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Steering magnet design for a limited space

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DISCLAIMER

STEERING MAGNET DESIGN FOR A LIMITED SPACE

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Abstract

We compare two extreme designs of steering magnets. The first one is a very thin steering magnet design which occupies only 6 mm in length and can be additionally installed as needed. The other is realized by applying extra coil windings to a quadrupole magnet and does not consume any length. The properties and the features of these steering magnets are discussed.

INTRODUCTION

A steering magnet is not a major component in a beam line, however it is usually needed in any real set up. Also it is hard to estimate the required field strength before the beam line construction, since the strength desired is determined by misalignment errors of other devices. Sometimes it is difficult to find enough space to install steering magnets because of other constraints on the length of the beam line. In this report, we assume a beam transport line which connects a radio frequency quadrupole (RFQ) and a drift tube linear accelerator (DTL) as an example of a condensed section. Typically, to obtain a proper longitudinal emittance matching, the distance between an RFQ and the first DTL has to be kept as short as possible.

In Brookhaven National Laboratory (BNL), we have a 750 keV proton RFQ which accelerates 80 mA of H^- beam and 500 μA polarized H^- beam. Also a new linear accelerator chain is being built as a part of RHIC-EBIS project. In this new injector, we will have a 300 keV/u RFQ for heavy ion beams provided by a high current electron beam ion source (EBIS). Table 1 shows required steering field strength to obtain 1 mrad kick for the both beam transport lines.

Table 1: Required Field Strengths for 1 mrad Deflection

Energy	Species	A/q	Gap	Steering field
750 keV	H^-	1	51 mm	125 Gauss cm
300 keV/u	He^{2+}- Au^{32+}	< 6.25	32 mm	<500 Gauss cm

POSSIBLE ERRORS DUE TO MISALIGNMENTS

There are two possible major error sources in the section. The first is an alignment error between the RFQ and the DTL as shown in Fig. 1. The angle error of the two linacs is expressed as α. The angle β is a position error defined by the offset distance and the length between two deflection points. These errors can be easily corrected by 0.5 ~ 1 mrad kick.

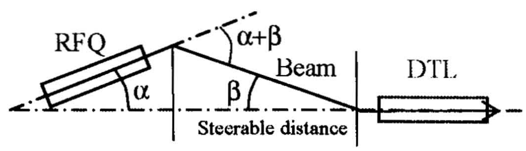

Figure 1: Alignment error of linacs.

The second error source is misalignments of quadrupole magnets in the section. For example, in the RHIC-EBIS project, we will install four quadrupole magnets. The maximum field gradient of the quadrupole is 7 kGauss/cm and its effective length is 8.2 cm. The effect of the misalignments is very large. A 0.2 mm position error of the quad gives 1150 Gauss cm of dipole field which is larger than 2 mrad deflection.

In total, we need at least 3 mrad deflection for each steering magnet in the section.

THIN STEERING MAGNET

Figure 2 shows two types of steering magnets those were designed for the H^- beam line at BNL. The thickness of these magnets is 6.35 mm. The both pole shapes were identical and were controlled to minimize integrated sextupole component along the beam axis which is well below 5 units (unit = 1/1000 of dipole component) at a 15 mm reference radius. The return yoke thickness was increased up to 12.7 mm to have uniform field flux distributions. At 4800 Aturn, the maximum field in the iron was controlled to reach 1.5 T which is just below the saturation range of the material. The field flux distribution is shown in Fig. 3. The holes are to accommodate bolts of neighboring devices. The maximum dipole field reaches 415 Gauss.

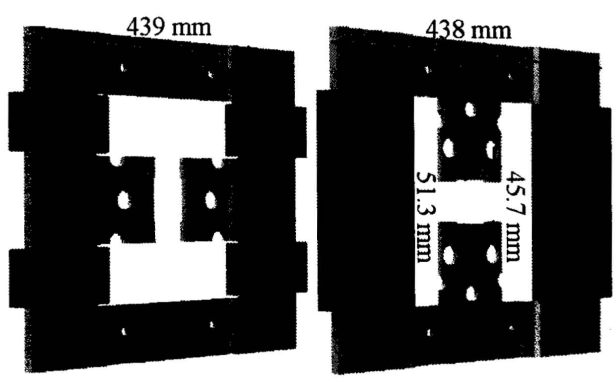

Figure 2: Horizontal and vertical thin steering magnets.

Work performed under the auspices of U.S. DOE.

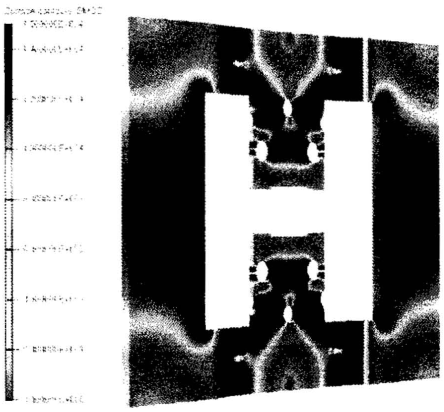

Figure 3: Magnetic field in vertical thin steering magnet.

These thin magnets can be installed within a minimal space. However, we need to pay special attention to neighboring magnetic devices like quadrupole magnets. The effective length of the dipole component is much longer than the pole thickness which covers the next device's region. Also since the driving currents are far from the beam area, the induced magnetic fluxes are delivered through long magnetic paths. The magnetic flux may find a shorter passage created by the next magnetic materials including supporting structures. These effects should be minimized.

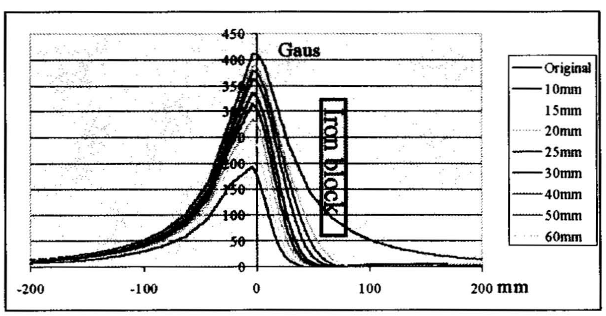

Figure 4: Magnetic field on the axis of vertical thin steering magnet.

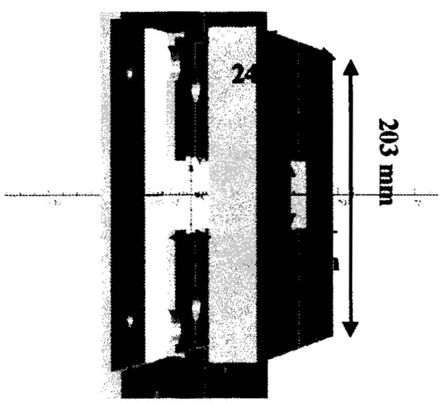

Figure 5: Steering magnet with an iron block.

Figure 4 shows the reduction effect of a neighboring iron block. The thickness of the block is 30 mm and other dimensions are indicated in Fig. 5. The distance, *d*, between the steering magnet surface and the block was scanned. Figure 6 shows the integrated field strength as a function of *d*. The result shows that the effective length of the left side of the magnet, no iron block side, is still long enough and the steering magnet works although the field strength becomes less. This implies that the fieled flux starts not only from the pole face but also from the vertical surface planes near the pole faces.

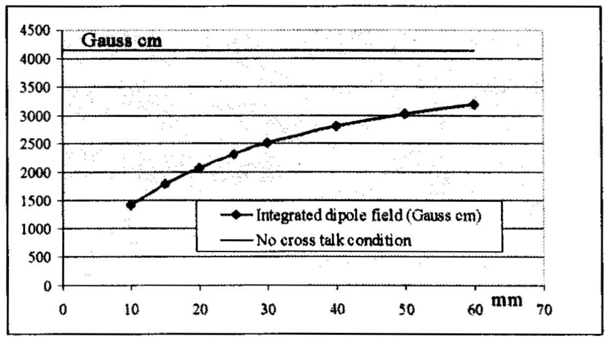

Figure 6: Dipole field integral vs. the block position.

STEERING COILS ON QUADRUPOLE MAGNET

Alternatively we can add some steering windings on an existing quadrupole magnet. In this case, no extra space is needed. Figure 7 shows a variety of possible windings.

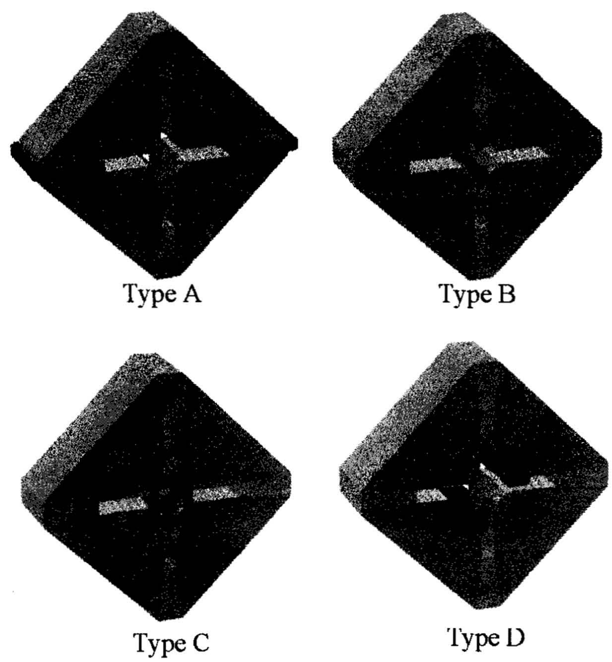

Figure 7: Steering windings for quadrupole magnet.

One of major disadvantages of these steering fields is the presence of a strong sextupole component. Since magnetic flux is guided by the quadrupole yoke, we do not have any effective way to control the multipole components. In table 2, the predicted performances are listed. In these simulations, a prototype design of the quadrupole for the RHIC-EBIS project was used which has 80 mm of thickness, 32 mm bore diameter and 7.0 kGauss/cm of field gradient. The pole shape was designed to minimize 12 poles and 20 poles along the axis. No modification was applied to obtain a better steering field quality.

Table 2: Field Performance of the Steering Windings

Type	Ampere turn for 1000 Gauss cm	Sextupole/Dipole	Decapole/Dipole
A	361	19.9 %	0.93 %
B	2880	-81.7 %	32.6 %
C	249	27.6 %	2.1 %
D	324	25.7 %	-0.92 %

The field components were integrated within +- 200 mm on the axis.

The feature of each magnet is summarized.

Type A

By increasing openings for the quadrupole windings, a large current can be easily applied to the steering coils. The direct contribution from the coil current can not be expected. In the fringe region, the dipole component is enhanced. In the central area of the magnet, the local sextupole component increased up to 28 % of the dipole field. The uniformity at the center is similar to type C and D.

Type B

Usually not much space was left for the windings. In many cases, the main qudrapole windings need to be modified. It is difficult to induce high field. In the model, a current density of 500 A/cm^2 was assumed and the obtained field at the center of the magnet only showed 14.4 gauss. The field uniformity is not acceptable for most cases.

Type C

It has a relatively good current vs. strength efficiency. Again, the winding spaces are limited. However, if the coil can be water cooled, it can induce a few hundred Gauss cm.

Type D

The space is limited, however it is relatively easy to wind the coils. The steering dipole field has an angle of 45 degree and the operation may need special attention.

Multipole Consideration

Above all the types from A to D have large sextupole components. Here let's assume 30 % of sextupole distortion over pure dipole field. The reference radius was set to 10 mm from the beam center. If the sextupole to dipole ratio has positive sign, the vertical field strength at horizontal median plane is increased. For example, the field at a point 15 mm horizontally apart from the axis is 167.5 % of the center field strength. This means that, near the beam pipe, the steering kick provided will be more than 60 % more. Similarly the field at a point vertically apart from the center is reduced by the same amount. If the beam size is large in the quadrupole, the emittance growth should be carefully examined.

Combined Solution

Type B has opposite sextupole polarity from A, C or D. By combining Type B windings to Type A or C, the sextupole ratio can be mitigated. Figure 8 shows an example of the combined field of Type A and Type B. The lines are the horizontally scanned field strengths at the magnet center (not integrated on the axis). The assumed currents were 204. Ampere turn and 385 Ampere turn in Types A and B respectively. In this condition, the sextupole is almost zero, however the combined field has non-uniformity mainly due to the decapole induced by Type B. A reasonable field quality can be achieved within 10 mm of radius area.

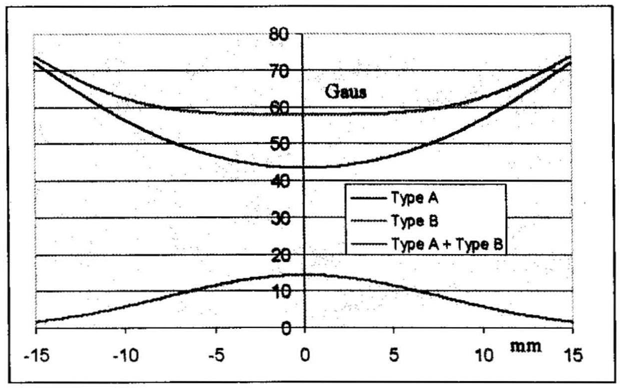

Figure 8: A combined solution of the steering windings.

SUMMARY

Two extreme cases of steering magnets for a tight space are investigated. The thin steering is efficient, however, the cross talk effect is large. The steering windings on a quadrupole magnet could be applied to a relatively smaller size beam. The combined solution may give acceptable steering force quality. Let us note that if the position of the quadrupole can be moved precisely, it can be used as a high quality steering magnet. This could be another solution.

In the all above magnetic simulations were done by using OPERA3D-TOSCA [1] with the default setting BH property.

REFERENCES

[1] OPERA3D-TOSCA, Vector Fields Co., UK.