The Magnetic Fusion Program in China ——Roadmap and Progress

Presented by Yuanxi Wan[1, 2]

[1] University of Science and Technology of China, Hefei, China
[2] Institute of Plasma Physics, CAS, Hefei, China
E-mail: wanyx@ipp.ac.cn or wanyx@ustc.edu.cn

December 16-17, 2014

35 th FPA , Washington USA

Content

- Road Map of MFE in China
- Strategy and Progress
- Summary

Roadmap of MFE development in China

Background

- China is facing serious energy problem now and future
- Burning plasma has been achieved on JET,TFTR, (JT-60)
- Some progress of MF research has been achieved

  before China join ITER project
- Government made big decision to join ITER project
- Significant progress of MF research has been achieved

  since China join ITER project

- A national integration design group for CFETR was founded by MOST at 2011
- The progress on the conceptual design and some R&D of CFETR has been achieved
- **A special group for drafting the MF roadmap in China has been organized by MOST few months ago**
- According to the roadmap it is hoped the proposal for CFETR construction can be approved soon

The Road Map

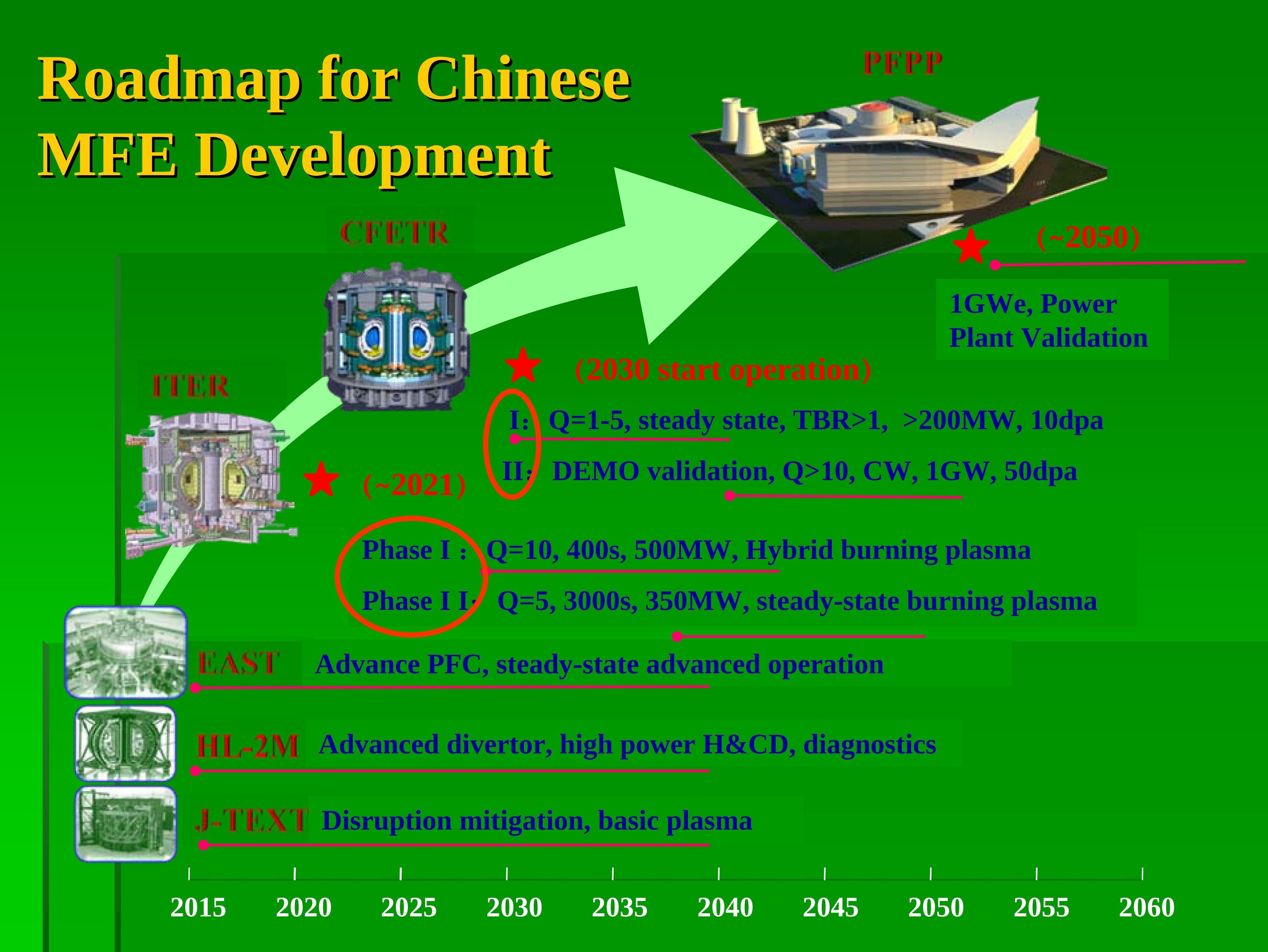
of MFE development in China

(the first draft)

by the roadmap draft group

Milestones of the Roadmap

1. 2006-2045: Join and fully support the construction, operation and experiments of ITER; enhance the support for pe-xperiments on EAST, HL-2M and J-TEXT;
2. 2020: Start to construct the Chinese Fusion Engineering Testing Reactor (CFETR) .
3. 2030: Complete the construction of CFETR (P_f ~200MW and test of SSO and tritium self-sustained)
4. 2040: Complete the upgrade of CFETR (P_f ~1 GW, Q_{eng} > 1).
5. 2050-2060: Complete the construction of Prototype Fusion Power Plant (PFPP) (~1GWe, Power Plant Validation)


Roadmap for Chinese MFE Development
PFPP
(~2050)
1GWe, Power Plant Validation
CFETR
(2030 start operation)
I: Q=1-5, steady state, TBR>1, >200MW, 10dpa
II: DEMO validation, Q>10, CW, 1GW, 50dpa
ITER
(~2021)
Phase I : Q=10, 400s, 500MW, Hybrid burning plasma
Phase I I: Q=5, 3000s, 350MW, steady-state burning plasma
EAST
Advance PFC, steady-state advanced operation
HL-2M
Advanced divertor, high power H&CD, diagnostics
J-TEXT
Disruption mitigation, basic plasma
2015
2020
2025
2030
2035
2040
2045
2050
2055
2060

Technical Route adopted by the Roadmap

- By superconducting-tokamak and bootstrap current plus the external CD to achieve the SS burning plasma operation
- By the efficient breeding blanket and advanced tritium factory technology to achieve the Tritium self-sustained.

The main challenges

1. To achieve and sustain the high performance burning plasma to be SSO or long pulse with high duty cycle time in fusion reactor;
2. Tritium should be self–sustainable by blanket and high efficient T- plant;
3. The materials of first wall and blanket should have suitable live time under the high heat load and flux fusion neutron irradiation ;
4. High Efficient electricity generation on fusion reactor (Q_{eng} > 1)
5. Reliability, RH, Nuclear Safety and Environmental Impact (License);
6. Overall Integrated design of fusion reactor.

Content

- Road Map of MFE in China
- Strategy and Current Progress
- Summary

Strategy for MFE development in China

- Fully support ITER project to be success
- Enhance the support on domestic research which is related with the missions of the roadmap;
- fully support the further design and R&D of CFETR to insure the roadmap can be realization

Progress of the experiments on

EAST, HL-2A and J-TEXT

Roadmap for Chinese MFE Development

PFPP

★ (~2050)

1GWe, Power Plant Validation

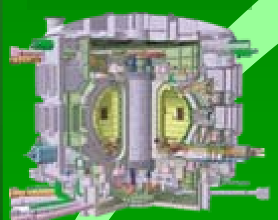
CFETR

★ (2030 start operation)

I: Q=1-5, steady state, TBR>1, >200MW, 10dpa

II: DEMO validation, Q>10, CW, 1GW, 50dpa

ITER



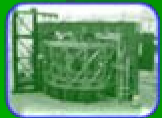
★ (~2021)

Phase I : Q=10, 400s, 500MW, Hybrid burning plasma

Phase I I: Q=5, 3000s, 350MW, steady-state burning plasma

EAST Advance PFC, steady-state advanced operation

HL-2M Advanced divertor, high power H&CD, diagnostics



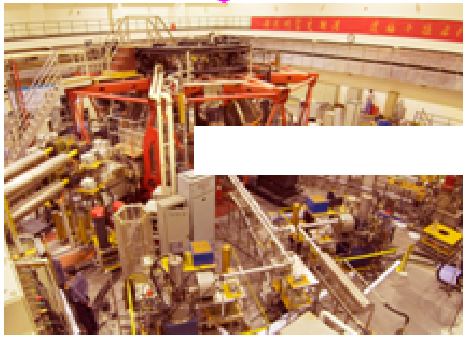
J-TEXT Disruption mitigation, basic plasma

2015 2020 2025 2030 2035 2040 2045 2050 2055 2060

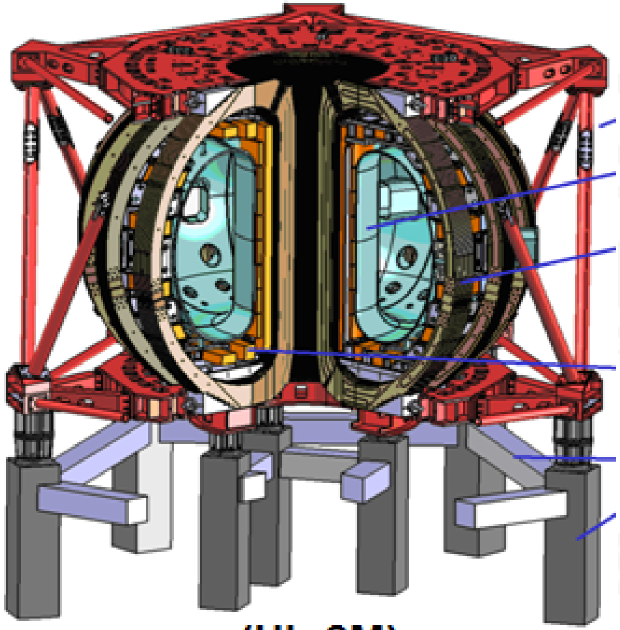
HL-2A is upgrading to HL-2M

in SWIP

(HL-1M)



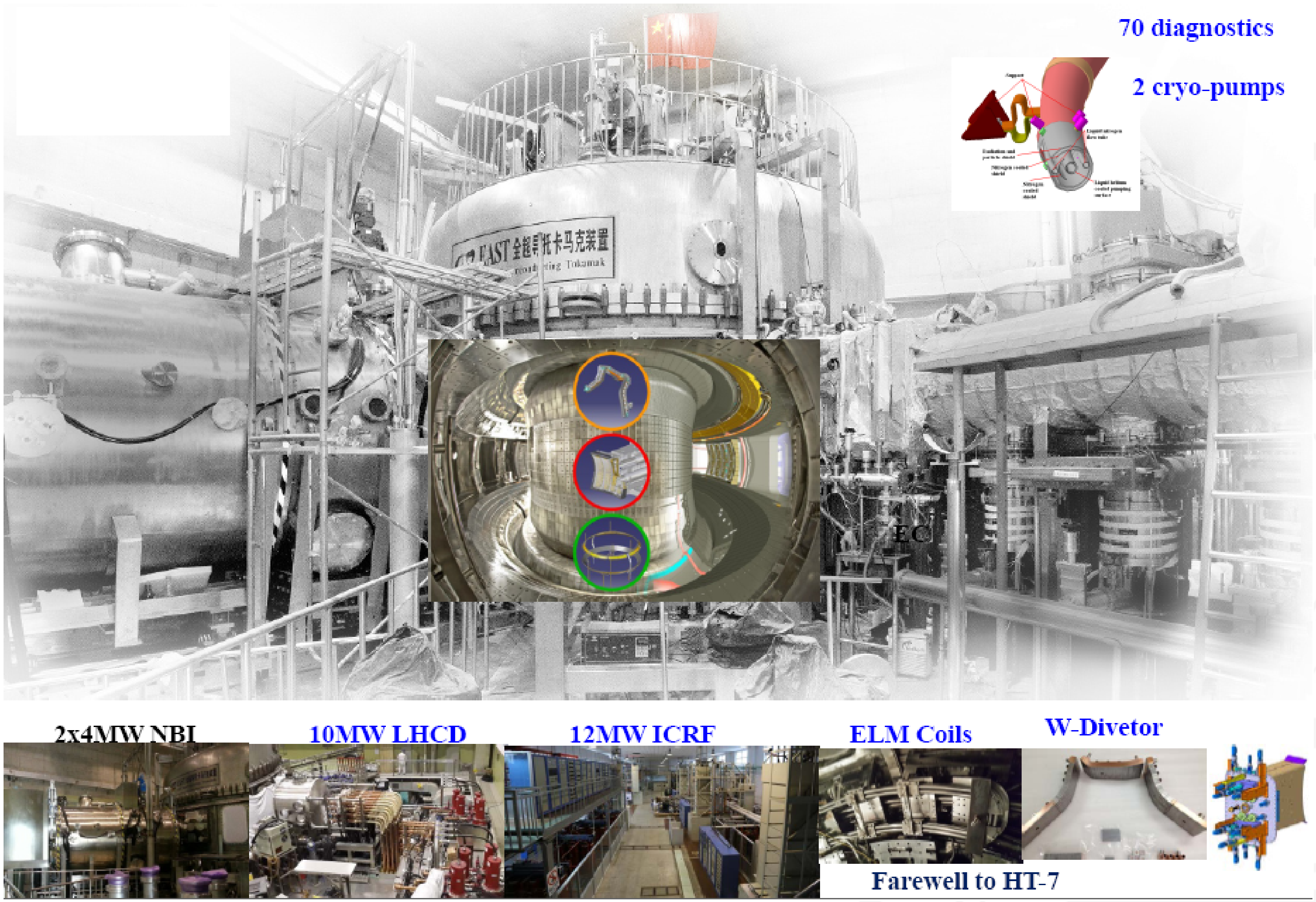
(HL-2A)



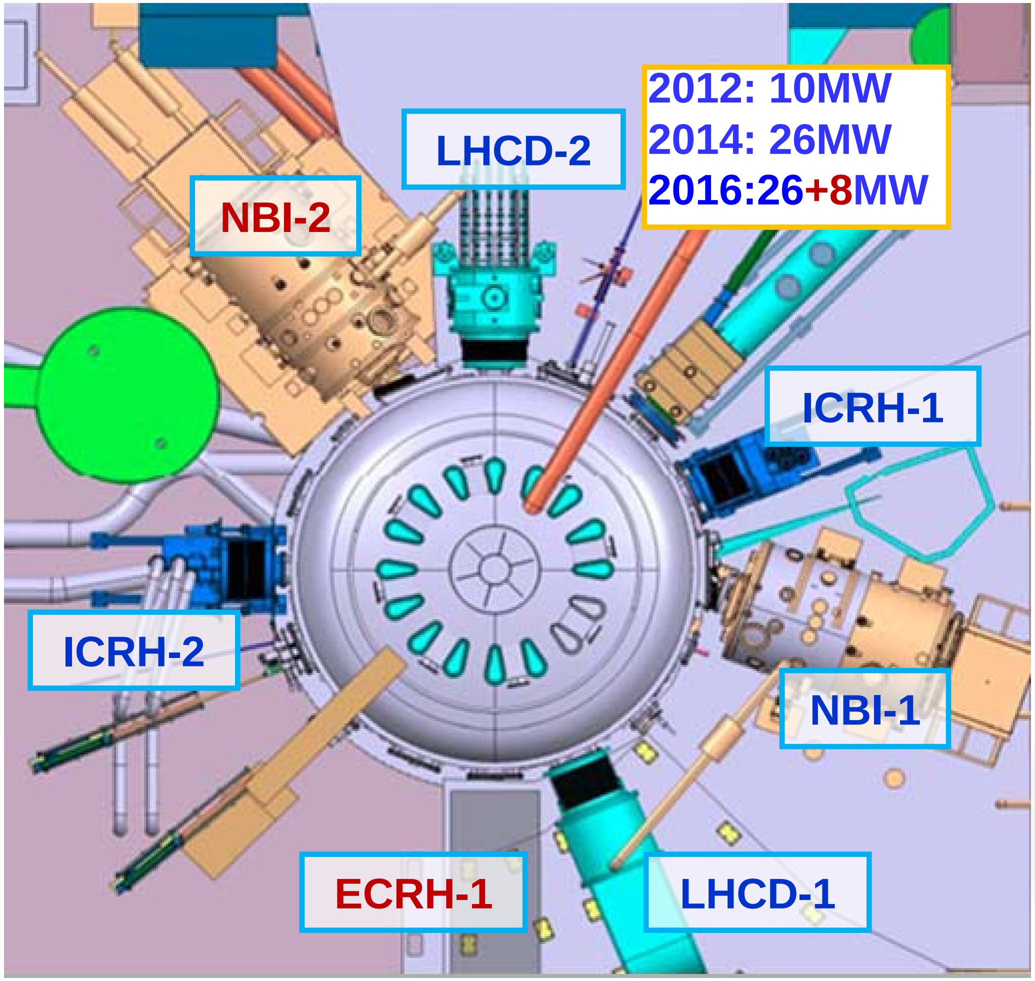
(HL-2M)

In SWIP

EAST: ITER/CFETR pre-experiments



H & CD capabilities on EAST allow truly advanced SS operations



- **LHCD 4+6 MW (2.45/4.6GHz)**
  - Fast Electron Source
  - Edge Current Drive /Profile
- **ICRH 6+6 MW (25-75MHz)**
  - Ion and Electron Heating
  - Central Current Drive
- **NBI 4+4 MW (co/counter, 80kV)**
  - Sufficient power to probe β limit
  - Variable rotation/ rot-shear
- **ECRH 4 MW (140GHz)**
  - Dominant electron heating
  - Steering mirror, j_ϕ tailoring

ITER-like RF-dominant H&CD, capable to address key issues of high performance SS operations

Progress of CFETR

conceptual design

Roadmap for Chinese MFE Development

PFPP

(~2050)

1GWe, Power Plant Validation

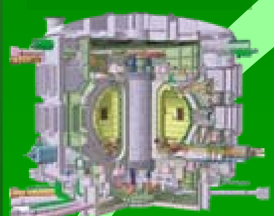
CFETR

(2030 start operation)

I: Q=1-5, steady state, TBR>1, >200MW, 10dpa

II: DEMO validation, Q>10, CW, 1GW, 50dpa

ITER



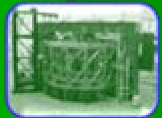
(~2021)

Phase I : Q=10, 400s, 500MW, Hybrid burning plasma

Phase I I: Q=5, 3000s, 350MW, steady-state burning plasma

EAST Advance PFC, steady-state advanced operation

HL-2M Advanced divertor, high power H&CD, diagnostics

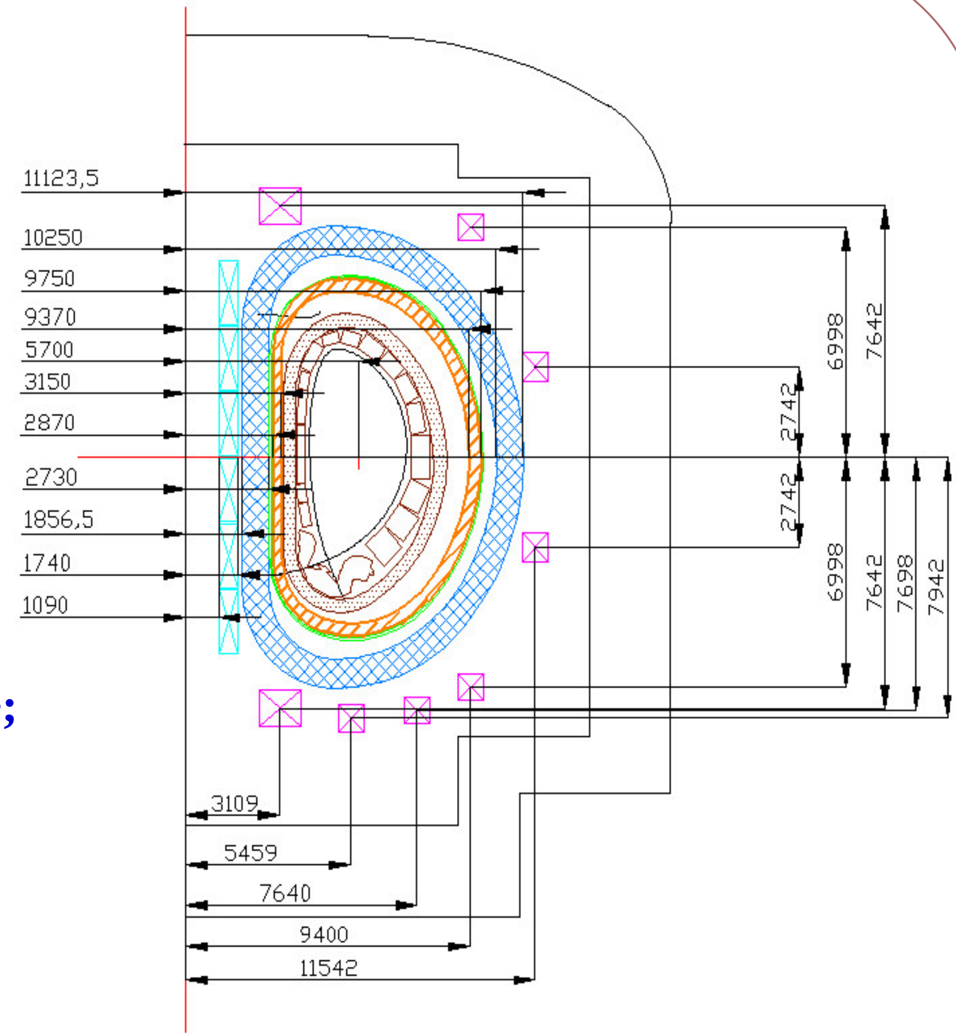


J-TEXT Disruption mitigation, basic plasma

2015 2020 2025 2030 2035 2040 2045 2050 2055 2060

CFETR Machine Configuration

- B_t= 4.5 -5T;
- I_p= 8-10MA;
- R = 5.7m;
- a = 1.6m;
- κ = a/b=1.8～2.0;
- β_N ～2.0； q_{95} ⩾3;
- Triangularity δ = 0.4-0.8;
- Single-null diverter;
- Neutron wall loading ≈0.5MW/m²;
- Duty cycle time = 0.3-0.5;
- TBR ～ 1.2
- Possible upgrade to R~5.9 m, a~2 m, B_t= 5T, I_p~14 MA

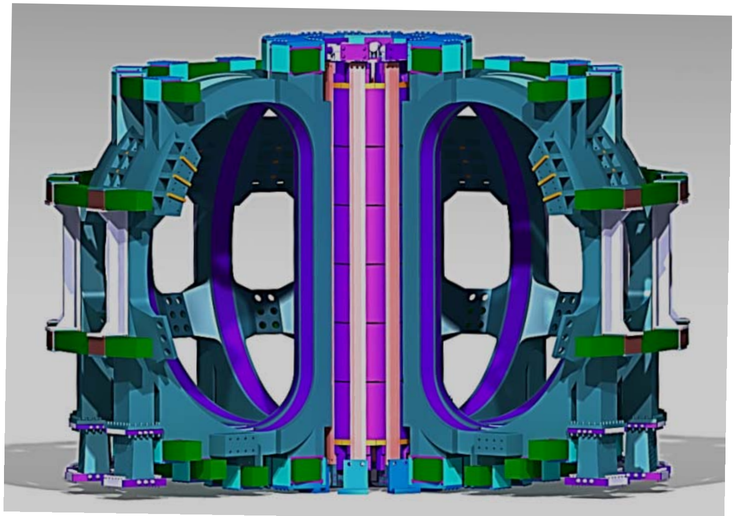


Key parameter investigation

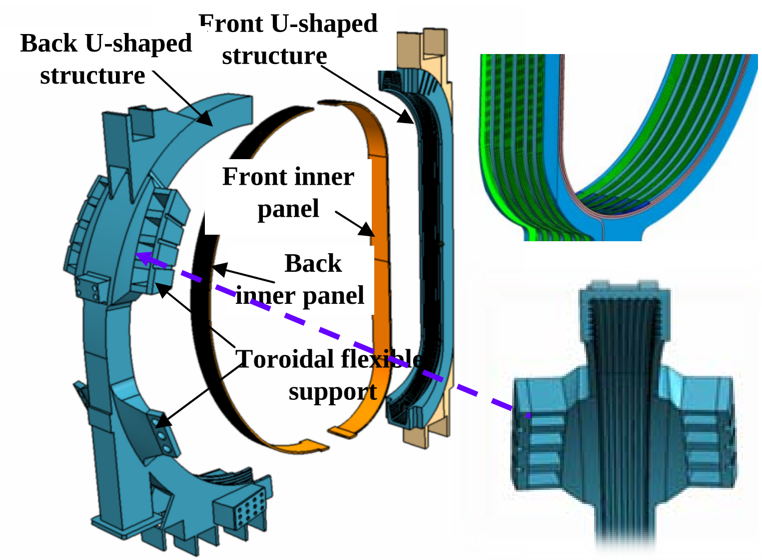
Operation mode	A	B	C	D	E	ITER -SS	Upgrade
I_p(MA)	10	10	10	8	8	9	15
P_{aux}(MW)	65	65	65	65~70	65	59	65
q_{95}	3.9	3.9	3.9	4.9	4.9	5.2	3.9
W(MJ)	171~174	193	270~278	171	255	287	540
P_{Fus} (MW)	197~230	209	468~553	187~210	409	356	1000
Q_{pl}	3.0~3.5	3.2	7.2~8.5	2.7~3.2	6.3	6.0	15
T_{i0}(keV)	17.8~18.5	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	1.8	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	1.3	1.5	1.57	1.2
$T_{burning}$(S)	1250	SS	2200	M/SS	SS		??

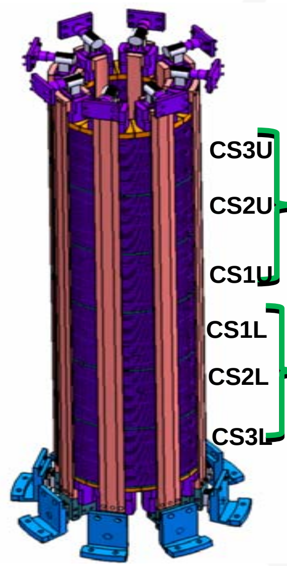
ThPO-3 B. Wan, etc.

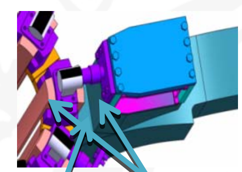
CFETR Magnet System



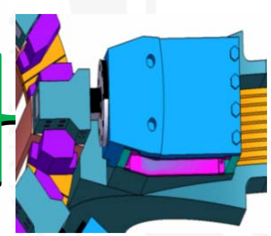
CFETR main parameters (ITER-Like/Super-X/Snowflake)				
Parameter	ITER-Like	Super-X	Snowflake	ITER
Number of TF coils	16	16	16	18
Plasma current (MA)	10	10	10	15
Central magnetic field(T)	5.0	5.0	5.0	5.3
Maximum current of TF coil (kA/turn)	67.4	67.4	67.4	68
Major radius(m)	5.7	5.7	5.7	6.2
Minor radius(m)	1.6	1.6	1.48	2.0
Ohm field coil center radius(m)	1.415	1.415	1.415	2.055
Maximum Volt second	160	160	160	240-250
Elongation	1.8/2.0	1.8/2.0	2.17/2.14	1.70/1.85
Number of PF coils	6	8	8	6



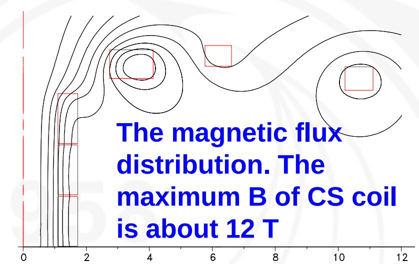


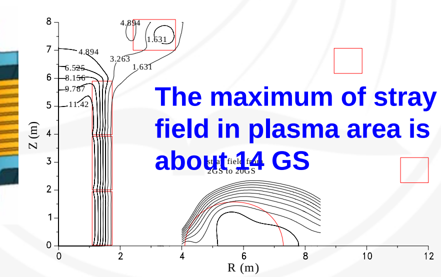


Tightening Tie Plate block



Bottom support structure



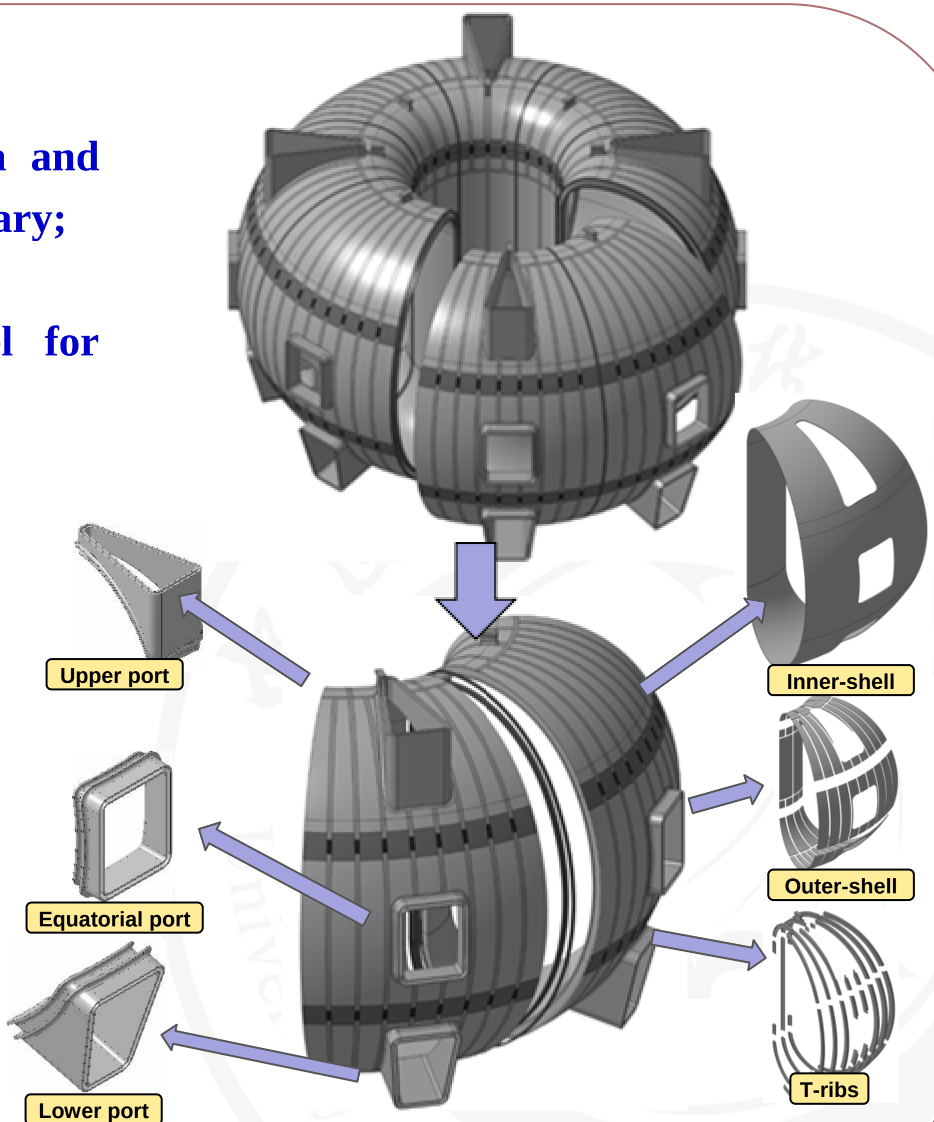


CFETR Vacuum Vessel

- A torus shaped double wall structure;
- To provide high vacuum for plasma and primary radiation confinement boundary;
- To support in-vessel components
- Important space of the Vacuum Vessel for plasma;
- First safety barrier;

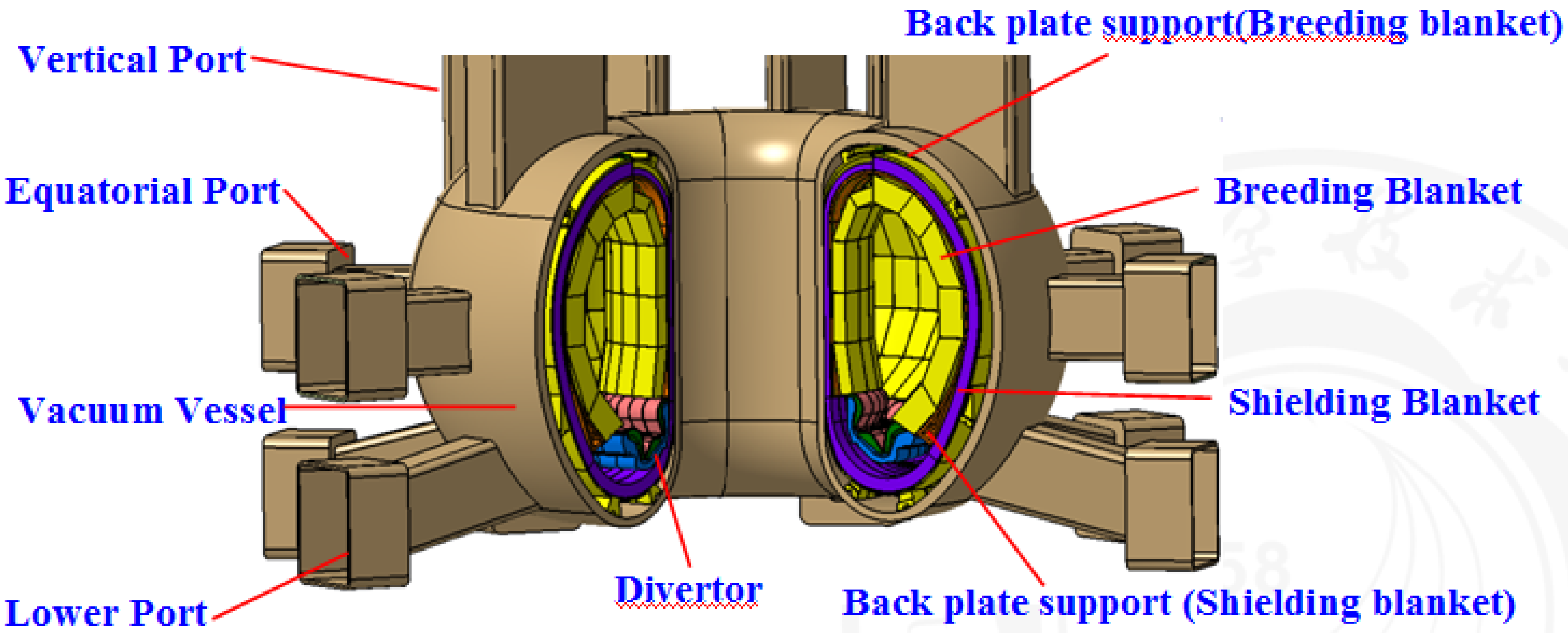
The vacuum vessel:
4 upper ports
8 equatorial ports
8 lower ports.

These ports are used for equipment installation, vacuum pumping, maintenance, etc.



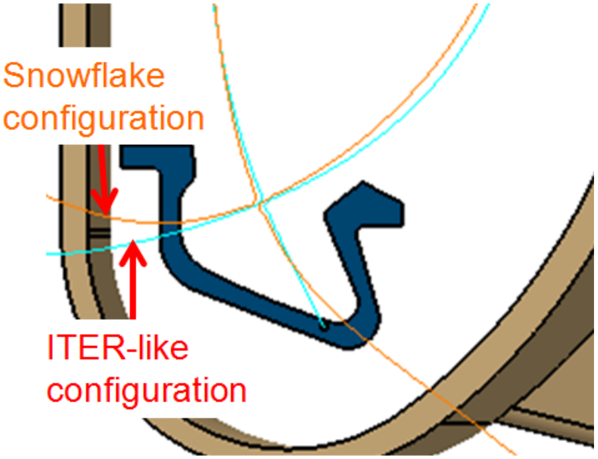
CFETR Blanket

◆ **Blanket configuration**

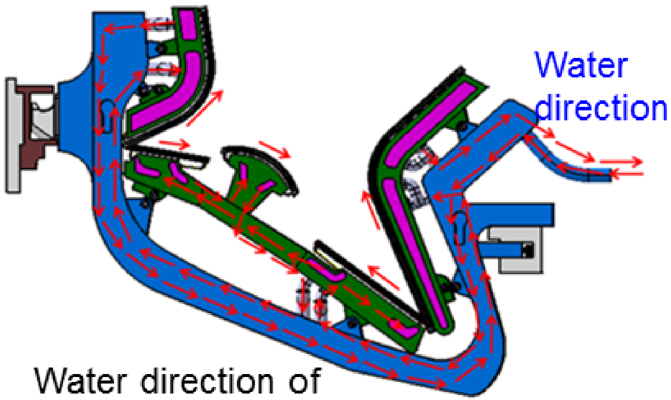


The CFETR blanket system composed of tritium breeding blanket and shielding blanket.

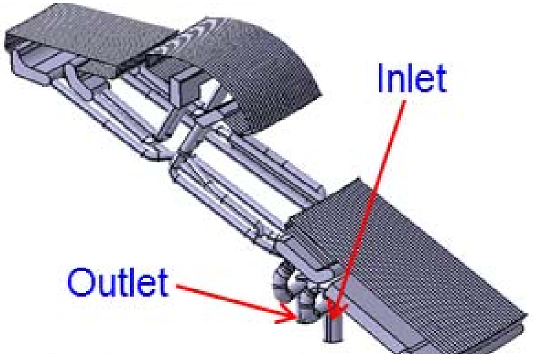
CFETR Divertor



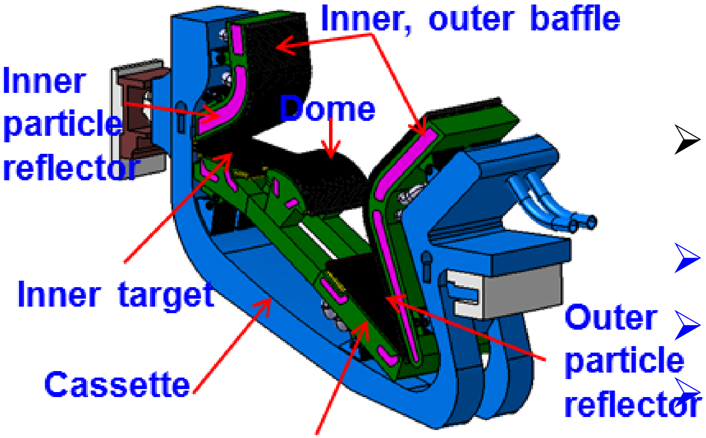
Divertor plasma configuration



Water direction of snowflake divertor



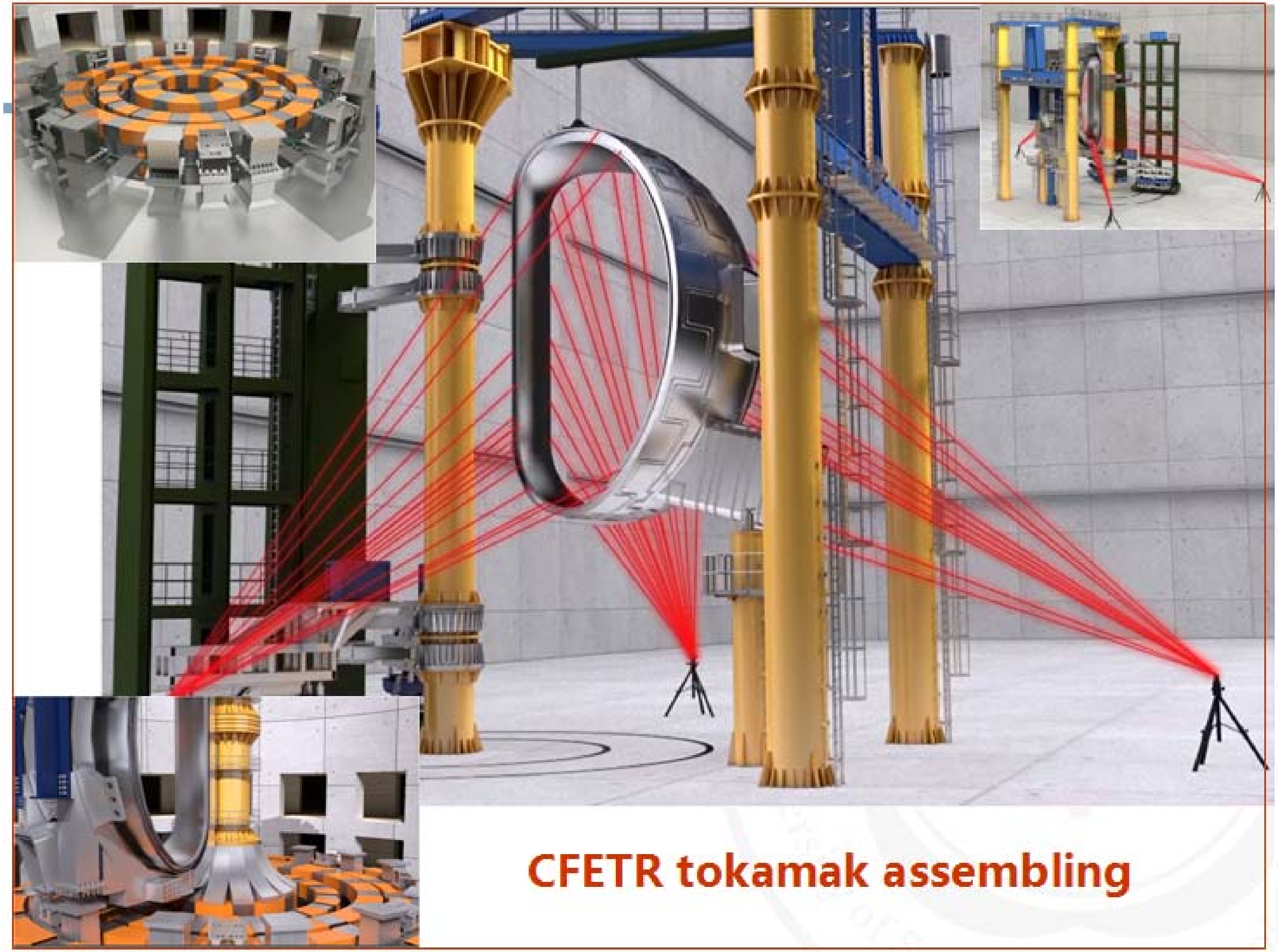
Cooling channel model



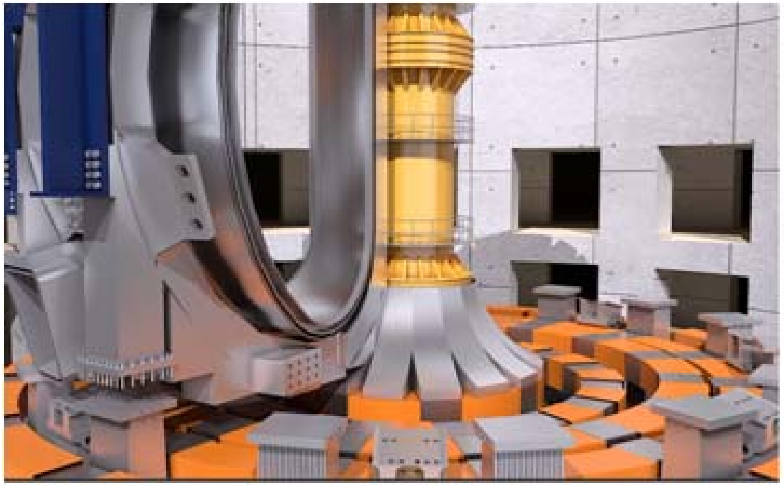
Snowflake divertor design

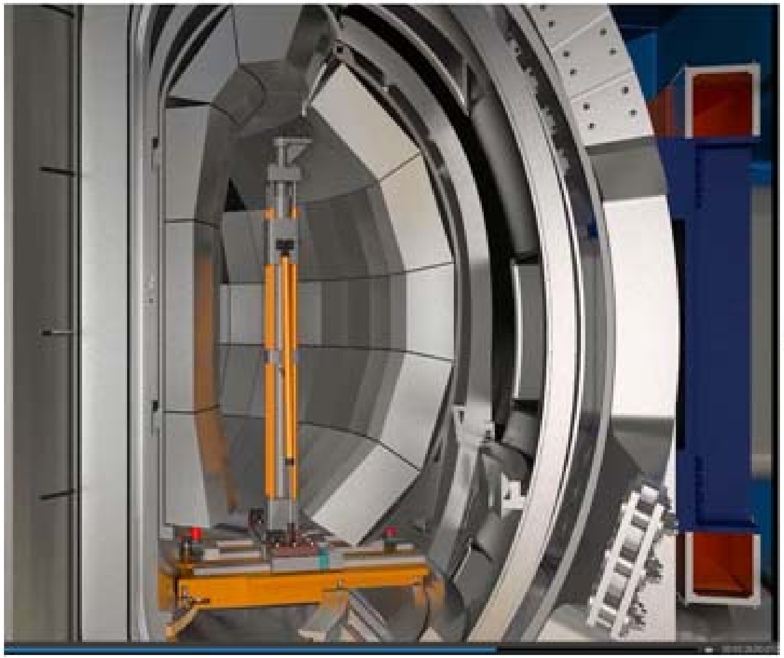
- Three configurations: ITER-Like, Snowflake and Super X.
- New structure with 'vertical reflector': inner baffle, inner particle reflector, inner target, dome, outer target, out particle reflector and outer baffle.
- Cassette structure for easier RH handling. Shared cassette between snowflake and ITER-like divertor.
- Small incident angle ~16° .
- Closed 'V' shape configuration.
- Pumping gap between dome and targets.
- Divertor cooling scheme was developed.
- Support design compatible with RH was finished.

CFETR tokamak assembling



CFETR blanket with the RH

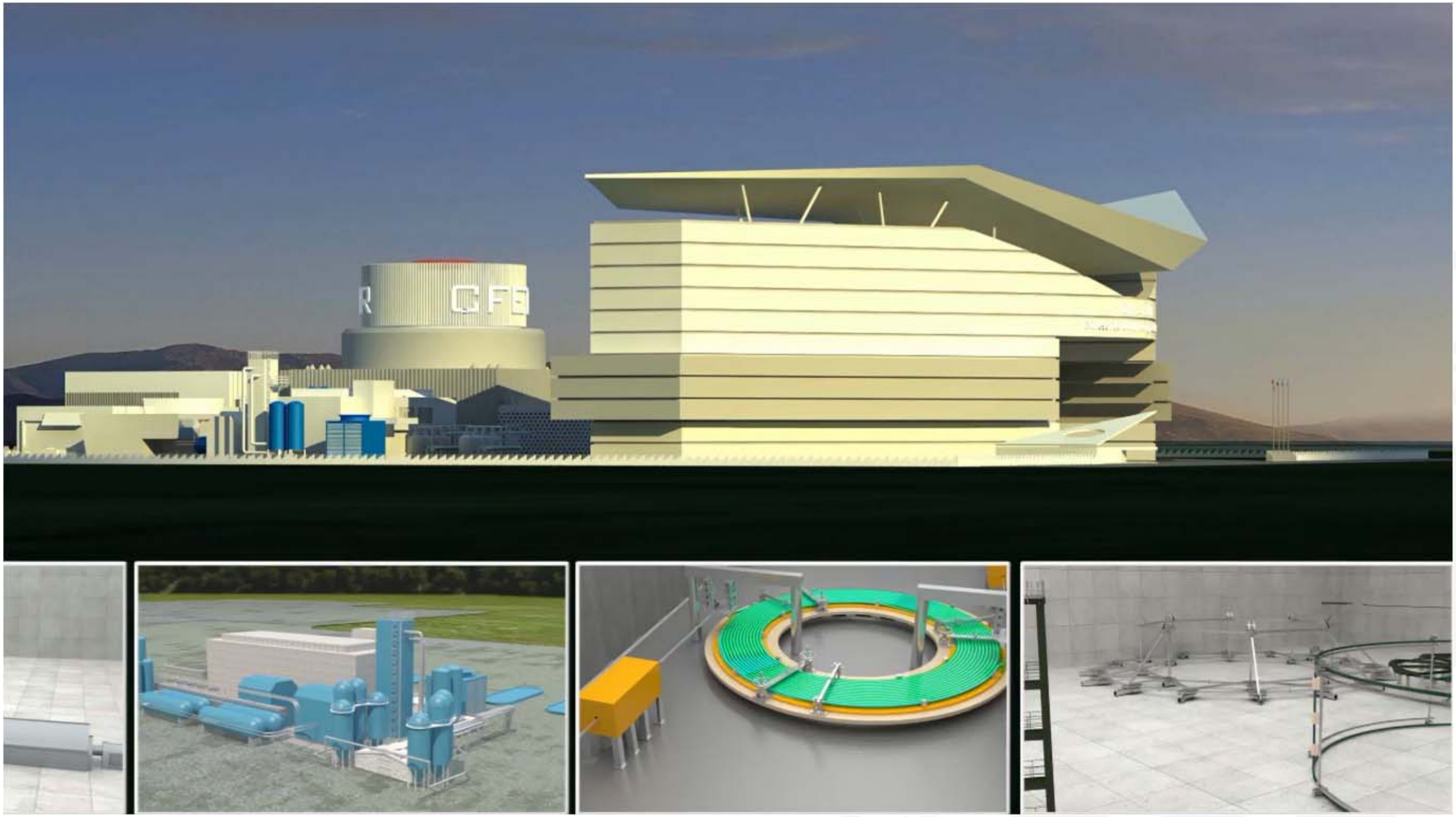




CFETR
blanket with the RH


CFET

Progress of CFETR Conceptual design



Progress of CFETR Conceptual design

1. Layout design and system Integration
2. Plasma physics and technology
3. Superconducting magnet and cryogenics
4. Vacuum vessel & vacuum system
5. In-vessel components:
   - blanket & diverter
6. Heating & Current Drive system
7. Diagnosis & CODAC
8. Electrical power & control system
9. Fuel circulation system & waste disposal
10. Radiation protection & safety, RAMI
11. Remote control and maintenance system
12. Auxiliary supporting system
13. Project management

Progress of CFETR R&D via ITER CN PA

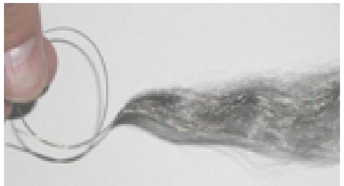
- Superconducting Technologies: Strands; Cabling, Jacketing and so on;
- Coil winding and magnets: PF6, CC, EML;
- Feeders;
- Power supply and control system: AC/DC converter
- Blanket: SB,TBM
- ....

Progresses of CN PA also for CFETR R&D

Strands manufacture

by Western Superconducting Technologies Co., Ltd.

Φ 0.820mm:
5000~10000m
NbTi filaments



NbTi & Nb_3Sn superconducting strands manufactory line

Progresses of CN PA also for CFETR R&D

Progress of Conductor PA

- 3 jacketing lines and conductor integrating facility were set up in ASIPP.
- 2 parallel buildings were set up for conductor integrating, NDE, cabling, acceptance test.
- All conductors produced by CN DA were accepted with their first tests.
- The first ITER oversized components, PF5 conductor, arrived at ITER site in June.

900m CICC jacket line

Conductor fabrication process

Ceremony for 1st shipping

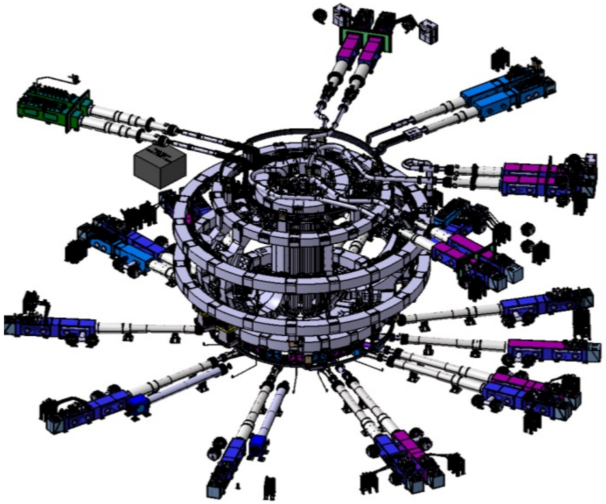
TF conductor arriving Italia

TF conductor arriving Japan

PF conductor arriving ITER site

Progresses of CN PA also for CFETR R&D

Significant progresses of ITER HTC feeder achieved

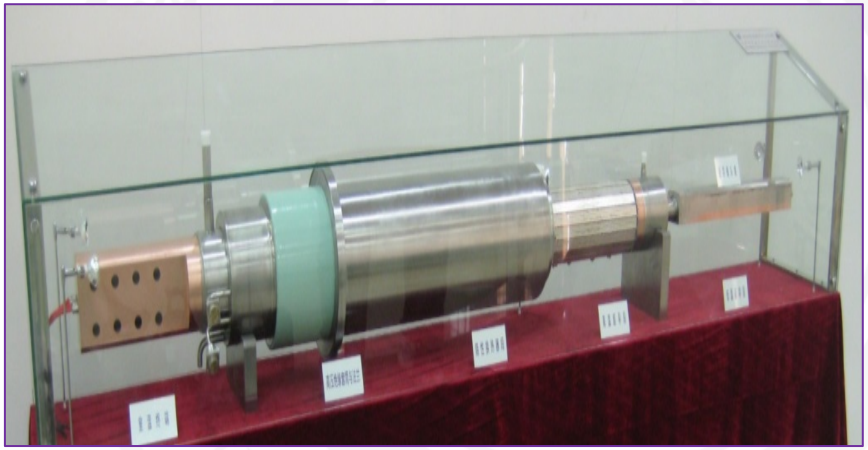


Overview of Feeder system in ITER

- **31 Feeder systems. No two pieces are identical.**
- **>1000 tons, >tens thousands of different parts.**
- **Feeder PA is on stage II. Critical technologies were developed in ASIPP. Mock-ups will be developed before production.**
- **72 HTS current leads (including prototypes and back-ups) will be supplied. 10/52/68kA three types current leads are designed and developed. 7 mock-ups were finished.**

PF5 in-cryostate feeder trial

Verification of Busbar

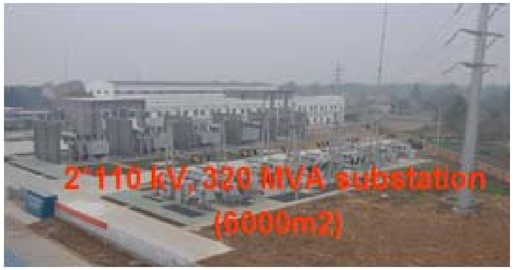


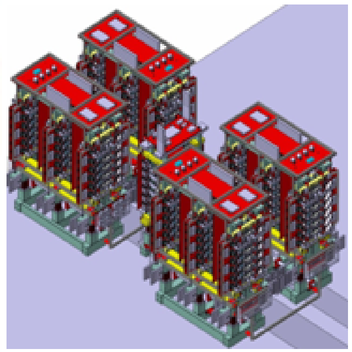
Current lead prototype

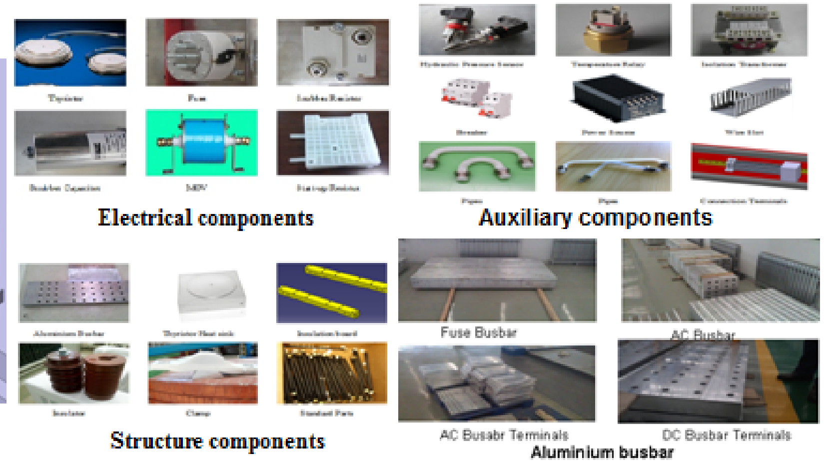
Progresses of CN PA also for CFETR R&D

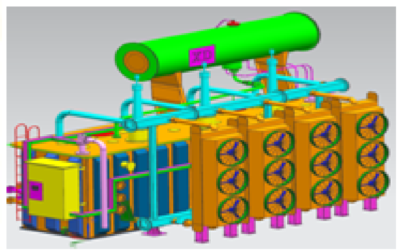
Progress of power supply PA:

All equipment is in manufacturing



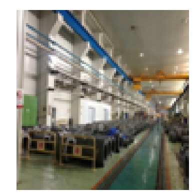







Winding


Tank material


Iron core material

PS Test Facility can meet all ITER PS test requirement

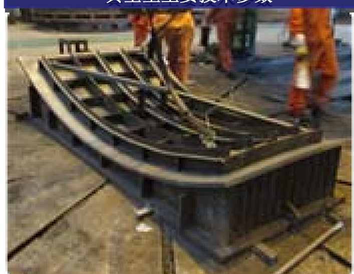
Progresses for CFETR R&D by EDP

- 1/16 VV mock-up
- 1/6 CS magnet
- Tritium technologies: T-Plant, Breeding material
- Materials : CLAM; first wall- W, neutron source
- RH
- ………………………

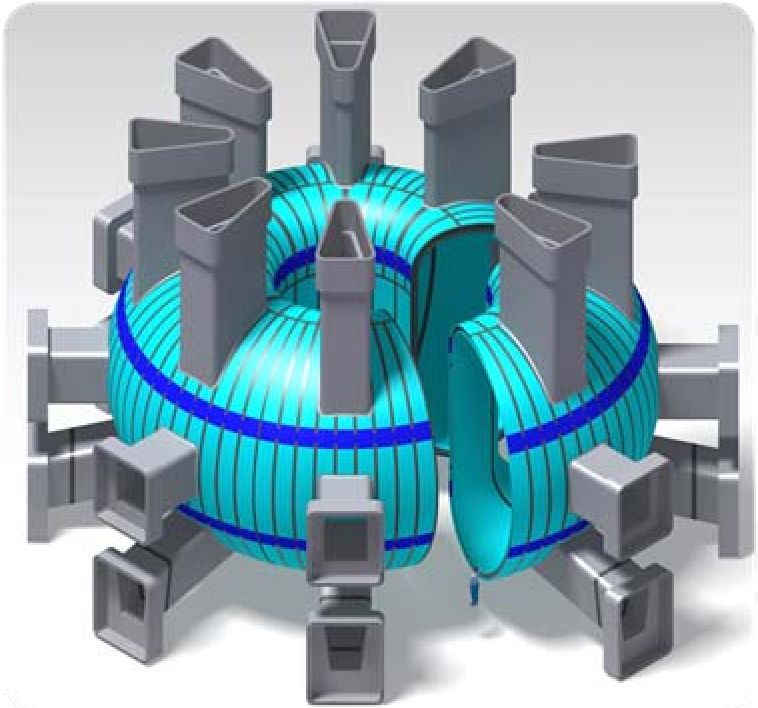
CFETR 1/16 VV mock-up

Size（尺寸）	Value （值）
Torus outside diameter（外径）	19.5m
Torus inner diameter（内径）	5.74m
Torus height（高度）	11.4m
Shell thickness（壳体厚度）	50mm
Weight（重量）	155.3*16=1242.4t
Structure（结构）	Double wall（双层壳体）
Welding joint（焊接接头要求）	Full penetration （全焊透）
Allowable leakage（允许漏率）	1×10-8Pa·m3·s-1
Magnetic permeability（磁导率）	1.05
Welding quality (焊接质量)	ISO-5817 B

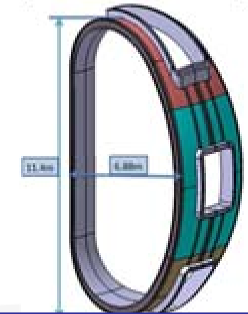
VV Main Parameters
真空室主要技术参数



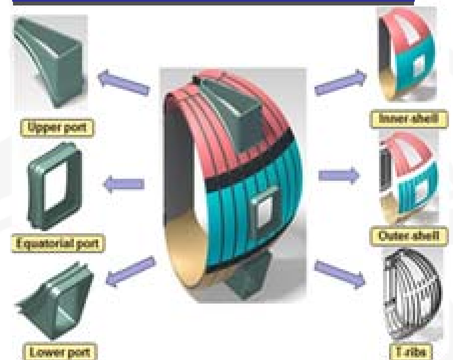
Shell Forming
壳体成形



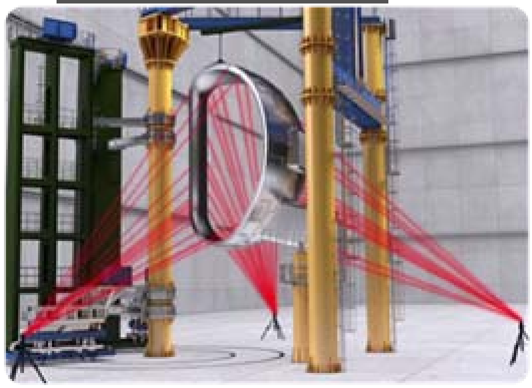
Overview of CFETR VV Design
CFETR真空室全貌



CFETR VV 1/16 Sector Mock-up
真空室1/16模型件设计

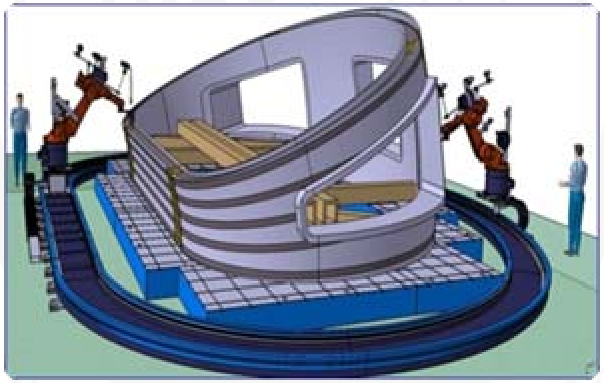


Design of 1/8 Sector of VV
真空室1/8段组成



Laser Tracker Measurement on VV Sector
真空室扇段的激光跟踪测量

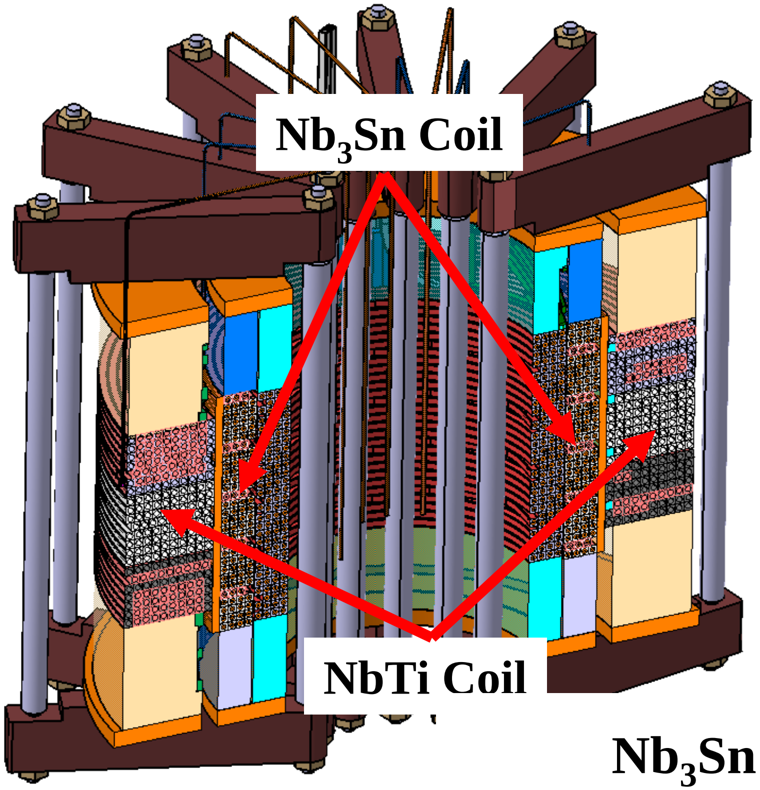
R&D of Narrow Gap TIG Welding on VV
窄间隙焊接预研 试验



Assembly of VV Poloidal Sectors
扇段组装

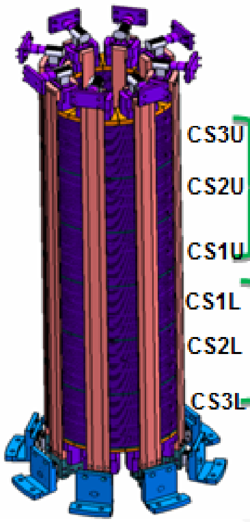
1/32 section mock up of the CFETR VV

One Section(1/6) of CFETR CS Model Coil

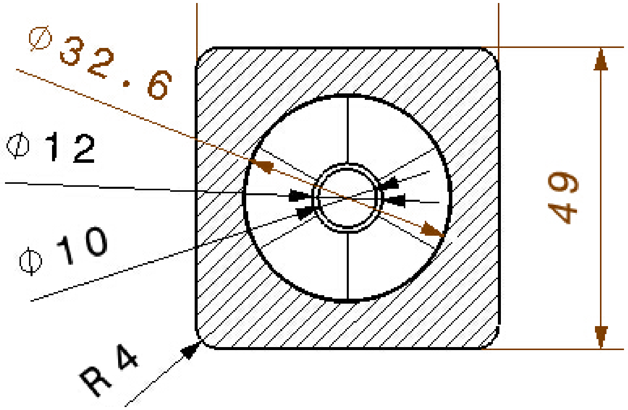


Coil Parameters

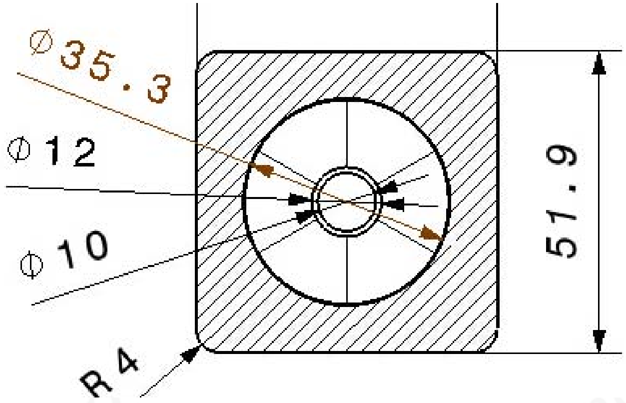
Design Parameters of CFETR CS Model Coil	
Max. field	12 T
Max. field rate	1.5 T/s
Inner radius	750 mm
Coil structure	Hybrid magnet **Inner: Nb_3Sn coil** **Outer: NbTi coil**
Conductor type	Nb_3Sn CICC NbTi CICC



Nb_3Sn Conductor



NbTi Conductor

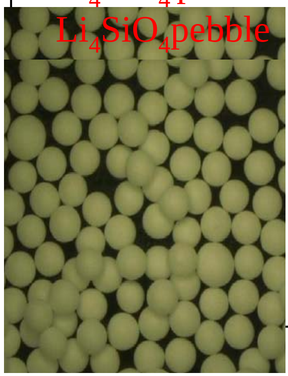


CFETR T-plant technologies

Progress of preparation of solid tritium breeder

CAEP independently developed a frozen- wet preparation technology of solid tritium breeder, currently has a preparation capability of kilograms in lab.

Li_4SiO_4 pebble



Preparation level of Kg class

Compressive strength(a.v.) >20 N

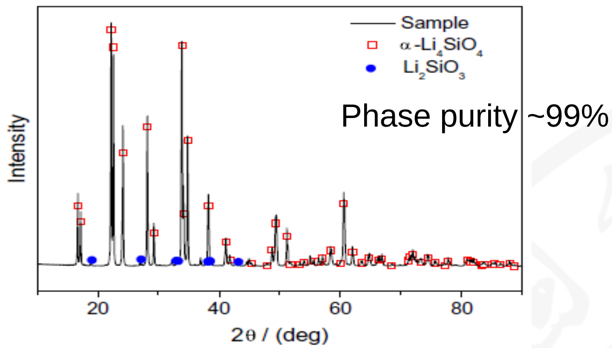


Fig. 4. XRD pattern of the powder.

Characteristics	Value
Diameter (mm)	0.63 ± 0.02
Density (% TD)	>80
Sphericity	≤1.02
Packing density ($g\,cm^{-3}$)	1.2
Surface area ($m^2\,g^{-1}$)	60.57
Li content (%)	22.75
T_m (°C)	1224
Grain size (μm)	3–5
Crush load (a.v) (N)	20

X. Gao, et al. J. Nucl. Mater, 2012
X. Gao, et al. J. Nucl. Mater, 2012

Tritium permeation barrier

- Formation of tritium permeation barrier (TPB) on vessels and pipes for tritium confinement is the first choice to minimize tritium loss and its environmental radiological risk.
- A series of oxides, aluminides, carbides and nitrides of TPB have been studied, and high tritium permeation reduction factor (PRF) can be obtained.

TPB type	Oxides	Carbides and nitrides	Compounds
Materials	Al_2O_3, Cr_2O_3, Er_2O_3, $(Ar,Cr)_2O_3$	TiN, TiC, SiC	Al_2O_3/FeAl, Er_2O_3/SiC, SiC/TiC@Al-Cr-O
Process	chemical and physical process	physical process	chemical and physical process
PRF	400~10000	>1000	300~3000

Materials research: LAM; first wall-W

China Low Activation Martensitic steel （CLAM）

Production and properties

- Nominal compositions: 9Cr1.5W0.2V0.15Ta0.45Mn0.1C
- 4.5 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)

1/3 CLAM FW

1/3 P91 TBM

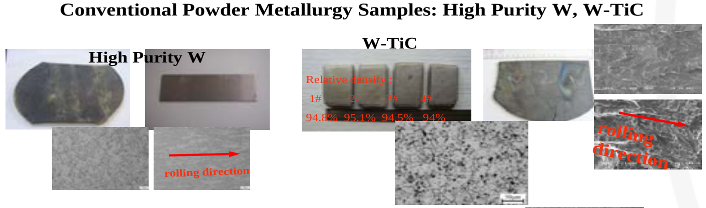
Properties of CLAM steel is comparable with those of the other RAFMs, e.g. Eurofer97, JLF-1.

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



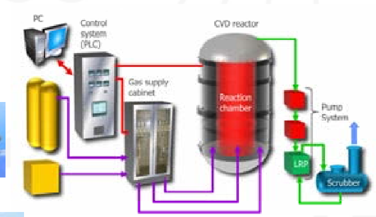
SPS Samples: Pure W, W-TiC, W-La2O3

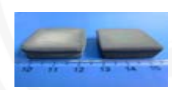
Pure W Φ80×10mm

W-TiC Φ80×10mm

(Chemical vapor deposition) CVD-W

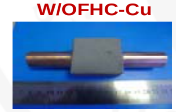
Deposition rate: 0.2-1mm/h

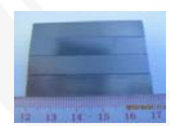




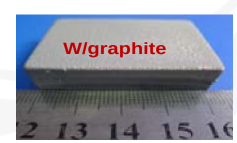
W/FGM-W/Cu

W/OFHC-Cu

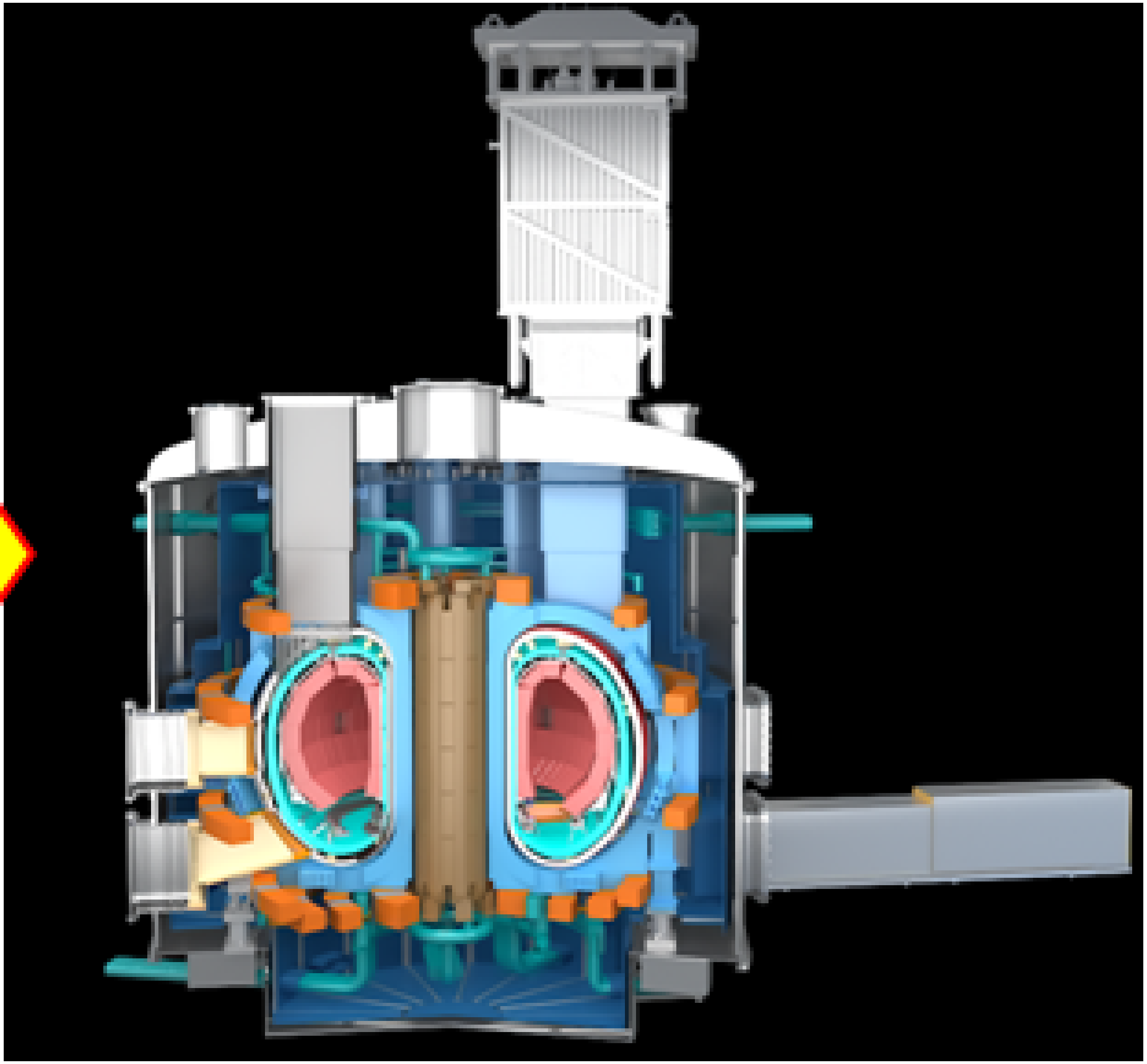




W/RAFM Steel

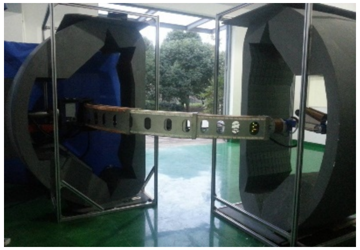


CFETR RH strategy

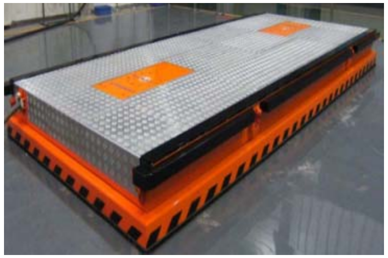


Some Achievements of RH project

1. Tokmak RH flexible In-Vessel Viewing System



2. ITER parts Transfer Cask

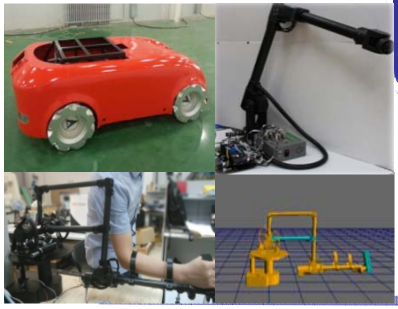


3. Blanket RH maintenance system

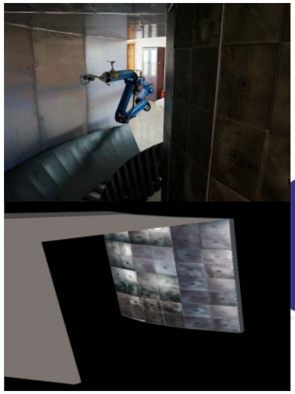
4. large scale heavy load maintenance robot arm system

5. RH master-slave robot and man-machine interactive control system

6. multifunction inspection and rescue robot



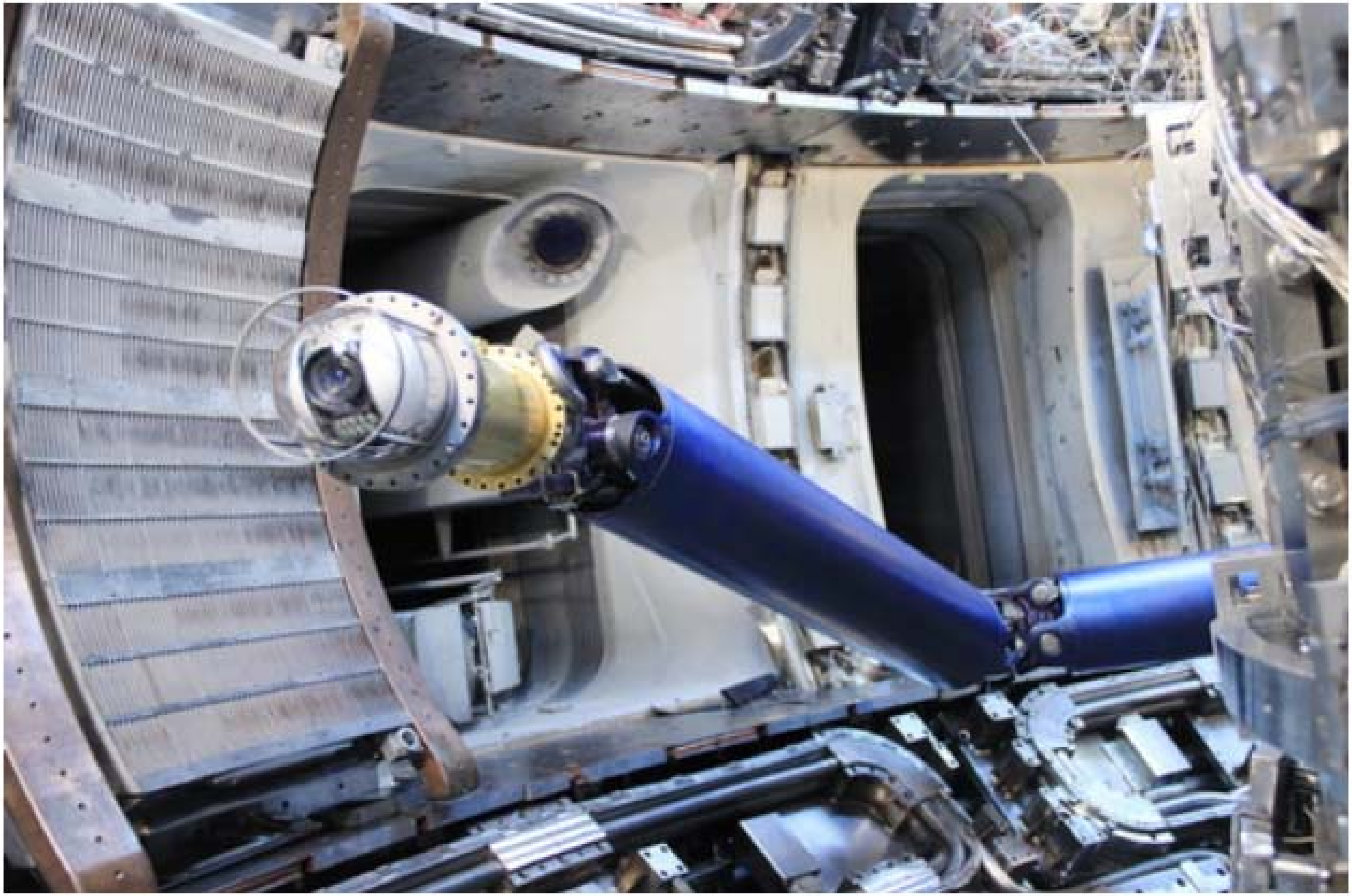
7. vision grabbing and scene modeling



8. system integrating and testing

~ 80%

RH test on EAST



RH test on EAST

CFETR Further plan

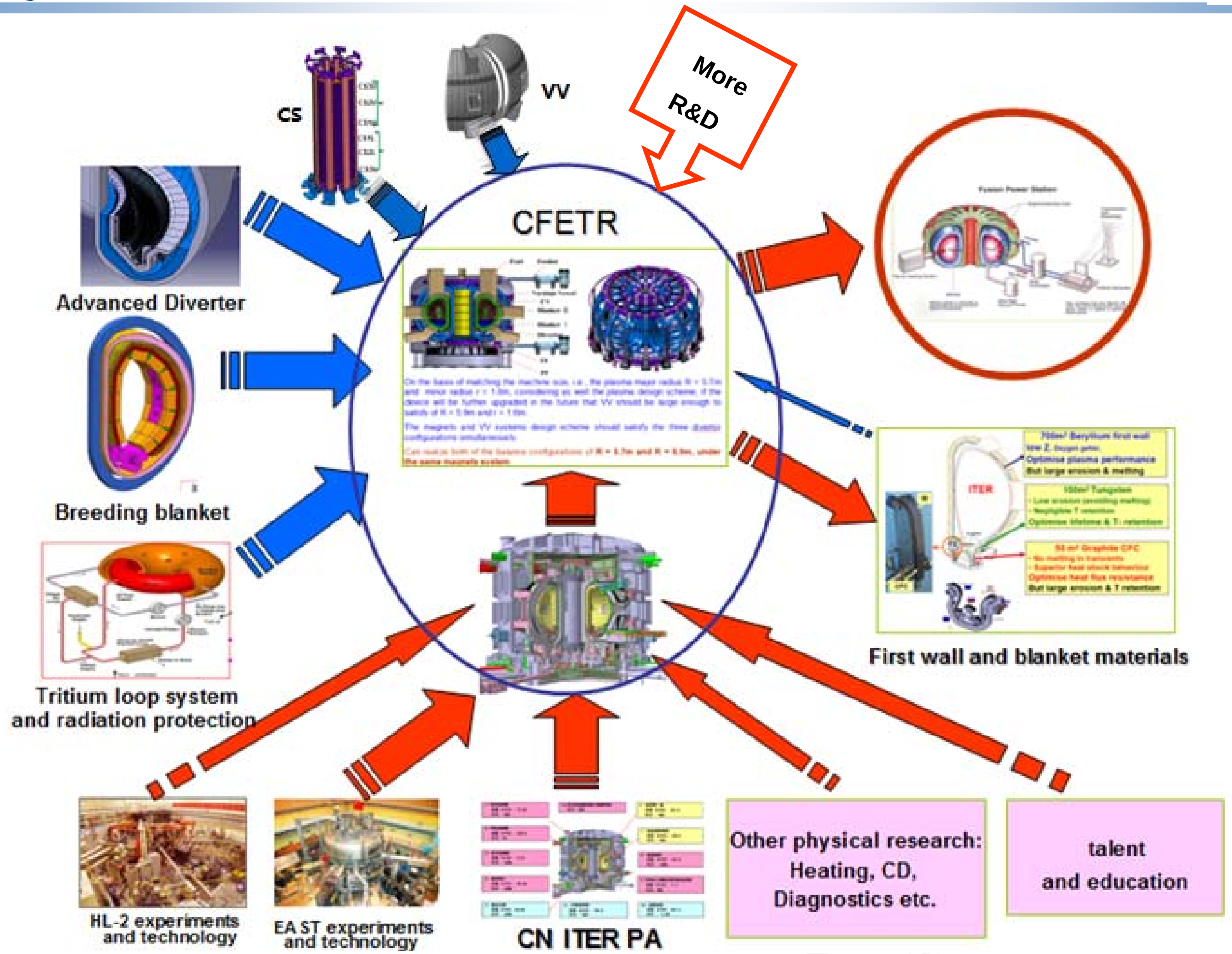
- 2012- 2014: provide the engineering conceptual design of CFETR
- Complete two proposals in 2015 :

  1. more key R&D items for CFETR

  2. Construction proposal for CFETR

It is hope that CFETR can be approved soon and to be constructed around 2030.

Design and R&D strategy for CFETR



Summary

- The MFE roadmap is under discussion in China
- Integrated Design and R&D of CFETR are in progress
- The wide international exchange and collaboration for CFETR are welcome !

Thanks for your attention !

CFETR-ASSEMBLY (1).mov