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# Overview of CHS Experiments

MATSUOKA Keisuke, OKAMURA Shoichi, KUBO Shin, IDEI Hiroshi, IGUCHI Harukazu,
FUJISAWA Akihide, IDA Katsumi, MORITA Shigeru, TANAKA Kenji, MINAMI Takashi, TOI Kazuo,
OSAKABE Masaki, YOSHIMURA Yasuo, AKIYAMA Ryuichi, TAKAHASHI Chihiro, SAKAMOTO Ryuichi,
INOUE Noriyuki, OHDACHI Satoshi, EJIRI Akira, SASAO Mamiko, NOMURA Izumi, ISOBE Mitsutaka,
PETERSON Byron, LEE Seishu, KURAMOTO Hideharu, MUTO Sadatsugu, OZAKI Tetsuo, GOTO Motoshi,
KADO Shinichiro, SAGARA Akio, NISHIMURA Shin[1], TAKAYAMA Sadatsugu[1], SHIRAI Yoshiaki[1],
PAVLICHENKO Rostislav[1], KONDO Takashi[1], HASEGAWA Yasuhiro[1], TAKECHI Manabu[2],
OHKUNI Kotaro[2], MATSUNAGA Go[2], TAKAGI Shoji[2], SHIMIZU Akihiro[2] and FUJIWARA Masami
*National Institute for Fusion Science, Toki 509-5292, Japan*
[1]*Graduate Univesrity for Advanced Studies, Hayama 240-0193, Japan*
[2]*Dep. of Energy Eng. Science, Nagoya Univ., Nagoya 464-8603, Japan*

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## Abstract

Recent experimental results from CHS are overviewed. Plasma parameters are extended to higher electron temperature at higher densities in an ECH plasma by introducing 106 GHz gyrotron and to higher ion temperature in an NBI plasma by realizing the so-called high Ti mode. Understanding of heliotron/torsatron plasma physics is deepened by profile measurements, especially by electric potential measurements with HIBP. On the basis of CHS results obtained so far, it might be concluded that the energy confinement improvement over the international stellarator scaling and elimination of the loss cone for high energy ions are important issues to be addressed for the low aspect ratio heliotron/torsatron. Those are thought to be closely related to the helical ripple. The quasi-axisymmetric configuration having essentially no helical ripple is proposed to overcome the ripple problem.

## Keywords:

CHS, heliotron/torsatron, plasma-wall interaction, confinement improvement, high Ti mode, HIBP, radial electric field, plasma rotation, helical ripple, quasi-axisymmetry

## 1. Introduction

CHS experiments [1] have been continued since 1988 to elucidate heliotron/torsatron plasma characteristics and to improve its performance. So far, the description of equilibrium of low aspect-ratio helical plasma has been established [2] and contributions to the ISS95 scaling law have been made [3]. The H-mode is realized by modifying the edge $\iota$ profile with OH current [4], although the energy confinement time is improved by about 20 %. The $<\beta>$ value of 2.1 % has been obtained [5, 6], which paved the road to the value of 5 % necessary for the reactor although the experimental verification of ballooning stability has remained. To study the high energy ion confinement, NB injection with variable injection angles [7] and ICRF heating were done, which showed poor confinement of perpendicularly-accelerated high-energy ions, although ICRF based on the electron heating was successful [8].

It is widely recognized that the improvement of the energy confinement time by factor 2 from ISS95 scaling is necessary for the reactor. The radial electric field

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*Corresponding author's e-mail: matsuoka@nifs.ac.jp*

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shear and/or the plasma rotation shear are required to reduce the anomalous transport. In CHS the toroidal plasma rotation driven by NB is suppressed because of the magnetic pumping by its helical ripple [9]. Making the ion pressure peaked is one of methods to produce the radial electric field shear for the confinement improvement in such a machine as CHS. Here, recent experimental results from CHS are introduced by taking its future prospect into consideration.

## 2. Experimental Results

### 2.1 Plasma performance improvement with plasma-wall interaction

The plasma-wall interaction is one of key elements for the confinement improvement. Recently two new approaches were applied for a coating method and for a divertor scenario. The plasma-touching surface was successfully coated with boron by the real time boronization (RTB) method [10] in which decaborane vapor was directly puffed into an NBI heated plasma. This method was developed for the steady-state superconducting LHD where a helium glow discharge for boronization is not available. After one day operation of RTB the oxygen content normalized by the electron density is decreased by factor 2 or 3 and the stored energy increased by 20−30 % as well as the density limit. However, it might be difficult to make boronization on shadow regions of in-vessel components with RTB.

The local island divertor (LID) [11] by utilizing the $m=1/n=1$ island produced with the perturbation coils was successful in controlling the edge recycling and in improving the confinement, where the magnetic axis position $R_{\mathrm{axis}}$ is 0.995 m. Total 16 coils were placed on the top and bottom of CHS at the vertically elongated plasma cross-section (the toroidal field period is 8 in CHS). The exhaust efficiency of less than 1% was demonstrated with LID and the leading edge problem of the pump limiter was mitigated by inserting it into the island. Under the same gas puff condition the average electron density decreases roughly by half with the LID operation and at the same electron density the stored energy increases by 20−30 %. This improvement results from an increase in the electron temperature in the core region, which might be caused by the low recycling. It should be noted that this divertor configuration owes to the $\iota$ profile inherent in CHS where the edge $\iota/2\pi$ is about 1.

### 2.2 Extention of plasma parameter range

By introducing a new 106 GHz gyrotron the total input power (53 GHz+106 GHz) for electron heating has been doubled and the parameter of ECH plasma has been extended; central electron temperature Te(0) of 2 keV at the average electron density $n_e$ of about $1\times10^{19}$ m$^{-3}$, $T_e(0)$ of 1 keV at $n_e$ of $3.5\times10^{19}$ m$^{-3}$ when $R_{\mathrm{axis}}$ is 0.921 m and the magnetic field strength B is 1.76 T (at R = 1m, which corresponds to 1.9 T at $R_{\mathrm{axis}}$) [12]. Low density plasmas are well inside the collisionless regime of which transport is important for helical systems. To make the transport analysis of ECH plasma without any assumption the one-pass absorbed power should be obtained experimentally. It has been possible by subtracting the transit power through the plasma from the incident power. The transit power is estimated by measuring the temperature rise on the SiC plate and this method can also be applied for estimating the incident power when there is no plasma. Indication of the collisionless transport is expected to be studied in the central region due to the relative importance of the neoclassical effect to the anomalous one.

The central ion temperature of 800 eV which is the highest value so far was obtained in the so-called high Ti mode, where two neutral beams were balance-injected with the total port-through power of 1.6 MW at $R_{\mathrm{axis}}$ of 0.921 m [13]. Here the electron density profile is made to be peaked by neutral beam fueling, where no gas puffing is applied and the wall is conditioned with titanium gettering between shots. On the other hand, when the gas is puffed and the density profile is flattened, the ion temperature is lower than that in the high Ti mode at the same average electron density. The highest ion temperature is obtained at $n_e$ of about $1.5\times10^{19}$ m$^{-3}$ and Ti decreases as the density increases (at the same time the density profile gets flattened). The peaked ion pressure profile is favorable for producing the radial electric field in CHS in which the plasma rotation is strongly damped by its large helical ripple. The confinement improvement for ion is found to be not due to the poloidal plasma rotation shear but due to the enhanced radial electric field shear from the force balance analysis on bulk ions and impurity ions (carbon in this case). However, the electron temperature in the high Ti mode is lower than that in the L-mode, of which reason has not been understood. The electron temperature is comparable to the ion temperature in the high Ti mode. This means that the ion confinement is significantly improved, because NBI, the unique heating source, delivers its energy preferentially to electrons under the experimental condition. The global energy confinement time of high Ti mode is almost comparable to that of the L-mode in CHS. Figure 1 shows the parameter range of CHS plasmas. The larger

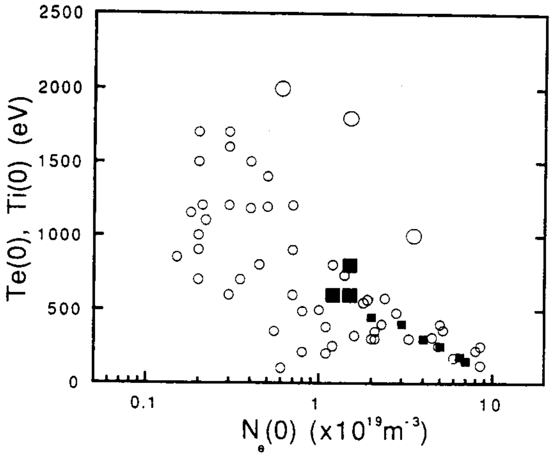

Fig. 1 Central electron (circles) and ion (squares) temperatures as a function of central electron density in ECH and NBI plasmas. Range of electron temperature extends to higher densities due to 106 GHz gyrotron and high Ti mode has realized higher ion temperatures (refer to larger symbols).

circles and larger squares represent recent results of the central electron and ion temperatures, respectively.

### 2.3 New findings with HIBP

HIBP measures potential fluctuations accompanied by the burst-like magnetic fluctuations, of which amplitude is the largest in CHS plasmas and which are observed in a low $\beta$ (less than 1 %) NBI plasma with co-injection and at $R_{axis}$ of 0.921 m. The mode numbers of the burst mode are $m=2/n=1$. Electric potential fluctuations are found to be accompanied with the magnetic fluctuations. At the growing phase of the burst mode the maximum amplitude of the potential fluctuation is about 40 V and it is located at $\iota/2\pi=1/2$ surface [14]. Identification of the burst mode is under discussion on the basis of the picture of interchange modes.

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In general, the potential is positive when the density is low (order of $10^{18}$ m$^{-3}$) and tends to be negative at higher densities. The potential profiles are essential for estimating the resonant loss of NB ions deeply trapped in the helical ripple during their slowing down [15]. To investigate the effect of the potential on the ion energy spectrum, ECH is applied to NB heated plasmas having the negative potential with $n_e$ of about $1\times10^{19}$ m$^{-3}$. FNA (fast neutral analyzer) has shown preliminary data on the energy spectrum; the dip at the energy of around 2 keV, which exists at the NB heating phase, disappears when ECH is applied [16]. This may be due to the fact that the resonant loss-cone loss existing at the negative potential is eliminated by the change in the potential to the positive direction.

Electric potential pulsation which continues during the discharge, like ELMs, has been found in an ECH + NB plasma with $n_e$ of about $1\times10^{19}$ m$^{-3}$, $B$ of 0.9 T and $R_{ax}$ of 0.921 m. There are two types of the pulsating potential. The global type, where the whole potential profile pulsates with the pivot point at $r/a$ of about 0.5, is seen at a lower electron density and with a higher ECH power, and the local type, where only central part of the potential pulsates, at a higher electron density and with a lower ECH power. The potential bifurcation of both types may be explained with the neoclassical theory based on the nonlinear relation between the radial current and the radial electric field [17].

### 2.4 Configuration improvement by inward shift

In heliotron/torsatron, an inward shift of the magnetic surface makes the magnetic configuration more omnigenous. This is because the equi-B surface determined mainly by the helical coils is shifted inward relative to the magnetic surfaces. In CHS where the positive pitch modulation of 0.3 is adopted in the helical coil for the purpose of good accessibility, it is necessary to move the magnetic surface significantly for omnigeneity. Strongly inward shifted configuration ($R_{axis}=0.888$ m) finally becomes to have $\sigma=+1$ characteristics [18], where the bottom of the ripple has the same magnetic field strength. This might be the unique method to improve the CHS magnetic field configuration from the neoclassical point of view. ECH plasmas with low collisionality in this configuration are expected to show better confinement because the role of neoclassical transport becomes important as the collisionality decreases. However, no significant improvement has been seen up to now in the global energy confinement time in comparison with the LHD scaling. Detailed measurements on electron temperature profiles are needed especially in the core region where the neoclassical transport manifests itself against the anomalous one.

## 3. Summary and Discussion

A steady progress is seen in CHS experiments and the plasma parameter range is extended according to the increase in the heating power and to the confinement improvement; the central electron temperature of 2 keV and the ion temperature of 800 eV have been obtained. By measuring the electric potential with HIBP our knowledge on potential-related physics is increased, for example, its effect on the resonant loss of deeply trapped ions. New findings on electric potential pulsation will also give insight to physics understanding of toroidal plasmas. On the basis of experimental results on several issues obtained so far (confinement time scaling, access to high $\beta$, high energy ion orbit, divertor configuration), it might be concluded that most critical issues are the confinement improvement and the loss cone of ion orbits, which are closely related to the future prospect of low aspect ratio heliotron/torsatron configuration. From the experiment of $\sigma=+1$ configuration the effort of reducing the neoclassical transport might not be enough to improve the confinement. High Ti mode shows importance of the radial electric field shear. The helical ripple inherent in heliotron/torsatron prevents spontaneous or externally-driven plasma rotations because of the magnetic pumping. If the rotation shear and/or electric field shear is essential to the suppression of anomalous transports, experiments are recommended in a helical machine where the viscosity against the plasma rotation is low. One of such configurations is now under consideration, which is quasi-axisymmetric having essentially no helical ripple [19, 20]. On the other hand, ease of divertor configuration is also very important for the future machine. Configuration optimization which is compatible with divertor functions will be needed in the research of helical plasmas.

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