25th Topical Conference on Radio-Frequency Power in Plasmas

Conceptual design of ICRF heating systems for CFEDR

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Chinese Fusion Engineer Demo Reactor (CFEDR)

Technical readiness

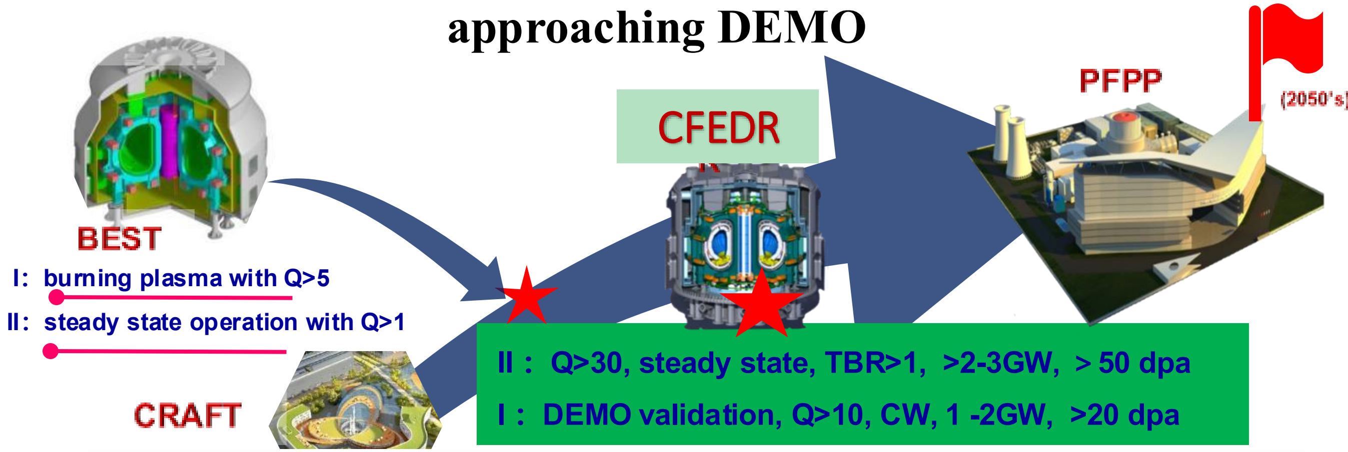
- **EAST**
  Steady-state long-pulse physical operation

- **ITER**
  Near 20 years' R&D experience

- **CFETR**
  The engineering design completed

- **CRAFT**
  The construction launched in 2019

CFEDR mission remains the same as CFETR for approaching DEMO



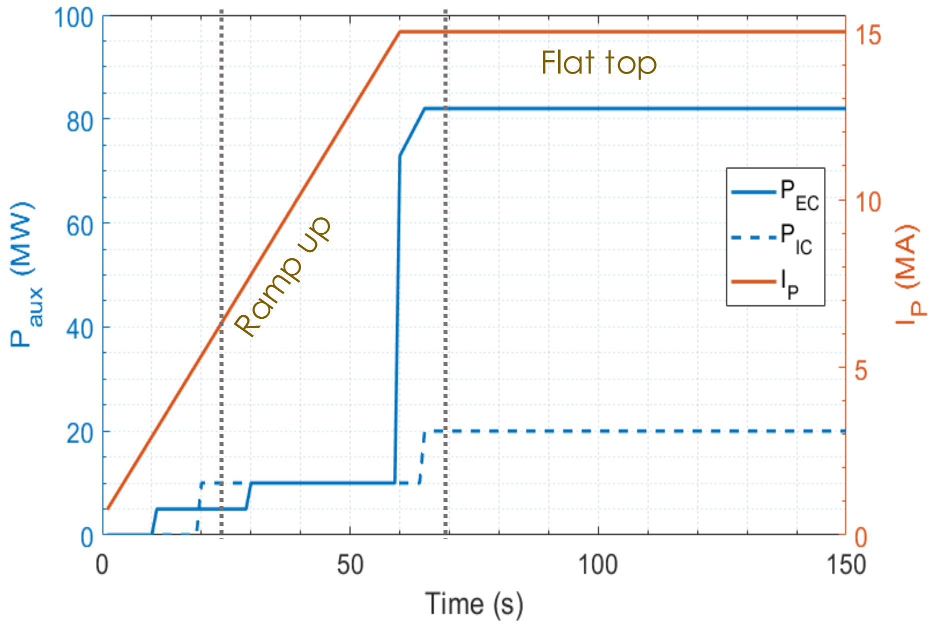
Parameters	CFEDR Conventional H-mode	CFETR Steady-State (SS)	ITER (Q=10)
P_{fusion} (MW)	1510	1033	500
R (m)	7.8	7.2	6.2
a (m)	2.5	2.2	2.0
B_{t0} (T)	6.3	6.5	5.3
$P_{heat}=P_{\alpha}+P_{aux}$ (MW)	403	292	173

Vincent Chan presentation, in the 1st CFEDR physical design IAC meeting

Requirements for RF Heating

◆ ICRF & ECRH are required for CFEDR conventional H mode operation (SAT1 15MA)

- **Parameters of (SAT1 15MA) baseline**
  - R_0 = 7.8 m , a = 2.5 m
  - R_{mag} = 8.28 m
  - B_0 = 6.3 T, B_{mag} = 5.9 T
  - SOL = 0.2 m
  - β_n= 2.56
  - P_{fus} = 1510 MW



- **Functions of heating mix:**
  - ➢ **ECRH**
    - Pre-ionization
    - Heating
    - Current drive
  - ➢ **ICRF**
    - Heating
    - L-H transition assisted

➢ **Ramp up phase : 10 MW IC + 10 MW EC**

➢ **Flat top phase: 20 MW IC + 82 MW EC**

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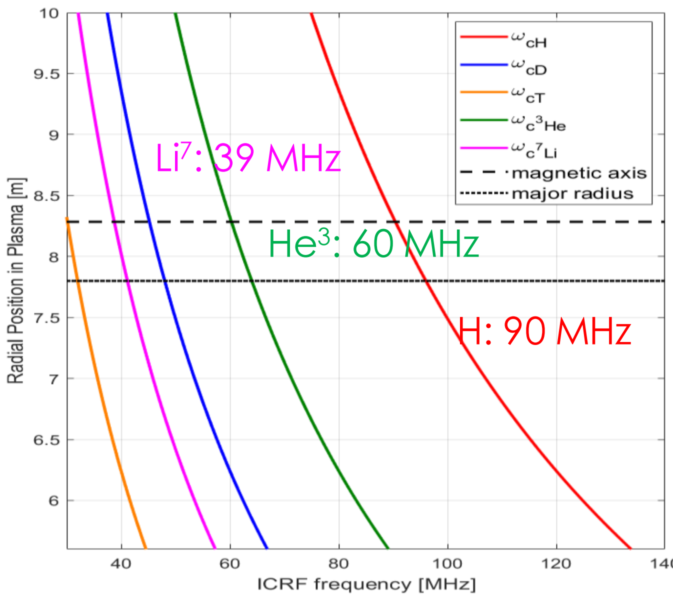
ICRF Heating Scenarios for CFEDR

Potential ICRF ion heating schemes :

- **3He minority heating** with **60 MHz** on-axis. Both minority ion 3He and majority ion T could be heated through fundamental and harmonic cyclotron resonance respectively (TFTRI[1], JET[2],ITER&DEMO[3-5]).
- **H minority heating** with **90 MHz** on-axis. Both minority ion H and majority ion D could be heated through fundamental and harmonic cyclotron resonance respectively.

Radial position of cyclotron resonance : $R = R_0 \frac{q_i B_0}{2\pi f m_i}$



Fundamental resonance positions versus RF frequency. Core ion heating can be achieved with 3He and H minority heating scheme

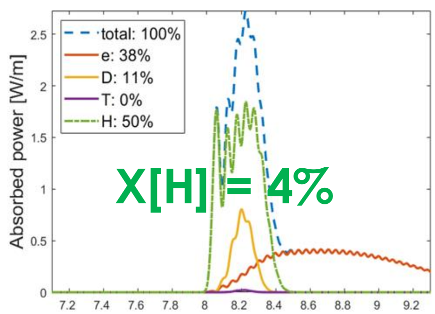
[1] J.R. Wilson et al 1995 Phys. Rev. Lett. 75 842
[2] D.F.H,Start efer1g98 Phvs. Rev. Lett. 80 4681
[3] D.Van Eester et al 2002 Nucl. Fusion 42 310
[4] R.J. Dumont and D.Zarzoso 2013 NF. 53 013002
[5] D. Van Eester et al 2019 Nucl. Fusion 59 106051

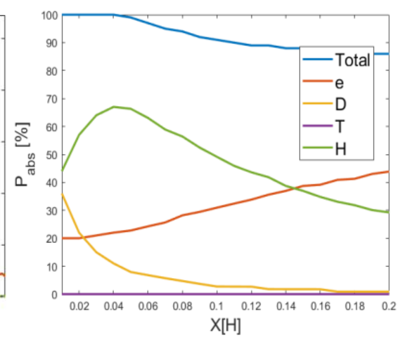
ICRF Heating Scenarios for CFEDR

D-T plasma
N_{tor} = 35, B_0=6.3T,
R_0=7.8m, T_{e0}=30keV,
T_{i0}=24keV,
n_{e0}=14e19m^{-3}

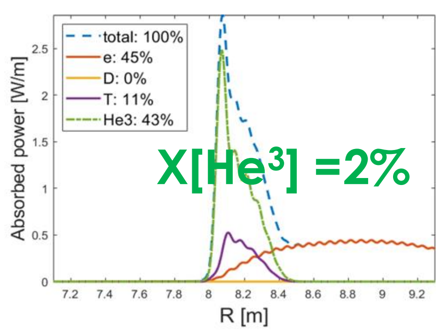
- **Both H and He^3 minority heating are very efficiency by selecting appropriate ion concentration**
- **Operating range of H minority heating is larger than He^3 minority**
- **For both 60 MHz and 90 MHz, total absorbed power is larger than 90% when refractive index, N_{tor} >25**

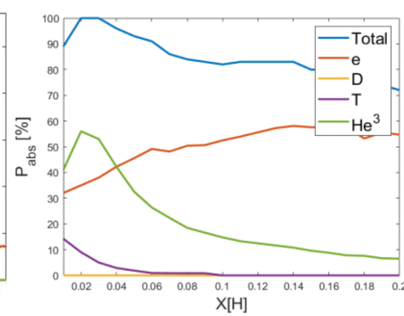
f=90 MHz H minority heating

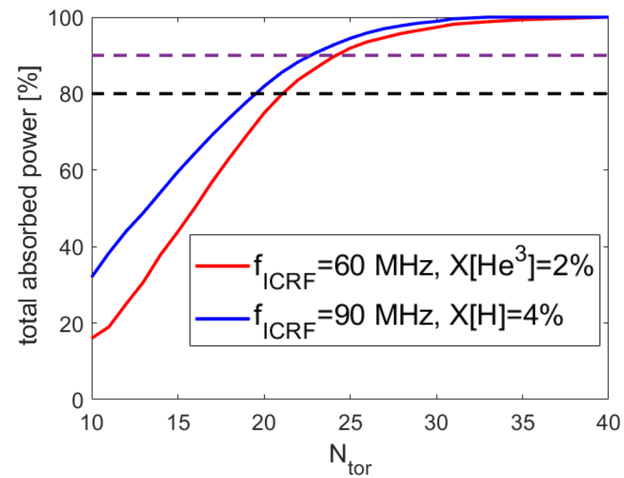




f=60 MHz He^3 minority heating



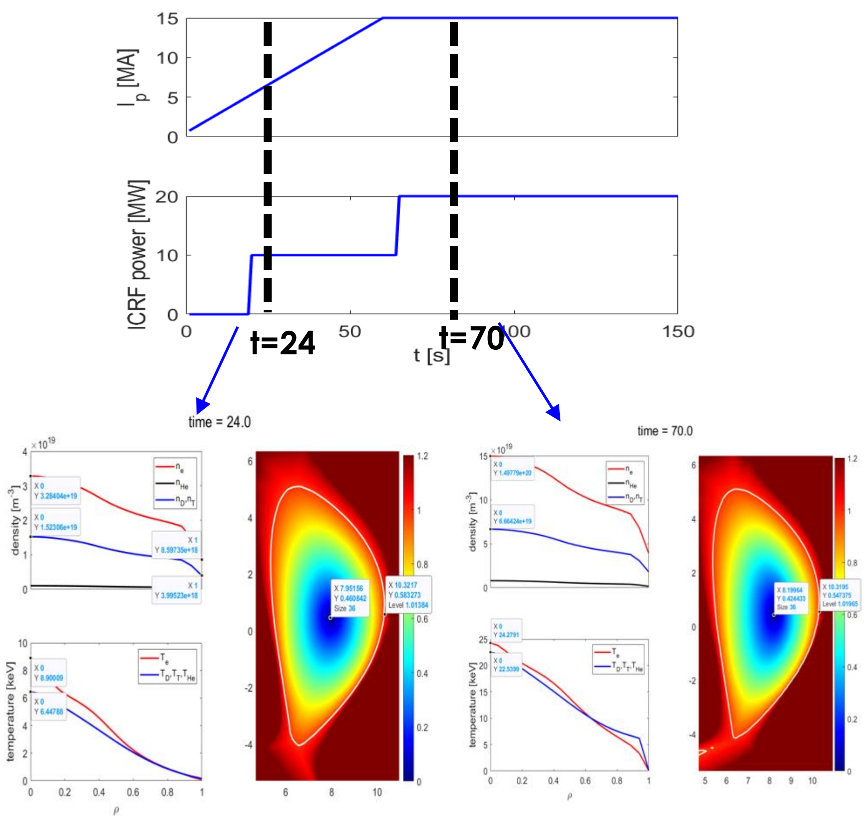




Total absorbed power:
> 80% , N_{tor} > 20
> 90% , N_{tor} > 25

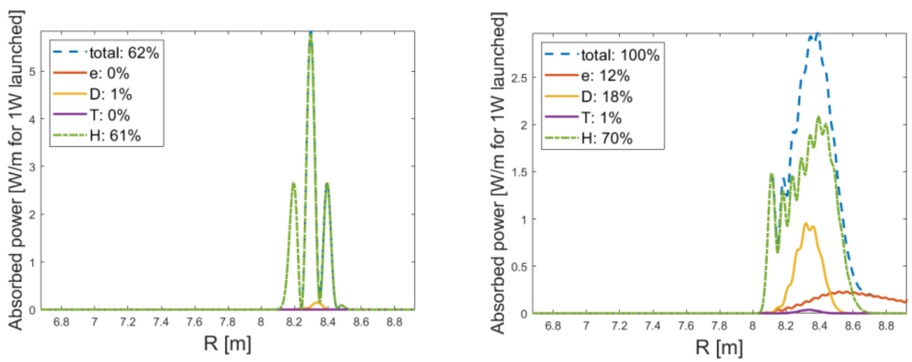
ICRF Heating Scenarios for CFEDR

- At t=24 s (ramp up phase), the total power absorption of H and 3He heating are ~62% and 54%, respectively
- At t=70 s (flat top phase), both H and 3He minority heating cases, power absorption can be achived~100%



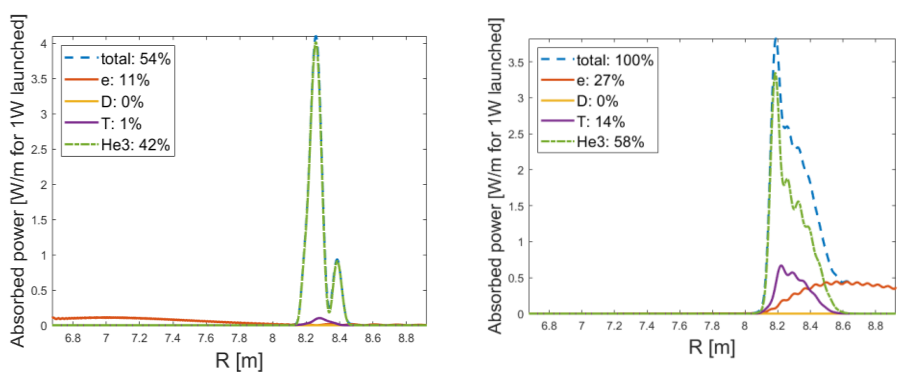
D-T plasma (1:1) ,N_{tor} = 35, B_0=6.3T, R_0=7.8m

t=24 s	t=70 s
T_{e0}=8.9keV, T_{i0}=6.4keV, n_{e0}=3.3e19m^{-3}, n_{i0}=1.5e19m^{-3}	T_{e0}=24.2keV, T_{i0}=22.6keV, n_{e0}=14.9e19m^{-3}, n_{i0}=6.7e19m^{-3}



f=90 MHz

H minority heating



f=60 MHz

He3 minority heating

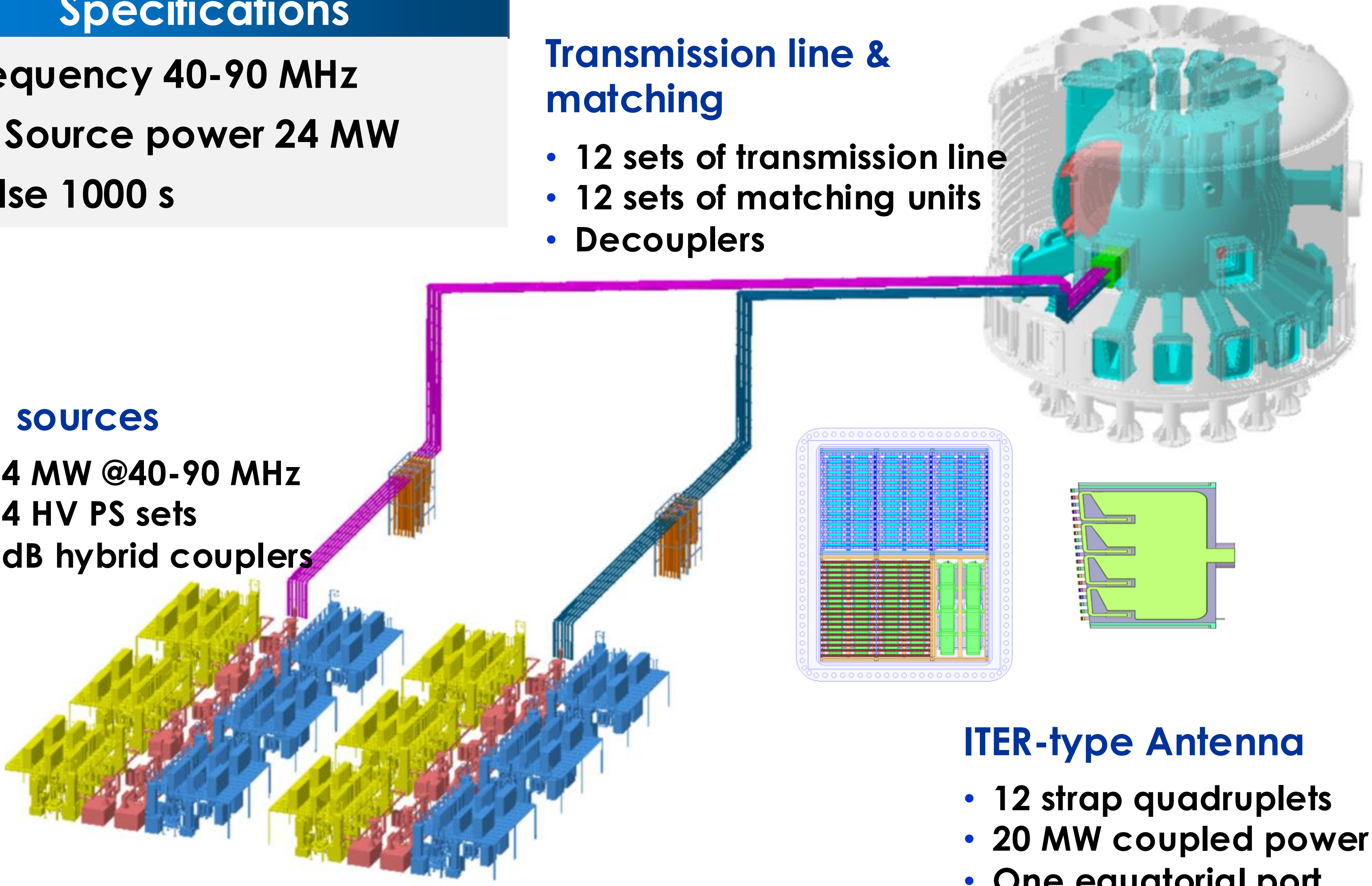
CFEDR ICRF system overview

Specifications

- Frequency 40-90 MHz
- RF Source power 24 MW
- Pulse 1000 s

Transmission line & matching

- 12 sets of transmission line
- 12 sets of matching units
- Decouplers



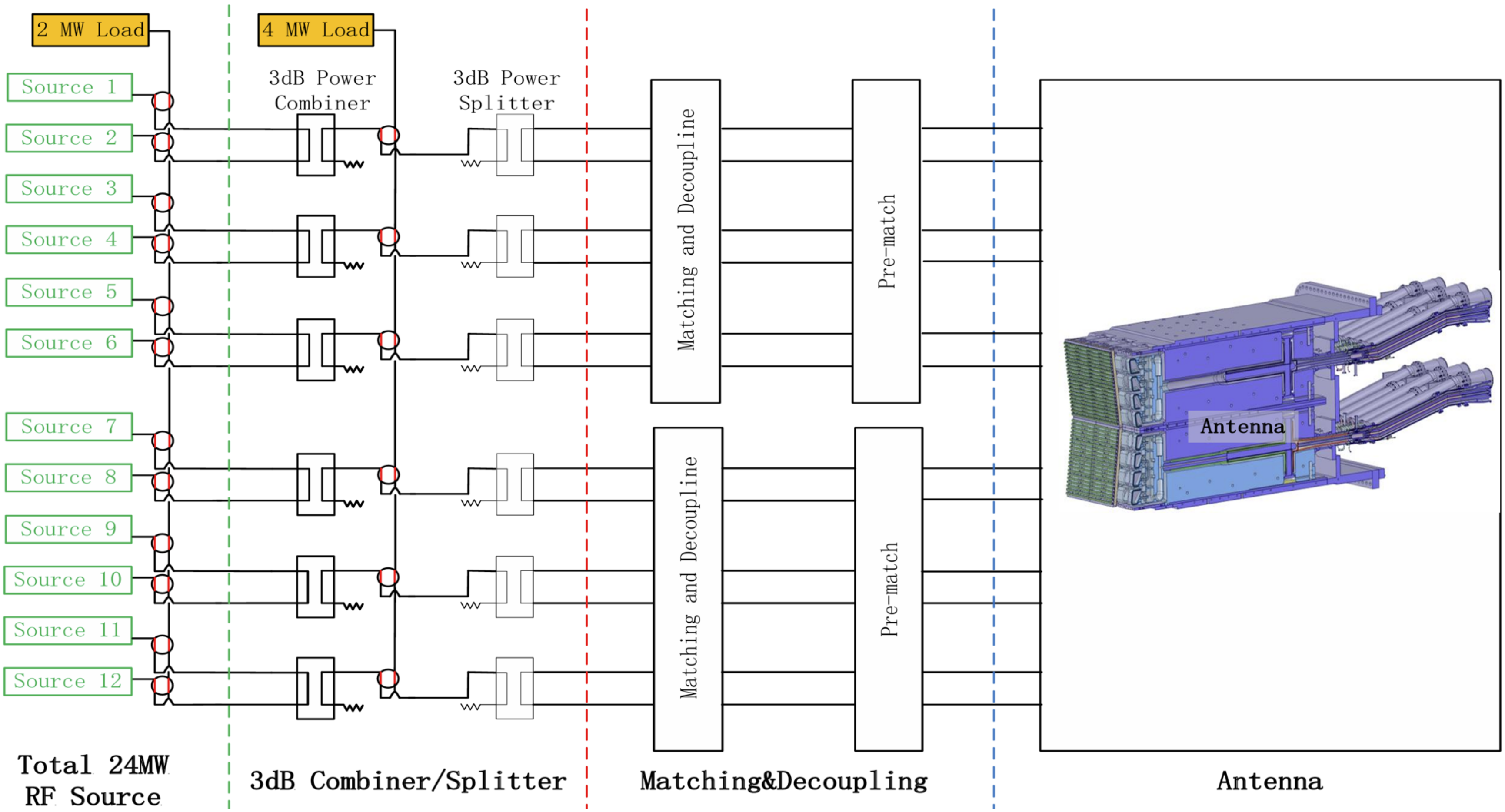
RF sources

- 24 MW @40-90 MHz
- 24 HV PS sets
- 3dB hybrid couplers

ITER-type Antenna

- 12 strap quadruplets
- 20 MW coupled power
- One equatorial port

ICRF system topology layout

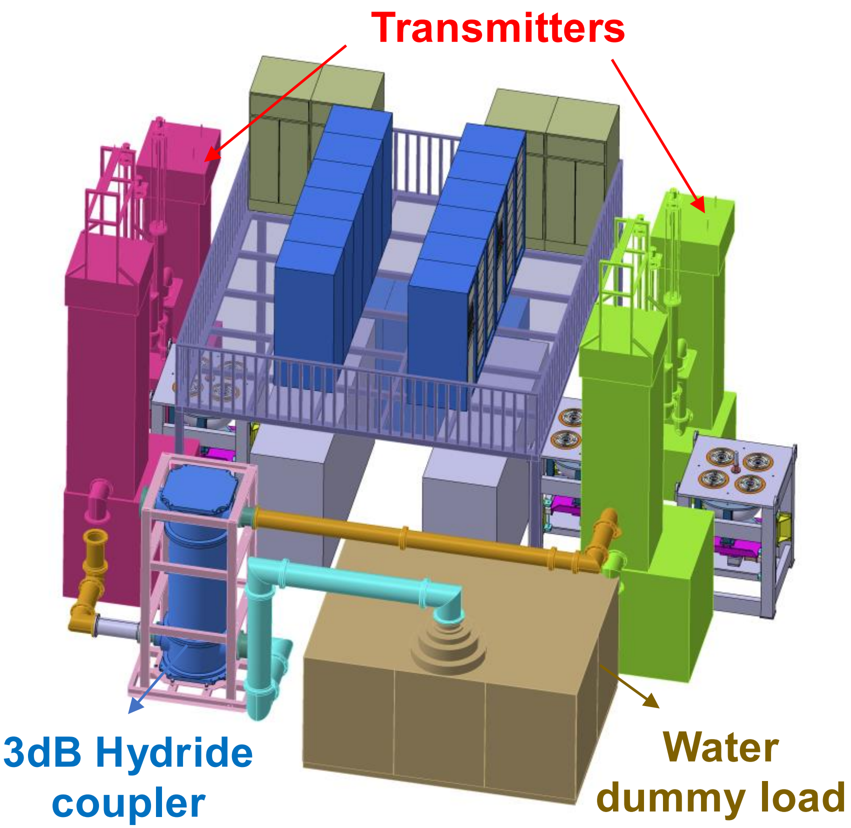


Total 24 MW source power(twelve 2MW RF source combined units), six 4MW 3dB combiner and six 4MW splitters, launched into an antenna through twelve transmission lines.

RF sources (transmitters)

☐ RF Sources

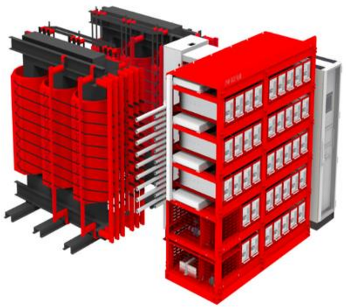
- 24 transmitters, two by two combiner and then split twelve transmission lines for one antenna
- 2MW RF source unit includes two RF transmitters of1MW, a 2MW 3dB hybrid power combiner and a water dummy load
- Two 2MW transmitter units are combined by using a 4MW combiner and a 4MW splitter also is needed for load resilience



2MW RF Source unit

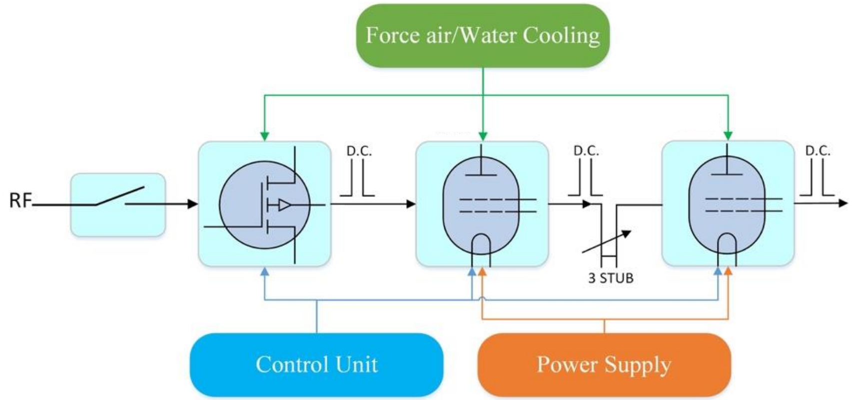
RF sources (transmitters)

- Transmitter is mainly composed of RF amplifier, High Voltage Power Supply(HVPS), Control unit and cooling system
- RF amplifier chain has 3 stages: a SSPA(6kW, solid-state), DPA (100kW, tetrode) and FPA (1MW, tetrode)
- Three stubs are used for matching units between DPA and FPA for wide bandwidth
- DPA HVPS and FPA HVPS are DC 16kV/15A , DC 24kV/130A, respectively

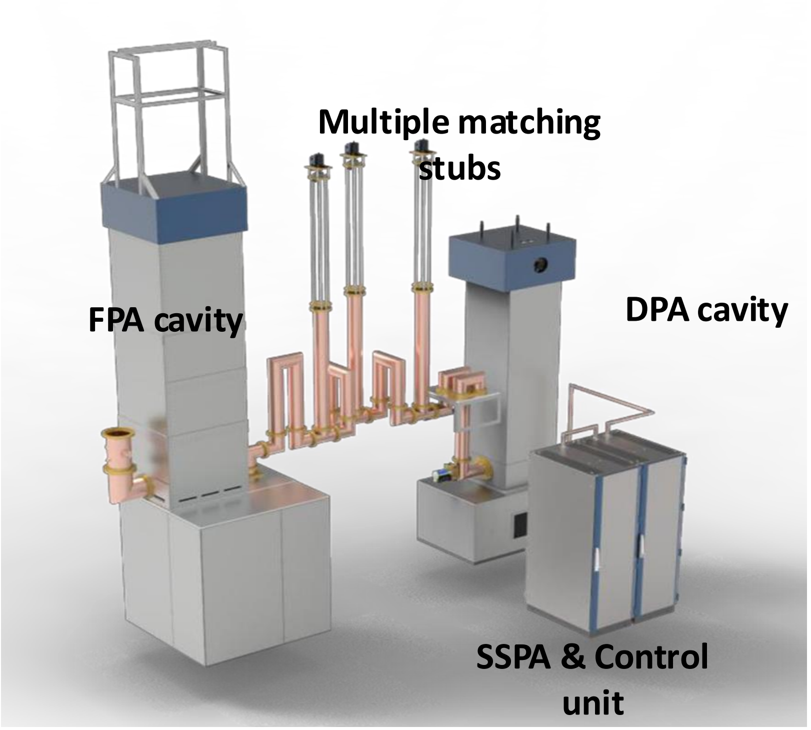


HVPS for FPA
DC 24kV/130A

HVPS for DPA
DC 16kV/15A

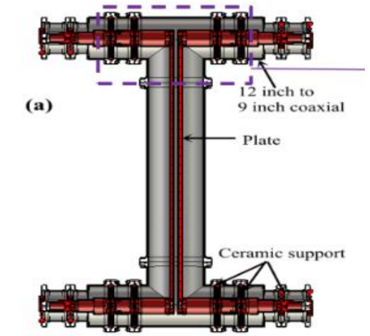


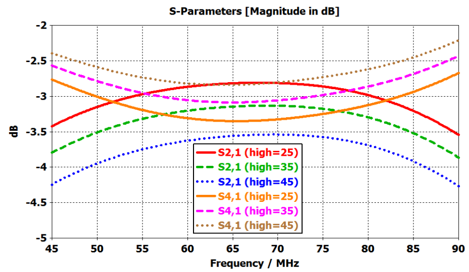
RF transmitter amplifier chian

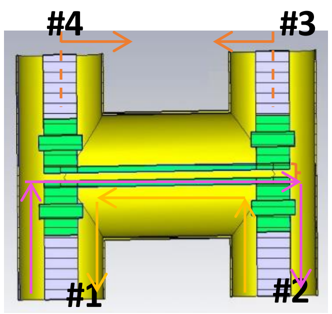


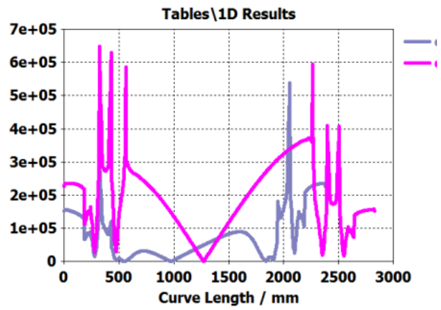
RF sources (combiner)

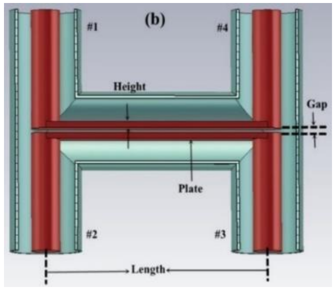
- 2MW 3dB hybrid coupler using12inch coaxial line combine with 2 individual transmitters
- 4MW 3dB hybrid coupler use large size coaxial line(outer diameter of 500mm, inner diameter of 200mm) for high power combine
- Simulations show that 3dB bandwidth is about ±10MHz, therefore it should design three sections to meet the requirements for full frequency range.

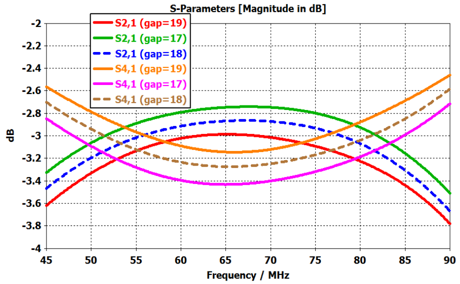


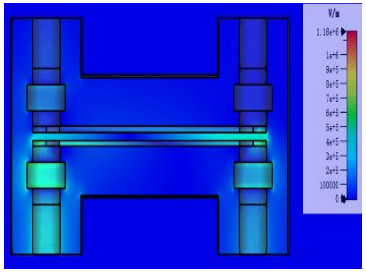


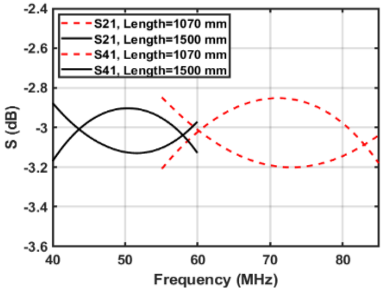












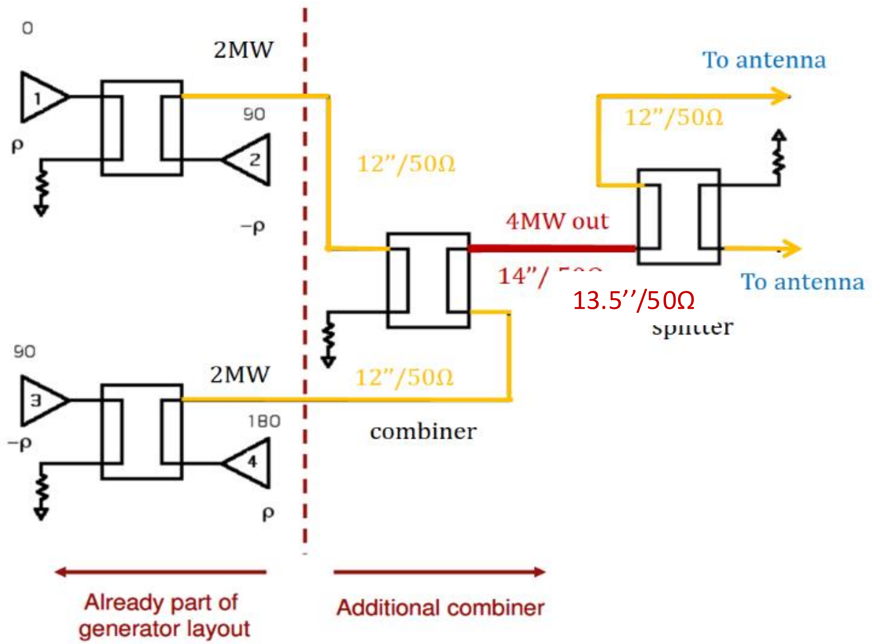
2MW 3dB hybrid combiner

4MW 3dB hybrid combiner

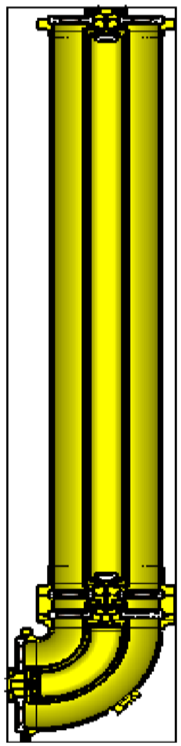
Transmission line

- Transmission Lines (TL)

- 13.5 inch, 50Ω coaxial line for 4MW power combination section
- 12 inch, 50Ω coaxial line for two RF transmitters combination section
- High VSWR section will be with water cooling inner conductor and 3bars N2 gas



Transmission line layout

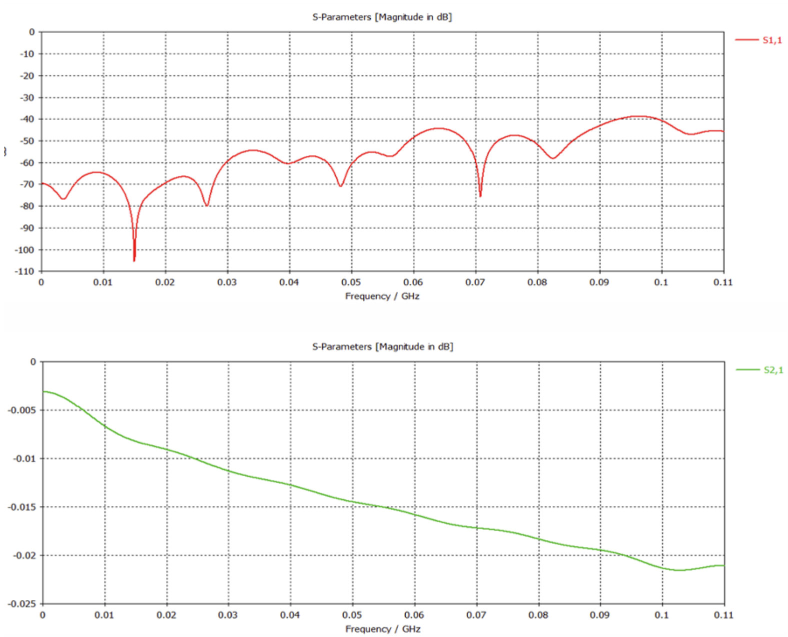


TL with water cooling & gas

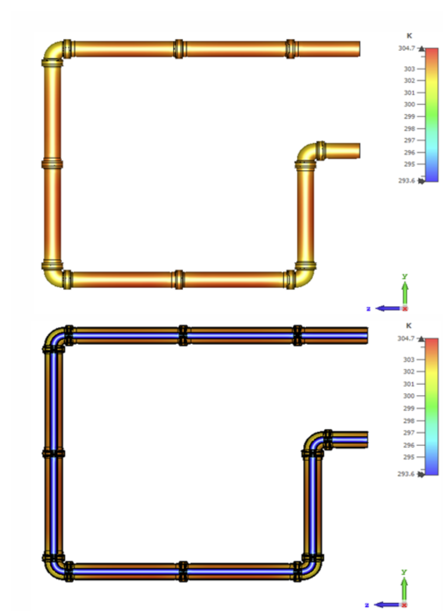
Transmission line

- RF simulations 12“ line return and insertion loss of 15 m line
- Thermal simulations with matched/reflection cases at 2.5 MW, 40 and 80 MHz.
- Approx. 23.5°C matched and 47°C total reflection at 40 MHz.
- Approx. 33.6°C matched and 79°C total reflection for 80 MHz.

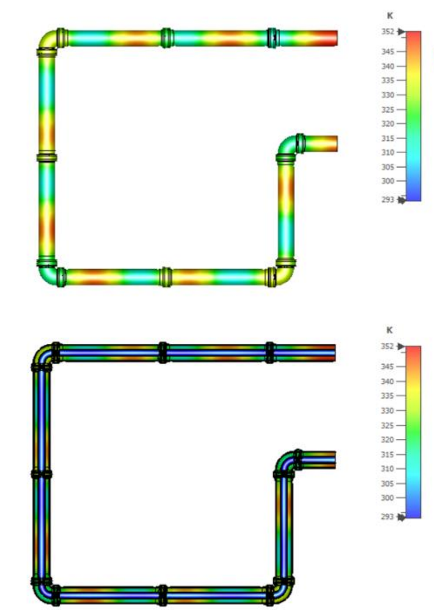
12“ coaxial transmission line,15m



S-parameters



Matched case

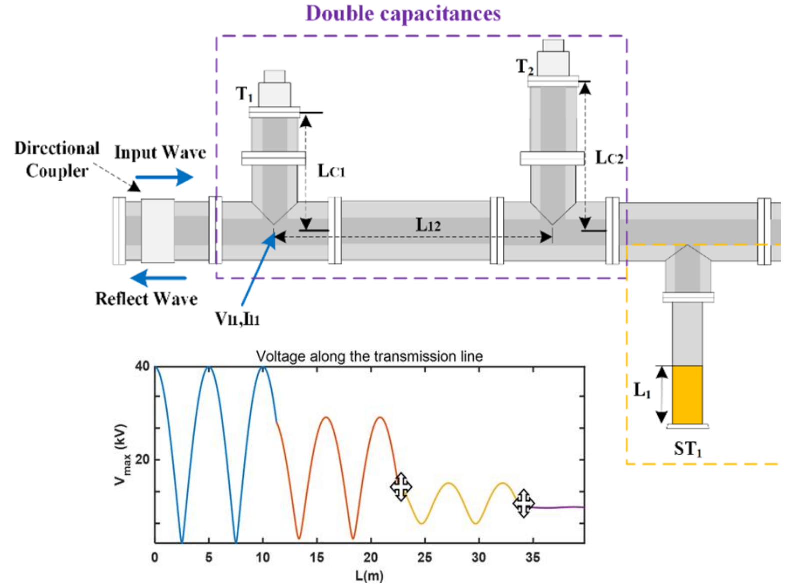


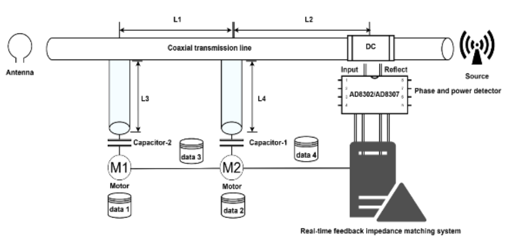
Total reflection

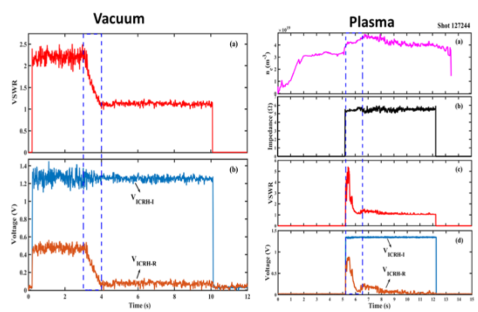
Matching system

☐ Matching system

- One liquid stub with double capacitor tuners can match a large region of the smith chart for CFEDR
- The 1st stub is for lower VSWR, the 2nd and 3rd capacitors can be fast varied and easily achieved the matching point
- The fast impedance matching system(water-cooled capacitors) has been validated on EAST experiment

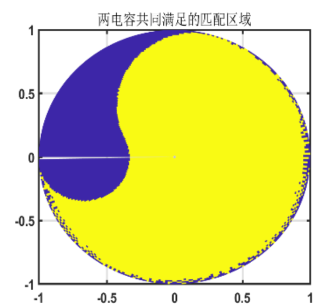






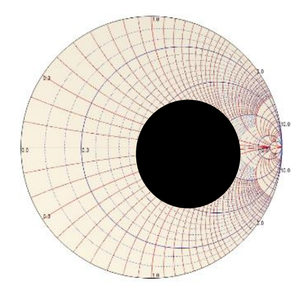
Fast impedance matching control system validation on EAST

Matched region



Matched region by double capacitors

Lower VSWR region



Lower VSWR by 1st stub

Poster Liu L.N

Antenna

- ITER size： width x height = 1.560 m x 2.054 m ($S \approx 3.204\ m^2$)
- EU-DEMO size： width x height = 1.540 m x 2.760 m ($S \approx 4.250\ m^2$)
- CFEDR size： width x height **= 2.400 m x 2.860 m (**$\mathbf{S \approx 6.864\ m^2}$**)**

	Number of antennas	Equatorial port area[m2]	Power per Antenna [MW]	Maximum voltage [kV]
ITER	2	3.204	20	45
EU-DEMO	3	4.25	17	45
CFEDR	1	6.864	20	45

Design goals： 20 MW coupled power into plasma

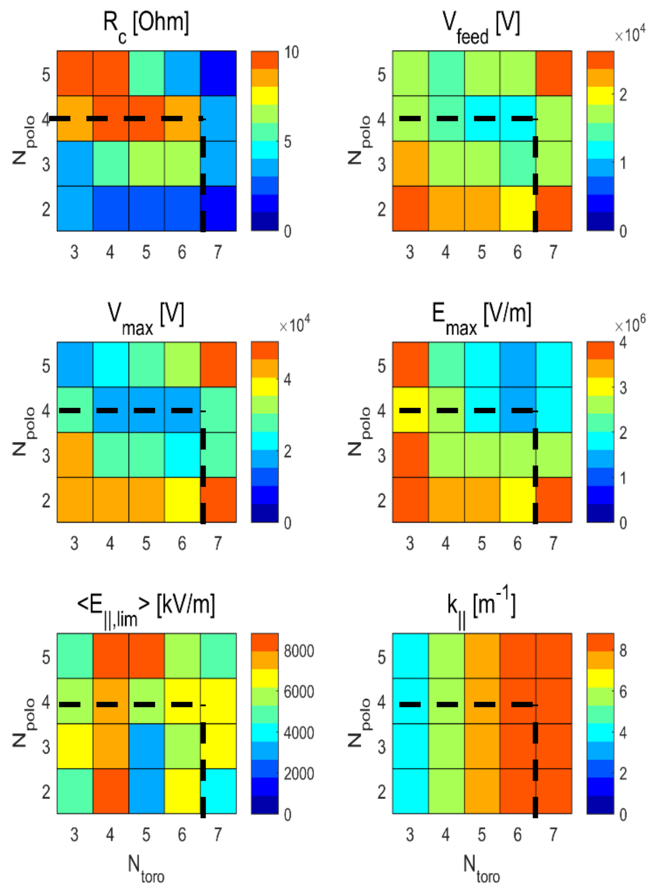
Antenna

◆ Optimized structure for half-antenna:

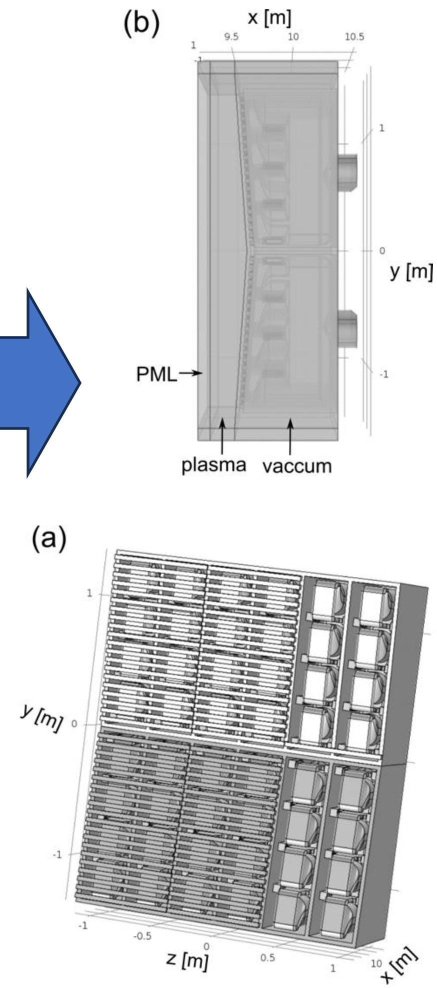
- poloidal 4 sub-straps, toroidal 6 straps
  - ➢ Maximum R_c
  - ➢ Minimum V_{max}
  - ➢ Small $E_{||}$

◆ Backup structure:

- poloidal 3 sub-straps, toroidal 6 straps



3D conceptual model for CFEDR ICRF antenna

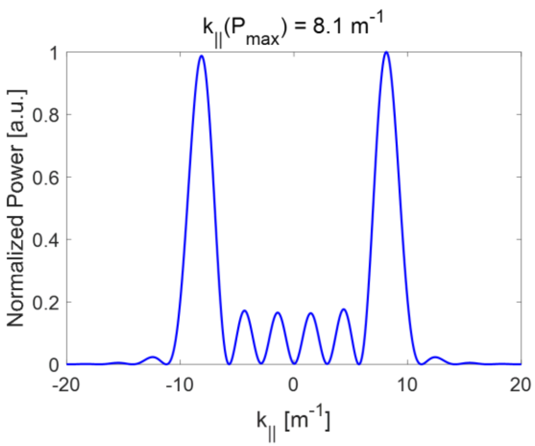


Poster Jiang Y. H

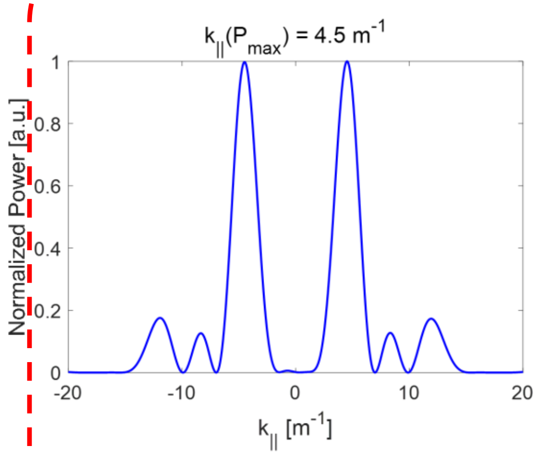
Antenna

☐ Optimized antenna phase

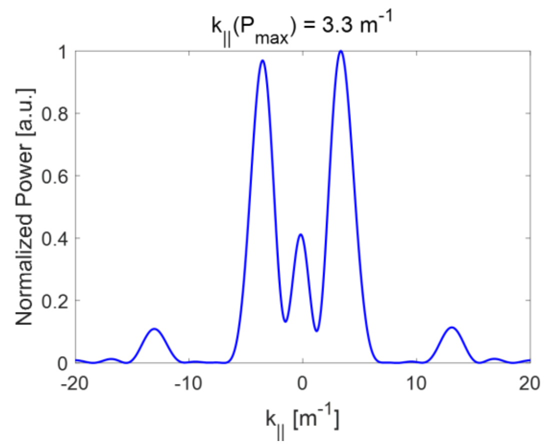
(0, pi, 0, pi, 0, pi)



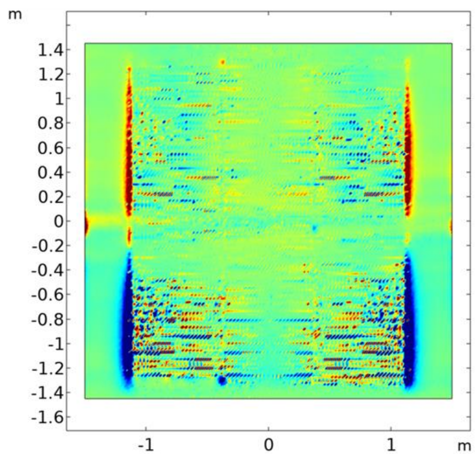
(0, pi, pi, 0, 0, pi)



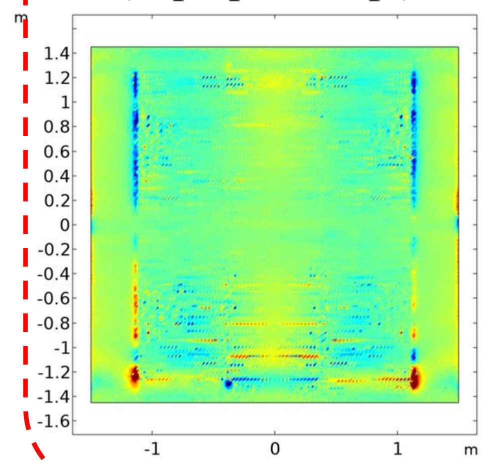
(0, 0, pi, pi, 0, 0)



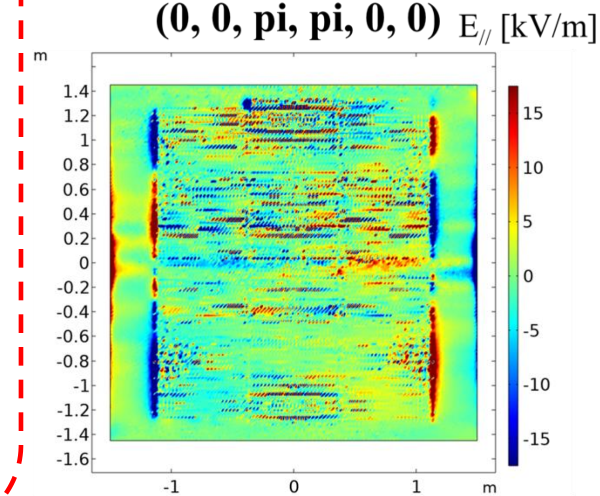
(0, pi, 0, pi, 0, pi)



(0, pi, pi, 0, 0, pi)



(0, 0, pi, pi, 0, 0)



Poster Jiang Y. H

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Comprehensive Research facility for Fusion Technology (CRAFT)

☐ Objectives

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

Lists of all testing facilities of CRAFT

• 1. SC Material testing facility	• 11. CFETR divertor development
• 2. SC Conductor testing facility	• 12. CFETR divertor testing facility
• 3. SC magnets testing facility	• 13. blanket development
• 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、office building
	2、Cooling water system	4、Campus site

CRAFT ICRF system

High power RF transmitter

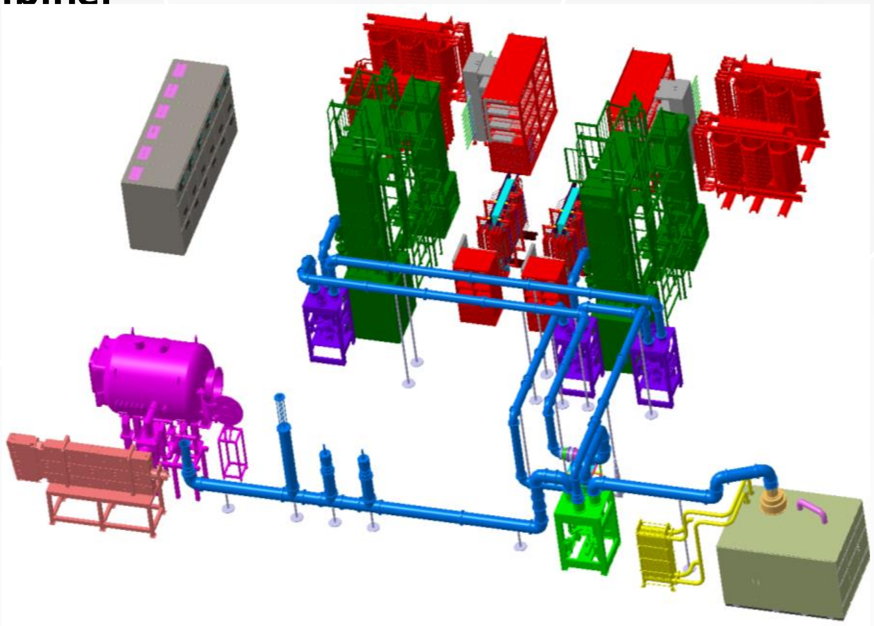
- Power : 1.0 MW
- Frequency： 40-80MHz
- Pulse： 1000s

High power combiner

- 3MW 3dB hybrid combiner
- 3MW water dummy load

High Voltage Power Supply

- DPA: DC 16kV 15A
- FPA: DC 24kV 130A
- Protection time＜5μs



ITER-type antenna

- RF windows
- Vacuum testing tank
- Antenna RF Module (SLM strap, TST etc.)

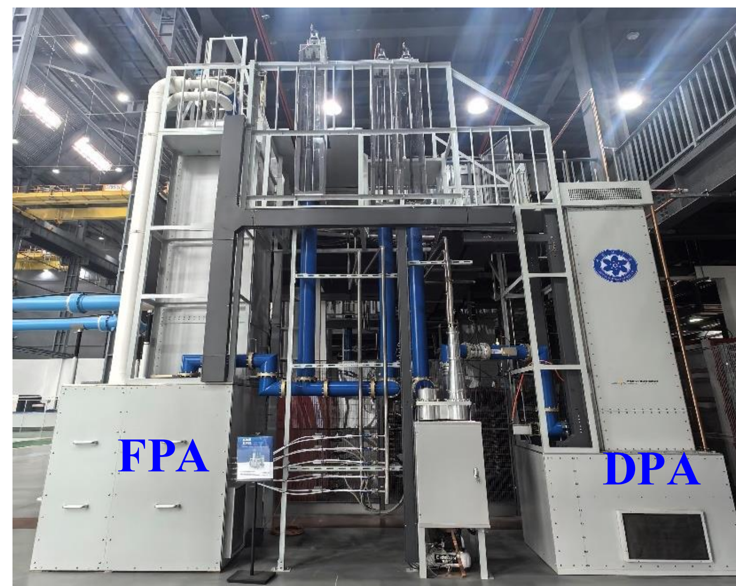
Transmission line & Matching

- 9/12’ coaxial line
- 9/12’ RF Switch
- Stub/capacitors

RF Source

- CRAFT RF transmitter R&D aims to validate the MW- long pulse operation in a big bandwidth for CFEDR
- Two transmitters including 3-stage amplifiers, HVPS and cooling system have been completed in CRAFT campus
- The commissioning of transmitter and high-power combination will be finished at the end of 2025

HVPS(10kV, transformer and PSM for transmitter)

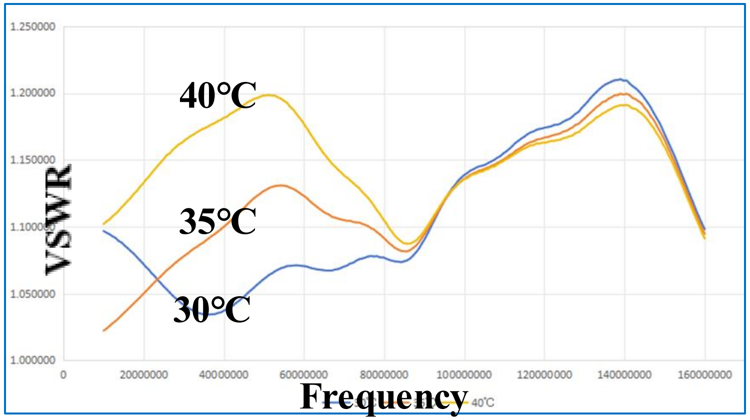


FPA, DPA,SSPA and control unit

3MW combiner & dummy load

- A 3dB coupler of 3MW using for two transmitters power combination
- We designed two 3dB couplers with frequency rang of 40-60/60-80MHz
- For the commissioning of transmitter and power combine, also a 3MW dummy load has been developed

3MW dummy load,CW



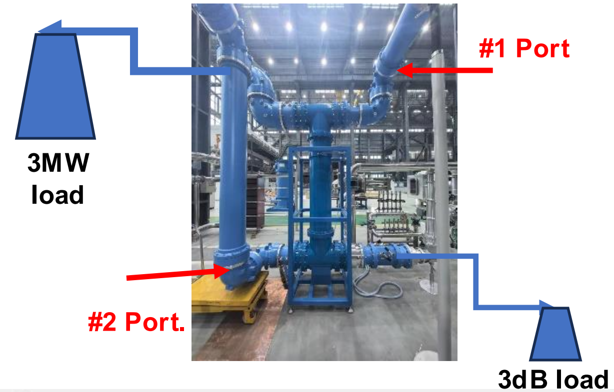
3dB@60-80MHz

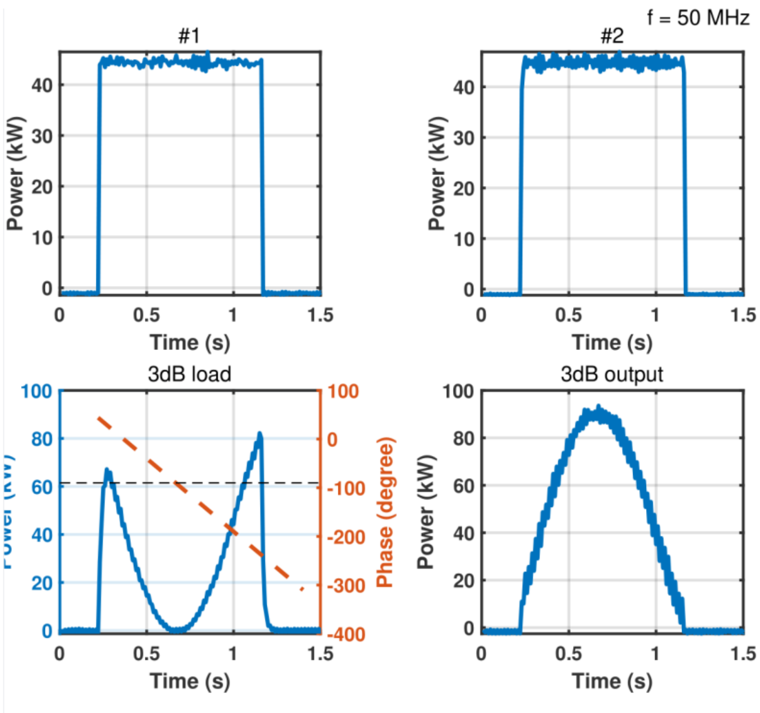
3dB@40-60MHz

- Due to the VSWR is more sensitive with water temperature, the controlling of water flow and temperature are very important

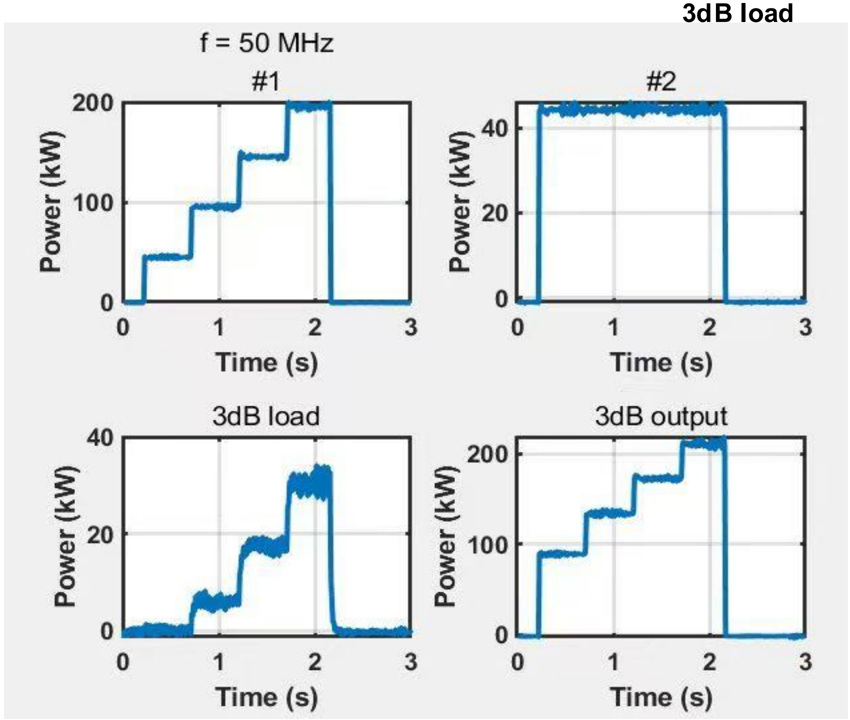
3dB combiner & dummy load

- Scanning the phase of two ports(#1 and #2), good combining efficiency can be achieved by selecting the correct phase (-90°±10°)
- The power balance of two ports has few effect on the 3dB combining efficiency





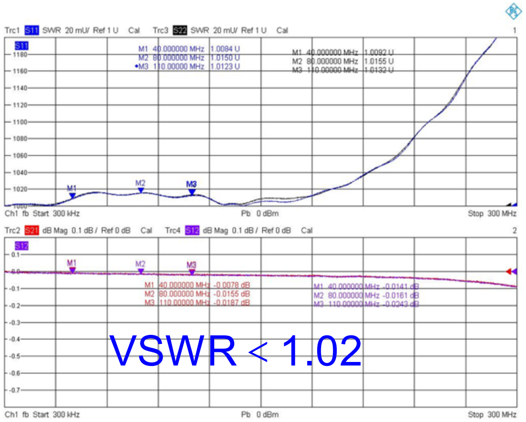
Phase difference testing



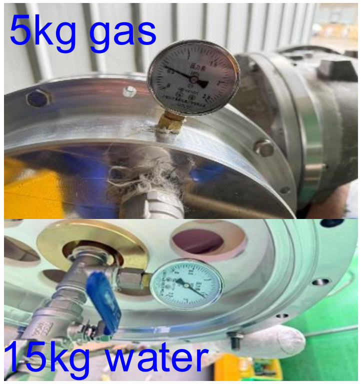
Power balance testing

Transmission line

- All TLs have been conducted RF performance testing and gas/water pressure testing before installation
- RF performance testing show that VSWR < 1.02 at 40-100MHz, with 5kg gas pressure and 15kg water pressure keeping 24h



RF performance testing



Gas/water pressure

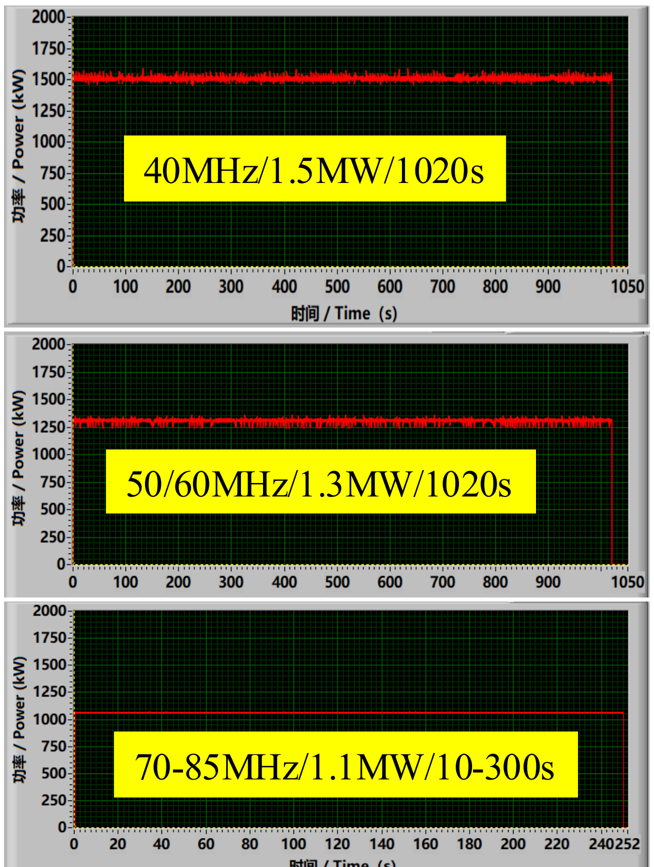
Straight lines

90° elbow

TL overview layout

Transmitter commissioning

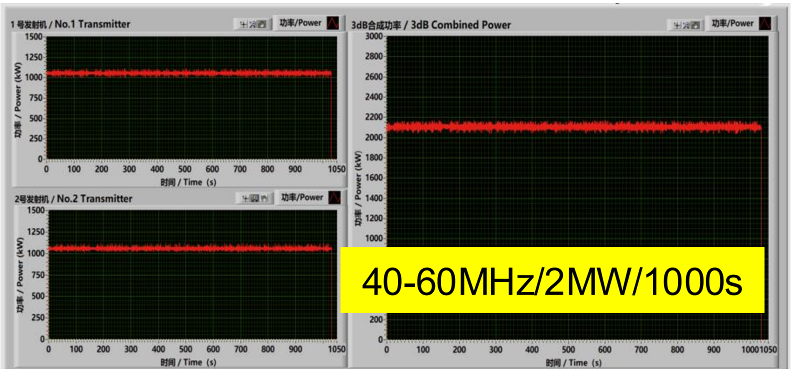
- Each transmitter is undertaken MW-long pulse commission at 40-85MHz
- At 40-50MHz/1.5MW/1000s and 50-60MHz/1.3MW/1000s have been achieved
- RF commission at frequency of 70-85MHz is on going. There is occasionally oscillations at some frequences.

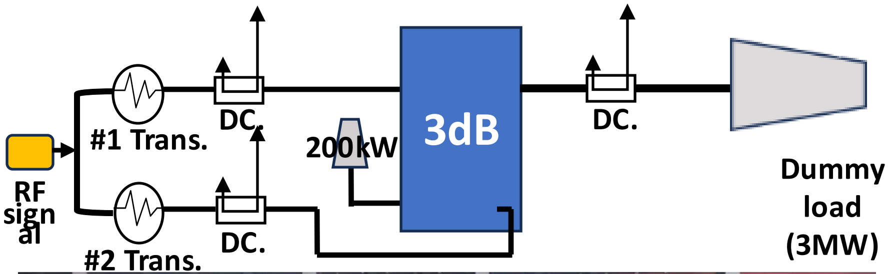


Each transmitter conducted MW-long pulse RF commissioning

3dB combiner commissioning

- Two transmitters integrated with 3dB coupler, transmission lines and dummy load, combined RF commission has been carried out
- A 2MW/1000s with 2×1.05MW and 3MW/5s with 2×1.55MW at frequency of (40-60)MHz have been achieved
- When completing the transmitter RF commission, We will change 3dB coupler for power commission of 60-80 MHz

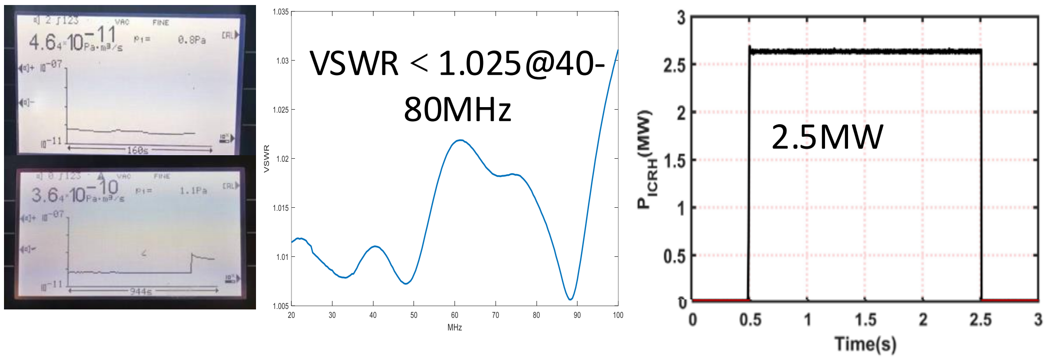




Two transmitters integrated with 3dB coupler

RF windows R&D

- RF Windows is used for separation the device vacuum from pressurized transmission lines
- A 50 ohm RF windows, 9 inch with 99% conical alumina has been developed
- Leaking testing, RF testing and high power has been successfully carried out

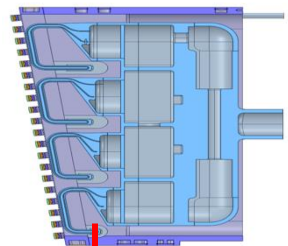


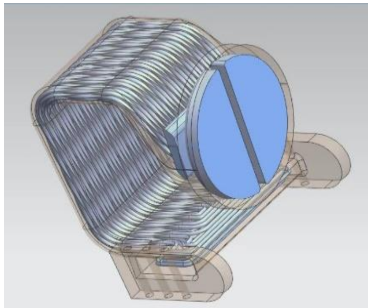
Leaking testing, RF testing and high-power testing

RF windows prototype

ICRF antenna R&D

- A SLM 3D printer is used for strap fabrication to mitigate the leakage risk of the cooling channel
- TPMS cooling chamber optimization to meet process requirements
- Comparison of the SLM 3D material and SS316L, there is no much difference of them





SLM 316L Vs. SS316L

No.	Performance	SLM 316L	SS316L
1	Thermal Cond. W/(m•K)	14.74	14.28
2	Density (kg/m3)	7980	7930
3	a_m, 10^{-6}/K	17.11	15.9
4	E, GPa	185.9	200
5	Poisson ratio	0.27	0.3
6	C_p, J/(kg K)	501	472
7	Relative permeability	1.028	1.03
8	Hardness (HB)	203	217
9	Toughness (J/cm2)	> 173	> 100
10	Tensile strength (MPz)	630	500
11	Yield strength (MPa)	447	200
12	Elongation (%)	61	60

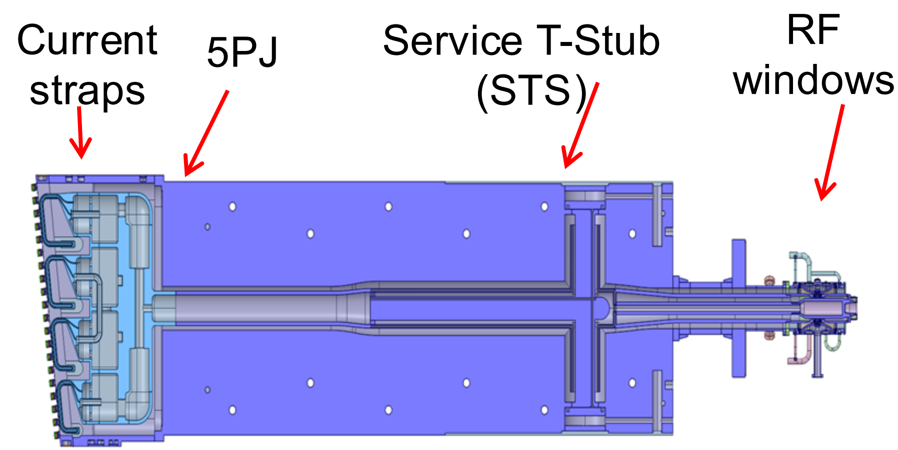
SLM strap copper coating (60μm)

SLM strap detection

SLM 3D printer of strap

ICRF antenna R&D

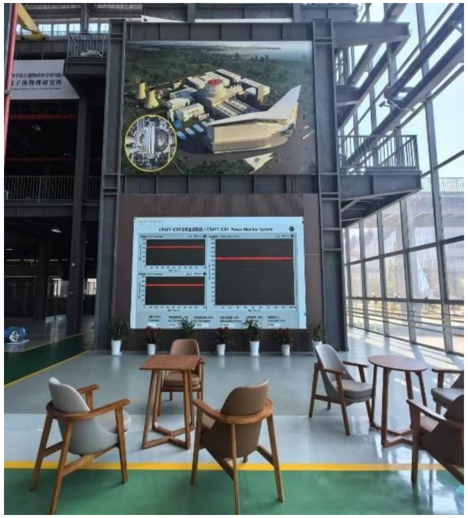
- ITER-type antenna RF module including four straps, a Port-Joint (PJ) , a service T- stub and a transformer has been developed
- Key components of RF module are integrated with SLM strap, 4PJ, transformer, STS and RF windows



vacuum tank

RF module

CRAFT ICRF system overview



CRAFT Project goes well on the schedule (2025.10)

Summary

- **Based on the conventional H-mode operation scenario and required injected power of ICRF from scenario modeling, preliminary simulations have been done**
  - to determine the system working frequencies,
  - to confirm the potential heating schemes
  - To evaluate the power absorption/ heating efficiency
  - **Conceptual design of IC main system were undertaking**
  - to determine the RF source working frequencies range/comp
  - to optimize transmission line and matching units
  - to optimize heating, antenna spectrum/coupling
- **The key components R&D of ICRF system in CRAFT will contribute to CFEDR, commission will be finished at the end of 2025.**
- **Integrated simulation and design are needed to further explore the technical availability.**


THANKS
China Fusion Engineerring DEMO Reactor