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Design and construction of an electrostatic quadrupole doublet lens for nuclear microprobe application

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ABSTRACT

An electrostatic quadrupole doublet lens system has been designed and constructed to provide strong, mass-independent focusing of 1–3 MeV ions to a 1 μm^2 spot size. The electrostatic doublet consists of four sets of gold electrodes deposited on quartz rods that are positioned in a precision machined rigid frame. The 38 mm electrodes are fixed in a quadrupole doublet arrangement having a bore diameter of 6.35 mm. The coating process allows uniform, 360° coverage with minimal edge defects. Determined via optical interferometry, typical surface roughness is 6 nm peak to valley. Radial and coaxial alignment of the electrodes within the frame is accomplished by using a combination of rigid and adjustable mechanical supports. Axial alignment along the ion beam is accomplished via external manipulators. COMSOL Multiphysics® v5.2 and Propagate Rays and Aberrations by Matrices (PRAM) were used to simulate ion trajectories through the system.

1. Introduction

This paper describes a novel design of electrostatic quadrupole lenses that are aligned in two stages: outside and inside the beamline. Techniques used in this design employ precision machining and some of the smoothest electrode surfaces achievable at a fraction of the cost and bulk of most microprobe focusing systems. The electrostatic doublet described in this paper is positioned upstream of the Louisiana doublet [1] at the University of North Texas (UNT) microprobe; although it uses the existing beamline and slit arrangement, it is currently being tested independently of the magnetic lenses.

This doublet is a prototype design of a future orthomorphic design consisting of three or more lenses and a shorter working distance. This future iteration is expected to produce smaller spot sizes and greater acceptance while maintaining most of the design, construction, and alignment procedures presented in this paper.

1.1. Microprobes

Ion beam microprobes for 1–3 MeV protons are widely used in research fields such as biology, geology, environmental sciences, material science, and several other fields [2–4]. Typical microprobe systems use between two and five magnetic quadrupole lenses to produce ~1 μm^2 beam spot sizes [5–8]. More recently, sub-30 nm spot sizes have been reported [9]. The quadrupole arrangement provides strong focusing of the ion beam in a direction (x) orthogonal to the beam axis while defocusing in the other orthogonal direction (y) [10]. For this reason, at least 2 quadrupole lenses must be used to focus an MeV ion beam to a symmetric spot on a plane orthogonal to the ion beam axis [10].

Typical ion microprobe systems consist of two sets of slits, drift spaces, and focusing elements. The object slit is used to define the object of the imaging system. After a long drift space, the divergence slit limits divergence of the beam. Focusing elements consist of lenses such as magnetic quadrupoles, electrostatic quadrupoles, a super conducting solenoid, a plasma lens. The object aperture is demagnified and projected onto the target plane [10].

Typical applications of ion beam microscopy involve magnetic rastering of an MeV beam of light ions (H or He) across a few square millimeters of a target to gather spatially resolved data from various ion-target interactions. Common microprobe analyses include particle induced X-ray emission (PIXE), Rutherford backscattering spectroscopy (RBS), scanning transmission ion microscopy (STIM), Nuclear reaction analysis (NRA), ion beam induced charge (IBIC), ion beam induced luminescence (IBIL), and other analyses [10].

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1.2. Magnetic focusing: pros and cons

Within the microprobe community, magnetic quadrupole lenses provide the most common method of beam focusing [1]. The prevalence of magnetic systems is likely due to the relative simplicity of precision machining iron and the advantage of positioning the yoke outside the beam tube. Probably one of the most significant disadvantages of magnetic microprobe systems arises from the mass-dependent nature of magnetic focusing [10]. The magnetic field required to focus an ion beam increases as projectile ion mass and energy increases. Eventually the ferromagnetic material in the poles reach magnetic saturation, thereby limiting the ability to focus heavier ions without the utilization of superconducting materials or lengthening the magnets [10]. Magnetic saturation of the yoke limits the feasibility of typical microprobes to fairly light ions ($Z = 1 \simeq 14$) for micron or sub-micron spot sizes [1]. The quadrupole magnetic field required to focus an ion of mass M is given by Eq. (1).

$$\frac{B}{B_p} = \frac{1}{q}\sqrt{\frac{ME}{M_p E_p}} \quad (1)$$

Eq. (1): Magnetic pole tip field (B) ratio to focus an ion beam relative to the field required to focus a proton beam (subscript p) of the same energy. Charge state (q) is linearly related, while mass (M) and energy (E) have exponential relations.

Minimum spot size limitations are also dependent on the distance between opposing pole tips, length of quadrupole lenses, energy of the ion beam, working distance, aberrations of the lens, and energy resolution of the accelerator producing the beam [10]. These quantities are quantifiable and discussed in the Results section.

Another issue with magnetic lenses and the relatively large currents required to focus a micron-sized beam is resistive heating. Magnetic quadrupoles use on the order of 50 A to focus a 3 MeV proton to a spot size on the order of 1 μm. Thermal expansion of the iron yoke can cause the focusing arrangement to shift out of alignment.

1.3. Electrostatic focusing: pros and cons

Electrostatic quadrupole lenses have the distinct advantage over magnetic lenses in that they are capable of focusing ions independently of mass (Eq. (2)) [10]. However, while the mass independence of these systems is an attractive feature, other design and operational feature considerations have prevented electrostatic systems from becoming widely utilized. As beamlines are usually metallic, Gauss' law dictates that the electrodes producing the focusing quadrupole fields must be inside the stainless steel beam tube [11]. This creates significant difficulties in aligning such a lens in situ. Electrical arcing due to high electric potentials can limit attainable fields, and in consequence, focusing power.

$$\frac{V}{V_p} = \frac{1}{q}\frac{E}{E_p} \quad (2)$$

Eq. (2): Electrostatic pole tip field (potential, V) ratio to focus an ion beam relative to the field required to focus a proton beam. Notice the mass independence and the linear relation of all variables.

Another disadvantage of an electrostatic microprobe is that chromatic aberrations are more severe than in magnetic microprobes [10]. The nature of this relationship is evident when comparing the linear dependence of ion energy in the electrostatic case to the exponential dependence of energy in the magnetic case seen in Eqs. (1) and (2). Note that Eqs. (1) and (2) are for lenses of the same length.

To mitigate this effect, the National Electrostatic Corporation (NEC) 9SH Pelletron at The University of North Texas (UNT) has upgraded the accelerator by installing a capacitive liner [12]. The liner reduces voltage ripple on the terminal from 387 V_{rms} to 85 V_{rms} at 2.5 MV. This upgrade is expected to improve the minimum spot sizes for both magnetic and electrostatic microprobes.

1.4. Present state of microprobes

Quadrupole microprobe systems consisting of magnetic [1,5,6,13–16] and electrostatic [15,17–22] lenses have been designed and optimized by several accelerator groups using similar finite element analysis (FEA) software and matrix techniques. Most magnetic quadrupole focusing systems report minimum spot sizes around 1 μm^2 [10]. However, a few groups report sub-100 nm MeV ion resolution [9,23]. Only a few electrostatic microprobe systems capable of micron (0.8 μm–20 μm) resolution have been developed. High Voltage Europa developed a commercially available system capable of producing a resolution of approximately 6 μm while the Columbia electrostatic microprobe achieved sub-micron (0.8 μm) resolution [17,18].

1.5. Electrostatic doublet at the University of North Texas

This is a report on design and construction parameters for an electrostatic quadrupole focusing system using unconventional methods and materials. The doublet consists of a precision machined stainless steel frame and 4 quartz rods with thermal evaporated electrodes. Each rod has 2 consistently spaced, coaxial electrodes on some of the smoothest available rod. By design, both lenses of the doublet are aligned with each other upon assembly. This design allows alignment of the lens to be performed in two parts: electrode alignment, which is done under a microscope, and doublet alignment, which is done on the beamline. Intrinsic to the design of the doublet, rotational alignment is fixed. Eliminating rotational misalignment of a quadrupole focusing system minimizes a dramatic second-order parasitic aberration [24]. This technique simplifies one of the greatest challenges of optimizing an electrostatic microprobe, alignment.

Aside from obtaining a focusing system suitable for heavy ion microscopy, the goal of developing the electrostatic doublet discussed in this paper was to test the design and determine the feasibility of producing a combined focusing system consisting of more than two lenses using the coaxial electrode and electron discharge machined frame technique. This design will produce a smaller spot size (or greater beam current) while mitigating the effects of spherical aberration by confining the beam close to the lens axis throughout the focusing system. The electrostatic microprobe will be used for several heavy ion research applications including one pending grant funding involving spatially resolved RBS of fissile isotopes.

2. Materials and methods

The electrostatic doublet was designed according to the matrizant calculations of Alexander Dymnikov [19] and simulated in COMSOL Multiphysics® V5.2, and Propagate Rays and Aberrations by Matrices (PRAM) [10]. COMSOL is capable of modeling an enormous variety of devices and processes and is suitable for simulating ion beam focusing. PRAM is specifically for microprobe application and quantifies system parameters such as demagnification and aberration coefficients belonging to the transfer matrices of various beamline elements [10].

The doublet was constructed with four quartz rods, each of which having two coaxial sections coated with a bonding layer