CONCEPTUAL DESIGN OF A 5 T/mm QUADRUPOLE FOR LINEAR COLLIDER FINAL FOCUS

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Abstract

The luminosity required of a future linear $e^+ e^-$ collider in the TeV energy range puts high demands on the final focus elements. In particular, if a classical quadrupole arrangement is chosen, the last magnet should be capable of producing a gradient of several tesla per millimeter. We have studied the performance limits of a quadrupole having soft ferromagnetic poles of sufficiently simple geometry to allow fabrication to sub-micron tolerances, excited by blocks of commercial permanent magnet material. It is shown that it should be possible to obtain a good quality quadrupole of less than 1 mm aperture, with up to 1.4 T pole-tip field.

Introduction

Studies are presently underway for the next generation of electron-positron colliders[1,2]. In order to produce a useful interaction rate, these linear machines, with a maximum centre-of-mass energy in the 1-2 TeV range, require extremely small transverse beam dimensions at the collision point. This can hopefully be achieved by a final focus optics based essentially on magnetic quadrupoles, but incorporating sophisticated chromatic corrections[3,4]. The most critical focusing element is the last quadrupole before the interaction point: we seek a magnet producing a gradient in the 1-10 T/mm range, with a channel through which the spent (and disrupted) beam can pass, and the axis of which can be aligned with a precision of some tens of nanometers. In order to minimize the interference with the experimental apparatus which will be installed around the interaction point, these magnets should themselves preferably be of relatively small transverse dimensions; this constraint, together with the fact that the quadrupoles may be immersed in the field of a spectrometer magnet would indicate the choice of pure permanent magnet technology, and this line of approach is indeed being followed up[5]. It may however be less difficult to satisfy the other constraints by calling on a hybrid approach with permanent magnets providing the magnetomotive force for a quadrupolar field produced by poles of simple geometry, made from soft magnetic material. The purpose of this study is to explore such a possibility.

The Model

The cross-section of the model chosen for study is shown schematically in Fig. 1. Referring to this figure, magnetic flux originating in rectangular blocks, 1, of permanent magnet material, is guided to the pole-tips via suitably shaped soft magnetic material, 2. The upper and lower halves of the quadrupole, each of which resembles somewhat a recording head, are positioned with respect to one another by means of non-magnetic spacers, 3, providing a passage, 4, for the spent beam. Magnetic shunts, 5, give the possibility of adjusting the field in each half magnet.

The pole region is shown in detail in Fig. 2; the coordinate axes and pole parameters are also defined here. The gap, 2g, between the poles is determined for each half-magnet by a local non-magnetic spacer, the thickness of which can be accurately gauged. The poles have only flat surfaces. The bore radius r_b is defined as the distance from the axis to the 45° plane.

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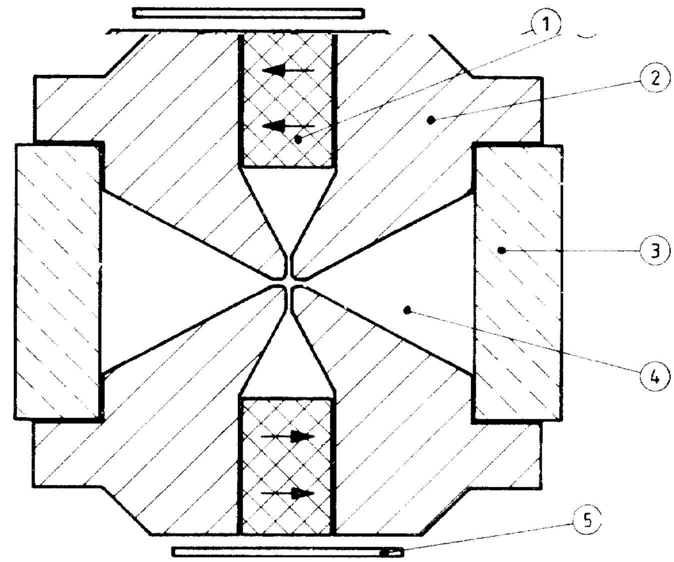

Fig. 1 Schematic cross-section of the quadrupole

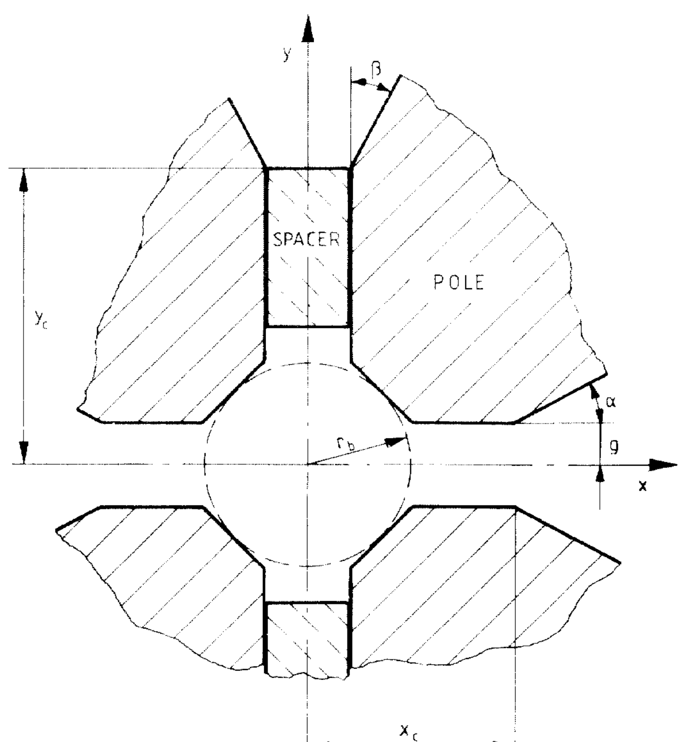

Fig. 2 Characterization of the pole region

The model has been chosen with regard to achieving a mechanical definition of the pole geometry to as high an accuracy as possible. The determination of the magnetic axis follows, provided the uniformity of the material of the poles can be assured. At present, this would seem to be the preferred approach due to the difficulty of defining the magnetic axis to sufficient accuracy by means of magnetic measurements.

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We shall see in the next section that, thanks to local fourfold symmetry, even with a seemingly crude flat surface approximation to the ideal hyperbolic pole shape, a rather clean quadrupolar field can be obtained.

Results of Computations

The basic parameter study was performed using the program POISSON, simulating the magnetized permanent magnet material with sheet currents, and using a standard permeability table corresponding to low-carbon steel. Subsequent trial runs were made with other permeability tables, corresponding to such materials as vanadium-cobalt steel (saturation induction 2.3 T) and amorphous metal (saturating at 1.7 T): as was to be expected, the maximum gradient depends linearly on these saturation characteristics. Typical flux lines in one quadrant are shown in Fig. 3.

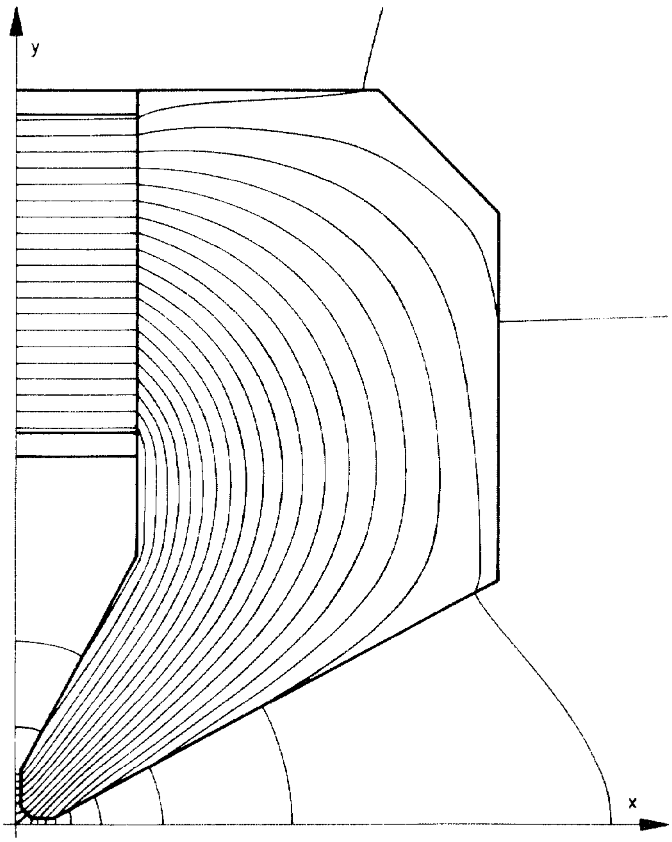

Fig. 3 Flux lines in one quadrant of the magnet

Referring to Fig. 2 for the definition of the parameters, it has been verified that the taper angle of the pole, α, should be in the range 25° to 30°; α and β should be similar, but not necessarily identical. Likewise, provided x_c is greater than 1.6 r_b, and y_c is greater than or equal to x_c, the quadrupole field is symmetric within the bore radius. The influence of the ratio g/r_b on the variation of gradient across the aperture is shown in Fig. 4. The maximum gradient which can be obtained is also weakly dependent on this ratio as can be seen in Fig. 5. Nominally, i.e. assuming low-carbon steel type characteristics for the poles, it can be seen that the gradient corresponds to a pole-tip field of about 1.4 T. It has been verified that this can be trimmed over the range 10 to 100 % of full field by suitable choice of thickness and position of the magnetic shunt.

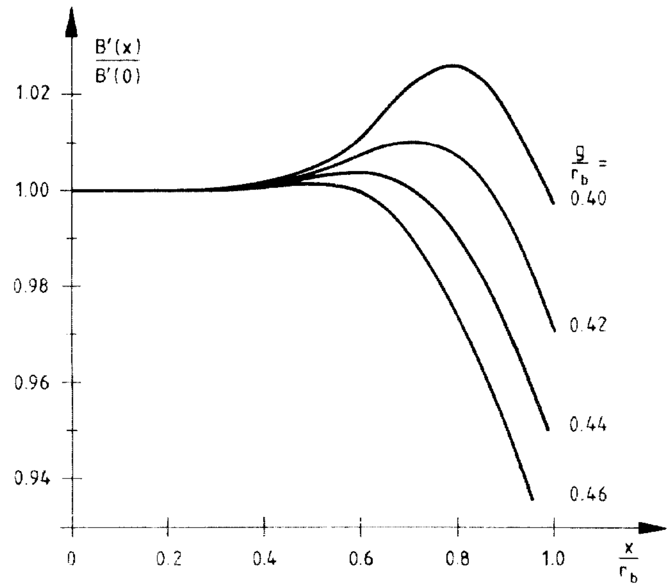

Fig. 4 Gradient quality across the aperture

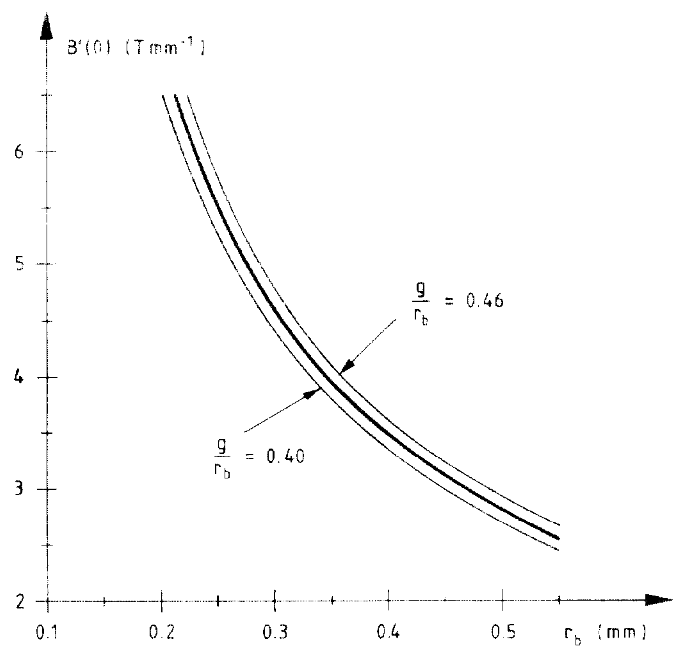

Fig. 5 Maximum gradient vs. bore radius

Studies have also been made on how to take advantage of the fact that the required good field area is usually elliptical rather than circular. It is found that any departure from fourfold symmetry in the immediate vicinity of the bore leads to significant complication of the pole geometry for similar gradient quality. For the example of Fig. 6, the nominal gradient is 4 T/mm, with good field as shown in Fig. 7. The gain is about 15 % if we consider the larger useful aperture in the vertical plane, and if the reduced aperture in the horizontal plane is acceptable.

The effect of errors in pole geometry has been computed by introducing displacements of the corners of one or more poles. Typically for a symmetric quadrupole of bore radius 0.5 mm, the influence of random errors of up to 1 μm would appear to be acceptable. The asymmetric magnet is more sensitive to such errors.

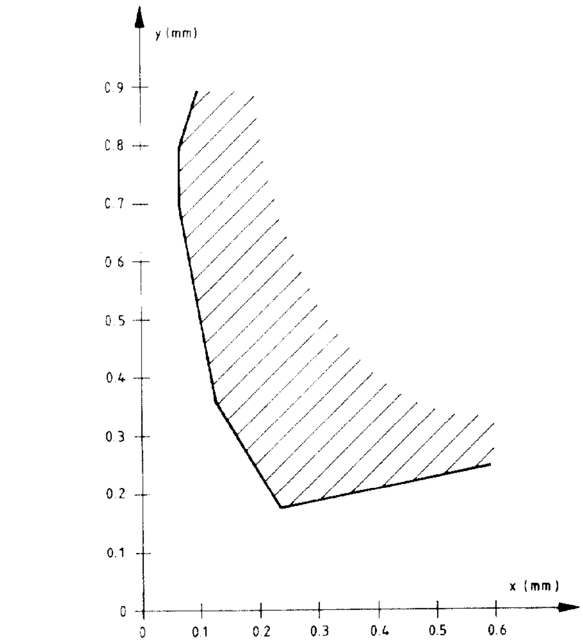

Fig. 6 Possible pole geometry for an asymmetric magnet

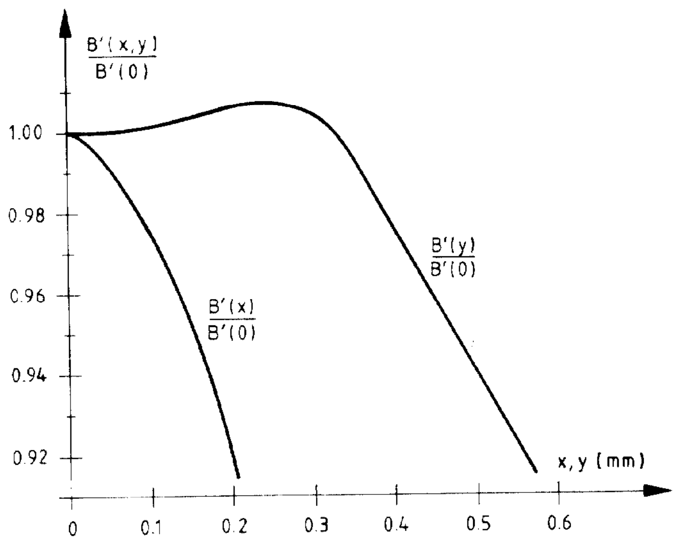

Fig. 7 Typical asymmetric gradient quality

Practical Considerations

Materials

For the permanent magnet material, commercial samarium-cobalt should be suitable. Its magnetic performance is adequate for this purpose, and its stability with regard to temperature and radiation is far superior to that of neodymium-iron-boron. The initially higher value of $(BH)_{max}$ of this latter material only leads to an improvement of a few percent at most in the strength of the magnet discussed here.

As regards the poles, we seek a material having high permeability and high saturation induction. The size of the magnetic domains in regular bulk magnet steel being of the order of some tenths of a millimeter, it is unlikely that this material will be satisfactory as such. In the form of stacked splat-cooled sheet, however, this, or even better, iron-cobalt alloys may prove to be suitable[6]. Amorphous metal would be a natural choice, but the highest value of saturation induction currently achievable is about 1.7 T.

Construction

It is envisaged that a complete 1-2 m long magnet will be assembled from individually optimized 20-100 mm long modules. This will provide convenient units for micro-machining and measurement, and the possibility of longitudinal sculpture of the gradient and cross-section. The lateral spacers will be part of a rigid girder structure, fine adjustment of the axis being achieved by displacement and/or deformation of this girder using a series of piezo-electric jacks. Coarse changes in gradient will be obtained by adding or taking away modules, fine changes by equipping one of the modules with adjustable magnetic shunts or coils. The similarity of the basic half-module to a recording head would suggest that techniques exist for obtaining the required sub-micron tolerances[7].

Magnetic measurements

The small aperture of these magnets limits the choice of techniques which can be applied to their measurement. The classical method of integrating the voltage induced across a wire when it is displaced in the field would however appear to be viable. As the magnet can be assembled around the wire, we envisage displacing a module relative to a fixed wire to generate the signal. High demands are placed on the quality of the integrator, and the system will have to be carefully shielded against noise. Techniques using the forced vibration of the magnet table and/or the natural vibration of the wire are also under investigation.

Conclusion

Micro-quadrupoles generating magnetic gradients of up to about 5 T/mm appear to be feasible. For the purposes of optics and aperture studies, one should assume a pole-tip field of 1.4 T. The possible advantages of the hybrid permanent magnet/soft pole design for this application warrant further studies and model work in parallel with that underway for the pure permanent magnet design.

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