NEW EXTRACTION LINE FOR THE LNS CYCLOTRON

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Abstract

The LNS Superconducting Cyclotron will be modified to allow the extraction by stripper of ion beams with power up to 10 kW. Choosing properly the position of the stripper and the focusing magnetic channels along the extraction path it is possible to convoy the trajectories of the selected representative ion beams across a new extraction channel.

To transport these beams to the existing beam transport line and to the experimental rooms it is mandatory to design a new extraction line. The extracted beams have a maximum energy spread of about ±0.4% so the new extraction line has to compensate the correlation energy-position of the beam and to produce an achromatic waist at the common starting point of the existing transport lines.

The features and the performance of the new extraction line are here described.

INTRODUCTION

The upgrade of the LNS Superconducting Cyclotron was triggered by the needs of some nuclear physics experiments [1,2], which are relevant for the future activities of our laboratory and that require beam current intensity about two orders of intensity higher than the present. The main characteristic of the Superconducting Cyclotron is its compactness and the relative small extraction radius. This means that generally the inter-turn separation stays below 1 mm. At the same time our Cyclotron has to deliver all the ions species in a broad energy range. For these reasons, the solution to extract the beam is based on a couple of electrostatic deflectors (ED). Unfortunately, the low inter-turn separation and the EDs does not allow to extract ion beam with extraction efficiency higher than 60%, which translates in a maximum achievable beam power of 150 W [4]. To overcame this limit, the extraction by stripper, just for ion species with A<40, was proposed [5]. For ions with mass A<40 and for energies higher than 15 AMeV the stripping extraction allows to achieve extraction efficiencies higher than 99% [6], and a beam powers up to 10 kW will be feasible. The main change proposed by the upgrading project is to replace the existing cryostat and the superconducting magnet with a new one having a larger vertical gap for the extraction beam and the use of a new extraction channel. This last request is mainly due to the difficulty to extract the beam trajectories of the stripped beams from the existing extraction channel [5]. The stripping extraction is not feasible for all the ions delivered by our cyclotron and moreover the energy spread for the beam extracted by stripper is about 0.3% vs. 0.1% of the beam extracted by EDs, and their emittance are significantly larger. The mechanical

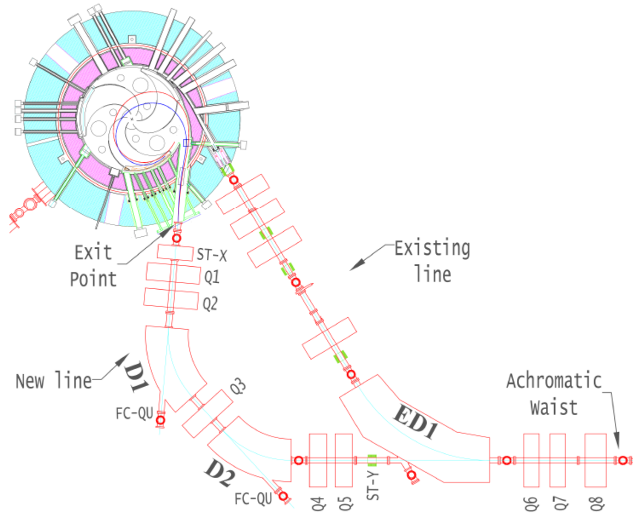

Figure 1: Plan view of the INFN-LNS cyclotron and its extraction beam lines. The new extraction line starts at the exit point and the end is at the achromatic waist.

difficulties to design a universal extraction line and the request of nuclear experiments forced us to have two extraction lines (EL), see Fig. 1. The main differences between the two EL are the final direction of the beam and also the trajectories across the fringing field of the cyclotron. The new extraction channel crosses the fringing field faster than the previous one. This allows to achieve not too big transversal beam sizes along the extraction path not and, also, the position and angular dispersion values vs. energy (R_{16} and R_{26}) are lower than to the previous values achieved with the existing extraction channel [7], see fig. 2.

The advantages to have lower values for R_{16} and R_{26} is compensated by the broader energy dispersion. Indeed, the extraction by stripper will produce an energy spread of 0.3% for the 90% of the beam but up to 0.4% for the 99% of the beam.

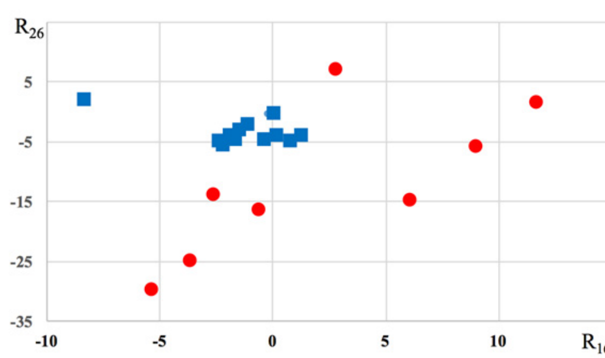

Figure 2: Values of R_{16}[mm/%] and of R_{26} [mrad/%] for the existing extraction line (red dots) and for the new extraction line (blue square).

Table 1: Parameters of the Transversal Emittance at the Extraction Point for a Set of Representative Ions

Ion	Energy AMeV	ε_x mm-mrad	x mm	x' mrad	σ_{12} mm/mrad	ε_y mm-mrad	y mm	y' mrad	σ_{34} mm/mrad	R_{16} mm/%	R_{26} mrad/%
^{12}C	61	1.51 π	15.2	14	0.99997	3.37 π	11.2	12.8	0.999724	0.1	-3.683
^{20}Ne	60	4.19 π	2.74	3.64	-0.9075	3.38 π	4.19	4.19	0.999724	-1.7	-4.461
^{20}Ne	71	3.22 π	4.29	2.05	-0.9308	3.11 π	3.10	3.44	0.95645	-1.93	-3.79
^{18}O	60	2.93 π	10.2	11.1	-0.9997	3.39 π	14.6	14.1	0.999864	1.22	-3.71
^{18}O	61	2.85 π	4.66	3.95	-0.9879	1.68 π	14.3	15.9	0.999973	-8.40	2.11
^{18}O	65	27.3 π	13.3	6.79	-0.9532	3.37 π	6.44	6.11	0.996323	0.1	-0.368

THE NEW EXTRACTION LINE

The new EL starts at the exit point shown in Fig. 1, and transports the beam up to the so called achromatic waist where the beam transport line is common for both the beam extracted by ED and by stripper, see Fig. 1.

The beam line has been studied for six reference cases representative of all the ion beams expected to be extracted by stripping. The ellipse parameters and the radial and angular dispersions of these six ion beams at the exit point are presented in Table 1.

These parameters have been evaluated transporting 8 particles describing the boundary of the radial emittance ellipse from the stripper position to the exit point and similarly for the axial emittance. The value of the initial normalised emittance is 1 π mm•mrad for all the ions. This value is about 30% higher than the value used in the previous study for ED extraction [6] and takes into account the expected larger emittance due to the higher beam current.

Moreover, the trajectories of the stripped beams across the cyclotron are quite different from the trajectories extracted by EDs. Due to the higher magnetic field gradient crossed along the extraction path, the beam shapes at the exit point have a significant distortion. To fit the radial and axial beam ellipses at the extraction point it has been necessary to use a large beam emittance to take into account the ellipse with banana-like shape produced by the non-linearity of field region crossed by the beams. In table 1, the geometrical emittance values are shown. Note that the radial emittance of the beam extracted by stripper should have a value reduced of about 50% just due to the stripper effect, but this is hidden in the values of table 1 due to the distorted ellipse at exit point. Although, the energies for the 5 cases are similar, the transversal emittance values are not. In particular, for the case of ^{18}O at 65 AMeV it has been necessary to increase the radial emittance value up to 27 π mm-mrad to take into account the significant beam shape distortion. The axial emittance values are more regular than the radial emittance ones.

The effort to design the new extraction line similar to the existing one after a few trials failed. It was evident that to match the low dispersion values of the beam with the R_{16}=-17 mm/% and R_{26}=-15 mrad/% with a single 95° bending magnet was not an easy task, expecially if the transversal size of the beam has to maintain acceptable values. For this reason, a solution based on two symmetric bending magnets with a focusing quadrupole in the middle has been chosen. Adjusting the strength of the central quadrupole, this system can be tuned to have the R_{16} value in a broad range, from +7 to -28 mm/% and similarly for R_{26}. This flexibility allows to fit easily the low values R_{16} and R_{26} of the extracted beams. Moreover, the use of two bending magnets allows to insert four vertical focusing edges with benefical effects on the vertical beam sizes.

Due to the space constraint between the exit point from the cyclotron and the existing beam line, it is mandatory to compact the size of the bending magnet. For this reason the bending radius was reduced to 1.6 m and the separation distance has been fixed to 80 cm to allow the insertion of a quadrupole but also of some diagnostic element.

Beam Line Description

The magnetic rigidities of the beams extracted by stripper are lower than 2.7 Tm, about 33% lower than the maximum magnetic rigidity of the beams accelerated by the cyclotron. According to the layout of Fig. 1, the first active element of the new EL crossed by the beam coming out from the cyclotron is a steering magnet, which has to steer the beams in a range of ±0.5°. This steering magnet has an effective length of about 300 mm and the requested maximum magnetic field is lower than 8 kGauss. In the present studies the effects of this steering magnet have been neglected.

The other magnetic elements are two quadrupoles and two symmetric bending magnets with a horizonthal focusing quadrupoles. This first part of beam line has the role to cancel the energy position and energy angle correlation of the beam. After this section there are two additional quadrupoles that have to reduce the vertical beam envelope to avoid to hit the vacuum chamber of the ED1 bending magnet of the existing line, see Fig. 1. In particular, for each case the vertical beam size has to be smaller than 26 mm, that is the free gap of the vacuum chamber of the ED1 bending magnet.

Finally the latest 3 quadrupoles are the same as in the existing line and they have to produce a small beam spot at the achromatic waist position as shown in Fig. 1.

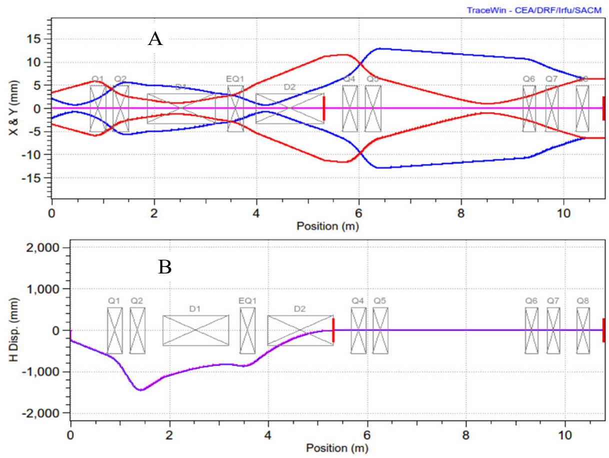

Figure 3: A) radial (blue line) and axial (red line) beam envelope of ^{20}Ne at 71 AMeV, and A) horizontal dispersion vs. length line. This is typical of those studied.

SIMULATION RESULTS

In Fig. 3 the radial and axial beam envelopes, and the dispersion along the transport line are shown for the case of ^{20}Ne at 71 AMeV. Similar beam envelopes have been achieved also for the other cases of Table 1, exception done for the carbon beam at 60 AMeV, as explain below, see Fig. 4. The mechanical and magnetic parameters of the eight quadrupoles and of the two dipoles are shown in Table 2. The characteristics of the eight magnetic quadrupoles and of the two bending dipoles are presented in Table 2. The maximum magnetic field of the two dipoles is 1.7 T, a little too high, but this is the price to pay to have a bending radius of 1.6 m, which reduces the dipole size. On the other hand, the characteristics of the quadrupoles are not critical. For all the cases we are able to compensate the initial chromatism of the beam and put the position and angular dispersion (R_{16} and R_{26}) equal to zero at the exit of the second dipole. Also the vertical size of the beams stay below 26 mm in the region of ED1 magnet.

The critical case is the carbon beam, shown in Fig. 4, that has a large radial beam envelope just at the position of the second quadrupole and also the vertical beam size at the position of ED1 is larger than the vacuum chamber size. These problems are strongly related to the shape of carbon beam coming out from the cyclotron. Indeed, looking at Table 1, the positive values of both σ_{12} and σ_{34} shown that the radial and axial size are both divergent and the sizes are quite large in both the directions.

Table 2: Characteristics of Quadrupoles and Dipoles

Quads.	Length	Diameter	Field
Q1,Q2	30 cm	80 mm	0.69 T
Q3,4,5,6,7	27 cm	70 mm	0.65 T
Q8	37 cm	70 mm	0.71 T

Dipoles	angle	Radius	Gap(mm)	Field
D1,D2	47.5°	1.6 m	50,80	1.7 T

Probably, it could be convenient to find out a different position of the stripper to extract this ion or to change a little the extraction energy to have a more convenient beam shape at the exit point. Indeed, in Table 1 we see that the radial beam size of ^{18}O beam extracted at 60 AMeV or at 61 AMeV change significantly.

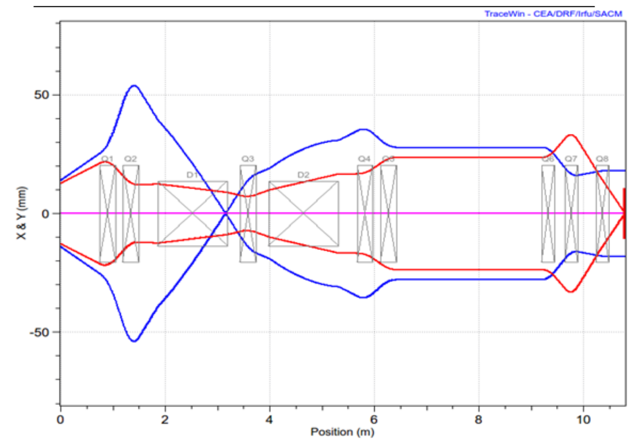

Figure 4: Radial (blue line) and axial (red line) beam envelope of ^{12}C at 61AMeV. The worst case among those studied.

CONCLUSION

The results of the simulations shown that the new EL here presented can transport the beams at the common achromatic waist position for five of the six cases here simulated. Producing an achromatic beam is not a problem while for one case the minimization of the beam size envelope poses serious problems. Further investigations on different extraction trajectories could solve these problems. A serious problem of the new EL is the lack of space to insert beam diagnostics and vacuum pumps. A solution is to use the straight exits of dipole 1 and 2 to check and tune the beam.

REFERENCES

[1] F. Cappuzzello *et al.*, "Heavy-ion double charge exchange reactions: A tool toward 0νββ nuclear matrix elements", European Phy. Journal, Vol. 51, pp. 145, 2015

[2] G. Raciti *et al.*, "Intermediate energies tagged RIBs", NIM B 266 (2008) 4632;

[3] D. Dell'Aquila *et al.*, "New experimental investigation of the structure of ^{10}Be and ^{16}C by means of intermediate-energy sequential breakup", *Phys Rev C*, DOI: 10.1103/PhysRevC.93.024611, (2016)

[4] D. Rifuggiato *et al.*, "Operational Experience with the EXCYT Facility", *Proc. HIAT09*, Venice, Italy, June 2009, paper MO-06, p. 5.

[5] L. Calabretta *et al.*, "Overview of the future upgrade of the INFN-LNS superconducting Cyclotron" Modern Physics Letter A, April 2017

[6] Atomic Data and Nuclear Data Tables, Vol. 51, No. 2, July 1992, Table 2, p.187

[7] E. Fabrici and A. Salomone, "The extraction system for the Milan Superconducting Cyclotron", INFN/TC-87/4, 4 May 1987.