Corrections and Additions to Optics Design for the ISAC Off-line Source

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1 Abstract

This note summarizes the subsequent improvements to the off-line source beam optics design after release of the initial design note.[1]

2 Introduction

An initial design note [1] was issued summarizing the design of the beam optics layout from the source to the LEBT. Since then several suggestions have been made during the design review process to improve the performance. These have been incorporated in the final design. The changes are summarized here. In addition a more detailed study of the analyzing magnet is reported.

3 Beam Optics Changes

Two changes were implemented. In the first it was shown [2] that the large beam size in Q2 (see Fig. 1) led to large chromatic aberrations. To reduce the size of the beam the drift space from source aperture to the quadrupole triplet was shortened from 200 to 138 mm and the length of the first and third quadrupoles were shortened from 80 mm to 50 mm. The beam envelopes for the new optics design are shown in Fig. 2. A comparison of half beam sizes at various beamline positions for the *old* and *new* designs and for two different initial beam conditions are given in Table 1. For beam aberrations to be kept small[3]

$$a_b << \epsilon f^2 L$$

where a_b is the beam half size, L is the effective length and

$$f = \frac{Ea_q^2}{VL}$$

is the focal length where E is the beam energy, a_q is the quadrupole half aperture, and V is the voltage. For our case $a_q = 2.5$ cm, $E = 60$keV, and $\epsilon = 50\pi$mm mrad. For Q2, with $V = 5$ kV and $L = 10$ cm, the limit is $a_b^4 << 3$ cm^4 to minimize the effects of chromatic aberrations. For Q6 with $V = 4$ kV and $L = 5$ cm, the limit is $a_b^4 << 9$ cm^4. From Table 1 we see that, for larger emittances, aberrations are a problem in Q2. In the new design, even with the increased beam size at Q6, we are below the aberration limit in all quads. This gain comes at the cost of a slightly bigger beam size at the object slit so for the best resolutions we will be losing more beam. For a slit width of 2.5 mm and $\rho = 30$ cm we can

Table 1: Comparing beam half sizes at various beamline positions for *old* and *new* beamline designs.

Position	$\epsilon = 50\pi, \alpha = 0, \beta = 0.08$ old	new	$\epsilon = 40\pi, \alpha = 0, \beta = 0.1$ old	new
Q2	13	9	10	7
Q5	13	8	11	7
Q6	10	13	9	12
Object Slit	2	2.5	1.9	2.37

expect a resolution of 1/60 which is sufficient to resolve the masses of interest for the RFQ commissioning. The quadrupole voltages are also higher but in all cases are less than 6 kV.

The second change was required because it was found that the original position chosen to match the source beam into the LEBT was incorrect. In the original case the beam was matched to the middle of the LEBT periodic section in the long drift between quadrupole doublets. The beam was made to converge in the horizontal axis and diverge in the vertical when in fact the reverse was demanded by the downstream optics elements. The situation was corrected by choosing a matching point in the short drift between two quads comprising a doublet (see Fig. 3). The match conditions were

- $x_{max} = 6.36$ mm, $y_{max} = 6.36$ mm
- $x'_{max} = 23.9$ mrad, $y'_{max} = -23.9$ mrad

To reduce the number of different components the matching quadrupoles were dimensionally changed to mirror those changes to the initial triplet. The final phase ellipses in the upper right corner of Fig. 2 show the new matched beam conditions; the beam converges in x and diverges in y.

The input file to TRACE-3D is given in Appendix A. The main parameters of the optics system are given in Table 2. 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 2 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 3.

Table 2: Main parameters of the off-line ion source beam optics analyzing and matching section.

Element	Length (cm)	Strength
drift	13.8	
Q1	5.0	-5.16 kV
drift	3.8	
Q2	10.0	5.3 kV
drift	3.8	
Q3	5.	-5.3 kV
drift	5.0	
object slit		
drift	51.9	
bend	31.4	6.5 kG
drift	51.9	
image slit		
drift	5.0	
Q1	5.0	-3.7 kV
drift	3.8	
Q2	10.0	0.68 kV
drift	3.8	
Q3	5.	3.7 kV
drift	28.0	

4 Design Studies for the Analyzing Magnet

In the previous note it was reported that two existing magnets had been identified as suitable for use as an analyzing magnet for the off-line source. The so called CIRCLEMAG has subsequently been rejected due to the aberrations inherent in a circular pole design.[4] The second magnet, the so called HASIMAG, will be customized to provide a satisfactory magnet. Here we report various design studies completed to determine the exact nature of the HASIMAG customization.

The HASIMAG is a C-magnet with 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. 4. The optics design calls for a 60° bending magnet with a bending radius of 30 cm ($B\rho = 194$ kG-cm) with entrance and exit faces perpendicular to the central ray.

The suggested alterations are as follows:

- the pole gap be reduced from 16.5 cm to 5 cm
- the yoke area be doubled by adding a second yoke arm, thus configuring the magnet in a H-type geometry

Table 3: Mechanical specifications of the quadrupole sections of the beamline.

Element	Length (cm)	Strength
drift	14.4	
Q1	3.8	-5.16 kV
drift	5.0	
Q2	8.8	5.3 kV
drift	5.0	
Q3	3.8	-5.3 kV
drift	5.6	
object slit		
image slit		
drift	5.6	
Q1	3.8	-2.7 kV
drift	5.0	
Q2	8.8	3.5 kV
drift	5.0	
Q3	3.8	-1.1 kV
drift	28.6	

- the new pole be cut in a truncated wedge geometry fitting within the 30 cm×30 cm dimension of the upper pole

A cross-section of the lower pole configuration, together with the yoke and the coil are shown in Fig. 5. The 2-D code POISSON was used to answer the following questions:

- what pole width is required to generate sufficient uniform field
- how deep must the pole be and still give a satisfactory field
- what is the effective area of the pole considering the effective field boundary
- what is the excitation of the coil necessary to achieve the design field
- is a field clamp required to achieve the specified field
- what is the optimum shape of the field clamp

Two types of 2-D POISSON calculations were done to simulate the three-dimensional magnet geometry. To study the field uniformity and excitation requirements a cross-section along the width of the magnet was used as shown in path A of Fig. 6. To study the entrance and exit fringe fields a cut along path B of this figure was used with an artificial yoke added to return the flux.

4.1 Uniformity Studies

The existing pole depth is 4.8 inches with a half gap of 3.2 inches. One inch of the lower pole is unuseable because of chamfers that must be machined off. The upper pole, consisting of the remaining part of the existing poles, could range in depth from 0 to 3.8 inches. Therefore the new pole could have a depth anywhere from 3.2 to 7 inches deep to make up a total pole depth of 7 inches.

The magnet geometry and associated fields for the uniformity studies are shown in Fig. 7(a) and (b). In (a) the pole depth is 5 inches and in (b) the pole depth is 3 inches. The field uniformity results for each geometry are shown in Fig. 8. The plot shows that there is no significant reduction in the uniform field in choosing the smaller pole depth. However the depth of the pole will effect the fringe field and this study is presented in the next section. In the example the pole extends from 9 inches to 18 inches. A field uniformity of 1×10^{-3} begins 2 inches or 1 gap width in from each end giving a total uniform region of 5 inches for this configuration. A uniformity of 1×10^{-4} occurs 1.4 gap units in from the edge, corresponding to 3.4 inches of uniform field in this configuration. From the TRACE-3D result the selected beam will be ∼5 cm wide at the center of the magnet. For a 60° bend with ρ =30 cm the arc of the path spans 4 cm of width giving a total required width of the uniform region of 9 cm or 3.5 inches. Thus the magnet with the 9 inch wide pole and square edges seems adequate.

4.2 Fringe Field Studies

The fringe field extends out from the edge of the pole. The effective field boundary (EFB) given by

$$x = \frac{1}{B_o}\int_{-s}^{\infty} B_z dx - s$$

where B_o is the field in the uniform region a distance s inside the pole edge, is used to define the effective magnet edge. Another parameter K1 defined by

$$K1 = \int_{-s}^{\infty} \frac{B_z(x)(B_o - B_z)}{gB_o^2} dx$$

is used to characterize the fringe field shape. In the example shown in Fig. 7 the EFB was found to extend 0.6 gap units outside the pole edge. This gives, for the pole illustrated in Fig. 5, an effective cross-sectional area of ∼140 in^2. The total yoke cross-sectional area is 98 in^2. Therefore for the design pole field of 6.5 kG we will expect 9.4 kG in the yoke, well below saturation. From POISSON simulations we would need a total of 24,500AT (corresponding to 415 A for the 64 turns of the magnet) to reach this field.

The fringe field at the entrance and exit of the magnet was studied with the 2-D representation shown in Fig. 9. From the plan view of Fig. 5 it is apparent that the coil does not follow the contour of the pole but is instead square. To study this effect, the position of the lower pole edge in Fig. 9 is varied from 3 inches to 7 inches in steps of 1 inch. A lower pole depth of 5 inches was used in the study. The resultant fringe field strengths are shown in Fig. 10(a) and in Fig. 10(b) the position of the fringe field is normalized with respect to the pole edge position. It is apparent that the fringe field shape and extent changes as the pole edge position is changed.

A field clamp can be added to control the fringe field. A POISSON study was undertaken to optimize the field clamp and pole geometry to minimize the effect of the rectangular coil on the EFB. The POISSON geometry and associated dimensions that were varied in the study are shown in Fig. 11. Two types of clamps were looked at. In Type I the position of the stem of the clamp is fixed and the tip length is varied to follow the lower pole position. In Type II the size of the tip is fixed and the clamp is varied by moving the stem relative to the upper pole. The various cases that were studied are summarized in Table 4.

Table 4: Summary of field clamp and magnet geometries for fringe field studies.

Series	Clamp	Pole Depth (inches)	Pole $\rightarrow$ Tip (inches)	Tip Length (inches)
A	none	5		
B	I	3	4	varies
C	II	3	4	2
D	II	4.5	4	2
E	I	7	4	varies
F	II	7	4	2
G	II	7	3	3
H	II	4.5	3	3

The effective field boundary values for the various geometries given in Table 4 are summarized in Table 5. Given are the EFB values normalized to the pole edge and the gap (2 inches) as a function of the pole edge position. A summary quality factor $\overline{\Delta \mathrm{EFB/dx}}$ is included giving the average normalized EFB change per inch of pole edge displacement. A factor of 0.017 corresponds to a change in the entrance angle of 1°.

Table 5: Fringe field characteristics for various field clamp and magnet geometries.

Edge (inches)	A	B	C	D	E	F	G	H
3	0.87	0.635	0.629	0.59	0.592	0.586	0.501	0.509
4	0.81	0.605	0.601	0.575	0.583	0.578	0.497	0.503
5	0.76	0.575	0.571	0.56	0.573	0.570	0.493	0.496
6	0.72	0.550	0.549	0.55	0.562	0.562	0.489	0.490
7	0.70	0.530	0.539	0.54	0.549	0.555	0.485	0.489
$\overline{\Delta \mathrm{EFB/dx}}$	0.043	0.026	0.022	0.012	0.011	0.008	0.004	0.005

A few conclusions can be drawn from the data. In general the use of a clamp improves the stability of the fringe field, and the improvement factor increases with pole depth. Also a type II clamp is marginally better than a type I clamp. Finally the stability is better as the separation between clamp tip and pole edge is reduced from 2 gap units (4 inches) to 1.5 gap units (3 inches). Reducing the clamp to edge separation beyond this leads to saturation of the clamp. For these studies a clamp with a 0.75 inch stem and a 0.5 inch thick tip is used. As a result of these studies a field clamp of Type II is recommended with a magnet and clamp orientation defined by series H. The fringe field amplitude for this case are plotted in Fig. 12(a) and 12(b). Thus a 4.5 inch plate can be used for the lower pole and the upper pole would consist of the existing upper pole cut back to a depth of 2.5 inches from 4.8 inches. If for some reason another size plate was available it could be used as long as it was larger than 4.5 inches.

The clamp also improves the stability of the characteristic fringe field factor, K1. A comparison of EFB and K1 values with and without the field clamp are shown in Table 6. The clamp data comes from the calculations using geometry H.

Table 6: Effect of coil position on fringe field with and without field clamp.

	No Clamp		With Clamp	
Coil Position (inches)	EFB (gaps)	K1	EFB (gaps)	K1
3	0.87	0.600	0.509	0.321
4	0.81	0.565	0.503	0.319
5	0.755	0.535	0.496	0.317
6	0.72	0.51	0.490	0.315
7	0.695	0.50	0.489	0.316

The clamp also tends to straighten the EFB thus reducing aberrations. With no clamp the contours of equal field strength in the fringe field tend to curve (see Fig. 13) yielding a curved EFB.

4.3 Conceptual Drawings and Specifications

Fig. 14-18 are concept drawings of the HASIMAG modifications showing the major dimensions in inches. An EFB of 0.5 gaps (1 inch) has been assumed in setting the dimensions of the new lower pole (see Fig. 17). Since the bend radius is 30 cm (11.811 inches) and the bend angle is 60°, the chord of the beam arc inside the effective field boundaries is 11.811 inches. The width of the pole at the center of magnet is set at 9 inches. The beam enters the EFB at 3.5 inches from the narrow pole edge. This sets the width of the narrow pole edge at:

$$A = (11.811/2 - 1/\cos 30 - 3.5\tan 30) * 2 = 5.460\text{inches}$$

and the width of the wide edge at

$$B = (11.811/2 - 1/\cos 30 + 5.5\tan 30) * 2 = 15.852\text{inches}.$$

The lower pole should be at least 4.5 inches deep. The pole surface should be flat to <0.001 inches and the poles should be fixed with a nominal gap of 2.00 inches and be parallel to ±0.002 inches over the full width and length.

The clamp is shown in Fig. 18. The clamp tip extends 3 inches from the clamp stem (window frame) and is positioned to align with the lower pole edge with a 3 inch separation. For the tip 0.5 inch plate is sufficient but the stem and yoke attachment require 3/4” plate. These dimensions assume that the clamp is fabricated from magnet steel. The clamp position should be somewhat adjustable to allow fine tuning of the EFB during mapping.

References

[1] R. Laxdal, *Beam Optics Design for the ISAC Off-Line Source*, TRIUMF Design Note.

[2] R. Baartman, private communication

[3] R. Baartman, TRIUMF design note, TRI-DN-95-21.

[4] J. Doornbos, private communication.

5 Figure Captions

Fig. 1: Beam envelopes from TRACE-3D for the initial study.

Fig. 2: Beam envelopes from TRACE-3D for the new study.

Fig. 3: A schematic drawing of the LEBT periodic section showing the old match point and the new match point.

Fig. 4: A sketch of the HASIMAG.

Fig. 5: A plan view of the HASIMAG showing the coil, yoke and a truncated wedge pole shape.

Fig. 6: The two magnet configurations used to study the HASIMAG with POISSON. Path A is used to study field uniformity and Path B is used to study the fringing field.

Fig. 7: POISSON output showing field lines for HASIMAG cross-section for (a) a pole depth of 5 inches and (b) a pole depth of 3 inches.

Fig. 8: Plot of field uniformity vs. position along pole in inches for the two different magnet geometries shown in Fig. 7. The pole edges are at 9 inches and 18 inches.

Fig. 9: Magnet geometry to calculate entrance and exit fringe fields.

Fig. 10(a): Fringe field strengths for various pole edge positions. In (b) the fringe field strengths are normalized to a pole position of 5 inches for comparison.

Fig. 11: Magnet geometry to calculate entrance and exit fringe fields with field clamp.

Fig. 12(a): Fringe field strengths for various pole edge positions with field clamp. In (b) the fringe field strengths are normalized to a pole position of 5 inches for comparison.

Fig. 13: Field clamp straightening out lines of constant magnetic field strength at the exit of a dipole.

Fig. 14: Side view of existing and modified analyzing magnet (1/4 scale).

Fig. 15: Front view of analyzing magnet at two different locations (1/4 scale).

Fig. 16: Plan view of analyzing magnet (1/4 scale).

Fig. 17: Plan view of new wedge pole with specifications (1/2 scale).

Fig. 18: Front and side view of field clamp (1/4 scale).

6 Appendix A

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)=138.
! next comes a quadrupole triplet section
!
! first quad (element, strength (T/m), length (mm))
nt(2)=3 a(1,2)=-25.8 a(2,2)=50.
! first drift
nt(3)=1 a(1,3)=38.
! second quad
nt(4)=3 a(1,4)=26.5 a(2,4)=100.
! second drift
nt(5)=1 a(1,5)=38.
! third quad
nt(6)=3 a(1,6)=-26.5 a(2,6)=50.
!
! 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),
! gap (mm), K1
nt(9)=9 a(1,9)=0. a(2,9)=300. a(3,9)=50. a(4,9)=.32
! 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)=50. a(4,11)=.32
! 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)=-18.39 a(2,14)=50.
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```
! first drift
nt(15)=1 a(1,15)=38.
! second quad
nt(16)=3 a(1,16)=3.41 a(2,16)=100.
! second drift
nt(17)=1 a(1,17)=38.
! third quad
nt(18)=3 a(1,18)=18.27 a(2,18)=50.
! drift to matching point
nt(19)=1 a(1,19)=280.
xm=10.
xpm=30.
ym=30.
dpm=10.
dwm=10.
dpp=10.
$ end
```