RF-Heating and Plasma Confinement Studies in HANBIT Mirror Device

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Abstract. HANBIT is a magnetic mirror confinement device. Recently, with almost finishing the first campaign for the basic system development, it started the second campaign for the high-temperature plasma confinement physics study in mirror configuration. Here, we introduce briefly the HANBIT device and report initial physics experiments results on RF-plasma heating and confinement in the simple mirror configuration. It appears that the discharge characteristics of HANBIT are quite different from those in other mirror devices, and an explanation is presented to clarify the difference.

1. Introduction

HANBIT is a magnetic mirror confinement device, refurbished from the old TARA machine [1]. After re-installation of main vacuum-vessel system in Korea in 1995, main effort had been made in developing and improving basic diagnostics and heating and diagnostic systems over the first-phase from 1996 to 2000 [2]. Recently, with almost achieving the first-phase goal, HANBIT started the second-phase campaign for the high-temperature plasmas physics study in mirror configuration. Here, we introduce briefly the HANBIT mirror device and report initial physics-experiments results of plasma production, heating, stability, and confinement in HANBIT device.

It is noted that the overall dimension and configuration of HANBIT are similar to the original TARA, but has a difference in that the anchor and plug exist only in one side. Even with this axially asymmetric configuration, it is basically possible to study the MHD stabilization by anchor or the confinement improvement by thermal barrier formation in plug. During the initial physics experiments, however, we have more concentrated on the basic physics study of RF-heating, stability, and confinement in the simple mirror configuration of the central-cell. The scheme based on the RF-ponderomotive or side-band coupling effect [3-4] has been explored to provide the basic stabilization of the MHD interchange mode in this configuration. The other stabilization schemes using the anchor or hot-electron ring, and the confinement improvement ways using the thermal barrier or RF-plugging are to be studied in the future. It is also noted that HANBIT has mainly used a 500kW RF-power system with a slot antenna for the plasma production and heating. As well-known, the slot antenna was originally developed for the slow wave beach heating in the TARA [5], but here we try to utilize it for the plasma production and heating in the fast wave and ion cyclotron resonance heating regimes.

In Sec. 2 we introduce briefly the overall magnetic configuration, RF-heating, and diagnostics systems in the HANBIT device. The initial physics experiments results are then presented and discussed in Sec. 3, and finally a conclusion and future work plan are given in Sec. 4.

2. HANBIT Mirror Device

The HANBIT mirror device consists of a simple mirror-type central cell, an anchor, a plug, and two end tanks. The anchor with a minimum-B configuration and the plug of a simple mirror-type are attached to each end of the central cell, and then connected to pan and cusp tanks, respectively. The central cell has the length of about 5m, the limiter radius of 0.18 m, the B-field intensity of 0.1 T - 0.3 T (at mid-plane), and the mirror ratio of about 10. Figure 1 shows the typical B-field profile and antenna locations in the HANBIT device.

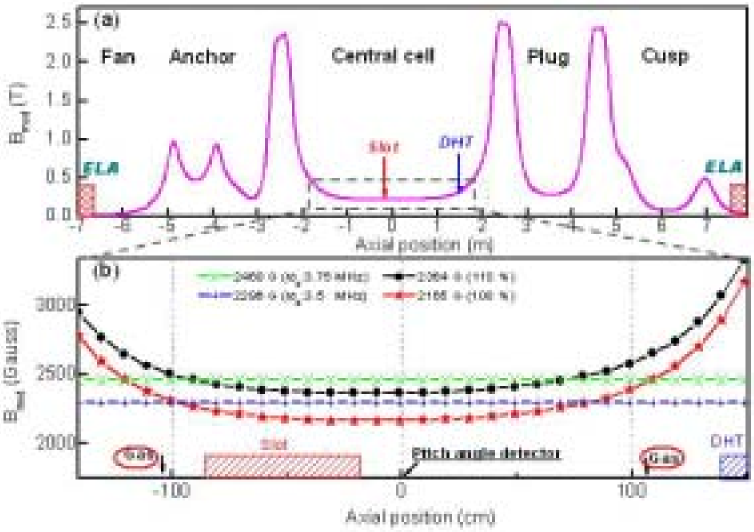

FIG. 1 Overall magnetic configuration and a schematic drawing of central cell with antenna locations

For plasma production and heating, HANBIT mainly uses the 500-kW RF amplifier in the frequency range of 3.2-15 MHz with a slot antenna located near mid-plane of central cell. Here, the slot antenna has the configuration, which is basically a mixture of the well-known double-half turn (DHT) [6] and Nagoya-type-III antennas [7], so can be used to excite the m=±1 fast and/or slow waves through the DHT part or produce initial plasmas through the E_z field of Nagoya-type part. In addition to this 500-kW slot antenna system, HANBIT has also a 100-kW double-half turn antenna system near mirror throat, which is to be utilized for the fast wave or beach heating in the near future. Besides these RF systems, 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 which is under installation in central cell for ECH experiment.

For the measurement of plasma parameters, HANBIT also has several diagnostic tools, such as a microwave interferometer, electrostatic probes, a Thomson scattering system, diamagnetic loops, a charge-exchange neutral particle analyzer, H-alpha monitors, VUV/XUV spectrometers, and an end-loss-ion energy analyzer (ELA) etc. In addition, several new diagnostics, such as a reflectometer, diagnostic neutral beam system, x-ray crystal spectroscopy, soft x-ray imaging system, Fabry-Perot interferometer, and laser-induced florescence (LIF) system are under test or development.

3. Initial Physics Experiments Results and Discussions

Initial physics experiments have been mainly focused on identifying discharge characteristics and getting some stable plasma production and operation modes, utilizing the 500-kW slot-antenna system and varying discharge conditions such as fueling rate, RF power, and B-field intensity in central cell ($B_{c.c}$) etc. RF-power waveform and matching condition have been also adjusted to get an optimum plasma production. It appears that the slot antenna system works well for the initial plasma production in various conditions when we supply a proper pre-filling gas pressure in the range of a few 10^{-4} torr. This relatively high neutral pressure is believed to be necessary since the breakdown occurs mainly by the E_z-field of slot antenna, to which the usual Townsend-type breakdown condition is applied.

Unlike the initial plasma production, subsequent plasma heating and plasma parameters evolution appear to be sensitive to the discharge conditions. Particularly, discharge characteristics are found to have a significant difference between the two regimes of $\omega > \omega_{ci}$ and $\omega < \omega_{ci}$, suggesting the existence of two distinct operation modes, where ω is the RF frequency and ω_{ci} is the ion cyclotron frequency at the mid-plane of central cell. A typical example is shown in Fig. 2, where a big jump in plasma line-density is observed around B_{cc}~106% (which corresponds to B_{cc}~ 0.23T where the ion cyclotron resonance condition, $\omega \sim \omega_{ci}$ is satisfied) when we varies B_{cc} over the range of 0.12 T – 0.3 T (or ω/ω_{ci} ~ 0.8 – 1.9) at a fixed RF frequency of ω = 3.5 MHz. Recent data show further that the density profile, ion temperature, plasma beta, and wall recycling rate etc. have also a substantial change at around $\omega \sim \omega_{ci}$. For example, plasma density profile is almost flat over most of plasma region in the $\omega > \omega_{ci}$ case, but changes to a radially peaked profile in the $\omega < \omega_{ci}$ one, as shown in Fig. 3. Plasma beta and ion temperature measured by diamagnetic loop and end-loss analyzer etc. also show a big increase by about 3 – 4 times when ω becomes smaller than ω_{ci}. Furthermore, the wall-recycling rate appears to increase substantially in the $\omega < \omega_{ci}$ regime, which correlates well with the ion temperature increase and the resulting fast neutrals generation through the charge exchange process. Finally, it is noted that the reproducibility of a discharge is typically observed to be better in the $\omega < \omega_{ci}$ regime.

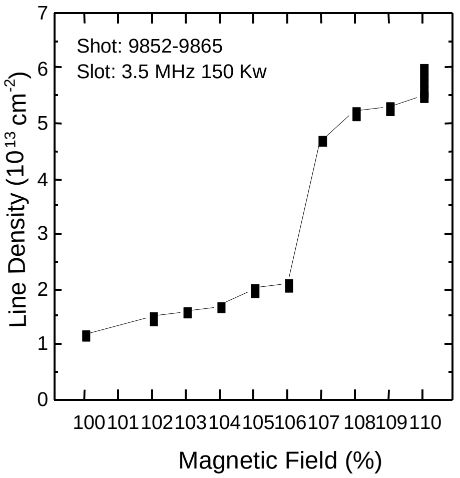

FIG. 2 Line-integrated density variation as a function of the central cell magnetic field intensity

It is interesting to note that these results in HANBIT are quite different from what were observed in the other simple mirror devices, such as HIEI [7] and Phadrus or Phadrus-B [3,6]. A main conclusion from these previous work was that MHD stable, high-density plasma modes with a radially peaked density profile can be obtained well in the $\omega > \omega_{ci}$ regime. An explanation of this difference between HANBIT and the others may be now obtained if we note that, as pointed out by Majeski et al [6], in order to get a stable high-density plasma in the $\omega > \omega_{ci}$ regime it is critical to excite a radially peaked plasma wave, such as m=+1 fast wave, which can then stabilize the MHD interchange instability through the ponderomotive force. In other words, this means that a well-designed antenna, which can excite the fast wave in the target plasma, is essential to get the stable high-density plasma mode in the $\omega > \omega_{ci}$ regime.

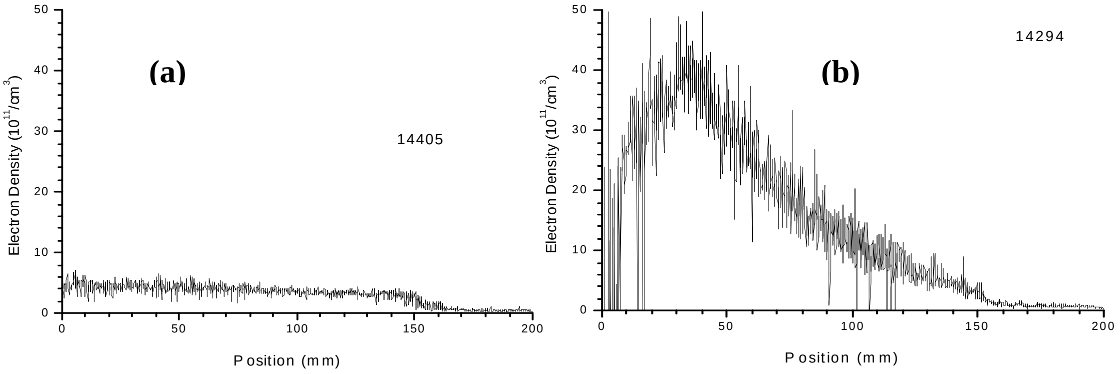

FIG. 3 Plasma density profiles when (a) B_{cc}~104% or ω/ω_{ci} =1.03 and (b) B_{cc}~110% or ω/ω_{ci} =0.97 with the same RF input power of 150 kW.

If we now compare the slot antenna in HANBIT with the DHT antenna in Phadrus-B [6], it is found that, while both can excite the m=+1 fast wave, the dominant parallel wavelength of the slot antenna is about 4 times shorter than the DHT antenna. Note the shorter wavelength of the slot antenna is mainly due to that it was originally developed for the excitation of slow wave, rather than fast wave. If we now remember that the parallel wavelength of a fast wave in uniform plasma decreases with plasma density, like $\lambda_{||} \propto (n_e)^{-1/2}$ (when ω is near ω_{ci}), we can see that for the excitation of fast wave the slot antenna requires the plasma density about one order larger than the DHT antenna case. From the usual dispersion relation in uniform cold plasma, it is indeed estimated that optimum density for the HANBIT slot antenna is order of 10^{12} cm^{-3} (while order of 10^{11} cm^{-3} for the Phadrus-B DHT antenna). We then note that in Phadrus-B the initial plasma is produced by ECH, up to the order of n_e ~10^{11} cm^{-3}, so meeting well the optimum density condition for the fast wave excitation there. This explains why stable high-density plasma modes can be produced well in Phadrus-B. Meanwhile, in the HANBIT device initial plasma is mainly produced from the E_z field of the slot antenna. For the fast wave excitation in HANBIT this E_z field should now produce the plasma density up to the order of 10^{12} cm^{-3}. At the present it is not so clear whether this is possible or not. However, it can be shown that the possibility to buildup such a high density is much lower in the $\omega > \omega_{ci}$ case, than the $\omega < \omega_{ci}$ one. This may then provide an explanation why the stable high-density modes are much easily obtained in the $\omega < \omega_{ci}$ regime, than the $\omega > \omega_{ci}$ one, in HANBIT.

To see how a difference can occur in the density build-up between the two regimes, we note first that a slow wave can exist, in addition to the fast wave, in the $\omega < \omega_{ci}$ regime. Since the parallel wavelength of the slow wave is usually much shorter than the fast wave, it can now couple to the slot antenna even in the low-density regime of order 10^{11} cm^{-3}. This means that there is now a large possibility for the slow wave to be excited, during the plasma production period by the E_z field, in the $\omega < \omega_{ci}$ regime. When the slow wave is excited near $\omega \sim \omega_{ci}$, a strong ion heating can then occur through the ion cyclotron resonance heating (ICRH) (note the resonance can occur over a bandwidth of $\Delta\omega = |\omega_{ci} - \omega| < k_{||} V_{ti}$ with a finite ion temperature). It is noted that this model has a good qualitative agreement with the observed features in HANBIT, which show a substantial increase in the ion temperature and the wall-recycling rate when ω becomes smaller than ω_{ci}.

We now show that the ion heating by the slow wave can enhance greatly the density build-up even at the same power of E_z field. Firstly, it is well-known that in the simple mirror configuration the confinement time is almost determined by the parallel loss-cone transport, and by the ambipolar diffusion condition the parallel confinement time is then substantially increased by raising the ion temperature. Secondly, we note that the stabilizing RF-ponderomotive force can be increased by the slow-wave excitation. In the case of the E_z field, it can give a stabilization near edge since it is almost near field there so will have the profile $\partial |E_z|/\partial r > 0$ in the inside region of plasma boundary (it is believed that this stabilizing effect from the E_z field may mainly support the small edge density build-up in the $\omega > \omega_{ci}$ regime). Unlike the E_z field, the slow wave is more-like plasma wave being excited in the plasma region, but expected to be rapidly damped near surface by the ICRH in HANBIT condition (no beach heating), so having the profile peaked in a point of the inside region of plasma boundary. An additional stabilizing ponderomotive force is then possible from the slow wave in the outside region of the peak point, making a steeper density gradient build-up feasible near edge. Finally, we note with the ion heating a substantial amount of fast neutrals can be generated, particularly in the HANBIT, which has no hard wall-conditioning system like baking yet, and this will help further the edge density build-up by increasing the fueling by the wall recycling.

In summary, it has been shown that a larger density build-up is possible in the $\omega < \omega_{ci}$ regime since there the slow wave excitation and the ion heating are expected well. This additional density build-up may then greatly enhance the possibility of the m=1 fast wave excitation by the slot antenna, providing a plausible explanation of why in the HANBIT the stable high-density plasma mode with a radially peaked density profile is obtained in the $\omega < \omega_{ci}$ regime, rather than the $\omega > \omega_{ci}$ regime, unlike the other machine.

4. Conclusion and Future Work

Initial physics experiments in the HANBIT mirror machine have shown the discharge characteristics quite different from those in the other mirror machines. To explain the difference a model has been developed in which the absence of stable high-density modes in the $\omega > \omega_{ci}$ regime is attributed to the difficulty of the m=1 fast wave excitation from the HANBIT slot antenna. Meanwhile, the high-density mode can be generated much easily in the $\omega < \omega_{ci}$ regime because there the slow wave excitation and ion heating are possible, whcih can then enhance greatly the possibility of m=1 fast wave excitation. While the model presented here can explain many features observed in the initial HANBIT experiments, there still remain many points, which need a more clarification. There is also a possibility that the observed mode transition may be related to the RF side-band coupling force effect, which is known to give a destabilization in the $\omega > \omega_{ci}$ regime, while a stabilization in the $\omega < \omega_{ci}$ regime. A more careful check thus seems to be still necessary for the complete conclusion.

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