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# MAGNETIC FIELD CALCULATIONS FOR THE PROPOSED SUPERCONDUCTING CYCLOTRON AT THE UNIVERSITY OF MILAN.

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## Introduction.

The purpose of this paper is to report some of the field properties for the proposed superconducting cyclotron at the University of Milan. A detailed design study of the cyclotron has been published elsewhere(1), while some of the main machine characteristics are also briefly summarized in ref.(2).

A number of different geometries both for the main coils and the polar sectors have been tested, leading to a choice which seems to meet substantially all machine requirements in spite of possible uncertainties on the calculations. On one hand the present configuration shows comfortable margins with respect to beam dynamics properties, as will be seen in the following. On the other it is expected that a thorough check will be possible with the forthcoming operation of a 1:6 scale model.

## Calculation Methods.

As it is well known, the general problem of solving Poisson's equation, for a given geometry, currents distribution, and iron magnetic properties, has so far a satisfactory answer only in bidimensional-like cases. For "true" threedimensional geometries, like this one, solutions are still lengthy and difficult to achieve, and, moreover, comparison with experimental data is still scarce and not fully reliable.

A superconducting cyclotron, where operation is substantially restricted to magnet excitation levels (22 Kgauss $\leq \bar{B} \leq$ 41 Kgauss in our case), for which complete saturation of the iron can be assumed, offers however a convenient way out. We have therefore adopted a method similar to that of Blosser et al.(3), namely:

- the field generated by the main coils is calculated via Legendre functions.
- the field from the polar configuration is calculated as given by a surface distribution $\sigma = M \cdot n$, M being the saturation magnetization moment of the iron.

The final magnetic field is then given by the superposition of the two terms. Fast calculations of the latter (typically 15') are allowed by programs written for UNIVAC 1108 and CDC 70/76 computers.

## Main Coils Geometry

In our case, at a maximum average field of $\sim$ 41 Kgauss, the main coils should contribute up to $\sim$ 60% of the field. Their geometry is therefore important for the overall field configuration, unlike the case of a conventional cyclotron. Based on "a priori" design considerations, (K of the machine $\sim$ 540, polar radius of 90 cm) a minimum internal radius of the coils of 103 cm was determined, while the minimum distance between the upper and lower coils has been fixed in 30 cm in order to allow space for injection and extraction equipment. Hence-forth follows a requirement of 6.5 x $10^6$ Aturns for the coils.

Studies of possible coils cross sections showed that in order to achieve a fringing field decrease as steep as possible, for the sake of easier beam extraction, a rectangular cross section with a height to width ratio of $\sim$2:1 is best suited. While this ratio is certainly not critical, it turned out clearly that a 1:1 ratio would have unwanted effects on the average field shape.

In order to ease somewhat the problem of reaching an isochronous field for energies as different as 50 MeV/nucleon and a few MeV/nucleon(2), we have investigated the merits of splitting the coils into two or more independently excited sections. While more than two sections raise several construction problems, just two seem quite useful in controlling the radial behaviour of the field. This is shown in fig. 1, for three self-explanatory examples, where variations of ± 10% are made around the nominal $3.10^6$ Aturns per coil. The geometry sketched in fig. 1 has therefore been chosen as the most favourable one.

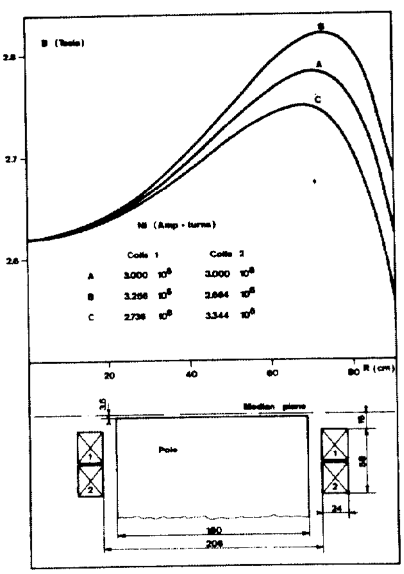


Fig. 1. Average field produced by different excitation of the coils sections.

## Polar Sectors Geometry.

A number of polar geometries have been investigated, on the basis of three, heavily spiralling sectors. Need for large spiral angles comes from low flutter values, typically 0.02 - 0.03. The machine concept calls for three dees in the valleys, driven by coaxial $\lambda/4$ lines passing vertically through the magnet. A center hole is also needed for stripping foil insertion or an internal ion source. The aim of these studies has been therefore:

i) to find a suitable geometry, where perturbations produced by the holes above could be tolerable, or correcting shims envisaged.
ii) to maximize the gap between the hills, in order to accomodate deflectors etc., while still granting good axial focusing properties.
iii) to ensure, also with trim coils, the achievement of the required isochronous field for all ions.

While skipping a lot of intermediate results, we just mention that spirals of the type $\vartheta = kR$, with k values of at least 1.3 $m^{-1}$ proved necessary, while gaps of 6 cm in the hills and 60 cm in the valley were initially investigated. It was found however that a minimum gap of 7 cm was also adequate. The parameters of the final geometry chosen are summarized in Table 1.

TABLE 1.
Polar geometry parameters.

| | | |
|---|---|---|
| Polar radius | | = 90 cm |
| Hill gap | | = 7 cm |
| Valley gap | | = 70 cm |
| Spiral constant (entry) | $= k_d$ | = 1.6 $m^{-1}$ |
| Spiral constant (exit) | $= k_s$ | = 1.8 $m^{-1}$ |
| Hill width at center | | = 45° |
| Diameter of R.F. holes in the pole | | = 25 cm |
| Distance of the holes from the center | | = 49 cm |
| Diameter of central hole | | = 12 cm |

A sketch of this geometry is shown in fig. 2. The

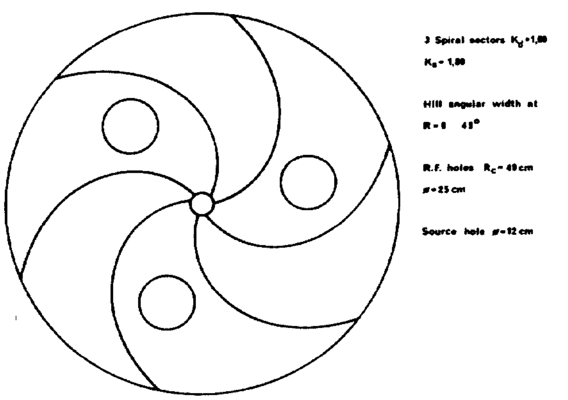


Fig. 2. Sector geometry.

radial profiles of the hills and valley, as they stand now, are shown in fig. 3. One can notice, for the valley, the outer shim which reduces somewhat the fringing

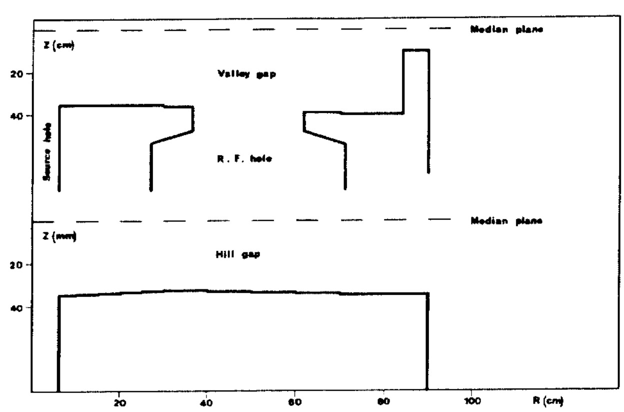


Fig. 3. Sketch of valley and hill profiles.

field and helps in keeping an isochronous field up to a large radius, and the shimming in the region of the R.F. hole. As for the hill profile, we may note that its shape around the positions of the R.F. holes, as apparent from fig. 3, is due of course to the necessity of compensating somewhat for the average magnetic field reduction due to the holes themselves.

The calculated amplitudes and phases of the field harmonics, from the 3rd to the 9th are shown in fig. 4. Perturbation on these parameters from the pre-

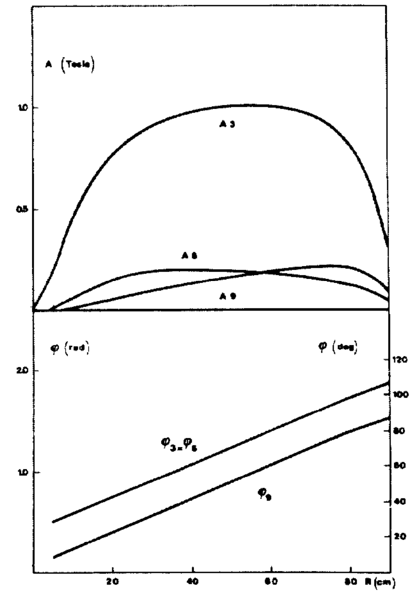


Fig. 4. Harmonics and phases of the field produced by the configuration of Fig. 2.

sence of the R.F. holes seems quite acceptable. As far as yoke geometry is concerned, both open and closed yokes are under consideration. Calculations have been carried out with "POISSON" programs, for cylindral closed yokes only. For easier access we have considered also the possibility of a 360°, 20 cm high, cut in correspondence of the median plane. Results seem quite encouraging both from the point of view of fringing field behaviour and average field level. However, the choice of a final yoke geometry will be made only after field measurements on the model.(2)

## Magnetic Field Properties.

Achievement of isochronism and adequate axial focusing are of course the main points of any analysis of magnetic field properties. As far as axial focusing is concerned, fig. 5 shows the $\nu_z$ values calculated for a number of particles, from equilibrium orbit code runs

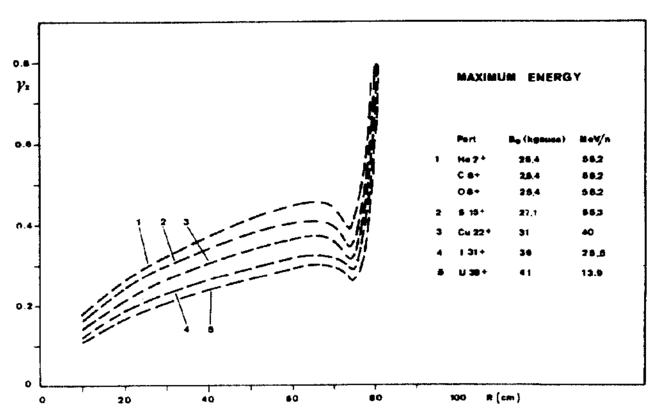


Fig. 5. Axial focusing frequency for a representative set of ions accelerated to maximum final energy.

in a supposedly isochronized magnetic field whose harmonic amplitudes and phases are those of fig. 4. The results, relevant to the maximum attainable energies of the listed ions, show that the focusing properties of this polar configuration are in fact quite good. In fact it could be speculated that a further increase of the hill minimum gap, above 7 cm, could be possible without jeopardizing this aspect of beam dynamics. However, this modification of the present geometry will not be investigated until magnetic field data are available.

An example of the degree of isochronism which can be reached by this polar configuration, and independent excitation of the two sections of the main coils, is shown for heavy ions at the maximum field level, in fig. 6. One can get as close as 80-100 Gauss,

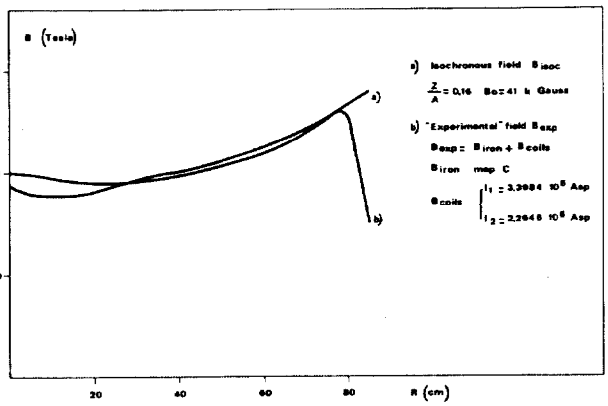


Fig. 6. Example of field correction by indipendent excitation of the two sections of the coils.

which is already remarkable, but, as expected, trimming coils are certainly needed. A set of 11 trim coils, spaced at nearly equal radial intervals and disposed on the surfaces of the hills is presently envisaged. After calculation of their form factors several tests of field isochronization have been performed. An example is given in fig. 7, for an average magnetic field of 36 Kgauss showing that isochronism can indeed be well approximated.

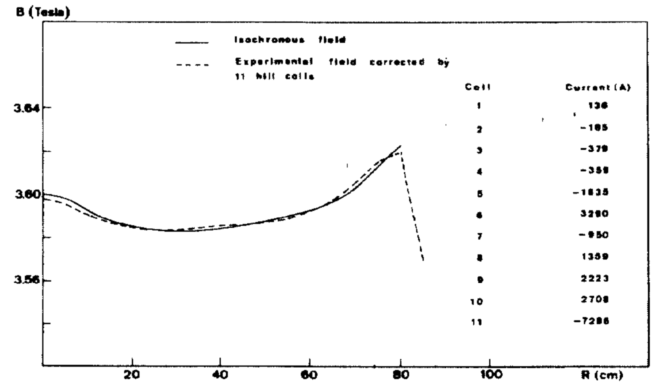


Fig. 7. Example of field isochronization with use of trimming coils.

In summary it looks therefore like the polar configuration which comes out of these studies fulfills the goals set for the machine. Results from magnetic field measurements on the model may of course change somewhat this design, but it is expected that no major changes will be needed both as far as sector geometry or trim coils are concerned.

## References.

1 - E.Acerbi et al. - Studio del progetto di un ciclotrone superconduttore per ioni pesanti. - Report INFN - TC (June 1976).

2 - E.Acerbi et al. - Model magnet for the proposed superconducting cyclotron at the University of Milan. Proceedings of this Conference.

3 - H.G.Blosser, D.A.Johnson - Focusing properties of superconducting cyclotron magnets. - Nucl. Instr. and Meth. NIM 121 (1974) pg. 301.