Advance in Heating and Current Drive by RF Waves towards Long-Pulse Operation on EAST

by

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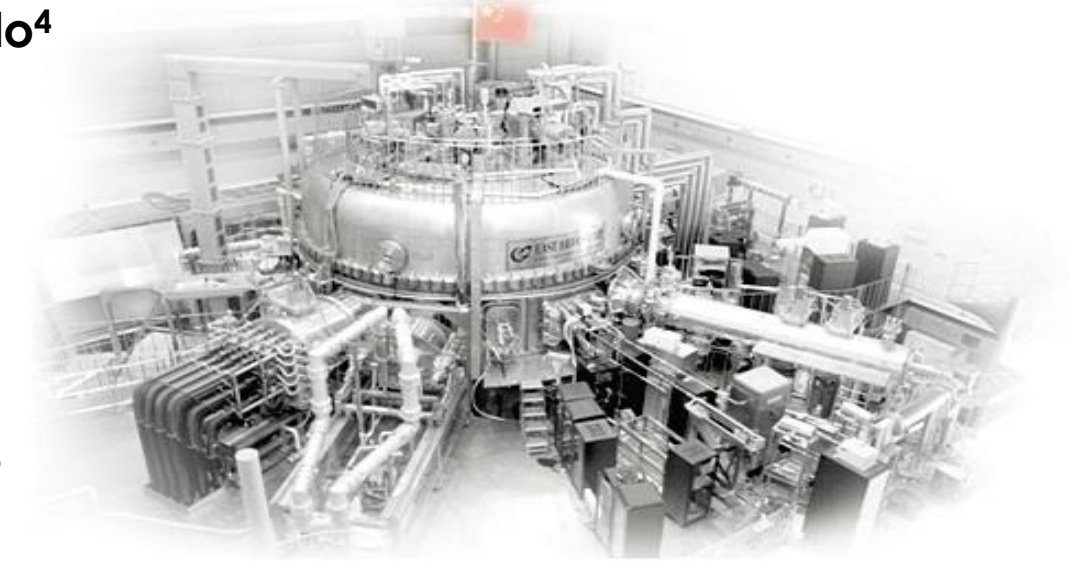

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Outline

- EAST Tokamak and H&CD systems
  - LHCD system
  - ECRH/ECCD system
  - ICRF system
- Advance in long-pulse heating and current drive by RF waves
- Challenges of RF systems in high-power and long-pulse operation
- Efforts to extend high-power and long-pulse operation
- Summary and prospects

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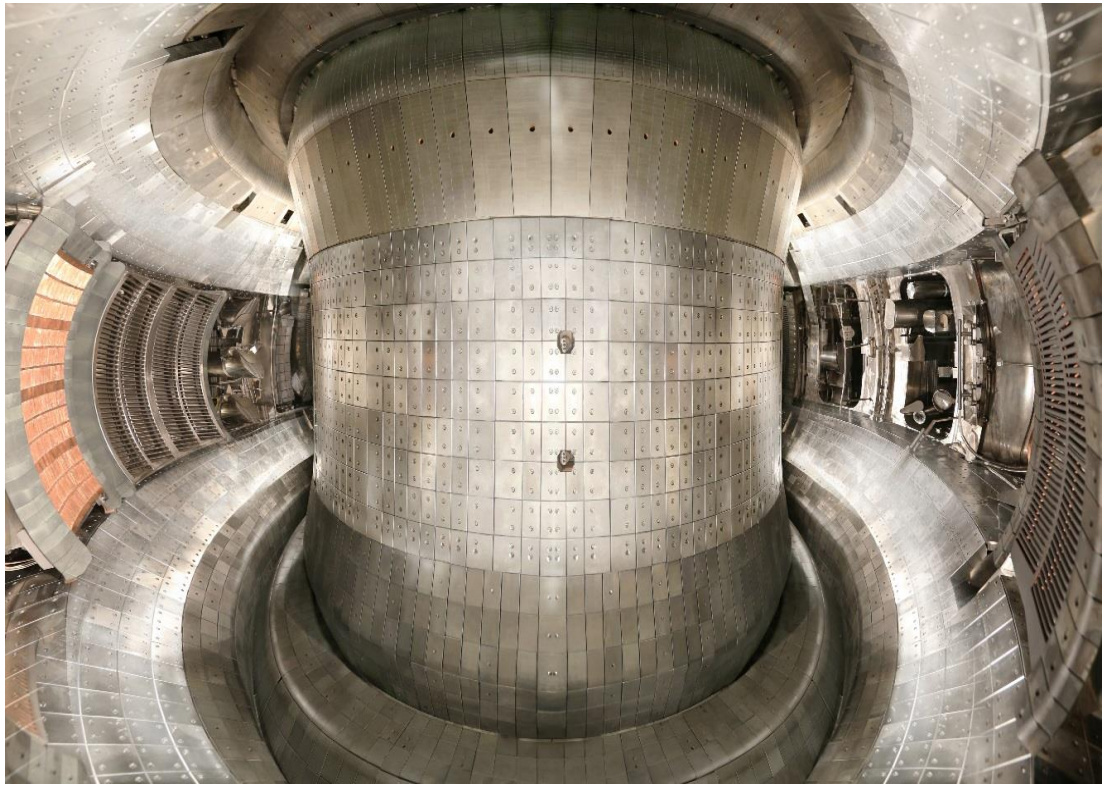
EAST Overview

Main parameters:

B_t	3.5 T
R_0	1.89 m
a	0.45 m
k_{max}	~ 1.8
I_P	1.0 MA



H&CD systems:

LHCD	10 MW
ECRH	4 MW
ICRF	4 MW
NBI	8 MW

- **Feature:**

  Steady-state long-pulse operation

- **Mission:**

  conducting ITER-like steady-state advanced plasma science and technology research

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LHCD System before 2021

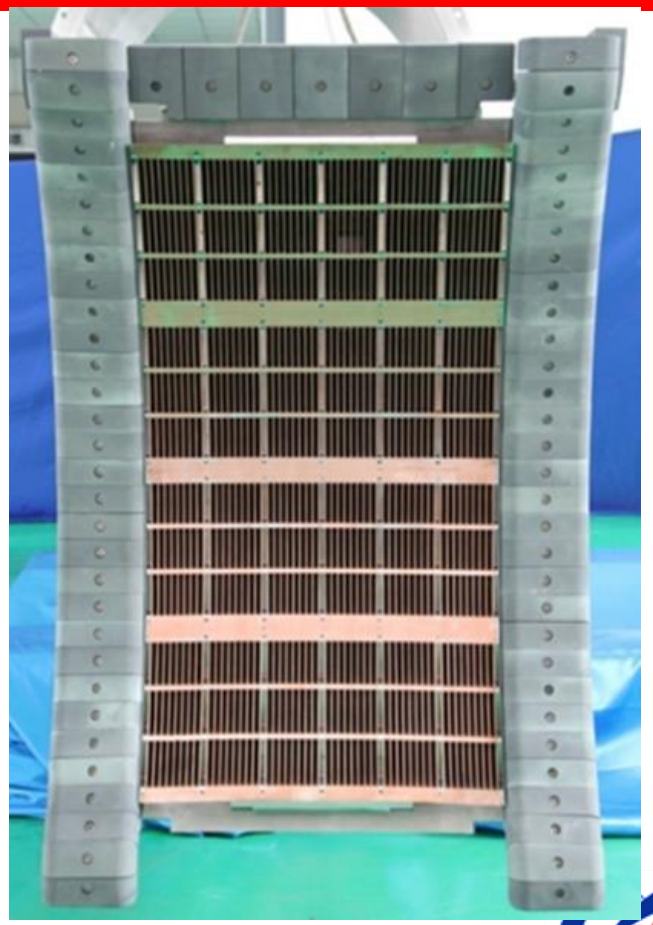
LH1: 4 MW/2.45 GHz

- 20 klystrons
- Long-pulse (>1000 s)
- FAM launcher (before 2021) with actively water cooling

Fusion Eng. Des. 147 (2019) 111250

LH2: 6 MW/4.6 GHz (developed in 2014)

- 24 klystrons
- Long-pulse (>1000 s)
- FAM launcher with actively water cooling



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LHCD System after 2021

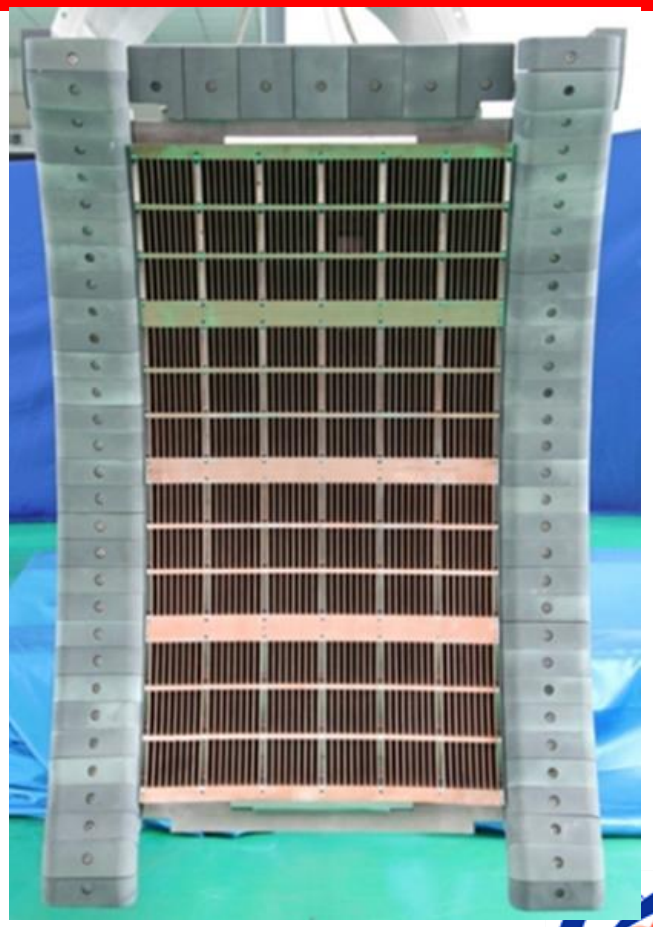
LH1: 4 MW/2.45 GHz

- 20 klystrons
- Long-pulse (>1000 s)
- PAM launcher (after 2021) with actively water cooling
- It will be replaced by a new 4.6 GHz system in next two years

Fusion Eng. Des. 147 (2019) 111250

LH2: 6 MW/4.6 GHz
(developed in 2014)

- 24 klystrons
- Long-pulse (>1000 s)
- FAM launcher with actively water cooling



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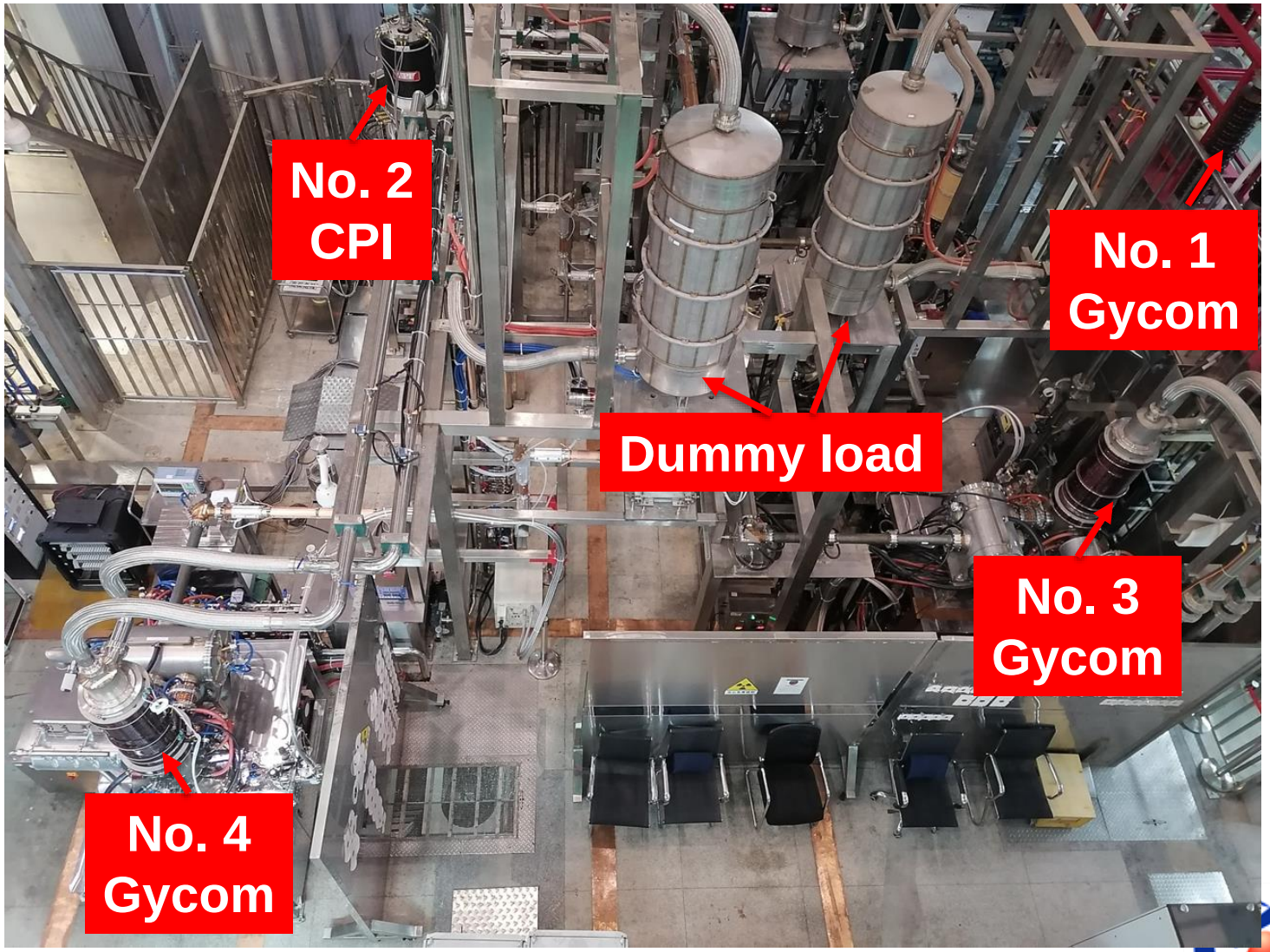
ECRH/ECCD System

- Four 140 GHz (2X mode) gyrotrons, 4 MW (nominal) power installed.
- Long-pulse operation (100 – 1000 s) with actively water cooling launchers
- No. 1: undergoing repair (air leakage issue).
- No. 4 from GYCOM: dual frequency gyrotron (0.6 MW/105 GHz and 0.9 MW/140 GHz)
- Additional two gyrotrons systems under development



Fusion Eng. Des.164 (2021) 112222
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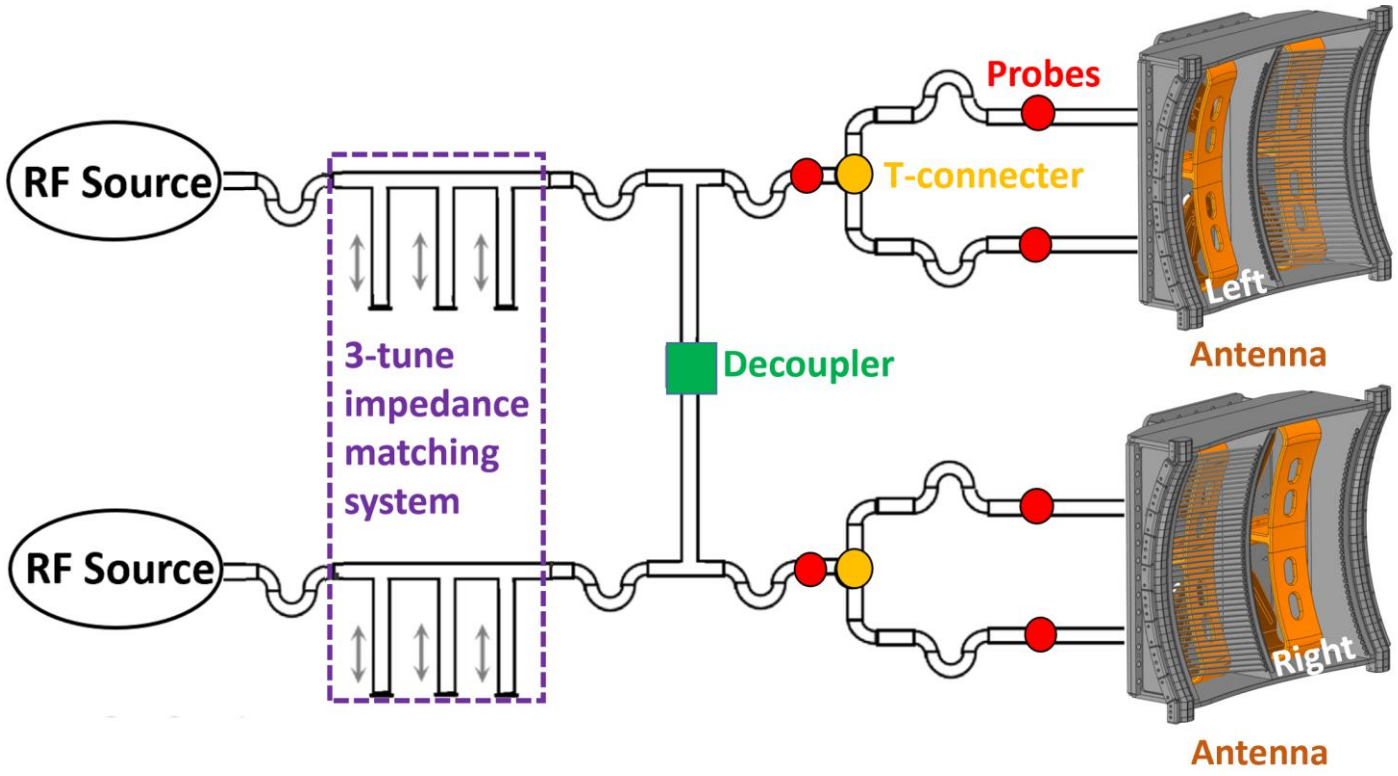
ICRF System

Two ICRF antennas: P = 2 × 2 MW



New antenna (from 2021) with k ≈ 7.5 m^{-1}, t = 1000 s

- **Each strap fed by 2 coaxial feeders and field aligned faraday screen.**
- **Current straps, Faraday shield and protection tiles are actively cooled.**

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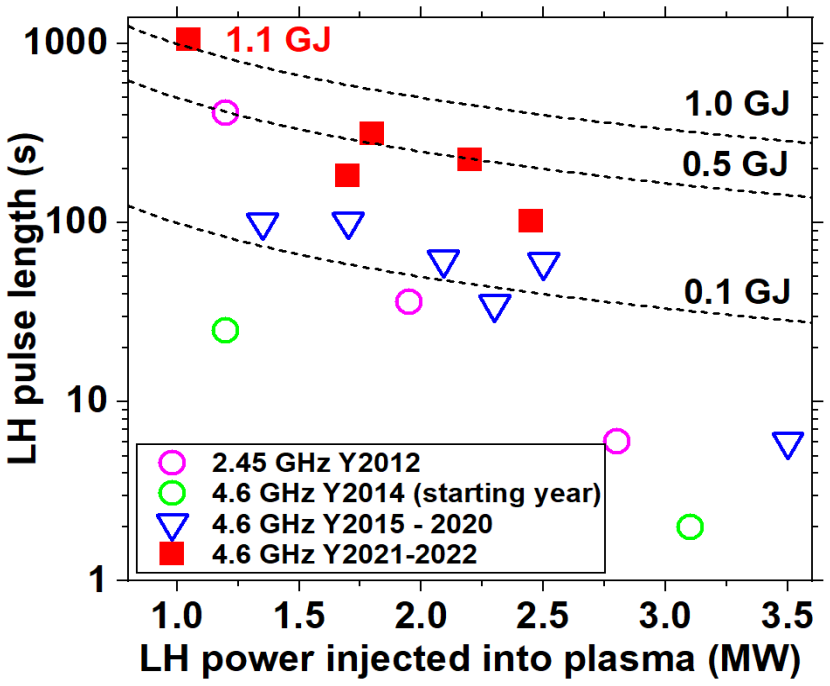
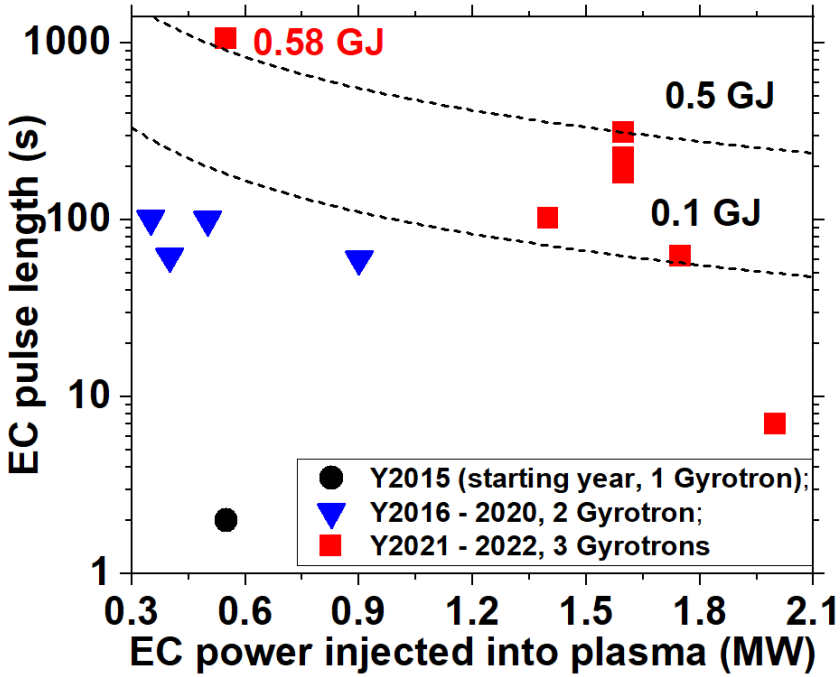
Advance in Long-Pulse Operation of RF Systems

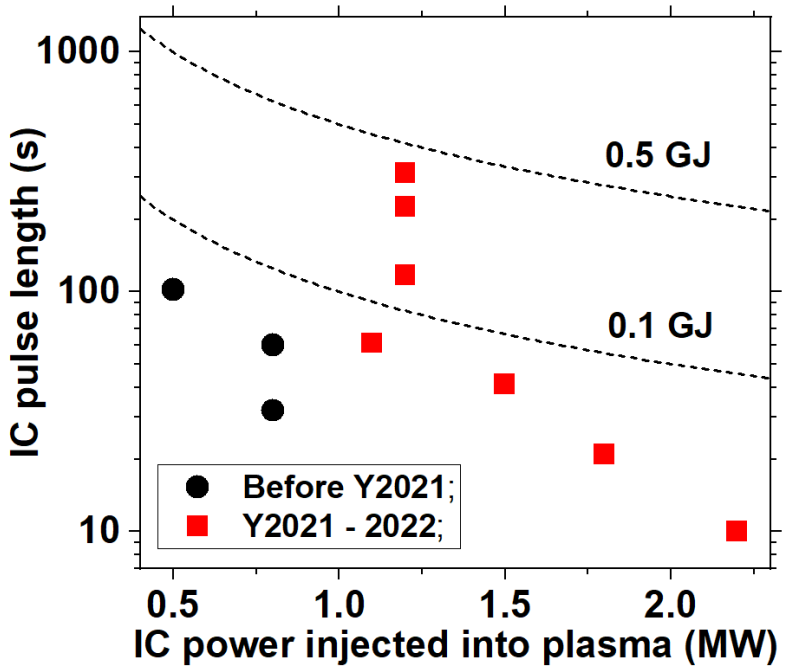
LH system



EC system



IC system



- LH system: 2.45 GHz, 411 s with 1.2 MW, maximum power: 2.8 MW. 4.6 GHz, 1056 s with 1.1 MW, 310 s with 1.8 MW, 102 s with 2.4 MW, maximum power: 3.5 MW.
- EC system: 1056 s with 0.55 MW, 310 s with 1.6 MW, maximum power: 2.0 MW.
- IC system: 310 s with 1.2 MW, 1.8 MW routinely.

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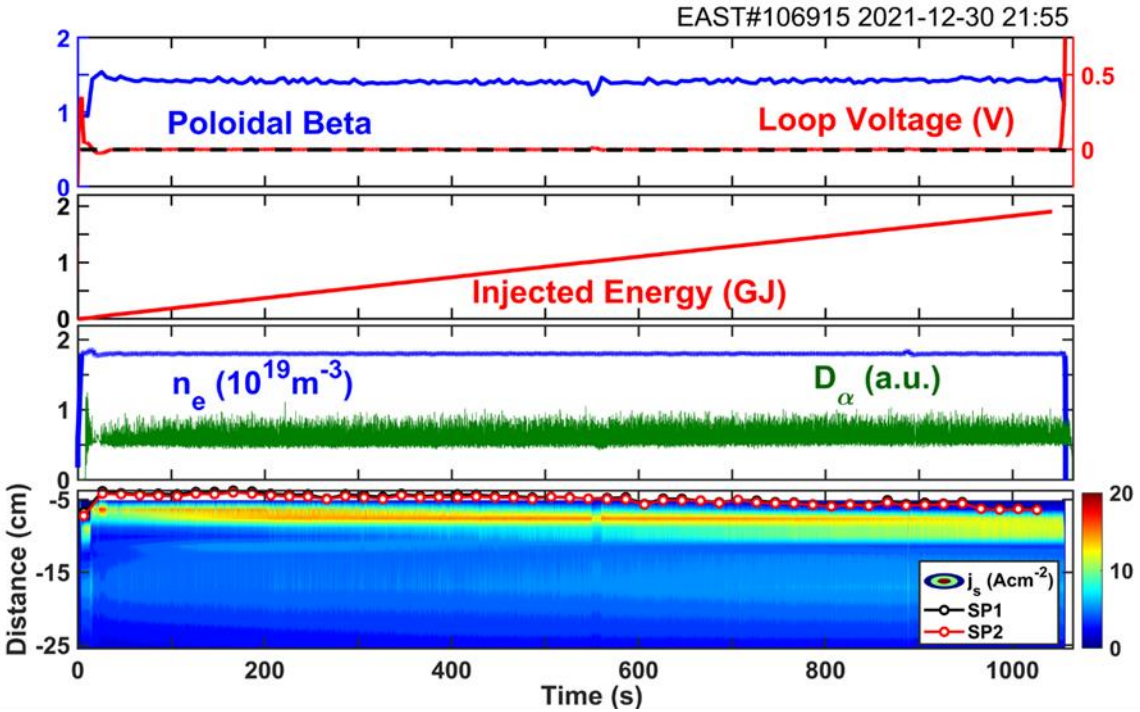
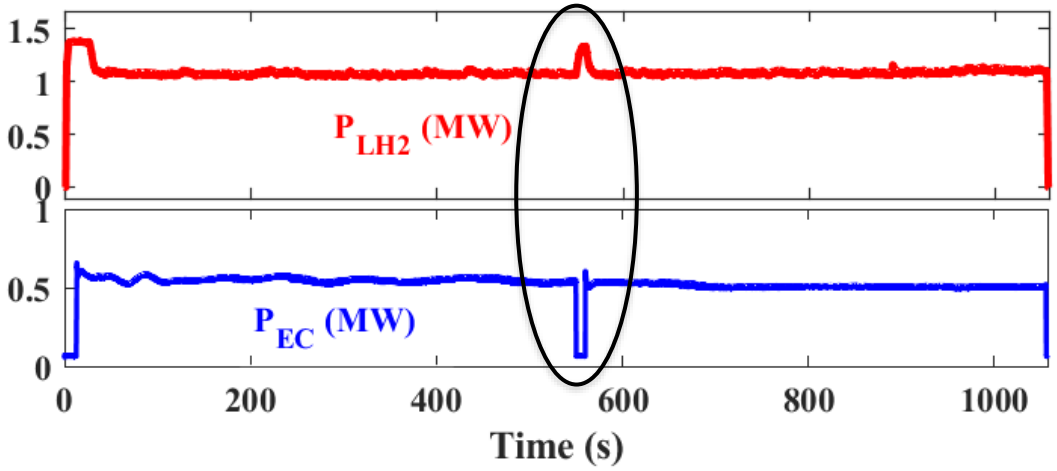
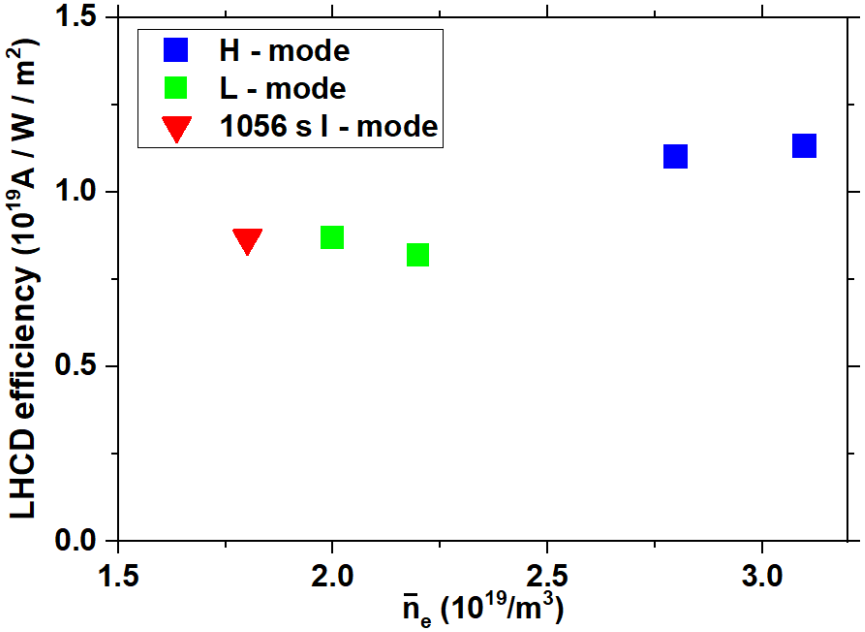
Thousand-Second Improved Confinement Plasma with Super I-Mode by LH and EC Waves







- **ETB at the edge and ITB at the center. Confinement (H_{98}~1.2) comparable to H-mode**
- **LH power ~ 1.1 MW feedback controlled by flux consumption and CD efficiency ~ 0.87 (10^{19}A/W/m^2).**
- **EC system (0.55 MW) restarted when the gyrotron was overcurrent.**

Y.T. Song et al. Sci. Adv. 2022 (in press)

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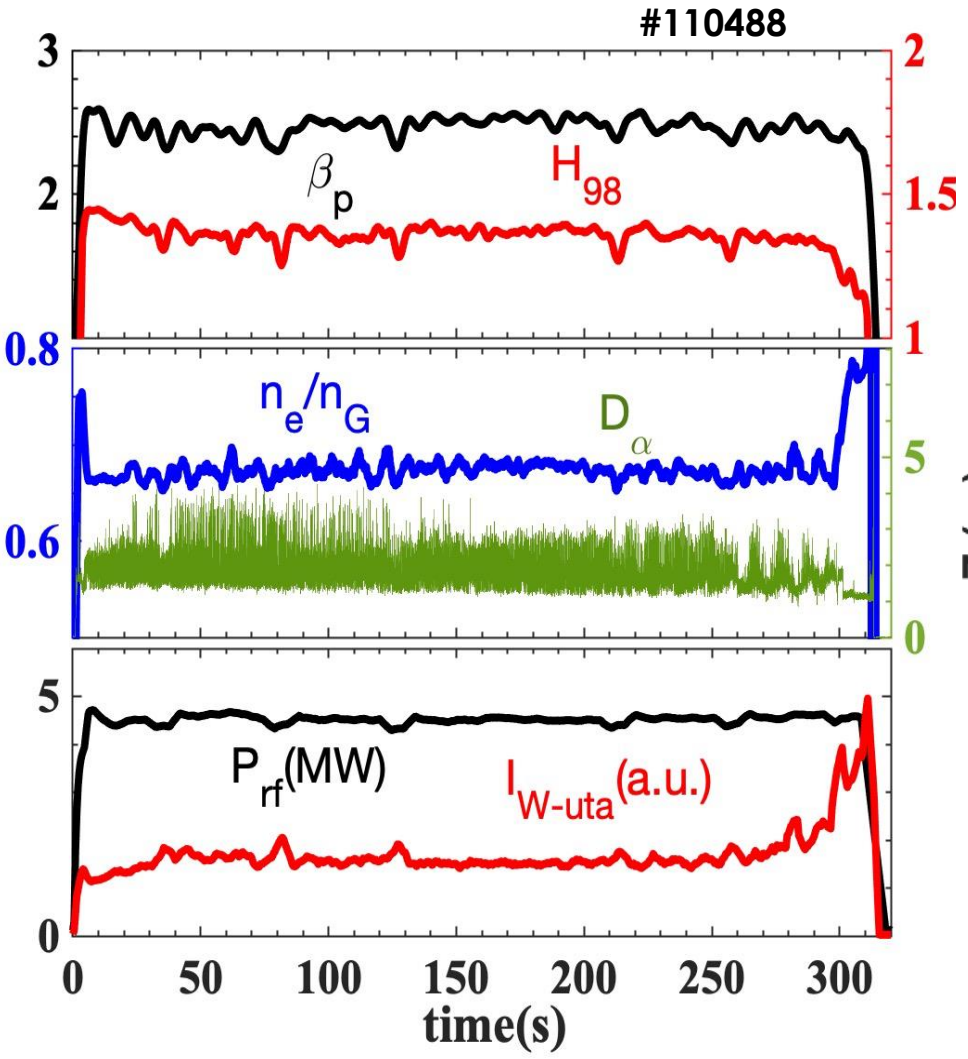
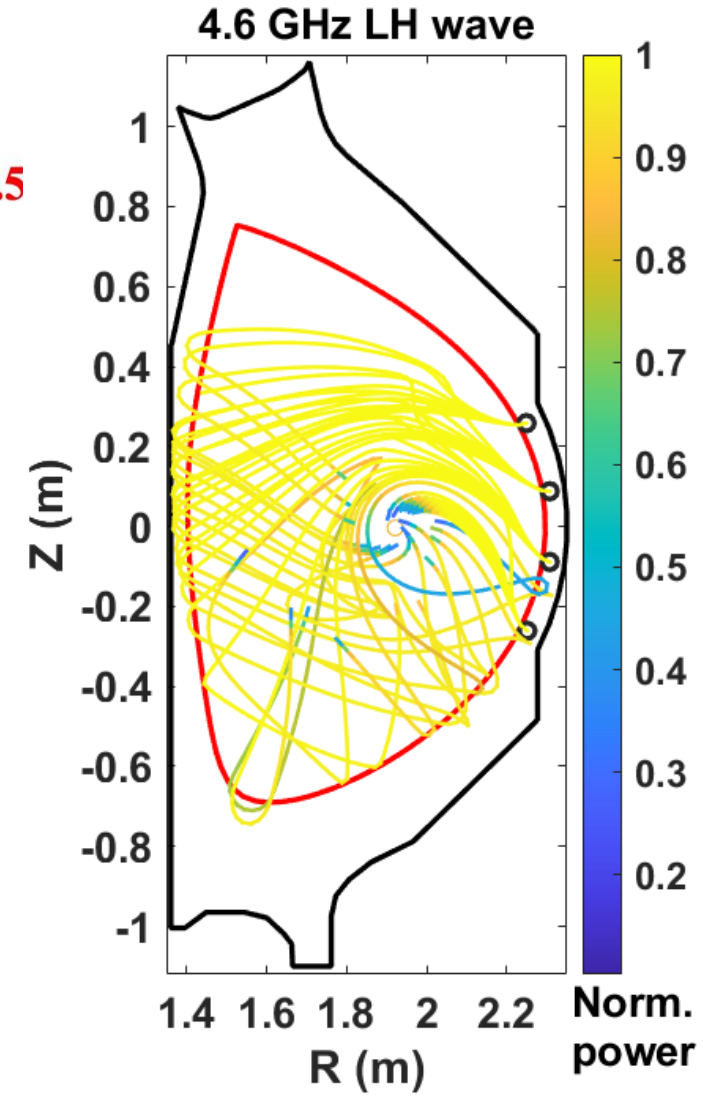
Long-Pulse H-mode Operation up to 310 s with LH, EC and IC Waves





- **Fully non-inductive plasma with dominant e-heating**
  - **RF-only**: P_{LH}~1.8 MW, P_{EC}~1.6 MW, P_{IC}~1.2 MW
  - **H_{98y2} >1.3**, f_{Gr}~0.7, Zero injected torque, Small ELM (f_{ELM} >2.5kHz)
  - β_P~2.5, β_N ~1.6, f_{BS}>50%
  - **Good accessibility for LH wave** with $N_{||0}$ = 2.04 and most of the power absorbed at ρ < 0.4

J. Huang et al. Annual APS Meeting Division of Plasma Physics 2022

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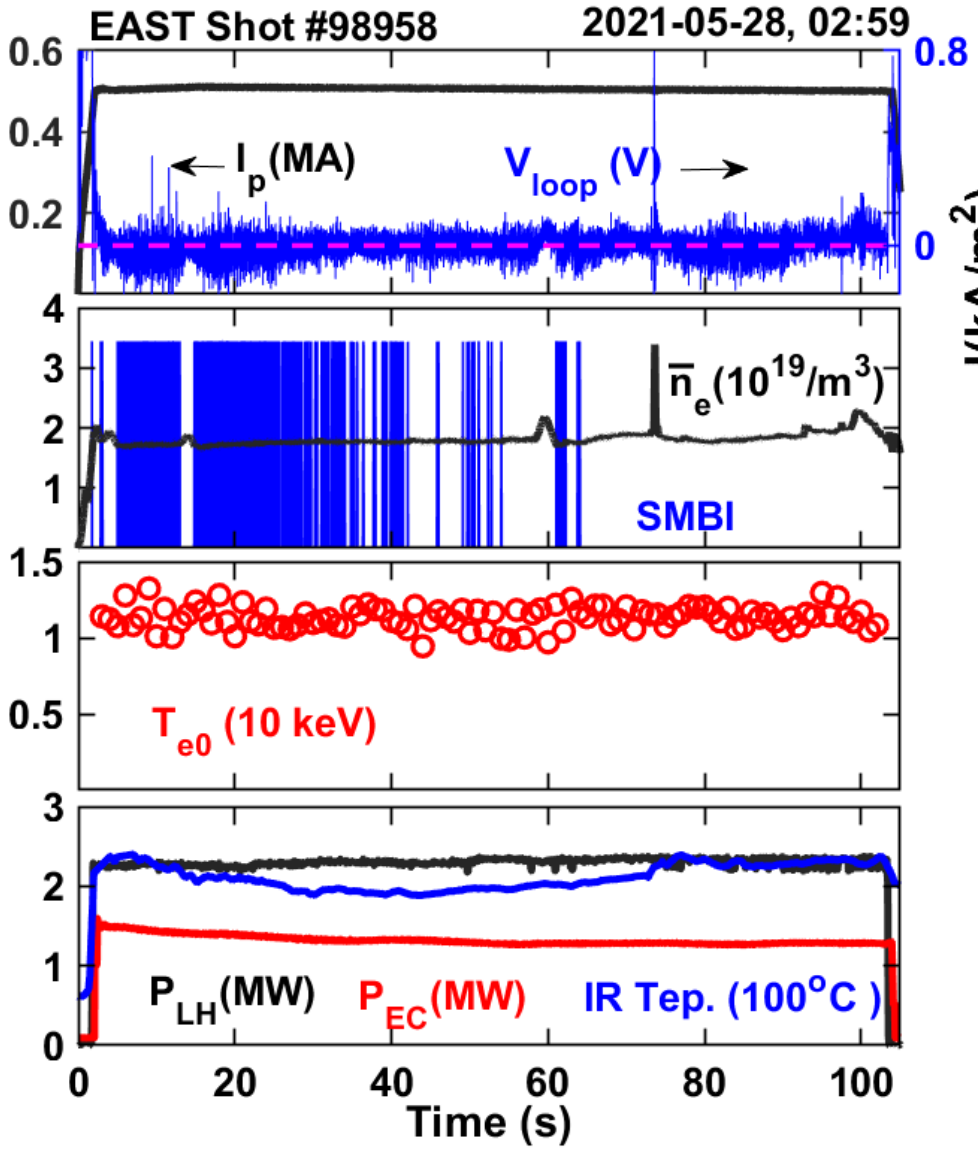
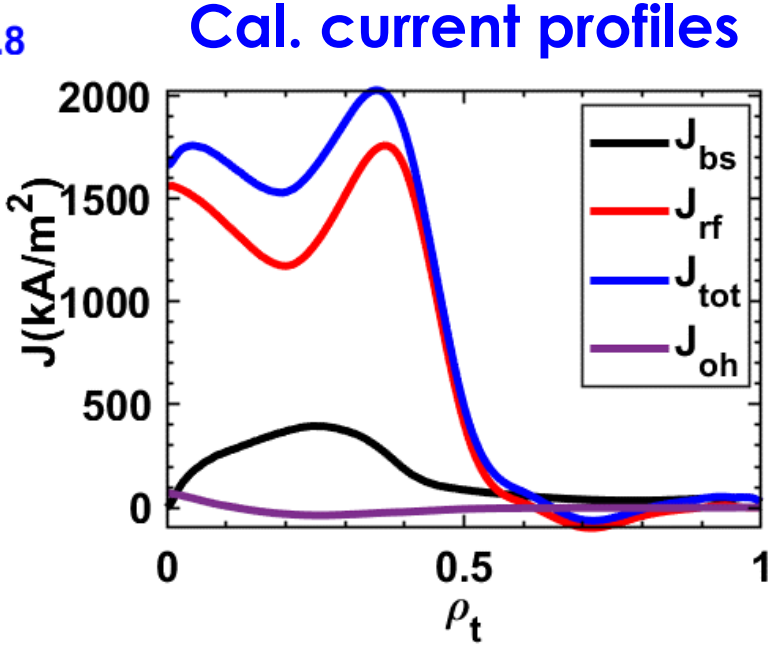
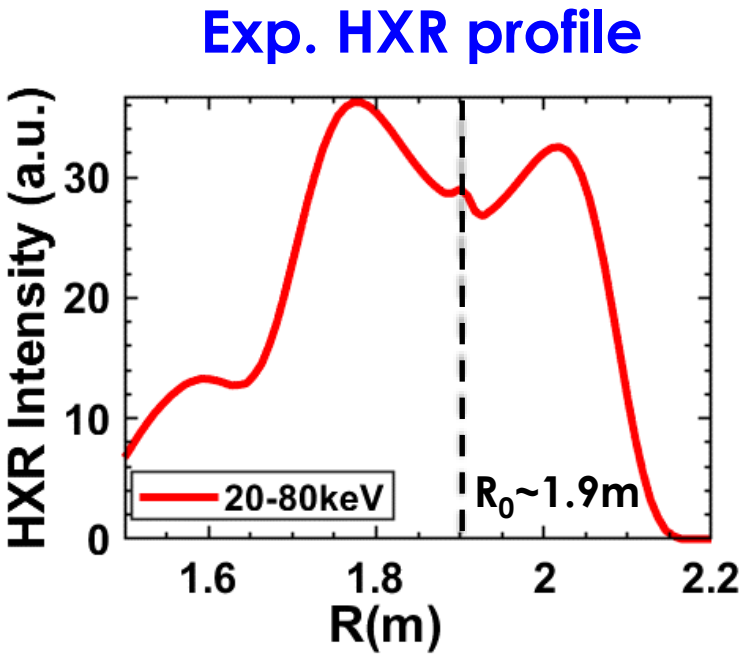
Long-Pulse (> 100 s) Operation with High T_e by LH and EC waves







- T_{e0} > 10 keV, P_{LH2} ~ 2.4 MW, P_{EC} ~ 1.4 MW
- EC power heating at plasma center
- LH current peaked at ρ ~ 0.35 due to slightly high $N_{||}$=2.26, consistent with HXR profile, which help to optimize the magnetic shear

X.Z. Gong et al. Plasma Sci. Technol. 2022

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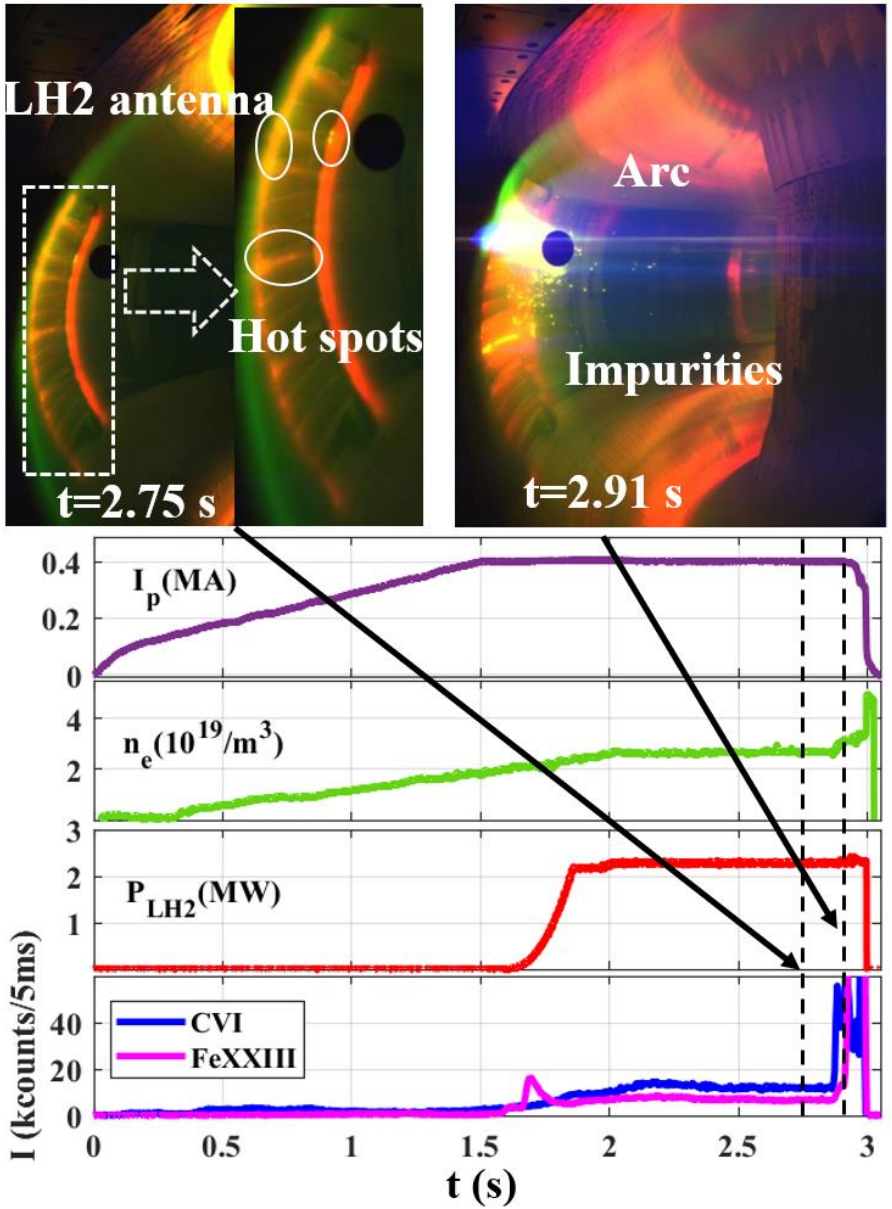
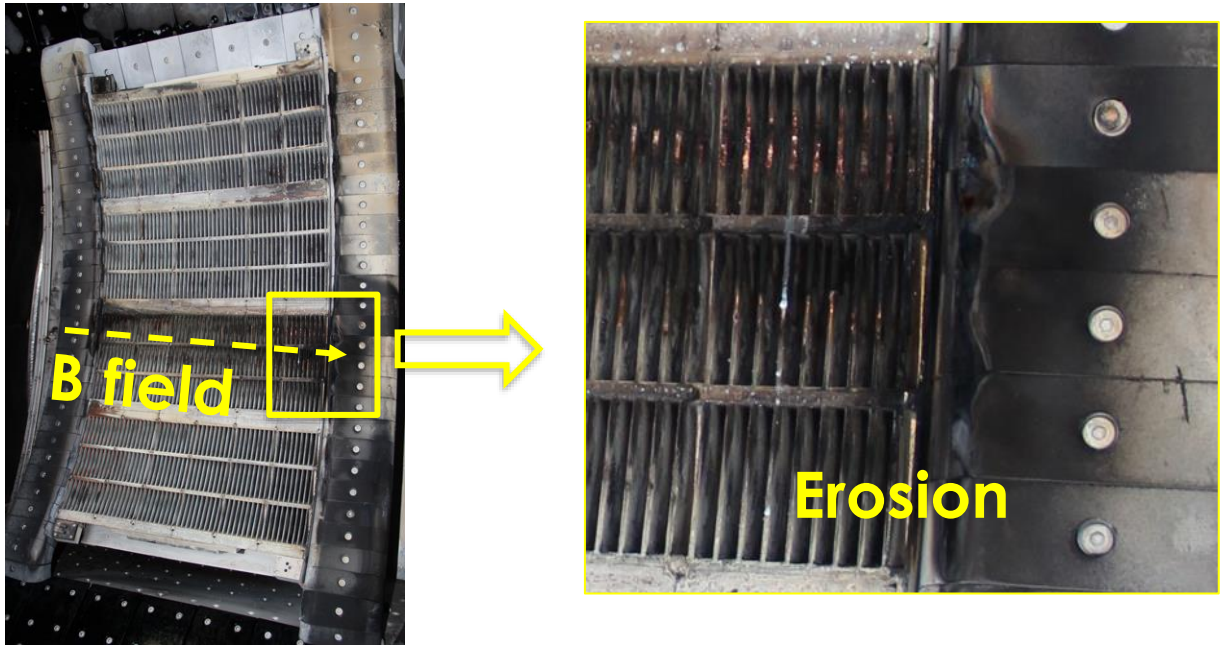
Interactions of Edge Plasmas with LH Antenna





- **Fast electrons** in front of LH antenna generated **by high $N_{||}$ spectrum components** can cause high heat flux.
- **Hot spot, arcing events**, followed **by impurity emission** lead to plasma disruption, damage on the antenna and on the guard limiters

M. Wang et al. Nucl. Eng. Technol. 2022

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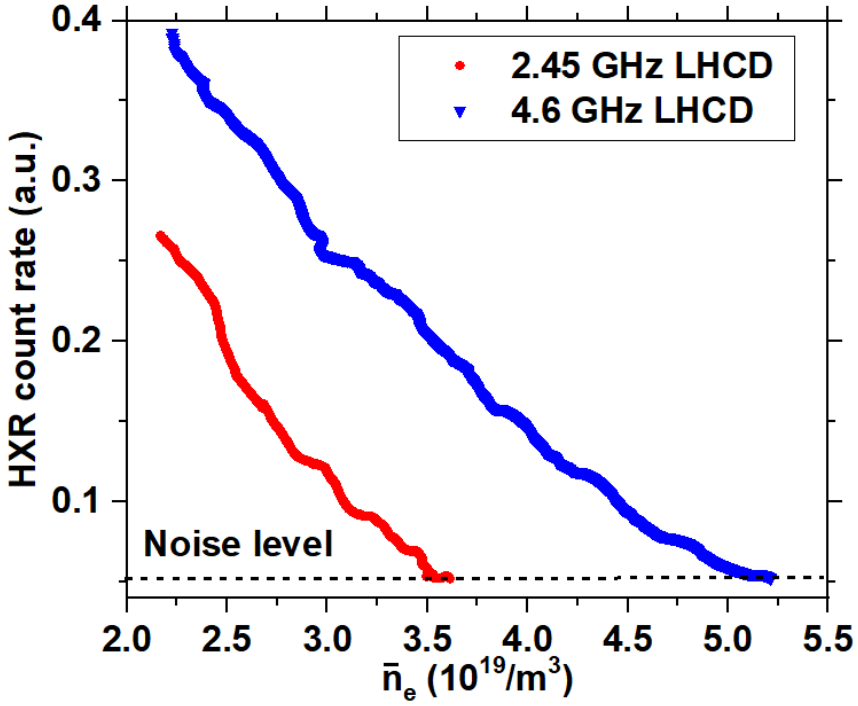
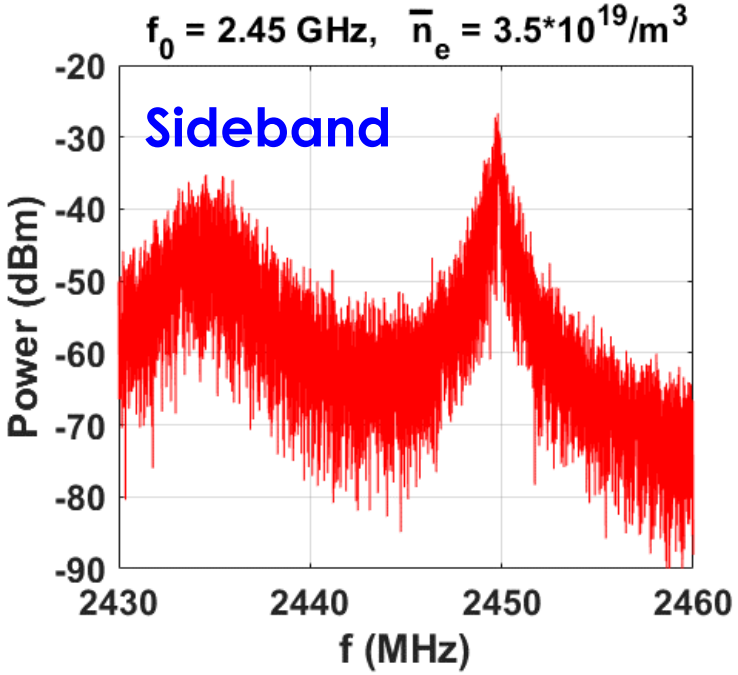
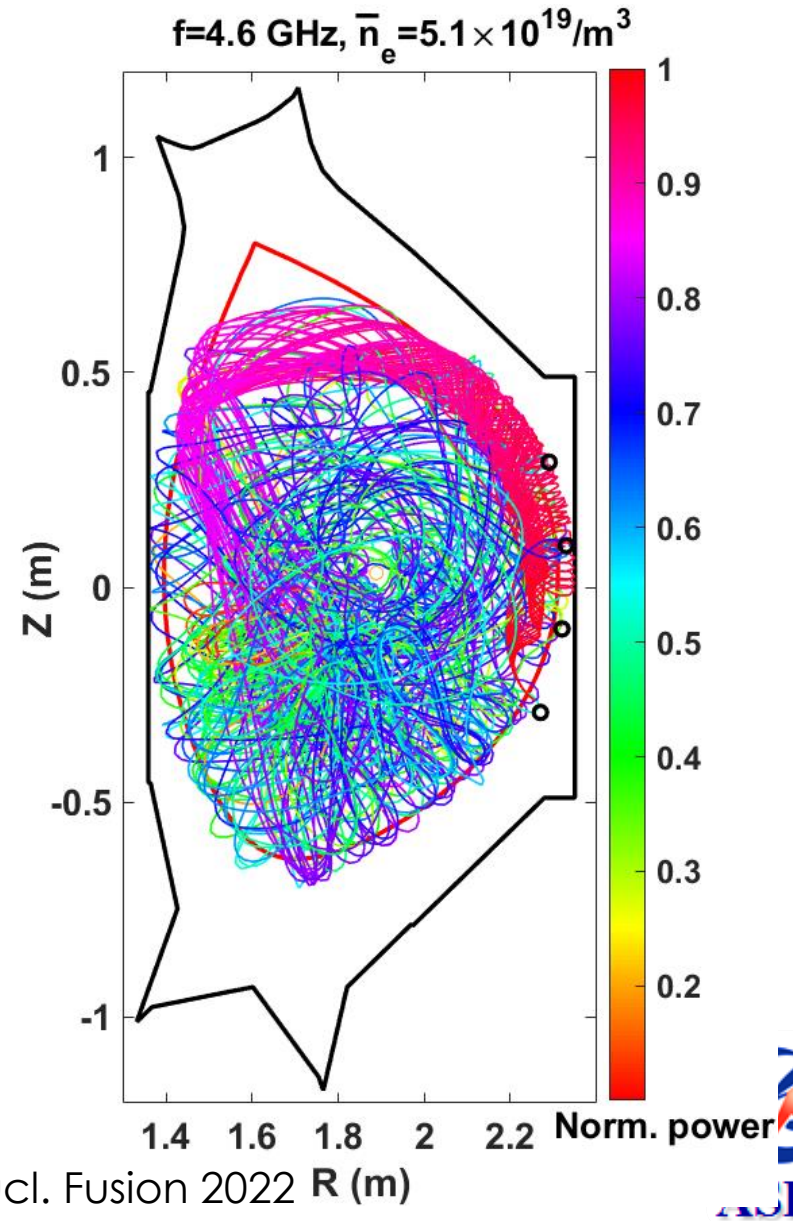
LHCD Density Limit







- **LHCD density limit was observed for both 2.45 GHz and 4.6 GHz waves. 4.6 GHz wave shows a higher LHCD density limit.**
- **Parasitic losses due to PDIs and poor wave accessibility and are the dominate mechanisms for 2.45 GHz and 4.6 GHz waves respectively.**

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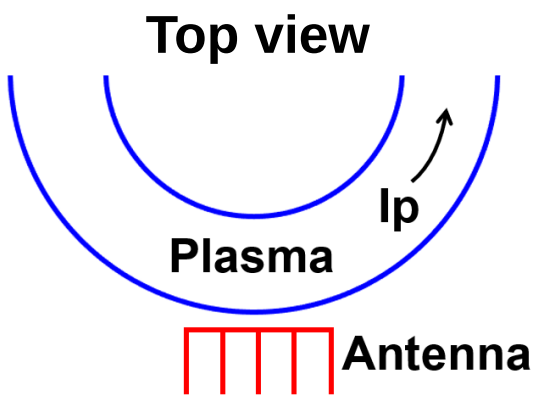
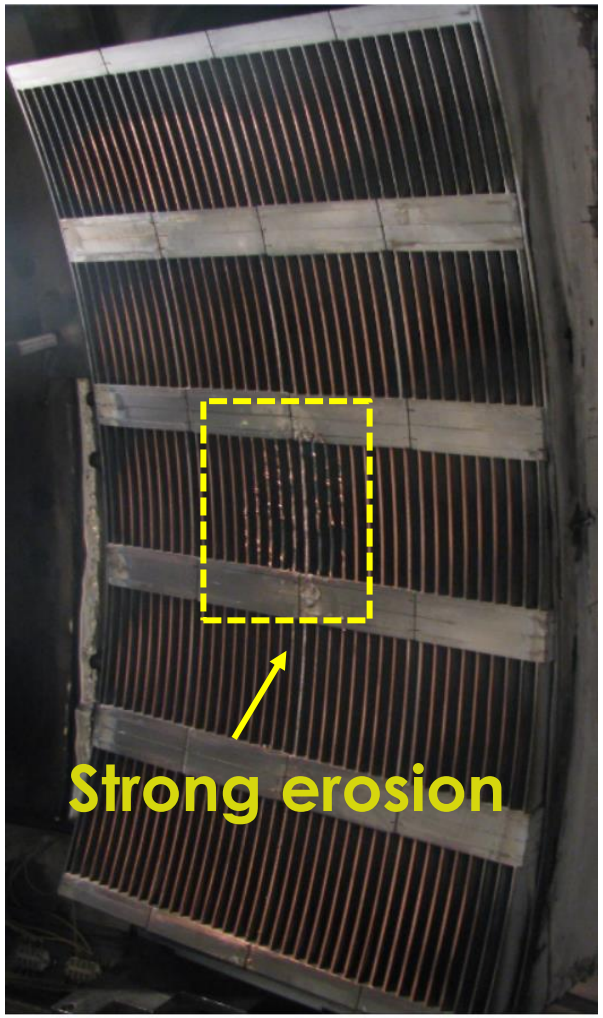
Optimization of LH Antenna Shape

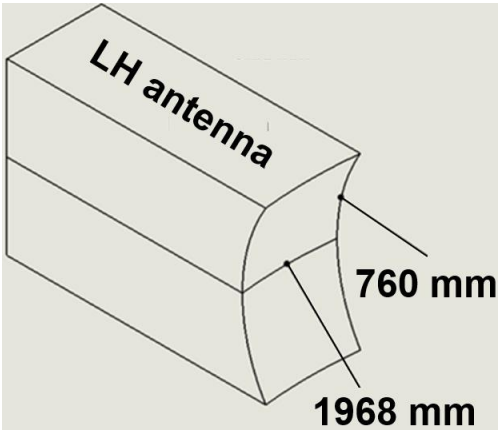
Slab in toroidal direction before 2012

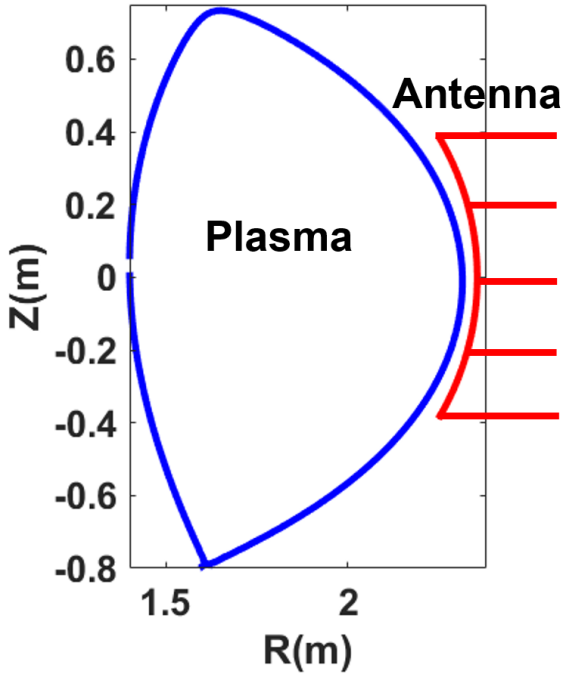




- Strongest erosion in the **middle** of the antenna

Curved surface after 2012





- Toroidal and poloidal radius of curvature = 1968 and 760 mm, which best fit the magnetic field curvature.
- However, due to the **variation of plasma configuration**, there are still some erosions on the antenna surface.

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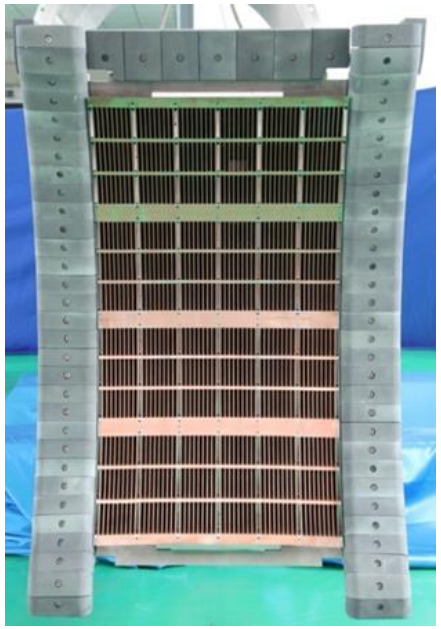
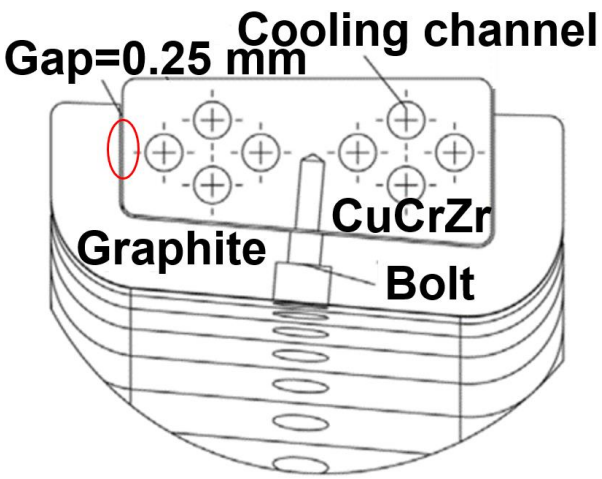
Upgrade of LH Antenna Guarder Limiters

Graphite tiles before 2017



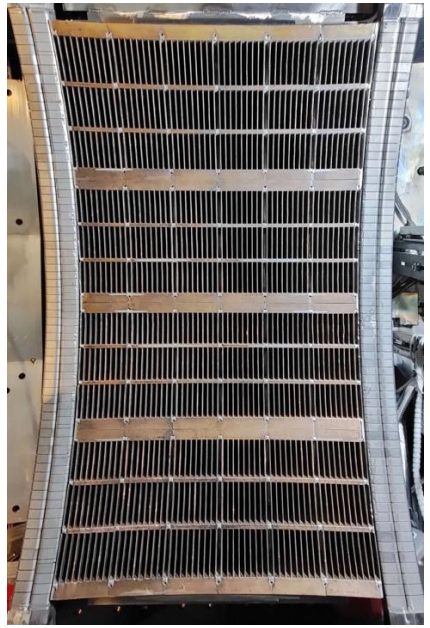
Limiter structure



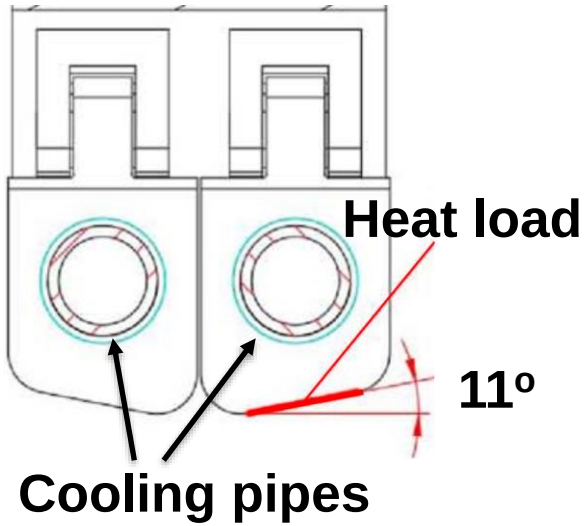
- Graphite tiles plated with SiC, CuCrZr heat sink with stainless support frame.
- low thermal conduction due to poor contact
- Design target ~ 2.0 MW/m^2.

C.L. Liu er al. Fusion Eng. Des. 2017

Tungsten limiters after 2017



Limiter structure



- Explosive welding technology applied
- Tungsten block with a wedge-shape
- Design target ~ 12.9 MW/m^2.

L.L. Zhang er al. Fusion Eng. Des. 2018

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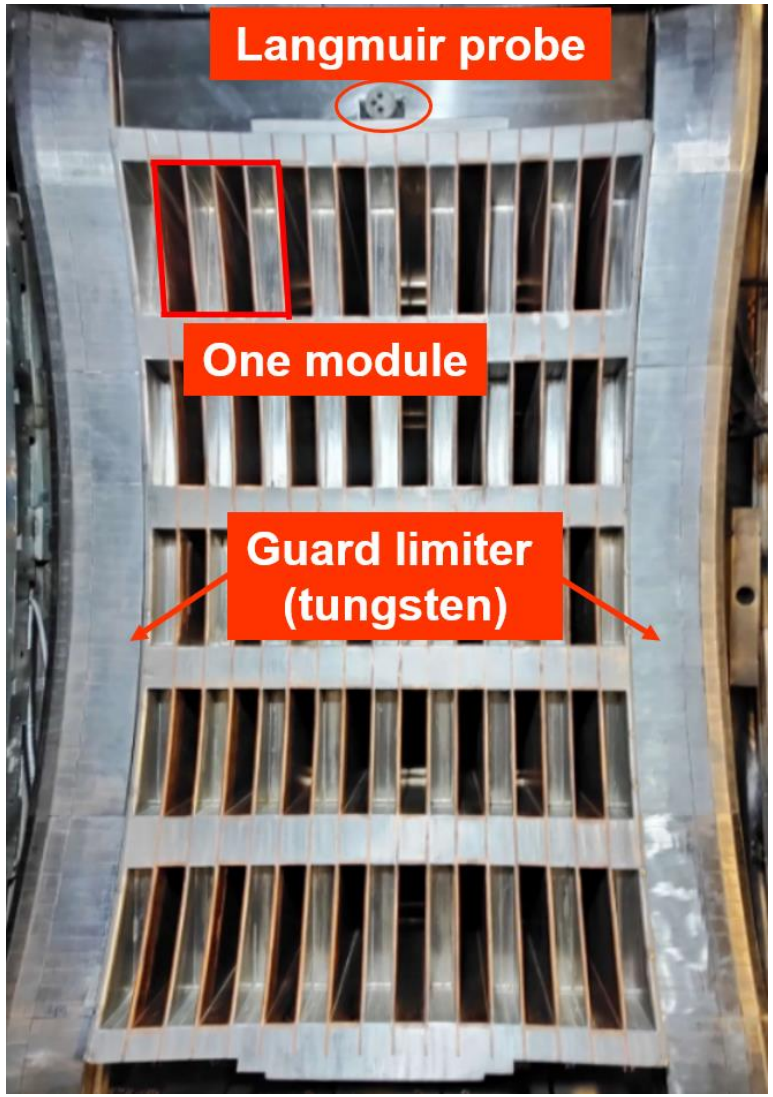
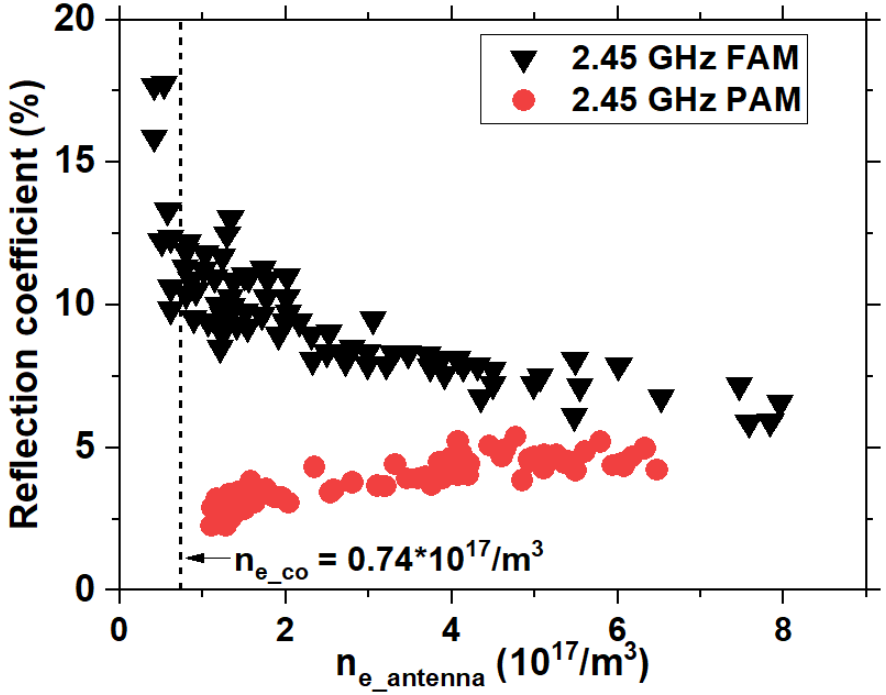
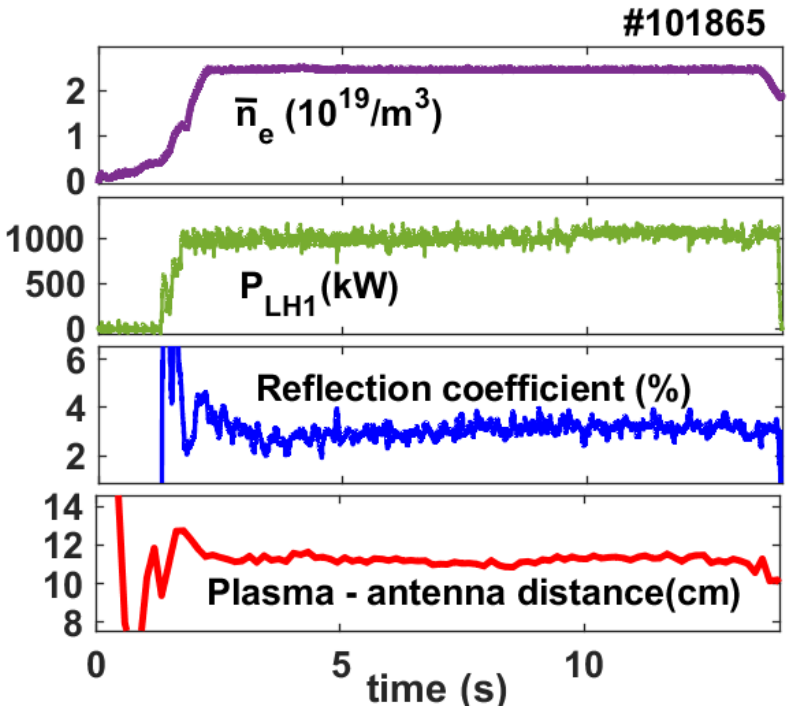
Long-Distance Coupling of LH Power with A New PAM Launcher at 2.45 GHz







- The new PAM antenna shows **better coupling** than the old FAM with **density close to n_{e_co}**.
- Good coupling (RC ~ 3%) has been achieved with plasma-antenna **distance up to 11 cm**.
- This PAM antenna provides valuable **engineering experience** for new 4.6 GHz PAM development in future.

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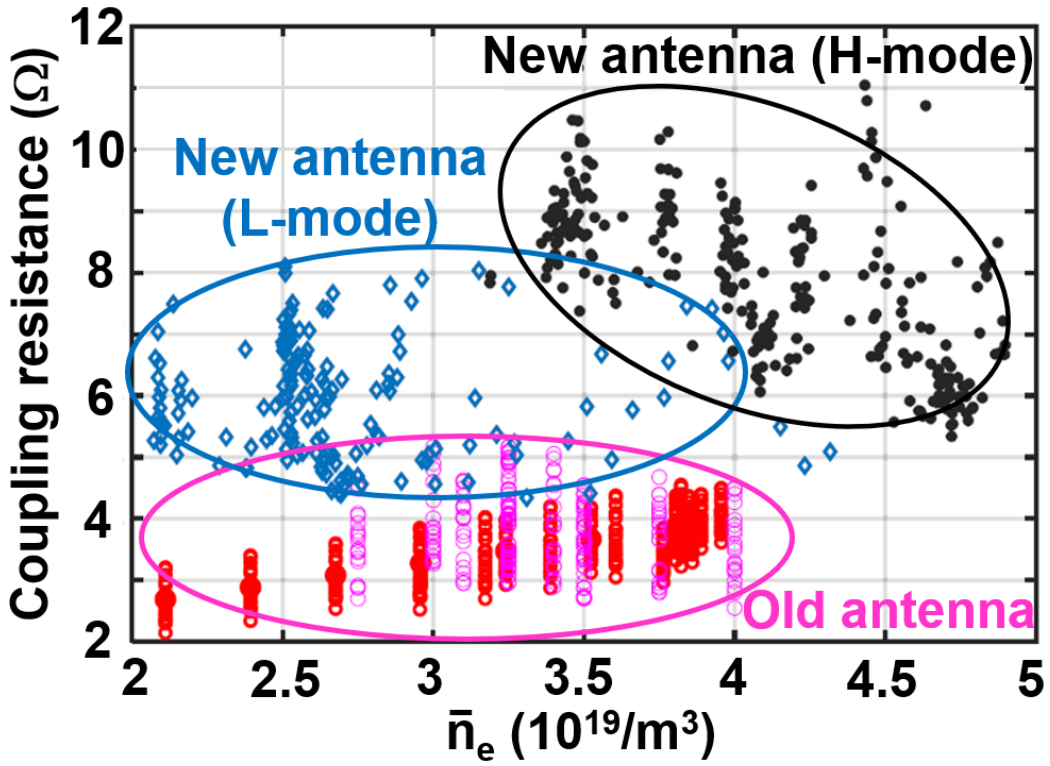
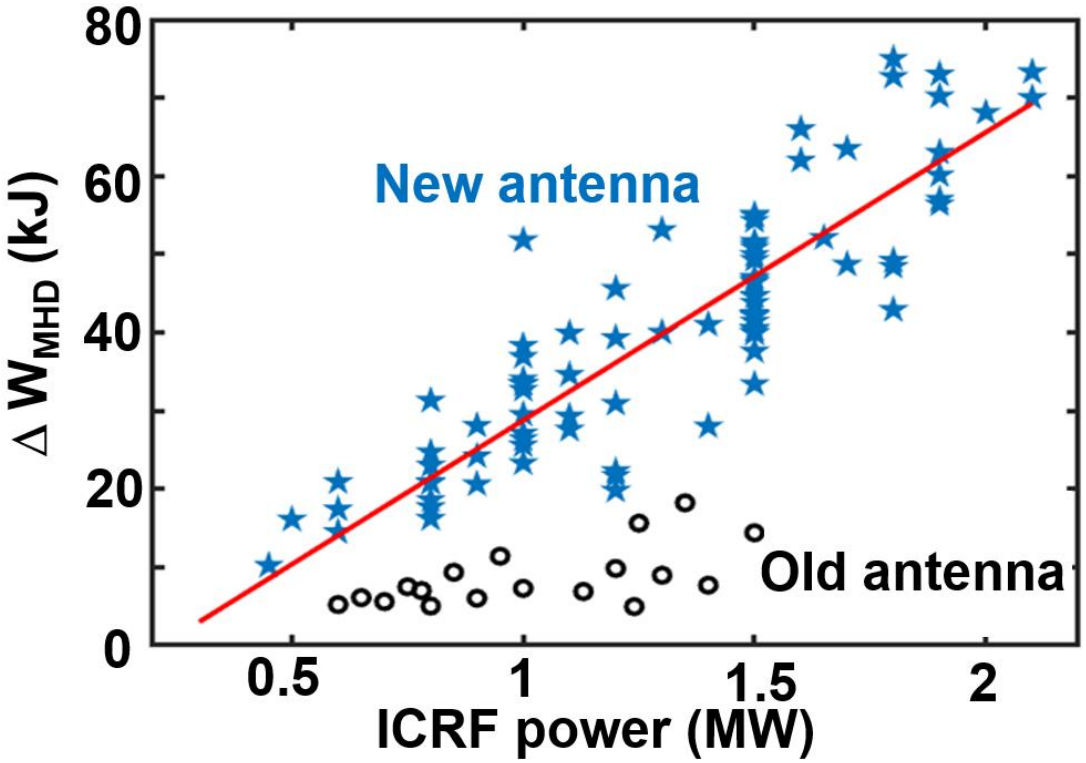
Better Coupling of A New ICRF Antenna Characterized with Smaller parallel Wave Number





- **Coupling resistance** of the new antenna (first experiments in 2021) is **much larger** than the old one.
  - $k_{||}$ decreases from 13-14 to 7.5 /m, corresponding to n_{e_co} decreases from 8 to 2.8×10^{18} /m^3
- **Better heating** efficiency in H-mode than the old antenna.

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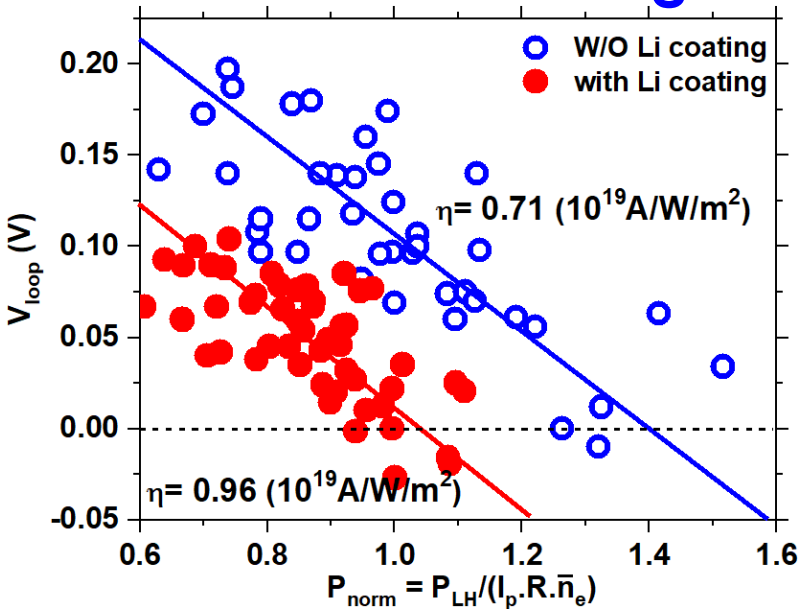
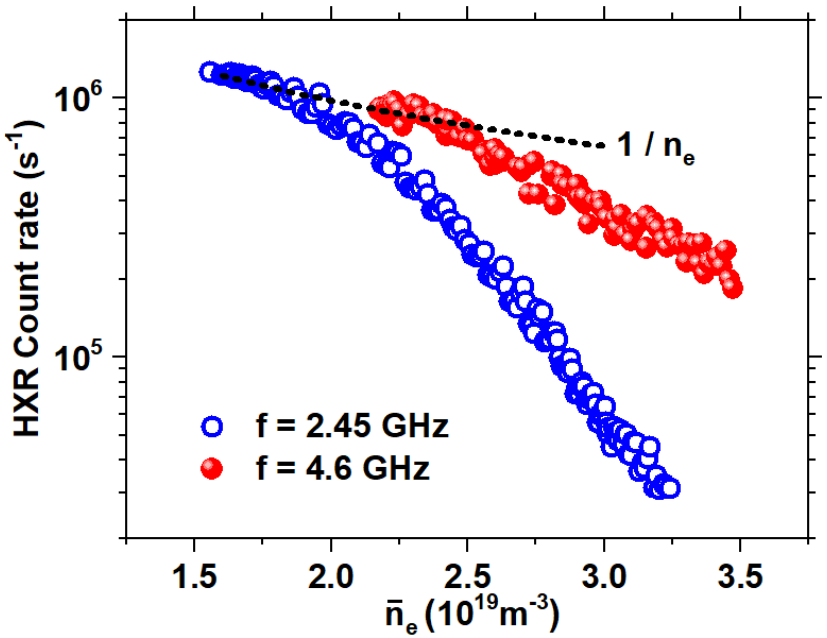
Methods to Improve CD Efficiency at High Density

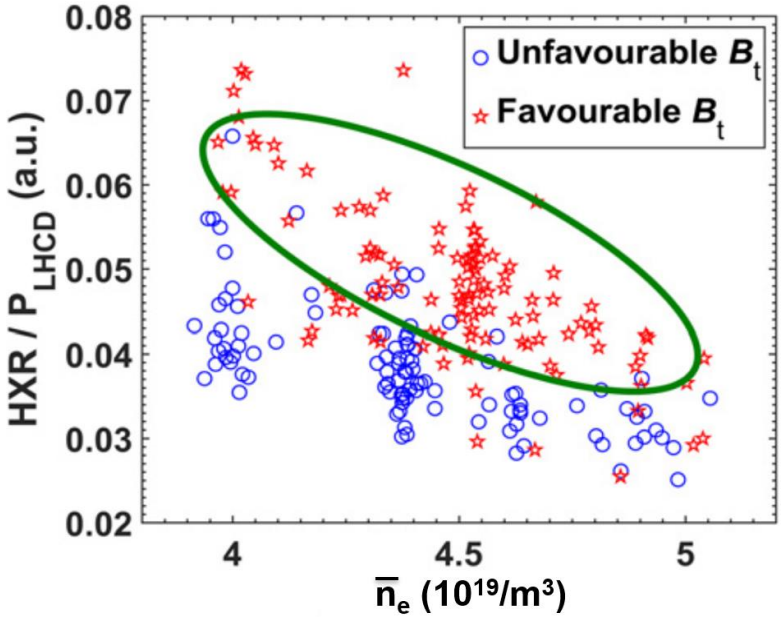
Lithium coating



Higher wave frequency



Favorable $B_t \times \nabla B$



- **Lithium coating**: **higher temperature** in SOL to reduce PDI behavior and collisional power loss
- **Higher wave frequency**: **PDI growth rate** is inversely proportional to the squared ratio ω_0/ω_{LH}
- **Favorable B_t**: **lower density, higher temperature** at the plasma edge **and lower Dα**

X. Lin et al. Nucl. Fusion 2021. M.H. Li et al. RF conference 2022

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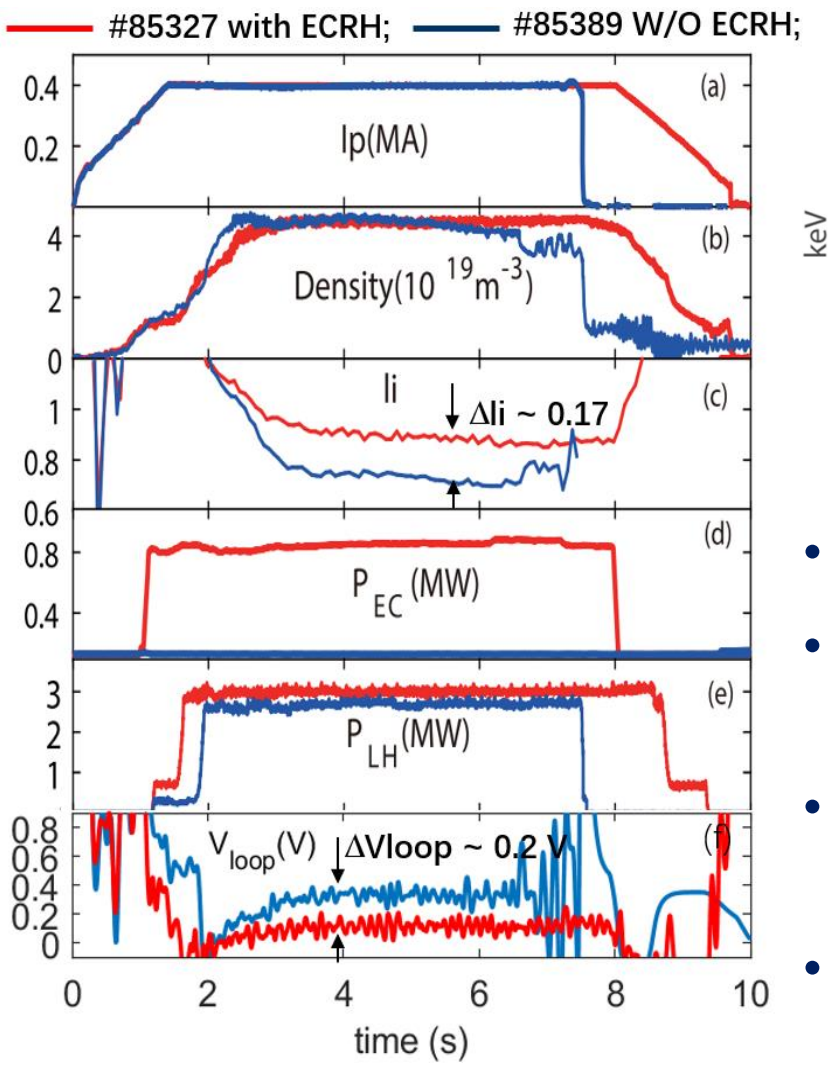
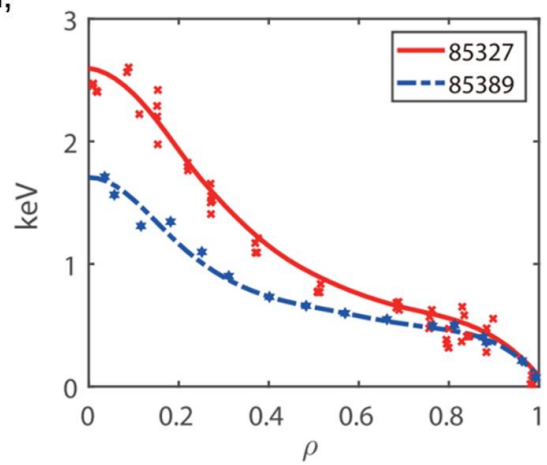
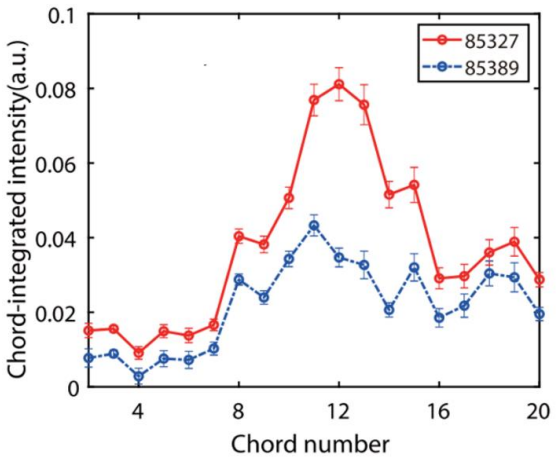
Temperature Effects on LHCD by EC Wave



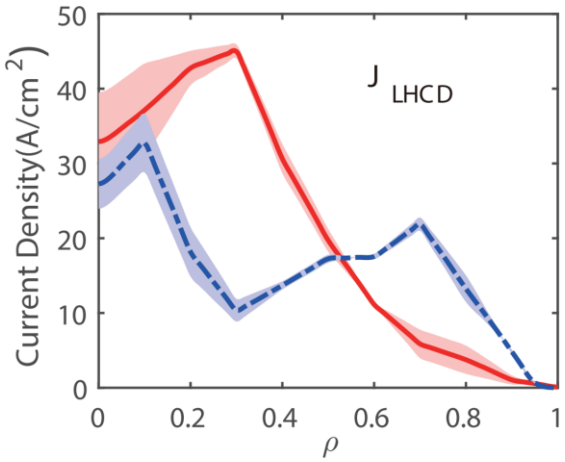
Te profiles



HXR profiles



Simulated J_{LH}



- **Higher Te with additional 0.8 MW ECRH**
- **Vloop is lower by ~ 0.2 V and HXR count rate is higher by ~ 73%, indicating higher CD efficiency.**
- **Internal inductance is higher by ~ 0.17 with ECRH, indicating more LH current driven in the plasma core**
- **Ray-tracing/Fokker–Planck modeling shows a higher LH current density in the core region.**

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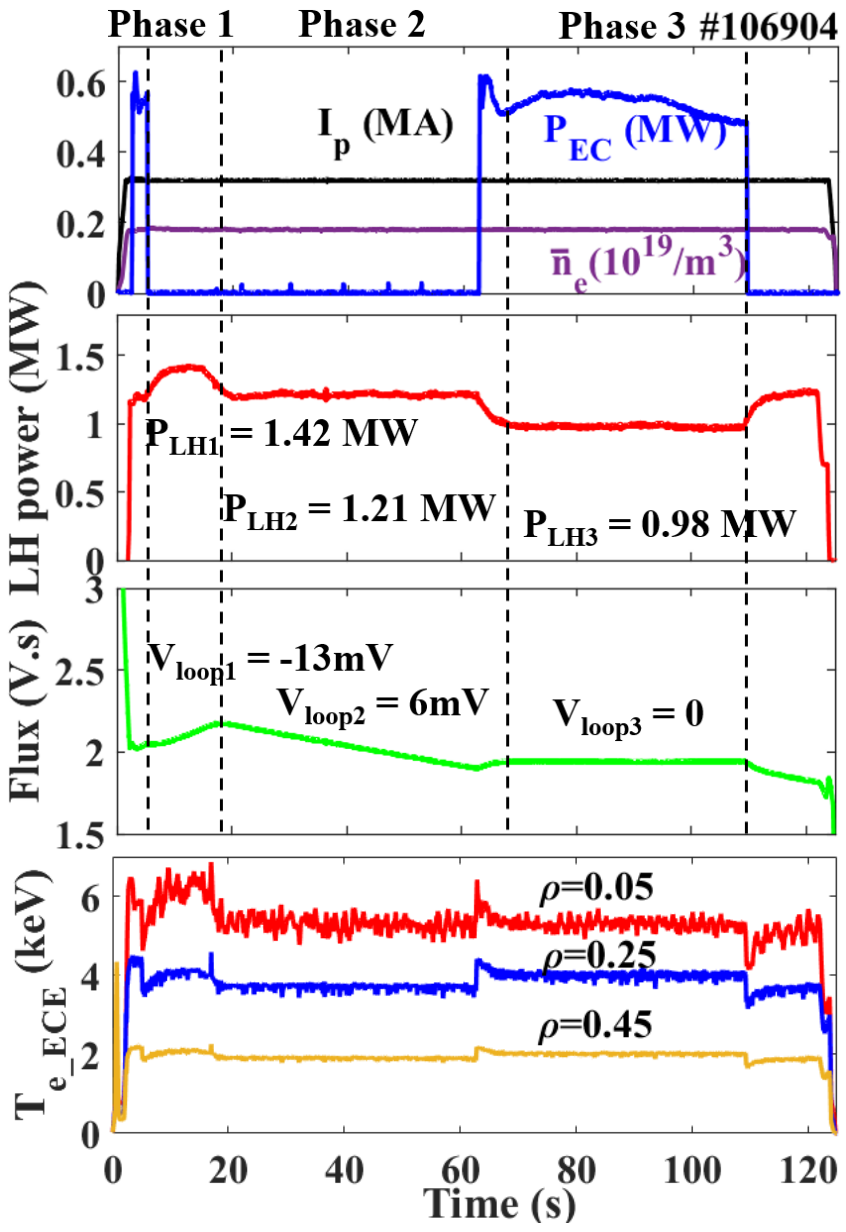
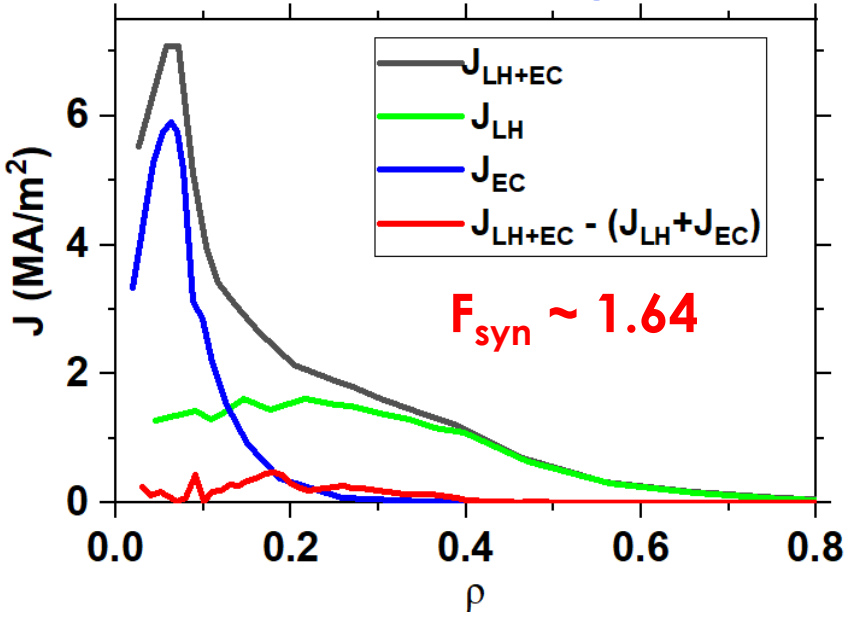
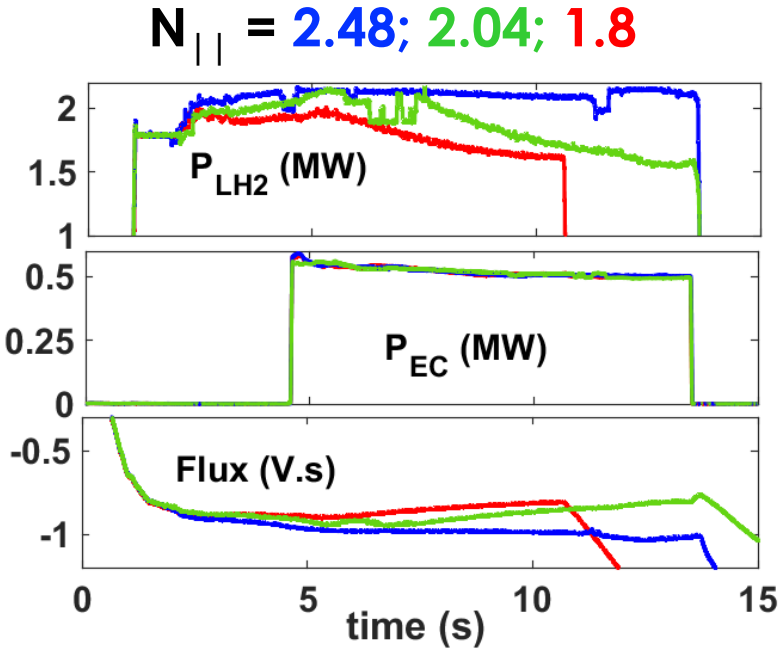
Synergy Effect between LHCD and ECCD







- During the application of 0.5 MW ECCD ($N_{||}$ ~ 0.34), the LH power drops by~ 0.3 MW.
- The synergy factor defined as $F_{syn} = \Delta I / I_{EC}$ with $\Delta I = I_{LH+EC} - I_{LH}$, is estimated to be ~ 2.1 ± 0.1, while the modeling results show a lower F_{syn} (~ 1.64).
- The synergy effects show a dependence on $N_{||}$ of LH wave.

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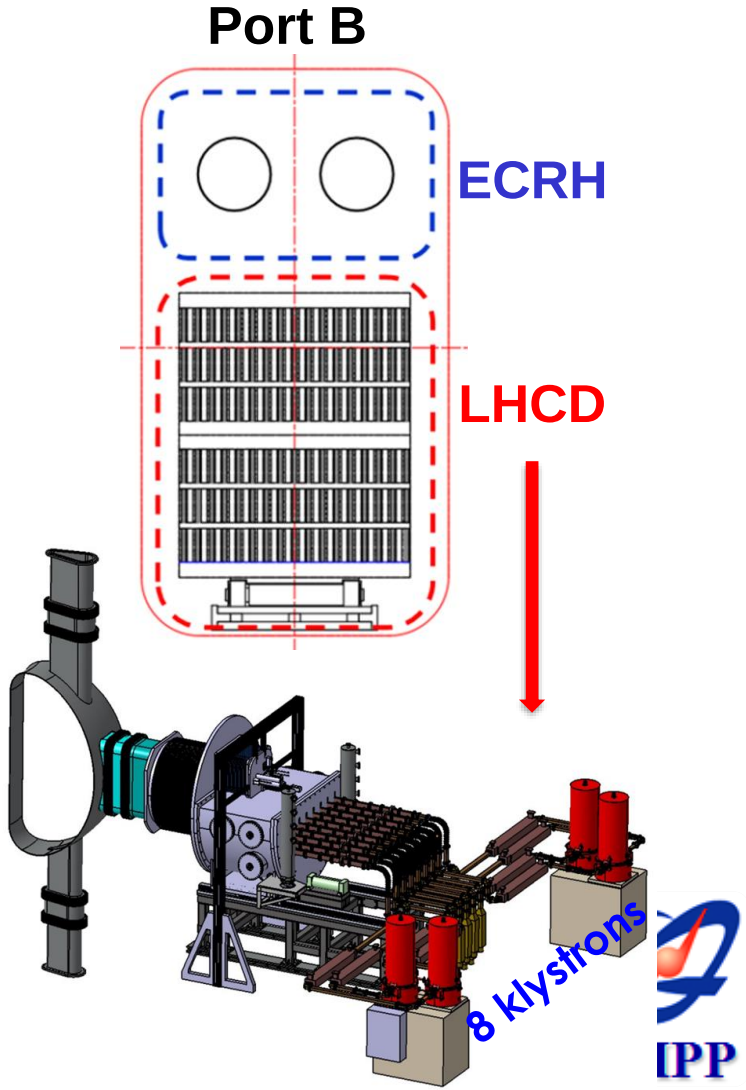
Summary and Prospects

- In order to mitigate the interactions of edge plasmas with LH/IC antennas, increase the plasma heating effect and CD efficiency, efforts have been made:
  - Optimizing the LH antenna shape, upgrading the guard limiters, upgrading the LH antenna with PAM, upgrading the IC antenna with smaller wavenumber, using lithiation coating and favorable Bt to optimizing the edge plasmas.
- Significant advance has been achieved in long-pulse operation by RF waves:
  - 1056 s I-mode plasma, 310 s H-mode plasma and 100 s pulse length with T_{e0} > 10 keV.
- Two-gyrotron EC system and a new LH system with PAM launcher are under development, which are expected to extend the long-pulse operation to higher plasma parameters on EAST in future.

New EC and LH systems use the same port B



Thank You

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