Confinement Characteristics of ECH Plasmas in Heliotron J

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Abstract. Studies of global energy confinement and toroidal plasma current behavior for the second harmonic 70GHz ECH at B = 1–1.5 T are described with emphasis on the magnetic configuration effects in the helical-axis heliotron "Heliotron J". At low densities of $\bar{n}_e < 0.4\times10^{19}\ \mathrm{m}^{-3}$, the electron temperature reached $T_e \approx 1$ keV in the core region, indicating the production of the collision-less plasmas of the electron collisionality $\nu^* << 0.1$, where $\nu^* = \nu/(v_e/\pi R_0 q)$. For medium densities of $0.5\times10^{19}\ \mathrm{m}^{-3} < \bar{n}_e < 2\times10^{19}\ \mathrm{m}^{-3}$, the preferable energy confinement time, about 1.5 times larger than that of the ISS95 scaling, was obtained under the condition of localized central heating at B ≈ 1.25 T for the standard configuration of Heliotron J. The measurements of the toroidal current under perpendicular microwave injection revealed the change of the current flow direction as a function of the poloidal magnetic field. The measured current behavior was found to be qualitatively consistent with that of the bootstrap current predicted from neoclassical theory. The observed flow reversal showed that a proper selection of the field configuration could control the bootstrap current in the helical-axis heliotron. In addition, the current control through the electron cyclotron current drive scenario with oblique injection of microwave was experimentally demonstrated.

1. Introduction

Heliotron J [1] is a flexible, concept-exploration facility with a highly pitch-modulated L/M = 1/4 helical coil (R_0 = 1.2 m, $B_0 \le 1.5$ T) aiming at experimental optimization of the helical-axis heliotron concept [2]. The initial experimental results in this device were reported in the previous IAEA Fusion Conference [3]. After that, ECH plasma production and heating experiments have been continued using 53 GHz and 70 GHz systems [4, 5]. Energy confinement studies have emphasized two goals: (1) enhancing the parameters of ECH plasmas and (2) understanding their heating and confinement properties including the toroidal current control with special regard to the configuration effects.

The experiment has revealed that the sensitive dependences of plasma confinement on the magnetic configuration in Heliotron J. The dependence of the stored energy, W_p^{dia}, on the central rotational transform $\iota(0)/2\pi$ was examined from $\iota(0)/2\pi \approx 0.44$ to ≈ 0.65 under the 53 GHz second harmonic ECH condition (oblique injection with non-focusing TE_{02}-mode, the injected power: P_{in} ~ 0.4 MW) [5], where the auxiliary vertical coil current (I_{AV}) is controlled to change $\iota(0)/2\pi$. The attainable W_p^{dia} gradually decreased for the configurations of $\iota(0)/2\pi <$ 0.53 or $\iota(0)/2\pi >$ 0.53. In addition, a dip in W_p^{dia} was observed near the $\iota(0)/2\pi$ = 4/7 resonance condition. Although the severe reduction of the plasma radius <a> at resonance conditions in the $\iota(0)/2\pi \le 0.5$ region is avoided due to the presence of magnetic shear, "natural" magnetic islands appeared in the confinement region may explain rather low W_p^{dia} in these configurations.

With the 53 GHz system, an interesting heating mode was found to exist in the higher magnetic field ($B_0 \approx 1.4$–1.5 T), where neither fundamental nor second harmonic resonance layers for electromagnetic waves exist in the core region [5]. The stored energy W_p^{dia} obtained by this heating was comparable with that by the second harmonic ECH ($B_0 \approx 0.95$ T). In this mode, $\bar{n}_e$ can be increased up to 3.8×10^{19} m^{-3} without radiation collapse, which is close to the cut-off density for the fundamental O-mode (3.5×10^{19} m^{-3}). One plausible explanation of this heating is a slow-X to electron-Bernstein mode conversion [6]. The accessible window for this conversion can be opened in the limited toroidal and poloidal angles around the corner section of Heliotron J. The strong inhomogeneity of the magnetic field can make the parallel refractive index larger than unity during the propagation in the toroidal direction, resulting in the strongly Doppler shifted resonance condition.

In the standard (STD) configuration, a part of the "whisker" field lines outside the last closed flux surface cross the wall, forming the toroidally and poloidally localized divertor footprints [7]. The overall distribution of the diverted plasmas was consistent with the expectations from the numerical field line tracing. However, unexpected up-down asymmetry of the density and floating potential profiles was found on the two symmetric divertor legs, possibly due to the asymmetric particle flow caused by the ∇B drift [8].

The 70 GHz system (a well-focused Gaussian beam with a launching angle control system, $P_{in} \approx 0.4$ MW) has been constructed in order to realize a localized ECH/ECCD experiment in Heliotron J [9]. The beam diameter of the injected waves is ~ 40 mm in e^2-folding power at the magnetic axis for the perpendicular injection. Owing to the three-dimensional magnetic field structure and spatial magnetic axis, a wide range of injection angle and polarization with precise control is required to achieve the efficient single pass absorption. To evaluate the ECH single pass absorption, ray-tracing simulations have been performed with the TRECE code [10], which was originally developed for TJ-II and has been modified for Heliotron J.

2. Confinement Characteristic of 70 GHz ECH Plasmas

The dependence of the plasma production/heating by 70 GHz ECH on the confinement field strength was examined for the STD configuration [3]. The injection angle of the microwaves was fixed to be perpendicular to the magnetic axis. The attainable value of the stored energy is plotted in FIG. 1 as a function of the magnetic field B_0 on the axis. The optimal heating was found when the second harmonic resonance layer was located near the magnetic axis. The stored energy was increased as $\bar{n}_e$. It was possible to increase $\bar{n}_e$ up to near the cut-off density for the second harmonic X-mode (3×10^{19} m^{-3}). The stored energy of > 2 kJ was obtained, which was higher than that obtained so far in the 53 GHz second harmonic ECH with almost the same injection power. Due to the restriction of the available field strength, another effective heating in the higher field, which was observed in 53 GHz ECH, was not examined.

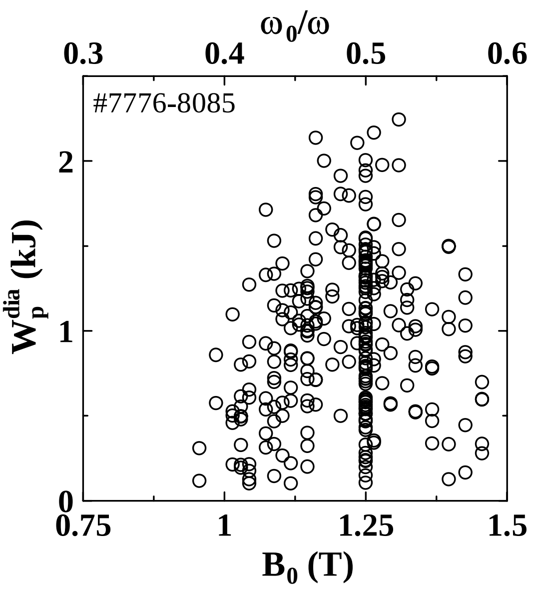

FIG. 1. Plasma stored energy W_p^{dia} as a function of the magnetic field B_0 on the axis for the STD configuration.

Figure 2 shows a comparison of the experimental energy confinement time τ_E^{exp} with the corresponding ISS95-scaling prediction, τ_E^{ISS95}, for different three regions of the magnetic field strength. The highly localized central heating for r/a < 1/4 (1.18 T < B_0 < 1.34 T) could increase the ratio $\tau_E^{exp}/\tau_E^{ISS95}$ above unity (about 1.5 times larger than that of the ISS95 scaling), but the off-axis heating could decrease it down unity. The good confinement (τ_E^{exp} /τ_E^{ISS95} > 1) was achieved in a density region 0.5×10^{19} m^{-3} < $\bar{n}_e$ < 2×10^{19} m^{-3}, where the collisionality at the half radius is in the range of 0.05 <ν* < 0.5.

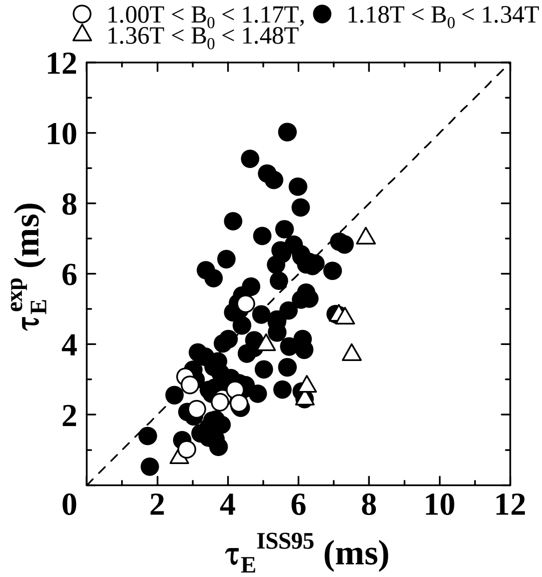

FIG. 2. Comparison of the experimental energy confinement time τ_E^{exp} with the ISS95-scaling.

According to the DKES-calculation for the STD configuration [2], the ripple loss in the low-ν* regime can be suppressed and the neoclassical diffusion coefficient is expected to be comparable to that of the equivalent tokamak. In order to confirm this prediction experimentally, it was a “necessary condition” for the Heliotron J experiments to enlarge the possibility of collisionless plasma production. During this 70 GHz ECH experiment, at low densities of $\bar{n}_e$ ≤ 0.4×10^{19} m^{-3}, the electron temperatures measured by the SX absorber foil method reached T_e^{SX} ≈ 1 keV, indicating the production of the collisionless plasmas of ν* << 0.1.

3. Toroidal Current Control

In the helical-axis heliotron, the small bootstrap current can be controlled with tailoring the Fourier components of the confinement field in the Boozer coordinates, especially by the bumpiness control. One of the key issues of the Heliotron J study is to confirm this scenario experimentally and examine the compatibility of the bootstrap current control with the confinement improvement.

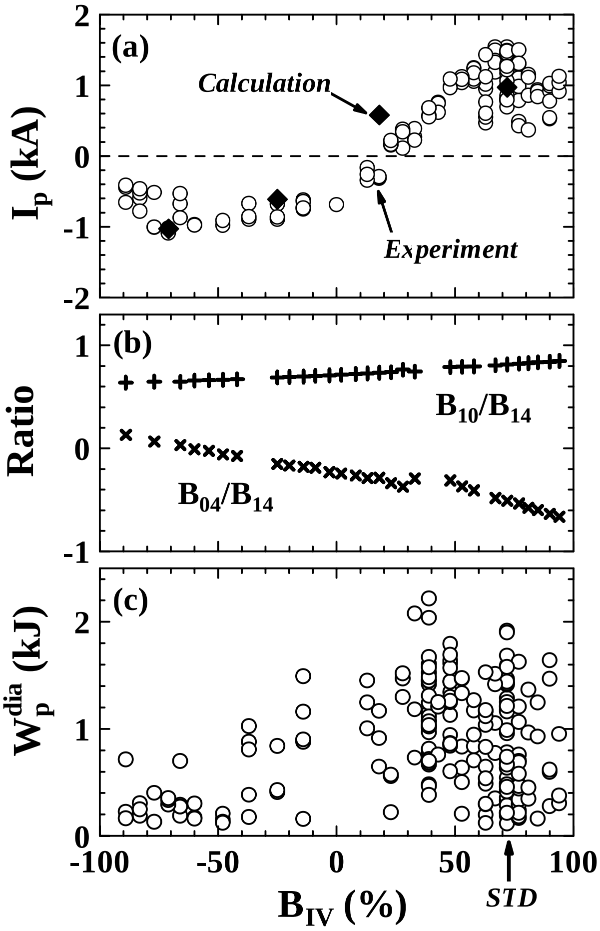

FIG. 3. Effects of B_{IV}-scan on (a) toroidal plasma current, (b) the ratios of toroidicity B_{10} and bumpiness B_{04} to the helicity B_{14} of the confinement field at r/a ~ 2/3 (calculation) and (c) the stored energy.

The non-inductive toroidal currents in ECH plasmas of Heliotron J have been measured with Rogowski coils. For the perpendicular ECH, it was observed that the toroidal current varied not only its value but also its flow direction when the poloidal magnetic field was changed by controlling the poloidal field strength B_{IV} excited by the inner vertical coil as shown in FIG. 3 (a). The arrow in the figure denotes the B_{IV} value for the STD configuration (B_{IV}~ 72%). In Heliotron J, the modification of B_{IV} can provide the change in the harmonic contents of the magnetic field, mainly the bumpiness, B_{04}, as shown in FIG. 3 (b). The direction of the positive current in FIG. 3 (a) is the same as that of the intrinsic rotational transform. The amount of observed I_p was less than 2kA. The corresponding change of $\iota/2\pi$ is less than 0.015, thus it is small enough to affect the plasma performance except for the case that is very close to the resonance condition. The reversal of the total magnetic field demonstrated the change of the current flow direction, while the absolute value of the current was almost kept the same. These results supported the interpretation that the measured current must be ascribed to the neoclassical bootstrap current. As a reference, the results from the model calculation of the neoclassical bootstrap currents by using the SPBSC code [11] are also plotted in FIG. 3 (a), showing the qualitative agreement with the measurement.

Figure 3 (c) shows the observed W_p^{dia} for the B_{IV}-scan experiment. As decreasing B_{IV}, the value of W_p^{dia} gradually decreased. A dip in W_p^{dia} near B_{IV} ~ 60% corresponds to the resonance condition of $\iota(0)/2\pi$ = 4/7, which is similar to the $\iota(0)$–scan experiment with 53 GHz ECH. The observed gradual drop of W_p^{dia} in the region of B_{IV} < 30% can be explained as being partly due to the degradation of particle confinement which is caused by the decrease in $|B_{04}/B_{14}|$ (see FIG. 3 (b)). In addition, more detailed study of configuration effects on the plasma confinement is necessary including the plasma-wall interaction effects since B_{IV}-scan also causes the shift of magnetic axis and the change of the plasma radius. It is interesting to note that the higher W_p^{dia} values are observed near both the upper and lower sides of this resonance condition. As for the compatibility of the bootstrap current control with the confinement improvement, more fine-tuning studies of each component by using combined control of several coil sets will be necessary to understand the role of each component experimentally and to optimize the helical-axis heliotron concept.

It is well known that ECH microwaves can drive the toroidal current by changing the injection angle in the toroidal direction (ECCD). In this case, the toroidal current can be suppressed also by using the ECCD method. Figure 4 plots I_p as a function of the toroidal injection angle φ for lower ($\bar{n}_e$ < 0.5×10^{19} m^{-3}) and higher ($\bar{n}_e$ > 0.5×10^{19} m^{-3}) density cases, where the center heating condition was kept by adjusting the poloidal injection angle and the polarization angle. The direction of I_p in the lower density case is negative for φ > 0° and consistent with that of the current driven by ECH. Although clear φ–dependence of I_p was observed for –2° < φ < 5°, the dependence was not clear for 5° < φ. On the other hand, for the higher density conditions, the direction of I_p was always positive as shown in the figure possibly due to the large "bootstrap current" in this high-density region. As increasing the toroidal injection angle, however, the reduction of I_p was observed. The amount of this decrease is close to the value observed in the

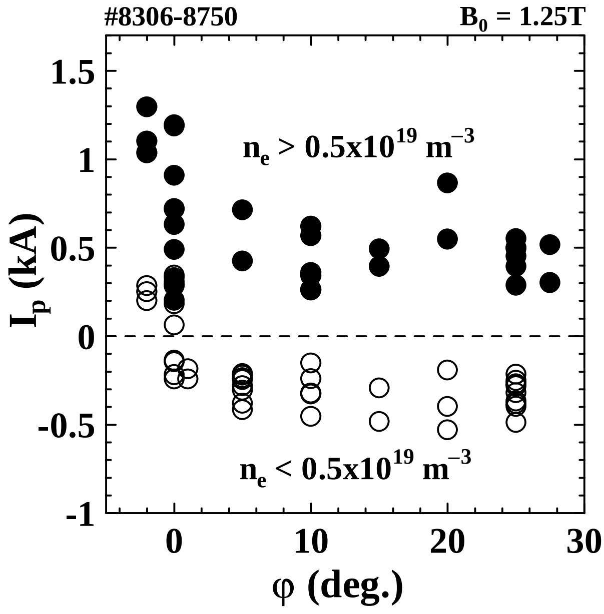

FIG. 4. Dependence of I_p on the toroidal injection angle of the microwave beam.

low-density case, suggesting that the "bootstrap current" is partly compensated by the "ECCD current". In order to understand the observed current behavior, simulation studies are being performed taking into account the complex configuration of Heliotron J besides the efforts to collect detailed database including profile data of plasma parameters.

4. Summary

Studies of global energy confinement and toroidal plasma current behavior for the second harmonic 70 GHz, 0.4 MW ECH at B = 1–1.5 T have been carried out with special regard to the magnetic configuration effects in Heliotron J. The obtained results so far are summarized as follows.

1. The observed energy confinement characteristics were compared with the ISS95 scaling, and the results showed the existence of good confinement plasmas whose energy confinement time was about 1.5 times larger than the ISS95 scaling.

2. Measurements of the toroidal current revealed the configuration effects of the neoclassical bootstrap current, showing qualitative consistency between experiment and neoclassical theory.

3. The ECH launching angle dependence of electron cyclotron current drive was also observed and it proved a good possibility of the total toroidal current control based on the ECCD scenario.

From these ECH experiments, it is concluded that, while a detailed and more precise data analysis is required to clarify the physics properties of the observed good confinement behavior, Heliotron J can provide a unique chance in advanced helical systems for extending their plasma properties to a new regime and finding the keys to improve the confinement.

Acknowledgements

This work was partially supported by the Grant-in-Aid for Science Research of MEXT in Japan and by the Collaboration Program of the Laboratory for Complex Energy Processes, IAE, Kyoto University.

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