

MAGNET DESIGN STUDIES FOR THE EUROPEAN LIGHT ION MEDICAL ACCELERATOR

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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 coil and sector magnets 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. Details of the coil and iron design are presented, implications of beam dynamics considered, and the optimal shape of the pole sectors derived.

Introduction

As presented in extenso elsewhere [1], several reasons of operational nature have led to the consideration of a superconducting cyclotron as a likely choice for the European Light - Ion Medical Accelerator (EULIMA). A four 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 investigated, and the feasibility of several major machine components (such as the RF system, injection and extraction systems) has been determined.

One of the main efforts of the EULIMA feasibility study has been devoted to the design of the magnet. 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 levels of approach need to be employed, each with a greater degree of accuracy. At the first instance, a modified hard-edge model was employed to study a series of possible magnet geometries, each 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 I. At this point we should point out that due to large forces involved, the interplay between the magnetic and mechanical design of the sector magnets is unusually strong in our single superconducting coil concept, the mechanical features of the structure being equally important as the efficiency of the resulting magnet system.

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.

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

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Table I.
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

magnet poles into saturation, and contribute on the average 1 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.

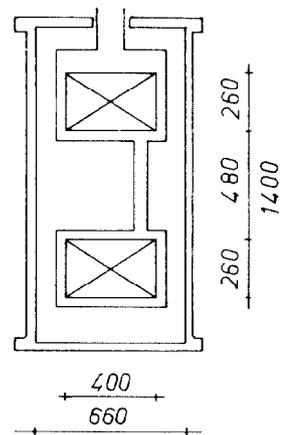


Fig. 1. The global dimensions of the superconducting coil and its cryostat

Assuming that the iron field contribution in the median plane derives from the saturated poles only, the least squares error of the total field in relation to the isochronous profile for $z/\Lambda = 0.50$ beam and 2.23 T central field, is given in Fig. 2a for different coil height (h_c) and width (c_c). Similarly, were the coil to be split into two independent sections for better field control, the mean isochronous error of the resulting field would follow the curves in Fig. 2b. In both cases, the total height of the coils is also shown, giving an idea of the total space needed for the coils, and conversely, of the necessary void in the iron yoke. As may be seen, the field error is smaller in the case of a splitted coil only for total coil height smaller than 70 cm and a splitting factor of $\alpha = 0.90$. Hence, we considered only the integral coil ($\alpha = 1$) for further optimization. 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 total coil height, which imply global cryostat dimensions shown in Fig. 1.

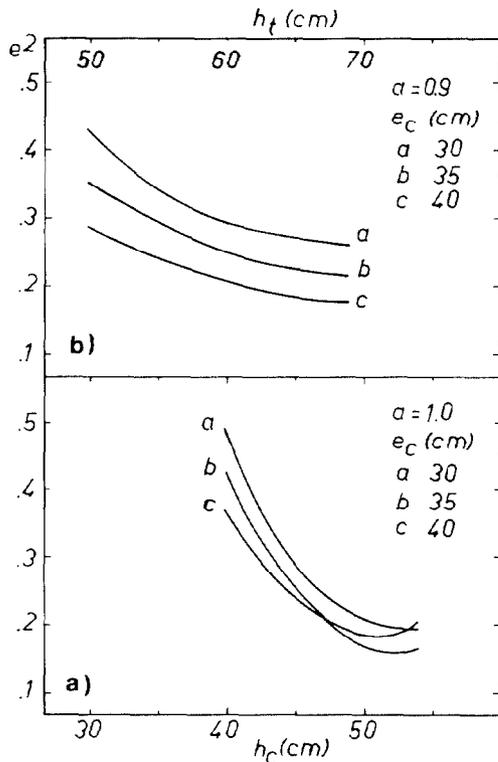


Fig. 2. Residual isochronous field error for different main coil shapes

The Yoke Design

As a first approximation to the 3D magnetic field maps, which are essential for obtaining realistic shapes of the magnet sector, we assumed that the iron in the vicinity of the median plane is completely saturated by the action of the superconducting coils. The corresponding iron field was calculated on the basis of a fast integration technique [2], giving the average field contribution of the iron, and more importantly, the transverse focusing field. Superposing the coil field, an initial sector angular width and spiral angle could be determined, as given in Fig. 3a. Obviously, these values must be corrected for the median plane contribution of the yoke.

The magnet yoke of the EULIMA sectors 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, and furthermore, act to a certain degree, in opposite senses. 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 relatively small number of finite-element volumes (5000). Although nothing indicates that either model should a priori be more precise, the ease of manipulating the input and output files, the possibility of checking the results at the

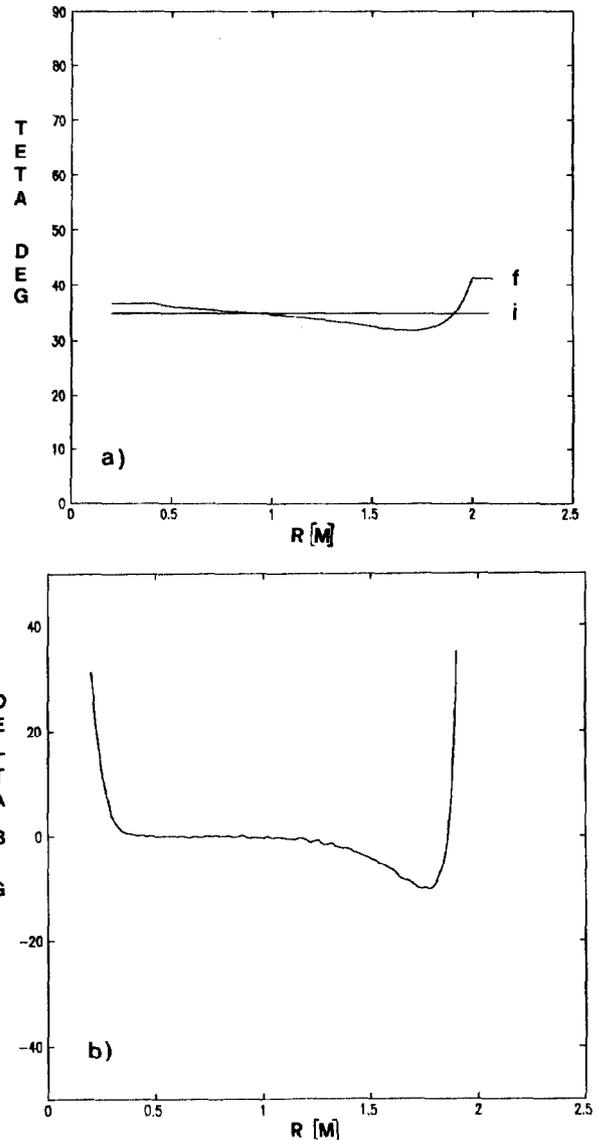


Fig. 3. Initial and final sector angular widths (a), and residual isochronous field error (b)

output level, and the much more efficient use of computing resources, determine TOSCA as a preferred package for EULIMA modeling.

As discussed in ref. [1], the TOSCA runs confirmed the assumption of complete saturation of the sector pole pieces, thus justifying the procedures employed in our preliminary studies, as well as in further refinements of our calculations. The differences between the finite-element and integral approach results [2,3], are of the order of 100 Gauss, and may be attributed to the yoke contribution which is not taken into account by the integral method. Hence, in determining the final shape of the pole edge, it suffices to locally change the width of the pole with saturated azimuthal shims, taking into account the now determined but otherwise constant yoke contribution.

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 structure 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, transversal beam stability and the choice of the working path of the machine.

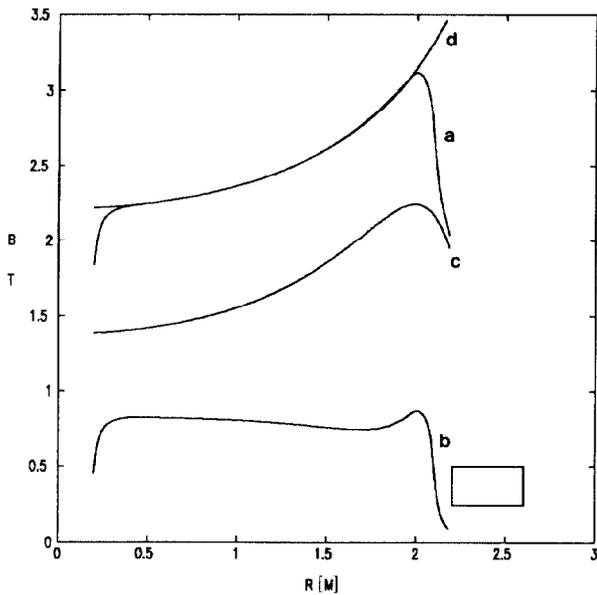


Fig. 4 Radial dependence of the total average field (a), the iron (b) and coil (c) components, and the isochronous field (d)

In Fig. 4, we present the radial profiles of the average magnetic field $\langle B(r) \rangle$, the iron field $\langle B_I(r) \rangle$, 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. 3a. Obviously, its initially constant value has to be modified if the resulting isochronous error is to be minimized, resulting in the new angular width, also given in Fig. 3a. The corresponding isochronous field error, shown in Fig. 3b, is acceptably small for all radii. Nevertheless, remembering that the accelerating field spans over a large distance ($r_0 = 2.1$ m), and that a high RF harmonic ($h=7$, and $\Delta E_{kin} = 1$ 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.

The axial and radial focusing frequencies, ν_z and ν_r , resulting from orbit integration in isochronized magnetic field, behave as expected for a four-fold geometry (Fig. 3 of ref [1]). In order to better control the beam behaviour, an arbitrarily varying spiral angle has been introduced, and its possible 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. 5. 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. One should note, however, that a very tight control of the sector spiral must be ensured for a particular extraction regime to be precisely followed (e.g. resonant extraction near the $\nu_z = 3/2$ resonance).

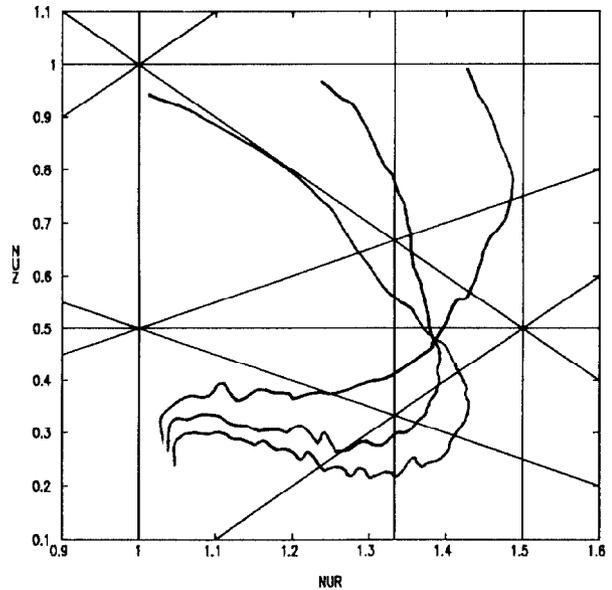


Fig. 5. Working paths in the (ν_r, ν_z) diagram

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 $^{16}\text{O}^{8+}$ beam in this fixed energy machine, could be derived. We point out that the design of the magnetic field in this machine concept is strongly coupled to the mechanical structure of the yoke and other machine components. 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.

Acknowledgments

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