Beam Optics Design for the ISAC Off-Line Source

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1 Abstract

This note summarizes the beam optics of the short beamline connecting the off-line source with the LEBT. The section is comprised of an electrostatic triplet to radially focus the diverging beam from the source onto a slit, a dipole magnet and selection slit for mass selection, and a second electrostatic triplet section to match the beam to a periodic LEBT section.

2 Introduction

A stable off-line source is required to :

- commission the accelerators after installation
- tune the accelerators in preparation for radio-active beam during routine operation
- supply the low-energy area with stable beam

The source must first and foremost be able to supply sufficient quantity of stable isotopes covering the operating accelerator mass range from A=6 to A=30. In addition the production of higher masses of stable ions may be of interest to the experimenters in the low energy area. A 2.45 GHz micro-wave cusp source has been chosen to supply the stable beam.[1] The beam will pass from the source through an analyzing system to select the ion of choice, be transported and bunched in the LEBT and then injected into the RFQ. A schematic drawing showing the layout of the off-line source, beam-line components and RFQ is shown in Fig. 1.

3 Beam Optics

The transport of the beam from the off-line source to the RFQ comprises two basic sections; the matching/analyzing section from the source to the low energy beam transport (LEBT) and the LEBT itself which transports the beam to the RFQ. Since the LEBT has been previously defined [2] the matching/analyzing section must be designed to match the input requirements of the LEBT. The matching analyzing section will require three separate subsections:

- a focussing section to grab the diverging beam from the source and focus the beam horizontally onto horizontally defining slits
- an analyzing magnet with sufficient resolution to resolve the masses of interest
- a matching section from final slit to LEBT

3.1 Analyzing Magnet

The simplest analyzing magnet system is comprised of a bending magnet with entrance and exit faces normal to the beam path and with a uniform field B. This magnet provides a focus only in the bend plane. Either a circular pole magnet or a wedge magnet can be considered. The ions are deflected through an angle θ with a radius of curvature ρ. For non-relativistic particles

$$B\rho(kG \cdot cm) = \frac{A}{0.3Z}\sqrt{2 \cdot \frac{T(MeV)}{A} E_o(MeV)}$$

where A is the number of nucleons and Z is the charge on the ion, T/A is the kinetic energy per nucleon and E_o is the proton rest energy. The RFQ is specified to accept ions of mass $6 \leq A \leq 30$ with input energy T/A=2 keV/nuc. This sets the required range of magnetic rigidity at $39 \leq B\rho \leq 194$ kG·cm. Also the source high voltage is required to range from 12 kV to 60 kV. To supply low energy experiments with ions of mass A>30 it is only necessary to reduce the high voltage to maintain a constant $B\rho$. Thus for a minimum voltage of 12 kV a maximum mass of A=150 is achievable. An operating diagram showing the relation of $B\rho$ and source high voltage as a function of ion mass is shown in Fig. 2.

For a given path length S in the magnet the particle will bend through an angle $\theta = S/\rho$. For a circular pole magnet with effective pole radius r_e the bend angle is given by the following relation

$$r_e = \rho \cdot \frac{\sin\theta}{1 + \cos\theta}.$$

We consider the symmetric case with radial magnification of M_x=-1. In this case the distance L_{ix} from magnet to image equals the distance L_{ox} from object to magnet (see Fig. 3). In this case

$$L_{ix} = L_{ox} = \rho \cdot \cot\frac{\theta}{2}.$$

The values of the slit to magnet distances normalized by ρ as a function bend angle are shown in Fig. 4. Assuming an image slit width equal to the object slit width w_o the mass resolution is given by $R_m = 2w_o/\rho$ [3]. (As we narrow the image slit this value approaches $R_m = w_o/\rho$ but the intensity is reduced.)

To separate ions to mass 150 will require a resolution of $R_m \leq 1/150$. Assuming a 1 mm object slit this sets $\rho \geq 30$ cm. For ρ=30 cm the maximum field required is B_{max}=6.5 kG. The choice of bending angle will effect the size of the magnet and the slit to slit distance. The slit to slit distance for various bend angles assuming a bend radius of 30 cm are shown in Fig. 5. The size of the bending magnet either circular pole or wedge is reflected in Fig. 6 and Fig. 7 respectively where the magnet width is as defined in Fig. 3. Bend angles in the range from 45° to 90° are a compromise between system length and magnet size. Two existing on-site magnets have been identified that can configured to provide a 60° bend. (Brief descriptions of these two magnets are given in Appendix A). A bend angle of 60° requires a circular pole diameter of 34.7 cm or a wedge pole width of 30 cm. The slit to magnet distance is then 1.73ρ or 51.9 cm.

3.2 Source Parameters

The source has been defined in a separate note[1]. The source transverse emittance is within 0.1πmm-mrad normalized (50πmm-mrad unnormalized). Therefore for a source aperture of diameter 4 mm we expect beam divergences of $\leq$25 mrad. The beamline simulation code TRACE-3D was used to calculate the required beam optics. The constraints were as follows:

- most of the beam from the source through a set of 1 mm object slits
- a 60° analyzing magnet with ρ=30 cm
- beam matched to periodic section of LEBT
  - $x_{max} = y_{max} = 5$ mm
  - $x'_{max} = 13.6$ mrad, $y'_{max} = -13.6$ mrad

The beam envelops for the TRACE-3D solution are shown in Fig. 8. Th x envelop shows that all the beam would be focussed to an object of $\sim$2 mm at the defining slit. Thus the full emittance will not pass through a 1 mm slit so to get the design resolution of R =1/150 some beam may be lost. However for the light ions a 2 mm slit width is more than sufficient. In the vertical direction the beam comes to a waist at the center of the analyzing magnet. The final phase ellipses in the upper right corner of the figure are matched to the acceptance of the LEBT; the beam converges in x and diverges in y.

The input file to TRACE-3D is given in Appendix B. The main parameters of the optics system are given in Table 1. Note that TRACE-3D calculates quadrupoles assuming they are magnetic. To transform the gradients input to the program in B/a, we use the relation

$$V(kV) = \frac{E(keV) \cdot a^2}{B\rho} \frac{B}{a}$$

where E(keV) is the ion energy and a is the radius of the quadrupole aperture. The values quoted in Table 1 assume an aperture $a = 2.54$ cm.

In practical terms the effective length of the electro-static quadrupole differs from the mechanical length. For an aperture $a = 2.5$ cm with a ground plane in between quads and effective separation of 3.8 cm the mechanical length is 1.25 cm shorter than the effective length, 0.6 cm on each end. The mechanical lengths of the quadrupole triplet sections are summarized in Table 2.

References

[1] K. Jayamana, Design Note

[2] R. Baartman, private communication.

[3] J.J. Livingood, *The Optics of Dipole Magnets*, Academic Press, New York, 1969.

Table 1: Main parameters of the off-line ion source beam optics analyzing and matching section.

Element	Length (cm)	Strength
drift	20.0	
Q1	8.0	-3.2 kV
drift	3.8	
Q2	10.0	4.6 kV
drift	3.8	
Q3	8.	-2.8 kV
drift	5.0	
object slit		
drift	51.9	
bend	31.4	6.5 kG
drift	51.9	
image slit		
drift	5.0	
Q1	8.0	-2.7 kV
drift	3.8	
Q2	10.0	3.5 kV
drift	3.8	
Q3	8.	-1.1 kV
drift	32.0	

4 Figure Captions

Fig. 1: A schematic drawing showing the layout of the off-line source, beam-line components and RFQ.

Fig. 2: An operating diagram showing the relation of $B\rho$ and source high voltage as a function of ion mass.

Fig. 3: Schematic showing both circular and a truncated wedge pole geometries in plan view together with parameters of the analyzing system and magnet.

Fig. 4: The values of the slit to magnet distances normalized by ρ as a function of bend angle.

Fig. 5: The slit to slit distance for various bend angles assuming a bend radius of 30 cm.

Fig. 6: The radius of a circular pole as a function of bend angle for $\circ$=30 cm.

Table 2: Mechanical specifications of the quadrupole sections of the beamline.

Element	Length (cm)	Strength
drift	20.6	
Q1	6.8	-3.2 kV
drift	5.0	
Q2	8.8	4.6 kV
drift	5.0	
Q3	6.8	-2.8 kV
drift	5.6	
object slit		
image slit		
drift	5.6	
Q1	6.8	-2.7 kV
drift	5.0	
Q2	8.8	3.5 kV
drift	5.0	
Q3	6.8	-1.1 kV
drift	32.6	

Fig. 7: The width of a wedge pole (from beam entrance to exit) as a function of bend angle for ○=30 cm.

Fig. 8: The beam envelops from TRACE-3D.

Fig. 9: A sketch of the HASIMAG.

Fig. 10: A sketch of the CIRCLEMAG.

Fig. 11: A suggested truncated wedge pole shape for the HASIMAG.

5 Appendix A

Two existing TRIUMF magnets have been identified as possible candidates for the analyzing dipole. The first is the so called HASIMAG. It is a C-magnet with a two water cooled coils each with 32 turns, a 25 cm square pole and a gap of 16.5 cm. A sketch of the magnet is shown in Fig. 9. The second, hereafter referred to as CIRCLEMAG, is a large H-magnet with a 30 cm circular pole and gap of 15 cm. It has no coil at present. A sketch of this magnet is shown in Fig. 10. Both magnets would require customization to be suitable for the present application.

In the case of the HASIMAG the yoke area would be doubled by adding a second yoke arm, thus configuring the magnet in a H-type geometry. The pole gap would be reduced to 5 cm and with the new pole cut in a truncated wedge geometry fitting within the 25 cm×25 cm dimension of the upper pole. A suggested pole shape is shown in Fig. 11 with an effective field boundary extending 0.6 gap factors from the entrance and exit edges. In this configuration the existing 64 turns excited with 500 A would produce a field of ~7.8 kG.

The CIRCLEMAG would, as mentioned, need a new coil. Because of the huge mass it is envisaged that an air coil may be sufficient. The yoke is sufficient that saturation is avoided over the whole field range. In this case the gap would be reduced to 3 cm and the poles nickel-plated to form the vacuum wall. An excitation of 19500 AT is sufficient to produce a 7.8 kG field. The additional pole would have an effective diameter of 34.7 cm. Given that the effective field boundary extends $\sim 0.6g$ from a square edged pole where g is the gap this gives a true pole diameter of 31.1 cm.

6 Appendix B

The input data file for the TRACE-3D calculation is listed below. Comments are indicated with an exclamation mark (!).

```
    $data
! units=mm, mrad, t/m, mamps, mv/m
er=27945.048 q=1. w=0.06 xi=0.0 !rest mass=30*931.5016 for heavy ions
emiti=50. 50. .00001
beami= 0. 0.1 0. 0.1 0.0 1000.0
freq=105.0 ichrom=0.0
n1=1 n2=19. smax=2.
! here's a drift (element, length(mm))
nt(1)=1 a(1,1)=200.
! next comes a quadrupole triplet section
!
! first quad (element, strength (T/m), length (mm))
nt(2)=3 a(1,2)=-16. a(2,2)=80.
! first drift
nt(3)=1 a(1,3)=38.
! second quad
nt(4)=3 a(1,4)=23.2 a(2,4)=100.
! second drift
nt(5)=1 a(1,5)=38.
! third quad
nt(6)=3 a(1,6)=-14. a(2,6)=80.
!
! now a drift to the object slit
nt(7)=1 a(1,7)=50.
! now the drift to the bender
nt(8)=1 a(1,8)=519.
! bending magnet
! entrance to bender (element, rotation angle, bend radius (mm),
! bend angle (deg))
nt(9)=9 a(1,9)=0. a(2,9)=300. a(3,9)=60.
! bend portion (element, bend angle (deg), bend radius (mm), index)
nt(10)=8 a(1,10)=60. a(2,10)=300. a(3,10)=0.
! bender exit
nt(11)=9 a(1,11)=0. a(2,11)=300. a(3,11)=60.
! drift to image slit
nt(12)=1 a(1,12)=519.
! drift to matching triplet
nt(13)=1 a(1,13)=50.
! now comes the matching quad triplet
! first quad
nt(14)=3 a(1,14)=-13.8 a(2,14)=80.
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! first drift
nt(15)=1 a(1,15)=38.
! second quad
nt(16)=3 a(1,16)=17.5 a(2,16)=100.
! second drift
nt(17)=1 a(1,17)=38.
! third quad
nt(18)=3 a(1,18)=-5.3 a(2,18)=80.
! drift to matching point
nt(19)=1 a(1,19)=340.
xm=10.
xpm=30.
ym=30.
dpm=10.
dwm=10.
dpp=10.
$ end
```