Exploration in LH coupling and current drive towards long-pulse operation on EAST

by

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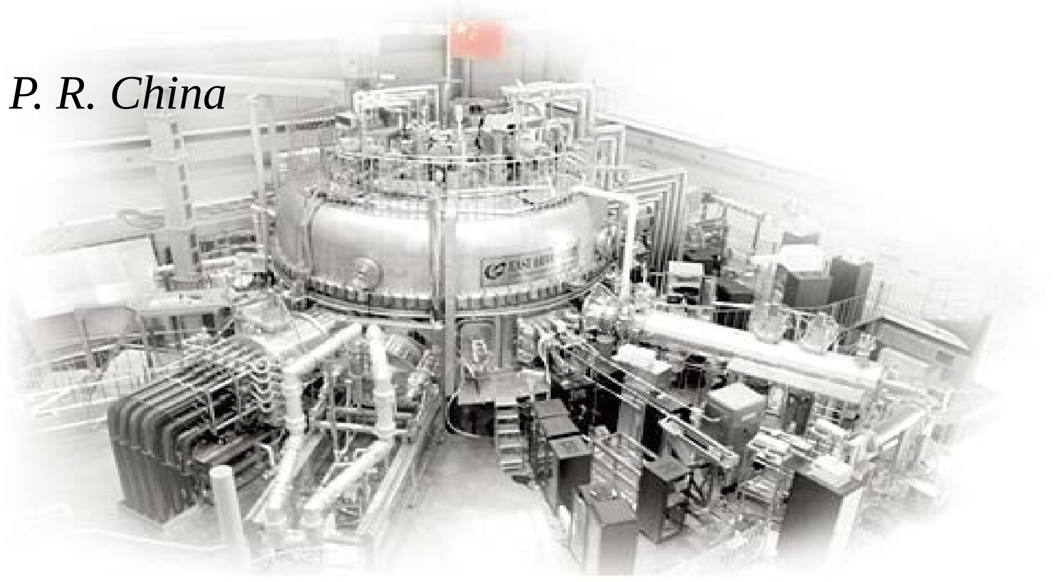

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Outline

- EAST Tokamak and LHCD systems
- Challenge in LH coupling and current drive
- Exploration and achievement in LH coupling
  (Feedback control, PAM antenna, and hot spot)
- Recent progress in improving LHCD capability
  (PDI bifurcation, methods in improving CD efficiency)
- Significant advance in long pulse plasma with LH wave
- Summary and next plan

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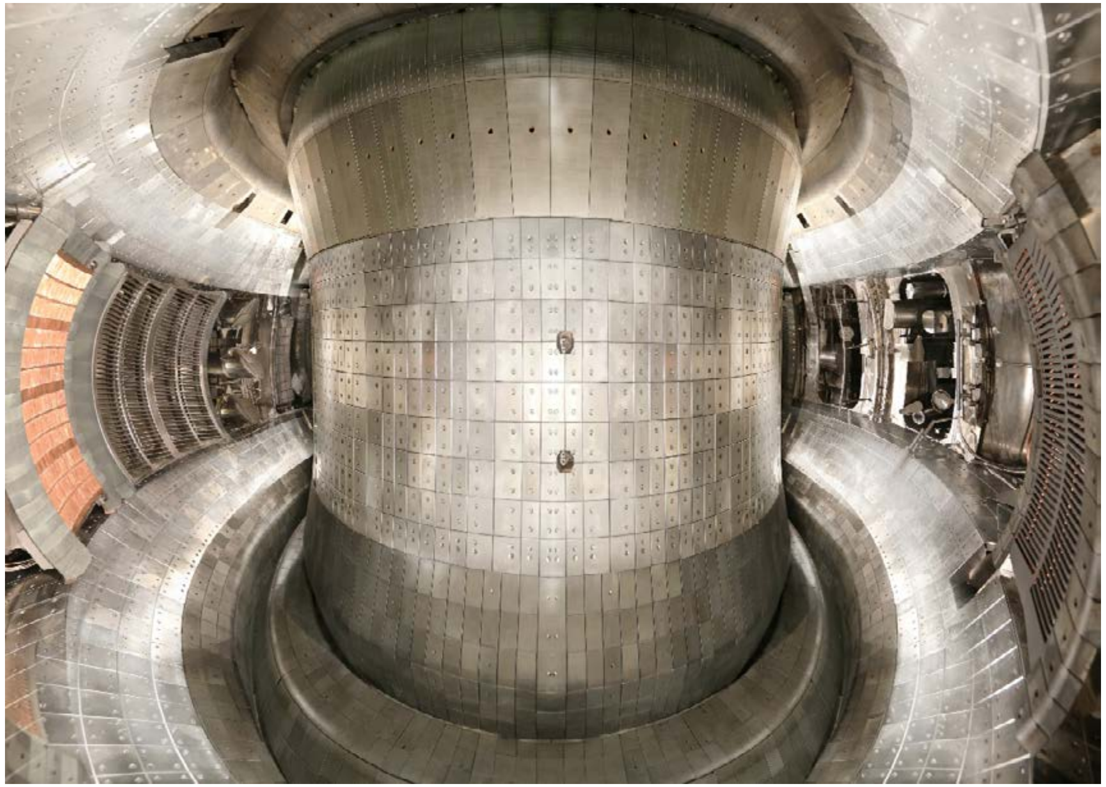
EAST Overview

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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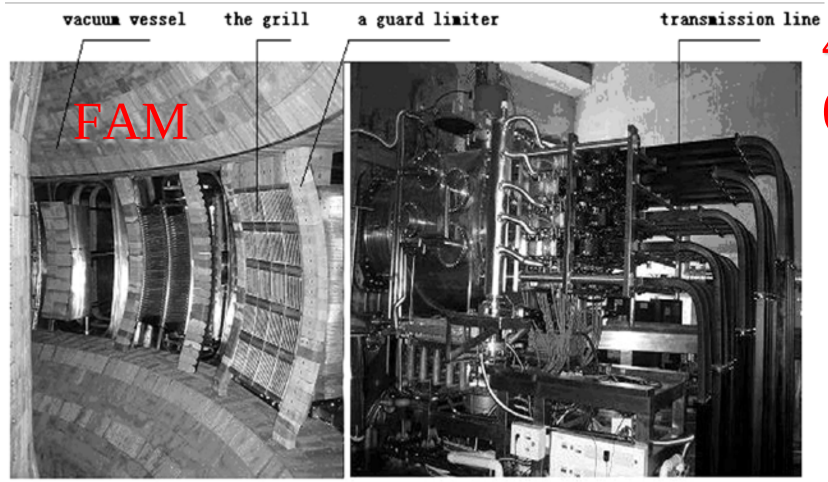
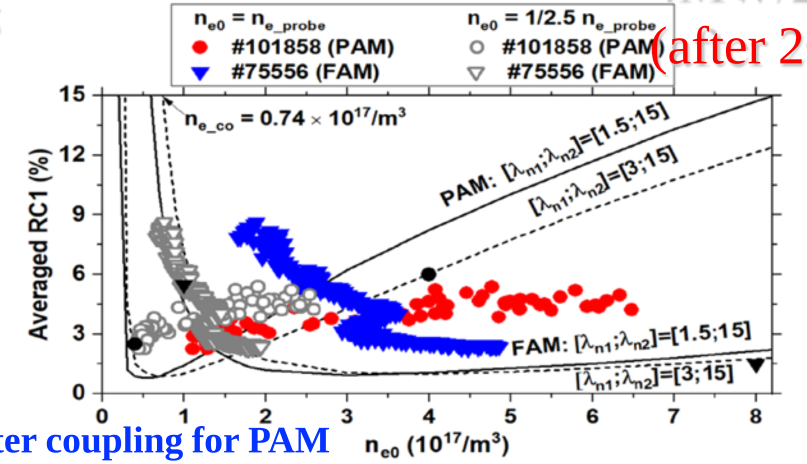
LHCD system in EAST

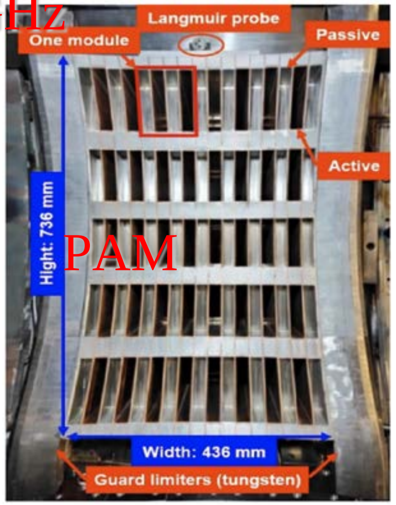


4MW/2.45GHz
(before 2021)



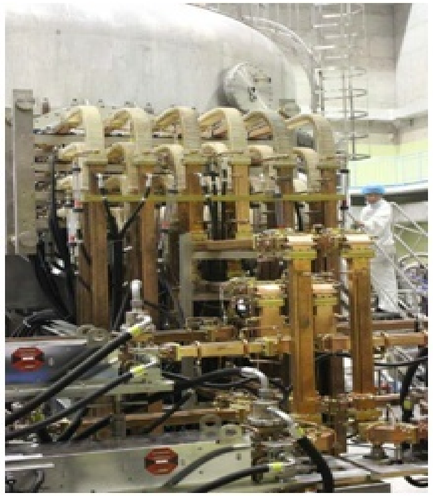
Better coupling for PAM

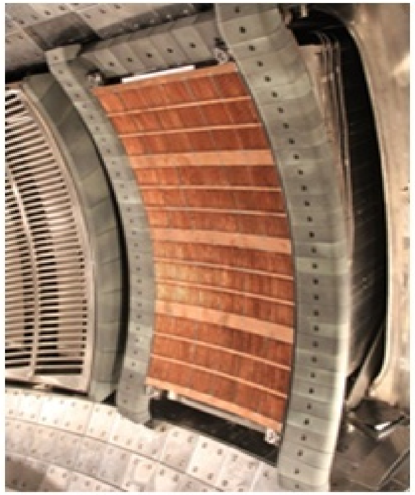
4MW/2.45GHz
(after 2021)



20 main waveguides arranged in an array of 5 rows and 4 columns. (20 klystrons)

Fusion Eng. Des. 147 (2019) 111250





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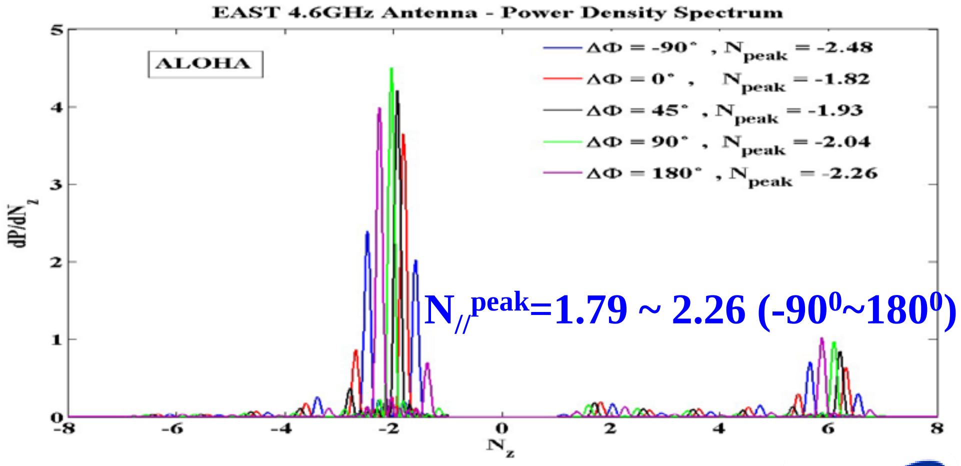
6MW/4.6GHz (FAM)
(developed in 2014)

Max. power injected: ~ 3.5MW



$N_{//}^{peak}$=1.79 ~ 2.26 (-90^0~180^0)

24 main waveguides arranged in an array of 4 rows and 6 columns. (24 klystrons)

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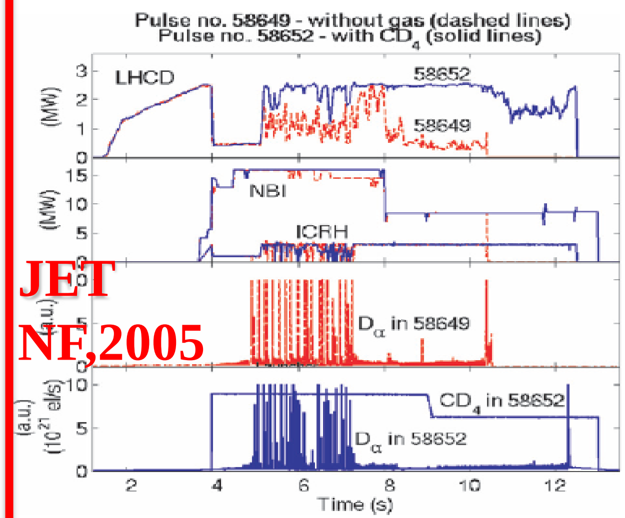
Challenge in LH coupling and possible Strategy

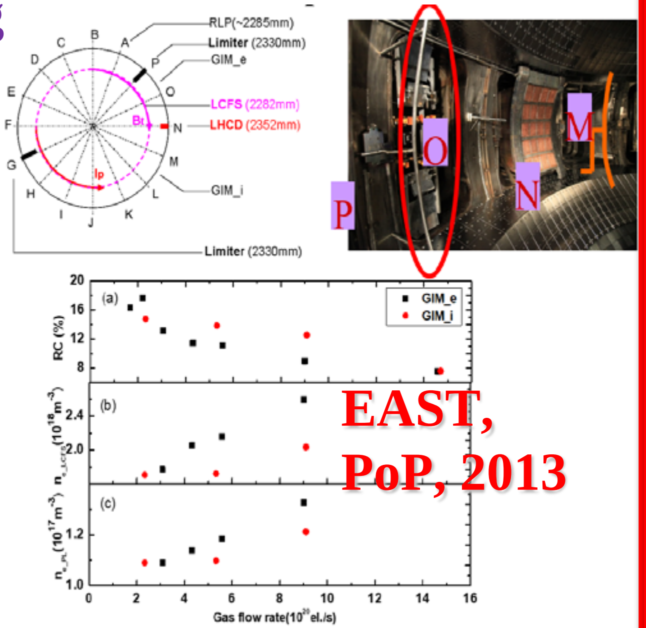
1. Good coupling for steady state operation

Strategy 1: Local gas puffing



JET NF,2005

LGP in ele-side is better than that in ion-side



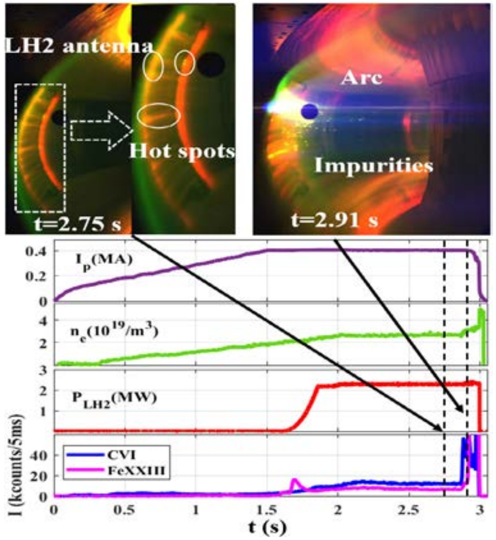
EAST, PoP, 2013

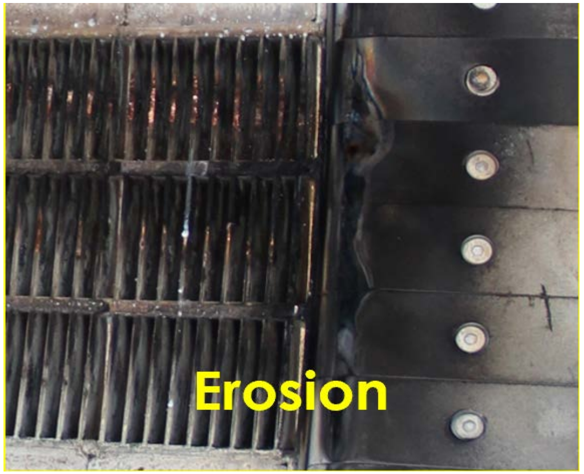
However, the density at the grill is constantly changing during the discharge, and pre-setting gas programs can fail to improve LHW coupling, or even extinguish the plasma.

Therefore, a feedback control via gas fueling is necessary

Strategy 2: PAM antenna is a possible candidate for good long distance coupling.

2. 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 could be generated, leading to plasma disruption, damage on the antenna and the guard limiters.

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Strategy: 1. Reduce high $N_{\|}$ spectrum components (PDI)
2. Upgrade LH Antenna Guarder Limiters

Motivation: To sustain good LHW-plasma coupling in long pulse plasma.

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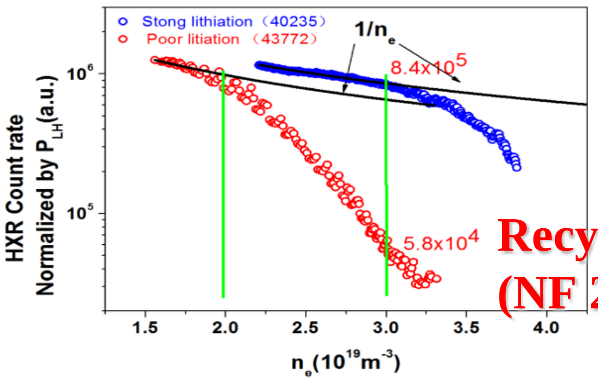
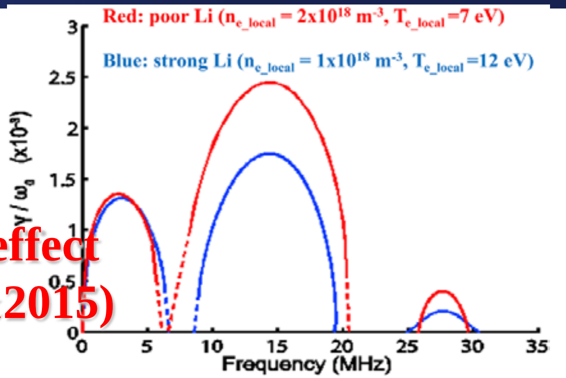
Challenge in LHCD

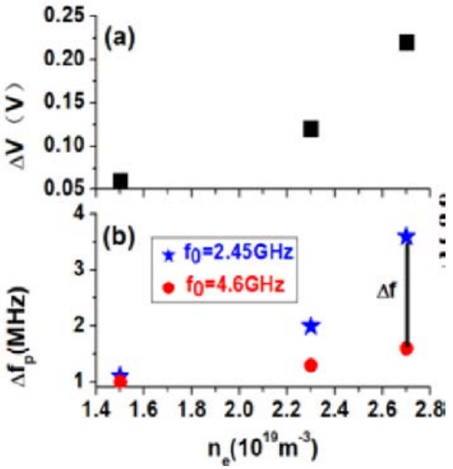
Challenge: Current drive capability decreases rapidly, particularly at high density.





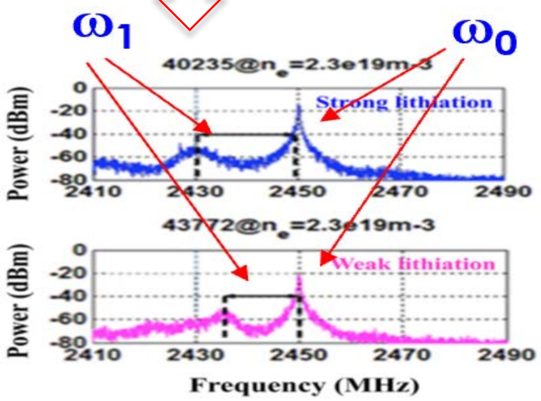
Recycling effect (NF 2013&2015)

PDI（Parametric Decay Instability）is one of important candidates for the Decrease of LHCD efficiency at high density. Improving CD capability by reducing recycling or improving LH source frequency is documented in EAST.



- **Typical Features of PDI:** Peaks at ω_1 (ion cyclotron quasi-mode (**ICQM**) driven) and Spectrum broadening around ω_0 (ion-sound quasi-mode (**ISQM**) driven)
- **Two main channels: ISQM** mainly observed at low plasma density and **ICQM** usually appeared at relatively high density.

Which one is dominant with the density variation? (not clear yet)



Freq. effect (NF,2018)

Motivation: **To enhance LHCD capability at high density,**

- **Study the transition of PDI channels with varying plasma density**
- **Reduce PDI and improve CD capability** effectively

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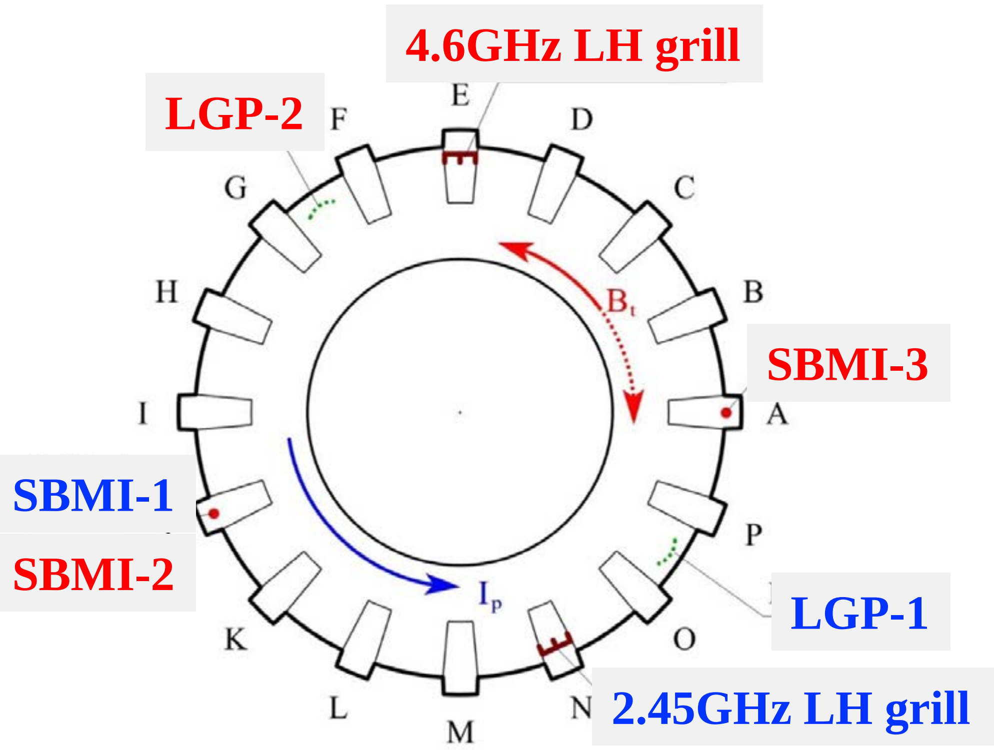
Experimental setup arrangement of the gas fueling system in EAST



☻ 5 fueling systems, which could be used to enhance the electron density in front of the LH antenna, including

--2 LGP systems fed by a piezoelectric valve (LGP-1 and LGP-2)

--3 SMBI systems (SMBI-1, SMBI-2, and SMBI-3)

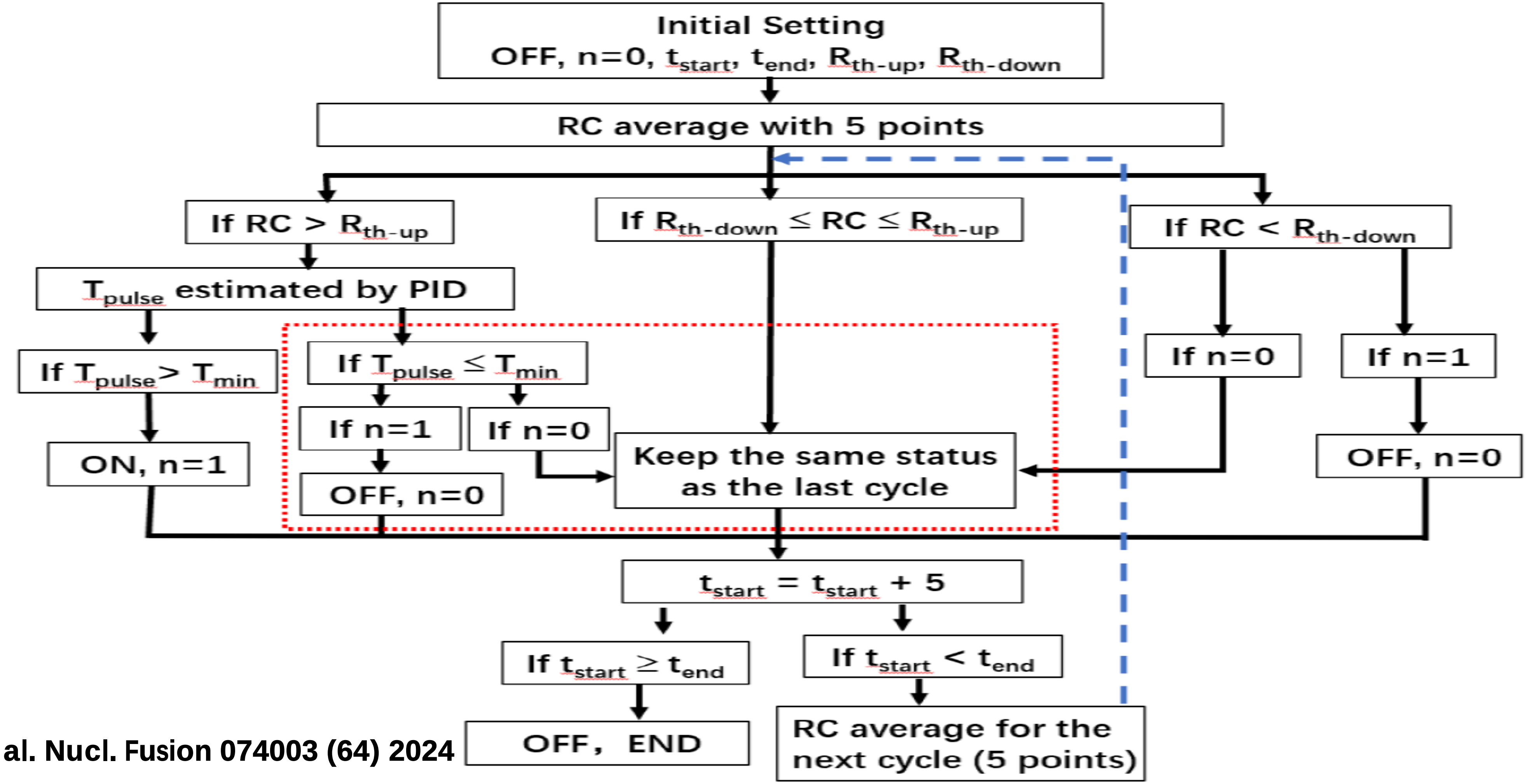
☻ Taking 4.6 GHz LH antenna as the reference, LGP-2, SMBI-1, and SMBI-2 locate at the electron-drift side, whereas LGP-1 and SMBI-3 locate at the ion-drift side.

☻ LGP-2， SMBI-2, SMBI-3 and 4.6GHz LHCD are chosen for the study.

Design of wave–plasma coupling feedback control

□ Using a proportion integration differentiation (PID) method

□ Taking RC of LH power as the reference, due to the uncertainty of edge density measurement.



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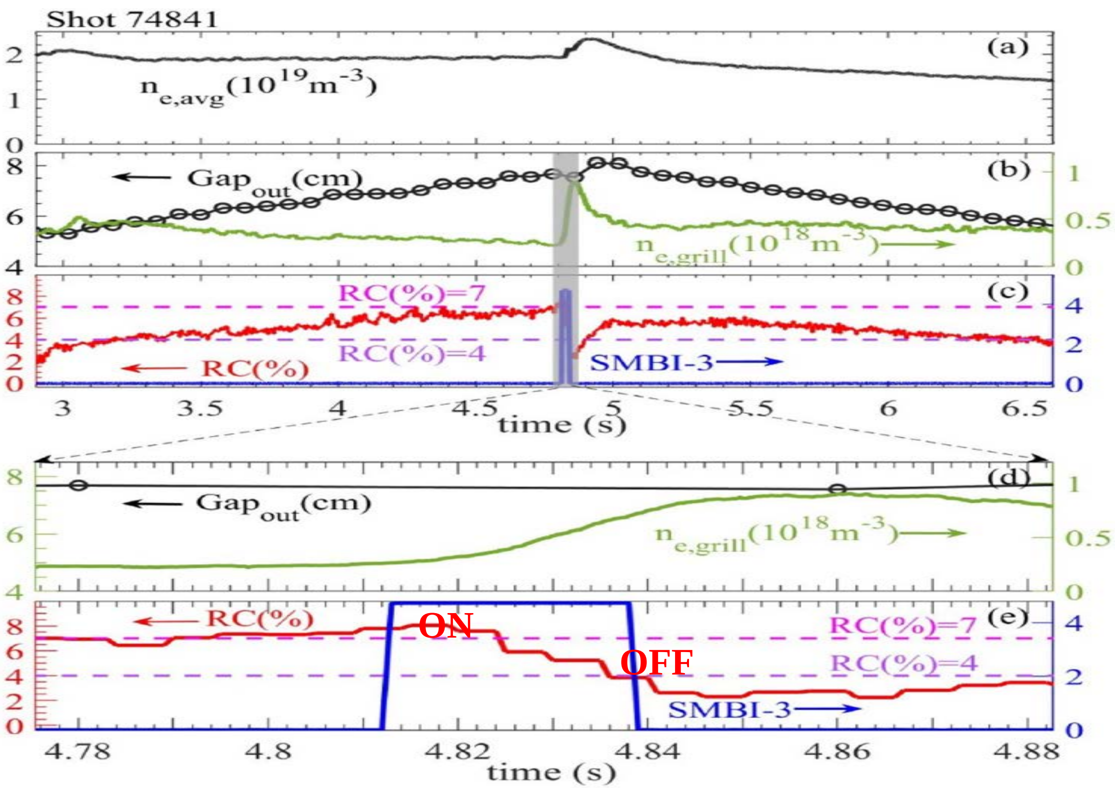
Test of single SMBI pulse indicates that the feedback control progress works correctly and is valid for LHW–plasma coupling improvement.



□ $R_{th\text{-}up}$ and $R_{th\text{-}down}$ are set as 7% and 4%

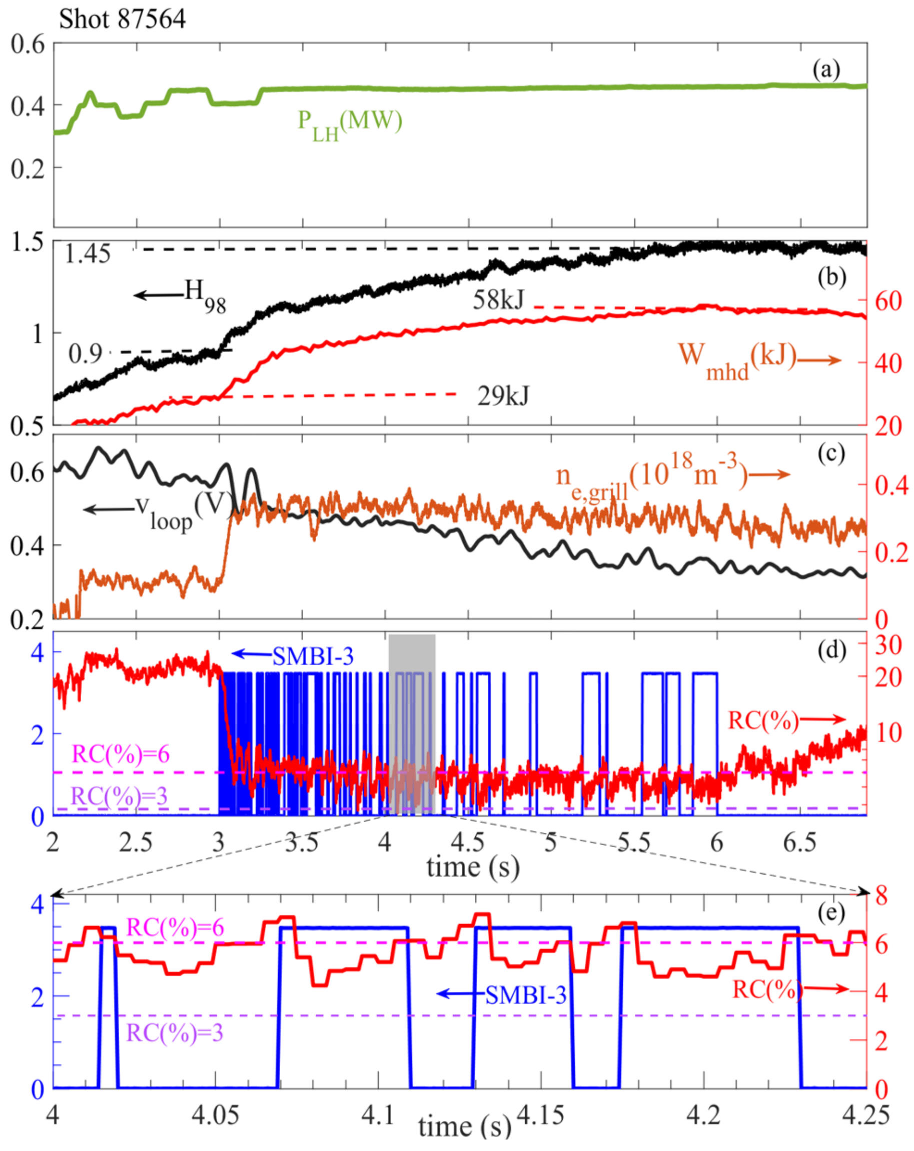
□ Gap_{out} was scanned from a small value (~1.8 cm) to a larger value (~4.0 cm), and then back to a ~1.8 cm, to change the LHW–plasma coupling actively

□ With the increase in Gap_{out}, the density at the grill decreases gradually to 2.5 × 10^{17} m^{-3}, accompanying the increase in the RC.

□ When RC reaches ~7%, SMBI is switched on, leading to the density at the grill increasing and the RC decreasing quickly.

□ When RC decreases to 4%, SMBI is switched off, being consistent with the increased edge density of 7.5 × 10^{17} m^{-3}, which satisfies wave–plasma coupling conditions.

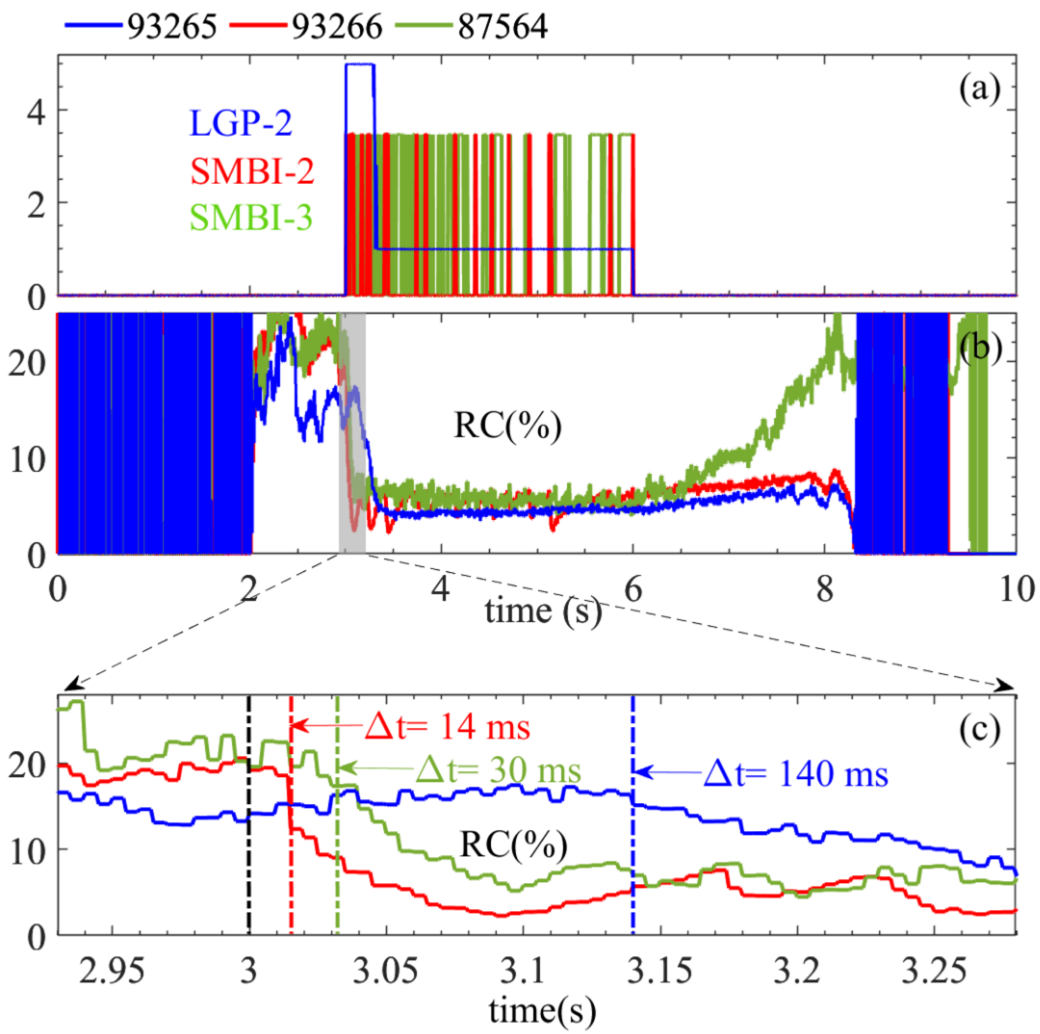
Experiments with multi-pulse SMBI indicate LHW coupling power is improved by the feedback, being helpful for CD capability, stored energy, and plasma performance



- □ $R_{th\text{-}up}$ **and** $R_{th\text{-}down}$ **are set as 6% and 4%,respectively.**
- □ **The feedback control is applied from 3 s to 6 s.**

- □ **After the feedback application,** $n_{e,grill}$ **increases quickly to 3.0 ×10**^{17} **m**$^{-3}$ **from 1.1 × 10**^{17}**, and the RC decreases sharply to a value around 6% from 20% .**
- □ **During the process of multi-pulse SMBI,** $n_{e,grill}$ **remains at about 3.0×10**^{17} **m**$^{-3}$ **and the RC between 3% and 6% is almost maintained.**
- □ V_{loop} **decreases from ~0.6 V to ~0.4 V,** W_{mhd} **increases from 29 kJ to 50 kJ,** H_{89} **(**$=\tau_E/\tau_{EITER89\text{-}P}$**) increases from 0.9 to 1.5,implying a certain improvement in the plasma performance.**

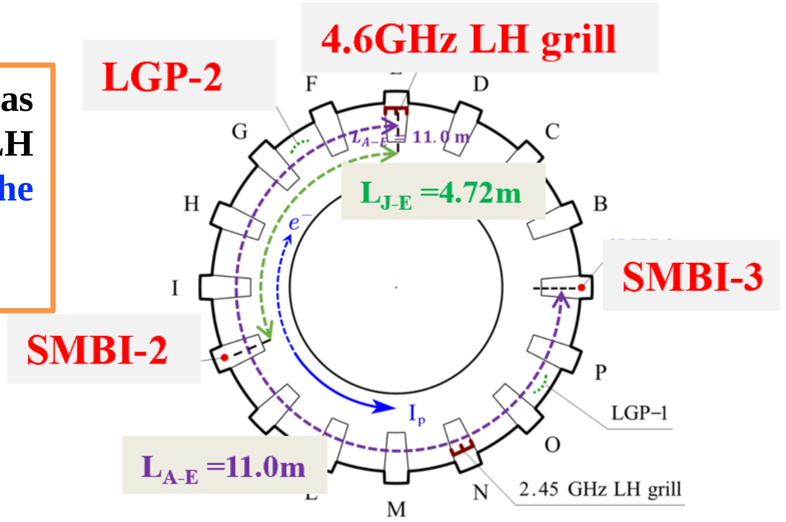
Comparison of response between LGP and SMBI



1. LGP-2 *vs* SMBI-2, located in the electron-drift side of the LH antenna
⇒SMBI-2 is better than LGP-2, mainly due to different response time of fueling system.

2. SMBI-2 *vs* SMBI-3, located at the electron-drift side and the ion-drift side
⇒ **SMBI-2 is a little better than SMBI-3, being consistent with the discrepancy in the magnetic connection length.**
$(\Delta t_{SMBI-3} / \Delta t_{SMBI-2} \sim L_{J-E}/L_{A-E})$

After the gas is ionized near the gas injection, the movement of electron to LH grill **from electron-drift side along the magnetic field line is considered**.
(Clock-wise direction)



The fastest feedback response time is SMBI fed on the electron-drift side and the slowest response is LGP, between which is SMBI fed on the ion-drift side.

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Summary in LHW–plasma coupling feedback control

□ It is the first time that LHW–plasma coupling feedback control has been designed and realized in EAST via the PID method by choosing the RC LHW power as the reference for gas puffing feedback.

□ The feedback control can work correctly and maintains good LHW–plasma coupling effectively for a long time.

□ The improvement in LHW power due to coupling feedback is helpful for current drive capability, stored energy, and plasma performance.

□ The response time of the RC with SMBI is faster than that by the piezoelectric valve, and SMBI puffing on the electron-drift side of the LH antenna is preferred for the control.

Studies offer an effective way to sustain good LHW coupling in steady-state operation in the future.

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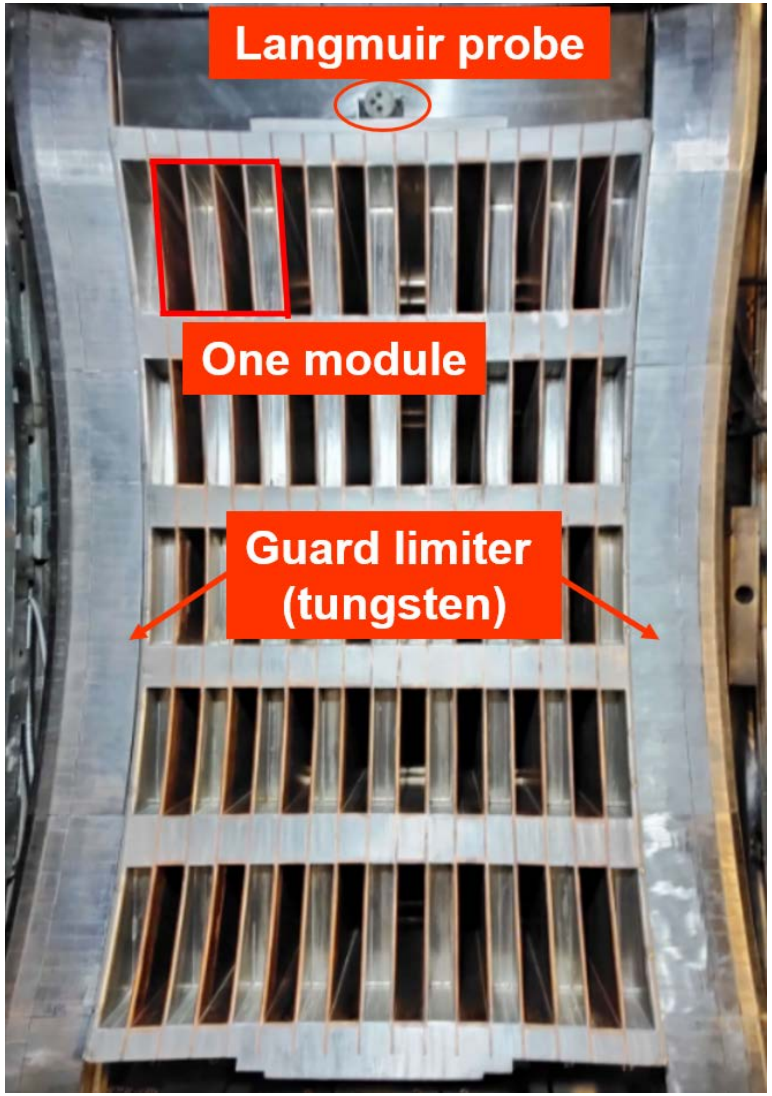
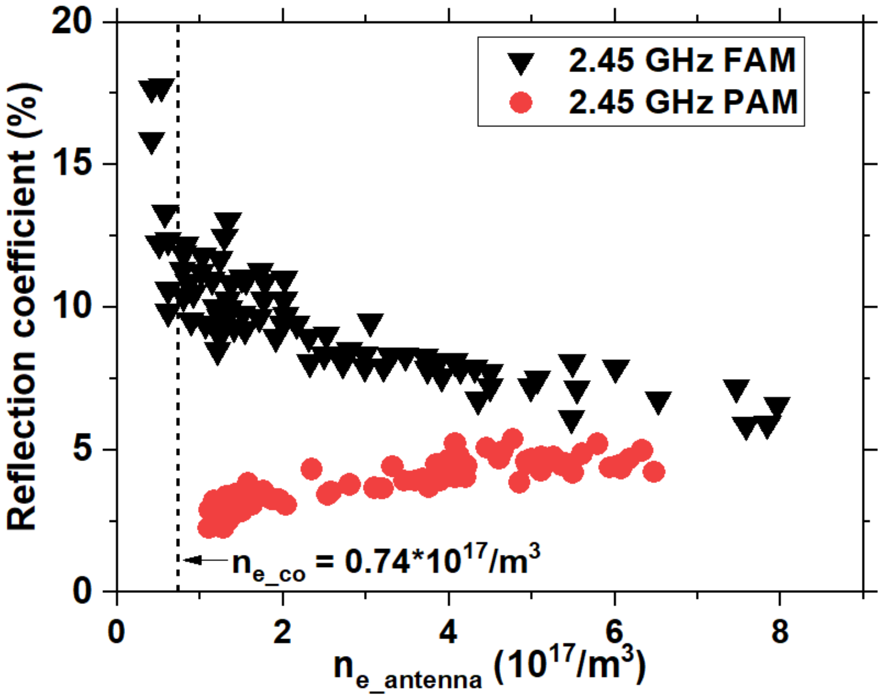
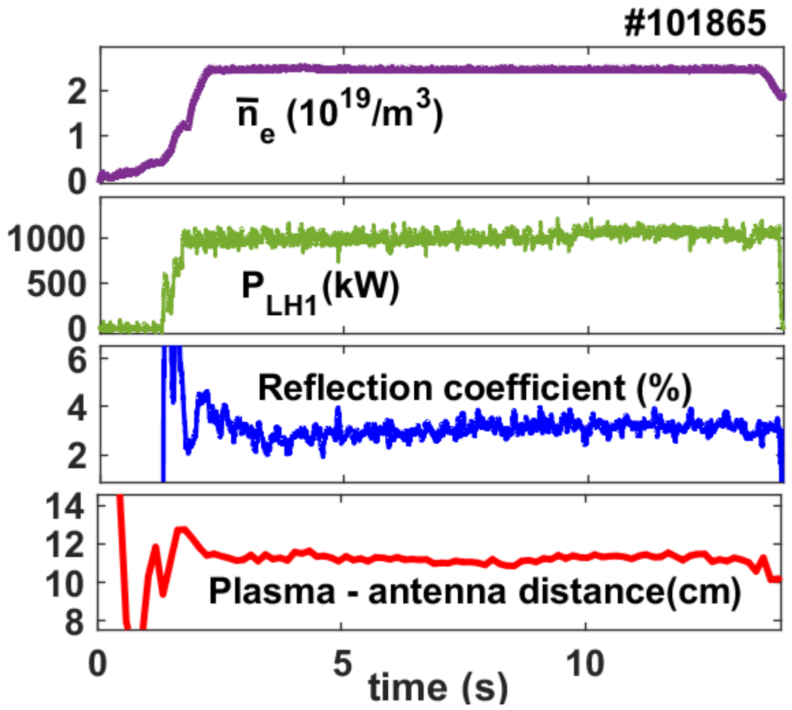
Long-Distance Coupling of LH Power with A New PAM Launcher at 2.45 GHz







- 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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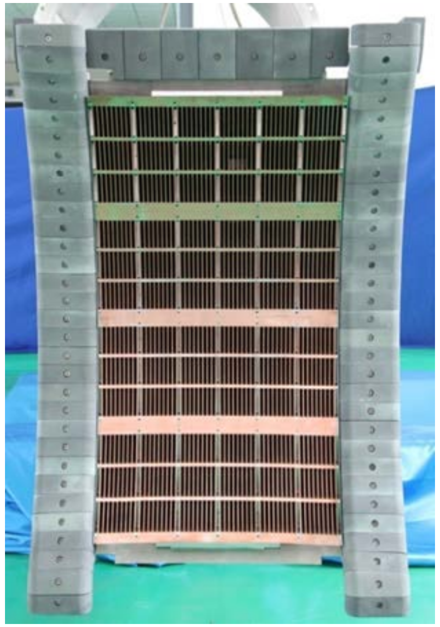
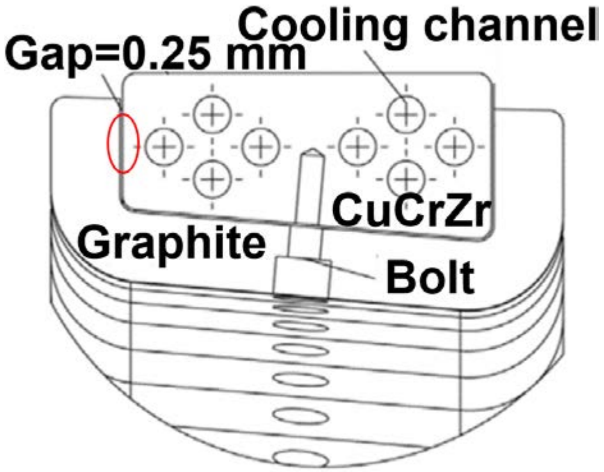
Upgrade of LH Antenna Guarder Limiters

Graphite tiles before 2017

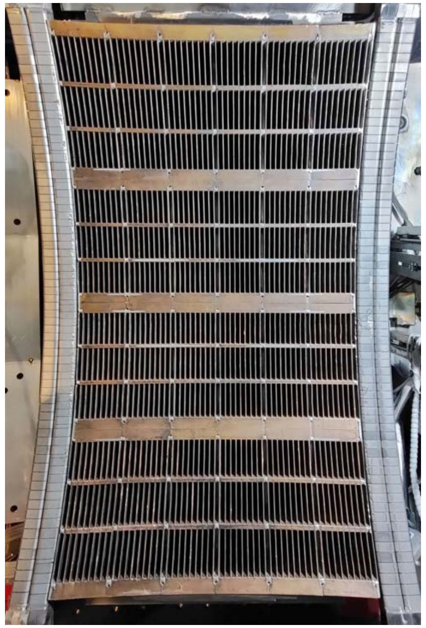


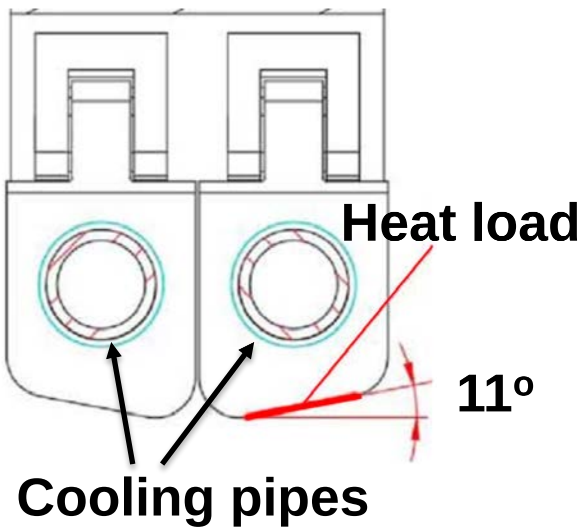


- Graphite tiles plated with SiC, CuCrZr heat sink with stainless support frame.
- low thermal conduction due to poor contact
- Design target ~ 2.0 MW/m^2.

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

Tungsten limiters after 2017





- 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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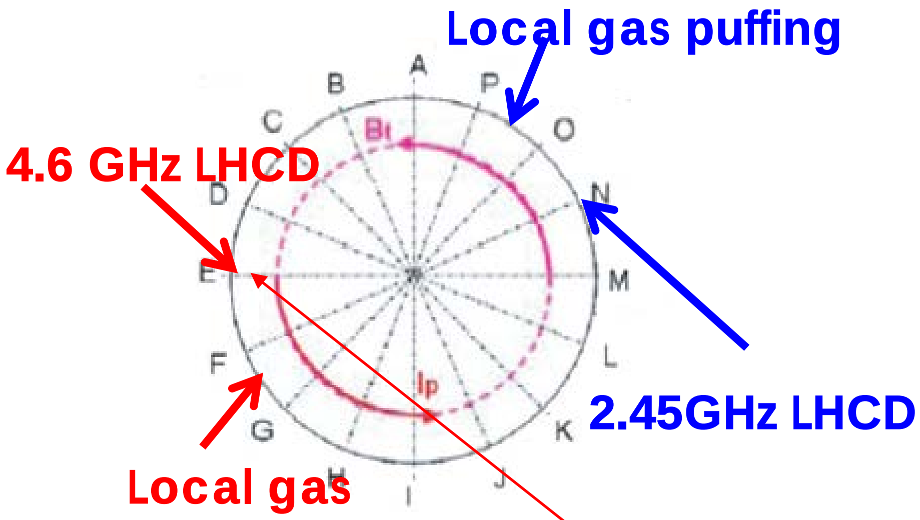
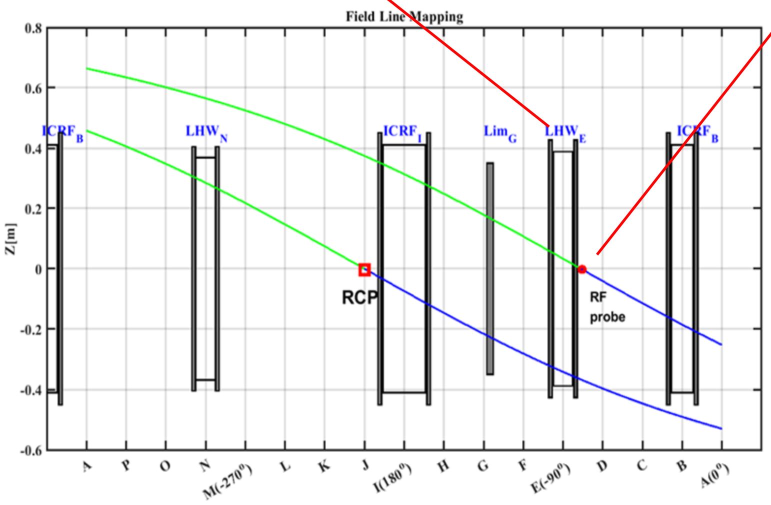
Diagnostic for PDI measurement



Top view



Topology in toroidal and poloidal direction

Probe array **installed near LH antenna**

$$k_{\parallel} = \Delta\varphi / \Delta x$$

Loop **antenna for frequency spectrum**

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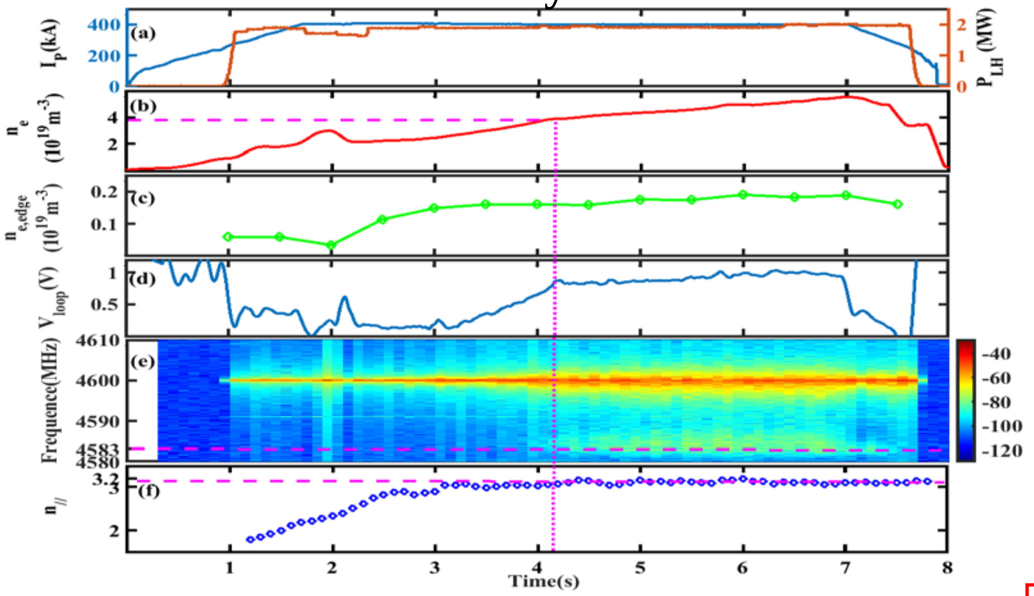
Typical waveforms of PDI transition experiments

Plasma density ramp-up was applied for the study



Before t=4.2s

With density increase, the loop voltage increases, implying the decrease of current drive capability.

The LH frequency spectrum becomes wider and the measured $n_{\|}$ increases with density, implying the enhancement of PDI

After t=4.2s

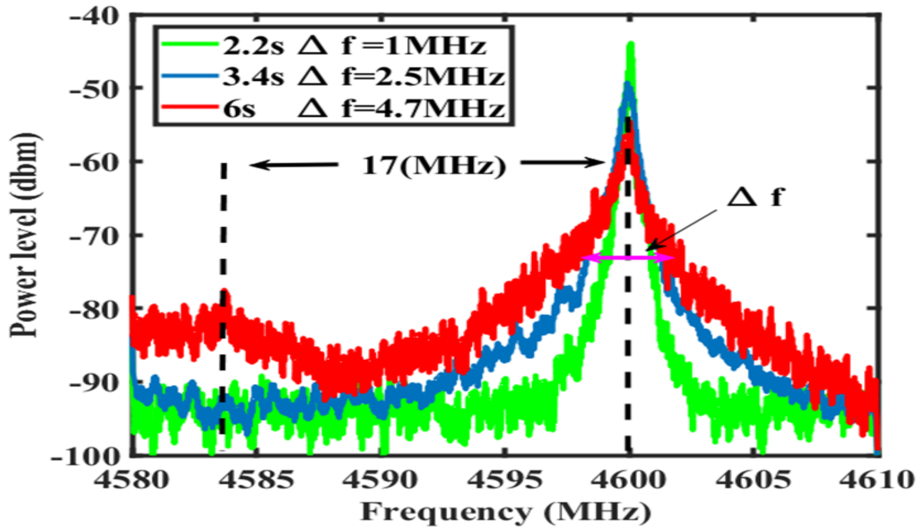
Vp and $n_{\|}$ doesn't increase further,

The width of the frequency spectrum doesn't increase further, whereas accompanying a sideband at f=4580

It is speculated the decrease of CD is mainly ascribed to PDI.

The change of frequency spectrum suggests the transition of PDI channel from ISQM to ICQM.

Frequency spectrum measured by RF loop antenna

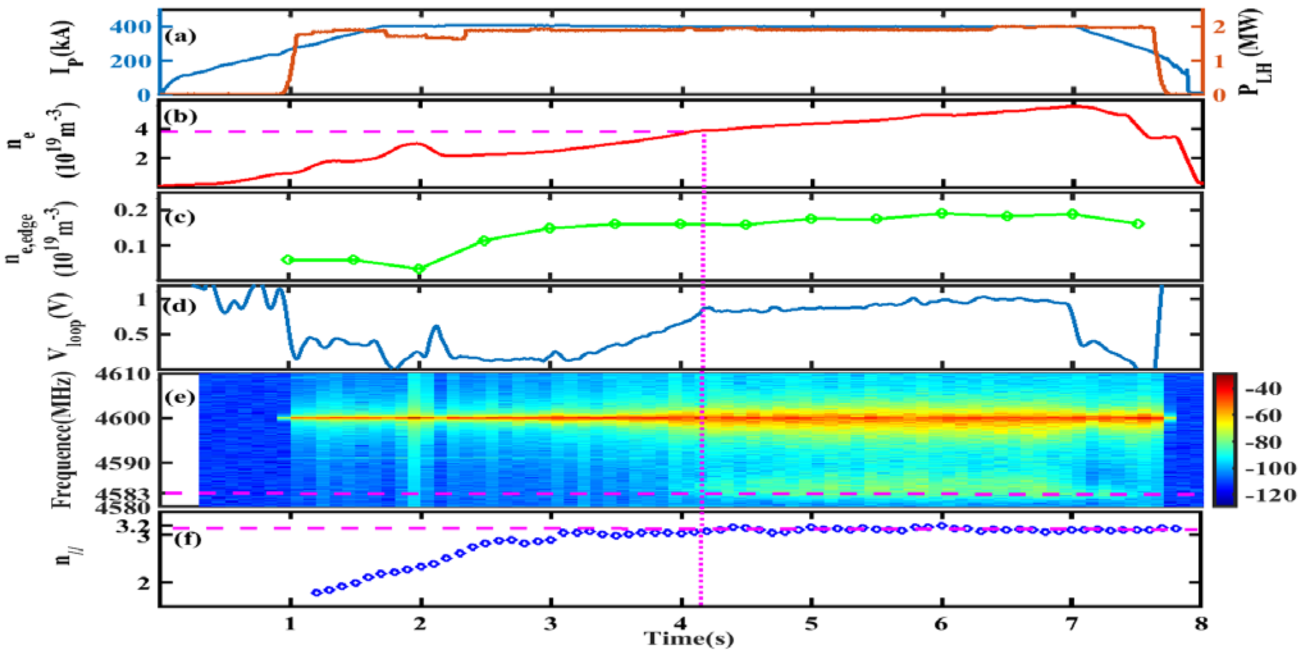


•The frequency spectrum broadenings (Δf) increases with density, accompanying the amplitude decrease of pump wave in the central frequency.

• Especially, the appearance of a 17MHz sideband down-shifted from the pump wave at t=6.0s.

The PDI process is also documented by another frequency spectrum measurement with an RF loop antenna

Linkage of PDI and edge density



•The electron density in edge region ($n_{e,edge}$) firstly increases to a certain value and then almost doesn't increase further at t=4.2s, nearly consistent with the evolution of *n*// and frequency spectrum.

• It is speculated that The change of *n*// and frequency spectrum are mainly ascribed to the change of electron density in the edge region, further PDI calculation **(mode growth rate and n//)** is necessary as follows.

Change of PDI channel

Calculation of the growth rate of the PDI-driven mode

$$\gamma_{ISQM} = \omega_r \left\{ \left[4 + \frac{u^2}{4c_s} \frac{\omega_{pi}^2}{\omega_0 \omega_r} \sin^2 \delta_1 (1 + \eta_1^2) \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \right) \right]^{\frac{1}{2}} - 2 \right\}^{\frac{1}{2}}$$

$$\gamma_{ICQM} = \frac{u^2}{c_s^2} \frac{\omega_{pi}^2}{8\omega_0} \left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2} \sin^2 \delta_1 (1 + \eta_1^2) F(\xi_1, bi)\right)$$

Inputs for the PDI simulation :

1) reflective index of the pump wave ($n_{\parallel 0}$) and sidebands ($n_{\parallel 1}$)

2) frequency of ISQM and ICQM (f_{ISQM}, f_{ICQM})

3) electron temperature and electron density.

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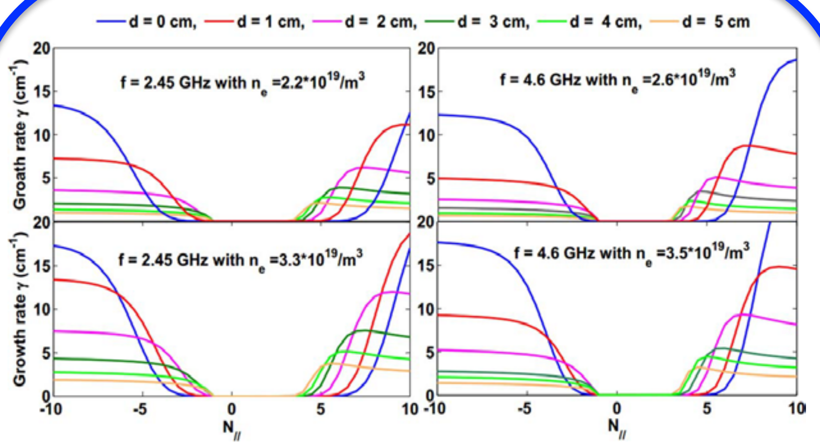
Inputs for the PDI simulation of mode growth rate



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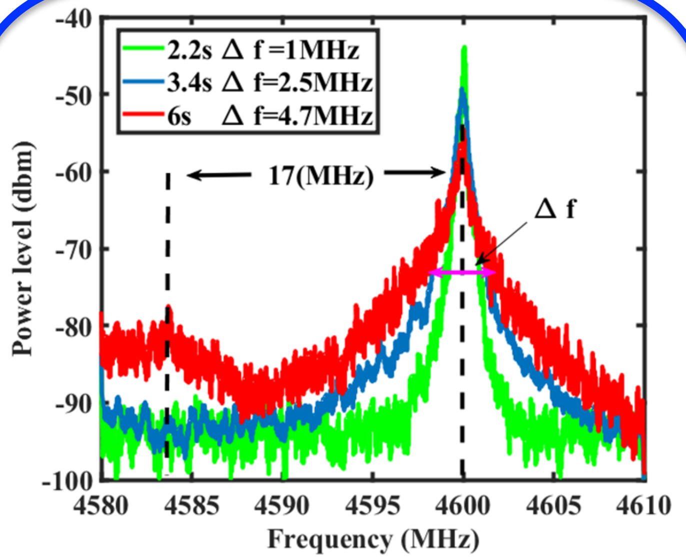
$n_{\parallel 0}$ =2.1 (the initial peak value of wave launched by LH antenna)

$n_{\parallel 1}=6$

1)$n_{\parallel 1}$ is larger than $n_{\parallel 0}$.

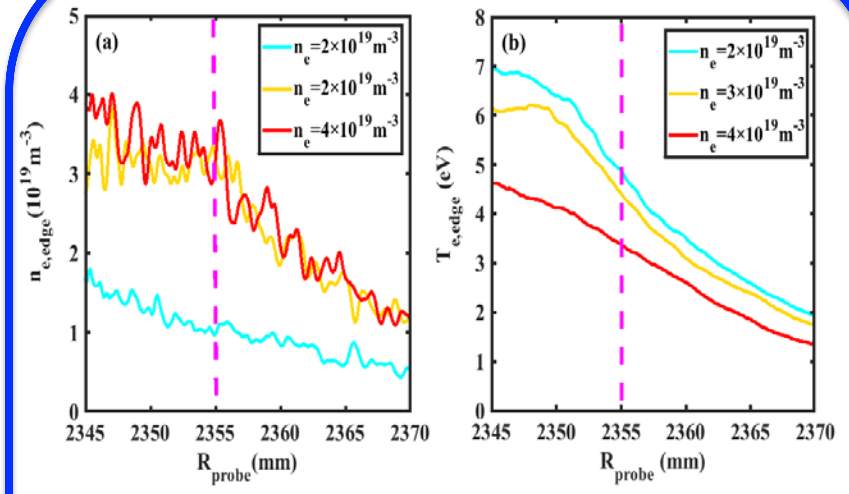
2) the PDI-driven mode growth rate is very small at low $n_{\parallel}$, and the mode with high $n_{\parallel}$ cannot propagate effectively.



f_{ISQM}=2.5MHz, f_{ICQM} =17MHz

The measured broadening is about 1MHz, 2.5MHz, and 4.7MHz at the three densities. (ISQM)

The appearance of a 17MHz sideband down-shifted from the pump wave at t=6.0s. (ICQM)



Electron density: density scanning

Electron temperature: Te= 5eV

with the density increase, there is no much change in the electron temperature close to LH antenna (R=2360mm).

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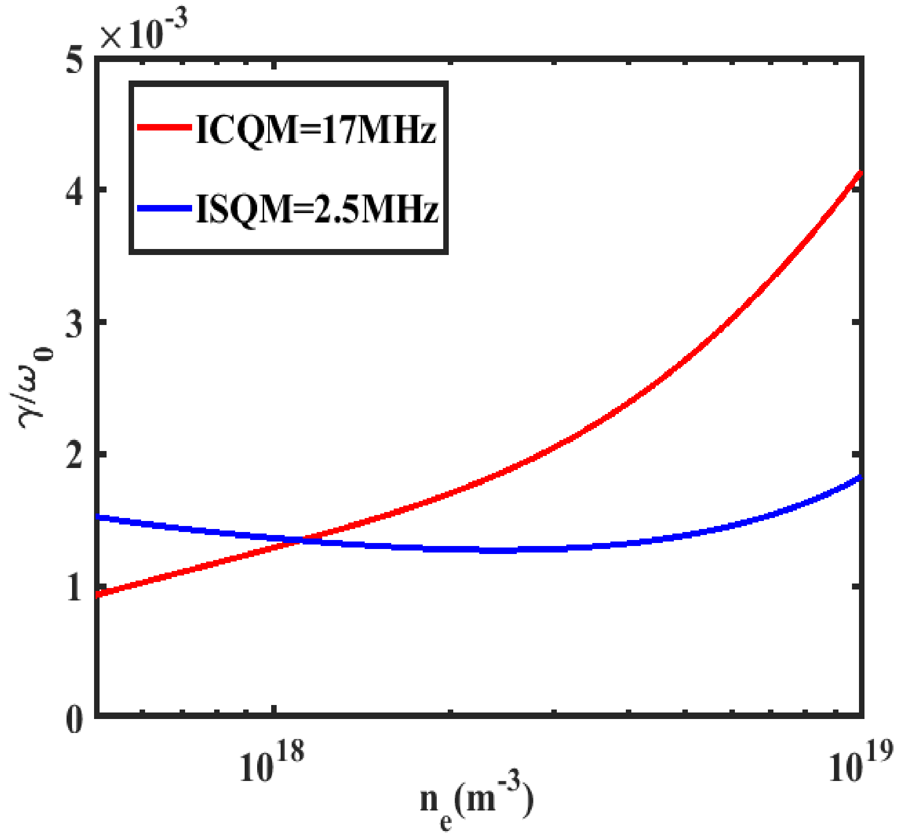
Calculation results of γ_{ISQM} and γ_{ICQM}



ISQM

γ_{ISQM} first decreases and then increases with the density increase.

Though γ_{ISQM} does not vary very much, **the ISQM decay does occur during the whole density range.**

ICQM

γ_{ICQM} increases from a value less than 1×10^{-3} to 4×10^{-3} rapidly, implying that **ICQM decay becomes stronger with increasing density.**

At density of about $1.1 \times 10^{18} m^{-3}$, it exceeds the value of ISQM.

Simulation results nearly agree with the measured frequency spectrum and explain that **with edge density increase, PDI partly transits from ISQM to ICQM channel.**

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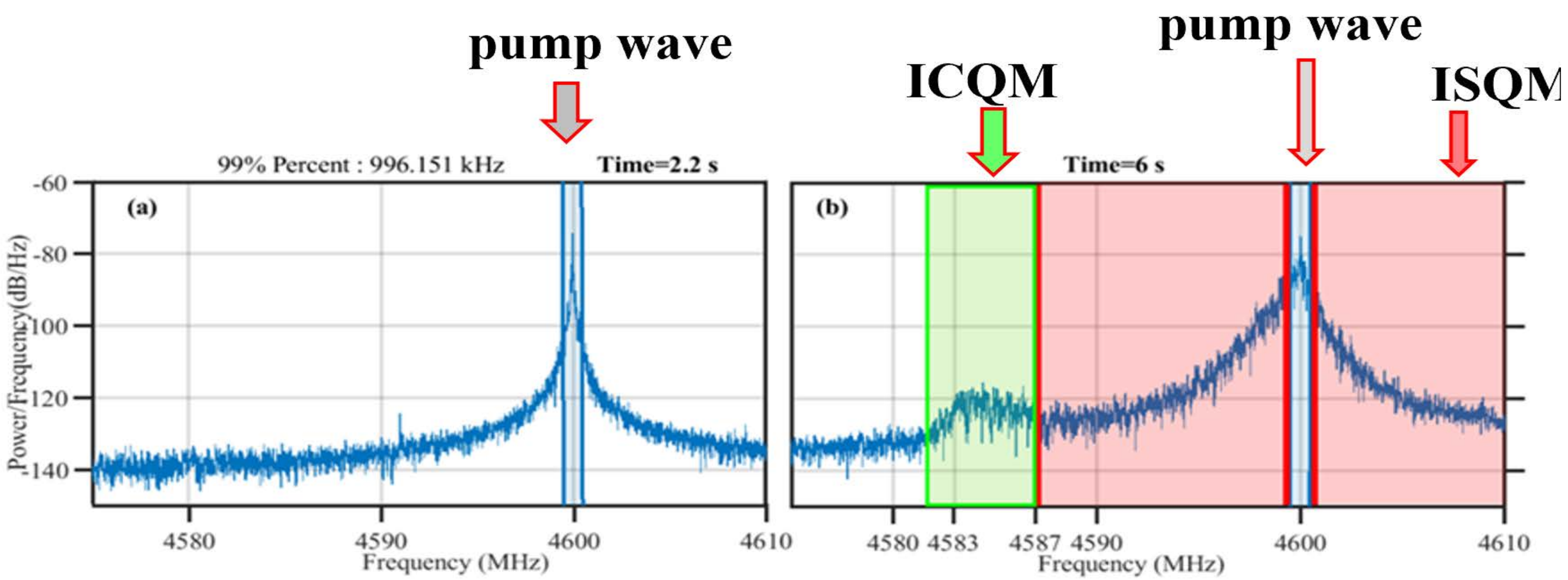
Spectrum division for the power fraction calculation

In order to calculate the evolution of $n_{\parallel}$, it is necessary to estimate the **LH power fraction, including pump wave, ISQM, and ICQM**.



(a) without PDI

(b) with PDI

Pump wave marked with the blue region (center:4600MHz)

three parts for pump wave marked, ISQM marked with the red region and ICQM marked with the green region (center:4583 MHz)

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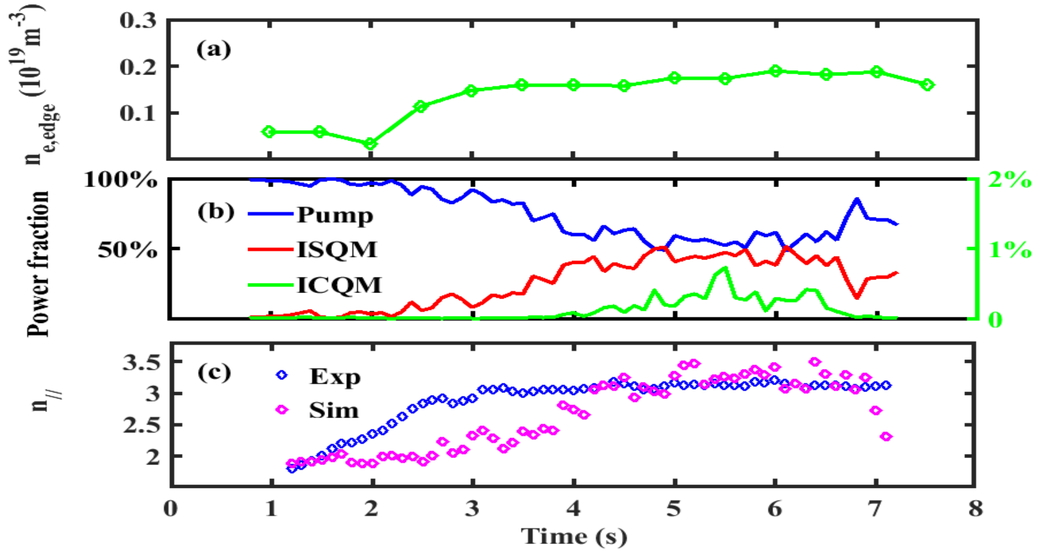
Calculation results of power fraction and $n_{//}$



•With edge density increase, the fraction of pump wave decreases; meanwhile, ISQM decay channel gradually increase. Furthermore, at *ne,edge≈2.0×10*^{18}*m-3*, the fraction of ICQM begins to increase, implying that the occurrence of ICQM.

• Compared to ICQM, ISQM is a dominant decay during the whole process.

$n_\parallel$ is further calculated by taking $n_{\parallel 0}$ =2.1 and $n_{\parallel 1}$ =6

• $n_\parallel$ increases with edge density and it almost keeps constant when the density doesn't increase further, indicating the influence of edge density on PDI.

• Calculation is nearly in agreement with the experimental measurements, demonstrating the effect of PDI on $n_\parallel$ and suggesting that the increase in experimental $n_\parallel$ is mainly caused by the increasing power fraction of PDI-driven mode and the high $n_\parallel$ components driven by PDI.

●Analysis suggests that the bifurcation of the PDI channel is mainly ascribed to the change of electron density in the edge region, leading to the change of $n_\parallel$ and frequency spectrum.

● Results demonstrate the dominant role of edge parameters in determining PDI behavior and affecting current drive efficiency.

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Summary in PDI bifurcation

Experimental PDI bifurcation of the lower hybrid wave with 4.6GHz in EAST were studied for the first time, indicating the effect of PDI on current drive efficiency.

•Results show that the ISQM exists during the whole density ramp-up process, and part of ISQM is transited to the ICQM at higher density, suggesting the change of the PDI channel.

• Calculation of the mode growth rate driven by PDI shows that above a certain edge electron density, the rate of ICQM will exceed that of ISQM, quantitively explaining that with density increase, PDI partly transits from ISQM to ICQM channel.

• Further calculation of $n_{\parallel}$ evolution with the electron in the edge region are nearly in agreement with the experimental measurements, indicating the effect of PDI on $n_{\parallel}$ and demonstrating the reasonability of the measurement of $n_{\parallel}$.

Studies demonstrate the dominant role of edge parameters in determining PDI behavior and affecting current drive efficiency.

G H Yan et al. Nucl. Fusion 086018 (64) 2024

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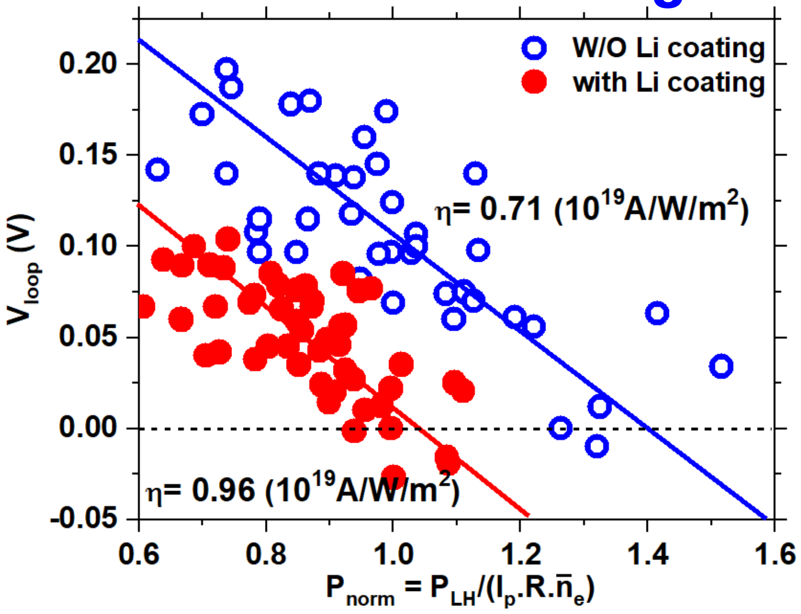
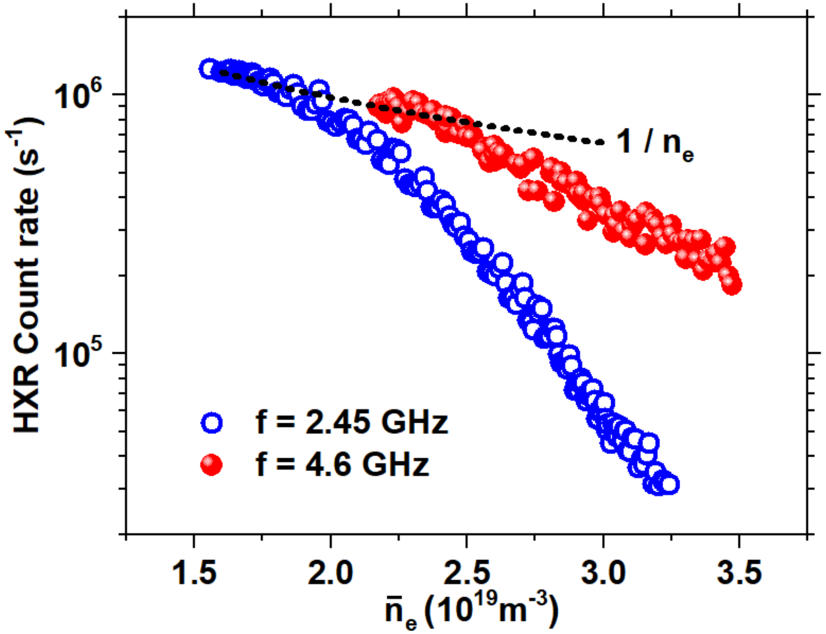
Methods to Improve CD Efficiency at High Density

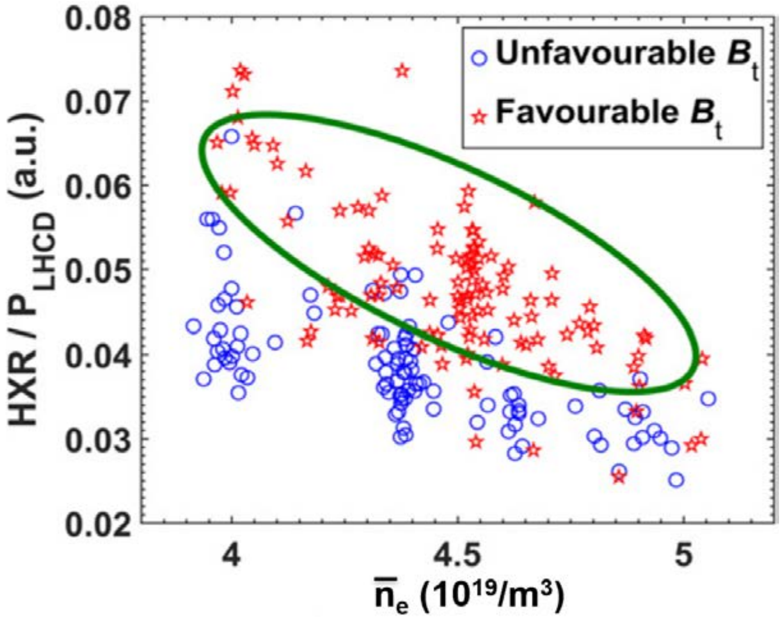
Lithium coating



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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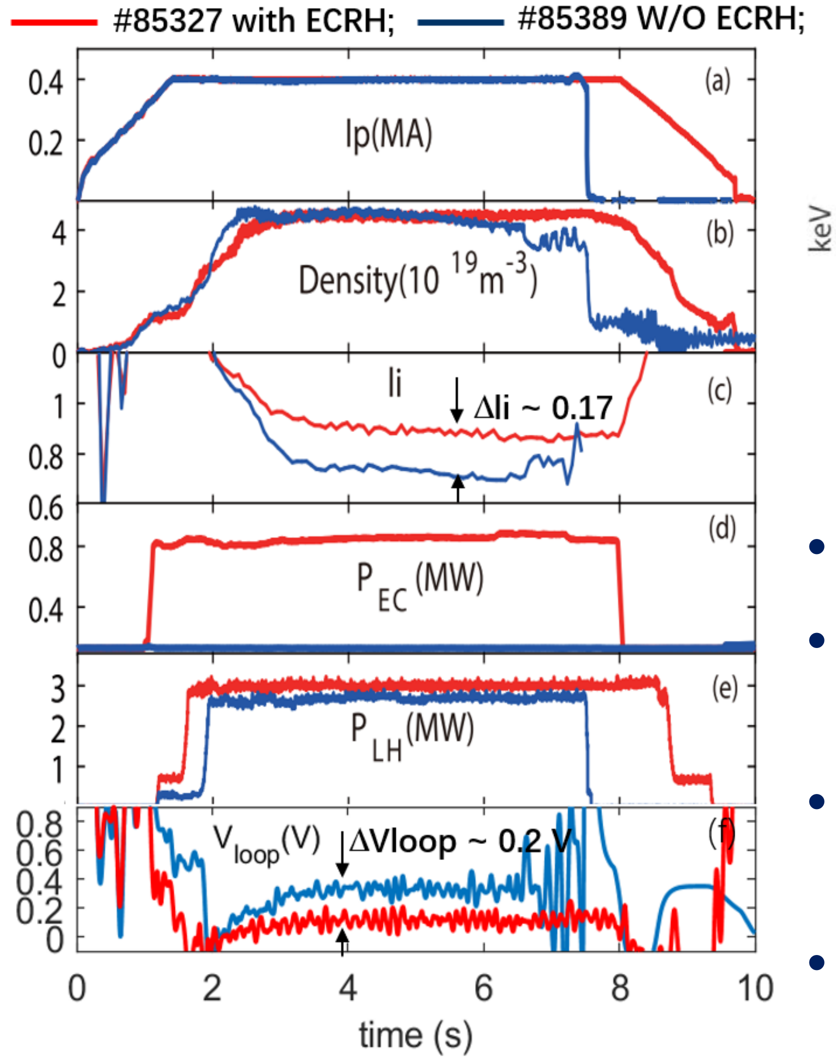
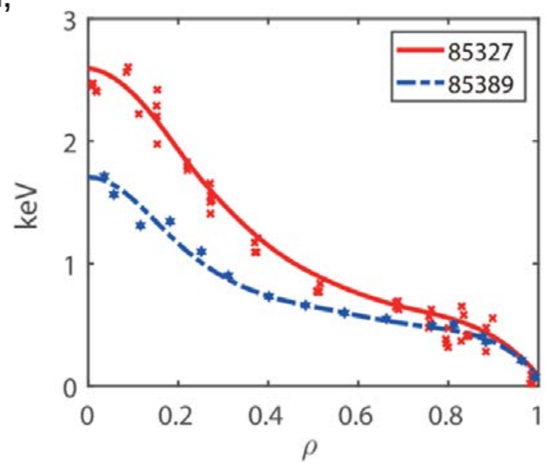
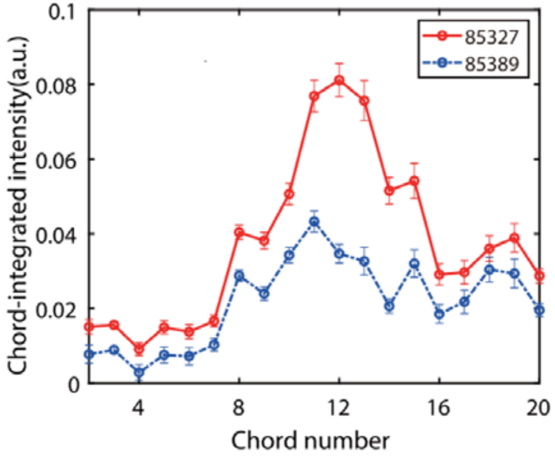
Temperature Effects on LHCD by EC Wave



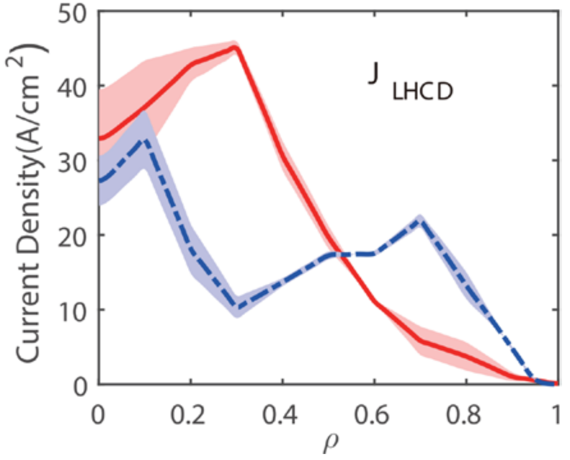
Te profiles



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.**

J.Y. Zhang et al. Plasma Sci. Technol. 2022

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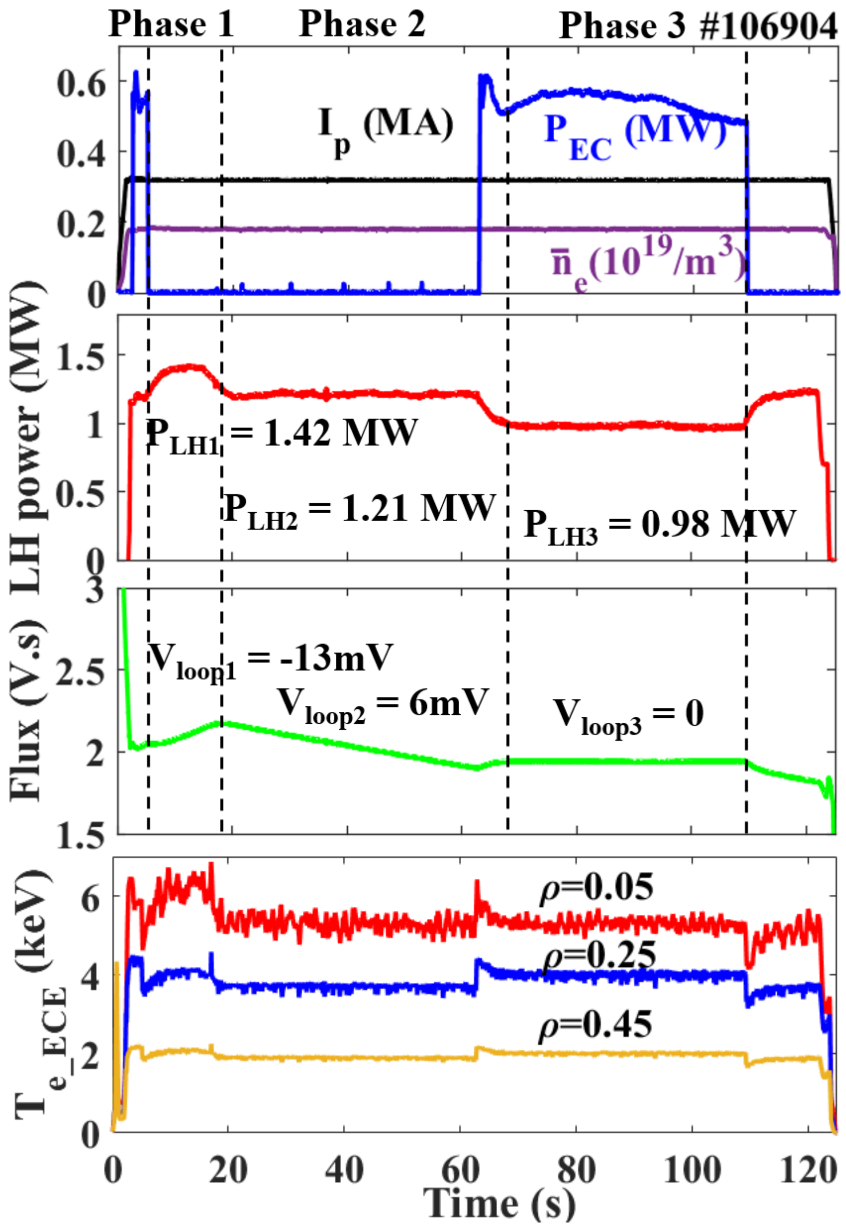
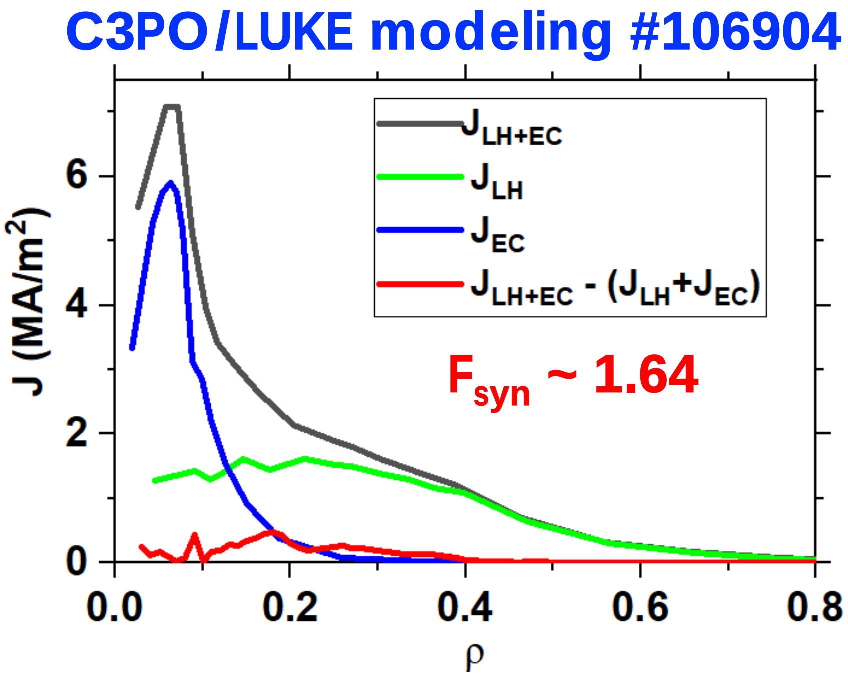
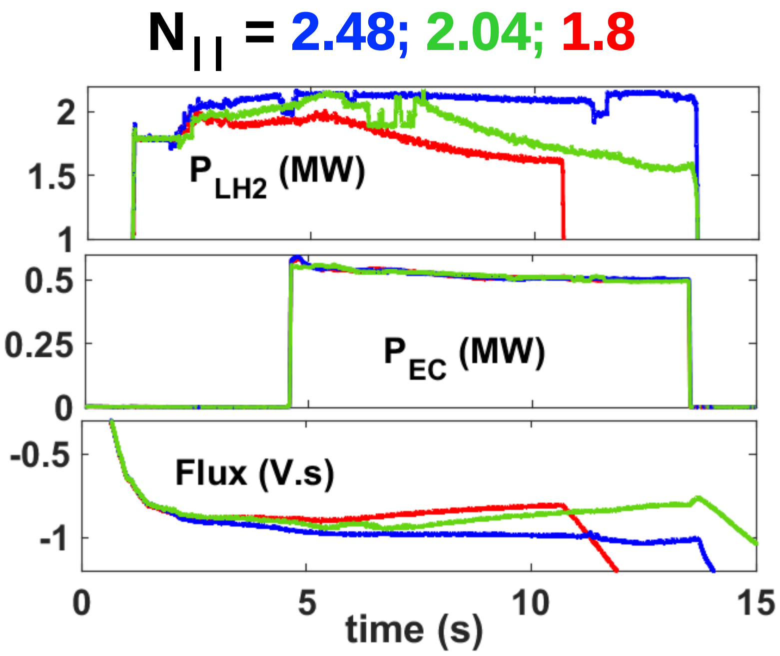
Synergy Effect between LHCD and ECCD







- 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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Outline

- ❑ EAST Tokamak and LHCD systems
- ❑ Challenge in LH coupling and current drive
- ❑ Exploration and achievement in LH coupling
  (Feedback control, PAM antenna, and hot spot)
- ❑ Recent progress in improving LHCD capability
  (PDI bifurcation, methods in improving CD efficiency)
- ❑ **Significant advance in long pulse plasma with LH wave**
- ❑ Summary and next plan

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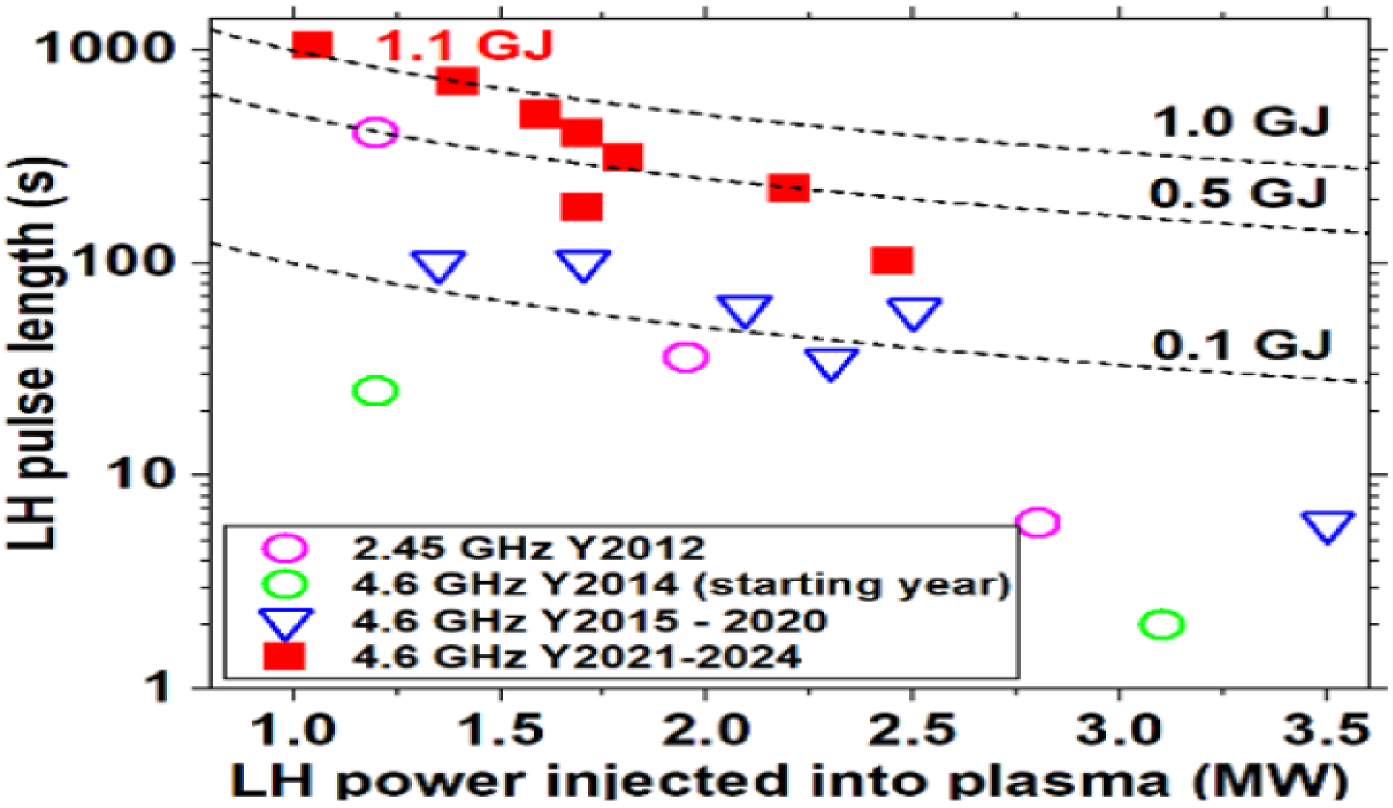
Advance in Long-Pulse Operation of LH Systems



- f = 2.45 GHz, 411 s with 1.2 MW, maximum power: 2.8 MW.
- f = 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.

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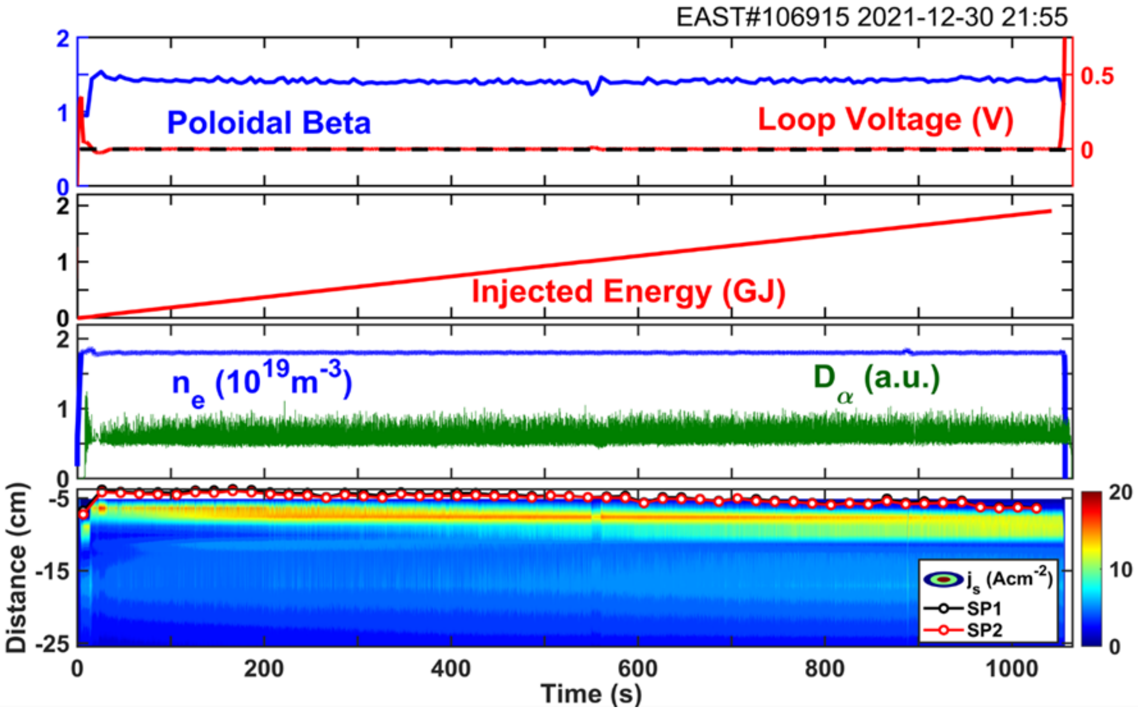
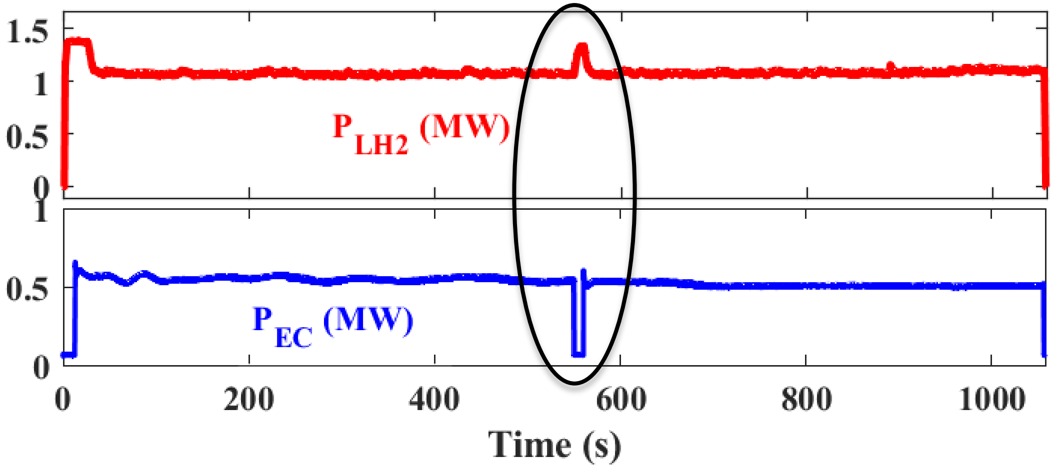
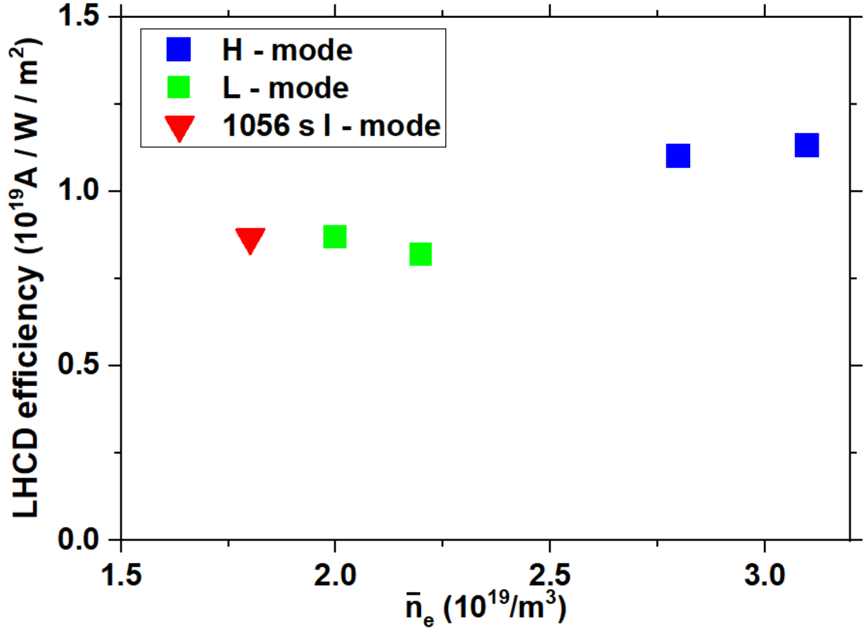
Thousand-Second Improved Confinement Plasma with Super I-Mode by LH and EC Waves







- 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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Summary and next plan

Summary

□ LH couplings, including feedback control, PAM antenna performance, and avoiding hot spot, were explored for long pulse plasma in EAST

□ Studies for improving LHCD capability, including PDI bifurcation and synergy of LH + EC, have been explored in EAST.

□ Significant advance in long pulse plasma with high performance in EAST was introduced.

Next Plan:

A new LH system with PAM launcher (f=4.6GHz) is under development, which is expected to extend the long-pulse operation to higher plasma parameters on EAST in future.

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Thank You for Your Attention