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Preliminary Measurement of Space Charge Neutralization Level for Proton Beam

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Abstract: For high-intensity low-energy ion beams, space charge effect is a main cause of beam divergence and emittance growth. Fortunately, residual gas molecules in the drift space tend to be ionized and neutralize the beam space charge spontaneously. The level of Space Charge Neutralization (SCN) is measured through the detection of created secondary ion energy distribution in the beam region. A so-called non-interceptive Three-grid Energy Analyzer (TEA) has been designed and manufactured at Institute of Modern Physics, Chinese Academy of Sciences (IMP). This paper will present the details of the TEA detector and the application to diagnose proton beam SCN level in the Low Energy Beam Transport (LEBT) line. As a preliminary result, for an 18.5 mA proton beam a best compensating point appears at the vacuum pressure of 1.5×10^{-3} Pa. And the neutralization level is advanced with the growth of beam current in a constant vacuum pressure.

Key words: space charge effect; neutralization level; three-grid energy analyzer

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1 Introduction

High-intensity proton sources have been widely employed as the preliminary injectors for many accelerator based facilities, such as ADS (Accelerator Driven sub-critical System) program in China and IFMIF (The International Fusion Materials Irradiation Facility) in Japan, *etc.* Proton beams extracted from the ion sources, which usually have a relatively low energy, will be delivered and matched to the downstream acceleration element, such as RFQ, through a Low Energy Beam Transport (LEBT) line. For high-intensity low-energy ion beams, space charge effect will have big impact on the beam emittance and beam profile[1]. Fortunately, when the beam passes through the LEBT the space charge will be largely neutralized by secondary electrons that are mainly created from the interaction of the beam with residual gas molecules[2]. As an important issue concerning the transmission of intense ion beam, the level of the Space Charge Neutralization (SCN) is very worth a thorough investigation, especially in terms of the LEBT design and study.

Benefiting from MSU and CEA-Saclay's experiences in the measurement of SCN level[3−5], a so-called non-interceptive Three-grid Energy Analyzer (TEA) has been designed and fabricated at IMP, which has now been installed on the LEBT of a high-intensity 2.45 GHz proton source[6] to measure the SCN level. Similar research had also been performed at Peking University by Dr. S. X. PENG and her team[7]. This paper presents the design of the TEA device and the experimental results.

2 Experimental method

When the beam passes through the LEBT, it will interact with the residual gas molecules, producing secondary ions and electrons. Under the influence of the beam self-potential, the electrons will be trapped inside the beam and reduce the self-potential of the beam

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in the radial direction, so as to neutralize the space charge effect therein. However, the secondary ion will carry a kinetic energy from the beam self-potential and be expelled outside of the beam.

Assuming that the ion beam is a uniformly charged cylinder, the distribution of the electric potential in the radial direction of the beam could be described as following formulas according to Gauss Theorem:

$$\phi(r)=\begin{cases}\dfrac{I}{4\pi\varepsilon_0 v_{\mathrm{b}}}\left(1+2\ln\dfrac{r_{\mathrm{p}}}{r_0}-\dfrac{r^2}{r_0^2}\right) & (r\leqslant r_0)\\ \dfrac{I}{2\pi\varepsilon_0 v_{\mathrm{b}}}\ln\dfrac{r_{\mathrm{p}}}{r} & (r_0\leqslant r\leqslant r_{\mathrm{p}})\end{cases}, \tag{1}$$

where I is the total beam current, ε_0 the vacuum permittivity, v_{b} the velocity of the beam, r_0 the radius of the beam, r_{p} the radius of the pipeline. Using $\Delta\phi_{\mathrm{un}}$ and $\Delta\phi$ to represent the electric potential drop between the center and the edge in the radial direction of the beam before and after neutralization, respectively, the SCN level f can be defined as[8]:

$$f=1-\frac{\Delta\phi}{\Delta\phi_{\mathrm{un}}}. \tag{2}$$

According to Eq. (1), $\Delta\phi_{\mathrm{un}}=\phi(0)-\phi(r_0)=I/4\pi\varepsilon_0 v_{\mathrm{b}}$. Therefore, to achieve f, the electric potential drop $\Delta\phi$ is the only parameter needed to be measured. Since the secondary ions produced inside the beam are born cold[4] and the vacuum pipe of LEBT is grounded, measurement of the ion-energy distribution could be interpreted in terms of the beam-potential distribution in radial direction. So $\Delta\phi$ could be quantified by measuring of the kinetic energy distribution of the secondary ions that are expelled from the beam. To detect the kinetic energy of the secondary ions, a so called TEA was developed.

3 Three-grid energy analyzer

Fig. 1 shows the schematic diagram of TEA. It mainly consists of collimating apertures that are used to restrain the incident angle of the secondary ions, three parallel girds (G_1, G_2, G_3) and the secondary ions collector C. G_1 is grounded and G_2 is loaded with a positive sweeping voltage, so there will be a uniform retarding field between G_1 and G_2, when the secondary ions come into the analyzer from the collimating apertures, some of them that have higher kinetic energy than the retarding field will pass through G_2 and reach the collector, then a current signal will be displayed on the picoammeter which is connected to the collector. When we change the sweeping voltage on G_2, the information of the secondary ions energy distribution can be achieved. G_3 is biased with a negative high voltage(typically set to -150 V[3]), which acts as an electron repeller, both to resist the electrons from entering the collector and suppress the secondary electrons produced by secondary ion bombardment upon the collector.

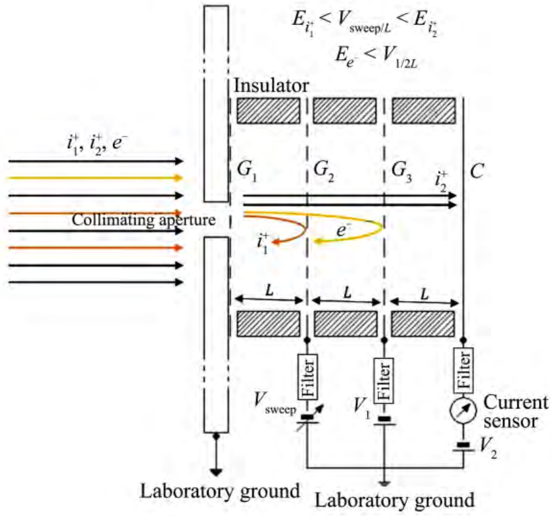

Fig. 1　(color online) Schematic diagram of the TEA.

Simulations have been made with SIMION 8.0[9] to determine the mechanical parameters of the analyzer, including the incident angle of the secondary ions and the details of the grid. Fig. 2 shows the simulation model of the analyzer. G_1, G_2, G_3 are three parallel grids with a distance of 6 mm[10] between each other, C is the collector. Each mesh has a maximum transmission of 90% due to the fact that wires block the path of the incoming ions[3]. 3 000 $^{40}\mathrm{Ar}^+$ ions are used as the secondary ions in the simulation, which are sent out from y-z plane (having a 0.1 mm distance from G_1), with a uniform kinetic energy distribution ranging from 5 to 10 eV. Flying the secondary ions and sweeping the voltage on G_2, the ion spectrum could be obtained.

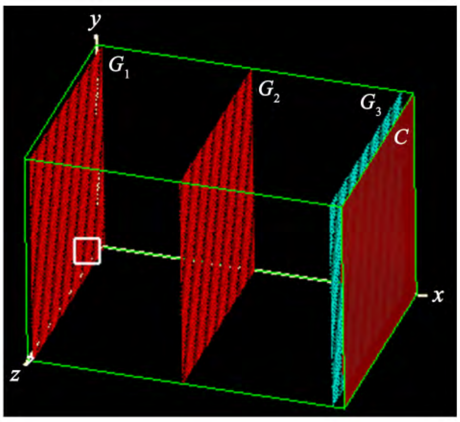

Fig. 2　(color online) 1/4 simulation model of the TEA.

Fig. 3 illustrates the simulation results in which x-axis is the sweeping voltage on G_2 and y-axis is the number of ions reached the collector. Fig. 3(a) shows the influence of incident angle to the ion spectrum. The spectrum is distorted when the ions sub-vertically enter the analyzer. And if the incident angle is oversized, the ions will be scattered seriously between the grids, resulting in an inaccurate inflection point of the ion spectrum. According to the simulation analysis, incident angles between $-10° \sim 10°$ is the most suitable. The influences of the width and thickness of the wire to the ion spectrum are demonstrated in Fig. 3(b) and Fig. 3(c). From Fig. 3(b), with a narrower wire width (20 μm), a better ion spectrum could be achieved. Fig. 3(c) shows the inflection points of the ion spectrum becomes more close to the theoretical value when the thickness of the wire is increased from 10 to 80 μm, but more ions been killed with a thicker wire.

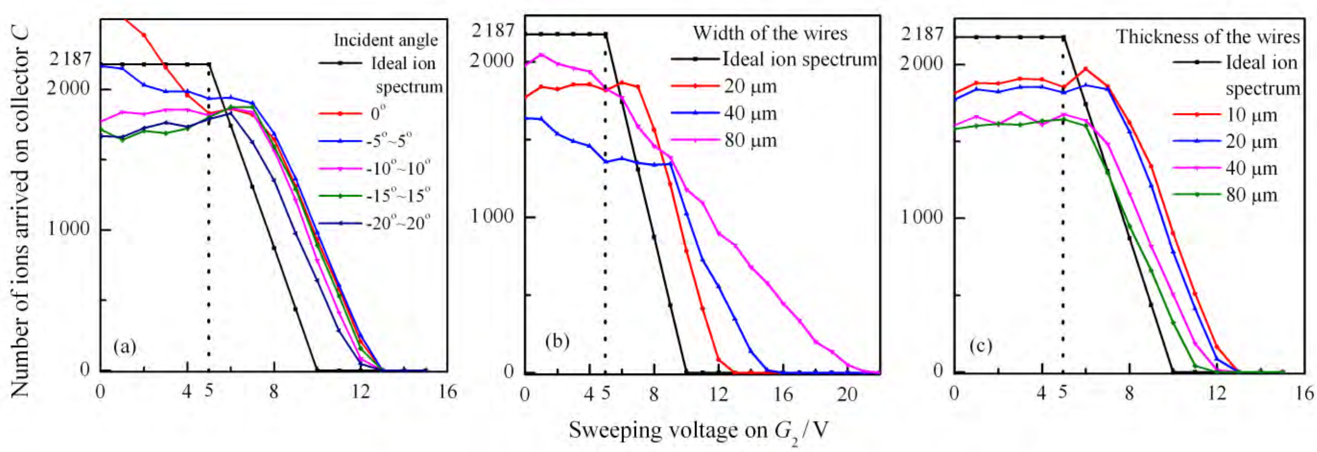

Fig. 3 (color online) The simulation result with x-axis as the sweep voltage on G_2, y-axis as the amount of ions reached the collector. Picture (a), (b), (c), show the influence of incident angle of the secondary ions, width and thickness of the wires to the ion spectrum, respectively.

The potential distribution between each grid is very sensitive to both width and thickness of the wire, a narrower and thicker wire is more likely to create a flat potential distribution between the grids, but with the sacrifice of the transmission efficiency of the secondary ions. Taking all the aspects discussed above into account, a copper grid, whose width and thickness of the wire are both 18.5 μm, with the maximum transmission of 90%, is selected.

Fig. 4(a) shows the mechanical design of the analyzer with Solidworks 2013, which is housed in a grounded hollow cylinder. In order to ensure a good collimating effect but not reduce the entrance area, the collimating apertures are composed of 9 square apertures (each square covers an area of 1 cm^2) and the depth of each collimating aperture is 79 mm, which makes the incident angle between $-10.15° \sim 10.15°$. Each grid is sandwiched with two aluminum sheets and insulated by ceramic materials, and the distance between each grid is 6 mm. Collector C is connected to a picoammeter (Keithley 6 485) with a coaxial cable. Picture of the TEA is showed in the Fig. 4(b).

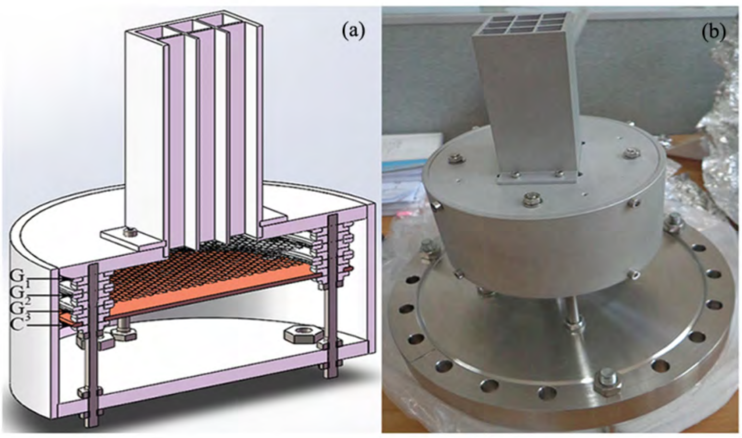

Fig. 4 (color online) Cut isometric view of the TEA's mechanical design with Solidworks 2013 (a); Picture of the TEA (b).

4 Experimental result and analysis

The measurement was carried out on an ECR proton source platform with a 2-solenoid LEBT [6] at IMP, as shown in Fig. 5. The TEA device and vacuometer are mounted perpendicular to the beam in the diagnostic chamber. The distance from the collimating apertures of the analyzer to beam axis is of 21.3 cm.

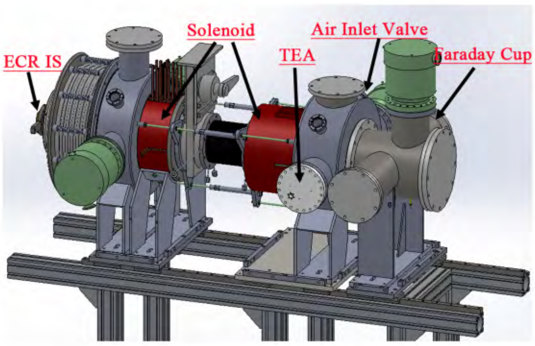

Fig. 5 (color online) The layout of the measurement platform.

Fig. 6 shows a measured ion spectrum from an 18.5 mA proton beam at 40 keV energy under the vacuum pressure of 1.5×10^{-3} Pa in the LEBT line, in which the x-axis represents the sweeping voltage, and the y-axis represents the current signal of the secondary ions on the collector. By fitting the curve with 3 straight lines, as shown in the Fig. 6, two inflection points appear, which are denoted with A and B. ϕ_B and ϕ_A can be considered as the electric potentials in the center and the edge of the beam, respectively. Therefore, the potential drop $\Delta\phi=\phi_B-\phi_A=2.7$ V. According to equation (1) in section 2, for this beam $\Delta\phi_{un}=\phi(0)-\phi(r_0)=I/4\pi\varepsilon_0 v_b=60$ V. Therefore, $f=1-\Delta\phi/\Delta\phi_{un}=95.5\%$.

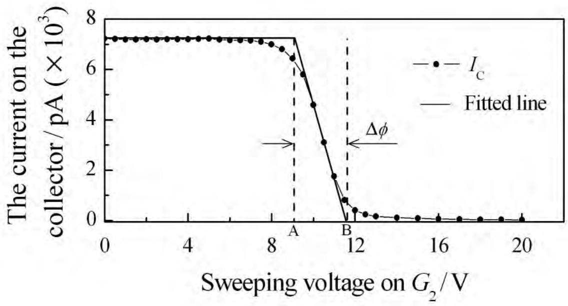

Fig. 6 Example analysis of the ion spectrum on collector with an 18.5 mA proton beam at 40 keV energy and 1.5×10^{-3} Pa vacuum pressure. x-axis is the sweeping voltage on G_2, y-axis is current signal obtained on the collector.

With a proper SCN level detector, it is worth studying the aspects that could have impact on f. Fig. 7(a) shows the measured f as well as the beam current obtained on the faraday cup at different LEBT vacuum pressures for an initial proton beam current of 18.5 mA with 40 keV energy. In this measurement, the vacuum pressure remains 7.1×10^{-4} Pa without injecting additional gas, but adjusted by injecting argon gas from the air inlet valve (as shown in Fig. 5) and the ion source condition remains unchanged. It is indicated that a best compensating point appears at the vacuum pressure of 1.5×10^{-3} Pa. Besides, the beam particle loss increases due to the scattering while increasing the residual gas pressure.

Fig. 7(b) shows f vs. the proton beam intensity for a 40 keV energy beam at the LEBT vacuum pressure of 1.8×10^{-3} Pa. f decreases slowly from 96% to 82% with beam current decreasing from 19 mA to 3.7 mA, but dramatically to 66% when the beam current decreases to 1.35 mA.

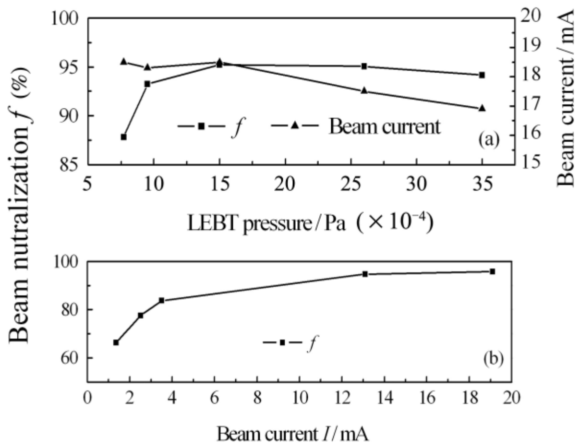

Fig. 7 Plot of beam neutralization level f vs. (a) the LEBT vacuum pressure, and (b) total beam current.

5 Summary and outlook

A so-called non-interceptive TEA has been designed and manufactured at IMP to measure the SCN level. Preliminary experiments for proton beams were performed, in which the SCN level was measured at different vacuum pressures in the LEBT and with different beam current intensities, respectively. The results indicate that a best compensating point appears at the vacuum pressure of 1.5×10^{-3} Pa for an initial proton beam current of 18.5 mA with 40 keV energy. In addition, f increases with increasing the beam current intensity.

In the future work, measurement with highly charged heavy ion beams will be made.

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低能强流质子束空间电荷补偿度研究

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摘要： 对于低能强流离子束来说，空间电荷效应的存在将导致束流发散、发射度增加等一系列问题，从而降低束流品质。幸运的是，当束流由离子源引出通过低能传输线时会与其中的剩余气体发生电离反应，产生二次电子与二次离子；二次电子在束流自身产生的电场作用下，在束流中积累并中和部分空间电荷，达到抑制空间电荷效应的效果。为了测量空间电荷中和程度，中国科学院近代物理研究所研制了一台三栅网式能量分析仪用以测量电离过程中产生的二次离子能量来间接计算空间电荷中和度。实验结果表明，对于40 keV, 18.5 mA 的质子束，真空度为 1.5×10^{-3} Pa时得到最佳补偿度；真空度一定的情况下，空间电荷补偿度随束流流强增加而变大。

关键词： 空间电荷效应；空间电荷补偿度；三栅网式能量分析仪

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