Progress in the Study of Plasma Heating, Stability, and Confinement on HANBIT Mirror Device

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Abstract. HANBIT is a magnetic mirror confinement device, which consists of a simple mirror-type central cell, an anchor, a plug, and two end tanks. HANBIT started its physics experimental campaign in 2001, following the development phase of basic heating and diagnostic systems over 1996 to 2000. Initial physics experiments were concentrated on the basic physics studies of RF-heating, stability, and confinement in a simple mirror configuration of the central-cell, trying to identify the discharge characteristics and stable plasma operation modes. A main result from this initial study was that a stable, high-density plasma mode exists in the slow wave regime of $\omega \leq \Omega_{ci}$ in HANBIT, unlike the results from other mirror devices where the stable modes were mostly observed in the fast wave regime of $\omega > \Omega_{ci}$, where ω is the RF frequency and Ω_{ci} is the ion cyclotron frequency at the mid-plane of central cell. Since the last IAEA conference, a significant effort has been made to clarify the physics origin of this new stable mode. Also, an attempt has been made to produce the high-density mode in the fast wave regime of $\omega > \Omega_{ci}$, as observed in the other mirror devices. In addition, an intensive study is on the way to increase the plasma beta and ion temperature, mainly through the beach wave heating by the DHT antenna system.

1. Introduction

HANBIT is a magnetic mirror confinement device, which consists of a simple mirror-type central cell, an anchor, a plug, and two end tanks. The central cell has the length of about 5 m, the limiter radius of 0.18 m, the B-field intensity of 0.1-0.3 T, and the mirror ratio of about 10. For the plasma production and heating HANBIT utilizes two RF antenna systems; one is the slot antenna located near the center region with the maximum deliverable power of 500 kW at the typical operating frequency of 3.5 MHz, and the other is the DHT antenna located near the mirror throat with the maximum rate of 100 kW at 3.75 MHz. In addition, HANBIT has a 2 kW, 14 GHz Klystron system in plug for pre-ionization or hot-electron ring experiment, and a 200 kW, 28 GHz gyro-klystron system is under test for ECH experiment.

At the last IAEA conference we reported [1] a distinct operation window in HANBIT in which a sharp change in density and temperature, plasma β and confinement time along the change of the magnetic field appears clear in most of the experiments as shown in Fig. 1. Discharge characteristics are found to be quite different as the frequency of the launched wave, ω, passes the local ion cyclotron frequency, Ω_{ci}. The magnetic field of the central cell varied over the range of 0.2~0.3 T (ω/Ω_{ci} ~0.8-1.15) at a fixed frequency of the launched RF wave of $\omega/2\pi$=3.5 MHz. Some of the interesting characteristics are as follows [1,2]. The plasma density profile is almost flat over the plasma region in the $\omega > \Omega_{ci}$ case while it changes to a radially peaked profile in the $\omega < \Omega_{ci}$ case. The parallel ion temperature measured by the end loss analyser (ELA) also showed a substantial increase in the $\omega < \Omega_{ci}$. For the same case, the wall recycling rate is high enough to sustain the discharge without further gas fuelling. It is interesting to note that the increase in the wall recycling rate in the $\omega < \Omega_{ci}$ case is well correlated with the ion temperature increase and subsequently the increase of fast neutrals by the charge exchange processes. Ion heating can also contribute to the density build-up for $\omega < \Omega_{ci}$ regime. By the ambipolar diffusion condition, the confinement time is defined mostly by the ion transport, increasing with the ion temperature. Therefore better ion heating in the $\omega < \Omega_{ci}$ regime can contribute to the increase in the confinement time. All theses facts can contribute to enhance the density build-up. For the regime of $\omega > \Omega_{ci}$, difficulties to excite the fast wave from the slot antenna refrain the HANBIT plasmas from sustaining stable high-density modes.

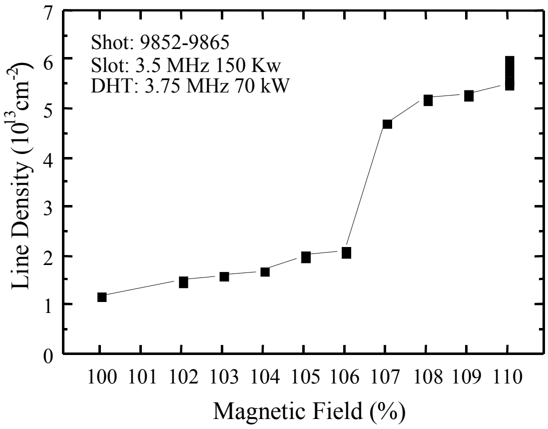

Fig. 1. Variation of peak line-density as a function of magnetic field at the central cell. Magnetic field of 106% corresponds to ω=Ω_{ci}.

During the series of experiments in HANBIT, neutral particle density is found to be one of the key factors to determine the discharge performance. The neutral density affects the confinement time and the energy loss through the charge exchange process. One of the operational difficulties of the HANBIT has been the plasma production with higher pressure because of the lack of any reliable pre-ionization method. Instead of the plasma gun, which has been producing high gas load, the electron cyclotron heating by klystrons and the reflex discharge system has been applied. A model has also been developed for DEGAS2 code for HANBIT edge simulation. Then a 1-D radial transport code calculated the transport equations of plasma particles including neutrals with given power density profile.

This year, four experimental campaigns are planned for obtaining a reference database, for improving machine performance, and for advanced physics experiments. Ion heating experiments at low pressure with two antennas, pre-ionization experiments with different methods, neutral transport and edge physics studies, and stabilization by the RF-induced effects are few of the main themes. Preliminary results for some of the above topics have been obtained and will be presented. This report presents the highlights in experimental results with analysis in section 2 followed by the summary with discussions.

2. Discharge Characteristics of HANBIT Plasmas

A particular feature observed during the initial experimental phase in HANBIT was a significant change of the discharge characteristic near the ion cyclotron resonance point of $\omega \sim \Omega_{ci}$. A big jump in the plasma density or beta was observed near the resonance point. Figure 2 shows such an example with a recent measurement of the perpendicular ion flux (by using the pitch angle detector) and the perpendicular ion temperature (inferred from the diamagnetic loop measurement) near ω/Ω_{ci} ~1. A substantial effort has been

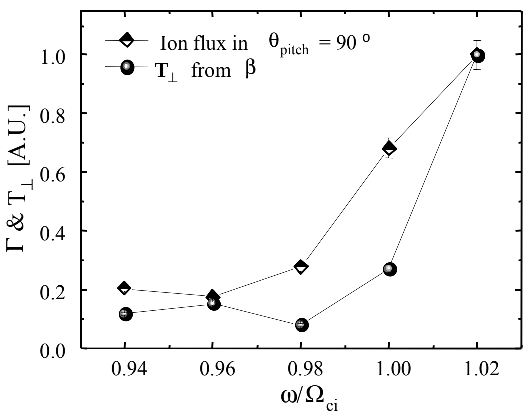

Fig. 2. The perpendicular ion flux and temperature as a function of ω/Ω_{ci}

made to understand the observed phenomena, particularly on how a stable, high-density mode can exist in the slow wave regime of $\omega \leq \Omega_{ci}$, unlike the results from the other mirror devices [3].

In terms of RF heating, the observed feature appears to be closely related to the excitation of a slow wave, which occurs only in the regime of $\omega \leq \Omega_{ci}$. A detailed study has been performed to understand the plasma wave excitation process from the HANBIT slot antenna, by utilizing a 2D numerical code [4] developed for the simulation of RF heating in HANBIT plasma and geometry models. When the plasma is produced by mostly E_z field near the antenna, for $\omega < \Omega_{ci}$, the slow wave and the fast wave can be excited from the slot antenna. However, since the wavelength of the launched slow wave is favorable with the boundary condition while that of the fast wave is few meters, it can be coupled to the plasma more easily, increasing the density further. But for $\omega > \Omega_{ci}$, only fast wave can propagate but the density threshold for the fast wave cannot be met in HANBIT. It is found that in the regime of $\omega \leq \Omega_{ci}$ and in the typical plasma density of 10^{11}~10^{12} cm^{-3} the slow wave is dominantly excited from the HANBIT slot antenna. The fast wave can also be excited, but only at the larger plasma density of $> 10^{12}$ cm^{-3}. This model of the slow wave excitation is consistent with the substantial increase of ion temperature and wall recycling rate observed in the regime of $\omega \leq \Omega_{ci}$. Figure 3 shows a typical spatial structure of the excited slow wave, obtained from the numerical calculation. The wave has a substantial radial and axial variation, as expected well for the slow wave with a short wavelength. Also, the beach wave heating effect appears to be small, which is mainly due to that the HANBIT slot antenna is located near the center of central cell where B-field intensity is minimized.

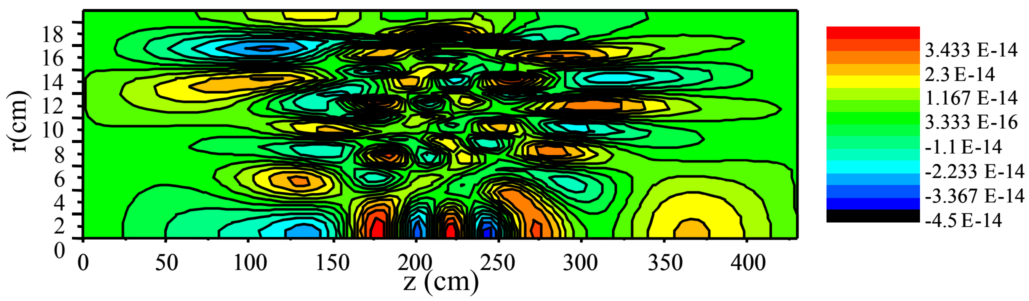

Fig. 3. The spatial structure of the slow wave component (E_+) at ω/Ω_{ci}=0.97 and for a parabolic density profile with $n(0)=1x10^{12}$ cm^{-3}.

The numerical results of the hybrid code simulating RF heating in HANBIT geometry showed as in Fig. 4 that the plasma resistance induced by the launched waves has a profile resembled with the density profile as a function of the magnetic field. Plasma impedance of the slow wave shows sharp increase at around $\omega = \Omega_{ci}$, which corresponds to the sharp transition in density. Wave heating is more plausible in the $\omega < \Omega_{ci}$ region by the slow wave heating. Fast wave is difficult to propagate in HANBIT discharge condition and then the contribution to the heating could be

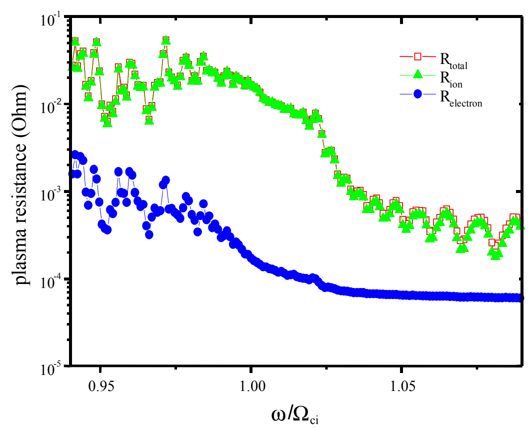

Fig. 4. Plasma resistance calculated by the plasma heating code

quite low unless the condition changes favorably such as the density increase. Therefore the ion temperature and the plasma beta are normally higher in the $\omega < \Omega_{ci}$ region.

It was also found that the resulting ion temperature increase then induced two important effects at $\omega < \Omega_{ci}$. One effect was the increase of confinement time and the other was the activation of wall recycling. By changing the magnetic field strength and the configuration, a search of the optimum condition for the ion heating had been pursued. The parallel ion temperature was measured to be uniform in space at the detector and to be independent to the magnetic field, e.g. ω / Ω_{ci}. The temperature, however, was very sensitive to the amount of fuelling gas. With 20% less gas, the temperature increases almost twofold. If an ion is heated by the wave or passes over the resonance layer, it is kicked perpendicularly to the magnetic field. To estimate how much heating is being occurred, the Faraday cup measured the pitch angle of the ions. This term has been measured in detail under the various conditions. It is revealed that at $\omega = \Omega_{ci}$ the relative strength of the vertical temperature to the parallel one seems to be higher than any other case. However, the bulk ion heating was not observed and this was attributed to the high neutral pressure. Clearly, when ions are heated by ICRF wave, higher-energy fast neutrals can be generated through the charge exchange interaction. This charge exchange process is assured to be the major channel of the energy loss in HANBIT discharges. Therefore reducing the number of neutral particles is the key to increase the ion temperature by the heating.

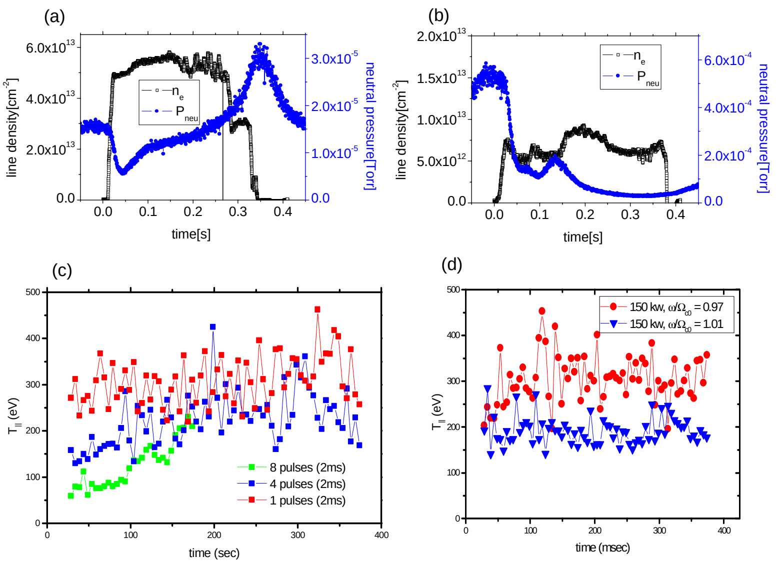

Fig. 5. Behaviour of density and neutral pressure for discharges (a) with and (b) without pre-ionization. Parallel ion temperatures of end-loss ions measured by ELA for discharges (c) with different gas puff rate and (d) with different magnetic field.

One of the techniques to lower the neutral pressure is to apply the pre-ionization method before the main pulse. A low power, klystron was prepared for this purpose for HANBIT. Figure 5 shows a preliminary discharge signals with pre-ionization. Reduced neutral pressure is evident at the initial phase of discharge. General discharge characteristics with pre-ionization are as follows. The operation window becomes wider and reliable. The discharges are more stable. Most important changes are the higher ion temperatures and confinement time. But the neutral pressure is usually getting back to the similar value of the shots without pre-ionization after the wall recycling is invoked. The fuelling gas rate and the magnetic fields are changed while the parallel temperatures and the currents of the end-loss ions were measured by the ELA. Figures 5. (c) and (d) clearly show that the temperature is inversely proportional to the amounts of puffed gas and the value of ω / Ω_{ci}. Ion temperature increases more than five times than that in the discharges without pre-ionization. The line density as a function of magnetic field also shows different characteristics. No density transition is observed at $\omega \sim \Omega_{ci}$ as shown in Fig 7. The parallel temperature is larger at ω / Ω_{ci} =0.97 compared to the temperature at ω / Ω_{ci} =1.0. This is contrary to the cases without pre-ionization.

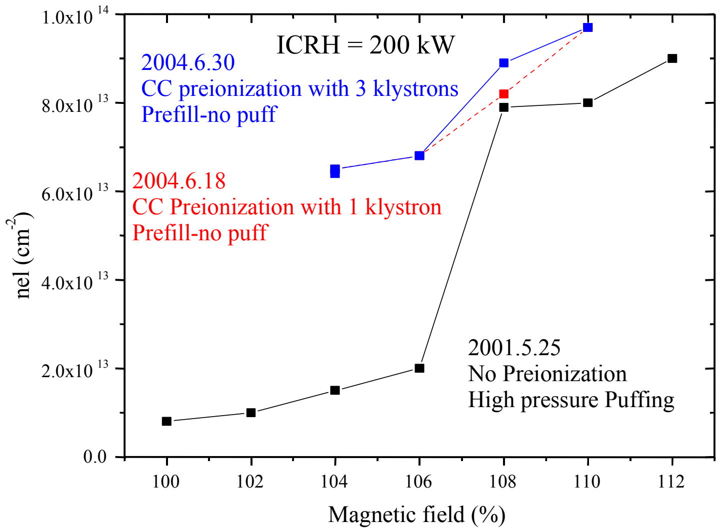

Fig. 6. Behavior of density as a function of the magnetic field at the central cell for discharges with and without pre-ionization. Magnetic field of 106% corresponds to ω=Ω_{ci}.

The effect of neutral particle is analyzed by using the DEGAS2 code [5]. With reasonable assumptions, the code results provide profiles of plasma parameters such as the ion temperature, density, and the absorbed power by each species. The comparison of the code results with the experiments shows a reasonable agreement. The absorbed power is larger in ω < Ω_{ci} case than the case in ω > Ω_{ci}, agreed with the results of heating simulation and the experimental results as shown in Fig. 6. The ion temperature reaches up to few hundreds eV with pre-ionization correlates with the ELA results. The recycle coefficient can also be estimated by the code and is agreed with the measurements, γ~1.4.

These simulation results are also very well matched with the results of the 1D radial transport code simulation [6]. The code predicts that the plasma density would follow the profile of the power absorption by electrons mostly but the ion temperature and its profile would be determined mainly by the neutral density. The code also predicts that if the neutral pressure decreases one order from the present state, the plasma β will increase rapidly.

In addition to the slow wave regime, an attempt has been also made to get a stable, high-density mode in the fast wave regime, as observed in other mirror devices. It appears not so easy to excite such a mode from the HANBIT slot antenna, mainly due to that the parallel wavelength of the HANBIT slot antenna is much shorter than the wavelength of fast wave in the density regime of 10^{11}~10^{12} cm^{-3}. However, when we increases substantially the ratio of ω/Ω_{ci} by reducing the B-field or increasing the RF frequency, a high-density mode has been observed. This new mode appears to have a similar magnitude of plasma density as the high-density mode in the slow wave regime, but more sensitive to the fueling rate etc., so requiring a more careful operation condition.

3. Discussions and Summary

As mentioned above, a narrow operation window in the magnetic field strength exists in HANBIT in which the discharges were successfully made. In terms of MHD stability, the fluctuation amplitude measured by edge probes shows a significant reduction when ω becomes smaller than Ω_{ci}, suggesting strongly that the plasma becomes unstable in the regime of ω > Ω_{ci} but stable in $\omega \le \Omega_{ci}$. The spectral analysis of the fluctuations observed in the unstable region clearly demonstrates that the excited mode is a flute-type interchange mode. The mode has the parallel wave number of n=0 and the azimuthal wave number of m=1, rotating in the ion diamagnetic drift direction. When the RF power increased, the operation window is extended to a slightly higher value of $\omega = \Omega_{ci}$. A typical behaviour of the line density for two different cases is as follows; (a) HANBIT plasmas become unstable as the ω / Ω_{ci} is larger than 1 at a fixed RF power, and (b) HANBIT plasmas become stable as the RF power increases above certain threshold value even at $\omega > \Omega_{ci}$.

In most of the HANBIT discharges terminated abruptly during the operation, the interchange mode was universally observed. A detailed analysis [7] has been performed to clarify the stabilization mechanism of the interchange mode in the regime of $\omega \leq \Omega_{ci}$. Previously the cold plasma ponderomotive force theory could not represent the experimental observations. A local theory for RF stabilization of the interchange mode stabilization in the cold plasma limit has been developed to elucidate the HANBIT results. This theory includes the nonlinear sideband wave coupling effect as well as the equilibrium ponderomotive force effect and it also takes the plasma-neutral collision effects into account. The theory is based on a set of two fluids cold plasma approximation with plasma-neutral collisions in the presence of strong RF fields. It appears that the side-band coupling force plays a main role for the stabilization in the slow wave regime, unlike the fast wave regime where the ponderomotive force was dominant [3]. A more detailed result of this MHD stability analysis in HANBIT will be reported in another paper in this conference [8]. The prediction of this theory is shown in Fig. 7 and the prediction is reasonably agreed with the HANBIT data. The existence of the window is clearly shown in preference to $\omega < \Omega_{ci}$. The existence of plasma-neutral collisions can extend the operation window slightly larger than $\omega \sim \Omega_{ci}$, which agrees well with the experimental observations, too. The prediction also successfully reproduces the effect of the RF power on the stability.

Couple of ideas have been adopting for improving stability of HANBIT device, which has anchor at only one side. The hot electron ring formation in Plug, which can help improve the plasma stability in the Central Cell has been pursued last years by increasing ECH power from 2 kW to 5 kW with three klystrons. However, the preliminary experiments showed disappointing results. The beta values did not increased much and the power absorption profile became broader in higher power. Kinetic stabilizer concept [9] was drawn our interest recently and a conceptual study has been performed. Initially 2. 45GHz magnetron would be used to increase the pressure in the Cusp region.

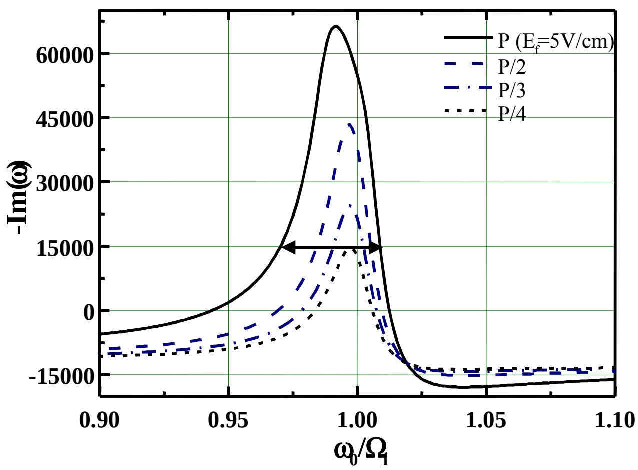

Fig. 7. Theoretical prediction of the existence of the operation window as a function of the applied RF power and the ration ω/Ω_{ci}.

Summarizing all these analyses by experiments, calculations and simulations, HANBIT may provide more stable, high performance discharges in the $\omega < \Omega_{ci}$ region. The pre-ionization plays an important role to reduce the neutral pressure at the initial phase of discharges, successively increasing ion temperature, beta and the confinement time. Even in the $\omega > \Omega_{ci}$ region, lower neutral pressure helps generate ion with higher temperatures successively producing more fast neutral particles invoking higher gas recycling resulting in the density rise.

Acknowledgment

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