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AXIAL INJECTION IN THE SUPERCONDUCTING CYCLOTRON

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Abstract

The Superconducting Cyclotron has started working in the axial injection mode.
Until September 1999 it worked as a booster of the Tandem, and the beam was radially injected in the median plane. Now the beam is produced by an ECR source and injected along the axis. Therefore, the Cyclotron has been provided with an inflector and a central region. The design calculations are here presented. The pieces of the axial equipment are shown as manufactured by the company.

The inflector and the central region were assembled in December 1999. In January 2000, the first beam in the new mode has been injected, accelerated and extracted.

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1 INTRODUCTION

The K800 Superconducting Cyclotron has been operated as a booster of a 15 MV Tandem until September 1999 [1)]. There are several reasons why a few years ago it was decided to replace the 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. The high intensity objective is due to 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 the replacement of the stripper system with the axial injection system, i.e. the inflector and the central region.

The design study of the central region has taken 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. To do that, the 2^{nd} harmonic mode of acceleration has been chosen.

In the new injection mode, the cyclotron is 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 a reference case, according to the relation: $V/(\omega_o B_o)$=const. The maximum source voltage is 30 kV.

2 DESIGN CALCULATIONS OF THE AXIAL INJECTION EQUIPMENT

2.1 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 [3)] 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 is 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.

2.2 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. 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.

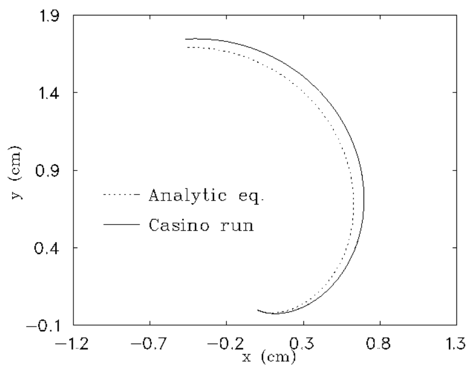

FIG.1: Central ray trajectories inside the inflector: projections on the median plane.

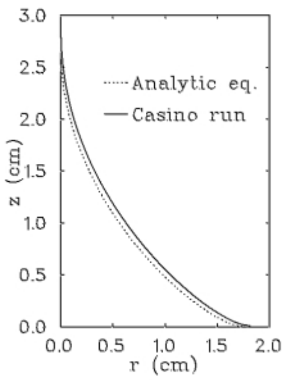

FIG. 2 : Vertical motion inside the inflector

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* [4)] was used to simulate the inflector traversal of the particles. This code works with the electric field calculated by *Relax3D* [5)] . 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 Fig. 1 and Fig. 2).

2.3 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 [6)], which has been refurbished to be coupled to the K1200. At MSU, the whole system is designed 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. 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* [7)] 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. Here the last ground slit of the central region performs a rough phase selection, reducing the phase range to approximately 35^o (from 200^o to 235^o, see Fig. 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 has been designed to perform fine phase selection out of the central region. It consists of three ”wedges” that cut phases according to the simulations made in the reference [8)].

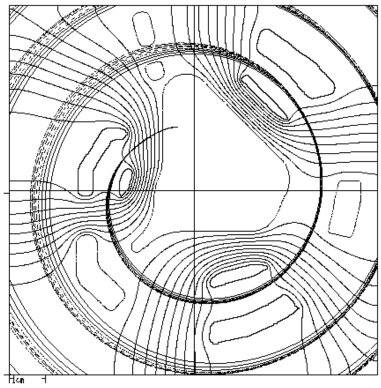

FIG. 3: The 2nd harmonic central region of the LNS Superconducting Cyclotron. Central trajectories with starting times from 200° to 235° are plotted. The square is 10 x 10 cm.

Calculations have been done to demonstrate that it is possible to partially compensate radial off-centering by means of a first harmonic bump of about 10 gauss, provided by the trim coils.

The z-motion in the first 20 turns is displayed in Fig. 4. Three different τ values were considered, for each of them eight particles belonging to the initial beam ellipse were run. The vertical motion appears to be well confined.

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.

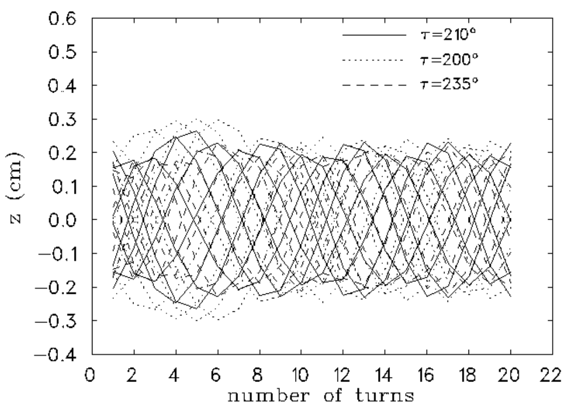

FIG. 4: Z-motion in the first 20 turns

2.4 Axial line – Cyclotron matching

The matching between the line and the cyclotron in the new mode was considered. It was 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.

2.4.1 From the inflector exit towards extraction

The evolution of the beam ellipse from the inflector exit towards extraction was studied by means of Z3*Cyclone*: 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 (Fig. 5). 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.

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.

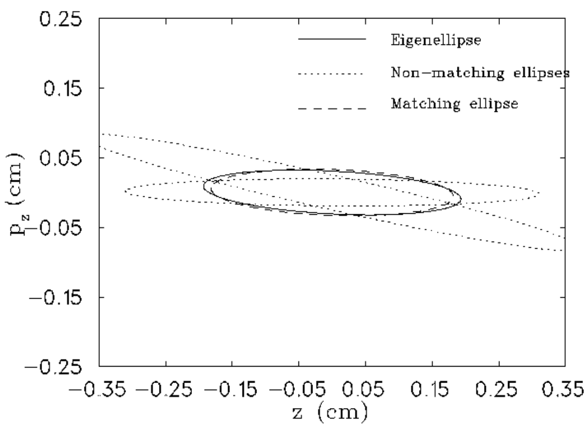

FIG. 5: Matching in the vertical plane from the inflector exit towards extraction

2.4.2 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* [9)]. 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.

3 MACHINING OF THE CENTRAL REGION, INFLECTOR AND PHASE SLITS

The central region and the spiral inflector were constructed according to the specifications resulting from the calculations reported in the previous paragraph. A 3D model of the different parts (dee tips, ground plug and posts, spiral electrodes and housing of the inflector) was derived from those specifications and sent to the company together with the drawings of the inflector accessories (high voltage leads, vacuum pieces, etc).

A few pictures of the main pieces, as machined by the company, are shown. Figures 6 to 9 show in the order: the upper and lower plugs, the spiral inflector and the dee tips.

In order to do fine phase selection, three wedges, whose maximum width is 2 mm, have been installed inside the cyclotron, one in each dee. The three main holes of the dees host the mechanism that allows to adjust their position. The slits are 20 cm far from the center, and can be moved by 1 cm in the median plane; they can also be removed from the median plane, going down inside the dees. In Fig. 10 a detailed view of one slit is shown.

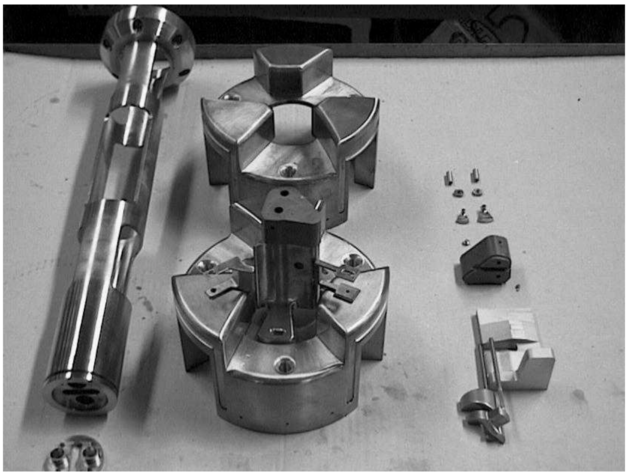

FIG. 6 : Upper and lower central plugs

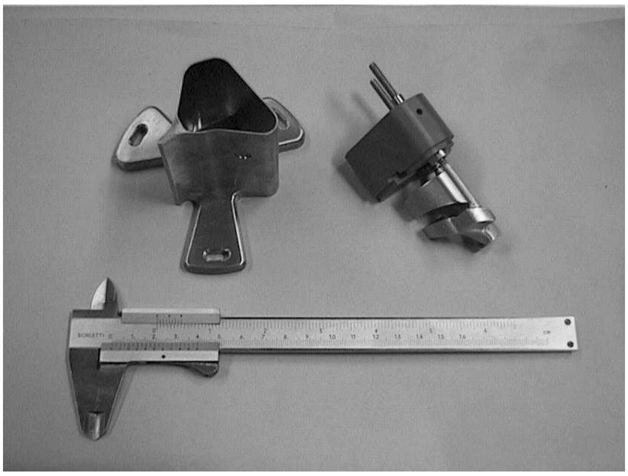

FIG. 7: The spiral inflector with its housing

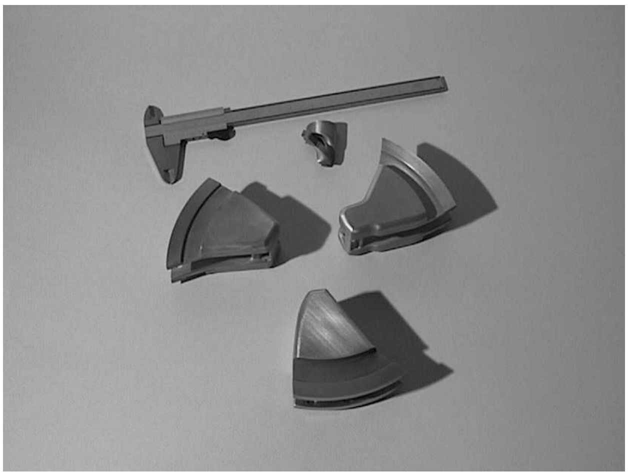

FIG. 8: The three dee-tips

FIG. 9: Detailed view of one dee-tip

FIG. 10: Detailed view of one phase slit

4 BEAM OPERATIONS

The above described elements of the axial injection system, i.e. the inflector and the central region, were installed in December 1999. In Fig. 11 a picture of the assembled central region is shown. Phase slits can also be seen. In January 2000, a $^{58}Ni^{16+}$ beam, produced by the superconducting ECR source SERSE, and accelerated to 17.7 KV, was transported through the axial beam line to the inflector, bent onto the median plane of the Cyclotron, and accelerated by the puller and the central region, reaching the extraction radius with an energy of 30 MeV/amu. The operative parameters were very close to the calculated ones.

The beam was also extracted with the same parameters as in the radial injection working mode.
Injection efficiency is presently about 5%, and may be improved up to a maximum of 10%, since the central region selects approximately 35° RF. The beam was continuous as produced by the source, but in the next days we will switch on an axial buncher working in the same RF frequency range as the cyclotron. Given this result and the operational experience of the MSU National Superconducting Cyclotron Laboratory [10], we think that in the near future the cyclotron will be able to deliver 1 pμA of light ion beams at an energy of 70-90 MeV/amu, as requested by the EXCYT project.

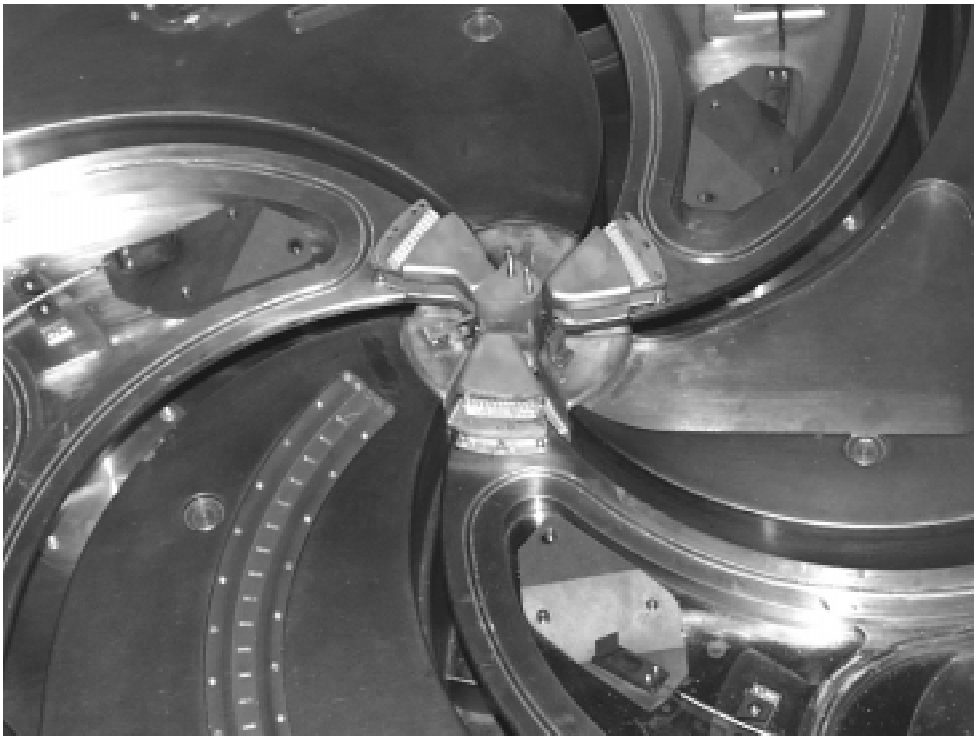

FIG. 11: View of the central region and phase slits assembled in the median plane

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