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A linear time-of-flight mass spectrometer with relatively high resolution for diagnostic of high energy ion beam

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ABSTRACT

A special linear time-of-flight mass spectrometer, with relatively high mass resolution of 120 full width at half maximum (FWHM), for vacuum arc discharge ion source was developed. The instrument comprises a two-electrode ion extraction system, an ion gate, a drift tube, an einzel lens system and a micro channel plate (MCP) detector. Wire type ion gate is used for precise extraction of high energy (up to 40 keV) ion beam, and the drift tube length is 1.5 m. The extracted ion bunch is focused by the einzel lens system before it arrives the MCP detector, in order to improve the detection efficiency. The low mass ions in plasma extracted during the first few microseconds of discharge process are mainly O^+ (*m*/*z* 16), C^+ (*m*/*z* 12), O^{2+} (*m*/*z* 8) and C^{2+} (*m*/*z* 6). The instrument we have described can be a valuable diagnostic tool for high energy ion beam composition. It can be used both in fundamental research and in technological applications such as ion implantation.

1. Introduction

Vacuum arc discharge has been investigated and utilized extensively during the last two decades, for ion source developments [1–6]. Vacuum arc ion sources and ion implantation facilities based on these kind of discharge have been developed in scientific centers of many different countries around the world [7–12] including Lawrence Berkeley National Laboratory, Berkeley, CA and the High Current Electronics Institute, Russia. Vacuum arc ion sources were used in a range of applications including ion implantation for materials surface modification, particle accelerator injection for fundamental nuclear physics research, and other applied purposes [4,5,11–17]. Recent experiments with sophisticated diagnostic methods have revealed the existence of multiply stripped ion constituents in the plasma, formed by the vacuum arc [3,18,19]. Time-of-flight mass spectrometer (TOF MS) as one of rapid detection tools has been widely used in plasma diagnostics. A TOF experimental setup was used by Nikolaev et al. for measuring the angular distribution of ions formed in the vacuum arc ion source plasma and for diagnostics of upgraded vacuum arc ion source [1,7]. Oztarhan et al. have built a vacuum arc ion source based metal ion implantation facility equipped with TOF for measuring the charge state distribution of ions [13,20]. It is worth mentioning that, an improved TOF MS system for vacuum arc source was described firstly by Brown et al. in 1987 [17], and he had done a lot of work for analysis of ion beam produced by the metal vapor vacuum arc (MEVVA) ion source using TOF MS [3,6,17,18,21].

We summarized different designs of the linear time-of-flight mass spectrometer used in combination with vacuum arc ion source. The length of drift tube is 1–2.5 m generally. Ion gate with narrow pulse was used in order to chop ion beam accurately. There are many kinds of ion gate structures reported in the literatures. In the most cases the gate of the analyzer consists of five pairs of axially symmetric metal rings or short tube sections, the electrodes are spaced 1 cm apart along the axis. This design was referred to as concentric rings ion gate, which is applied a pulse of up to 5 kV with duration of ~100 ns [22]. And in other case, a pair of parallel plates spaced by 4 mm was used as the spectrometer gate. Deflecting voltage pulse of up to 1 kV with duration of ~150 ns and rise time of 25 ns was applied between the ion gate plates [23]. Such a system is no longer a device for measuring the ion beam parameters only but it can be used to diagnose any plasma. Even so the general linear

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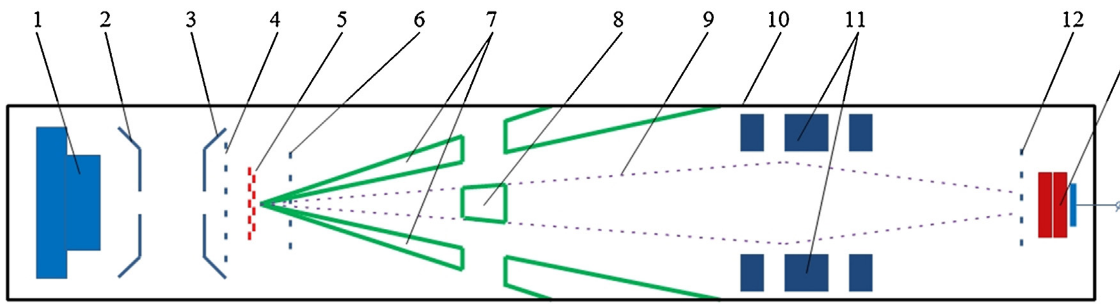

Fig. 1. Simplified schematic of the linear time-of-flight mass spectrometer. (1 – plasma source, 2 – emission electrode, 3 – collimating aperture electrode, 4 – shielding grid before-ion gate, 5 – ion gate, 6 – shielding grid after-ion gate, 7 – deflected ion beam, 8 – ion beam without deflection, 9 – trajectories of detected ions, 10 – drift tube, 11 – einzel lens system, 12 – before-MCP grid, and 13 – MCP detector).

TOF MS used for vacuum arc ion source discharge could not distinguish isotopes of some metal elements or multi-charged ions well enough because of low resolution. There are several factors limiting the mass resolution performance:

(1) High energy ion beam with wide space and energy spread is hard to adopt by ion optical system.
(2) The structure of the ion gate and the characteristics of the high voltage pulse applied to the ion gate have a significant impact to accurately form the ion bunch.
(3) The proper choice of the field-free drift tube length helps both to separate low-mass component ions effectively and also to detect high-mass component ions before they could be scattered too far because of their initial energy divergence.
(4) The fast ion detector which forms quite narrow pulse ions signal plays important role.

The performance improvement of the instrument can greatly extend the application range of this kind of spectrometers. The paper describes principle of operation, design features, parameters and performance of the linear time-of-flight mass spectrometer for studies of ion composition of plasma generated by a plasma discharge source.

2. Design and principle of the instrument

2.1. Structure of the instrument

The simplified schematic of the linear time-of-flight mass spectrometer is shown in Fig. 1. The instrument comprises two-electrode ion extraction system, ion gate, drift tube, einzel lens system and MCP detector. High energy plasma is generated by test source based on a hollow cathode discharge principle. Acceleration of the ion beam occurs at the edge of the plasma source via +40 kV DC accelerating voltage applied to the source 1 relatively to the ground. Ions are extracted from the plasma through 10 mm ID apertures in emission electrode 2 and collimating electrode 3.

The design of the ion gate 5 consists of two sets of parallel, interleaved wires fixed in the plane perpendicular to the ion beam axis. At mean time there are two grids (shielding grid before-ion gate 4 and shielding grid after-ion gate 6) set for electric field shielding. Use of this gate designs is an effective way to form short ion bunches. These devices require lower voltages, can be more compact and exhibit lower capacitance than an alternative like a pair of deflection plates. In case one set of wires is kept at ground potential while the voltage is applied to another set of wire, the ions are deflected by an angle α as defined in Fig. 2(a). Once identical potential is applied to both sets of wires, generally chosen to coincide with the beam line ground potential, the gate is open and most of the ions penetrate undisturbed (see Fig. 2(b)). The deflection angle α for round wires is given by Eq. (1) [24–26]:

$$\tan\alpha = \frac{\pi}{2\ln(\cot(\pi R/2d))} \times \frac{V_{wire}}{E_{kin}/q} \quad (1)$$

The deflection angle depends on the wire diameter $2R$, the distance between wires d and the ratio of voltage applied to the wires V_{wire} over the ion's kinetic energy E_{kin} and the ion charge state q. α decreases when the ion is in the vicinity of the gate's electric field while the potential is switched. Depending on the requirements of the system these parameters can be set so that the ions are deflected in such a way that they cannot reach the detector area (a state referred to as gate closed in this paper). Deflected ions are deposited laterally from the beam line. Our ion gate photograph is shown in Fig. 2(c). Stainless steel wires are winded on the ceramic substrate. The deflecting pulse voltage can be adjusted from 0 kV to 10 kV with duration of ~100 ns and is applied between two sets of wires. Due to relatively short deflection time compared to the ion transport time, the ions in the drift space are separated by their velocities which are proportional to $\sqrt{2U/(m/q)}$, where m and q are the ion's mass and charge, and U is a constant accelerating voltage.

2.2. TOF mass analyzer

All electrodes of ion-optic system and ion gate are aligned coaxially with horizontal axis of the drift tube 10, einzel lens system 11 and MCP detector 13 (with a before-MCP grid 12 for electric field shielding) as shown in Fig. 1. The mass spectrometer path length (the drift tube length) is 1.5 m. This flight length for the ions with energy in the range of several tens of keV was chosen from simulation results. It is an optimal compromise between the spectrometer compactness and resolution. Meanwhile the interference between high voltage pulse noise and low m/q ion signal was excluded by this choice. In the open mode all electrodes of ion-optic system and the drift tube are connected to the ground but the plasma source is biased to the total accelerating potential with respect to the ground. The accelerated ions separated by mass-to-charge ratio reach MCP detector with diameter of the effective area 10 mm, which is biased to −1.3 kV from the ground. The output detector signal is proportional to the ion current corresponding to the mass-to-charge ion composition of the plasma. Using MCP detector one should take into account the dependence of the ion-electron emission coefficient γ on the ion energy. This dependence can affect measurement results when the plasma contains a considerable fraction of different ions. The presence of stray capacitances in the detector circuits increases width and decrease current peak amplitudes of the ion beam components. The technical solutions used to diminish this problem involved optimization of the electrodes structure in the TOF mass analyzer (such as round corner machining, the adjustment of their material, size and thickness), arrangement of additional shielding