The role of fast electrons on the non-inductive current ramp-up in QUEST

S. TASHIMA[1], H. ZUSHI[2], M. ISOBE[3], S. OKAMURA[3], H. IDEI[2], K. HANADA[2],
S. K. SHARMA[1], T. RYOUKAI[1], M. ISHIGURO[1], H. LIU[1] and the QUEST group

[1] *IGSES, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan*

[2] *RIAM, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan*

[3] *National Institute for Fusion Science, 509-5292,Toki, Japan*

ABSTRACT

The role of energetic electrons during the non-inductive current ramp-up is investigated in electron cyclotron heated plasma (≤ 60kW) in the spherical tokamak QUEST. The pulse height analysis of the hard X-ray (HX) is carried out with a fast time resolution of ≥1 ms, and acceleration of the electrons are studied by measuring the evolution of spectrum. It is found that wall recycling condition affects the formation of the tokamak configuration from an initial open magnetic field configuration. The vertical magnetic field B_z dependence of driven current I_p (~ 11 kA) is compared with those of HXs for studying contribution of fast electron. For high recycling case, I_p and HXs show peaks at an optimal low value of $B_z/B_t = 7 \times 10^{-3}$, however, for low recycling case, both increase monotonically with $B_z/B_t = 7 \times 10^{-3} - 21 \times 10^{-3}$.

1. Introduction

For steady state operation of the fusion tokamak devices effective current start-up and maintenance of the driven current are one of the important research fields. Non-inductive current start up including pressure-driven current (bootstrap current) has been studied using RF methods (i.e., electron Bernstein current drive EBCD) [1-5]. Deep understanding of Physics of the wave conversion, creation and confinement of the energetic electrons, and current ramp-up from the open magnetic field configuration is still required to establish this method in fusion-grade plasma experiments. We measured HXs from the energetic electrons created by the RF waves and compared those with the behaviour of I_p. In both conditions, i.e. open and closed field line configurations, the B_z dependence of I_p and HXs is studied for understanding the role of the energetic electrons on current ramp-up.

2. Experimental set up

QUEST is a medium sized spherical tokamak device [6]. Slab plasma has the height of 2 m and width 0.1 -1 m depending on RF power P_{RF} and tokamak plasma has the major (R_0=0.68 m) and averaged minor (<a>=0.4 m) radii, respectively. Toroidal magnetic field B_t is 0.125 T at R_0

and I_p is ~ 10 kA driven by the RF waves. The obliquely injected waves in both O and X modes at f_{RF} = 8.2 GHz (< 200 kW, continuous operation) are used for these experiments [7]. Plasma current was raised in two steps, during the constant B_z phase followed by the rapid ramp-up phase resulting in I_p rise. Two semiconductor detectors (CdZnTe and CdTe) view tangentially the plasma on the mid-plane and detect the emission from the energetic electrons in the energy range up to 200 keV [8]. Tangent radii R_{tan} are 0.372 m (CZT) and 0.5 m (CT), respectively. When the electron energy is high, the radiation lobes of bremsstrahlung emission strongly shift forwardly along the electron drift direction by the relativistic effect. Forward (backward) emission is detected by CT (CZT) when I_p (>0) is driven in the CCW direction or the electrons carrying current flow in the CW direction. In this paper, I_p and HXs are compared as a function of B_z during these phases, open and closed magnetic fields.

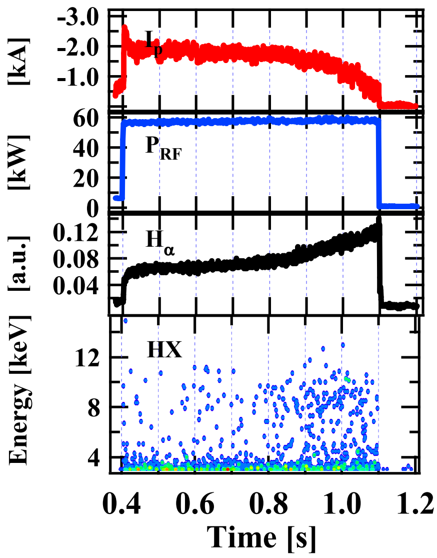

Fig. 2 The discharge by ECRH (8.2GHz), waveforms of I_p, P_{RF}, H_α and HXR spectrum (CT)are shown.

3. Experimental results

3.1 Open magnetic field configuration

The discharge waveforms are shown in Figure 1. After the pre-ionization at small P_{RF}, the main power (~50 kW) was injected from 0.4 s to 1.1 s. Both B_t and B_z were constant. I_p peaked at ~ 3 kA immediately, remained at ~ 2 kA and finally decayed. This reduction was ascribed to the variation in H_α, i.e. particle recycling. The temporal evolution of HX energy spectrum shows a rapid rise of electrons in the order of 10 keV at the beginning, and steady sustainment for the discharge. There was no significant difference in spectrum between the CW direction and CCW direction. In the later of the discharge, however, the count was increased, which may be due to the density rise. Although

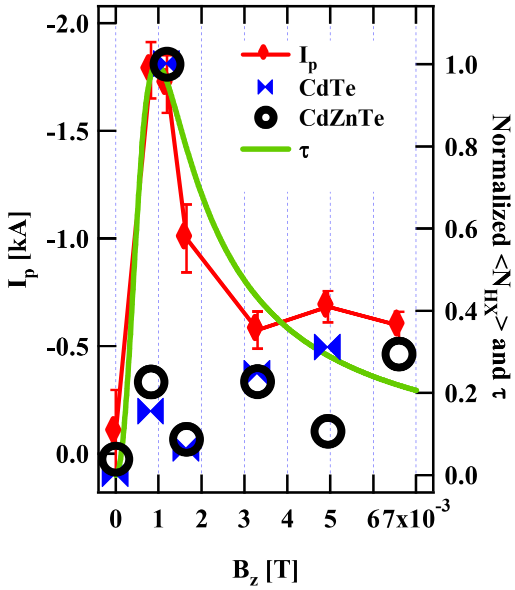

Fig. 2 $\langle I_p \rangle$ and $\langle N_{HX} \rangle$ dependence of B_z

the direction of I_p (> 0) could be controlled by the direction of B_z (< 0), no closed magnetic surfaces were observed by measuring the CCD images for visible light. Without B_z, I_p fluctuates in both direction, while the averaged value is 0. By varying B_z to 6.6 mT, $\langle I_p \rangle$ and HX counts $\langle N_{HX} \rangle$ averaged for 0.45 s to 0.8 s are plotted as a function of B_z, as shown in Figure 2. It is found that $\langle I_p \rangle$ peaks at B_z of 1 mT, which is similar to those in early experiments using 2.45 and 8.2 GHz [8]. Under this condition characterized by high particle recycling, $\langle I_p \rangle$ never increased with increasing B_z. $\langle N_{HX} \rangle$ shows a similar tendency to that of $\langle I_p \rangle$, suggesting that the energetic electrons contribute to I_p even in the open field.

3.2 Closed magnetic field configuration

After the wall conditioning, the reduction in H_α level by ~ 1/20 (compared to that in Fig. 1) during the discharge results in increasing I_p with increasing B_z from 1 to 3 mT, as shown in Fig.3. P_{RF} of 35 kW was enough to ramp up I_p to ~ 11 kA from the initial value of ~ 1 kA. When B_z was started to increase at 0.45 s, I_p was jumped to 4 kA at 0.49 s, and the closed surfaces were formed [9]. After that, during that the plasma size grew, the I_p ramp-up rate was controlled 10-20 kA/s to avoid the positive inductive current driven by V_{loop} (< 10 mV). The HX (> 10 keV) became significant at the time at which I_p abruptly jumped, then acceleration up to ~ 150 keV of the energetic electrons was observed during the ramp-up phase. In those experiments, the spectrum of CCW direction is larger than spectrum of the CW direction. Figure 4 shows similar tendency of I_p and $\langle N_{HX} \rangle$ on B_z, suggesting that I_p is carried by the energetic electrons. Here $\langle N_{HX} \rangle$ is averaged over 4 ms.

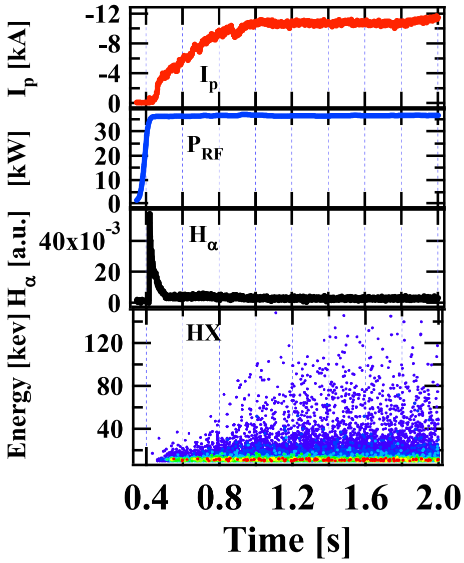

Fig. 3 The wave form of P_{RF}, B_z, H_α I_p and HXR spectrum.

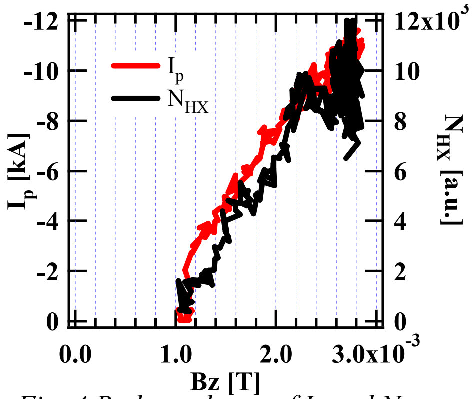

Fig. 4 B_z dependence of I_p and N_{HX}

4. Discussion and Summary

Even in the open field a poloidal equilibrium balancing the parallel loss along the spiral field lines and radial E×B drift loss has been proposed [10]. In figure 2, it is shown that the B_z

dependence of the confinement time (τ) agrees well with that of I_p, where τ is calculated using the typical values of $n_e=2\times10^{17}$ m^{-3}, $T_e=10$ eV and slab plasma parameters. Thus it is suggested that the observed I_p is the toroidal component of Pfirsch-Schlüter current I_{PS} cancelling the charge separation in the open magnetic field. On the contrary, $<N_{HX}>$, whose energy is ~ a few keV, also shows the similar tendency. When this model is extended to include the energetic electrons, the temperature anisotropy $(T_\perp/T_\parallel)=10^2$ does not change the result significantly if $T_{e\parallel}$ is fixed to be 10 eV. Although it can be expected that the toroidal precession I_{tp} of trapped particles can carry a toroidal current if E×B drift of the banana particles is reduced as B_z increases, the collisions with neutrals may prevent them from carrying I_p. When the recycling is much reduced, sheet currents (I_{PS} or I_{tp}) may form the field null region in the high field side, and then a closed flux surface may be drastically established [11].The B_z dependence of I_{tp} or stagnation orbit particles [12] is under study.

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