HIGH INTENSITY SUPERCONDUCTING CYCLOTRON BEAMS FOR A RADIOACTIVE ION BEAM FACILITY

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ABSTRACT

One of the major limits to the beam intensity in the Superconducting Cyclotron is presently set by the extraction system, which consists of an electrostatic deflector. A valid alternative to electrostatic extraction could be extraction by stripping. The feasibility of this method has been studied taking into account the major constraints of the machine and particularly of the cryostat. This study includes some investigation on the magnetic channel system to be used in the extraction trajectory and on the consequent perturbation of the three-fold symmetric field.

1. INTRODUCTION

In the project for a Radioactive Ion Beam (R.I.B.) facility at L.N.S.[1] the Superconducting Cyclotron is planned to be employed as the primary accelerator, delivering ion beams with energies up to 100 MeV/a.m.u.

Of course many efforts have to be made in order to achieve a reasonably high intensity of the primary beam. Several efficiency factors have in fact to be taken into account when estimating the total intensity of the radioactive beam delivered in the target, due to the production, transportation, ionization, mass analysis and acceleration processes.

The S. C. is by now strongly intensity-limited by the extraction process, which is performed by electrostatic deflection: in order to extract fully stripped ions at the maximum energy (focusing limit: 100 MeV/a.m.u.), the gap size of the deflector must be 6 mm to obtain the electric field of 140 kV/cm planned in the design. Then the probability for the whole beam to hit the deflector increases; in the case an intense beam (some pμA) is to be extracted, the beam power exceeds the expected limit, which is about 0.5 kW.

Moreover the electrostatic solution gets more and more worrying the more intense is the beam to be extracted: space charge effects produce distortions of the emittance figure in the transverse phase space when the beam is electrostatically deflected.

Therefore an extraction method leaving out the electrostatic deflector would be desirable. The feasibility of extraction by stripping in the Superconducting Cyclotron is studied for some cases and here discussed.

2. EXTRACTION TRAJECTORIES WITH THE STRIPPING METHOD

The extraction by stripping method has already been adopted in a compact isochronous cyclotron[2] for heavy ions. During the feasibility study for the Superconducting Cyclotron, a fundamental constraint has been considered: the cryostat is not to be modified. An immediate consequence of this assumption is that the extraction trajectory has to be similar to the trajectory in the electrostatic extraction: the beam has to enter the yoke and exit through the extraction channel (Fig. 1[3]).

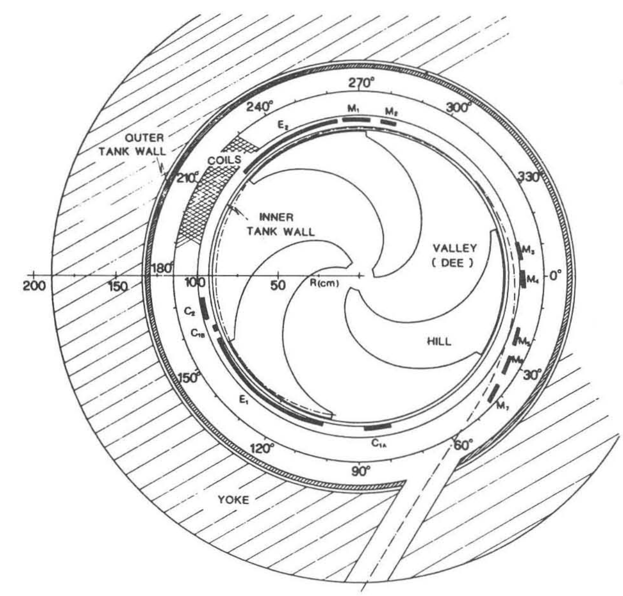

Fig. 1. Beam trajectory in the electrostatic extraction system.

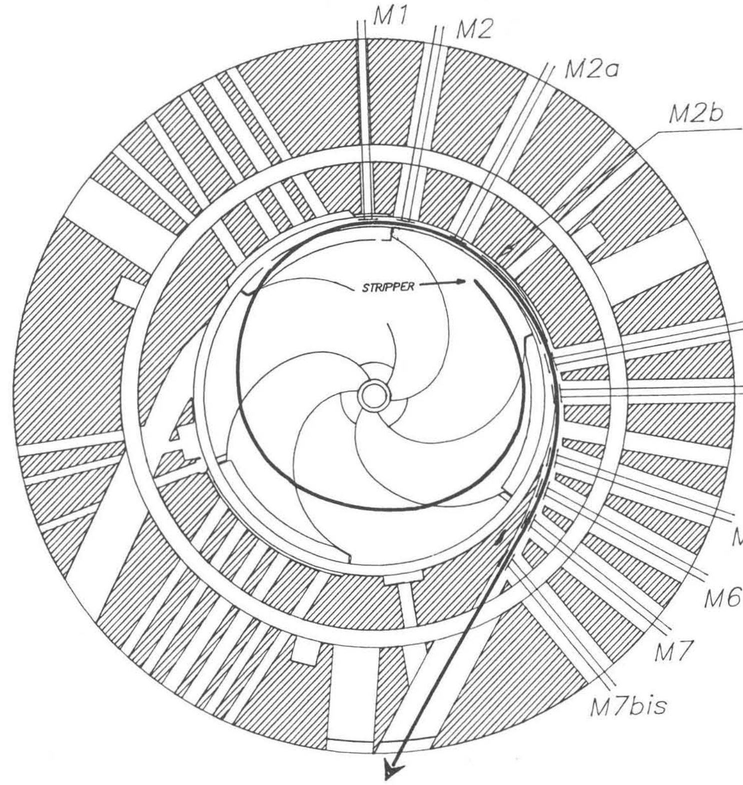

Fig. 2. Extraction trajectory with the stripping method.

A one-two units charge change of the ion at the end of the acceleration process makes the orbit go inward in about half a turn and then outward in the following half turn. Depending on the stripping radius and angle, and on the charge "jump", after one turn the stripped ion can either go inward or definitely and abruptly exit from the Cyclotron. The second possibility cannot be accepted if the extraction channel has to be penetrated: then, according to the first case, at the position where the orbit reaches the maximum radius after one turn, before going inward, it is extracted by magnetic channels (Fig. 2).

In the original project of the Cyclotron, a set of iron channels is planned to radially focuse and help to deflect the beam along the extraction path. Two channels are placed immediately after the second deflector, six channels are placed along the extraction channel (Fig. 1).

The "Spiral Gap" code[4] was used to simulate the acceleration of the ion, starting from the equilibrium orbit at 30 MeV/a.m.u., until the stripper. Another code,[3] using the same integration routine, takes into account the effect of the field decreasing channels and allows to simulate the extraction trajectory.

The behaviour of the beam along the extraction path has been studied in the radial and axial phase space after having ascertained that there is no destructive effect on the beam in the path between the stripper and M1. The eigen-ellipse at 30 MeV/a.m.u., calculated at the position 0°, was transported until the extraction point (θ=92°, r=~216 cm). The emittance was calculated supposing that the beam emittance injected by an E.C.R. source is 100π mm·mrad.

Keeping in mind the final purpose of this study, i.e. the employment of the Cyclotron as the primary machine in a R.I.B. facility, we decided to begin the feasibility study considering an ion with mass A<30. Since at the Cyclotron energies every ion with A<30 hitting a foil stripper becomes fully stripped, the extraction efficiency reaches almost 100%.

As it can be easily understood, the strength of the magnetic channels is as small as the difference between the charges before and after stripping is small. Then the first case to be investigated was ^{16}O, q_i=7, q_f=8, q_i and q_f being the charge states before and after stripping. According to recent results an E.C.R. source can produce $^{16}O^{7+}$ with intensity of 25 pμA.[5]

In order to study the case mentioned, the field at the center of the machine was assumed to be B_o=32.2 kGauss, which corresponds to a maximum energy of 78 MeV/a.m.u for the 7^+ ion. In this case we found that:

- the stripper should be placed at r_s=81.6 cm, θ_s=316° (Fig. 2), where the beam energy is about 75 MeV/a.m.u., to allow the beam to reach the radial range (90.0-91.6 cm) of M1 at its angular position (θ=264°);

- all the magnetic channels planned have to be used, including M2bis and M7bis;

- an extra channel has to be employed between M2bis and M3; since there is no hole for magnetic channels, a fixed device should be designed;
- the strength values of the channels is around 6 kGauss, apart from M1 and M2, which maintain the same values as in the electrostatic extraction case (1-2 kGauss) because they are definitely assembled inside the cryostat;
- the magnetic channels have to provide a certain field gradient to focuse the beam; in Fig. 3 a possible, not optimized, solution shows that assuming field gradients of 1-3 kGauss/cm, the beam is much smaller than the extraction channel size (~3 cm height, ~4 cm width).

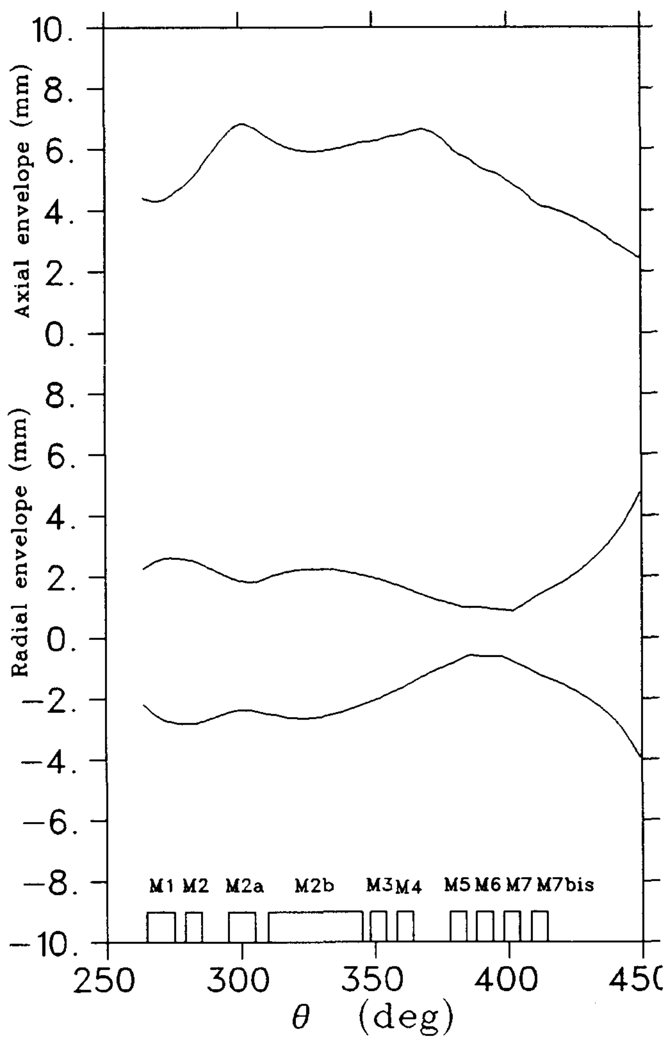

Fig. 3. Radial and axial beam envelope along the extraction trajectory.

3. MAGNETIC CHANNELS

An attempt was done to design iron magnetic channels whose strength is about 6 kGauss. Since the width of the extraction channel is ~4 cm, the three-bar configuration, adopted for the mainly focusing channels of the electrostatic extraction, was discarded, not allowing to achieve a considerable strength. Two two-bar configurations, which seemed to fulfil the requirements, were realized. The first one was a not focusing, two equal bars channel, which should provide a field of about 6.8 kGauss in the gap according to the calculations[6]; the second one was a two different bars channel, which should provide a constant gradient of ~1 kGauss/cm in the gap (8 mm) and a field of 6.0 kGauss in the center.

As explained in,[7] the measurement of the field inside the gap showed that the difference between the calculated and the measured field is about 1 kGauss in the zero-gradient channel and 2 kGauss in the other one; moreover in the second one the gradient is not constant. A separated functions solution (with only focusing and only deflecting magnetic channels) would require the strength of the only deflecting channels to be more than 6 kGauss.

The use of passive channels produces a relevant problem concerning the beam dynamics of the Cyclotron: the perturbation of the three-fold symmetric field. In fact the first harmonic produced by two-bar 6 kGauss channels at r~82 cm, which is more or less the radial position of the resonance $\nu_r=1$, ranges from some gauss to tens of gauss, depending on the azimuthal extent of the channel. Therefore, it has to be compensated by iron bars appropriately placed in the available holes of the yoke. However the first harmonic contribution of the fixed channel can hardly be compensated by simple iron bars.

Since many problems arise, as noticed, from the use of passive channels, we think that efforts should be devoted to look for the possibility of employing active channels.

4. STUDY OF SOME CASES

In order to verify the statement done before on the relationship between the charge change and the channels strength, we studied the case ^{16}O, $q_i=6$, $q_f=8$: we found that the stripped beam reaches the radial range of M3 at its angular position ($\theta=348°$) after about one turn, but it is not possible to make the beam go through the extraction channel due to the big change in magnetic rigidity.

Another confirmation comes from the study of the case ^{20}Ne, $q_i=9$, $q_f=10$. The charge state 9^+ is produced with an intensity of ~1 pμA,[8] but higher intensities are expected in future. A Ne beam is particularly good to be employed in a R.I.B. facility as a primary beam. The magnetic field at the center of the Cyclotron was assumed to be 31.4 kGauss, which corresponds to a maximum energy of 78 MeV/a.m.u for the 9^+ ion. The stripper position results to be $r_s=82.6$ cm, $\theta_s=318°$, which is not so different from the Oxygen case. However, in this case we found that the strength of the channels is about 5 kGauss, lower than in the previous case.

5. CONCLUSIONS

The theoretical feasibility study of the new extraction method proposed needs to be extended to a wide set of ion species that can be produced with high intensity by E.C.R. sources.

More important, the technological feasibility must be ascertained: the possibility of realizing magnetic channels with the mentioned requirements has particularly to be verified. Finally, the possibility of placing the stripper system in the position found out by the calculation needs some investigation.

6. REFERENCES

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