ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP014

3D MAGNETIC OPTIMIZATION OF THE NEW EXTRACTION CHANNEL FOR THE LNS SUPERCONDUCTING CYCLOTRON

L. Neri†, L. Calabretta, D. Rifuggiato, G. D'Agostino, A. D. Russo, G. Gallo, L. Allegra, G. Costa, G. Torrisi, Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud, Catania, Italy

Abstract

The upgrade of the Superconducting Cyclotron operating at INFN-LNS is the main objective of the general upgrade of the LNS facility, consisting in the enhancement of light-medium ion beam intensity. To overcome the present maximum power of 100 W of the beam extracted by electrostatic deflector and achieve a beam power as high as 10 kW, the implementation of the extraction by stripping method has been proposed. Intense ion beams with mass in the range 10 to 40 amu (^{12}C, ^{18}O, ^{20}Ne, ^{40}Ar) in the energy range of interest (15-70 MeV/u) will be delivered to the NUMEN experiment, as well as used for production of in-flight radioactive beams. The present work consists in the optimization of the magnetic channels needed to limit the radial and axial beam envelopes. The design of the magnetic channels has been accomplished by fully three-dimensional magneto-static simulations using Comsol Multiphysics and a custom transport code developed in Matlab along the last year at INFN-LNS. The effect of a magnetic shielding structure in the extraction channel is presented, together with the possibility of producing a magnetic gradient from an asymmetric coil.

INTRODUCTION

A custom transport code was developed at INFN-LNS to support the design of different parts of the extraction by stripping system. In particular stripping foil area, extraction channel geometry and magnetic channels. The tool is fully three dimensional and starting from the measured middle-plane magnetic field map deduce the three-dimensional magnetic field map in the acceleration region of the cyclotron. The stationary beam envelope in the radial and vertical phase-space diagrams are found for all the beams of interest. An example of what called auto-ellipses is shown in Fig. 1 in the case of $^{18}O^{6+}$ at 45.6 AMeV, nominal beam condition considered in all this paper for comparison reason.

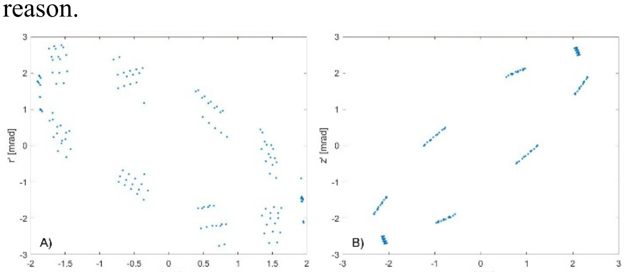

Figure 1: Auto-ellipse beam particle distributions of $^{18}O^{6+}$ at 45.6 AMeV, A) radial phase-space diagram, B) vertical phase-space diagram.

The size of the beam envelope was chosen to be close to the normalized beam emittance of 1π·mm·mrad for 99% of the beam envelope, value estimated for our accelerated beam. The stationary beam envelope along a full turn was also calculated, and the intersection with the stripping foil region (shown in red in Fig. 2) were saved every approximately 0.03 degree. The showed magnetic field map is a merge between measured map in the acceleration region, and the remaining part coming from a fully 3D magnetic model of the entire cyclotron joke and superconductive coils. Acceleration region was not extracted from the 3D simulation because of missing trimmer coil in the simulation model. The black contour of Fig. 2 marks the walls of the vacuum chamber. If the beam trajectory crosses this black contour the code mark the particle as lost. In the centre of the cyclotron a black circle represents a beam forbidden area in correspondence of the central region.

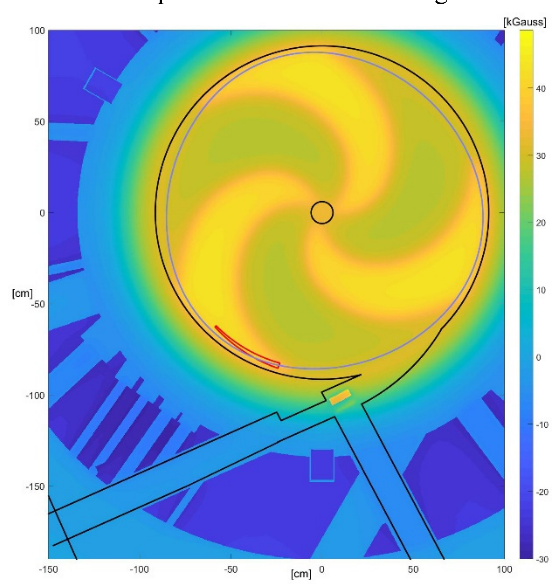

Figure 2: Magnetic field map of the cyclotron with vacuum region delimited by black line, foil region in red and stationary trajectory in blue.

After, the beam is fully stripped by the stripping foil the trajectory changes drastically. By selecting carefully, the stripping foil location it is possible to drive the deflected beam through the new extraction channel. Figure 3 shows the fully stripped trajectory in blue. Immediately after the cyclotron joke there are red dots representing hit of lost particles. Figure 4 shows the behaviour of the stripped beam by showing in light blue the magnetic field along the central particle trajectory. In black the number of remaining particles divided by two (for graphical reason). Then the beam envelope is represented showing the maximum distance between the central particle and the farther beam

† neri@lns.infn.it

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP014

particle in the middle plane (in red) and in the vertical coordinate (in blue). The abscissa is in arbitrary time unit. The beam envelope suffers of strong variation in correspondence of the magnetic field drop when the beam exit from the acceleration region. This is due to the magnetic field gradient.

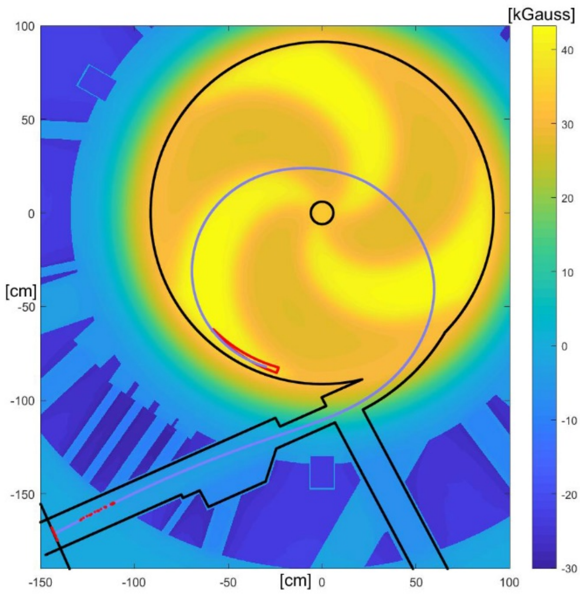

Figure 3: Fully stripped beam trajectory (light blue line) superimposed in magnetic field map (colour map), vacuum chamber (black line), stripping area (red line) and beam losing point (red dots). (mettere line nere e line rosse, togliere titolo, mm negli assi)

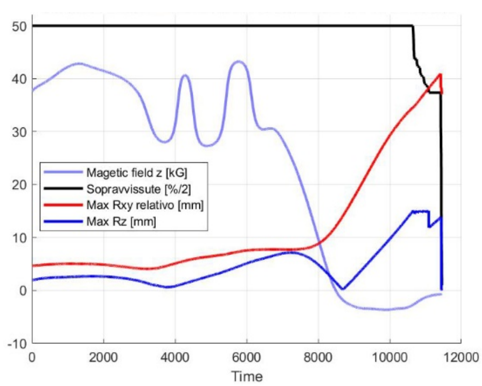

Figure 4: Beam behaviour along the fully stripped trajectory.

Strong defocusing is observed for the envelope in the middle plane, while strong focusing occur in the vertical direction. The result is that after the cyclotron the envelopes of the beam are bigger than the acceptance of next set of quadrupoles for both directions. Further disagreement with respect next acceptance is that the transverse and the vertical envelope of the beam need to be one convergent and the other divergent, doesn't matter the order. Figure 4 shows a focusing point of the vertical envelope and consequently a divergent beam, both vertically and horizontally.

MAGNETIC OPTIMIZATION

Scope of the magnetic optimization is to counteract the magnetic field drop effect trying to move the focusing point as far as possible, keep vertical envelope convergent and reduce the divergency of horizontal envelope. The magnetic element typically used in this scenario is a magnetic channel composed by three ferromagnetic bars shaped to obtain a magnetic gradient. Two different magnetic channels were planned for our cyclotron named respectively MC1s and MC2s. Different steps were done during different years of the design upgrade of our cyclotron summarized in the following paragraph for MC1s. The main parameter that identify the strength with which the magnetic channel act on the beam is the magnetic field gradient orthogonal to beam trajectory.

Current Sheet Approximation

First magnetic optimization step [1] was done by using Opera and the current sheet approximation. This computational method is fast but suffer of precision when considering that the magnetic channel extends up to 30 mm out of the middle plane and the magnetic field is not uniform as in the present case. The preliminary achievement was to define a preliminary geometry able to perform a gradient up to 180 mT/cm. With beam particle transport code, we have seen that this gradient amount is not enough. Stronger gradient is needed and higher accuracy in the magnetic simulation is needed to obtain a more homogeneous magnetic field gradient with respect to what obtained with this method.

FEM and Genetic Algorithm Approach

For a more accurate simulation we moved to a FEM description of the problem using Comsol Multiphysics as solver and developing environment. To increase the magnetic field gradient, we investigate the use of permendur vanadium, while to perform a more efficient geometry optimization we used a genetic algorithm approach implemented with a custom Matlab code. Genetic algorithm approach implies several thousand of tries, consequently the test of the geometry needs to be as fast as possible. This was done by using a 2D description of the problem. The design was done in case of the magnetic channel inserted in a uniform magnetic field. More details can be found in [2]. Magnetic channel performances were improved in amplitude, from 180 to 250 mT/cm and in uniformity. But when we used this result in the 3D model of the entire cyclotron, we found that the assumption of uniform magnetic field was a poor estimation. Figure 5 shows the magnetic field over a slice perpendicular to the magnetic channel, and centred with respect it, in the case of 3D simulation.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP014

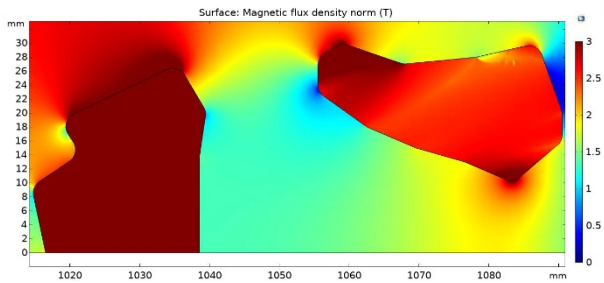

Figure 5: Slice of 3D magnetic field in correspondence of the MC1s centre.

Symmetry with respect middle plane was used and so only half of the magnetic channel is shown. It is evident that there is a magnetic field gradient from left to right in the central region, but with a more detailed analysis, Fig. 6, it is clear that the uniformity is poor. Figure 6 shown the magnetic field gradient in the region where the beam crosses the magnetic channel. We considered not only the gradient produced in correspondence of the middle plane, blue line, but also 5 mm (green line), 10 mm (red line) and 15 mm (light blue line) far from middle plane. The length of the four lines is equivalent to the expected beam size outside of the middle plane.

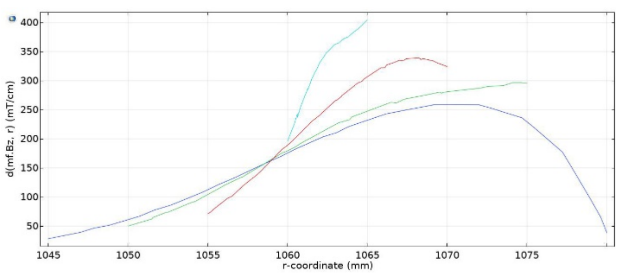

Figure 6: 3D magnetic field gradient at the centre of MC1s, see the text for the meanings of the lines.

3D-Equivalent Optimization

3D magnetic simulation of cyclotron and magnetic channel is more realistic with respect 2D simulation but can't be used with a genetic algorithm approach because of the huge amount of time needed for each simulation (20 hours) and the huge amount of try needed for the optimization algorithm (≈ 1000). However, we found how to improve the reliability of 2D simulation and made a 3D-equivalent simulation. Figure 7 shows the 3D model with a blue line centred with respect MC1s. From a 3D magnetic simulation without MC1s we extracted the magnetic field profile along this line. Then a genetic algorithm approach was used to generate a 2D cyclotron-like geometry, showed in Fig. 8, that generate 3D-like magnetic field profile. Finally, we used this environment to perform a 2D geometrical optimization using the genetic algorithm approach. The result (Fig. 9) was excellent with an extreme agreement between 2D and 3D simulation, see Fig. 10.

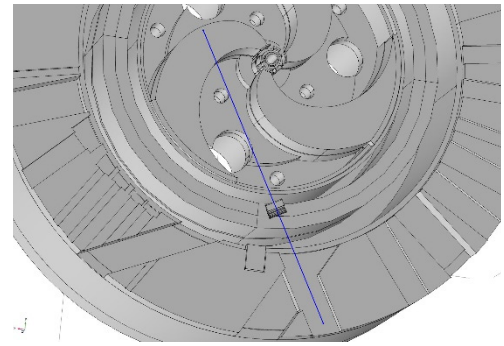
Figure 7: 3D magnetic simulation drawing of half of cyclotron joke, superconductive coil and MC1s, blue line is the reference for the magnetic field profile with which MC1s need to be optimized.

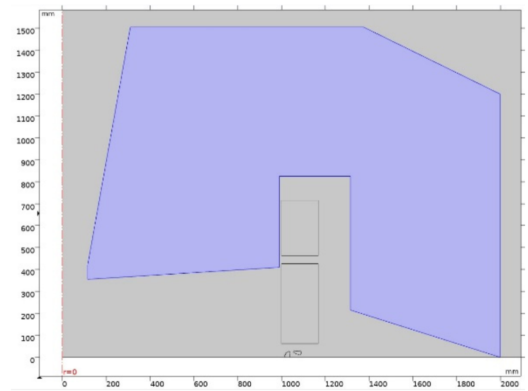
Figure 8: 2D geometry able to provide same magnetic field profile of 3D simulation, low carbon steel 1010 in light blue, the two rectangular superconductive coils, and close to the middle plane at coordinate r = 0 and y = 1000 the drawing of the magnetic channel.

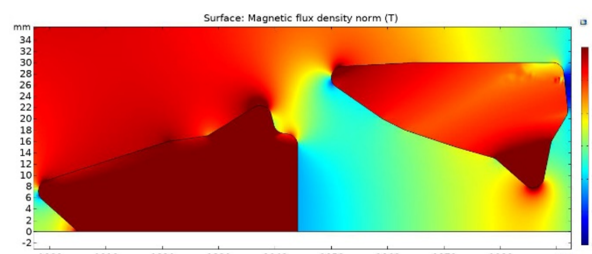

Figure 9: Slice of 3D magnetic field in correspondence of the MC1s optimized with 3D-equivalent method.

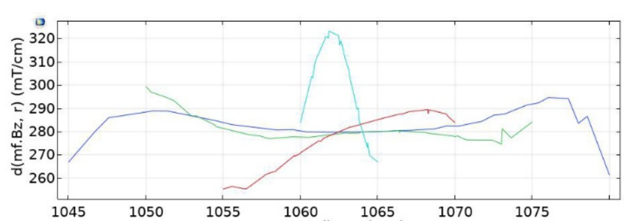

Figure 10: 3D magnetic field gradient at the centre of new MC1s.

ISBN: 978-3-95450-205-9 doi:10.18429/JACoW-Cyclotrons2019-MOP014

RESULT

The evolution in magnetic optimization ended with best result achievable with state-of-the-art software and algorithm. The optimum magnetic gradient and uniformity achieved were tested with our beam transport code. Figure 11 shown the beam envelope for the new MC1s that is almost inside the acceptance of next quadrupoles elements. The strong magnetic field gradient of MC1s was able to move the focusing point of vertical envelope from 8800 to 10800 time unit (corresponding to a position quite near to exit of the yoke), no particle were lost, and the horizontal size of the beam was reduced from 40 to 20 mm radius. Figure 12 shown the extracted beam envelope in the two-phase space planes, ellipse-like shape and consequently emittance was preserved due to the optimum homogeneity of the magnetic field gradient of the new MC1s.

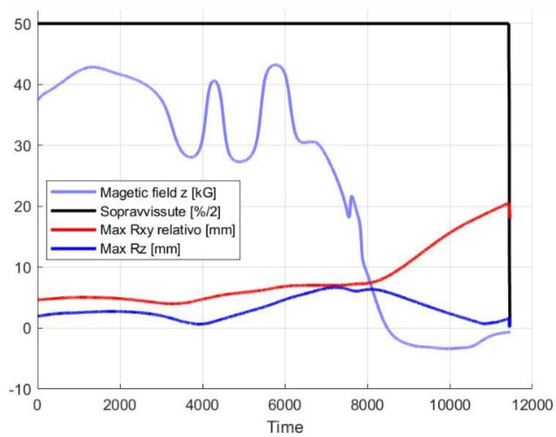

Figure 11: Beam behaviour along the fully stripped trajectory in the case of new MC1s.

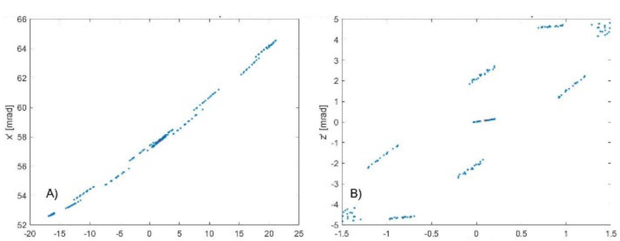

Figure 12: Beam particle distributions of extracted O_{18}^{6+} at 45.6 AMeV, A) radial phase-space diagram, B) vertical phase-space diagram.

CONCLUSION

The optimization of MC1s reached satisfactory result and no more steps are needed for it design. An additional magnetic channel is required to achieve a better match between beam envelope and acceptance of the first set of quadruplets after the cyclotron. For this second element instead to modify the existing magnetic field to obtain a magnetic field gradient, it was chosen a different magnetic approach. The magnetic field coming from the joke was shielded as much as possible and the magnetic field gradient was generated by an asymmetric coil. Coil current of asymmetric coil and obtained magnetic field gradient intensity introduce a new tuning parameter that will make easier the matching of the different beams of interest with the transport line. The design of this active channel is in progress.

REFERENCES

[1] L. Calabretta *et al.*, "Overview of the future upgrade of the INFN-LNS superconductive cyclotron", *Mod. Phys. Lett. A*, vol. 32, no. 17, 2017. doi:10.1142/S0217732317400090

[2] L. Calabretta, O. Karamyshev, L. Neri, and D. Rifuggiato, "New method to design magnetic channels with 2D optimization tools and using Permendur Vanadium", presented at the 14th Int. Conf. on Heavy Ion Accelerator Technology (HIAT'18), Lanzhou, China, Oct. 2018, paper TUOZA01.