Progress of Steady State Experiment in LHD

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  – Experimental setup
  – Experimental result
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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
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

Large Helical Device (LHD)

ECH: 77,84,168 GHz
NBI: 25-100 MHz
ICRF: 25-100 MHz

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

LHD Device and Experimental Hall

NBI
Local Island Divertor (LID)
Plasma vacuum vessel

$P_{\text{ICH}} \sim 3 \text{MW, } 1\text{-}2 \text{MW/CW}$
$P_{\text{ECH}} \sim 3 \text{MW, } 0.6 \text{MW/CW}$
$P_{\text{NBI}} \sim 23 \text{MW, } 0.2 \text{MW/2min}$
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)
  - Switchable 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)
Initial LHD ECH long pulse experiment
756 sec discharge (shot #48821)

- $R_{\text{axis}} = 3.5 \text{ m}$
- $B = 2.829 \text{ T}$
- $P_{\text{ECH,in}} = 72 \text{ kW (84GHz)}$
- $n_{e,av} = 2.4 \times 10^{17} \text{ m}^{-3}$
- $T_{e0,ECE} = 240 \text{ eV}$
  - 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

- $B=1.48\,T$, $R_{ax}=3.6\,m$
- 2nd harmonic heating (84GHz)
- $P_{in}\sim110\,kW$, 65 minutes
- $T_{e0}>1.0\sim1.5\,keV$
- $n_e>1.5\times10^{18}\,m^{-3}$
- 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.)

- 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}\text{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

- **Hall for Heating Devices**
  - #1 IPA
  - #2 IPA
  - #A IPA
  - #B IPA
  - ~4kW
  - ~100kW

- **RF transmitter**
  - #1 DPA
  - #2 DPA
  - #A DPA
  - #B DPA
  - ~100kW

- **Basement of LHD**
  - #1 FPA
  - #2 FPA
  - #5-A FPA
  - #6-A FPA
  - ~1MW

- **LHD Hall**
  - Liquid stub tuner
  - Impedance matching device
  - 3.5U Antenna
  - 3.5L Antenna
  - 4.5U Antenna
  - 4.5L Antenna
  - 7.5U Antenna
  - 7.5L Antenna

- **Antenna**
  - ~1MW

*IPA: Intermediate Power Amplifier*
*DPA: Driver Power Amplifier*
*FPA: Final Power Amplifier*

Changeable from 25 to 100 MHz
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

- **Start**
- **Acquire** $V_f, V_r, \phi$
  - **Loop A**
    - **Acquire liquid heights from pressure gauges**
    - Yes
  - **Loop B**
    - **Calculate liquid heights**
    - **Adjust liquid heights**
    - **Calculate optimum liquid heights**
    - No
    - $V_r < \alpha$?
      - **Calculate antenna impedance**
      - $\alpha$: threshold voltage

Symbols:
- $V_f$: forward voltage
- $V_r$: reflected voltage
- $\phi$: phase between forward and reflected waves
Real time Impedance matching was successfully used for steady state operation

- 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

Fixed magnetic axis
$R_{\text{axis}} = 3.55 \text{m}$

Magnetic axis sweep
$R_{\text{axis}} = 3.65 - 3.69 \text{m}$

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

- Divertor temperature at inboard side increased quickly
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

• $R_{ax} = 3.64-3.67m$, $n_e \sim 0.4 \times 10^{19} m^{-3}$, $T_e \sim T_i \sim 1$keV

• Plasma was terminated by sudden increase of density caused by influx of iron impurity
Higher power operation was tried with improved divertor plates

\[ \Delta T_{\text{div}}(7\text{-I upper}) \]

- 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

Higher power trial after improvement of divertor plates

• 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

- $P_{\text{total}}=1\text{MW}$
- $P_{\text{ICRF}}=909\text{kW}$ (3.5U, 7.5L (two antennas))
- $P_{\text{ECH}}=100\text{kW}$
- $T_{\text{duration}}=800\text{sec}$

- Plasma discharge time was extended in high power injection
Reducing localized temperature rise of divertor plates by mode-conversion heating

- 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 ratio will required to heat plasma core region

\[ f = 28.4 \text{MHz}, \quad B_{ax} = 2.75 \text{T} \]

H/(H+He) = 30%
H/(H+He) = 66.5%
Hydrogen fueling by repetitive pellet injection was effective to keep the plasma performance.

- Without repetitive pellet injection:
  - Plasma was sustained during ICRF pulse.
  - Mode-conversion resonance moves inside with hydrogen ratio.

- With repetitive pellet injection:
  - Plasma was sustained during ICRF pulse.
  - Mode-conversion resonance moves inside with hydrogen ratio.

- ECH target plasma.
- Plasma was terminated during ICRF injection.
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.

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**Graphs:**

- **Power [kW]**
  - $P_{\text{ICRF}}$
  - $P_{\text{ECH}}$
- **$n_e [\text{m}^{-3}]$**
- **$T_{\text{e0}} [\text{keV}]$**

**Shot 68711**

**Plots:**

- Mode-conversion heating
- Minority heating

**Data Points:**

- $n_e$ vs. ICRF Power [MW]
  - $n_e \text{ max} [10^{19} \text{ m}^{-3}]$
Local heat load was scattered by mode-conversion heating

- Minority heating $R_{ax} = 3.64-3.67$ m
- Mode-conversion heating $R_{ax} = 3.6$ m (fix)

Scattering of heat load by electron heating

Duration and power are normalized with #68711
ICRF antennas are located at 3.5 and 7.5 port
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