4th meeting for CN-EU DEMO cooperation, KIT, March 19-22, 2024, Germany

Overview of

Comprehensive Research fAcility for Fusion Technology (CRAFT)

Jiangang LI for CRAFT team

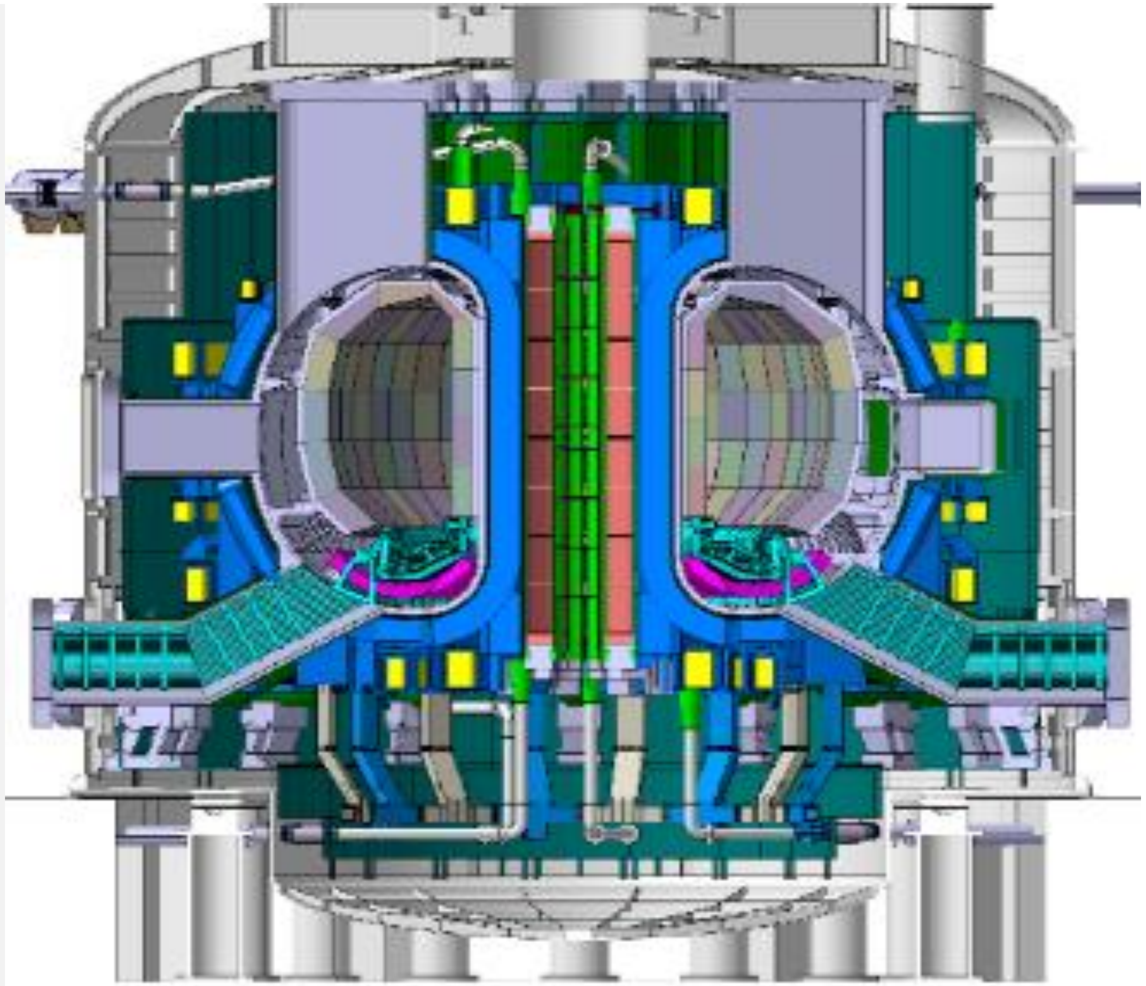
Chinese Fusion Engineering Test Reactor

R=7.2m, a=2.2m, Bt =6.5T, Pf = 1-2GW, TBR >1, 65000t

Main Goals of CFETR

Full cycle of fusion power plant

- Fusion power > 1500 MW
- Duty time ~50%
- Burning plasma with Q ≧ 10~30
- Tritium self-sustaining （TBR ≧ 1)
- Material and components validation
- Electricity generation



Physics design by V.Chan. It will be CN-DEMO. Can we build it successfully?

Objective of CRAFT

- Explore and master fusion DEMO level key technologies
- Establish the method and standard for manufacture the key material, components and system for CFETR.
- Building key prototype systems for CFETR
- Testing and validating the method, technology and system for a successful construction of CFETR
- Building RAMI for key CFETR systems
- Training next generation of fusion scientist , engineer and mangers.

Lists of systems & facilities of CRAFT

• 1. SC Material testing facility	• 11. **CFETR divertor development**
• 2. SC Conductor testing facility	• 12. CFETR divertor testing facility
• 3. TF magnets testing facility	• 13. **Blankets developments**
• 4. CFETR CSMC and testing facility	• 14. **ECRH System**
• 5. **CFETR HTS coil and testing**	• 15. **NNBI system**
• 6. **CFETR TF and testing**	• 16. **LHCD system**
• 7. Cryogenic testing facility	• 17. **ICRF system**
• 8. Power supply testing facility	• 18. Blanket testing facility
• 9. Large Linear plasma testing facility	• 19. RH & testing facility
• 10. Mater Control facility	• 20. VV and installing testing facility

Auxiliary system	1、Power distribution system	3、Campus
	2、Cooling water system	4、Buildings

1. SC Material testing facility

➢ Scientific objectives

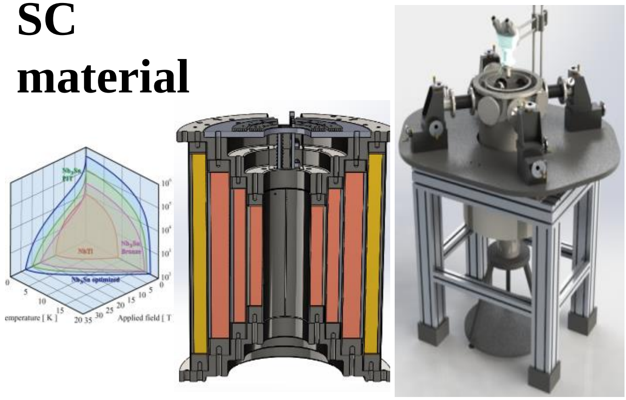
- To master scientific and the intrinsic physical properties and service behavior of materials for superconducting magnets in complex and extreme environments, and to carry out engineering application research.

➢ Composition and main parameters

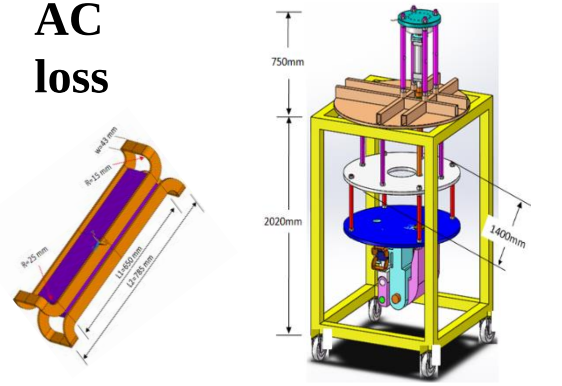
1. SC material performance research platform:19 T, 2 kA
2. AC Loss research platform: 0.01-0.2 Hz,1500 kN/m
3. Structure material performance research platform: 2500 kN
4. Thermo-hydraulic research platform: 3.8-300 K
5. NDE technology research platform: 350 kV (X-Ray)
6. High voltage research platform: 0-100 kV

Will be finished on Nov.2024

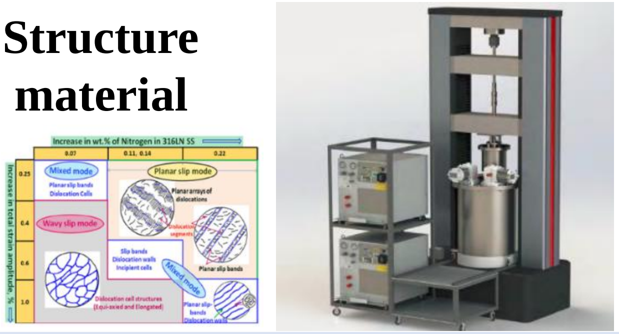
SC material



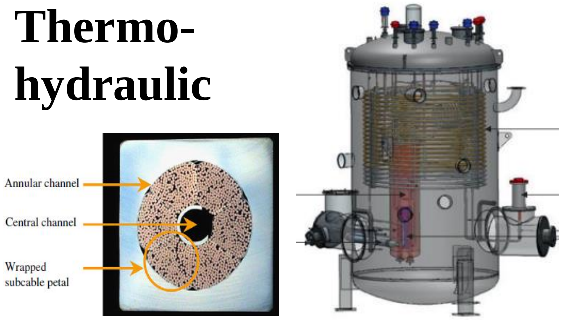
AC loss



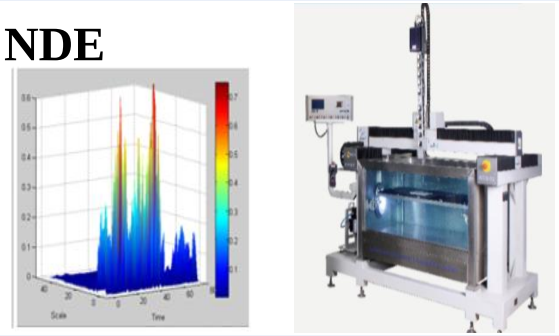
Structure material



Thermo-hydraulic



NDE



High voltage

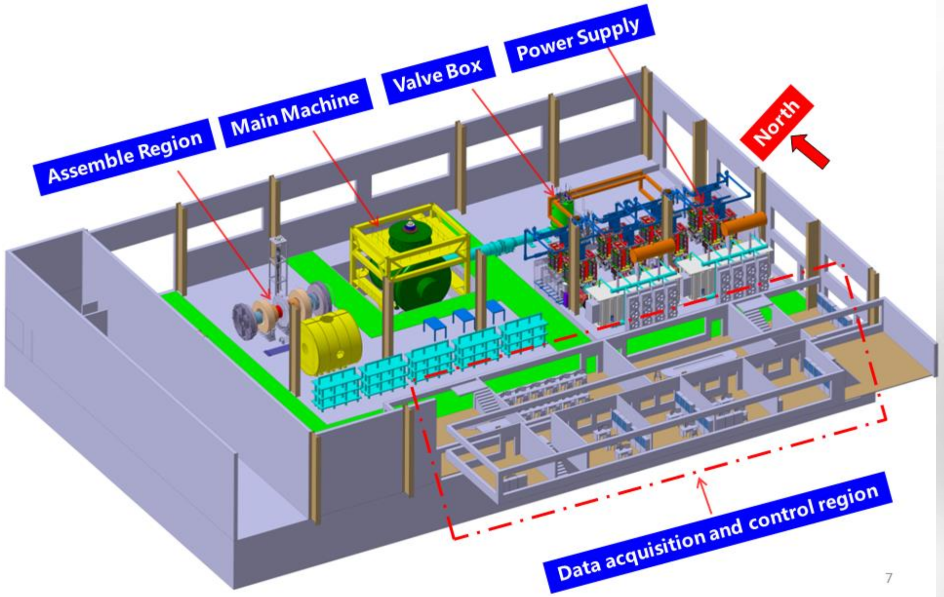
2. SC Superconductor Testing Facility

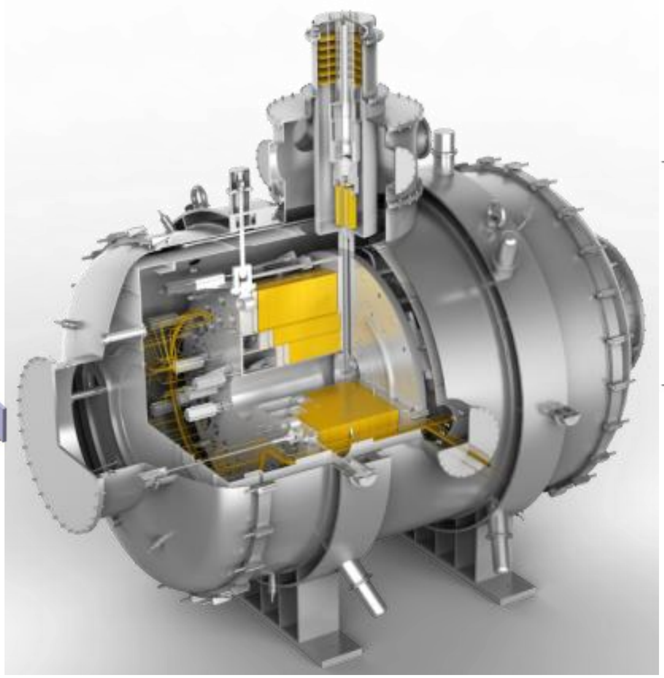
➢ Scientific Objective

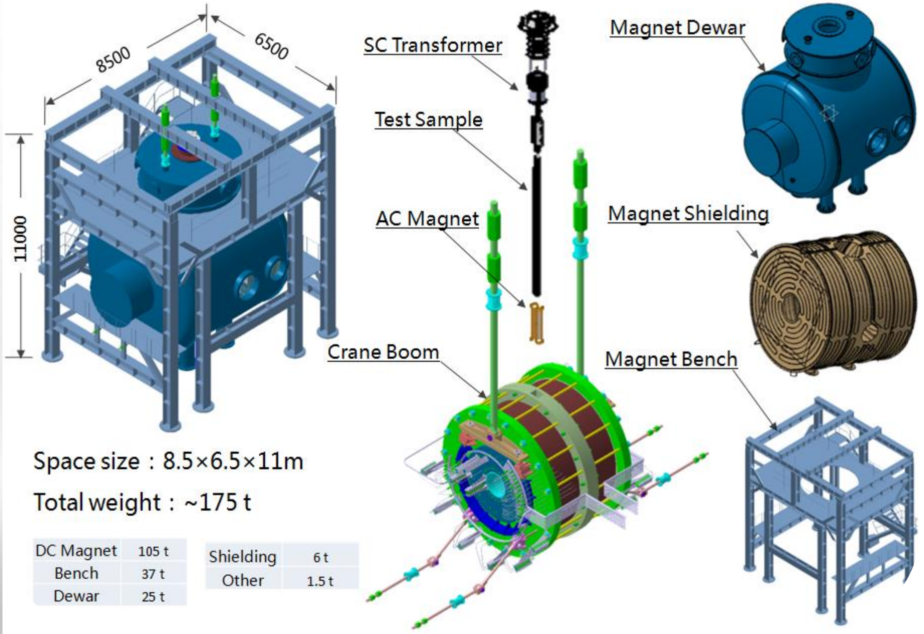
- To study the electro-magnetic behaviors (T_{cs}, I_c, AC loss, MQE) of composite structure superconducting conductor under mult-field coupling condition;
- To evaluate the reliability of SC conductor in future fusion reactor operation condition;

➢ Main Technique Parameters

- Maximum magnetic field: **16.5 T (B_{back}=15 T)**
- Tested space: **100 × 160 × 550 mm**
- Field homogeneity: **≥ 98 %** (tested space)
- Maximum tested current: **100 kA**







2. SC Superconductor Testing Facility

☐ 15 T DC magnet – Dummy Model Coil Wind

- **HF&MF layer coil winding line**

Length:22 m, Width: 8 m, Working height: 1.8 m

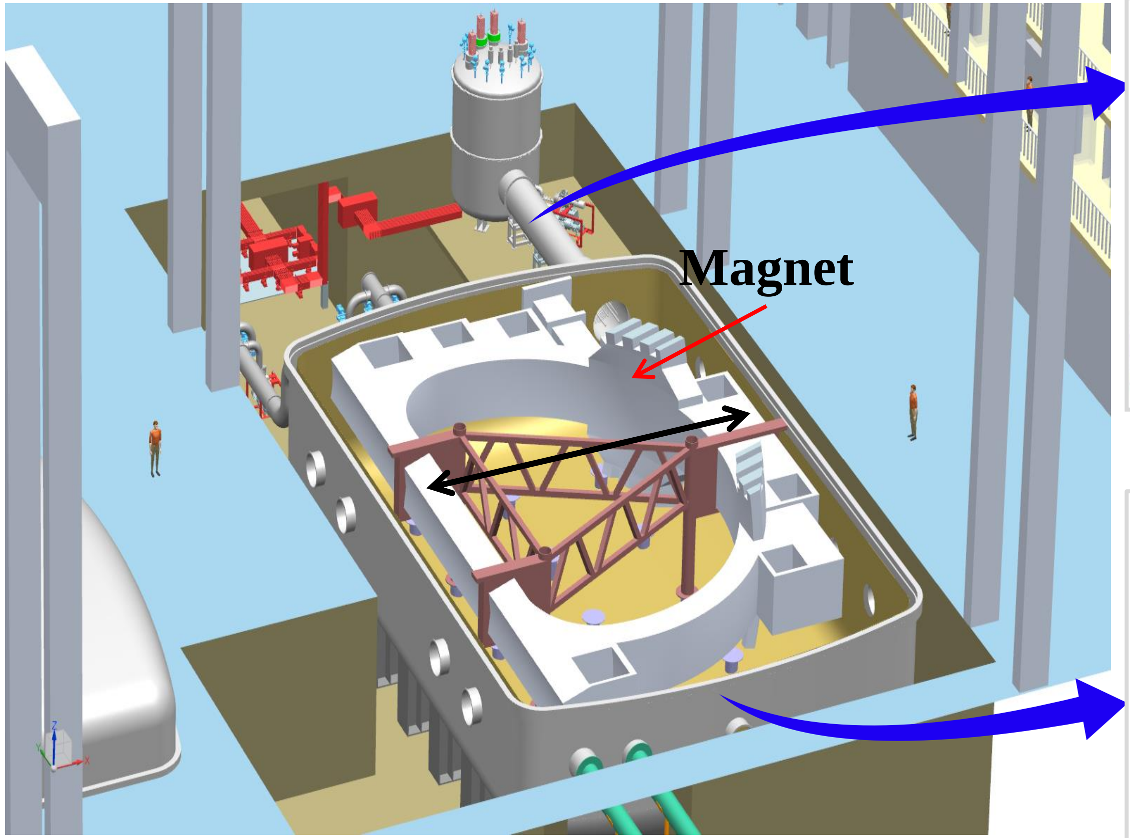
- **LF pancake coil winding line**

Length 32 m, Width 10 m, Working height: 1.8 m

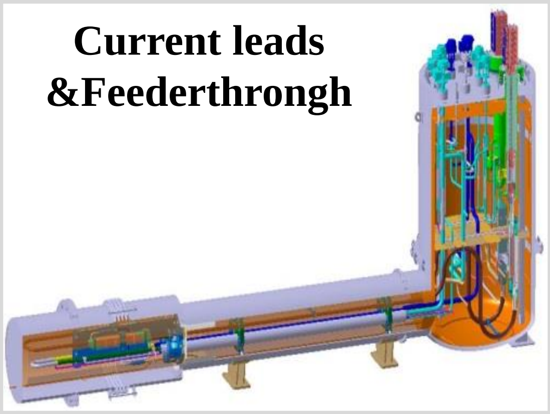
- Manufacture and commissioning of **two coil winding lines** for 15 T DC magnet **have been completed**;
- **The two dummy model coils** (MF model coil and LF QP pancake coil) **have been wound**, the geometric dimensions are in line with the expected values; **one year delay**

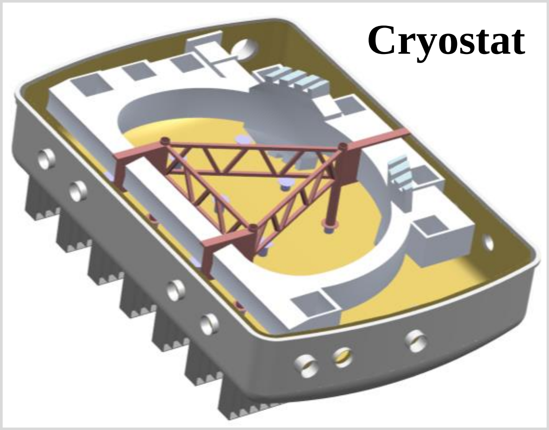
3. TF magnets testing facility

To perform the large-scale SC magnet research on mechanics, thermology and electromagnetics properties.
To evaluate the SC magnet system compatibility, reliability, stability, and magnet safety in fault state and verify the reliability of magnet engineering technology.



Large-scale Magnet Performance Research

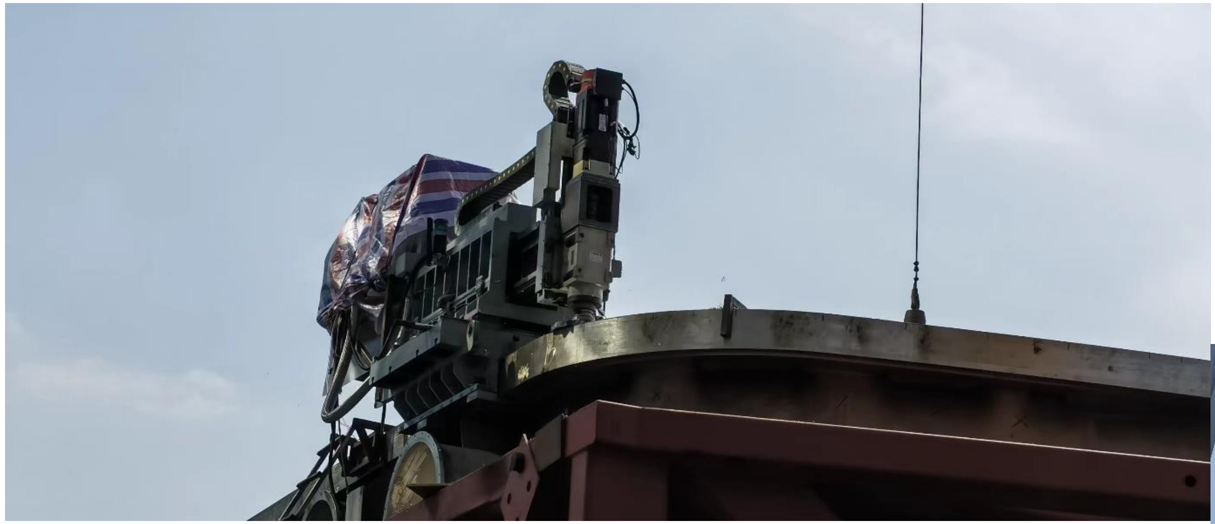


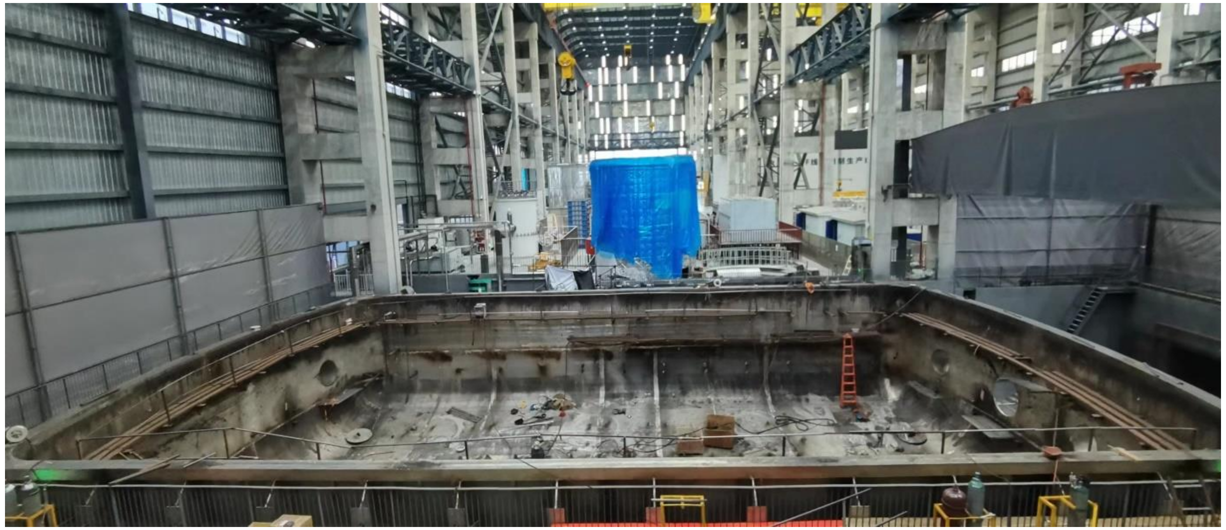


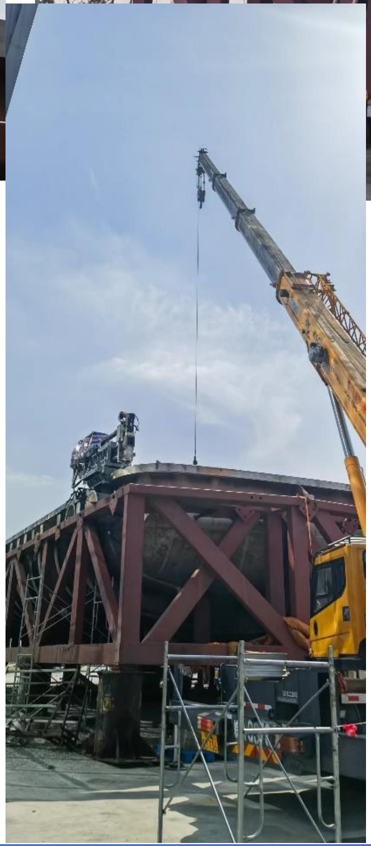
- Quench detection system
- Protection system
- Cryogenic system
- Fast discharge
- Vacuum system

Item	Description
Cryostat main dimension	**Length>28.5m；Width>14m；Height>6m**
Operation temperature	4.5K
Current leads operation current	100kA/60kA
SHe pressure	3-6 Bar
SHe massflow	>500 g/s

3. TF magnets testing facility







1. TF magnets testing facility is about one year delay
2. Start fully test on July
3. Start test 1st TF pancake on Nov.
4. Start test BEST TF (3 each time) from next Feb

4. CFETR CSMC and testing facility

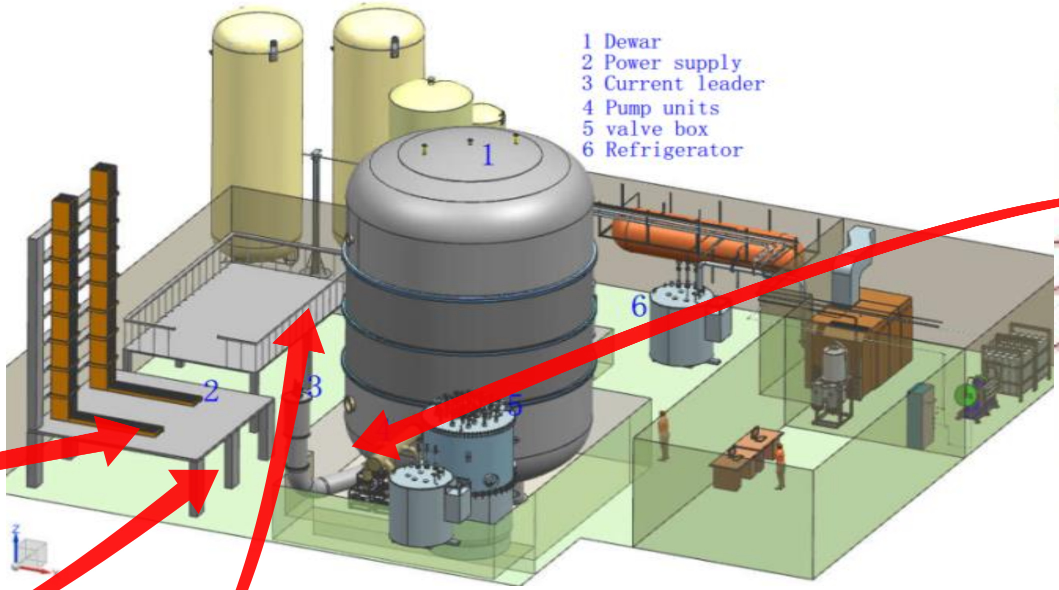
Objective:

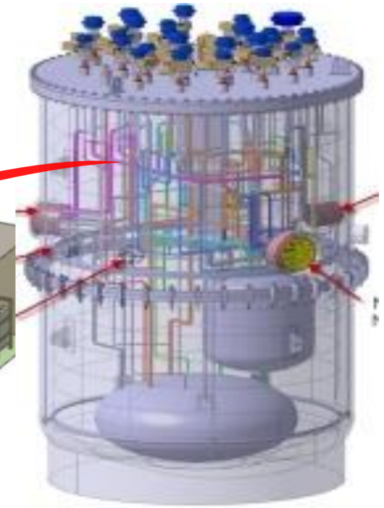
Develop magnet technology of CFETR Nb_3Sn CS

Carry out experiments on electromagnetism, magnetism, thermodynamics performance of magnets under fast magnetic field environment

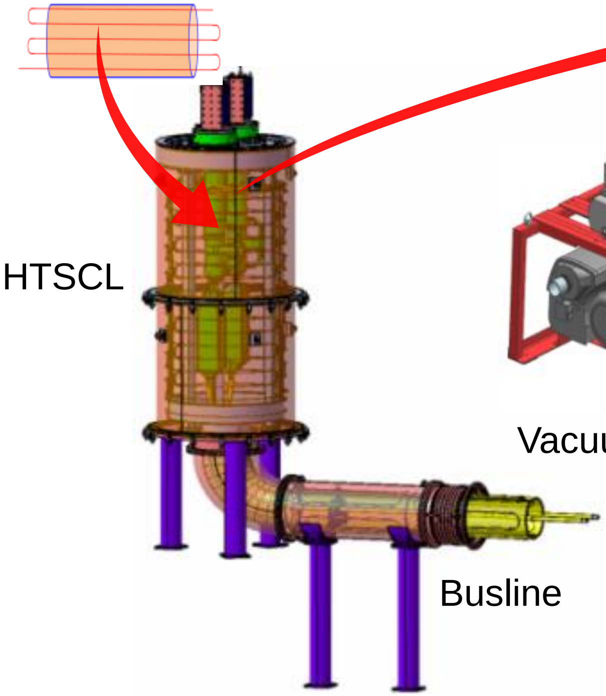
Evaluate the safe operation characteristics of magnets

Quench detection



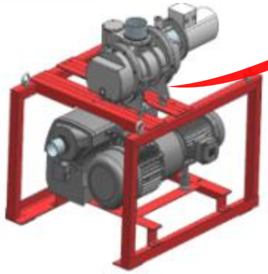


Cryogenic system

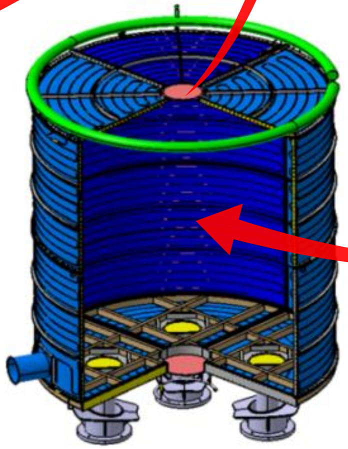


HTSCL

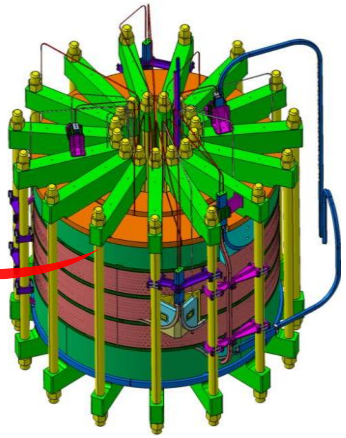
Busline



Vacuum pump



Thermal shield



12T SC CSMC magnet

Φ_{in}	1500mm
I_{op}	47 kA
dB_{max}/dt	5 T/s
R_J	< 1 nΩ
T_{OP}	4.5K

CFETR CS model coil (CSMC) and testing facility

Major progress

- ✓The Dewar and vacuum system has been manufactured and transported to the No.8 factory;
- ✓On-site installation and off-line **high voltage and high current commission** of power supplies will be finished in Aug.;
- ✓The installation of Cryogenic system will be finished in July and commission will begin.
- ✓ **The assembly of five coils is expected to be completed by the end of September.**




Will be finished in the end of April

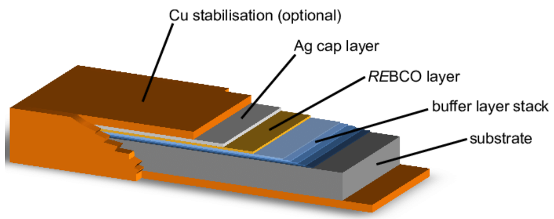
5. HTS magnet technology development

The objectives

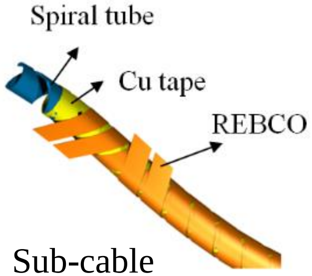
- Explore HTS CICC conductor and magnet technologies
- Evaluate operation reliability for the next fusion device

	Parameters	Values
Coil	Operation current / I_{op}	46.5 kA
	Peak field / B_{max}	19.6 T
	Inner radius	475.5 mm
	Outer radius	703.5 mm
	Number of turns / per module	5 x 30 turns
	Conductor length per module	556 m
CICC	Cable OD	32 mm
	Jacket OD	~ 41 mm
	REBCO Tape(width x thickness)	4 x 0.1 mm
	No. of sub-cable	6
	No. of SC tapes	212

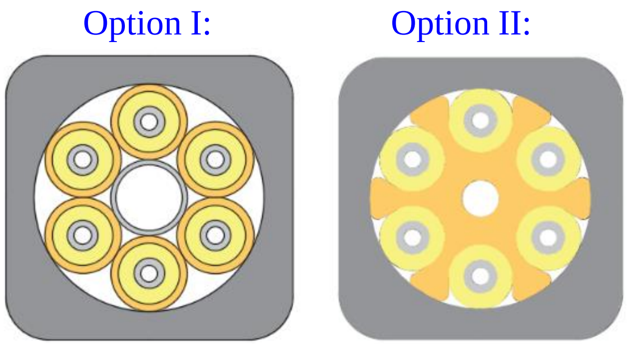
Preliminary design concepts



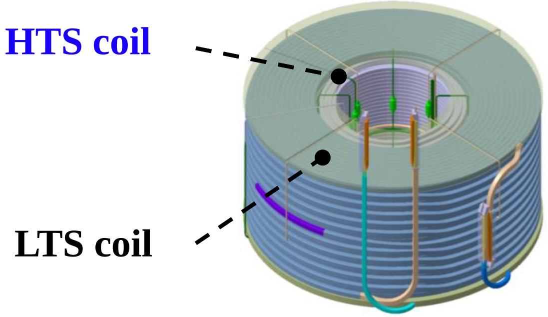
Candidate material: REBCO tape

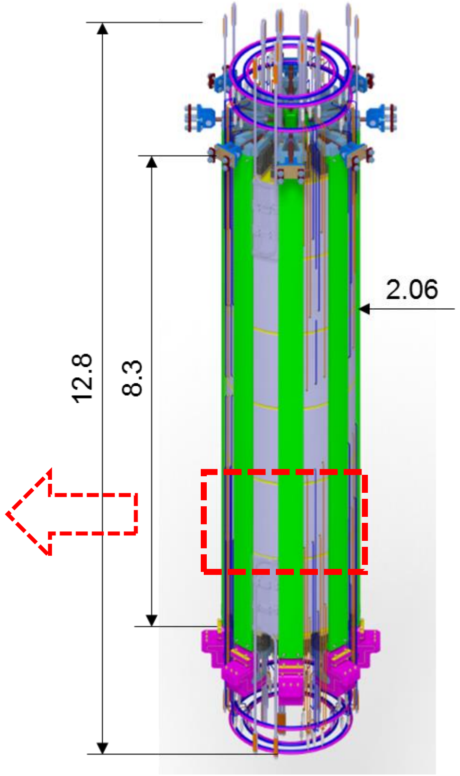


Sub-cable



CICC design under developing





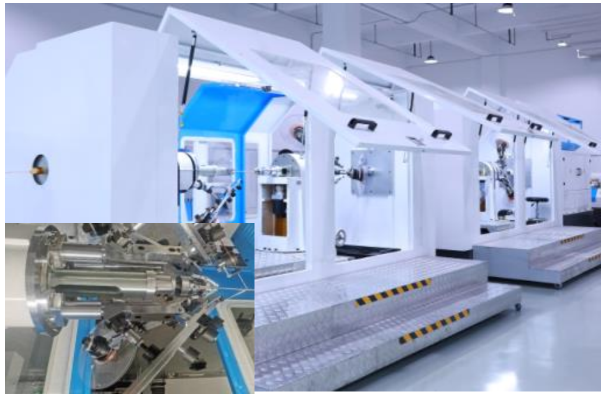
HTS magnet technology development

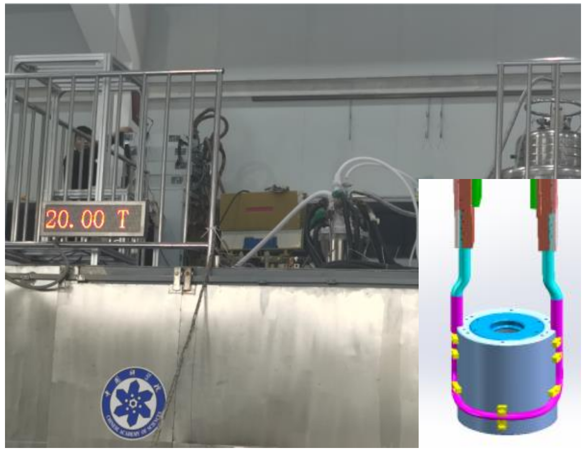
Sub-cable:

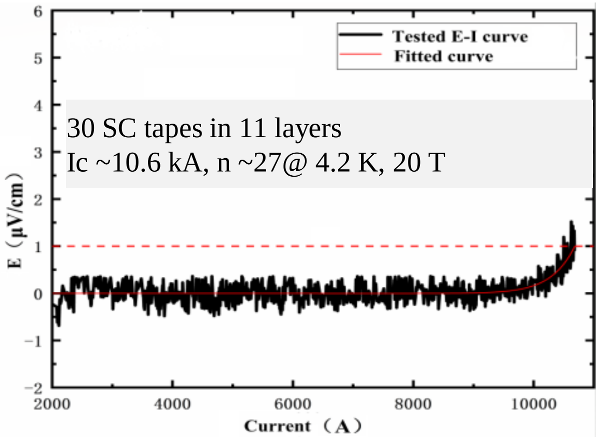
- Develop automatic cabling machine
- Sample performance → **I_c=10.6kA@20T, 4.2K**
- Long cable manufacturing → **L=110.6m**

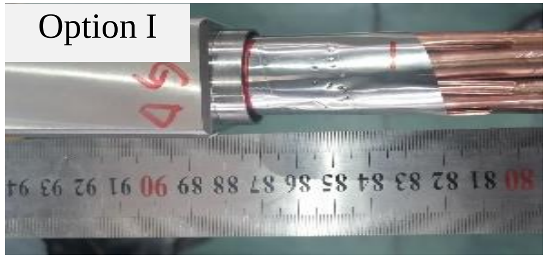
Full size conductor:

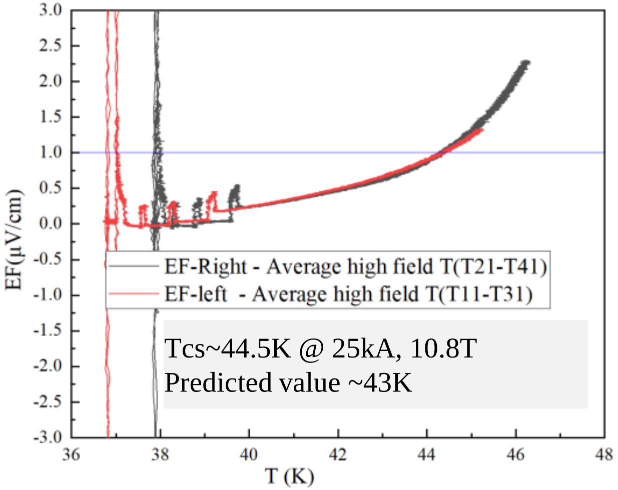
- Two sample legs were prepared → **2.7m per leg**
- Sample performance → **47kA@10.8T, 4.2K, stable**
- New optimized samples expected to finish in October











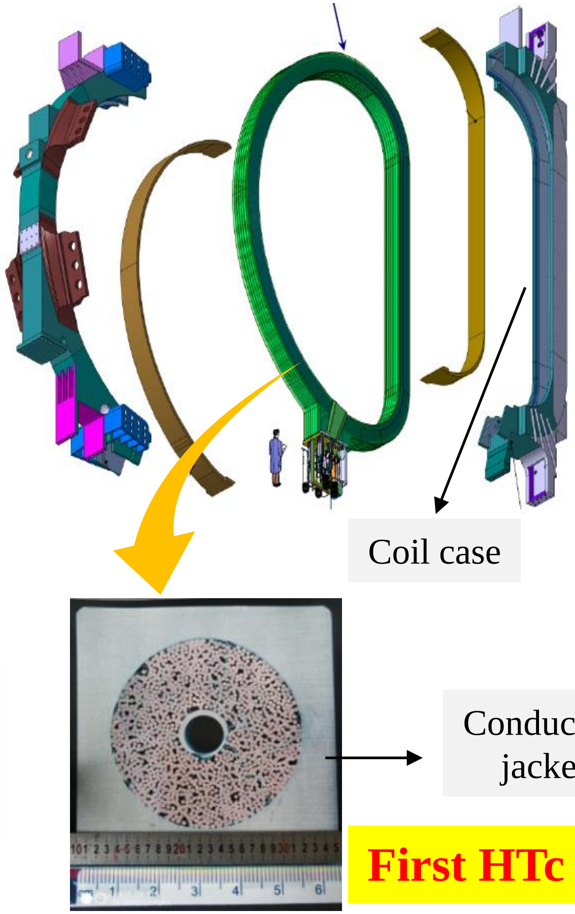
Final CICC conductor test will be April, Sultan

High strength Structural Material for CS&TF

- Modified N50 was developed for magnet of future fusion reactor.
- China has the mass production capacity of jackets, forgings and welding material.
- The production of jackets with a total length of 2000 m and 2 full-size forgings has been completed.

TF coil case

Conductor jacket



Coil case

Conductor jacket

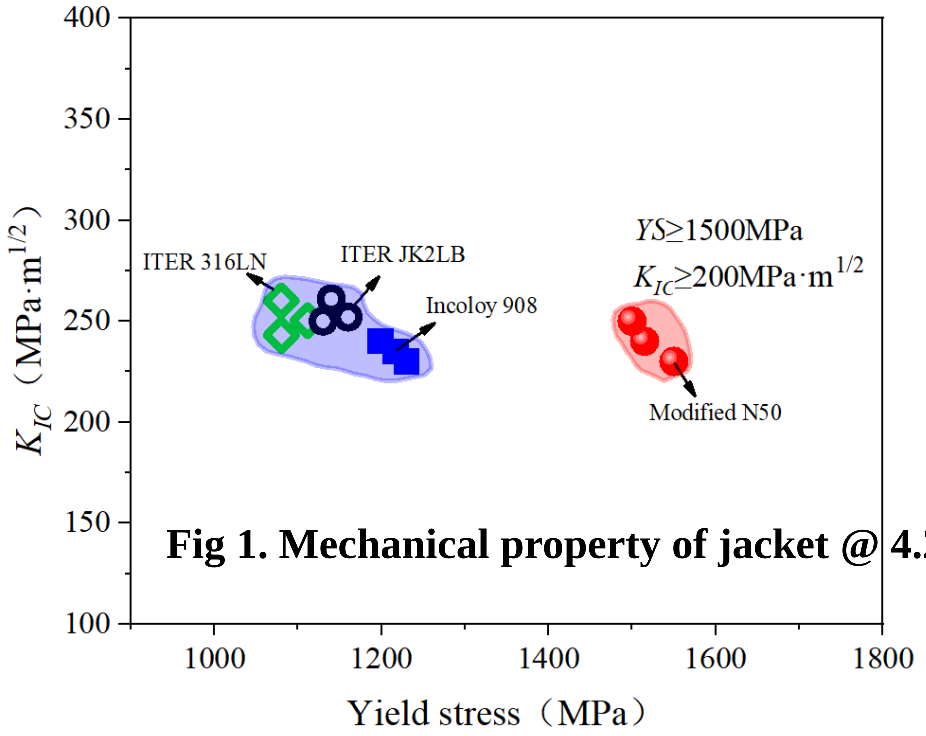


Fig 1. Mechanical property of jacket @ 4.2 K

First HTc CS coil will be finished and tested in the end of 2025

6. CFETR TF and testing

➢ Objective:

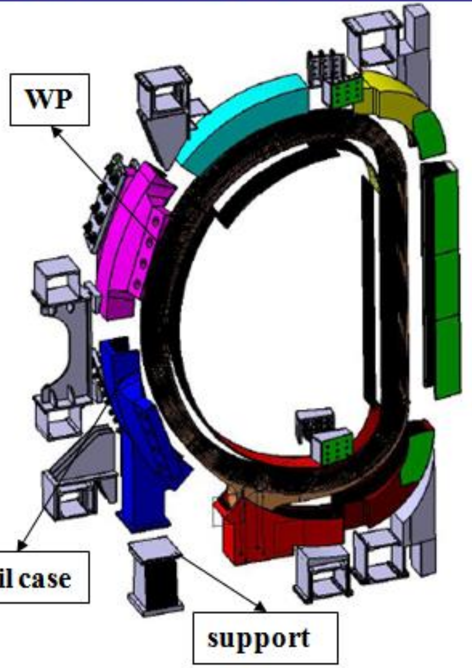
- To construct **a prototype TF coil** meeting the physical and engineering requirements of CFETR
- To develop and validate of fusion reactor **large-scale superconducting coil** manufacturing technologies and standards

➢ Main Technique Parameters:

Items	Value
I_{op}	95.6 kA
B_{max}	~14.5 T
Total Storage Energy of 16 TF coils	~120 GJ
Total Inductance of 16 TF coils	26.3 H
T_{op}	4.5 K
Insulation Voltage	＞10 kV
Height × Width	21.7 × 12.3 m
Total weight	~743 t

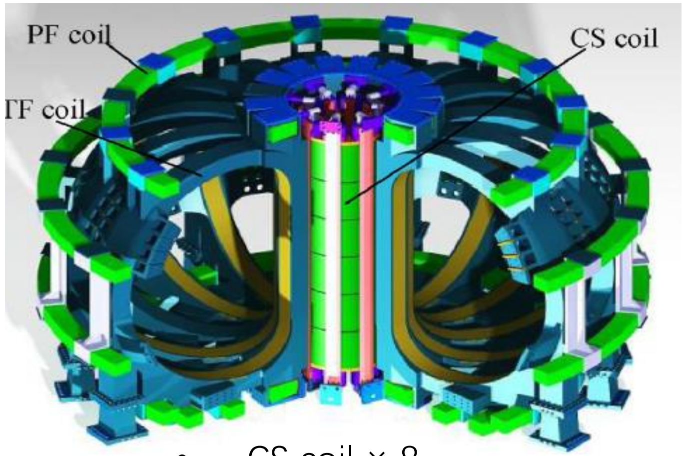
➢ System Description:

✓ Preliminary design model



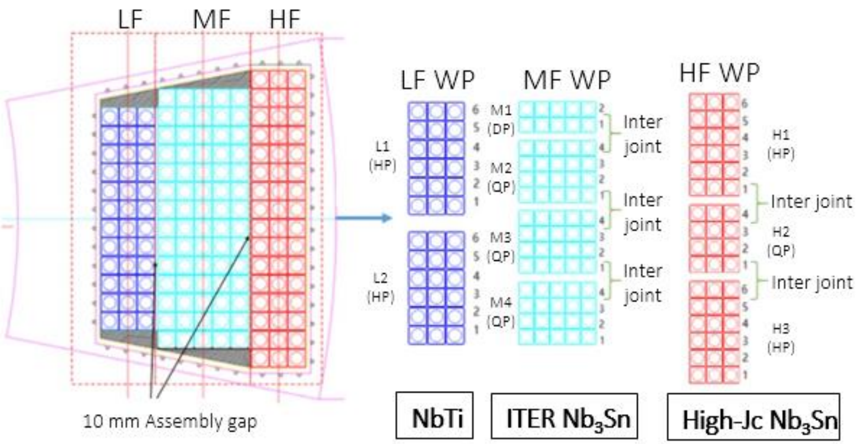
WP, coil case, coil support

✓ CFETR magnet system



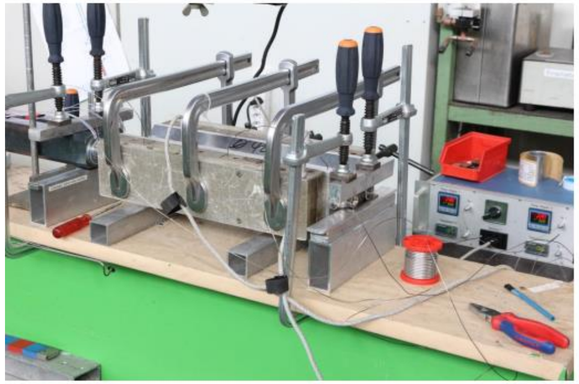
- CS coil × 8
- TF coil × 16
- PF coil × 7

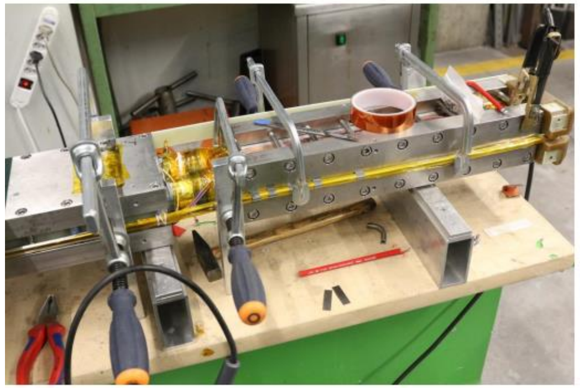
- **3 grades conductors** has been adopted



CRAFT TF Coil Progress

Coil Internal Joint (216) Technology





SULTAN sample

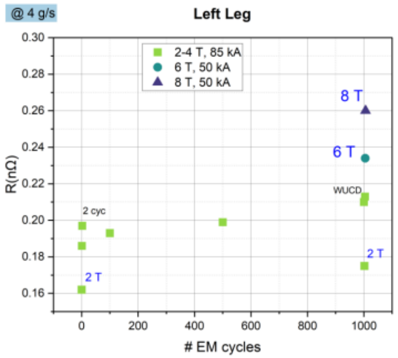


Figure 13: Resistance (nΩ) vs number of performed EM cycle for the left leg at 4 T and 85 kA. The points recorded at 2 T, 6 T/50 kA and 8 T/50 kA are also shown.

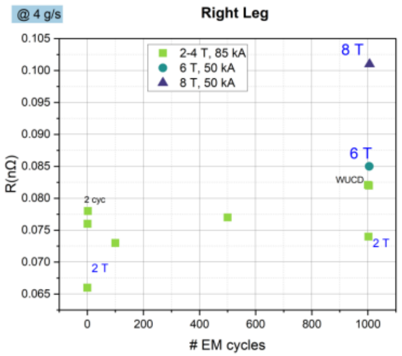


Figure 14 : Resistance (nΩ) vs number of performed EM cycle for the right leg at 4 T and 85 kA. The points recorded at 2 T, 6 T/50 kA and 8 T/50 kA are also shown.

- ✓ after 1000 excitation cycles and 2 WUCD, **joint resistance < 0.3nΩ @ 4T x 85kA,** and the resistance changes little.
- ✓ after 1000 excitation cycles, joint resistance **< 0.3nΩ @ 8T x 50kA.**

The technology is firstly developed for hybrid graded winding coil in the world, performance is excellent!

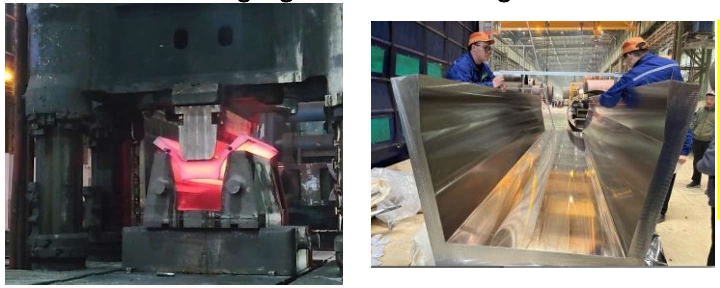
Coil Case Design and Manufacturing

- High Strength high-Mn austenitic stainless steel (JJ1) Forging Material development

Forging 1-10T ESR ingot

- ✓ yield strength@4.2K > 1000MPa
- ✓ fracture toughness @4.2K > 200 $MPa \cdot m^{1/2}$

New material in China which is +20% on yield strength @4.2K than ITER-316LN!



Forging 2-30T ESR ingot

- **QA/QC**
- **High performance SC wirl (Sultan)**
- **Long length cable**
- **CICC conductor (sultan)**
- **Long length CICC conductor (950m)**
- **Isolation material**

CRAFT TF Coil Progress

ASIPP

Winding Pack Design and Fabrication

- **Winding line and critical equipment**

Winding line
(commissioned in Oct,2022)

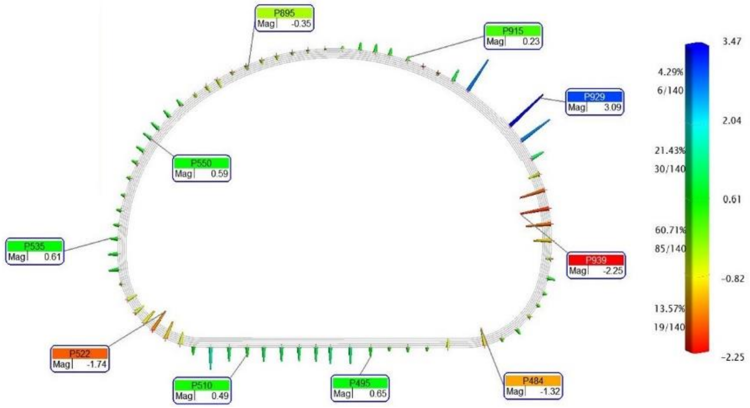
heat treatment furnace
(Under Commissioning)

turn insulation wrapping system
(Under Commissioning)

- **Internal joint fabrication**

Procedure and tooling are qualified.

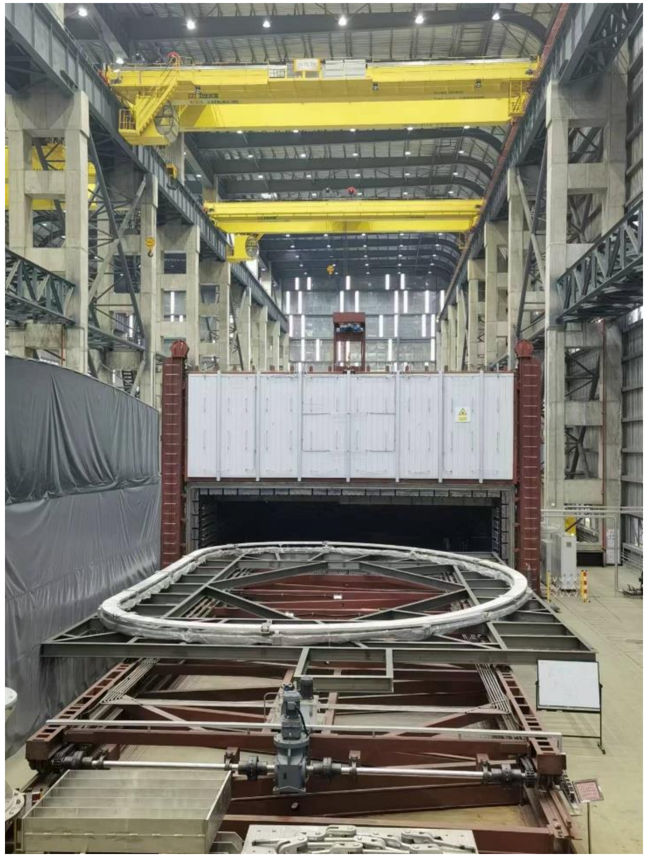
- **Dummy coil winding**



Procedure and tooling are qualified.
Dimension within tolerance.

CRAFT TF Coil Progress

4 /9 coils have been made



Heat treatments will start next month

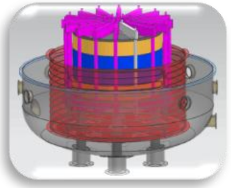
TF coil will be fully tested in Sep. 2025 (5 month delay)

7. Cryogenic testing facility

Objectives: To provide the cryogenic testing facility for CRAFT SC system.

To build a research and test platform aiming the technology development of future CFETR cryogenic system.

Cryogenic Public Service Platform ↔ **Cryogenic Key Technology Research Platform**



SC Magnet testing facility

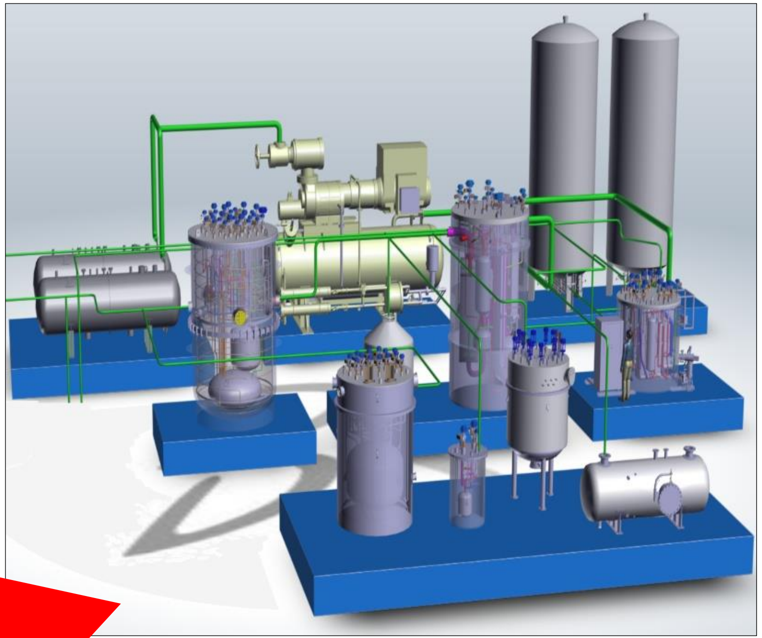
SC Conductor testing facility

SC Material testing facility

Helium Refrigerators

- 4kW/4.5K refrigerator
- 1kW/3.8K refrigerator
- 200W/4.5K refrigerator
- 250W/1.8K refrigerator

Total average cooling capacity over **7.2kW/4.5K**



CRAFT Cryogenic System

- Cryogenic Heat and Mass Transfer
- Cryogenic Fluid Machinery Property
- Cryogenic Process, Control
- and Safety Simulation
- Cryogenic Measurement and Calibration

Will be finished on end of 2024

8. Power supply testing facility

➢ Objective

- To solve the key issues of current tokamak coil power supply ;
- To develop the advanced (next generation) tokamak coil power supply ;
- To support the research and test of large current super-conductive magnet systems .

➢ Parameters

Feeding Coils:

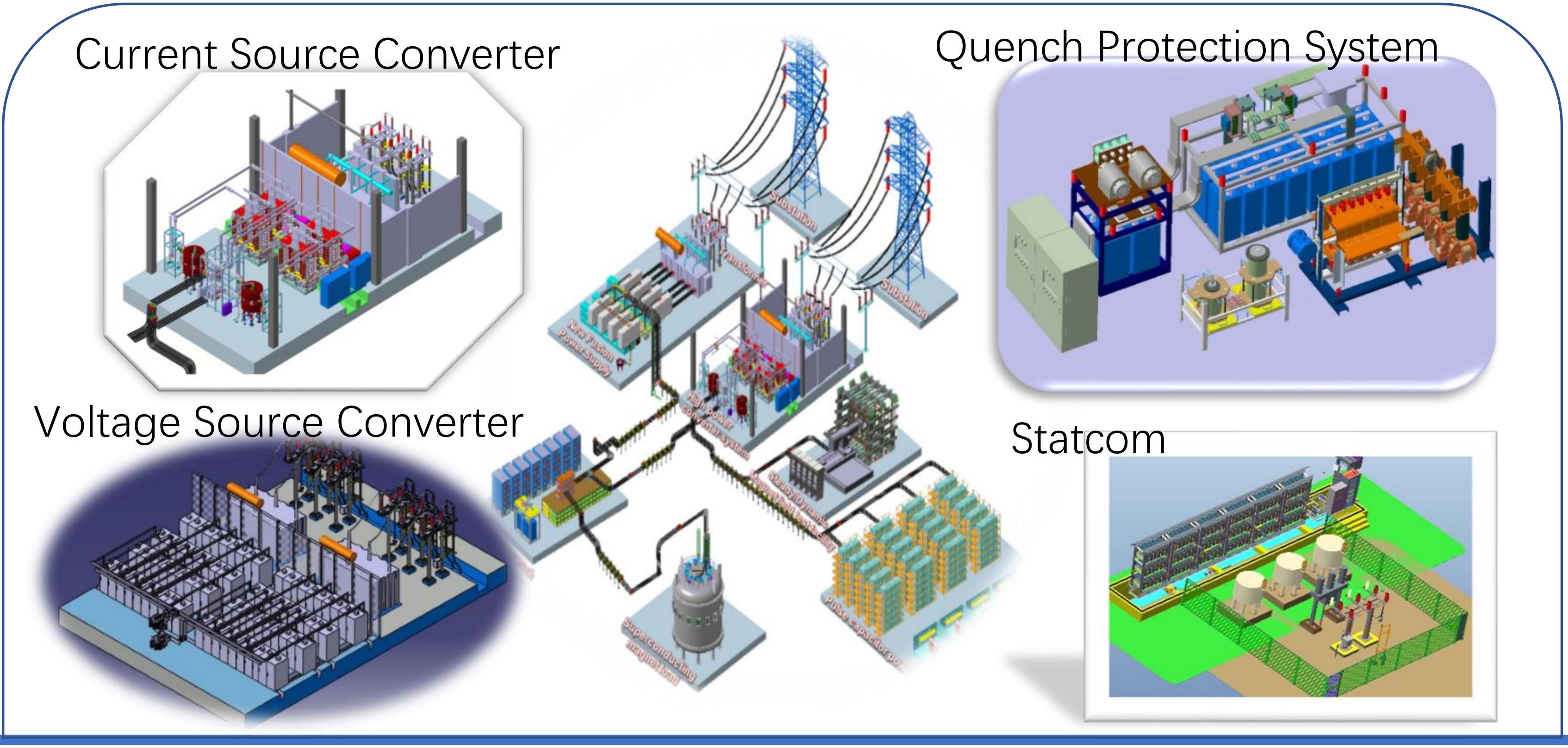
Current Source Converter:100 kA, 250 V

Voltage Source Converter: 60 kA, 3000 V

In case of quench :

Dissipated Power: 1GJ

Breaking time: <0.5 s



Advanced Coil-Grid Compatible Power Supply

New World Record Achieved

- 100 kA DC vacuum circuit breaker for quench protection system
- 100 kA pyrobreaker for quench protection system
- 2.1m* 2.1m *2.1m large scale SMF (Static Magnetic Facility) put into use



New Technology Adopt

- Low frequency -harmonic reactive power integrated compensation, **protype applied to industry**
- Energy storage power compensation technology, **protype applied in coal power industry**
- 15 kA Voltage source converter applied in **EAST.**



Project goes well, commissioning started.

9. Large linear plasma testing facility

Objectives: To address key R&D issues of plasma-facing materials and components for CFETR in appropriate physical regimes, size and time scales of plasma-material interactions.

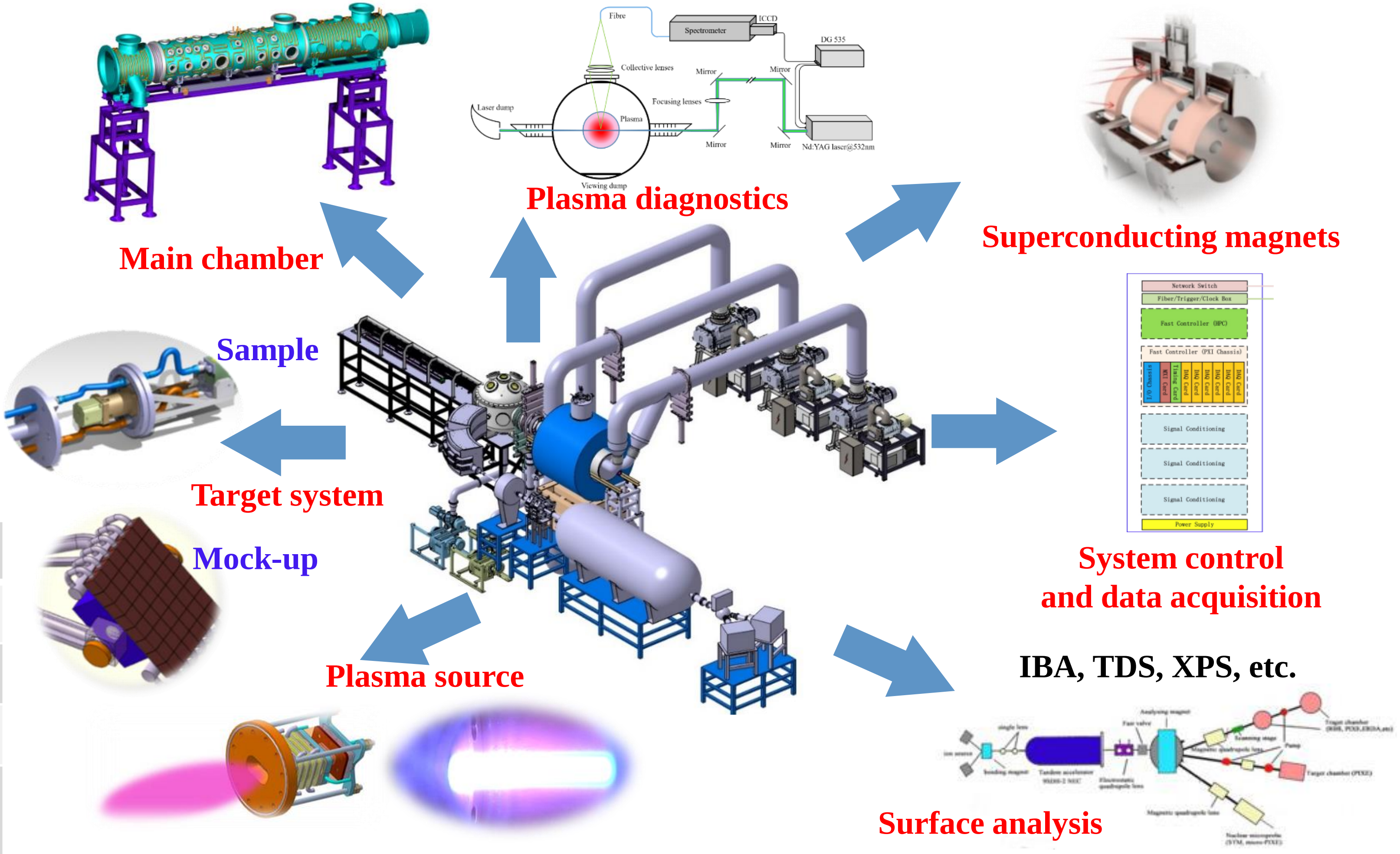
➢ Capabilities

Delivering DEMO divertor-relevant plasma streams of high heat and particle fluxes for material/mockup testing

In-situ/in-vacuo analysis for material surfaces

➢ Machine parameters

Shot length	~1000 s - hours
Magnetic field	~3 T
Particle flux	10^{24} -10^{25} m^{-2}s^{-1}
Plasma dimension	30-100 mm
Max. Sample/mock-up size	250×250 mm

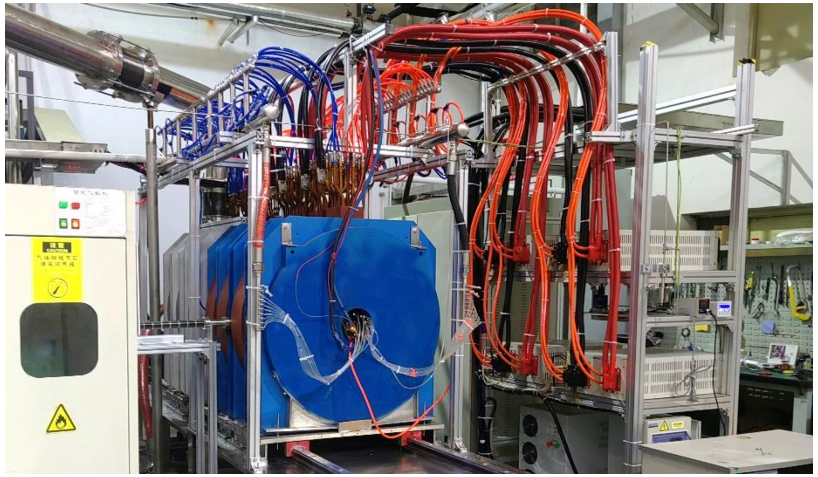


Large linear plasma facility

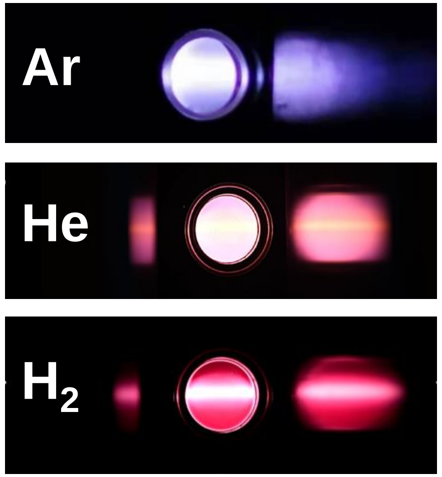
Progress

- Machine design is finalized and key components (e.g. SC magnet) are under manufacturing.
- A pilot machine (1T) has been built to develop plasma source technology.
- ~10^{24} $m^{-2}s^{-1}$, >24 h steady-state plasma discharge has been achieved.

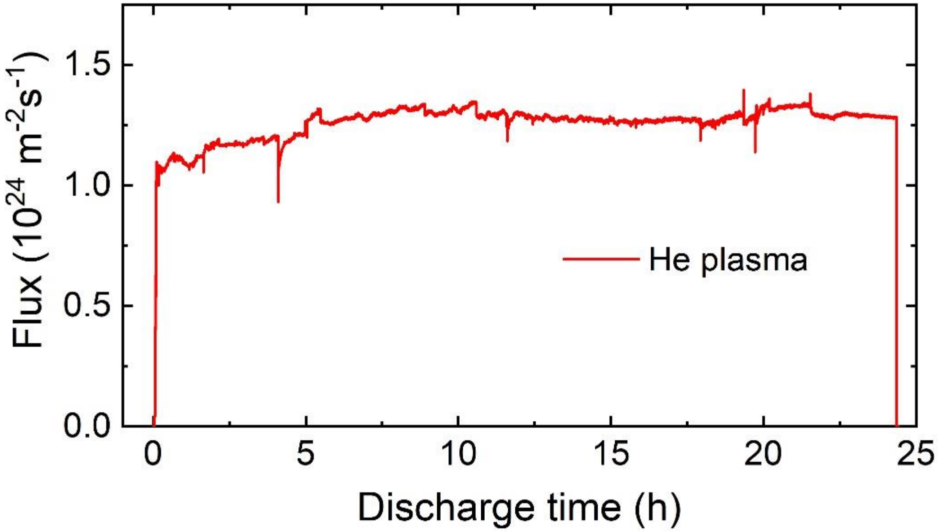
Pilot machine



Typical discharges



>10^{24} $m^{-2}s^{-1}$ flux for >24 hours



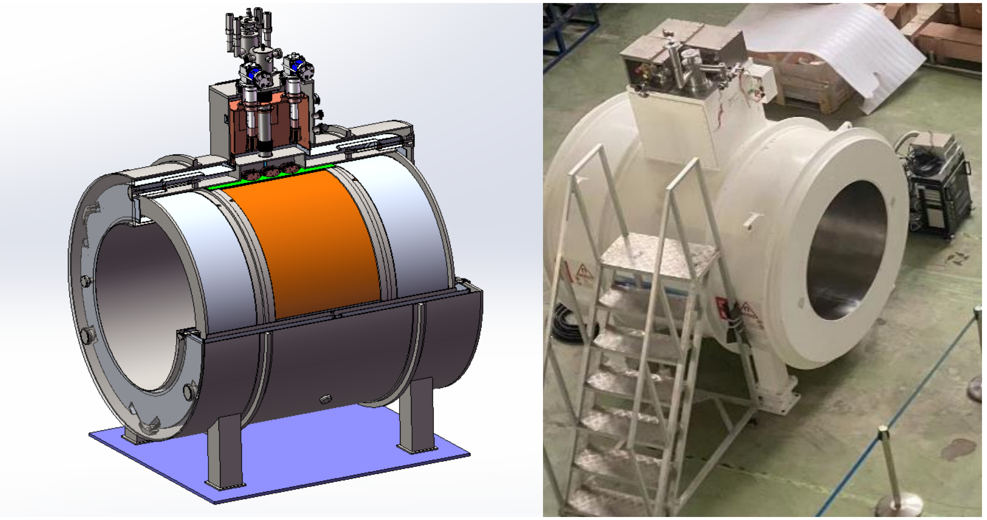
Will be finished on end of 2024

Large linear plasma device

Recent progress of the large linear plasma device

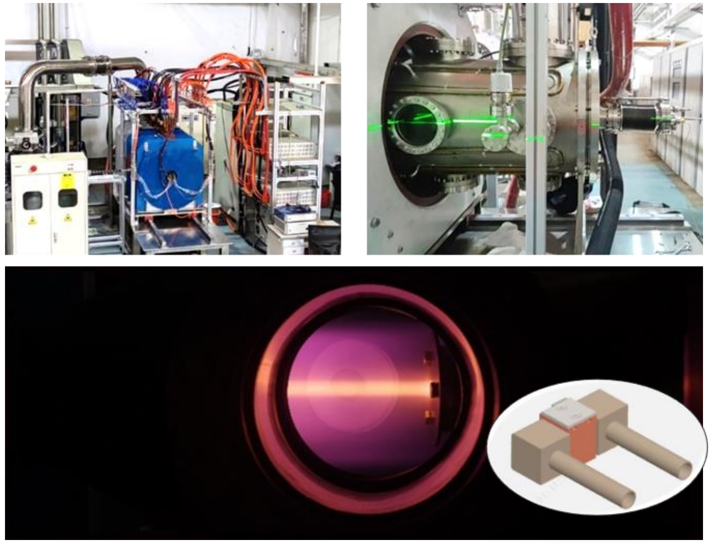
- The 3 T SC magnet has been fabricated successfully and is under cryogenic test.
- Manufacturing of vacuum chambers and supporting structure will be finished at the end of March, 2024.
- A prototype machine with ~10^{24} $m^{-2}s^{-1}$ particle flux is open to users for PWI experiments for one year.

The 3 T SC magnet under testing



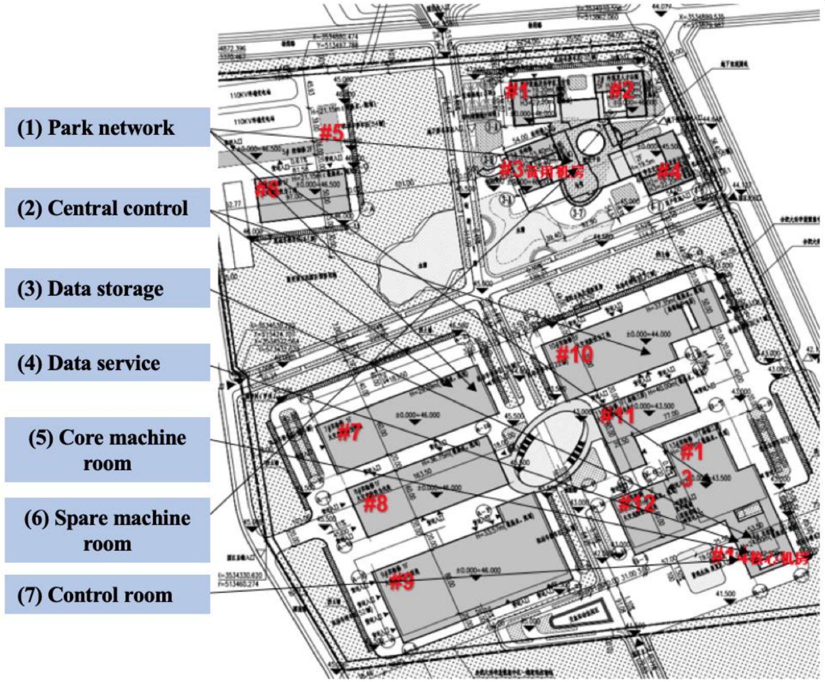
Vacuum chambers and supporting structure

The prototype machine for PWI exeriments



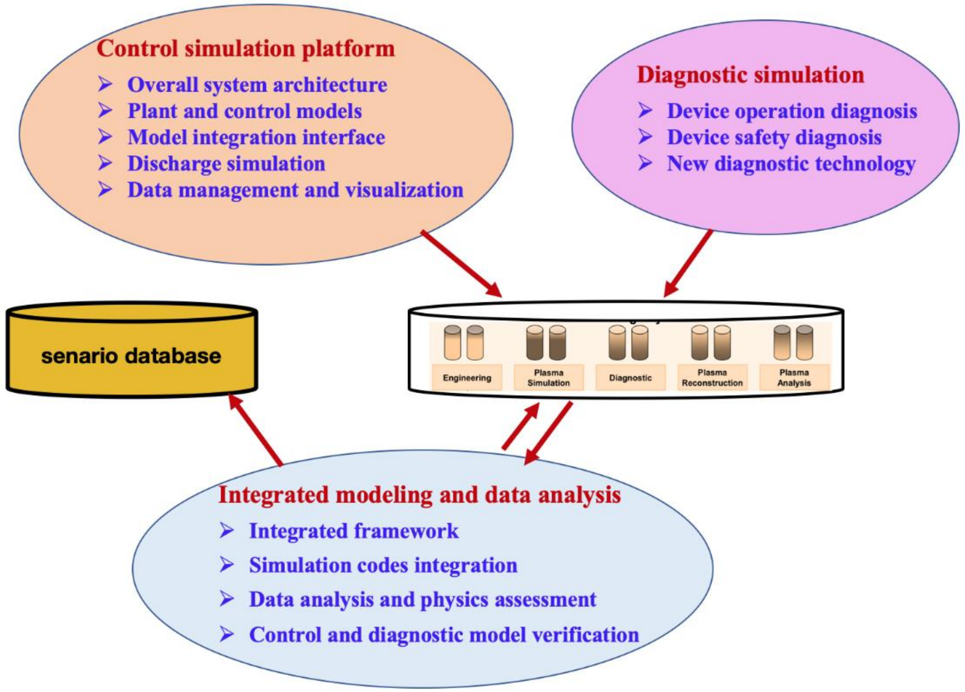
10. Mater Control facility

➢ **Scientific objectives : providing IT support for CRAFT campus and establishing numerical tokamak for CFETR plasma control system and discharge scenarios assessment.**



Campus IT support (in use)

- Network communication
- Data storage and service
- Timing and synchronization
- Interlock and monitoring



Numerical Tokamak (XIAO, YUAN on 20th)

- Control simulation
- Design and verification of discharge scenarios
- Event analysis and handling
- Discharge assessment
- Diagnostic technical development

11. CFETR divertor development

□ Construction objectives:

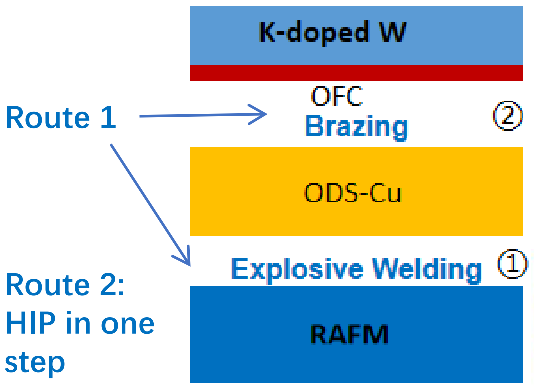
By optimizing preliminary design and implementing R&D of small, medium-sized test mock-ups and prototype fabrication, it will detemine the final engineering design of CFETR divertor.

□ Main technical parameters

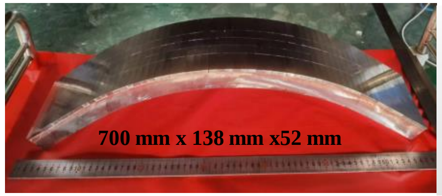
- Heat load capacity in strike point area sustaining steady state heat flux of 20 MW/m^2
- Profile error of plasma facing surfaces (PFCs) is less than 1 mm

□ Key technologies progess:

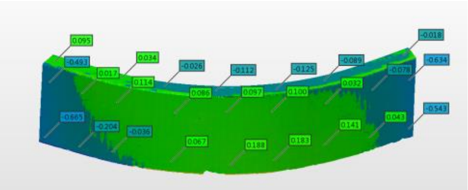
- **Material connection technology for fusion reactor materials**



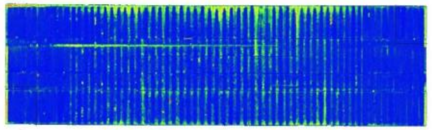
Two material connection routes



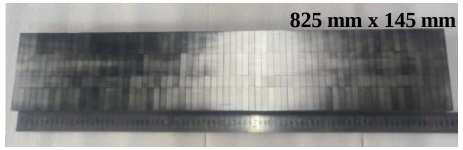
Curve section



PFC surface profile

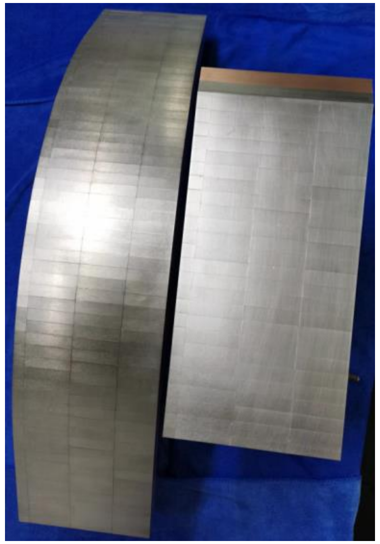


OFC/ODS-Cu UT results



Straight section

Route 1



Route 2

Medium-sized test mock-ups of two routes：

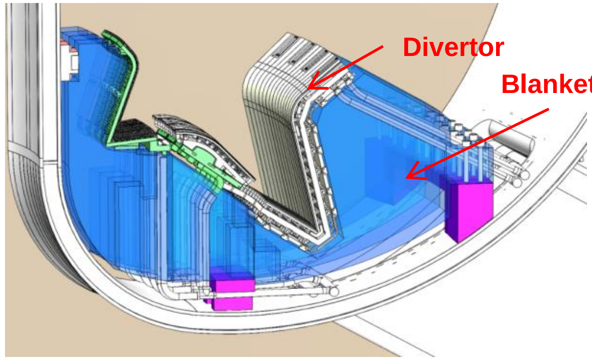
UT: no defects exceeds Φ2 mm equivalent.

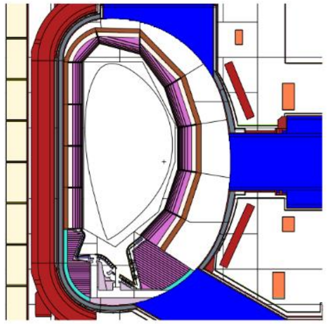
Profile error of PFCs: less than 1 mm.

7 MPa pressure test: meets reqiured He leakage rate of 1 x 10^{-10} $Pa·m^3/s$.

CFETR divertor development

● Hybrid divertor-blanket integration

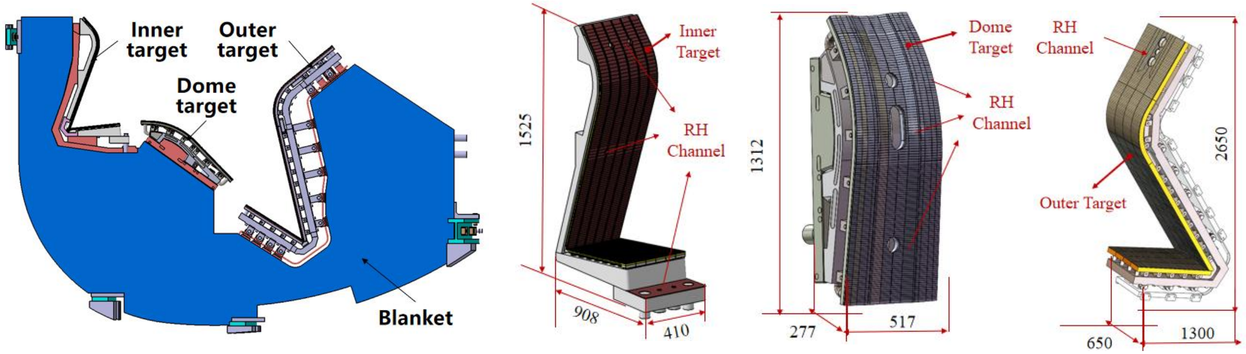




Blanket (conceptual design) and divertor (enginnering design)

Blanket design	I（Without any windows)	II（I + Considering all auxiliary systems)	III (II+Hybrid divertor-blanket)
TBR	1.147	1.029	1.175

● Independent RH dismounting technology for targets

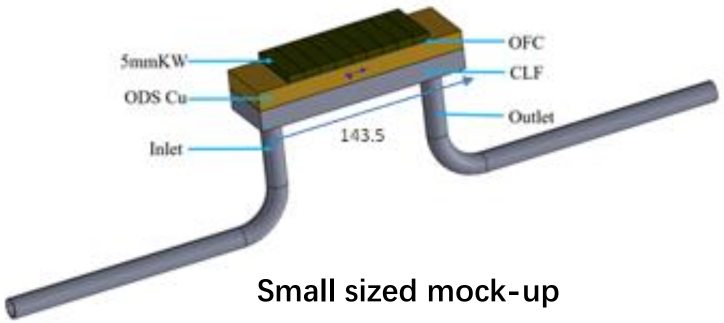


Enginnering design of divertor

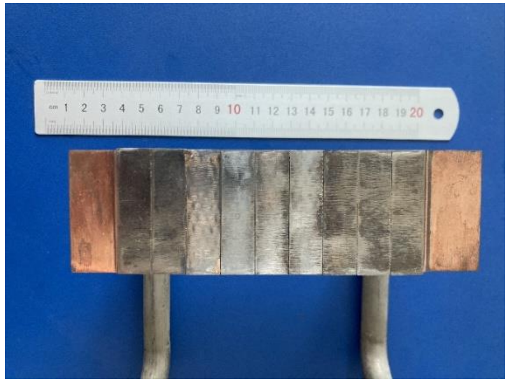
The divertor is ready for prototype fabrication:

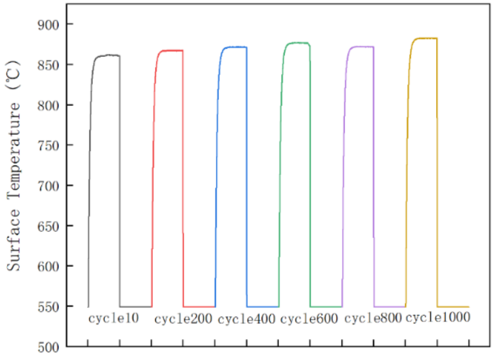
- All targets could RH from plasma side in design
- Preliminary feasibility analysis meets the requirements

● High heat load (20MW/m^2, SS) handling technologies

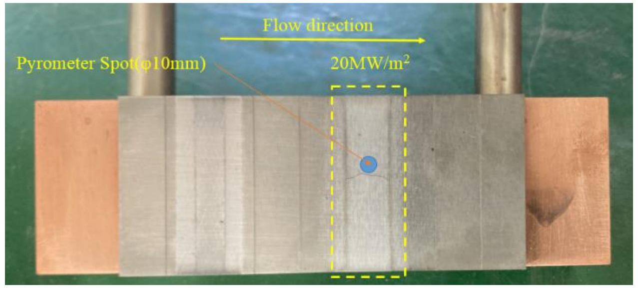


Small sized mock-up





Route 1



Route 2

20 MW/m^2, 1000 cycle (15s on, 15s off), HHF testing passed

XU's talk on 20th

12. CFETR divertor testing facility

Objectives: Provide testing environment of high thermal radiation loads and thermal hydraulic performance for water-cooled and helium-cooled divertor and blanket. The integrated testing for prototypes divertor to verify its performances.

➢ Key parameter

- **Steady state heat flux with EBG: 20MW/m^2**

Parameter	EBG-I	EBG-II
Max. power	800 kW	60 kW
Max. accelerating voltage	60 kV	120 kV
Pulse length	0.2s~∞	1ms~∞
Deflection angle	±15deg	±15deg
Deflecting direction	xy	xy
Deflection frequency	10kHz*deg	10kHz*deg
Min. beam spot Diameter	5mm(60kV)	1mm(120kV)

- **Water coolant loop**

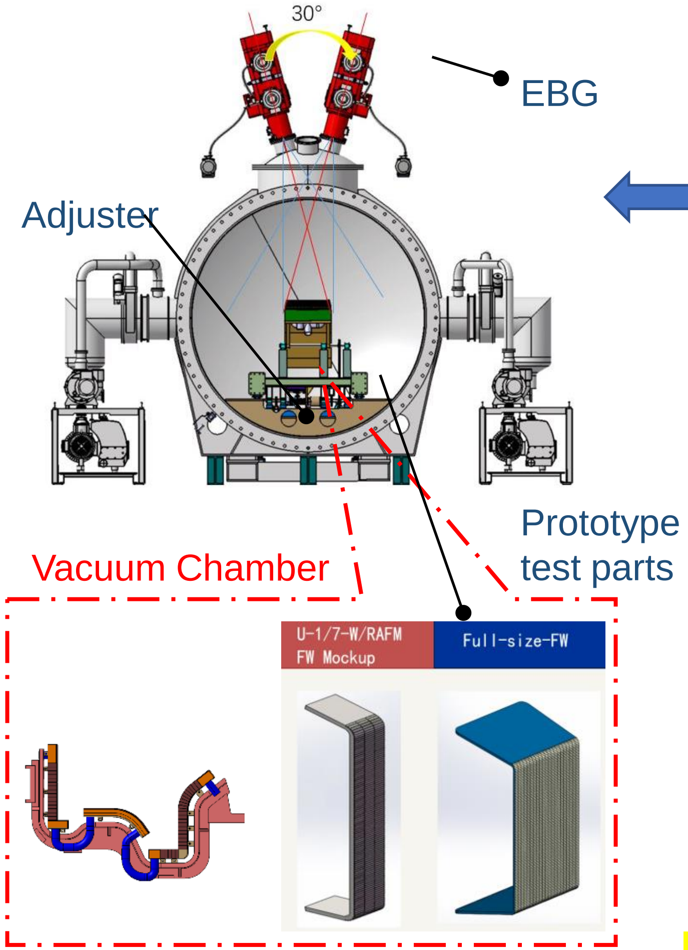
Operation pressure	Coolant temp.	Max. mass flow rate
15.5 MPa	285-325 ℃	120 m3/h

- **Helium coolant loop**

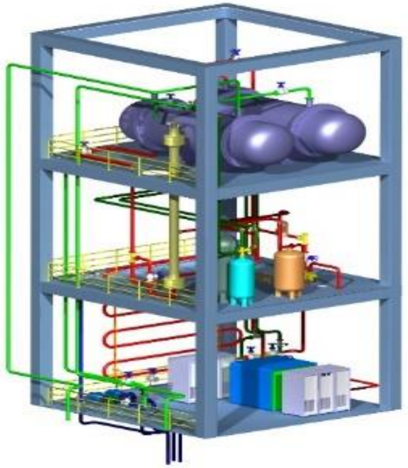
Operation pressure	Coolant temp.	Max. mass flow rate
8 MPa	300-500 ℃	3 kg/s

- **Vacuum chamber**

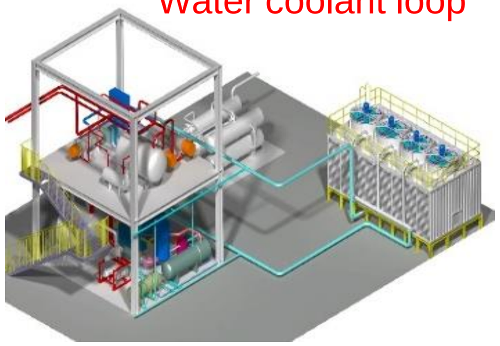
Diameter	Length	Pressure limit
3 m	4 m	1 MPa



Divertor First wall of blanket



Water coolant loop

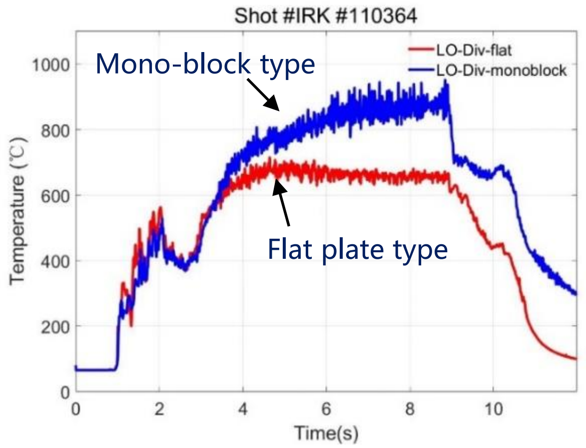


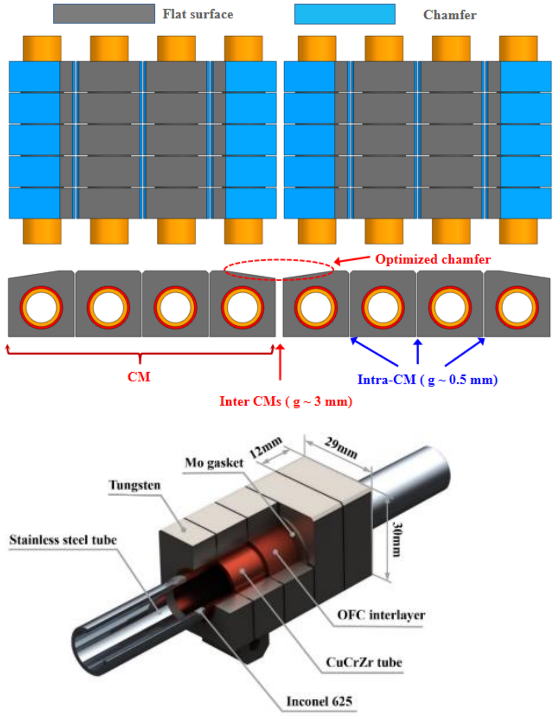
CO2 coolant loop

Started in operation from 2023

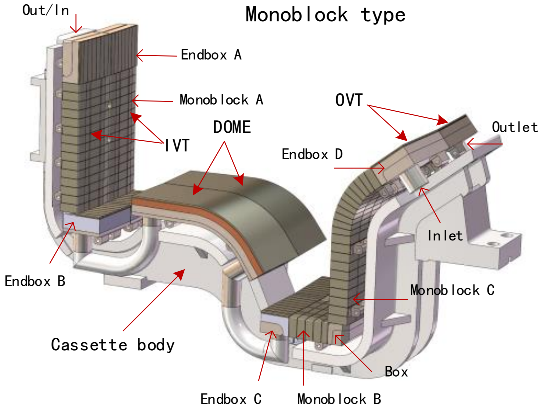
EAST Lower divertor Validation

Technical specification & parameters			
	Mono-block type	Flat plate type	Notes
Quantity of Modules	42	6	Total：48
Heat flux capability	10MW/m²	20MW/m²	Steady state
Cooling water	Max flow velocity：8m/s，Inlet：20℃		Total：650 ton/h
Work pressure	3MPa，Test：3.8MPa		



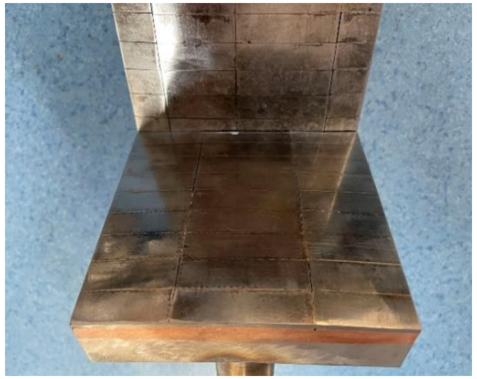


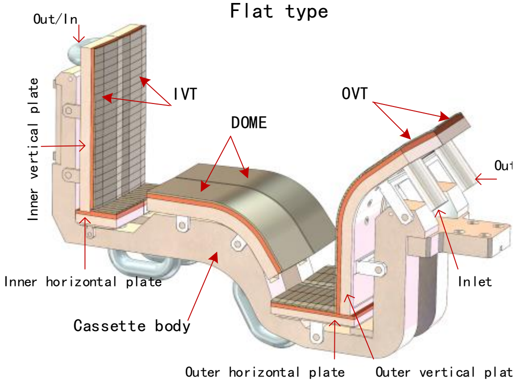
Mono-block type
ITER-Like design
Steady state:10MW/m²

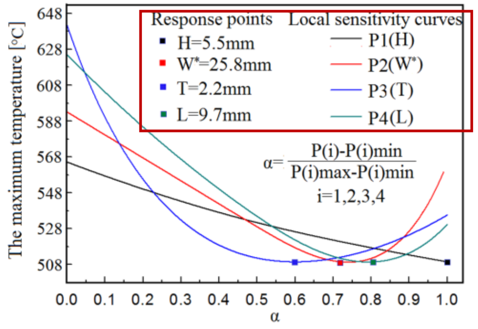


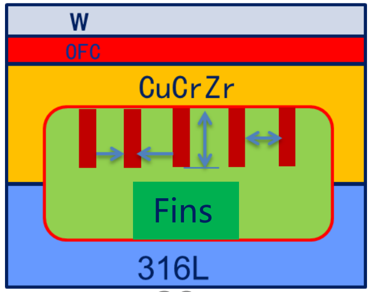
Flat plate type
Hyper-vapotron design
Steady state:20MW/m²

Based on the parameterized design method, the optimal fin geometry size was obtained with the goal of reducing the maximum temperature.



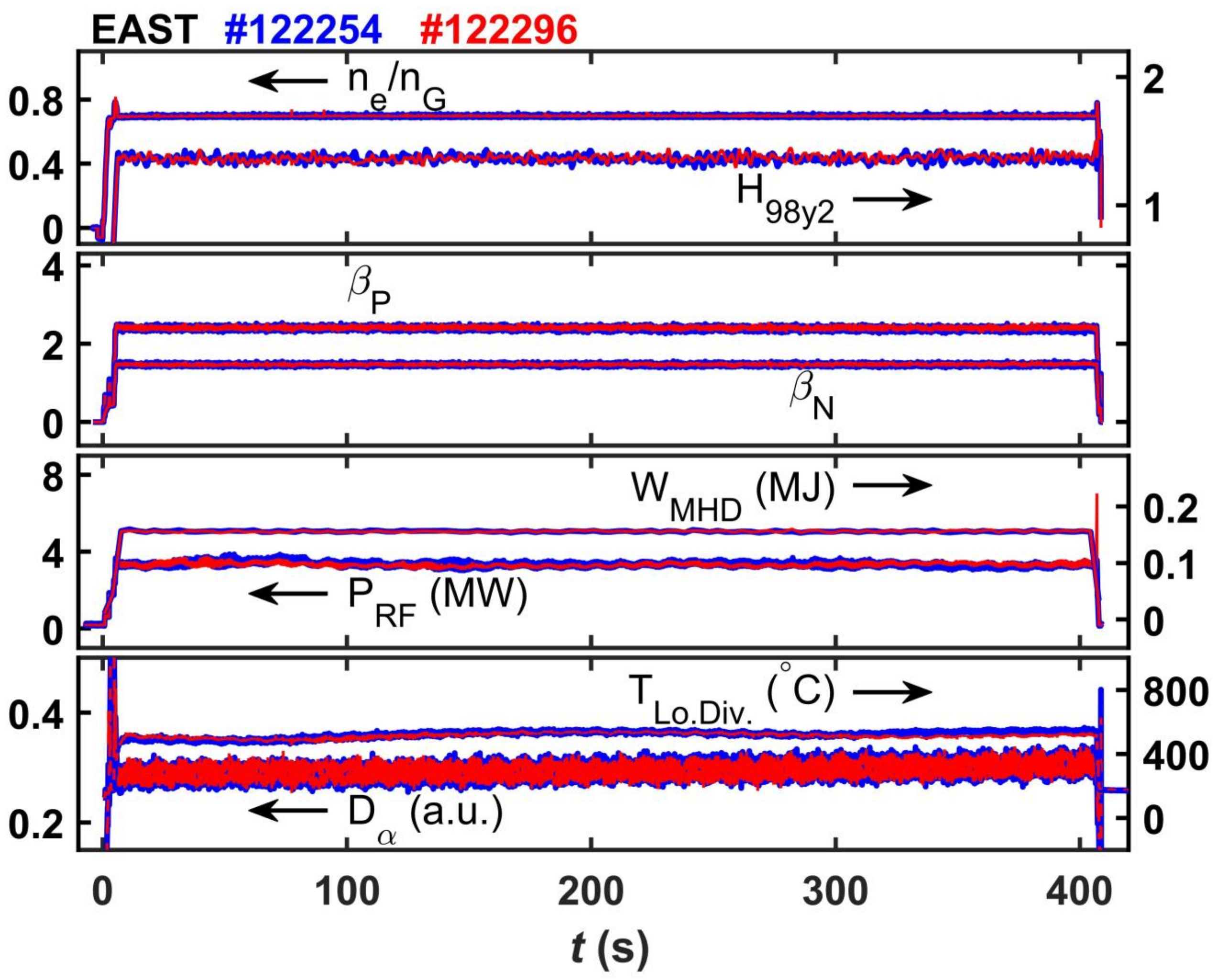






400s H-mode in EAST

✓ Demonstration of Reliable 403 Seconds Stationary High Confinement Plasmas



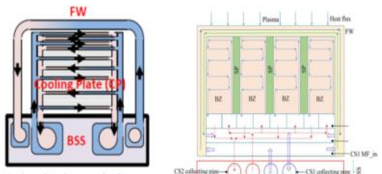
- A full non-inductive with n_e/n_{GW}~0.7 and f_{BS}>50%) by RF heating with zero torque injection
- $H_{98,y2}$ ~1.35 /T_e>8.5keV with ITB by electron dominant heating
- Key issues on particle balance and heat load with actively cooling W-divertor (R~0.92 and $T_{Surf@Div}$<600℃)
- Small ELMs throughout the discharge, with high core performance (β_P~2.5/ β_N~1.5)
- Heat loads on new divertor is about 8.7 MW/m2.

13.blanket :Water cooled ceramic breeder

Design strategy

Hydraulic decoupled concept for blanket heat removal

- Two independent cooling systems (CSs): CS1 for FW and CS2 for BZs.
- Easy to adjust mass flow for CS1 and CS2 independently during multiple power operation (0.2/0.5/1/1.5GW)

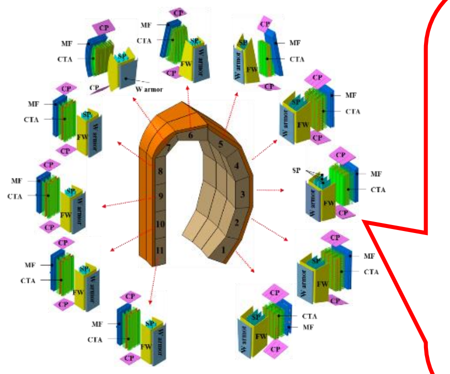


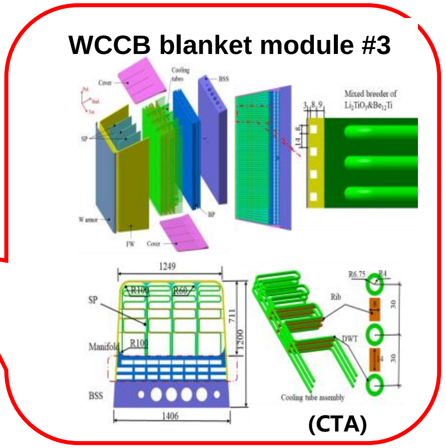
Hydraulic decoupled concept

Material selection

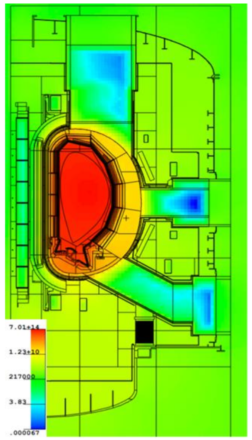
	material	parameters
Coolant	Pressurized water	15.5 MPa, 285℃/325℃
Structure	RAFM/ODS steel	Allowable temp. ≤550/650 ℃
FW armor	Tungsten	Allowable temp. ≤1300 ℃
Breeder and multiplier	Li_2TiO_3 & $Be_{12}Ti$ mixed bed	Allowable temp. ≤900 ℃ and >400℃ (tritium release)
Purge gas	He+0.1%H_2	0.1-0.3MPa， 0.1-10 cm/s

Structure features for normal blanket modules





Neutron flux distribution



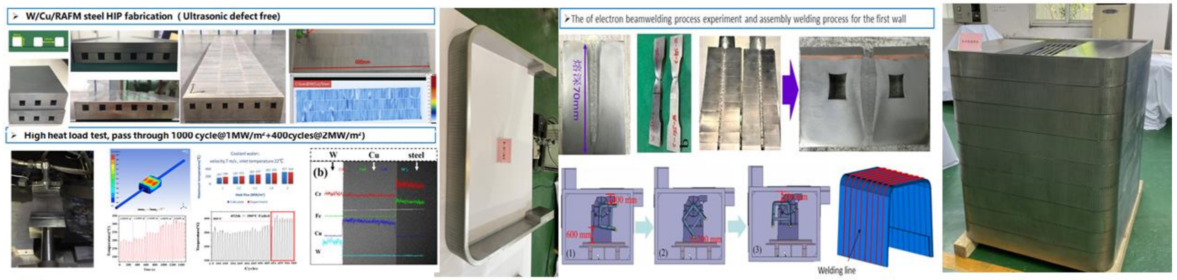
- Stiffening plates (SPs) divide the steel blanket box into several sub-zones to enhance the structure.
- The FW is a U-shaped plate bended in the radial-toroidal direction and cooled by water.
- Cooling tube assemblies (CTAs) are embedded in BZs filled with mixed pebble beds for heat removal.
- The ribs are bonded with SW/SP to enhance the blanket box structure.

Global TBR is 1.17, 33% efficiency

R&D activities

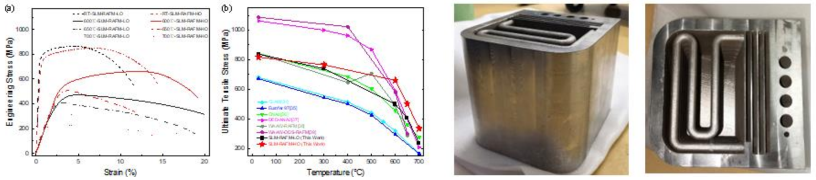
Fabrication technology

- HIP+EBW technology

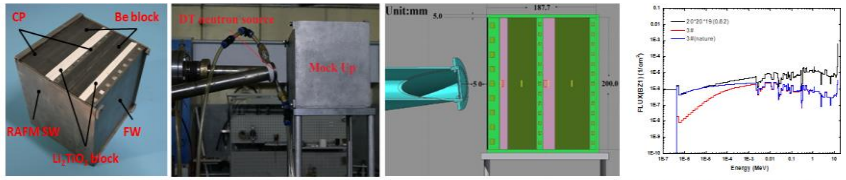


- 3D printing technology

- High temperature mechanical properties of SLM-ODS-RAFM are significantly improved.
- The additive manufacturing work of U type WCCB module was completed.



Neutronics experiment



WCCB Mockup (20×20×19 cm) (scaled module #3 of WCCB V2013)

Experiment setup

Monte Carlo model and neutron flux comparison between WCCB blanket module #3 and the scaled mockup

- TPR measurement by online lithium glass detector and offline liquid scintillator
- Calculated/Experimental results of TPR are consistent

Supercritical CO2 cooled Lithium-lead (COOL) blanket

Design strategy

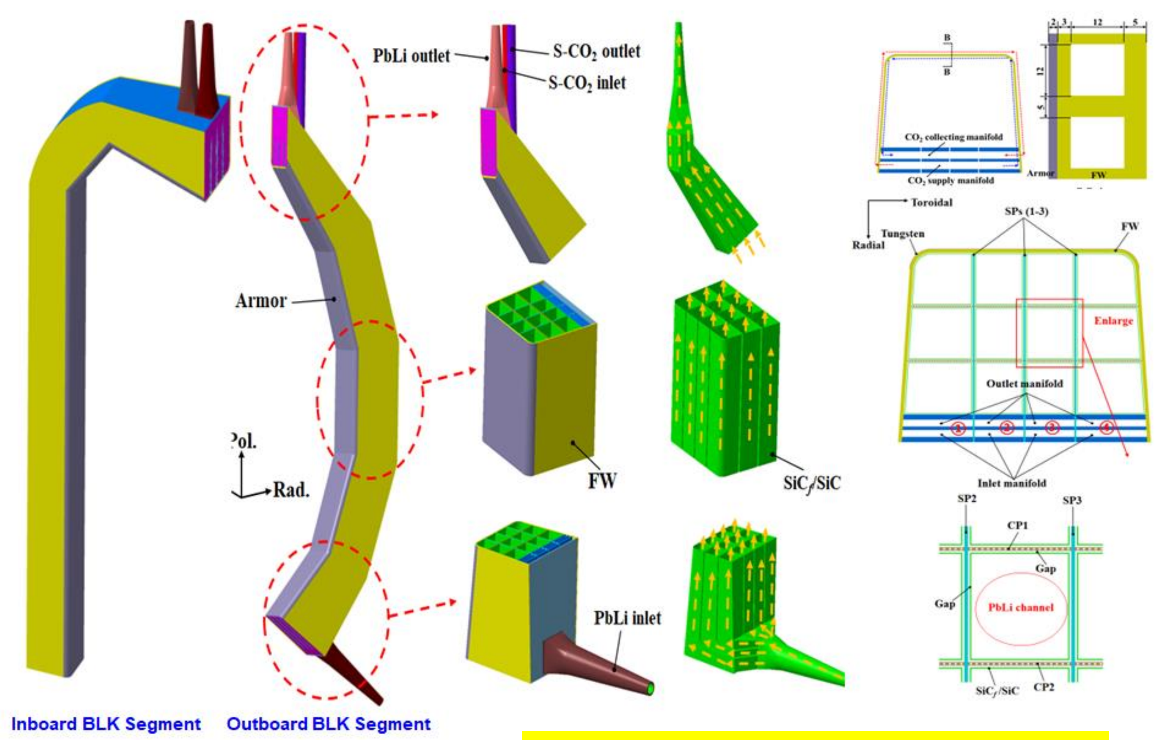
- **Coolant conditions:** (1) $S\text{-}CO_2$ for structures: 8 MPa, ~350/400 ℃ over DBTT for RAFM; (2) PbLi for BZs: ~0.01-0.1m/s, 460 ℃ /600-700 ℃.
- **Temperature limits:** within material allowable temperature range (@1.5 GW, $0.5MW/m^2$ on FWs)
- **Low MHD effect and weak corrosion:** (1) PbLi-RAFM interface: < 480 ℃ for avoiding strong corrosion; (2) SiC FCIs: thermal and electric insulating to decrease RAFM temp. and reduce MHD effect.
- **High thermal efficiency:** (1) outlet temp. of PbLi: 600-700℃; (2) efficient PCS: $S\text{-}CO_2$ recompressing Brayton cycle.

Advantage

- **High thermal efficiency**: high PbLi outlet temp. and more suitable for efficient power conversion
- **Acceptable construction cost:** (1) cheaper neutron multiplier of Pb; (2) abundant CO2 in natural world
- **Controllable MHD effect and metal corrosion:** using electrical and thermal insulating Flow Channel Inserts (FCIs)
- **Enhanced heat removal capacity of S-CO2**: larger density than helium (over 10 times @8MPa, 400℃)

Structure features

Global TBR is 1.18, 45% efficiency

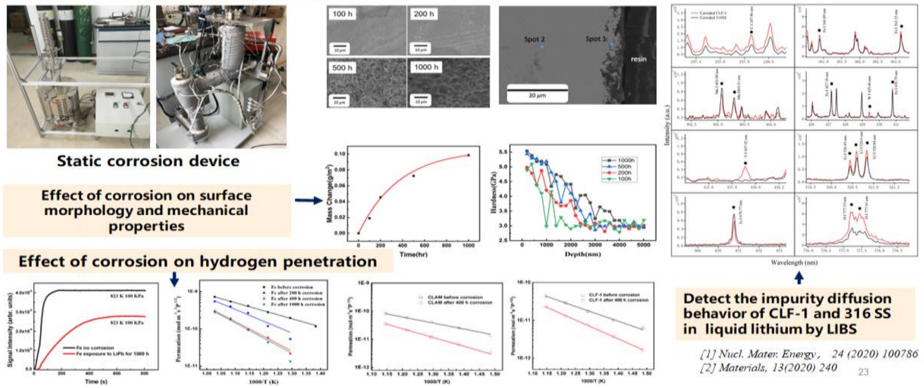


- Single-Module Segment
- U shaped FW coated with Tungsten armor, containing 127 channels, cross section of 12mm*12mm
- S-CO2 manifold configured in the back
- SPs and CPs divide breeding unit into several PbLi breeder zones
- PbLi flows through parallel channels from segment bottom to top
- FCIs to mitigate the MHD effect and corrosion
- 5mm gap between FCI and steel wall

CHEN's Talk on 21th

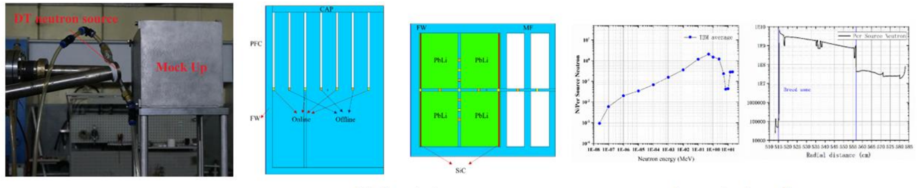
R&D activities

Corrosion compatibility of liquid metals



[1] Nucl. Mater. Energy, 24 (2020) 100786
[2] Materials, 13(2020) 240

Neutronics experiment for COOL mockup (out-of-pile)



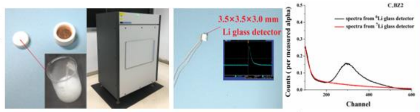
Experiment design

Mock-up design

mockup neutronics performance

Parameters of DT neutron generator

Mode	DC	Pulse
Beam Spot	<10mm	<6mm
D^+ Intensity	0~1.5 mA	0~40 μA
Neutron Intensity	0~3E11 /s	0~1.0E10 /s



Off-line TPR measurement

On-line TPR measurement

- Mock design
- Experiment under DT neutron field
- TPR measurement by online and offline technology

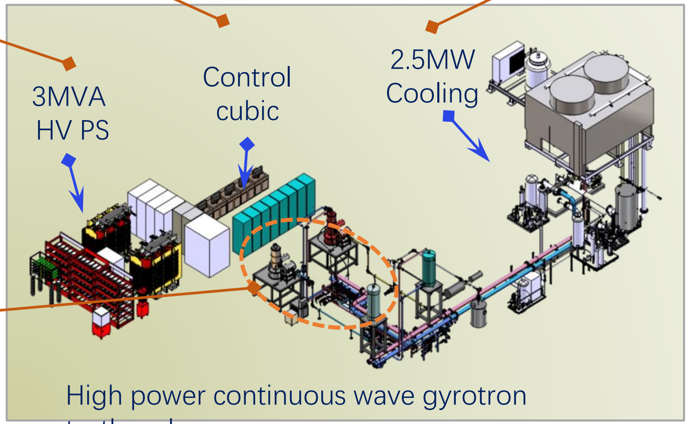
14. ECRH facility

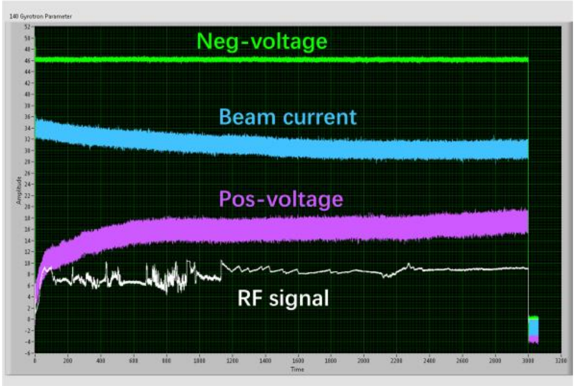
- **Aims:** to address the technical issues as well as to pursue technical solutions for critical components of the future advanced CFETR ECRH system.
- R&D efforts focus on the design and performances assessment of key components, (conditioning of gyrotrons, trans and launcher.

Specifications		
1	Frequency	170 GHz
2	Output power	2 MW
3	Pulse length	>60 s

◆ Development and installation of high power CW gyrotron testbench

170GHz
0.4s, 0.56MW





Test performance validated – 700kW, 3000s pulse duration

Will be finished in the July of 2025

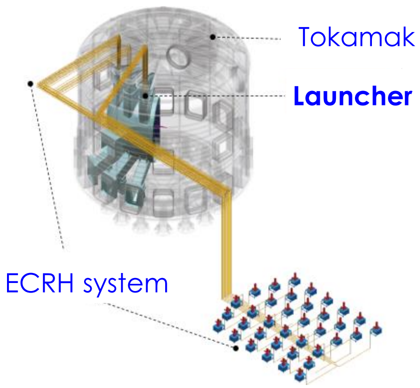
14. ECRH facility

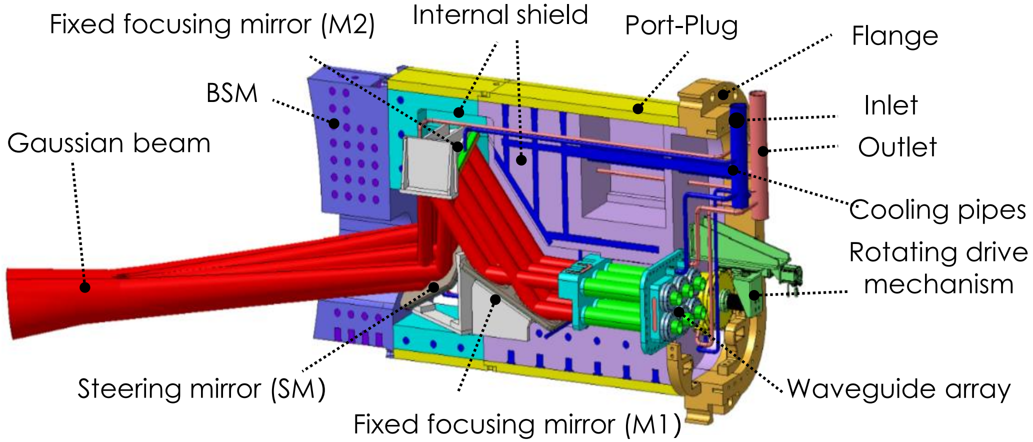
◆ Mockup design of multi-convergency launcher is ongoing

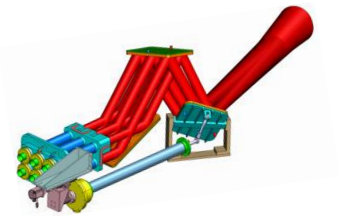
- The multi-beams injection equatorial launcher is designed based on the front steering (FS) concept
- The beam convergence characteristic has been determined by quasi-optical optimization
- Preliminary analysis of thermal-mechanical performances and EM force distributions has been done

Technical challenges

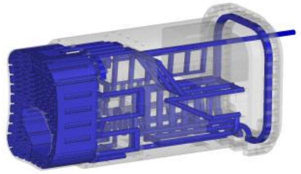
- Reliable operation
  - Large-size irregular focusing mirror
  - SMA (Steering Mechanism Assembly)
  - Cooling, EM…
- Irradiation resistance
  - Material (mirror, Port-plug…)
  - Shielding properties
  - Interface with BSM
- Remote handing
  - Interface with RH
  - The launcher suitable for RH maintenance



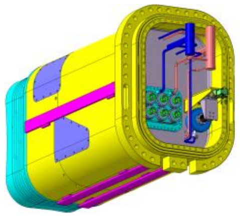




Quasi-optical unit

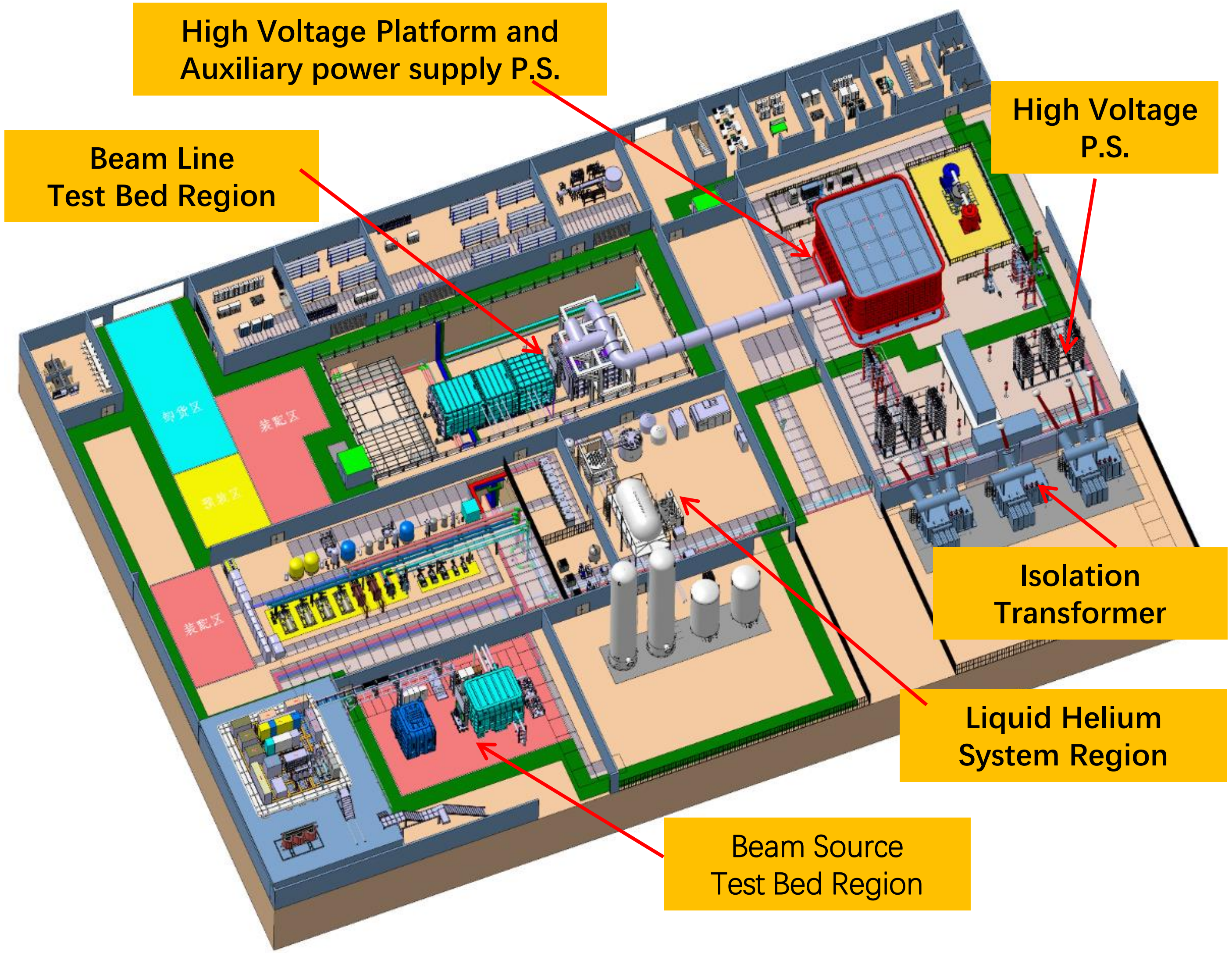


Shielding unit



Interfaces with RH, VV…

15. NNBI System of CRAFT Project



Comprehensive Research Facility for Neutral Beam Injection System Based on Negative Ion Source

- **Establish a comprehensive research facility for neutral beam injection system based on negative ion source.**
- **Developing negative ion source technology for NNBI and cultivating a professional talent team.**
- **Establishing a technical and talent foundation for next generation of fusion experimental device in china.**

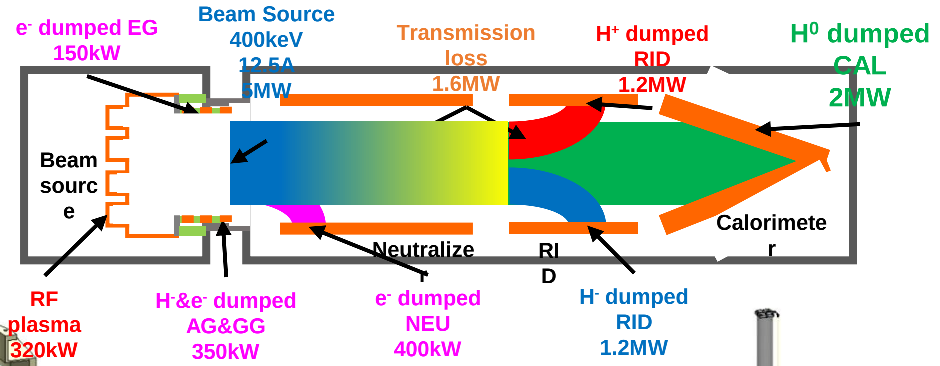
Parameters	Target Aim
Beam Species	H^0
Beam Energy	200-400keV
Neutral Beam Power	2MW
Beam Duration Time	100s

15. NNBI system

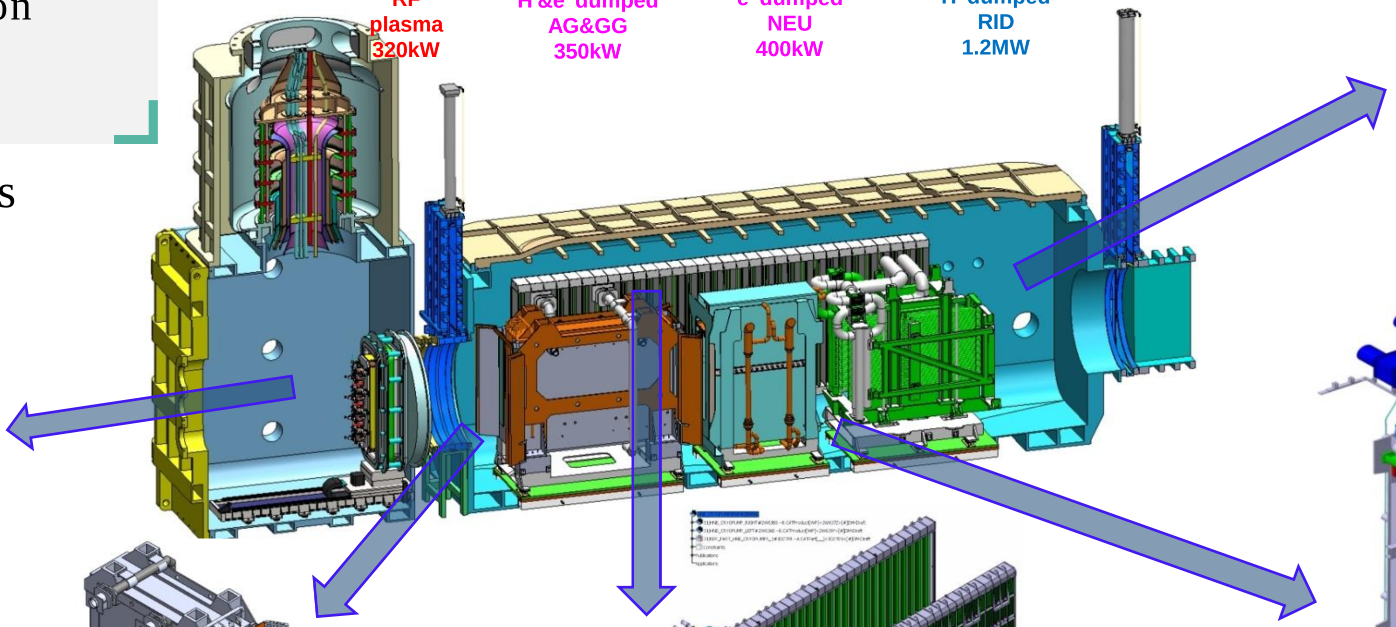
➢ Key technology

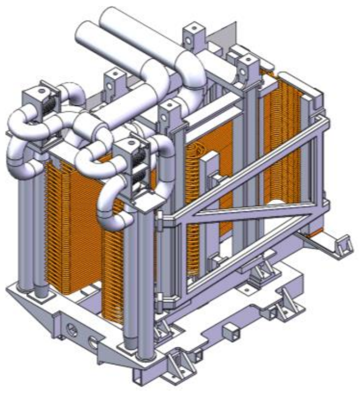
- Negative ions generation
- Negative beam acceleration
- HVPS and transmission
- High speed cryopump

- 400keV, 2-4MW, 1000s

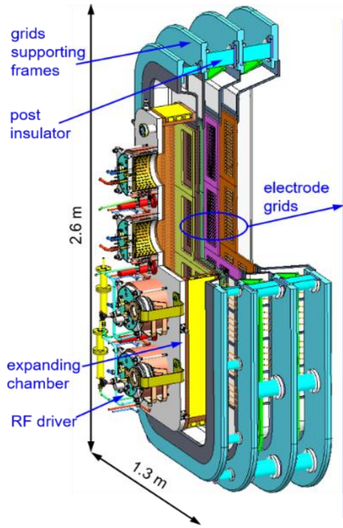


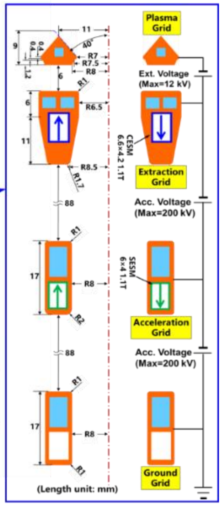
CRAFT NNBI components

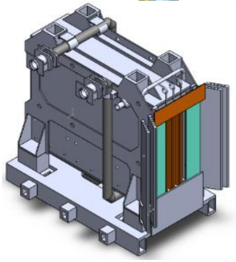


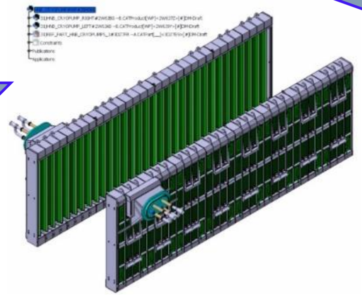


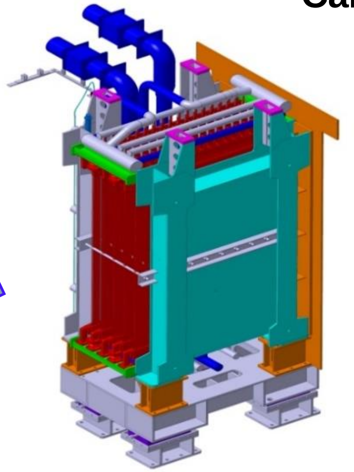
Calorimeter











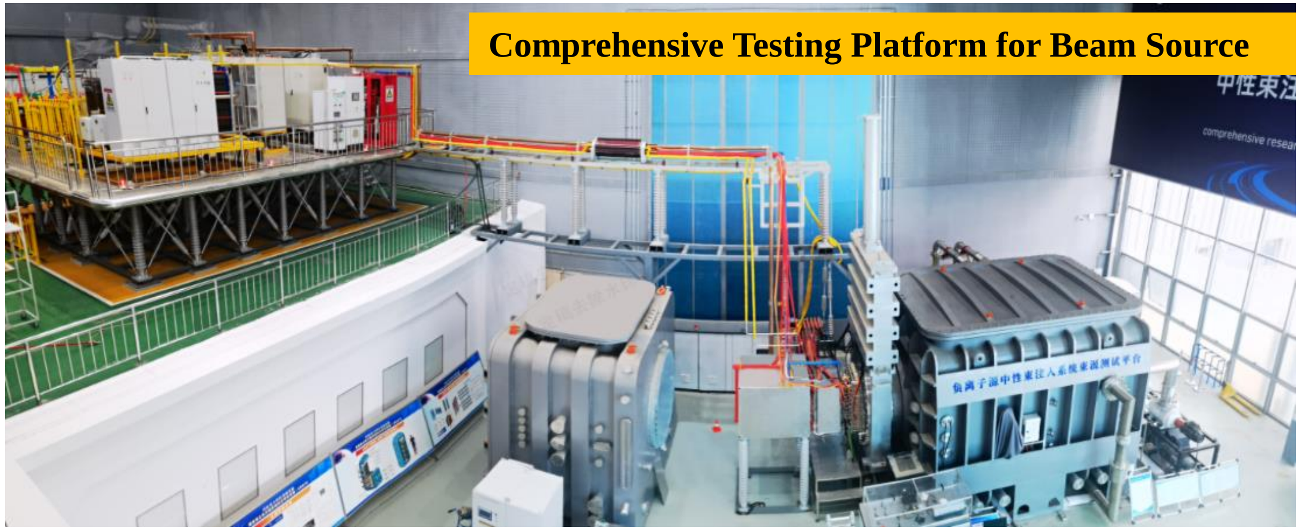
Giant negative beam source

Neutralizer

Cryopump panels

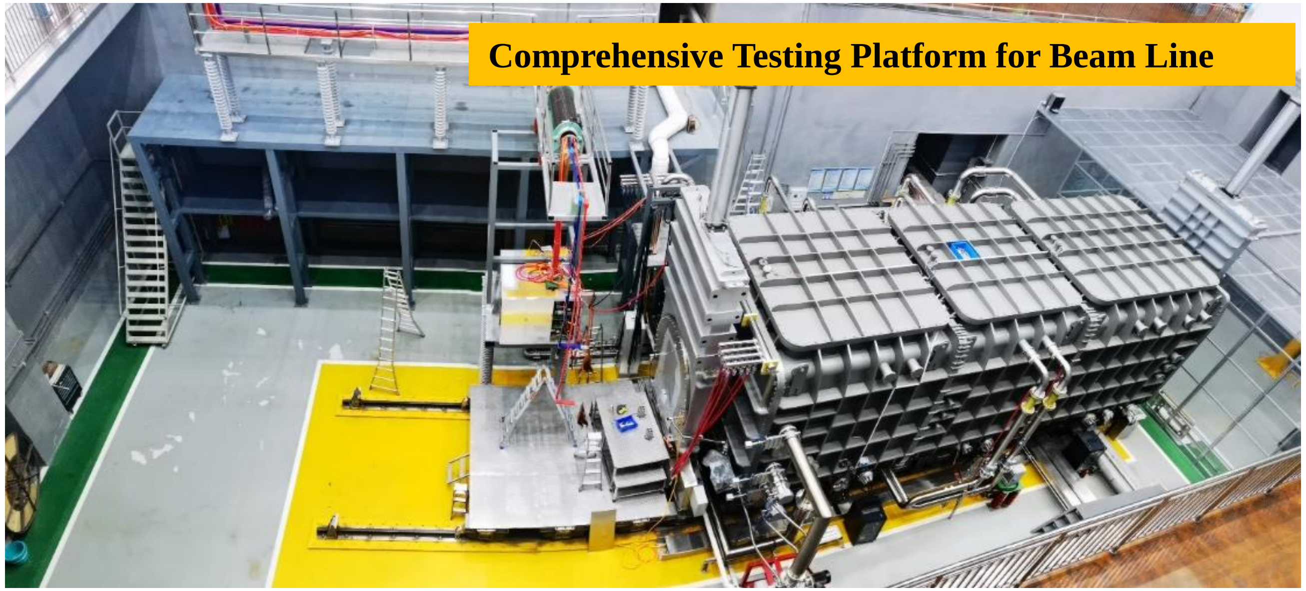
Electrostatic residual ion dump

System Construction Status


Comprehensive Testing Platform for Beam Source


Liquid Helium System@1kW


Control Center


Comprehensive Testing Platform for Beam Line


High Voltage Platform @400kVDC

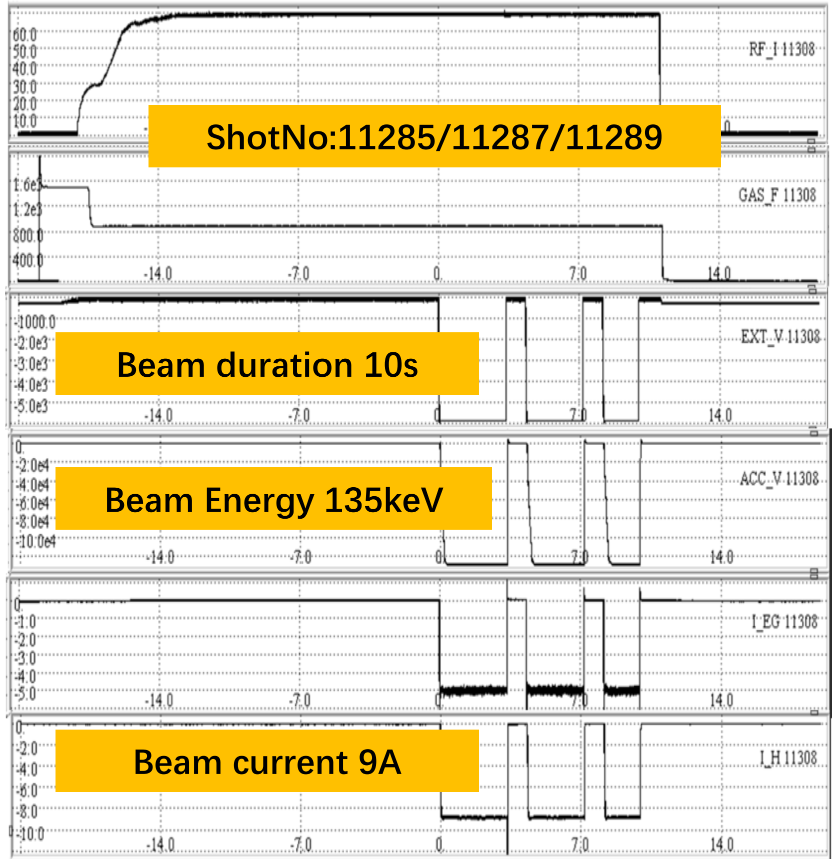

Water-Cooling System


High Voltage P.S. @200kVDC

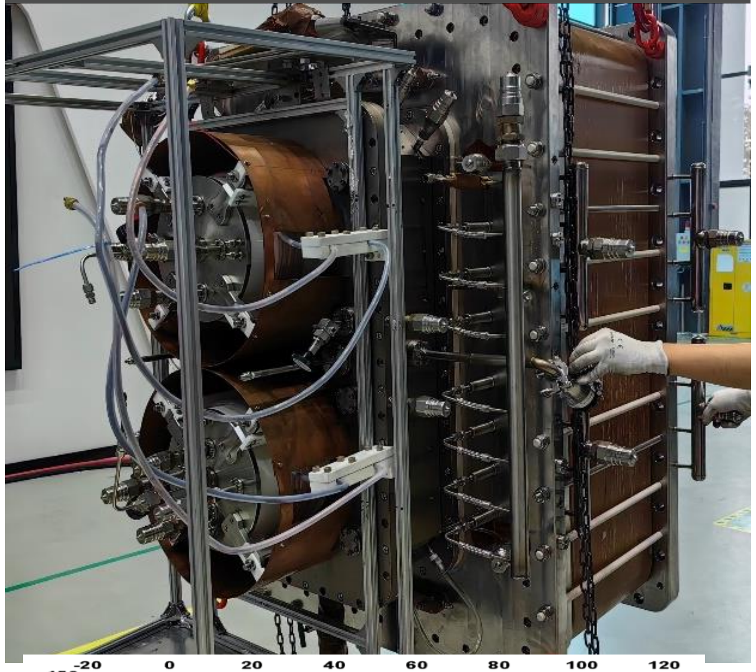
Latest Experimental Results

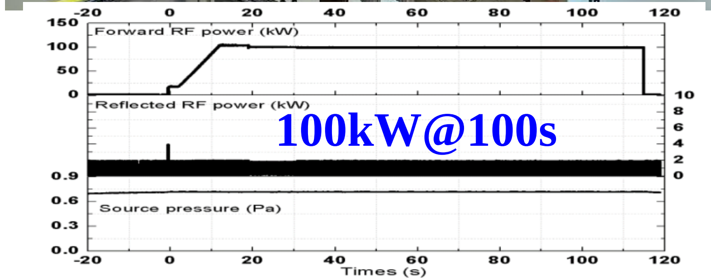
- Mastering key technologies for the generation and extraction of long pulse negative ions.
- Tackling key technologies such as high-voltage insulation, beam optics, and electron control.

The first round of high-power negative ion acceleration experiment

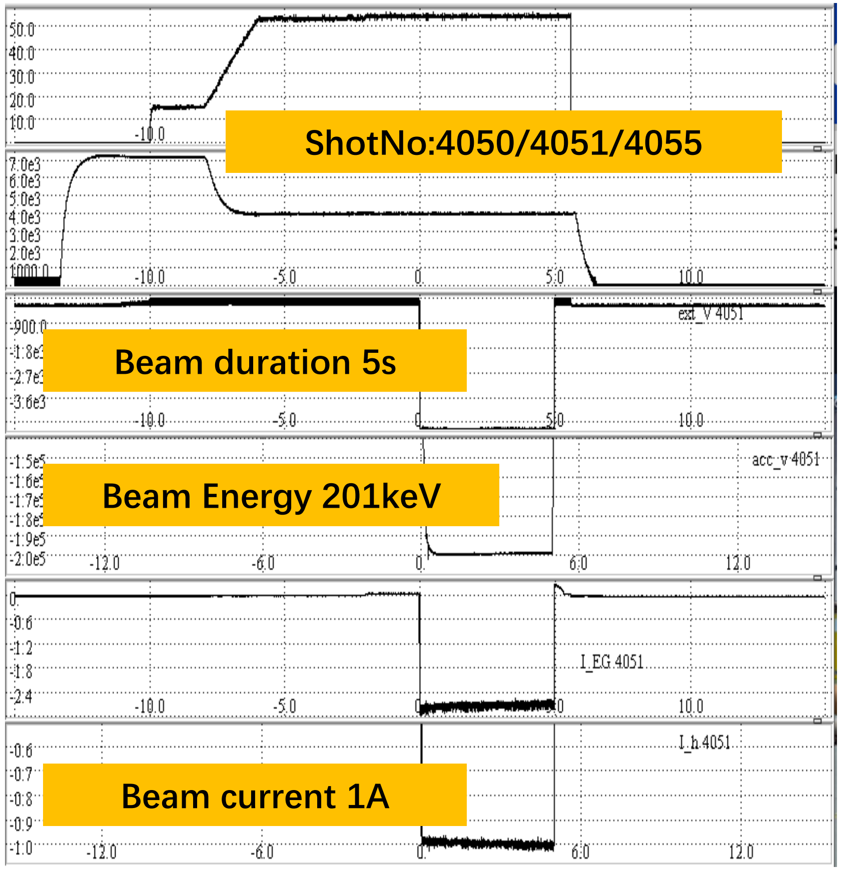


Dual driver negative ion beam source (single stage acceleration)





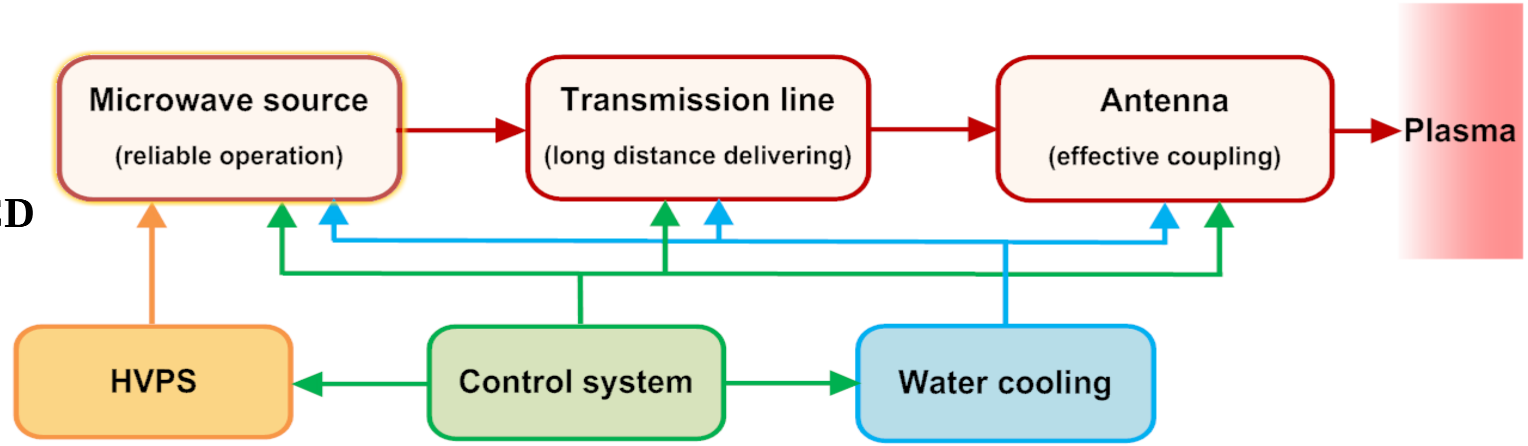
The first round of high-energy negative ion acceleration experiment



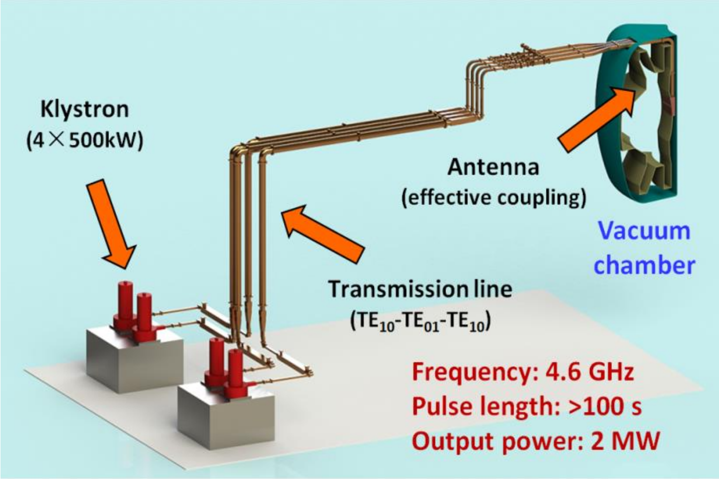
16. LHCD system

Objectives

- Explore the feasibility of CFETR LHCD system.
- Developing all technologies needed for CW LHCD system.
- Building all components of LHCD.
- Integrated testing of 2MW system.
- RH compatibility testing of antenna with blanket.



Schematic diagram



System layout

Klystron

- 500 kW
- >1000 s

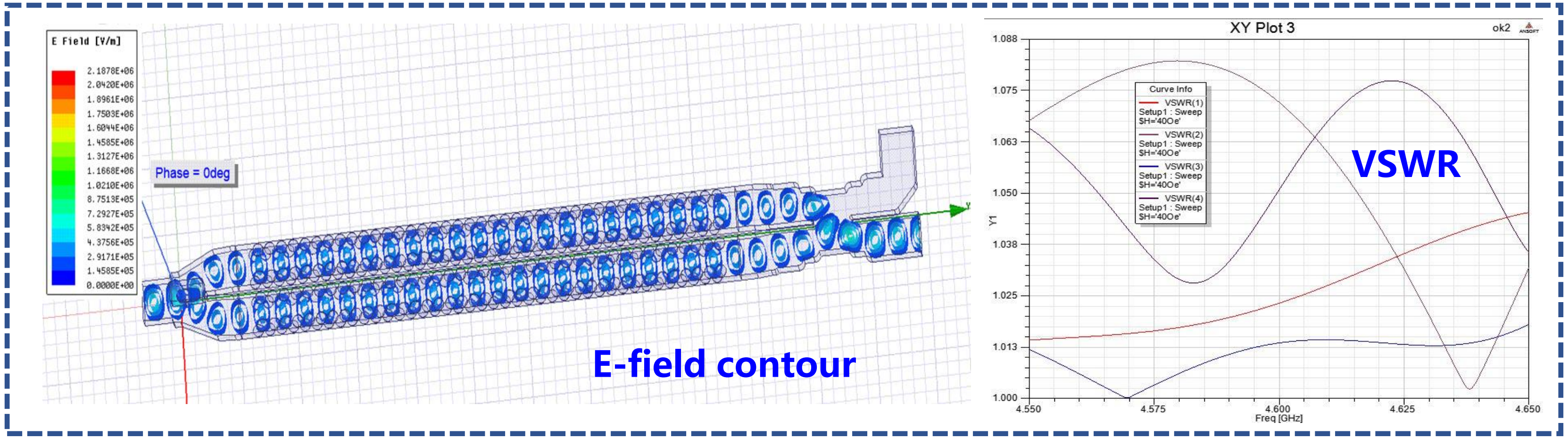
Key technology

- Developing 4.6GHz 500kW klystron
- The design and manufacturing of the near field coupling antenna.
- 500kW microwave components, oversized circular waveguide power transmission technology.
- The intelligent operation and control, to improve operating efficiency and to enhance reliability.

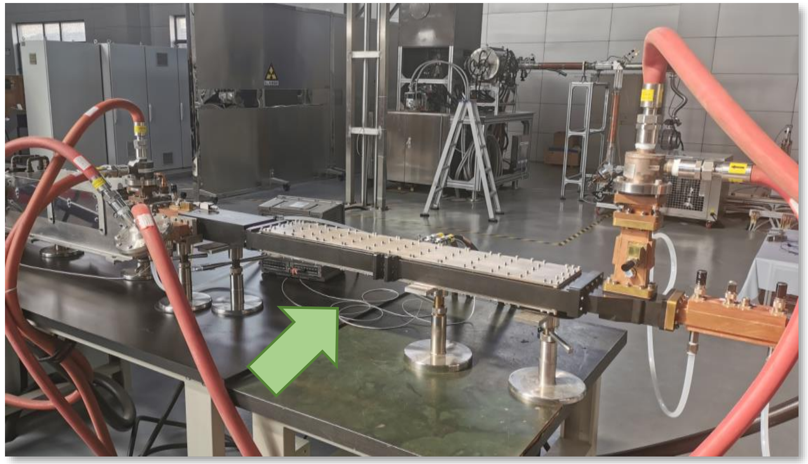
Will be finished in the end of 2024

LHCD system

- The prototype of 4.6GHz 250kW/CW isolator has been designed and processed by Chinese manufacturer, passed 240kW/1000s high power test with matched load, and 240kW/1000s high power test with 70kW reflected power.

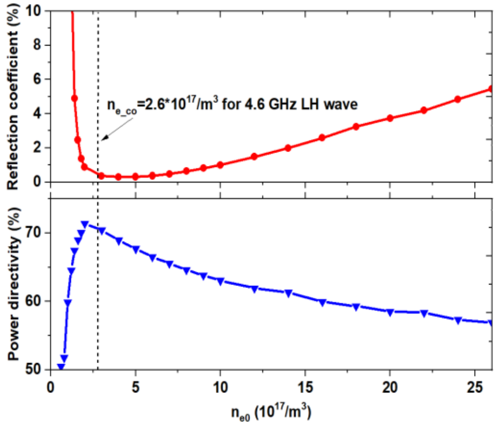


Electromagnetic simulation for 4.6GHz 250kW isolator

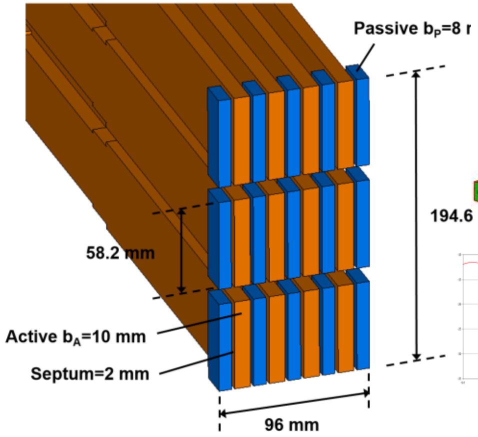


4.6GHz 250kW isolator on the test bench

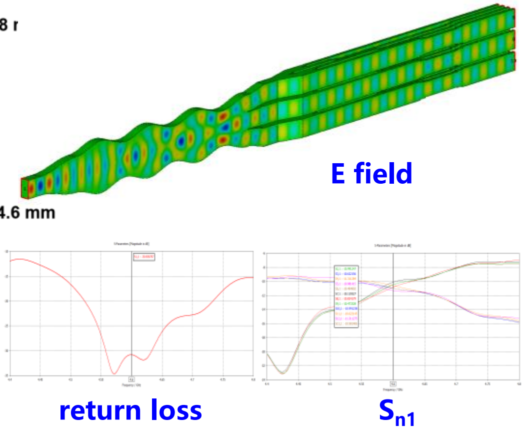
- Current drive simulation and coupling characteristics analysis have been performed, inner structure of the antenna has been optimized. Pre-research of key components has been completed.



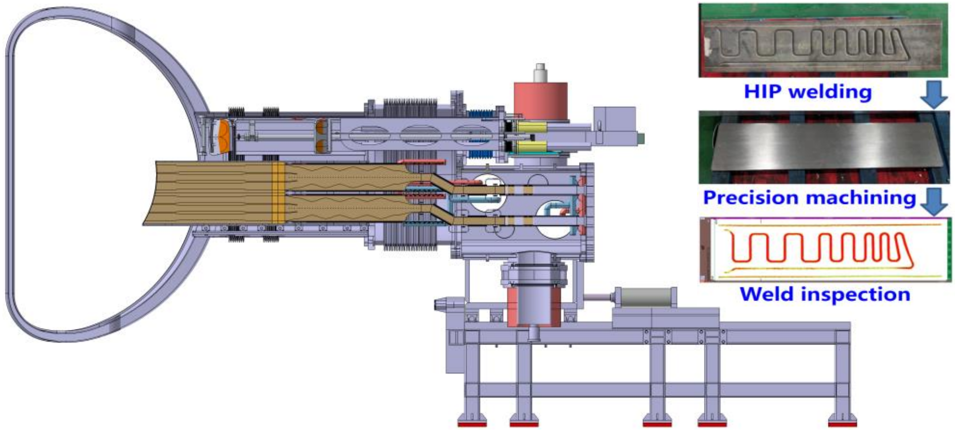
Reflection, Directivity Vs ne



Antenna front structure



Microwave simulation



Antenna system CAD model

17. ICRF System

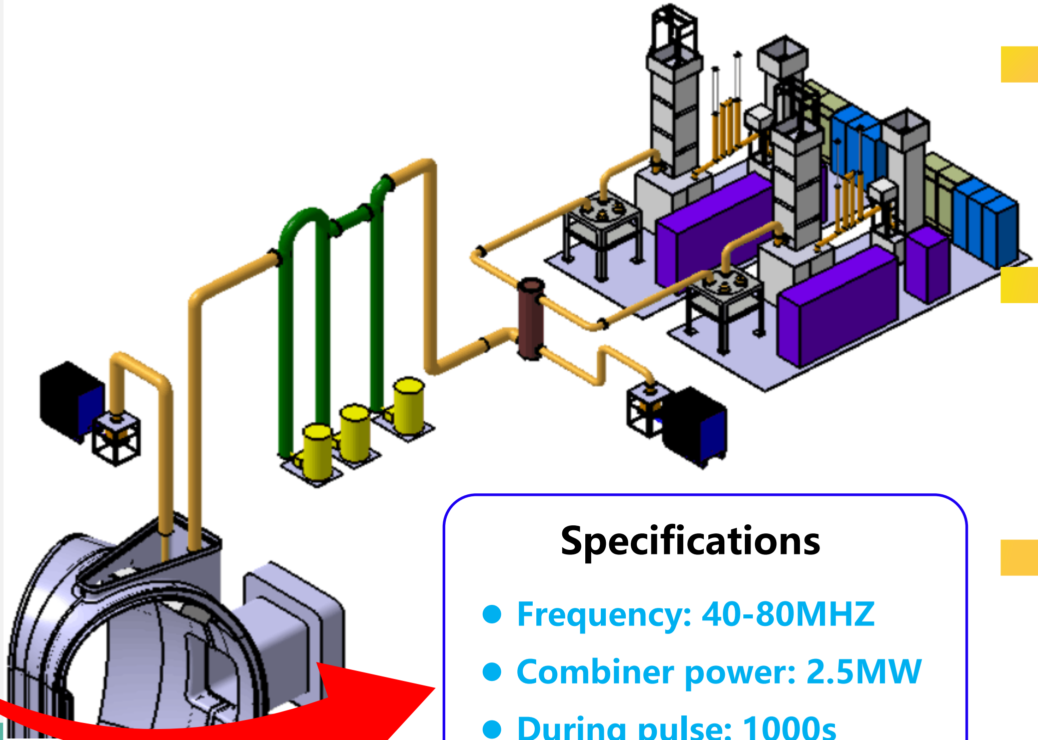
➢ **Objectives**

To provide a testing facility with 2MW RF power for finding a solution to use ICRF in CFETR
Solving technical challenges and developing required technologies.
Manufacture, testing and validating of the key components for the CFETR ICRF system.

➢ CRAFT ICRF System

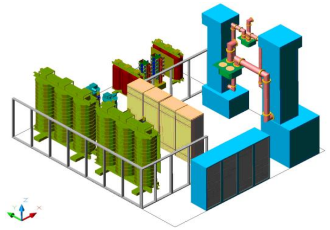
- **RF generator and power supply**
  - 2×1.5MW,40-80MHZ,CW
  - HVPS with PSM and IGBT
- **3dB hybrid couplers**
  - 2×1.5MW combination to 3MW
- **12 inch，50Ω, coaxial transmission line**
- **Matching system**
- **Distribution antenna**
  - TWA antenna, 8 radiation straps

2MW generator ⟷ **Porotype Antenna**

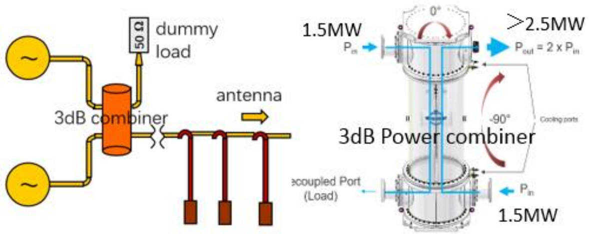


Specifications

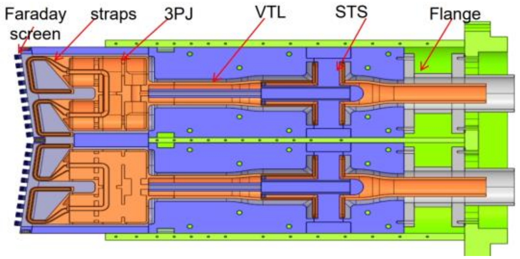
- Frequency: 40-80MHZ
- Combiner power: 2.5MW
- During pulse: 1000s



RF generators and power supply



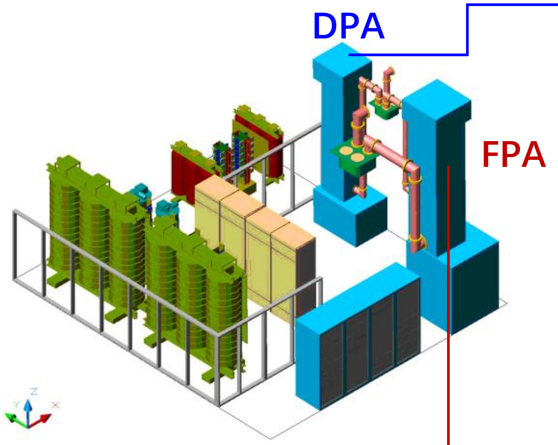
3dB hybrid combiner

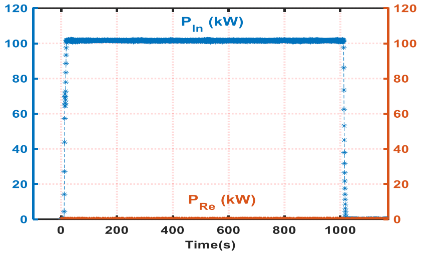


ITER-like Antenna

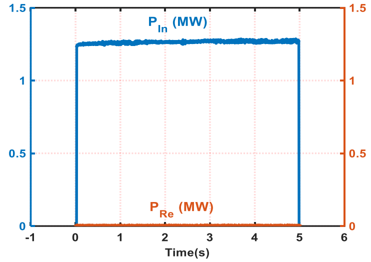
CRAFT ICRF system

- **Transmitters**: Contract for 2 transmitters & HVPS, 2024 test.
- R&D : The prototype of DPA tetrode high power testing has achieved expected results ;The first FPA tube sample has been developed and achieved a test result of 1.2MW in 5 seconds, testing still on going.
- **Transmission line :** 12inch coaxial transmission line and elbow are preparing for testing.
- R&D : A quadrature hybrid coupler has been developed for combiner 2×1.5MW amplifier; combining testing with EAST high power transmitter, and successfully obtained 3MW combiner power.

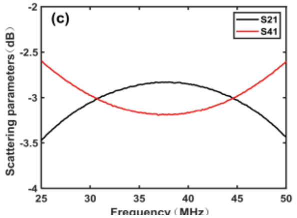


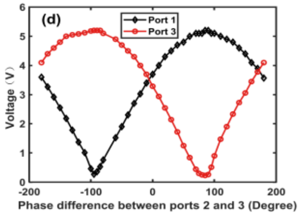


DPA tube prototype testing , 100kW,1000s

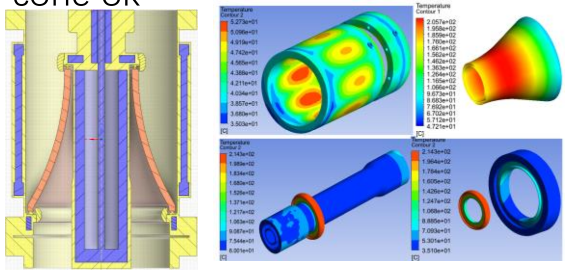


FPA tube R&D, 1.5MW, 1000s



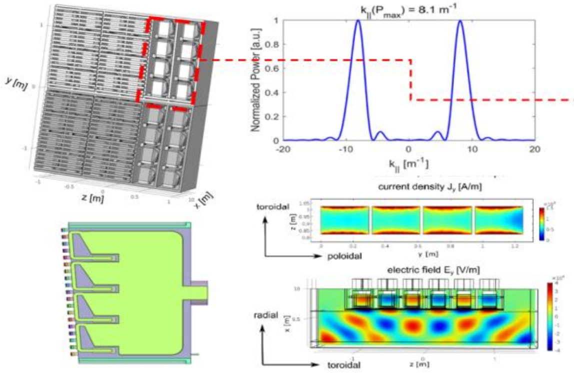


RF windows: RF design and thermal calculations finished; full scale ceramic cone ok

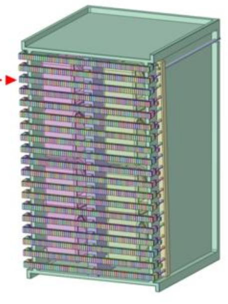


Will be finished in the end of 2024

- **Antenna:** CFETR RF antenna optimization and conceptual design of the antenna structure on-going. A scale of 1/6 module of CFETR antenna is fabricated for testing



CFETR ITER-type antenna



CRAFT antenna (1/6 CFETR antenna)

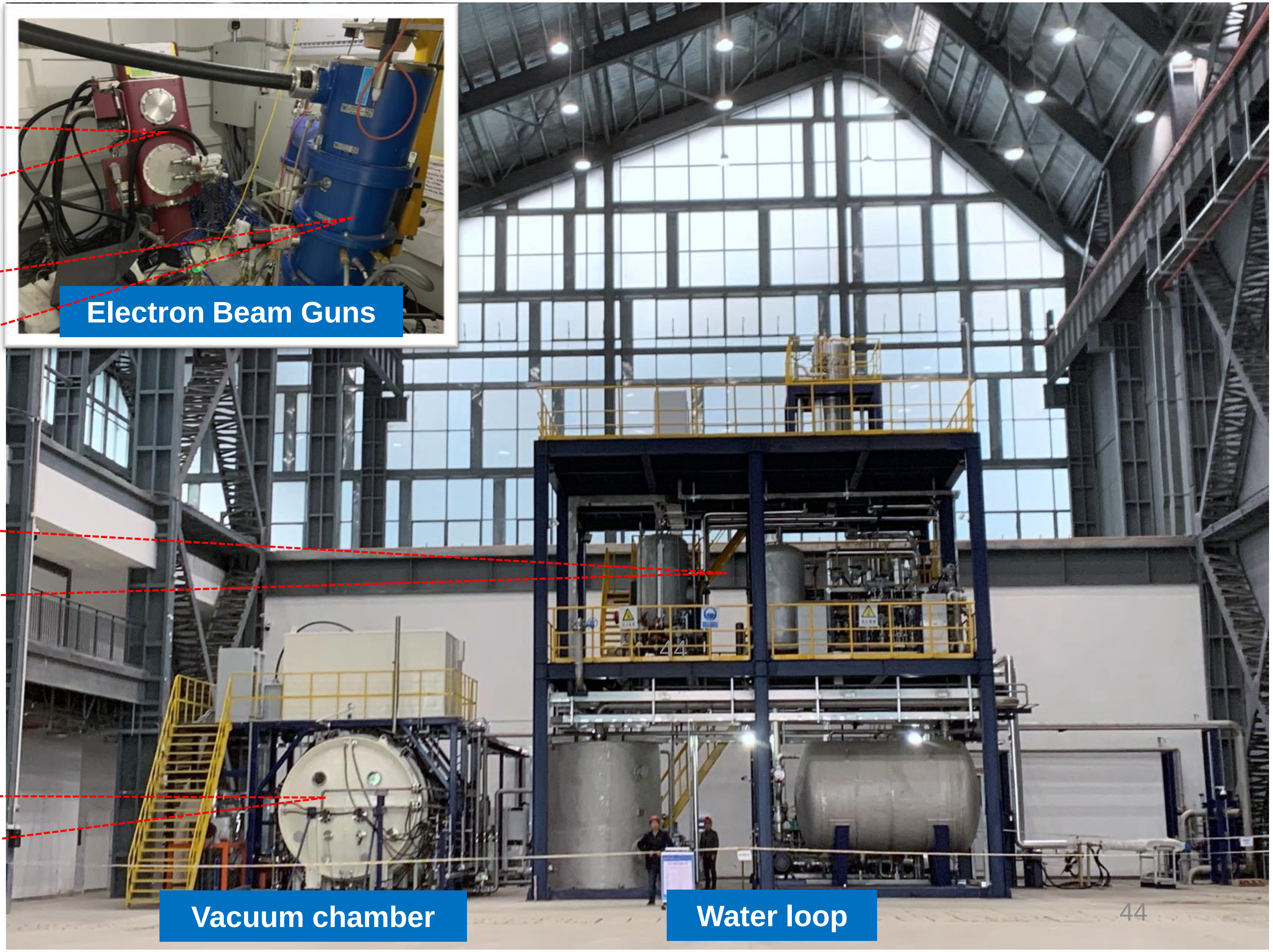
18. Blanket testing facility

800 kW Electron Beam Gun
- Max. accelerating voltage: 60 kV
- Deflection angle: ±15°
- Frequency: 10 kHz
- Min. spot diam.: 30 mm

60 kW Electron Beam Gun
- Max. accelerating voltage: 120 kV
- Deflection angle: ±10°
- Frequency: 10 kHz
- Min. spot diam.: 1 mm

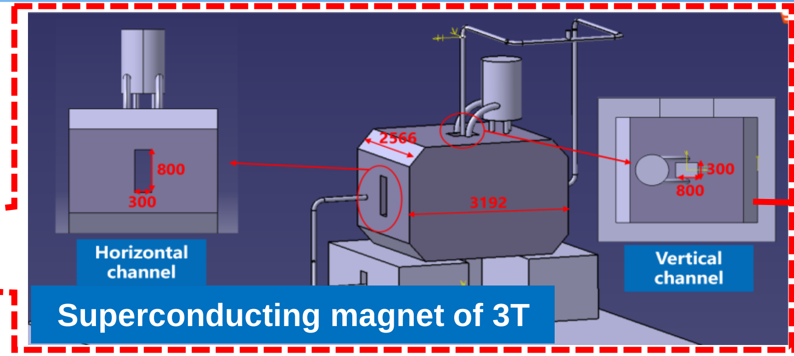
Water loop
- Operating pressure: 15.5 MPa
- Inlet/outlet temp. of the test section: 285 °C/325 °C
- Max. high pressure flow rate: 25 m^3/h
- Max. low pressure flow rate: 160 m^3/h

Vacuum chamber
- Inner diameter 3000 mm
- Length 4000 mm
- Vacuum: 10e-3 Pa

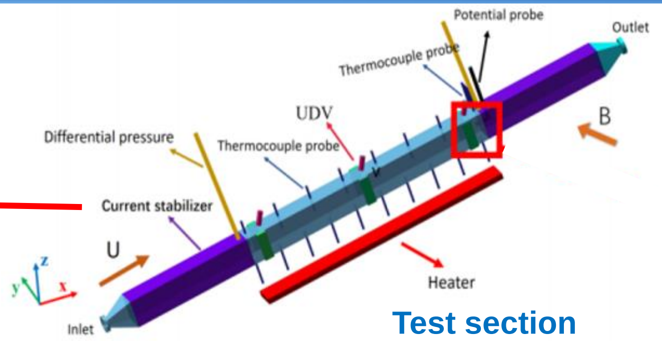


High temperature PbLi loop

3D layout

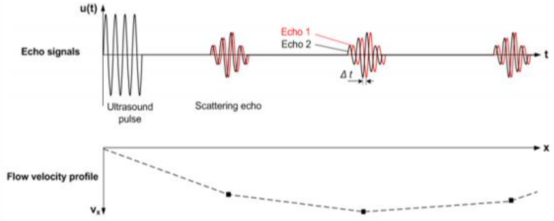


Superconducting magnet of 3T



Test section

Ultrasonic Doppler Velocimeter



Main parameters	
Operating pressure	1.5 MPa
Design temperature	High temp. section (310s) 750 ℃ Low temp. section (316L) 550 ℃
PbLi operation temperature	270-700 ℃
PbLi flow rate	30 m^3/h
PbLi inventory	10 t
Magnetic field	0~3 T, uniformity of 8% in 0.25 m×0.6 m×1.0 m region
Oil design parameter	1.6 MPa, 350 ℃, 130 m^3/h
Water design parameter	0.5 MPa, 80 ℃
Heating power	1.5 MW

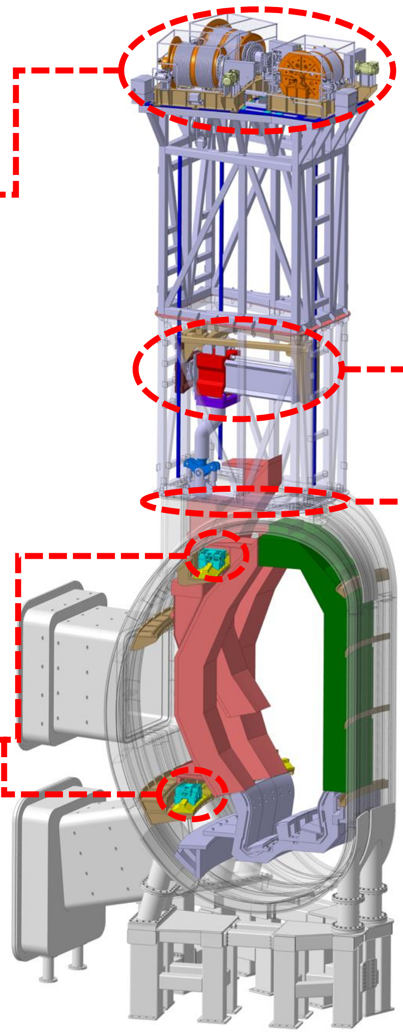
- **Turbulent heat transfer experiments**
  - Thermal boundary layer flow on forced convection
  - PbLi flow in complex geometry channel
- **MHD effects experiments**
  - Phase diagram and turbulent transition mechanism under different Re/Ha
  - The effects of FCI on the flow and heat transfer
  - MHD flow in complex geometry channel
  - Multi channel under electromagnetic coupling effect
- **Mixed convection experiments**
  - One-side heat flux conditions
  - Large magnetic/heat source

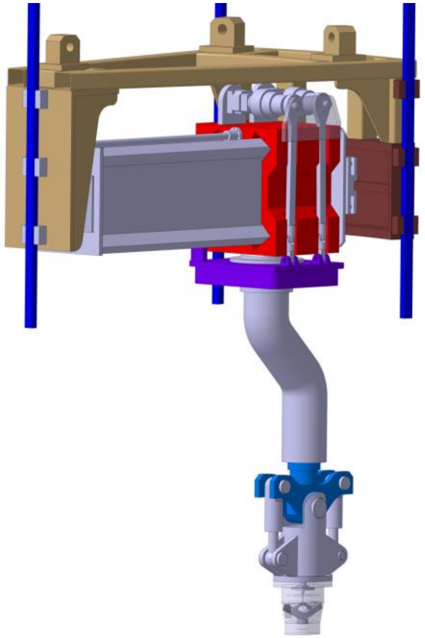
19. RH Testing Facility

The blanket remote handling system is developed to install/remove all the 5 blanket segments beneath of each vertical port. The blanket segment is 60t in weight and 7 meters in height.

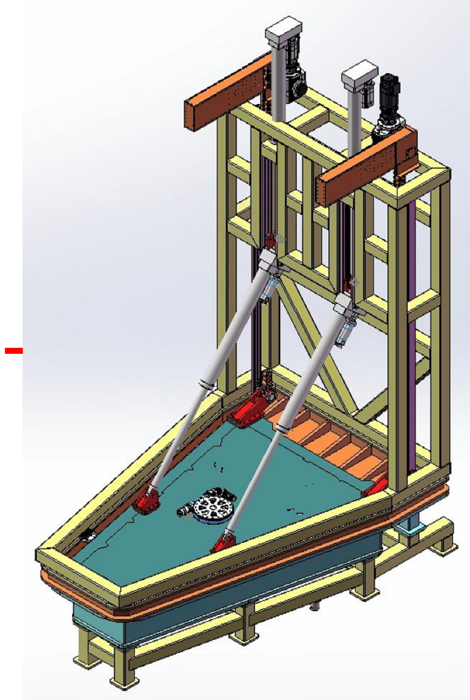
Three winches work together to lift the Blanket. The lifting cask frame and crane system were successfully delivered in April 2023.

Blanket toroidal Mover system, repositioning accuracy ±1 mm. Two mover system finish the factory acceptance test in June 2023.





Blanket Transport Manipulator with 7 degree of freedoms (under joint developing with EUROfusion)



Double door test bench for opening/closing mechanism and leak tightness verification ($2.5 \times 10^{-3} h^{-1}$). This test bench will be manufactured in 2023.8.

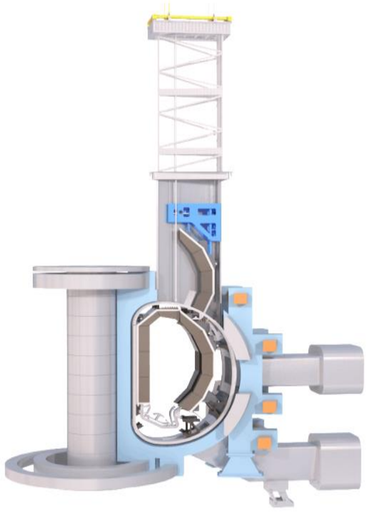
Cooperation with EU-DEMO RH group

19. RH Testing Facility

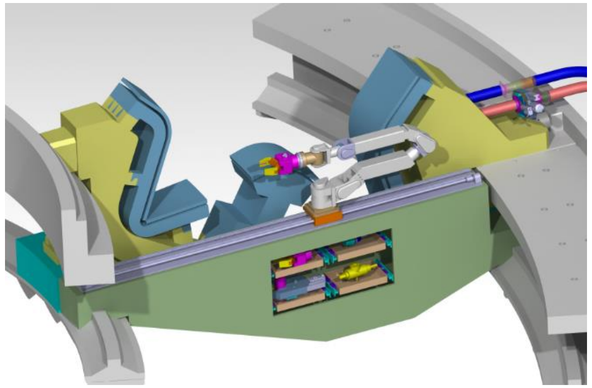
➢ Key technology

- High reliability, heavy load maintenance mechanism
- Maintenance tools (cutting, welding, bolting …) and end-effectors (dual-arm, snake-arm …)
- Remote handling compatibility design
- Remote control technology

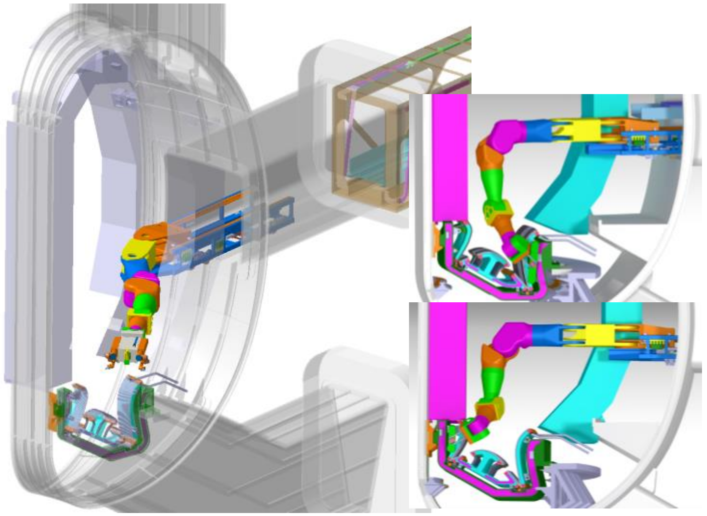
Flexible dual arm
Payload: 25 kg
Repeatability: ± 1 mm



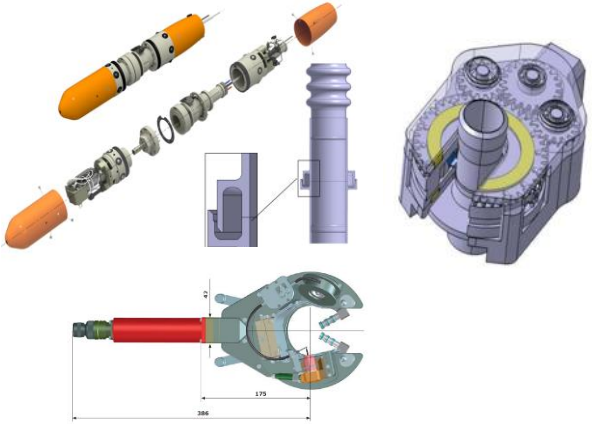
Divertor RH
Payload: 15 t
Position accuracy: ± 10 mm



Blanket RH
Payload: 60 t
Position accuracy: ± 20 mm



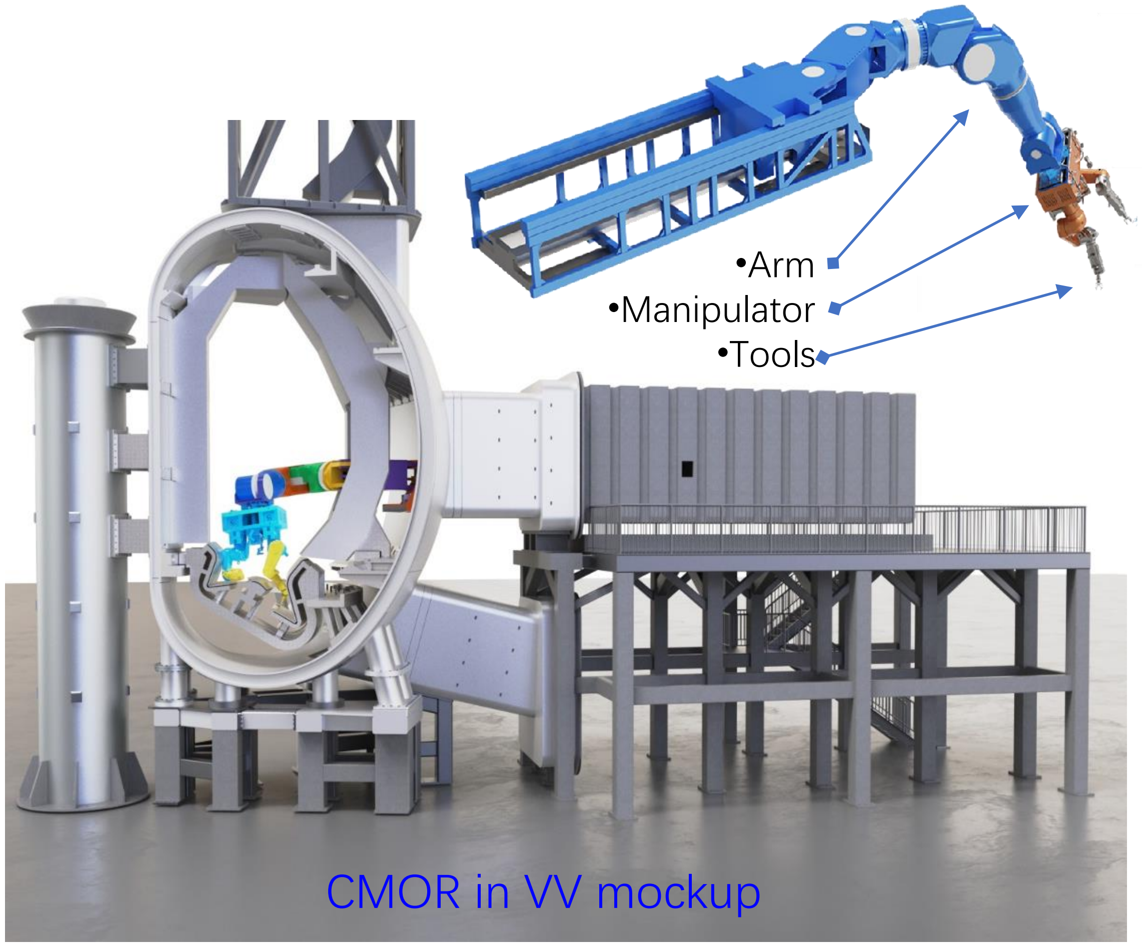
Heavy-duty manipulator
Payload: 2.5 t
Repeatability: ± 10 mm



RH Tools: cutting, welding, bolting

Remote Handling System

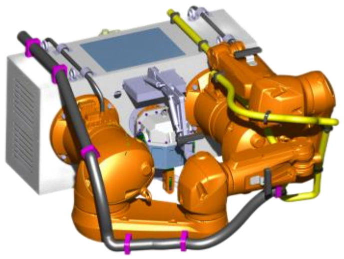
CMOR(CFETR Multipurpose Overload Robot), used for maintenance the first wall componentse, is one of the most powerful motor driven robot with 10 meters long and 2.5 tones capacity.



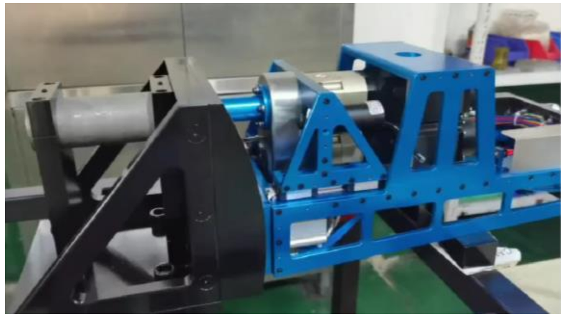
CMOR in VV mockup

CHENG's talk on 21th

- Joint prototype and testbed have been manufactured and qualified
- Full scale robot is under construction, will be completed in June 2024



- Dexterous manipulator being assembled
- 30kg per arm, 100kg for crane

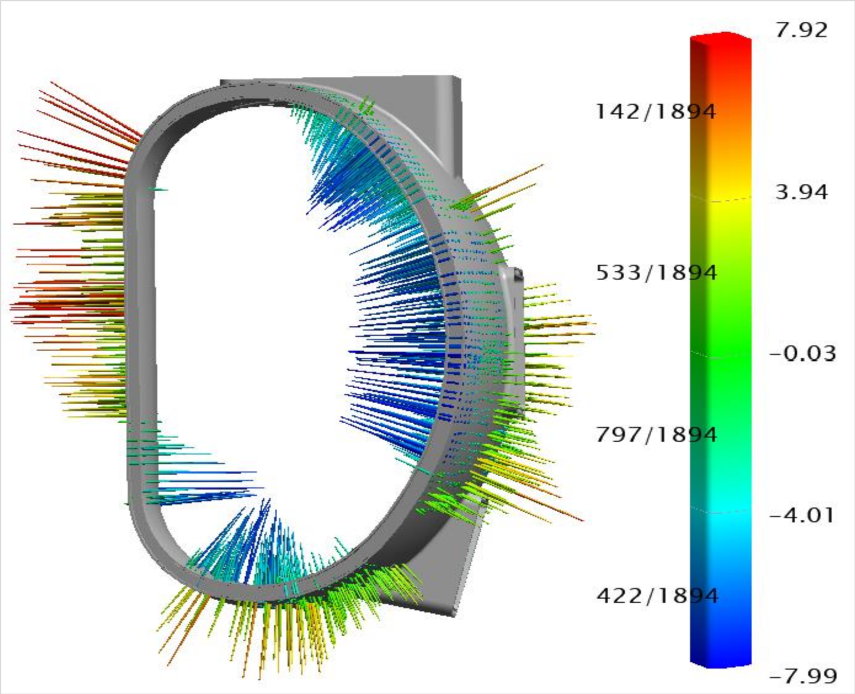


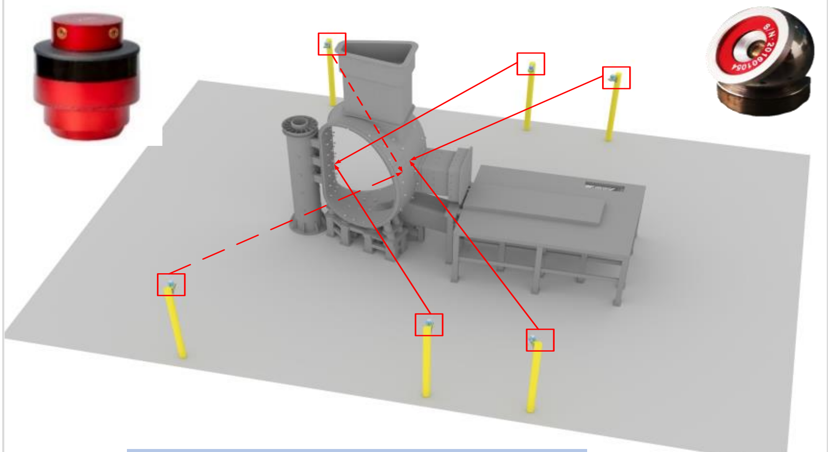
- Qualified in-bore cutting tool for divertor
- ø51mm with 3mm thickness

20 VV and installing testing facility

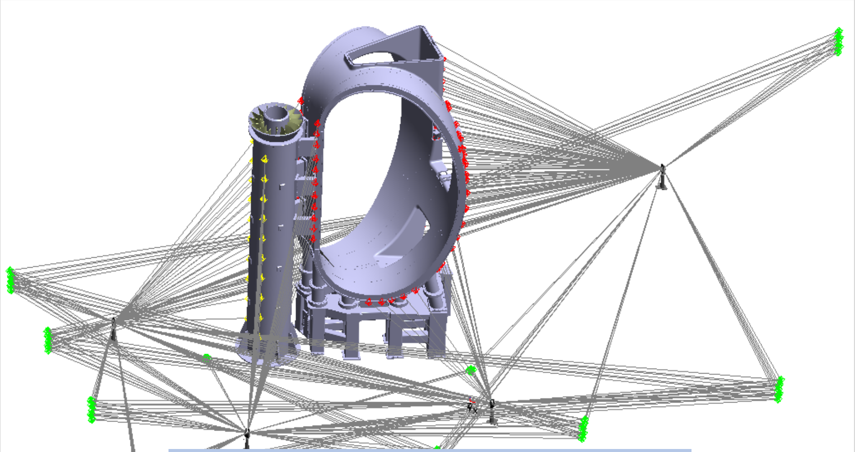
➢ Manufacturing completion

- ✓ Based on precision measurement and reverse engineering, Assembly accuracy ≤ 1mm
- ✓ In-site weld length : ~190m
- ✓ Groove type: 50mm full penetration
- ✓ Welding quality: ISO-5817 level B
- ✓ Surface deviation ≤ ±8mm

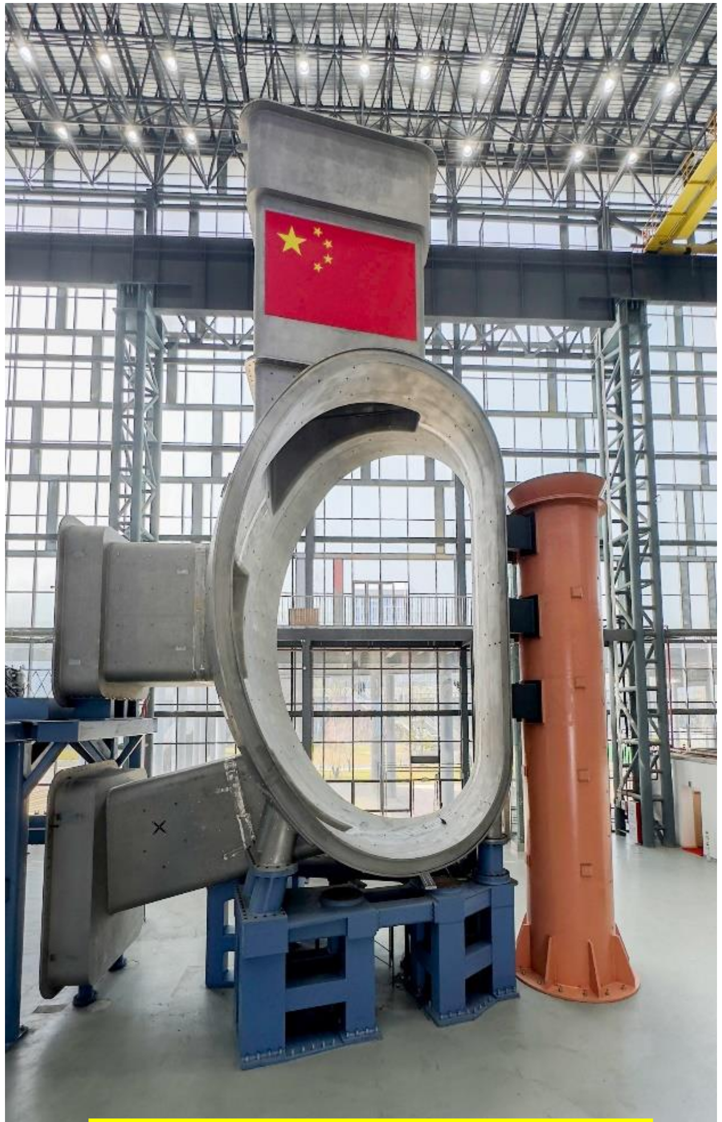




iGPS dynamic measurement



Measurement controlling network



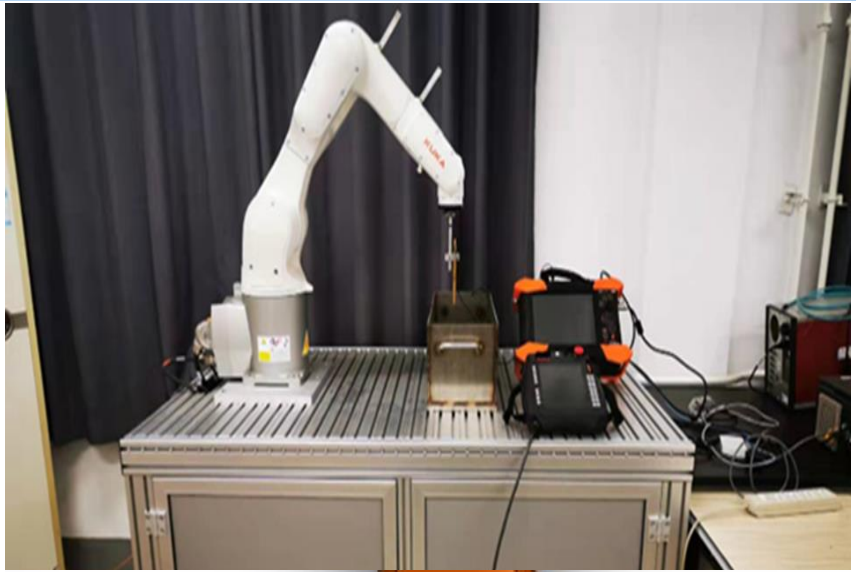
finished on May of 2023

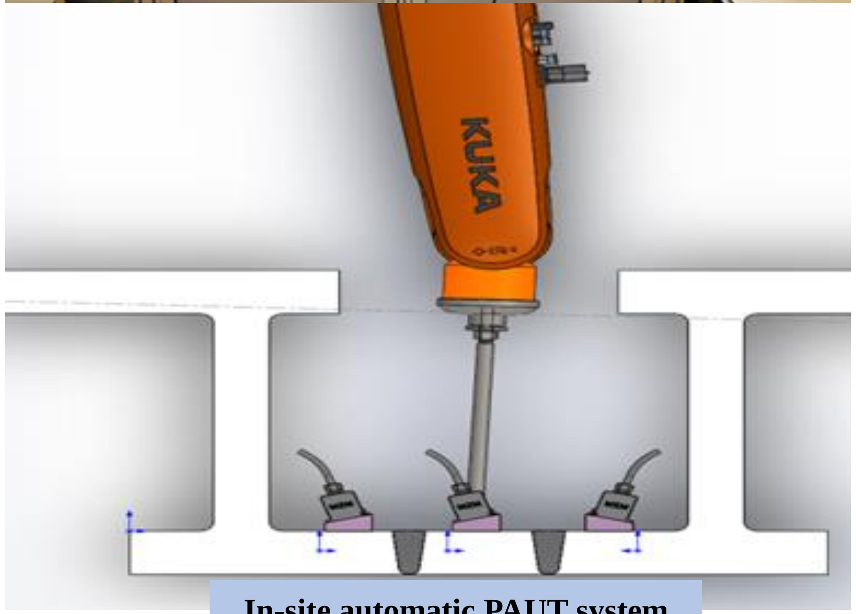
VV and installing testing facility

➢ Completion of automation system

- In-site automatic machining system, NG-TIG welding system, automatic PAUT system have been built and applied in the assembly process of sectors.

In-site machining system





In-site automatic PAUT system

Campus and Buildings

B1-4	Office & guest house
B5	110kV substation
B6	Cooling water
B7	Power supply
B8	Superconducting
B9	Cryogenic
B10	H&CD
B11	Vacuum vessel +remote handling
B12-13	Divertor, blanket test facility
B14	Exhibition room & general control hall

Campus of CRAFT

Summary

- CRAFT is a national big science facility aiming to develop key technologies and systems for CFETR.
- The construction of CRAFT started on Sept. 20, 2019 which should be finished within 5 year and 10 month with joint founds from central and local governments.
- CRAFT will use not only the technologies from ITER, but also those which need to be developed in future with significant challenges and efforts.
- CRAFT will provide a solid technical base for successful construction of CFETR in future. **Completeness is 79%.** It is within budget and about **8 month delay**.
- CRAFT will fully open to world fusion community, joining construction and future integrating experiments are welcomed.


Thanks！