Real-time feedback and plasma controls for steady-state plasma operation

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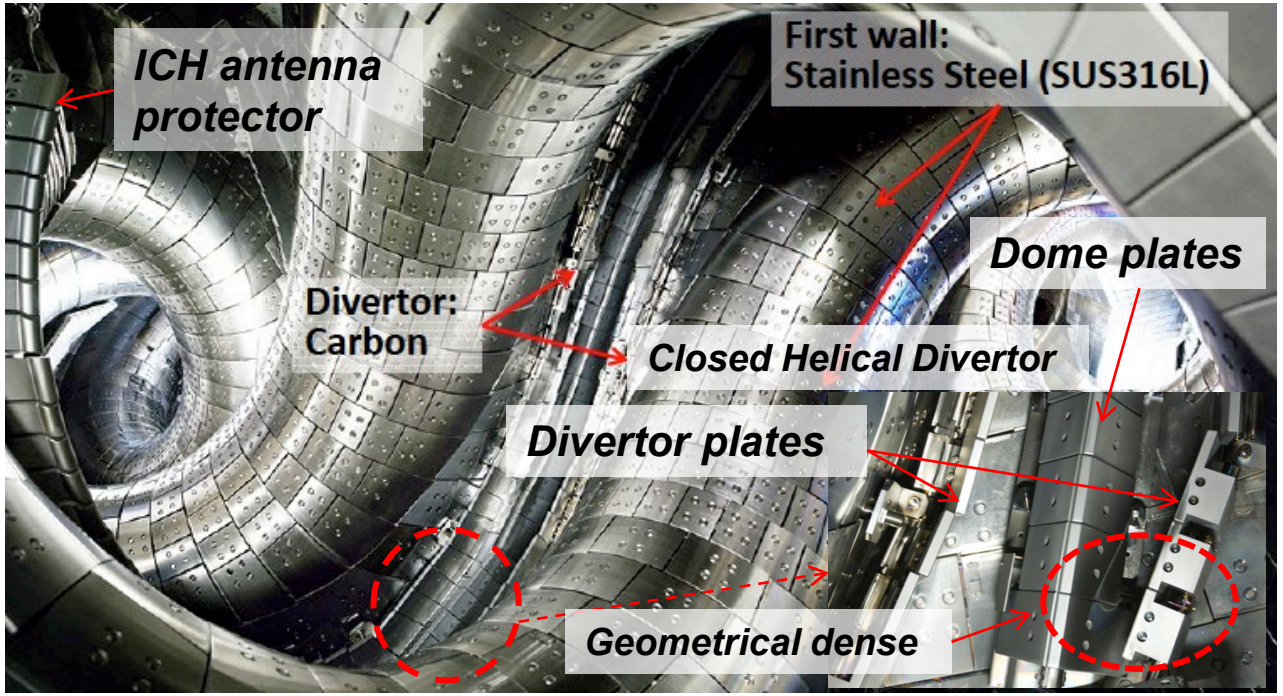
Contents

- **Technology**
  Radio-frequency plasma heating for ICH and ECH
  Real-time feedback control aiming at plasma parameters is kept constant.
  New challenges of fusion reaction rate control by changing ICRF heating power

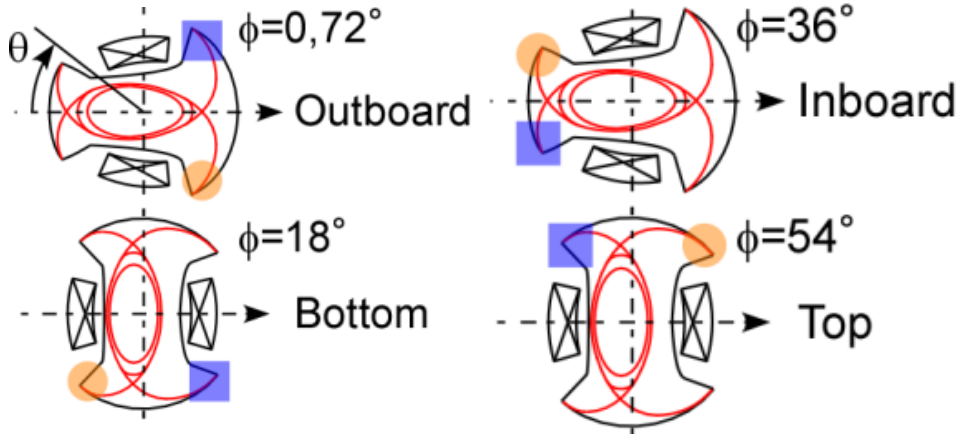
- **Physics**
  The observation for the time evolution of particle confinement time using superimposed hydrogen fueling in He(H) and D(H) plasmas

- **Summary**

Large Helical Device (LHD)



Plasma cross-section



Typical parameters:

Volume:

Inside vessel ~ 210 m^3

Plasma ~ 30 m^3 (R_{ax} ~ 3.9m, a ~ 0.6m)

Surface:

PFCs ~ 780 m^2

First wall ~ 730 m^2 (SUS316L)

Divertor plate ~ 50 m^2 (Graphite)

Achievement plasma parameters:

T_i~ 8.1 keV (n_e~1x10^{19} m^{-3})

T_e ~ 12.9 keV (n_e~1x10^{19} m^{-3})

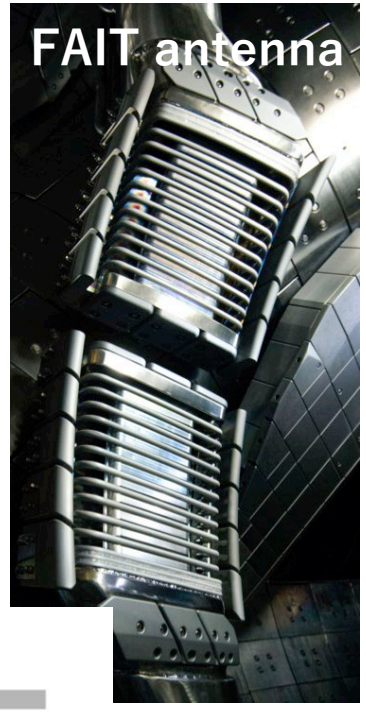
n_e ~ 1.2x10^{21} m^{-3} (T_i ~ T_e~ 2 keV)

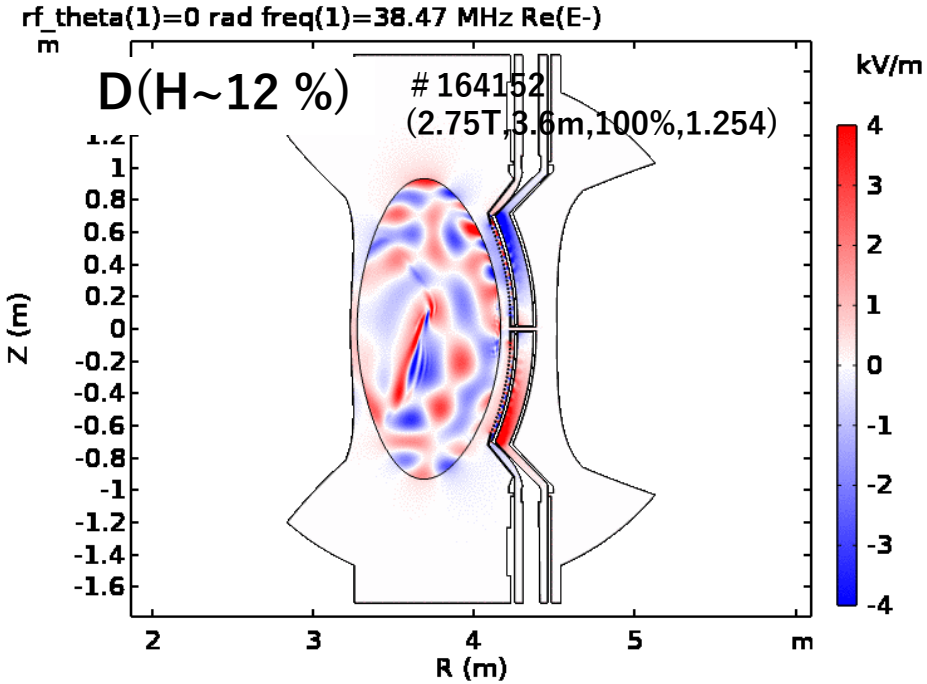
β ~ 5.1 % (0.425T), 3.4 % (1T)

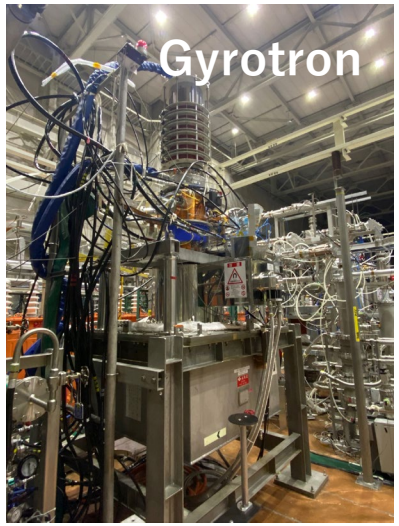
τ_d ~ 54 min (0.5MW, n_e~0.4x10^{19} m^{-3})

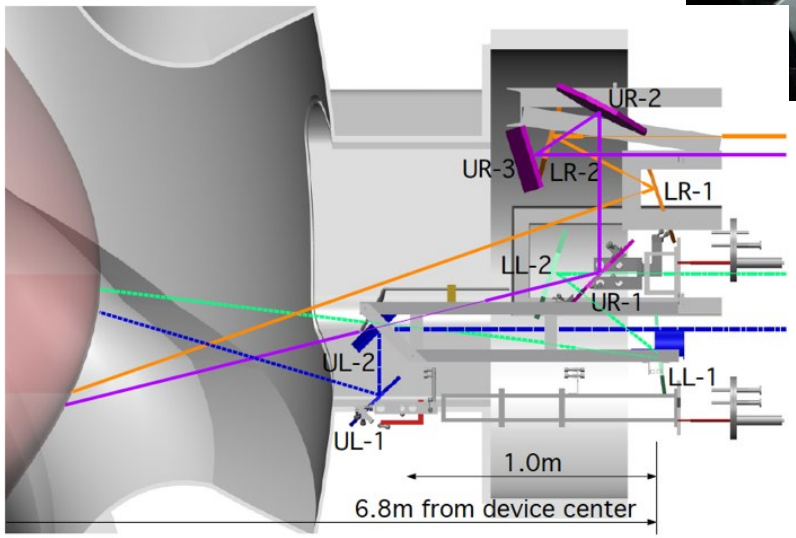
48 min (1.2MW, n_e~1x10^{19} m^{-3})

Radio-frequency heating for long-pulse operation



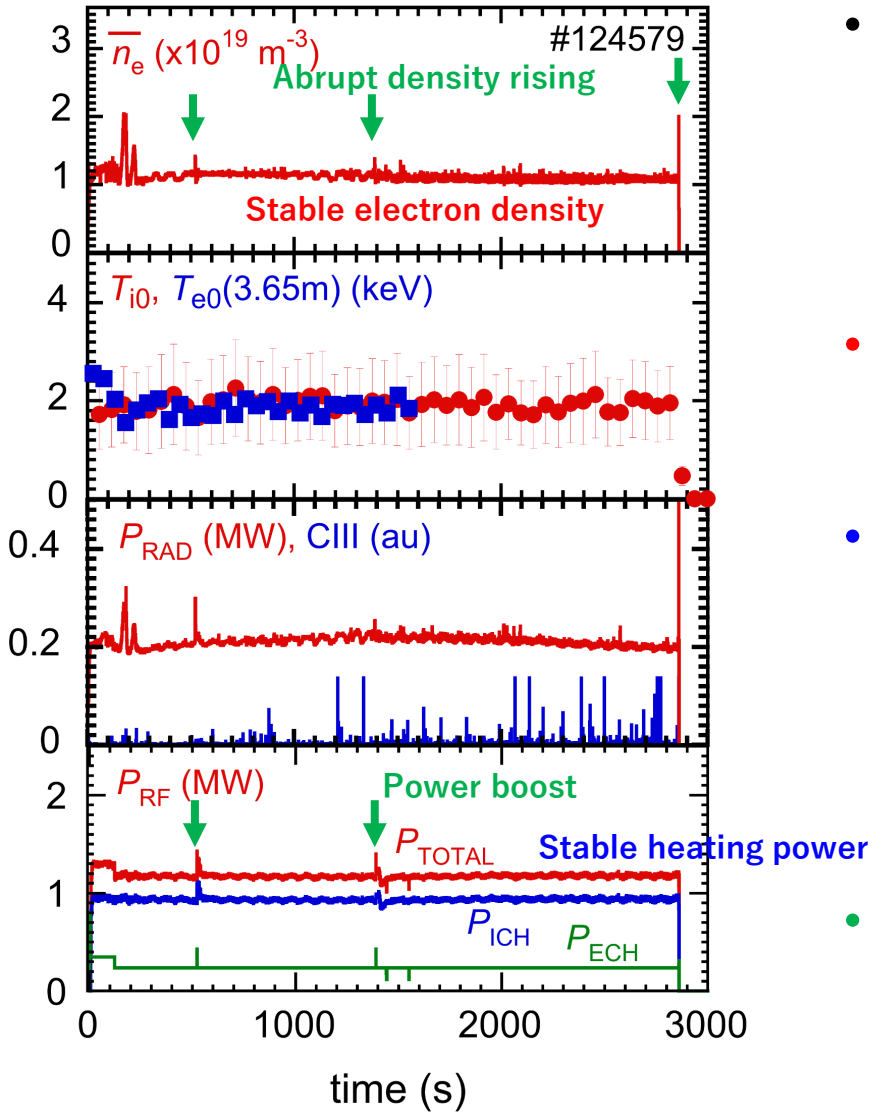






- Two ICRF antennas, toroidal and poloidal array antennae, are installed for ICF heating with 38.47MHz and 1MW on each strap.
- Six gyrotrons sources. 77GHz x2 and 154 GHz x3, 56 GHz x1 are prepared for ECH

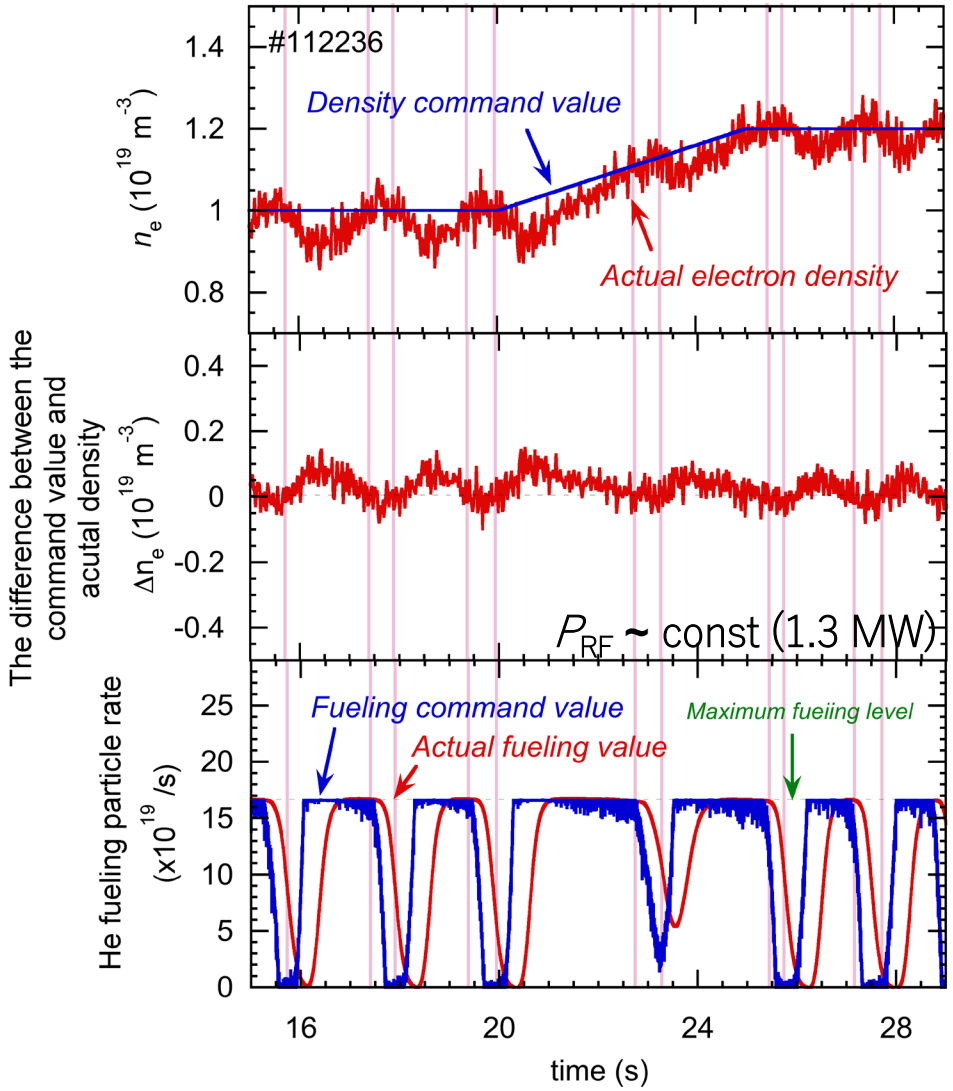
Real-time control for long-pulse operations



- In long-pulse operation in 48 min discharges, we challenged using real-time feedback controls, and plasma duration was kept constant.
  $n_e \sim 1.2\text{x}10^{19}$ m^{-3}, $T_i \sim T_e \sim 2$ keV, $P_{RF} \sim 1.2$ MW (P_{ECH}~0.26 MW), $W_{heat} \sim 3.4$ GJ
- Electron density: The gas fueling rate was determined by the PID algorithm using the comparison with target density and measured electron density with the feedback time of 10 μs.
- ICRF heating: Tetrode tube of the final amplifier has non-linear gain, which is associated with vacuum condition in the tube. Real-time signal level power control is conducted with the gain, absolute power/signal power, kept constant. The Feedback speed is 10 μs, but the signal power level is gradually changed by mitigating low-level noise.
- In sudden impurity penetration events, mitigating the temperature drop by the rapidly increasing electron density, a heating power boost was tried for ICH and ECH.

Technology in long-pulse operation

Delay time between target and actual electron density during real-time feedback control



$$\Delta n_e(t) = n_{target}(t) - n_{fir}(t)$$ *: Differential part*

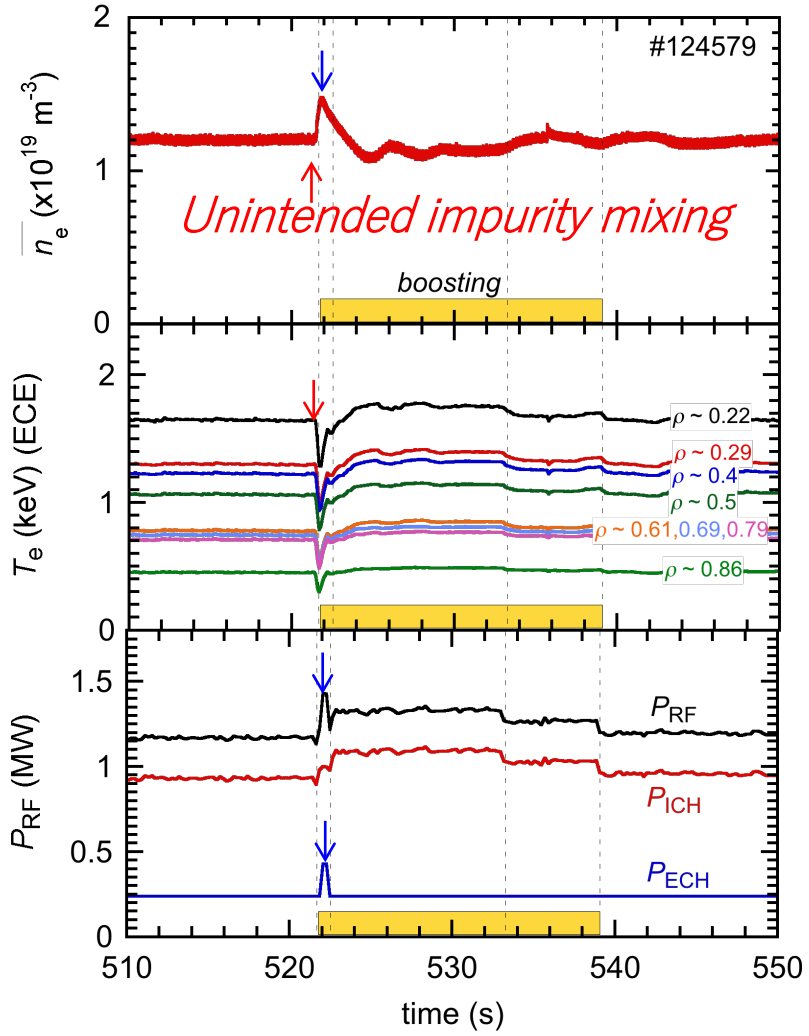
$$V_{fuel}(t+dt) = \alpha_1 \Delta n_e(t+dt) + b_1(t+dt)$$ *: fast*

$$b_1(t+dt) = V_{fuel}(t) + \frac{1}{dt}\int_t^{t+dt} \beta_1 \Delta n_e(t)dt$$ *: slow*

- Electron density followed the command value using the PID method.
- Adequate gas-fueling was achieved with time delay for gas-fueling during long-pulse discharges.
- The response time between the control voltage and electron density is associated with the conductance and gas fueling device. (0.1s ~the response time of MFC)

A heating power boost is helpful to keep plasma parameters stable

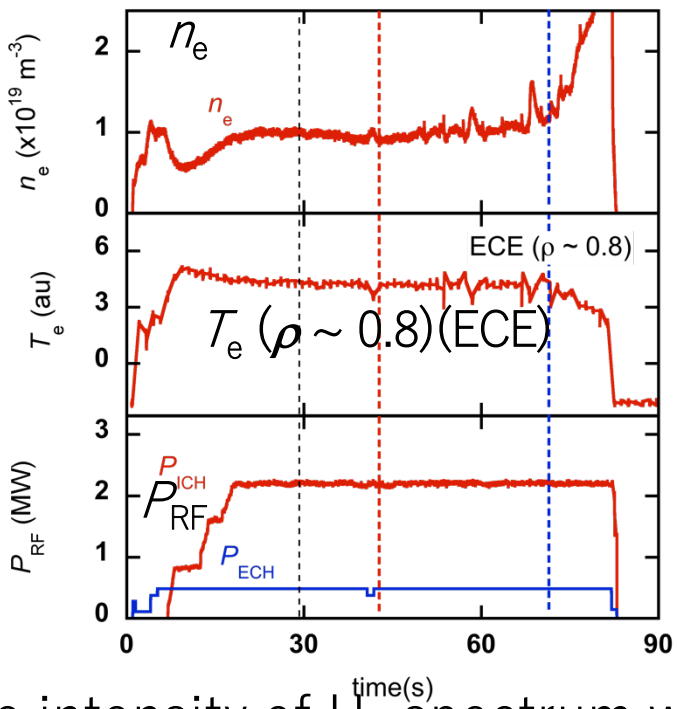
The boost of RF heating power was worked to maintain the plasma parameters effectively.

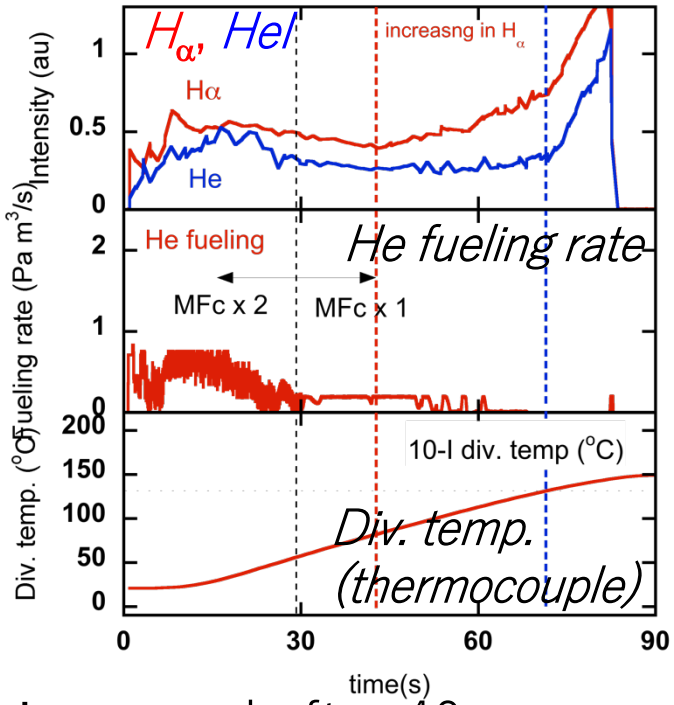


- An unintended event happened at t ~ 522 sec, and boosting RF heating power was carried out at the short-time delay (< ms).
- By boosting RF power, plasma density and temperature were recovered to similar levels just before the event, and robust plasma with the long- pulse and higher-performance was demonstrated by these developments in the LHD.

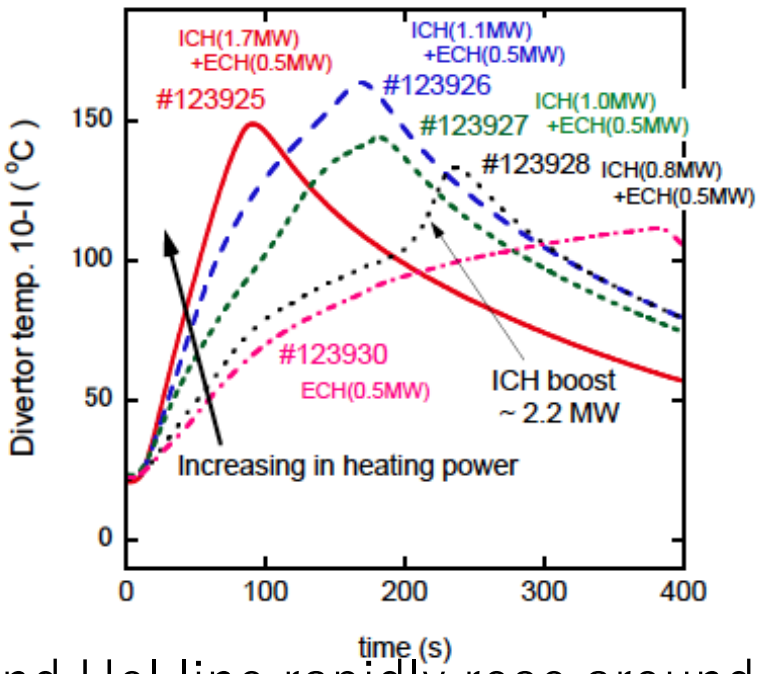
However, the next critical issue of breaking steady-state plasma appeared…

Desorption gas from divertor plates make plasma duration time short, when heating power was increased.





*Reversed magnetic field configuration

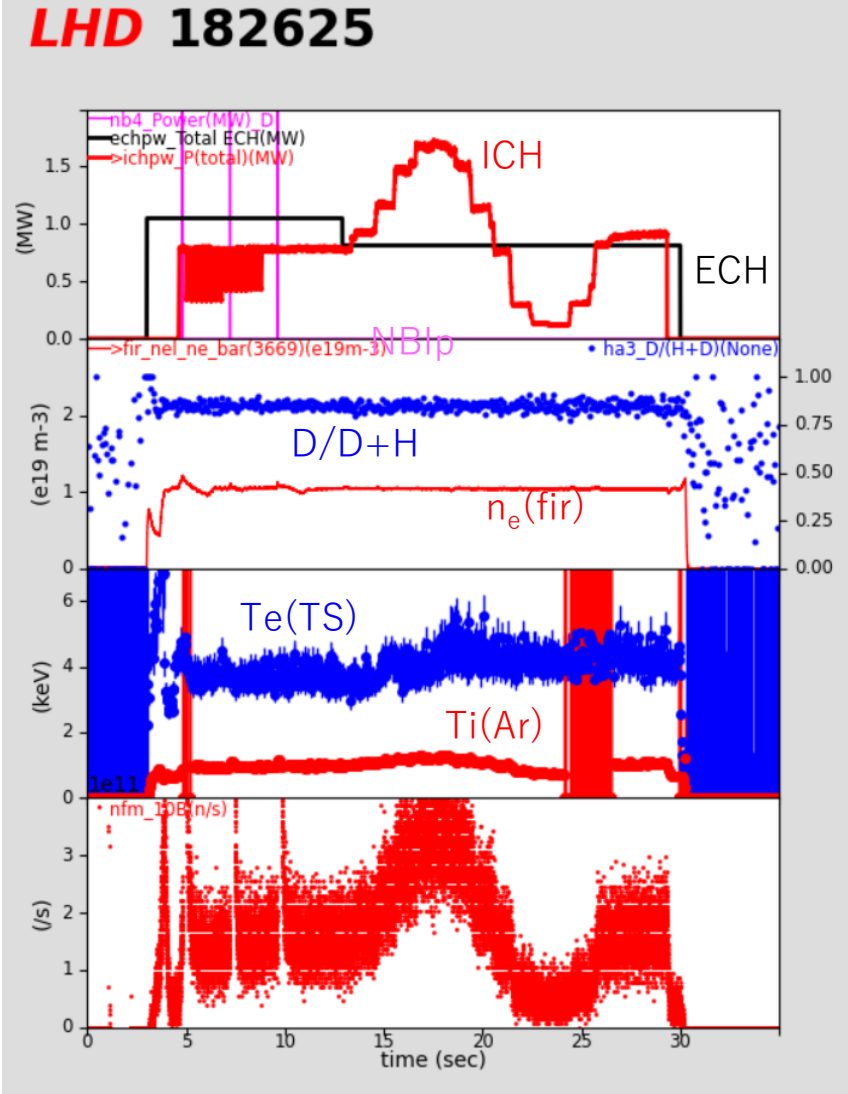


The intensity of H_a spectrum was increased after 40 sec, and H_a and HeI line rapidly rose around 70 sec.

After 30 sec, The fueling was stopped with keeping density constant. The desorption of He particles seemed to occur around divertor plates because the difference between t ~ 0 sec and t ~ 70 sec for the first wall temperature was negligible.

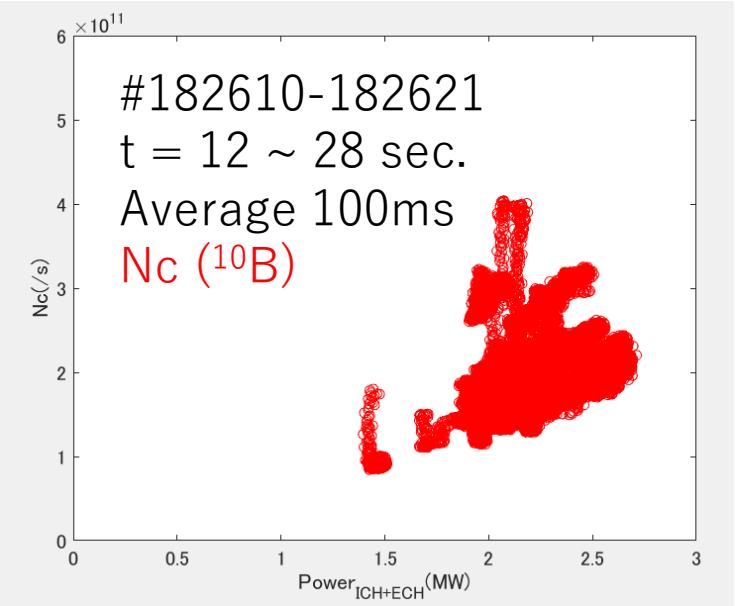
As increasing heating power, the clear start time of desorption was shorted, and de-gas of the divertor plates were necessary to maintain plasma duration.

Fusion reaction rate associated with ICRF heating power

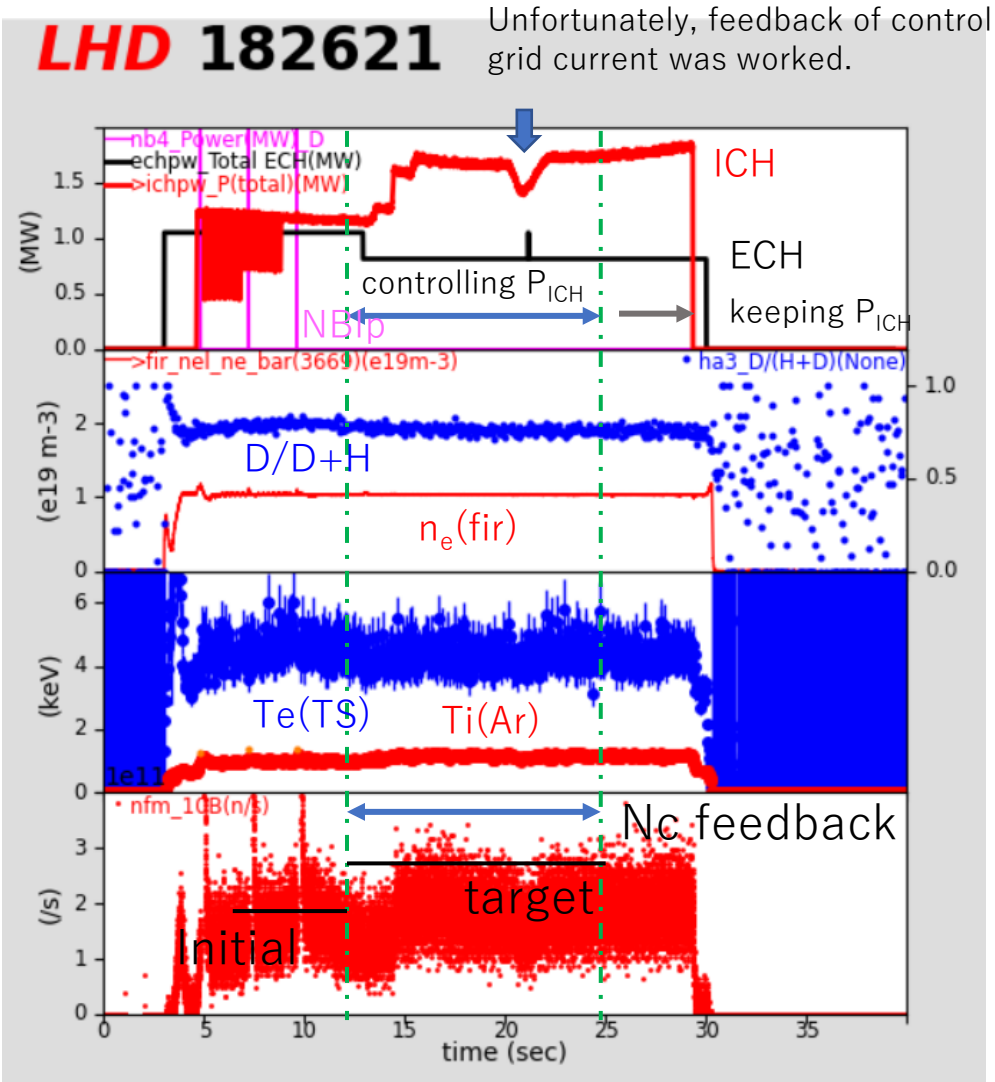


Thanks to K. Ogawa for his cooperation.

- Ion and electron temperatures were increased with ICH + ECH power, and neutron count rates were associated with the heating power.
- However, ICRF heating can enhance the neutron reaction rate by increasing the bulk ion temperature and increasing fast ion production with the larger cross-section for neutron reaction.
- In SN18260~182621 for ICH + ECH heating in D(H) plasmas, there were various neutron count rates with the same heating power.
- In a fusion reactor, it is essential to control the fusion reaction rate fully, and we must demonstrate the fusion reaction rate to target levels.



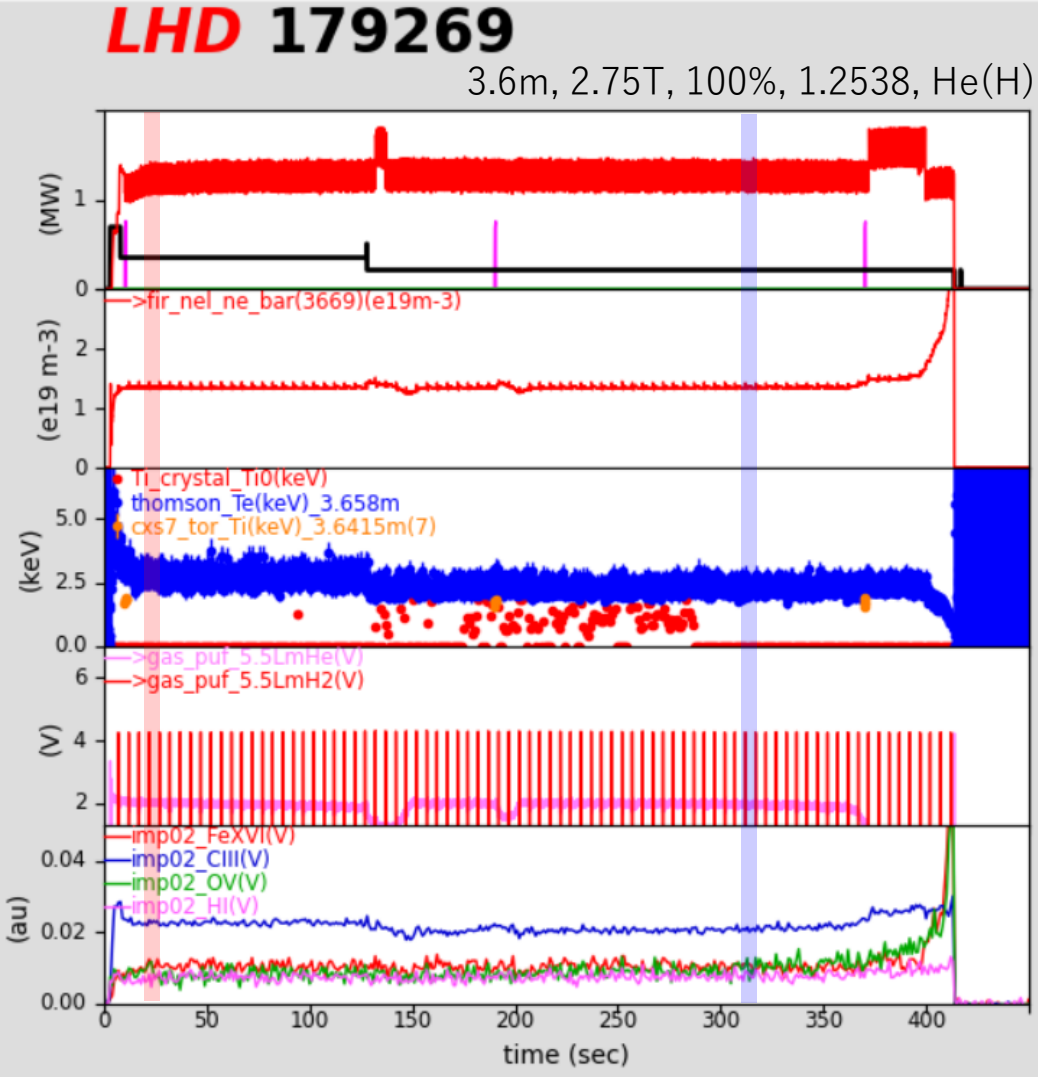
First challenge of the demonstration of neutron reaction rate with real-time control to the target level



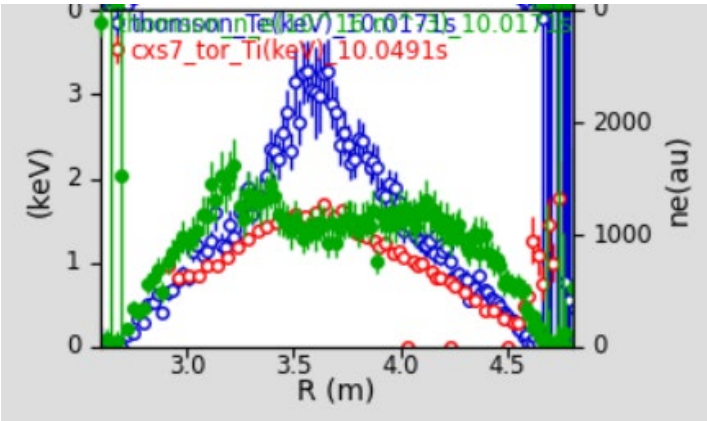
- Neutron count rate (Nc) was conducted between t = 12 to 25 sec, and ICRF power was not controlled at the end of feedback.
- Nc reached the target rate in a few seconds, except that the output of the ICRF was reduced by the control grid current feedback to protect the amplifier.
- It is the first trial in fusion plasma experiments to control neutron reaction rate to the target level with a real-time feedback system.
- As the next step, we will apply the Nc feedback control on the longer plasma durations and decrease the delay time between target Nc and actual Nc.

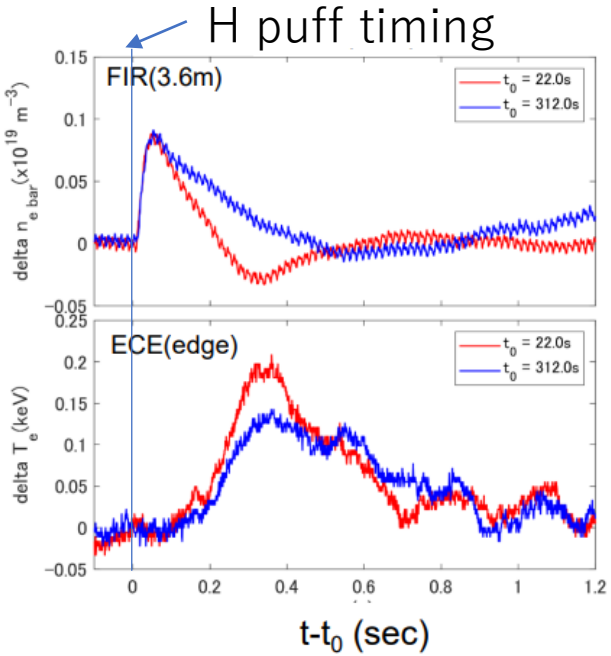
Physics
in long-pulse operation

Particle confinement time is gradually changed during long-pulse operation in He(H) plasma (1)



Temperature profiles t = 10s

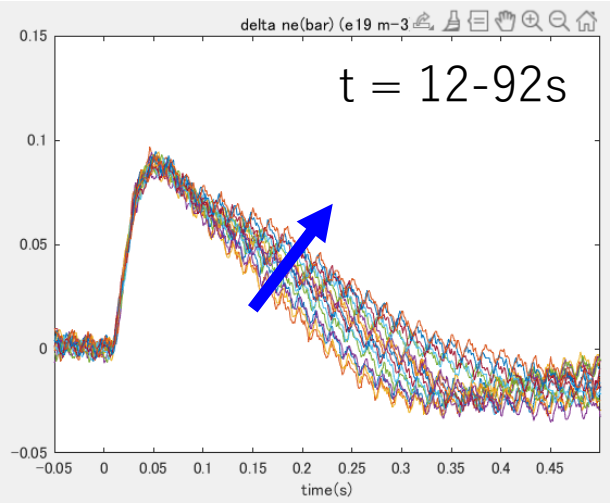


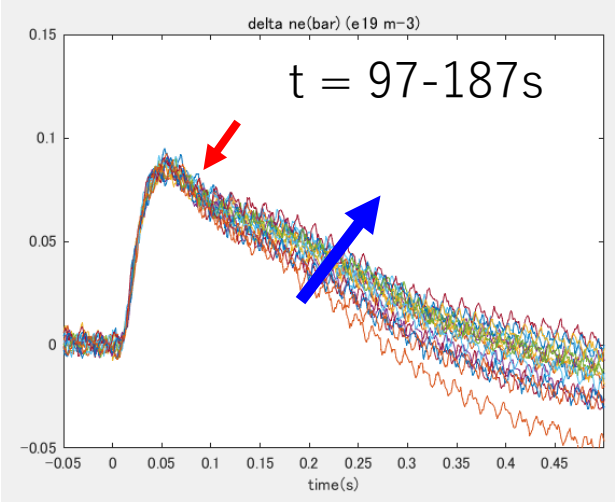


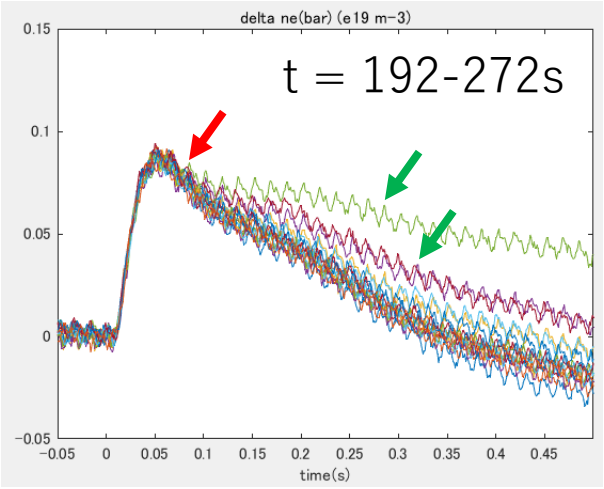
- Particle confinement time was confirmed by periodically superimposing hydrogen puffing while supplying gas to keep the electron density constant with real-time feedback control (no gas fueling n_e over target density).
- There were two decay times of particle confinement in early and later plasma duration phases with the saturation of the first wall to accumulate the particles, **but** ….

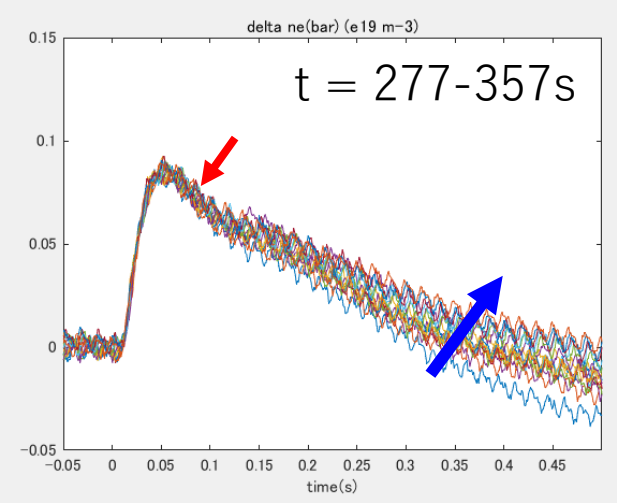
Particle confinement time is gradually changed during long-pulse operation in He(H) plasma (2)

Super imposed hydrogen fueling was conducted in every 5 sec from t = 12 sec.









The density recovery phase is gradually increased

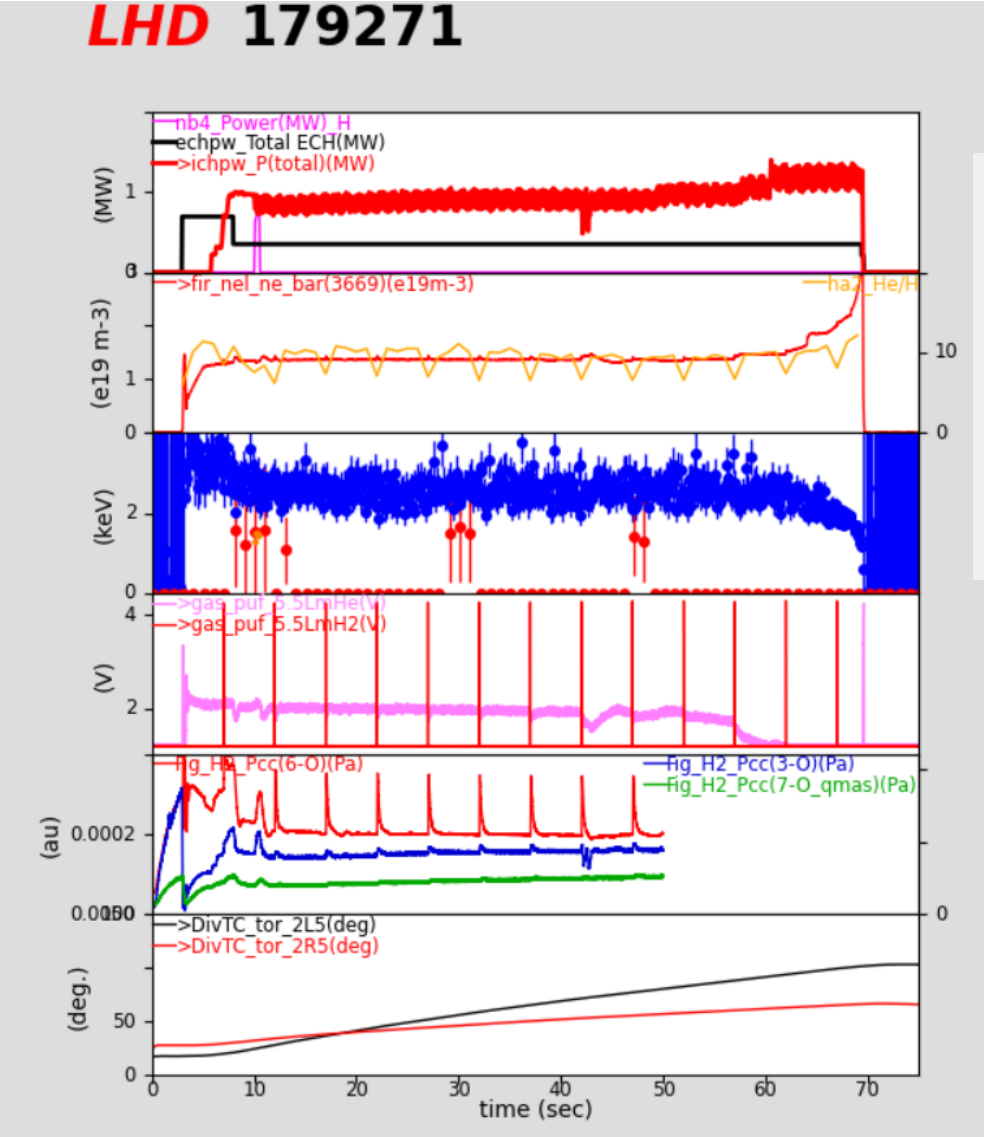
There were **two recovery slopes** in the early and later phases, and the early phase was the same.

No significant difference in density recovery time was observed except in exceptional cases

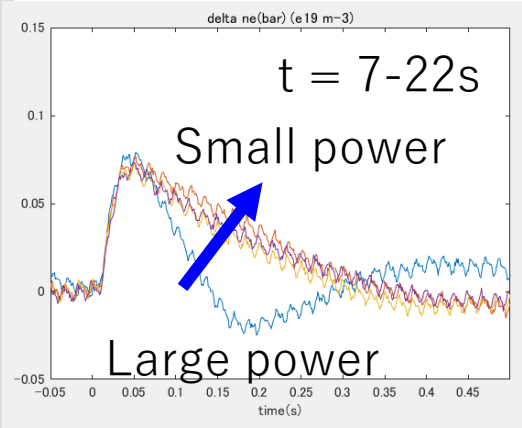
No difference in recovery time for the first 100 ms, but recovery time in the second half began to increase again

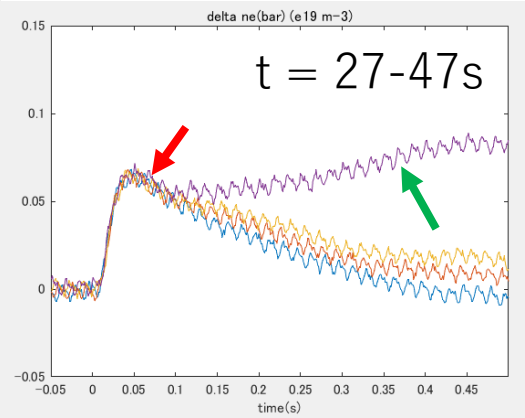
The causality investigation of this phenomenon is ongoing, and we will challenge the long-pulse operation in this campaign.

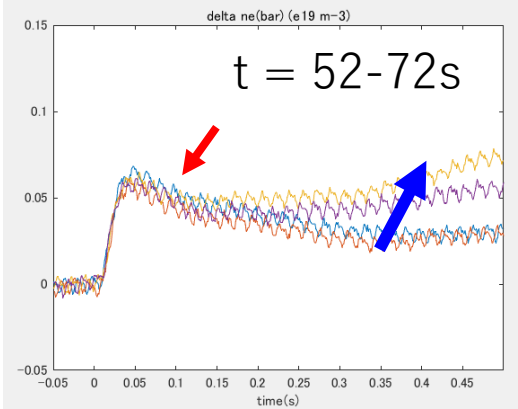
Particle confinement time is gradually changed during long-pulse operation in D(H) plasma (3)



Super imposed hydrogen fueling was conducted in every 5 sec from t = 7 sec.







The density recovery phase is associated with heating power.

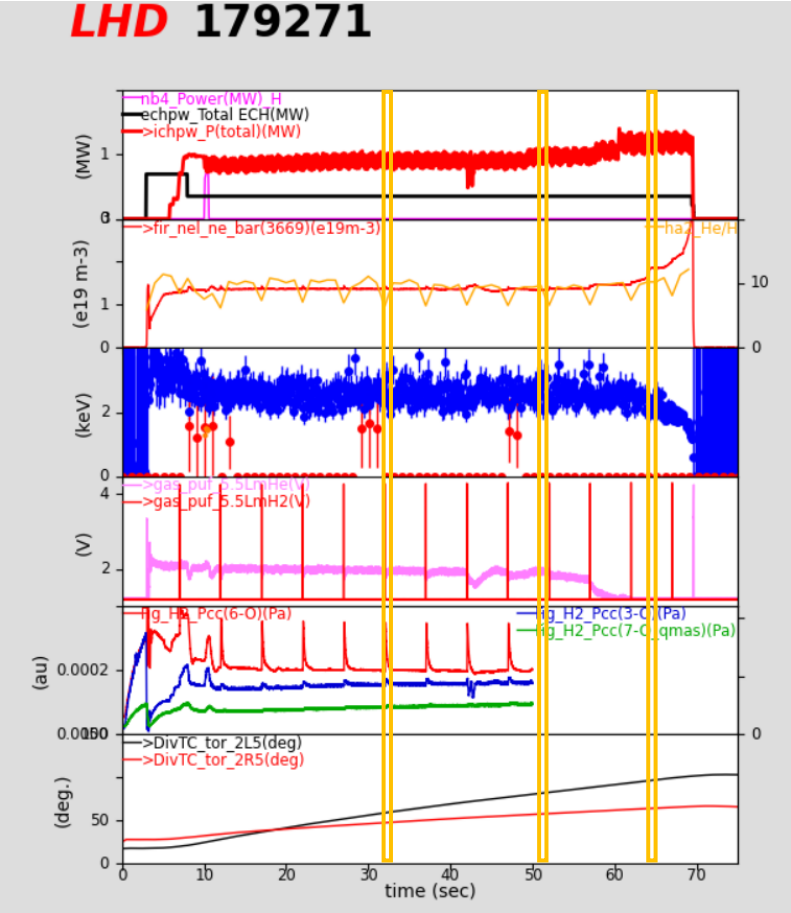
No difference in the recovery slope appeared.

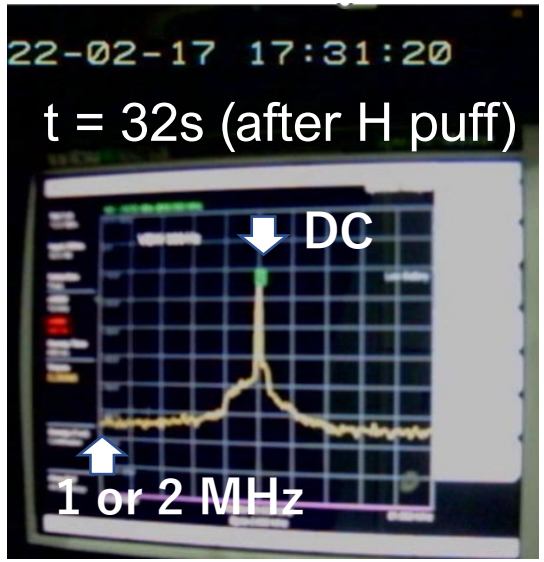
Uncontrollable density region

The trend of the density recovery phase seemed to be different in D(H) and He(H) plasmas.

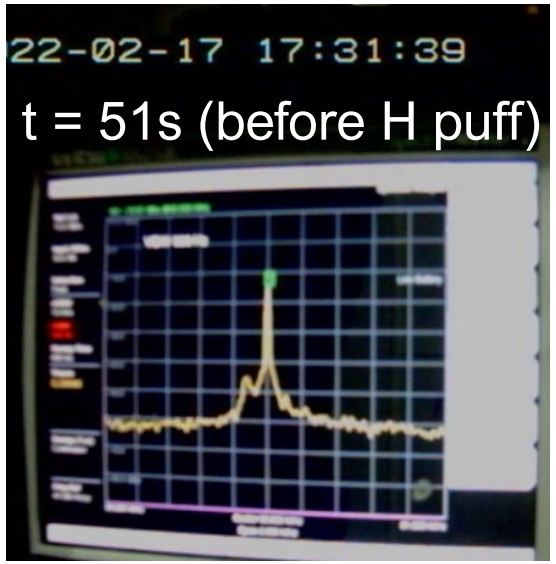
Sudden turbulence phenomena were observed with fluctuation measurement

Turbulence behavior measured by microwave Doppler reflectometer





After superimposed hydrogen puffing with gas fueling, there was an asymmetric profile for perturbation.



In the fueling phase, just before superimposed hydrogen puffing, there was a peak spectrum associated with turbulence.

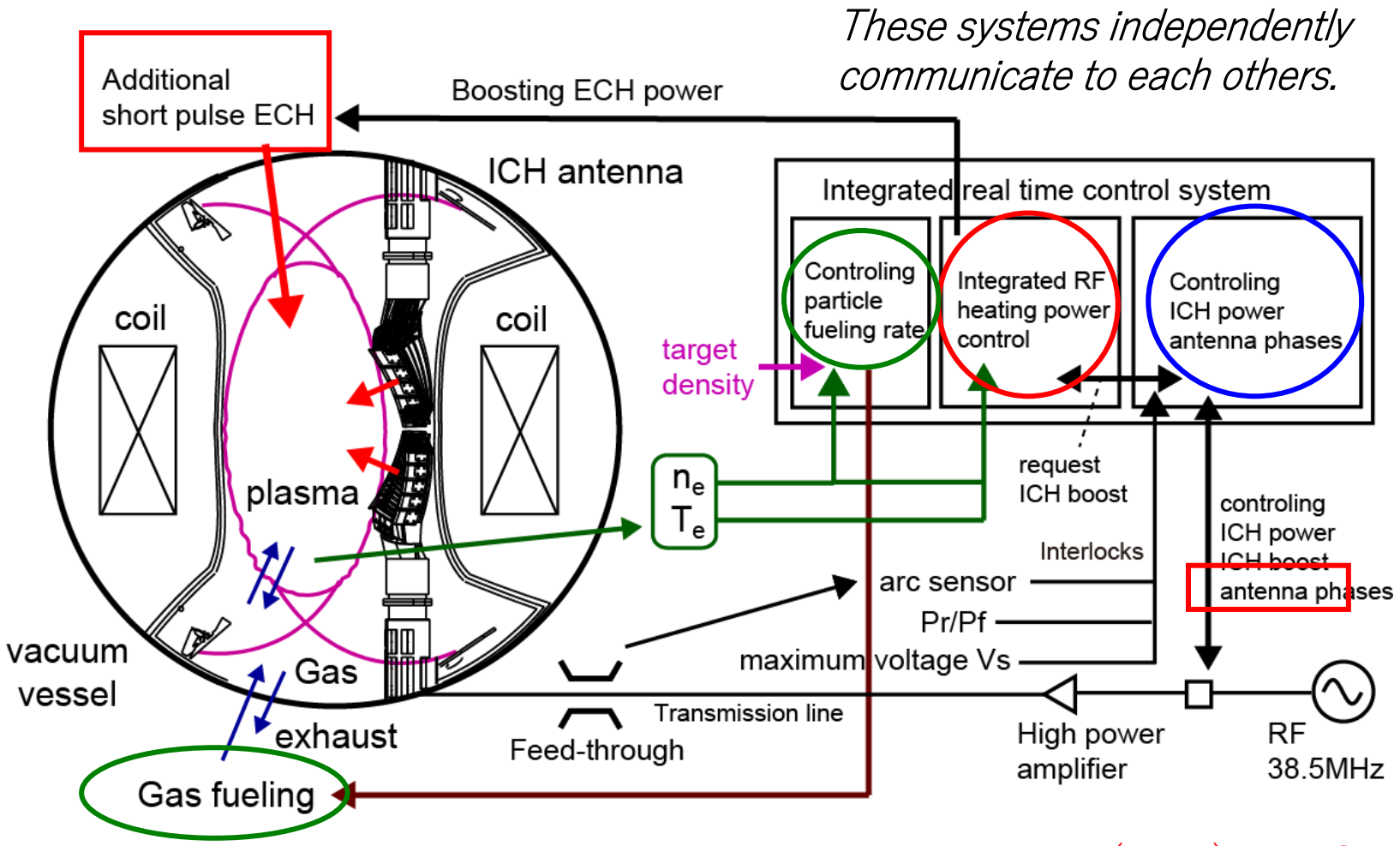
In the fueling phase, there was a symmetric profile for perturbation measured by fir.

In this campaign, we challenge to measure the turbulence behavior in long-pulse operations.

Summary and Conclusions

- Real-time feedback control is well worked to make stable plasma parameters in the LHD.
  - Electron density, heating power, and detection of boost event were conducted using an FPGA circuit with a time scale of 10 μs, but the response times were associated with the capability of fueling system and evaluation method in real-time.
  - Fusion reaction rate control was demonstrated in the LHD, and we will optimize the control parameter for the PID circuit to change ICRF heating power.
- Particle confinement time study has been conducted by superimposed hydrogen fueling in He(H) and D(H) plasmas on the long-pulse operation
  - Particle confinement time was gradually increased with plasma duration time, and there were two slopes just after hydrogen fueling.
  - Comparing the particle confinement time with He(H) and D(H) plasmas, its time in He(H) was gradually increased at first.
  - In long-pulse operation, sudden turbulence phenomena were observed a few times, and the revealing of the causality is ongoing.

RF heating systems and boost control relieves critical perturbations of plasma duration



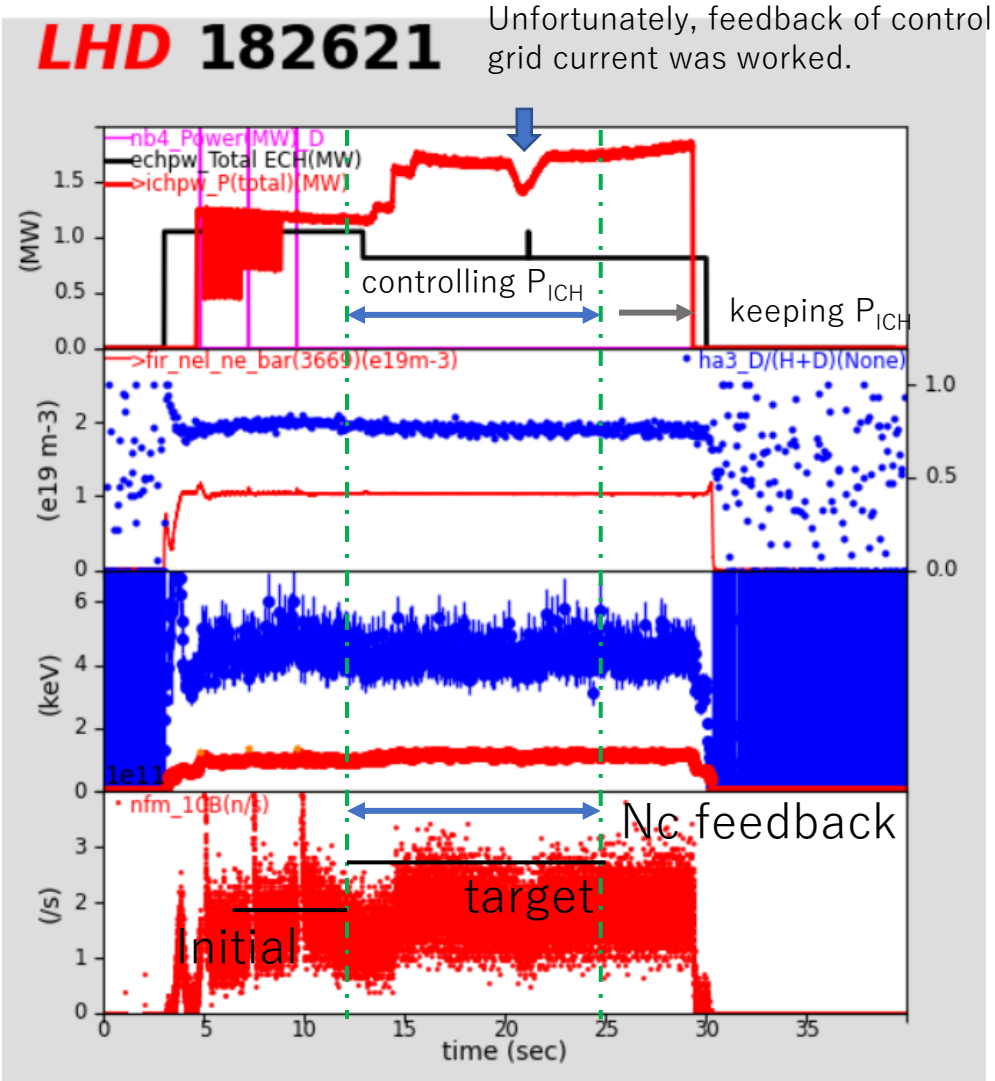
Power control of ICRF waves with real-time feedback control

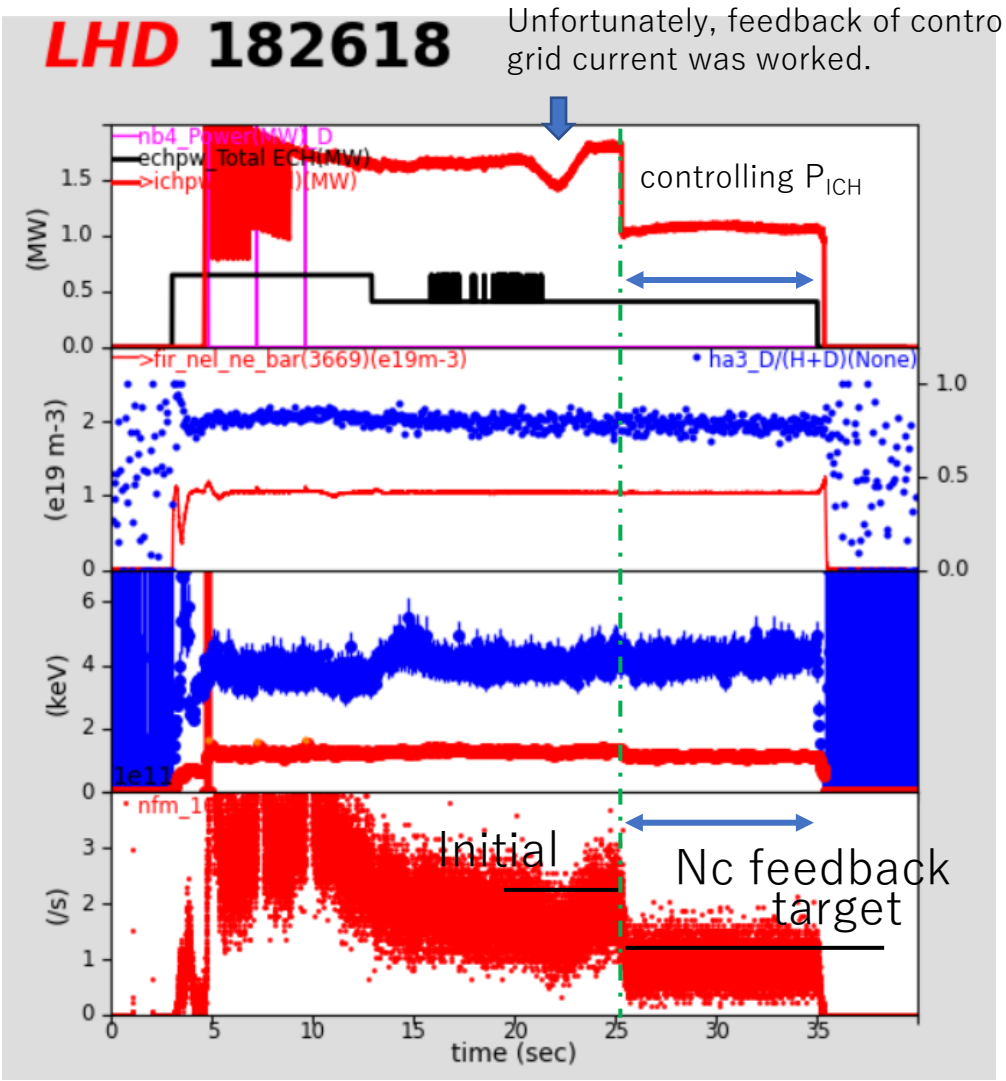
- Standing voltage limitation
- Ig_1 and Ig_2 current limitation
- Keeping Gain
- Fast interlock

An automatic *recovery* scheme for lunching RF power is required for the stable long-pulse plasma duration.

Critical time scales of plasma collapse are less than 0.2 sec (~ τ_E), and **fast recovery with a response time below $\tau_E/4$** is recommended to keep plasma parameters experimentally.

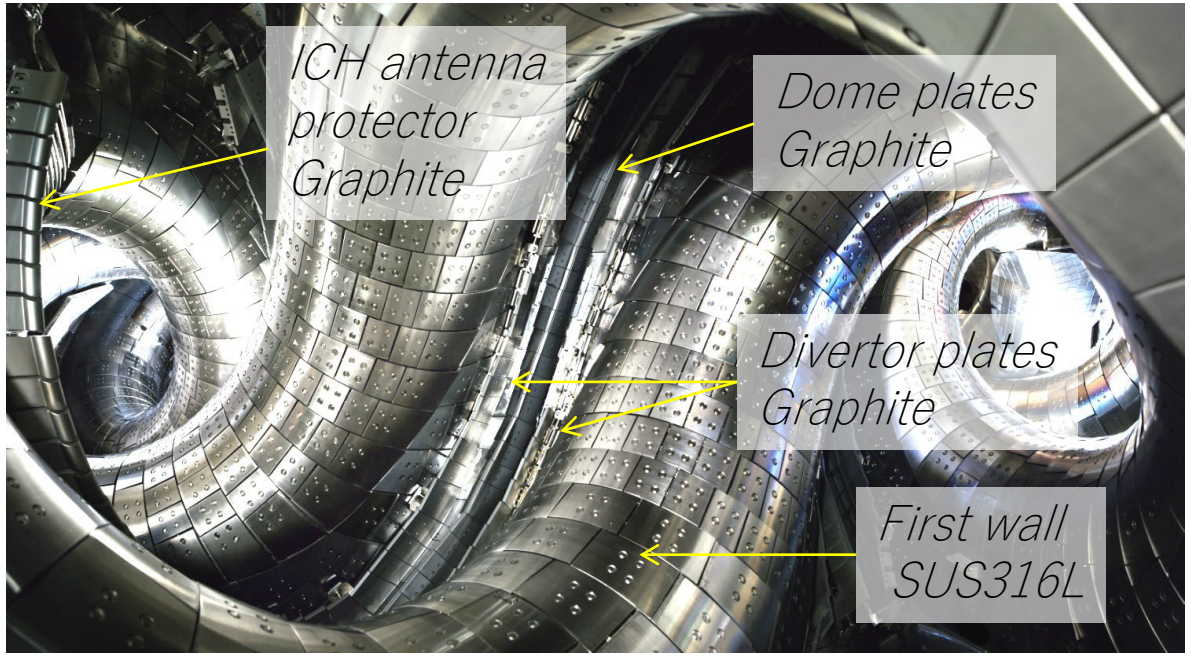
First challenge of the demonstration of neutron reaction rate with real-time control to the target level





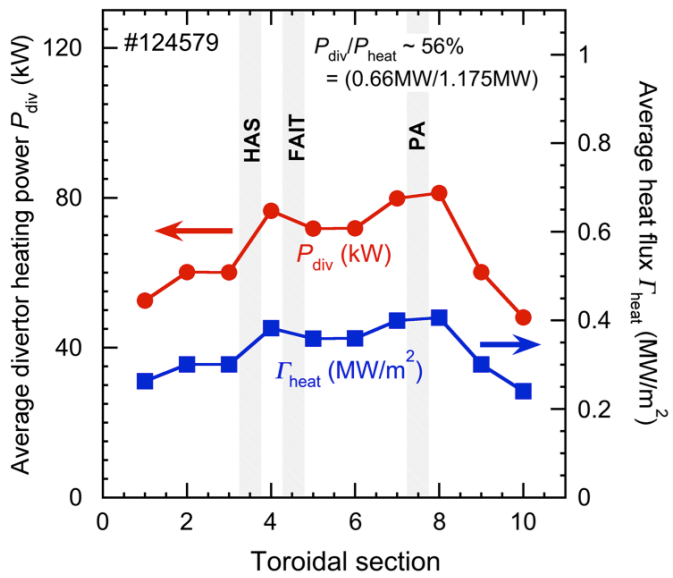
Thermal equilibrium condition, toroidal uniformity of divertor heat load, and total heat balance

P_{RF} ~ 1.2MW, n_e ~ 1.2x10^{19} m^{-3}, T_e~ T_i ~ 2 keV, 48 min.



Name	Protector surface (IR)	Divertor surface (IR)	Divertor (thermocouple)	First wall (thermocouple)
Temp. (°C)	300-900	460	180-270	40 -110
Saturation time-scale	~ 800 s	~ 600 s	~ 700 s	> 3000 s
Material	Graphite	Graphite	Graphite	SUS316L

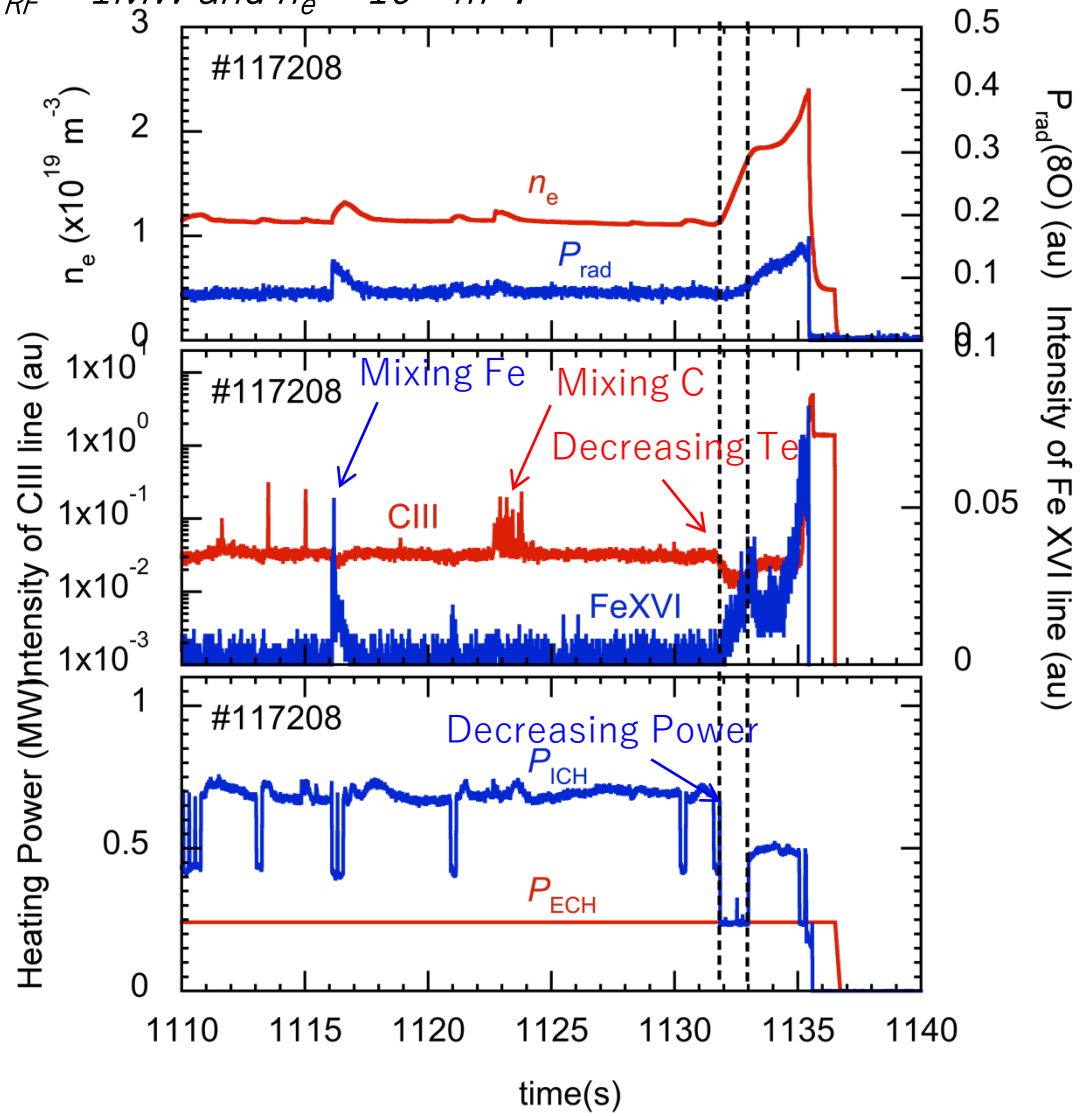
Toroidal nonuniformity of divertor heat load:



Total power balance:
Radiation P_{rad}: 17 %
Divertor P_{div}: 56 %
Other P_{other}: 27 % (direct loss, protectors)
Average heat flux
Γ_{heat}: 0.33 MW/m^2
(0.25 ~ 0.4 MW/m^2)

One of the critical issues for the collapsing of the long-pulse plasma with T_e ~ 2keV and P_{RF} ~ 1 MW was caused by the degrading heating power.

Time evolution of the plasma collapse for early long-pulse discharge with P_{RF} ~ 1MW and n_e ~ 10^{19} m^{-3}.



The chart of the collapse for steady-state plasma durations

Decreasing heating power

Te, Ti ↓ ⬇ There is no additional heating support, and then …

Increasing the amount of the intensities for impurity lines (FeXVI, CIII)

n_e ↑ ⬇ Failing the control of density keeping, and then ..

Increasing the density and the radiation

Unstable ⬇ The health of plasma is extremely reduced, and then …

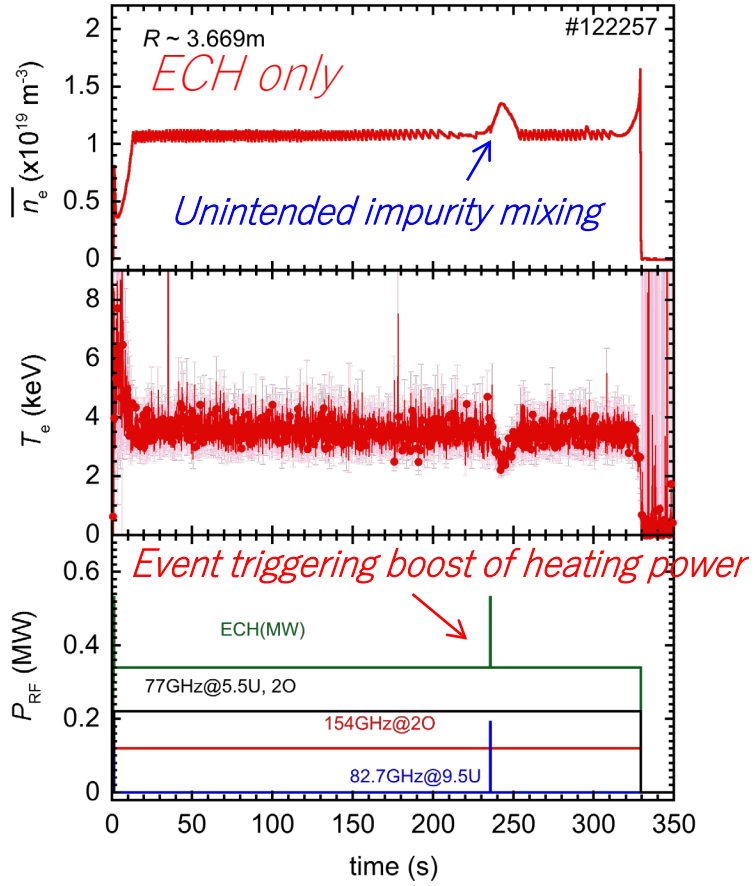
Plasma collapse

P_{rad}/P_{RF} > 40 %.

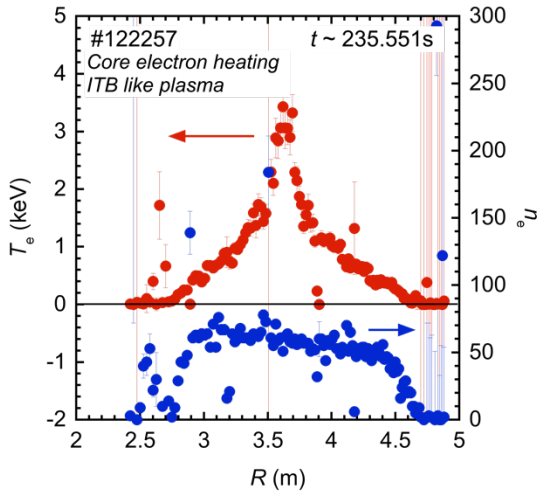
Impurity mixing easily occurs with low temperatures.

Core electron heating and event-triggering boost of heating power make a robust steady-state plasma

Core electron heating power was increased (77GHz and 154GHz), P_{ECH} ~ 0.34MW.

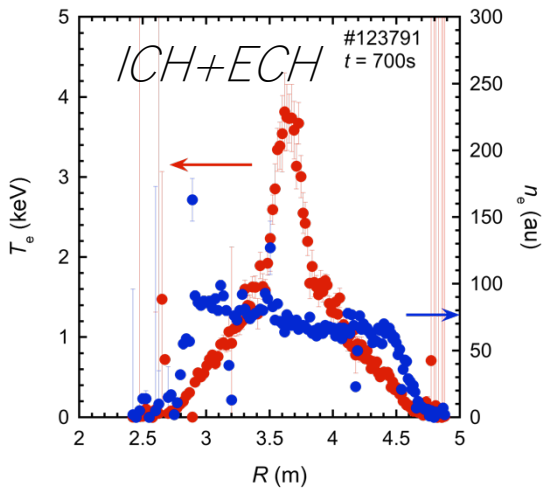


e-ITB plasma was sustained during SSO.



e-ITB plasma was sustained using ECH+ICH, too.

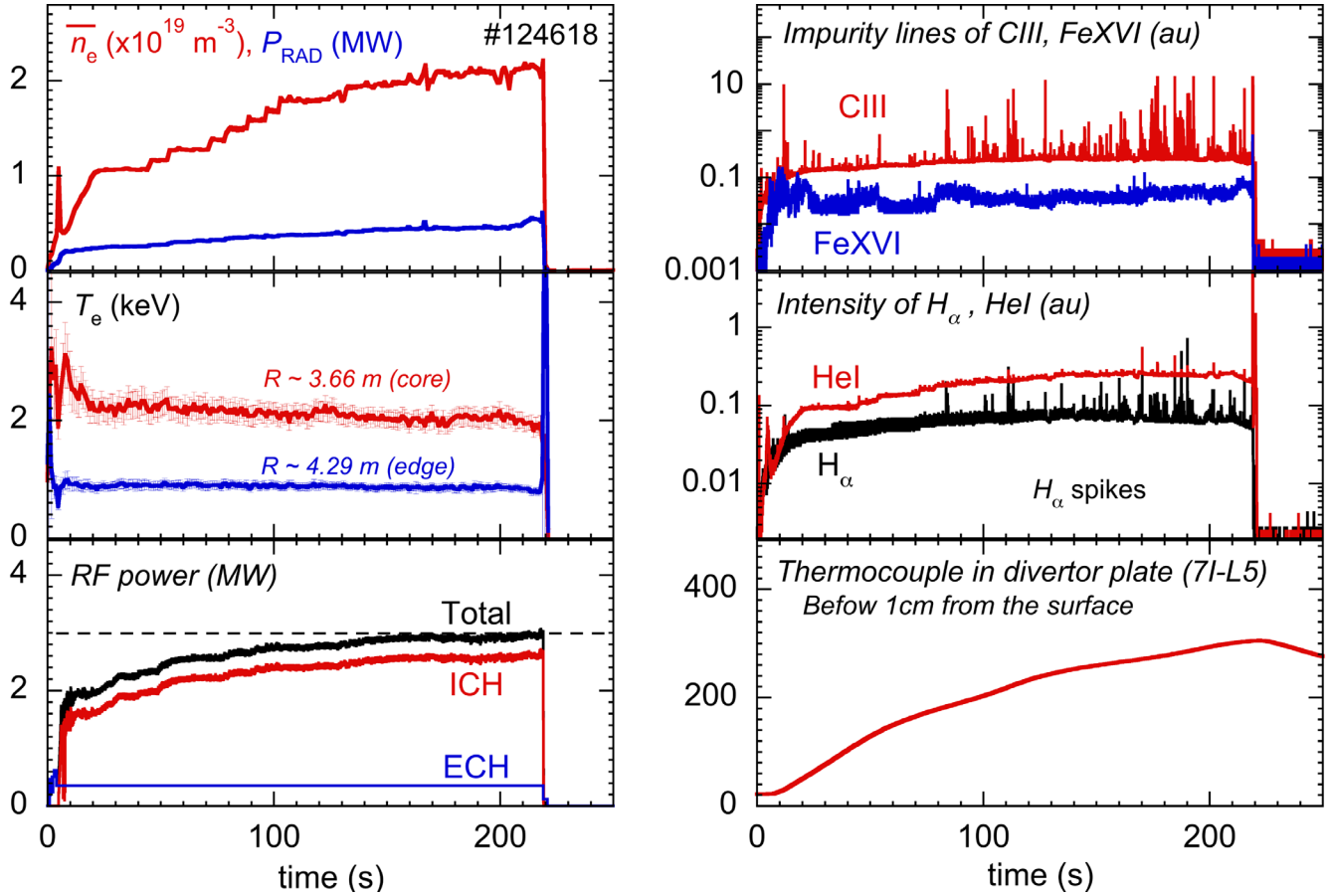
$P_{ICH+ECH}$ = 0.93MW (P_{ECH}=0.33MW)
n_e ~ 1x10^{19} m^{-3}, 11 min.



- *Increasing the power (>0.3MW) of core electron heating (77, 154GHz) quickly made e-ITB plasma during SSO, and it stably kept core electron temperature high.*
- *Event triggering boost of heating power was effectively carried out to maintain the plasma.*

First trial of the high-power steady-state heating (2-3MW) with the design value of the LHD.

Command values of RF heating power and electron density were manually increased after confirming the health of heating devices and LHD devices.



The apparent correlation between H_α and CIII was first observed, and it was a key role to understand the impurity invasion.