Design of the Electromagnetic Field for an E//B Neutral Particle Analyzer*)

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The electromagnetic field of a new E//B neutral particle analyzer (NPA) capable of mass resolution and energy resolution has been designed. The E//B field is composed of a magnetic field and an electric field which are parallel and in tandem. Layout of the field is designed so that both the mass and energy resolution are realized on the detector plane.

Keywords: NPA, E//B, mass resolution, energy resolution, neutral

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1. Introduction

In the high-temperature fusion plasma, the neutral particle born in the charge-exchange reaction between a hot ion and a neutral, keeps almost the same energy with the ion reactant. The neutral particles are not confined by magnetic field, so a significant number of them can escape from the plasma without suffering a collision. An equipment to detect these escaped neutrals and provide the energy or/and mass spectrum is named neutral particle analyzer (NPA) [1]. Different types of NPA have been built in the world [2–8]. NPA is the key tool for fast ion physics study [9] and fusion fuel density ratio (T/D) measurement [10].

An E//B NPA plays an important role due to its ability of providing both mass and energy information. The behaviors of ICRF-heated H^+ ions in the presence of the magnetohydrodynamic (MHD) instabilities in TFTR was provided with the NPA, and results indicated that strong, low frequency MHD events caused a strong redistribution of H^+ ions [11]. An E//B NPA is installed on LHD for the measurement of counter neutral beam particles. Significant changes of the energetic neutral spectrum is observed in TAE bursts [12]. The abilities of NPA to measure the plasma hydrogen isotope composition in ITER burning scenarios were assessed and it was found that, for the range of values of T/D density ratio variation equal to 0.2 - 10 (edge measurements) and 0.15 - 10 (core measurements), NPA can meet the required accuracy 10% and time resolution 0.1 s of the measurements [10].

A new E//B NPA has been started to design in this financial year. The new NPA is motivated by two purposes. First, to study the frontier physics of fast ion in the present experiment devices. Second, to perform prospective study for the measurement of fuel ratio in fusion reactor. E//B NPA is a conventional tool in plasma experiment. This new E//B NPA is a tandem type NPA like CNPA built in Ioffe Physicotechnical Institute, Russia. The new NPA will be capable of mass (D/H) resolution. The magnetic field is designed to be created with a permanent magnet for smaller size and simpler maintenance. However there are two difference of this NPA from CNPA. First, the energy range of the new NPA is designed to be 20 - 200 keV for the detection of fast ion on HL-2 M, while the energy range is 0.66 - 36 keV (D) / 0.8 - 80 keV (H) for CNPA. Second, stripping cell of the new E//B NPA is designed to be a gas tube to avoid replacement of the damaged stripping foil. We plan to install this NPA on HL-2 M device. Because the energy range of the negative ion source neutral beam heating is up to 200 keV, so the upper limit of the energy detection range is 200 keV. The lower limit is set to 20 keV because we are only interested in the fast ions, instead of the background ions.

2. Design of the E//B Analyzer

A combination of electric field and magnetic field is designed to realize the mass and energy resolution. Figure 1 shows the layout of the preliminary design for the E//B field. Figure 1 (a) is the top view of the E//B field. The magnetic field region is labeled with "⊙B" and the electric field region is labeled with "⊗E". An ion trajectory is bent by the strong magnetic field in the magnetic region, but the trajectory remains in the same plane vertical to the magnetic field. The ion trajectory is bent in the direction vertical to the previous trajectory plane due to the electric force, as shown in Fig. 1 (b). Between the magnetic field region and the electric field region there is a blank region

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to isolate the plate electrode from the magnet.

The physics basis why this design could resolve both mass and energy is as follows. As shown in Fig. 1 (b), supposing the shift of the trajectory in y direction is y_1 in the electric field region, and y_2 in the free-flying region, we could derive,

$$y_1 = \frac{eEx_1^2}{4\varepsilon}, \tag{1}$$

$$y_2 = \frac{eEx_1x_2}{2\varepsilon}, \tag{2}$$

e is the elementary charge. E is the electric field. x_1 is the displacement in x direction in electric field region and x_2 is the displacement in x direction in free-flying region. ε is the initial kinetic energy of the ion. The total shift of the trajectory in y direction is,

$$y = \frac{meEx_1}{2p^2}(x_1 + 2x_2), \tag{3}$$

p is the initial momentum of the ion. Ions with the identical initial momentum fly along the same trajectory in the magnetic field region. From the top view in Fig. 1 (a), one sees the same trajectory even in the electric field region and the free-flying region, shown with the red dash line. Therefore ions with the identical initial momentum have the same x_1 and x_2. However, ions will shift differently in y direction according to their masses, because in the right side of equation (3), only m is a variable for ions with identical momentum. Therefore, if the total displacement of hydrogen ion in y direction is y, then the total displacement of deuterium ion in y direction is $2y$, as shown in Fig. 1 (b). Ions with identical momentum but different masses will reach detectors at different positions in y direction.

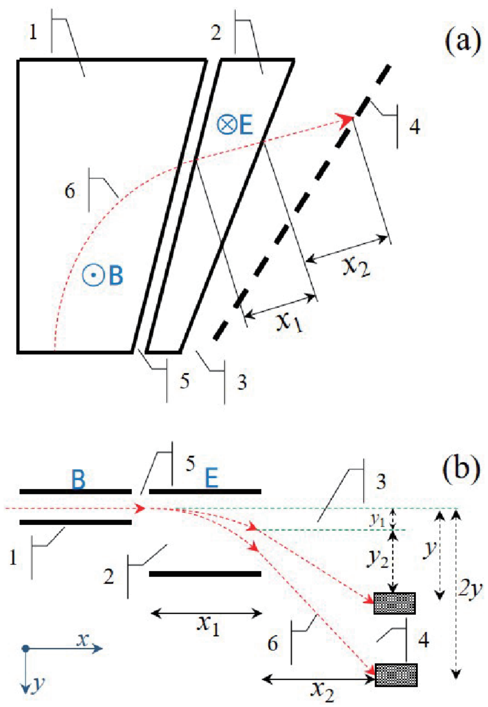

Fig. 1 Layout of the preliminary design for E//B analyzer. (a) The top view of the E//B analyzer; (b) the side view of the E//B analyzer. 1. Magnetic field region; 2. Electric field region; 3. Free-flying region; 4. Detector plane; 5. Blank region; 6. Trajectory of ion.

3. Simulation of the Ion Trajectory

The simulation is done with a Multiphysics simulation software COMSOL [13]. The parameters for simulation are set as follows. The magnetic field region is an inverted right trapezoid. The length of the upper side of the trapezoid is 20 cm, the length of the bottom side is 7 cm, and the height is 30 cm. The magnetic field is set to 0.5 tesla. The electric field region is an inverted trapezoid, with 10 cm top side, 2 cm bottom side and 30 cm height. The electric field is set to 5 kV / cm. The absolute value of the voltage applied to the plate is important in determining the insulation distance. The gap in the electric field plates is designed to be 1.2 cm. The electric field is set to 5 kV / cm. So the absolute value of the voltage applied to the plate is 6 kV. The width of the blank region is 1 cm. The free-flying region is an inverted trapezoid, with 10 cm top side, 2 cm bottom side and 30 cm height. Both the hydrogen and deuterium ions have been put in the simulation.

Simulation result of the ion trajectories is shown in Fig. 2. Figure 2 (a) is the bird view and Fig. 2 (b) is the detector plane view. In Fig. 2 (b), the ions are clearly separated into two lines. The upper line of the hit points are hydrogens and the bottom line of the hit points are deuteriums. Separation of the two lines is about 1 cm on the detector plane.

The position of the D^+ and H^+ ions onto the detec-

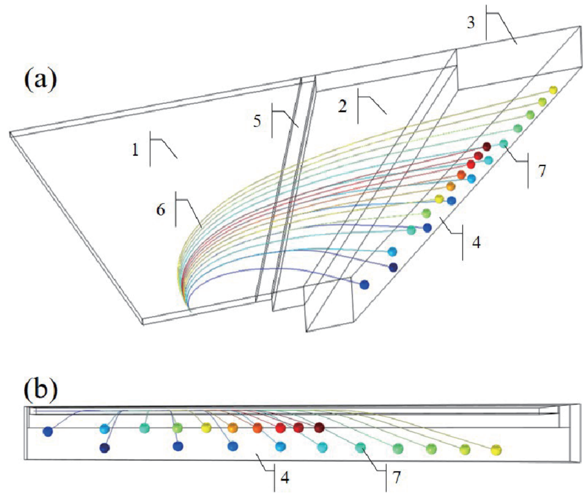

Fig. 2 Simulation result of the ion trajectories for hydrogen and deuterium ions of energies ranging from 20 keV to 200 keV at intervals of 20 keV. Different colors stand for different velocities. (a) The bird view; (b) the detector plane view. 1. Magnetic field region; 2. Electric field region; 3. Free-flying region; 4. Detector plane; 5. Blank region; 6. Trajectory of ion; 7. Hit point of ion.

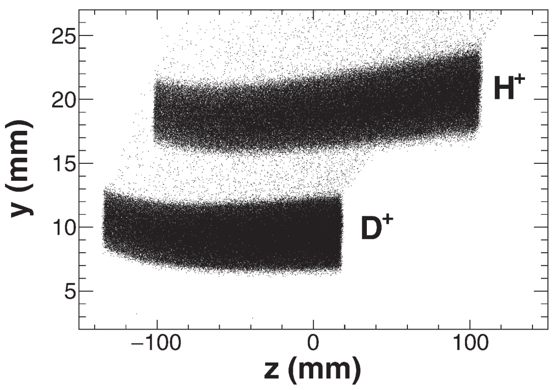

Fig. 3 GEANT4 simulation of ion position and energy in the detector surface of E//B analyzer. The scattering plot of ion positions in *y*-*z* axes (*z* direction is the flying direction of the incident neutrals). The bands at *y* around 10 and 20 mm corresponding to D^+ and H^+, respectively. The ion energies are 20 - 200 keV for both D^+ and H^+.

tor surface of E//B analyzer is simulated using GEANT4 toolkit [14]. Both the electric and magnetic fields are along y direction. The strength of electric and magnetic fields are 5 kV / cm and 0.5 tesla, respectively. The ion source is located at 25 cm upstream of magnetic dipole. A Gaussian distribution of ion spot with sigma of 1 mm is used for the ion source. The ion momentum direction is along *z* direction with a Gaussian distribution with sigma of 0.38 degree in the angle. An ion beam spot size at the detector position is determined by the position/pinhole size of the stripping cell and the position/diameter of the collimator. In this simulation, two collimators with a hole of 3 mm diameter to limit the ion spot are arranged at 3 cm and 18 cm upstream of magnetic dipole. The two collimators are corresponding to the actual collimator (at 3 cm) close to the magnetic field and the rear aperture of the stripping cell (at 18 cm). The total 10^6 events are simulated for D^+ and H^+ ions (both 5×10^5 events). Figure 3 shows the simulation results of ion positions in the detector surface. One can see in Fig. 3 that the two separated bands in *y*-*z* axes indicates a clear separation of D^+ and H^+ ions in the hitting position at the detector surface under the setup of E//B analyzer. Therefore in this setting of collimators, 1 cm is enough for D/H separation for the energy range of 20 - 200 keV.

4. Summary

The E//B field of a new NPA capable of mass resolution and energy resolution has been designed. The E//B field is composed of a magnetic field and an electric field which are parallel and in tandem. Both the analytical method and the simulation demonstrate that a carefully designed E//B field is able to realize both the mass and energy resolution on the detector plane. The position of the D^+ and H^+ ions onto the detector surface of E//B analyzer is simulated using GEANT4 toolkit. The result shows that, if there are two collimators with a hole of 3 mm diameter to limit the ion spot are arranged at 3 cm and 18 cm upstream of magnetic dipole, 1 cm is enough for D/H separation for the energy range of 20 - 200 keV.

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