AXIAL INJECTION IN THE LNS SUPERCONDUCTING CYCLOTRON

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At the LNS the K800 Superconducting Cyclotron has been in operation since 1994 as a booster of a 15 MV Tandem. Several years ago it was decided to provide the machine with an axial injection system so as to operate in stand-alone mode. By a proper choice of the source (a superconducting ECR one), it was also intended to improve the performance of the cyclotron as far as the intensity of all ion beams and the energy of ions with mass higher than 100 a.m.u. are concerned. Several studies have been done in the past to design the axial injection system of the cyclotron, i.e. the inflector and the central region. In the meantime, a new idea has come up, namely to use the cyclotron as a primary machine to produce radioactive ion beams. The new design takes account of the "high intensity" request, and at the same time allows the acceleration of ion beams in the whole mass range, in 2nd harmonic mode (energy range 8÷100 MeV/a.m.u.). Beam dynamics features of the designed system are presented. A phase selection system will also be installed to reduce activation of the electrostatic deflectors.

1 Introduction

The K800 Superconducting Cyclotron is presently operated as a booster of a 15 MV Tandem [1]. There are several reasons which many years ago led to the decision of replacing the present radial injection mode with the axial injection mode. Firstly, the need to have a simpler and more reliable accelerator system, not consisting any longer of two accelerators. Secondly, the possibility of improving the performance of the cyclotron, in terms of intensity and maximum energy. Related to the previous point is the role that the machine will assume, as a primary machine, in the EXCYT project for the production of radioactive beams [2].
The new injection mode implies, of course, the replacement of the stripper system with the axial injection system, i.e. the inflector and the central region.
A study was accomplished [3] many years ago to design a central region following a mirror inflector. At that time the designed system was not constructed because it was decided to couple the machine to the Tandem.
A preliminary study of a central region following a spiral inflector [4] was also accomplished, but at that time it had not yet been decided that the machine would deliver the primary beam for the production of radioactive beams.
The design study presented in this paper takes account of the need to accelerate ion beams intense enough for the production of secondary beams, still maintaining the possibility of accelerating each ion type in a wide energy range, within the operating diagram of the cyclotron.
In the new injection mode, the cyclotron will be operated in constant orbit mode: this means that the source voltage, as well as the dee voltage and the inflector voltage, will be scaled, as compared to the reference case, according to the relation: $V/(\omega_o B_o)$=const. The maximum source voltage was assumed to be 30 kV, which was an increased value compared to the one assumed in the previous mentioned studies. With the new value, a better transport of the beam is expected along the line, and also space charge effects are expected to be less effective.

2 Axial injection beam line

Most of the axial injection line, namely from the ECR source to a point on the cyclotron axis, 4465 mm distant from the median plane, was designed a few years ago as a purely transport line, consisting of solenoids as focusing elements. Four quadrupoles were inserted at the end of the horizontal section to have the possibility of rotating the beam ellipse at the final point, named matching point (MP). The remaining vertical section has recently been designed [5] looking for beam envelope confinement and a small beam size at the entrance of the inflector. The result is a couple of solenoids, one of which will be positioned quite close to the cyclotron yoke, 300 mm far away, and therefore has a special iron yoke, designed taking account of the magnetization induced by the cyclotron fringing field.

3 Inflector

For the spiral inflector, the electric field value has been chosen so as to make the exit radius as large as possible. This allows to have more space to allocate the central region posts. With an injection voltage of 30 kV, the chosen electric field of 22 kV/cm gives an exit radius of 17.5 mm.
The gap of the inflector has been assumed to be 6 mm, 2 mm more than the gap considered in the previous studies. This is also an important feature for the "high intensity" operation. With the above value of the electric field, the electric radius A, given by $A=2E/(q\varepsilon)$, E being the energy and ε the electric field, is 2.7 cm. Since the magnetic radius $\rho_m=p/(qB)$ is 1.123 cm, the K value, given by $K=A/(2\rho_m)$, related to the amount of spiral, is 1.20.

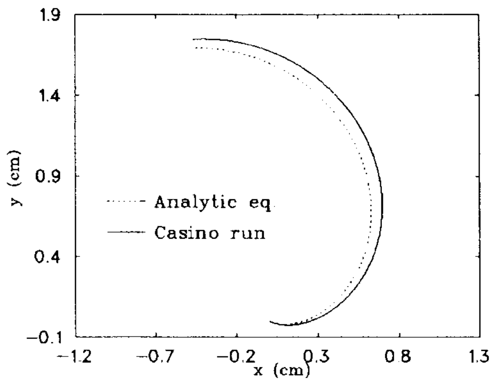


Figure 1: Central ray trajectories inside the inflector: projections on the median plane.

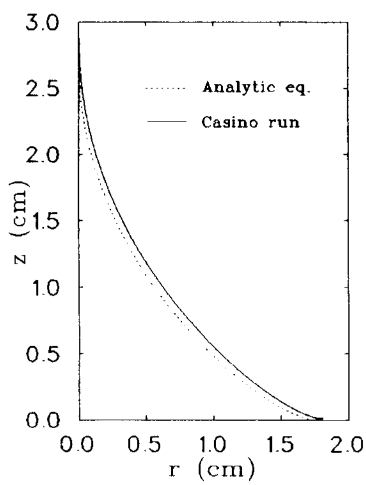


Figure 2: Central ray trajectories inside the inflector: vertical motion

After having chosen the parameters of the inflector following the above procedure, the first preliminary design of the central region was accomplished (see next paragraph). Then, a more accurate design study was done: the program *Casino* [6] was used to simulate the inflector traversal of the particles. This code works with the electric field calculated by *Relax3D* [7]. The above inflector parameters were used to have the input file for *Relax3D*.

The results of the performed simulations show that the trajectory of the reference particle inside the inflector is different when considering the analytical formulas and the output of *Casino*. This is mainly due to the effect of the fringing field, not considered in the former case. More important, in the latter case the condition $z=p_z=0$ does not occur, which means that the particles do not reach the median plane with zero divergence.

Nevertheless, when running the same case with different inflector voltage, i.e. using the same electric field file and scaling the voltage, the analytic trajectory can be approached and the $z=p_z=0$ condition fulfilled (see figures 1,2). With $E_{infl}=0.9481E_{anal}$, an exit radius of 1.81 cm was found, 0.6 mm larger than the analytic value, with a slightly different (3.2°) exit angle. Since, as said above, only the preliminary design of the central region had been done, the new exit position and angle of the inflector was assumed as the initial condition for the central region.

4 Central region

As mentioned in the Introduction, the central region will work in constant orbit mode, which is mandatory due to space constraints. The acceleration mode that covers most of the allowed energy range is h=2: beams with energy 8÷100 MeV/amu can be accelerated, the small range 2÷8 MeV/amu being excluded.

The preliminary design of the central region was based on the new design of the central region of the MSU K500 cyclotron [8], which has been refurbished to be coupled to the K1200. At MSU, the whole system is conceived to deliver intense primary beams to produce radioactive ion beams by fragmentation.

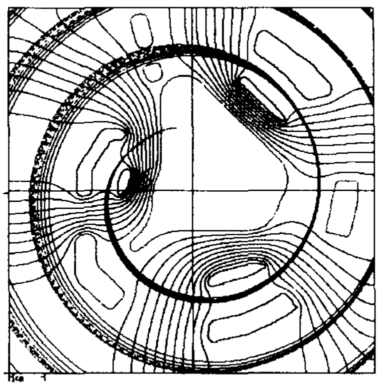
Then it was evident that there is a common objective with the MSU, namely to use compact superconducting cyclotrons to produce intense beams. Of course, there are different operating energy ranges and ion type varieties, the MSU K500 central region having been designed to accelerate only beams to be re-accelerated by the K1200. Consequently a number of adjustments were made on the shape and position of the posts to allow the beam to be correctly accelerated in the central region. A few minor changes were introduced when the inflector accurate study gave the new position at the inflector.

Here follows a short description of the main features of the design, achieved by means of the code *Relax3D*, for the electric field calculation, and *Z3Cyclone* [9] for the orbit study.

The beam exiting from the inflector is immediately accelerated by the puller, consisting of two posts at the RF voltage, which create the first accelerating electric field. The RF and ground posts are shaped and positioned so as to create an electric field as parallel to the trajectory as possible and allows particles to gain as much energy as possible. While inside the central region, the beam stays well confined, but at the end of the first turn there is a radial dependance upon phase, and here the last ground slit of the central region performs a rough phase selection, reducing the phase range to approximately 35° (from 200° to 235°, see figure 3), which corresponds to the acceptance of the cyclotron.

Without selection, particles with phases out of this range could possibly be accelerated to a region close to extraction and cause activation when lost somewhere. Here in the central region the energy is low and therefore the beam

power is not at all dangerous. Then the central region is the ideal place to do phase selection; however, due to a strong mixing effect between the longitudinal and the transverse motion, the definition of the phase range is not sharp when considering beam ellipses instead of central rays, and consequently we may get only rough selection.
A slit system [1] has been designed to perform fine phase selection out of the central region. It consists of three "pins" that will cut phases according to the simulations made in [10].



5 cm

Figure 3: The 2[nd] harmonic central region of the LNS Superconducting Cyclotron. Central trajectories with starting times from 200° to 235° are plotted.

In figure 4 the r-pr acceleration plot is shown for different phases belonging to the considered phase range. This plot gives an idea of how centered the beam is out of the central region, the perfectly centered beam being the one with a smooth r-pr curve.
The corresponding x-p_x plot (figure 5) gives an idea of the off-centering extent. Both figures 4 and 5 show how it is possible to partially compensate radial off-centering by means of a first harmonic bump, provided by the trim coils.

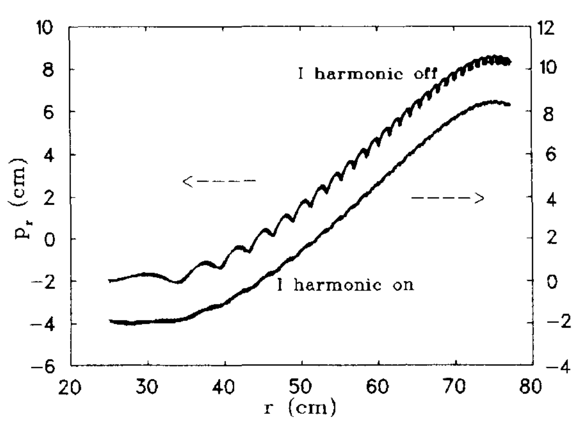


Figure 4: Radial phase space plot for the τ values considered

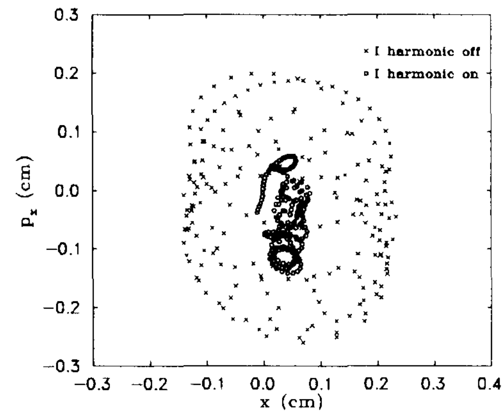


Figure 5: Off-centering correction by means of a I harmonic bump

The z-motion in the first 20 turns is displayed in figure 6, where no particular problem appears. Three different τ values were considered, for each of them eight particles belonging to the initial beam ellipse were run.
Having the main features been ascertained for the configuration found out, the radial and axial motion have been studied in detail paying particular attention to the matching between the injection line and the cyclotron.

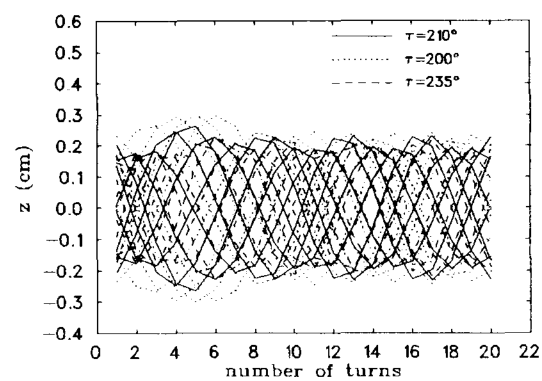


Figure 6: Z-motion in the first 20 turns

5 Matching

The matching between the line and the cyclotron in the new mode has been considered. It has been decided to consider the following features separately: the evolution of the beam ellipse from the inflector exit towards extraction, and the beam ellipse transport from the "matching point" to the inflector exit.

5.1 From the inflector exit towards extraction

The latter was studied by means of *Z3Cyclone*: eight particles belonging to the ellipse contour were accelerated through the central region towards the extraction radius for a fixed number of turns (50). At the end of this path the eigenellipse was calculated; the aim of this study was to define the shape and orientation of the starting beam ellipse, at the inflector exit, that matches the calculated eigenellipse. It was found that the coupling effect between the radial and the vertical motion is negligible. For the vertical one, no emittance growth effect has been observed, so the matching condition was found out quite easily by a trial-error procedure (figure 7). The radial motion is affected by non-linear effects, which cause some emittance growth. Consequently, finding out the matching condition is not so easy as in the vertical case. The solution that minimizes possible mismatch effects is the beam ellipse having the same shape and orientation as the calculated eigenellipse, with a bigger area.

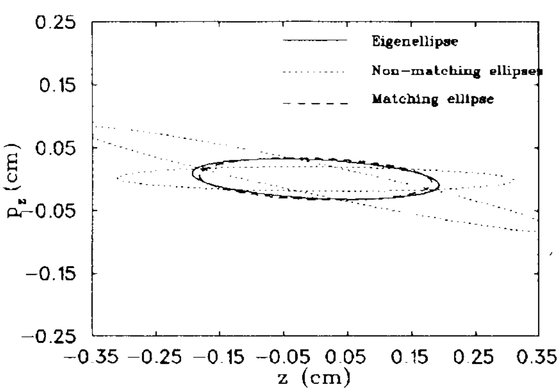


Figure 7: Matching in the vertical plane from the inflector exit towards extraction

The beam ellipses found out as a result of this study were assumed as starting point to study the beam behaviour when crossing the yoke and the inflector.

5.2 From the beam line through the yoke and the inflector

The beam optics simulations in the solenoids, in the Cyclotron yoke and in the spiral inflector were performed with *Cosy Infinity* [11]. A set of routines has been written in *Cosy* language to calculate the beam trajectories through the fields of the cyclotron axial channel and the inflector.
A fine tuning of the line (from the matching point ahead) has been accomplished aiming at the matching of the beam emittance with the cyclotron acceptance and at the reduction of the beam emittance growth resulting from the coupling. The matching has been done by minimizing the function $F=F_x+F_y$,

$$F_x=(<x>w_x/x_a)^2+(<p_x>/(w_x p_{xa}))^2,$$

x_a, p_{xa} being the maximum width and angle of the ellipse at the inflector exit, found by the procedure described in the previous sub-section, w_x, w_y experimentally adjusted weights.
The minimum of F is achieved by variation of the fields of the last two solenoids and the four parameters of the two uncoupled transverse beam ellipses at the matching point, the values of which are provided by the preceding transport line. Such a matching procedure results in a negligible beam emittance growth and provides almost matched beam ellipses with slight differences in orientation and half axes when compared to the given ellipses at the inflector exit.

6 Conclusion

The axial injection complex (central region and inflector) of the LNS Superconducting Cyclotron has been designed considering that the machine is requested to deliver primary beams for the production of radioactive isotopes. However, almost the whole operating diagram will be covered, which guarantees acceleration of a large variety of ion species with a large energy range. Nuclear physics experiments at intermediate energies will in fact be accomplished in the next years, continuing the research program that began two years ago with the first cyclotron beams.
The central region parts and the inflector are planned to be installed in the cyclotron in January 1999.

References

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