

A CENTRAL REGION UPGRADE OF THE k800 SUPERCONDUCTING CYCLOTRON AT INFN-LNS

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Abstract

The Superconducting Cyclotron (CS) at INFN-LNS in Catania is currently under an upgrade process. The plan is to deliver beams of ions with mass number $A \leq 40$ with power up to 10 kW by means of beam intensity increase. This ambitious goal can be achieved by increasing the efficiency of the injection and extraction processes. An extraction efficiency close to 100% is expected by extracting the specific ion beams from the CS by stripping and no longer by electrostatic deflectors. The beams are injected axially and bent onto the median plane with a spiral inflector. Currently, the injection efficiency is around 15% including the effect of a drift buncher placed in the axial injection line. In order to increase the injection efficiency, the study of an upgraded CS central region is ongoing at INFN-LNS. In this paper, the results of simulations of beam tracking through the cyclotron axial bore, the spiral inflector, the central region and further up to the extraction system are presented.

INTRODUCTION

The Superconducting Cyclotron at INFN-LNS, known as CS, is a multi-particle variable energy cyclotron able to deliver a large variety of stable ion beams with energies ranging from 10 MeV/amu to 80 MeV/amu.

The isochronous magnetic field, varying in the range of 2.2–4.8 T, is produced by the combined contribution of two superconducting main coils, three fully saturated iron spiralled pole sectors, the yoke and twenty trim coils wound around each hill. The main cyclotron parameters are listed in Table 1.

Table 1: Main Parameters of the INFN-LNS Superconducting Cyclotron

Bending limit k_B	800
Focusing limit k_F	200
Centre field [min-max]	2.2-4.8 T
Pole radius	900 mm
No. of sectors	3
No. of superconducting coils	2 pairs
No. of trim coils	20 (for sector)
No. of dees	3 (in valleys)
RF frequency range	15–48 MHz
Harmonics h	1, 2, 3, 4 (only 2 used)

The CS has about 25 years track record of producing ion beams to support the nuclear physics community at INFN-

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LNS. The ion beams delivered by the cyclotron have allowed a huge variety of experimental research in the fields of nuclear reaction mechanisms, nuclear structure, nuclear astrophysics, applied physics and also the treatment of ocular melanoma by proton beam.

Unfortunately, the maximum beam power the CS is able to deliver does not exceed 100 W, due to beam power lost on the first of the two electrostatic deflectors that compose the extraction system. The current extraction efficiency is about 60%. Despite the LNS ion sources are able to deliver beam current much higher than the present injected current, the constraint on the maximum beam power extracted prevent the ion sources to work at the maximum performance.

The future mission of the INFN-LNS is to serve the users with high intensity beams of the order of 10^{13} - 10^{14} pps for systematic studies of nuclear reactions of interest for the neutrino physics community and for the production of intense RIBs (Radioactive Ion Beams) by in-flight fragmentation technique. In more detail, the NUMEN project [1] at INFN-LNS aims to access quantitative information relevant for nuclear matrix elements for neutrino-less double beta decay by means of the study of heavy-ion induced double charge exchange reactions. A key aspect of the project is the use of the CS for the acceleration of the required high intensity ($\sim 10^{13}$ - 10^{14} pps), high energy resolution ($\sim 0.1\%$ FWHM) and low emittance heavy ion beams and of the MAGNEX large acceptance magnetic spectrometer [2] for the detection of the ejectiles. Moreover, the improvement of the CS performance, together with the construction of the new FRAGMENT In-flight SEPARATOR (FRAISE) at INFN-LNS [3], will allow to obtain high intensity beams of ions very far from stability valley.

In order to deliver high intensity beams of ions with mass number $A \leq 40$ and energy higher than 15 MeV/amu, a highly advanced upgrade plan of the INFN-LNS Superconducting Cyclotron is under way.

The stripping extraction is a valid solution to overcome the present limitation of the extraction process. According to data in Ref. [4], for the ion beams and energies required by the NUMEN and RIBs production projects, the percentage of ions fully-stripped after the stripping process is higher than 99%. Consequently, it is foreseen to achieve an extraction efficiency close to 100%. The implementation of the stripping extraction is not trivial in the case of the CS because it has to continue to deliver all the ion beams currently demanded by the LNS users. More details on this aspect of the CS upgrade project can be found in Ref. [5]. The use of a stripper foil for the extraction of the ion beams of interest for NUMEN and RIBs production will allow to inject in the cyclotron and consequently to deliver beam

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current higher than the actual one since the limitation of the maximum beam power of 100 W will be overcome. In addition, the improvement of the overall efficiency, involving the processes of beam injection, acceleration and extraction, is crucial in the case of the CS and it is strongly constrained by the NUMEN requirement on the small energy spread. The study of the beam injection and acceleration in the first turns in the machine is an important aspect of the CS upgrade project because ion beam intensity, emittance and energy spread at the extraction are largely determined by the cyclotron central region.

THE EXISTING CENTRAL REGION

The central region of the INFN-LNS Superconducting Cyclotron is equipped with a spiral inflector, an electrostatic deflector that provides a 90° bending of the ion beams from the vertical direction into the cyclotron median plane. The spiral inflector has a bending radius A of 27 mm and a constant distance between the electrodes d equal to 6 mm, being the so-called tilt parameter k' equal to zero. A copper housing surrounds the spiral inflector in order to isolate the device from the RF fields driving the CS. A copper collimator with a circular aperture of 6 mm in diameter, placed at a distance of about 40 mm from the spiral inflector entrance, allows to protect the spiral inflector electrodes from the ion hits.

A set of electrodes attached to the dees and the dummy-dees composes the CS central region. Pillars crossing the median plane are placed on these electrodes. The vertical gap between the accelerating electrodes in the CS centre is 19 mm. The CS central region operates in the so-called constant orbit mode [6] in order to be valid for the acceleration of all the ions within the operating requirements of the LNS cyclotron [7]. This imposes the existence of a precise scaling law for the voltage of the ion source, spiral inflector and dees. Figure 1 shows the photos and the Opera-3d [8] model of the existing central region of the INFN-LNS Superconducting Cyclotron.

IMPROVEMENT OF THE BEAM TRANSMISSION IN THE CS CENTRAL REGION

The approach used consists of the following steps:

- i) Construct an Opera-3d model of the cyclotron magnet and use it to create the isochronous field map for the chosen reference ion ($^{16}\text{O}^{8+}$ ion accelerated at the maximum energy of 100 MeV/amu) and a detailed 3D field map in and around the inflector volume.
- ii) Design the existing central region geometry. Solve the geometry with Opera-3d and obtain a 3D potential map around the median plane as needed by the tracking code.
- iii) Study the beam optics through the axial bore of the LNS cyclotron in order to find the best match with the optical properties of the CS axial bore. The transverse normalized beam emittance at the entrance of the cyclotron axial bore was defined as 1π mm-mrad.

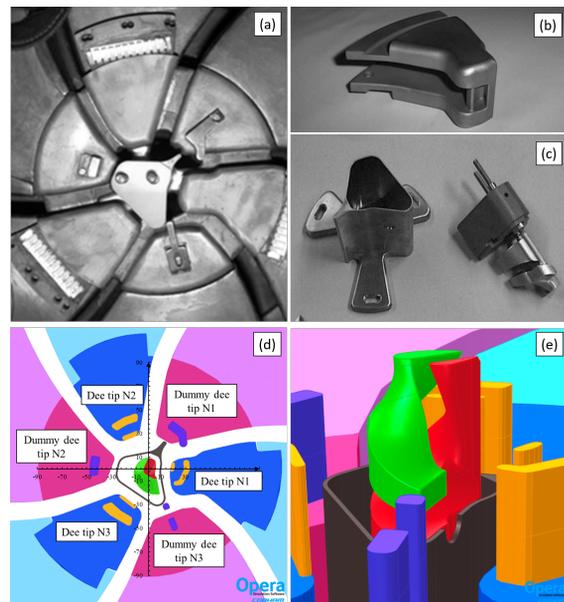


Figure 1: Existing central region of the INFN-LNS Superconducting Cyclotron: (a) Photo of the central region, (b) Photo of one of the dee-tips, (c) Photo of the spiral inflector and its housing, (d) and (e) Opera-3d model of the central region.

- iv) Evaluate the RF phase acceptance for different angular positions of the whole inflector assembly with respect to the vertical CS axis in order to estimate the optimum orientation of the spiral inflector.
 - v) Evaluate the present injection efficiency by beam tracking from the axial bore entrance of the CS, through the present spiral inflector up to the central region exit.
 - vi) Optimize the position of the pillars to increase the clearance reserved to the ions for their escape from the central region.
 - vii) Increase the dee voltage to reduce the radial hits of the ions with the electrodes intersecting the median plane.
- The necessity to change slightly the position of the pillars and to apply dee voltage higher than the nominal value comes from the desire to reduce the radial losses on the pillars, that are the main causes of the low ion transmission in the CS central region. In more detail, three different models of the CS central region have been considered in the study: the existing design of the CS central region, that we name model I, and two new modified geometries, that we name model II and III respectively, obtained from the existing one changing slightly the position of the pillars of 1-2 mm. The differences between the three models of the CS central region are shown in Fig. 2. Each colour in the figure refers to a different model. For a better understanding of the changes, only the elements, which have been moved, are shown. On the left of the figure the differences between model I and II are shown and on the right the ones relative to model II and III. For each of the created models of the CS central region, the injection efficiency has been evaluated for four values of the dee voltage: 86 kV (the nominal value), 90 kV,

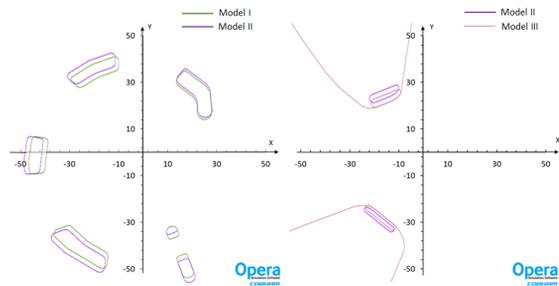


Figure 2: On the left differences between the models I and II and on the right the ones relative to the model II and III of the CS central region.

95 kV and 100 kV. The values of the injection efficiency in percentage for the above-mentioned cases are reported in Table 2. These suppose particle RF phases on a interval of 30° at the starting tracking position.

The results of the simulations show that the use of dee

Table 2: Injection Efficiency in Percentage as Function of the Different Models of the CS Central Region and the Dee Voltage

	Dee voltage			
	86 kV	90 kV	95 kV	100 kV
Model I	29.7 %	39.2 %	43.5 %	41.1 %
Model II	25.0 %	38.1 %	47.3 %	52.5 %
Model III	35.6 %	43.2 %	50.5 %	53.0 %

voltages higher than the nominal one has the effect to help a higher number of ions to move away from the pillars reducing the hits. For a better understanding of the process, Fig. 3 shows the beam in the existing CS central region when the voltage applied to the dees is 86 kV and 100 kV respectively.

As reported in Table 2, the maximum improvement of the injection efficiency is obtained for the CS central region geometry corresponding to model III and for the dee voltage equal to 100 kV. The increase in the injection efficiency between the present situation and the 100 kV dee voltage in model III case is really relevant being almost of 78%. Supposing to inject into the CS a DC beam and considering

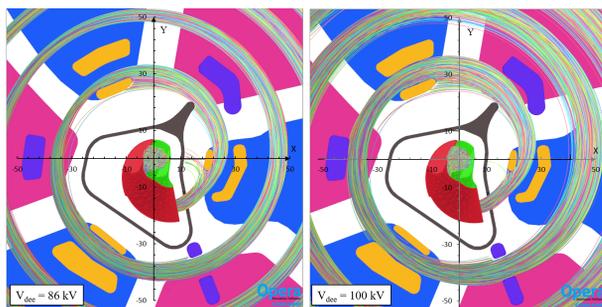


Figure 3: Beam particles in the existing CS central region, when the voltage applied to the dees is equal to 86 kV (on the left) and 100 kV (on the right).

a buncher able to guarantee a buncher efficiency of 50% within 30° RF phase width, the injection efficiency becomes close to 25% and therefore increases of a factor 1.7 with respect to the actual one. Although the simulations on the injection efficiency have been carried out for dee voltages higher than the operating limit of the RF cavities (≈ 82 kV), the obtained results are valid in the case of acceleration of beams of all the ion species with low and medium energies since they require a dee voltage less than or equal to this limit according to the scaling law for the dee voltage imposed by the working mode of the CS central region.

CONSIDERATIONS ON THE TOTAL EFFICIENCY AND BEAM ENERGY SPREAD AT THE EXTRACTION

The NUMEN requirement about the small beam energy spread limits the maximum beam power that the CS could deliver. The expected maximum beam energy spread at the extraction for all the ion beams to be extracted by stripping is about $\pm 0.3-0.4\%$, according to the analytical formula reported in Ref. [9]. Simulations have confirmed this value, that is higher than the NUMEN requirement of about a factor 4 [5]. The beam energy spread is being taken into account within the simulation study and new solutions for its reduction are under investigation.

The beam energy selection outside the CS for the energy spread reduction could be performed by using the dispersive property of FRAISE, but this implies that only a portion of the accelerated beam could be transported to the NUMEN experimental hall. An alternative to this solution could be the use of a degrader placed in the FRAISE line. This solution would allow to reduce significantly the beam energy spread without significant loss of beam intensity. In addition, a study is ongoing at LNS in order to investigate either the use of phase slits installed inside the cyclotron, just outside the central region, for reducing the RF phase interval of the beam and the use of the existing harmonic coils installed at outer radii in the cyclotron for producing a first harmonic precession able to increase the separation between last turns at the stripper position. However, simulations have demonstrated that the main contribution to the beam energy spread at the extraction is due to the large emittance injected in the central region of the LNS cyclotron. The energy gain per turn contributes only partially to it. Also a good quality of the accelerated beam is required since an initial beam offset in the central region implies a further increase of the beam energy spread at the extraction. More details about these aspects can be found in Ref. [10].

CONCLUSION

The project of the CS and the INFN-LNS facility upgrade (POTLNS PON Ricerca e innovazione 2014-2020) has been recently approved and funded by MIUR. In this paper the results of the preliminary study of a CS central region upgrade has been presented. The present study has allowed to

establish a roadmap to be followed for the improvement of the CS performance.

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