DESIGN OF THE AXIAL INJECTION OPTICS FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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SUMMARY

It is planned to equip the Milan superconducting cyclotron with an axial injection system in order to take advantage of developments in advanced heavy ion sources. This paper presents the beam optic design relevant to:

i) beam transport, including charge state analysis, from the source to the cyclotron
ii) beam injection through the axial hole and matching to the cyclotron acceptance

Inflection into the median plane is accomplished by an electrostatic mirror; center region studies indicate that a mirror off axis by 12.5 mm is more effective for the considered maximum injection voltage of 20 kV.

INTRODUCTION

The Milan superconducting cyclotron[1] is a three sectors machine with an effective K=800 and K_{foc}=200 . It was designed as a booster for a 15 MV Tandem. However recent results in the development of high charge states heavy ion sources strongly suggest to equip the machine with an external ion source, of the ECR type, and an axial injection system.

The main problem associated with an axial injection system for a superconducting cyclotron are discussed in detail in ref.2 and are here only summarized.

Center region An electrostatic mirror is the only viable solution for beam inflection into the median plane at moderate injection voltages, in the range 15-20 kV. Off axis injection, realized with two electrostatic deflectors, is more effective.

Beam matching The mirror couples the two transverse phase spaces at its exit with a consequent increase of the emittances: a rotator system can minimize the beam quality deterioration.

Beam confinement The field along the axial hole of a superconducting cyclotron extends up to twice the yoke height from the median plane. To keep the beam confined during the traversal of this region active elements, like solenoids, are mandatory.

Field characteristics Sharp axial field gradients in the yoke traversal should be avoided since they can induce severe distorsions on the beam. This calls for an optimization of the plug geometry.

The specific solutions to these problems adopted for the Milan axial injection system and the beam transport from the source to the cyclotron are described in the following.

GENERAL OUTLINE

The layout of the external injection system is presented in fig.1 . The source is placed in a dedicated pit, located outside the main building, housing the cyclotron, at a distance of ~15 m. A tunnel connects the two pits.

The source, operating at a maximum voltage of 20 kV, is expected to deliver a beam[3] with emittance of 300 mm mrad in both planes and a momentum spread of .5% . A telescopic and achromatic system allows the charge state analysis of the beam with a charge resolution dQ/Q=1/45.

The beam transport line, from the exit of the charge analysing system to the bottom of the cyclotron, consists of symmetric quadrupoles doublets (magnetic) and 90° achromatic bending units. Two quadrupoles keep the beam confined in the vertical 90° bending unit. On the vertical beam line four magnetic quadrupoles perform the matching while a telescopic rotator, made up of four solenoids, provides the optimal angle of rotation. Two solenoids keep the beam confined in the traversal of the axial field of the cyclotron. The beam is then steered off axis by 12.5 mm, as follows from center region studies[4], by two electrostatic deflectors located around z=60 cm from the median plane. An electrostatic mirror operating with voltages up to 17.5 kV inflects the beam into the median plane.

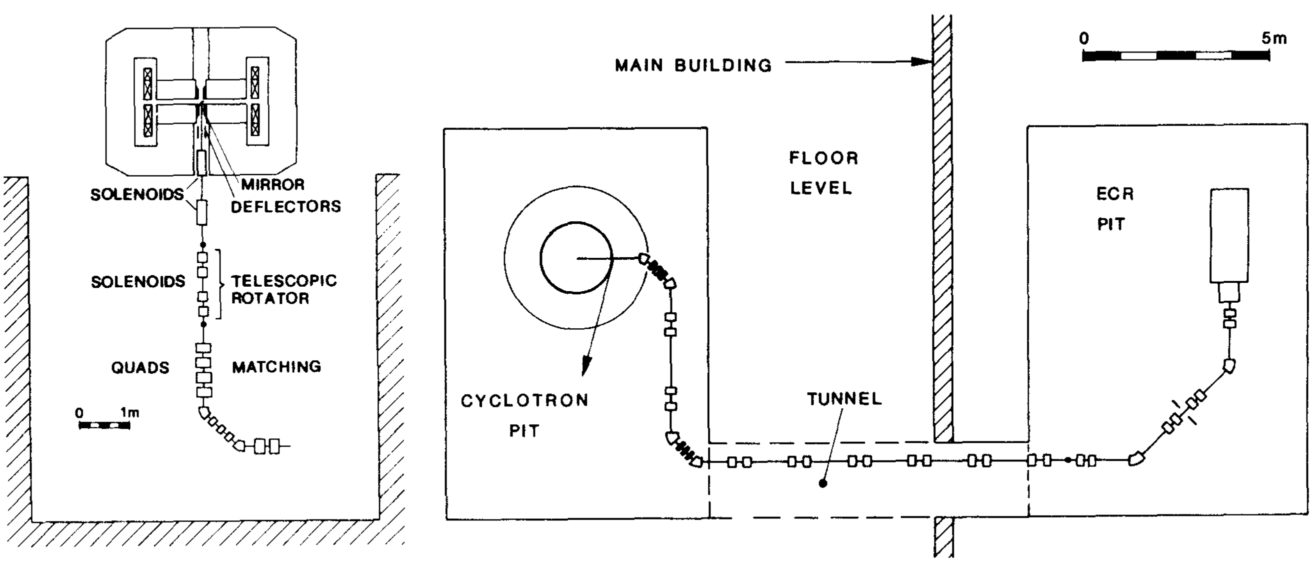

Fig. 1 - Layout of the injection system. Left: detailed view of the axial injection line. Right: top view of the source location, charge state analysis system and beam transport line.

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Maximum beam rigidity is 45 kgauss·cm as follows from the requirement of a constant orbit mode operation for the cyclotron. Radius of curvature at the mirror exit is 9.2 mm corresponding to a fully stripped ion injected at 20 kV in a central field B_o=31.3 kgauss for a final energy of 100 MeV/n. Central field level at the cyclotron midplane is variable from 22 to 48 kgauss.

CHARGE STATE ANALYSIS

The system performing the charge state analysis, illustrated in fig.2, consists of a -I cell with mirror imaging around its middle point. The parameters of the system are given, in a selfexplanatory way, in fig.1 . The addition of a -I cell, obtained by mirror imaging the first cell around the analysing slit, provides a system fully telescopic and doubly achromatic. The beam envelopes and the dispersed ray path in the first cell are given in fig.2 for the assumed waist size of 8mm x 12mrad in both planes at the source exit. At the analysing slit the system has no angular dispersion, i.e. in TRANSPORT[5] notation R_{26}=0, and a radial dispersion R_{16}=15.87 mm/% .

The charge state resolution, given by

$$dQ/Q = 2w_i/R_{16}$$

where w_i is the size of the image and the width of the slit, is dQ/Q=1/45 , well over the anticipated maximum charge state (38^+ for the uranium beam) .

Other noteworthy features of the system are:

- the axial beam envelope has a waist inside the bending magnet therefore minimizing the vertical aperture requirement
- enough space is provided at the source exit, as well as at the end of the system, to insert diagnostic equipment like emittance measuring devices

BEAM TRANSPORT

The transport of the beam from the analysing system to the bottom of the cyclotron is performed with 8 unit cells, consisting of doublets, with phase shift $\mu = \pi/2$ and two achromatic 90° bending units.

The first six doublet cells have a length of 1.6 m ;

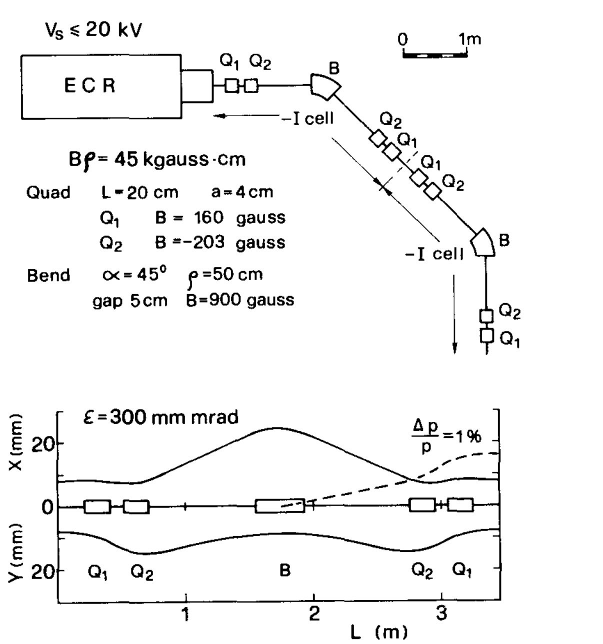

Fig. 2 - Configuration of the charge state analysing system. Main parameters are indicated together with the beam envelopes and the dispersed ray path.

two of these cells give a -I matrix transformation as illustrated in fig.3 where all the parameters of the system together with the beam envelopes are shown. The beam at the exit of the analysing system is not matched to the cell acceptance. Whether or not to match the beam to the cell is a matter of optimization since the increase in the cell length for matched beam, and given aperture requirements, is obtained using additional quadrupoles.

The achromatic 90° bending unit consists of two 45° magnets and three quadrupoles and is symmetric around the middle point. The bending radius and the quadrupole lengths (and apertures) have values as low as practicable to keep the unit compact. The transformation matrix for the unit is -I in the axial plane and -I followed by a drift length L=.207 m in the radial plane. The parameters of the system are given in fig.4 together with typical beam envelopes.

The two doublet cells inserted between the two 90° bending unit have a slightly increased length L=2 m, to provide, from the exit of the analysing system to the exit of the last 90° bending, a total transformation matrix I times a drift length L=+.207 in the radial plane and L=-.207 in the axial plane.

AXIAL INJECTION LINE

The axial injection line is subdivided in the following sections:

- matching section
- telescopic rotator
- solenoids system for beam confinement
- inflection of the beam into the median plane

Each section is detailed described below.

Matching section

This section includes the two quadrupoles on the horizontal beam line, the 90° vertical bending unit and the four quadrupoles for the matching (see fig.1).

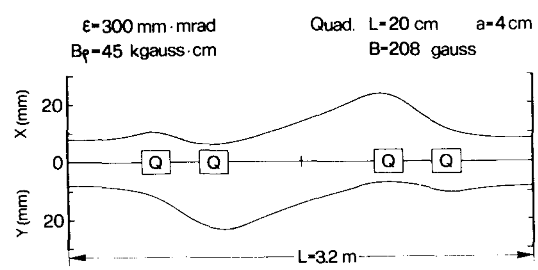

Fig. 3 - Main parameters of the telescopic cell and beam envelopes through the system.

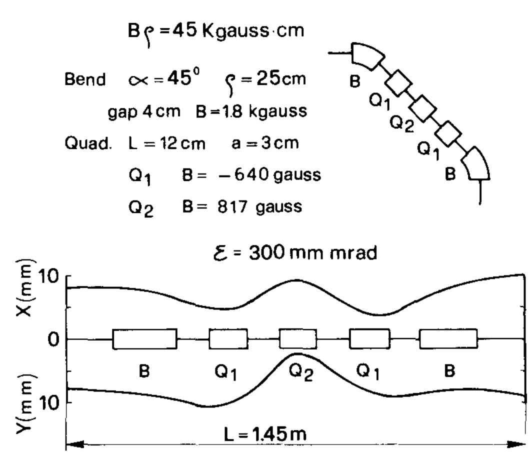

Fig. 4 - Configuration of the 90° achromatic bending unit. Main parameters are indicated together with typical beam envelopes through the system.

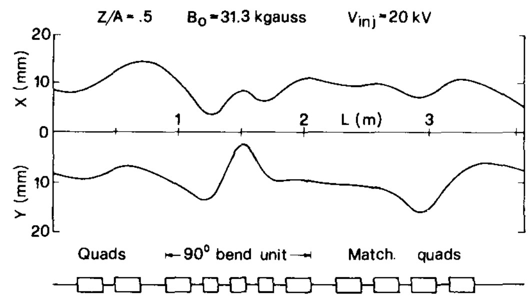

Fig. 5 - Beam envelopes through the matching section for the indicated ion.

The two quadrupoles, symmetrically excited, are used to maintain the beam well confined in the traversal of the achromatic bending unit. In fig.5 typical beam envelopes for a fully stripped ion injected at 20 kV are given. The beam is matched for focusing frequencies $\nu_r=1$ and $\nu_z=.5$ at the mirror exit. Beam confinement is excellent also for other values of ν_z and ν_r or for other injected ions. The fields of the matching quadrupoles, which have aperture radius a=4 cm, are lower than 400 gauss. Flexibility of the system can be increased, if required, using for the matching also the two quadrupoles at the beginning of the section. Exchange of the phase space at the end of the section (i.e. a rotation $\alpha=90°$) can easily be obtained, reversing the polarity of the four matching quadrupoles, due to the symmetry of the beam at the entrance of the section.

Telescopic rotator

Two cells, of two solenoids each, form a telescopic system with a -I transfer matrix. The system is designed to provide equal angles of rotation $\alpha/2$ in each cell maintaining the telescopic condition. The parameters of the system and the required solenoids fields to produce a rotation $\alpha=0°$ and $\alpha=45°$ are given in fig.6 .

The total angle of rotation needed is the sum of the following two terms:

- angle required for optimal matching, subtracted of the angle given by the axial field of the cyclotron
- angle between the coordinates system of the vertical injection line and the mirror

Reduction of this angle in the range $-\pi/4$, $\pi/4$ can be obtained ,if required, exchanging the phase spaces at the end of the matching section.

Beam confinement

The magnetic field along the axial hole of the cyclotron is presented in fig. 7 for three typical injected ions covering the field operating range of the machine (22-48 kgauss). The iron configuration around the axial hole is also scketched in the figure. The central plug has been tapered to provide a smooth field decrease along the axis in order to minimize beam distorsion. It is assumed,consistently with the POISSON[6] field calculations, that no axial field,or at least negligible, exists beyond z=300 cm from the cyclotron median plane.

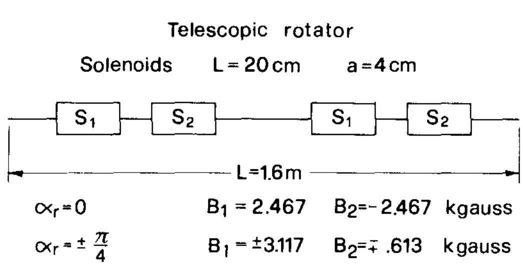

Fig. 6 - Main parameters of the rotator system.

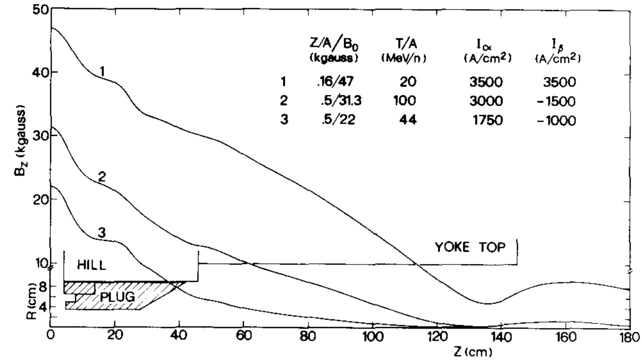

Fig. 7 - Magnetic field along the cyclotron axial hole for the listed ions.

At low central field levels, in the range 22-30 kgauss, the axial field region is confined in the yoke bore.

Two solenoids,each 50 cm long, are used for beam confinement,One is located inside the yoke bore between z=100 cm and z=150 cm from the median plane,the other one is between z=200 cm and z=250 cm.

The radial beam envelope for two typical injected beams, a fully stripped ion and an uranium beam accelerated at the maximum energies in the cyclotron,are presented respectively in the fig. 8,9 . Injection parameters,together with the positions and the field values required in the two solenoids, are also given. For both cases the beam is matched,at the mirror exit, to the eigenellipses corresponding to $\nu_r=1$ and $\nu_z=.5$ .For the uranium beam is not required the excitation of the solenoid placed in the yoke bore since the cyclotron axial field is sufficiently strong (B= 5 kgauss) to keep the beam confined.

As visible from the fig. 8-9 for both cases the matched beam at z=300 cm from the median plane is close to a waist with an half size of 6-8 mm.

Positions and field values of the two solenoids have not yet been optimized; the proposed solution is however effective in beam confinement and matching requirements.

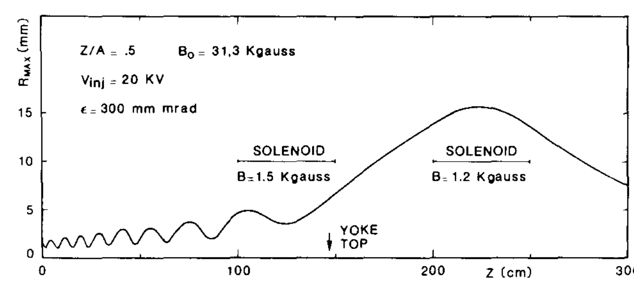

Fig. 8 - Radial beam envelope for a fully stripped ion injected at 20 kV .

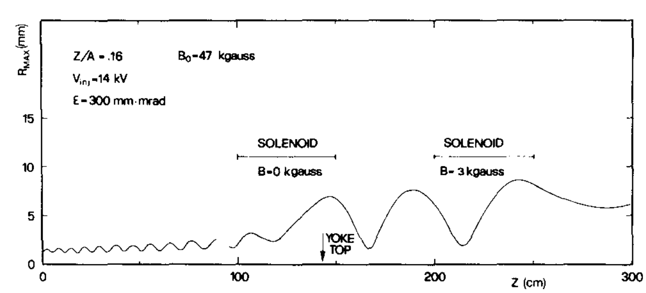

Fig. 9 - Radial beam envelope for a heavy ion (U^{38+}) injected at 14 kV .

TABLE I - Mirror parameters

Overall diameter	$\Phi = 25$ mm
Mirror angle	$\alpha = 47°$
Radius of curvature of the injected particle	$\rho = 9.2$ mm
Max. injection voltage	$V_s = 20$ kV
Max. displacement from the grid	$d = 2.7$ mm
Grid-electrode gap	$D = 3.5$ mm
Mirror voltage	$V = 17.5$ kV

Inflection into the median plane

A mirror has been selected for the inflection of the beam into the median plane. The mirror parameters are given in Table I .Criteria in the selection of the mirror parameters have been:

- overall size as small as practicable
- max. electric field between grid and electrode lower than E= 50 kV/cm
- radius of curvature of the injected beam ρ=9.2 mm to clear the center region electrodes

An increase of emittance is produced at the mirror exit due to the intrinsic coupling introduced for the two transverse subspaces. Minimization of this effect can be obtained by selection of a proper rotation of the coordinates system for the injected uncoupled beam as described in ref. 2 .

The emittance increase is of the order of 50% or more as illustrated in the fig. 10 for the case of a fully stripped ion injected at 20 kV . At the left is plotted the uncoupled phase space,with emittance of 300 mm·mrad ,produced at the exit of the matching section and corresponding to the beam envelopes presented in the fig.5 . The beam size at the mirror entrance is ± 1.5 mm in both planes with the indicated emittances. At the mirror exit the phase space area is increased to 500 mm·mrad. The beam is matched to the focusing frequencies ν_r =1 and ν_z = .5 .Different requirements at the mirror exit could possibly limit the emittance increase and should therefore be investigated with the acceleration of the beam through the center region.

We point out that these emittance values, namely 500 mm·mrad ,are consistent ,although close to the upper limit, with the single turn extraction of the beam.

Acceptance of the mirror, here defined in terms of the region between grid and electrode where the electric field can be considered uniform, is lower being of the order of 400 mm·mrad and strictly dependent on the beam requirements at the mirror exit.This calls for a careful compromise between injected phase space area, mirror overall dimension and emittance increase at the cyclotron midplane.

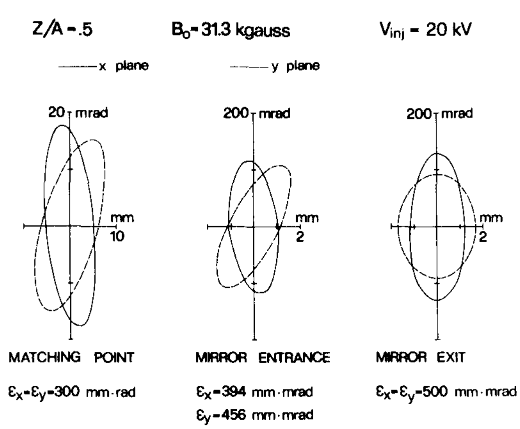

Fig. 10 - Phase space plots at the macthing point (z=300 cm from m.p.), mirror entrance and mirror exit for a fully stripped ion injected at 20 kV

Two center regions have been investigated[4] with the mirror either on axis or off axis by 12.5 mm . The mirror on axis solution is critical for the given maximum injection voltage of 20 kV and mirror overall diameter Φ = 25 mm . The off-axis solution is instead very flexible allowing to choose injection energies in the range 10-20 kV by simple rotation of the mirror around its axis. Off-axis injection,accomplished with two electrostatic deflectors located close to the plug entrance, has been therefore selected.

The WKB approximation gives the following relation between the central ray displacement x_i at position z_i from the median plane and field B_i and the displacement x_0 in the central field B_0

$$x_i = x_0\sqrt{B_0 / B_i}$$

At z = 50 cm from the median plane,i.e. at the exit of the two deflectors (each 10 cm long) located between z = 50-60 cm and z =62-72 cm, the central ray displacement is in the range 28-16 mm for the central field values range 22-48 kgauss and x_0=12.5 mm. The required electric fields in the deflectors are lower than E = 2.6 kV/cm ; this implies,for full aperture of the order of 12 mm maximum voltages V = ± 15 kV.

Detailed investigations have still to be carried out to obtain a reliable solution . Critical points are:

- electric field uniformity inside the deflectors
- non linear effects on the phase space due to the fairly large off axis displacement in the deflectors and close to the plug entrance

Another obvious implication of the off axis solution is that the buncher has to be located as far as 80-90 cm from the median plane.Bunching efficiency has to be carefully investigated since the required phase width in the cyclotron should be in the range ± 3° RF to limit the energy spread of the extracted beam.

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