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High-intensity extraction from the Superconducting Cyclotron at LNS-INFN

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Summary. — The LNS Superconducting Cyclotron (CS) has successfully worked for more than 20 years, with an extracted beam power limited to 100 W. Its peculiarity is to provide a broad range of ion species from hydrogen to lead in the energy range between 10 and 80 AMeV. Recently, the demand for higher beam intensities came from the experiment NUMEN, which investigates the nuclear matrix element of the neutrinoless double beta decay through double exchange reactions. Also, the in-flight radioactive beams produced at FRIBs@LNS are interested in the high intensity primary beams. Both activities deal with low cross section reactions and require an increase in beam intensities for light ions up to a factor 100. Nevertheless, other experiments will take advantage of the upgrade and there will be even the possibility to produce medical radioisotopes. The solution proposed in this study makes use of extraction by stripping to provide high-intensity beams up to 10^{14} pps. Major machine modifications, including the cryostat and the superconducting coils, are mandatory to guarantee these new performance. However, heavier ions acceleration will be guaranteed, maintaining the extraction by electrostatic deflectors. An overview of the studies carried out is here presented.

1. – Introduction

LNS is one of the four Italian national laboratories of the INFN. There are two accelerators, a tandem mainly used for astrophysics researches and a Superconducting Cyclotron, "Ciclotrone Superconduttore" (CS), both produce the beams transported to different experimental halls, two of which are equipped with two 4π detectors, Chimera and Medea, one with a magnetic spectrometer, Magnex, and further apparata, among which a proton therapy facility to treat eye cancer.

The CS is a three sector isochronous cyclotron, see ref. [1]. It is very compact with a pole radius of 90 cm, and a total external radius and height of 190.3 cm and 286 cm. Equipped with two pairs of superconducting coils and a RF system operating in the range of 15 to 48 MHz, it is able to provide all ions up to uranium in a wide range of energies, between 10 and 80 AMeV. A disadvantage of the compactness is the lack of orbit separation between the last turns.

Since the extraction is accomplished through electrostatic deflectors, the extraction efficiency is 50% causing thermal issues on the first deflector, ED1, when the extracted beam power exceeds 100 W.

Recently, the users' demand of a higher beam power is becoming more and more urgent. The main idea is to extract the beam by stripping through a new extraction channel dedicated to a narrow range of particles and energies. This technique is widely used in commercial and research cyclotrons, see ref. [2].

However, the goal is to design the simplest extraction system possible to extract the largest possible number of ions, up to argon, within the energy range of 10–70 AMeV.

The high number of extracting ion masses and/or energies increases the difficulty for the definition of a unique extraction channel. Indeed, after the stripping foil, the extraction trajectories are quite different for different ion types, as it is possible to spot in fig. 1 where only two trajectories are drawn.

As a first consequence, the extraction channel has to be wider than the one requested for the electrostatic extraction, since in that case the differences between trajectories are smaller. Moreover, also the vertical section of the extraction channel has to be broadened.

It is worth mentioning, the new extraction method will not be the only one. Intense ion beams will be extracted through the new extraction channel approximately six months per year, while for the other six months the extraction will be done through the two electrostatic deflectors, as is done in the present days, with beam intensities enhanced but in the same order of magnitude than the present ones. Anyway, the handling system of the stripping foils, ref. [3], is not compatible with the first electrostatic deflector, then, it is mandatory to open the machine to switch from one method of extraction to the other.

Here the state-of-the-art of the project is presented.

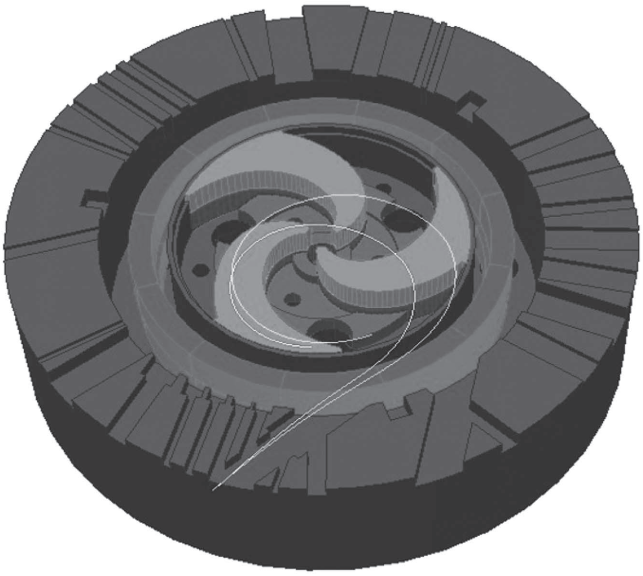

Fig. 1. – View of half cyclotron: hills, valley, return yoke and superconducting coils are shown. The two trajectories are examples of extraction trajectories after the stripping foil.

Firstly, the physics cases and a new possible application in medical radioisotope production are introduced in sect. **2** as well as the explanation that makes LNS the suitable laboratories to perform these experiments. The reasons that led to the choice of stripping extraction and what are the conclusions on the CS performance after the beam dynamics analysis are discussed in sect. **3** and **4**, respectively. Then, in sect. **5**, the results on the 3D iron optimization to design the magnetic elements needed to focus the beam and to compensate the first and second harmonic components of the field are shown. Finally, an estimation on time schedule is given.

2. – Physics cases and applications

The LNS experiments that will take advantage of the upgrade of the CS are NUMEN, ref. [4], and other experiments planning to use radioactive secondary beams.

NUMEN uses an innovative technique to investigate the Nuclear Matrix Elements (NME) of the neutrinoless double beta decay, which is now strongly pursued both experimentally and theoretically, through the study of Double Charge Exchange (DCE) reactions. LNS is equipped with a magnetic high-resolution spectrometer, MAGNEX, which is the tool of choice to achieve the NUMEN goal. First experimental results have already been obtained at LNS, but, although very promising, they have underlined the necessity to increase the beam intensity.

On the other hand, FRIBs@LNS, ref. [5], which is the LNS facility to produce in-flight radioactive ions beams around the Fermi energy could use a more intense primary beam to produce intense secondary beams by projectile fragmentation. This would allow the upgrade of the FRIBs@LNS facility, which will deliver fragmentation beams in an energy range complementary to SPES beams, ref. [6].

Moreover, the upgraded CS could be used in medical radioisotope production. In particular, ^{211}At can be produced through ^{209}Bi(alpha, 2n) ^{211}At, using He^{1+} accelerated up to 28 MeV, ref. [7].

3. – The choice of stripping extraction

The goal of the update is to reach 1–10 kW beams when light ions are accelerated in the energy range of 10–70 AMeV. For ions up to neon, see table 2 on page 187 of ref. [8], if the accelerated particles have energy higher than 10 AMeV, the probability that they are fully stripped by stripping foil is higher than 99%. Therefore, with easy estimations, it is possible to declare the possibility to reach, for some case, almost 10^{14} pps beams provided to the users, which is an improvement of two orders of magnitude with respect to the present performance. Moreover, the extraction by stripping of argon at 60 AMeV, which is of interest for the FRIBs@LNS facility, has also been studied.

As mentioned above, the chosen beams cover a wide range of masses and energies. When the ions cross the stripping foil, the charge-to-mass ratio suddenly changes, while the main magnetic field remains constant. The trajectories, that before the stripping foil had a three-fold circle-like symmetry, become completely different and off-centered. As a consequence, each case has to be studied separately, and for each ion and energy, the best radial and azimuthal position of the stripping foil has to be evaluated to ensure extraction through the same channel.

Since the first simulations, it has been clear that the extraction of the stripped ion beams through the existing extraction channel is not the best solution, ref. [9]. Indeed, due to the sudden fall-off of the coils fringing field, which defocuses the beam radially, the transversal beam envelopes become rapidly radially large and many magnetic channels are mandatory to ensure acceptable extraction performance.

To reduce the extraction path as much as possible and to limit the defocusing effect, it has been decided to design a new extraction channel dedicated to these high intensity beams. Moreover, to extract these intense beams, it is mandatory to have an extraction channel with a wide cross-section, which can be broadened only redesigning the cryostat and the superconducting coils to enlarge the clearance between upper and lower coils. The change of the cryostat is then mandatory to reach these intensities and represents the main engineering challenge and cost.

The stripping extraction is by definition a multi-turn extraction. That means an energy spread is introduced and has to be evaluated carefully to determine the final extraction efficiency, details will be explained in the next section.

Other smaller modifications have been planned to improve the CS performance, for more details see ref. [7].

4. – Technical approach

The CS has been working for the past 20 years. Thus, measured magnetic maps are available and specific local codes, GENSPE and ESTRAZ, that had been developed at MSU, refs. [10, 11], have proved to be trustworthy.

The chosen technical approach combines these tools with more modern 3D computations using the code OPERA 3D of Cobham, which is the international standard code to solve magnetostatic issues. In this way, the present performance of the CS can be verified with modern tools and, on the other hand, present codes limitations can be overcome.

The feasibility study, concluded in 2014, proved the goodness of the upgrade project, as well as the necessity of a dedicated extraction channel, which will be drilled about 30 deg following the existing one.

However, it was already clear the necessity of a full beam dynamics study to design a feasible extraction channel able to host trajectories so different between themselves. In 2015, the first engineer study of the new coils was successfully concluded in collaboration with the Plasma Science and Fusion Center of MIT, see ref. [12].

At first, for each ion and energy of interest, a 3D map has been created combining the measured maps on the median plane and the field out of the median plane calculated by Maxwell's equations. Then, using GENSPE, the beam dynamics parameters along the closed orbits have been found. For every energy, it gives the radius, the radial component of the momentum, the isochronism, the phase slip and the axial and radial betatron oscillations for the reference particle and for a set of 8 particles that describe the beam eigenellipses in the (x, x') and (y, y') phase space. A normalized beam emittance of 1π mm-mrad, which is almost twice the measured normalized emittance of the beam delivered by the LNS ion sources, has been considered at this step.

These parameters work as input for the code ESTRAZ and for the 3D tracking with OPERA. Once a set of possible positions for the stripping foil is found with OPERA, the radial and axial envelopes along the extraction channel up to a point outside the cyclotron is computed with ESTRAZ, which is also used to identify the number and specifications of the magnetic elements to add after the pole radius. These, called magnetic channels (MCs), provide a constant focusing gradient $\mathrm{d}Bz/\mathrm{d}R$ (quadrupole component) and slightly steer the beam to make it reach a common exit point. Choosing the proper radial and azimuthal position of the stripping foil for each case, which means fixing the

TABLE I. – *List of the ions to be extracted by stripping and specifications of the stripping foil position. Note that for historical reasons, the azimuthal angles of the stripper foils are in the CS reference coordinate system, which uses the non-conventional clockwise direction for positive angles.*

Ion	$\frac{Q_{acc}}{Q_{ext}}$	Energy[A MeV]	Θ[deg]	R_{Strip}[cm]
^{12}C	4/6	45.8	112	88.2
		60.8	108	87.9
^{18}O	6/8	29.2	60	84.2
		29.2	118	87.7
		45.5	68	84.7
		45.5	110	87.1
		60	80	84.6
		60.9	106	88
		65	88	84.9
^{20}Ne	7/10	29	122	87.7
		45.6	114	87.9
		60.3	108	87
		71	108	87.9
^{40}Ar	14/18	60	60	84.4

extraction energy, it is possible to fix the position and length of the new extraction channel.

The acceptability criteria given to the trajectories are mainly related to the mechanical constraints: the maximum axial beam envelope along the extraction trajectories has to be lower than ±15 mm inside the pole region and ±25 mm after; the trajectory has to stay at least 60 mm away from the center of the cyclotron to avoid any interference with the central region.

On the other hand, the specifications of the MCs have been decided after the analysis of the ESTRAZ results. For all ions and energies of interest reported in table I, after the second MC, the radial envelope, evaluated taking into account the energy spread, is always lower than ±1.8 cm, while the maximum gradient needed is 1.8 kG/cm. To respond to these requirements, the MCs have to be big, and, at the same time, cannot exceed the axial clearance of the new extraction channel, which is 60 mm, vs the clearance of the existing extraction channel that is 34 mm, see ref. [12]. Then, the maximum acceptable axial dimension of the beam along the magnetic channels, also considering the energy spread, is ±30 mm.

Eventually, the beam dynamics study led to a solution with only two magnetic channels for all ions see fig. 4. Both produce a constant gradient of 1.8 kG/cm over a radial coverage of 3.5 cm, which is almost twice the maximum radial envelope of the worst case studied. This has been done to use the same MCs for all cases, only considering a linear displacement of 60 mm. In this way, it is possible to take advantage of the steering effect in addition to the constant gradient for all the beams treated. In the state-of-the-art design the maximum steering field possible is ±2.5 kG.

Moreover, the stripping foil positions have been confined to two main areas, one laying in one valley and one on the following hill, see fig. 2. See also fig. 3 where two examples of

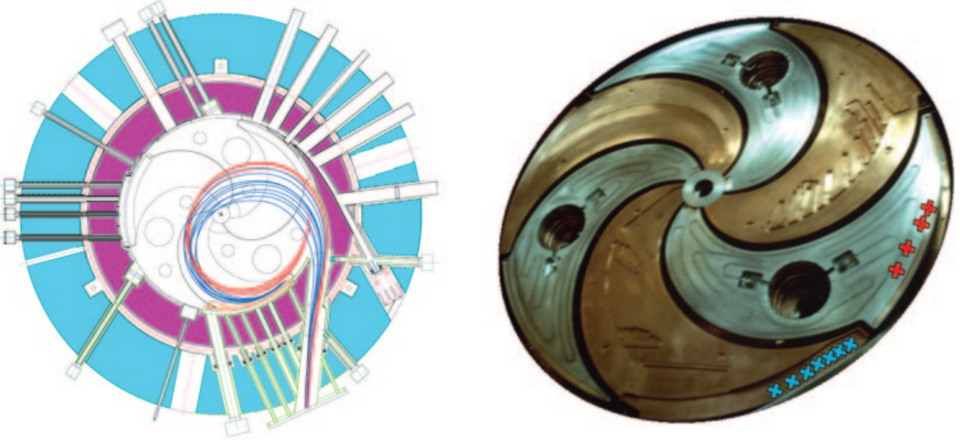

Fig. 2. – Two views of the median plane of the cyclotron: on the left side, the drawing shows all the extraction trajectories of ions reported in table I; on the right, there is a real picture over the median plane and the crosses indicate the stripping foil positions (white on the hill, black on the valley).

the radial and axial envelopes of two extracted trajectories are reported vs the length of the trajectories after the stripping process. The envelops are well below the constraints and the behaviour of them is smooth in all directions. MC1S and MC2S indicate the magnetic channels, for a 3D view see fig. 4. In the case of neon, fig. 3(b), the beam is extracted with the two MCs in the outer position and the beam does not pass through them. For more envelopes see ref. [7].

The effect of the energy spread introduced when the beam crosses the stripping foil is also shown. After an analytical analysis according to ref. [13], a 0.3% energy spread value has been chosen for all the ions and energies. Recently, another LNS code, the modified SPIRALGAP code ref. [11], has been used to evaluate the energy distribution at the stripping foil position. A bunch of ^{18}O, charge state 6^+, has been accelerated from 1 AMeV up to 65 AMeV. The results of these simulations show that more than 99% of the particles stay inside an energy spread of ±0.4%, but 91.4% stay in the 0.3% and 97.3% in the 0.35% of energy spread. One of the next studies will be to evaluate again all the envelopes considering the 0.4% of energy spread and, if necessary, the design of the magnetic channels will be slightly adjusted.

5. – 3D iron optimization

In this section, the procedure to define the iron profile of the MCs is described once the specifications have been fixed through the code ESTRAZ.

3D simulations are mandatory to achieve an exhaustive design. Indeed, in the region where the MCs will be placed, the gradients of the main field are important. More in detail, in this area the lines of the main magnetic field are not vertical across the iron bars, since they are closing themselves around the main coils, so they are the magnetization vectors inside the MCs, see fig. 5.

Moreover, differently from the existing magnetic channels that are used for beams with the size of few mm in the radial and axial direction, the new MCs have to host beam of one order of magnitude bigger, which leads to a completely different dimensions range.

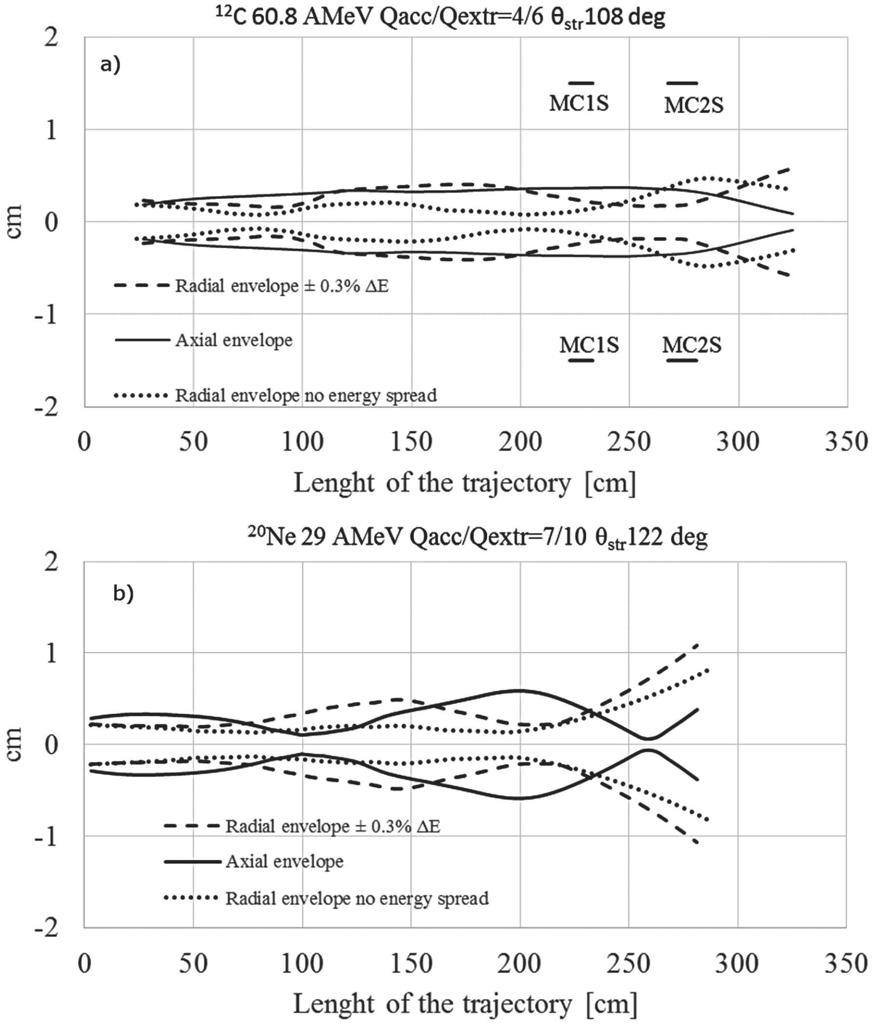

Fig. 3. – (a) Radial and axial envelopes of 60.8 AMeV of ^{12}C extracted trajectory, MC1S and MC2S indicate the magnetic channels. The case of 29 AMeV of ^{20}Ne is also shown in (b). For both, the effect on the beam dimensions due to the energy spread is also shown.

As a starting point it has been used the Current Sheet Approximation (CSA), which gives the possibility to study the shape of the MCs using a coil of negligible thickness, that occupies the same volume of the MC in iron. This is true only in the case when the iron piece is in a uniform field higher than 0.5 tesla. In this case, the MC produces a linear field and a consequent constant gradient.

However, when the same iron piece is in a main field with high gradients, the field produced by the MC is not any more linear and the gradient looks like the dotted line of fig. 5.

3D magnetostatic calculations are the key to compensate this difference, at each iteration the shape of the pieces has been slightly changed, until the linearity of the field is found (full line of fig. 5). Note that, possible effects related to the lengths of the two

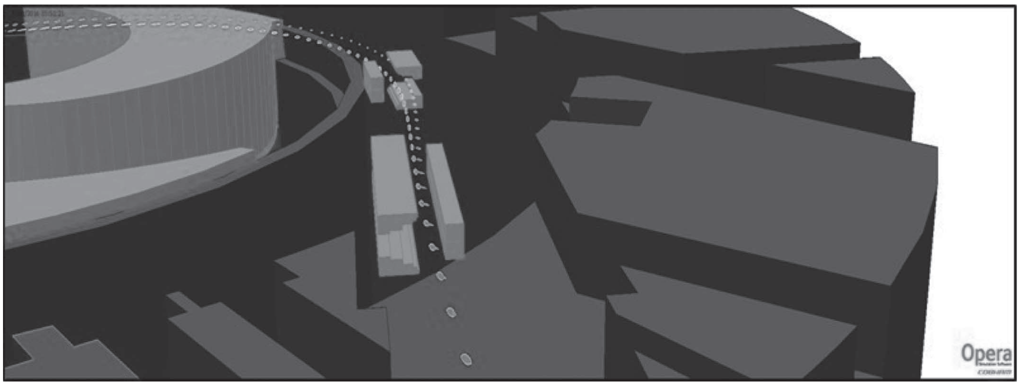

Fig. 4. – 3D view of the two magnetic channels. Two example trajectories are also shown through transversal sections.

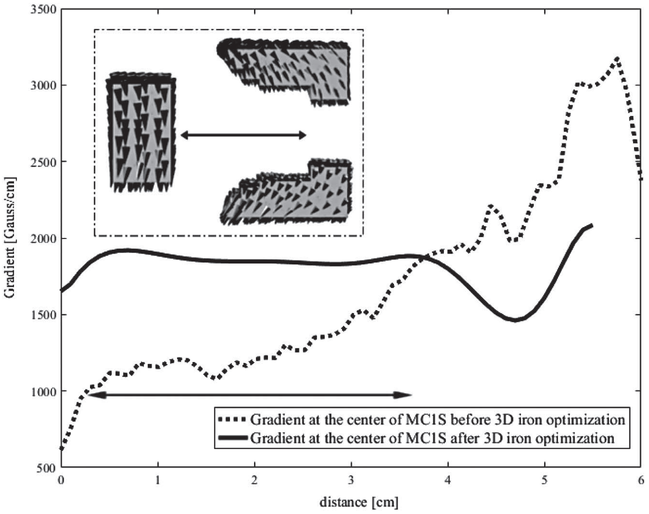

Fig. 5. – The gradient of the field produced at the center of the first magnetic channel is shown before (dotted line) and after (continuous line) the 3D optimization process. Also, a sketch of the non-vertical magnetic lines across the iron bars are shown.

MCs, respectively of 120 mm and 300 mm, has been considered negligible at this level of computation. Actually, there could be differences in the fields and gradients at the entrance and at the exit of the MCs and 3D tracks in OPERA3D are ongoing to look into details and to define small refinements in the shape and positioning of the MCs.

As for the existing MCs of the CS, compensating bars are necessary to compensate the introduced first harmonic perturbation, which is responsible for the beam precession. Even in this case, 3D simulations are useful to fix the exact positions and dimensions that are $120 \times 30 \times 35\,\text{mm}^3$ across the median plane, almost the same dimensions of the first block of the first MC, which is the closest iron piece to the accelerating region. Along all the acceleration, with the introduction of the compensating bars, the first harmonic component stays always below 2 gauss for $R < 900\,\text{mm}$, while without the bars it can reach 15–20 gauss. Similarly to the MCs, the two compensations bars have to move of 60 mm maximum when the accelerated particle changes.

To design the mechanical system allowing for these movements, a complete computation of the forces has been done considering different values of current flowing inside the main coils. The highest force is on the first MC when it is in the outer position and the field level is the highest. This value is 8.3 kN, which is high, but still acceptable, ref. [3].

Finally, there is another interesting application of the CSA to reduce the first and second-harmonic field components introduced by the drilling of a new big extraction channel. Without any iron yoke optimization, the Fourier analysis along the acceleration radii gives values of C1 and C2 that are too high to guarantee a correct extraction of the beams.

Using CSA, it is possible to reproduce C1 and C2 separately, and then identify the iron modifications necessary to cancel both of them. As for the shape of the MCs, CSA can be used as starting point, after 3D computations are mandatory, but the optimization process in this way can be faster.

After the optimization of the yoke C1 stays always below 3.8 gauss and C2 below 1.8 gauss along the entire acceleration path, against the starting values that reached 90 gauss and 50 gauss respectively. For more details see ref. [14].

These results are important not only for the high-intensity beams, but also for all the accelerated ions since, as explained before, electrostatic extraction will be maintained.

6. – Conclusions

All the studies that have been carried out for the past 3 years confirm the goodness of the CS upgrade project to increase the beam intensities for light ions in the energy range of 10–70 AMeV. The physics study has to be completed: other species have to be evaluated if eligible for the high intensity, and energy spread remains to be evaluated using 3D computation tracking. The final shapes and positions of the magnetic elements could change, respecting all considerations done above, and keeping forces and harmonic components of the field under control.

The new magnet is expected to be completed in 2020, while the first beam is expected in 2021.

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REFERENCES

[1] Calabretta L. *et al.*, *Commissioning of the K800 INFN cyclotron*, in *14th Int. Conf. on Cyclotrons and their Applications, ICCA95 (Cape Town, South Africa, 1995)* (World Scientific) 1996, pp. 12–19.

[2] Calabretta L. and Seidel M., *IEEE Trans. Nucl. Sci.*, **63** (2016) 965.

[3] Gallo G. *et al.*, *Mechanical Aspects of the LNS Superconducting Cyclotron Upgrade*, in *21st Int. Conf. on Cyclotrons and their Applications, ICCA16 (Zurich, Switzerland) THP09* (JACoW).

[4] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **51** (2015) 145.

[5] Raciti G. *et al.*, *Nucl. Instrum. Methods B*, **266** (2008) 4632.

[6] Prete G., *Phys. Procedia*, **26** (2012) 274.

[7] Calabretta L., Calanna A. *et al.*, *Mod. Phys. Lett. A*, **32** (2017) 1740009.

[8] Shima K., Kuno N., Yamanouchi M. and Tawara H., *At. Data Nucl. Data Tables*, **51** (1992) 173.

[9] Calanna A. *et al.*, *Proposal to increase the extracted beam power from the LNS-INFN Superconducting Cyclotron* in *13th Int. Conf. on Heavy Ion Accelerator Technology HIAT15 (Yokohama, Japan, 2015)* (JACoW) pp. 23–26.

[10] Gordon M. M., *Part. Accel.*, **16** (1984) 39.

[11] Gordon M. M. and Johnson D. A., *Part. Accel.*, **10** (1980) 217.

[12] Radovinsky A., Calanna A. *et al.*, *IEEE Trans. Appl. Supercond.*, **26** (2016).

[13] Tomic S. S. and Samsonov E. V., *Phys. Rev. E*, **65** (2002) 036504.

[14] Calanna A. *et al.*, in *Conf. Proc. IPAC17*, `accelconf.web.cern.ch/AccelConf/ipac2017/papers/wepva054.pdf`.