CENTER REGION STUDIES FOR AXIAL INJECTION IN THE MILAN SUPERCONDUCTING CYCLOTRON

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SUMMARY

A center region suitable for axial injection into the Milan superconducting cyclotron has been under study for some time. Due to lack of space an electrostatic mirror has been selected for inflection of the beams in= to the median plane. Both possible geometries, namely with the mirror either on the machine axis or off axis have been investigated. The results so far available in= dicate that the on-axis solution requires injection vol= tages in excess of 20 kV. By comparison the off-axis so= lution looks much more effective, even though the off- axis displacement of about 12.5 mm is fairly large.

INTRODUCTION

A center region suitable for axial injection into the Milan superconducting cyclotron has been under study for some time. This paper presents the first results obtai= ned in studing the first harmonic operation mode.

The requirements of a good center region for the Mi= lan superconducting cyclotron are more stringent than those for a conventional cyclotron. Particles with high charge to mass ratios bend very strongly during the first revolution thus leaving a really limited space for the deflector which brings the beam into the median pla= ne of the machine, for the puller and the other electro= des. As a consequence special attention must be paid to:
i) the clearance problems in the first revolution;
ii) the distance between the ground and high voltage e= lectrodes which should be large enough to avoid sparking.

The presence of many electrodes in a reduced space also implies a rather complicated electric field in the center of the cyclotron. There is practically no elec= tric field free area in the first few turns. Therefore all orbit calculations in the center region must be ba= sed on accurately assessed electric fields. In this work a three-dimensional computer code has been used instead of performing electrolitic cell measurements.

The aim of this work is to study the beam behaviour from the exit of the deflector and to design a geometry for the center region which shall be able to accelera= te them. The beam transport from the source to the ma= chine and its trasmission to the median plane is de= scribed in another paper presented at this conference[1]. Here we only recall that: 1) in order to deflect the beam into the median plane of the machine an electrosta= tic mirror has been selected. This choice is due to the little room taken by the mirror and its easy shielding from the RF field. 2) The outer shell of the mirror has been designed with a diameter of 25 mm. This requirement follows the necessity to preserve field quality within the mirror. 3) So far the maximum injection voltage is supposed to be 20 kV since higher injection voltages would require a too high electric field within the mir= ror in order to deflect the beam.

Two types of geometry were studied: one with the mir= ror on the magnet axis and one off the axis.

GENERAL OUTLINE

The machine has been designed to accelerate ions to final energies ranging from 35 to 100 MeV/n in the first harmonic mode[2]. The cyclotron operating diagram is shown in Fig.1 in the plane $(Z/A, B_o)$ where, as usual Z/A is the charge to mass ratio and B_o is the center field value for which the field has been isochronized. As it can be seen a large variety of particles ($0.3 \leq Z/A \leq 0.5$ and $22 \leq B_o \leq 46$ kG) can be accelerated up to final energies of 35-100 MeV/n. The choice to design a fixed orbit geometry has been made. This requires that ions with different Z/A follow the same trajectory in different magnetic fields:this can be achieved with a proper scaling of the dee voltage which must be propor=

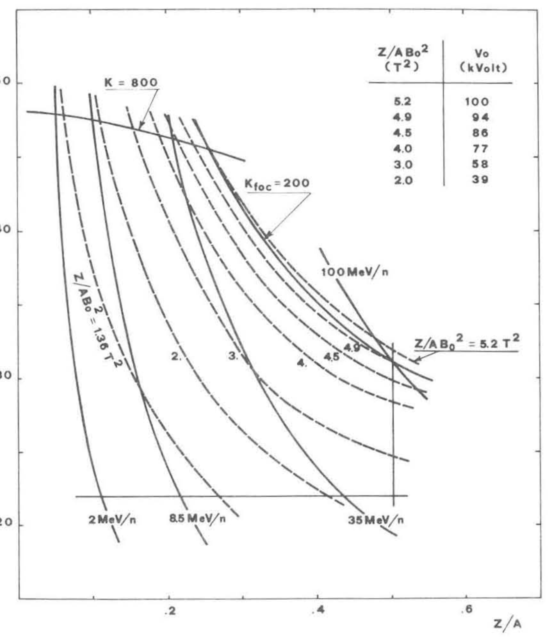

FIG.1 - Lines with constant final energy are shown on the operating diagram in the plane $(Z/A, B_o^2)$ to= gether with lines of constant $Z/A\ B_o^2$ values (dotted lines).

tional to the factor $Z/A\ B_o^2$ (3). From the lines of constant $Z/A\ B_o^2$, shown in Fig.1, it can be seen that the higest value for $Z/A\ B_o^2$ is 5.2 T^2. The ions with such a value of $Z/A\ B_o^2$ must be accelerated by a peak dee voltage of 100 kV which is the maximum anticipated va= lue.

The ion with Z/A=0.5 and B_o=31.3 kG has been selected to study the center region for the first harmonic ope= ration mode. This choice is due to the fact that it is the maximum final energy ion, it has the worst $\Delta(\sin\phi)$ and it comes out to be one of the most difficult to be extracted[4]. According to Fig.1 this ion requires a dee voltage of 94 kV.

Since the maximum injection voltage has been assumed to be 20 kV, the center region should be able to acce= lerate ions with injection voltages lower than this value.

The procedure to get a working center region geometry usually involves a sequence of tentative designs which are tested with orbit computation, after the electric field has been determined. This allows to check whether the accelerated beams clear the electrodes successfully

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gain enough energy, have adequate vertical focusing and emerge from the center region properly centered.

ELECTRIC FIELD COMPUTATIONS

The electric field produced by the dees and by the electrodes which cross the median plane was computed, for each center region design, using the code RELAX3D[5]. This code is an efficient iterative FORTRAN code which solves the Poisson (Laplace) equations for a general 3-dimensional geometry described by a regular 3-dimen= sional mesh.

A typical map corresponding to a region of 140x140x16 mm with a mesh step of 1 mm can be produced with a con= vergence error less than 1% in a CPU time of about 90 min on the computer VAX/780.

It must be outlined that, being the mesh size the sa= me in each direction all over the map, the spatial re= solution is the same in every region of the mesh. As a consequence for each design of the center region the electric potentials have been computed with two diffe= rent mesh sizes: i) 0.35 mm for the region between the mirror and the puller. (This allows to get a good elec= tric potential resolution in this region which is the most critical due to the closeness of the electrodes) ii) 1 mm for a region of about 70 mm radius around the axis of the machine.

ORBIT COMPUTATIONS

The code 3D-CYCLONE[6] has been used for orbit computa= tions. This programm consists of three parts. Part I follows the ion from the mirror exit to just beyond the puller. Part II tracks the orbits for a few turns until the boundaries of the computed electric field is rea= ched. Part II follows the orbits as far as desired into the machine. All three parts use the same magnetic field map, which has been computed from the final iron design of the Milan superconducting cyclotron[7]..

This code is able to compute the axial motion in parts II and III (8). A separate code has been developed to compute the axial motion in the mirror to puller re= gion, due to the interest in knowing as accurately as possible the beam behaviour in this region.

CENTER REGION WITH AN ON-AXIS MIRROR

An iterative procedure has led to the design, for the center region with an on-axis mirror with 12.5 mm ra= dius, shown in Figs.2 and 3. The mirror and the electro= des which cross the median plane are shown as shaded a= reas and the contours of the dees and dummy dees are al= so shown. The trajectories performed by the ion with Z/A=0.5 and B_o=31.3 kG for different injection voltages (20,30,40,50 kV) are also presented.

In spite of the process of optimization performed for this center region, ions with injection voltage of 20 kV do not clear the electrodes (Fig.2). Only injec= tion voltages larger than 30 kV allow the beams to be properly accelerated (Fig.3).

Good performances with beam injected at 20 kV can be obtained using a mirror having a 10 mm radius, as shown in Fig.4.

Injection voltages in excess of 20 kV or diameter less than 25 mm for the outer shell of the mirror do not seem, at present, easily available due to costruction

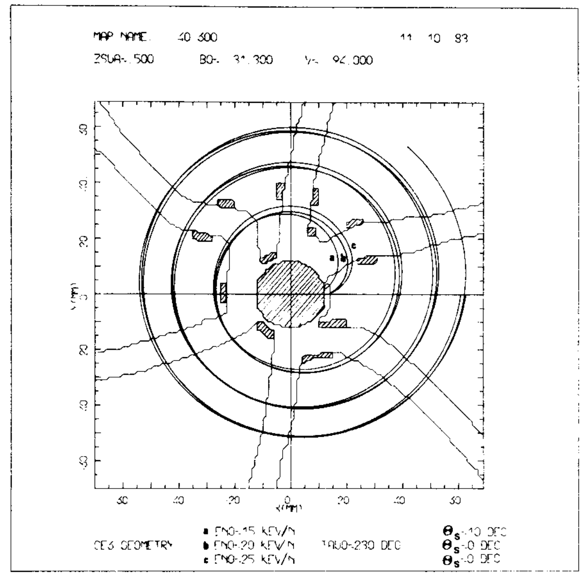

FIG.3 - Trajectories performed by the ion Z/A=0.5, B_o=31.3 kG with different injection voltage and a 12.5 mm radius on-axis mirror.

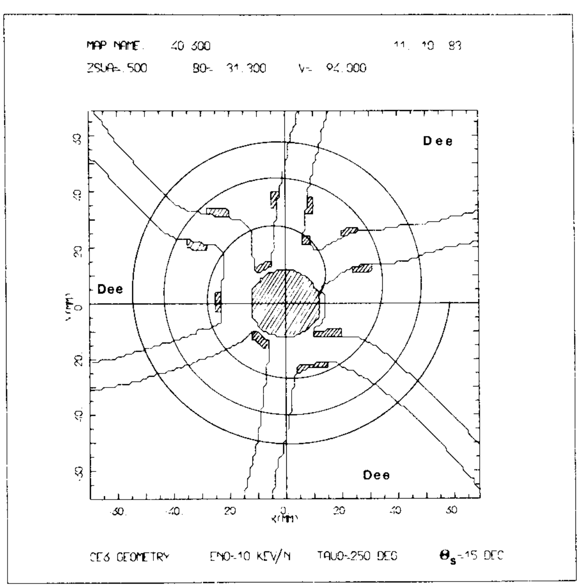

FIG.2 - Trajectory performed by the ion with Z/A=0.5 and B_o=31.3 kG for an injection voltage of 10 kV and an on-axis 12.5 mm radius mirror.

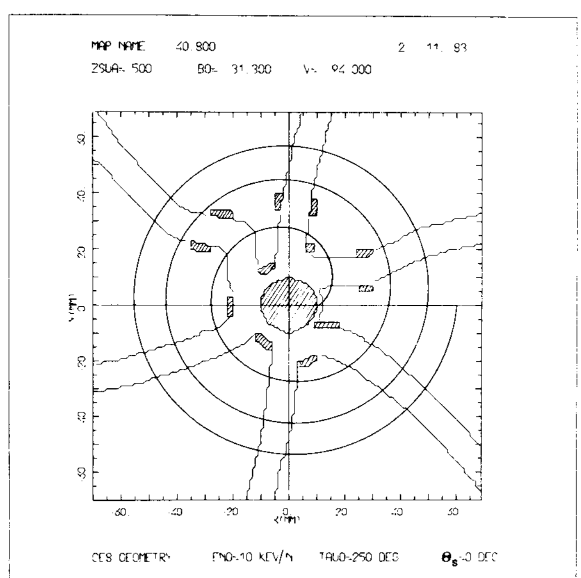

FIG.4 - Trajectory performed by the ion with Z/A=0.5, B_o=31.3 kG with an injection voltage of 20 kV and an on-axis mirror with a 10 mm radius.

problems for the mirror itself. As a consequence the study of a center region with an on-axis mirror has not been further developed. However future improvements in mirror design could open new perspective in this direction.

CENTER REGION WITH AN OFF-AXIS MIRROR

An iterative procedure has allowed to design the geometry with an off-axis mirror shown in Figs. 5-7. It must be pointed out that: i) the off-axis dispacement of the mirror is 12.5 mm; ii) to prevent discharges, the distance between the ground and the high voltage electrodes is everywhere larger than 10 mm.

The trajectories of the ion with Z/A=0.5 and B_o=31.3 kG tracked from the mirror to the end of the computed electric field, for an injection voltage of 20 kV and for starting times τ_o=300±5 deg are shown in Fig.5. The starting point (R=1.91 cm, ϑ=41.4 deg) for these

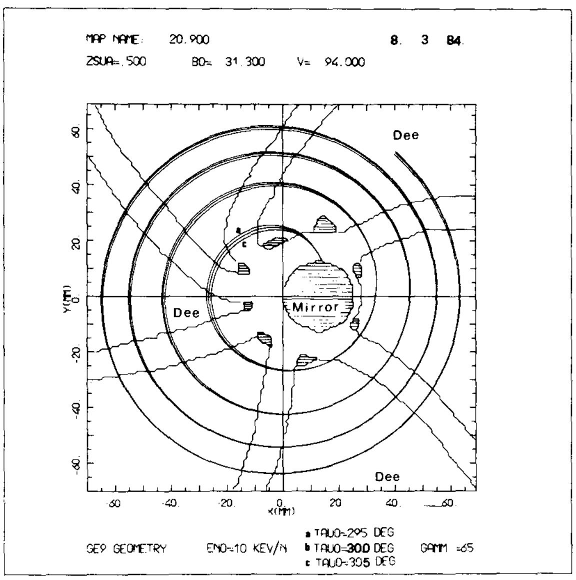

FIG.5 - Trajectories of the ion Z/A=0.5, B_o=31.3 kG for an injection voltage of 20 kV and starting times τ_o=300±5 deg.

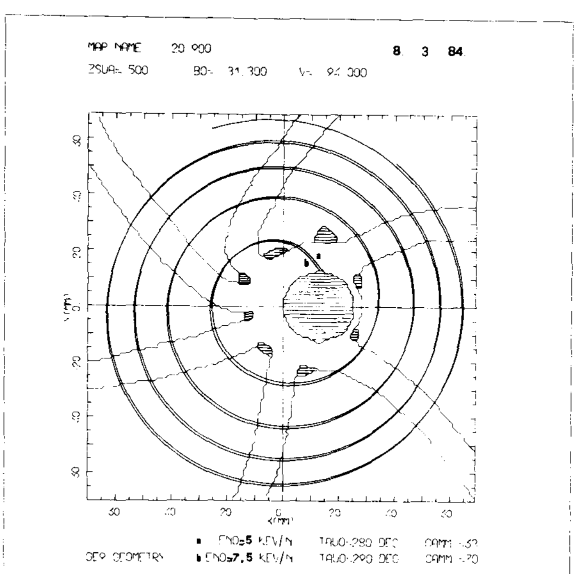

FIG.6 - Trajectories of the ion Z/A=0.5, B_o=31.3 kG for 15 and 10 kV injection voltages.

trajectories and the starting time τ_o=300 deg have been chosen as a compromise among the requirements of clearing the electrodes, having an acceleration phase able to give a proper axial focalization and having an acceptable beam centering.

This center region design exhibits good performance also for beams with injection voltages lower than 20 kV. The trajectories of the ion with Z/A=0.5 and B_o=31.3 kG with injection voltages of 10 and 15 kV are shown in Fig.6. The centering errors for these trajectories and the energy gain in the first turn are listed in Table I.

TABLE I

Injection energy (keV/n)	τ_o (deg)	Energy gain in the first turn (keV/n)	Centering error (mm)
5.	280	125.	1.5
7.5	290	125.	2.3
10.	300	125.	2.8

As evident from Figs.5-6, the beams injected with different energies exit the outer shell of the mirror in different points. The optimal position for the mirror slit for each case is obtained by rotating the mirror around its axis.

The beam behaviour in the radial and axial phase space has been studied as well. The results relative to injection voltage of 20 kV and a central ray starting time τ_o=300 deg will be shown in the following.

An upright ellipse centered on such a trajectory, with an emittance of 100π mm mrad at the mirror exit, has been selected to study the beam behaviour in the plane (x,p_x). The trajectories of four particles which define such an ellipse are shown in Fig.7. As it can be seen the beam just clears the electrodes and therefore some improvements in radial acceptance are still required.

To study the beam behaviour in the plane (z,p_z) the transfer matrix as a function of the azimuth has been computed from two indipendent trajectories. The values of ν_z have been computed from the transfer matrix as a

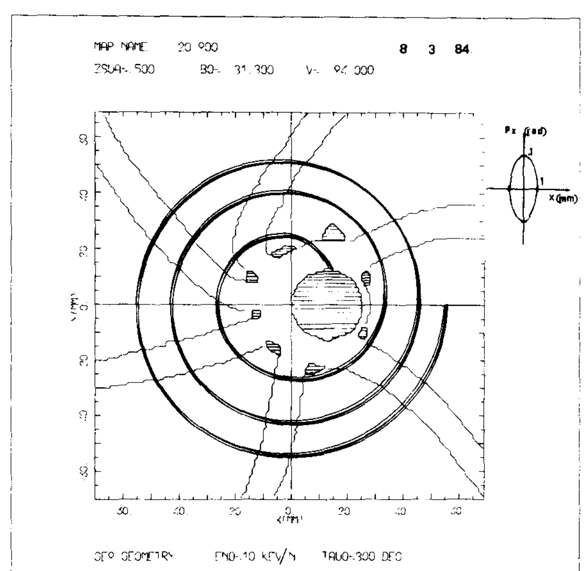

FIG.7 - Trajectories of the particles which define a beam with an emittance of 100πmm mrad in the space (x,p_x), at the mirror exit.

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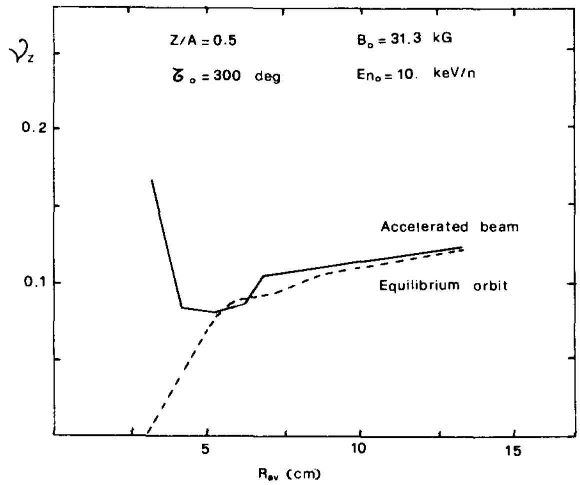

FIG.8 - ν_z as a function of average radius as computed from the transfer matrix, for a staring time τ_o=300 deg and an injection voltage of 20 kV and from the equilibrium orbit data.

function of the average radius and are presented in Fig.8. A comparison with the equilibrium orbit data shows that the electric field focusing dominates in the first few turns.

The eigenellipse at R=13.27 cm and energy En = 2.16 MeV/n is shown in Fig.9. It has an area which correspond to an emittance of 500 mm mrad at the exit from the mirror (En=0.01 MeV/n). The eigenellipse tracked back to the mirror, using the transfer matrix, is also shown. Rather large z values are obtained at the mirror exit together to relatively small values of ν_z . This implies that axial electric focalization must be improved in the first few turns.

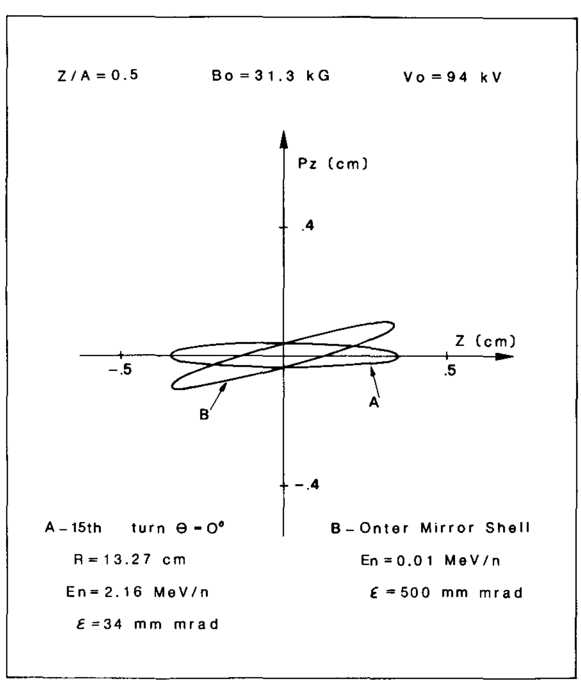

FIG.9 - Eigenellipse at R=13.27cm and En=2.16 MeV/n together with the eigenellipse tracked back to the mirror.

CONCLUSIONS

The results so far obtained can be summarized as follows:

1) The center region with an on-axis mirror exhibits a very critical behaviour when the beam injected at 20 kV are deflected by a mirror with a 25 mm outer diameter. Better performances are obtained only when injection voltages larger or equal to 30 kV or mirror with an outer diameter of 20 mm are used. Since these requirements seem presently difficult to achieve also the studies for a center region with an off-axis mirror have been developed although the "on-axis" solution would be better from the point of view of an easy trasmission from the outside of the machine.

2) The off-axis center region geometry has an off-axis displacement for the mirror of 12.5 mm. The center region design still requires further improvements from the point of view of: i) radial acceptance; ii) axial acceptance: the axial focusing must be increased; iii) beam centering. This can be achieved by proper changes in the gaps shape and position in the first revolution and then adjusting the fine centering of the beam by rotating the mirror around its axis. Nevertheless the results so far obtained show the flexibility of this design in the choice of the injection voltage, ranging from 10 to 20 kV by rotating the mirror around its axis.

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