UPGRADE OF THE LNS SUPERCONDUCTING CYCLOTRON

A. Calanna, L. Calabretta, D. Rifuggiato, G. Cuttone, G. D'Agostino, INFN-LNS, Catania, Italy
M. Maggiore, INFN-LNL, Legnaro, Italy
A. Radovinsky, PSFC T&ED MIT, Cambridge, MA 02139, USA

Abstract

The INFN-LNS Superconducting Cyclotron (CS) has been working for about 20 years delivering ion beams from protons to gold in the wide energy range from 10 A MeV to 80 A MeV. The beam extraction is presently accomplished by means of two electrostatic deflectors and a set of magnetic channels. Recently, the experiment NUMEN [1, 2] has been highly recommended by the scientific community. The requirements on target are light ion beams (A<30 amu), within an energy range of 15-60 A MeV and a beam power of 5-10 kW, which means to increase the extracted power by a factor 10-100. To achieve this goal we have studied extraction by stripping using the existing extraction channel with an increased transversal section. In addition, a new extraction channel has been designed to broaden as much as possible the range of the extracted ions and energies. To allow the realization of these new channels, a new superconducting magnet is needed including a new cryostat. The major changes and the expected performances for the upgraded cyclotron, as well as the state-of-art of the design, are presented.

INTRODUCTION

The goal of this feasibility study is to investigate extraction by stripping in the Superconducting Cyclotron (CS) to achieve beam power intensity in the range 5-10 kW for light ions with A<30. Even if the NUMEN experiment, which proposes to measure the element of nuclear matrix using double charge exchange reactions [1, 2], is the main reason to increase the beam power, many other experiments currently accomplished at LNS will take advantage from this upgrade. These experiments make use of radioactive ions beam produced with in-flight technique at FRIBS@LNS [3]. Production of radioisotopes of medical interest can be considered too.

Presently, the vertical gap along the CS extraction channel is only +/- 12 mm, while the radial allowed beam dimension does not exceed +/- 5 mm. These mechanical constraints are not enough to plan an extraction of 5-10 kW of beam power. Moreover, a cold channel will be mandatory. For these reasons, we have to replace the whole cryostat. We have investigated the benefits of an increased cross-dimension of the existing channel as well as the feasibility of a complete new channel.

However, the CS peculiarity is its versatility, which has to be maintained since there is a consistent demand of beam types in a wide mass and energy range. For this reason, we plan to equip the CS with both extraction modes: extraction by stripping and extraction by electrostatic deflectors.

In this paper, we describe the approach and codes we used and we show few results that demonstrate we are ready to move towards the technical design. We have already committed to the Plasma Science and Fusion Centre of MIT a study on the feasibility of a new cryostat, which includes the new extraction channel. Some extract of the report they provided on the viability and costs have been reported too.
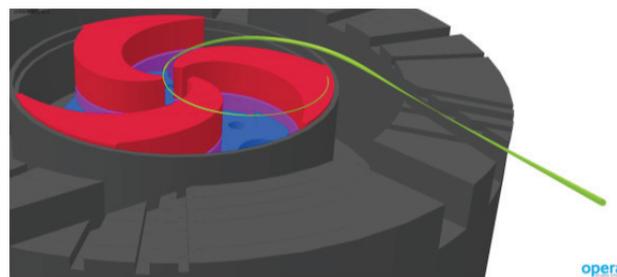
Figure 1: example of extraction trajectory of 12C at 45 AMeV achieved using the code OPERA.

TECHNICAL APPROCH

The main tools we used for this study of feasibility originate from two codes, GENSPE and ESTRAZ, developed at MSU by Gordon [4]. We updated them to suit and solve our needs. All the results have been validated and visualise through a FEM software, OPERA 3D.

Since this study is about an upgrade of an existing machine, measured magnetic maps are available. For this reason, we decided for an approach different from the usual. We created the magnetic model computing the components of the magnetic field outside the median plan solving the Maxwell equations. This 3D map can be visualised and analysed in the Post Processor module of OPERA 3D to track the particles both along the closed orbits and the extraction orbits.

Specifically, our procedure for each ion is now described.

At first, we identify the beam dynamics parameters along the closed orbits using GENSPE. Its input parameters are the magnetic map on the median plane, ion type, RF parameters, beam normalized emittance out of the inflector, which has been chosen to 1 π mm.mrad, about 2.5 larger than the value of the source emittance. The outputs of GENSPE give details on each closed orbit with a given step of energy. That means information on the radius, the radial component of the momentum, the isochronism, the phase slip and the axial and radial betatron oscillations.

Next, we create the magnetic 3D model and we can track the radial and axial envelopes using the output of GENSPE along the last closed orbit.
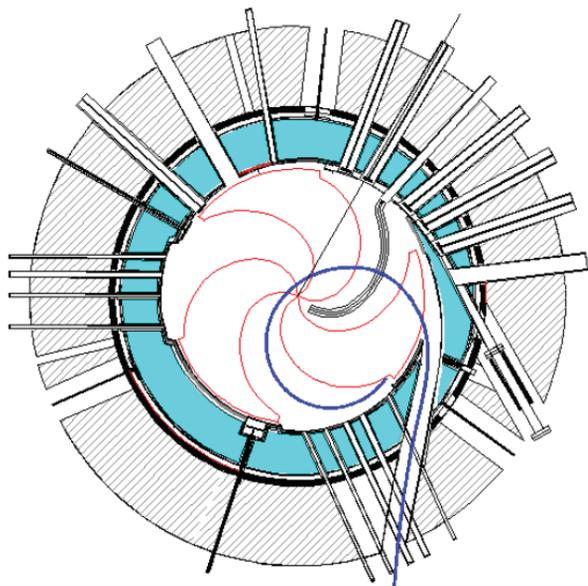
Figure 2: example of extraction trajectory of 12 C at 45 A MeV achieved using the code Estraz. Influence if the 3 MC have been considered.

Table 1: Magnetic Channel Specifications for the Case Extraction trough the New Extraction Channel

ion	Energy MeV	Th strip	MC1 kGauss /cm	MC2 kGauss /cm	MC3 kGauss /cm
^{12}C	30	112°	-2	-2	1.7
^{12}C	45	104°	-0.35	-1.35	0
^{12}C	60	96°	-1	-1.5	0
^{18}O	20	122°	1	-1	-0.5
^{18}O	30	116°	-0.35	-1.35	0
^{18}O	45	112°	-1.5	-1.5	-1.5
^{18}O	60	96°	-1.35	-1.35	0
^{20}Ne	30	50°	-1.5	-1.5	0
^{20}Ne	60	110°	-0.35	-1.35	0

In this way, we can quickly identify in OPERA 3D the best angle to perform the stripping extraction. Our requirements are mainly related to the mechanical constraints. Indeed, we rejected all axial beam envelopes bigger than +/- 2.5 cm and all trajectories that are closer than 7 cm to the centre of the machine. As mentioned before, we are considering two magnetic channels, so the accepted trajectories had to go through the centre of either one channel or the other. We assume that all the medium-light ions here considered have a charge state equal to their Z after the stripping, which means they are fully

stripped of their electrons. After the change in the charge state, the beam trajectory is strongly deformed and the three-fold symmetry is lost. The particles orbit generally around the centre of the cyclotron if the ratio between the final charge state over the accelerating charge state, Q_f/Q_{acc}, is smaller than 1.5. This combined approach overcomes the issue of tracking extraction when the orbit does not rotate around the centre of cyclotron, indeed this cannot be simulated by the code GENSPE or ESTRAZ on their own, but it can be with the OPERA 3D tracking command.

Finally, we have all information to define the best parameters for the magnetic channels, field and gradient using ESTRAZ. We accepted correction fields up to 2 kGauss and gradients up to 2 kGauss/cm. The maximum accepted axial dimension of the beam along the magnetic channels is +/- 3cm.

Furthermore, we also considered the energy spread introduced due to the fact the stripping extraction is a multi-turn extraction [5]. The value of the energy spread introduced varies according to the accelerated ion, but it always stays around 0.3 %.

An example of the outcome is in Fig.1 and Fig. 2 that represent the trajectory of the stripped beam inside and outside the cyclotron. Fig. 3 shows the radial and axial beam envelope computed with the procedure described.
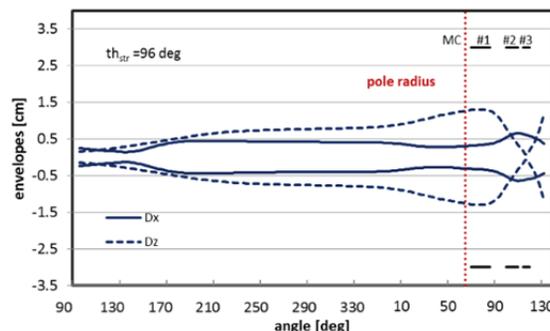
Figure 3: Radial and Axial beam envelope along extraction trajectory of 12C at 45 A MeV. Energy spread +/-0.3 %.

In Fig.4, there is a sketch of all the ions studied. Table 1 contains few details on the stripper positions, as well as the needed gradients of the MC for the case extraction through the new channel. An internal document has been produced and submitted to INFN board for evaluation of costs and feasibility. It contains more detailed information on the evaluation procedure of the beam radial and axial evolution, for both the extraction channels, and the energy spread for each case.

NEW CRYOSTAT AND SUPERCONDUCTING MAGNET

The design with two extraction channels requires building a new cryostat, including a new set of superconducting coils. In particular, it requires a stress analysis of the cryostat structure to evaluate the maximum size of each penetration across the cryostat.
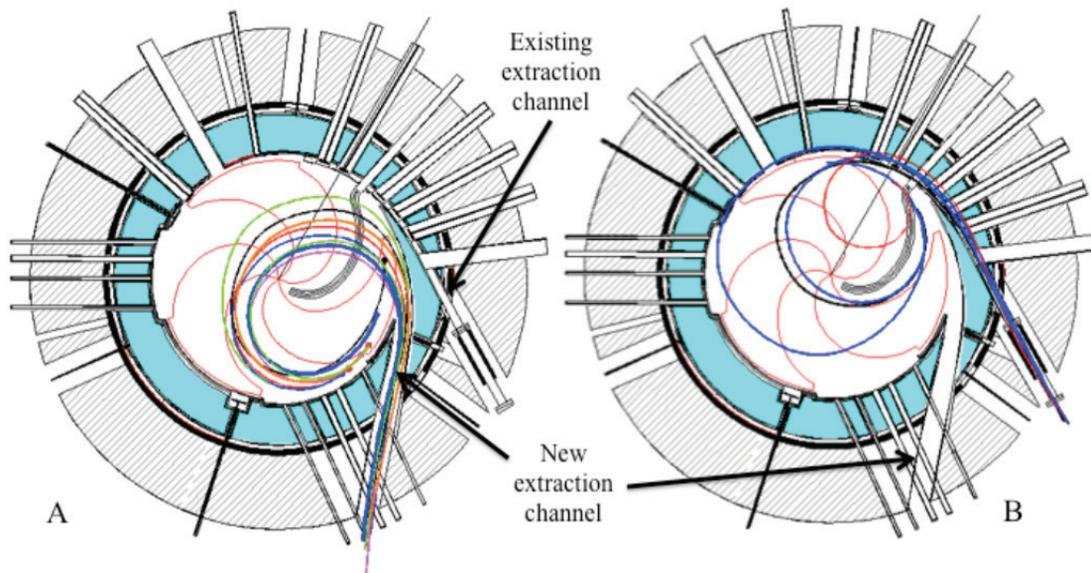
Figure 4: The extraction trajectories produced by stripper foils extracted through the new (A) and the existing (B) channels

The Plasma Science and Fusion Centre of MIT (Cambridge, MA) [6] have prepared a study report for the "New superconducting magnet for the LNS Cyclotron".

Here are the main results of this study.

• The form factors of the new coils are very similar to the previous coils with differences below 0.05 %;

• The new cryostat fits the same outer size of the previous cryostat;

• The new magnet can be operated also with a 5 W of nuclear heating due to the 200 W beam losses; the expected beam losses along the extraction channels should be lower than 100 W;

• There is more room for the liquid nitrogen shields;

• Hoop stresses in the self-supporting coils are quite safe;

• The size of the Liquid Helium Vessel allows fitting in the mid-plane of the LHe vessel two extraction channels with a vertical gap of the room temperature wall larger than 60 mm (+/-30 mm) and the radial width of the extraction channel larger than +/- 100 mm around the reference trajectory (20 cm total width), without any significant effects on the safety of the superconducting coil;

• The expected liquid helium consumption will be <20 lt/hour (at 4 K) and the Liquid nitrogen consumption <18 lt/hour (at 77 K).

The main difference with the present coil is the design of the cold mass. The existing coils consist of a set of double pancakes wound with pretension [7]. This solution is cryostable and it has worked very well. In the new coil design the maximum overall current density is 54 A/mm^2 instead of 35 A/mm^2 in the old design.

To simplify the construction process and to reduce the costs we choose to build the new coils epoxy impregnated (potted) using helium pooled cooling scheme. This choice is supported by the worldwide experience, for the construction of this kind of coil. Moreover, the evaluation of the hot spot of the coil during a quench shows that the temperature rise can be maintained below the 155 K by using just external dump resistors and without internal heaters.

The expected construction time is estimated to be shorter than 3 years and the cost of the magnet and cryostat should stay below 5 M€.

CONCLUSION

The present study demonstrates that it is possible to achieve the required beam power with good focusing properties to respond to the NUMEN experiment demands.

REFERENCES

[1] M. Cavallaro et al. INFN-LNS activity report 2013-2014.

[2] C. Agodi et al.:INFN-LNS activity report 2013-2014.

[3] Raciti G. et al. Nucl. Phys.; Sec A; Vol834; Issue: 1-4; March 1; 2010; pp. 780c-783c.

[4] Gordon, Particle Accelerators,1984,Vol.16, pp 39-62.

[5] S. S. Tomic and E. V. Samsonov, Phys. Rev E, Volume 65, 036504.

[6] A. Radovinsky et al. TBP Magnet Technology 2015.

[7] E. Acerbi et al., www.jacow.org, Cyclotron 1981, p. 16.