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

S. TASHIMA[1], H. ZUSHI[2], M. ISOBE[3], H. IDEI[2], S. OKAMURA[3], K. HANADA[2], K. NAKAMURA[2], A. FUJISAWA[2], K. MATSUOKA[2], M. HASEGAWA[2], Y. NAGASHIMA[2], M. ISHIGURO[1], S. KAWASAKI[2], H. NAKASHIMA[2], A. HIGASHIJIMA[2]

[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*

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 $I_p^{initial}$ 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_{mirror} of the toroidal field B_t on $I_p^{initial}$ is studied to verify the dominant mechanism or evaluate the fraction of mechanisms. Here, R_{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 Ip and equilibrium is also investigated. High beta poloidal β_p equilibrium with an inboard null is found at high B_z/B_t and high R_{mirror}. The role of the energetic electrons created by ECH on $I_p^{initial}$, and formation and sustainment of high poloidal beta β_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= ± 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_{res1} = 0.3 m. The typical plasma density n_e is below the cut-off density n_{cut} (~ 8.6×10^{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 $N_{\parallel}$. Up to 50 kW of rf power is injected in the O-mode at $N_{\parallel 0} < 0.4$. The R_{mirror} is varied from 0.85 to 2 by choosing three pairs of poloidal field coils. For R_{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 $2\times R_{res1}$. The semiconductor detector CdTe, whose size is $3\times3\times1$ mm^3, is used to detect bremsstrahlung emitted by energetic electrons in the energy range < 1MeV. 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 ±0.1 m at R_{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 $I_p^{initial}$, three kinds of open configuration, whose R_{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_{RF} is 17 kW and the line density $n_e l$ is < 1×10^{17} m^{-2}. The magnetic reconstruction using flux loop signals indicates that a closed magnetic surface is not formed for $I_p^{initial}$ below 4 kA. Figure 1 shows the B_z dependence of $I_p^{initial}$ and HXR flux (Γ_{HX}) in the energy range of 10 – 60 keV. In the case (a), no current is observed for B_z < 0.8 mT, $I_p^{initial}$ peaks at ~ 1 kA at B_z ~ 1 – 1.2 mT and decreases to zero for B_z > 1 mT. The peak of Γ_{HX} (~ 50 counts/sec) also corresponds to the peak of $I_p^{initial}$, but no high energy (> 30 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 1.4mT, and remains at 1kA ± 0.2 kA for 1.6 mT < B_z < 2.8 mT. At B_z = 1.4 mT Γ_{HX} shows the maximum, and at B_z = 1.6 mT it is reduced and it is increased gradually again with increasing B_z. At the B_z > 1.6 mT, the high energy component of HXR (>30 keV) is increased. In the case (c) $I_p^{initial}$ also

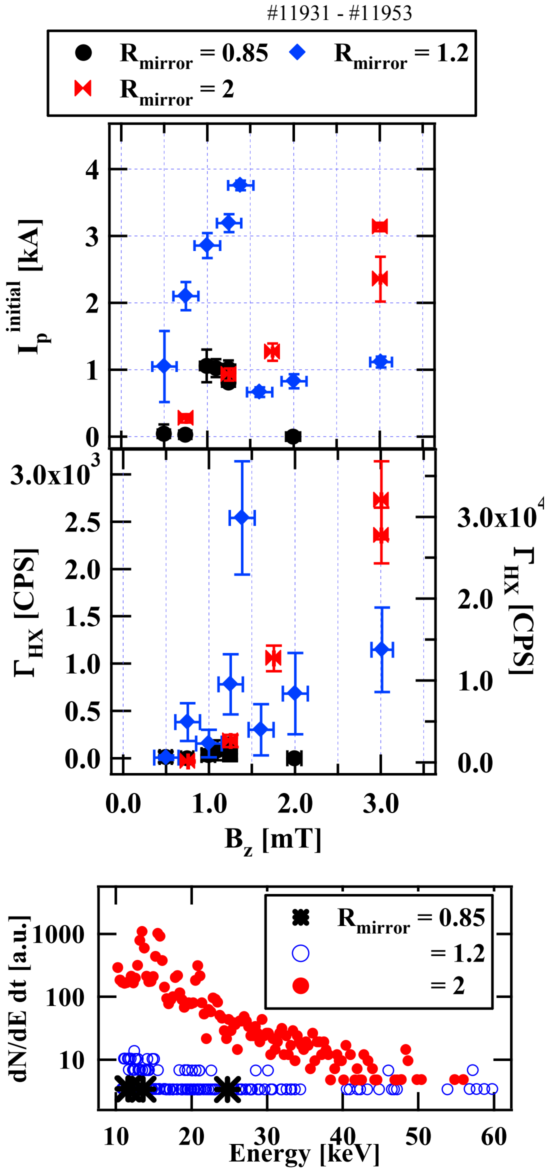

Figure 1 The B_z dependence of I_p and Γ_{HX} and energy spectra for R_{mirror} = 0.85, 1.2 and 2 at B_z = 2mT

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 $I_p^{initial}$ is observed. Although $I_p^{initial}$ is < 3 kA, Γ_{HX} is increased up to 3×10^4 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.

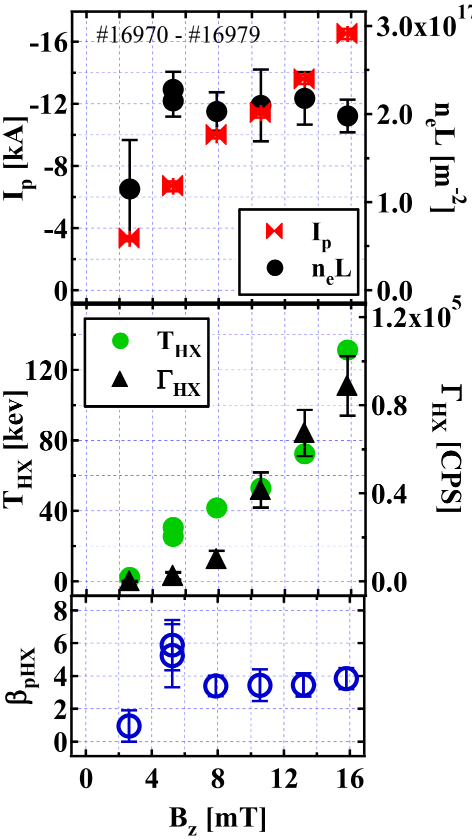

Figure 2 The B_z dependence of I_p, n_eL, T_{HX}, Γ_{HX} and β_{pHX} in the case(c)(R_{mirror} = 2).

(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 $n_e l$ is ~ 2×10^{17} m^{-2}(n_e<n_{ecut}). Figure 2 shows the B_z dependence of I_p, Γ_{HX} (>50 keV) and T_{HX}. Here, T_{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 ~ 0.8 MeV. If the number density of energetic electrons n_{ehot} is assumed 0.1 n_e [9], β_{pHX} $=n_{ehot}T_{HX}/(B_p^2/2\mu_0)$ can be evaluated, where B_p is the poloidal magnetic field. β_{pHX} is ~3.8 and almost independent of B_z. Figure 3 shows the reconstructed magnetic flux w ith the inboard poloidal field null due to high β_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 β_p equilibrium.

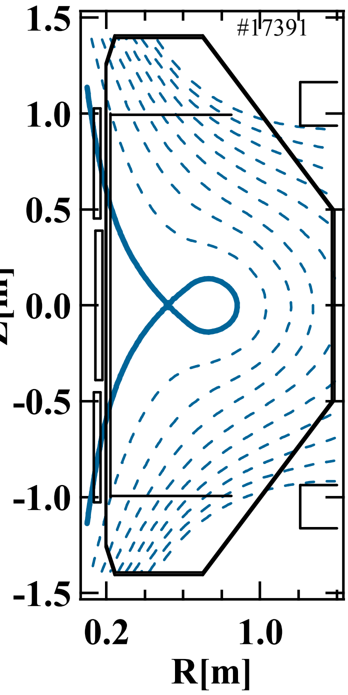

Figure 3 The magnetic flux contour of inner poloidal null configuration.

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=0.6m and Z=0 m show that when B_z is 1.2 mT co-moving electrons at 10 keV can be confined for the pitch angle(θ) of > 60° and at 30 keV for θ > 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 θ ~ 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 θ > 65° can be well confined. The width Δθ of the trapped particles increases to 45°with for R_{mirror} =2. Therefore, it can be concluded that the trapped electrons dominate $I_p^{initial}$ at high B_z and large R_{mirror}.

In the case of R_{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], β_p is evaluated as 3.87, which is consistent with β_{pHX}. Here, I_p = 11 kA, B_z = 10 mT, a = 0.15, R = 0.73 and l_i = 1.2 are used. As shown in Fig. 2, since both Γ_{HX} and T_{HX} relate with B_z linearly, the hot pressure $n_{ehot}T_{HX}$ is proportional to B_z^2. Thus, non-inductive current driven by EC waves leads to the high β_p equilibrium due to the better confinement of the energetic trapped particles.

References

[1] C.B. Forest, et al., Phy. Rev. Lett. **68** (1992) 3559
[2] C.B. Forest, et al., Phys. Plasmas **1** (1994) 1568
[3] T. Maekawa, et al., Nucl. Fusion **45** (2005) 1439
[4] A. Ejiri, et al., Nucl. Fusion **46** (2006) 709
[5] V. Shevchenko, et al., Nucl. Fusion **50** (2010) 022004
[6] L. E. Zakharov Sov, et al., J. Plasma Phys. **14** (1988) 75
[7] Rome J.A, et al., Nucl. Fusion **19** (1979) 1293
[8] T. Shimozuma, et al., Journal of the Physical Society of Japan **54** (1985) 1360
[9] M. Ishiguro, et al., Review of Scientific Instruments **82** (2011) 113509
[10] Peng Y-K.M, et al., Nucl. Fusion **18** (1978) 1489
[11] S. Tashima, et al., Journal of Plasma and Fusion Research **9** (2010) 316
[12] V. D. Shafranov, et al., Reviews of Plasma Physics Vol. 2, (Consultants Bureau, New York, 1966)