

PROPOSAL TO INCREASE THE EXTRACTED BEAM POWER FROM THE LNS-INFN SUPERCONDUCTING CYCLOTRON

A. Calanna¹, L. Calabretta¹, D. Rifuggiato¹, G. Cuttone¹, G. D'Agostino¹, A.D. Russo¹,
A. Radovinsky²

1) INFN-LNS, Catania, Italy 2) PSFC T&ED MIT, Cambridge, MA 02139, USA

Abstract

The LNS Superconducting Cyclotron, CS, is an isochronous 3-sector compact machine with a wide mass-energy range of heavy ions: beams from protons to lead from 10 to 80 AMeV have been delivered for the past 20 years. However, the extracted current density does not exceed the tenth of enA, corresponding to a beam power of 100 W. Recently, the demand to increase the beam intensity of light ion of a factor 10 to 100 was posed by nuclear physicists. A feasibility study proved a new mode of extraction by stripping would allow for an extraction efficiency of 99% and consequently a high intensity provided by the cyclotron. Here the design of the actual central region as well as the feasibility study of the new extraction for this range of ions is presented. It emerges that the present cryostat is not compatible with the new extraction geometry; therefore, a new cryostat has to replace the present one.

INTRODUCTION

The goal of the study presented is to investigate the possible gain on the extracted beam power from the CS.

Two approaches were chosen. At first, we studied the feasibility of a new mode of extraction from the cyclotron that could radically improve the beam power on target. Today, two electrostatic deflectors and a set of magnetic channels perform the beam extraction. The extraction efficiency is low since almost the 50% of the accelerated beam is lost on the first electrostatic deflector. When a beam power of 100 watt is extracted, the same power is dissipated in the electrostatic deflector septum. Going beyond this value produces serious instabilities in the voltage holding. Extraction by stripping for light ions, with $A < 20$, within the range of 15-70 MeV/amu should guarantee an extraction efficiency of 99% or more because the probability to have $q=Z$ after the stripper foil is $>99\%$ for this range of ions and energies [1]. This can increase the maximum beam intensities up to a factor 10-100, to reach beam power values of few kW.

Furthermore, a parallel study started to design a new dedicated central region optimized for these ions and energies. The new central region will be operated with the RF cavity voltages higher of a factor two respect to the present one. Like the existing central region, it will be working in the so-called constant orbit mode, which means the cavity voltage to accelerate the beam scales with the beam energy. Now, a 3D model of the actual

central region has been created and the first tracking orbits have been performed thanks to the peculiarity of OPERA 3D, which allows the combination of magneto-static and modulated electric fields. A sketch of the CS actual central region is shown in Fig. 1.

The NUMEN experiment, which proposes to measure the element of nuclear matrix using double charge exchange reactions [2, 3], is the main reason to increase the beam power. However, many other experiments, currently accomplished at LNS, will take advantage from this upgrade. These experiments make use of radioactive ions beam produced with fragmentation in-flight technique at FRIBS@LNS [4]. Production of radioisotopes of medical interest can be considered too.

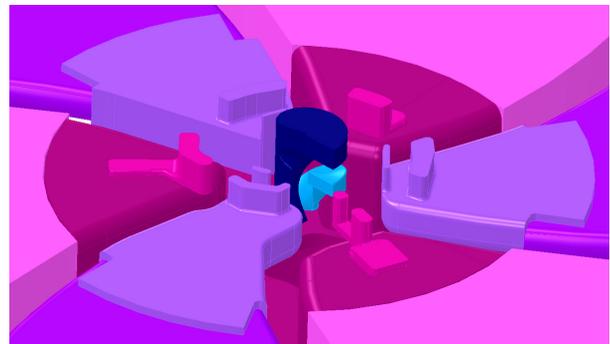


Figure 1: Drawing of the CS actual central region.

The present extraction mode will be maintained, which means the CS will provide all the beams accelerated up to date since there is a huge demand for these beams. For this reason, after the upgrade, the beams will be extracted from the CS with both extraction modes: extraction by stripping and extraction by electrostatic deflectors.

RESULTS OF THE FEASIBILITY STUDY FOR THE STRIPPING EXTRACTION

Since the CS is an operating cyclotron, measured maps are available. From them, we created 3D maps of the field in the gap between the poles solving the Maxwell's equations. Then we imported them on the Post- Processor module of OPERA 3D to have the field on the whole gap and to track particle trajectories. In this way, on one hand we created a new modern tool to reproduce all beam dynamics features that have been computed during the past 20 years with two old codes developed initially at MSU by Gordon [5], GENSPE and ESTRASZ. On the other hand, this new tool allows to easily visualize single

particle trajectories and envelopes and, moreover, it overcomes some limitations of the ESTRASZ code. That means we have now all the instruments to compute stripping extraction for every ion and energy whatever the charge state of the accelerating particle is.

Details on the technical approach can be found on [6]. For each ion and energy, the last closed orbit was tracked for the reference particle. Then the best azimuthal position for the stripping foil was chosen tracking the extraction trajectory of the particle after the stripping foil with the limitation that the reference particle had to stay at least 7 cm away from the centre of the cyclotron to avoid interference with the central region components. We computed axial and radial envelopes assuming a normalized emittance of 1π mm mrad at the stripping foil, which is a conservative value since it is almost twice what we measured from the source. Moreover, since the stripping extraction is a multi-turn extraction [6], we took into account also the energy spread introduced by this process[7]. The conditions to fulfil to accept the trajectories were related to mechanical constraints on the extraction channel of the cyclotron. We accepted axial envelopes less than ± 1.5 cm inside the acceleration gap and less than ± 3 cm in the gap between the coils and in the extraction channel through the yoke.

An example of an extraction trajectory in the cyclotron median plane is shown on Fig. 2 in dark blue. In red there are the dees boundaries, in cyan the coils and the striped area represents the yoke. The yoke is full of penetrations since there are two electrostatic deflectors that need 5 and 4 arms respectively to slightly change the deflector position to adapt to the accelerated particle and 9 penetrations for the correcting magnetic channels, diagnostic devices, and the radial probe. In Fig. 3 radial and axial envelopes related to Fig. 2 are shown.

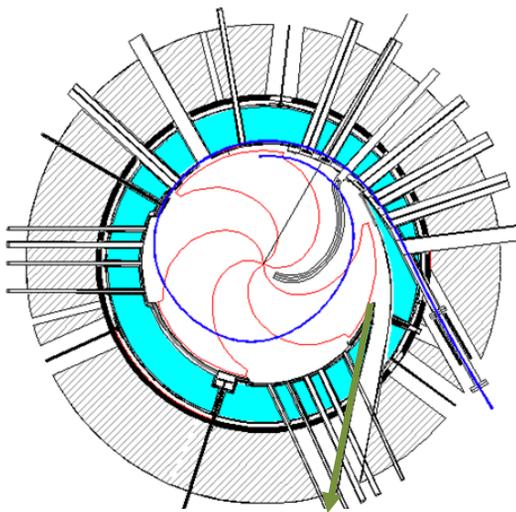


Figure 2: Example of extraction trajectory of ^{18}O at 70A MeV. 7 MC have to be considered on.

After the pole radius, it is possible to insert some magnetic channels providing small changes to the magnetic field to focus and slightly steer the beam along the extraction channel. For the case shown in Fig. 2 and Fig. 3, 8 magnetic channels are necessary to maintain the beam dimensions and direction within the specifications.

The maximum field correction we accepted in the magnetic channels is 0.2 T and the maximum gradient is 0.2 T/cm. A preliminary study on the shape of these magnetic channels has been accomplished.

The green arrow in Fig. 2 indicates a penetration that does not exist yet. Indeed, during the computation process, we discovered that a lot more ions can be extracted with fewer corrections when considering a new penetration rotated of about 30 deg.

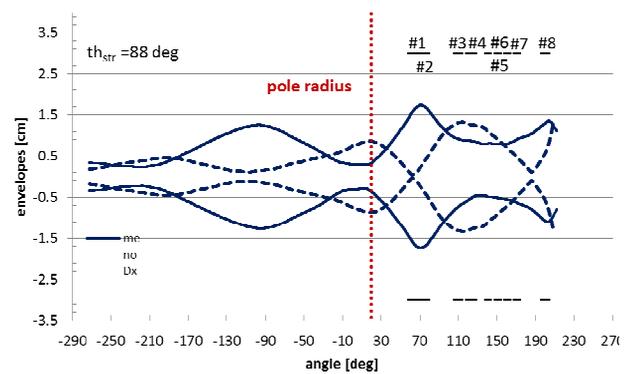


Figure 3: Radial and axial beam envelope along the extraction trajectory of ^{18}O at 70A MeV. The energy spread considered is 0.5 %, which is overestimated.

This new penetration is the one indicated with the green arrow in Fig. 2. An example of extraction path along the new extraction hole is shown in Fig. 4. In Fig. 5 radial and axial envelopes associated with Fig. 4 are shown.

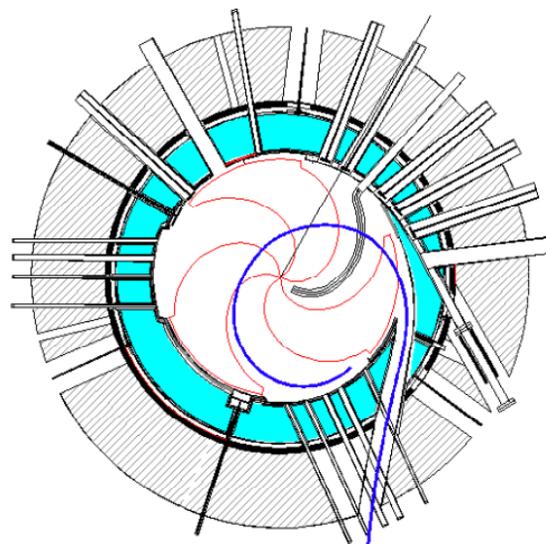


Figure 4: Example of extraction trajectory of ^{18}O at 45.5A MeV. 3 MC have to be considered on.

In this case, the radial and axial envelopes are smaller and smoother. Moreover, only 3 magnetic channels are necessary and the field and gradient needed are smaller. A full table of the ions and energy calculated through the new magnetic channel, together with another example and the intensities of the field and the requested gradients are reported on [6]. In ref. [6] there is also an overview of all the beams and energies extracted by stripping through the existing extraction channel.

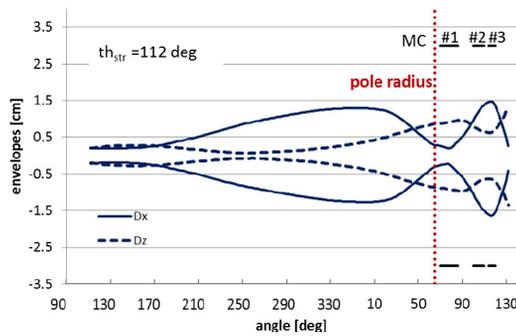


Figure 5: Radial and axial beam envelope along extraction trajectory of ¹⁸O at 45.5 A MeV. The energy spread considered is 0.5 %, which is overestimated.

FURTHER CONSIDERATIONS

Although the computations seem to show the necessity of the new extraction channel, there are other considerations to be done.

As Fig. 2 and Fig. 4 show, there are lot of penetrations in the yoke, which lead to lot of sub-systems. The introduction of a new extraction channel has to be carefully studied. In fact, the cross-section of the new channel has to be wider of the existing one, which in vertical is only +/- 12 mm, to have a beam of 5-10 kW extracted. Quite probably, a cooling system for the two channels is mandatory. As a consequence of the modifications described, a new cryostat is necessary, including a new set of superconducting coils. In particular, a stress analysis of the cryostat structure has to be evaluated.

The Plasma Science and Fusion Centre of MIT (Cambridge, MA) [8] prepared a study report for the “New superconducting magnet for the LNS Cyclotron”. Some details of the report are in [6]. The specifications we asked for were:

- the form factors of the new coils must be very similar to the previous coils with differences below 0.05% because we all the beams within the present operating diagram must be guaranteed;
- the new cryostat must have the same outer size of the previous cryostat, but the distance of the first coil from the median plan has to be increased to allow a possible clearance of +/- 3cm for the beam to pass;

- hoop stresses in the self-supporting coils and the influence of broadened extraction channel has to be conservative;
- the expected liquid helium and nitrogen consumption had to be reduced respect to the actual ones.

The PSFC main conclusion was that such a cryostat is feasible with the present state-of-art of superconducting cable. 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 [9]. This solution is very cryostable and it has worked very well. In the new coil design the maximum overall current density is 54 A/mm² instead of 35 A/mm² in the old design. Moreover, the new coils epoxy according to their suggestion will be impregnated (potted) using helium pooled cooling scheme. This choice is supported by the worldwide experience, for the construction of this kind of coil.

The PSFC provided even an estimation of costs, in these days at LNS we are evaluating more in detail each part of their calculation to write down a full technical design report, which will include all the modifications to the cyclotron. Indeed, we plan to change all the trim coils and to replace the liner to increase as much as possible the accelerating gap. Other minor changes are also planned to guarantee better reliability. Figure 6 shows a first design of the new beam line out the cyclotron connecting the new extraction channel to the existing beam line.

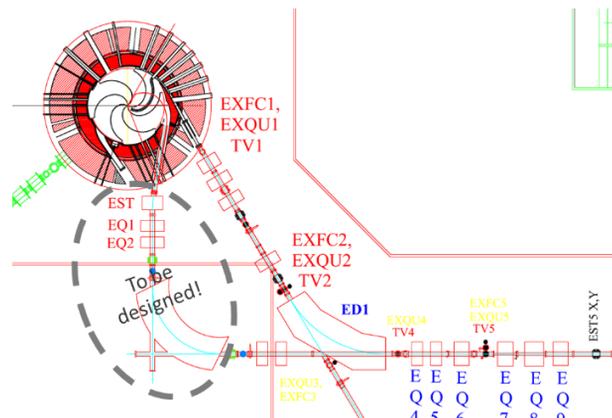


Figure 6: First design of the new beam line connecting the new extraction channel with the existing beam lines.

CONCLUSIONS

The present study demonstrates that it is possible to achieve a extracted beam power 100 times bigger out of the CS. The focusing strength requests to the magnetic channels are higher than for the existing channels, but it seems feasible thank to the larger sizes of the new extraction channels. The optical property of the beam extracted by stripper are similar to the previous and satisfies the requirement of NUMEN and other new experiments.

REFERENCES

- [1] Atomic Data and Nuclear Data Tables, Vol. 51, No. 2, July 1992, Table 2 pp.187.
- [2] M. Cavallaro et al., INFN-LNS activity report 2013-14.
- [3] C. Agodi et al., INFN-LNS activity report 2013-2014.
- [4] Raciti G. et al., Nucl. Phys. Sec. A, Vol. 834, Issue 1-4, March, 2010, pp.780c-783c.
- [5] Gordon, Particle Accelerators 1984, Vol.16, pp.39-62.
- [6] Calanna et al., "Upgrade of the LNS superconducting cyclotron", IPAC2015, Richmond, VA, USA, May 2015, paper THPF037.
- [7] S.S.Tomic, E. V. Samsonov, Phys. Rev. E, Vol. 65, 036504.
- [8] A. Radovinsky et al. TBP Magnet Technology 2015.
- [9] E. Acerbi et al., www.jacow.org, Cyclotrons 1981, p. 169.