High-power and long-pulse operation of ICRH system in EAST tokamak

by

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Oct 16, 2024

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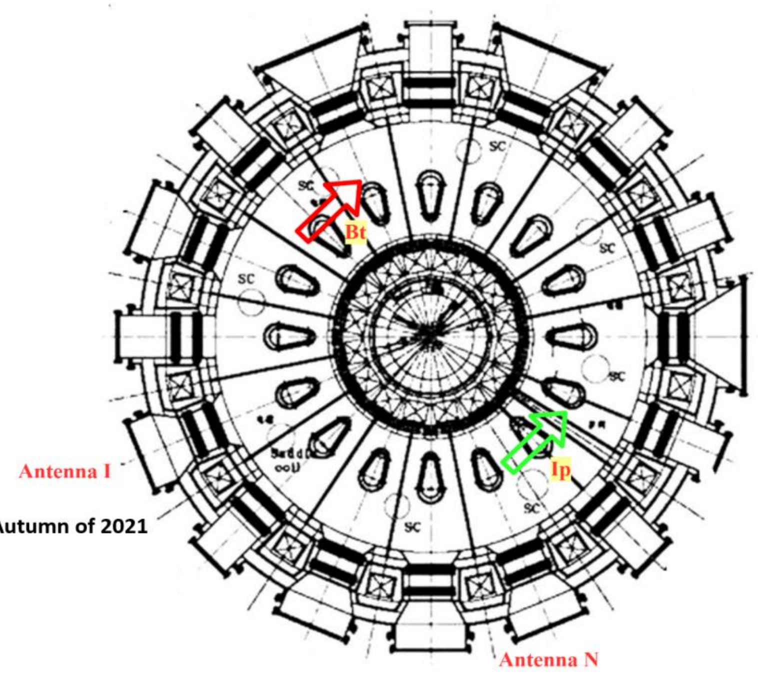
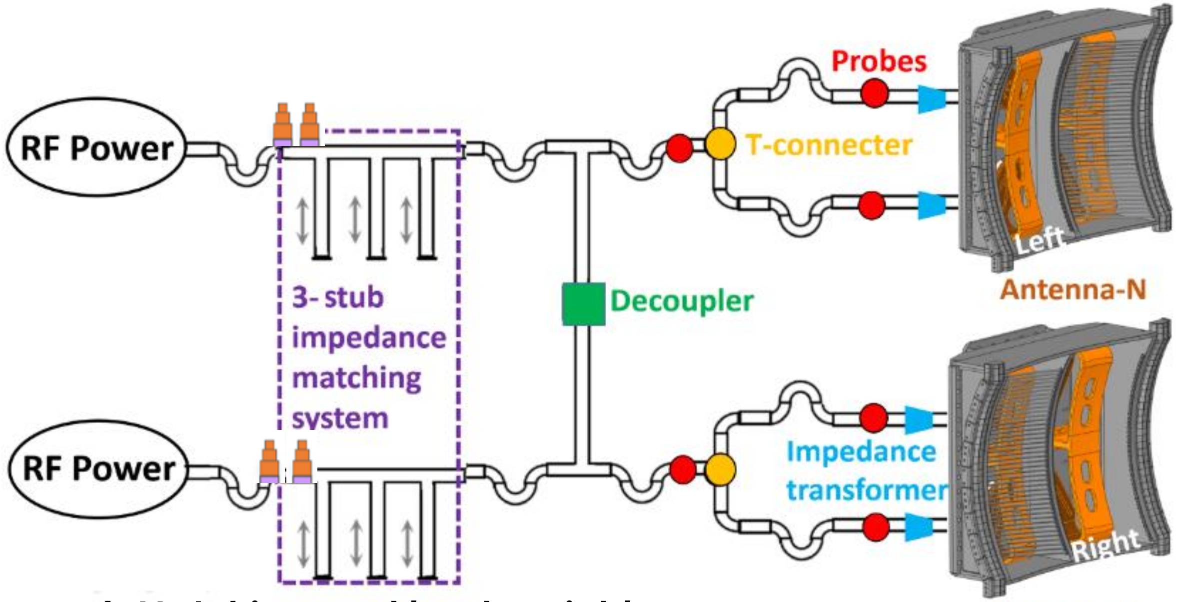
How to achieve long-pulse high-power ICRF system operation

1. Better coupling
2. Spectrum control
3. Water cooling
4. Fast impedance matching and load-variation tolerance transmission system



Autumn of 2021

Spring of 2021



4. Matching and load-variable tolerance transmission system

1. ICRF antenna with low $k_{//}$

3. Water cooling of limiter and Faraday screen

2. Antenna phasing measurement and control

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Outline

- **New ICRF antenna with low $k_{//}$**
- Antenna phase measurement and control
- Water cooling of limiter and Faraday screen
- Antenna fast matching and load tolerance transmission system

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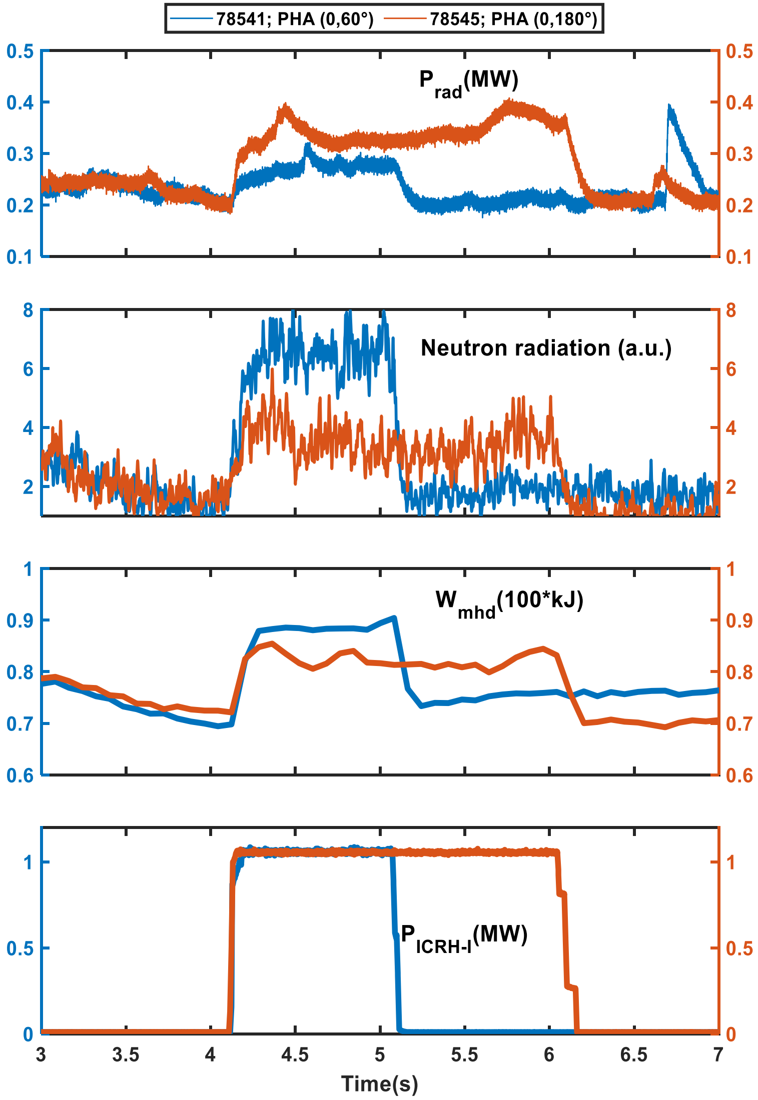
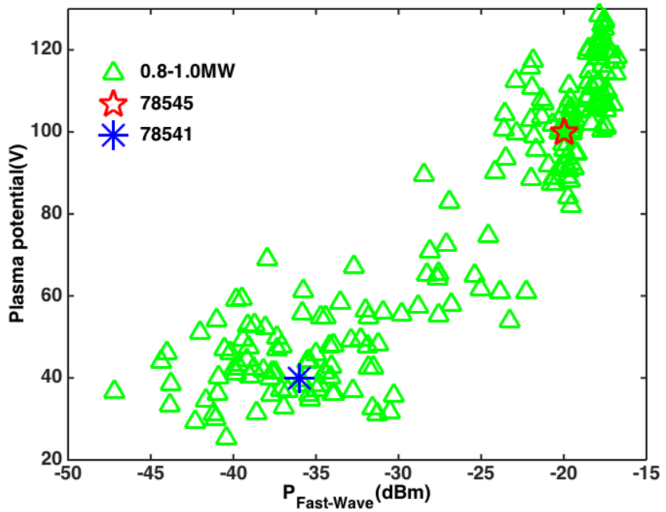
The heating efficiency shows higher with lower $k_{//}$ for old ICRF antenna

Nucl. Fusion 59 (2019) 044004

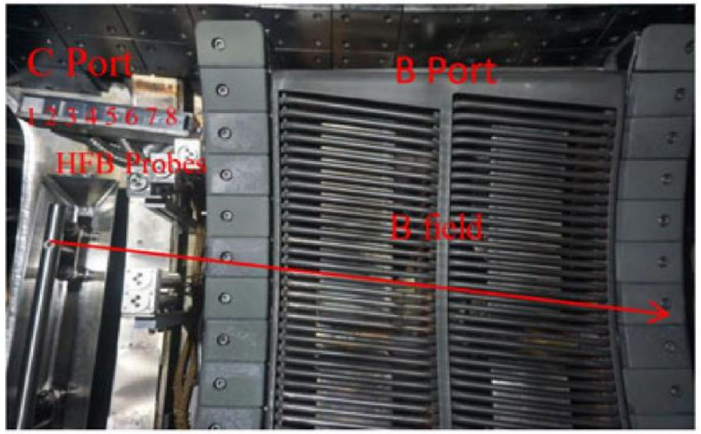
$k_{//}$~5 (0, π/3) $k_{//}$~13 (0, π)



Plasma potential for those two shots



Old ICRF antenna in Port B



- The stored energy and the neutron radiation is larger with lower $k_{//}$;
- The power radiation and the plasma potential is smaller with lower $k_{//}$;
- **Decreasing $k_{//}$ could increase heating efficiency.**

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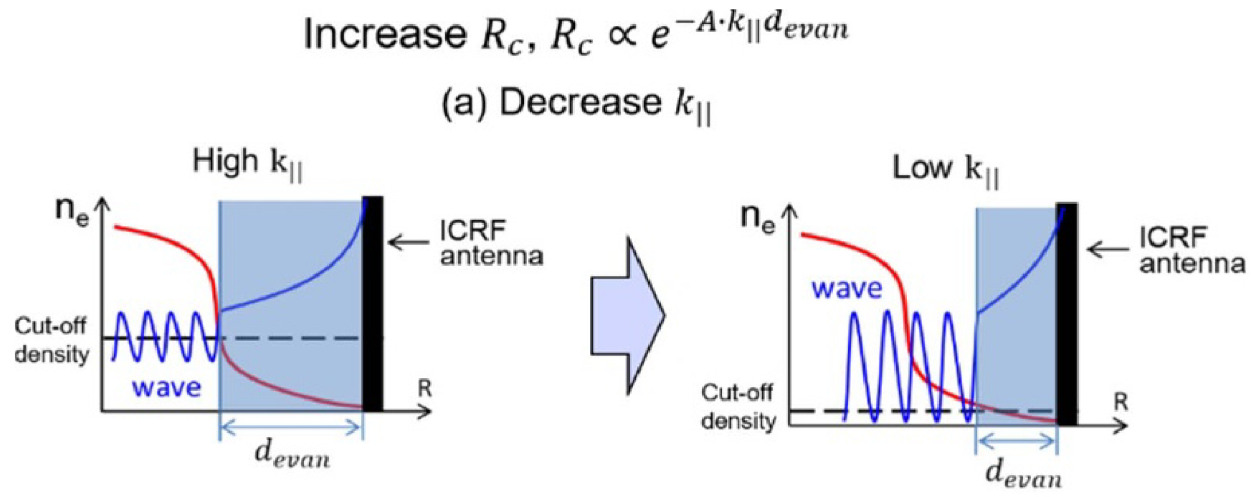
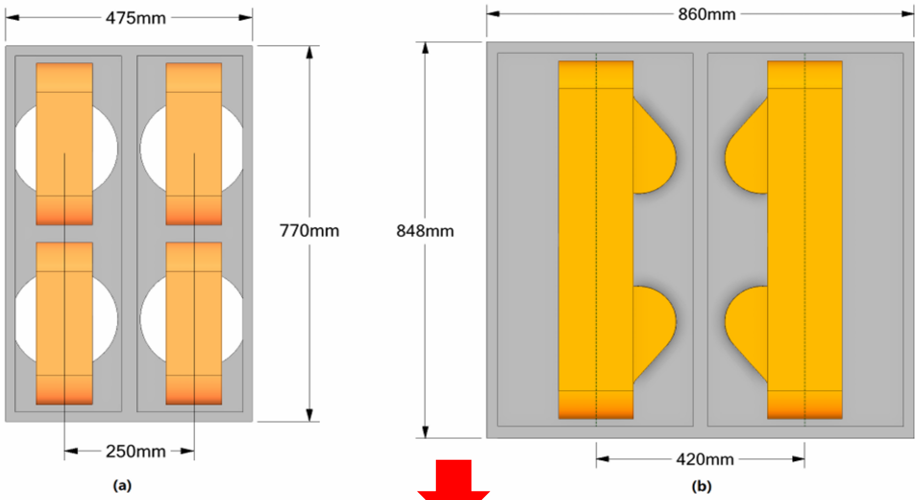
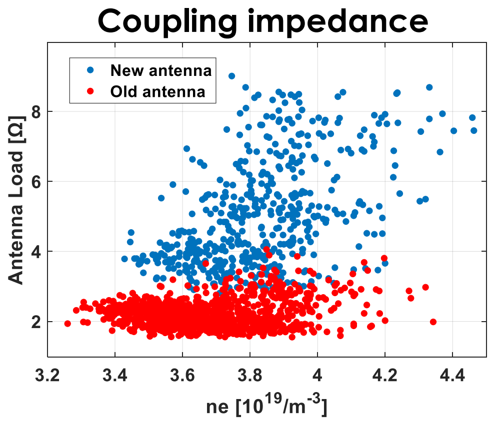
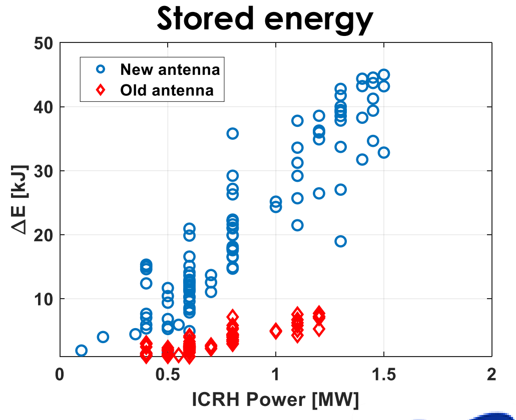
The new ICRF antenna designed and operated in EAST



$k_{//}$=13 m^-1 → $k_{//}$=7.2 m^-1







- **The new antenna shows better coupling and heating efficiency**
  - The coupling exponent increase with the decrease of $k_{//}$;
  - The new antenna display higher coupling and better heating.

Nucl. Fusion 62 (2022) 086038

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- **Antenna phase measurement and control**
- Water cooling of limiter and Faraday screen
- Antenna matching and load tolerance transmission system

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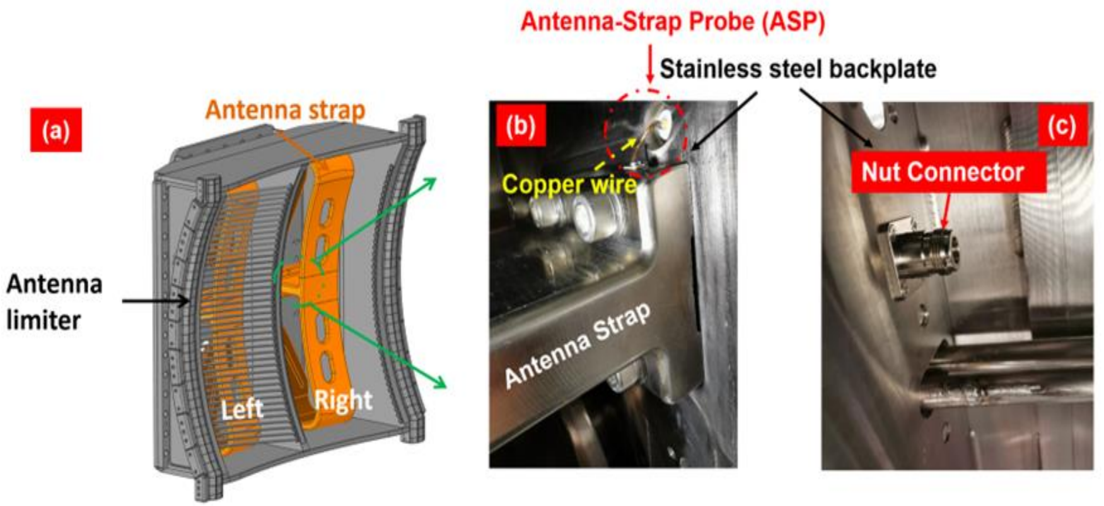
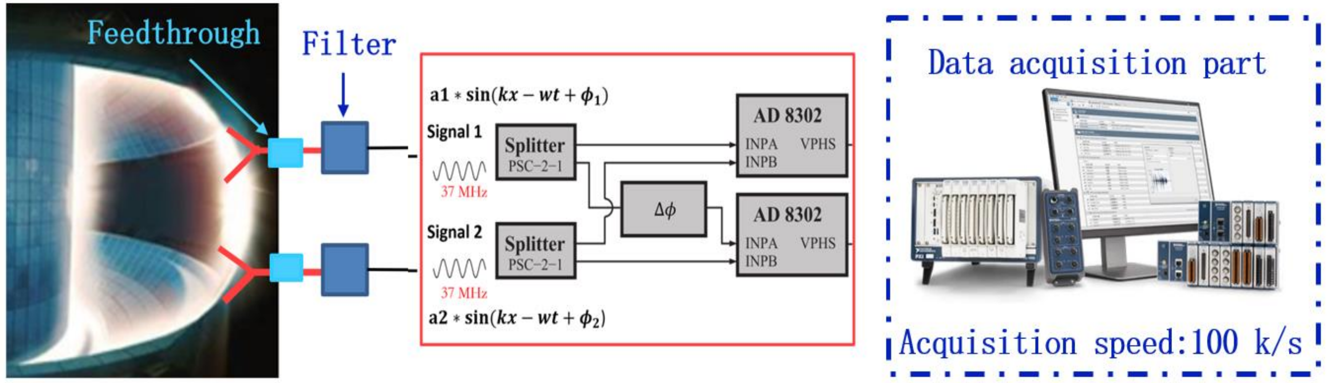
Antenna phasing measurement using antenna strap probe based diagnostic system

Nuclear Engineering and Technology 54 (2022) 3614-3619

ICRF antenna strap probe



ICRF antenna phasing detecting system



- **Antenna phasing detected by antenna strap probes** which can avoid the influence of the standing waves.
- The chip of AD8302 have a good detection accuracy in two signals phasing detection.

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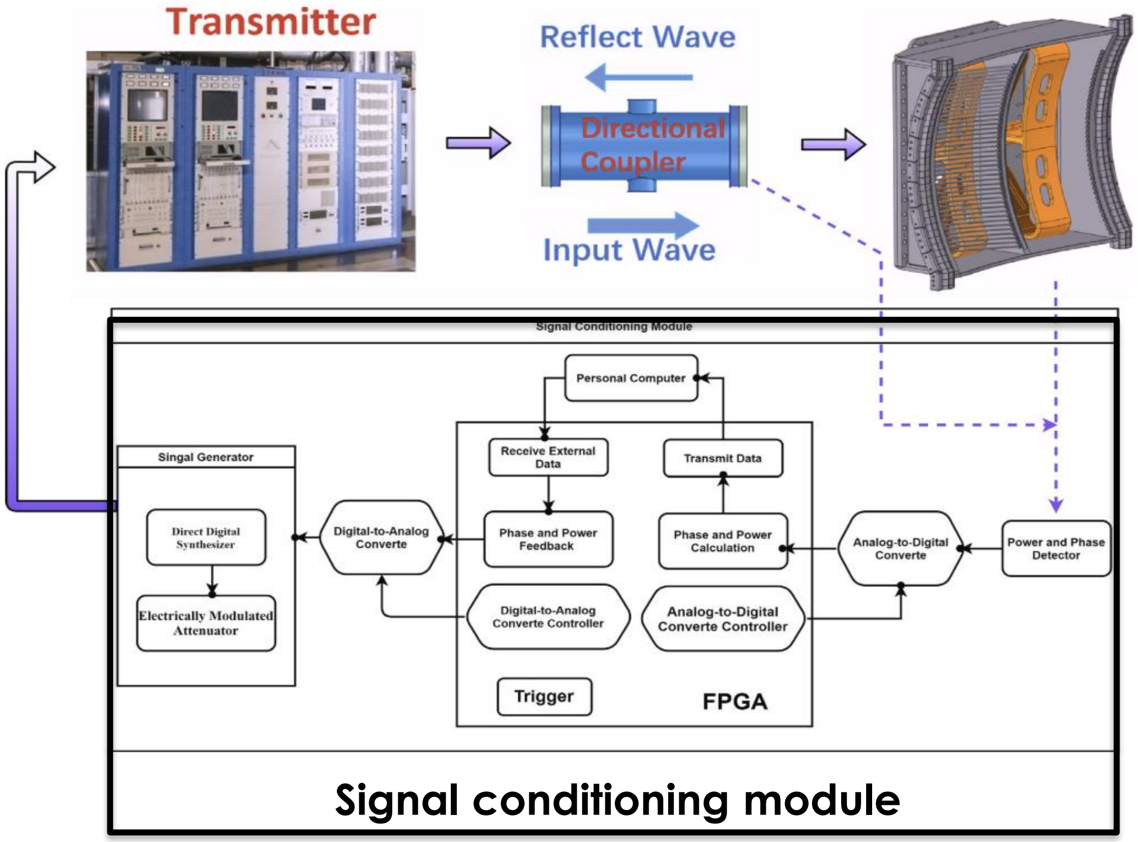
Design of phase feedback control system for ICRF system in EAST

The schematic diagram of phase feedback control system.



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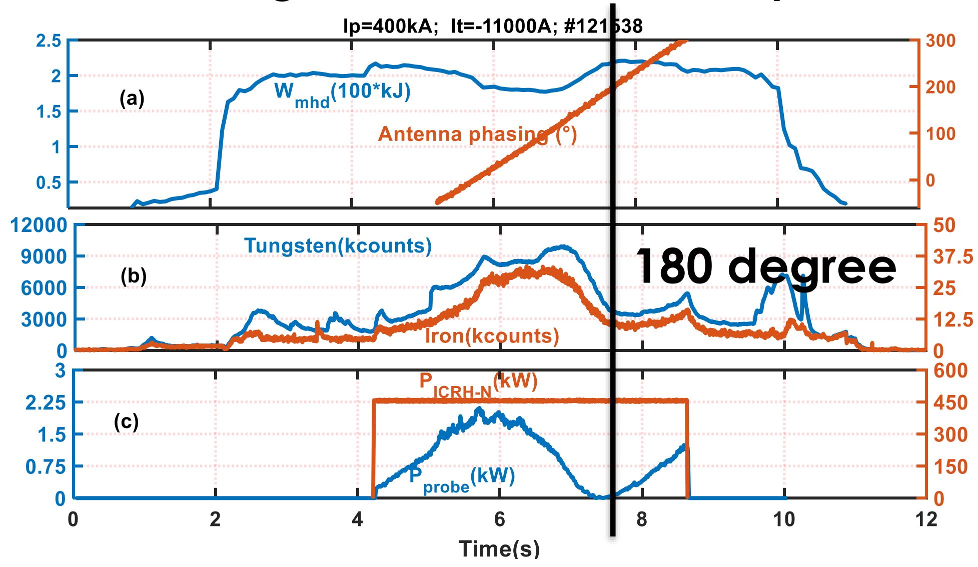
ICRF heating with different antenna phase.



- **Achieve antenna phase feed back control.**
  - Strap probe based diagnostic;
  - Signal conditioning module based FPGA;
- **Best heating happens at 180°**

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Outline

- New ICRF antenna with low $k_{//}$
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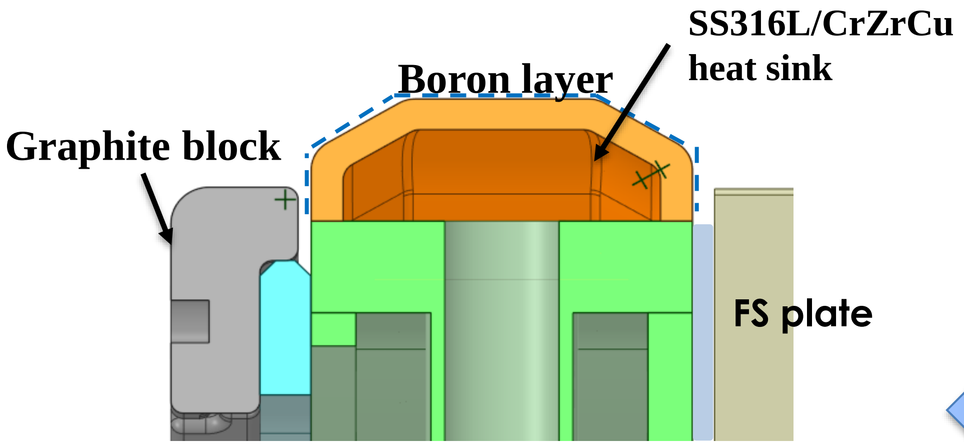
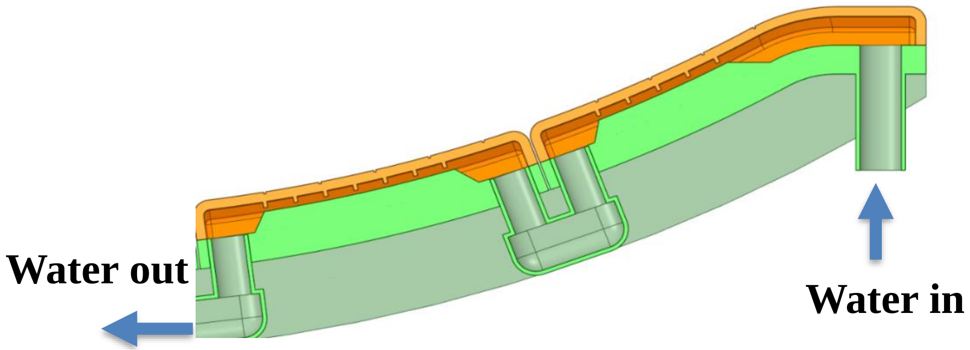
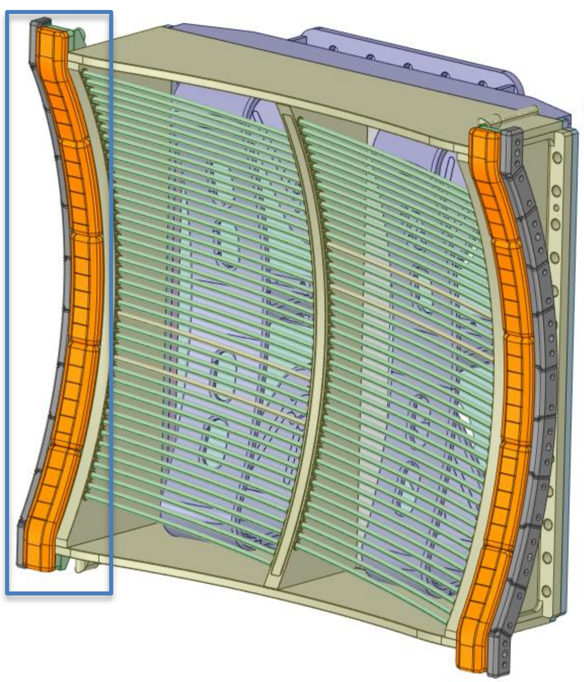
- **Water cooling of limiter and Faraday Screen**
- Antenna matching and load tolerance transmission system

New kind of ICRF antenna limiter with CFC materials





The section view of heat sink



- **CFC material have been used in antenna limiter.**
  - The tiles are attached to the heat sink, the heat is more easily taken away;
  - The tiles is thin, better for the heat taken away.

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•The old Faraday Screen corrosion during EAST experiments

Faraday Screen corrosion

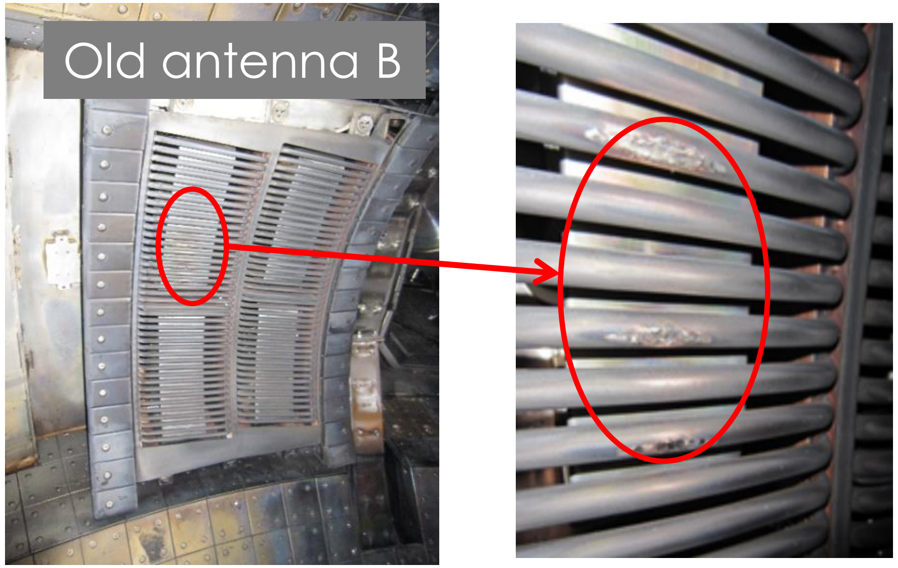
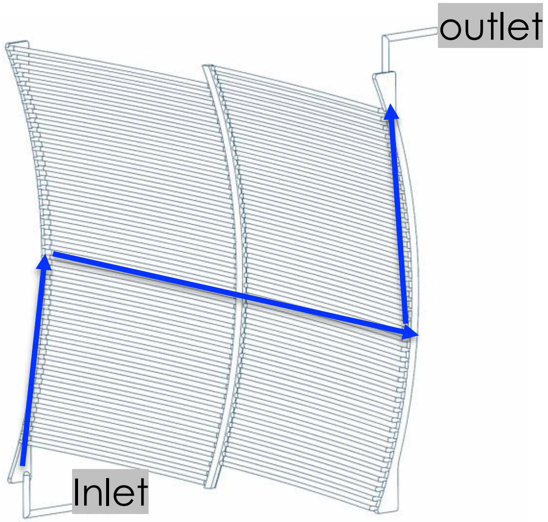
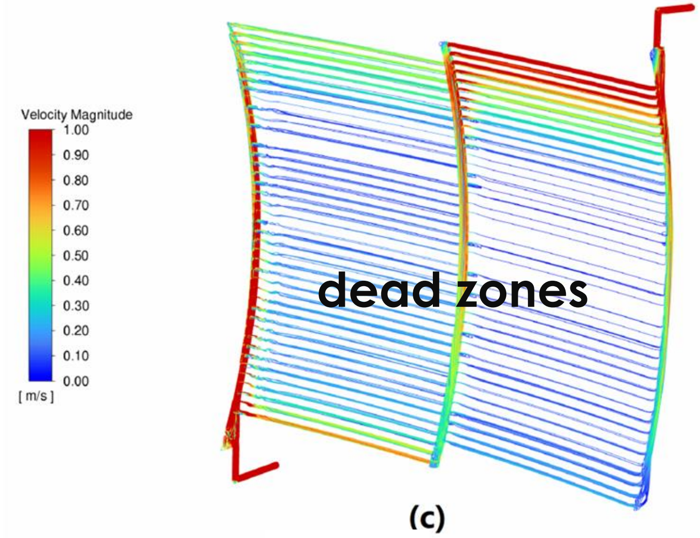


Diagram of the Faraday Screen



Pressure less than 2.5 bar

Simulated water flux in the Faraday Screen



Water pressure 2bar

- A structure similar to the old Faraday Screen has been rebuilt to simulate the water flux through the tube.
- **For the old Faraday Screen, the water can not go through a large part of the tubes (blue part)**

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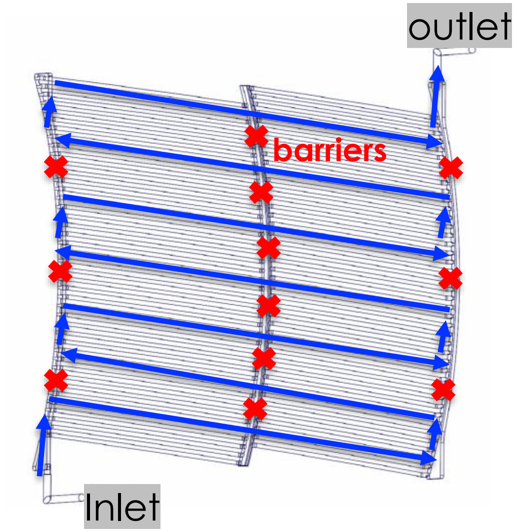
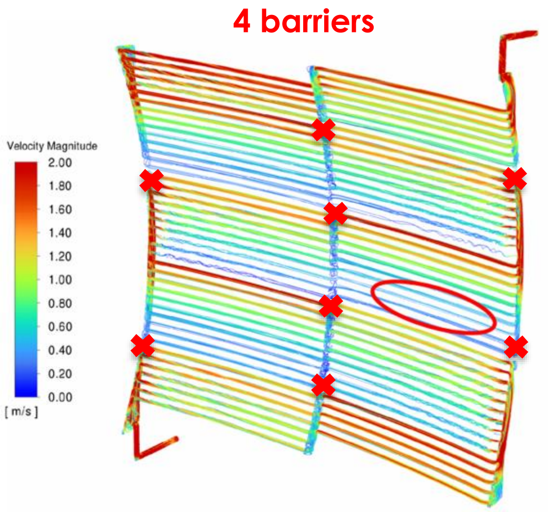
Optimization of Faraday Screen to avoid dead zones

Diagram of the Faraday Screen

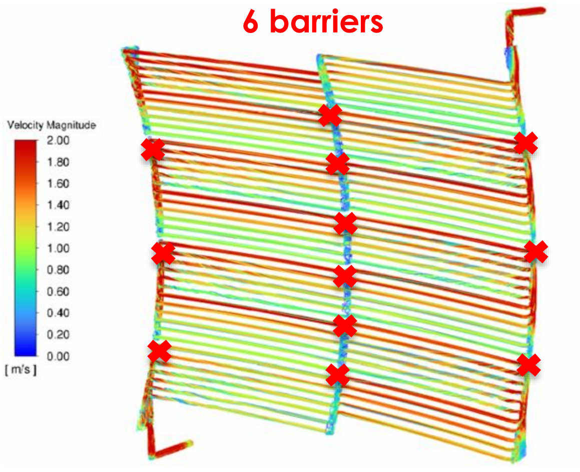


pressure less than 2.5 bar

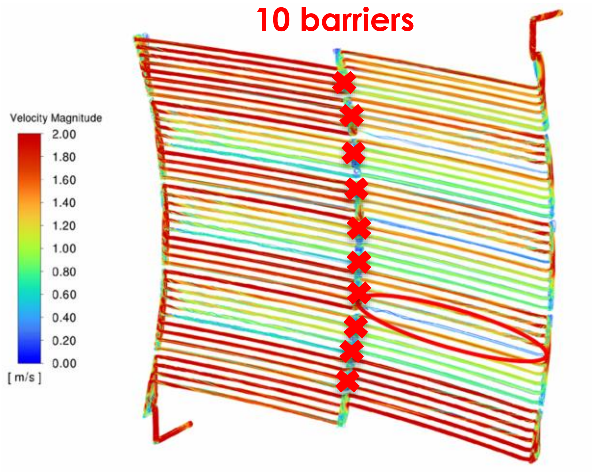
Simulated water flux in the Faraday Screen



Minimum velocity of water flux ~0.2m/s



Minimum velocity of water flux ~1 m/s



Minimum velocity of water flux ~0.5m/s

- **Adding barriers to make the water come through every tubes with larger speed;**
- Simulated results show that 6 barriers is one of the best choice for increasing the minimum speed in the tubes.

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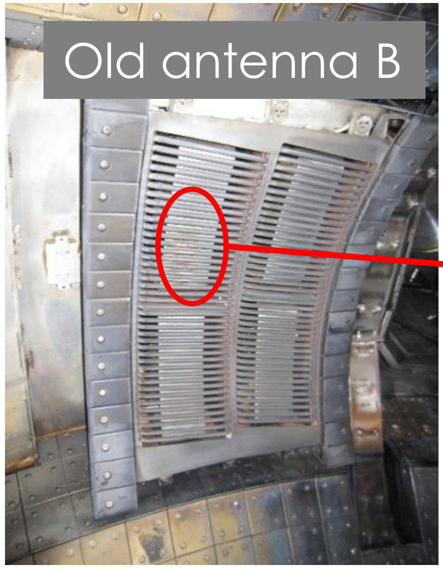
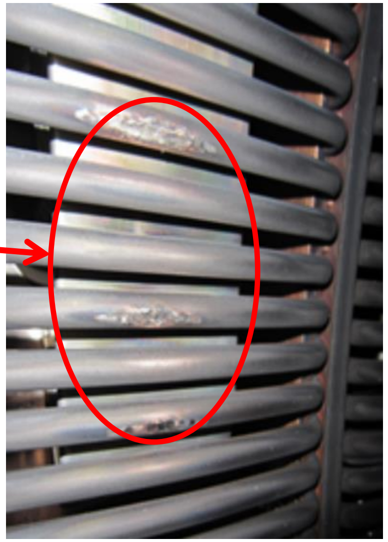
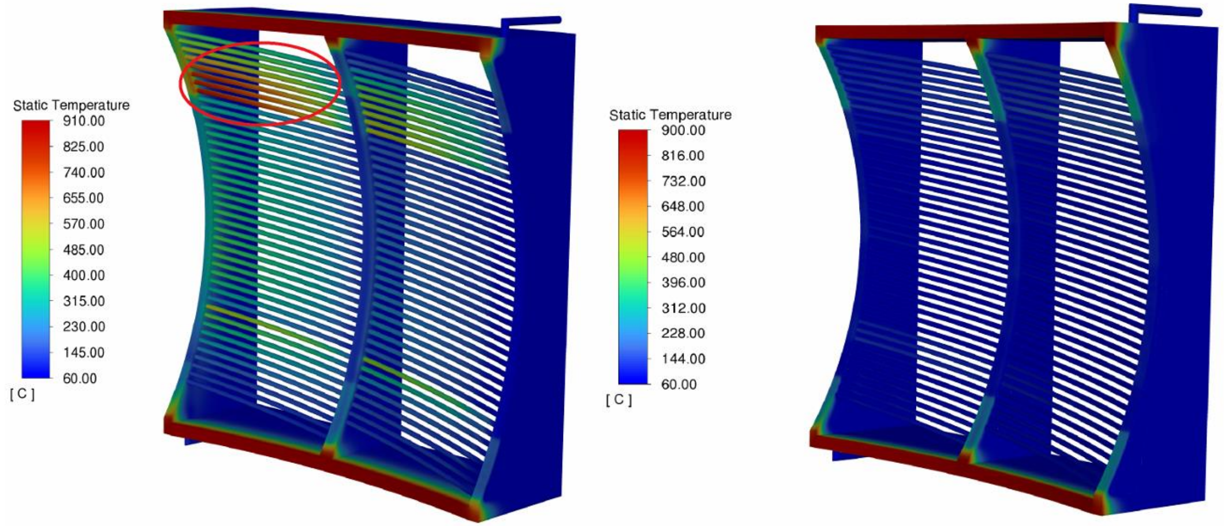
Thermal analysis of the new Faraday Screen in EAST

Faraday Screen corrosion





Simulated static temperature of the Faraday Screen



Without barriers **With six barriers**

Plasma heat flux: ~0.25 MW/m^2 (by EMC3-EIRENE for shot 107554); RF lose: 0.02 MW/ m^2 (CST with 1 MW)

- Without barriers: the static temperature of Faraday tubes is up to 900℃ with water pressure of 2 bar ;
- With barriers: the static temperature of Faraday Screen tubes is low, but the temperature in top/bottom plate is up to 900 ℃.

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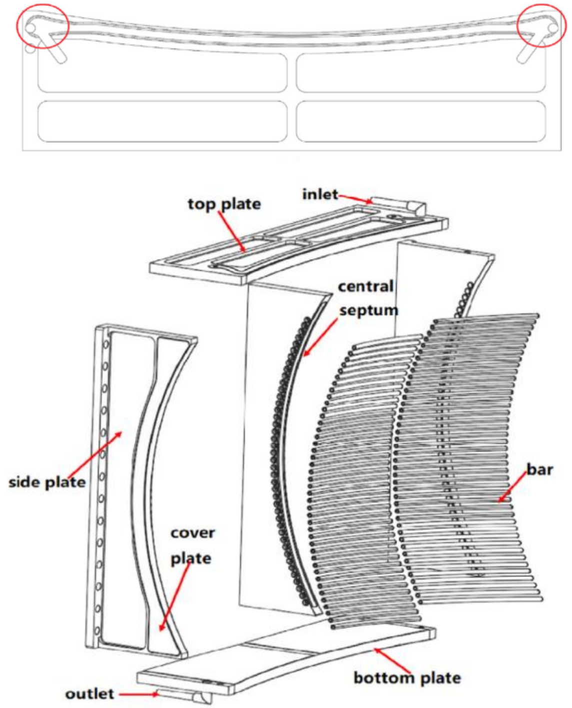
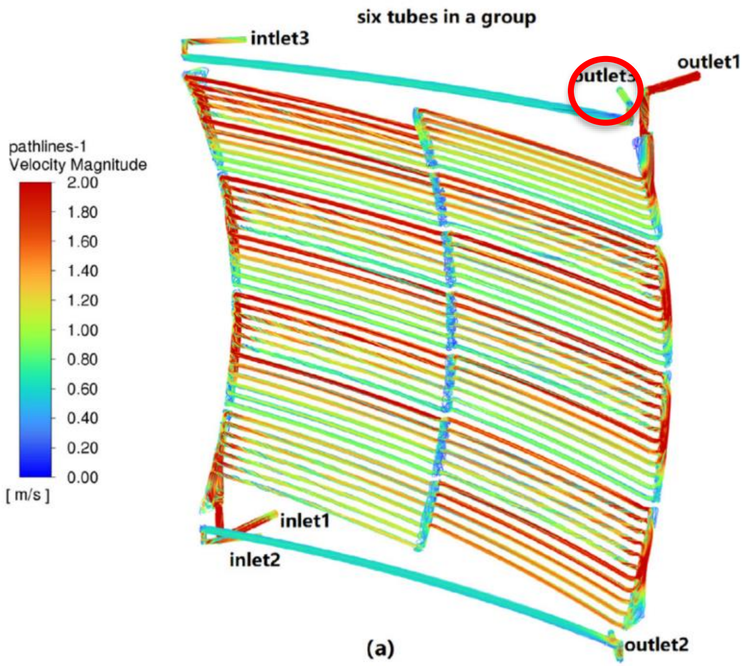
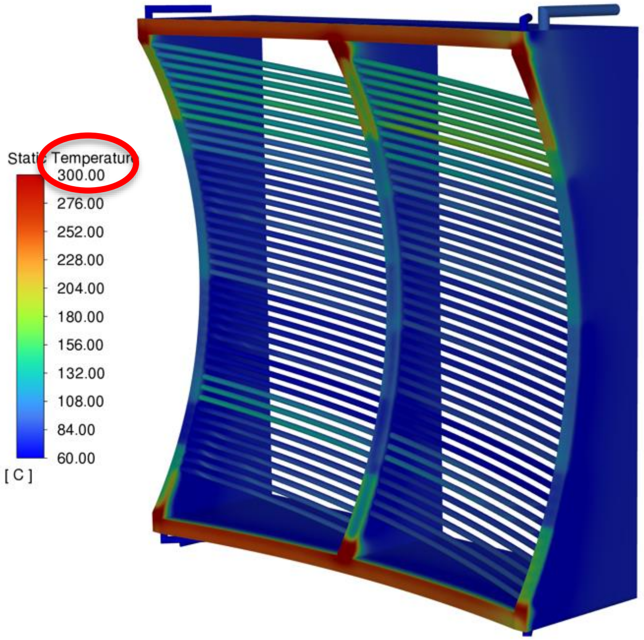
Thermal analysis of the new Faraday Screen with top/bottom plate cooling



Add water tubes in the top/bottom plate



Simulated water flux speed



Simulated static temperature

- The minimum water speed in the top/bottom plate is 0.5 m/s with 2 bar water pressure;
- **Temperature of Faraday Screen is less than 300 ℃.**

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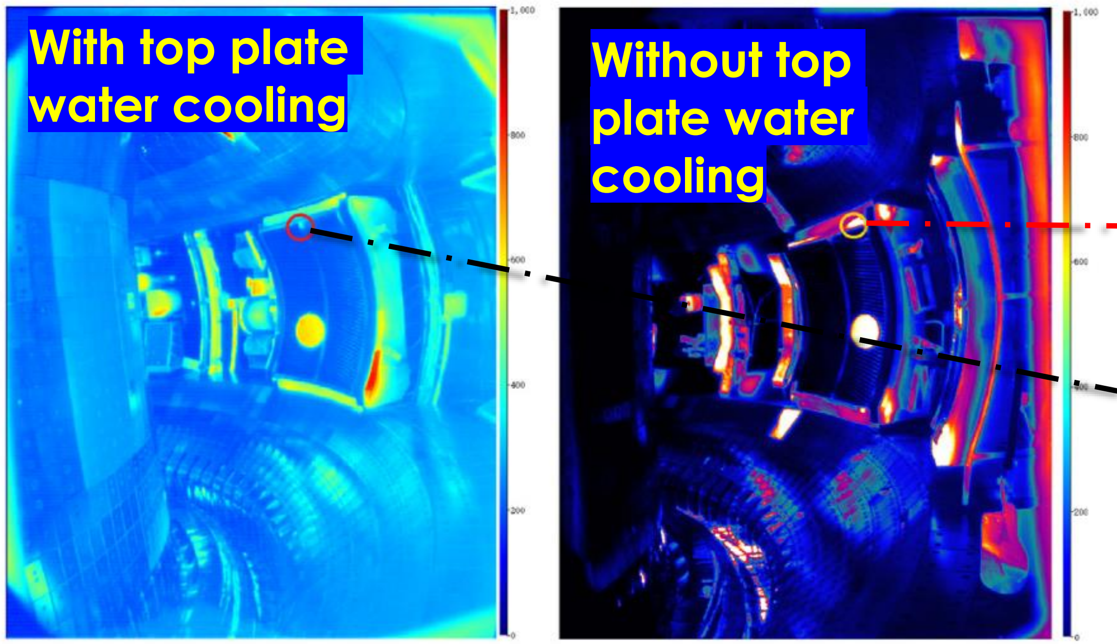
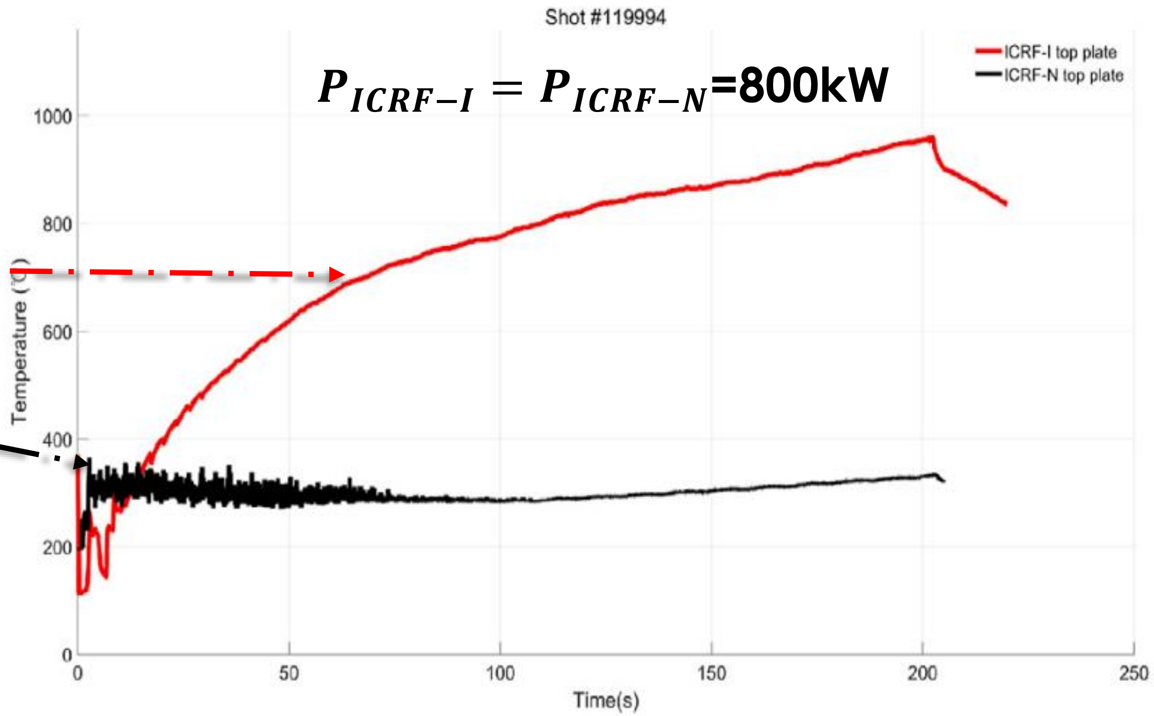
Temperature evolution of the new Faraday Screen in long pulse of EAST experiments



Temperature by IR camera



The highest point of FS temperature evolves

- **The temperature profile of ICRF antenna with 0.8 MW power :**
  - It is less than 400 ℃ in top plate with water cooling ;
  - It is up to 1000 ℃ in the top plate without water cooling;
  - In Faraday Screen tubes regain, it is less than 400 ℃.

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- **Antenna fast matching and load tolerance transmission system**

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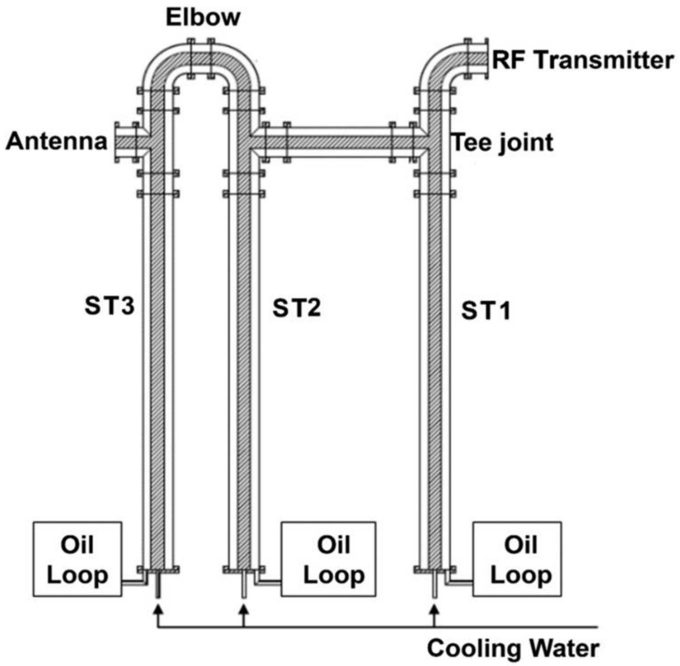
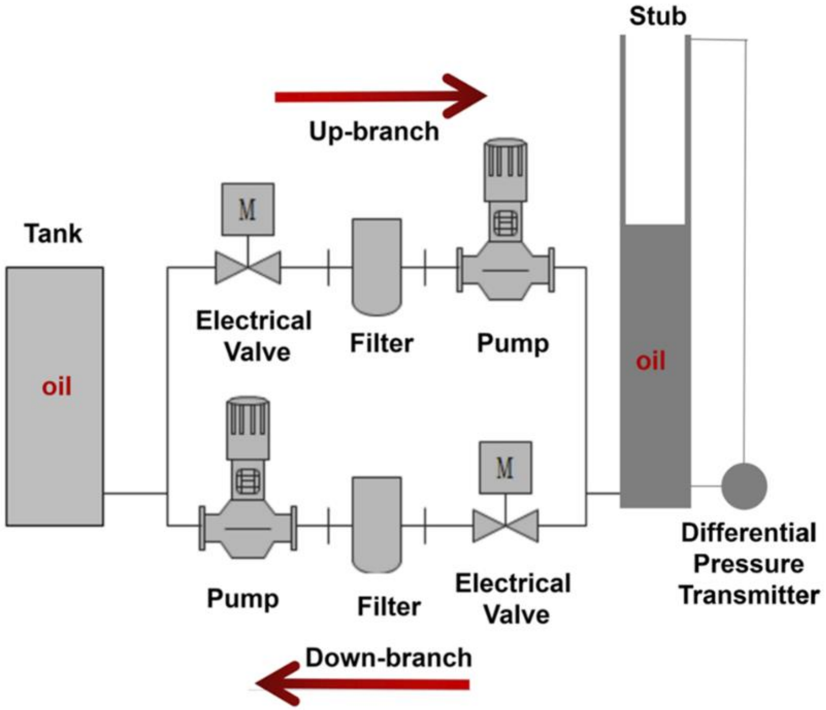
Triple liquid stub tuners for ICRF antenna impedance matching

Triple oil stub tuners for ICRF antenna impedance matching

Schematic diagram of the oil loop.

Before the year of 2021





- Advantages: High voltage and high current tolerant in long pulse;
- Dis-advantages: Slow moving of the oil level.

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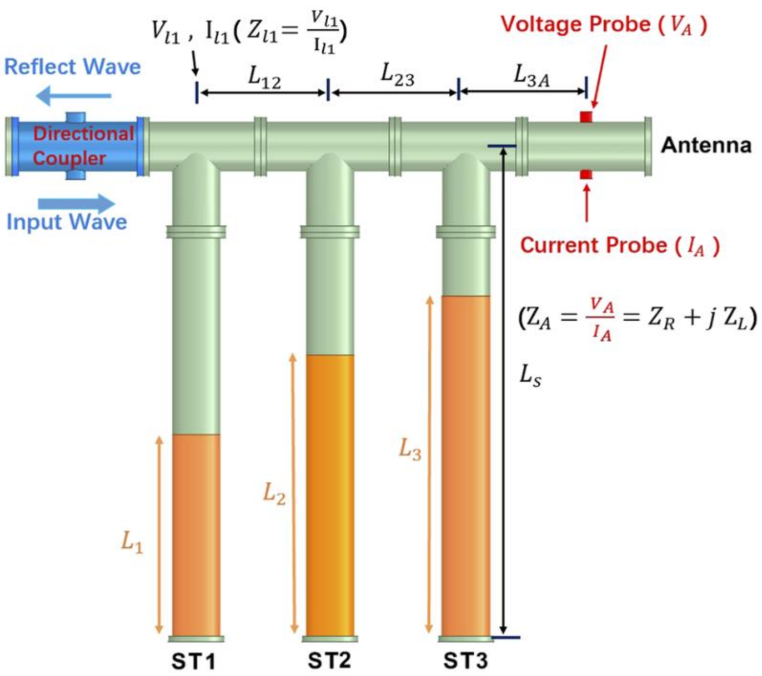
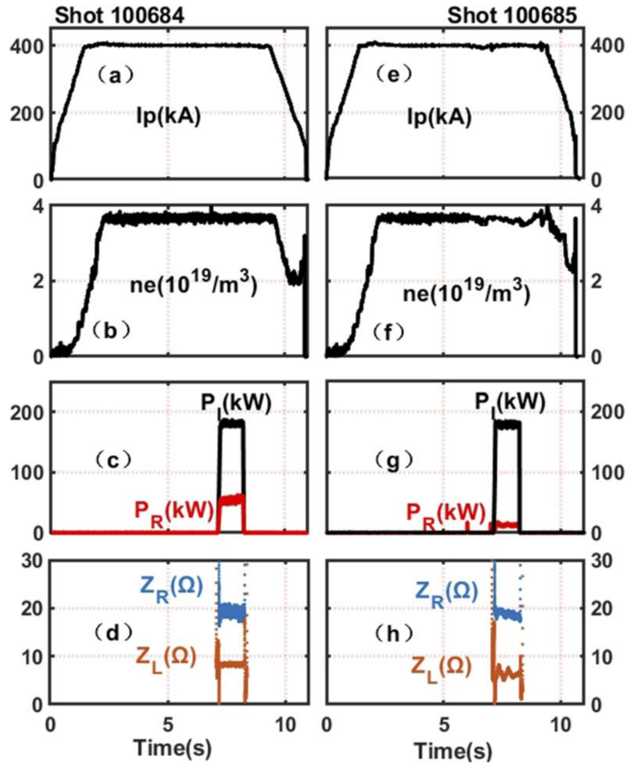
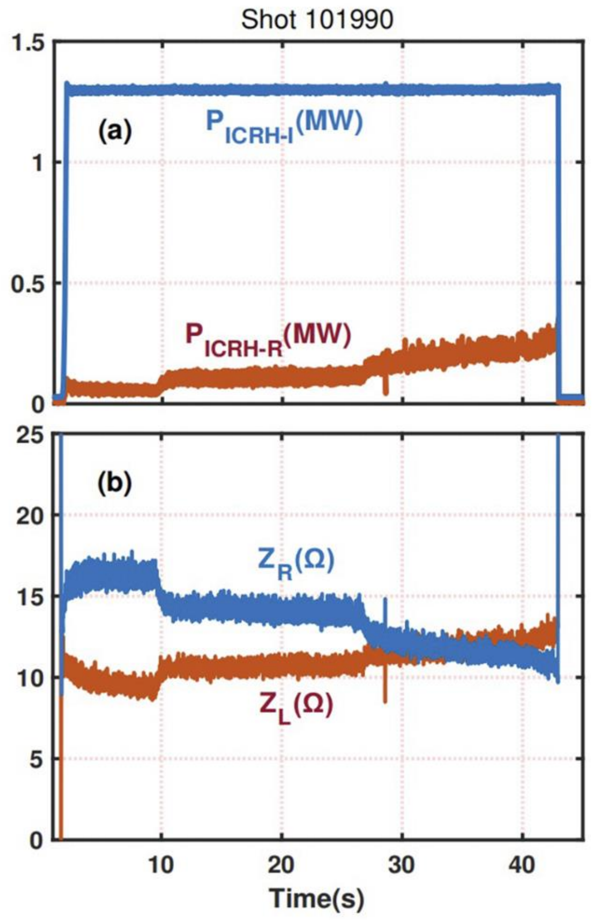
Impedance matching based on triple liquid stub tuners

Rev. Sci. Instrum. 93, 043506 (2022)







ICRF long pulse operation

- **Impedance matching by on triple liquid stub tuners :**
  - Calculate the oil level to matching the antenna load;
  - Impedance matching achieved between two shots;
  - **During long pulse operation, the change of antenna load leads to large reflection power.**

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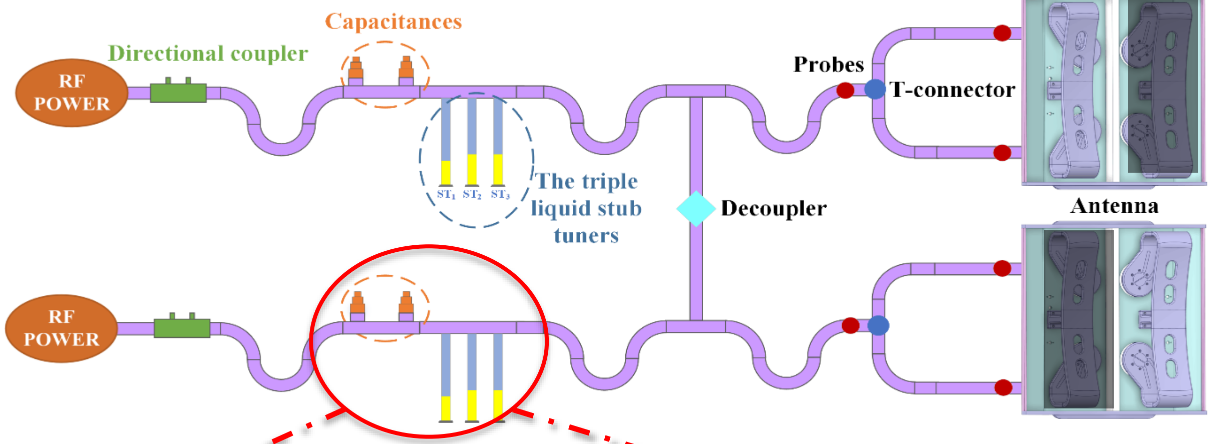
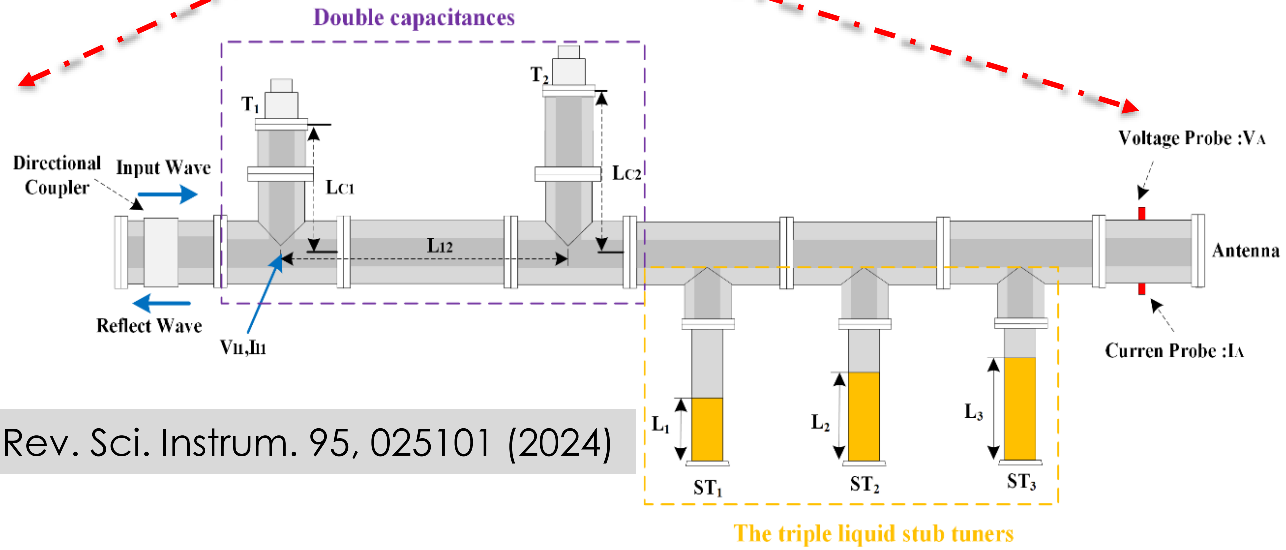
Upgrade of matching system by double stub capacitors

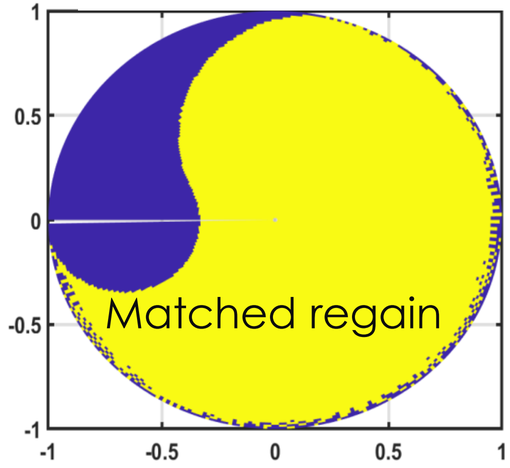
The diagram of ICRF system





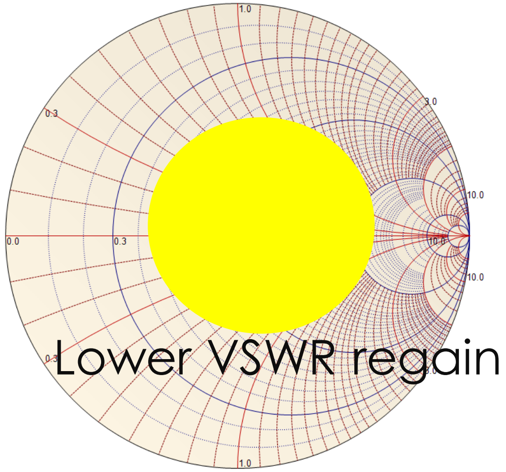
Rev. Sci. Instrum. 95, 025101 (2024)

Smith Chart



Matched regain by double stub of capacitors

Smith Chart



Lower VSWR regain achieved by liquid stub

- The double stub capacitors can match yellow regain of the smith chart, which can satisfied the need for impedance matching in EAST.
- Variable water-cooled capacitors had been used.

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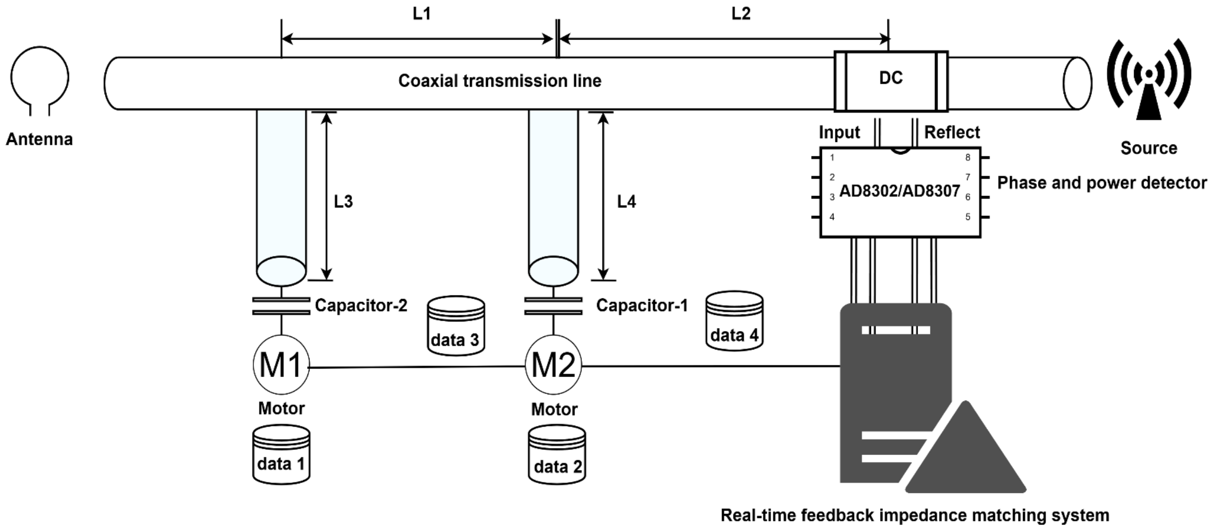
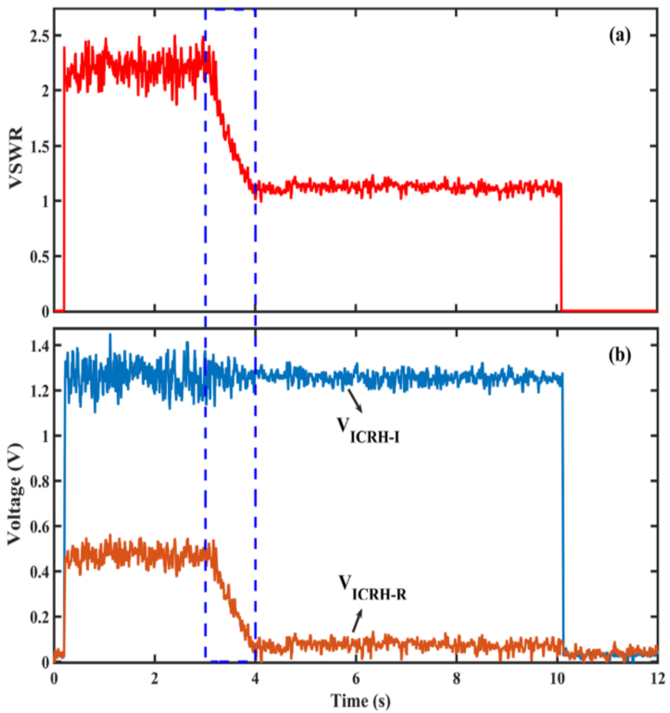
Real-time impedance matching by double-tube of capacitors

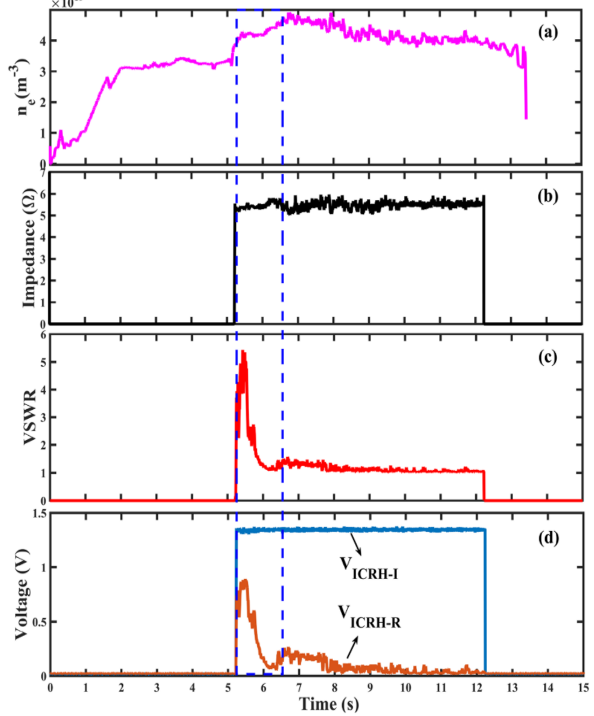
The diagram for real-time impedance matching



Vacuum



Plasma



- **Real-time impedance matching of ICRF system achieved:**
  - Impedance measurement, motor controlling;
  - Both vacuum and plasma situation, the matching had been achieved in 1 second;
  - **It can not match the impedance changing during ELMs and L-H mode transition.**

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The characteristic of the 3-stub impedance matching system

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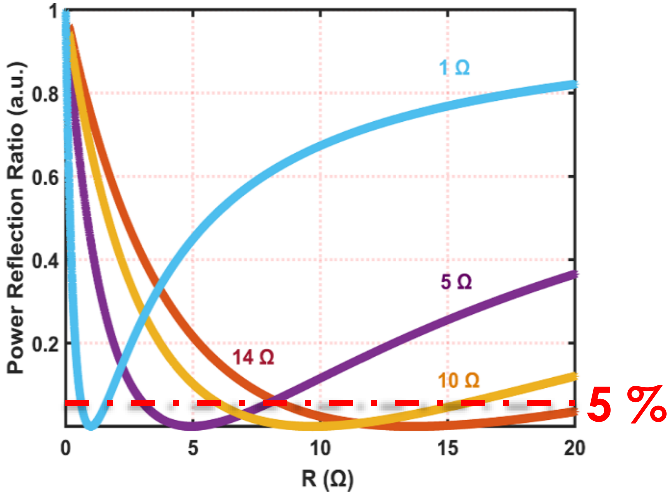
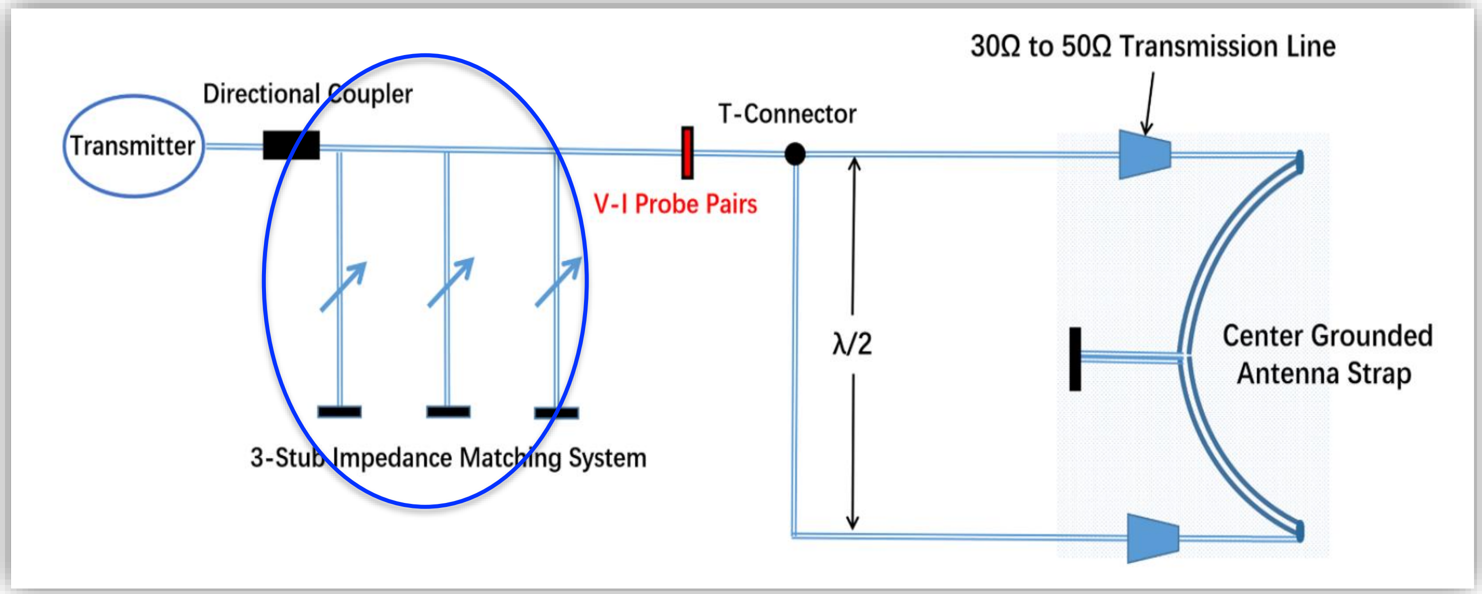


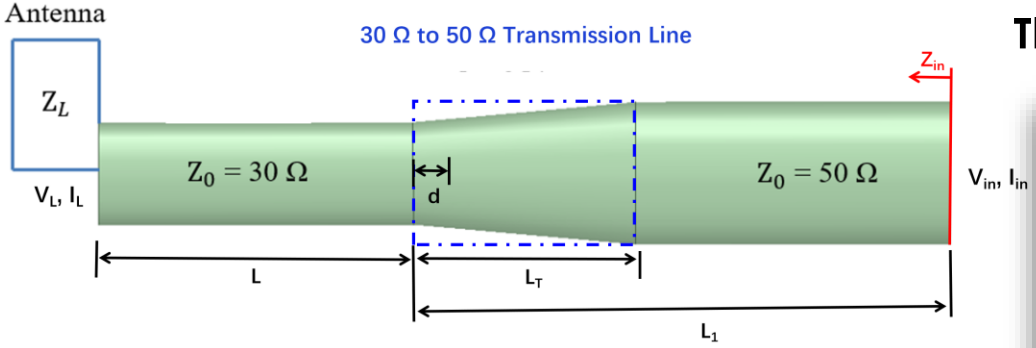
The relationship between input impedance R and the reflection power Ratio.

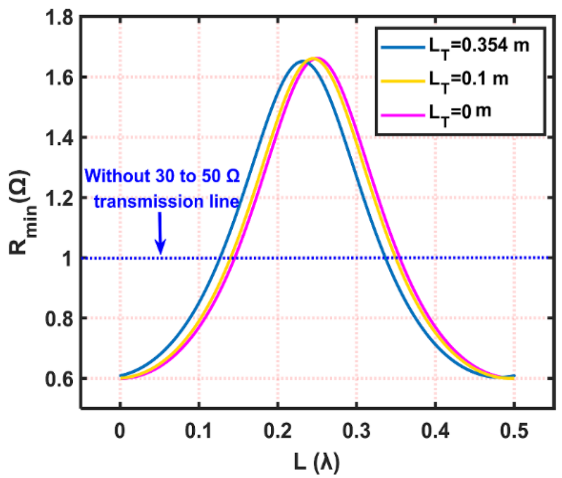
The schematic diagram for one antenna strap of the ICRH system in EAST



- **Load-variation tolerance of 3-stub tuners appeared with larger input impedance**
  - The power reflection ratio is below 5 % when the input impedance varied from 10 Ω to 20 Ω;
  - **Increasing the input impedance to increase the load-variation tolerance.**

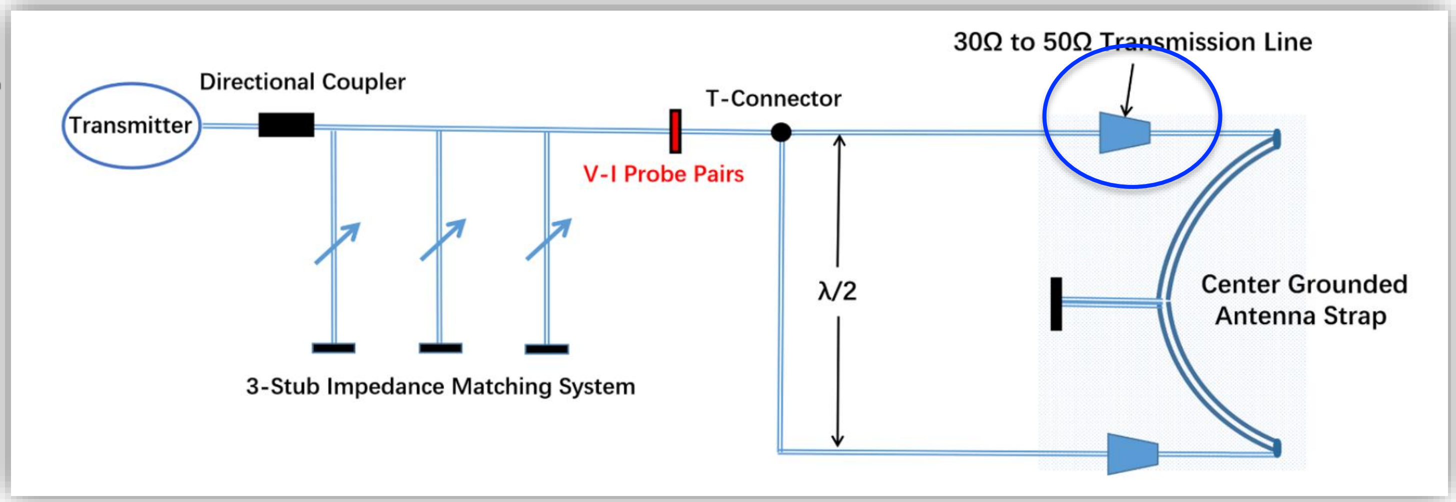
The characteristic of the 30Ω to 50 Ω transmission line in different location





Relationship between the input impedance and location in the standing wave (The antenna load chosen as 1 Ω).

The schematic diagram for one antenna strap of the ICRH system in EAST



- The 30 Ω to 50 Ω transmission line can **increase the input impedance by 1.6 times** when it stored at the maximum voltage of standing wave.

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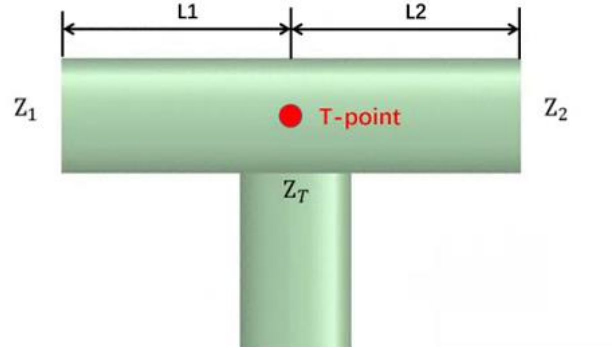
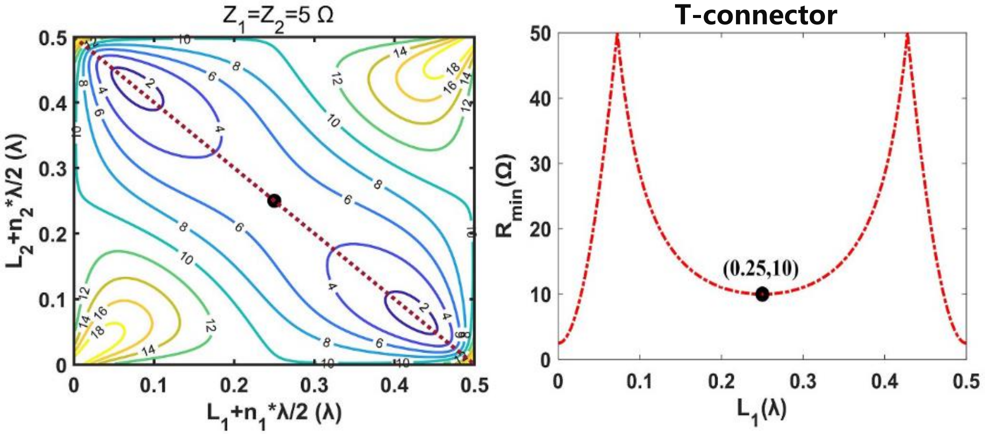
The characteristic of the T-point structure in different location

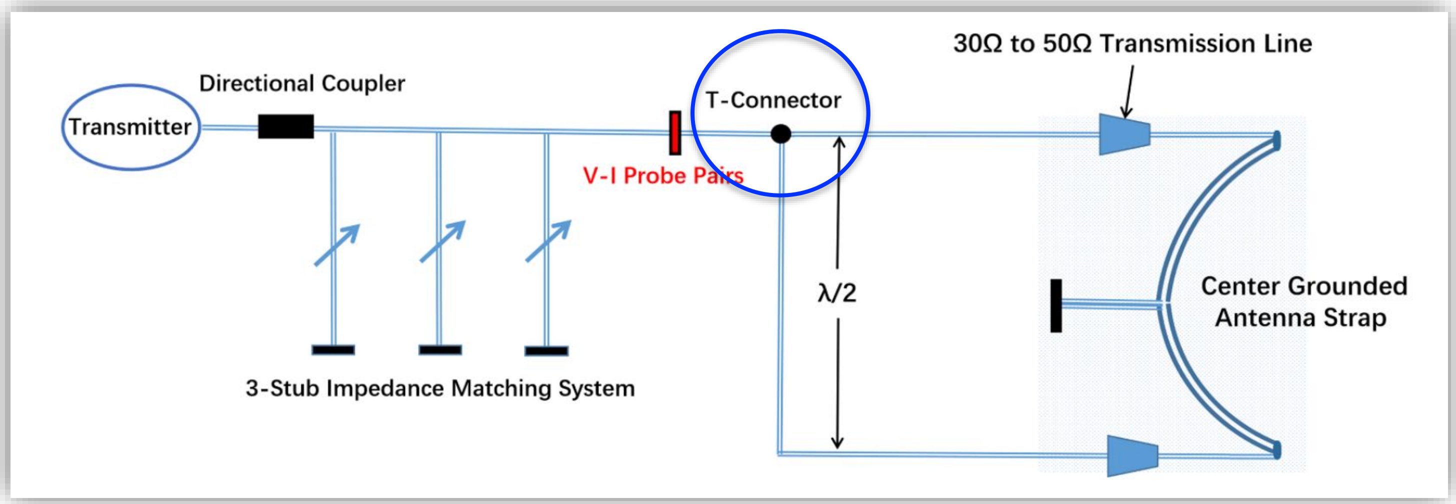
2024 Nucl. Fusion 64 066025





Left: the VSWR contours in case of symmetric resistive Z1 = Z2 = 5Ω; right: the impedance at T-point along the dotted line in the left figure.

The schematic diagram for one antenna strap of the ICRH system in EAST



- The T-connector structure can **double the input impedance** when stored it at the maximum voltage of standing wave.

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Load-variation tolerance character appeared in EAST experiments

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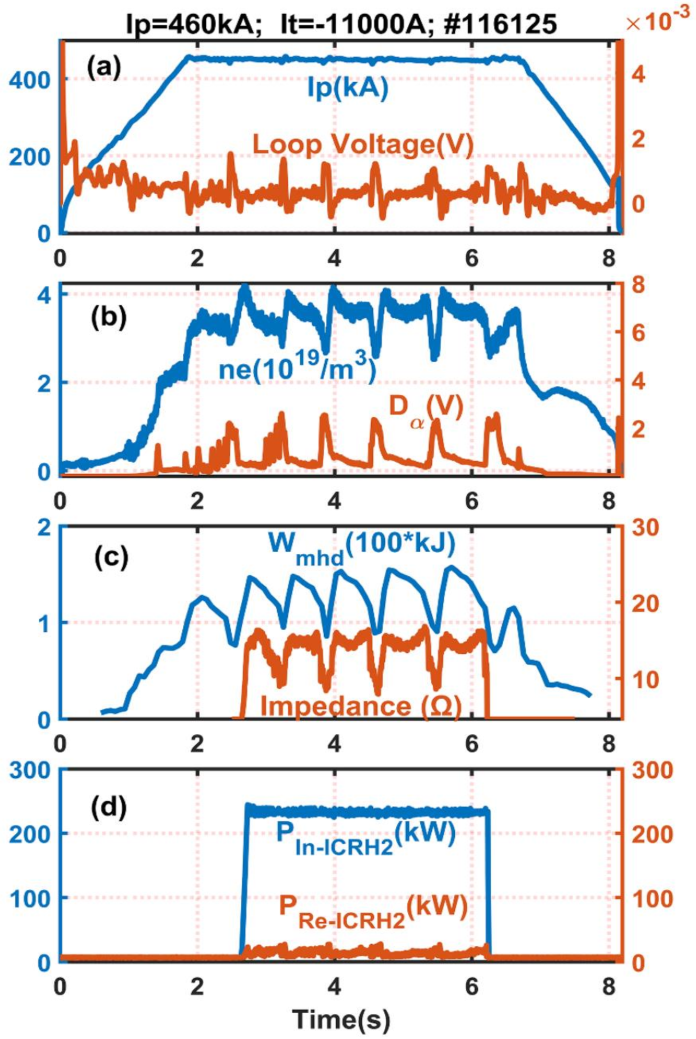

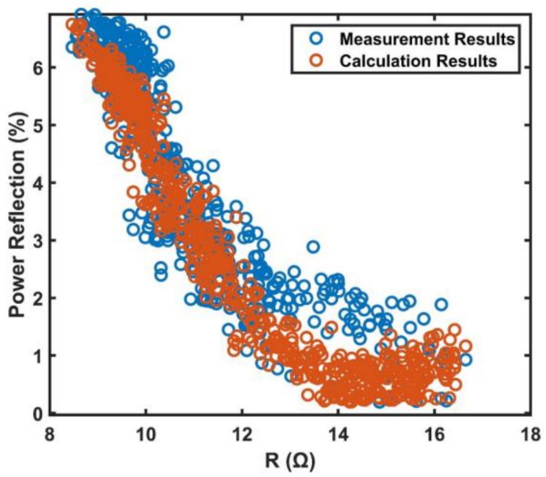

- **The ICRF system in EAST tokamak show the load-variation tolerance character**
  - The impedance varied from 8 Ω to 16 Ω, the reflection power is less than 7%;
  - The measurement results matched the calculated results well.

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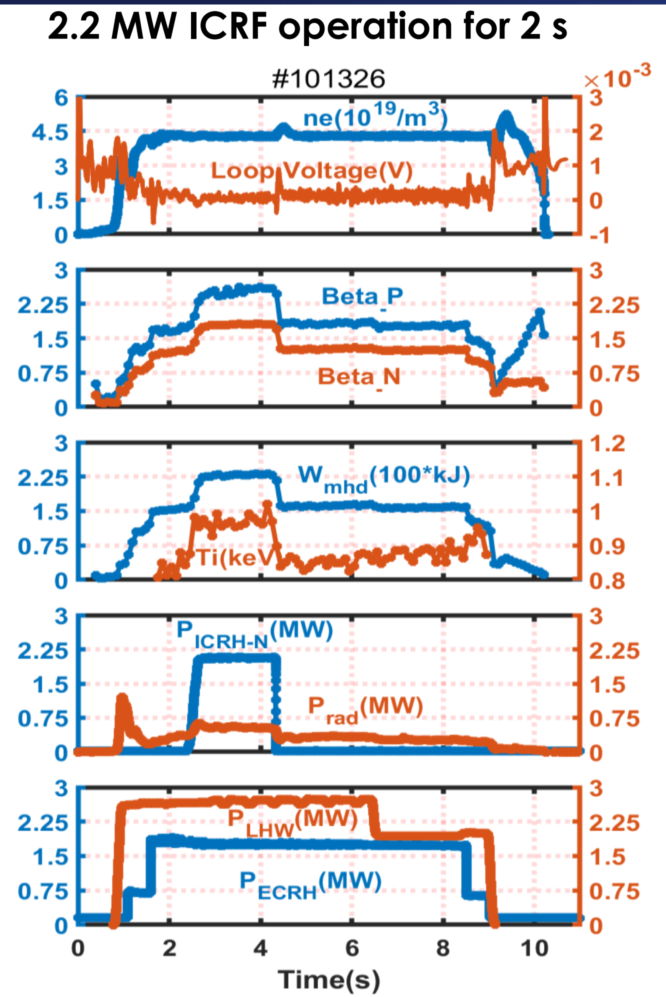
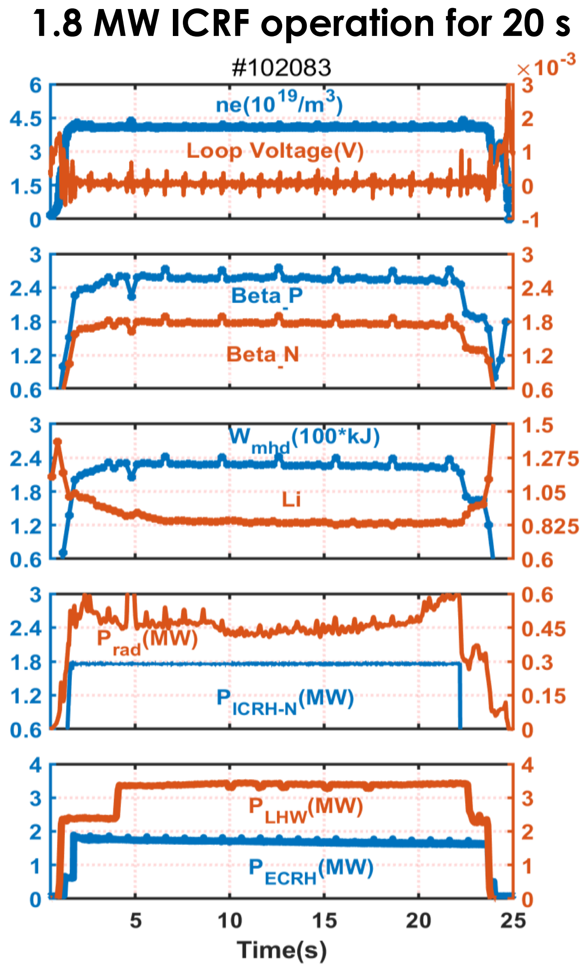
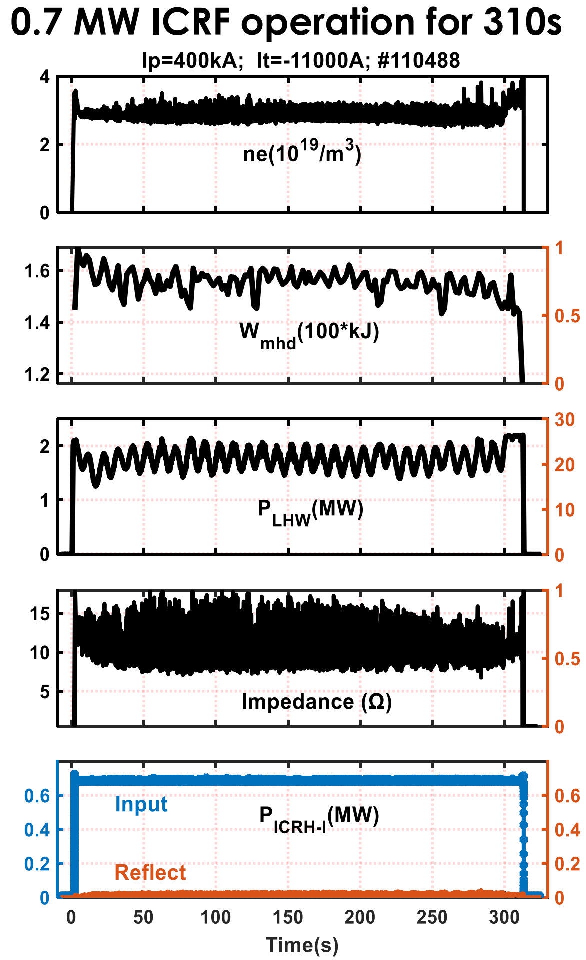
High-power and long-pules operation of ICRF system in EAST



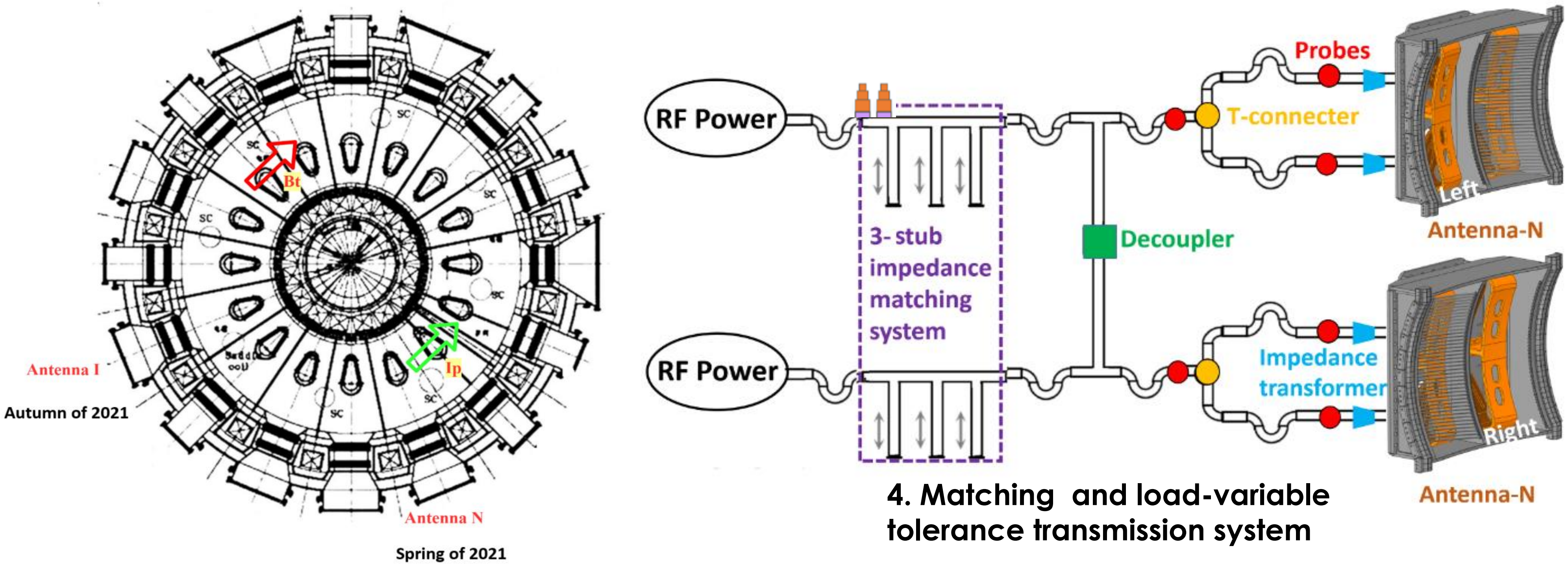




- High power of 2.2 MW, low power radiation 0.1MW/ 1 MW, remarkable heating effect;
- Static state operation for 310 s.

ASIPP

Conclusion



1. ICRF antenna with low $k_{//}$

2. Water cooling of limiter and Faraday screen

3. Antenna phasing measurement and control

4. Matching and load-variable tolerance transmission system

- **Better coupling, efficient water cooling, fast impedance matching and load-variation tolerance transmission system** help us to achieve high power and long pulse operation of ICRF system in EAST.

Thanks for your attention