ADVANCED NEUTRAL PARTICLE ANALYZER FOR FUSION PLASMA DIAGNOSTICS

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An advanced neutral particle analyzer for the diagnostics of hot plasma has been designed and fabricated in the Budker Institute of Nuclear Physics. The analyzer measures the ion energy distributions of both bulk plasma ions as well of fast ions created by neutral beam injection. The main feature of the analyzer is the ability to simultaneously measure hydrogen and deuterium atoms. The design of the analyzer, calculation of registration efficiency, and possible applications for plasma diagnostics on GOL-3 and GDT facilities are presented.

I. INTRODUCTION

Analysis of energy distribution of charge-exchange neutrals is an informative tool for fusion plasma diagnostics. Both passive and active (beam-assisted) diagnostics of charge-exchange particles are widely used on most plasma facilities; different types of neutral particles analyzers based on using electric or magnetic fields for particles separation have been designed [1-5]. At the same time, resent achievements in electronics and particle detection techniques allow to design new type the analyzer with advanced performance and additional possibilities for plasma diagnostics.

A new Advanced Neutral Particle Analyzer (ANPA) has developed by the Budker Institute of Nuclear Physics (BINP) for application in fusion plasma devises. The analyzer will provide localized (in conjunction with diagnostic neutral beams) fast measurements of the ion dynamics in plasma devices, in particular GOL-3 [6], GDT [7], and MST [8]. The analyzer will provide measurements in a broad energy range - from hundreds of eV for measurements of bulk ion plasma temperature to tens of keV to study the confinement of fast ions, formation of high energy ion tails, etc. In addition, the analyzer is capable to separate hydrogen and deuterium atoms and includes a built-in ion source for in-situ calibration.

II. ANALYZER DESIGN

For informative application for plasma diagnostics the designed analyzer should satisfy follows requirements:

- Measured temperatures of bulk plasma 0.4 - 3 keV
- Measured energies of fast ions - up to 30 keV
- Energy resolution 10-20%
- Temporal resolution 100 µsec
- Possibility of separation of hydrogen (protium) and deuterium ions

These requirements can be achieved by using magnetic field for energy analysis supplemented by electrostatic mass separation. The general operation principle of the analyzer is conventional for such types of diagnostics. (see e.g.[4]) Energetic neutrals appear in plasma due to charge exchange (CX) of plasma ions with

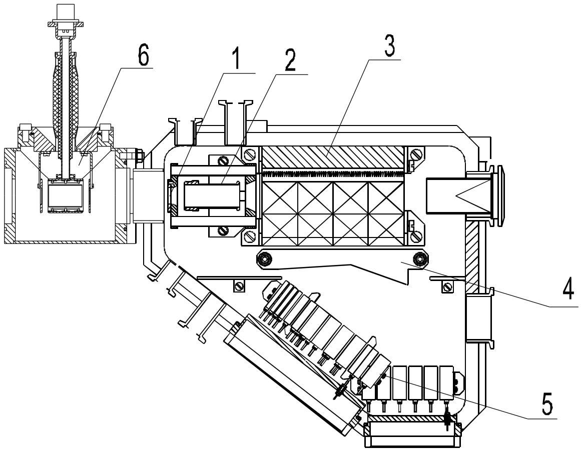

Fig.1 Schematic of the ANPA; 1 – stripping foil, 2 – electrostatic lens, 3 – magnet-separator, 4 – mass-separating capacitor, 5 – detectors, 6 – calibration ion source

either background hydrogen atoms or fast neutrals from diagnostic or heating beams. The CX neutrals travel across the magnetic field and enter the entrance aperture of the neutral analyzer.

For energy and mass-analysis, the CX neutrals must be converted to ions. In the ANPA, it is proposed to use a solid carbon film for stripping of neutrals. The are several advantages of using a solid stripping target including elimination of gas puffing that affect the plasma, constant target thickness during the shot, and a possibility to post-accelerate ions. The latter is especially important for magnetic analyzers where a shift of the working energy range can significantly simplify the analyzer design. At the same time, a solid film can introduce severe energy losses and scattering for low-energy neutrals. Actually, the equilibrium thickness required for stripping of neutrals is only a few atomic layers and is sufficiently less than a reasonable film thickness. To mediate the ion scattering caused by an excessively thick film an electrostatic focusing electrode can be placed behind the film in order to improve the ion collection and the overall neutral detection efficiency.

The stripping unit consists on two electrodes. A stripping foil is mounted on the “target” electrode biased to +7 kV. Through varying of this voltage one can adjust specific energies of the channels of registration. When the electrode is not biased the full energy spectrum, up to 40 keV, is measured. A second electrode – “focusing lens” – is negatively biased and serves for electrostatic focusing of the ions. As a result, the divergent ion flux passed through the film is formed into a quasi-parallel beam that enters the magnet-separator.

The magnet-separator is a C-shaped yoke that includes permanent NdFeB magnets and specially profiled poles. The maximal magnetic field in the magnet gap is 0.6 T. The pole shape is optimized for focusing of the ions in two dimensions (horizontal and vertical) onto the detector array. The ion trajectores in the magnet depend on ion velocity, so the exit point deflection of an ion is proportional to $(m_i \cdot E)^{0.5}$, where m_i and E – the mass and the energy of the ion.

After the magnet, the ions pass through a mass-separating capacitor with a transverse (with respect to the ion velocity) electric field. The distance between the plates is 15 mm and the working voltage is 8 kV. The shape of the plates was calculated so that the ion exit deflection angles are independent on the energy. The electric field in the capacitor causes a vertical shift of the ions that is proportional to mass of the ion. At the detector plane the shift is 14 mm for protons and 28 mm for deuterium ions. This difference is sufficient for spatial separation of ions with different masses. Thus, after passing the magnet and the capacitor the ions are dispersed in two dimensions according to their energies and masses. Measuring of ion current in the given point allows one to determine the flux of neutrals of specified mass and energy.

Miniature secondary electron multipliers (Channeltron, BURLE inc.)(SEMs) are used for ion detection. A high SEM sensitivity allows for detection of a single ion. The count rate of a SEM can exceed 10 MHz so a statistically reliable count rate can be provided within a 100 μs time window.

Up to 22 detectors can be mounted in the analyzer which allows to cover an energy range 0-30 keV. Switching off the bias voltage on the stripping foil allow to shift this regions even to higher energies. The energy ranges for every detector channel that are determined by their positions and the dimensions of their entrance windows are presented in Table I.

TABLE I. Energy Ranges of Registration Channels of the ANPA

Channel number	Energy range, keV H ions	Energy range, keV D ions
1	0 - 1.2	-
2	2.6 – 4.4	-
3	5.9-7.7	0-0.5
4	9.1-10.9	1.1-2
5	12.3-14.2	2.7-3.6
6	15.6-17.4	4.3-5.2
7	18.8-20.7	7.9-8.8
8	22.1-23.9	9.5-10.5
9	25.3-27.2	11.2-12.1
10	28.6-30.4	12.8-13.7
11	-	16.1-18.9
12	-	19.1-21.9
13	-	24.1-26.9
14	-	29.1-31.9

III. NEUTRAL DETECTION EFFICIENCY

Several factors influence the efficiency of neutral detection - the efficiency of neutral conversion to ions in the stripping foil, scattering of ions in the foil, the value of the secondary emission coefficient for ions with specific energy. Therefore, in-situ calibration of the channels sensitivity is required in real experiments. Here, we will provide some preliminary estimations of the sensitivity in order to determine the dynamic range of the system and the range of measured plasma temperatures.

The stripping target equilibrium yield can be estimated using the data from R.Bartiromo et al [9]. Between 6 keV and 30 keV the equilibrium yield increases from 15% to 45%. Below 6 keV the ion yield is approximately 10%.

Ion scattering in the stripping foil is calculated by the SRIM code [10]. The quantity of ions scattered into a given solid angle after passing the stripping film is presented in Fig.2 for deuterium ions with energies 0.8, 2,

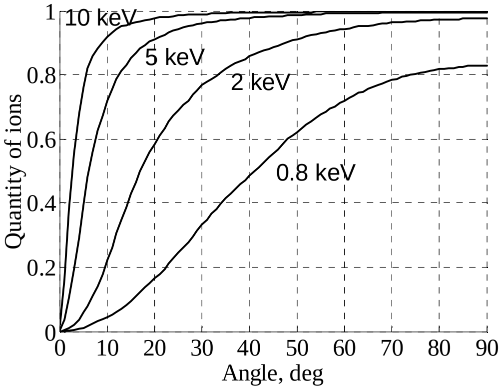

Fig. 2 The quantity of deuterium ions scattered to given solid angle after passing 10 nm carbon film, energies of incident particles 0.8, 2, 5, and 10 keV

5, and 10 keV. Ion trajectories simulations show that the optical system of the ANPA collect ions with angles up to 20°, that is the collection efficiency is about 20% for low-energy ions and quickly increases with the ion energy.

Assuming that the flux of neutrals from the plasma has Maxwellian distribution, it is possible to calculate the ion flux into the ANPA registration channels. The relative signals from the first five channels vs the plasma temperature are shown in Fig.3 for deuterium neutrals. For the plasma temperatures over 0.4 keV the ratio of the channel intensities is less than 100 for three or more channels. Therefore, the ANPA can be used for measuring the bulk plasma temperature exeeding 400 eV.

IV. MEASUREMENTS OF D/H SEPARATION

The ability of the ANPA to separate the ions by masses opens a possibility of analysis of the dynamics of different types of ions. The main idea of such experiments is identification of the source of ions using mass-separation. For the GOL-3 device an important experimental task is to measure the rate of longitudinal (along the magnetic field) transport of the ions. Puffing a small amount of a specific gas (e.g. hydrogen or helium into deuterium bulk plasma) and measuring the dynamics of those ions at a distance from their source provides information about the ion diffusion in the multi-mirror magnetic field. For the GDT device a similar technique can be applied for studying the efficiency of different methods of plasma fueling.

For plasma heating via neutral beam injection the admixture of atoms with different masses allows to study simultaneously the dynamics of populations of hot ions with two different masses. This dynamics depends on a specific mechanism of ion energy losses , which can be identified in this experiment.

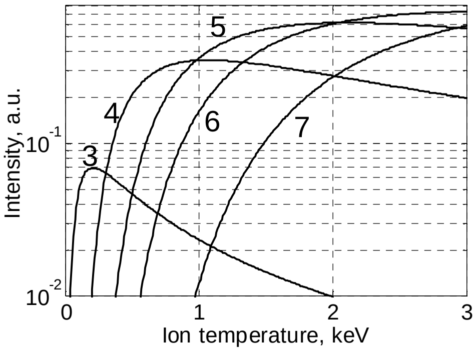

Fig.3 Relative intensities in first five channels of analyzer for deuterium neutrals from plasma with temperatures 0-3 keV, the indexes correspond to the Table 1.

V. CONCLUSIONS

An Advanced Neutral Particle Analyzer - ANPA was designed and fabricated in the Budker Institute of Nuclear Physics. The analyzer allows to perform a wide range of experiments to study the properties of hot plasma. The ability of analyzer to provide isotope D/H separation open possibilities to provide special experiments for measurement of ion transport in the open magnetic systems.

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