EXTRACTION BY STRIPPING IN THE INFN-LNS SUPERCONDUCTING CYCLOTRON: STUDY OF THE EXTRACTION TRAJECTORIES

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Abstract

The INFN-LNS Superconducting Cyclotron will be upgraded to allow for the extraction by stripping for ion beams with masses below 40 amu. By choosing properly the position of the stripper, it is possible to convoy the trajectories of the selected representative ion beams across a new extraction channel (E.C.).

Here we report the design study for the new E.C. and the simulations of the beam envelopes for a set of ions to find out the parameters of the magnetic channels necessary to focus and to steer the beams through the new extraction line. Two new compensation bars have been designed to compensate the first harmonic contribution of the new magnetic channels. The results of these simulations will be also presented.

INTRODUCTION

The INFN-LNS Superconducting Cyclotron (CS), designed over thirty years ago, is an isochronous three-sector compact accelerator with a wide operating diagram: ion species from H to Pb are accelerated with energy in the range 10-80 AMeV.

The beam extraction system, composed of two electrostatic deflectors followed by a set of magnetic channels, does not allow to achieve a beam power exceeding 100 W, due to the power dissipation on the electrostatic deflectors.

The stripping extraction is a valid alternative to increase the extracted beam power up to 2-10 kW for the ion species with mass less than 40 amu. A preliminary study demonstrated its feasibility [1] if a new extraction channel (E.C.) is drilled. Indeed, the extraction by stripping through the existing extraction channel for the ions of interest is less convenient because a wider clearance is required to allow intense ion beams pass through. Furthermore, the quadrupole component for the magnetic channels varies in a range of values wider than those necessary for the new extraction channel.

In Fig. 1 the median plane of the CS with the existing and the new extraction channels is shown together with the trajectories of two selected ions.

Thanks to high beam power, the INFN-LNS users will be also able to make researches on low cross section processes in nuclear physics. In particular, a high beam power is required by the NUMEN experiment, which proposes to measure the element of the nuclear matrix in the neutrino-less double beta decay using double charge exchange reactions [2,3], and the production of radioactive ion beams by in-flight fragmentation technique will also be enhanced [4].
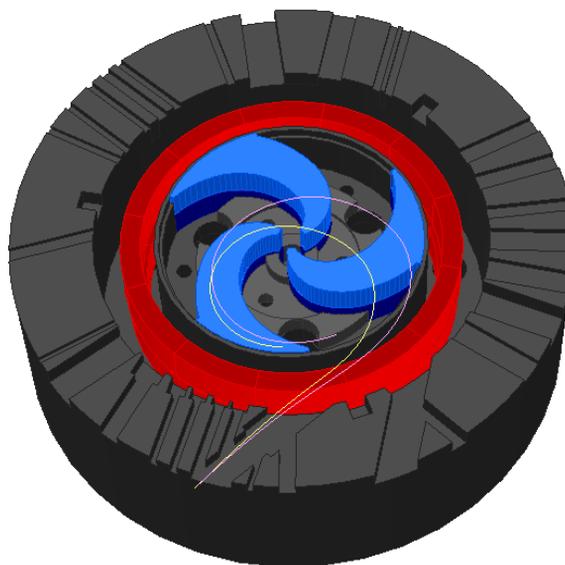
Figure 1: Extraction trajectories of some studied ions through the new extraction channel.

To accomplish the stripping extraction, a significant upgrade of the CS will be necessary, mainly because a new cryostat with new superconducting coils [5] is mandatory to have a larger vertical gap in the extraction line and additional penetrations are necessary to host new magnetic channels and new compensation bars. A general description of the CS upgrade operations is presented in ref. [6]. In addition, the existing extraction mode will be maintained to satisfy the demand of ion beams in a wide mass and energy range by the INFN-LNS community.

STUDY OF THE STRIPPING EXTRACTION

The ion species considered in the present study of the stripping extraction are ^{12}C, ^{18}O, ^{20}Ne accelerated with charge state q=Z-1 or Z-2 or Z-3 at energies in the range 15÷70 AMeV.

We assumed that all these ions of interest, at energies higher than 15 AMeV, are fully stripped of their electrons after crossing the stripper foil [7].

After the change of the charge state, the trajectory of each ion has a strong first harmonic precession and this could bring the beams to come out from the cyclotron field.

The study of the stripping extraction has been performed mainly through two codes, GENSPE and

ESTRAZ, initially developed at MSU by Gordon [8] and updated accordingly to our needs.

For each ion we used the corresponding isochronous field map to accelerate it with mass A and q=Z-1 or Z-2 or Z-3 at the required energy. The code GENSPE, with this isochronous field map as input, has been used to determine the parameters (energy, radial position and beam size) at the stripper position. For our simulations, we assumed a normalised emittance of 1 π mm.mrad. This value is quite conservative since it is more than twice the normalized emittance value of the beam delivered by our ion source.

We used the code ESTRAZ to simulate the trajectories of fully stripped ion beams for different azimuthal positions of the stripper, from the stripper foil to outside the cyclotron yoke. ESTRAZ allows also to compute the radial and axial envelopes of the beam along the extraction trajectories starting with the initial conditions found out by GENSPE code. Unfortunately, the EXTRAZ code performs the trajectory integration with step of 2°. So, we can simulate the starting point of the extraction trajectories only at discrete azimuthal positions. We plan for the near future to perform finer simulations using Spiralgap code or Cobham OPERA 3D [9].

All the present results have been validated and visualised through the FEM software by Cobham OPERA 3D. Details on the technical approach are reported in Ref. [1].

The first aim of our study was to define the cross-section and direction of the new E.C. in the CS: we fixed an exit point from the CS, which has to be crossed by all extracted trajectories in order to have an easier connection between the new extraction channel and a new extraction beam line.

For each ion, we found out the best azimuthal position of the stripper in order to have an extraction trajectory as close as possible to the exit point.

Other constraints must be satisfied by our extraction trajectories, too. They have to pass at least 70 mm away from the CS centre, to avoid any interference with the central region components; and, due to mechanical constraint, axial beam envelopes have to be lower than ±15 mm inside the pole and ±25 mm along the new E.C., which starts from the pole radius and ends after the yoke.

We were able to size down the region where to place the strippers foils in two main areas for all ions of interest, one is on the hill, [106°<$\theta_{stripper}$<122°], just where the electrostatic deflector 1 (ED1) is placed and one on the valley, [60°<$\theta_{stripper}$<88°], just before the ED1.

Table 1 contains some details on the ions studied and stripper positions.

This means that the cyclotron will be operated roughly 6 months per year to deliver ions using the existing ED1 and the other 50% of the year to deliver high power beams using stripping extraction through the new E.C.

Differently from the actual 30 mm of vertical gap along the EC, we fixed the vertical gap of the new E.C. equal to 60 mm to allow for the insertion of focusing magnetic channels so as to let intense ion beams pass through.

Table 1: List of ions to be extracted by stripping and stripper position specifications

Ion	Q_{acc}/ Q_{ext}	Energy (AMeV)	θ strip. (degrees)	R strip. (cm)
^{12}C	4/6	45.8	112	88.17
^{12}C	4/6	60.8	106	87.89
^{18}O	6/8	29.2	60	84.17
			118	87.73
^{18}O	6/8	45.5	68	84.65
			110	87.13
^{18}O	6/8	60	80	84.55
		60.9	106	88.04
^{18}O	6/8	65	88	84.86
^{20}Ne	7/10	29	122	87.64
^{20}Ne	7/10	45.6	114	87.90
^{20}Ne	7/10	60.3	108	87.04
^{20}Ne	7/10	71	108	87.81

Since the stripping extraction is a multi-turn extraction, the extracted beam will have a significant energy spread that we assume to be ≈ 0.3 % for all the considered cases. This energy spread value was initially evaluated using analytical formulas [10], but was also confirmed by some simulations using the SPIRALGAP code to evaluate the radial and energy distributions of a 20.000 accelerated particles from 1 AMeV up to the stripper position. The initial particle distributions were uniform in the range ±10° RF and inside the radial and axial eigenellipse at 1 AMeV.

One of the most relevant results of this study is that only two passive magnetic channels (MCs), named MC1S e MC2S, along the new E.C., are sufficient to permit the extraction of the beams of all ions of interest with different charge states and energies. Although MC1S and MC2S dimensions are quite far from standard as it will be illustrated below, this result reduces considerably the complexity of the stripping extraction system.

The magnetic channels will be inserted out of the radius pole to compensate the radial defocusing effect of the fringing field of the CS and to slightly steer the beam direction along the new E.C. They are iron correctors characterized by a deflecting magnetic field and a constant focusing gradient dBz/dR within the beam aperture.

For each ion, we determined with ESTRAZ the best values of the dipole and quadrupole component for the magnetic channels able to maintain the beam dimensions within the fixed values and able to direct the beam as near as possible to the exit point.

We fixed the gradient for both magnetic channels at 1.8 kG/cm, which is the highest value found for this study (it is relative to ^{18}O at energy 65 AMeV). Simulations demonstrated that this gradient permits the extraction of all ions. As an example, Fig. 2 illustrates the radial and

axial beam envelopes of ^{18}O at energy 65 AMeV computed with ESTRAZ. On the other hand, simulations show that the steering action of each magnetic channel must be different for each ion. That means that the reference trajectory has to enter the MC in a different point. Then, it is necessary to move the channels opportunely. The maximum horizontal displacement for both MC1S and MC2S is 60 mm. This value is the same for B1S and B2S, which are two compensating bars to restore the three-fold symmetry of the main field.
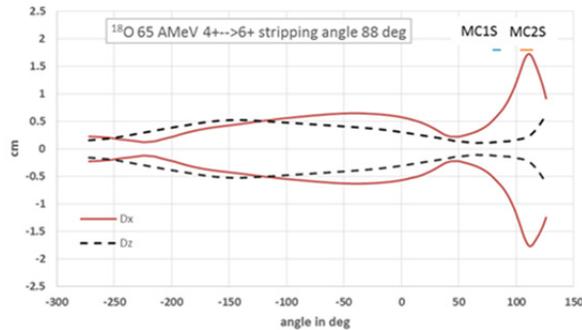
Figure 2: Radial and axial beam envelope of ^{18}O at 65 AMeV along the extraction trajectory. The energy spread is 0.3 %.

The first harmonic component of the field is mainly created by the first block of MC1S, which is the closest to the centre of the machine. The two iron bars have size 120x30x35 mm and have to be installed at $\pm120°$ respect to the position of the first block of MC1S and at R=950÷990 mm. Figure 3 shows a picture of the new compensation bars B1S and B2S and of the new magnetic channels MC1S and MC2S within the CS.
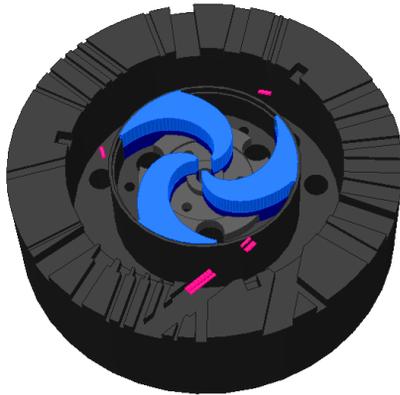
Figure 3: Picture of half CS showing the new magnetic channels and the new compensation bars relative to the new stripping extraction.

DESIGN OF THE MAGNETIC CHANNELS

The design of the magnetic channels is a key point in the present study, due to the request of a large clearance necessary to accommodate the new, larger, beam envelopes.

The magnetic channels used in the existing E.C. of our cyclotron were computed using the three bars technique [11], and the current sheet approximation, CSA, [12], which is valid in the case of uniform magnetization of the iron in an external magnetic field higher than 0.5 T.

Although MC1S, MC2S, B1S and B2S lay in the region of magnetic field higher than 0.5 T and this approach could imply a faster computation time, it cannot be used in our case. Indeed, to use the CSA, the new magnetic channels should be placed in a region of the CS where the main magnetic field is fully perpendicular to the median plane. This is not our case, therefore even if the value of the magnetic field is high enough to magnetize the iron, the magnetization vectors are not perpendicular to the median plane, then the field produced by iron MCs is different from the one produced using only coils as CSA does.

Moreover, the new MCs have more than three bars, since the gradient of the field produced by three bars, as it is in the existing MCs, is constant on a length of only few mm, much lower than the present requirements of 4 cm.

However, as a starting point to define the profiles of the MCs, we simulated the channels in CSA. Once we got the profiles to produced the needed field, we evaluated the field differences with the case of the MCs made by iron volumes and placed where they really will be. Then, we compensated them slightly changing the iron profiles in few interactions of field computation with OPERA 3D. As an example, in Fig. 4 the half of the final geometrical configuration found for the magnetic channel MC1S are shown, as well as the deflecting magnetic field and gradient really seen by the particles.
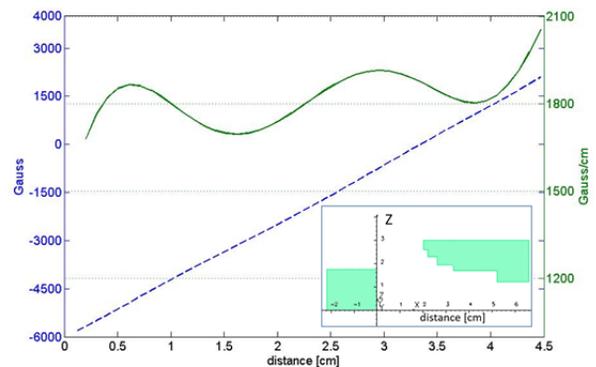
Figure 4: Geometry, dipole and quadrupole component of the magnetic channel MC1S (z=0 is the plane of symmetry).

FORCES

For the new magnetic channels and compensation bars, we evaluated the forces acting on them. Defining the z-axis perpendicular to the acceleration plane, Table 2 contains the components of the forces along the x and y directions for the magnetic channels and compensation bars in the two extreme configurations.

We evaluated also the vertical forces between the two pieces of iron, which are above and below the median plane, for each magnetic channel at each MC position.

This value does not change too much and stays always below 1.4 kN. In contrast with what happens when two iron pieces are in a vertical uniform magnetic field, the two symmetric pieces of the MCs repel each other. Indeed, they are between the upper and lower coils where the lines of the magnetic flux bend themselves around the coils attracting the iron pieces.

Table 2: Forces Acting on MCs and Compensation Bars

	At The Inner Position		At The Outer Position	
	Fx (N)	**Fy (N)**	**Fx (N)**	**Fy (N)**
MCS1	-588	6759	-936	8216
MCS2	-1330	-2490	-1060	-2330
B1S	2693	-1282	3864	-1729
B2S	2474	-1710	-3429	-2490

CONCLUSIONS

With this study we achieved the goal to fix the features of the new extraction channel necessary for the stripping extraction. We decided the cross-section and best azimuthal position for the new channel. We identified two main areas for positions of the stripper foils, and we accomplished the beam dynamics study to extract all ions of interest with the help of only two movable magnetic channels, whose iron profiles are able to generate the needed dipole and quadrupole components for each case. We also fixed angular and radial positions and dimensions of two iron bars, whose task is to compensate the first harmonic component produced by the two magnetic channels.

Furthermore, we performed the study of the forces on all these new elements.

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