DESIGN AND PERFORMANCE OF A PERMANENT MAGNETIC QUADRUPOLE FOR A LOW ENERGY LINAC BEAM LINE

Y.J.E. Wintraecken, A.T.A.M. Derksen, J.I.M. Botman, L.W.A.M. Gossens, H.L. Hagedoorn and C.J. Timmermans
Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, the Netherlands
B.C. Goudswaard
Goudsmit Magnetic Systems BV, PO Box 18, 5580 AA Waalre, the Netherlands

Abstract

Permanent magnets which show the highest magnetic flux density, have been used in constructing an insertable Permanent Magnetic Quadrupole (PMQ). The PMQ is part of an electron irradiation facility for polymer research at the Eindhoven University of Technology. For polymer irradiation that requires a homogeneous dose distribution, the PMQ is inserted and the expanded electron beam will irradiate the target completely. Design criteria of the quadrupole are discussed. The quadrupole geometry has been optimised using CEDRAT finite element software. The influence of mechanical alignment errors (0.15 mm) and variations in permanent magnet properties (0.5%) on the magnetic field have been simulated. Sixteen NdFeB magnets (42x42x10 mm^3) have been used to produce a quadrupole with an aperture radius of 50 mm. Before insertion, the magnetic flux density of all magnets has been determined versus magnetic field and temperature. After construction the lens strength of the quadrupole has been determined using the floating wire technique. The flux density has been measured using a Hall probe. Results show a magnetic field gradient that varies less than 0.5% within a radius of 25 mm. Alignment errors have been determined comparing simulation and measurement.

1 INTRODUCTION

Electron beams are often used to study new polymer materials by altering their chemical and/or mechanical properties At the Eindhoven University of Technology, a polymer irradiation facility has been setup comprising a 5 MeV linear electron accelerator, a short beam line section and the irradiation unit.
Most experiments done with the linear accelerator require a scanning beam spot on the target. However, some specific experiments require a fully irradiated target with an even dose. For this one needs to diverge the electron beam, making use of an ion optical element. For this application an easily insertable permanent magnetic quadrupole (PMQ) was designed and constructed.

2 QUADRUPOLE DESIGN

The position of the quadrupole within the radiation facility is shown in Figure 1. The position depends on the total focal strength of the PMQ. Yet, the set-up allows a position variation of the PMQ of 20 mm.

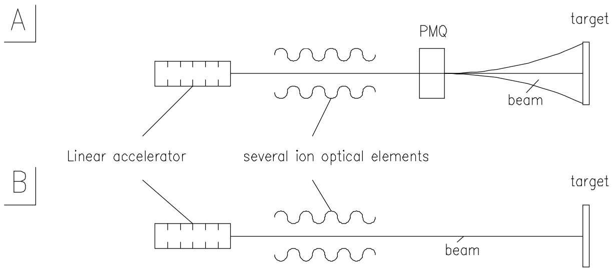

Figure 1 Schematic set-up of the irradiation facility
A) Full target irradiation; PMQ inserted
B) Small beam spot target irradiation; PMQ is not present

Criteria imposed to the quadrupole assembly are:

- the lens strength of the PMQ equals: ***G l*** = 0.25 ± 0.05 T where ***G*** and ***l*** are the gradient and the length of the magnets used for the quad-rupole assembly respectively;
- a maximum variation of 0.5 % of the gradient is tolerated within an inner radius of 25 mm;
- the assembly must be removable from the beam line, without interfering and/or rebuilding other parts of the electron optical system.

Additional features of the quadrupole:

- as the linear accelerator will produce a 5 MeV electron beam, permanent magnets are used. Adjustment of the PMQ lens strength is not necessary;
- the inner diameter of the pole faces measures 100.0 mm ± 0.1 mm;
- Regular quadrupoles have truncated poles, because of the required space for the coils. As PMs are applied there is no need for cutting the poles. Therefore the pole faces are almost ideal;

- NdFeB magnets are applied, because of their reproducibility, high remanence and high coercive force;
- low cost, no need of a power supply.

For easy insertion, the quadrupole has been divided into two parts. A sketch of the designed quadrupole is given in figure 2.

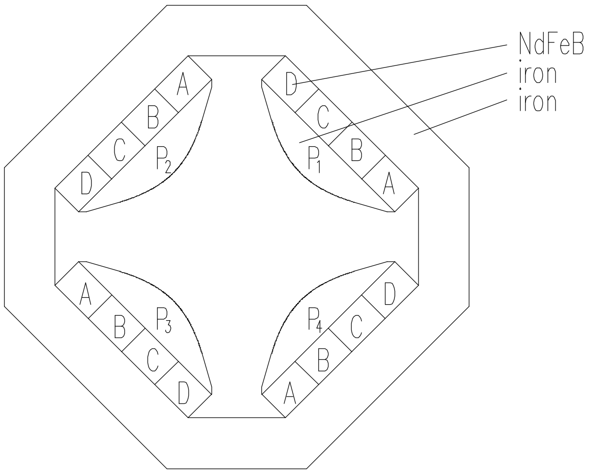

Figure 2 Sketch of the quadrupole

The two parts are put together using positioning pins, which results in a maximum constructional asymmetry of 0.05 mm. The PMQ is covered by two stainless steel plates of 4 mm thickness. They are cut using laser techniques, reaching an accuracy of 0.02 mm. The plates are used to align the four pole pieces and keep the set-up in position. As the PMs measure: l x w x <u>h</u> = 42 x 42 x <u>10</u> mm^3 (<u>h</u> is the magnetisation direction) the total length of the set-up amounts to 50 mm. The four pole pieces as well as the core region are made using wire sparking. The accuracy of all pieces is within 0.02 mm. The error in the dimensions of the sixteen permanent magnets amounts to a maximum of 0.05 mm, resulting in a total maximum constructional asymmetry error of 0.15 mm. A non-removable stainless steel frame will be used to position and align the PMQ in the beam line.

3 FINITE ELEMENT RESULTS

It is expected that material properties of iron will hardly distort the required field. The main contributions to field errors will be induced by constructional asymmetry of the four pole pieces and spread of the permanent magnet properties.

Simulated results of constructional asymmetry of the poles are shown in figure 3. Note that even if there is no constructional asymmetry of the poles simulations indicate a variation in the gradient of the flux density. This must be ascibed to the accuracy of the finit element simulations.

Figure 4 shows the influence of variation of remanence of one PM, keeping the remanence of the other 15 PMs equal .

Combining figures 3 and 4, one gets a good indication of the simulation error (0.20 ± 0.05 %). One can also estimate the variation in the gradient **G** because the design is not ideal (0.12 ± 0.05 %).

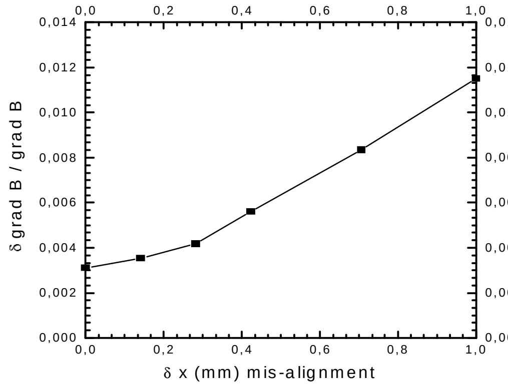

Figure 3 Influence of pole constructional asymmetry on the gradient

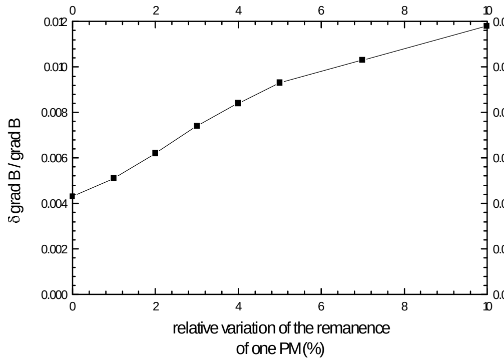

Figure 4 Influence of a relative decrease of the remanence of 1 PM (15 PMs keeping their remanence) on the gradient

Table 1 Alignment errors of the different poles in x,y directions (constructional asymmetries indicated by +/-; all constructional asymmetries measure 1 mm)

p1		p2		p3		p4		dG/G
x	y	x	y	x	y	x	y	
+	+	-	-					0,025
+	+			-	-			0,033
+	-	-	-					0,027
+	-	-	-	-	+	+	+	0,034

the names of the poles and magnets are given in figure 2.

Results of some typical constructional asymmetries on the gradient of the flux density are given in Table 1. It can be concluded that symmetrical constructional errors hardly effect the accuracy of the PMQ properties, while asymmetric constructional errors will double or triple variation in the gradient.
Table 2 shows the influence of the amount of PMs with a different remanence on the gradient.

Table 2 Influence of variation of the remanence of the PMs; x indicates the presence of a PM with 10% decrease in remanence

p1	p2	p3	p4	dG/G
A B C D	A B C D	A B C D	A B C D	
x x	x x			0,047
x x x x				0,054
x	x	x	x	0,021
x x x x		x x x x		0,026

the names of the poles and magnets are given in figure 2.

Note that even for 8 PMs with a 10% decrease in remanence the influence is less than for 4 PMs, as long as symmetry is present. As only variations in remanence of the PMs of less than 0.5% are expected the magnetic properties of the PMs hardly contribute to the field distortion.
Simulations indicate a gradient variation of 0.5 %, if the mechanical alignment error amounts to 0.15 mm (as calculated in section 2).

4 MEASUREMENTS

Firstly, magnetic properties of the permanent magnets have been measured. We determined the work point flux density of the single NdFeB magnets. The flux density amounts to: $\boldsymbol{B} = 1106.86 \pm 2.34$ mT (16 PMs).
Secondly, the focal strength of the PMQ has been measured using the floating wire technique. At set distances the current is varied in such a way that above a certain current it sets the wire in motion.
Measurement of the magnetic strength of the quadrupole give: $G\,l = 0.25 \pm 0.01$ T
Thirdly, the field map of the PMQ has been determined with a Hall probe. The result of the measurement is shown in figure 5. The quadrupole has a variation in the gradient of $(\delta G/G) = 0.5$ % and the PMQ is well suited to be used in the linear accelerator beam line.
Finally, measurement and simulation were compared. Matching simulation and measurement gives an alignment error of 0.13 ± 0.05 mm. The main contribution to this error is the dimensional tolerance of the permanent magnets (± 0.05 mm). Permanent magnets will become the largest field error contributors if the dimensional tolerances are reduced below ± 0.01 mm. At such an accuracy shimming of the poles as well as reduction of the dimensional tolerances of the iron poles and core (± 0.01 mm) becomes necessary.

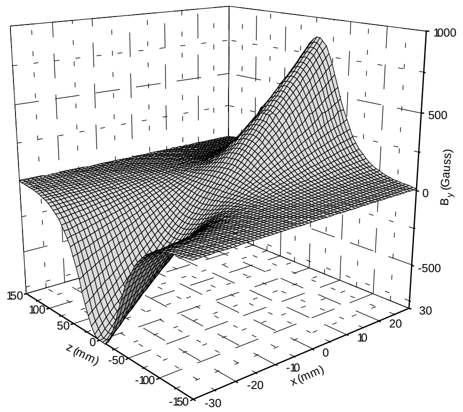

Figure 5 Measured flux density of the PMQ using a Hall probe

5 CONCLUSIONS

Finite element software helps to optimise the geometry of magnet designs and can be used to determine constructional errors.
The PMQ described showes a gradient homogeneity within 0.5%, sufficient for application in the irradiation facility at the Eindhoven University of Technology.
At present, properties of permanent magnets contribute hardly to the field distortion. However, variation in their size are the main contributors to field distortion.
Permanent magnetic assemblies are, at present price levels, low cost systems. This implies future possibilities for ion optical elements that do not need adjustments.

6 ACKNOWLEGDEMENT

The authors are indebted to J. Pijpers and T. van Dorst, of Goudsmit Magnetic Systems BV.

7 REFERENCES

[1] W. van Duijneveldt et. al., Modification of a medical linac to a polymer irradiation facility, Nucl. Instr. Meth. B79 (1993), 871

[2] A.T.A.M. Derksen et. al., An irradiation production unit for polymer research, these proceedings