THE AXIAL INJECTION PROJECT FOR THE MILAN SUPERCONDUCTING CYCLOTRON

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Summary

It is planned to built an axial injection system for the Milan superconducting cyclotron. The beam delivered by a compact ECR source, operating up to 20 kV, will be injected on axis and inflected into the median plane by an electrostatic mirror.

The design of the system and the results of beam matching calculations are presented.

Introduction

The K=800 superconducting cyclotron[1] now under construction at the University of Milan has been designed as a booster for the 15 MV Tandem of LNS in Catania.

Original plans called for a test of the machine with an internal ion source before the installation in Catania and the coupling to the Tandem. Consideration was however given, already at the beginning of the project, for an axial injection system, to be added later, in view of the developments of the ECR ion sources.

Following the indications of earlier[2] feasibility studies a preliminary design for an axial injection system was completed in 1983. Due to the difficulities associated with the design of the central region an off-axis injection, steered by four electrostatic deflectors, was chosen[3].

In summer 84 a complete review of the design was undertaken: close examination of the problems associated with the operation of the deflectors, namely the difficulty to control and monitor the off-axis displacement, strongly suggested to pursue studies for a central region compatible with an on axis injection.

A different harmonic mode, h=2 (versus the previously envisaged h=1), was also selected due the possibility to cover the full energy range of the machine (8-100 MeV/n).

At the end of 85 a decision was taken to built an axial injection system and a small ECR source discontinuing the development of the internal ion source.

Beside the test of the cyclotron the axial injection system will be used to accelerate very ligth ions (deuteron,alfa) and will provide an alternative to the injection from Tandem for ligth ions at intermediate energies.

General outline

A schematic layout of the axial injection system is presented in the fig. 1-2 . Beam injection into the cyclotron is from the bottom since the access to the machine median plane requires to lift the upper pole cap of the magnet.

Lack of space around the machine vault and the need to reduce at minimum the length of the beam line forced to place the ECR source at the bottom of the cyclotron pit. Space is limited also inside the pit so that a compact ECR source is required.

Severe constraints have been placed on some focusing element of the beam line since the access to the cyclotron axis is restricted by the pillars supporting the cyclotron and by the RF cavities (see fig. 1).

The horizontal part of the beam line consists of a 90° charge state analyzing magnet and four quads to provide indipendent matching in the two transversal planes. A 90° bending unit brings the beam on the cyclotron axis and a telescopic system, realized with the four solenoids S1-S4, transports the beam up to 3 m

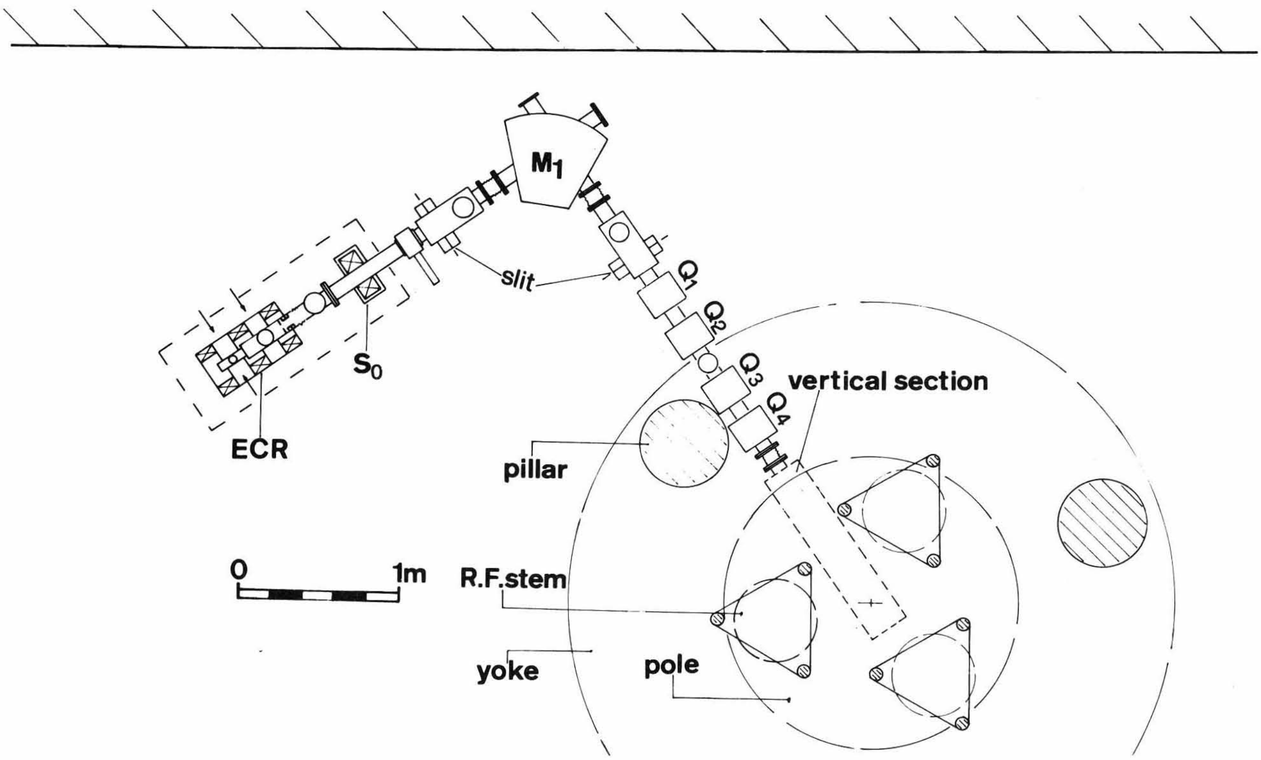

Fig. 1 - Top view of the cyclotron pit showing the source and the beam line.

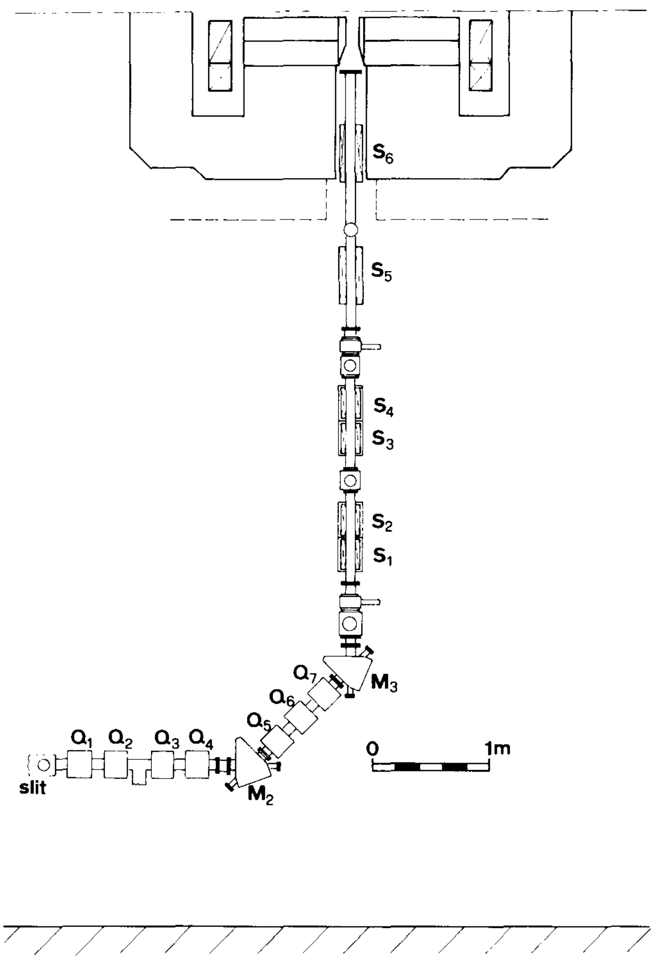

Fig. 2 – Schematic view of the vertical part of the beam injection line.

from the median plane where the axial field of the cyclotron reachs significant values. The two solenoids S5-S6 keep the beam confined during the traversal of the yoke up to the median plane. A beam spot size of about 2 mm is formed at the entrance of the electrostatic mirror which inflect the beam into the median plane of the cyclotron.

Beam rigidities are in the range 20-45 kG cm as follows from operation of the machine in constant orbit mode. The radius of curvature of the inflected beam is ρ=9.2 mm and maximum injection voltage is 20 kV.

The ECR source

As already mentioned the ECR source has to provide beam useful for the test of the machine and be in the future a dedicated source for ligth ions.

No effort could be made for an indipendent design of the source so that attention was placed on already existing sources.

The LIS source[4],now under construction at the KFA in Julich, fit very well the requirements since:

- it is a small, low cost source
- it is a proved design with good performances up to argon beam

It was therefore decided to built a similar source: a source with up to date performances and providing also metallic ions can be added later after installation of the machine in Catania.

The source has two plasma chambers operating at 5 GHz with RF power below 1 kW. Beams of N5+ and Ar8+ are extracted with intensities above 10 μA . Very ligth ions ,like deuteron and alfa, are in excess of 200 μA .

The source will operate in the range 5-20 kV; the expected emittances can be calculated by the relation:

$$\varepsilon = \frac{1}{2}\,\pi\,\frac{r^2\,B}{B\rho}$$

For an extraction hole r=4 mm and field B=2.2 kgauss the emittances are in the range 300-130 mm mrad for the beam rigidities Bρ=20-45 kgauss cm.

Beam transport

The short solenoid So refocus the extracted beam at the entrance slits of the analyzing magnet M1. The focal length of the solenoid, which is 17 cm long and has a 2 cm thick iron shield, is f=30 cm at maximum beam rigidity.

Measurements[5] taken at Julich indicate that the position and the size of the virtual source do not coincide with the extraction hole of the source as has been assumed for the calculation of the strength and position of the solenoid lens So. This aspect will be taken into account during the first test of the source.

The beam envelope along the transport line for a matched beam with a 300 mm mrad emittance is presented in fig. 3. A nominal beam size of 8 mm has been assumed at the entrance slits of the analyzing system.

Charge state selection is provided by a 90°magnet, with wedge angles β=26.5° ,radius 30 cm and gap 6 cm, running up to 3 kgauss. This field value, corresponding to twice the maximum rigidity of the injected beam, has been chosed to allows an almost complete charge state analysis of the beam for the tuning of the source .

The acceptance of the analyzing magnet for a beam with cilindrical symmetry and waist at the object slit is over 900 mm mrad as given by the vertical acceptance and with a maximum divergence, at the slit position, of 30 mrad .

The four quadrupoles Q1-Q4 provide an indipendent matching in the transversal planes or, alternatively, can be used to produce beam with cylindrical symmetry. The quadrupoles have effective length 20 cm , aperture 8 cm and maximum pole tip field 800 gauss.

The 90° vertical bending unit, with two dipole and three quads, is achromatic and is equivalent to a -I matrix with length of 30 cm in the dispersive plane and 5 cm in the other plane.

Quadrupoles are identical to q1-q4 ;the two 45° bending magnet have a radius of 30 cm and a 5 cm gap. The acceptance of the system at the entrance of the magnet M2 is limited by a max. divergence of 20 mrad in the dispersive plane and 30 mrad in the other plane.

The four solenoids S1-S4 form a telescopic system, consisting of two equal cells, with a -I matrix transformation. The system, called in the following rotator, is designed to provide a variable rotation angle for optimum beam matching maintaining the telescopic condition.

The solenoids have an effective length of 30 cm, an effective field 2.4 kgauss and aperture 8 cm.

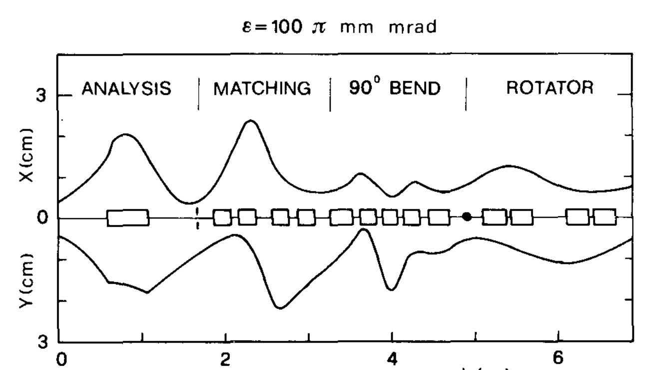

Fig. 3 – Beam envelope along the beam transport line.

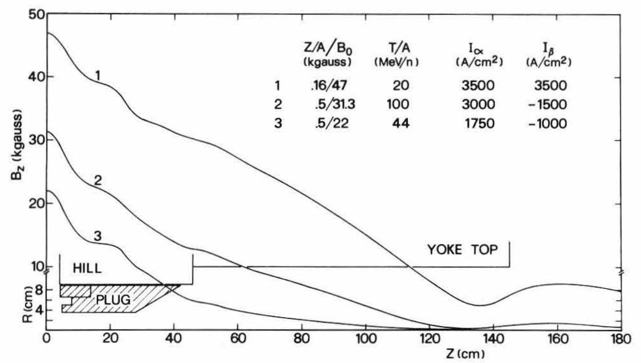

Fig. 4 - Magnetic field along the axial injection hole for three field levels covering the operating range of the machine.

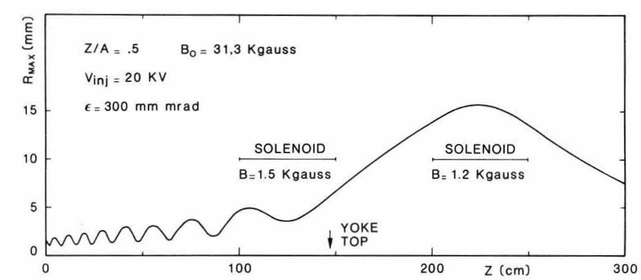

Fig. 5 - Radial beam envelope along the cyclotron axis for a beam of fully stripped ion.

Beam matching

The magnetic field along the axis of the cyclotron is plotted in fig. 4 for three different field levels covering the operating range of the machine 22-48 kgauss. The configuration of the iron in proximity of the yoke hole is also sketched.

At low excitation the axial field region is confined inside the yoke bore while at maximum excitation, due to the saturation of the iron yoke, the fringing field tail extends up to few meters from the yoke.

It is assumed that no axial field exists beyond z=3m from the median plane, although field values of the order of few hundred gauss are anticipated. The fringing field tail could mainly perturb the setting of the telescopic rotator without influence on the general design of the beam line.

Two solenoids are required to keep the beam confined during the traversal of the yoke hole. The positions of the two solenoids, S5-S6 in fig. 2, are determined by the high field and low field case respectively.

Positions, lengths and field values of the solenoids will be optimized after magnetic field measurements; for the calculated fields the indicated positions are effective for the beam confinement.

The beam envelope at an intermediate field level is plotted in fig. 5 where are also indicated the relevant parameters of the solenoids. This case has been calculated assuming a beam with cyclindrical symmetry focused to a waist size of 2 mm at the median plane.

Other cases are quite similar and confirm that the beam can be confined with a maximum size of ~ 30 mm.

An electrostatic mirror has been selected for the inflection into the median plane . The mirror, with an outer shell diameter ϕ=25 mm and a distance grid-electrode of 3.5 mm, operate at voltages up to 17.5 kV corresponding to a maximum electric field of 50 kV/cm. The acceptance of the mirror is of the order of 400 mm mrad for beam spot sizes at the entrance in the range 2-3 mm .

A central region has been designed[6] for operation in the h=2 harmonic mode due to the possibility to accelerate beam in the energy range 8-100 MeV/n. The possibility to operate in the h=1 mode, which presents some advantages for the most relativistic ions, has however been preserved.

The acceptance of the central region, for the two mode of operation, is of the order of 500 mm mrad in both planes. At the inflector exit waist sizes of approximately 2 mm in the horizontal plane and 3 mm in the vertical plane are required for the matching.

The main problem associated with the matching of the beam is the control of the increase of the emittance due to the coupling between the two transversal planes produced by the axial magnetic field and by the inflector. Also a transversal-longitudinal coupling is introduced as will be shown later.

The effects of the coupling are illustrated in fig.6 for three cases corresponding respectively to a beam with cilindrical symmetry and different waist sizes at the median plane and to a matched beam.

As can be seen in the figure there is always an increase of the emittance at the median plane (i.e. at mirror entrance) which is depending on the beam size.

For a beam with a cylindrical symmetry the increase can be calculated[2] with the formula :

$$\varepsilon^2 = \varepsilon_i^2 + \left(\frac{\pi r^2}{2\rho}\right)^2$$

where ε_i is the emittance of the injected beam, r the beam radius at the median plane and ρ the radius of curvature of the inflected beam.

A further increase of the emittance is produced by the inflector, due to the intrinsec coupling of the transport matrix, as shown in fig. 6 for the cases of beams with cylindrical symmetry.

The increase of emittance produced by the axial field and by the inflector can be minimized, not canceled, by selection of a proper rotation angle between the coordinate system of the injected beam and the inflector as described in ref. 2.

The third case in fig. 6 corresponds to a matched beam at the inflector exit and has been calculated with the optimal value of the rotation angle to minimize the total emittance increase.

The control of the rotation angle within the useful range can be obtained with the telescopic rotator without changing the telescopic condition.

It must be pointed out that at the exit of the inflector there is a coupling between the three phase spaces (transversal and longitudinal) ; the matching conditions, beside the difficulty of calculation , can be obtained only with some approximation.

The control of the beam size at the inflector entrance is quite important for the control of the emittance increase, although critical to obtain due to the difficulty to place diagnostic devices ,with good resolution, close to the median plane.

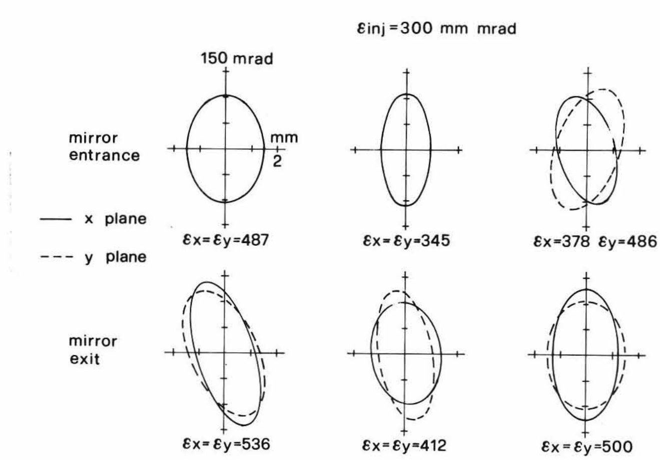

Fig. 6 - Phase space plot at mirror entrance and exit for three different cases (see text for details).

Bunching system

The phase acceptance of the central region[6] is quite limited and has been calculated in ±10° RF corresponding to a 6% transmission efficiency for an injected D.C. beam.

A bunching system is therefore necessary to improve the transmission. High efficiency is possible, under ideal conditions, with values close to 50% for a simple (sinusoidally driven) buncher and 70% for harmonic buncher. These figures are drastically reduced ,in the case of axial injection into a superconducting cyclotron, by the second order path length differences in the axial field and first order transit time differences in the traversal of the inflector.

Using the WKB approximation for the paraxial trajectory in the axial magnetic field it can be shown that the transit time difference is given by:

$$\Delta\Phi = h\ (\dot{x}^2+\dot{y}^2)\ \mu$$

where h is the harmonic mode of acceleration, $\dot{x}$,$\dot{y}$ the beam divergences at the median plane,and μ is the Larmor angle

$$\mu = \frac{1}{2}\int \frac{B(z)}{B\rho}\ dz$$

calculated from the starting position up to the median plane .

This formula is well verified by numerical computation and it is particularly useful in the design stage for its simplicity since does not require any detailed knowledge of the trajectory.

Two positions have been considered for the buncher; well inside the yoke hole (z= 75 cm from median plane) and just outside the yoke (z =150 cm). The value of the Larmor angle with these starting positions , for the magnetic field plotted in fig.4 , are given in the Table I .

Table I – μ values (radians)

z (cm)	.16/47	.5/31.3	.5/22
75	28	20	16
150	40	24	20

In the worst case (high field, buncher at z=150 cm) assuming a beam divergence at median plane of 100 mrad the transit time difference ,respect to the central ray, reach the maximum value of 45° RF.

In order to limit the transit time effect the buncher should be placed as close as possible to the median plane and the beam size should be large.

These options are not practical since:

- the buncher can be placed,at minimum , at 60 cm from the median plane due to the central plug extending up to z=50 cm
- the beam size cannot be too large at the median plane to avoid an increase of emittance and loss of beam inside the inflector.

The advantage of placing the buncher at z=75 cm (respect to z=150 cm) is significant only for the high field cases and does not justify the complication of having the buncher inside the yoke hole.

Moreover in the high field case, i.e. high rigidity of the injected beam, the emittance of the source is lower so that some compensation can be achieved.

Therefore the nominal value z =150 cm has been selected for the position of the buncher.

Transit time variation are also produced in the traversal of the mirror. A first order analysis gives the following relation[2] :

$$\Delta\Phi = h\ (-.065\ x_o + .029\ y_o - .0012\ \dot{y}_o\ )$$

with ϕ in rad. and x,y,$\dot{y}$ the phase space coordinates (in mm, mrad) at the mirror entrance (the electric field is in the y-z plane). For a beam with 2 mm size and 100 mrad of divergence the transit time differences are in the range ±13° RF.

From the above consideration is evident that the bunching efficiency will be quite lower than the theoretical values.

A computer code has been used to evaluate the efficiency of the buncher. The transit time differences have been calculated with the analytical formulas for a beam simulated with 10000 ions . An emittance of 300 mm mrad has been assumed for the injected beam focused at the median plane to a waist of 2 mm size.

Uniform distribution in the initial RF phase and gussian in the other phase space coordinates have been assumed (the beam is given at 2σ contours) with an energy spread of the beam source .02% .

Two cases were considered corresponding to high field case (μ=50) and low field case (μ=25) and simple or harmonic buncher.

The calculated efficiencies are given in Table II

Table II – Bunching efficiency (±10° RF)

buncher	μ = 50	μ = 25
simple	20%	26%
harmonic	25%	36%

The bunching efficiencies, although quite reduced respect to the ideal case, are still significant and give an improvement of at least a factor 4 (for the harmonic buncher) respect to the injection of a DC beam. These values are somehow optimistic since other important effects are not taken into account like space charge,voltage instability, non linearities during the crossing of the buncher and the mirror traversal.

An improvement of the transmission by a factor 3-5 (dependig on the field level) can be expected for the harmonic buncher.

The feasibility of an harmonic buncher with a single gridded gap will be investigated in the near future. The fundamental frequency of the buncher is in the range 15-48 MHz with peak voltage amplitude up to 300 volt.

Status

The ECR source is under construction; first test will start early next year.

All the elements of the beam line have been defined with the exception of the solenoids S5-S6 ; they will be designed after the mapping of the axial field of the cyclotron . A prototype of the electrostatic mirror is under development.

It is planned to test part of the beam line (up to, and including, the rotator) at the end of 87 before final installation of the system into the cyclotron pit.

Ackwnowledgement

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