ION-OPTICS SYSTEMS OF MULTIPLY CHARGED HIGH-ENERGY IONS FOR HIGH EMITTANCE BEAMS

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Methods are presented for the calculation of high-emittance ion-optics systems based on magnetic quadrupole lenses for beams of protons and heavy ions with energies from 1 to 10 Mev/nucleon. The strong focusing of the system makes it possible to form beams with linear dimensions less than 0.1 mm. The system for increasing the deflection triples the deflection angle of the beams during scanning. The systems are designed for use with beams from the cyclotron at the A.F.Ioffe Physical Technical Institute of Russian Academy of Sciences, St.-Petersburg.

INTRODUCTION

The development of technological processes based on the use of beams of protons and heavy ions accelerated to energies of 1 to 10 Mev/nucleon, as well as the use of such beams for determining the elemental composition of samples and elemental concentration profiles have stimulated the development of ion-optics systems that form high-energy beams of various configurations. Quadrupole magnetic lenses (QML) are the heart of such systems now. The literature on the basic principles of QML calculation and operation is quite extensive (see, for example, [1,2]). The chief lines of investigations now are optimization of experiments and widening the scope of exploiting of accelerators with high emittance ion beams. Both of these problems have risen during creation of microprobe and nuclear track membrane equipment for our cyclotron.

An analysis shows that the most convenient ion-optic systems that solves these problems are triplet or quadruplet of QMLs. We have derived a system of algebraic equations for the calculation of parameters of the triplet and the quadruplet that provide stigmatic operation. In the thin-lens approximation the system of equation for triplet has the form

$$f_2^2[f_1^2 L(L-g) - a^2(s_1+s_2)(L-a)]$$
$$+ f_1 f_2 a[-L s_1 s_2 + 2 s_2 (a+s_1)(s_2+g)$$
$$+ s_1 s_2 (a+s_1-s_2-g)] - f_1^2 s_2 (a+s_1)^2 (s_2+g)$$
$$+ a^2 s_1^2 s_2 (s_2+g) = 0,$$
$$f_3 = \frac{g[-f_1 s_2(a+s_1) + f_2 a(s_1+s_2)]}{a s_1 (s_2+g) - f_1 f_2 L}.$$

Here a is the distance from the source of charged particles (or its preliminary image - PI) to the center of the first lens, s_1 and s_2 are the distance between the centers of the first and second and the second and third lenses, respectively; g is the distance from the center of the third lens to the target, $L = a + s_1 + s_2 + g$ is the total length of the system, and f_1, f_2, and f_3 are the absolute values of the focal lengths of the first, second, and third lenses, respectively.

SCANNING UNIT

The nuclear track membrane production implies uniform irradiation of thin (10 μm) wide (35 cm) film by Ar ions of 40 MeV energy. A transport mechanism advances the film with velocity of 2 - 15 cm/sec, so that the high frequency scanning system is required in another direction.

In scanning a beam in one direction it is possible to arrange the QMLs in such a way that the system, in adding to focusing the beam, which can be scanned at any frequency, also increases the deflection severalfold. This property of lenses is due to the diverging action in the lens and has been previously used in the design of some electron-beam device [3]. The necessary condition for increasing the deflection is that the diverging plane of the last lens coincide with the plane of deflection. The deflection element must be placed in front of the last lens, and therefore a property of these systems is that the distance between the last and the next-to-last lenses is large. As a rule the beam is focused between these two lenses in a plane perpendicular to the deflection plane; i.e., a linear focus is obtained.

The parameters of two systems we have calculated: a triplet and a quadruplet. They increase the deflection by a factor of about three. The beam entering the lenses was in our case astigmatic, with the distance $a = 3400$ mm in the deflection plane and $a = 2250$ mm in the perpendicular plane. The other parameters for triplet were $s_1 = 590$ mm, $s_2 = 3070$ mm, $g = 4900$ mm. The beam was focused on the target in both planes, i.e., it was stigmatic at the exit from the system. The focal length of the QMLs were, respectively, $f_1 = 761$ mm, $f_2 = 935$ mm, and $f_3 = 1147$ mm. The identical lenses were used, so that their ratios of the number of ampere-turns was 1.50 : 1.23 : 1.0, respectively.

Fig.1 shows a diagram of the path of an undeflected beam in the triplet, where the solid lines represent the beam in the deflection plane and the dashed lines represent it in the perpendicular plane (C means converging, D - diverging). The deflection system was located in front of the third lens, with the distance between the center of deflection and center of this lens equal to 1970 mm.

The deflector is a parallel-plate capacitor 60 cm length (about 100 pf). Voltage amplitude about 40 kV is necessary for our conditions. An inductive coil were added (20 - 200 μH) to create resonance circuit with Q-factor 500 and to use only 1 kW output generator. The resonance frequency can cover 100kHz - 2MHz. To compensate of non-uniform irradiation due to sinus law of scanning the amplitude modulation of voltage was used.

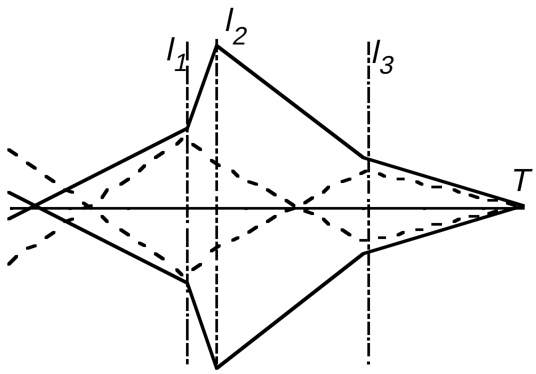

FIG.1 Trajectories in the triplet with increased deflection. Solid lines, the DCD plane (the deflection plane); dashed lines, the CDC plane; dot-dashed line, centers of the lenses; T - target.

For increase the angle of capture of the beam by the lens system we used also a forth quadrupole lens. It was placed in front of the first lens of triplet, with the distance between the center of the first lens and the center of the additional lens equal to $s_0 = 1100\,\text{mm}$ (Fig.2). The geometric parameters of the triplet were kept the same, and in order to maintain the increased deflection the excitation of the last lens was not changed. With optimization of this system it gave the following results. The angle of capture of the beam in the deflection plane could be increased by factor of 1.3 to 1.5. The focal lengths of the QMLs were $f_0 = 2300\,\text{mm}$, $f_1 = 731\text{mm}$, $f_2 = 992\text{mm}$, and $f_3 = 1147\text{mm}$ (the subscript 0 refers to the additional lens). The ratios of the ampere turns of the lenses were of 0.5 : 1.57 : 1.17 : 1.0.

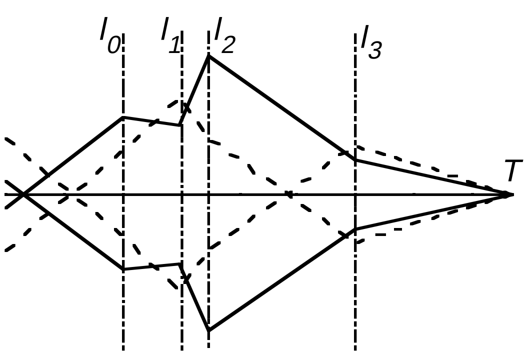

FIG. 2. Trajectories in the quadruplet with increased deflection. Solid lines, the CDCD plane (the deflection plane); dashed lines, the DCDC plane; dot-dashed line, centers of the lenses; T - target.

MICROPROBE UNIT

The lens system forming the microprobe must be located close to the target in order to operate with large linear demagnification. In this arrangement, however, the beam losses a great deal of intensity, particularly if it has a high emittance.

We have found a compromise that gives a probe with a spot size that does not exceed 0.1 mm. The intensity losses can be 96 - 98%. If we take into account the actual intensities of the beams from the cyclotron and the limitations of the permissible current density in the microprobe, this coefficient of use the beam is entirely warranted. In this triplet design the distance L was 5000 mm. The distance a was chosen to be 4626 mm, the distances $s_1 = s_2 = 132\,\text{mm}$, and $g = 110$ mm. The focal lengths were $f_1 = f_2 = 98\text{mm}$ and $f_3 = 65\,\text{mm}$. This system provides a demagnification factor of 86 in the CDC plane and 24 in the vertical DCD plane. For lenses with a pole length of 100 mm, an aperture radius 10 mm, and pole faces close to hyperbolic, the required field strength at the poles of the first and second lenses is 3500 Oe, and for the third lens it is 5400 Oe for focusing protons with an energy of 7 MeV.

CONCLUSION

Two important problems in formation and control of high-energy ion beams of large initial emittance have been examined. The systems that focus ion beams down to the level of a microprobe and systems that provide effective scanning by means of essential increase in deflection angle have been designed.

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