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Calculations for the Quadrupole Triplets for the S-Band Linear Collider Test Facility

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Abstract

- The test facility for the S-Band Linear Collider will consist of an injector, four accelerating sections and a spectrometer for beam analysis. A quadrupole triplet will be positioned between each of the accelerating structures to ensure focussing. As the quadrupoles of the triplet are relatively short, (the central quadrupole is 100mm long and the two outer magnets 50mm each with an aperture radius of 17.5 mm), accurate three-dimensional calculations of the magnetic field and the effect that the fringe fields will have on the beam are important. The required field gradient was 17 T/m with a pole tip field of 0.3 Tesla. The triplet was modelled using the magneto-static module of the program MAFIA with 800,000 unknowns. The saturation of the yoke between the magnets and the integrated gradient of the field were investigated. Calculations were made both for the design and also for comparison with test measurements on delivery of the finished triplet: considerations of current compensation and error tolerances are discussed.

1 INTRODUCTION

In the test facility for the S-Band Linear Collider, [1] focussing will be necessary between each of the four accelerating sections. As it is desirable to obtain focussing with a minimum of astigmatism, quadrupole triplets were used. Much better stigmatic properties are obtained with a triplet than a doublet so that there is very little difference in the horizontal and vertical foci.

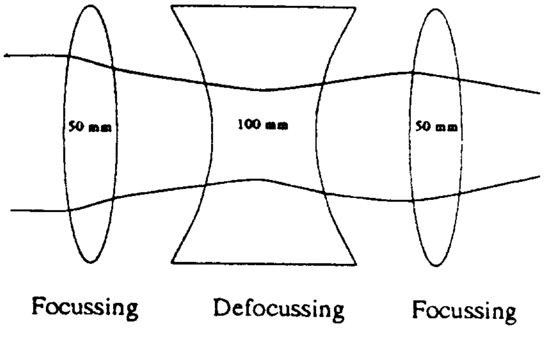

Figure 1. Diagram of a triplet lens, with particle orbits.

These triplets are designed to have the same weight and total length as a linear collider quadrupole so that vibration tolerances and alignment specifications for the projected linear collider can be tested.

A triplet consists of three quadrupole magnets, where the length of each of the two outer magnets is half that of the central one, see Figure 1.

The central quadrupole is 100 mm long and the two outer magnets 50 mm, separated by a distance of 50 mm, each with an aperture radius of 17.5 mm. As the quadrupoles are short and a relatively strong focussing is required, accurate three-dimensional calculations of the magnetic field and the effect that the fringe fields will have on the beam are important. The required field gradient was 17 T/m with a pole tip field of 0.3 Tesla. Further details about the lattice of the test facility for the S-Band Linear Collider [2] and the overall design [1] have been described in other reports.

2 GEOMETRY AND MESH

The hyperbolic pole contour was optimised using the Vector Fields 2D electromagnetic finite element program Opera[7]. A contour was obtained which suppressed the higher multipoles at a radius of $10mm$ to the order of 10^{-5} The pole contour is hyperbolic with axes = $40mm$ as far as a point 5 mm from the edge of the pole whence it continues along the tangent to the curve.

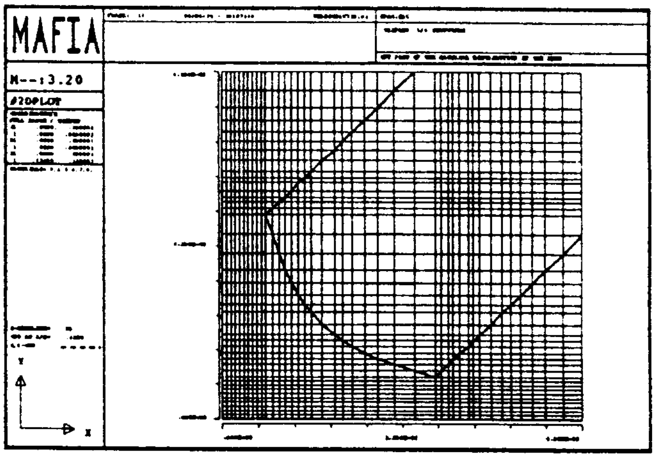

Figure 2. The mesh at the pole tip.

This contour was then reproduced in three dimensions by careful discretisation, see Figure 2., and calculated using the MAFIA electromagnetic module, S [3]. The program is based on the Maxwell Grid Equations which uses a finite difference method and a staggered mesh thus avoiding discontinuities across material boundaries. A detailed account of the theory is included in [4]. Taking advantage of the symmetries of the problem only one eighth of the geometry had to be calculated, see Figure 3. 270,000 mesh points were needed.

3 CURRENT COMPENSATION

In the calculation of the optics for the Test Facility [2] it was assumed that the horizontally defocussing quadrupole, QD, of the triplet is twice as strong as each of the two focussing quadrupoles, QF. The magnets are to be measured in a setting where the total integrated gradient is zero. In this arrangement the measurement is most sensitive. In order to reproduce this in the field calculations, it is necessary to scale the currents flowing in the coils of the outer quadrupoles relative to those of the central one, so that this situation is approximated as nearly as possible. Due to the fringe fields less current is needed in the outer quadrupoles, the end fields between the magnets of the triplet cancel each other to a large extent.

As the $\int H_y dz$ is proportional to the total current, one is justified in integrating the y component of the H (or B) field close to the z axis and scaling the current in the outer quadrupoles with respect to the central one with the ratio of the two integrals.

For the compensation the calculation of the magnetic fields was carried out, first with current only flowing round the defocussing pole and then only round the focussing pole. Then the integral was calculated of the y component of the B-field from the mid-plane to the end of the meshed area (from z=0.0 to 0.3m) in both cases, in order to include all fringe fields.

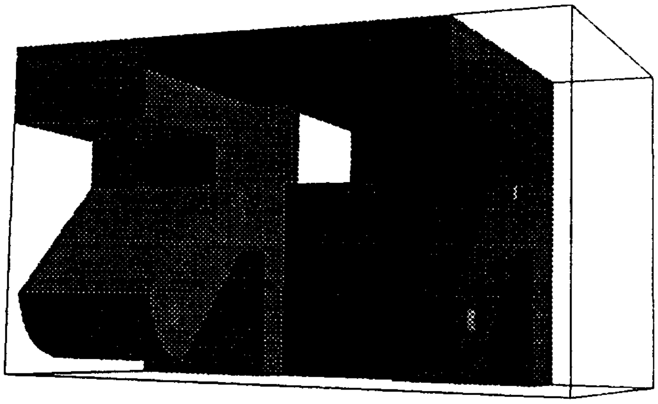

Figure 3. Three dimensional model of one eighth of the triplet.

4 THE CALCULATION

The same current density was used for the QD in the three dimensional calculation as in the two dimensional version. The coil cross section was $364.5 mm^2$, with $2071.5 Amp.turns$ giving a current density of $5.683 A/mm^2$. This current was distributed in 2 rows of 6 filaments round each pole.

Figure 4 displays equipotential lines of the absolute value of the B-field in a y-z plane at x=0 m, showing the field distortion of the fringe fields, while Figure 5 shows the B-field in an x-y plane at z=.125 m, the centre of the QF magnet, As the beam in an accelerator is mainly affected by the integral of the magnetic field which it passes through, the gradient of $\int B_y dz$ was plotted along the xaxis, see Figure 6.

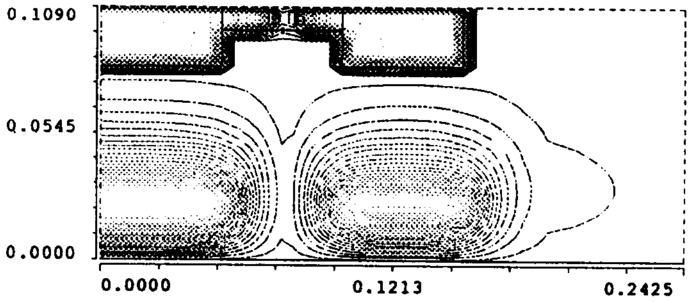

Figure 4. Contour plot showing equi-potential lines of the absolute B-field in a z-x plane at y=0.

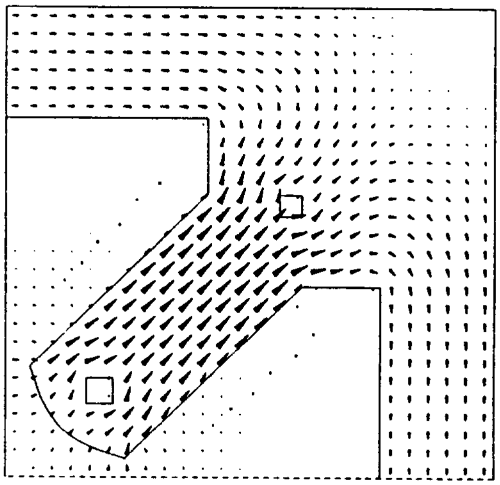

Figure 5. Arrow plot of the B-field in an x-y cut through the QF magnet.

The first column of Table 1 lists the integrated field values near the axis which were used for the current compensation. The second column contains the field gradient near the origin with the pole tip field in the third column.

Table 1: Field values

	$\int B_y dz$ (Tm)	*gradient* B_y (T/m)	$\lvert B\rvert$pole tip (T)	12-pole
QD	-5.1910^{-4}	-16.84	0.29	$1.2 \cdot 10^-5$
QF	4.0510^{-4}	12.01	0.21	$2.4 \cdot 10^-5$
QF_{old}	5.8410^{-4}	--	--	--
2D	--	-16.83	0.295	$1.7 \cdot 10^-5$

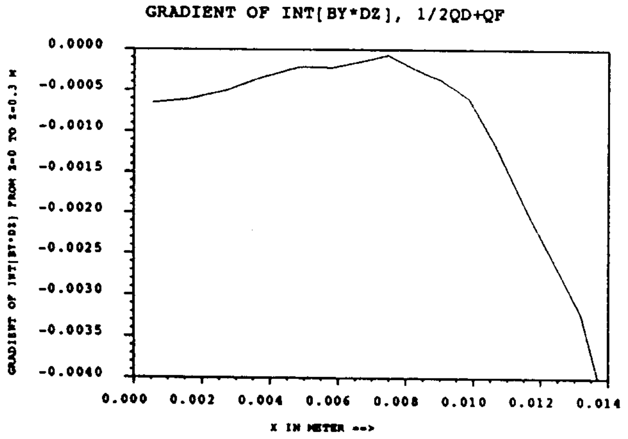

Figure 6. The $\delta/\delta x(\int \mathrm{B_y dz})$ at points along the x-axis after current compensation

One concern was that the iron of the rather thin connecting plates between the quadrupoles, (these appear in a darker shade in Figure 3), would saturate and thus affect the reproducability of the field. This configuration was necessary to provide access for the power supply, as the QD quadrupole has a separate power supply and the QF's will be powered in series. The calculations showed that the permeability remains above 70 Vs/Am and that in general little flux flows in the connecting yoke.

5 ERROR ESTIMATION AND LIMITS

A criterion was needed which would be both easy to measure and simple to calculate [5]. As a measurement of the non-linearity of the field in the beam aperture at a radius, r_1, the values of the B-field on the x-axis at $x = r_1$ and at $x = r_2$, where $r_2 = 2 \cdot r_1$, were combined to form the error function

$$\mathrm{Err_{r_1}} = \int_0^{0.3} (\mathrm{B_y(r_1)} - (\mathrm{r_1/r_2}) \cdot \mathrm{B_y(r_2)})\mathrm{dz}$$

$\mathrm{Err_{r_1}}$ was then calculated at all points along the z-axis and integrated in z with each of the magnets excited separately and then for the whole triplet. This shows the integrated difference between the linearly extrapolated value at double the radius and the non-linearly calculated value. These values can be measured by means of a rotating coil. An arbitrary limit was imposed for each quadrupole

$$limit(quad) = \mathrm{Err_{r_1}} < 1.3 \cdot 10^{-5}\mathrm{Tm}$$

and for the entire triplet

$$limit(triplet) = \mathrm{Err_{r_1}} < 3.0 \cdot 10^{-6}\mathrm{Tm}$$

This would enable the measurement of other effects on the beam position and emittance such as instabilities and wake fields, without the need to estimate the contribution from the field error. Figure 7 shows that with the present geometry and current densities, this limit can be fulfilled within a radius of $9.5mm$. The curves are scaled so that they can be represented on one plot. The solid line is $\mathrm{Err}_{10mm}(QD)$, the dashed line shows $-\mathrm{Err}_{10mm}(QF)$ and the dotted line is

$$(limit(quad)/limit(triplet)) \cdot \mathrm{Err}_{10mm}(1/2QD + QF)\ ,$$

thus the horizontal line represents the tolerance for all three curves.

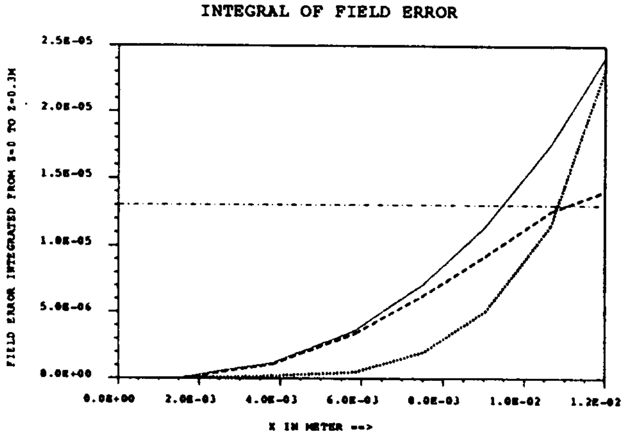

Figure 7. The scaled non-linear field errors at 10 mm.

Multipole expansions of the integrated fields at a radius of $10mm$ were also investigated. The main contribution comes from the 12-pole, at $1.2 \cdot 10^{-5}$.

6 CONCLUSION

The design for the quadrupole triplet for the S-band Test Facility has been verified by calculation. The required gradient and pole tip field can be achieved without undue saturation of the iron. The tolerances for the field errors are satisfied within a radius of $9.5mm$. As the magnets are still under construction the calculations will be compared with measurements at a later date.

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7 REFERENCES

[1] N.Holtkamp for the S-Band Study Group: "Status of the S-Band Linear Collider Study" DESY M-93-05 Sept 1993.

[2] R.Wanzenberg: "A Lattice for the S-Band Linear Collider Test Facility" DESY M-93-07 Oct 1993.

[3] F.Krawczyk und Th.Weiland: "A New Static Solver with Open Boundary Conditions in the 3D-CAD-System MAFIA," IEEE, Trans.in Mag.22/1(1988) pp.55-57.

[4] M.Bartsch et.al.: "Time Domain Electromagnetic Field Computation with Finite Difference Methods",IEEE 93, Berlin.

[5] J. Roßbach: " Error specifications for triplet quadrupoles of S-band Test Facility" May 1993, unpublished

[6] The MAFIA Collaboration: "Users Guide Version 3.x",CST GmbH, Lautenschlägerstr.38, D64289 Darmstadt, Germany.

[7] Vector Fields Ltd., 24 Bankside, Kidlington, Oxford, OX5 1JE, England.