Design activities of the ECRH system for CFETR

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Outline

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1. Introduction
2. Conceptual design of CFETR ECRH system
3. R&D activities on CRAFT
4. Summary

Aim and objectives of CFETR

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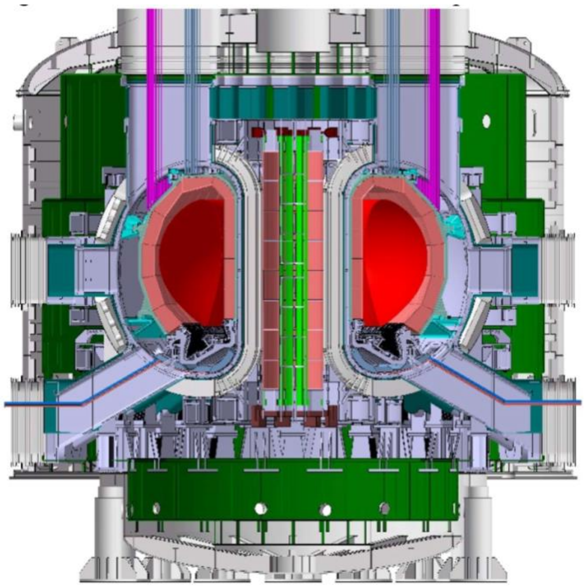
Chinese Fusion Engineering Testing Reactor (CFETR)



Ports:
16 uppers, 6 equatorials, 16 lowers

Aim:

Bridge the gap between ITER and DEMO, demonstrate fusion energy production

- **key technology developments**
- **DEMO validation**

Operation phases	Fusion power	Q	TBR	Neutron dose
Steady-state DT plasma	50~200 MW	1~5	>1	~10 dpa
DEMO validation	>1 GW	>10		~50 dpa

Evolution of CFETR design

Year	2010~2015	2015~2017	2017~Now
Parameters	R = 5.7 m a = 1.6 m B_T = 4~5 T	R = 6.6 m a = 1.8 m B_T = 6~7 T	R = 7.2 m a = 2.2 m B_T = 6.5 T

General design of CFETR

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CFETR operation intensively based on mix of Ext. H&CD systems

- **Higher B_T: 6.5T (4.5)**
- **Ip： 6～14MA,**
- **Larger size:**
  R= 7.2m (5.7),
  a=2.2m (1.6)
- **A=3.3,**
- **K= 2.0,**
- **βN ～2.0； q 95 ≥5;**
- **Triangularity δ= 0.4-0.8;**
- **Single-null diverter;**
- **Neutron wall loading < 0.5MW/m2;**
- **Duty cycle time = 0.3-0.5;**
- **TBR >1.0**

Skeleton dimensions for the CFETR machine

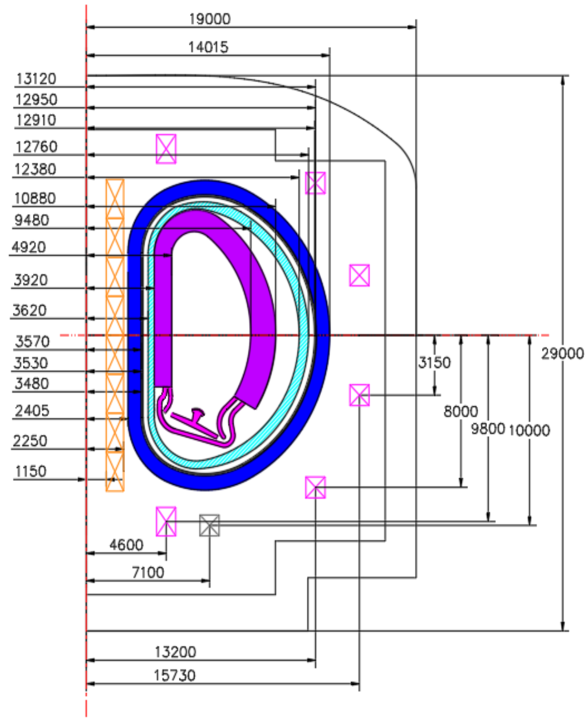

Table 1. CFETR plasma performance for CFETR **fully non-inductive (steady-state)** operating scenarios.

CFETR fully non-inductive $R = 7.2$ m, $a = 2.2$ m, $\kappa = 2$	Parameters	A.1 100 MW	A.2 200 MW	A.2 500 MW	A.3 1 GW	A.4 DEMO-level
Fusion power (MW)	P_f	120	229	482	974	2192
Power to run plant (MW)	$P_{internal}$	199	196	223	238	265
Gain for whole plant	Q_{plant}	0.46	0.70	1.14	1.98	3.79
Pfusion/Paux	Q_{plasma}	1.56	3.06	5.87	11.89	28.17
Net electric power (MW)	$P_{netelec}$	−107	−58	30	232	738
Neutron power at blanket (MW m^{-2})	P_n/A_{wall}	0.12	0.23	0.49	0.99	2.23
Toroidal beta	β_T	0.006	0.009	0.014	0.019	0.029
Normalized beta	β_N	1.00	1.20	1.50	2.0	3.0
Bootstrap fraction	f_{bs}	0.40	0.40	0.40	0.50	0.75
H factor over ELMY *H*_net	$H_{ITER98Y2}$	1.12	1.25	1.32	1.41	1.42
Ohmic fraction	f_{ohm}	0.0	0.0	0.0	0.0	0.0
Current drive power (MW)	P_{cd}	77	75	82	82	78
Plasma current (MW)	I_p	8.61	10.34	12.92	13.78	13.78
Field on axis (T)	B_T	6.5	6.5	6.5	6.5	6.5
Ion/electron temperature (keV)	$T_i(0)/T_e(0)$	18	24	32	36	32
Electron density (10^{20} m^{-3})	$n(0)$	0.48	0.52	0.61	0.78	1.31
Ratio to Greenwald limit	n_{bar}/n_{GR}	0.57	0.51	0.48	0.57	0.96
Zeff	Z_{eff}	2.45	2.45	2.45	2.45	2.45
Transport power per unit *R* (MW m^{-1})	P_{SOL}/R	8.52	9.42	11.66	15.69	30.70
*q*95_iter [2]	q_{95_iter}	8.87	7.39	5.91	5.54	5.54

Table 2. CFETR plasma performance for CFETR **hybrid mode** operating scenarios.

CFETR hybrid mode $R = 7.2$ m, $a = 2.2$ m, $\kappa = 2$	Parameters	B.1 100 MW	B.2 200 MW	B.2 500 MW	B.3 1 GW	B.4 DEMO level
Fusion power (MW)	P_f	114	250	558	1128	2192
Power to run plant (MW)	$P_{internal}$	190	196	202	222	75
Gain for whole plant	Q_{plant}	0.46	0.75	1.40	2.41	12.96
Pfusion/Paux	Q_{plasma}	1.54	3.35	7.65	15.30	795.16
Net electric power (MW)	$P_{netelec}$	−103	−49	80	312	891
Neutron power at blanket (MW m^{-2})	P_n/A_{wall}	0.12	0.25	0.57	1.15	2.23
Toroidal beta	β_T	0.006	0.009	0.014	0.019	0.029
Normalized beta	β_N	1.00	1.20	1.50	2.00	3.0
Bootstrap fraction	f_{bs}	0.40	0.40	0.40	0.50	0.75
H factor over ELMY *H*_net	$H_{ITER98Y2}$	1.01	1.09	1.18	1.19	1.54
Ohmic fraction	f_{ohm}	0.30	0.30	0.30	0.30	0.24
Current drive power (MW)	P_{cd}	74	74	73	74	3
Plasma current (MA)	I_p	8.61	10.34	12.92	13.78	13.78
Field on axis (T)	B_T	6.5	6.5	6.5	6.5	6.5
Ion/electron temperature (keV)	$T_i(0)/T_e(0)$	13	17	24	24	34
Electron density (10^{20} m^{-3})	$n(0)$	0.67	0.74	0.82	1.16	1.23
Ratio to Greenwald limit	n_{bar}/n_{GR}	0.79	0.72	0.64	0.85	0.90
Zeff	Z_{eff}	2.45	2.45	2.45	2.45	2.45
Transport power per unit *R* (MW m^{-1})	P_{SOL}/R	7.58	9.33	12.63	19.11	22.97
*q*95 iter	q_{95_iter}	8.87	7.39	5.91	5.54	5.54

[G. Zhuang et al，Nucl. Fusion 59 (2019) 112010]

Mission of ECRH task

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➲ **Scope:** conjunction with physical requirements and CFETR machine integration design requirements, to perform general design of ECRH system

◆ **Envisaged functions** for ECRH system: heating, current profile control, stabilizing MHD, assisted start-up

◆ **Correlations with other Working Tasks**

- **Physics**, **BSM**, **Machine integration, Remote maintenance,** Safety and Environment, Material, Magnets, Divertor, Tritium , Heat Transfer and site, Diagnostics and Control, et al

◆ **Challenges** - **Design to handle uncertainty (physical and technical)**

- Varying baselines have impact on EC parameters selection
- The CFETR physical design advances synchronously with the device design, still under optimization
- Readiness of technology

Approach for ECRH Design

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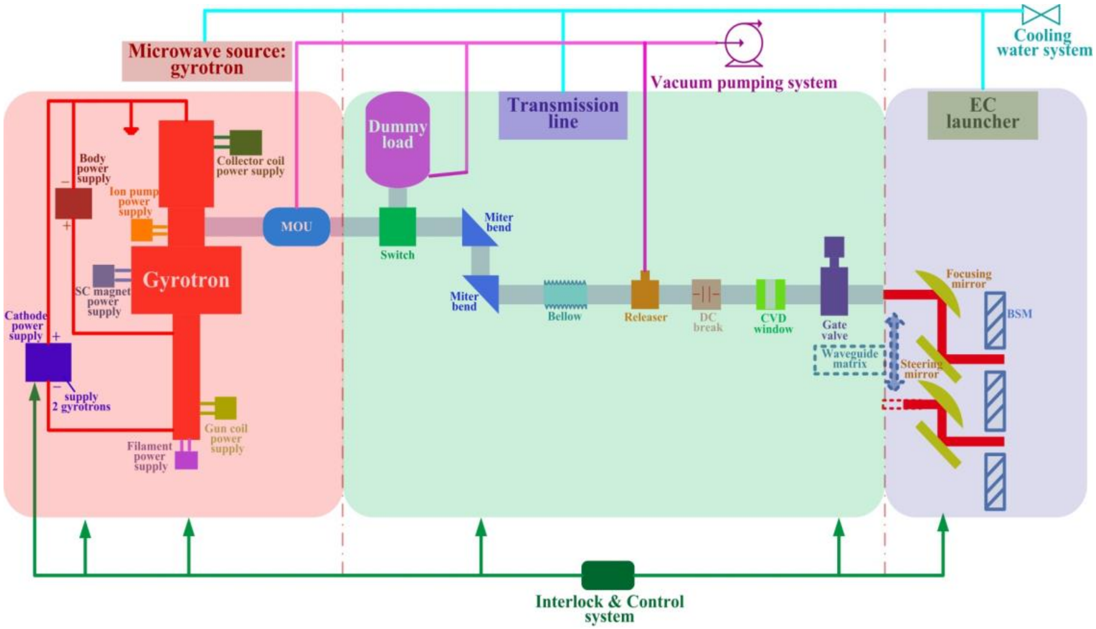
☐ System design principles:

Availability (efficiency), reliability, economy (cost)

☐ Design strategies

- **Trade-offs** between CFETR physical requirements and system engineering availability and reliability
- **Iterative design** with the development of integration design and physical design
- To explore the advanced technical requirements of the ECRH system

➲ **Perform system design with parameters of 30 MW/170GHz**



Current driven for top-injection

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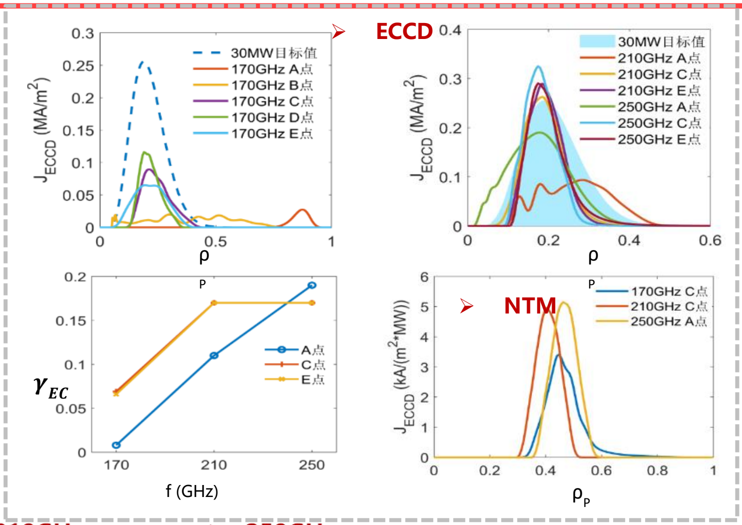
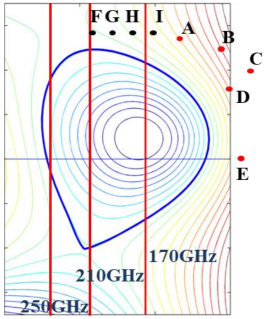
- Current driven at several potential launching points are calculated by taking into account the spatial limitation of upper window
- η_{CD} increasing with frequency
- Launched from top to optimize the CD efficiency



CFETR phase II hybrid



波束注入位置：主要取决于等离子体运行模式，同时兼顾工程集成设计需求

分析参数：

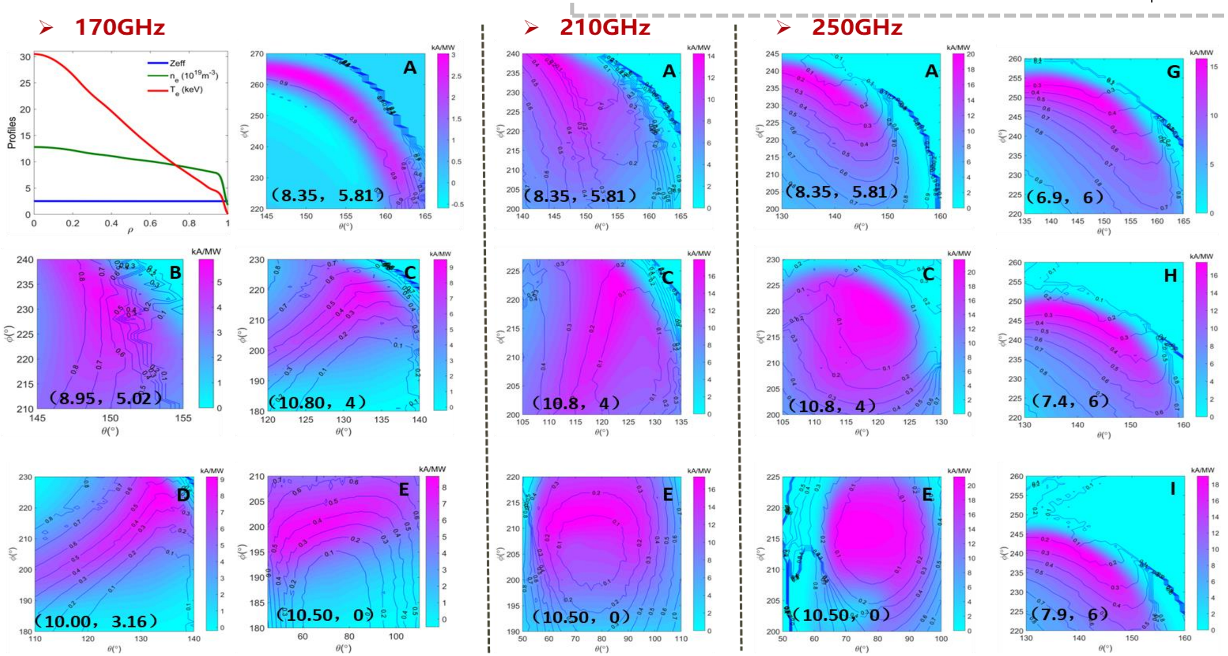
B_t=6.5T

R_0=7.2m

a=2.2m

T_{e0}=30.5 keV

n_{e0}=12.8×10^{19}/m^3



Quasi-optical design of launcher

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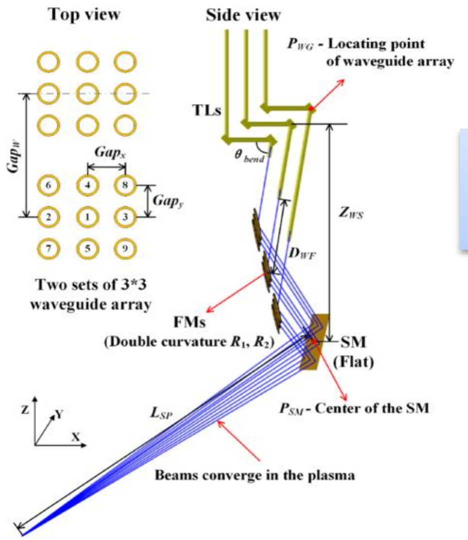
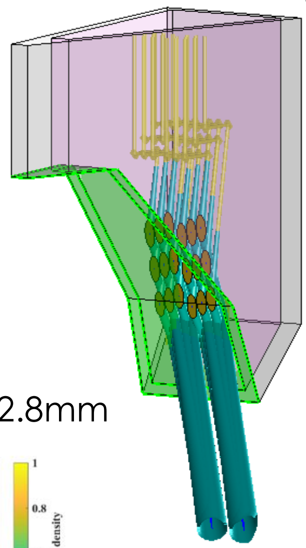
- Based on front steering launcher, quasi-optical routing design performed to improve the beam characteristics and minimize the wall occupation per unit of power
- Compatible for plug-in installation in a single port
- A 3D analysis code is developed to facilitate the quasi-optical optimization

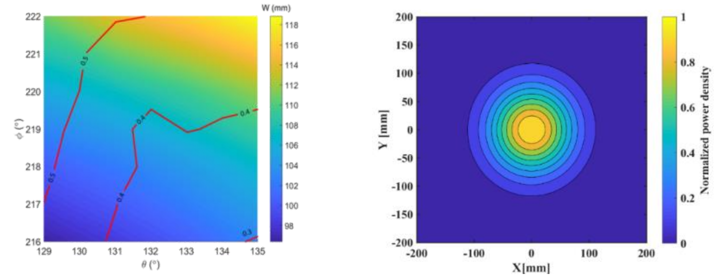
Quasi-optical modules with 9 beams converging



UL1 (ECCD)

- Two identical modules
- 9 beams injection each
- Mirror sizes
  - FMs: 418mm×456mm
  - 436mm ×456mm
  - 454mm ×456mm
  - SM: 810mm×474mm
- Optimized beam Radius: 97.21mm~122.8mm





[C. Zhang, et al., Fusion Eng. Des., 2021, 166:112295]

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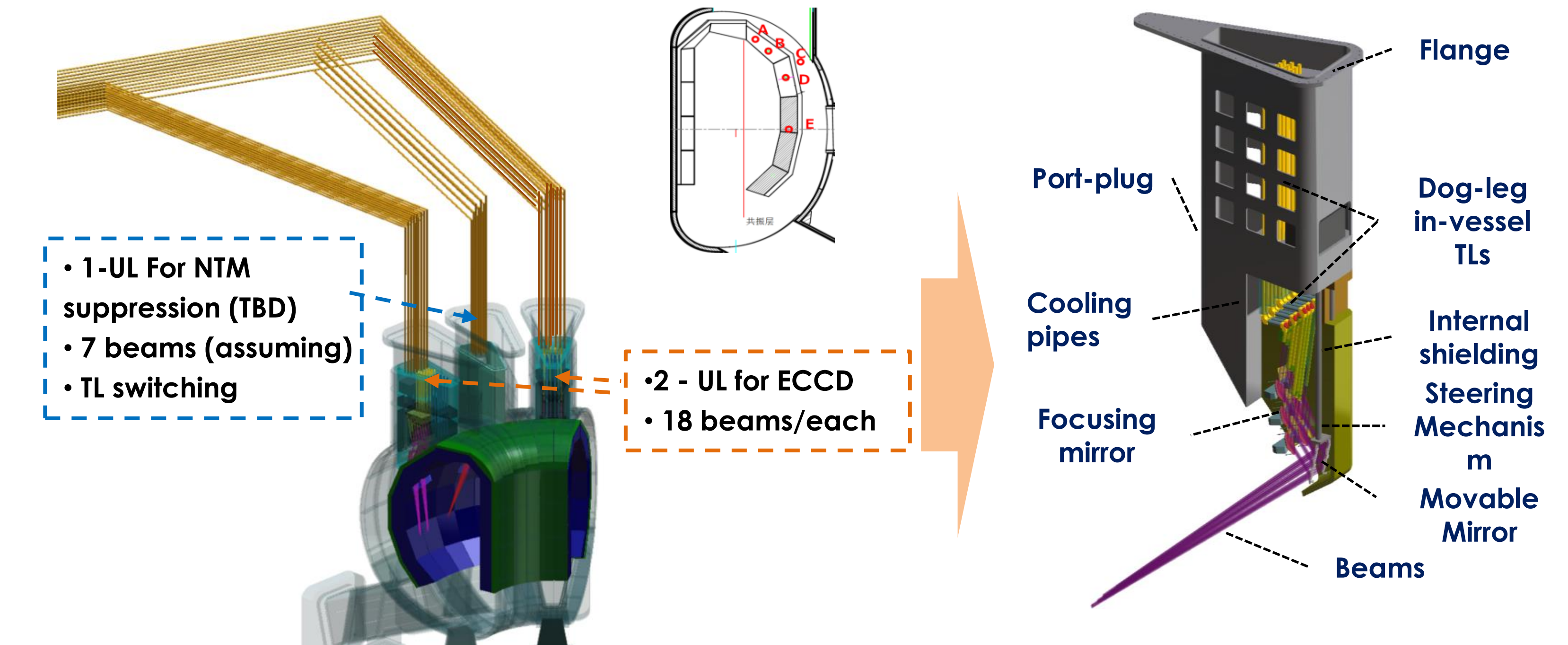
General design of launcher

- Three vertical ports allocated, function division: ECCD, NTM partition implementation
- Interface design and iteration could be started based on the present status



Sectional view of the UL

Schematic design of CFETR ECRH

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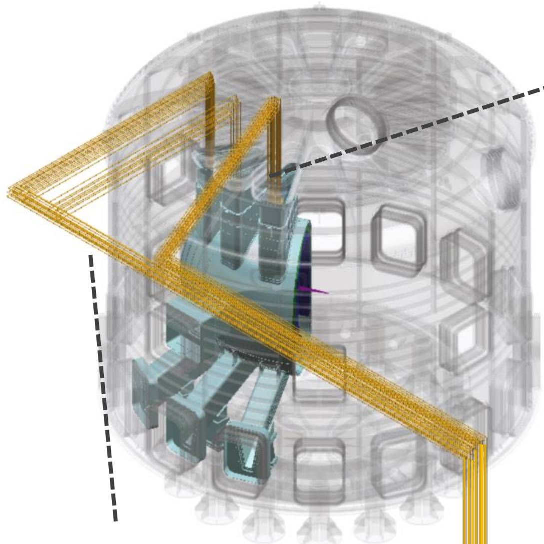
◆ **Interfaces between the ECRH system and other systems in the device are defined.**



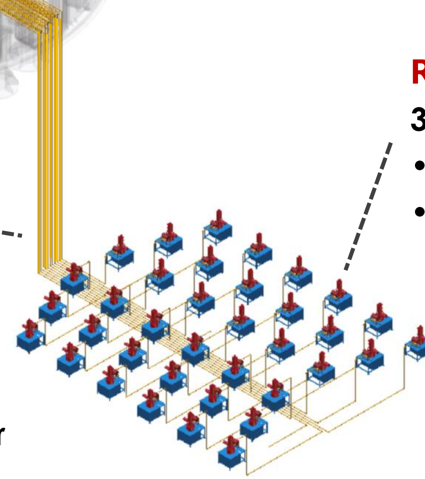
Upper launchers

- 2*15MW/18 beams
- 1* 5.8MW/7 beams

RF Source

36 Gyrotrons (1MW each)

- Cluster design: 5+1(spare) per group
- 1MW /CW load for each gyrotron



W/G TLs

➢ **TLs Features:**

- Efficiency target: 90%
- Power handling: 1MW CW per line
- Tritium compatible: CVD barrier window together with fast gate valve
- Using switches to direct the source power to different TLs and launchers

Schematic layout of 170GHz/30MW ECRH system

Integration in Breeding blanket

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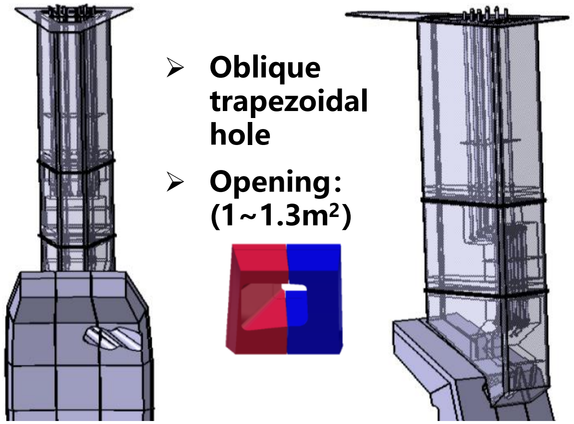
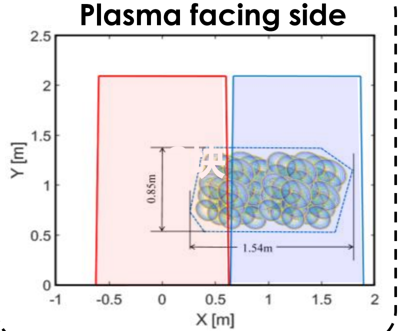
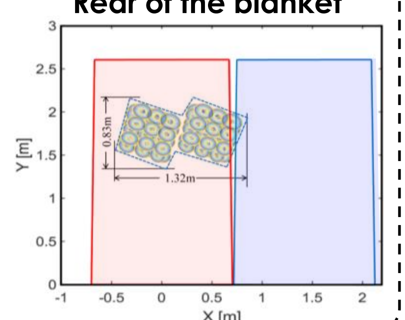
◆ Calculation of beam penetration through BSM and neutronic analysis

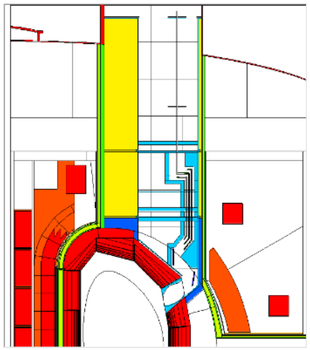
- Aperture in BB: 1~1.3 m^2

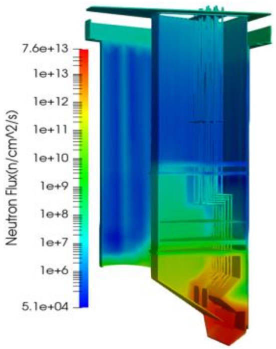






- Impact on TBR by neutronic analysis
  ΔTBR=0.012 for 18MW



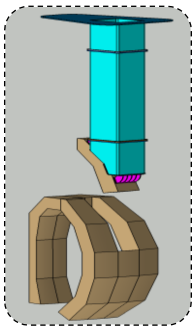


Configuration	Material
Shielding outside the frame	50% CLAM+50% H_2O
Shielding between VV and blanket	WC
WG	SS316LN
Mirror	Oxygen-free copper
PP/frame/shielding around the WG	80% CLAM+20% H_2O

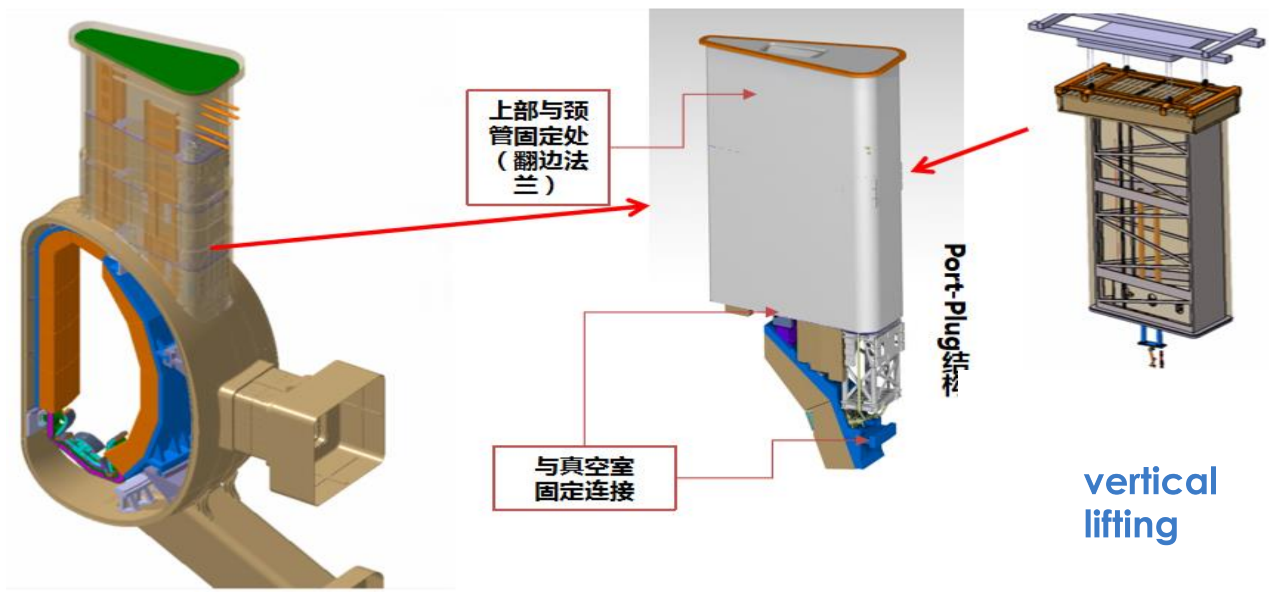
[P. Lu, et al., 2022 Nucl. Fusion, 62, 056011]

Remote maintenance scheme

- For remote maintenance, the blanket module 4# and ECRH launcher are integrated into an upper port plug
- Remote Handling accessible



integration of the blanket and ECRH



Outline

ASIPP

1 Introduction

2 Conceptual design of CFETR ECRH system

3 **R&D activities on CRAFT**

4 Summary

Objective of CRAFT ECRH

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Comprehensive Research fAcility for Fusion Technology (CRAFT)

- National big science facility (2019.9-2025.5)

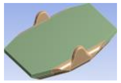
Objective of ECRH facility

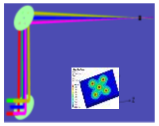
- **Establish an integrated high power, long pulse ECRH research and test facility for technologies exploration**
- **Pursue technical solutions for critical components and system commissioning**

Parameters: 170GHz，2MW

Key technology

- ➢ **Performances assessment of long pulse gyrotrons (output power, efficiency, stability)**
- ➢ **Development of low-loss transmission components**
- ➢ **Design, manufacture and performance validation of multi-beam quasi-optical launcher**





Development of gyrotron test bench

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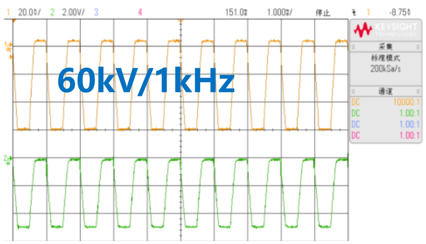
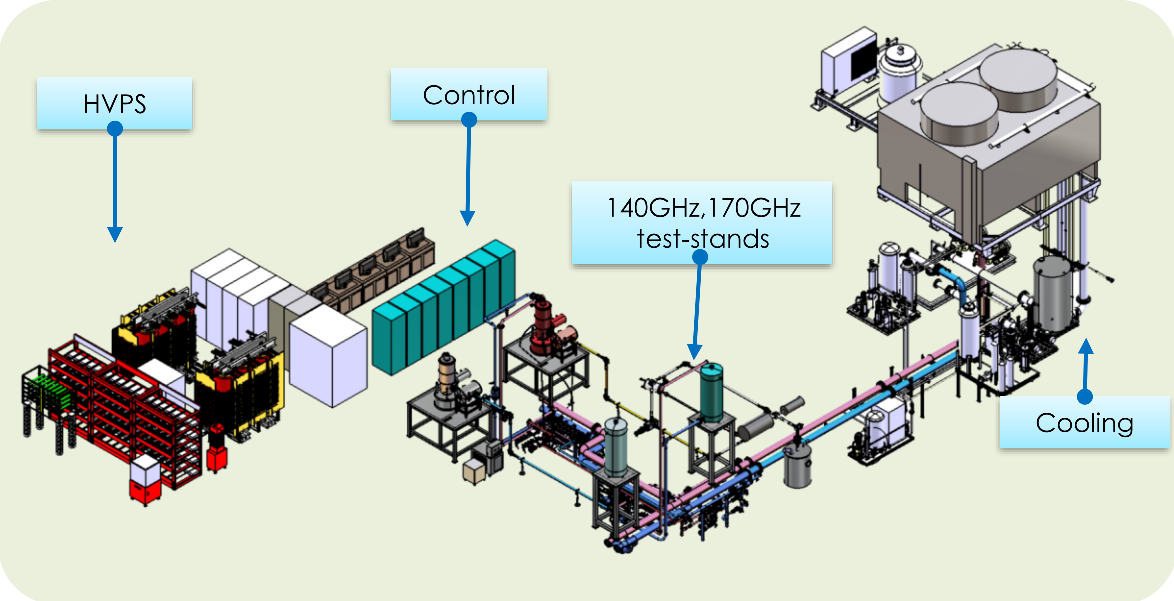
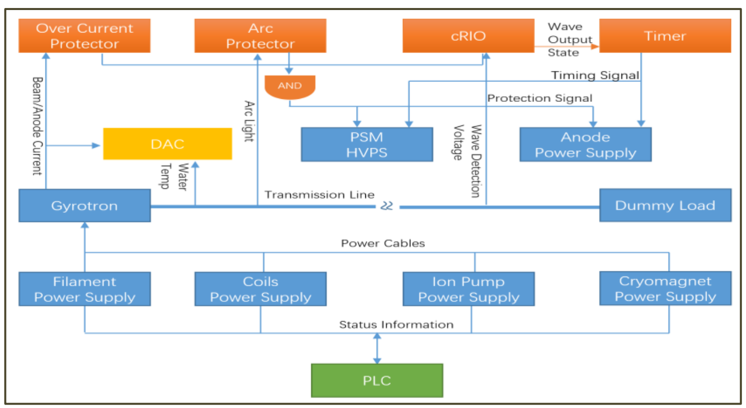
- Cathode PS : 60kV/50A PSM type， 1kHz modulation
- Anode PS: 35kV/100mA
- Auxiliary power supplies







Architecture of control system

Parameters of cooling distribution system

Loop	Medium purity	High purity	Constant
Capacity (kW)	2500	40	30
Inlet Temperature	≤35℃	≤35℃	≤15℃
Inlet pressure (bar)	10	5	5
Resistivity (MΩ.cm)	>3	>10	>3
Flow (t/h)	200	15	2
Monitoring	Flow, Pressure, Temp., Conductivity		

Development of gyrotron test bench

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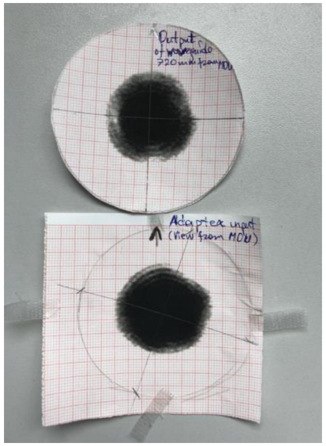
- **140GHz gyrotron test setup has been built for gyrotron commissioning and performance evaluation**



Long pulse operation of 140GHz gyrotron

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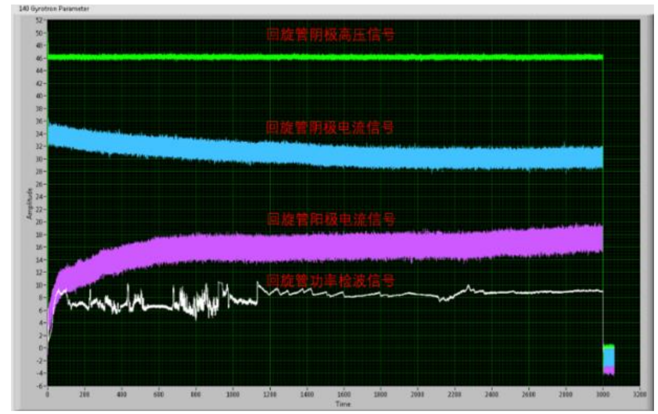
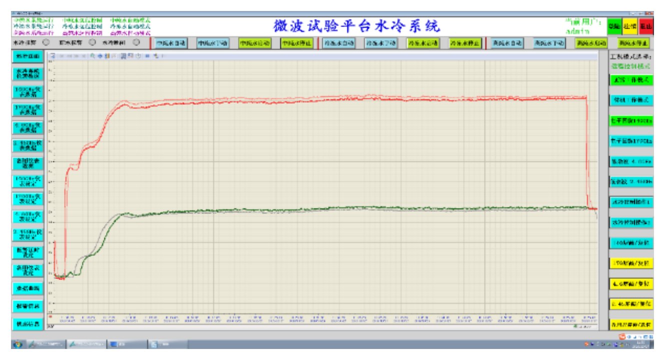
- Successful site acceptance test of 140GHz/700kW/3000s gyrotron
- Design and stability of the test bench validated





700kW, 3000s pulse duration

Plans for 170GHz gyrotron commissioning

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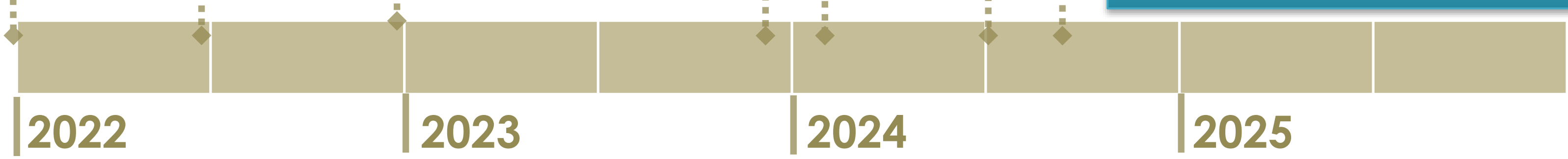
- 2021.12 Design of 170GHz teststand setup
- 2022.6 Gyrotron procurement
- 2022.12 170GHz teststand setup built
- 2023.11 Construction of 2MW test facility
- 2024.1 1st gyrotron arrived
- 2024.06 SAT of 2 gyrotrons completed
- Commissioning of gyrotrons

Target: high performance and high reliable operation



Development of launcher mockup

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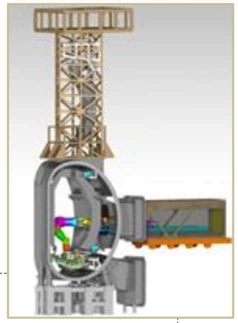
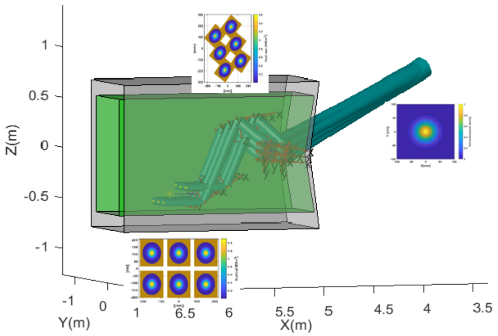
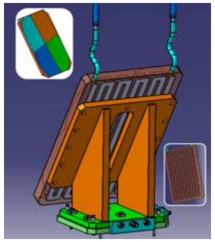
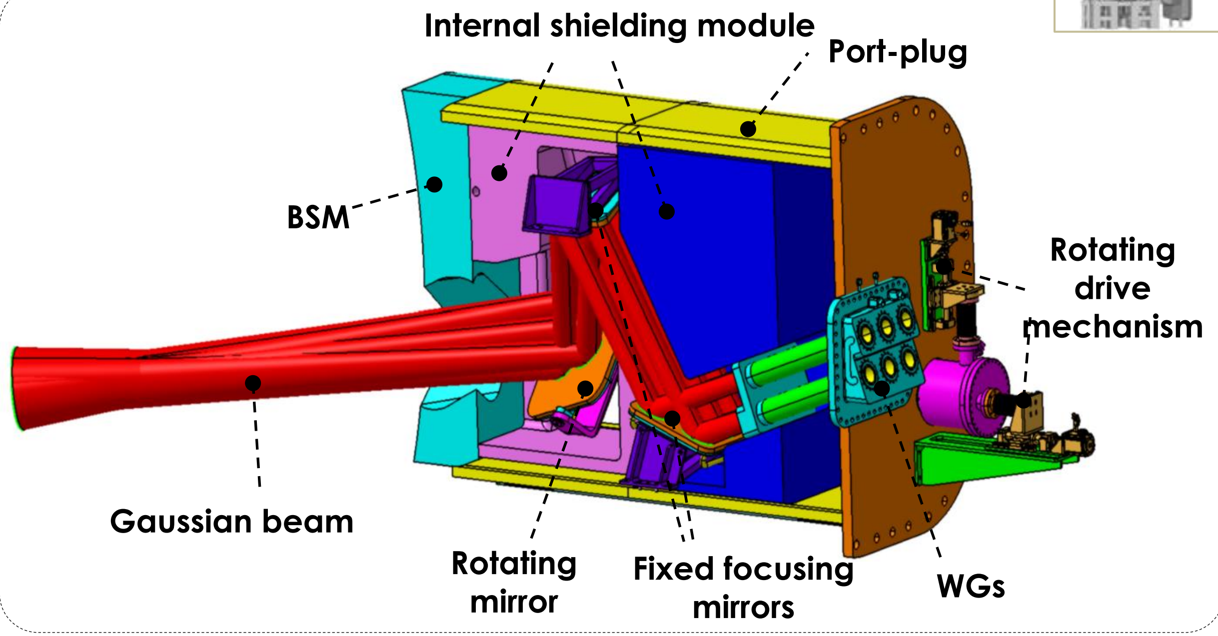
- Optimization of multi-beam convergence
- Structural design of the internal shielding and mirror is ongoing
- R&D of launcher components will be carried out









Sketch of beam routing and aperture layout

Summary

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- Conceptual design of 30MW 170GHz ECH system for CFETR is in progress for technical feasibility assessment based on the state of the art as well as to exploit some key technologies for the critical components.
- Efforts on the design of launcher are emphasized pending the final integration design.
- Performance and RF properties of ECH system will be assessed by closely working with Physics group.
- Need iteration with physical design.
- To explore the advanced EC technology, R&D activities are implemented rely on CRAFT ECRH test facility.
- Extensive international cooperation is welcome: jointly work, design review

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