COMPUTER CALCULATIONS OF A SOLENOID LENS
FOR FOCUSSING MEV PROTON BEAMS

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ABSTRACT

A superconducting solenoid lens for focussing proton beams up to 5 MeV to the order of one micron is installed on a scanning proton microprobe facility. The expected performance of the lens including the effect of the spherical, chromatic and mechanical aberrations on the resolution and throughput, studied by ray trace computer calculation is described.

The recent interest in developing a scanning proton microprobe (SPM) is prompted by its advantages over the well developed scanning electron microprobe (SEM) such as its high sensitivity to trace elements or its capability of in air analysis of hydrated or even live samples (1). The resolution of one micron is practical and important in the elemental analysis of biological samples in air. Hitherto, the magnetic quadrupole lenses have been used in SPM facilities (2,3) to focuss a few MeV proton beam to a few microns level.

Simple solenoids have not previously been used for focussing heavy ions principally because the thin lens requires an order of magnitude higher magnetic fields for focussing than does the analogous quadrupole lens. A 2 MeV proton has the same momentum, hence magnetic rigidity, as a 61 MeV electron and conventional magnetic solenoids cannot produce sufficient field strengths to give the short focal lengths desired for a focussing system. On the other hand,a state of the art superconducting solenoid can produce fields more than ample for the present application.

The focussing system is installed on a beam line of MIT-Lincoln Lab. 4 MeV Van de Graaff generator. A shematic view of the beam optics is shown in Fig.1. The object and image distances measured from the center of the lens, are 405 cm and 16 cm respectively, with the implication of a demagnetization of 25. The actual size of the solenoid coil is shown in Fig.2. A maximum field of 6.5 Tesla on the axis is attainable for 23 A.

Calculations were performed using a ray trace program (4), in which a subroutine to calculate the magnetic fields of a sheet solenoid coil was replaced by one to calculate the fields of a thick coil by the method of Garrett (5). The field distribution on the axis is shown in Fig.2. The ray trace results are as described below.

Results and Discussions

Detailed calculations were performed for 2 MeV protons, a commonly used energy in PIXE, under the geometry shown in Fig.1. The spherical aberration constant C_S defined by

$$\rho_s = MC_s\theta_{in}^3 + MC_s'\theta_{in}^5 + \ldots$$

is 3.08 x 10^7 cm, where ρ_s is the radius of the aberration disk at the gauss plane with the demagnification M and θ_{in} is the incident angle spread. For an image with diameter, d, the optimum object radius and limiting angle spread are proportional to d and $d^{1/3}$, respectively, so the throughput is proportional to $d^{8/3}$. In order to get a 1 μm diameter beam spot with the maximum throughput for the geometry shown in Fig.2, the object diameter must be limited to 19 μm and the angle spread must be limited by an appropriate aperture to ± 0.34 mr.

The effect of the chromatic aberration was estimated separately. The chromatic aberration constant C_{ch} defined in terms of the image radius, ρ_{ch} as

$$\rho_{ch} = MC_{ch}\,\theta_{in}\cdot(E - E_o)/E_o$$

is 9.41×10^3 cm at E_o = 2 MeV and with the same lens parameters. For example, the energy spread of 0.1 % deteriorates a 1 μm beam, effectively to a 2 μm beam.

The optimum intensity of the 1 μm dia. beam is expected to be more than 0.1 nA for the incident beam of 100 μA with the emittance of $\pi r\theta_{in} \sim 0.25\pi$ cm·mr. Such a focussing ability and other advantages—simplicity of design and operation, rapid change of focal length—make the superconducting lens a strong contender for ion beam focussing applications. More detailed description will be found elsewhere (6).

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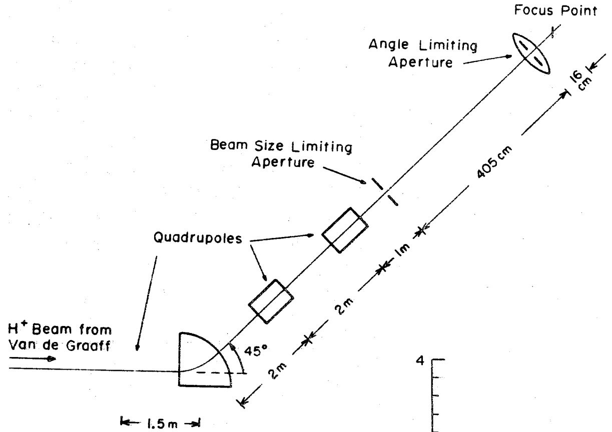

Fig.1. A shematic view of the beam optics.

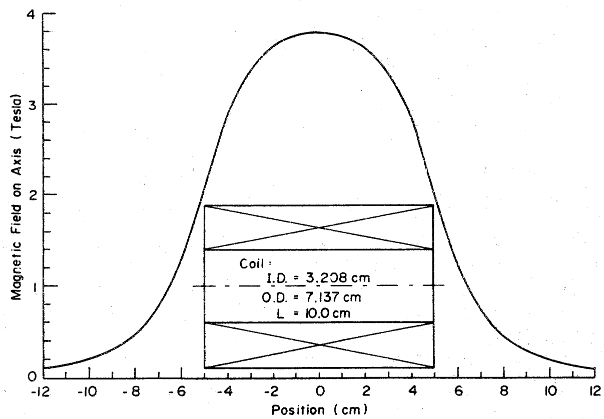

Fig.2. Calculated magnetic fields on the axis of the coil.

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