EXPERIMENTAL EVIDENCE OF BEAM DYNAMICS FEATURES OF THE LNS SUPERCONDUCTING CYCLOTRON

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At LNS the K800 Superconducting Cyclotron was commissioned as a booster of a 15 MV Tandem with a ^{58}Ni beam, accelerated to 30 MeV/a.m.u.. An overview of the beam dynamics studies accomplished for the parameters setting is presented. The main injection, acceleration and extraction experimental features are also discussed outlining the major problems encountered. The influence of centering errors on the beam behaviour was investigated. Efforts were made to improve the injection, acceleration and extraction efficiencies: the results of these operations are reported.

1 Introduction

The LNS Superconducting Cyclotron is a three sectors, K_{ben}=800, K_{foc}=200 compact machine, which is being operated as a booster of a 15 MV Tandem. A review of the features of the cyclotron is extensively reported elsewhere [1]. For its commissioning, a ^{58}Ni beam to be accelerated to 30 MeV/a.m.u. was chosen. This choice was made after having ascertained the possibility of utilization of this beam, but was primarily based on the requirement of not operating the machine at its maximum values.

Here we report the main features of the injection, acceleration and extraction studies accomplished to find out the nominal values of the machine parameters for this ion type.

Since the main experimental evidences occurred while running this first beam are intended to be reported in this paper, a short description of the beam diagnostic tools of the machine will be given. The main diagnostic device is a probe moving in the center of a hill along the corresponding spiral. This probe was originally designed as a current probe, but now a particular head is installed, which allows to choose the probe working mode between a current read-out system and a beam spot visualization system. The main probe has multiple use, since it allows to span the whole acceleration radial range (in the present case of radial injection), and to detect the beam in the extraction channel too. Injection operation is also accomplished using opportunely the main probe, as will be explained below.

Several current probes are installed along the extraction path, just before magnetic channels.

An alumina-TV camera system was installed at the entrance of the second electrostatic deflector, exploiting a hole originally dedicated to an injection current probe.

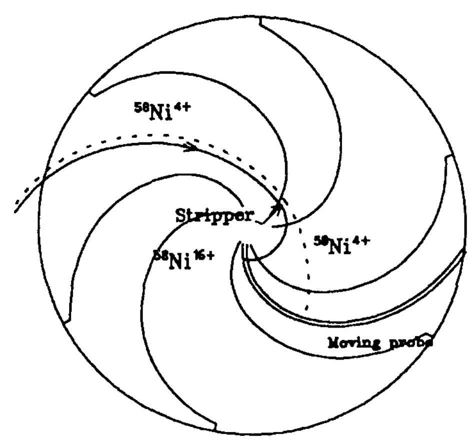

Figure 1: Pole region of the Catania Superconducting Cyclotron

2 Machine setting

2.1 Injection

The beam accelerated by the Tandem is radially injected[2] into the Cyclotron. It is transported to the Cyclotron entrance through a beam line consisting of three 60° dipoles and fourteen quadrupoles, ending with a steering magnet able to change the direction of the beam by a few degrees. As clearly shown in Figure 1, the injection path mainly occurs in a valley, then the beam reaches a stripper foil placed in the following hill. There the charge state of the accelerated beam will be increased by 3-5 times. The only data assumed are the final energy at the cyclotron exit (E_f) and the ion type. All of the other injection parameters, namely the charge state of the injected beam (Q_i) and its energy (E_i), the stripper position (r_{str} and θ_{str}) and the magnetic field to be provided by the steering magnet can be determined after having chosen two fundamental beam parameters: the charge state of the accelerated beam (Q_f) and the magnetic field value in the center of the machine B_o, corresponding to E_f. These two values were chosen taking account of both the charge state distribution after the stripper foil and the position of the ion in the operating diagram of the machine.

Values of the injection parameters were then found out as a result of a calculation procedure here described. Assuming a certain value for E_i and Q_i, the equilibrium orbit corresponding to E_i, diminished by the energy loss due to the stripper crossing, is calculated to be matched with the injection trajectory at the stripper position (with a precision of 0.1 °). As a result of this calculation, the stripper position (radius and azimuth) is defined. Since in most cases more than one solution exists, the value of Q_i is chosen taking account of the charge state distribution after the gaseous stripper of the Tandem, even if one more parameter, namely the gas pressure, is adjustable to modify that distribution respect to the equilibrium charge state distribution.

In order to realize a good matching between the Tandem and the Cyclotron, the beam behaviour was studied in the horizontal and vertical phase spaces. The radial and axial eigenellipses at the stripper position were calculated assuming an emittance value of 4.8π mm.mrad, which is about 4 times larger than the estimated one. The beam parameters values at the steering magnet position (beam ellipse parameters, linear and angular dispersion) are used to tune the matching section of the coupling beam line between the Tandem and the Cyclotron.

2.2 Acceleration

The magnetic field parameters values, namely the main coils and trim coils currents, were found out by running a fit procedure[3] which minimizes the trim coils power and allows to get the setting values to accelerate the chosen ion type. The program makes use of measured field data, such as the iron average field, the field modulation, the trim coils form factors and the trim coils modulation, and yields a 120° symmetric field map whose average field is the isochronous field properly deisochronized in the extraction region.

Equilibrium orbit properties were studied to get information on the radial position where resonances occur and on the phase curve of the accelerated ion assuming a certain dee voltage value. It was found that the resonances $\nu_r = 1$ and $\nu_r = 2\nu_z$ are located very close each other, within a distance of 2 mm. It was also verified that the resonance $\nu_r + 2\nu_z = 3$, particularly dangerous for the beam stability, is not crossed.

In order to study the accelerated beam properties and to find out the coordinates of the beam to be extracted, the Spiral Gap code[4] has been used to simulate the path of the beam during acceleration . The assumed dee voltage was 70 kV. A full (360°) field map was used, obtained from the already mentioned 120° symmetric one adding the measured significant imperfection harmonics of the base field and of the trim coils. This map takes also account of the contribution of the magnetic channels and compensating bars; for this reason it is a result of successive iterations: at first a certain configuration of channels and bars is assumed; after few extraction runs, the final configuration is found out.

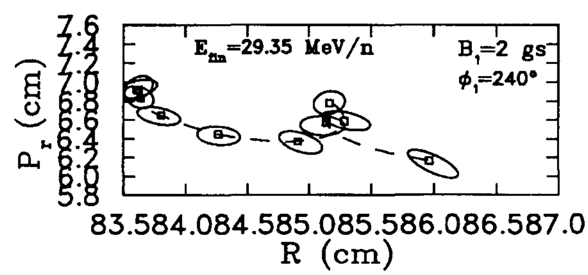

Figure 2: Radial phase space plot of the last turns at the first deflector position

Values of six more parameters came out from Spiral Gap runs, namely the current values of the last two harmonic coils, n. 19 and 20. They were calculated to provide the proper 1st harmonic amplitude and phase separating the last two orbits before extraction as much as possible (B_1, ϕ_1, see Figure 2) and compensating the measured 1st harmonic at the resonance $\nu_r = 1$ location. Of course, measured values of the trim coils form factors were used.

2.3 Extraction

A computer code[5] was used to find out values of the extraction parameters, namely the electric field of the two electrostatic deflectors, their position and the position of the passive magnetic channels and compensating bars.

Acceleration and extraction runs were accomplished at two different dee voltages, namely 50 and 70 kV, to have an idea of the variation of the extraction pattern caused by the dee voltage variation. It was found that the electric field values of the deflectors,

corresponding to the two mentioned dee voltage values, was 74.4 and 64.9 kV/cm respectively. This is mainly due to the energy difference of the extracted turn between the two cases, which results to be 0.12 MeV/n.
This was an additional reason to decide to make the commissioning of the Cyclotron with the dee voltage at 70 kV.

3 Machine operation

3.1 Injection

The main probe is presently the only diagnostic tool available for the injection operation. It is currently used during beam tests to detect the beam, not stripped, clearing the stripper at outer (referred to the center of the machine) side. In fact the radial position of the beam at the stripper azimuth can be varied by properly adjusting the steering magnet current; for the Ni beam, a variation of 0.5° at the entrance of the machine causes a variation of 2.5 cm of the beam radial position at the stripper azimuth. Since the beam is not stripped, as mentioned before, the trajectory beyond the stripper is quite different from the accelerated orbit (Figure 1). The radial position of the beam on the moving probe is calculated and coincides with the spot position observed in the beam tests. It was verified by simulation, and then experimentally confirmed, that this position does not strongly depend upon the bending angle provided by the steering magnet, which is obviously advantageous for operation. The shape and current of the injected beam is checked observing the stripped beam on the main probe, about 120° after the stripper position, at approximately the same radial position as the stripper.

3.2 Acceleration

Figure 3 shows a typical accelerated beam current distribution as measured on the main probe. Charge states different from the accelerated one, populated according to the charge state distribution corresponding to the Tandem energy, are visible at distances of a few centimeters one from the other one: from r=150 mm to r=250 mm, measured beam current is due also to their contribution. Beyond this radius, the accelerated beam, whose current value is almost constant up to 750 mm, is only a fraction of the injected beam, namely the one within the acceptance of the Cyclotron (about 40° RF). Then the accelerated beam current is determined by the efficiency of the low energy buncher, presently estimated as 30%. Until now no beam test has been accomplished with the high energy buncher on, mainly due to power supply failures.

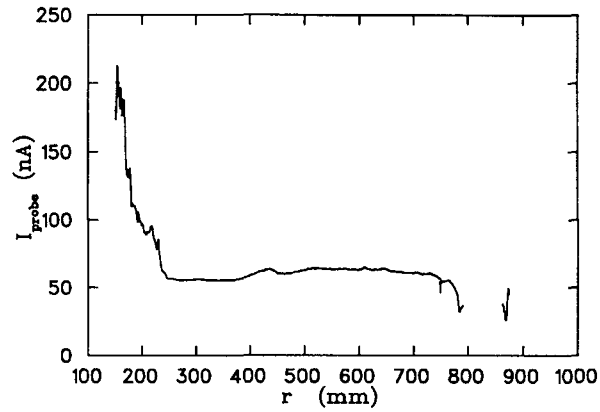

Figure 3: Accelerated beam current measured on the main probe

From r=770 mm to r=860 mm lack of reliable data is due to a trouble of the current read-out system. However, a slight, but clear, current loss occurs at extraction. In the first tests this loss even reached 60%. The most probable reason could be a sort of radial off-centering while crossing the resonance $\nu_r = 2\nu_z$, which couples the radial and axial motion.
A number of simulations were done in order to ascertain the off-centering effect on the axial width of the beam. Assuming the equilibrium orbit at injection as a starting point, the reference case was an orbit perfectly centered. The axial size of the beam (z_{max}) was found out by simulating the acceleration of the central ray and of eight particles belonging to the eigenellipse contour. Then the same procedure was applied to an off-centered beam (Δr=5 mm).
The result is shown in Figure 4, where a 2.5 mm axial increase can be seen, which qualitatively confirms the origin of the axial blow-up. It was also found that the dependance of z_{max} on the off-centering extent is quadratic up to Δr=6 mm, while for higher values the beam is completely lost. The application of the extraction bump by the last two harmonic coils also makes the axial size of an off-centered beam increase, while it practically has no effect on a centered beam.
The above described effect was confirmed by detection of activity from the upper and lower liners, located just in the radial region where the resonance occurs. Then trim coils n. 3 and 4 were used to provide a 1^{st} harmonic contribution able to minimize the vertical beam size after crossing the resonance.
The still present beam current loss near extraction (Figure 3) can be thought to originate from axial blow-up of the residual off-centered beam, whose phase if far from the central one.

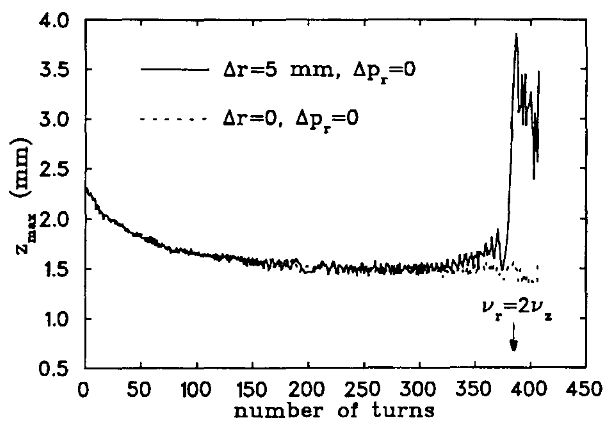

Figure 4: Effect of radial off-centering on the beam vertical size at the Walkinshaw resonance location

3.3 Extraction

The beam extraction has been accomplished positioning the two electrostatic deflectors and the magnetic channels as resulting from calculation. Although the nominal value of deflecting electric field is sufficient to extract the beam, in order to maximize the extracted beam current the voltage of the first electrostatic deflector needed to be increased by 7 kV. Excluding any sort of RF dee voltage mismatch between the desired value and the real one, since calibration[6] by means of x-rays method was carried out, the reason for this electric field increase can be supposed to be lack of measured field data in the extraction region.
Partially extracted beam can be detected in the extraction channel (r=970 mm) by the main probe, which allows to tune the first extraction elements position. Here the vertical position of the beam is about 5 mm below the median plane, while the beam seems to be vertically centred when accelerated. Experimental data on the beam vertical position along the extraction path are presently being collected to have as many elements as possible to find out the origin of this displacement. Having checked the right vertical positioning of the channels, we are beginning to investigate on the eventual effect of a vertical asymmetry of the vacuum chamber. In the meanwhile, the position of the beam on the main probe in the extraction channel has been corrected by means of a special magnetic channel (again passive), opportunely designed to provide a radial field component and consequently a vertical force. The experimental result is a vertical displacement of the beam on the main probe of about 3 mm, so its final position is only 2 mm below the median plane. However the whole question is still open, and we are presently forced not to use the last two magnetic channels because they are not crossed in the median plane and cause the beam to be vertically displaced and partially lost inside the extraction channel.
It was found from calculation that changing opportunely the phase of the controlled 1st harmonic provided by the last trim coils (n. 19 and 20), a good inter-turn separation was achieved one turn after (referred to the case shown in Figure 2), i.e. at 0.08 MeV/n more. Experimentally trying this extraction, which was operatively advantageous because it requires a smaller electric field (57.5 instead of 64.9 kV/cm), extracted beam current was found to be decreased by about 70% as compared to the previous case. This intensity loss could be due both to beam quality lowering in the last turn and to the already mentioned vertical displacement occurring close to the extraction radius.

4 Concluding remarks

Field data coming from the final magnetic measurements[7] have been utililized to carry out the commissioning tests of the Catania Superconducting Cyclotron. The immediate success of the first acceleration operation is a first preliminary evidence of the good accuracy of the measured data, to be hopefully confirmed by the acceleration and extraction of other types of ions.
A few remarks on the efficiency values estimated during the beam tests follow. The injection efficiency obtained is about 75%. The originally designed current probe in the injection channel, now replaced with a TV camera pointing to the entrance of the second electrostatic deflector, will be installed again to check it.
Taking account of the bunching (30%) and stripping (20%) efficiencies, the estimated beam current at the extraction radius coincides with the measured one.
The extraction efficiency is presently estimated to be at least 30%.

5 References

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