Mirror Stabilization Experiments in the Hanbit Mirror Device

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Abstract. The Hanbit device is a magnetic mirror machine which has a central cell, one anchor cell and one plug cell plus associated vacuum chambers. It is about half of the original TARA mirror device from MIT. The Hanbit device has been involved in a series of experiments on stabilization of the MHD flute type mode. Earlier work showed that it was possible to stabilize the m = -1 flute type MHD instability with RF power near the cyclotron resonance. This stability has been attributed to the sideband coupling process. We have now undertaken investigations to see if a divertor and the Kinetic Stabilizer (KS) of R. F. Post can stabilize the MHD instability. Divertors were used previously in experiments on the TARA mirror device and the HIEI mirror device. The Hanbit divertor configuration uses one of the central cell coils with reversed current as the divertor coil and two adjacent coils with increased current to compensate for the field droop and to prevent the field lines from intercepting the bare ICRH antenna. The divertor strongly reduces the m = -1 instability when the null point (x-point) is sufficiently inside the vacuum tank. However, the diverted plasma is directed into a wall and the divertor cannot be used to eliminate impurities. The KS uses microwave produced plasmas on field lines in the cusp tank region. According to the theory, by locating a stabilizing plasma pressure on the field lines at a region with a strong second derivative and large radius in the expanding field region outside the mirrors, the main plasma in the mirror central cell in regions with unfavorable field line curvature can be stabilized. Two coils on the cusp tank are configured to produce expanding field lines with a large positive radius of curvature. A 5-kW 2.45 GHz magnetron is used to produce the stabilizing ECRH plasma pressure in this region. A reduction of instability duration has been observed for high power plasmas. However, for low power plasmas that terminate violently with an m = -1 instability, the KS action makes the duration of the instability longer. Details of both experiments are given.

1. Introduction

Hanbit [1] is about half of the original TARA [2] tandem mirror device from MIT. We have undertaken investigations to see if the m = -1 MHD flute like instability can be stabilized by a mirror divertor [3-6] and the Kinetic Stabilizer (KS) of R. F. Post, et al. [7-9].

According to the simple theory [3], a divertor stabilizes the plasma by providing a region of low poloidal field at a separatrix in which the electrons can drift azimuthally. The high plasma conductivity causes the potential of perturbations with azimuthal numbers $|m| > 0$ to vanish and thus shorts out the electric field due to the interchange instability. There is no sheath so it is equivalent to an electron emitting end wall. In order for the separatrix to be effective, it must be in the vacuum chamber and connected to field lines at a smaller radius than the limiter. On the other hand, according to Pastukhov [10] the main stabilizing effect is compressibility. R. F. Post, et al. [7-9] proposed the kinetic stabilizer (KS) to stabilize the MHD instabilities in mirror devices. This idea was based on the concept of Ryutov [11] derived from the work of Rosenbluth and Longmire [12]. The stability of the Gas Dynamic Trap [13] has been attributed to this concept. Post's proposal was to use low energy ion beams to be injected along field lines in the expanding field region at the end of a mirror machine. We were unable to acquire such ion beams.

In Section 2 we describe the Hanbit device. We discuss the earlier divertor experiments in TARA and HIEI in Section 3. In Section 4 we discuss the divertor experiments in Hanbit. The design and earlier measurements on the KS plasma in the cusp region of Hanbit are discussed in section 5. In section 6 we discuss the KS experiments in Hanbit. There is a summary and conclusions in section 7.

2. The Hanbit Device

As mentioned above, Hanbit is a tandem mirror device formed from components of the original TARA device. It has a central cell, one anchor with a fan out tank, one plug, and a cusp tank. The central cell is ~5 m in length and has a plasma radius of 0.186 m determined by limiters. The field in the central cell is ~ 0.24 T and the mirror ratio is typically 10. For all the experiments described here the anchor coils were turned off so as not to influence the stability. The plasma was formed with power supplied to a slot antenna by a 3.5 MHz transmitter. Normally a power of 200 kW was used but the KS experiments used 200 kW and later 80 kW in order to produce more unstable plasmas.

3. Earlier Divertor Experiments on TARA and HIEI

A TARA tandem mirror divertor [3] was designed and built at MIT. Subsequent pioneering experiments [4] showed that the stability boundary was extended by the use of this divertor. The stability was enhanced by mapping the null radially into the plasma. According to Pastukov [10] due to the nature of the peaked plasma profile in TARA and the design of the divertor, it was not possible to fully stabilize the TARA plasmas. Y. Yasaka, et al. designed two divertors for the HIEI device [5] and found that the design that provided smaller radius nulls produced the best stabilization. Subsequent investigations [6] showed that stabilization was obtained for the null inside the limiter and that the density gradient was much larger for the divertor stabilized plasmas.

4. Hanbit Divertor Experiments

We could not modify the central cell tank or add additional coils so the central cell coils were reversed and used with a separate power supply as divertor coils. Experiments performed with a symmetric double divertor showed that it was not possible to establish plasmas with it. A single divertor in one end was chosen for the main experiments. Two adjacent coils were also powered by an additional coil to increase the field and prevent field droop due to the divertor coil. The diverted plasma was directed along field lines to the wall near the divertor coil and there was no possibility of removal of impurities or auxiliary pumping of the diverted plasma. Fig. 1 shows the field lines and |B| contours for a representative set of currents. The coils are numbered in sequence from right to left starting with 8 and ending with 27. Coil 13 is used as the divertor coil and coils 14 and 15 have increased current to compensate the field droop due to the divertor coil.

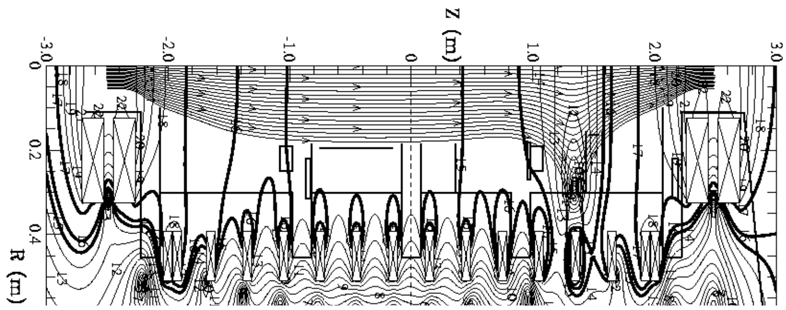

Fig 1. Far west end divertor using coil 13 plus coils 14 and 15 energized to strengthen field under the SLOT antenna for better matching. The horizontal SLOT antenna is shown just to the left of the dotted vertical line at the midplane under coils 18 through 20.

Fig 2 shows the field lines and |B| contours for the region in the vicinity of the wall under the divertor coil. The divertor current is -190% where 106% is the normal current for ICRH heating in the central cell. The field null point (x-point) is inside the vacuum vessel about 0.012 m. This is the field at which the divertor first stabilizes the m = -1 flute-like instability. More negative currents also stabilize it and less negative currents have no effect on the instability. The instability limit is very abrupt.

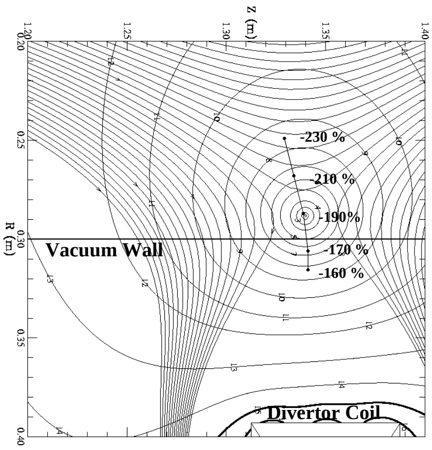

Fig. 2. Close up view of the divertor region for the west end divertor as in Fig 1. For a divertor current of -190%, the x-point is ~ 0.012 m inside the wall. The other points show the x-point location for several other currents.

Even with a single asymmetric divertor in the end far from the antenna, ramping on the divertor caused frequent ICRH power trips. It was not possible to establish the plasma with the divertor fully on. Normally the plasma wall conditioning was done with all the central cell (CC) currents 110% of normal and then switched to a configuration with the divertor coil 13 with zero current (0%) and the compensation coils 14 and 15 with currents of 170% of normal. This arrangement meant that the field under the SLOT antenna (i. e., under coils 18-20) was ~ 110%. After conditioning, it was possible to ramp on the divertor coil current from an initial value between 0% and -100% to a divertor current as negative as -230%. For these experiments we normally produced plasmas with 200 kW of ICRH power. Without a divertor, these plasmas were quite stable until the RF power ramp down at the end but always became unstable at low density near the end of the ICRH ramp. If the ICRH power tripped during a shot, the m = -1 signal at the end of the shot was rarely seen. A smooth ramp down to zero power was necessary to produce the m = -1 instability for plasmas created with a power of 200 kW. In our study we carefully excluded all shots with a trip. Figure 3a shows the signals from an azimuthal probe array on one of the limiters near the end of the ramp down.

The chronological sequence indicated by the dotted lines shows that these signals result from an m = -1 perturbation at the surface of the plasma. This is the normal sequence at the end of a shot using 200 kW of ICRH power. For this shot the divertor current was ramped on to a value of -160% in which case the x-point is about 0.015 m outside the vacuum vessel. Figure 3b shows the same probe signals resulting from ramping on the divertor current to -190% in which case the x-point is about 0.012 m inside the wall of the vacuum vessel. This is precisely the condition shown in Figs. 1 and 2.

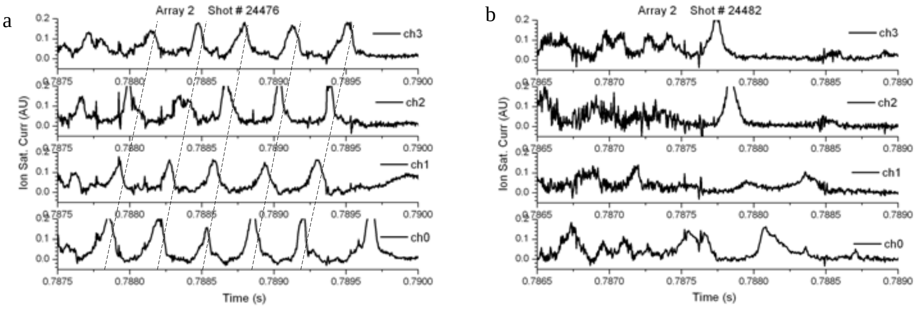

Fig 3 Signals from array 2 probes. (a) Signals with the divertor on but the x-point 0.015 m outside the vacuum vessel. (b) Signals with the divertor on and the x-point 0.012 m inside the vacuum vessel

For Fig 3b the sequence of signals is difficult to determine and is not the sequence for m = -1. In addition the signals are very small. We interpret this as MHD stability. A series of experiments showed that the divertor current ramped on to -190% or more negative would produce stability but less negative currents would not remove the m = -1 signature at the plasma termination. The calculations showed that the x-point is at the vacuum vessel wall for a divertor current of ~ -177%. The current must be larger than this because, according to the simple theory, not only must the x-point be inside the vacuum vessel but the magnetic field at the wall has to be high enough to contain the electrons near the null that provide the stabilization.

5. KS design and first KS plasma measurements

We reported earlier [14] on the experiments aimed at creating KS plasmas in the end region of Hanbit. We produced electron cyclotron resonant heated (ECRH) hydrogen plasmas in a tailored expanding field region in the cusp tank using a 5-kW 2.45-GHz magnetron. We reported that the temperature of the ECRH plasma was 15- 30 eV which was as much as a factor of 10 higher than the plasma escaping from the central cell and that the density was also higher. However, we were unable to attempt stabilization experiments since the ion cyclotron resonant heating (ICRH) central cell plasmas created at that time did not exhibit the flute-like m = -1 MHD instability. In the ensuing period we have found conditions to create this instability. The same magnetron was also used for the present experiments. It was not possible to control the turn on and turn off times precisely so magnetron was turned on before the ICRH plasma was created and turned off after the ICRH plasma terminated.

6. KS Experiments

A small reduction in instability duration at the ramp down was observed for plasmas created with 200 kW. However, it was not possible to remove the instability with the KS plasma. A search was made for high density (~ 1 $x10^{18}$ m^{-3}) plasmas that would disrupt with an m = -1 instability. By carefully controlling the magnetic field and gas puffing, a condition was found at 80 kW which normally terminates during the ICRH pulse due to this instability. As before, we carefully excluded all shots which had an ICRH trip because such shots never display the m = -1 signature. Figs 4a and 4b show the signals from an azimuthal array of probes on one of the limiters for two shots 25201 (KS off) and 25202 (KS on). For both of these shots the ICRH power remained on until long after the plasma terminated. The instability duration for the normal shot 25201 is about 5 ms and for the KS shot 25202 is about 17 ms. Although the frequency varies somewhat during the instability, the phase relationship between the probe signals is maintained for the entire instability duration. A precise measurement of the duration is difficult due to the noisy nature of the signal but it is clear that the KS plasma shot m = -1 signal duration is much longer than the duration for the shot without the KS plasma. If the hydrogen gas pressure in the cusp region was raised sufficiently high, both the normal shots as well as the KS shots showed a reduction in the instability duration. That is to say, high gas pressure in the cusp region decreased the instability duration for all of the plasmas. However, up to the limitations of the experiment, in no case did we find a condition without an m = -1 instability or with the KS plasma having a shorter instability period than the normal plasma. However, the KS plasma removed an earlier m = +1 signal prior to the terminating MHD instability.

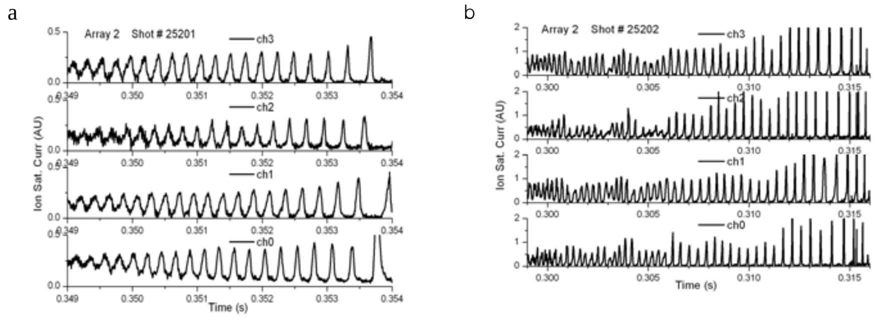

Fig 4. (a) Shot 25201 without Kinetic Stabilizer plasma. (b) Shot 25202 with Kinetic Stabilizer plasma. The m = -1 signal duration is longer for shot 25202 with the KS on.

7. Summary and Conclusions

The Hanbit device has been involved in a series of experiments on stabilization of the MHD flute type mode. Divertors were used previously in experiments on the TARA mirror device [3, 4] and the HIEI mirror device [5, 6]. The present configuration uses just one divertor coil in one end of Hanbit and produces a left-right asymmetry in the magnetic field. The plasma is difficult to establish and maintain with this configuration. However, for sufficiently high currents this divertor has been shown to be able to stabilize the m = -1 MHD flute-like instability at the end of a normal discharge. The stability condition is in good agreement with that expected from the calculated fields. KS experiments with low density plasmas showed a small decrease in the instability duration with the KS plasma but experiments with high density ICRH plasma showed that the m = -1 instability duration was increased by the KS plasma while an m = +1 instability earlier in the discharge was eliminated.

8. Acknowledgements

This research was supported by the Korean Ministry of Science and Technology under the Hanbit Project Contract. Discussions with many other NFRC staff members are gratefully acknowledged. In particular, we would like to acknowledge very useful discussions with V. P. Pastukhov of the Kurchatov Institute, Russia; I. Katanuma, Y. Sasagawa, and T. Cho of the Plasma Research Center at Tsukuba University, Japan; and T. K. Fowler of Lawrence Livermore National Laboratory, USA.

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