	13.00	19.00	15.00	17.50	17.00
Electron Temperature	Te(0)	15.00	13.00	19.00	15.00	17.50	17.00
Electron Density	n(0)	0.55	0.64	0.97	1.16	1.51	1.46
Ratio to Greenwald Limit	nbar/nGR	0.43	0.50	0.75	0.90	1.17	1.13
Zeff	Zeff	2.45	2.45	2.45	2.45	2.45	2.45
Stored Energy in Plasma	W	189	189	417	394	599	563
H factor over ELMY H_net	HITER98Y2	0.72	0.71	1.09	0.99	1.17	1.22
q95 Iter	q95_iter	5.65	5.65	6.15	6.15	6.15	6.15
H-mode threshold (MW)		70	77	110	124	149	146
Ptransport across separatrix		88	76	136	121	193	146
H98_gross		0.65	0.62	0.87	0.75	0.84	0.82

New version of design(7m, 6.5-7T)

CFETR		Cass A.1 200MSS	Case A.2 500MSS	Case A.3 1GWSS	Case A.4 1.5GWSS	Case A.5 1GW OH
plasma minor radius	a	2.19	2.19	2.19	2.19	2.19
plasma major radius	Ro	7.00	7.00	7.00	7.00	7.00
fusion power	Pf	196	503	1003	1446	1053
gain for whole plant	Qplant	0.67	1.34	2.63	3.99	2.70
Pfusion/Paux	Qplasma	2.84	7.29	17.21	30.31	17.74
Neutron load	Pn/Awall	0.21	0.53	1.06	1.53	1.11
normalized beta	BetaN	1.27	1.69	2.50	3.0	2.10
bootstrap fraction	fbs	0.40	0.50	0.60	0.75	0.60
Ohmic fraction	fohm	0.0	0.0	0.0	0.0	0.30
plasma current	Ip	12.01	12.93	12.93	11.91	12.93
field on axis	Bo	6.0	6.54	6.54	7.05	6.54
Ion Temperature	Ti(0)	26.00	32.00	37.00	34.00	17.50
Electron Density	n(0)	0.47	0.64	0.78	1.02	1.51
Ratio to GW limit	nbar/nGR	0.39	0.50	0.61	0.86	1.17
Zeff	Zeff	2.45	2.45	2.45	2.45	2.45
Stored Energy	W	276	465	657	789	599
Auxiliary Power	Paux	69	69	58	48	59
H factor over H_net	HITER98	1.19	1.47	1.43	1.43	1.17
q95 Iter	q95_iter	6.07	6.15	6.15	7.20	6.15

H/He: 1-2 years
DD: 1-2 years

DT< 100MW：1 years

DT：200MW, 5 years
SSO, T fuel cycle

DT：500MW
SSO, TBR>1, 3 years

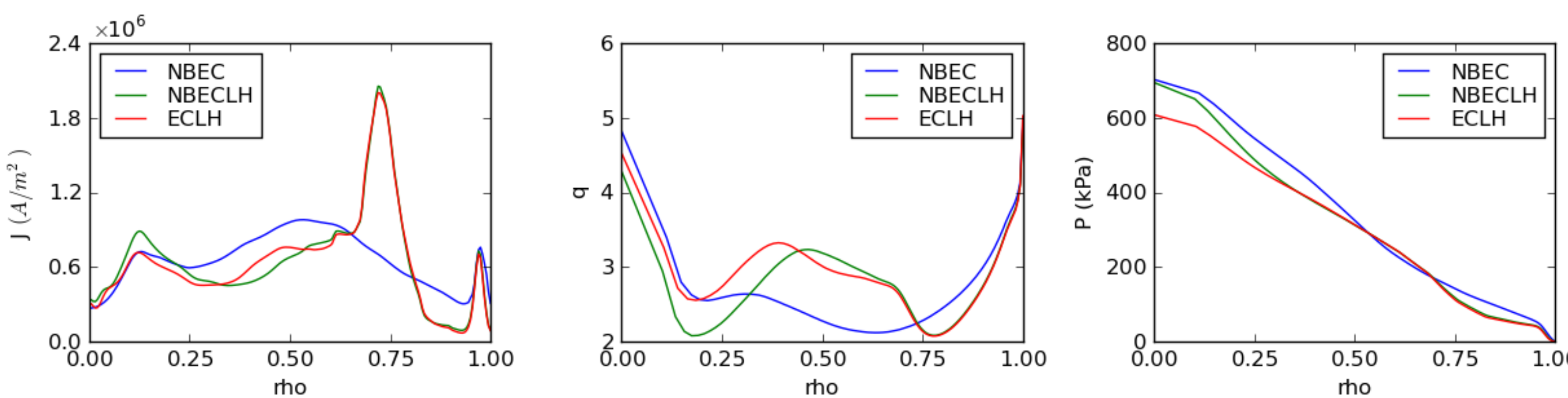
DEMO validation：
DT 1GW，5 years

Advance Scenario：
>1.5GW , Q~30
2-3 years

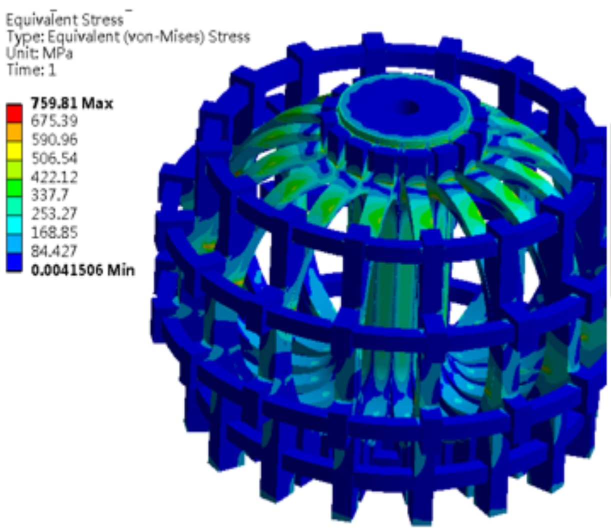
Total: 15-20 years

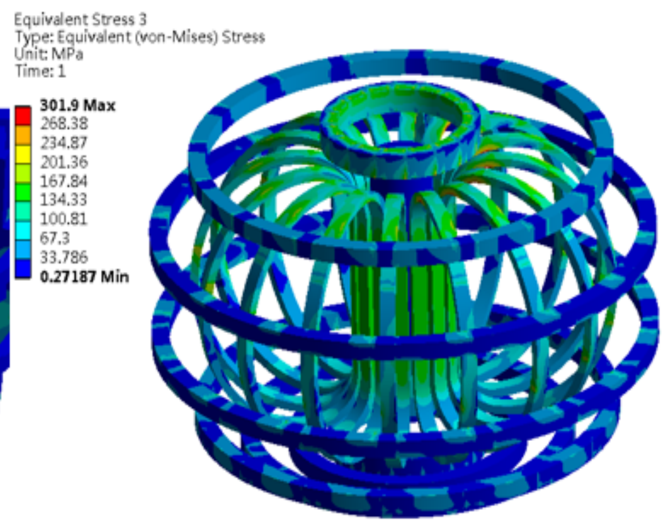
CFETR Physics design (SSO)

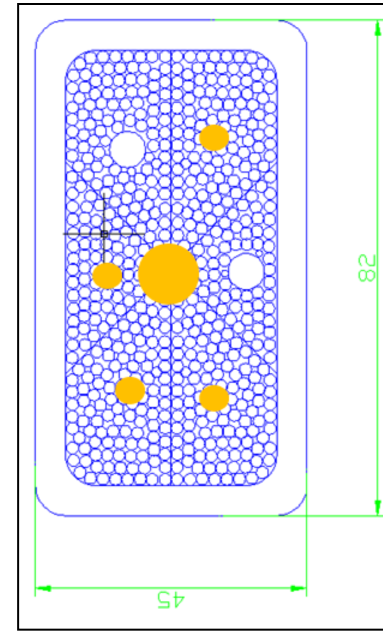
- 0D system code + 1.5D integrated modeling (OMFIT, EFIT, ONETWO, GATO,TGYRO/TGLF, NEO, ELITE)
- Off-aix NBI + ECCD, EC+LHCD are major H&CD tools together with bootstrap current for SSO
- Using 800 kV NBI(1.1MA/10MW) +190GHz ECCD for early phase operation.

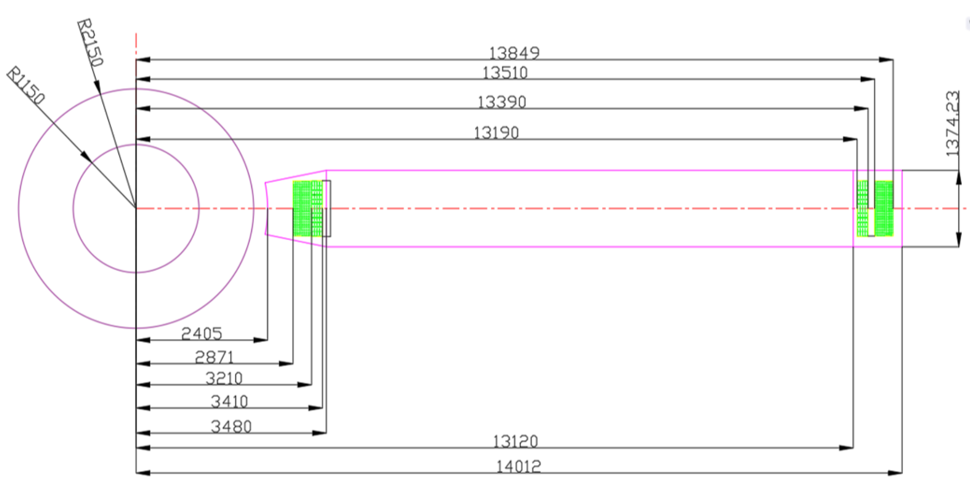


16 TF Coil design (High Performance Nb_3Sn)





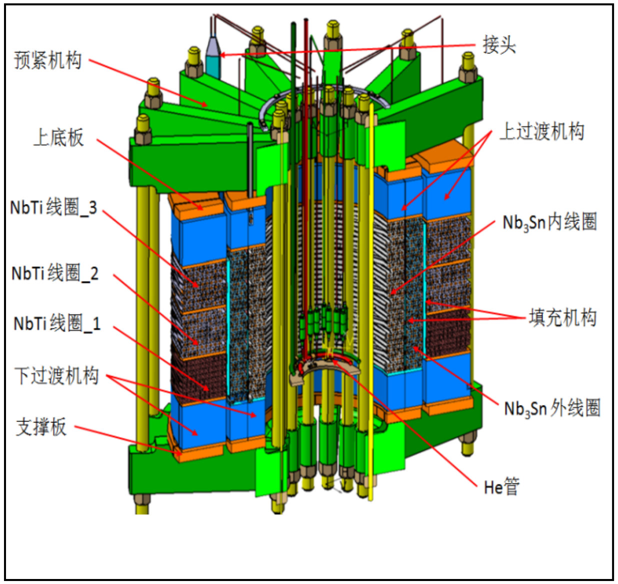




Parameters for TF magnet

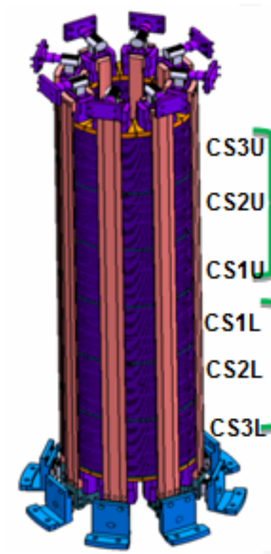
Parameters	Coil 1	Coil 2
strand	high J_c(2700A/mm^2) Nb_3Sn Φ1.0mm strand	
No. of SC strand	1350	270
Turns	66	154
Operating current for B_t=7.0T	58kA	
B_{max} in coil	**15.5T**	11.4T
Max Force	**760MPa**	

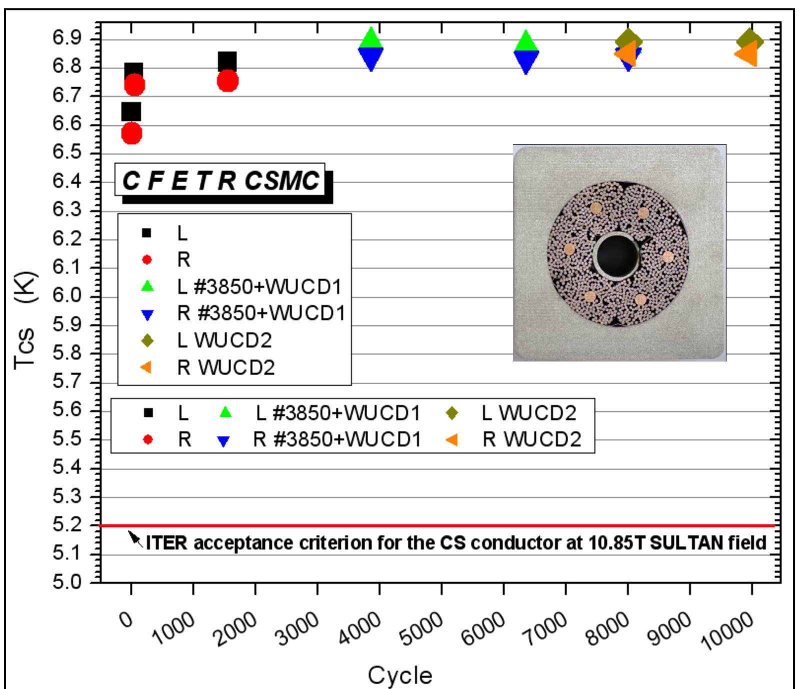
CS Model Coil –Nb_3Sn (baseline)

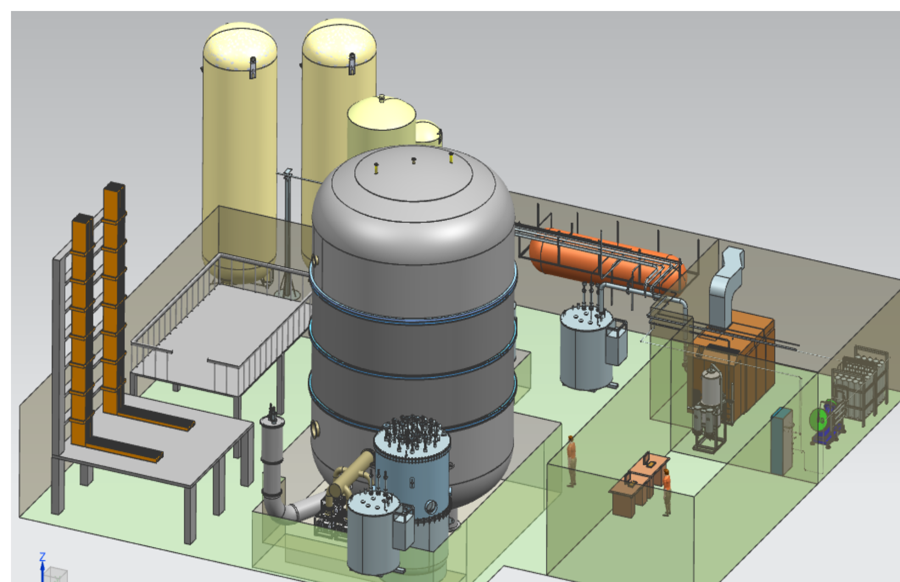


Coil Parameters

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

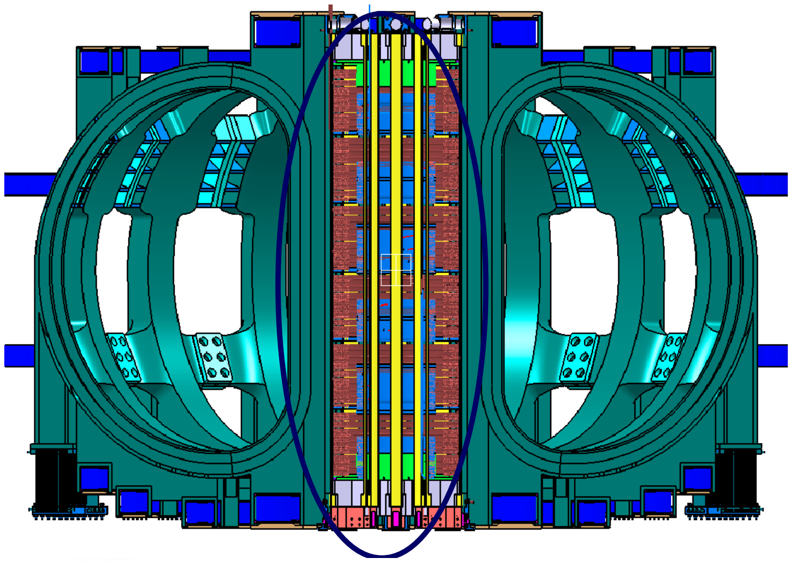


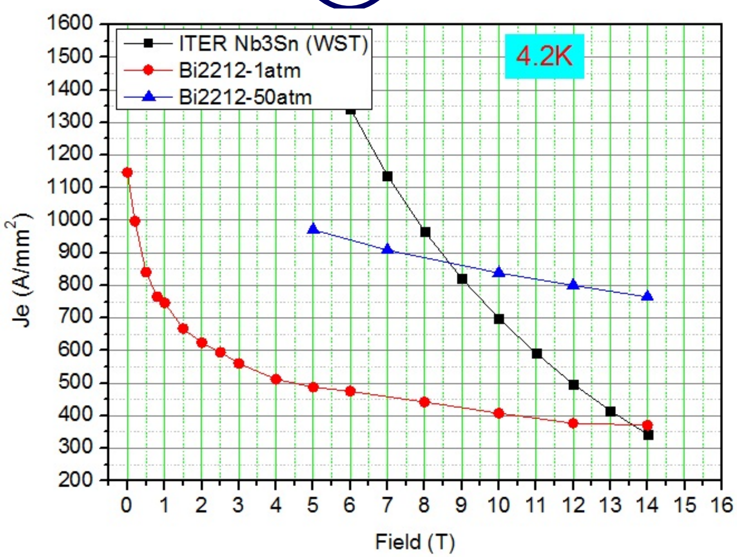




Start experiments @ 2017.12 in new ASIPP site （Huainan)

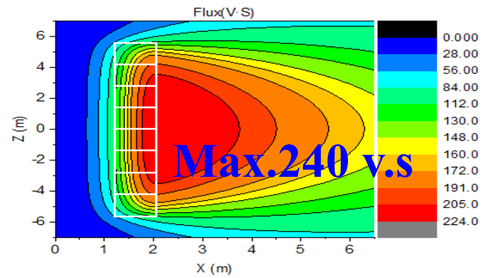
CS Model Coil (1/3 size) – 2212 CICC (Target)

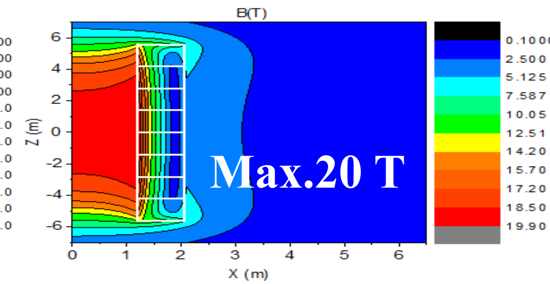




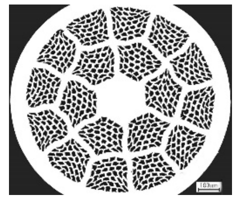
Bi2212-High temperature Superconducting Central solenoid

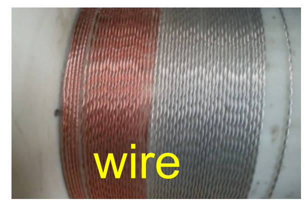
CS coils include eight Bi2212 coils. Each coil consists of 14 double pancake

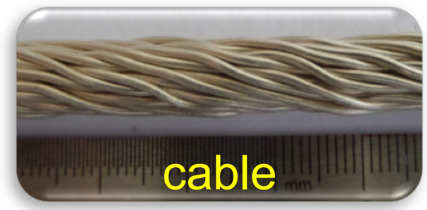




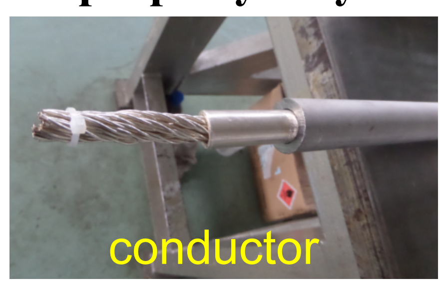
Conservative：enhanced Nb_3Sn: 360VS 4-6h
Ideal：2212CICC，2x480VS，~8h (for Ip=13MA)

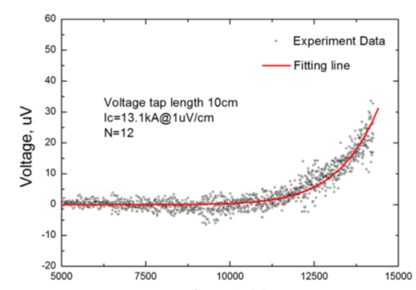






Batch production for 200-m long Φ1.0mm wires
4.2K, 14T: *Jce* > 750A/mm^2，ITER~ 320A/mm^2。
4.2K, 20T: *Jce* > 660A/mm^2，*ITER* ~ 200A/mm^2。
high pressure sintering process is on the way,
***Jc-B* property may be increased for 3 times.**





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

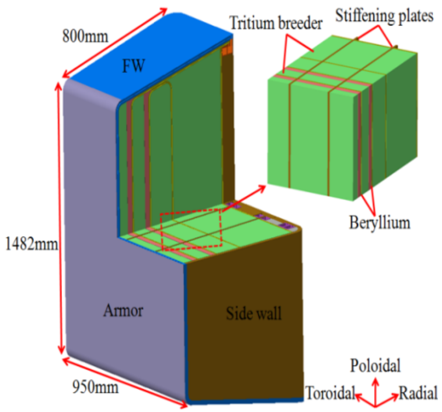
Main features

- **Coolant :** 15.5MPa, 285 °C inlet/325 °C 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.

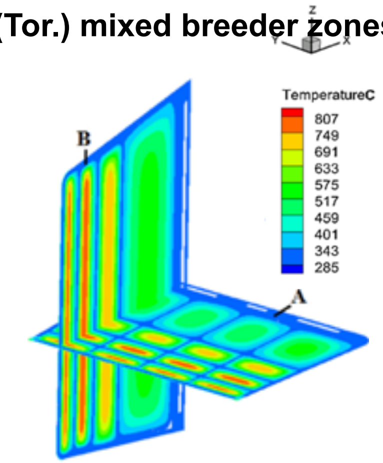
For Phase-I

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

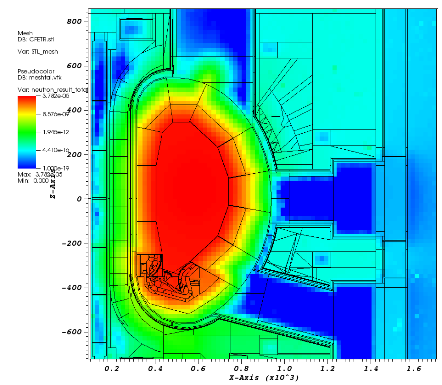
TBR: 1.21



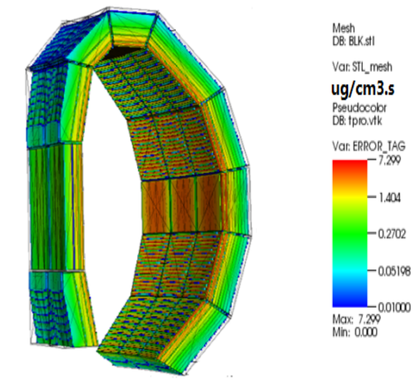
Module structure



Temp. distribution



Neutron flux distribution

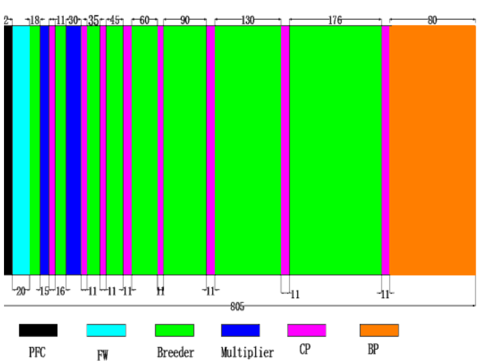


Tritium production rate
(PF0.8, ^{6}Li80% case)

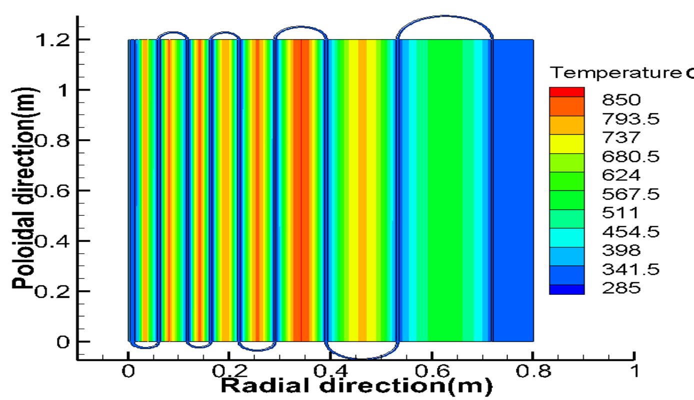
For Phase-II

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}

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

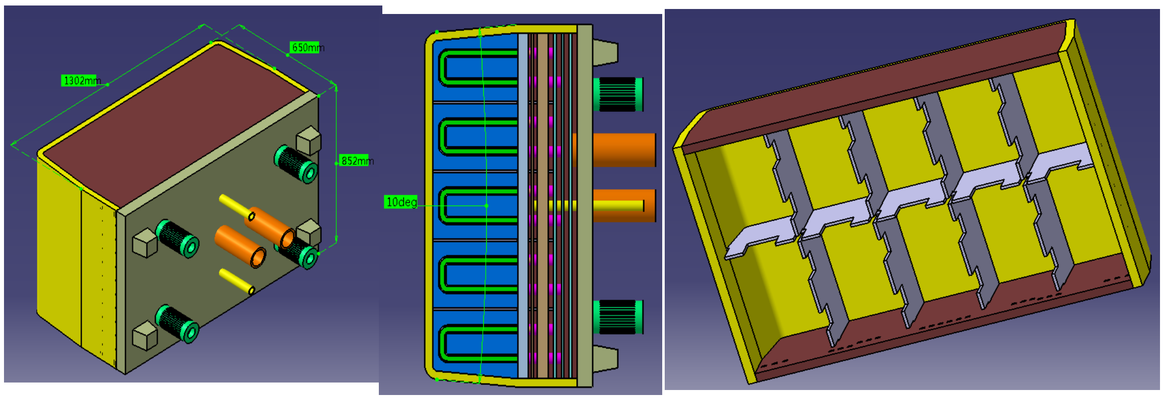
- Modularized breeding unit
- Multi-layer back plates manifold

Coolant : 8 MPa, 300 °C inlet/500 °C outlet

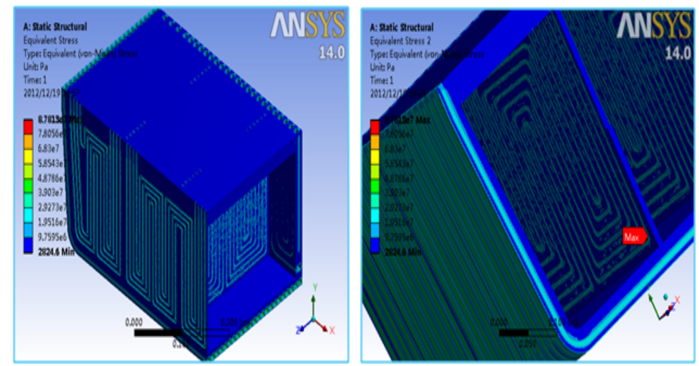
For Phase-I

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

TBR: 1.213



Typical module structure

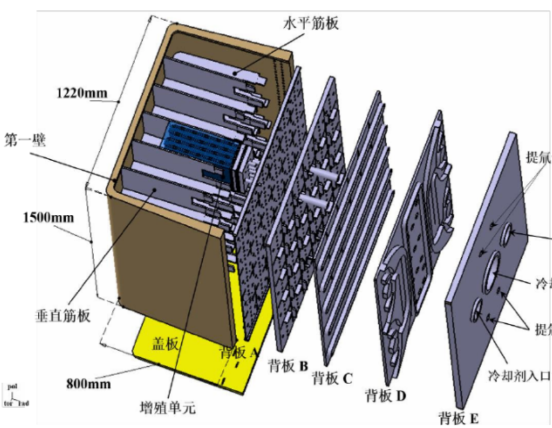


Stress analysis

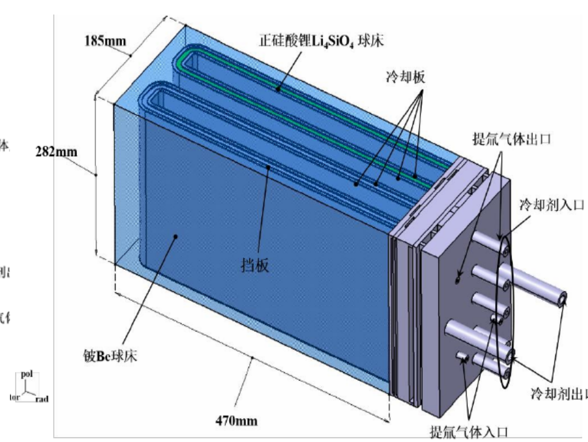
For Phase-II

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

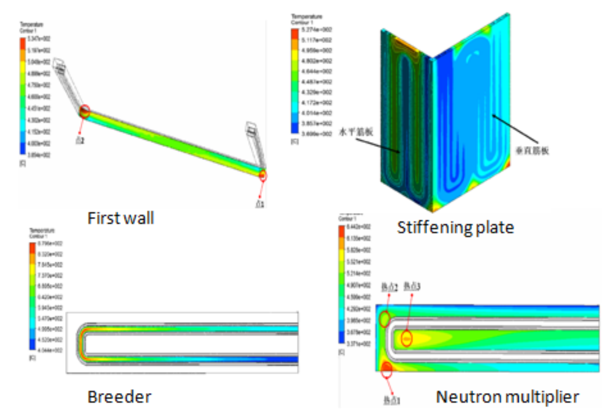
TBR: 1.15



Typical module structure

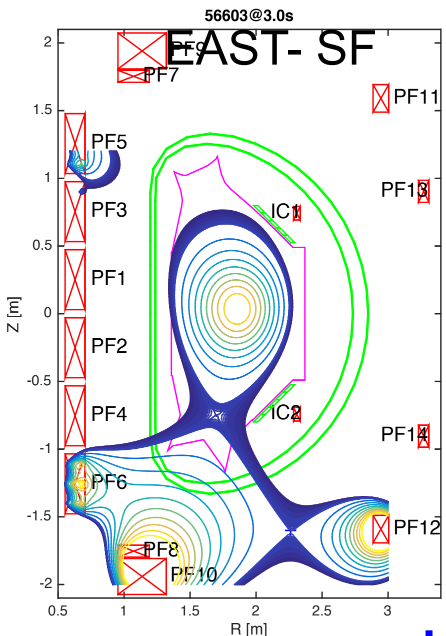


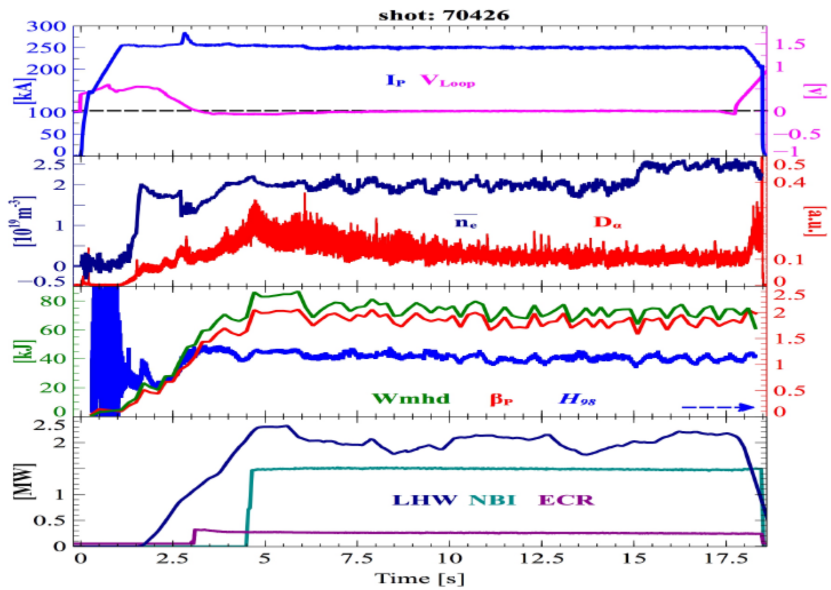
Modularized breeding unit

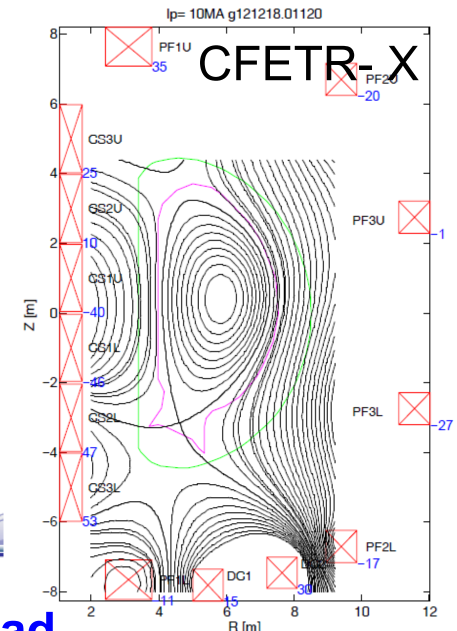


Temp. distribution

New Divertor validation







H_{98}>1.1,n_e/n_{GW}=1.1-1.3,Vp=0, 1/15 heat load

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

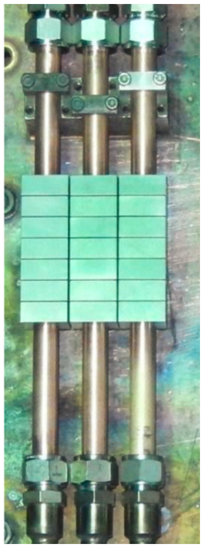
Engineering : design & manufacture of key components

W mono-block: >20MW/m²

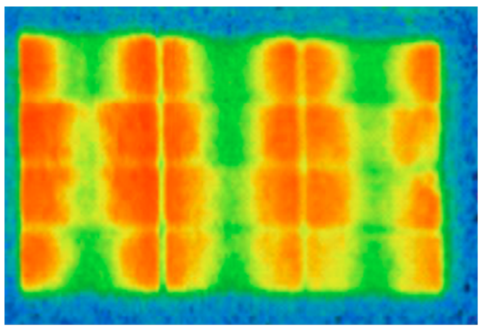
W-Cu mono-block : > 20MW/m² (5-10y)

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

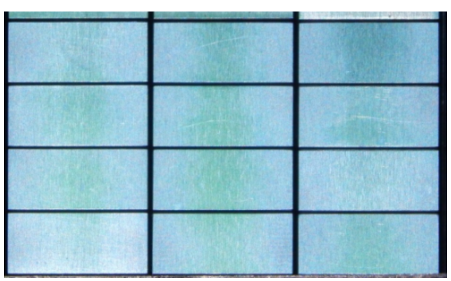
R&D for Divertor Target

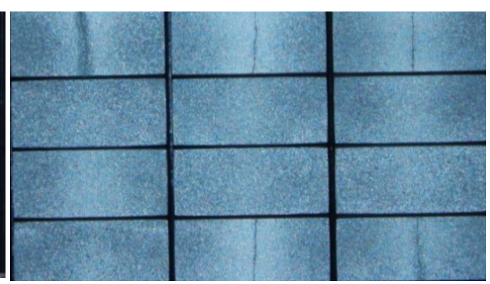


Monoblock W/Cu
5000 cycles at 10MW/m²
300 cycles at 20MW/m².



Flat tile W/Cu

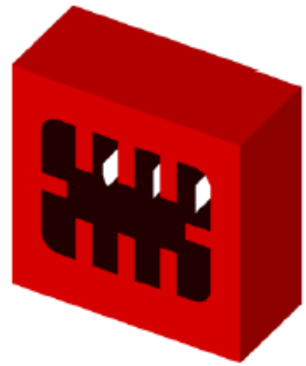


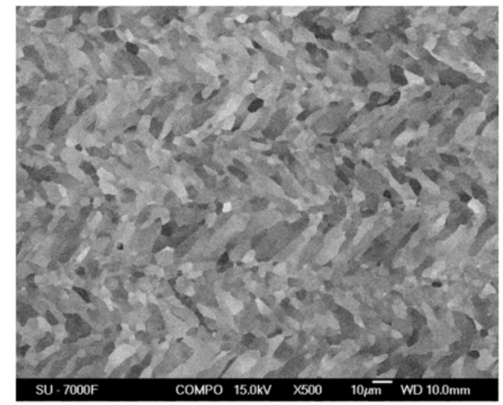


5000 cycles at 10MW/m²

1000 cycles at 20MW/m²

Efforts for 30MW/m²

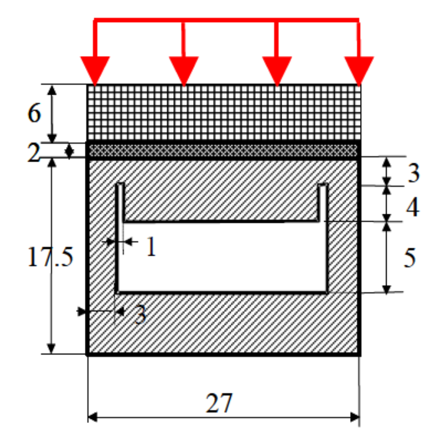




3D printing full W block: Tw=1700C

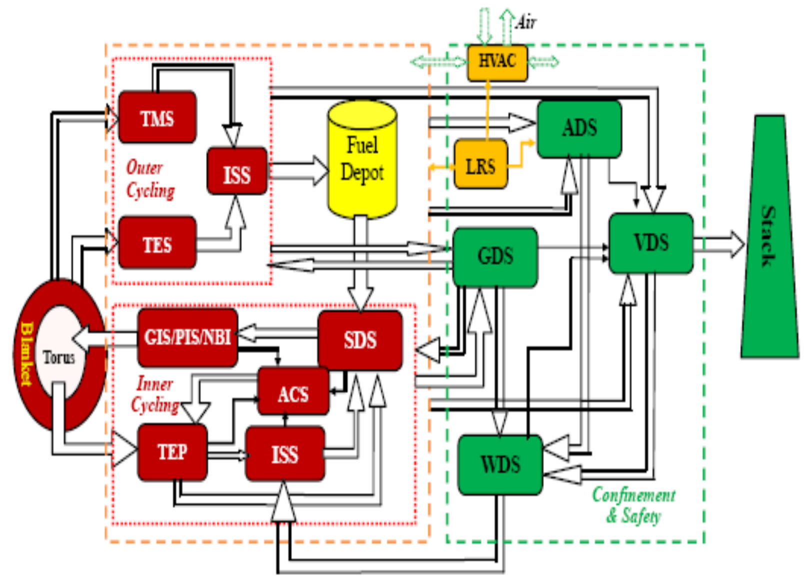
Flat tile

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

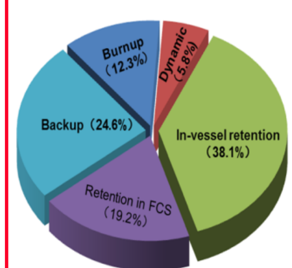


Tritium cycling systems (T-plant)

- 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



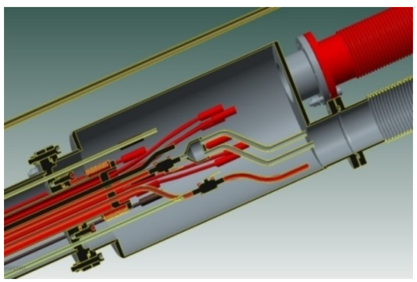
The makeup of startup tritium for CFETR.

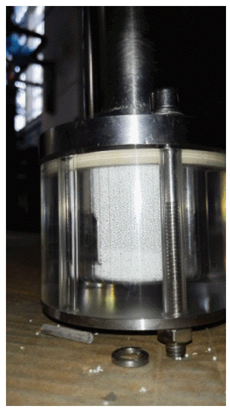
Burnup (g)	Dynamic (g)	In-vessel retention (g)	Retention in FCS (g)	Backup (g)	Total (g)
226	107	661	353	452	1799

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

In-Pile Tritium Release and Extraction Test

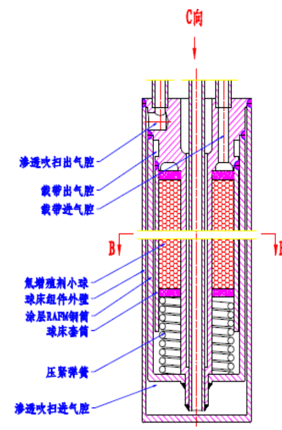
Maximum load 500 g
Tritium production1 Ci/day
Online refueling, irradiation
Irradiation temperature 300-750 ℃
Neutron flux ~5×10^{13}n $cm^{-2}s^{-1}$

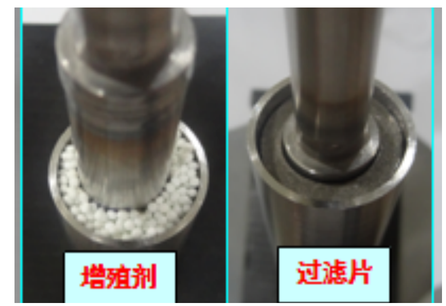


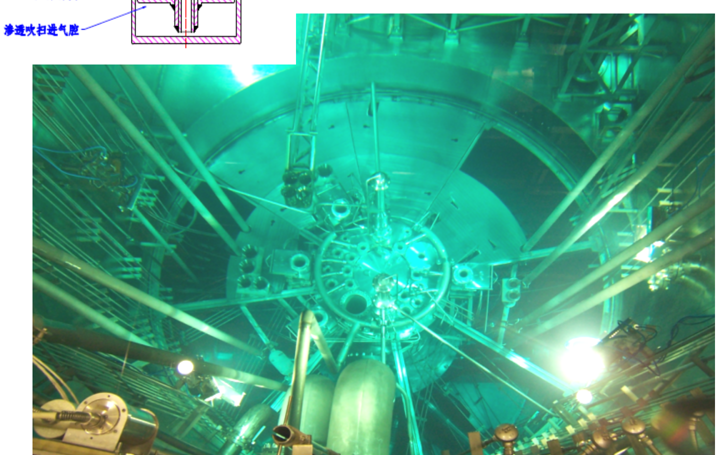


China Mianyang Research Reactor

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



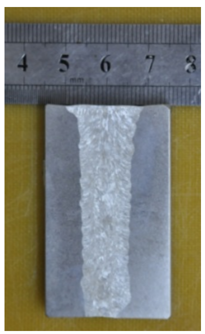




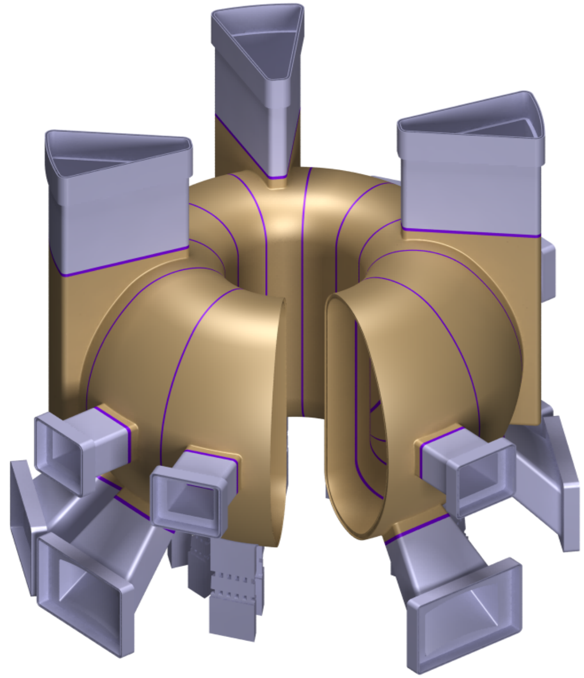
China Advanced Research Reactor

R&D on VV 1/8 mock-up

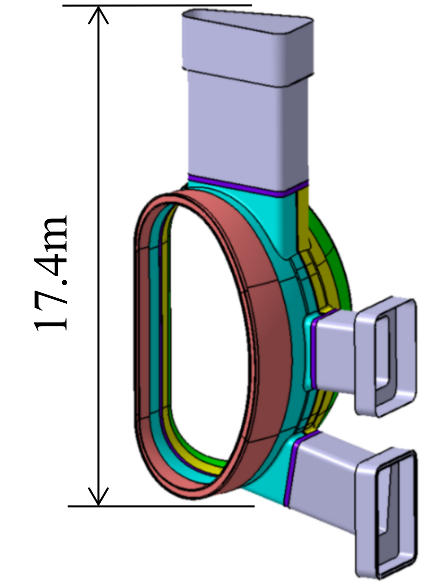
NG-TIG system



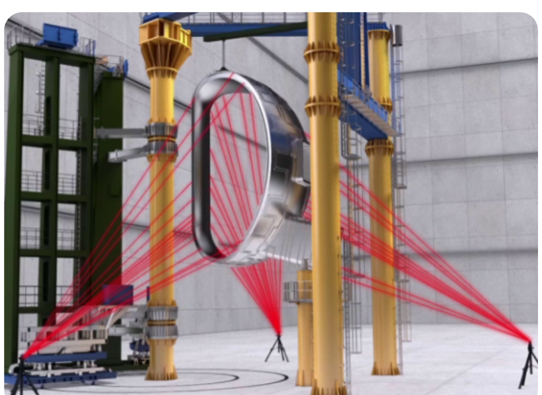
Welding samples



Overview of CFETR VV Design

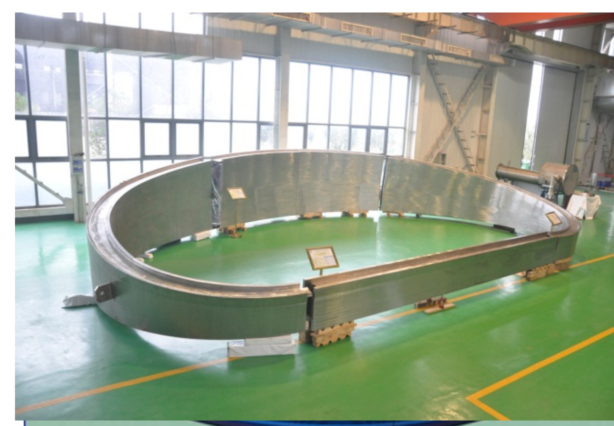


Test bench for installation , replacement of VV components by RH



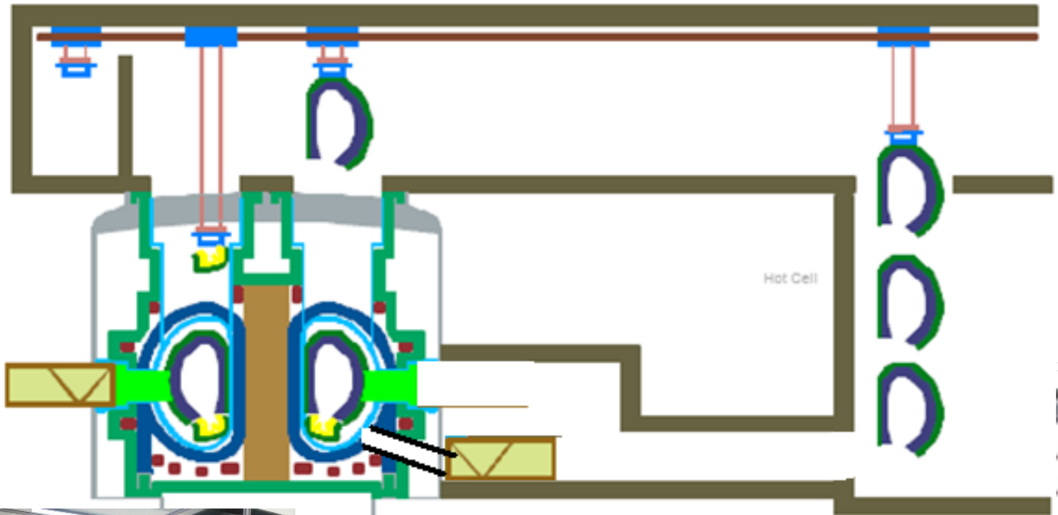
Laser Tracker Measurement on VV Sector

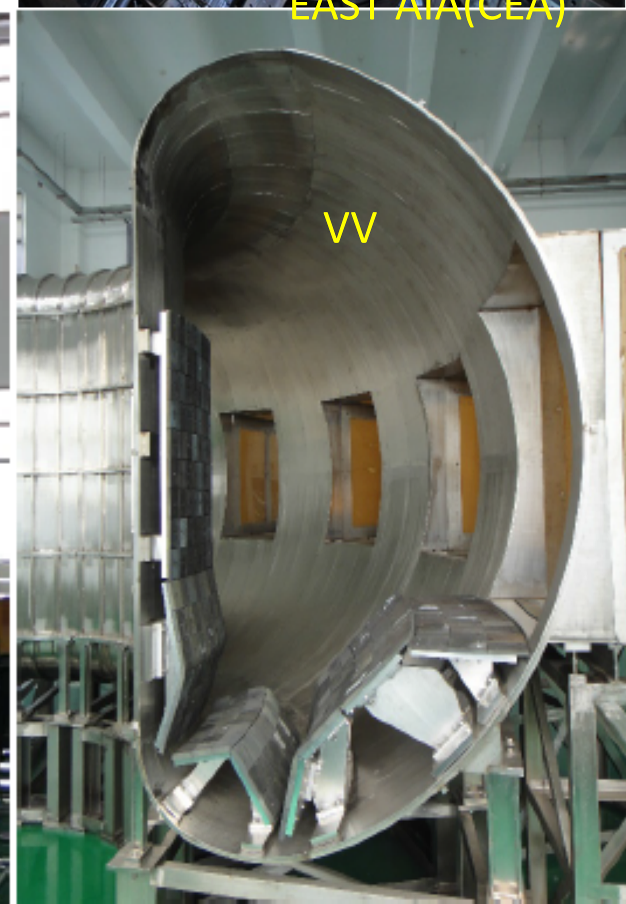
R&D of Narrow Gap TIG Welding on VV



Assembly of VV Poloidal Sectors

RH—Starts from design





Roadmap of materials

	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

Materials Research Activities

(Simulation, manufacture, validation)

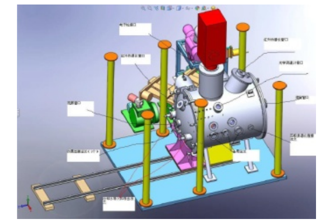
Low Activation Martesitic steel

- Nominal compositions: 9Cr1.5W0.2V0.15Ta0.45Mn0.1C
- 5 ton smelting with good control of main compositions

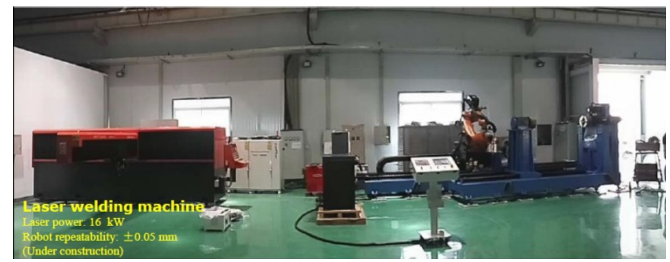
Irradiation properties and TBM Fabrication

- 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



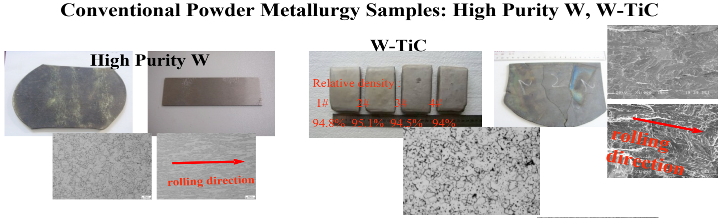
15kW laser welding (0.05mm)

Plasma-facing materials: W

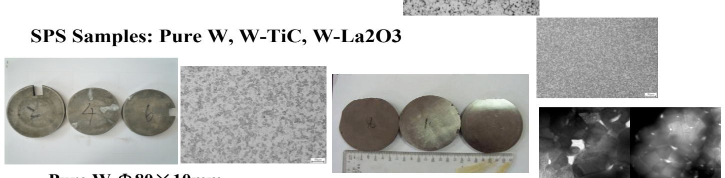
W material study scope: W alloy; W coating; W/Cu component

High heat-flux test facility

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



SPS Samples: Pure W, W-TiC, W-La2O3

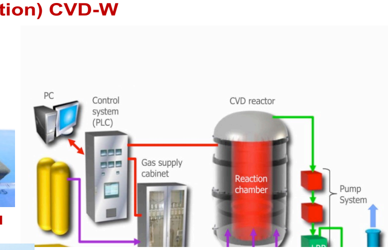


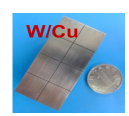
Pure W Φ80×10mm

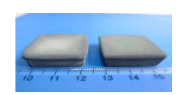
W-TiC Φ80×10mm

(Chemical vapor deposition) CVD-W

Deposition rate: 0.2-1mm/h

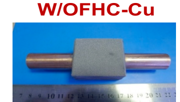


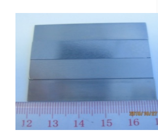




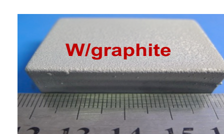
W/FGM-W/Cu

W/OFHC-Cu





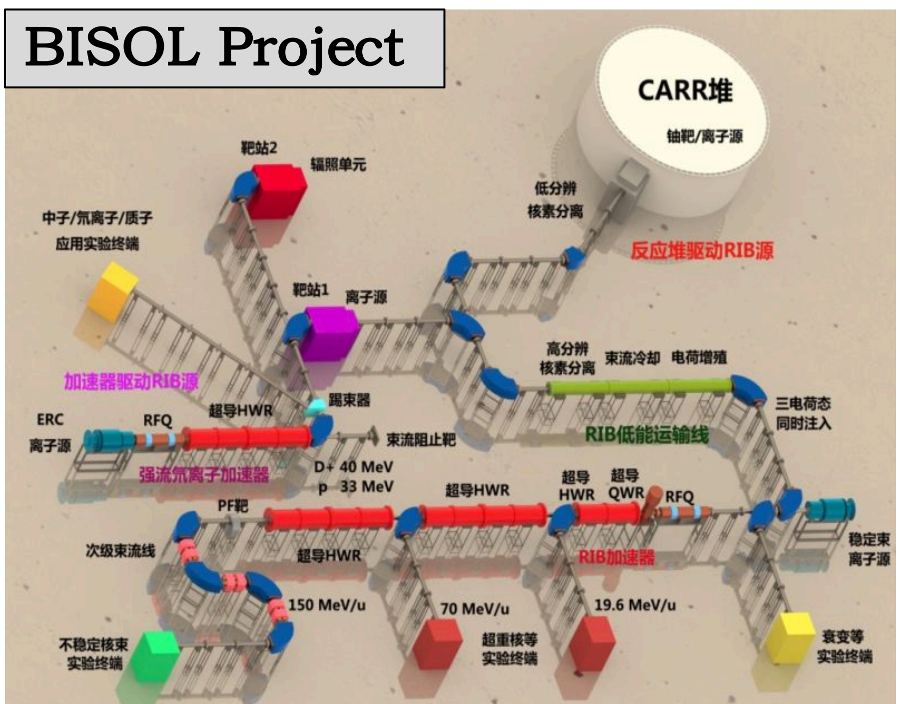
W/RAFM Steel



Material testing neutron sources

The Materials Irradiation Facility in China(CMIF)	
Target	High Neutron Flux Low Neutron Yield Small Sample Size ~1MW granular Be/C Target
Beam	50~100MeV@(5~30)mA (CW)
Cost	Low

	energy（MeV）	20	50
I	Flux (D+Be) Y ($n \cdot cm^{-2} \cdot mA^{-1} \cdot s^{-1}$)	$3.6*10^{13}$ *5 mA	$2*10^{14}$ *10 mA
II	Flux (D+Be) Y ($n \cdot cm^{-2} \cdot mA^{-1} \cdot s^{-1}$)	$9.81*10^{14}$ *20mA	$2*10^{15}$ *30 mA



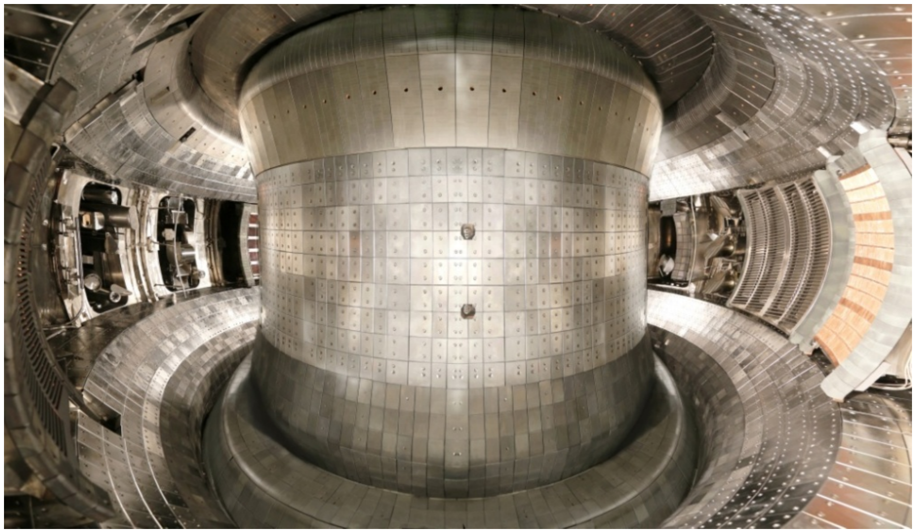
Hefei DT 14Mev: $1\text{-}5X10^{12}$ now

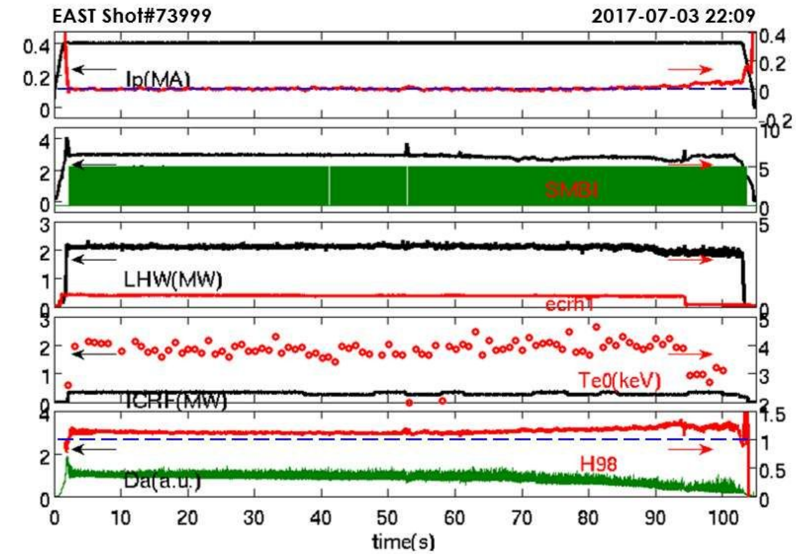
CMIF 6-20MeV: $2X10^{14}\text{-}2X10^{15}$

2020

BISOL 5-20MeV: $1\text{-}2X10^{15}$ 2025

Experiments validation(EAST+DIII-D)





Ip=0.4MA, <ne>~3.0X10^{19}/m^3 ,P_{RF}~3.0MW, H_{98y2}~1.1,USN,Te(0)~4.0keV

Bottom Divertor: CFETR – like, 20MW/m2, AD configuration

4MW CW 170GHz EC, new ICRF, HFLHCD(7.5GHz)

1、Q=1,100MW, L-mode , hybrid or Steady state

2、Q=3, 200MW, H (betaN =1.9,H=1.2, fbs50%), hybrid or SSO

3、Q=10,500MW, H (betaN =3, H=1.2, fbs60%), hybrid or SSO

4、Q=20, 1500MW, H (betaN =3,H=1.5, fbs80%), hybrid or SSO

CFETR 5 years Plan– Detail design + Large scale R&D

CFETR Detail Engineering design starts (30M$)

1. Physics design (14 tasks)

2. Nuclear design (16 tasks)

3. Tokamak detail engineering design (64 tasks)

4. Aux. Detail functional design (18 tasks)

5. Database IDM (6 tasks)

Fully Open to international cooperators

T-Plant + Plasma exhaust + breeding Blanket

CFETR 5 years Plan--Large scale R&D

Blanket:

small size mockup(14MeV),

thermal hydraulic Testing Full size, water & He gas configurations

Magnets:

full size CICC Nb_3Sn(TF), Nb_3Al (PF), Bi 2212 Conductor (CS)

CS mockup coil, 1/6Nb_3Sn, 1 : 1 prototype Nb_3Sn TF, small 2212 CS

Gyrotron:

10s 1MW , 140GHz, 170GHz,

design 230GHz

CFETR 5 years Plan--Large scale R&D

NNBI: -200keV, 3600s,

ECRH: full size 4MW,

ICRF: 2MW, full size

LHCD: 4.6GHz, 2MW, High field PAM

RH: Vertical + MPD

Assembling testing facility: installation and RH

Larger SC testing facility (CICC conductor, CS, proto type TF)

Experimental verification(8): EAST

SS L mode, SS H-mode, Hybrid long pulse… with diagnosis, control, divertor, up to 1000s 10keV

Education—Training next generation tenants

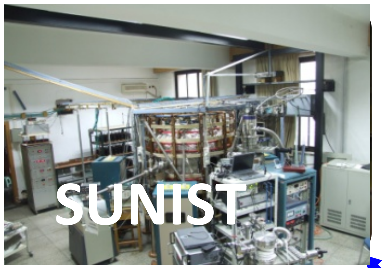
10 scientists + 10 engineers/year, 0.5M$/person 4 years

- **Encourage to join EAST, HL-2A experiments**
- **Encourage to join Th&Simulation**
- **Encourage to join CFETR**
- **Basic plasma science**
- **Fusion engineering and technology**

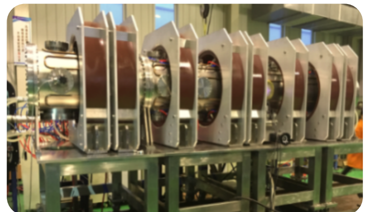
More than 30 top universities

Education—Training next generation tenants

清华SUNIST



等离子体所HPPX

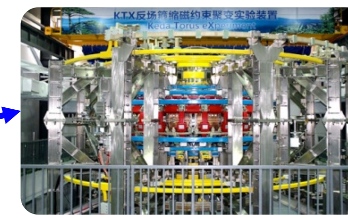


哈工大FLARE

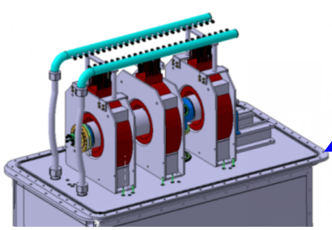
大学Helimak

等离子体所HT-7

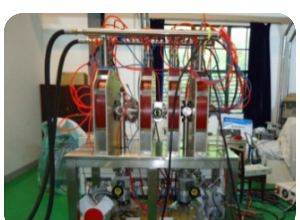
中国科大KTX



中国科大LMP

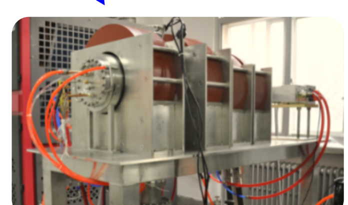


工物院氚渗透装置



北航STEP

浙大直线等离子体装置



兰州化物所LEPS

中国科大KMAX

International cooperation

- **More than 30 years cooperation with USA**

7 US-CN workshop, T&sim., Exp., Engineering, CFETR

- **20 years cooperation with EU**

Joint workshop, exp., Engineering, joint lab.

- **20 years cooperation with Japan**

CUP(10+5 years), A3, CN-JP-KO DAs, >1000papers

- **10 years cooperation with KO**

A3, CN-KO DAs, , CN-JP-KO Das

- **Good cooperation with RF, IN**

Summary

- CN-MCF development has made significant progresses during the past decade.
- EAST will play a key role for advanced steady-state operation during next decade.
- CN makes our best efforts for ITER success.
- CFTER engineering design starts and large scale R&D will start before the end of this years.
- It is hoped that the proposal for CFETR construction can be approved by government within next 5 years .

Thanks!