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A novel method to survey parameters of an ion beam and its interaction with a target

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ABSTRACT

Beam profile and composition of the pulsed ion beam from a vacuum arc source are valuable information for designing a high-intensity deuterium-tritium neutron generator. Traditional methods are notoriously difficult to obtain the information at the same time. A novel off-line diagnostic method is presented, which can obtain the transverse beam profile with high resolution as well as species of the ions in the beam. The method is using a silicon target with high purity to interact with the ion beam, and then use secondary ion mass spectrometry (SIMS) to analyze the interaction zone of the target to get the beam information. More information on beam-target interaction could get simultaneously. Proof-of-principle simulation and experimental works have demonstrated this method is practical.

1. Introduction

Pulsed high-intensity deuterium-tritium neutron generator has a wide variety of applications such as neutron radiography, nuclear material non-proliferation as well as explosive detection [1–4]. Beam profile and its composition are useful information for the design of the neutron generator. In particular, to get this accurate information significant if the specifications of the generator, such as the size, neutron yield and life are strictly stated. For traditional accelerators, the beam diagnostic techniques are diversified and capable. The main characteristics of some general beam diagnostic methods for transverse beam profile and species identification are reviewed in Table 1 briefly [5–8]. As shown, it is hard to use a definite way to get all the information at the same time. For large-size accelerators, using several diagnostic methods together to get the different parameters is acceptable. However, the compact small-size neutron generator has not been enough room to adopt these methods simultaneously without changing the original nature of the beam. In case, generally, we could get the beam information separately from different experimental shots by applying different diagnostic methods each time. Nonetheless, it is sometimes difficult to obtain all the information at one shot. We present a novel off-line beam diagnostic method. The main idea is to use a silicon target to get the beam information at one shot, and then utilize secondary ion mass spectrometry (SIMS) to reveal the beam information from the target. Here the target is almost like a memory chip to store the beam information, and the SIMS is exactly like a readout circuit. Simulations and experiments have done to demonstrate its ability and feasibility.

2. Principle analysis

SIMS is a material composition analysis tool in many fields with high sensitivity (ppm~ppb) [9]. Fig. 1 shows SIMS working flow. The incident ions (primary ions) from an ion source could kick out atoms in the ionized state from the sample. The kicked-out ions (secondary ions) are then guided into a time-of-flight (TOF) or magnetic spectrometry and analyzed. Due to the integration ion sputtering of the mass spectrometer, the SIMS is a powerful tool. Compared with other ways, such as X-ray Photoelectron Spectroscopy (XPS) and Auger Electron Spectroscopy (AES), it has not only advantages to tell light elements like hydrogen's isotopes but analysis three-dimensional distribution of the atoms in the sample with spatial resolution over 1 μm in transversal direction and 5–10 nm in depth. Naturally, the density of the checked atoms should be higher than the SIMS detecting limitation.

$$ {}_{1}^{2}\mathrm{H} + {}_{1}^{2}\mathrm{H} \rightarrow {}_{2}^{3}\mathrm{He} + {}_{0}^{1}\mathrm{n} + 3.27\,\mathrm{MeV} \quad (1) $$

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Table 1
General methods for beam profile and composition diagnostics.

Diagnostic Methods	Main Characteristics
Scintillator screen	• With time-resolution ability • With anti-electromagnetic disturbance • With non-linear effects, due to its temperature and incident ion species
Faraday cup array	• With good time-resolution ability and linearity • Could get charge amount and quantitative analysis • With poor spatial resolution and electromagnetic disturbance
Time-of-flight (TOF) spectrometry	• With identification of ion species and energy • Could get species information at specific time of the beam pulse • Sampling a point-like region from the whole beam
Magnetic spectrometry	• With identification of ion species • Sampling a point-like region from the whole beam

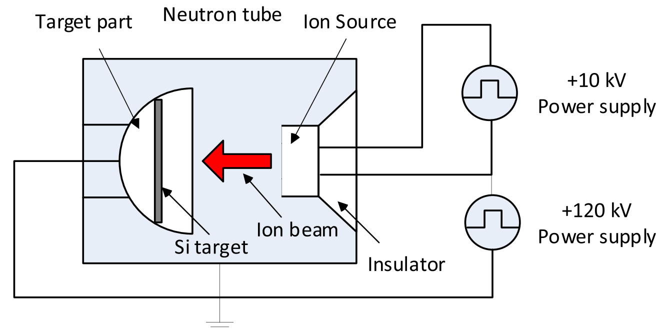

Fig. 2. Schematic of the off-line diagnosis for ion beam profile in a compact neutron generator.

For pulsed high-intensity neutron generator, the general structure is shown in Fig. 2. The main components of the generator are a kind of vacuum arc ion source with deuterated titanium electrodes, accelerator diode and a deuterated titanium target. Deuterium ions are generated by a vacuum arc discharge, then accelerated across a potential of ~120 kV to the deuterated target, where the deuterium-deuterium reaction occurs (Eq. (1)), releasing fast neutrons. The vacuum arc ion source can provide a deuterium ion beam current of hundreds of mA. A large number of metallic ions, molecular ions and neutral particles are also produced simultaneously during the discharge [5]. In one shot, the charge amount of incident deuterium ions in the pure silicon target is about several μC with several mm radius and several μm penetration depth. The average density of the incident ions which can be deduced is about 10^{16} cm^{-3}. Single-crystal silicon was used as the sample target for irradiation because of its high purity, low hydrogen content, and smooth surface. In principle, SIMS can do distinguish job well. It could provide the function to peel off the surface of the sample to obtain the depth profile of the detected ions. This function could deduce the energy information and the charge state information of the ions while avoiding disturbance from the contaminant from the target surface. As shown in Fig. 2, another two advantages for this diagnostic method are keeping the original properties of the beam unchanged and suitable for very compact structure.

3. Simulation and experiments

For compact pulsed high-intensity neutron generator, vacuum arc ion source is generally applied. It consists of a titanium deuteride cathode with a distinctive discharge feature that cathode material transits from solid to liquid, gaseous, and plasma states. Generally, Ti^+, Ti^{2+}, D^+, D_2^+ are the major components of the ion beams [5,10]. For better understanding and directing the SIMS analysis, SRIM [11] is utilized to simulate beam-target interactions before the experiment.

The calculated ion ranges distribution is shown in Fig. 3(a) while XY longitudinal distribution in Fig. 3(b). As shown in the figure, the mean projected ranges in silicon are different for certain ions. Metallic ions usually deposit near the surface, while the hydrogen ions penetrate into further. The energy of the ions is set at 120 keV per unit charge. The projected ranges for Ti^+, Ti^{2+}, D^+, and D_2^+ are about 0.114 μm, 0.217 μm, 1.14 μm, and 0.67 μm, respectively. The longitudinal straggling for metallic ion is less than 0.07 μm, while for hydrogen ion less than 0.15 μm. In the calculation, D_2^+ is thought as two D^+ with the energy of 60 keV, while Ti^{2+} with two charges owns the energy of 240 keV. The results of ranges for different ions in silicon target are different. In the SIMS analysis, it applied to peel off the surface layer after layer, which will make it easier to show the density of different elements in the target. The error caused by the straggling will be ignored. The ion beam profile can be approximately deduced by the SIMS results from the different position of the silicon target, while the information of ion energy and charge states is also analyzed by the elements in different layers.

The calculated results show that the backscattered ions are less than 0.05% of the incident ions. In other words, almost all ions are injected into the target. The measurement error caused by the backscattered ions will be ignored in the experiment. Otherwise, lateral straggling is less than 0.2 μm which will be ignored for the beam profile of about mm spatial resolution.

For principle demonstration, only select nine point-region of the silicon sample target for analysis on the SIMS after the

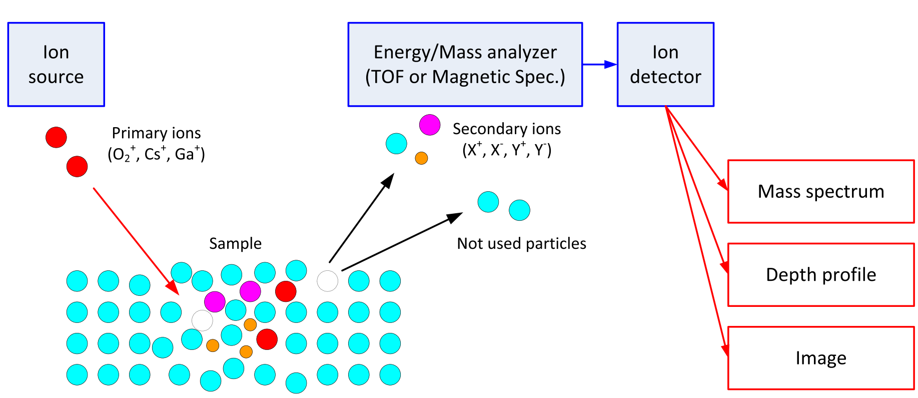

Fig. 1. Schematic diagram of SIMS.