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To cite this article: S. Kamio *et al* 2021 *Nucl. Fusion* **61** 114004

OPEN ACCESS
IOP Publishing | International Atomic Energy Agency
Nuclear Fusion
Nucl. Fusion **61** (2021) 114004 (5pp)
https://doi.org/10.1088/1741-4326/ac277b

Letter

First experiments on plasma production using field-aligned ICRF fast wave antennas in the large helical device

S. Kamio[1,*], V.E. Moiseenko[2], Yu.V. Kovtun[2], H. Kasahara[1], K. Saito[1,3], R. Seki[1,3], M. Kanda[1], G. Nomura[1], T. Seki[1], Y. Takemura[1], T. Wauters[4], R. Brakel[5], A. Dinklage[5], D. Hartmann[5], H. Laqua[5], T. Stange[5], A. Alonso[6], S. Lazerson[5], Ye. Kazakov[4], J. Ongena[4], H. Thomsen[5], G. Fuchert[5] and I.E. Garkusha[2]

[1] National Institute for Fusion Science, Toki, Japan
[2] Institute of Plasma Physics of the National Science Center 'Kharkiv Institute of Physics and Technology', Kharkiv, Ukraine
[3] The Graduate University for Advanced Studies, SOKENDAI, Toki, Japan
[4] Laboratory for Plasma Physics, ERM/KMS, Brussels, Belgium
[5] Max-Planck-Institut für Plasmaphysik, Greifswald, Germany
[6] Laboratorio Nacional de Fusion, CIEMAT, Madrid, Spain

E-mail: kamio@nifs.ac.jp

Received 6 July 2021, revised 29 August 2021
Accepted for publication 16 September 2021
Published 1 October 2021

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Abstract
The results of the first experimental series to produce a plasma using the ion cyclotron range of frequency (ICRF) in the large helical device (LHD) within the minority scenario developed at Uragan-2M (U-2M) are presented. The motivation of this study is to provide plasma creation in conditions when an electron cyclotron resonance heating start-up is not possible, and in this way widen the operational frame of helical machines. The major constraint of the experiments is the low RF power to reduce the possibility of arcing. No dangerous voltage increase at the radio-frequency (RF) system elements and no arcing has been detected. As a result, a low plasma density is obtained and the antenna-plasma coupling is not optimal. However, such plasmas are sufficient to be used as targets for further neutral beam injection (NBI) heating. This will open possibilities to explore new regimes of operation at LHD and Wendelstein 7-X (W7-X) stellarator. The successful RF plasma production in LHD in this experimental series stimulates the planning of further studies of ICRF plasma production aimed at increasing plasma density and temperature within the ICRF minority scenario as well as investigating the plasma prolongation by NBI heating.

Keywords: radio-frequency heating, plasma production, stellarator

(Some figures may appear in colour only in the online journal)

* Author to whom any correspondence should be addressed.

1. Introduction

In contrast to tokamaks, modern helical devices (stellarators and heliotrons) do not have ohmic heating capabilities, which is the major tool for initial plasma production and also current ramp-up in tokamaks. Plasmas can be produced in stellarators by radio-frequency (RF) waves and neutral beam injection (NBI). The routine RF tool for plasma production is the electron cyclotron resonance heating (ECRH) [1] which is installed in the majority of helical devices. The ECRH plasma production is reliable and robust. The advantage of ECRH is its capability for the plasma heating towards high temperatures. ECRH requires the presence of an EC resonance inside the region where a plasma is to be formed (the confinement volume). This causes restrictions to the possible magnetic field values. If there is a need to operate the helical device at magnetic fields other than suitable for ECRH, one need to look for other possibilities for plasma creation.

The NBI plasma production is almost insensitive to the magnetic field value. The greatest shortcoming of the NBI plasma production is the long duration of plasma production [2, 3] which is accompanied by beam shine-through that is often not tolerable for the in-vessel components. The difficulties are experienced at low plasma densities due to the low rate of plasma electron heating by the neutral beam, created by NBI. A pre-ionized target plasma can soften this problem [4–6]. The creation of a preliminary plasma by the ECRH method is used in the large helical device (LHD) [4]. A pre-ionization technique based on non-resonant microwave heating is practiced in Heliotron J [5, 6].

Plasma can be created by lower hybrid heating, but this heating method is not popular for stellarators because it is accompanied by a current drive which is difficult to control. Moreover, plasma production is possible with RF heating below the ion cyclotron frequency. This method is mainly used in small stellarators [7]. In the mid-sized helical device compact helical system (CHS) the plasma production was performed by a Nagoya type-III antenna [8]. At present, it is routinely used in the Uragan-2M (U-2M) machine only [9]. For LHDs, the plasma production frequency should be downshifted, compared to the ion cyclotron frequency [10]. This method was successfully attempted in LHD with the frequency lower than the ion cyclotron [11], but not continued further. Unfortunately, until now none of the experimental machines except U-2M have the RF equipment suitable for such a method of plasma production.

Plasma production by ion cyclotron range of frequency (ICRF) heating is used at tokamaks mainly for wall conditioning purposes (see, e.g. [12, 13]). The neutral gas pressure is high and the plasma density is low in such discharges. Consequently, the antenna loading is low and the power injected is also low. ICRF plasma production has been demonstrated with high neutral gas pressure for ion cyclotron wall conditioning in LHD [14].

Based on plasma production experiments in U-2M, comparable discharges have been proposed in reference [9] for plasma production in stellarators. The key requirement for this scenario is the presence of minority ions in the plasma for which an ion cyclotron resonance zone exists in the plasma column. This plasma production scenario implies the usage of ICRF heating strap antennas.

Then an electron heating in a wide plasma density range could be achieved. At high plasma densities the electron heating is provided in the mode conversion regime [15] which is widely practiced. The plasma initiation process in this case is theoretically described in reference [16]. At low plasma densities the direct slow wave excitation by the antenna is necessary to heat the plasma electrons. ICRF antennas with their straps oriented across the magnetic field lines are good for fast wave excitation and minority heating in the mode conversion regime. The slow wave excitation is a parasitic effect for these antennas. Since the necessary plasma production power is proportional to the plasma density (see, e.g. [17]), even a small antenna coupling to the slow wave appears sufficient, in practice, for successful plasma production at the initial stage.

The ICRF heating scenario, if successful, could be used for reduced field operation at 1.7 T in Wendelstein 7-X (W7-X) stellarator [18] with a hydrogen minority in deuterium working gas (heating frequency is $f \approx 26$ MHz). This scenario has successfully been demonstrated at U-2M, only, which is notably smaller than LHD and W7-X. Moreover, the magnetic field in U-2M is an order of magnitude lower. Experiments in a larger device such as LHD are therefore required for a solid prediction basis. In this letter, we present the first experimental results for ICRF plasma production in LHD using field-aligned antennas within the minority scenario.

2. Experimental arrangements

The ICRF heating system [19] in LHD includes a hand-shake form (HAS) antenna [20] and a field-aligned-impedance-transforming (FAIT) antenna [21]. Both antennas are composed of strap elements oriented perpendicular to the magnetic field. They have a broad $k_{||}$ spectrum which is good for plasma production. Each antenna consists of two parts, upper and lower, which can be enabled independently. Both occupy an outer part of the torus and are shielded by Faraday screens. It is believed that the Faraday screen suppresses slow wave excitation. In this sense, the situation for plasma production is less favorable than in U-2M which has an unshielded two-strap antenna.

Before, neither ICRF antenna was used for plasma production in LHD because of concerns about arcing. In previous studies a different antenna, which is not optimized for plasma heating was used [11], or experiments were conducted at a much higher gas pressure which is not suited for plasma startup but for plasma wall conditioning [14]. We note, that the LHD RF system is not equipped with 3 dB couplers with a dummy load (see, e.g. [22]) for absorption of the reflected power [19]. At the initial time of plasma production, when a no-load situation unavoidably appears, the voltage in the RF system increases and arcing is possible. By installing impedance transformers on HAS and FAIT antennas, the loading resistances were increased and transmission line voltages during ICRF injection were decreased [23]. However, the voltage of the

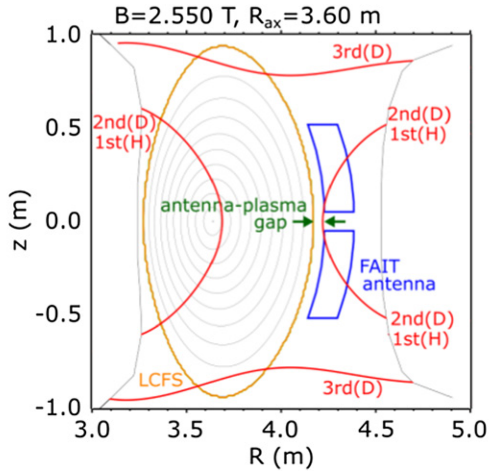

Figure 1. LHD cross-section at FAIT antenna location. Last closed flux surface, magnetic surfaces, ion cyclotron resonance layers for $B_t = 2.55$ T.

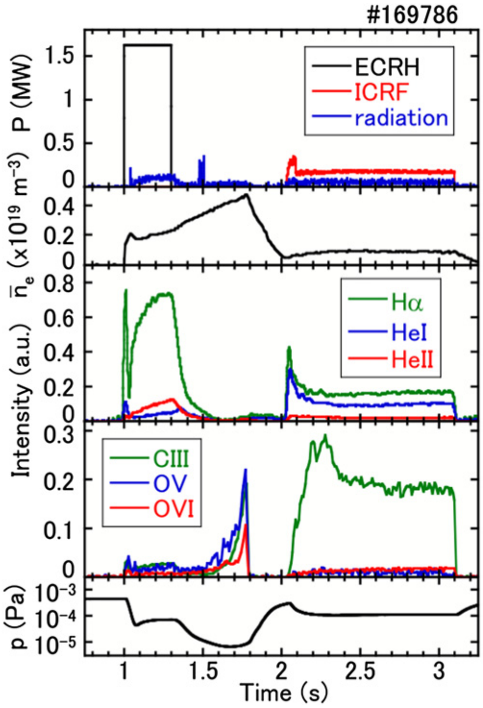

Figure 2. Time evolutions of injection powers P_{ECRH} and P_{ICRF}, radiation power P_{rad}, average electron density $\overline{n}_e$, optical emission intensities of H_α (656.3 nm), HeI (587.6 nm), HeII (468.6 nm), CIII (97.7 nm), OV (63 nm), and OVI (103.4 nm), and neutral gas pressure p. The working gas content is ~75% He + 25% H_2.

antenna head cannot be reduced by the impedance transformers. Therefore, the RF plasma production experiments were conducted at low power, of less than 100 kW per each antenna.

In the experiments, the magnetic field is 2.55 T at the magnetic axis. The frequency is 38.5 MHz for both antennas. For such a frequency, the hydrogen cyclotron zone crosses the plasma column and passes through it very near the magnetic axis (see figure 1). The gas is helium with a hydrogen minority.

3. Experiments

In the first experiments, powerful ECRH pre-ionization is used before the RF pulse. One of the shots of this series is displayed in figure 2. The ECRH starts first ($t = 1$ s), creates a plasma and ends at $t = 1.3$ s. The plasma breakdown is indicated by peaks of H_α and HeI spectral lines which accompany neutral gas ionization. It is also indicated by an order of magnitude decrease of the neutral gas pressure. The plasma density rises quickly ($t \approx 1$ s) to the value of 2×10^{18} m^{-3} and after wards slowly ramps up. After switching off the ECRH, the intensity of the spectral emission lines (CIII, OV, OIV) increases and the plasma density continues to ramp up to 4.7×10^{18} m^{-3} (at $t = 1.78$ s). Afterwards, the density starts decaying.

At $t = 2.03$ s, the ICRF heating starts (see figures 2 and 3). Initially, the upper part (U) of the HAS antenna is operated alone. It turns off after 60 ms of operation. Both parts (U and L) of the FAIT antenna start slightly later at $t = 2.04$ s and operate longer, up to $t = 3.1$ s with total power just below $P = 0.2$ MW (see figure 2). The plasma density quickly turns to the nearly constant value of 1×10^{18} m^{-3}. The CIII emission increases in comparison with the ECRH pulse together with OV and OVI lines, the decrease is a sign of low electron temperature. The high value of the neutral gas pressure and high HeI emissivity indicate that the plasma is only partially ionized. The antenna loading resistance values are given in figure 3. They are the sums of the vacuum and the plasma parts. The vacuum loading resistances are 2.9 Ω for FAIT (U), 1.6 Ω for FAIT (L) and 1.9 Ω for HAS (U) antenna. The best loading is observed for FAIT (U) and FAIT (L), HAS (U) loading is worse.

From this shot one can conclude that the FAIT antenna is able to sustain low density plasma without full ionization. The probable reason for the plasma density being lower than in the preceding ECRH pulse, is a lack of RF power. The ability of plasma sustainment is a necessary condition for RF plasma production, and this test was successfully completed with the FAIT antenna.

In the experiment presented in figure 4, the FAIT antenna achieves plasma production without ECRH pre-ionization.

The lower part (L) of the FAIT antenna is switched on at $t = 2.53$ s. Breakdown and creation of the plasma occur within a short time duration of ~10 ms. The average plasma density achieved at $t = 2.54$ s is $n = 1.3 \times 10^{16}$ m^{-3}. The antenna loading resistance in the initial period is close to the vacuum one. Then it grows to the value of $R = 3.45$ Ω and saturates. Then, a sequential appearance of an optical emission of atoms and ions with higher excitation thresholds is observed. Firstly, the HeI line starts to emit with a small time delay less than 10 ms. Then, H_α and CIII lines appear. The HeII line is observed 20 ms after HeI. When the HeI line starts fading, OV rises quickly. When the OV line reaches its maximum an OVI line appears. The OVI line irradiates for a short time, about 50 ms, and then vanishes. A relatively rapid increase in the plasma density is observed up to $t \approx 2.62$ s when the plasma density reaches the value $n \approx 4.6 \times 10^{17}$ m^{-3}.

Later, the plasma density gradually increases until the end of the RF pulse to a value of $n \approx 9.5 \times 10^{17}$ m^{-3}. The

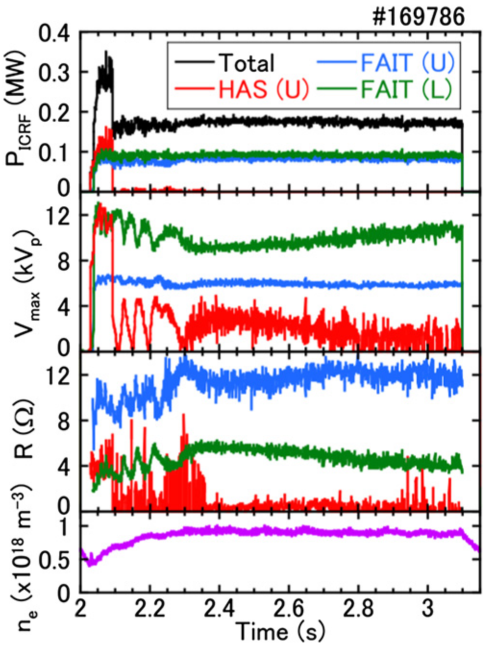

Figure 3. Time evolutions of RF powers P_{ICRF}, (total, and for antennas HAS (U), FAIT (U and L)), maximum voltages at coaxial line $V_{\max}$, loading resistances (including vacuum loading resistance) R, average electron density $\overline{n}_e$.

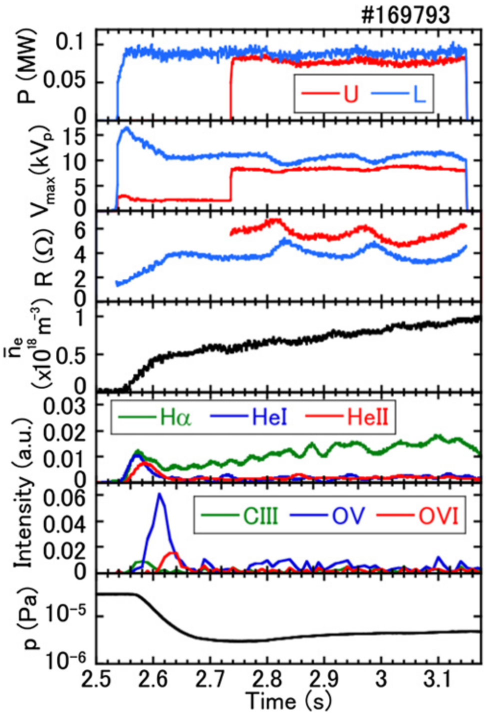

Figure 4. Time evolutions of ICRF power P_{ICRF}, (antennas FAIT U and L), maximum voltage at the coaxial line $V_{\max}$, loading resistances (including vacuum loading resistance) R, average electron density $\overline{n}_e$, optical emission intensities of H_α (656.3 nm), HeI (587.6 nm), HeII (468.6 nm), CIII (97.7 nm), OV (63 nm) and OVI (103.4 nm), and neutral gas pressure p. Working gas content is ∼81% He + 19% H_2.

neutral gas pressure decreases by an order of magnitude and then stabilizes up to the end of the shot. This sequence of events can be explained by the following: at the start, relatively quick plasma production occurs and plasma electrons are heated. The major part of the neutral gas becomes ionized. Then the impurity influx decreases the electron temperature so that only an H_α line remains visible. The impurity influx also causes a slow plasma density ramp-up during the entire pulse. It is remarkable that switching on the upper part of the FAIT antenna at $t \approx 2.73$ s causes no visible response of any involved diagnostics. This is also an indication that the ICRF power is not sufficient to ionize light impurities. To explain all these effects in detail, further experiments are needed.

4. Summary

An ICRF plasma production was for the first time demonstrated using field-aligned antennas in LHD in low neutral gas pressures. The achieved plasmas are suitable for further plasma heating, e.g. by NBI. As originally intended, the plasma production in conditions when an ECRH start-up is not possible could be shown. This way, this study shows a way to widen the operational frame of helical machines with already existing RF equipment.

In this paper, two kinds of experiments are presented. One utilizes ECRH pre-ionization, and the other is without an additional pre-ionization source. The created plasmas are of low density and low electron temperature and presumably contain a significant amount of impurities. No dangerous voltage increase at the RF system elements and no arcing has been detected. A major constraint of the experiments is the low RF power to reduce the possibility of arcing. As a result, only a low plasma density has been obtained with the pure ICRF startup, and the antenna-plasma coupling is low. However, even such a plasma can be used as a target for further NBI heating. This will open possibilities for exploring new regimes of operation at LHD and W7-X.

The successful RF plasma production in LHD in this experimental series will stimulate further studies in ICRF plasma production, aimed at increasing plasma density and temperature within the ICRF minority heating scenario and investigate the connection to further NBI.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom Research and Training Programme 2014–2018 and 2019–2020 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work also received funding from National Academy of Sciences of Ukraine (Grants P-3-22, and A-5-20). The authors wish to thank the LHD experiment group for their excellent support of this work.

ORCID iDs

S. Kamio https://orcid.org/0000-0003-0755-2433
V.E. Moiseenko https://orcid.org/0000-0001-9431-5617
Yu.V. Kovtun https://orcid.org/0000-0003-4948-0896
Y. Takemura https://orcid.org/0000-0003-3754-897X
T. Wauters https://orcid.org/0000-0002-2941-7817
A. Dinklage https://orcid.org/0000-0002-5815-8463
D. Hartmann https://orcid.org/0000-0002-3511-6500
A. Alonso https://orcid.org/0000-0001-6863-8578
S. Lazerson https://orcid.org/0000-0001-8002-0121
J. Ongena https://orcid.org/0000-0001-7456-4739
I.E. Garkusha https://orcid.org/0000-0001-6538-6862

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