TRANSVERSE PARTICLE STABILITY BANDWIDTH IN HIGHLY SPIRALED MAGNETIC STRUCTURES

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Abstract: In the frame of the European Light Ion Medical Accelerator project, a separated sector superconducting cyclotron has been studied in considerable detail. In this paper we present the results of an analysis of single particle dynamics in the proposed highly spiraled magnetic structure, and determine the natural transverse stability bandwidth related to spiral definition. Higher order effects in the fringing focusing are seen to increase the bandwidth by about 10%. The influence of other magnet imperfections on the working diagram of the machine is also analyzed.

Introduction

The physical basis and the detailed mechanisms underlying particle focusing in alternating gradient magnetic fields have been known for a long time, and their properties extensively applied in construction of various accelerating and beam guiding structures. In superconducting cyclotrons, due to the large axi-symmetric magnetic fields generated by the main superconducting coil, the azimuthal magnetic fields appearing in the transition interval from the high to low magnetic field regions are generally insufficient to excite stable transverse motion, and need to be complemented by the focusing forces that derive from the spiraling of the magnetic field lines. In the present generation of superconducting cyclotrons, the understanding and the ability to calculate the effects of a spiraled magnetic structure were refined to the point that certain optimization procedures, such as the adjustment of the spiraling law to the desired focusing history of the accelerated beam, have become possible.

A renewed interest in the particle beam motion in highly spiraled magnetic structures was recently raised by several proposals for building superconducting cyclotrons specifically designed for particle beam therapy with heavy ions in the range of 400-500 MeV/n [1,2]. Since these machines should preferably be hospital based, the successful design should lead to a compact, stand alone, reliable and economical facility. In conceptual sense, this implies that the particle beam should be preferably accelerated in a single stage machine. In order to preserve the advantage of compactness of the superconducting machines, a high spiraling of the magnetic field is needed in an accelerating region which is approximately twice as large as in present machines (with a bending constant greater by a factor of two). As a consequence, the operating conditions that could either limit or otherwise influence the precise control of the transverse stability of the accelerated beam should be identified, and, if possible, eliminated by adequate engineering solutions, especially if small beam losses (related to certain special demands, e.g. acceleration of marker beams, ^{15}C, ^{10}C) are to be achieved.

The role of edge focusing in superconducting high energy structures has been considered in some detail in recent machine proposals, [3]. Usually, a matrix-type formalism has been employed for the analysis of magnet parameters, since in cases of high energy guiding structures with a large number of sectors, this essentially linear method gives satisfactory results. However, this approach is not adequate for the analysis of the second order effects, that may be important for the transverse stability in highly spiraled guiding fields with a low period (where the scalloping of the orbits is relatively large), and in machines with a large turn number. In this report we discuss the influence of the higher order terms in edge focusing on the particle transverse stability bandwidth in these structures, as well as the effects of other magnet imperfections, in particular in relation to the superconducting separated sector cyclotron which is proposed as a possible solution for the EUropean Light Ion Medical Accelerator (EULIMA).

Magnet Conceptual Design

In considering possible conceptual solutions for a machine designed to accelerate fully stripped ($z/A = 0.5$) heavy ions ($12 < A < 20$) in the region of 400-500 MeV/n, imposed by the desirable range and depth dose curves for efficient treatment of deeply seated tumors, it was initially considered that a separated sector cyclotron with a single pair of axially symmetric superconducting coils could satisfy the basic project requirements, and that it could offer certain advantages for the engineering design [4]. The feasibility study of this concept proceeded by investigating the physical and engineering issues of the magnet sector and superconducting coil design, the RF system design, the injection scheme and possible extraction arrangements [5]. Although less favorable, since there is no free access to the magnet interior, a box-type magnet concept as an extrapolation of the first generation of superconducting cyclotrons, was also considered. In both cases, a four sector magnet geometry was assumed, with the particle frequencies and pole radii chosen in accordance with the required final beam energy and conditions of stable transverse motion throughout the acceleration region. The main parameters of these two solutions are given in Table 1. The main technical difference between the two concepts is that in the box-type magnet a two section main coil carrying opposite currents has to be used to compensate for the radially falling average field contribution of the valleys. Contrary to this situation, the isochronous field profile in the separated sector concept can be generated with a single superconducting coil.

In order to obtain 3D magnetic field distributions in the cyclotron median plane complete saturation of the iron surfaces was assumed, and a fast integral method of field computation employed [6]. The results of these calculations were confirmed by running a finite-element TOSCA model of the separated sector magnet, giving a median plane contribution of the yoke under 5% of the values obtained. On the other hand, as is well documented by measurements on the MSU machines, the Fourier harmonics of the field are well reproduced by the iron saturation hypothesis. Devising a convenient iteration scheme between the field calculations and the static beam properties, radial profiles of the sector entrance angle and of its azimuthal width, ensuring isochronous motion

Table 1

	Separated sector magnet	Box-type magnet
B_0 (T)	2.26	2.67
Ext. Radius (m)	2.0	1.7
RF (MHz)	69.6	82.0
RF harmonic	4	4
Magnet		
Sectors	4	4
Hill gap (cm)	5	5
Valley gap (cm)	-	52
Max. spiral(deg)	65	75
Ave. width(deg)	35	40
Coil		
Int. radius (m)	2.31	1.90
Height (cm)	37	80
Width (cm)	30	15
Splitting factor	1.0	0.80
J_c (A/cm^2)	2600	3440,-4500

and a chosen acceleration history in the (ν_r , ν_z) diagram, could be achieved in both cases. In Fig.1, the values of tanζ, where ζ is the spiral angle, are given as function of radius for the particular that the axial focusing frequency ν_z be near to 0.25, for the greatest part of the beam accelerating history. Due to the large values of the magnetic field flutter, this requirement cannot be fulfilled at small radii (below 80 cm for the separated sector magnet, and 40 cm for the box-type magnet), as shown by the zero spiraling of the sectors, which is also the case in the extraction region, where the field index $k=\gamma^2-1$ rapidly drops to zero.

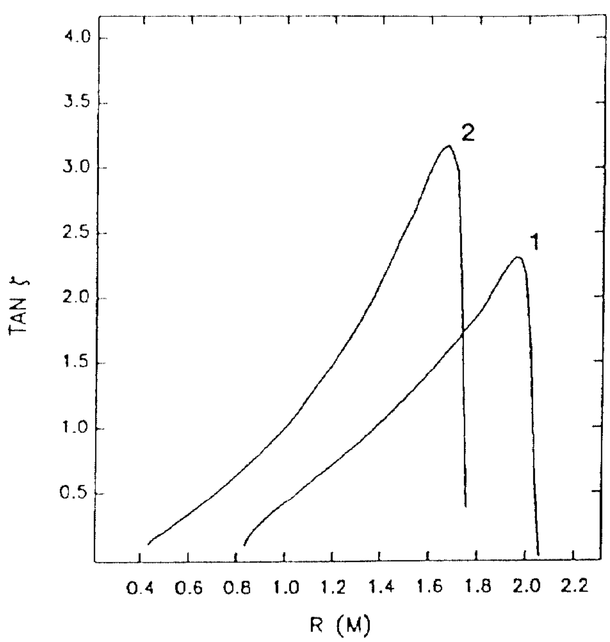

Fig. 1. The spiral angle enhancement tanζ, adjusting the axial focusing frequency of the z/A=0.5 beam to ν_z = 0.25 , in a separated sector (1) and box-type magnet (2) design of the EULIMA superconducting cyclotron

Magnet Imperfections and Single particle Dynamics

Spiral Angle Sensitivity

The maximal spiral angles attained in the two cases are 67.8 deg and 73.3 deg for the separated sector and closed-type superconducting magnet, respectively. Since these large spiral angles are covered in wide spans both in the (ν_r , ν_z) diagram and in the physical space, it seemed important to investigate the influence of small deviations from the optimal tanζ values that may arise as a result of local errors in field distributions. We found that for a local change of the spiral angle of +3 deg/m, corresponding to the tolerance of 1/10 mm in pole fabrication, the axial focusing frequency may deviate by as much 0.1. In these calculations special care had been taken to eliminate numerical errors due to interpolation which are known to give rise to oscillatory ν_z behavior. Consequently, these results illustrate the effects of the varying focusing strength, as a consequence of the spiral angle gradient, during particle scalloping inside the fringing field of a hill, which contribute about 5% to the ν_z values observed. We also note that the radial focusing frequency, contrary to ν_z , is insensitive to the local variations of the spiral angle, changing by less than 0.05% in the whole interval of tanζ values considered.

Transverse Focusing Bandwidth

In order to compare the two proposed superconducting concepts for the EULIMA facility from the point of view of spiral angle tolerances, we define the transverse focusing bandwidth as $\Delta\nu_z = \nu_{zb} - \nu_{zl}$, where ν_{zb} and ν_{zl} correspond to the focusing frequencies at the assumed tolerance limits. The corresponding values of $\Delta\nu_z$ are plotted in Fig.2 as function of particle energy. It may be seen that the separated sector design is by about a factor of two more sensitive to spiral variations, which corresponds to the ratio of the magnetic field flutter in the two cases.

The transverse focusing bandwidth defined above takes into account only the magnet imperfections that arise in the azimuthal fringing regions of the sector magnets. Obviously, these are not the only imperfections that can be expected in magnets of given dimensions, and the obtained bandwidth should be corrected for the higher multipole magnetic field components. Their influence on the nonlinear particle dynamics has been studied in detail in relation to particle nonlinearities in synchrotrons and storage rings, e.g. Guignard [7], and formulas for bandwidths of resonanances of different order have been deduced in terms of magnetic mutipole field derivatives and optical properties of the bending magnets. Simulating sector magnet positioning and tilt errors in the 360 deg magnetic fields, and studying subsequent particle dynamics, we have found that a random positioning error of 1 mm in displacement of the median plane of the sector magnet, increases the transverse stability bandwidth due to spiral imperfections by about 10%. It should be noted that these errors can be expressed as multipole field imperfections, and that in this particular case, which corresponds to the practical limits on positioning of large magnet sectors, the corresponding quadrupolar error is of the order of 10^{-3} .

The estimates of the transverse stability bandwidth should give a better insight into the problem of tailoring the resonance path of this fixed energy machine. As may be seen from the resonance diagram of the separated sector cyclotron, Fig.3, the radial focusing frequency steadily rises in the main accelerating region of the machine encompassing a range of values from 1 to 1.56. In the extraction region, the radial focusing frequency rapidly drops towards ν_r=1 as the beam enters the magnetic field fringing region. Due to large span of ν_r values in the accelerating region of the machine, as well as to a large range of ν_z values encountered in the final stages of the acceleration, a number of resonances of different order must be crossed. In particular, a (1.33,.33) point in the (ν_r, ν_z), where the $\nu_r + 2\nu_z = 2$ and $\nu_r - \nu_z = 1$ resonances cross, has to be contoured, since these (nonlinear) coupling resonances of

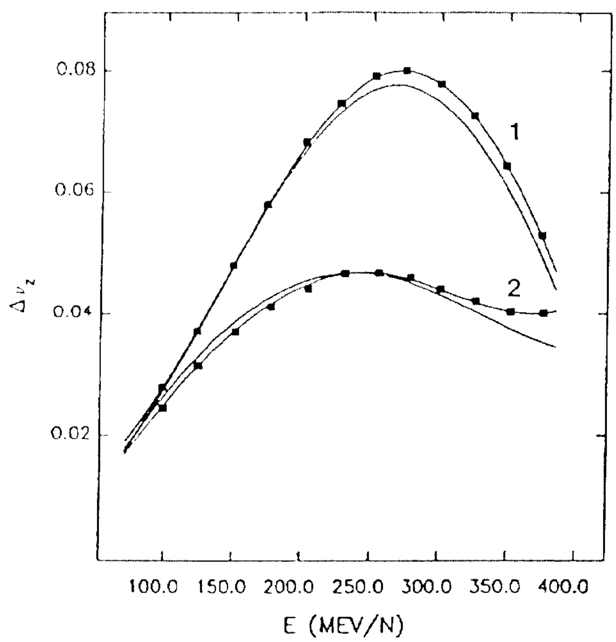

Fig.2 The axial focusing bandwidths (full symbols) in case of a separated sector (1) and box-type magnet (2) of the EULIMA superconducting cyclotron. The bandwidths given by the analytical aproximation $\Delta v_z = F\Delta\tan\zeta$ are shown for comparison

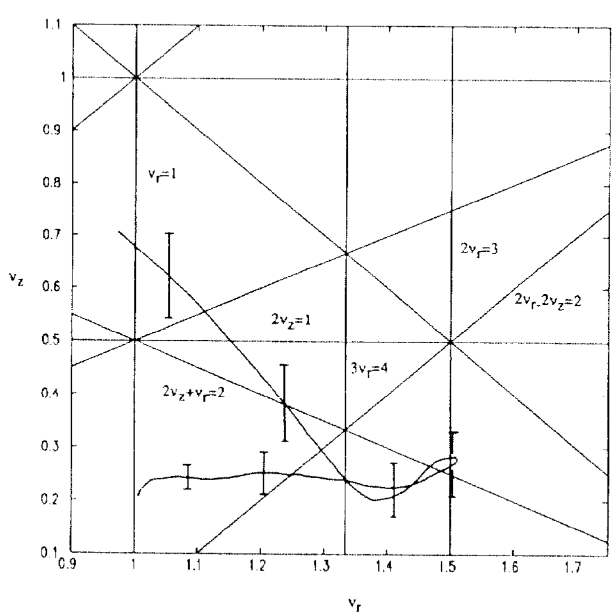

Fig.3. The working path of the separated sector cyclotron concept of the EULIMA accelerator, with an estimate of the transverse stability bandwidth due to spiral and higher magnet multipole imperfections indicated for the encountered critical points in the (v_r, v_z) plane

low order may induce substantial beam loss. Their total estimated bandwidth at the indicated point in the working diagram is calculated to be about 20% of the bandwidth arising from the spiral angle imperfection. The corresponding transverse stability bandwidth in the complete working diagram of the machine is also show if Fig.3, where it can be seen that the effects of several nonlinear resonances have been minimized by pulling the working path away from the critical points by at least the estimated bandwidth of these resonances.

Conclusions

In this paper we have presented the results of the analysis of single particle dynamics in the two proposed cyclotron concepts for the EULIMA heavy-ion accelerator. In particular, the effects of spiral imperfection in strongly spiraled magnetic fields, as well as the crossing of several nonlinear resonances of low order, has been studied in considerable detail. The transverse stability bandwidth has been defined, and in strongly spiraled magnetic fields, necessary for heavy ion acceleration to 400-500 MeV/n in superconducting structures, the stability bandwidth due to spiral imperfections has been estimated to be by an order of magnitude greater than the bandwidth of low order resonances driven by expected multipole errors due to the displacements and tilt of the magnetic stectors. The necessary tolerance limits for magnet pole fabrication due to spiral stability bandwidth are of the order of 1/10 mm, which will be difficult to meet since large pole pieces are involved.

Acknowledgments

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