Overview of the future upgrade of the INFN-LNS superconducting cyclotron

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The LNS Superconducting Cyclotron, named "Ciclotrone Superconduttore" (CS), has been in operation for more than 20 years. A wide range of ion species from hydrogen to lead, with energy in the range 10 to 80 AMeV, have been delivered to users. The maxi-mum beam power is limited to 100 W due to the beam dissipation on the electrostatic deflectors. To fulfil the demand of users aiming at studying rare processes in nuclear physics, an upgrade of the cyclotron is necessarily intended to increase the intensity of ion beams with mass lower than 40 a.m.u. up to a power 10 kW. This will be achieved by means of extraction by stripping. This solution needs to replace the cryostat including the superconducting coils. The present capability of the cyclotron will be maintained, i.e. all the ion species allowed by the operating diagram will be available, being extracted by electrostatic extraction. In addition to the high power beams for nuclear physics, it will be possible to produce medical radioisotopes like ^{211}At using an internal target.

Keywords: Cyclotron; stripper extraction; radioisotopes.

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1. Introduction

Research and commercial cyclotrons use extraction by stripping to deliver light ions like protons and deuterons, see Ref. 1, and heavy ion beams are also extracted with this technique from the AVF cyclotrons of the Flerov laboratory, see Ref. 2. Although this method has already been proposed in some studies of superconducting cyclotrons, see Refs. 3 and 4, up to now, it has never been applied.

Extraction by stripping is very convenient to achieve a high extraction efficiency. However, its application is not trivial when extracting ions with a wide range of

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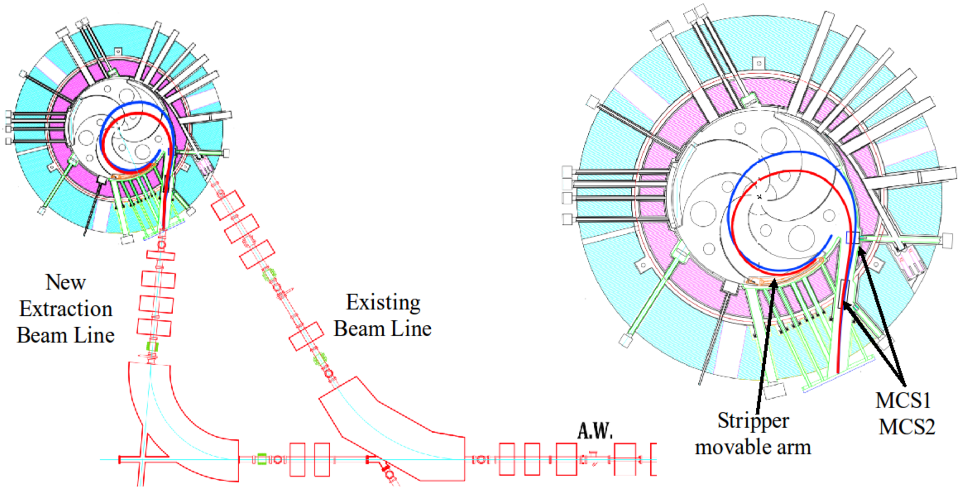


Fig. 1. (color online) Layout of the superconducting cyclotron with the existing and the new extraction beam lines. Two extraction trajectories, in red and blue, are also shown. Both the extraction lines produce an achromatic waist at the position A.W.

masses and/or energies. Indeed, in these cases, the extraction trajectories are quite different for different ion types, therefore a large Extraction Channel (Ex.Ch.) is needed, by far larger than the one requested by electrostatic extraction. This is a critical aspect for superconducting cyclotrons: the strong attractive force between the coils could produce serious deformations of the Liquid Helium (LHe) vessel inside the cryostat if a large Ex.Ch. is drilled through the LHe vessel. Moreover, the usual constraint of a small distance of the superconducting coils from the median plane reduces significantly the vertical gap available for the extraction of the beam. Here, we describe the modifications of the superconducting cyclotron, presently in operation at LNS-INFN, to realize a new extraction by stripping of light-medium mass ion beams.

The design of the CS, made by the Milano Group headed by Resmini, see Ref. 5, started in 1980, while it was commissioned in 1994, see Ref. 6. For the first six years the tandem accelerator was used to inject radially the beam into the CS that was operated as a booster. The charge state of the beam delivered by the tandem was increased by a factor 2–3 by means of a stripper foil placed on the tangent point between the injection trajectory and the accelerated orbit. Thanks to the fast development of the ECR ion sources along the '90s, it was decided to operate the CS in stand-alone mode. In this mode, ion beams with high charge states, produced by an ECR source, are injected axially into the CS. The central region of the CS was then modified to allow for axial injection. Today, the ion beams accelerated by the CS are produced by two ECR ion sources, one is a room temperature source called CAESAR and the other one a superconducting source called SERSE. The stand-alone operation allows to accelerate ion beams with intensity 2–3 orders of magnitude higher than in the previous mode (when the CS was operated as a booster of the tandem accelerator). In the near future, an ion source for proton beams only will be installed and another superconducting ion source called AISHA will be devoted to the production of light ions with high current and high charge states.

Unfortunately, the weakness of our CS is its extraction system, which consists of two electrostatic deflectors (ED1 and ED2) and of eight magnetic channels (MCs). Despite our efforts, we have not been able to extract beam currents over 150 W. This limit is mainly due to the low extraction efficiency of the CS that stays around 50–60% and to the thermal limits of our ED1. Although the ED1 is water cooled, it is not reliable when the beam loss exceeds 100 W.

Recently, a group of Catania nuclear physicists proposed to use the magnetic spectrometer with large solid angle and large momentum acceptance MAGNEX to measure the nuclear matrix element that is of relevant interest for the neutrino less double beta decay, see Ref. 7. This experiment, called NUMEN, plans to make use of carbon, oxygen and neon beams with intensity up to 10^{14} pps. The required energies are in the range 15–70 AMeV, which corresponds to a beam power in the range 1–10 kW. The management of LNS-INFN approved a program to upgrade the CS also because it will be relevant also for experiments that use radioactive ion beams produced by in-flight fragmentation. It is worth mentioning that the handling system of the stripper foils is not compatible with the ED1, then we plan to operate the cyclotron to extract intense ion beams through the new Ex.Ch. approximately six months per year, while for the other six months the CS will be operated to deliver ions using the two EDs to extract the beam in the present mode through the existing Ex.Ch.

In this paper, the main modifications that will be introduced in the cyclotron are described in Sec. 2. In Sec. 3, the study of the new Ex.Ch., and the beam dynamics features of the trajectories extracted by stripping are presented. The parameters of the MCs, necessary to control the beam envelope size along the Ex.Ch., and of the iron bars used to compensate the first harmonic are described in Sec. 4. Finally, in Sec. 5, we present the use of the stripping technique to produce ^{211}At.

2. Main Modifications of the Superconducting Cyclotron

The extraction of 1 to 10 kW beams is not feasible using the ED. A solution based on extraction by stripping has been investigated, see Fig. 1. Ion beams are accelerated with a charge state $q = (Z - 1)$ to $(Z - 3)$ and after crossing a stripper foil become fully stripped ($q = Z$). As a consequence of the increased charge state, the trajectory suddenly changes from the three-fold circle-like to a trajectory that is strongly off-centered, see Fig. 1. The stripping trajectories are different for each ion, and depend upon the charge-to-mass ratio before and after the stripping process, as well as on the radial and azimuthal position of the stripper foil. Our first attempts to extract the stripped ion beams through the existing Ex.Ch. failed since the beam envelopes

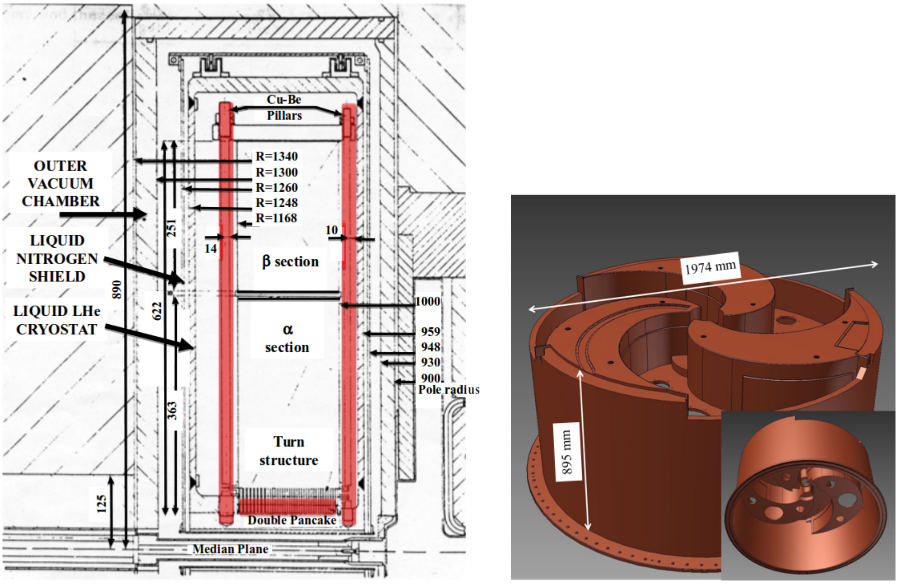


Fig. 2. (color online) Cross-section of the existing cryostat with alpha and beta coils, (left). The Cu-Be pillars and the two layers of the alpha coils that have to be removed are highlighted in red. The figure on the right shows one of the liners, copper made, that cover the pole and the trim coils.

turned to be larger than 30 mm, which exceeds the maximum acceptable beam size $\phi = 10$ mm. This is due to the sudden fall-off of the coils fringing field, which defocuses radially the beam. To reduce the extraction path as much as possible, so as to limit the defocusing effect, a new and shorter Ex.Ch. is necessary. To have a new Ex.Ch. it is mandatory to build a new cryostat including new coils. Other smaller modifications planned to improve the CS performances are also presented in this section.

2.1. *Main coils*

The existing superconducting coils are wound with the so-called technique of the double pancake. Although this solution is very conservative, it is also space consuming because a set of vertical pillars made of copper–beryllium are necessary to compress the two pairs of alpha and beta coils to prevent their radial displacement, see Fig. 2. To overcome these problems, we plan to reduce the coils size increasing the current density and using epoxy impregnated (potted) coils, see Ref. 8. Reducing the coils height, it is possible to replace the compressing vertical pillar by a set of springs placed on the top of the upper beta coil and on the bottom of the lower beta coils, see Ref. 8. Moreover, the vertical gap of the Ex.Ch. increases to 60.5 mm versus the present value of 30.5 mm and about 8–10 mm are available to install the liquid nitrogen (LN) thermal shield around the median plane. At present, the thermal shield consists of three independent circuits with a forced flow of LN.

This solution produces a significant consumption of LN. In the new design, a more reliable LN shield working in a natural convection mode will reduce significantly this consumption.

2.2. *Acceleration chamber improvements*

The replacement of the CS superconducting magnet gives us the opportunity to replace also the existing copper made liners with new ones. Indeed, the vacuum in the acceleration chamber is getting slowly worse along the years. The walls of the vacuum chamber are the internal wall of the cryostat and the surfaces of the two liners. These liners cover the upper and lower poles of the cyclotron, see Fig. 2(right). The liners separate the vacuum of the acceleration chamber from the poles and the trim coils wound around the top of the hills, where we have an intermediate vacuum of about 0.1 mbar. The residual pressure in the acceleration chamber is increasing along the years and the main reason of this worsening are the small leaks through the welded joints of the liners. The construction of a new set of liners gives the opportunity to increase the axial gap of the acceleration chamber from the present value of 24 mm up to 31 mm. This can be achieved quite easily if the set of the 20 trim coils wound around each hill of the cyclotron are replaced with a new set made with a smaller cable. The increase of the axial gap is convenient to have a better vacuum conductance and to minimize the beam losses due to beam haloes striking on the liner surfaces.

3. Beam Dynamics of Extraction by Stripping

The studies of extraction by stripping accomplished so far determine the features of the new extraction system necessary to guide the ion beams from the accelerated orbit inside the CS to a common position outside of the cyclotron. The new extraction system consists of two stripper devices together with their handling system to adjust the foil radial and azimuthal position, and of two magnetic channels MCS1 and MCS2 placed inside the new Ex.Ch. One stripper device stays on the hill where the ED1 is located, another one is located inside a RF dee, just before the ED1. ^{12}C, ^{18}O and ^{20}Ne, accelerated with charge states and energies shown in Table 1, are the ions of interest for the NUMEN experiment, therefore their extraction trajectories and beam envelopes have been simulated, see Fig. 3. According to Ref. 9, after the stripping process all these ions with energies higher than 15 AMeV are fully stripped with a population $> 99\%$. To calculate the trajectory and the beam envelope for each ion along the extraction trajectory, we used the codes GENSPE and ESTRAZ developed at MSU-NSCL, see Ref. 10, modified by us according to our needs. For each ion beam, at fixed energy and position of the stripper foil, the GENSPE code allows to evaluate the initial conditions of the reference particle and of eight particles that describe the beam eigenellipse in the (x, x') and (y, y') phase space. A normalized beam emittance of 1π mm-mrad has been assumed in our simulation. This value is more than twice the measured normalized emittance

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

Ion	$\frac{Q_{\mathrm{acc}}}{Q_{\mathrm{ext}}}$	Energy (AMeV)	Θ	R_{Strip}
^{12}C	4/6	45.8	112	88.2
		60.8	106	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

of the beam delivered by the LNS ion source. The code ESTRAZ assumes the initial conditions of the particles at the stripper foil evaluated through GENSPE to calculate the extraction trajectory of the reference particle and the radial and axial beam envelopes along the extraction trajectory. All extracted trajectories have to reach a common exit point. The maximum axial beam envelope along the extraction trajectories has to be lower than ±15 mm inside the pole region and ±25 mm outside the pole. Choosing properly the energy, the radial and azimuthal position of the stripper foil, see Table 1, the trajectories that match all the constraints were found out, see a sample of the trajectories studied and an indication of the final stripper positions in Fig. 3. The azimuthal angles of the stripper foils are in the CS reference

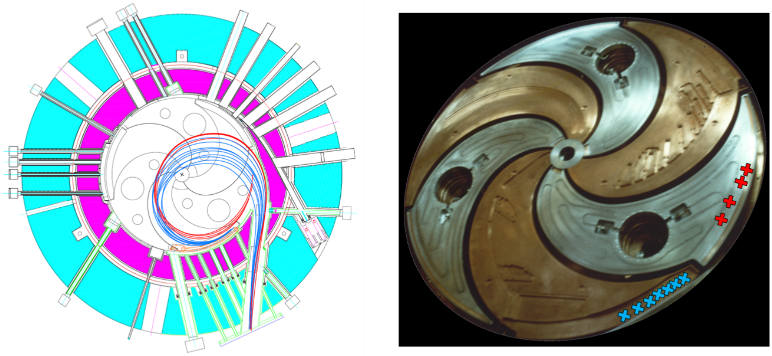


Fig. 3. (color online) The figure on the left shows the CS median plane with the new Ex.Ch. and the stripping trajectories of all the studied cases. On the right, a zoom of the positioning area of the strippers foils. The red and blue colors refer to the stripper positions in valley and in hill, respectively.

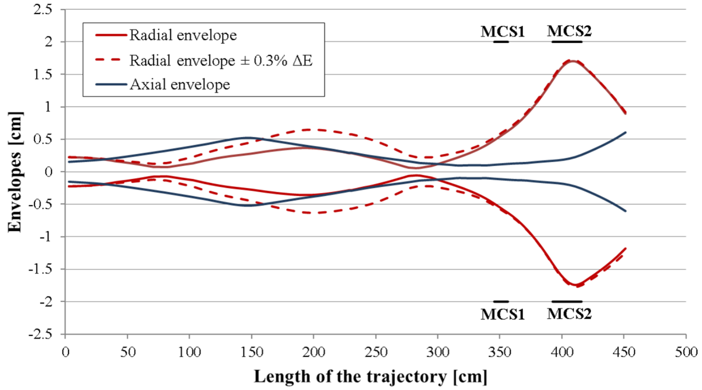
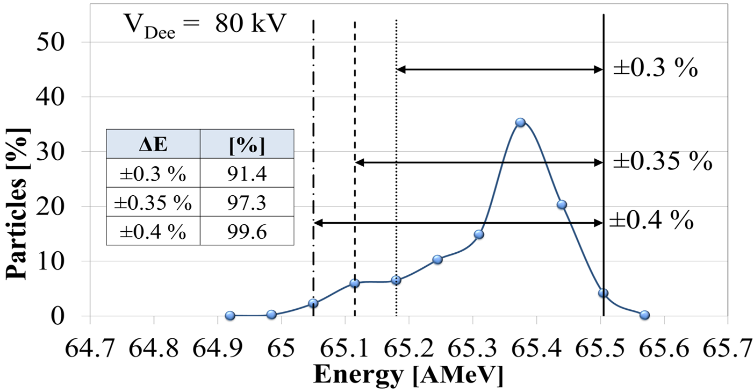


Fig. 4. Radial and axial envelopes for the ion beam ^{18}O at stripping energy equal to 65 AMeV along the stripping trajectory. The effect of an energy spread ±0.3% is also shown.

coordinate system, that uses the non-conventional clockwise direction for positive angles. To maintain the transverse beam envelope within the mentioned values and to steer the beams as near as possible to the exit point, two MCs will be used, consisting of three iron bars carefully machined and placed along the Ex.Ch. The MCs provide a constant focusing gradient dB_z/dR (quadrupole component) in a region of radius 18 mm around the nominal center of the channel. It has not been trivial to find out the positions and the characteristics of the two MCs that allow to fulfil the above-mentioned constraints.

Since extraction by stripping is a multi-turn extraction type, the effect of the energy spread on the radial envelopes has to be taken into account. Figure 4 shows the beam envelope for the case ^{18}O at 65 AMeV, computed by the ESTRAZ code, with and without an energy spread of ±0.3%.



ΔE	[%]
±0.3 %	91.4
±0.35 %	97.3
±0.4 %	99.6

Fig. 5. Particles vs. energy distribution at the stripper position. About 99% of particles have an energy spread of < 0.4 %.

To get information on the energy distribution at the stripper position a bunch of particles of ^{18}O, accelerated with charge state 6+, from 1 AMeV up to 65 AMeV, was simulated using the SPIRALGAP code, see Ref. 11. The results of these simulations produce the energy distributions presented in Fig. 5, where it is evident that almost 99% of the particles have an energy spread $< 0.4\%$. According to Fig. 4, at the position of the two MCs there is no energy–position correlation and then the expected extraction efficiency is about 100%. Of course, it is convenient to design the two MCs so as to transmit beams with energy spread near to $\pm 0.4\%$ minimizing the beam losses.

4. Design of the Magnetic Channels

The design of the magnetic correctors is a key point in this study due to the need of a large clearance necessary to accommodate the large beam envelopes. Moreover, high gradients are necessary. The values of fields (0.4 to 1.3 kGauss) and gradient (1.80 kGauss/cm) needed to guide and focus the various beams have been found out through the code EXTRAZ. The present electrostatic extraction system makes use of eight MCs, that are made of three iron bars. These channels have been simulated by means of the Current Sheet Approximation (CSA), which allows to simulate the shape of the MCs through an ideal flat coil around the volume of each iron bar. The CSA is valid only if the magnetic field lines are vertical across the iron bars. This is quite true if the iron bars stay at a distance of 10 mm from the median plane. The new MCs are larger and have a distance of about ±30 mm from the median plane. In this configuration, the field lines are not fully vertical to the iron bars, see Fig. 6(right). Moreover, the CSA method is valid only if the main magnetic field is higher than 0.5 T and almost uniform, this condition is not fulfilled in the fringing region between the upper and lower coils. For these reasons the use of CSA is valid only in the early stage of the MCs design. This is shown in Fig. 6(left), where the magnetic field produced by a MC placed in an external uniform magnetic field

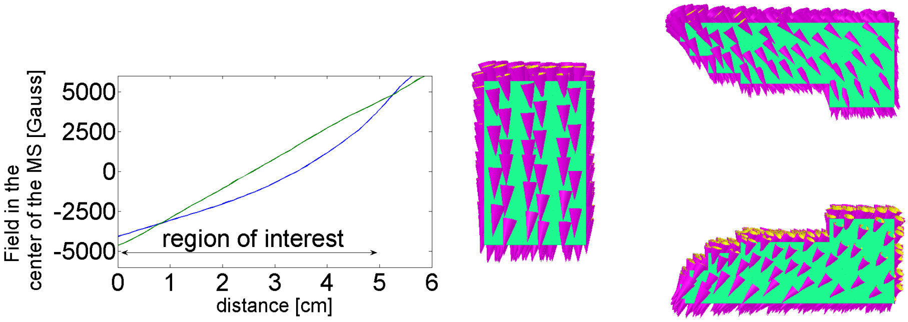


Fig. 6. (color online) The figure on the left shows magnetic fields at the center of MC when it is placed in a uniform external field (green line) and when the same MC is placed in real magnetic field (blue line). Indeed in this case, due to the main field, the magnetic lines are not vertical across the iron bars (right).

(green lines) and in the real magnetic field across our Ex.Ch. (blue lines) are shown. These 3D simulations were performed using the OPERA code. Moreover, to achieve the constant gradient in a region of about 35 mm, it was necessary to perform many iterations of 3D simulations to adjust the shape of the two symmetric bars.

Furthermore, the lengths of MCS1 and MCS2 are 120 mm and 300 mm, respectively. Due to the strong variation of the main magnetic field along the Ex.Ch., there are differences in the field and gradient at the entrance and at the exit of the MCs. Fortunately, this effect on the extracted trajectories is negligible. However, to achieve the best positions and dimensions of the MCs, we used magnetostatic 3D simulations. As a result of the design, both MCs are 60 mm high and 87.8 mm wide. They are composed of an iron bar crossing the median plane and two iron bars symmetric with respect to the median plane, see Fig. 6, that are carefully shaped to achieve the uniform gradient equal to 1.8 kGauss/cm for both the MCs. The minimum distance between the upper and lower piece is 24 mm. To place the MCs in the right position for each extraction trajectory, we need to move them in the direction perpendicular to the extraction trajectories. In this way, the same gradient is always applied to the beam, while the field on the reference trajectory can change of about 0.9 kGauss producing a steering effect on the beam making it to reach the exit point. Taking into account all the studied cases, a linear coarse of 60 mm is requested for both the MCs.

The MCS1 and MCS2 produce a first harmonic component of the magnetic field of the cyclotron. To compensate this first harmonic, we introduced two compensation bars. Their positions and sizes were evaluated with 3D simulations. The sizes of both the bars are $120 \times 30 \times 35$ mm through the median plan, almost the same dimension of the first block of MCS1, which is the closest to the accelerating region. The effect of the compensation bars is to reduce the first harmonic component from 15–20 Gauss to below 2 Gauss at all the radii inside the cyclotron pole, $R < 900$ mm. Similar to the MCs, the two compensation bars have to be movable at 60 mm in–out, according to the different ion beams to be extracted. Both the MCs and the compensation bars are strongly attracted by the main magnetic field. The forces acting on them were evaluated at different magnetic field levels. The highest force is on the first MC when it is in the outer position and the magnetic field is the highest. The maximum value is 8.3 kN and requires a proper design of the mechanical system. It is worth mentioning that since the field is not uniform the forces between the upper and lower part of the MCs are in opposite directions and in the worst case they are 1.4 kN. The housing of the two MCs has a proper shape to guarantee the mechanical stability when the strong repulsive magnetic force is applied.

5. Internal Target for Alpha Emitters Radioisotope Production

Alpha-induced reactions allow for the production of residual nuclei significantly far from the stable nuclei line and could provide radioisotopes for therapy that may not

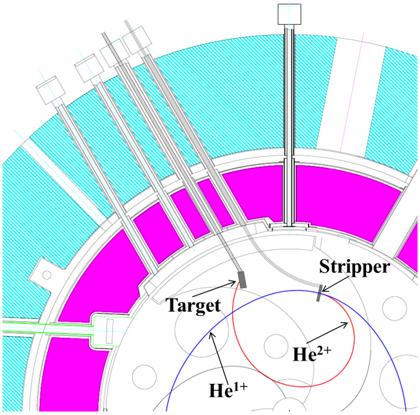


Fig. 7. Equilibrium orbit of He^{1+} at $E = 28$ MeV and the trajectory of the fully stripped He^{2+} from the stripper to the production target.

be available by means of commercial proton cyclotrons. In particular, the ^{211}At is an alpha emitter that is accessible through the reaction ^{209}Bi(α, 2n) ^{211}At and could be used as a therapy radionuclide, see Ref. 12. The maximum energy for the alpha beam must stay below 28 MeV to avoid the production of ^{210}At that produces the contaminant ^{210}Po. Unfortunately, it is not possible to extract helium beam from CS with Ex.Ch. by stripping nor with electrostatic deflection, but we found out a simple solution to irradiate a bismuth internal target. Due to the low energy of the helium beam the production of neutrons is quite low and the activation of the cyclotron is acceptable for a production regime dedicated to the research activity (10–20 days per year). Therefore, significant problems to the cyclotron maintenance are not expected for this activity. We plan to set the cyclotron to accelerate He^{1+} to 60 MeV and put a stripper at the radius of 625 mm, where the energy is 28 MeV. The target is then irradiated by the fully stripped He^{2+} after one turn at a radius of about 750 mm, see Fig. 7. The position of the stripper foil and of the target have been chosen to allow an easy insertion and extraction through the existing yoke penetrations, see Fig. 7, that are the ones used for the ED2 with proper modifications. The installation of a proper vacuum interface is under study, to insert and to remove the internal target without opening the cyclotron magnet maintaining the operation vacuum in the machine.

Due to the low energy of the beam, the secondary neutron flux is low and a beam power more than 500 W (18 μA @ 28 MeV) will be available for the target irradiation. A production of ^{211}At of more than 200 mCi is expected after an irradiation of 8 h.

6. Conclusion

The upgrade of the LNS CS aiming at increasing the intensity of light ion beams by two orders of magnitude is based on extraction by stripping. In order to make the new extraction mode possible, the superconducting magnet needs to be replaced with a new one fulfilling the geometry constraints imposed by the news trajectories. The tender for the new superconducting magnet is now completed. The order should be ready by 2017. The new magnet is expected to be completed in 2020. The expected time to dismount and to assemble the several parts is about 18 months, therefore the restart of the cyclotron is planned for the end of 2021. In the meanwhile, some crucial parts of the existing beam transport line have to be optimized to ensure a beam transmission efficiency better than 98%.

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