OPTMIZATION OF THE MAGNETIC ELEMENTS OF THE MULTI PURPOSE SPECTROMETER (MPS)

S. Frullani, F. Garibaldi, F. Ghio, M. Jodice, G.M. Urciuoli,
Laboratorio di Fisica, Istituto Superiore di Sanita' and I.N.F.N. sezione Sanita',
Viale Regina Elena, 299 00161 Roma, Italy
R. De Leo
Dipartimento di Fisica, Universita' di Lecce, I.N.F.N. sezione di Lecce
M. Nervi, M. Repetto,
Dipartimento di Ingegneria Elettrica,
Universita' di Genova, Via Opera Pia 11a, 16145 Genova, Italy

Abstract -- The CEBAF's Hall A MPS additional capability is planned to constist of two quadrupoles and one dipole room-temperature magnets. The physical characteristics of the single magnetic elements have been investigated with two- dimensional and three-dimensional codes. In the case of 2-D studies a very powerful optimization procedure implemented to the VF/PE2D code has also been used.

Introduction

The optical design requirements for the MPS [1] are fulfilled by the QDQ system whose general layout is reported in fig. 1. The spectrometer is planned as a possible additional capability to be installed in the Hall A of CEBAF. The funding of the project is being considered by the Italian Authority for Nuclear Physics (I.N.F.N.) within an International agreement with CEBAF and other parties.

The essential parts which constitute the spectrometer are the three room-temperature magnetic elements: a "Collins"[2] type quadrupole followed by a vertically bending dipole magnet and another conventional large aperture quadrupole at the exit of the system. The present design is also thought to fulfil non-optical requirements such as the possibility to place the whole system close to the accelerator beam pipe, to allow the detection of particles scattered at forward angles, and the possibility to allow for vertical movements (for out-of-scattering-plane measurements) thus having constraints on the weight of the device.

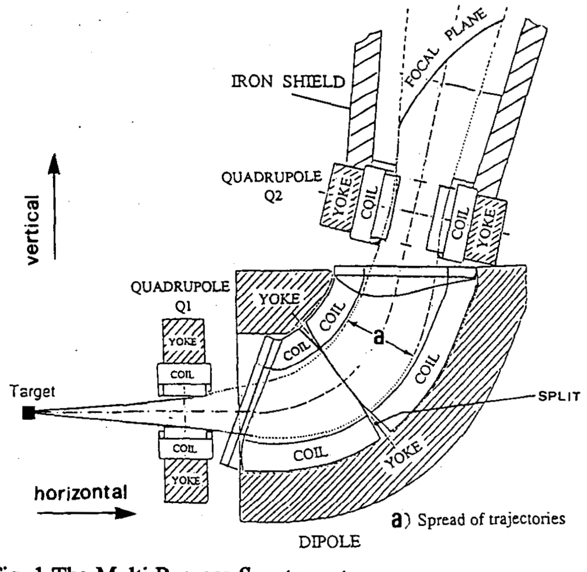

Fig. 1 The Multi Purpose Spectrometer

The Magnetic Elements

The main design properties of the dipole and quadrupoles of the MPS, are reported in tables I and II respectively. They were derived by using the tracing program RAYTRACE [3] that calculates the trajectories of charged particles in magnetic fields. The same program allowed to choose the right

TABLE I
Main dipole specifications

Magnetic length	3.15	meters
Gap	0.33	meters
Central Bend radius	2.409	meters
Central Bend angle	75	degrees
Entrance angle*	-21.3	degrees
Exit angle*	-19.7	degrees
Effective width	1.20	meters
Min/Max Central Field	0.2/1.8	Tesla
Max. Field deviation	$2.x10^{-4}$	
Weight	268	Tons

* Definition and convention according to [3].

TABLE II
Main quadrupoles specifications

	Q1	Q2
Type	"Collins"	conventional
Radius (m)	0.25	0.40
Magnetic length (m)	0.80	1.20
Quadrupolar field at the pole-tip (T)	0.901	0.883
Multipole strengths at the pole-tip:		
quadrupole (T)	-0.901	-0.883
sextupole (T)	0.105	0.085
octupole (T)	0.074	-0.031
decapole (T)	-0.014	0.017
dodecapole (T)	0.001	0.0125
Weight (Tons)	23	65

inclination of the entrance and exit pole faces of the dipole with respect to the central trajectory, as well as the shape of the faces (both are described by a fifth-order polynomial) in order to fulfil the optical design requirements. The intermediate "split" region in the dipole introduces multipoles that were again used to optimize the optical properties. The optimitation of the magnetic elements of MPS essentially consists of designing real magnet elements whose fields reproduce the fields used in the calculations performed by RAYTRACE. In fact RAYTRACE uses realistic magnetic fields but does not give the design of the magnetic elements that allows to get these fields.

Both quadrupoles have multipole terms of higher order up to dodecapole with room-temperature coils and iron pole piece design. The choice of a "Collins" type for the first quadrupole Q1, is due to the yoke shape. In fact, there is room for the beam pipe when the spectrometer is used at small scattering angles (compare the upper parts of figure 6a and 6b).

In order to investigate on the magnetostatic designs for the dipole and quadrupoles, the 2-D codes POISSON [4] and VF/PE2D [5] as well as the 3-D code TOSCA [6] have been employed. Designing the poles, yokes and coil geometries for the magnetic elements, different objectives have been taken into account. In the case of 2-D cross sections analysis, for example, the following items have been considered as objectives: *i)* Efficient magnetic circuit for the yokes in order to minimize iron volume; *ii)* The radial homogeneity of the magnetic field of the dipole as a 2-D problem; *iii)* The positions of the Effective Fields Boundaries (EFB) [7] of the dipole; *iv)* Their stability and field quality over the entire dynamic range of the dipole (0.2 to 1.8 Tesla); *v)* Harmonic analysis for the field of the quadrupoles.

The complexity of the structure, the range of variation of magnetic flux density values and the rather high field accuracy required, call for the use of automated optimization techniques. For practical reasons those are only applicable to 2-D computations, whose results then become the starting point for 3-D designs. The device being designed may be considered a black box with many unknown design parameters and with several objectives or design constraints. To this process an optimization technique can be applied, in the hypothesis of obtaining in some way the behavior of the device as a function of the entries.

Overview of the optimization process

Between the different classes of optimization procedures, those making only use of function values should be preferred. In fact the evaluation of the gradient of the objective function as a function of design variables, required by many methods, cannot in general be easily obtained by analytical means and should be evaluated by means of finite difference approximations. This is heavy in terms of computational cost and in general could lead to trouble if the increment values of the design parameters are not chosen appropriately.

Two different classes of zero-th order techniques can be devised: the deterministic one, in which the location of the points where the objective function is evaluated is determined by a rule embedded in the algorithm, and the stochastic one, in which the search towards the optimum point is performed in a random-based way. While the deterministic methods have the property of converging quite quickly to a minimum point, but give no warranty that this is the global minimum of the objective function in the constrained design variable space, the stochastic ones have a greater probability to reach the global minimum but require a much larger number of function evaluations. Because of the high cost of the evaluation of the objective function, the deterministic methods seem to be more suited to the use in an optimization loop in conjunction with finite element codes [8].

The Pattern Search method

The "Pattern search" method [9] is characterized by the "ridge following" property; in fact it tries to find a direction in the design variable space, the "pattern", along which there is the maximum reduction in the objective function value. Starting from a given point the algorithm perturbs each of the design variables with a given increment value. Once it has found a direction where the reduction of the objective function is maximum, it moves in that direction and starts again a new exploration. If it is not able to locate any better point in any direction, it halves the increment value and restarts. The convergence is reached when the increment value falls below a given limit.

A code based on this technique has been coupled in an iterative loop with the two dimensional finite element code, VF/PE2D, in order to implement the above-outlined scheme.

Dipole optimization strategy

The main field specifications to be taken into account in the design of the dipole were: central radius 2.409 m, central field ranging between 0.2 and 1.8 T, maximum field deviation $2*10^{-4}$ in a zone of 1.2 m across the central radius for every value of central field.

The overall structure for the magnet is a H-frame with saddle coil. The basic geometry of the magnet cross section is shown in Fig.2; its main characteristics are: the interposition of a Purcell filter [10] in order to improve the radial homogeneity of the field and a lateral profile of the pole shaped as an approximation of a Rogowski profile by two straight segments. The analysis of the structure as initially devised, showed a value of field deviation that was an order of magnitude greater than design at each central field value.

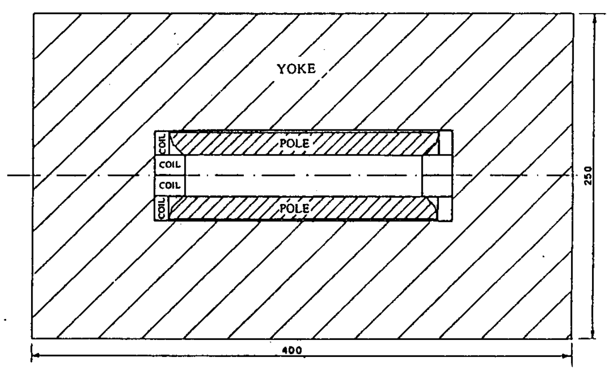

Fig. 2 Dipole cross section geometry

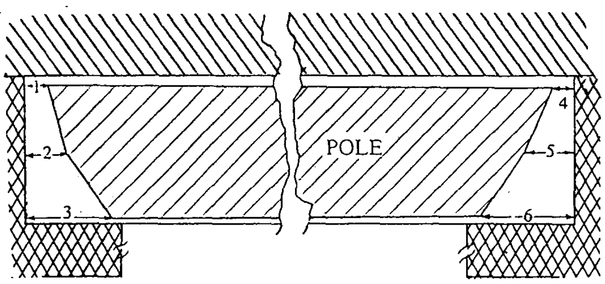

Fig. 3 Pole lateral profiles. The six design parameters to be varied in the optimization process are also shown.

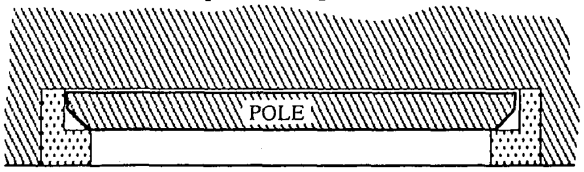

Fig. 4 Optimized poles lateral profiles.

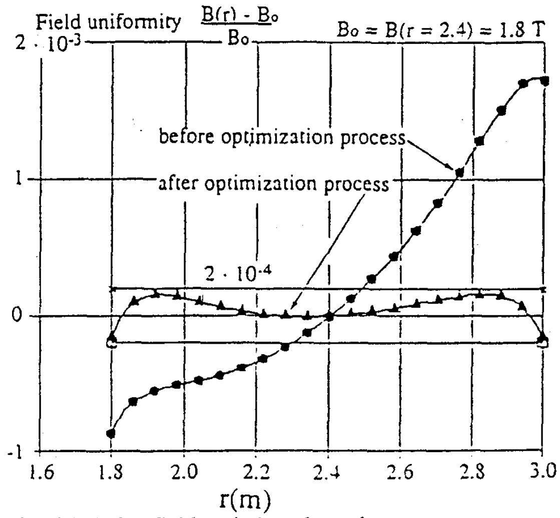

Fig. 5 Relative field variation along the gap

The wide range of the central field results in a significant variation in the yoke iron permeability. The strategy adopted to meet the design requirements was to optimize the shape of the pole at an intermediate field value of 1.8 T, and then check the behavior of the magnet at the other field values. Of course, owing to the characteristics of the dipole (the inner radius is much smaller than the outer one), the study was performed using the axial simmetry feature of PE2D and POISSON.

The first optimization attempted was based on the determination of the positions and the dimensions of passive shims to be placed on the pole face. This technique gave very poor results, due to the strong dependence of shims effectiveness over the field values. This technique was then abandoned in favour of a lateral shaping of the pole piece. The structure, because of the relatively small radius, is asymmetric with respect to the mean radius of the dipole, giving rise to an asymmetric field pattern along a line stretching radially in the gap: an asymmetric shaping of the pole lateral profiles could compensate this fact.

An optimization was then performed, using the procedure previously described; the design variables, which are left to vary during the optimization process, were the six radial positions of the vertices of the pole as shown in Fig.3, and the maximum value of the field deviation along the gap was the objective function. The final optimized profile is shown in Fig.4. The comparison of the behavior of the field uniformities obtained in the starting and in the final configurations is shown in Fig.5. This good result obtained at a reference value of the field proved to be much more stable with respect to saturation than the previous one with shims, and so it was taken as a reference for the design.

The quadrupoles

Due to the relatively short magnetic length as compared with the large aperture, both quadrupoles come to be "intrinsically" 3-D problems. An investigation of them through 2-D optimization techniques is therefore needed just to understand the sensitivity of the 2-D problem to the geometry, while a detailed investigation through 3-D codes is of great importance. Figures 6a and 6b show the 2-D solutions for half of the geometry of the Q1 and Q2 quadrupoles respectively.

3-D studies

In the case of the dipole the 3-D geometry has been fully investigated without considering, up to now, the central "split"region. The "split"should be obtained through a V-shaped cut produced on the poles surfaces following the polynomial behavior suggested by RAYTRACE along the radial direction in the middle of the dipole, being deeper and deeper going away from the central radius, as shown in figure 1,where the divergences between the "split" EFB increase.

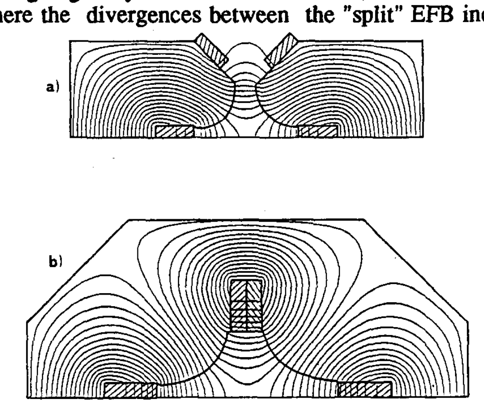

Fig. 6 a) Field flux lines in the quadrupole Q1
b) Field flux lines in the quadrupole Q2

This is a rather complex configuration to simulate with reliability that has certainly to be investigated in detail in the next step. Up to now the behavior of 3-D solutions for the dipole, without split, so having a large uniformity field region, has been studied. The pole profiles, optimized in 2-D, have been successfully checked in the uniform region for several excitations of the magnet.

Fig.7 shows the field in the gap of the dipole that we have to reproduce, that is the field that RAYTRACE indicates suitable for the optical requirements of MPS (as written above the split region was not considered at the moment). The value of the field in the uniform region was 1.75 T and, of course, the region of interest is confined to the part of the gap crossed by the trajectories of the particles. The 3-D solution that better fits the field shown in figure 7 is reported in figure 8. We still have regions where the required specifications of a maximal deviation less than 2 parts in 10^{-4} has not been reached yet, mainly in the fringing field regions. The positioning of clamp field [11] at the entry and exit faces of the dipole will certainly improve the agreement with the required field. Furthermore, an iterative process is needed by the use of the fringing field behavior as obtained with TOSCA to be adopted for the optical property calculations, so as to study a new solution again with TOSCA and so on. This process, we have already started to study, is expected to improve enough our actual solution.

At present we are just at a preliminary stage in the study of 3-D geometries for the quadrupoles. Two configurations have been considered. The results of a preliminary harmonic analysis show that the edges of the poles are the critical parts to be shaped in order to get the desired multipoles.

Conclusions

The studies so far performed have shown the feasibility to

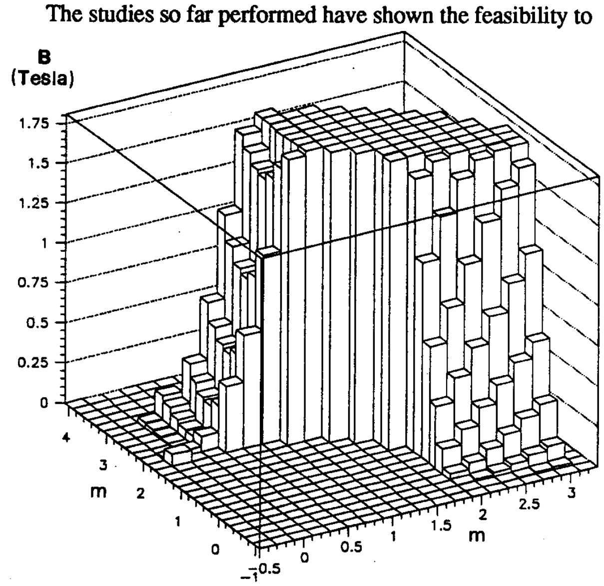

Fig. 7 Map of the required dipole field in the middle plane

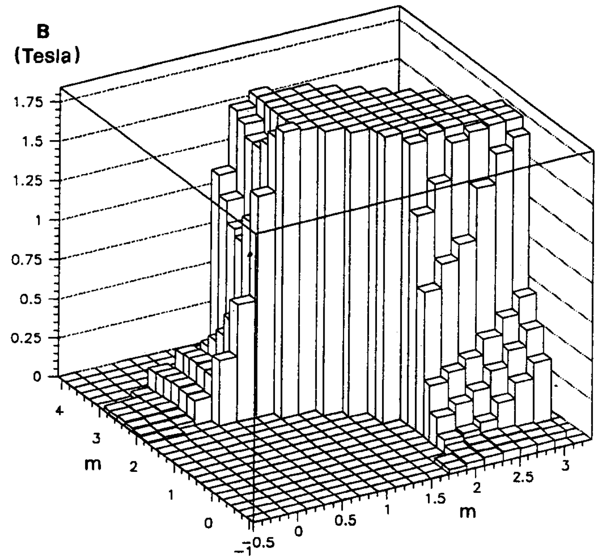

Fig. 8 Dipole field map: a TOSCA computation

reach the needed requirements for the designed components of the device, giving for the principal part, the dipole, reasonably stable solutions at different excitations of the magnet. 3-D investigations are still under study giving promising results.

References

[1] S. Frullani et al., "A Magnetic Multi Purpose Spectrometer", these Proceedings
[2] G.E.Fisher, "Iron-dominated magnets", SLAC-PUB-3726, July 1985
[3] S.Kovalski and H.A.Enge, Raytrace Manual, Laboratory for Nuclear Science and Department of Physics, M.I.T., May 1986
[4] POISSON reference manual, Los Alamos Accelerator Group, MS H829, Los Alamos National Laboratory, Los Alamos, NM 87545 USA, January 1987
[5] VF/PE2D reference manual (version 8.2), Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England
[6] TOSCA reference manual (version 6.0),Vector Fields Limited, 24 Bankside, Kidlington, Oxford OX5 1JE, England
[7] K. Halbach,NIM.,119,(1974) p 329
[8] G. Drago, G. Molinari, M. Repetto, G. Secondo, "Optimization in nonlinear magnetostatic problems", Proc. of the 4th International IGTE Symposium, Graz, Austria 10-12 October, 1990
[9] R. Hooke, T.A. Jeeves, "Direct search solution of numerical and statistical problems", J. Assoc. Comp. Mach., Vol. 8, 2 (April 1961), pp. 212-229
[10] H.A.Enge, NIM 28 119 (1964)
[11] K.Halback,NIM.,119,(1974), p.327