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Fully Non-Inductive Current Drive using Electron Cyclotron Waves in Millimeter and Microwave Range

QUEST 装置におけるミリ波・マイクロ波帯電子サイクロトロン波を用いた完全非誘導電流駆動

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In non-inductive current drive experiments only by the 28 GHz injection, 54 kA plasma current I_p was sustained for 0.9 sec. Higher I_p of 66 kA was non-inductively obtained by slow ramp-up of vertical field B_v using the 2nd harmonic 28 GHz Electron Cyclotron Heating and Current Drive (ECHCD). Non-inductive high-density / current plasma start-up, which is a key issue for fusion reactor design has been demonstrated using 2nd harmonic ECHCD. Density jump across 8.2 GHz cutoff density was observed in superposed 28 GHz/8.2 GHz injections. The 50 kA plasmas were sustained by the 8.2 GHz injection into the 28 GHz target plasma if the stable plasma shaping was obtained.

1. Introduction

The Q-shu University Experiments with Steady-State Spherical Tokamak (QUEST) was proposed at Kyushu University, and the QUEST device was constructed. Spherical tokamaks (STs) can attain a higher β than conventional tokamaks. The ultimate goal of the QUEST project is steady-state operation with relatively high beta (<10%) in the ST configuration under controlled plasma wall interactions. For steady-state tokamak operation, a plasma current drive method should be established. Electron Bernstein Wave Heating and Current Drive (EBWHCD) is an attractive candidate for sustaining steady-state ST plasmas. In ST experiments, the plasma frequency may become larger than the electron cyclotron frequency in the operating density range because of the low magnetic field, and electron cyclotron waves cannot propagate into the plasma beyond the cutoff. EBWHCD experiments require mode conversion processes from the electron cyclotron O/X-mode (electromagnetic) waves to the Electron Bernstein (electrostatic) Wave. In O-X-B mode conversion experiments, the launching angle and elliptical polarization state should be controlled to achieve high-efficiency mode conversion into the Bernstein wave. A Phased-Array Antenna (PAA) system that enabled us to control the launching angle and incident polarization state was proposed for the EBWHCD experiments in the QUEST. The CW PAA's performance was evaluated in the QUEST vacuum vessel at a high power level [1]. RF (8.2 GHz) plasma startup and sustainment experiments using the CW PAA system have progressed to expand the obtained plasma current region, but their densities were typically lower than the cutoff density, while a new high-density operational window for sustained plasma current was observed with the higher RF incident power [1]. In order to conduct high density and plasma current experiments on the EBWHCD subject, Kyushu University, University of Tsukuba and the National Institute for Fusion Science have begun bi-directional collaborative research on ECHCD experiments using a high-frequency power tube, gyrotron. If the high-frequency power source is available, accessible density in the experiments increases as square of the operation frequency. University of Tsukuba has developed a 28 GHz gyrotron with 1MW output [2]. The high power facilities to operate the gyrotron were prepared in Kyushu University, and the 28 GHz experiments have begun recently in Kyushu University under the bi-directional collaboration framework.

2. 28 GHz Plasma Start-up and Sustainment

Fully non-inductive current drive experiments have been conducted with the 28 GHz ECHCD system in the QUEST to demonstrate high-density/current plasma start-up and sustainment with 2nd harmonic ECHCD. Figure 1 shows time evolution of I_p, B_v and the plasma shaping parameters of aspect ratio A, elongation k and triangularity δ in the inner limiter-configuration. The I_p was ramped up at high ramp-up rate of ~ 0.5 MA/s. The 54 kA I_p was finally obtained by ramping up B_v, and was sustained for 0.9 sec. The plasma shaping was almost kept at stable configuration for 1.3 sec. The magnetic axis radius R_{ax} and A were 0.67 m and 1.4, respectively. In B_v ramp-up experiments, the I_p of 66 kA was non-inductively attained with the 28 GHz injection.

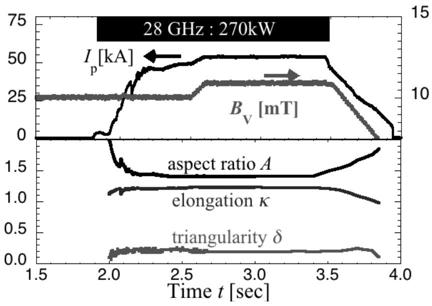

Fig.1. Time evolution of I_p, B_v, aspect ratio A, elongation κ and triangularity δ in the inner limiter-configuration.

3. Superposed 28 GHz and 8.2 GHz Injections

High-density plasmas beyond the 8.2 GHz cutoff density were tried to attain by the 28 GHz injection for EBWHCD experiments. 2nd harmonic and fundamental ECR layers were located at major radii of R = 0.32 m and 0.54 m for the 28 GHz and 8.2 GHz injections at toroidal magnetic field of B_0 = 0.25 T, respectively. Spontaneous density jump across the cutoff density was observed in the superposed injections. Figure 2 shows time evolution of I_p, line-averaged density, Hα intensity, R_{ax}, minor radius a. with and without the density jump. The gas fueling was applied at t = 2.9 sec to increase the density. The operating parameters including the gas fueling were identical in both discharges. Hα intensity was kept constant, and R_{ax} and a were slightly decreased in the density jump case. I_p was once decreased, but was recovered finally. In the density jump case, β_p* (sum of average poloidal beta β_p and half plasma internal inductance l_i) was first decreased by the decrement of a, and secondarily by the increment of I_p. The plasma was self-organized to be more stable shaping, and then the I_p was recovered in the high-density plasma. The flux signals showed inward shift of plasma current distribution, suggesting from the decrement of R_{ax}.

50 kA plasma was started and ramped up with the 28 GHz injection, and then the 8.2 GHz RF power was injected into the target plasma. Figure 3 shows time evolution of I_p, B_v, R_{ax}, a, β_p* and line-averaged density. The 50 kA plasma was sustained by strong B_v at β_p*~1.5 where it was also stable in the density jump study. In constant B_v, the plasma was shifted outward and the I_p was decreased to the 10 kA level. By the increased B_v, the minor radius a became small at R_{ax} ~ 0.6 m. Current driving loop voltage was significantly observed at the B_v ramp-up, but the 50 kA current level was non-inductively kept later. The density began to increase spontaneously under the stable configuration at β_p*~1.5, but was not beyond the cutoff. High current non-inductive EBWHCD experiments are planned in spontaneous or gas fueling over dense plasmas under the stable plasma shaping.

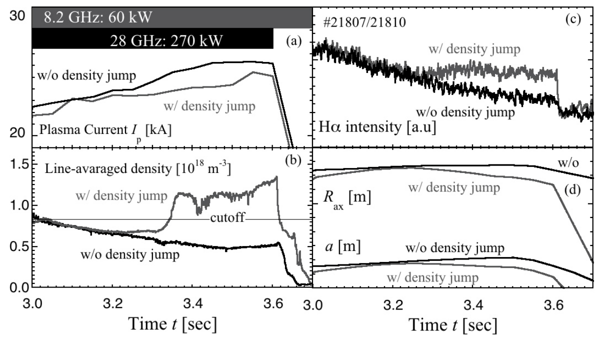

Fig.4: Time evolution of I_p, line-averaged density, Hα intensity, R_{ax}, a and β_p* w/ and w/o the density jump.

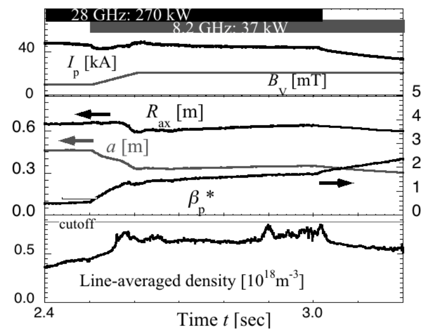

Fig.5. Time evolution of I_p, B_v, R_{ax}, a, β_p* and line-averaged density.

Acknowledgments

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References

[1] H. Idei, *et al.*, Proc. of FEC-IAEA2012.

[2] T. Imai, *et al.*, Proc. of FEC-IAEA2014.