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High-voltage scanning ion microscope: Beam optics and design

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ABSTRACT

This article is devoted to the conceptual design of a compact high-voltage scanning ion microscope (HVSIM). In an HVSIM design, the ion optical system is based on a high-brightness ion source. Specifically, the ion optical system is divided into two components: an ion injector and a probe-forming system (PFS) that consists of an accelerating tube and a multiplet of quadrupole lenses. The crossover is formed and controlled by the injector, which acts as an object collimator, and is focused on the image plane by the PFS. The ion microprobe has a size of 0.1 μm and an energy of 2 MeV. When the influence of the chromatic and third-order aberrations is theoretically taken into account, the HVSIM forms an ion microprobe.

1. Introduction

A conventional nuclear microprobe operates in combination with accelerators developed for nuclear physics experiments, which produce intense, but not necessarily bright, ion beams. Therefore, there is weak matching between the accelerator beam optics and the optics of the microprobe-forming systems (MPFS). The need for specialised microprobe facilities with resolutions of less than 100 nm for microscopic techniques that involve quantitative analysis and less than 10 nm in low-current mode was previously discussed in [1,2]. It was noted that such a nanoprobe should be a specific and fully optimised instrument. Currently, design work has begun on a compact nuclear microprobe at the Japan Atomic Energy Research Institute and at the Institute of Applied Physics of the National Academy of Sciences of Ukraine. In [3–5], the results of theoretical and experimental studies on this compactly designed system, which includes an injector based on a specialised duoplasmatron-like ion source and a 300 keV electrostatic accelerator, are presented. Another concept for a compact nuclear microprobe design is proposed in [6]. Here, the beam is extracted from the ion injector and formed by the object and angular collimators, and it is then focused by a quadruplet of magnetic quadrupole lenses onto a target. In [6], the calculation method for the immersion ion-optical system is based on a matrizant method [7]. The disadvantage of this design is that a system of collimators is located under the high-voltage terminal. Because of erosion of the collimator walls at a beam energy of approximately 10 keV, the operation of the system becomes more complicated. To overcome this problem, several approaches have been adopted from beam optics, namely, the scanning electron microscope approach, in which the object is a crossover point formed by an electron gun. In this case, the crossover size can be reduced by varying the voltage on the Wehnelt cylinder. However, this increases the beam divergence. Usually, a circular aperture, which limits the divergence angle, is used to reduce the influence of spherical aberrations. However, there is an essential difference between the optics of an accelerator-based nuclear microprobe and those of a conventional electron microprobe; the high magnetic rigidity of an MeV ion beam means that strong focusing lenses, such as quadrupole lenses, must be used in nuclear MPFS. Therefore, the task is to develop a quadrupole probe-forming system (PFS) with characteristics similar to those of an axially symmetric lens system. In such a case, the PFS optics will be aligned with the optical properties of the injector and accelerator. Such a construction of an ion optical system will yield a high-voltage scanning ion microscope.

The main tasks were as follows:

- to consider a compact microprobe design,
- to examine the possibility of replacing the object collimator with a crossover of a manageable size,
- to determine the aperture effect on the formation of the initial phase space of the beam at the output of the accelerating tube, and
- to determine the ion-optical parameters (especially the size of the crossover and the angular aperture) for a probe with a 0.1-micron spot size on the target.

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2. Requirements for the ion injector of the dedicated accelerator

There are many scientific tasks that require a high-brightness ion source to improve the spatial resolution of the nuclear microprobe. However, we must remember that the brightness of such a source is determined by two values: (a) the emission current density I_s, which is determined by the area of the emitting surface, and (b) the angular current density I_Ω, which is determined by the divergence angle of the ion beam. From Table 1, taken from [8], it is evident that a liquid metal ion source (LMIS) and a gas field ion source (GFIS) both exhibit high brightness because of the considerable decrease in the emission area.

However, these sources exhibit very low angular density because of the large divergence angle of the beam. Therefore, the use of these types of sources is complicated; this difficulty is associated with the poor agreement of the beam parameters with the optics of the accelerating tube as a result of spherical aberrations [9]. By contrast, a plasma ion source (PIS) has a considerably larger emission area and a higher angular density, which reflects the small divergence angle of the beam. Thus, plasma ion sources are more suitable for use in high-voltage scanning ion microscope (HVSIM) injectors, if injectors with aberration correctors are not considered. The main requirements for an ion injector are the following: an emission aperture with a diameter d_s of less than 100 μm, a divergence angle at the output of the source (at an energy of 100 eV) of less than 1 mrad, a beam energy spread ΔE on the level of several eV, an ion-optical system with a low aberration coefficient and variable demagnification up to 100, a beam current of approximately 10–100 nA, and a beam energy at the output of approximately 20 keV. A design that satisfies these requirements has been described in [3,10].

3. The design of the HVSIM ion optical system

Structurally, the HVSIM consists of several components (Fig. 1).

The first component is the ion injector (1). The primary task of the injector is the formation of a crossover point of a given size at the entrance to the accelerating tube for the ion beam, which has an energy of a few tens of keV. The crossover point is the object of the PFS, and therefore, no object collimator is necessary. In the accelerating tube (2), the beam is accelerated up to an energy of a few MeV.

The doublet (4) and triplet (6) of quadrupole lenses, with four independent power sources, are located after the accelerating tube. Previously, a similar system was considered in [11]. The use of four independent power supplies in the pentuplet of magnetic quadrupole lenses allows us to implement a PFS with aberrations and demagnification coefficients that have nearly identical values in both the xOz and yOz planes. This allows us to achieve better alignment of the optical properties of the injector (1) and the accelerating tube (2), which are axisymmetric, with those of the quadrupole optics pentuplet, which generally does not possess axial symmetry. The fabrication of the doublet and triplet of magnetic quadrupole lenses from a single piece of soft iron ensures the exact alignment of the lenses and simplifies their adjustment. The scanning system (5) is located between the multiplets (4 and 6). This scanning system arrangement reduces the required working space.

Table 1
Typical parameters of various source types [8].

	d_s (nm)	ΔE (eV)	$\Delta I/\Delta\Omega$ (μA/sr)	B (A/cm^2 sr)
PIS	5×10^4	5	3×10^3	10^2
LMIS	50	5	20	10^6
GFIS	1	1	0.1	10^7

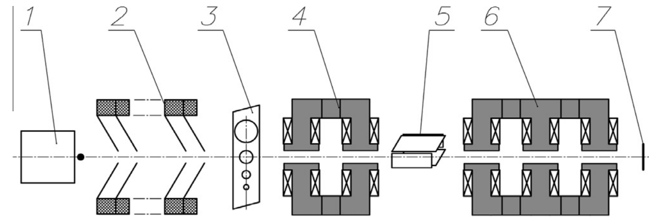

Fig. 1. The configuration of the ion-optical system. (1) – Ion injector, (2) – accelerating tube, (3) – set of angular apertures, (4) – magnetic lens doublet, (5) – scanner, (6) – magnetic lens triplet, (7) – target.

4. Formation of the initial phase volume at the entrance of the HVSIM

As in any other PFS, a beam with a certain phase volume is focused into a spot of a specified size. The divergence angle and beam size at the crossover are the parameters that determine the value of the phase volume. Therefore, it is necessary to control the beam size and divergence angle at the crossover point to obtain a probe of a specified size on the target. Both the crossover size and the divergence angle can be controlled by changing the electrode potential of the injector before the accelerating tube. As a consequence of Liouville's theorem, it is impossible to resize the crossover and the divergence angle of the beam independently. A decrease in the crossover size causes the divergence angle to increase proportionally. In the list of requirements for the ion source, we stated that the emission aperture must have a diameter of approximately 100 μm and a half divergence angle of approximately 1 mrad. Then, the emittance will be approximately $e_0 \approx 100 \times 2 \approx 200$ μm × mrad. As the beam is accelerated from the initial energy of $E_0 = 100$ eV to the final energy of $E_f = 20$ keV, the emittance will decrease as the square root of the ratio of these energies, $e_f = e_0/\text{sqrt}(E_f/E_0) \approx 200/14 \approx 14$ μm × mrad. After the injector, the beam size at the crossover is 10 microns. Thus, the angle of divergence is 14/10 = 1.4 mrad. This requires the divergence angle to be limited by the aperture. The placement of an angular collimator in front of the accelerator is undesirable because of the erosion of the collimator walls that will occur at a beam energy of approximately 10 keV. Additionally, in this case, the angular collimator would be subjected to the acceleration voltage. The most appropriate location for the collimator is the gap between the accelerating tube and the first lens multiplet, as shown in Fig. 1. In this case, the beam will still retain axial symmetry in this region, thereby allowing for the application of a circular aperture. The small aberration value of the accelerating tube simplifies the relation between the aperture size and its effect on the

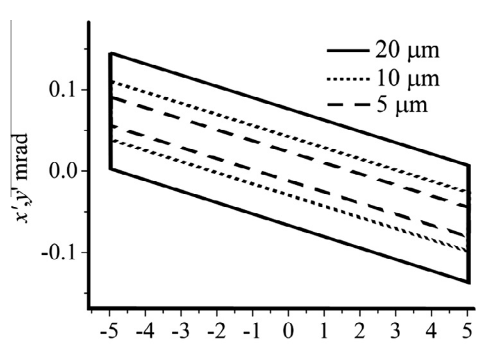

Fig. 2. The acceptance in the plane of the object crossover of the "accelerating tube-aperture" system for various diameters of the aperture behind the accelerating tube.