High brightness ^{3}He ion source for nuclear astrophysical application

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Abstract

A compact low energy and high current accelerator is designed for a study of fusion reaction in a nuclear astrophysics. The accelerator can produce an intense beam of several ion species such as proton, deuteron and helium isotopes more than 1mA. To provide extremely fine cross sectional measurement for fusion reactions ion beam production, extraction, transport to a windowless gas target is made using the GIOS and FUGUN computer codes. Multielectrodes for the ion extraction applied to the NANOGUN ion source can be expected to improve the beam quality and to raise a luminosity for beam to gas target interaction. To study the electron screening effects, an experimental apparatus is proposed and constructed. A combination of EBIS type plasma source as a target with a high current ECR ion source is also proposed. The present state of these design consideration and its development are described.

1 Introduction

A high brightness ion source and a precise low energy beam accelerator are indispensable tools in the study of fusion reaction in nuclear astrophysics. When a gas target is combined with a powerful ion source, such as a proton, deuteron or helium isotopes ion source, the result is a nessesal condition appropriate for the measurement of extreme low cross section events in this region. Although fusion reaction, $p+p \rightarrow d+e^+ +\nu$, is the operative reaction in the solar combustion of hydrogen, as well as the initial reaction in the chain for producing photons and neutrinos, the rate of $p+p \rightarrow d+e^+ +\nu$ is too slow($10^{-52}cm^2$) to be measured experimentally at 6keV, the energy range of the actual solar reaction. Of the reactions that follow after the basic reactions such as $d+p \rightarrow^3 He+\gamma$, $^3He +^3 He \rightarrow 2p+\alpha$, $^3He +^4 He \rightarrow^7 Be+\gamma$, we have focus on cross-sectional measurment of the $^3He +^3 He$ reaction at the effective energy $E_{cm} = 17-27keV$. This reaction manifests the so called neutrino problem in the sun and can be used to verify the standard solar model[1]. We are planning to construct a compact ion accelerator facility in the underground laboratory

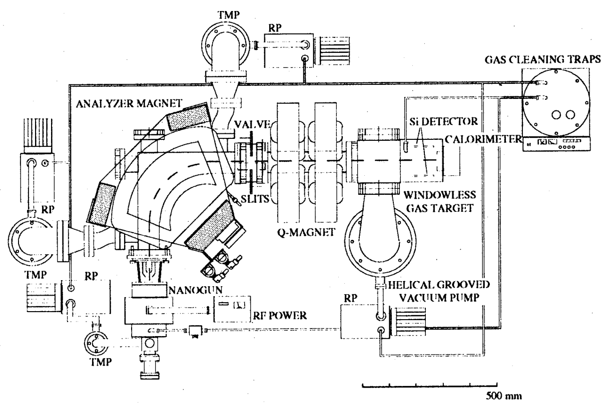

Figure 1: Total system of a compact accelerator, beam transport and a gas target for nuclear astrophysics.

at OTO cosmo observatory(1270mw.e.)[2]. The facility will consist of (1)ion source with intense current of ^3He 1+ or 2+ (more than 1mA at energies of 30-50keV) (2)low energy beam transport (3)windowless gas target and evacuating system (4)reliable beam calorimeter (5)detectors with the reaction identification (6)electronics and data acquisition system (7)preliminary test stand of a plasma target.The total system of a compact accelerator, beam transport and a gas target for nuclear astrophysics is shown in Fig.1. In this report we describe the current status of the development and design of this facility.

2 Ion source and extraction electrodes

Because of the proposed facility will be used to made extremely fine cross-sectional measurements of fusion reaction, a compact accelerator with a highly efficient, low-power ion sources having long-term stability is required.The numerous possible ion sources such as duoplasmatron, duopigatron and electron cyclotron resonance(ECR) ion sources, we chose an ECR ion source composed of a NANOGUN body and modified extraction electrodes that can be applied for 50kV potential[3]. This type of source is desirable because it has a simple structure without filament, it has fewer contaminant's and it remains for as long as three weeks or so. The required energy range of ^3He ions should be between 30 to 50 keV, in which the astrophysical S-factor data for $^3He+^3He$ fusion reaction can be deduced inside the gamow peak, although currently only the LUNA group has presented data in this peak[4]. The higher extraction voltage than that used for a usual ion source results in crucial problems on not only the source itself - i.e., the discharge and isolation of the rf feeding section - but also on the beam optics degradation caused by the space charge current. To obtain data on every hundred eV for the incident He-3 beam, it is desirable that condition at the target site be kept optically constant throughout the whole energy change. For this purpose we employ the multi-electrodes extraction system proposed by GANIL group[5] as well as calculated optimum electrode structures at each potential. The multi-electrodes extraction system is advantageous for two reasons: first it improve the beam emittance even under condition of a strong space charge force, and secondly, it moderates the electric field gradient ascribed from the higher extraction potential. Actually, we need add only one electrode to the original NANOGUN design in order to have two independently moving electrodes(a beam-forming electrode and the previous electrode). As will be discussed later, the size and divergence of the beam at the target should be limited so as to keep the aperture slit too less than a 7mm diameter. Accordingly, we used the computer code FUGUN[6] and optimize the potential, structures and positions of the electrodes as they affect the beam form so as to achieve a constant beam emittance and brightness within the expected range of energy changes.

As described in the following section, these goals are combined with a beam optics study for low energy beam transport between the source exit and target aperture slit. At energies 40keV and 50keV a substantial brightness could be achieved by simply applying the different potentials and positioning the beam-forming electrode as shown in Fig.2 and Fig. 3.

3 Low energy beam transport

Despite of the variance in total potential of the beam a nearly invariant beam form could be realized at the source exit using the beam-forming electrode. A low energy beam transport between the ECR ion source and a gas target should be designed to maintain a high beam intensity and other desirable beam qualities and by there allow precision measurement of the rare nuclear reaction, $^3He+^3He \rightarrow 2p+\alpha$. Generally, there is known to be a strong space charge effect in the beam transport at ion currents more than 1mA. It is essential that this effect be accounted for when calculating the beam optics. Wollnick et al. have developed a GIOS code that incorporates such effect, which we used for the present calculation of our beam transport.

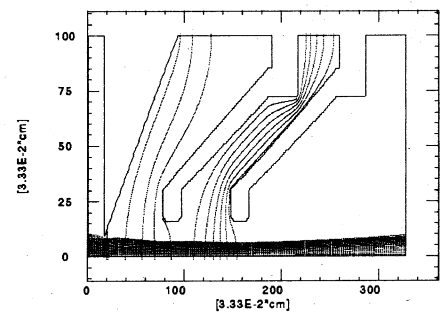

Figure 2: Theoretical simulation of a beam-forming electrode extraction system.Total voltage is 40kV

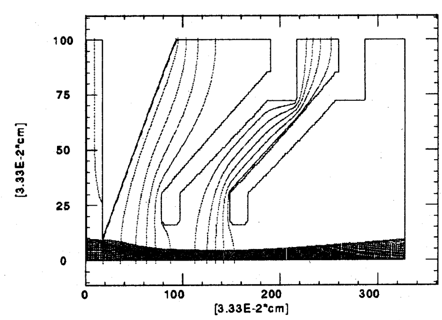

Figure 3: Theoretical simulation of a beam-forming electrode extraction system.Total voltage is 50kV

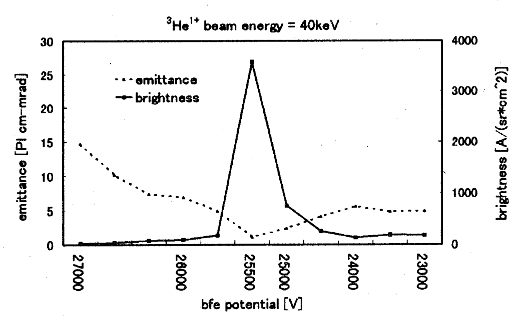

Figure 4: Brightness and emittance variation to a potential of a beam-forming electrode. It is calculated for ^3He beam energy at 40keV.

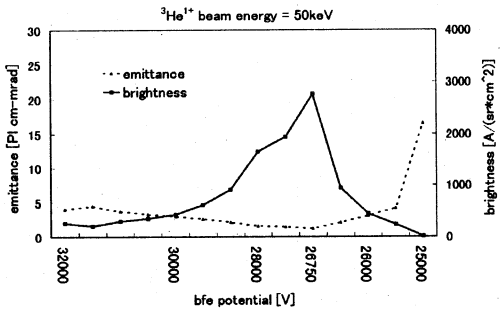

Figure 5: Brightness and emittance variation to a potential of a beam-forming electrode. It is calculated for ^3He beam energy at 50keV.

There are many candidates of beam transport scheme combining various focusing elements, such as (i) QQ-D-QQ (ii) solenoid+D+QQ (iii) electric lenses+D+QQ and (iv) 90 degree double focusing D, etc. Because it is easier to operate and has fewer elements we adopted the D(dipole 90 degree deflection angle)+Q+Q transport scheme for our system. To maintain the minimum silt aperture, we calculated the dimension of the beam at the target position by varying the various parameters of elements and drift lengths so as to create smaller dx and dy. In addition, we consider better and constant beam transmission efficiency from the ion source through the target. It is noted that strong focusing waist during the beam transport should be avoided for the sake of the divergence due to the space charge force. Simultaneously we consider dx' and dy' to be almost zero since at the gas target a strong divergence of the beam is not suitable for the measurement of an intensity via the calorimetric method. Our detailed analysis gave very attractive results such as a constant dx and dy and a nearly parallel beam form. This means we can expect minimal position drift for the Q-doublet at each beam energy between 50keV and 40keV. For this calculation we assume a beam source as 100π mm mrad and 5mm diameter source exit. The distance from dipole to an ion source exit is 27cm. This is close distance allowed to install an insulator for applying 50kV potential. For the dipole magnet (r=22cm, inlet and exit angles of the pole edge are each 22 degrees) the gap height and width are 70mm and 160mm, respectively. The system appeared to abandon sufficient resolution to discriminate DH^+ with $^3He^{1+}$. As stated at earlier, if improving the beam quality at the exit of the ion source using a multi-electrode system, we can greatly improve the beam form and divergence at the exact position of an aperture.

4 Project status

The dipole magnet and quadruple doublet with vacuum chamber are constructed and ready for operation in the under ground testing area beneath the east experimental hall of RCNP Osaka. September we will receive the NANOGUN ion source body and a 10GHz rf power amplifier. We are currently modifying the extraction electrodes and insulator for a 50kV potential. The evacuation system is ordered. By the end of the current fiscal year we should have all the equipment assembled and be ready to transmit the first beam into the gas target section.

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