MAGNET SECTOR DESIGN FOR THE EULIMA SUPERCONDUCTING CYCLOTRON

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ABSTRACT

In the frame of the European Light Ion Medical Accelerator project, which calls for the acceleration of a 400 MeV/n ^{16}O beam in a hospital based facility, a study of the superconducting magnet for the separated sector cyclotron has advanced. Several approaches to the 3D analysis of the magnetic field in a complicated structure have been employed, and attention is drawn to certain general properties of available methods. Implications of the magnet design on beam dynamics are considered, and the optimal shape of the pole sectors is derived. Trim coil design and stability tolerances in a fixed energy separated sector cyclotron, is also discussed.

INTRODUCTION

The European Light−Ion Medical Accelerator (EULIMA) is an international effort to design and build a hospital based accelerator which should produce light−ion beams of sufficient energy and intensity to be of clinical and biological relevance. As a basic option of the feasibility studies for EULIMA we have chosen to explore the inherent high intensity performance of a cyclotron in a region outside the "natural territory" of these machines. Consequently, as a most promising design, a separated sector machine designed for fixed−field operation and final O^{8+} (or C^{6+}) particle beam energy of 400 MeV/n and intensity of the order of 10^{12} pps, has been studied, and the feasibility of several major machine components determined[1].

One of the main efforts of the EULIMA feasibility study has been devoted to the design of the magnet, which, besides determining the beam dynamics conditions, enabled a better insight into the cost and implementation issues of EULIMA. Our present approach assumes that a single superconducting coil is employed, driving the sector magnets into saturation and contributing as much as 50% to the average magnetic field of about 3 T. Aside from the simplicity of having a single cryostat, this concept introduces several novelties into the machine design, which are related to the fact that, unlike other separated sector cyclotrons, the magnetic field in sector valleys is large and plays an important role in determining the machine parameters.

Although the task of magnet design is somewhat simplified in the case of the EULIMA cyclotron since it is to be considered as a fixed frequency machine, several approaches for magnetic field analysis were needed. In first instance, a modified hard−edge model was employed to study a series of possible magnet geometries, defined by the central field, the extraction radius and magnetic field periodicity, sector angular width and the spiral angle. We found that a beam of up to 500 MeV/n could be accelerated in a rather compact four sector design with an interior coil radius of less than 2.5 m. The parameters of the resulting basic design, which was further on examined in detail, are given in Table 1.

It should be pointed out that due to large forces involved, the interplay between the magnetic and mechanical design of the sector magnets is unusually strong in a single superconducting coil concept. Several design possibilities, described in more detail in ref.(2), have been considered in order to increase the mechanical rigidity of the structure and to enable adequate access to various machine components. The mechanical solutions influence in a different manner the magnetic field design (contributing as much as 0.1 T to the median plane field, in the case of the addition of a top cover plate), illustrating the interdependence of final machine parameters and the adopted engineering solutions.

Table 1.
Parameters of the EULIMA magnet

Number of sectors	4
Sector gap	50 mm
Sector angular width	35 deg.
Average sector spiral	30 deg./m
Coil internal radius	2.20 m
Coil external radius	2.60 m
Coil height	0.26 m
Coil distance from median plane	0.24 m
Current density	2650 A/cm^2
Yoke height	4.30 m
Yoke max radius	4.60 m
Iron weight	4 x 155 t

In this report we present certain details of the EULIMA magnet design. In particular, we discuss the main superconducting coil parameters and the magnet yoke design, and determine the optimal values for the sector angular width and spiral angle. Also, attention is drawn to certain aspects of beam dynamics related to the general tolerances in a fixed−energy separated sector cyclotron.

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SUPERCONDUCTING COIL PARAMETERS

The EULIMA magnet sectors are excited with a pair of cylindrical superconducting coils symmetrically located in a single cryostat, as sketched in Fig. 1. The total excitation field of the coils should drive the magnet poles into saturation, and contribute on the average about 1.5 T to the median plane field of the cyclotron. Furthermore, since the machine is conceived to operate at fixed frequency, the coil field should dominantly contribute to the control of the average field isochronous profile. All these factors play a role in determining the coil parameters: its internal radius, width and height, current density, and eventually, the coil splitting ratio.

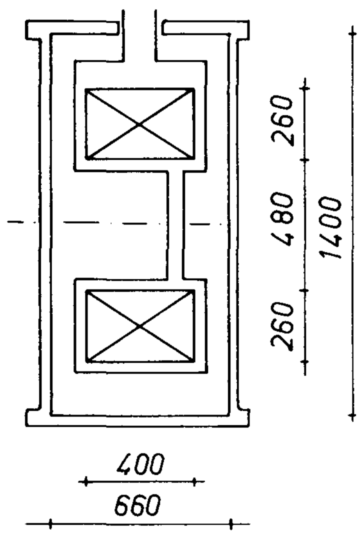

Fig. 1. A sketch of the superconducting coils and cryostat

Assuming that the iron field contribution in the median plane derives from the saturated poles only, we have looked at the dependance of the average field error, in relation to the isochronous profile for z/A = 0.50 beam and 17 MHz particle frequency, on the coil height and width, as well as on the spliting ratio of the coil. It was found that it is advantageous to split the coil in two independant (but very asymmetric) sections only when the total coil height is restricted to be smaller than 60 cm, which is not the case in our design, since the vacuum chamber plate is located at 68 cm. Hence, a singly excited coil has been assumed, and the values of 24 cm and 26 cm for the distance from median plane and coil height were found to give a satisfactory isochronous field and an acceptable cryostat height.

THE YOKE DESIGN

The yoke of the EULIMA sector magnets basically follows the design of similar separated sector machines in that it should supply the shortest path for the return flux. However, due to large magnetic forces, and loss of simple geometry due to the strong spiraling of the poles, special care should be given to achieving uniform flux distribution in the yoke on one hand, (which, as a consequence, minimizes the stray field), and a "naturally" rigid and stable mechanical structure of the yoke, on the other. These two aspects are strongly coupled in magnets of this physical size. An initial yoke structure with a conservative value of 1.45 for the ratio of yoke-to-pole cross-sections was chosen for further mechanical and magnetic studies.

Clearly, the complexity of the yoke shape demands that a full 3D magnetic calculation be done, preferentially with a finite-element code which can solve both the magnetic and structural problems. The ANSYS package seemed to fulfil these conditions, and a magnet model was defined with a 3D version of this code. However, having in mind that models of this physical size are very demanding on the computer resources, and that the results should be assessed with utmost care, especially if a precision of a few percent is desired, simultaneously with the work on the ANSYS model, we formulated a TOSCA model of the EULIMA magnet. The results of the two models were compared for the case of a relatively small number of finite-element volumes (5000). Although nothing indicates that either model should a priori be more accurate, the ease of manipulating the input and output files, the possibility of checking the results at the output level, and the much more efficient use of computing resources, determine TOSCA as a prefered package for EULIMA modeling.

In Fig.2, the azimuthal magnetic field distribution obtained from a TOSCA run is presented for several machine radii. For comparison, we also show the results for the same pole geometry assuming that the pole tips are completely saturated. The differences between the finite-element and integral approach results are seen to be less than 2000 Gauss, and may be attributed to the yoke contribution which is not taken into account by the integral method. Consequently, it seems that magnetic field design procedures based on the saturated iron hypothesis are quite adequate for the initial design.

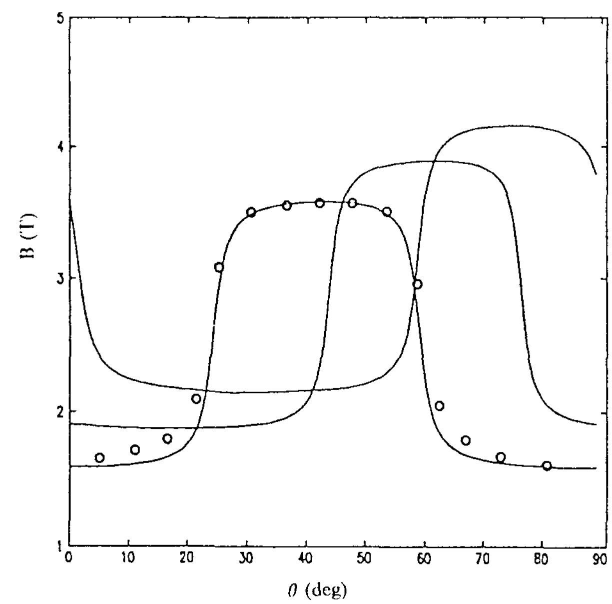

Fig.2 Comparison of median plane field profiles for integral approach (full lines) and TOSCA calculations (symbols)

THE POLE DESIGN

Once the basic structure of the magnet yoke has been determined, two classes of design problems need to be solved. Firstly, the initially satisfactory magnetic design of the yoke has to be analyzed in terms of mechanical stability, and suitable modifications introduced. This is necessarily an iterative process, as the presently envisaged solution for the vacuum chamber, which consists of a cylindrical body covered with a 80 mm thick disk that traverses the magnet sectors, mechanically couples the magnet yoke to other machine components. Thus, although consisting of separated sectors, the magnet behaves as a functional whole, all the more because of the coupling exerted by the cryostat.

On the other hand, the magnet feasibility study needs to resolve several aspects of the pole geometry which are reflected in such issues of the beam dynamics as are the orbit isochronism, transverse beam stability and the choice of the working path of the machine.

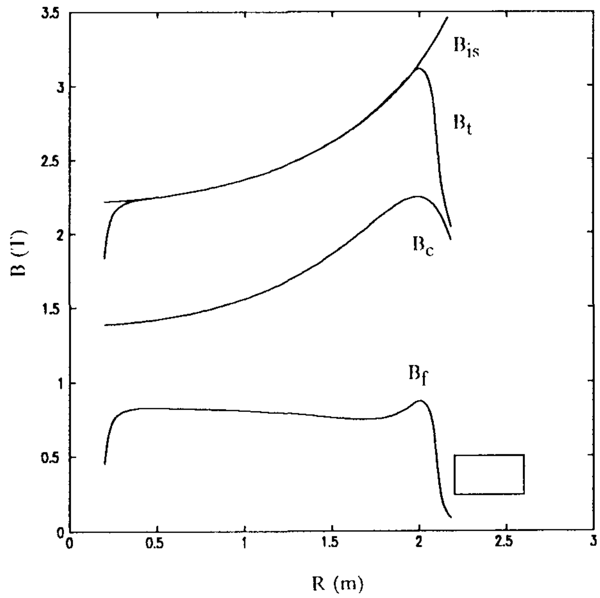

Fig.3 Radial dependance of the total average field, the iron and coil components, and the isochronous field

As discussed above, 3D magnetic field maps obtained by assuming that the iron in the vicinity of the median plane is completely saturated may be considered to be satisfactory for the initial design. The corresponding iron field was calculated on the basis of a fast integration technique[3), giving the average field contribution of the iron, and more importantly, the transverse focusing field. In Fig.3, we present the radial profiles of the average magnetic field $<B(r)>$, the iron field $<B_f(r)>$, as well as the coil field and the imposed isochronous field profile. The sector azimuthal width assumed for the relevant calculations is that of Fig.4. Obviously, its initially constant value must be corrected for the median plane contribution of the yoke. Hence, in order to minimize the resulting isochronous error it suffices to locally change the width of the pole with saturated azimuthal shims. In this way a new sector angular profile, also shown in Fig.4, is obtained. The corresponding isochronous field error, shown in Fig.5, is acceptably small for all radii.

Nevertheless, remembering that the accelerating field spans over a large distance (r_e = 2.1 m), and that a high RF harmonic (h = 7, and ΔE_{kin} = 1 MV/turn) acceleration is envisaged, it should not be expected that an isochronous profile could be maintained without a trim – coil system, even though a fixed field operation is assumed. In order to estimate the necessary parameters of the correction coils, we assumed that they are to be positioned on the pole tip faces, as has been frequently been done in separated sector machines, and radially distributed according to expected sensitivity of the beam to isochronous field error. Due to iron saturation, the field from strip – like conductors is easily calculated. In the injection

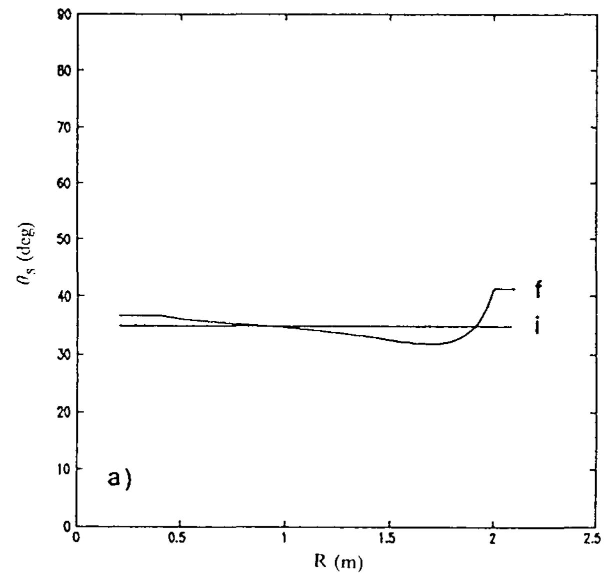

Fig.4. Initial and final sector angular widths

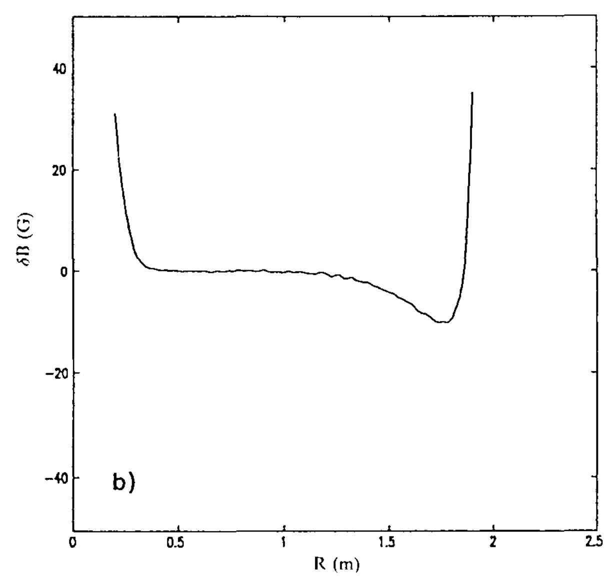

Fig.5. Residual isochronous field error

and extraction regions the correcting gradient of 20 G/A/m can be obtained, which is sufficient for correcting coherent field effects. Since the coils may be independently excited from sector to sector magnet, odd harmonics may also be corrected with this arrangement, which gives a first harmonic amplitude of about 5 G/A.

The properties of the beam dynamics, resulting from the orbit integration in the isochronized magnetic field, are illustrated in Fig.6, where the radial and axial focusing frequencies and field flutter are given vs machine radius. As expected for a four – fold geometry, the radial focusing frequency ν_r rises steadily, approaching near the extraction point the ν_r = 3/2 resonance. The axial focusing frequency ν_z is near 0.40 for all radii, which is mainly due to increasing spiral action which compensates for the field flutter drop beyond r > 0.8 m.

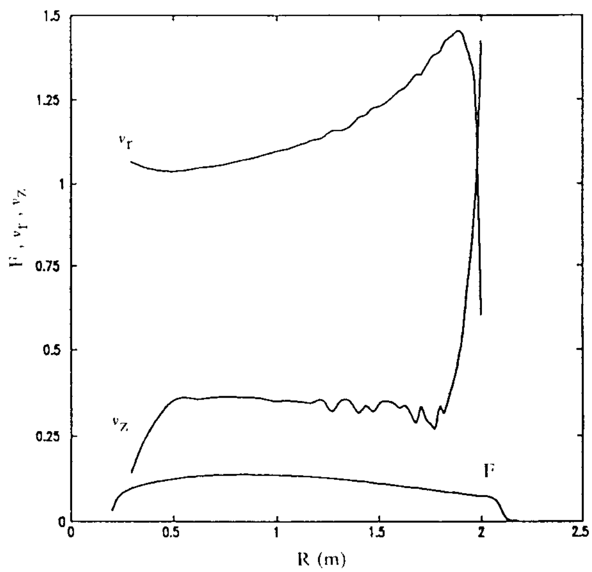

Fig.6 The focusing frequencies ν_r , ν_z and the field flutter

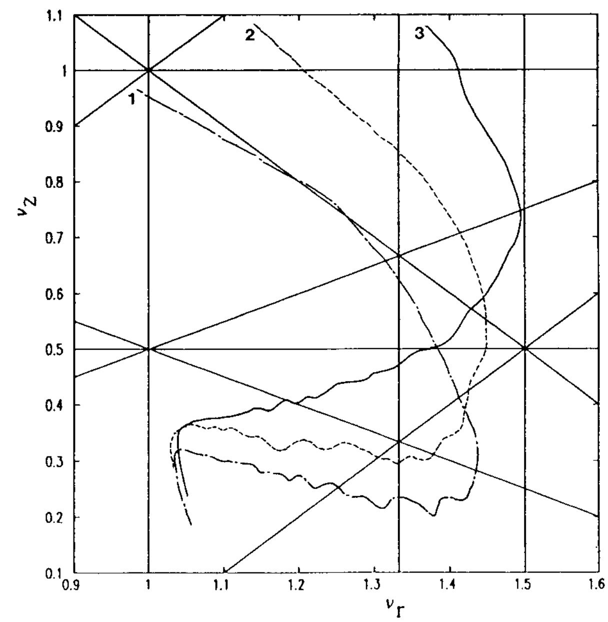

Fig.7. Working paths in the (ν_r , ν_z) diagram

In order to better control the beam behaviour, a possibility to impose a desired axal focusing strength in a given radial range (corresponding to a varying spiral angle) was introduced into the orbit codes, and the effects on beam focusing in various regions of acceleration observed. An example of possible working paths is shown in the (ν_r , ν_z) diagram, Fig.7, for spiral profiles of Fig.8. Although coupled through the field gradients, the pair of ν_z , ν_r values which determine the working path of the machine can be chosen in quite a large band, so that particular conditions at injection, acceleration proper, and beam extraction, can be met.

Since in a machine designed for acceleration up to 400 MeV/n a large interval of ν_r values has to be covered and a number of resonances of different orders crossed, it is vital for high intensity acceleration for the working path to be chosen following a sufficiently wide resonance bandwidth. This should minimize the sensitivity of the machine parameters to coherent effects, and allow realistic tolerances. Nevertheless, in the extraction region, where the radial density of the orbits is highest, a sensitivity of the axial focusing frequency on the spiral angle is estimated to be $(\Delta\nu_z / \nu_z)/\Delta\alpha_s$ = 10%/(deg/m), while the radial frequency is by an order of magnitude less sensitive. Hence, a tight control of the sector spiral must be ensured for a particular extraction regime to be precisely followed (e.g. resonant extraction near the ν_z = 3/2 resonance).

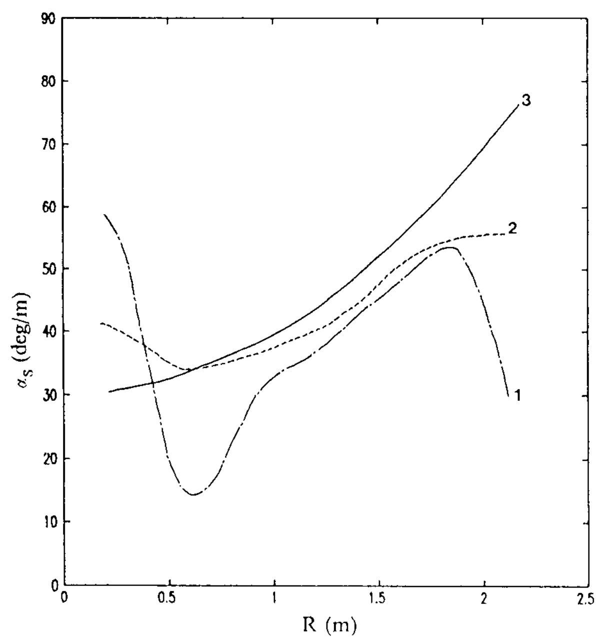

Fig.8. Spiral angle profiles determining various possible machine working paths

CONCLUSIONS

In this paper we have presented the initial results of the magnet design study of the superconducting separated sector cyclotron that is considered as a viable solution for the European Light Ion Medical Accelerator. The parameters of the superconducting coil and the yoke structure were determined, so that the sector angular width and spiral angle, which determine the focusing and isochronism of the accelerated $^{16}O^{8+}$ beam in this fixed energy machine, could be derived. As far as the beam dynamics is concerned, the sensitivity of the working path on the precise spiral shape of the poles should be noted, implying the importance of tight tolerances that should be met in the engineering design, if the ease of operation and high beam intensity is to be achieved.

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