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# PROSPECT OF STRONGLY INWARD SHIFTED CONFIGURATION IN CHS

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**Abstract**

Inward shifts of the vacuum magnetic axis position $R_{ax}$ in CHS have shown compatibility between good particle orbit and MHD stability, and the configuration with $R_{ax}$ of 92 cm has been adopted as the standard configuration. The internal transport barrier (ITB) on the electron energy was realized in the standard configuration. Recently both of ion energy transport and particle diffusion of impurity ion were found to be improved under the ITB formation. The MHD stability has been studied in strongly inward shifted $R_{ax}$ configurations including the $\sigma$=1 configuration where $R_{ax}$ is about 88cm, because the neoclassical transport is expected to be more improved. It is found that NBI plasmas with $\langle\beta\rangle$ of about 1 % have not shown any confinement degradation irrespective of expected ideal interchange instabilities because of the stronger magnetic hill. Strongly inward shifted $R_{ax}$ configurations have good prospect from the viewpoint of MHD stability and confinement improvement.

## 1. Introduction

Helical magnetic traps must satisfy the following requirements: 1) clean and robust magnetic surfaces with an external rotational transform, 2) good $\alpha$-particle orbit and good neoclassical transport, 3) high equilibrium- and stability-$\beta$ values, 4) good energy confinement, 5) adequate capability of heat and particle control. After confirming the vacuum magnetic surface of CHS having the aspect ratio of 5 ($R / a_p$ = 1m / 0.2m), the prospect of CHS heliotron/torsatron configuration was discussed on the above requirements [1] : 2) successful plasma discharge without radiation collapse only with ICRF heating, 3) high $\beta$ stability up to 2%, and 4) global $\tau_E$ scaling. The most important point was that the inward shifted configurations with $R_{ax}$ of 92cm showed the compatibility between good particle orbit and MHD stability [2, 3].

Since that time the confinement improvement has been the most important subject in CHS experiments. Improved modes of tokamaks are usually accompanied with a negative radial electric field $E_r$, where there is a positive feedback relation between the negative $E_r$ and the ion pressure gradient. In CHS, trials for confinement improvement following tokamaks have been made. The H-mode was obtained by controlling the edge rotational transform (adjusted to be nearly 1 just inside LCFS) through inducing the OH current in an NB heated plasma [4]. Here, the simultaneous increase in the line averaged electron density $n_e$ and the decrease in the H$\alpha$ signal were observed in spite of a constant gas puffing, which is usually seen in H-modes of tokamaks. However, the jump in the poloidal rotation velocity was not observed in CHS and the improvement factor is up to 15%. High ion temperature ($T_i$ ) mode in an NB plasma was realized by making the electron density peaked [5]. Here, the density was fuelled primarily with NB without gas puffing under intensive titanium gettering. The ion thermal diffusivity $\chi_i$ in high $T_i$ mode is lowered by factor of two than that in the L-mode, reflecting the steeper $T_i$ profile. Again, the improvement factor is not large, although the maximum $T_i$ of 1 keV was attained in the high $T_i$ mode of CHS.

Another concern has been MHD stability in strongly inward shifted configurations ($R_{ax}$ < 90cm) where the neoclassical transport is improved. Although the $\sigma$=1 configuration, where $R_{ax}$ is 88cm, was studied from the viewpoint of the neoclassical transport in the low-collisionality ECH plasma with low $\beta$ [6], MHD stability study of finite-$\beta$ plasma in the $\sigma$=1 configuration has not been done. As $R_{ax}$ is shifted inward the magnetic hill gets stronger, that is because the outermost flux surface is almost fixed being determined by the helical coils whereas $R_{ax}$ can be changed freely by controlling poloidal coil currents.

## 2. Internal Transport Barrier in CHS

The confinement improvement is closely related to $E_r$ and its shear. The $E_r$ in CHS is determined by the ambipolar condition between electron and ion fluxes caused by non-ambipolar diffusion, bulk viscosity, orbit loss, charge exchange loss and so on. In CHS the non-ambipolar diffusion is the dominant process. The neoclassical internal transport barrier (NITB) for the electron energy was realized, for the first time in helical machines, by applying the 2nd harmonic heating of ECH with the frequency of 53.2 GHz and the threshold power of about 200 kW when $R_{ax}$ and $B_t$ were 92.1 cm and 0.88 T, respectively [7, 8]. It was induced by the large positive $E_r$ shear that is due to the bifurcated electric potential inside the barrier. In a conventional helical machine like CHS, where large rotation shear can not be expected because of a large helical ripple, the $E_r$ shear should rely on the non-ambipolar radial diffusion of ions and electrons. It has been shown that $\chi_e$ gets close to the neoclassical value in the barrier region [9]. The bifurcation occurs more easily as the electron density decreases under the heating power kept constant or as the power increases under the constant electron density. The electron density $n_e$ of the ECH plasma with NITB is below about $3\times10^{12}$ cm$^{-3}$, and the central electron temperature $T_e$ (0) is in the range of a few keV. To increase $n_e$ where NITB is realized two methods were tried. Higher frequency of 106 GHz at the 2nd harmonic ECH results in NITB with higher $n_e$ of about $5\times10^{12}$ cm$^{-3}$. The hysteresis phenomena have been clarified between the central potential and $n_e$ when those parameters are plotted along the temporal evolution of the discharge. Once NITB is established it can be kept at higher $n_e$. This hysteresis could also be used as a promising scenario to obtain the high confinement at higher electron density.

Since the discovery of NITB for the electron energy in ECH plasma the next concern has been on the improvement in the ion thermal diffusivity and in the particle diffusion. The 53 GHz 2nd harmonic ECH with the power of 130kW is applied to low-$n_e$ NB plasmas with the central density $n_e$(0) of 3-4$\times10^{12}$cm$^{-3}$, because the heating source for ions is needed within the barrier. The plasma makes transition to the electron root and $T_e$(0) increases to about 2 keV, and it

lowers to a few 100 eV after the ECH pulse. The NITB is formed in the NB plasma with ECH; the electron pressure increases by about factor of 4 in spite of the reduced $n_e$ because of ECH. The ion temperature $T_i$ also increases by about 50 %, however the ion pressure decreases due to the reduced electron density. The substantial part of the increase in $T_i$ is attributed to the increased $T_e$. On the other hand, when the ECH power is injected to slightly-higher-$n_e$ NB plasma with $n_e$ (0) of 4-5×$10^{12}$ $cm^{-3}$, $T_e$ (0) increases by factor of 4-5 to 900eV, however there is almost no increase in $T_i$. The transport analyses on the lower-$n_e$ case show that the electron thermal diffusivity is much reduced and is almost on the same level of the neoclassical value, and the ion thermal diffusivity is reduced inside of NITB.
The particle transport of titanium impurity ion is studied with soft X-ray CCD camera. The photon counting mode provides us with the 2 dimensional spatial profiles of the peak energy of Ti K$\alpha$ line that is determined by $T_e$ and the diffusivity [10]. It has been found by using the MIST code that the diffusivity is of the order of 0.02 $m^2$/s inside of NITB being much smaller than the value of 0.1- 0.2 $m^2$/s without NITB.

3. MHD Stability in the Strongly Inward Shifted Configuration
Two NBs were switched from balanced-injection to co- (or ctr-) injection and IBW with 9MHz has been operational to produce the target plasma irrespective of the magnetic field strength $B_t$. Two co-injected NBs resulted in $T_e$ (0) of 7-800eV at $n_e$ of 4-5×$10^{13}$ $cm^{-3}$, in the configuration with $R_{ax}$ of 92.1cm and $B_t$ of 1.76T, of which plasma parameters had not been obtained in the balanced injection. By using two NBs the MHD study on strongly inward shifted configurations has been done. The average value <β> of 1.2 - 1.3 % has been obtained without an elaborate wall conditioning at $B_t$ of 0.75 T with $R_{ax}$ of 89.9cm. The plasma passes through the range of <β> where the interchange mode is well unstable from the Mercier criterion. However, MHD instabilities that degrade the confinement have not been observed. In the previous experiment MHD instabilities which reduced the stored energy were excited for $R_{ax}$ of 89.9cm at <β> of 0.8 % after a sudden increase in the stored energy and in soft X-ray signals without changing externally controllable parameters. The reason why the previous result is not reproducible has not been known. Even if $R_{ax}$ is shifted more inward to 88.8cm, that is the $\sigma$=1 configuration in CHS, the confinement of the plasma with <β> up to 0.8 % is not degraded, where the magnetic hill gets stronger. The same thing holds for the plasma with <β> up to 0.6 % with the further inward shift of $R_{ax}$ to 87.8cm. The decrease in the achieved <β> is primarily due to the decrease in the plasma volume as $R_{ax}$ is shifted inward. Mode analyses for the plasma with $R_{ax}$ of 89.9cm show that coherent m=2 modes rotating in the ion diamagnetic direction appear at <β> of about 1% where the position of iota of 0.5 is located near $D_I$ of about 0.2. Burst-type oscillations are observed at lower <β> as before. Because of the technical limitation that the IBW antenna can not reach the outermost magnetic surface of the strongly inward shifted configurations ($R_{ax}$ of 88.8cm or more inward) for the initial breakdown, the plasma produced at $R_{ax}$ of 89.9cm with low $B_t$ that is not available for 53GHz ECH was shifted dynamically inward to $R_{ax}$ of 88.2cm by controlling the poloidal field coil currents in 100 msec. During this phase the poloidal flux and the quadrupole component were

kept constant not to induce OH current and not to introduce an additional effect of plasma shape of elongation on confinement. It is shown that $T_e$ and $n_e$ are increased by the dynamic shift in spite of the reduced plasma volume. The reason of the increase has not been known yet, however it can be said at least that there is no confinement degradation.

4. Summary and Discussion

The NITB in the standard configuration with $R_{ax}$ of 92.1cm has shown the improvement not only in electron energy but also in ion energy and in particle diffusion for the low $n_e$ NBI plasma. Although the potential bifurcation phenomena including NITB have been studied in the standard configuration with HIBP, the NITB should be realized also for strongly inward shifted configurations because it is caused by the nonambipolar fluxes originating in CHS magnetic field structures. The NITB should be more prominent in strongly inward shifted configurations where the neoclassical transport is more suppressed [11]. The NITB mode is a promising candidate for improved confinement that is expected in helical systems having no symmetry in their magnetic field strength. The hysteresis inherent in bifurcation can be used to obtain improved plasmas with higher $n_e$. Compatibility between good particle trajectory and MHD stability holds for strongly inward shifted configurations, including the $\sigma$=1 configuration, of CHS with the low aspect ratio. From the physics point of view the strongly inward shifted configuration has a good prospect in the CHS future experiment.

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