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Observation of Mirror Trapped Ions and Development of a High Energy Neutral Particle Analyzer in GAMMA 10

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Abstract

Measurement of the velocity distribution function enables us to understand the confinement state of the magnetized plasma. We installed a conventional charge exchange neutral particle analyzer near the strongest magnetic field in GAMMA 10 and have measured the energy distribution of bounced ions in the region bordering on the end loss boundary. The obtained energy distribution is similar to the energy distribution of end loss ions in the experiment without the potential confinement. For the observation of velocity space distribution of trapped ions in the main confinement region, we have designed a new compact neutral particle analyzer with an ultra-thin carbon foil and a toroidal electrostatic analyzer. Compared with a conventional gas stripping one, it has higher detection efficiency for the neutral particles with the energy of more than several keV.

Keywords:

GAMMA 10, inner mirror throat, trapped ion, CXNPA, carbon foil, toroidal ESA

1. Introduction

GAMMA 10 is a minimum-B anchored tandem mirror with thermal barrier and ion confinement potential. The tandem mirror device takes an open end magnetic field and magnetic hills and valleys are present along the magnetic field line. The plasma is confined in the weak magnetic field region lying between the strong magnetic fields. The ratio of the strong magnetic field to the weak magnetic field decides the end loss boundary in the velocity space. Charged particles with large magnetic moment are confined deep in the trap region and the Coulomb collisions put the particles out of the trap region. In the GAMMA 10 device, the electrostatic potentials are utilized to achieve the better plasma confinement.

When the particles are kicked into the loss region, the particles are immediately flown out toward the both ends of the device along the magnetic field line. These particles include some information on the confinement state, so that the measurement of end loss particles has been carried out as a useful method to investigate the plasma inside the mirror device. On the other hand, the particles in the trap region have the direct information on the confinement state. However, few experiments have been done to investigate the velocity space distribution of mirror trapped plasmas.

In this study, we utilize the charge exchange neutral particle analyzer (CXNPA) for the measurement of trapped ions in the tandem mirror device. In the first place, we have measured the mirror trapped ions bordering on the end loss boundary and looked at the relationship with the end loss ions. The result is described in the Sec. **2**. In the second place, for the measurement of deeply trapped ions in the central cell, we design the new compact CXNPA. The examination on the analyzer's characteristics is conducted in the Sec. **3**.

2. Energy distribution of the mirror trapped ions near the loss region

As the first step, we have measured the trap ions near the end loss region and investigated the relations between the trapped ions and end loss ions by comparing the both energy distributions. For the measurement of the trapped ions, we installed a conventional gas stripping type of CXNPA near the inner mirror throat located between the anchor cell and the plug/barrier cell. The CXNPA is called CXIMT (CXNPA at Inner Mirror Throat). The axial profile of magnetic field strength and the location of CXIMT are indicated in Fig. 1. The kind of trapped ions are also shown. The inner mirror throat has the strongest magnetic field and decides the boundary between the end loss region and the mirror trapped region in the velocity space. CXIMT consists of a long collimation tube, a gas stripping cell, and a 63.6° cylindrical

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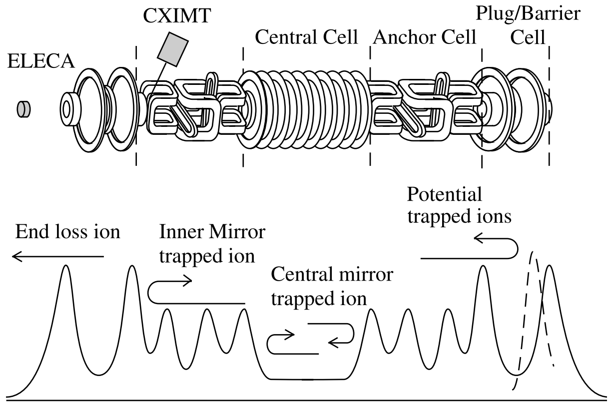

Fig. 1 The axial profile of magnetic field strength in the GAMMA 10, the kind of trapped ions and the location of CXIMT and ELECA. The confinement potential (dashed line) is generated in the plug/barrier cell.

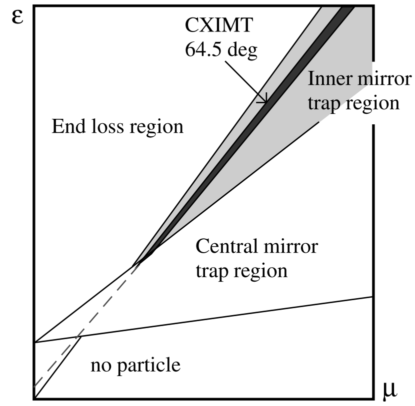

Fig. 2 Trap regions, end loss region and CXIMT measurement region in ε-μ space, without the confinement potential.

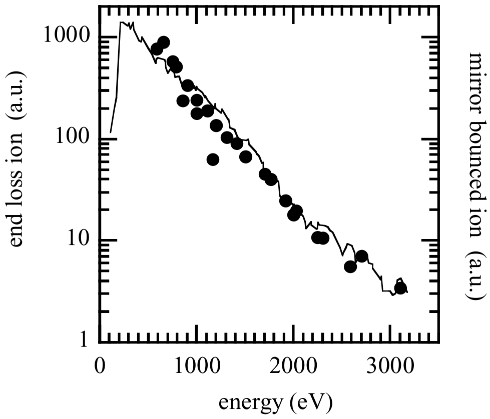

Fig. 3 Comparison of energy spectrum between end loss ions obtained by ELECA (solid line) and bounced ions taken by CXIMT.

type electrostatic analyzer [1,2]. The direction of the line of sight is opposite to the plasma flow from the central cell, therefore ions need to be bounced by the strong magnetic field at the inner mirror throat or electrostatic potential generated in the plug/barrier cell. The kind of bounced ions is distinguished by the mounting angle of CXIMT. The mounting angle is usually set 64.5 deg with respect to the central axis of GAMMA 10, and the inner mirror bounced ions are normally measured. On the other hand, in the case the mounting angle is changed to 60.5 deg, the potential bounced ions are measured.

The trap region and the end loss region without the potential confinement are indicated in Fig. 2. The vertical axis ε is the total energy and the horizontal axis μ is the magnetic moment of ions. The measurement region of CXIMT with the mounting angle of 64.5 deg is also indicated. In this experiment, the inner mirror bounced ions are measured with CXIMT and the end loss ions are obtained by the end loss ion energy component analyzer (ELECA) [3]. Figure 3 shows the energy distributions of the inner mirror bounced ions measured with CXIMT and whole end loss ions obtained by ELECA. From this comparison, we can find that the trapped ions near the end loss boundary have similar energy spectrum to the end loss ions.

When the confinement potential is not generated, the end loss boundary is simply decided by the ratio of the strong magnetic field to the weak magnetic field strength. In this case, the confinement state is treated same as that of the simple mirror. In the simple mirror device, it has been considered that the Coulomb collision frequency decides the confinement time in the mirror confinement experiment [4]. If a large amount of end loss ions are provided by the diffusion from the trap region, the end loss ion energy spectrum is to be similar to the energy distribution of trapped ion near the end loss boundary. The experimental result indicates that the ion-ion Coulomb collision is the main end loss process.

3. Design of compact neutral particle analyzer

3.1 Motivation and purpose

In the main confinement region in GAMMA 10, the plasma is strongly heated by ICH and NBI, and the ion temperature of several keV is often measured. These heating systems provide a strong influence on the plasma distribution in the velocity space and the plasma confinement. For the measurement of the velocity space distribution in the central cell, we have designed the new compact CXNPA which is capable to measure the pitch angle and energy distribution widely within a few plasma shots. For the measurement of pitch angle profile, downsizing the analyzer is needed.

3.2 Configuration of compact neutral particle analyzer

The schematic drawing of newly designed CXNPA is shown in Fig. 4. An ultra-thin carbon foil is used for the alternative to the gas stripping cell. The carbon foil is mounted on the mesh of fine texture (333 lpi, transmission rate of 70%) and placed in front of the energy analyzer. The

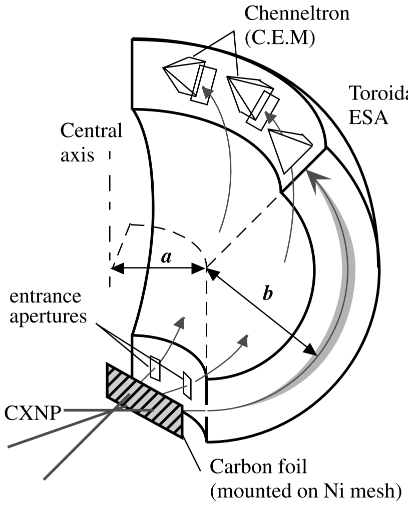

Fig. 4 The schematic view of a designed neutral particle analyzer.

toroidal electrostatic analyzer is applied for the measurement of angular and energy distribution. Channeltrons are used as a particle detector. The detectable pitch angle is limited to about ±35 deg by the structure of GAMMA 10 vacuum vessel. With this configurations, the size of the analyzer is to be about $20 \times 30 \times 30$ cm^3.

3.2.1 Ultra-thin carbon foil

An ultra-thin carbon foil can be used for ionizing the energetic neutral particles. When the energetic particles pass through the matter, they exchange the electrons. Within the depth of several Å from the entrance surface of matter, the charge equilibrium state is determined in proportion to the particle energy. The advantageous points are that the carbon foil is quite thin and, moreover, the conversion efficiency is much higher than that of gas stripping type. However, the energy straggling and angular scattering arise in the transmitted particles.

The application of ultra-thin carbon foil for the measurement of energetic neutral particles has been studied. Because of the considerable amount of studies and the credible experimental data [5,6], we use the 25 Å carbon foil. The ionization efficiency $f(H^+)$ in the case of 25 Å carbon foil is given by following equitation [5]

$$f(H^+) = -3.24 \times 10^{-4}E^2 + 0.0222E + 0.0342\ , \quad (1)$$

E is the incident neutral particle energy in unit of keV.

The energy straggling and the angular scattering can be examined by using the TRIM98 code [7]. TRIM98 code is the MonteCarlo simulation code for evaluating the interaction between the energetic particle and the matter. In the previous experiment carried out by the ISAS group [6], they compared the result of TRIM98 with the experimental result. In this paper, we refer their experimental conclusion and use TRIM98 code for the estimation of the characteristics of carbon foil. Figure 5 shows HWHM of the angular scattering and the energy straggling as the function of incident particle energy. The HWHM $\psi_{1/2}$ of the angular scattering is predicted

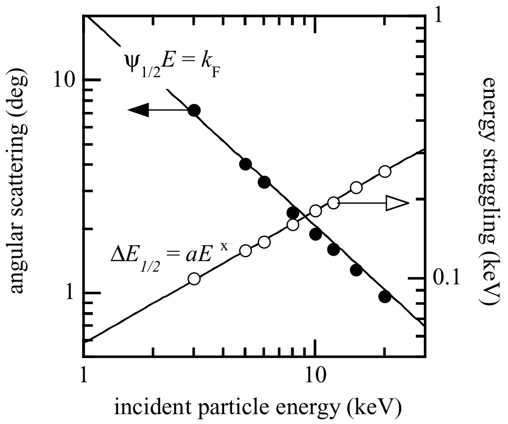

Fig. 5 HWHM of the angular scattering (closed circles) and the energy straggling (opened circles) of transmitted particles.

by the following equation [6].

$$\psi_{1/2} \cdot E = k_F \quad (2)$$

Where, k_F is a constant which is determined by the target material and the incident particle species. E is the incident particle energy. The formula describes the simulation result well. In the case that the target is a carbon foil (specification thickness of 25 Å, ACF-Metals) and the incident particle is the hydrogen atom, the constant k_F is about 20.77 keV deg. In terms of the energy straggling, we find that its HWHM is linearly approximated in the double logarithm plot. The energy loss in the matter is relatively small and the average energy of transmitted particle is proportional to the incident energy. From this result, we can estimate the incident particle distribution from the distribution of the transmitted particle.

3.2.2 Toroidal electrostatic analyzer

The detail of the toroidal electrostatic analyzer (ESA) is described in the reference [8]. The toroidal electrostatic analyzer can be used for the measurement of angular and energy distribution. The advantageous point of toroidal electrostatic analyzer is that the multi entrance aperture can be used in the toroidal analyzer as shown in Fig. 4. The focusing angle is decided by the ratio between the cylindrical radius a and the spherical radius b. With the configuration (a = 40 mm and b = 90 mm), the focusing angle is about 151 deg.

The entrance aperture restricts the widely scattered particles. The approval angle is set about 2.86 deg. The exit slit is placed at the deflection angle of 160 deg and the dimension is 10×8 mm^2. With this configuration, we examine the characteristics of the energy analyzer. For the calculation, the particle trajectories in the toroidal analyzer are simulated by using a Runge-Kutta method. From the numerical calculation, we find that the energy resolution is about 7.8% and the rate that injected particles through the entrance aperture pass the exit is about 89% at maximum.

3.3 Characteristic of designed NPA

Taking these properties into consideration, we compare

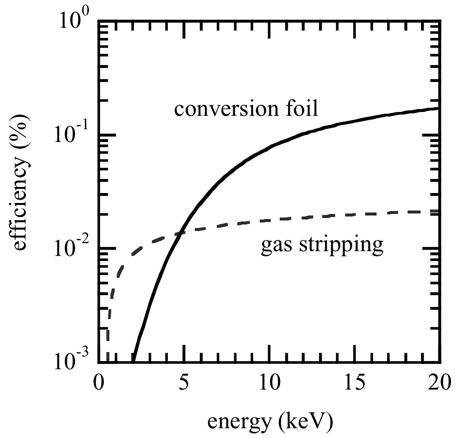

Fig. 6 Detection efficiency, including the conversion efficiency and the geometrical factor.

the detection efficiency between the gas-stripping type and the conversion-foil type. The comparison is shown in Fig. 6. For the low energy particles, gas-stripping type CXNPA outperforms the conversion-foil type. However, for the high energy neutral particles, as the conversion efficiency increases and angular scattering is diminished, the higher performance can be expected.

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