First experiments on RF plasma production at relatively low magnetic fields in the LHD

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Introduction

- ICRF-based methods can be used to generate plasma in stellarators and tokamaks. The ion cyclotron wall conditioning (ICWC) method is widely used in various tokamaks as well as in stellarators.

- The ICRF systems available at the facilities can also be used to realize RF discharges at frequencies significantly higher than IC $\omega_{RF} >> \omega_{ci}$. For the same frequency of the RF generators, his regime can be realized at low magnetic fields. The advantage of RF discharges ($\omega >> \omega_{ci}$) is the possibility of plasma generation in conditions where plasma generation by the available electron cyclotron resonance systems is not possible. RF discharge plasma is used for wall conditioning in tokamaks and small stellarators such as Uragan-3M (U-3M) and Uragan-2M (U-2M).

- Besides, plasma produced by RF discharges in relatively low magnetic fields can be used as a target plasma for Neutral Beam Injection (NBI).

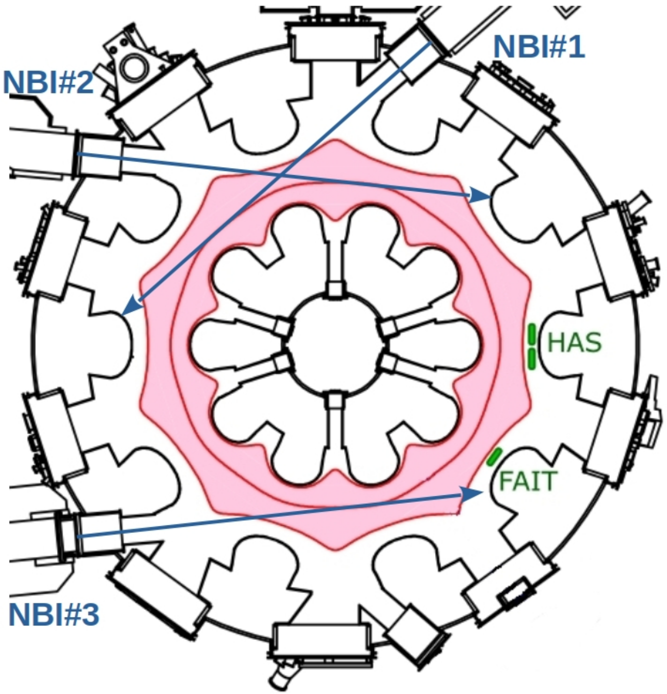
Introduction

- Experiments carried out on the small stellarators U-3M and U-2M demonstrate the possibility of realizing RF discharges ($\omega_{RF} >> \omega_{ci}$) and their potential application for wall conditioning in stellarators. However, their sizes and the RF heating frequencies are significantly lower than those of LHD and W7-X.

- ICRF heating of plasma in a magnetic field of 1.5 T at the LHD was investigated in [Mutoh T et al 2000 Plasma Phys. Control. Fusion 42 265]. ICRF heating at the second (B_0=1.375 T) [Saito K et al 2010 Fusion Sci. Technol. 58 515] and third (B_0=1 T) harmonics of the IC [Kamio S et al 2018 Nucl. Fusion 58 126004] has also been studied at the LHD. Lower valued magnetic fields were not payed much attention.

- The main goal of this work was to investigate the production of plasma by RF discharge ($\omega_{RF} >> \omega_{ci}$) in relatively low magnetic fields of 0.5-0.6 T at LHD, and also to test a possibility of using the produced by RF discharge plasma as a target plasma for subsequent heating with NBI.

Experimental details



Schematic view of the mid-plane cross-section of LHD

- **Experimental conditions:**
- (R_{ax}, B_t) = (3.6 m, 0.5 T), (3.6 m, 0.6 T)
- The working gas is deuterium.
- Plasma was produced in the experiments using HAS and FAIT antennas.
- The target plasma was heated using tangential NBI#1-3.

Wave propagation in Low Magnetic Fields

The first value of the critical density $N_{ec}^{(1)SW}$ can be estimated from the relation [27, 59]:

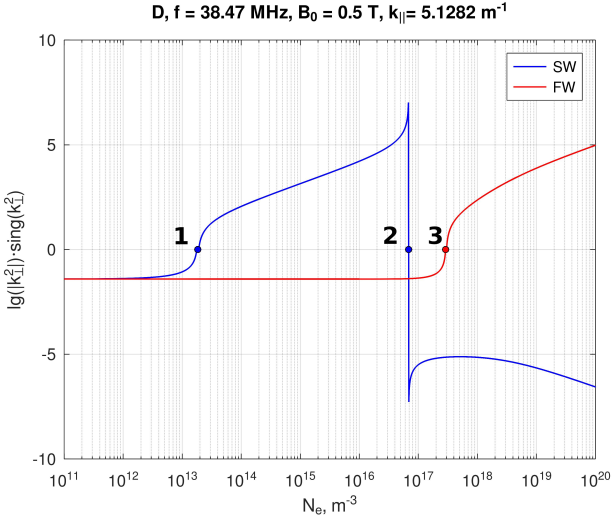
$$\omega_{RF}^2 = \omega_{pe}^2 + \omega_{pi}^2, \qquad (1)$$

The second critical point for SW determines the upper limit of the plasma density $N_{ec}^{(2)SW}$ above which SW cannot propagate. In this case the value of $N_{ec}^{(2)SW}$ can be found from the lower hybrid resonance condition, $k^2_{\perp,SW} \rightarrow \infty$ [52]:

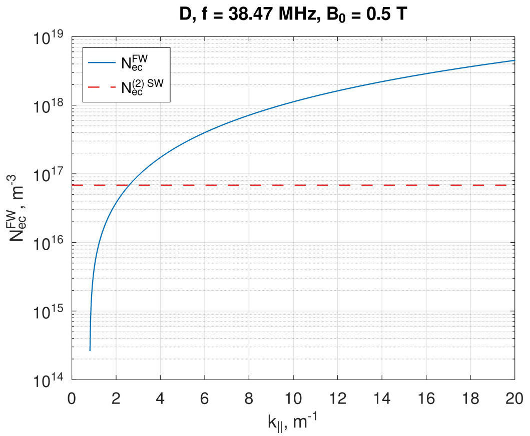
$$\omega_{RF}^2 = \omega_{LH}^2. \qquad (2)$$

For FW, the cut-off point is determined at $k_{\perp,FW} = 0$. Accordingly, the critical plasma density N_{ec}^{FM} for FW can be estimated using the dispersion equation, assuming that the poloidal wave component is small [59]:

$$\omega_{pi}^2 = (N_{\|}^2 - 1)\omega_{ci}\,(\omega_{RF} + \omega_{ci}) \qquad (3)$$

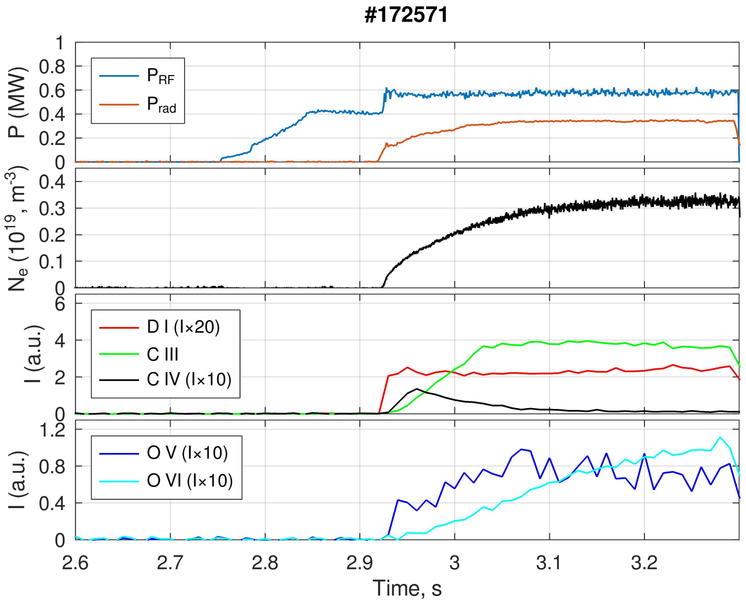


The square perpendicular wave numbers of SW and FW for frequency 38.47 MHz as a function of the deuterium plasma density. The cut-off points: (1) the SW critical density $N_{ec}^{(1)SW}$; (2) the SW critical density $N_{ec}^{(2)SW}$ (the lower hybrid resonance); (3) the FW critical density N_{ec}^{FW}.

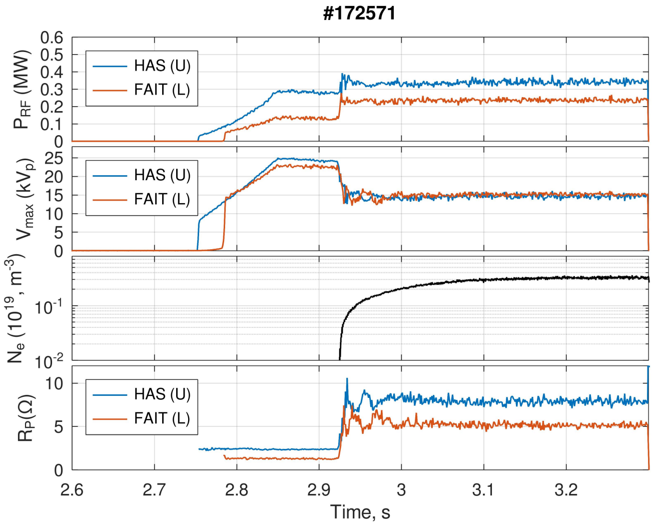


The dependence of FW critical density N_{ec}^{FW} a function of the parallel $k_{\|}$ wavenumber. The $N_{ec}^{(2)SW}$ a SW critical density, the lower hybrid resonance.

RF plasma production (B_t = 0.6 T)



Time evolutions of injection powers P_{RF} (total), radiation power P_{rad}, average electron density N_e, optical emission intensities of D I (D_α, 656 nm), C III (97.7 nm), CIV (154.9 nm), O V (63 nm), and O VI (103.4 nm). Initial pressure $p_0 = 7.4\times10^{-4}$ Pa. B_0 = 0.6 T.



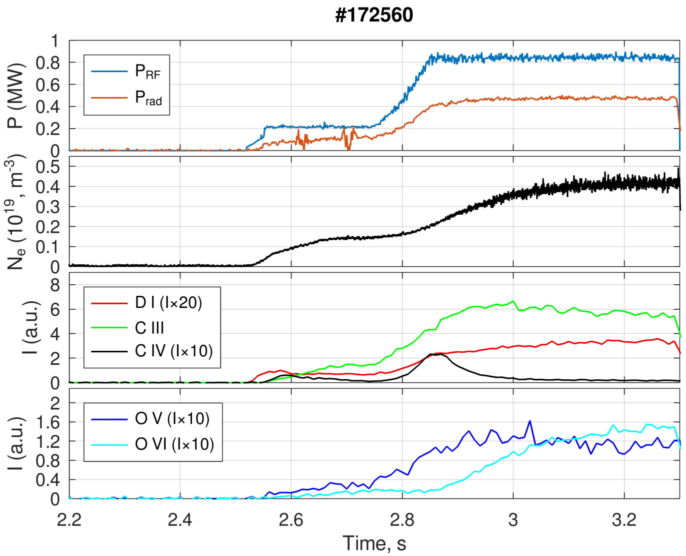
Time evolutions of injection power P_{RF} (HAS (U), FAIT (L)), maximum voltage at the coaxial line V_{max}, average electron density N_e, loading resistance (including vacuum loading resistance) R_p. Initial pressure $p_0 = 7.4\times10^{-4}$ Pa. B_0 = 0.6 T.

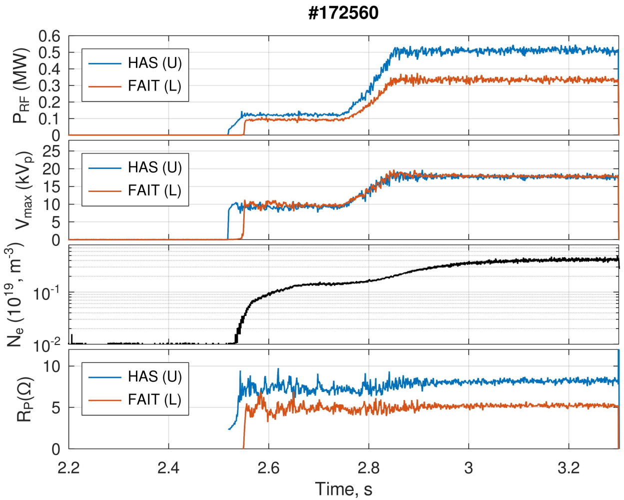
initial deuterium pressure of $(7.3\text{-}7.6)\times10^{-4}$ Pa.

breakdown time ranged from ≈ 170 ms to ≈ 350 ms

maximum plasma density of ≈ 3.3×10^{18} m^{-3} at an injected RF power of ≈ 0.58 MW

RF plasma production (B_t = 0.5 T)



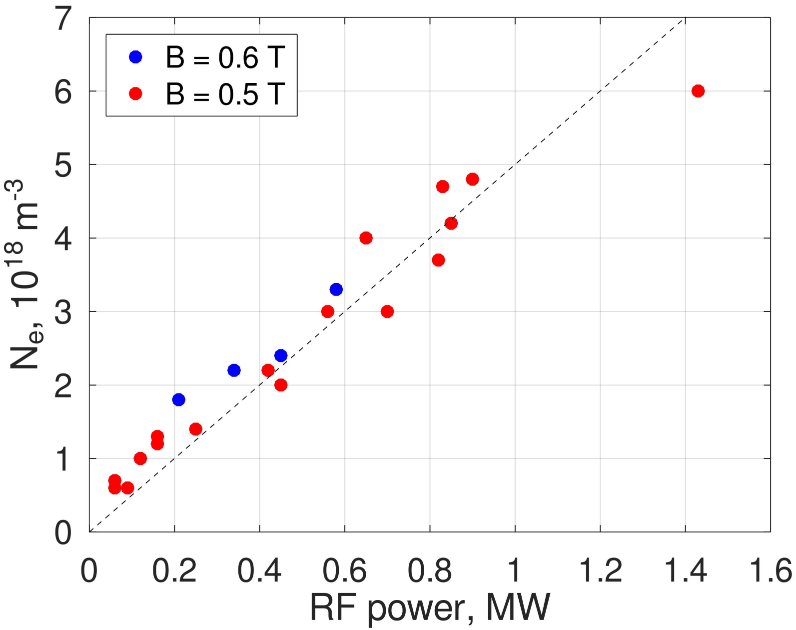


Time evolutions of injection power P_{RF} (HAS (U), FAIT (L)), maximum voltage at the coaxial line V_{max}, average electron density N_e, loading resistance (including vacuum loading resistance) R_p. Initial pressure $p_0 = 6.9\times10^{-4}$ Pa. B_0 = 0.5 T.

Time evolutions of injection powers P_{RF} (total), radiation power P_{rad}, average electron density N_e, optical emission intensities of H I (H_α, 656.3 nm), He I (587.6 nm), C III (97.7 nm), CIV (154.9 nm), O V (63 nm), and O VI (103.4 nm). Initial pressure p_0 = 6.9×10^{-4} Pa. B_0 = 0.5 T.

initial deuterium pressure of $(6.9\text{-}7.2)\times10^{-4}$ Pa.
breakdown time and the onset of plasma production in ≈ 10 ms
maximum plasma density of ≈ 4.2×10^{18} m^{-3} at an injected RF power of ≈ 0.85 MW

RF plasma production



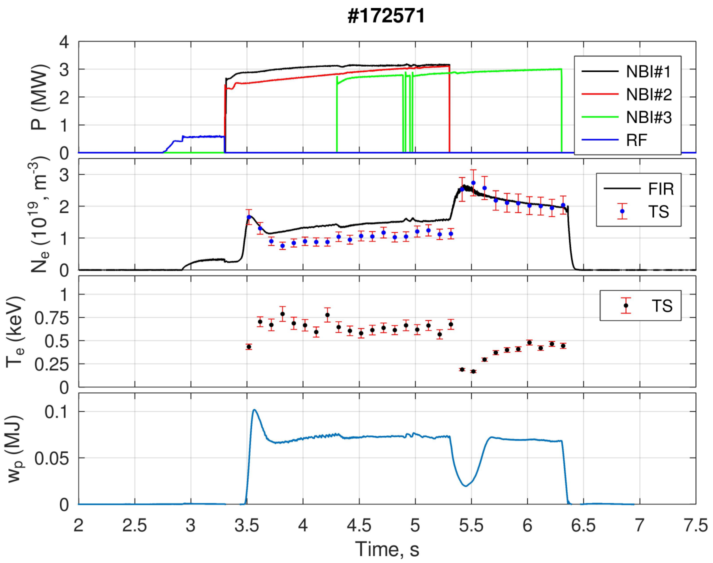
Dependence of maximum plasma density on RF power.

As can be seen, there is dependence of the density on the RF power close to linear, independent of the magnetic field in these experiments.

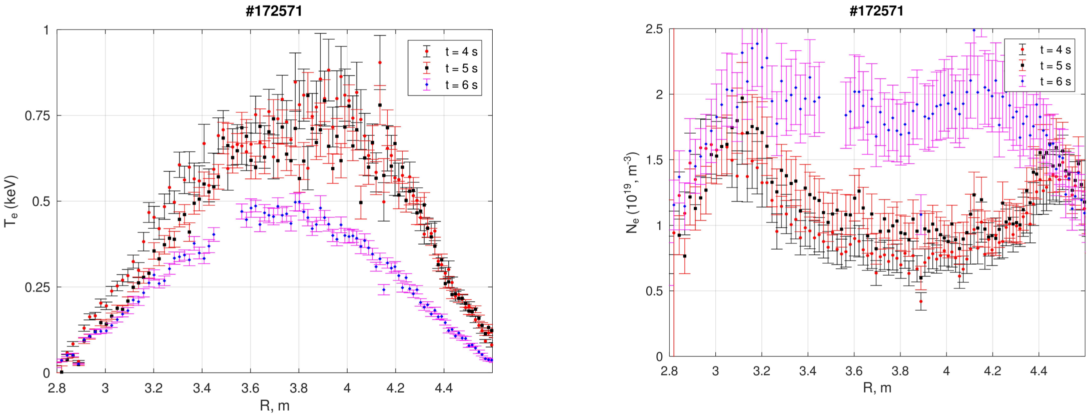
The over shot maximum density was ≈ 4.8×10^{18} m^{-3} at a power of ≈ 0.9 MW using two HAS (U) and FAIT (L) antennas.

Using three HAS (U) and FAIT (L) and (U) antennas at a power of ≈ 1.43 MW, the maximum density was higher, ≈ 6×10^{18} m^{-3}.

NBI into plasma target (B_t = 0.6 T)



Time evolutions of injection P_{NBI} (NBI#1, NBI#2 and NBI#3) and P_{RF} (total), average electron density N_e, electron temperature T_e, plasma energy content w_p, FIR (R = 3.669 m), TS (R = 3.602 m). B_0 = 0.6 T.



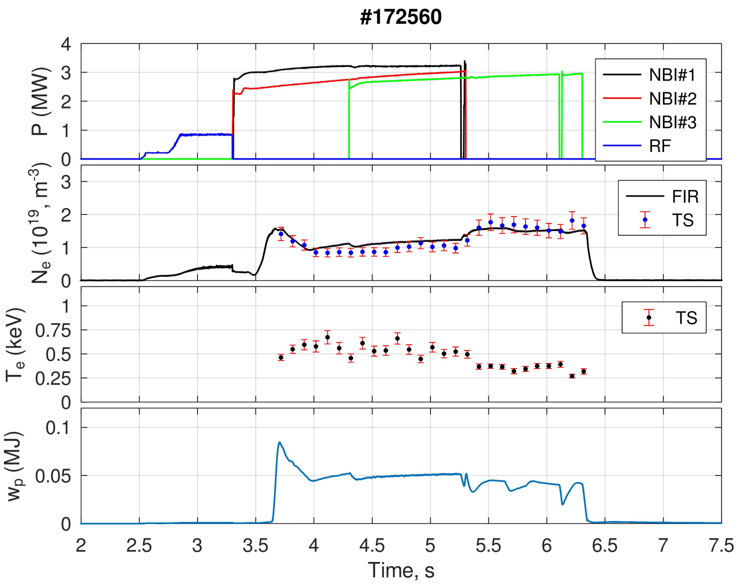
Radial distribution of electron temperature and density for different time moments. B_0 = 0.6 T

The maximum temperature of ≈ 0.5 keV is observed at the center of the plasma,

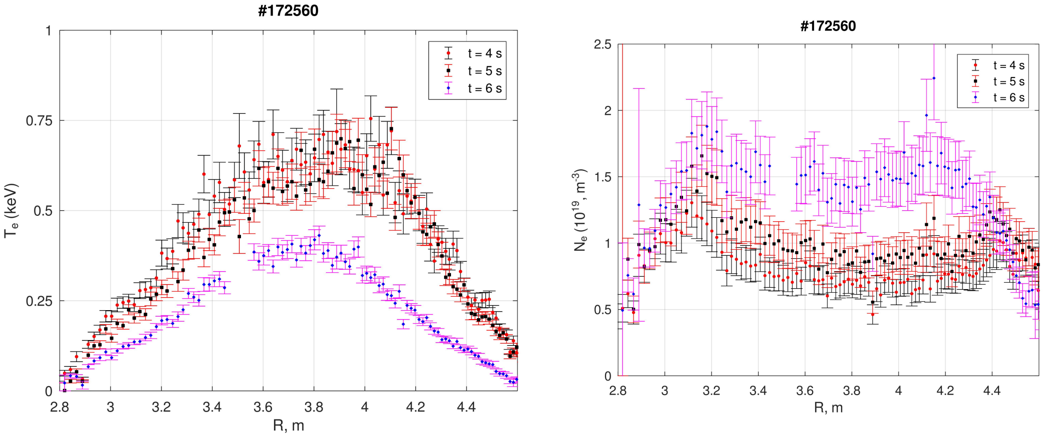
the maximum plasma density is ≈ 2.4 × 10^{19} m^{-3}.

The over shot the maximal value of <β_{dia}> is 2.17%, close to that one at 0.6 T magnetic field.

NBI into plasma target ($B_t = 0.5$ T)



Time evolutions of injection P_{NBI} (NBI#1, NBI#2 and NBI#3) and P_{RF} (total), average electron density N_e, electron temperature T_e, plasma energy content w_p, FIR (R = 3.669 m), TS (R = 3.602 m). $B_0 = 0.5$ T.



Radial distribution of electron temperature and density for different time moments. $B_0 = 0.5$ T

The maximum temperature of ≈ 0.72 keV is observed at the center of the plasma,

the maximum plasma density is ≈ 1.9×10^{19} m^{-3}.

The over shot the maximal value of $\langle\beta_{dia}\rangle$ is 2.6%, close to that one at 0.5 T magnetic field.

Conclusions

- Studies of plasma production by RF discharge ($\omega_{RF} >> \omega_{ci}$) in relatively small magnetic fields of 0.5-0.6 T at the LHD have shown the possibility of realizing such discharges in big helical devices. A deuterium plasma with a density of up to ≈ 6×10^{18} m^{-3} was obtained with an injected RF power of up to ≈ 1.43 MW. A linear dependence of the density on the RF power was observed in the experiments. The electron temperature was low.

- Plasma with such parameters can be used for wall conditioning of helical devices and also as a target plasma for further heating with NBI.

- Plasma of RF discharge serves well as target plasma for NBI. Further NBI application allowed us to reach electron temperatures up to ≈ 0.9 keV and densities up to ≈ 2.4×10^{19} m^{-3}. The maximum value of $\langle \beta_{dia} \rangle$ was 2.6% in these experiments. Such a scenario can be applied to big helical devices.

- These experiments open up the possibility of new regimes of operation at LHD and, in future, at W7-X.