Progress of Steady State Experiment in LHD

Presented by T. Seki

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Collaborators

T. Seki, T. Mutoh, R. Kumazawa, K. Saito, H. Kasahara, S. Kubo, T. Shimozuma, Y. Yoshimura, H. Igami, H. Takahashi, N. Ashikawa, S. Masuzaki, M. Tokitani, F. Shimpo, G. Nomura, C. Takahashi, M. Yokota, A. Kato, Y. Takita, S. Kobayashi, Y. Mizuno, S. Ito, H. Okada[a], K. Sakamoto[b], T. Imai[c], T. Kariya[c], R. Minami[c], Y.P. Zhao[d], J.G. Kwak[e], A. Komori, O. Motojima, and LHD Experimental Group

National Institute for Fusion Science,322-6 Oroshi-cho, Toki 509-5292, Japan
[a]*Institute of Advanced Energy, Kyoto University, Uji, Kyoto 611-0011, Japan*
[b]*Japan Atomic Energy Agency, 801-1, Mukoyama, Naka 311-0193, Japan*
[c]*Plasma Research Center, University of Tsukuba, Tsukuba 305-8577, Japan*
[d]*Institute of Plasma Physics, Academia Sinica, Hefei 230031, P.R. China*
[e]*Korea Atomic Energy Research Institute, Daejeon 305-600, Korea Rep.*

Outline

- Introduction
- Progress of ECH long pulse experiment
  – Experimental setup
  – Experimental result
- Progress of ICRF long pulse experiment
  – Experimental setup
  – Experimental result
    - Minority heating experiment
    - Mode-conversion heating experiment
- Summary & future plan

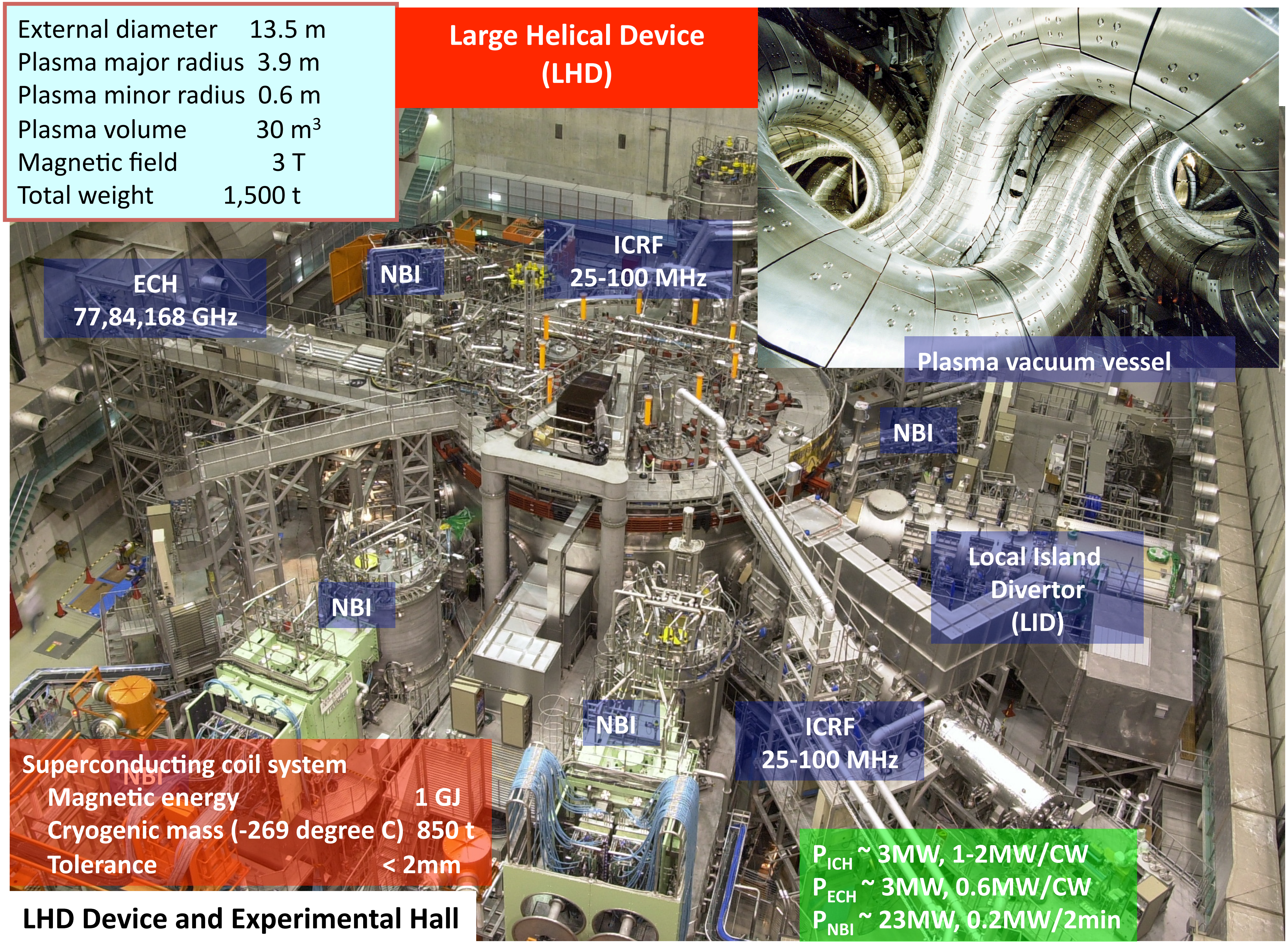
Introduction

Purpose and importance of steady state experiment in LHD

- Steady state operation is one of key issues for reactor plasma study
  - To demonstrate steady state operation is one of missions of LHD
  - Research of plasma-wall interaction, divertor physics, particle control, heat removal using long pulse plasma discharge
  - Obtain knowledge about steady state operation for future reactors
- Superconducting coil is needed for the discharge more than several minutes
  - Helical device has an advantage over tokamak device for steady state operation because of no need of driven current
- Stable and reproducible high power long pulse discharges are required
  - Establishment of method and technique
  - High power injection

Large Helical Device (LHD)

External diameter	13.5 m
Plasma major radius	3.9 m
Plasma minor radius	0.6 m
Plasma volume	30 m^3
Magnetic field	3 T
Total weight	1,500 t



Superconducting coil system

Magnetic energy	1 GJ
Cryogenic mass (-269 degree C)	850 t
Tolerance	< 2mm

P_{ICH} ~ 3MW, 1-2MW/CW
P_{ECH} ~ 3MW, 0.6MW/CW
P_{NBI} ~ 23MW, 0.2MW/2min

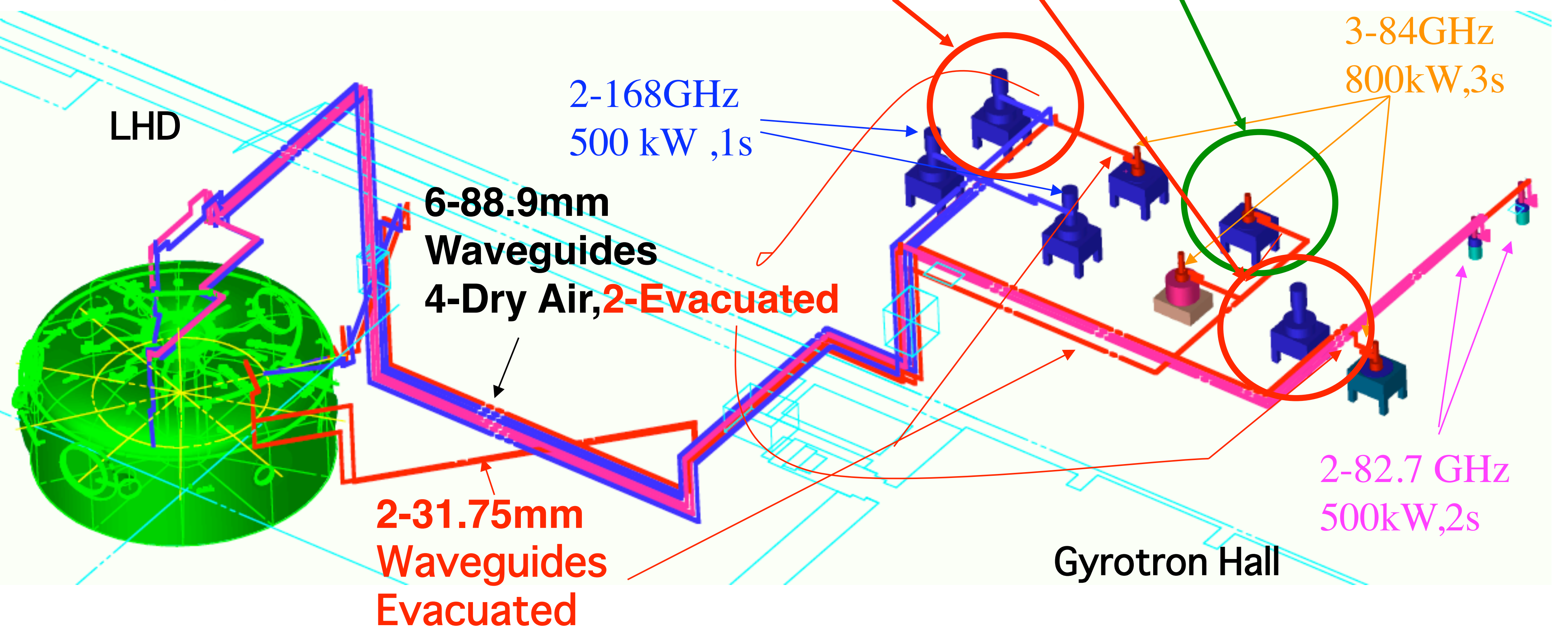
LHD Device and Experimental Hall

Progress of
ECH long pulse experiment

ECH system for LHD

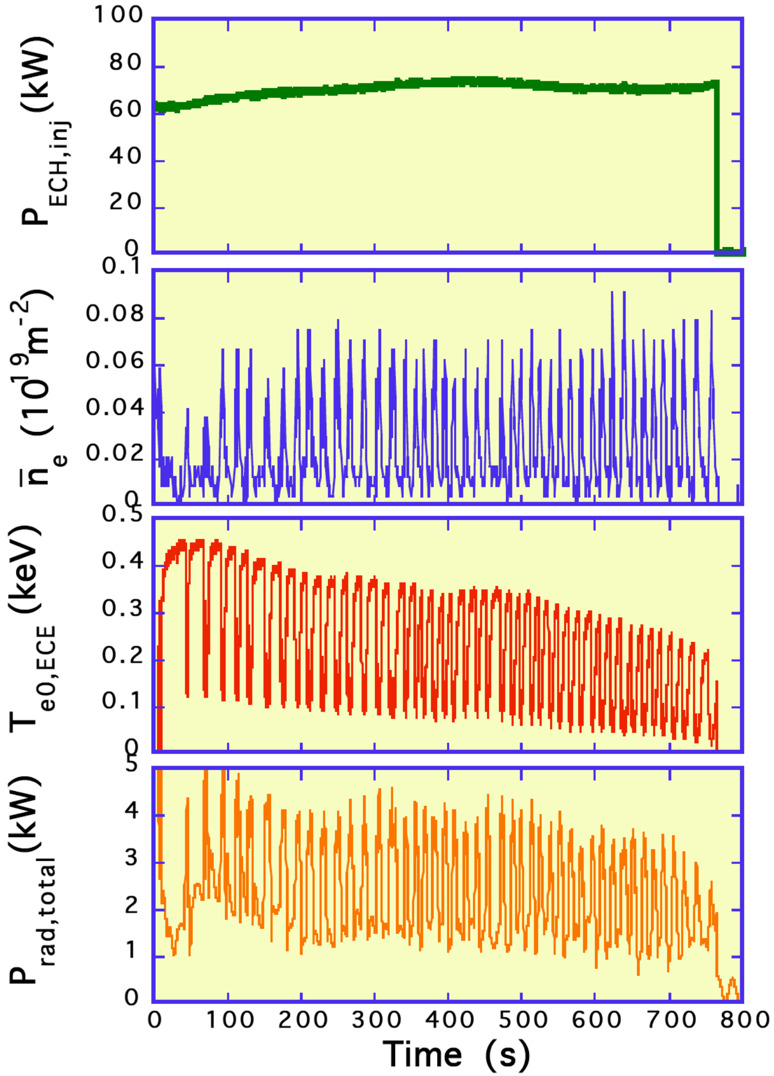
- 2-168GHz 500 kW 1s 88.9mm Corrugated Waveguide
- 2- 84 GHz 800 kW 3s 31.75mm Corrugated Waveguide (Evacuated)
  - **Swithable to 84GHz 500 kW 10s/ 200 kW 1000s**
- 1- 84 GHz 800 kW 3s 88.9mm Corrugated Waveguide (Evacuated)
- 2-82.7GHz 500kW 2s 88.9mm Corrugated Waveguide
- **2-77 GHz 1MW 3s/ 0.3 MW CW 88.9mm Corrugated Waveguide (Evacuated)**

CW gyroton

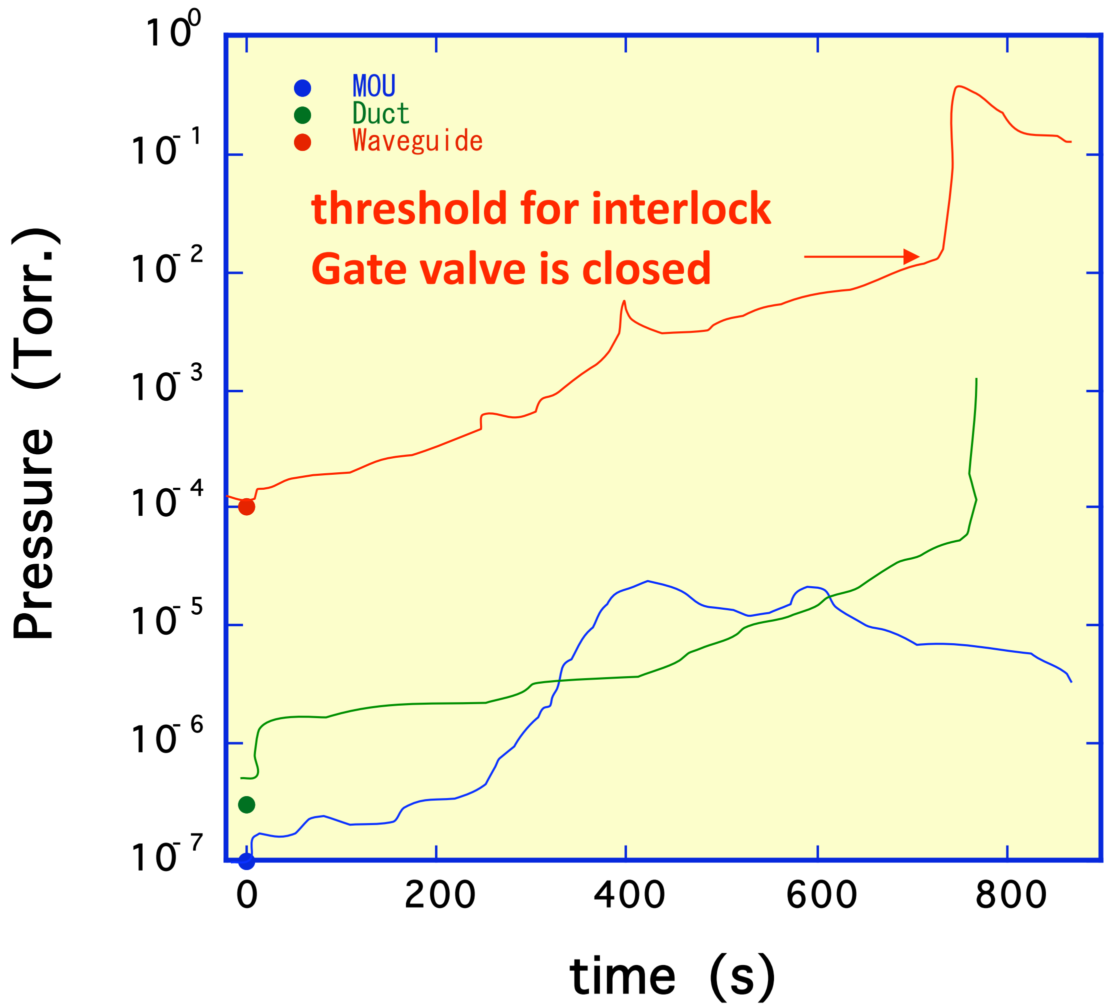


Initial LHD ECH long pulse experiment 756 sec discharge (shot #48821)

- R_{axis}=3.5 m
- B = 2.829 T
- $P_{ECH,in}$ = 72 kW (84GHz)
- $n_{e,av}$ = 2.4 x 10^{17} m^{-3}
- $T_{e0,ECE}$ =240 eV
  - repetitive gas puff
    - 2ms/1Hz
    - Manually switched not to cause radiation collapse
  - Stopped by pressure rise of ECH transmission line

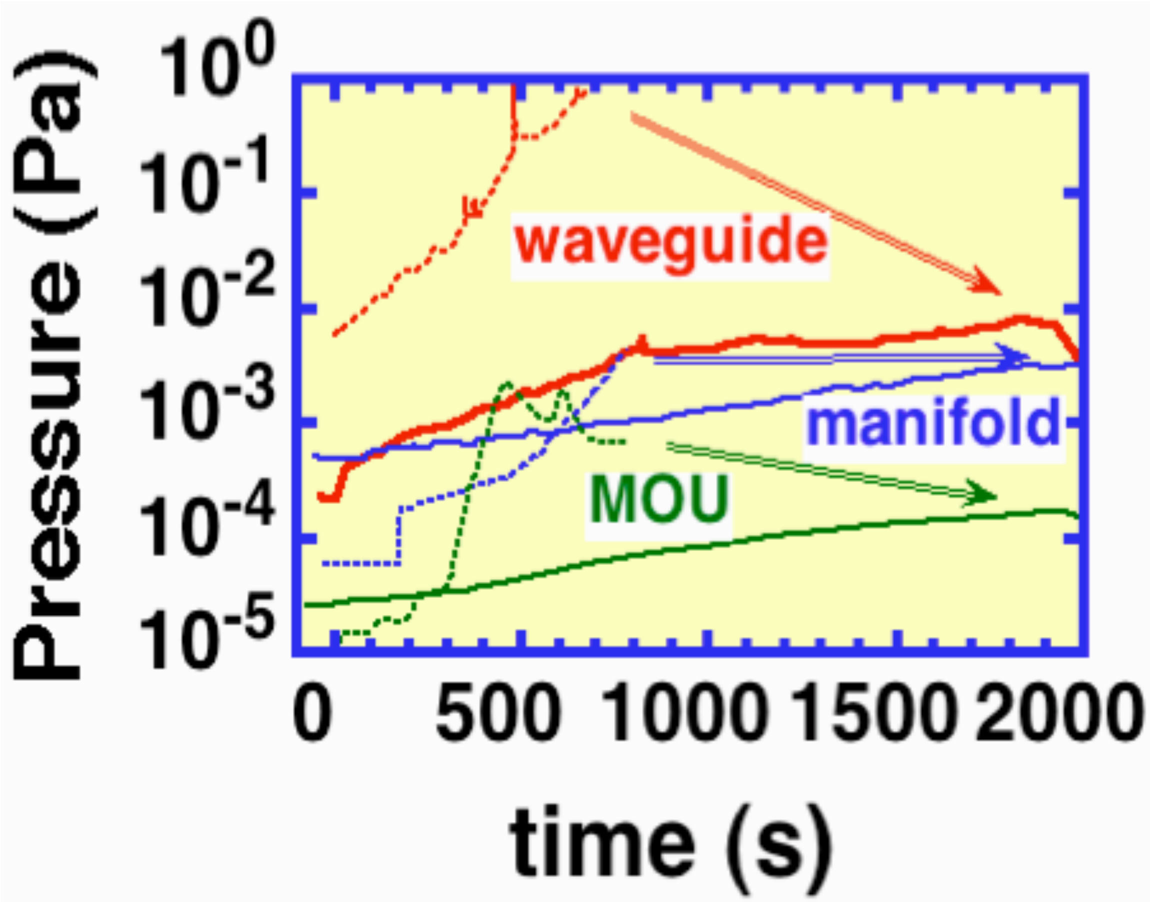


Pressure rise in MOU/waveguides



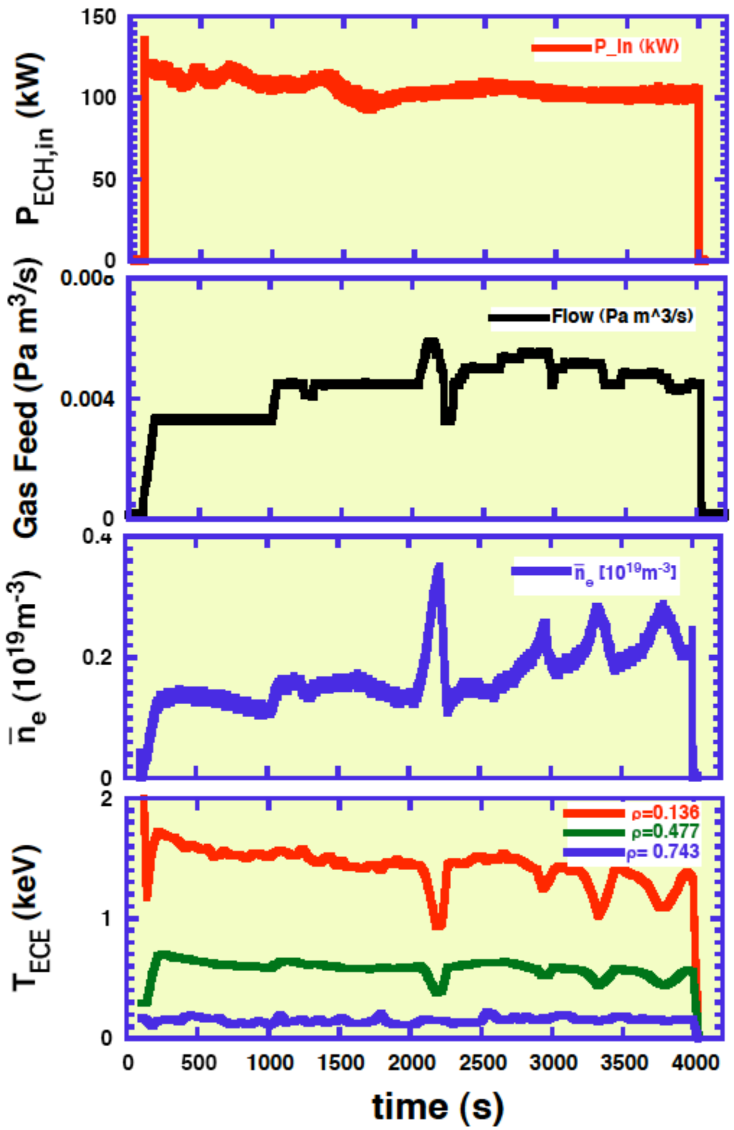
- Pulse stopped due to increase of pressure in the waveguide
  - Out gassing from wall
  - Poor conductivity in waveguide
- Initial and constant pressure rise may be due to increase of out gassing by temperature rise of waveguide wall
- Latter half increase of pressure may be due to a leak at DC break (damaged)

Improvement of evacuation system is effective for steady state operation



- Pumping port for waveguide system is increased up to 9 along transmission line
- Out gassing rate decreased due to efficient conditioning by increased pumping rate and enforced cooling of waveguide section
- Maximum pressure decreased shot by shot

ECH succeeded one hour plasma sustainment with 110 kW/65min injection

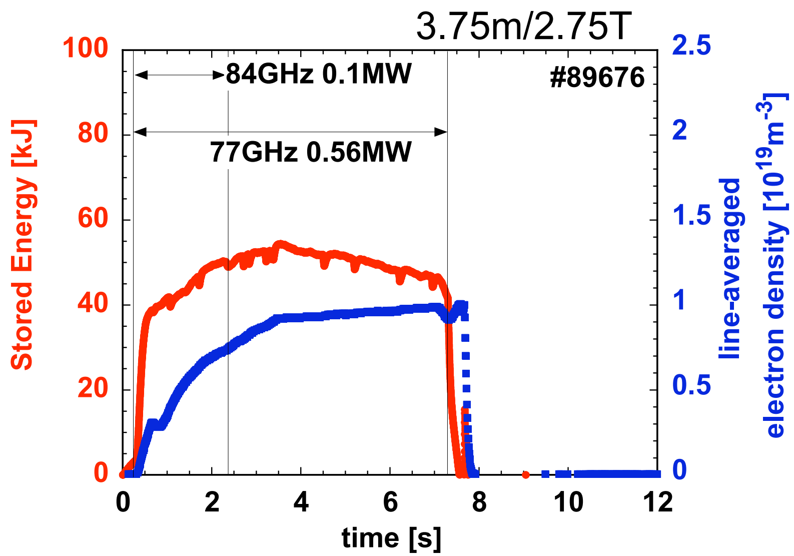


- B=1.48T, R_{ax}=3.6m
- 2nd harmonic heating (84GHz)
- P_{in}~110 kW, 65 minutes
- T_{e0}>1.0~1.5 keV
- n_e>1.5x10^{18} m^{-3}
- Gas feed controlled manually by mass flow controller
  - Tried to increase density after 2000s
- ECH terminated manually
  - Due to the data acquisition setting

New two steady state gyrotrons (77GHz) (developed with Tsukuba Univ.)

At Tsukuba

- 1 MW / 5s each
- 0.36 MW / CW（MOU output）each
  - –Same design with ITER 170 GHz gyrotron
- 88.9mm corrugated evacuated waveguide
- Cooled mirror antenna
- Center-focused electron heating
- CW ECH output from the antenna: 100kW (84GHz) + (210kW +350kW) (new 77GHz)
- Steady state experiment will be carried out soon



$10^{19}m^{-3}$ was achieved by 77GHz ECH injection

Progress of
ICRF long pulse experiment

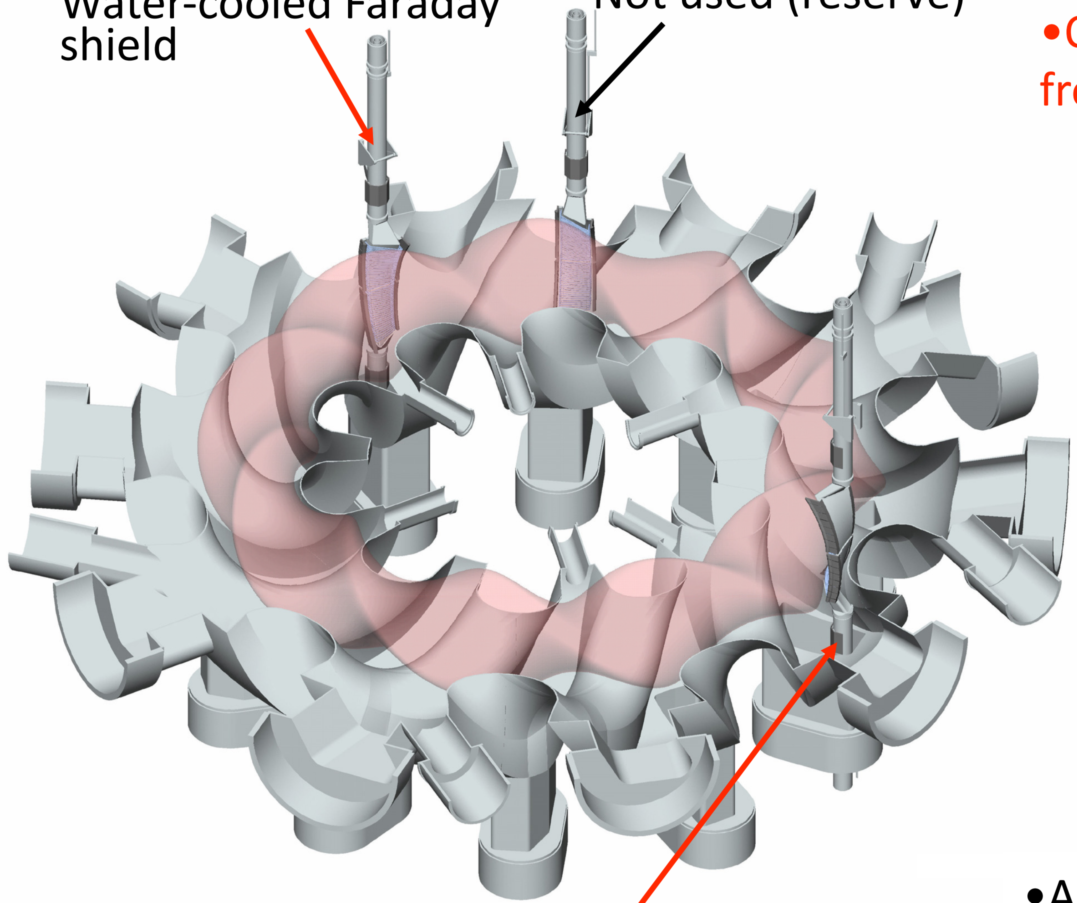
Experimental device
ICRF heating antenna

3.5UL antenna

Water-cooled Faraday shield

4.5UL antenna

Not used (reserve)

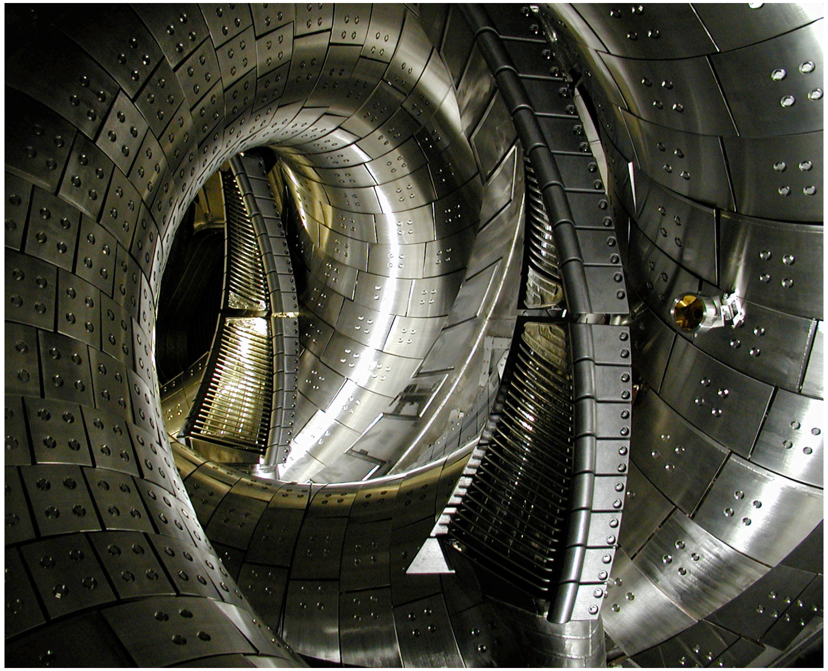


7.5UL antenna

Heat conduction cooling for Faraday shield

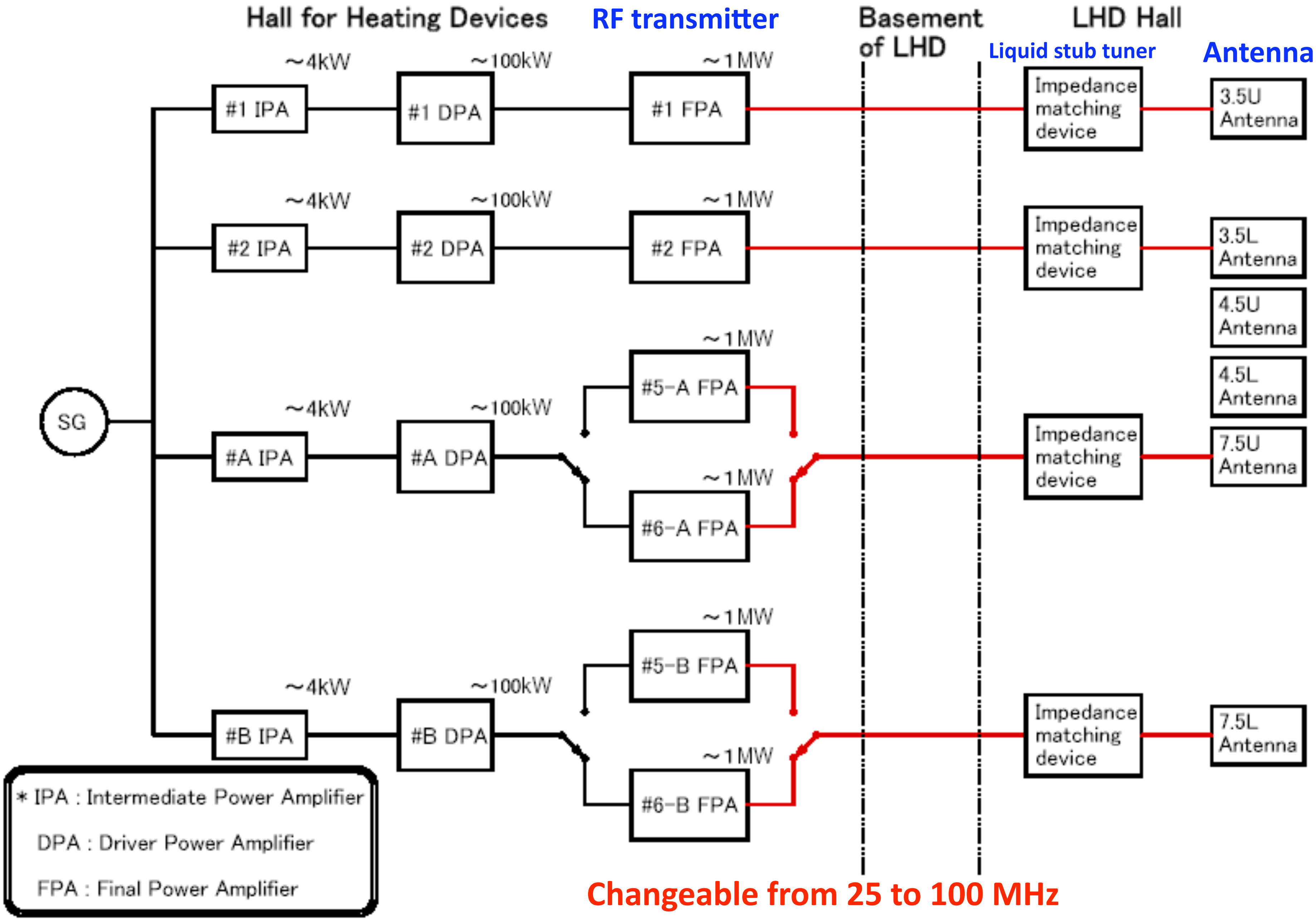
Loop antenna for fast wave launching

- Movable 15cm in horizontal direction
- Operated at wall position (13 or 14cm away from last closed flux surface)

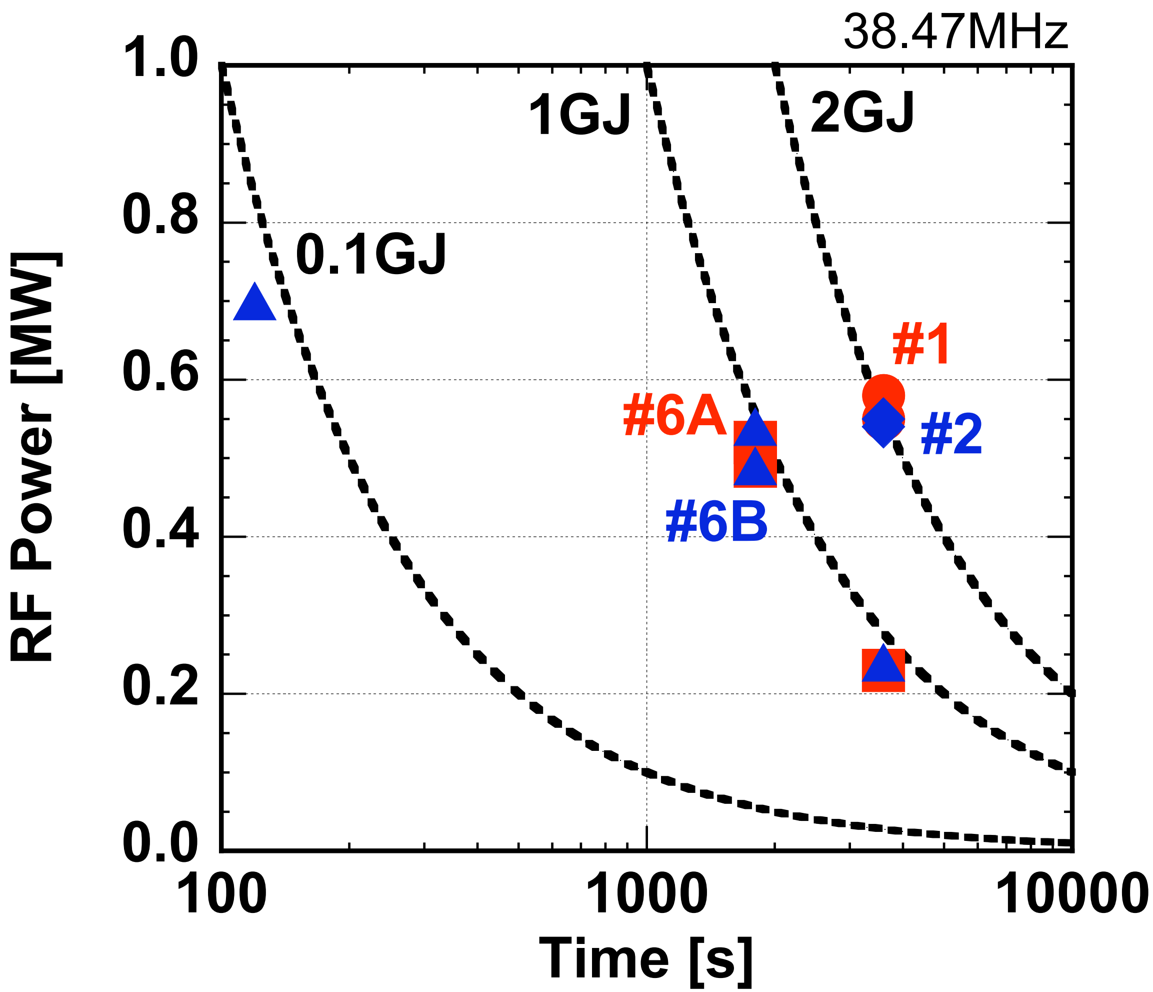


- Almost all parts are water-cooled

Diagram of ICRF heating system



Operational test of RF transmitters were carried out using steady state dummy load



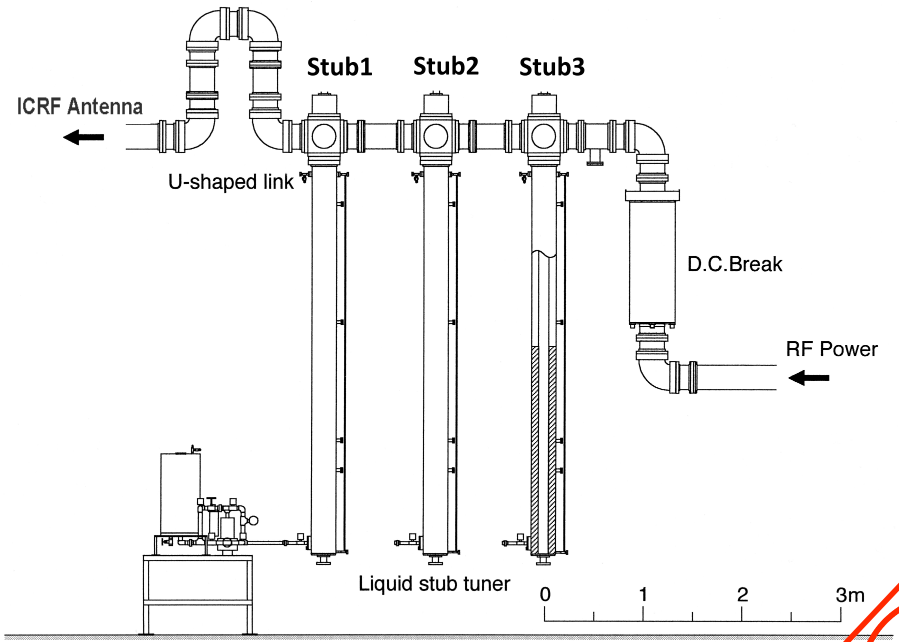
- #1: 4CM2500KG
  - =>3.5U antenna
  - 0.55MW / 1h
- #2: 4CM2500KG
  - =>3.5L antenna
  - 0.54MW / 1h
- #6A: TH525A
  - =>7.5U antenna
  - 0.52MW / 0.5h
  - 0.23MW / 1h
- #6B: TH525A
  - =>7.5L antenna
  - 0.49MW / 0.5h
  - 0.24MW / 1h

Total input energy: 6 GJ

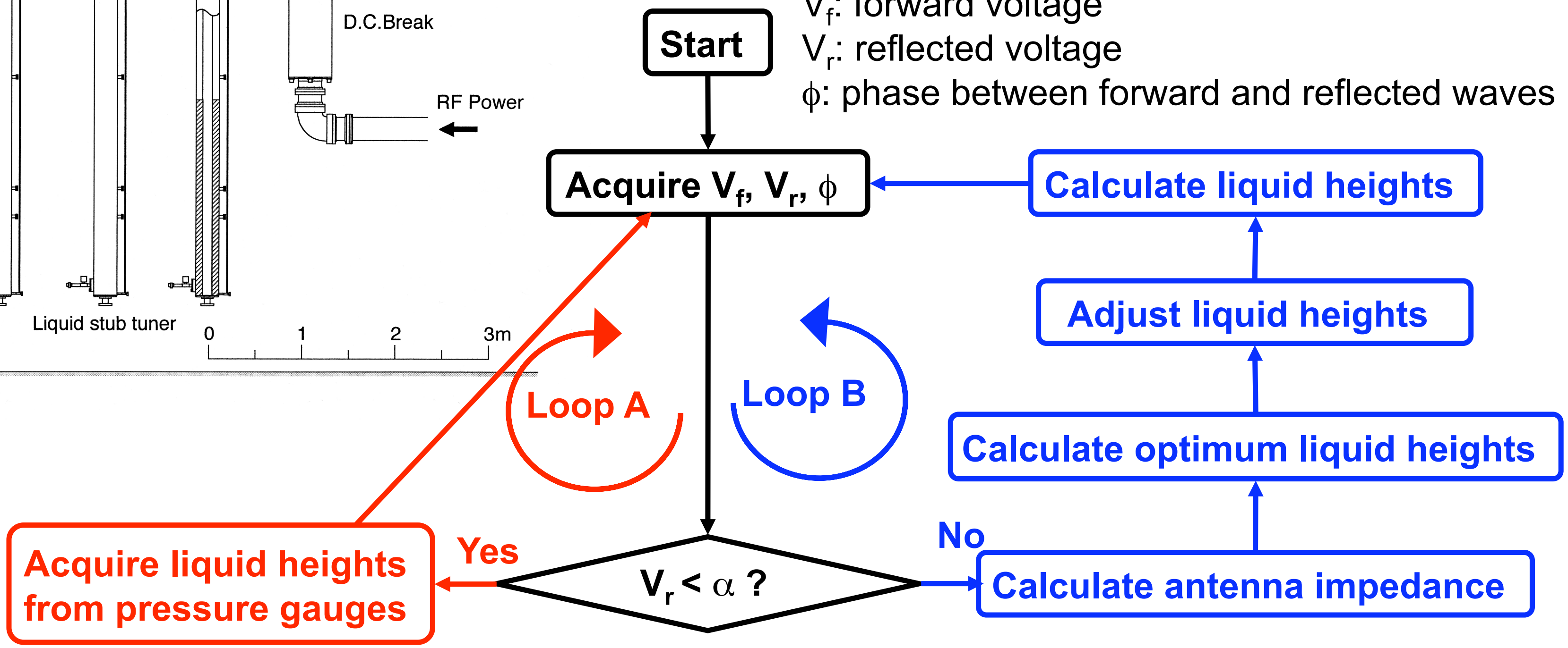
Real time impedance matching is very important for steady state operation

Liquid stub tuner system

Developed by NIFS



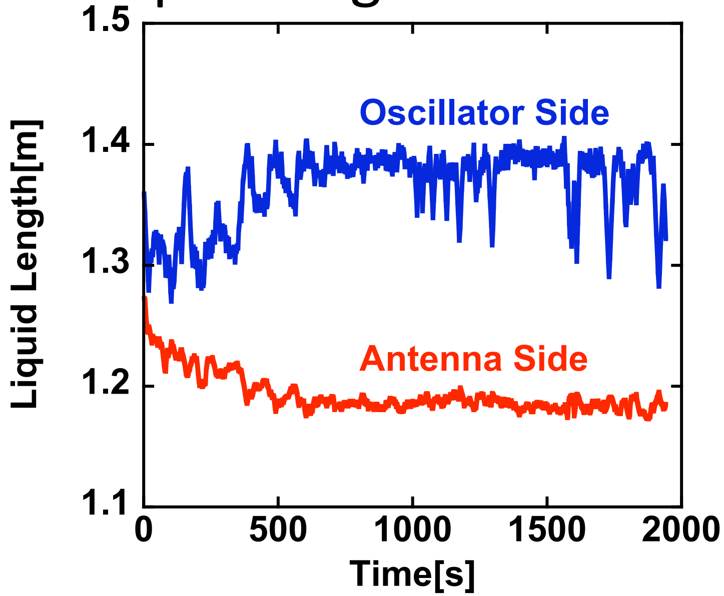
Flow chart of matching procedure



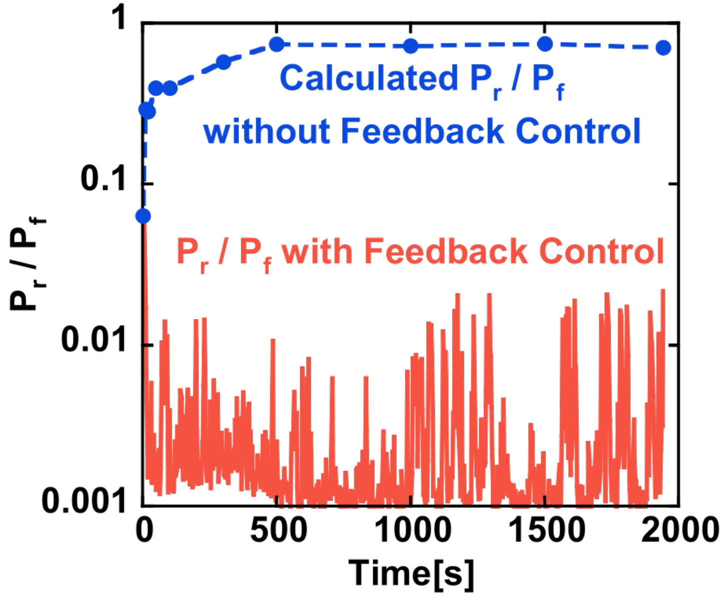
α: threshold voltage

Real time Impedance matching was successfully used for steady state operation

Time evolution of liquid length of stub



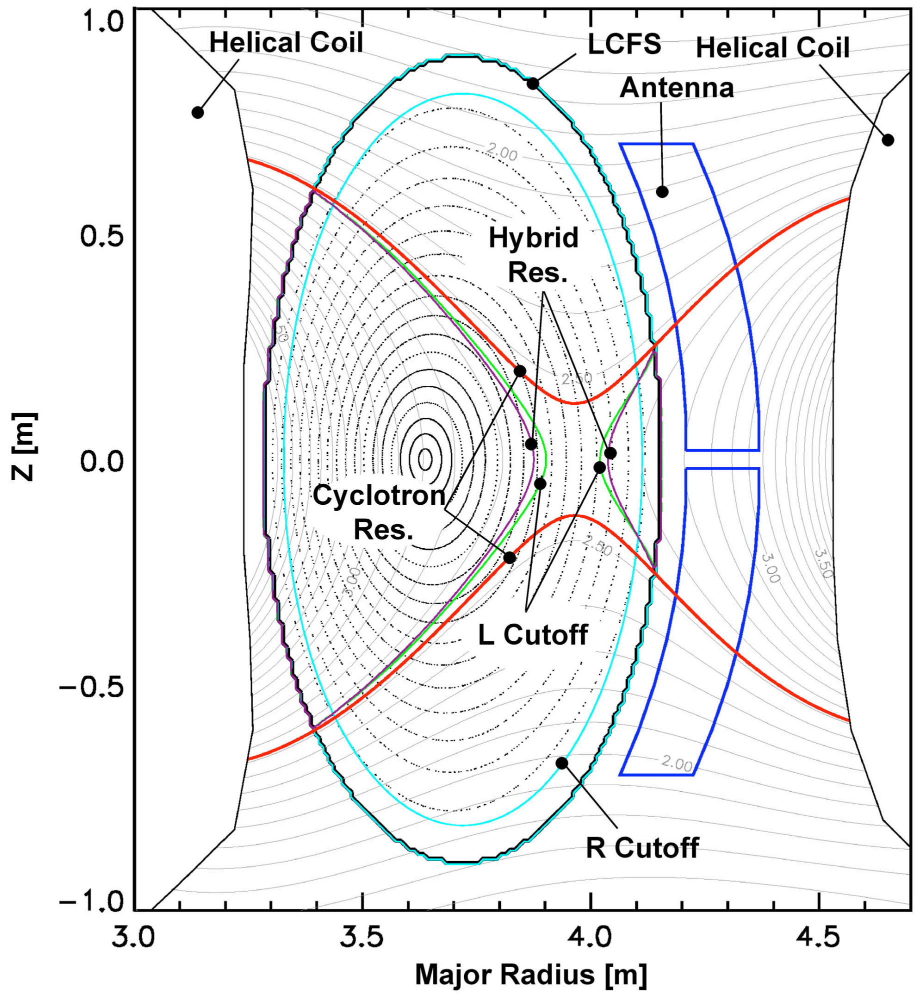
Time evolution of reflectivity



- Reflected power was reduced during RF injection by changing the liquid length with automatic feedback control
- Reflectivity was suppressed less than 2% in long pulse operation

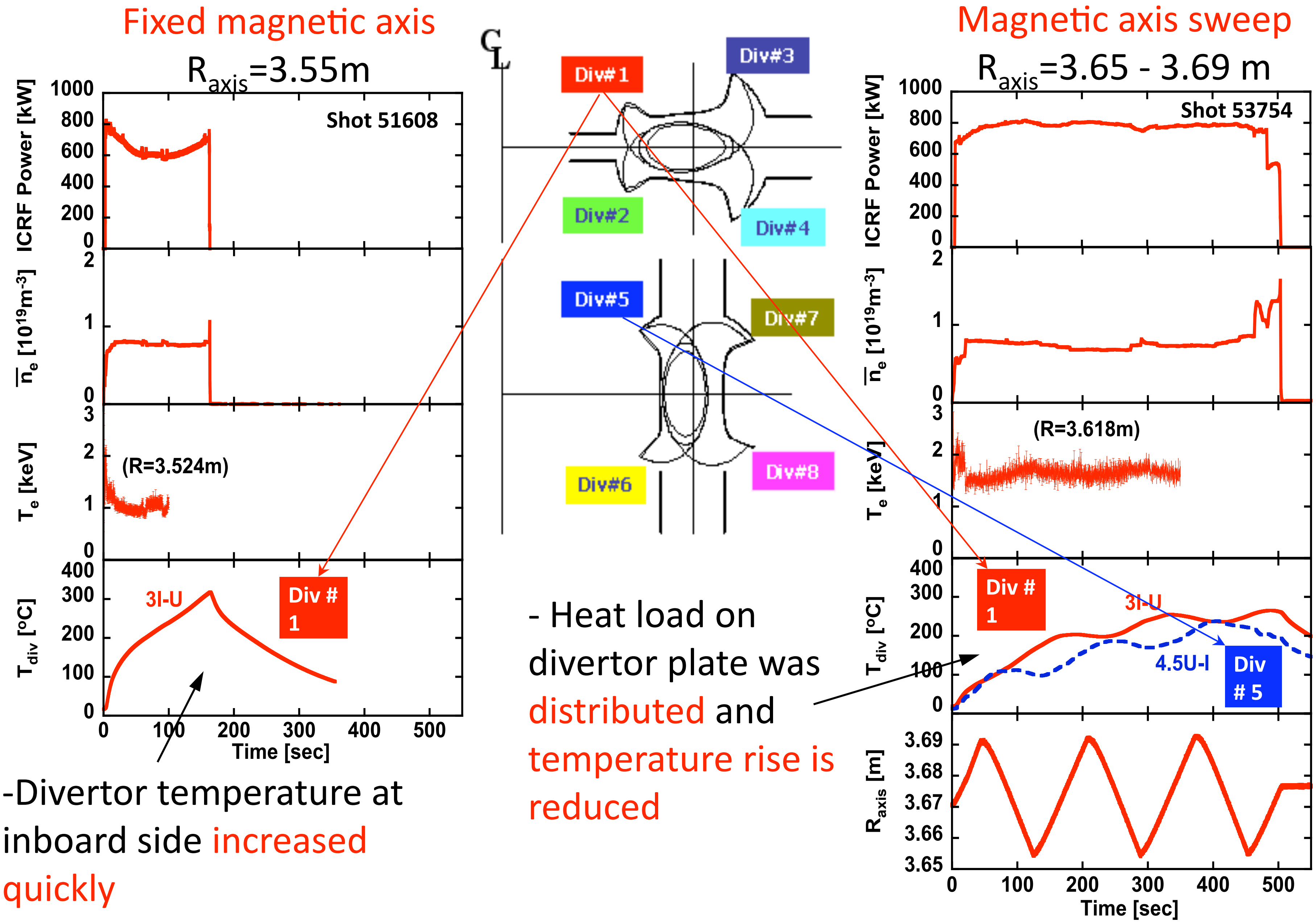
Experimental condition for ICRF heating

ion heating by minority heating



- Magnetic axis sweep based on B=2.75T, R_{ax}=3.6m
- Wave frequency: 38.47MHz
- He plasma mixed with minority H ions
- Ion cyclotron resonance layers are located at saddle point of magnetic configuration
- Heating efficiency in this configuration was the best in short pulse experiment

Mitigation of temperature rise of divertor plates was achieved by magnetic axis sweep

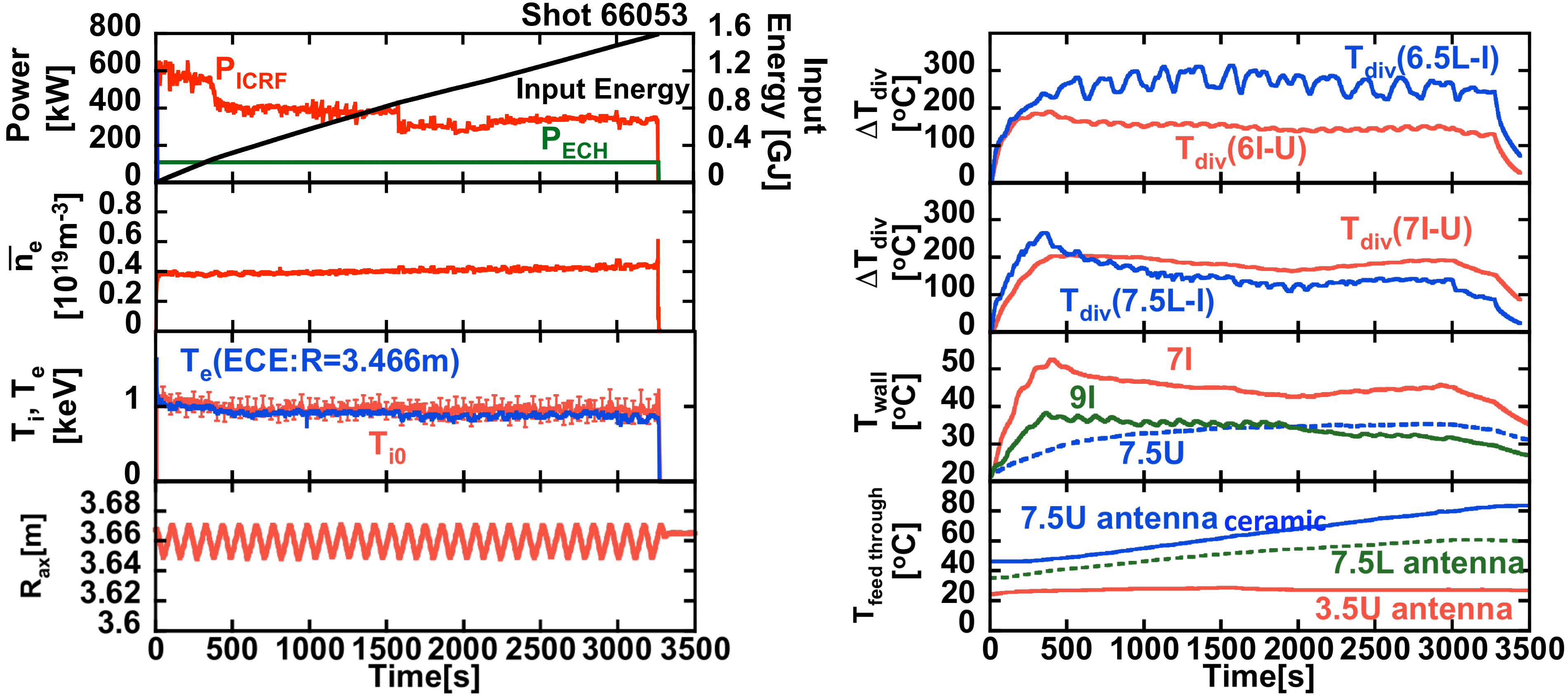


-Divertor temperature at inboard side increased quickly

- Heat load on divertor plate was distributed and temperature rise is reduced

Discharge of maximum input energy

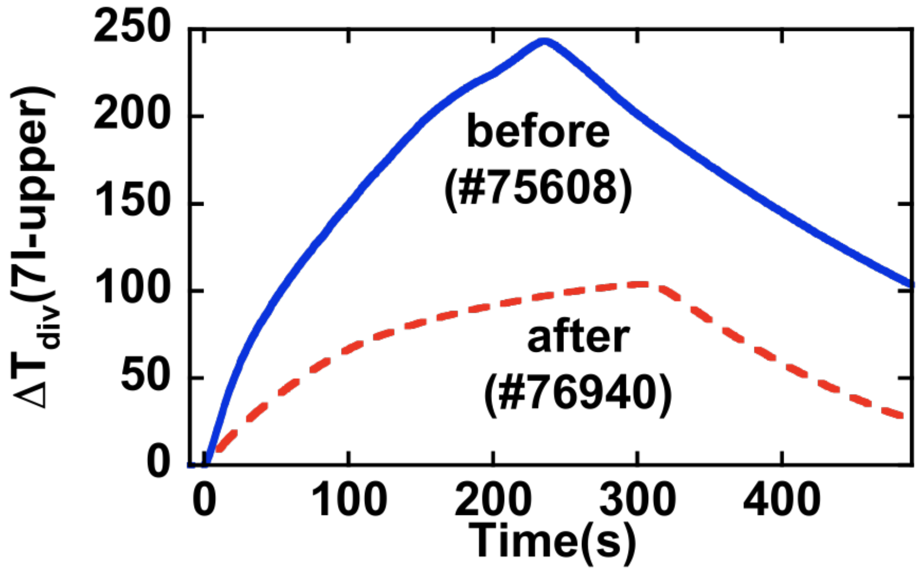
discharge time: 54min and 28sec, average input power: 490kW (ICRF,ECH), total heating energy: 1.6GJ



- Power control during plasma discharge with watching sparks in vacuum vessel
- R_{ax}=3.64-3.67m, n_e~$0.4\times10^{19}m^{-3}$, T_e~T_i~1keV
- Plasma was terminated by sudden increase of density caused by influx of iron impurity

Higher power operation was tried with improved divertor plates

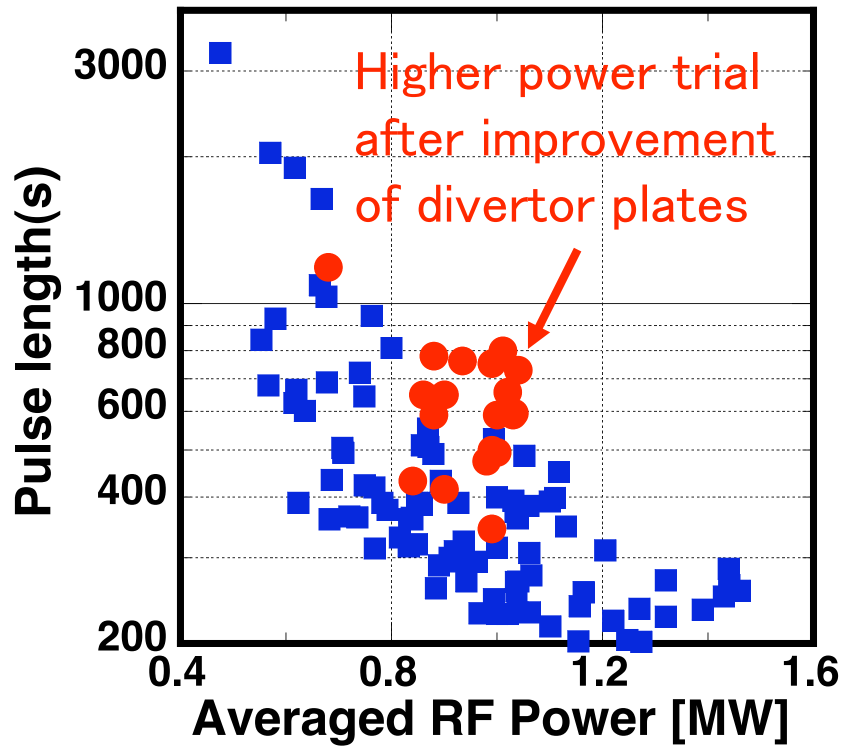
#75608(7.5U:283kW, 7.5L:289kW)
#76940(7.5U:307kW, 7.5L:241kW)



Temperature increase at 7-I upper divertor

- Temperature increase was reduced by improved divertor plates
- Intensive sparks near 7-I port were not observed

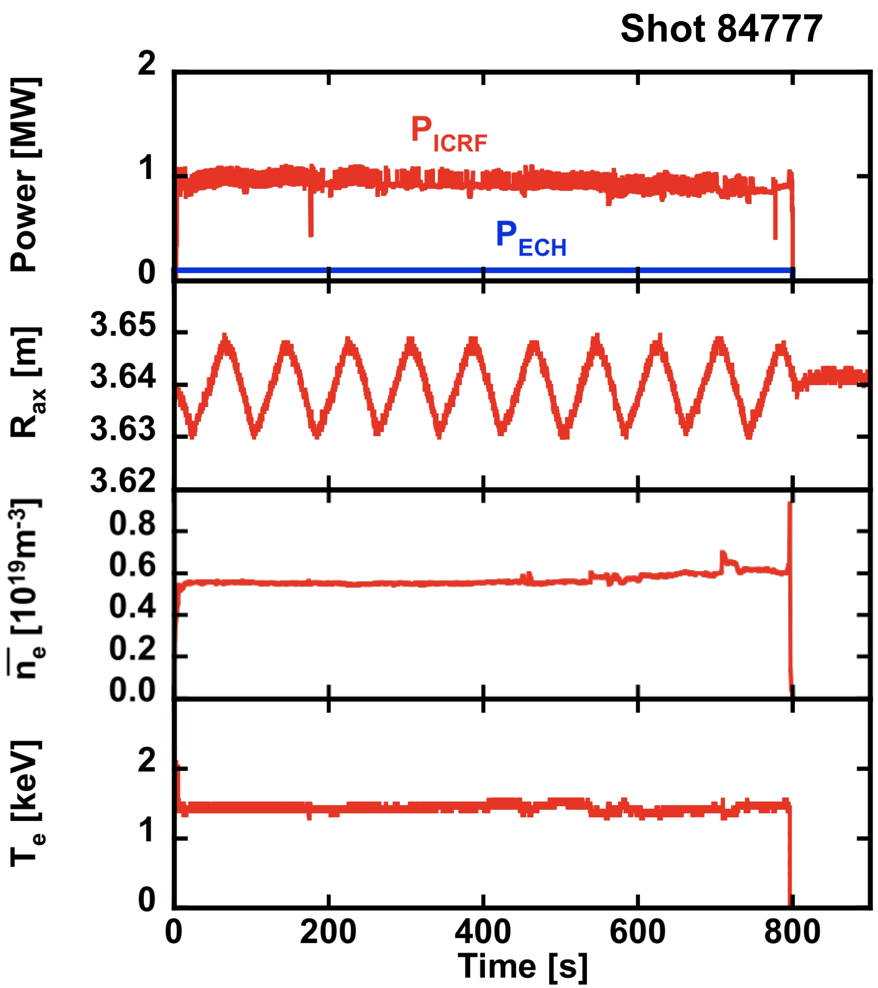
Relation between RF power and plasma pulse length



- Longer discharge time was achieved more than 1MW injection

Longest pulse discharge with MW level of heating power

B=2.85T(@R=3.6m), f=38.47MHz



P_{total}=1MW

P_{ICRF}=909kW (3.5U, 7.5L(two antennas))

P_{ECH}=100kW

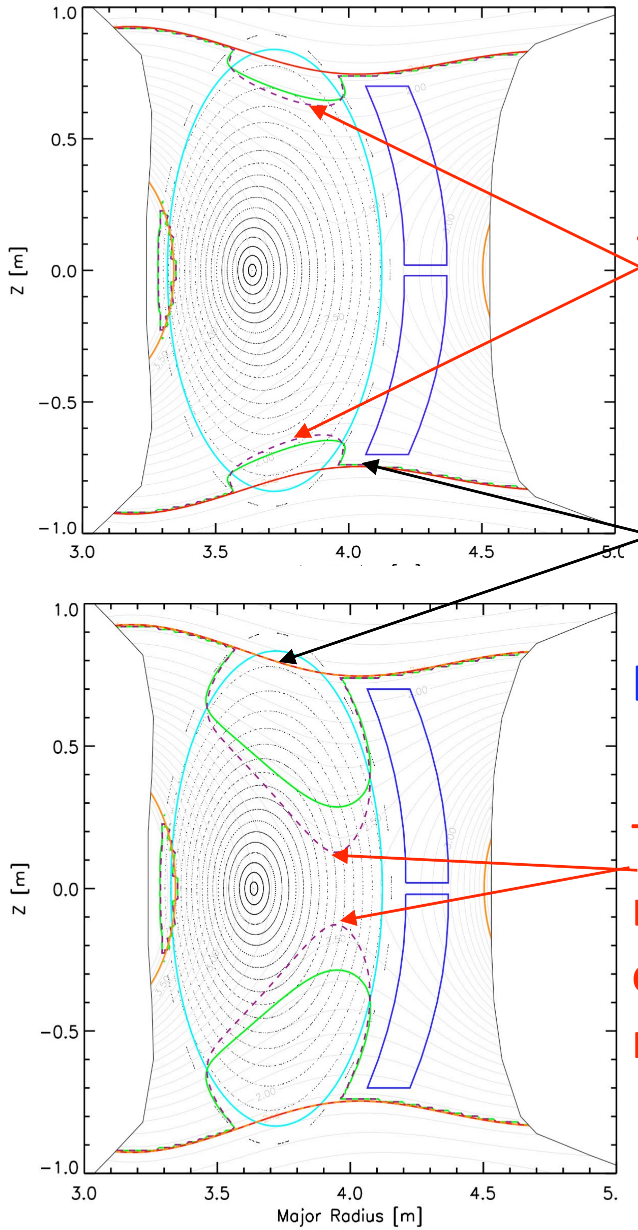
$T_{duration}$=800sec

- Plasma discharge time was extended in high power injection

Reducing localized temperature rise of divertor plates by mode-conversion heating

H/(H+He)=30%

f=28.4MHz, B_{ax}=2.75T



Two-ion hybrid resonance (mode-conversion resonance)

Ion cyclotron resonance

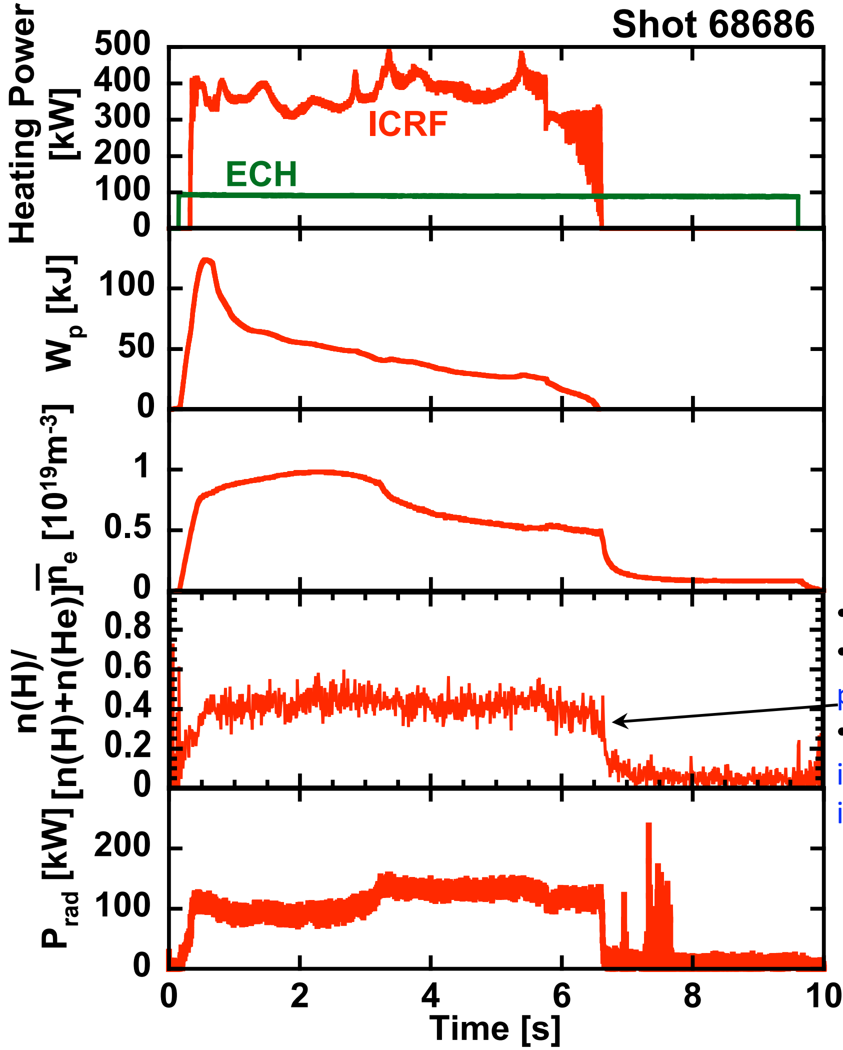
H/(H+He)=66.5%

Two-ion hybrid resonance (mode-conversion resonance)

- Hydrogen and helium mixed plasma
- Ion cyclotron resonance located at plasma peripheral region
  - Not at front of antenna
  - Weak coupling with ions
- Expect electron heating by mode-converted ion Bernstein wave
- High hydrogen ration will required to heat plasma core region

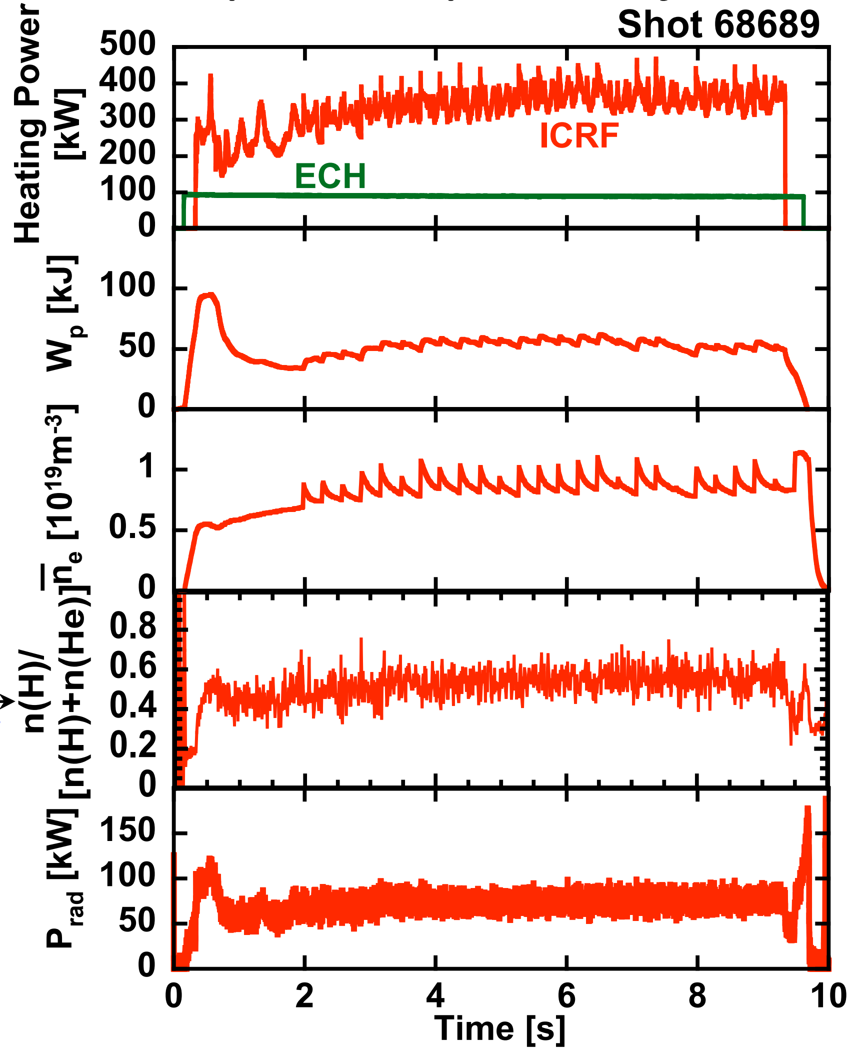
Hydrogen fueling by repetitive pellet injection was effective to keep the plasma performance

Without repetitive pellet injection



- From spectrometer
- Reflect the ratio at plasma surface
- Change of H ratio of inside plasma is important

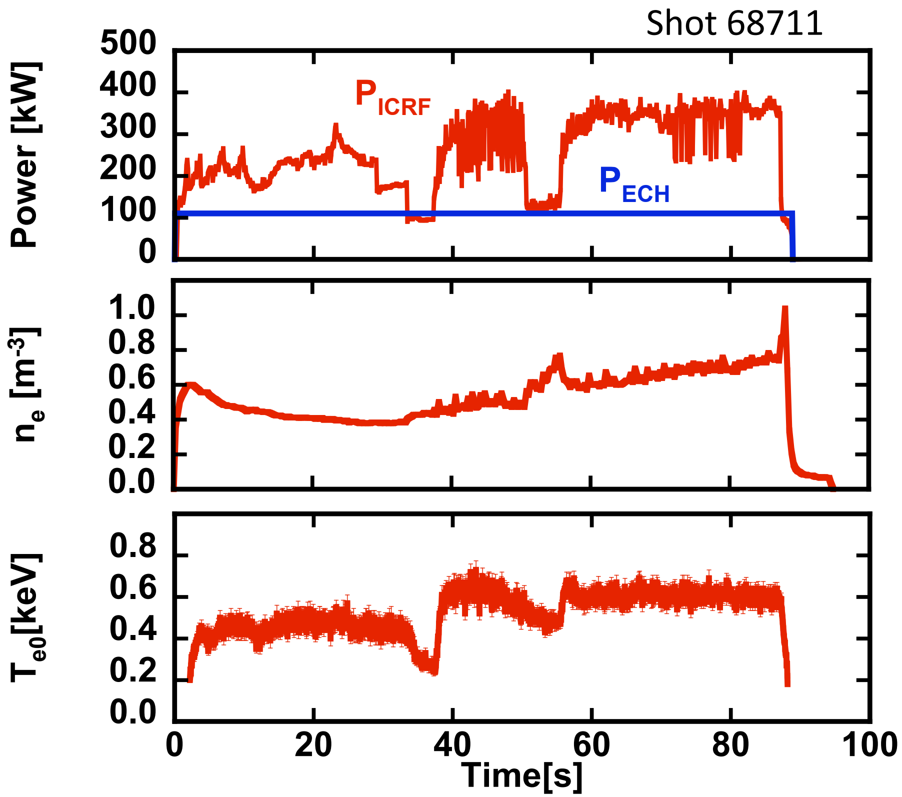
With repetitive pellet injection



- ECH target plasma
- Plasma was terminated during ICRF injection

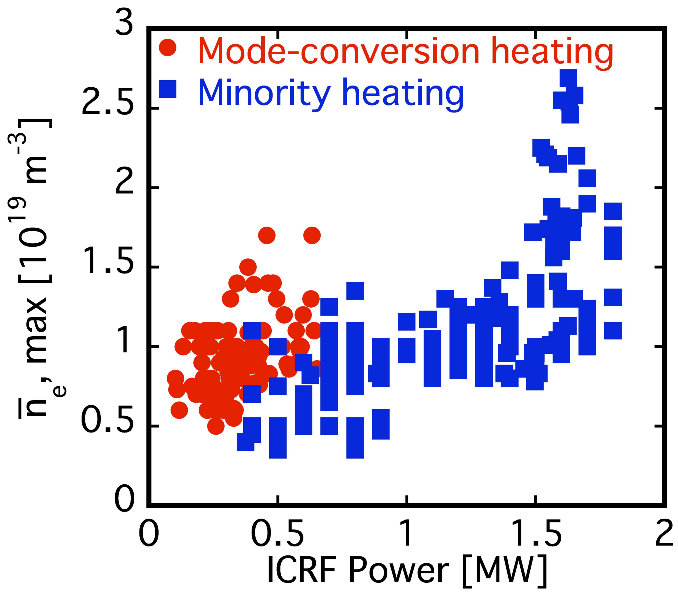
- Plasma was sustained during ICRF pulse
- Mode-conversion resonance moves inside with hydrogen ratio

Plasma was sustained more than one minute by mode conversion heating



- Plasma discharges more than one minutes was achieved
- Hydrogen ions are fuelled by repetitive pellet injection
- Spark was not observed
- Temperature increase at divertor plates and vacuum vessel was small (< 100 degree)
  - -Need to check at higher power and longer pulse operation

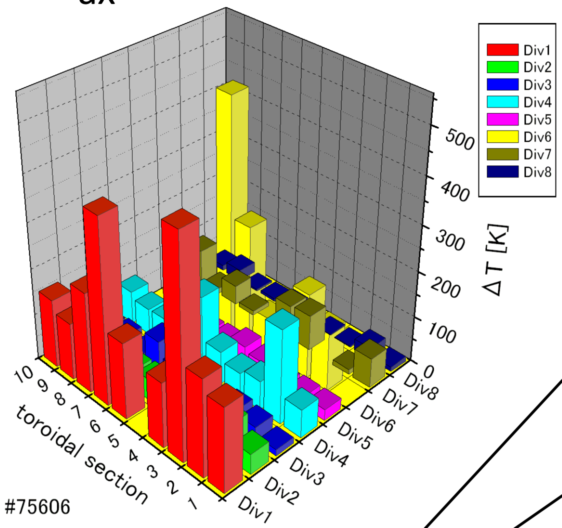
- Power was limited by voltage of transmission line
  - -Plasma loading resistance is small since the wave frequency is low
  - -High density operation increases loading resistance



Local heat load was scattered by mode-conversion heating

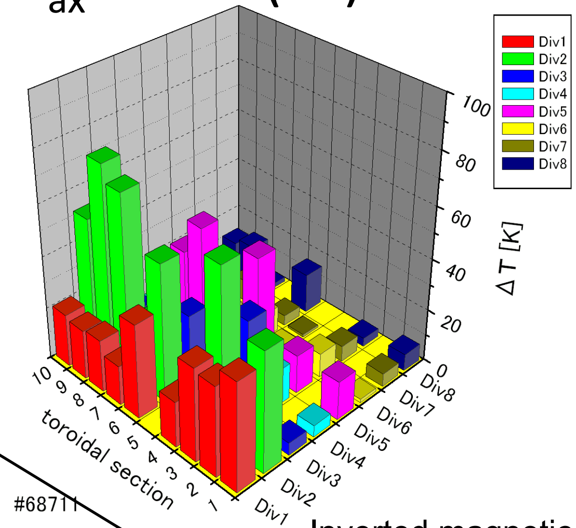
Minority heating

R_{ax}=3.64-3.67m

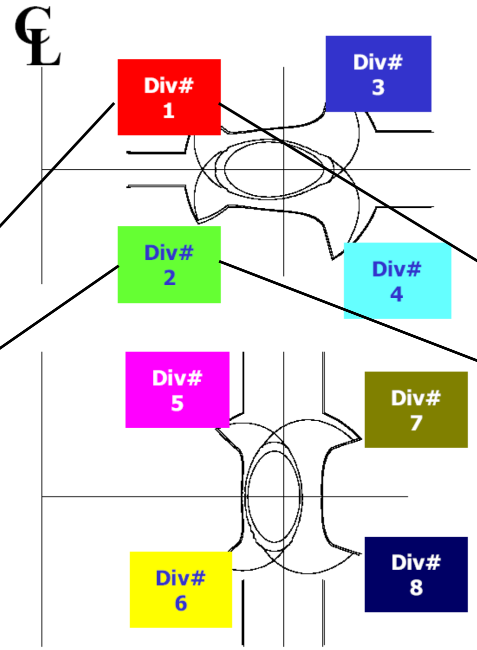


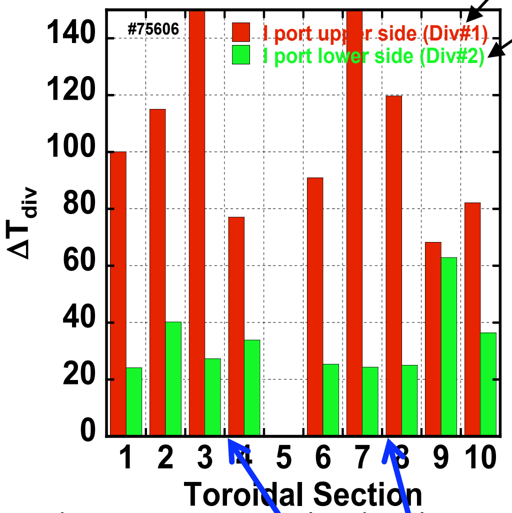
Mode-conversion heating

R_{ax}=3.6m (fix)

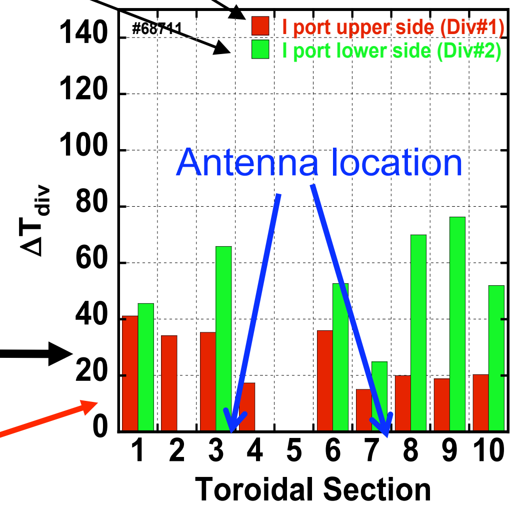


Inverted magnetic field





antenna: 3.5 & 7.5



Duration and power are normalized with #68711

ICRF antennas are located at 3.5 and 7.5 port

Scattering of heat load by electron heating

Summary

- Steady state operational region was much extended
  - 110kW / 65min by ECH
  - 490kW / 54min and 28sec, total input energy reached 1.6GJ (ICRF heating mainly)
  - 1MW / 800sec in high power injection (ICRF heating mainly)
- Key factors for steady state operation
  - Enforcement of pumping and cooling of transmission line for ECH
  - Scattering of local heat load on divertor plates for ICRF heating

Future plan

- ECH

-Higher power operation with new two 77GHz gyrotrons to achieve $10^{19}m^{-3}$ for ECH

-1MW CW is final target for ECH operation

- ICRF heating

-Trial of mode-conversion heating in higher density

-Longer pulse (>1hr) with higher power (>1MW) by minority heating

  - Reduce influx of iron impurity by high density discharge
  - 6 ICRF steady state transmitters will be available in next year

-3MW CW is final target for LHD