The role of energetic electrons on non-inductive current start-up and formation of an inboard poloidal field null configuration in the spherical tokamak QUEST

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1. INTRODUCTION

Non-inductive current start up and sustainment using electron cyclotron resonance heating (ECH), aiming at steady state operation of the fusion tokamak, has been studied on the several devices [1 - 5]. In the current start-up phase, three mechanisms for initial current $I_{p}^{\text{initial}}$ have been proposed as follows; the pressure-driven current $j_{pd}$ [6], co-moving electrons characterized by stagnation orbits $j_{co}$[7,8], and toroidal precession of trapped electrons $j_{pr}$. Since the direction of these currents depends on the sign of the vertical field $B_z$, the effect of curvature and the magnitude of $B_z$ or mirror ratio $R_{\text{mirror}}$ of the toroidal field $B_t$ on $I_{p}^{\text{initial}}$ is studied to verify the dominant mechanism or evaluate the fraction of mechanisms. Here, $R_{\text{mirror}}$ is defined as the ratio of $B_t$ at the wall and $B_t$ at the mid plane along the field lines. In the steady state phase, the fraction of $B_z/B_t$ on $I_p$ and equilibrium is also investigated. High beta poloidal $\beta_p$ equilibrium with an inboard null is found at high $B_z/B_t$ and high $R_{\text{mirror}}$. The role of the energetic electrons created by ECH on $I_{p}^{\text{initial}}$, and formation and sustainment of high poloidal beta $\beta_p$ plasma is studied with measurement of hard X-rays (HXR).

2. EXPERIMENTAL SETUP

QUEST is a medium sized device, whose inner and outer diameters are 0.2 m and 1.4 m, respectively. Two flat divertor plates are set at $Z = \pm 1$ m from the mid-plane. The major ($R_0$) and minor ($<a>$) radii of the plasma are 0.7 – 0.85 m and 0.2 – 0.4 m, respectively. RF waves at the frequency of 8.2 GHz are used to initiate plasma. $B_t$ is 0.29 T and the fundamental resonance locates at $R_{\text{res1}} = 0.3$ m. The typical plasma density $n_e$ is below the cut-off density $n_{\text{cut}}$ ($\sim 8.6 \times 10^{17}$ m$^{-3}$). Since the chamber aspect ratio is 1.33 and 1st -3rd harmonics co-exist, electrons can interact with ECWs at various parallel refractive indices $N_{||}$. Up to 50 kW of rf power is injected in the O-mode at $N_{||0} < 0.4$. The $R_{\text{mirror}}$ is varied from 0.85 to 2 by choosing
three pairs of poloidal field coils. For $R_{\text{mirror}} < 1$, the magnetic field lines are convex indicating the negative curvature. The ratio of $B_z/B_t$ is varied up to 10% at $2 \times R_{\text{res1}}$. The semiconductor detector CdTe, whose size is $3 \times 3 \times 1 \text{ mm}^3$, is used to detect bremsstrahlung emitted by energetic electrons in the energy range $< 1 \text{MeV}$. Pulse height analysis is used to obtain the energy spectrum with a time resolution of a few msec. The observation lines view plasma tangentially on the mid plane with the radial resolution of $\pm 0.1 \text{ m}$ at $R_{\text{tan}}$ of 0.5 m.

3. EXPERIMENTAL RESULTS

(a) current start-up

In order to investigate how energetic electrons confined in the open configuration contribute to $I_{\text{p\ initial}}$, three kinds of open configuration, whose $R_{\text{mirror}}$ and the decay index $n^* (= -d\ln B_z/d\ln R)$ are respectively, 0.85 and -0.02 at R=0.6 m for the case (a), 1.2 and 0.2 for the case (b), and 2 and 0.5 for the case (c), are chosen. $P_{\text{RF}}$ is 17 kW and the line density $n_e l$ is $< 1 \times 10^{17} \text{ m}^{-2}$. The magnetic reconstruction using flux loop signals indicates that a closed magnetic surface is not formed for $I_{\text{p\ initial}}$ below 4 kA. Figure 1 shows the $B_z$ dependence of $I_{\text{p\ initial}}$ and HXR flux ($\Gamma_{\text{HX}}$) in the energy range of 10 – 60 keV. In the case (a), no current is observed for $B_z < 0.8 \text{ mT}$, $I_{\text{p\ initial}}$ peaks at $\sim 1 \text{ kA}$ at $B_z \sim 1 - 1.2 \text{ mT}$ and decreases to zero for $B_z > 1 \text{ mT}$. The peak of $\Gamma_{\text{HX}}$ ($\sim 50 \text{ counts/sec}$) also corresponds to the peak of $I_{\text{p\ initial}}$, but no high energy ($> 30 \text{ keV}$) HXR are observed (see Fig 1c). In the case (b), it is observed that $I_p$ increases linearly up to 3.7 kA as $B_z$ increases to 1.4 mT, and remains at $1 \text{kA} \pm 0.2 \text{ kA}$ for $1.6 \text{ mT} < B_z < 2.8 \text{ mT}$. At $B_z = 1.4 \text{ mT}$ $\Gamma_{\text{HX}}$ shows the maximum, and at $B_z = 1.6 \text{ mT}$ it is reduced and it is increased gradually again with increasing $B_z$. At the $B_z > 1.6 \text{ mT}$, the high energy component of HXR ($> 30 \text{ keV}$) is increased. In the case (c) $I_{\text{p\ initial}}$ also
increases up to 3 kA with a proportional constant which is a factor of three smaller than that in the case (b). No reduction in $I_p^{\text{initial}}$ is observed. Although $I_p^{\text{initial}}$ is < 3 kA, $\Gamma_{\text{HX}}$ is increased up to $3 \times 10^4$ c/s at $B_z = 3$ mT, which is one order of magnitude higher than that in the case (b). The energy spectrum shows that energetic electrons build up towards the higher energy range.

**(b) inboard poloidal field null configuration**

Since the case (c) shows a favorable current start-up, current sustainment experiments have been performed under the condition of temporally constant $B_z/B_t$ up to 10%. $P_{RF}$ is 45 kW and $n_L$ is $\sim 2 \times 10^{17}$ m$^{-2}$ ($n_e < n_{\text{cut}}$). Figure 2 shows the $B_z$ dependence of $I_p$, $\Gamma_{\text{HX}} (>50$ keV) and $T_{\text{HX}}$. Here, $T_{\text{HX}}$ is determined from the slope of the energy spectrum. These three quantities increase with increasing $B_z$ and are well kept constant in time. At $B_z = 15$ mT $I_p$ reaches up to 16 kA and the maximum energy extends to $\sim 0.8$ MeV. If the number density of energetic electrons $n_{\text{shot}}$ is assumed 0.1 $n_e$ [9], $\beta_{\text{PHX}} = n_{\text{shot}} T_{\text{HX}}/(B_p^2/2\mu_0)$ can be evaluated, where $B_p$ is the poloidal magnetic field. $\beta_{\text{PHX}}$ is $\sim 3.8$ and almost independent of $B_z$. Figure 3 shows the reconstructed magnetic flux with the inboard poloidal field null due to high $\beta_p$. These results indicate that in the case (c) electrons created by ECH can be well confined and accelerated with increasing $B_z$, and then as a result they contribute to formation and sustainment of the high $\beta_p$ equilibrium.
4. Discussion and summary

The initial energy of electrons born near the cyclotron layer is evaluated at several keV [10], which can be supported by the fact that at the very beginning phase of the ECR, HXR ~ 10 keV has been measured [11]. Since they are collisionless, a physical picture based on particle orbits is possible. In the case (a), since the curvature of the field lines is convex, co-moving electrons with stagnation orbits and mirror trapped particles with banana orbits cannot be confined. Thus the pressure-driven current might be a plausible mechanism. In cases (b) and (c) the contribution of \( j_{co} \) and \( j_{pr} \) to \( I_p^{initial} \) might be discriminated by orbit calculations taking the magnitude of \( B_z \) into account. The orbits of electron, having energy from 10 -30 keV, launched at \( R=0.6\text{m} \) and \( Z=0\text{ m} \) show that when \( B_z \) is 1.2 mT co-moving electrons at 10 keV can be confined for the pitch angle\((\theta)\) of > 60° and at 30 keV for \( \theta > 0° \). Thus it is concluded that \( j_{co} \) contributes to \( I_p^{initial} \). However, when \( B_z \) is 3 mT, they can be confined only for \( \theta \sim 85° \). This strong \( B_z \) dependence of stagnation orbits is ascribed to that the energy is proportional to \( B_z^2 \). On the other hand, the trapped particles for \( \theta > 65° \) can be well confined. The width \( \Delta \theta \) of the trapped particles increases to 45° with for \( R_{\text{mirror}} = 2 \). Therefore, it can be concluded that the trapped electrons dominate \( I_p^{initial} \) at high \( B_z \) and large \( R_{\text{mirror}} \).

In the case of \( R_{\text{mirror}} = 2 \), the inboard null configuration is found to be sustained in steady state. From the equilibrium relation \( B_z = \mu_0 I_p/4\pi R(\ln(8R/a) + li/2 - 3/2 + \beta_p) \) [12], \( \beta_p \) is evaluated as 3.87, which is consistent with \( \beta_{PHX} \). Here, \( I_p = 11 \text{ kA} \), \( B_z = 10 \text{ mT} \), \( a = 0.15 \), \( R = 0.73 \) and \( li = 1.2 \) are used. As shown in Fig. 2, since both \( \Gamma_{HX} \) and \( T_{HX} \) relate with \( B_z \) linearly, the hot pressure \( n_{\text{hot}} T_{HX} \) is proportional to \( B_z^2 \). Thus, non-inductive current driven by EC waves leads to the high \( \beta_p \) equilibrium due to the better confinement of the energetic trapped particles.

References