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

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Abstract

The Superconducting Cyclotron (CS) at INFN-LNS is regularly operated with beam power up to 100 W. The present efforts in upgrading the cyclotron are directed towards an increase of beam power up to 10 kW for ions with mass number A≤40 and energies between 15 and 70 AMeV by means of increase of beam intensity. Moreover, a beam energy resolution of 0.1% is requested by the NUMEN project at INFN-LNS. We plan to achieve high beam power by increasing the efficiency of the injection and extraction processes. The current extraction efficiency is lower than 60%. We expect to increase it to a value close to 100% by extracting the specific ion beams by stripping and no longer by electrostatic deflectors. A spiral inflector is used to inject onto the median plane the ion beams produced by the two ECR ion sources. Including the effect of a drift buncher placed in the axial injection line, the current injection efficiency is about 15%. The study of an upgraded CS central region is ongoing at INFN-LNS. First results of simulation study aimed to increase the injection efficiency are presented.

INTRODUCTION

The Superconducting Cyclotron at INFN-LNS in Catania, known as CS, has about 25 years track-record of accelerating ion beams to support the nuclear physics community of the laboratory. Furthermore, it is also used for the treatment of ocular melanoma by proton beam.

It is a multi-particle variable energy cyclotron with a wide operating diagram. The CS accelerates ions with charge-to-mass ratio Q/A in the interval 0.1 - 0.5. For any Q/A, the maximum energy per nucleon is determined by either the bending limit $E/A = 800 \cdot (Q/A)^2$ or the vertical focusing limit $E/A = 200 \cdot Q/A$.

The CS is very compact with a pole radius of 90 cm. The isochronous magnetic field in the range 2.2 – 4.8 T is produced by two superconducting main coils, three fully-saturated iron pole sectors and twenty trim coils wound around each hill [1]. Three RF-cavities provide the accelerating voltage for the beams and operate in the frequency range 15 - 48 MHz in harmonic mode 2. Ion beams, generated by two ECR ion sources, are axially injected.

The extraction system consists of two electrostatic deflectors placed on consecutive hills and eigth passive magnetic focusing channels [2]. The extraction by electrostatic deflectors limits the maximum beam intensity because of losses and induced heat-load on the septum of the first device. The current extraction efficiency is lower than 60% and the maximum beam power that the CS can deliver is about 100 W [3]. The constraint on the maximum beam intensity prevents to inject in the cyclotron high current, although the ion sources are able of high performance.

The cyclotron will be under an upgrade process in the near future to increase the beam intensity. High beam intensity is required by the NUMEN project at INFN-LNS [4]. It aims at accessing experimental-driven information on nuclear matrix elements involved in the half-life of neutrinoless double beta decay, by high-accuracy measurements of cross section of heavy ion induced double charge exchange reactions. The project requires mainly beams of carbon, oxygen and neon with intensity up to $10^{13} - 10^{14}$ pps. The required energies for these beams are in the range 15 - 70 AMeV, which corresponds to a beam power in the range 1 - 10 kW. Furthermore, a good beam energy resolution (~1/1000) is required.

In order to deliver high beam intensity, it is planned to increase the overall efficiency, including beam injection, acceleration and extraction processes.

The extraction by stripping for ions with A ≤ 40 has been proposed. It will allow to inject into the cyclotron, accelerate and to extract beam current higher than the actual one. According to data in Ref. [5], for the ion beams and energies required by NUMEN, the percentage of fully-stripped ions after the stripping process is higher than 99%. Consequently, an extraction efficiency close to 100% is expected. The implementation of the stripping extraction is not trivial because it requires substantial changes in the cyclotron [6].

The improvement of the injection efficiency is another important aspect of the CS upgrade project to achieve the desired high beam intensity. The overall efficiency is strongly constrained by the NUMEN requirement on the energy spread. Therefore, the evaluation of the energy spread of the extracted beam is essential.

THE EXISTING CS CENTRAL REGION

During the first four years of operation, the CS worked as a booster of the 15 MV Tandem at INFN-LNS [7]. Since the year 2000, the machine works in stand-alone mode.

A spiral inflector is used for 90° bending of ion beams from the vertical direction into the cyclotron median plane. It has a bending radius A of 27 mm and the so-called tilt-parameter k' is zero. The electrode distance d is 6 mm and the aspect-ratio s/d is 2. The inflector is surrounded by a copper housing to isolate the device from the RF-fields driving the CS. A copper collimator with a circular aperture of 6 mm diameter is placed before the device entrance to protect the inflector electrodes from the ion hits.

The CS central region is composed of a set of electrodes attached to the dees and dummy-dees. Pillars crossing the

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median plane are placed on each electrode. 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 [8] in order to be valid for the acceleration of all the ions within the operating diagram of the cyclotron [9]. This imposes the existence of a scaling rule for the voltage of the ion source, spiral inflector and dees, as compared to a reference case:

$$\frac{V}{\omega_0 \cdot B_0} = constant \qquad (1)$$

where V is the peak voltage of the dees, ω_0 the ion orbital frequency and B_0 the magnetic field in the cyclotron centre.

Figure 1 shows the Opera-3d [10] model of the existing spiral inflector and central region of the CS.

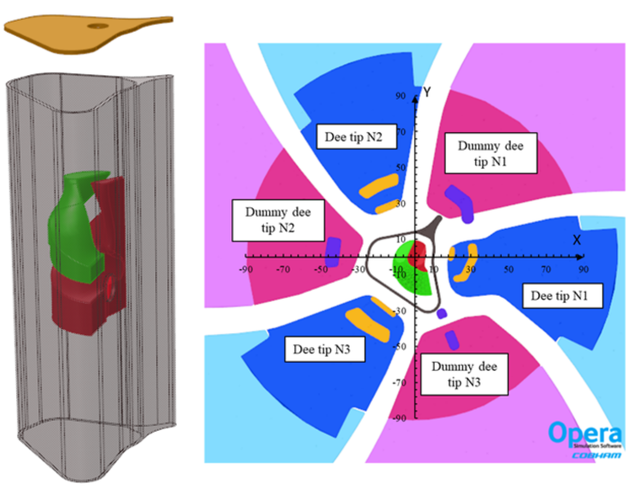

Figure 1: Opera-3d model of the existing spiral inflector (on the left) and central region (on the right) of the CS.

IMPROVEMENT OF THE TRANSMISSION IN THE CENTRAL REGION

The approach used can be divided in the following steps:

1) Choice of the reference ion. According to the scaling law given by Eq. (1), an ion that requires the highest dee and injection voltage has been selected within the operating diagram of the CS. Our choice is the ion $^{16}O^{8+}$ accelerated at the maximum energy of 100 AMeV.
2) Creation of an Opera-3d model of the cyclotron magnet and use it to create the isochronous field map for the chosen reference ion and a detailed 3D field map in and around the inflector volume as needed by the tracking code AOC.
3) Creation of an Opera-3d model of the cyclotron central region and use it to create a 3D potential map around the median plane and the inflector volume as needed by the tracking code AOC.
4) Study of the beam optics through the axial bore of the CS 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 equal to 1 π mm-mrad.
5) Evaluation of the RF phase acceptance for different angular positions of the whole inflector assembly with respect to the vertical direction to estimate the optimum orientation of the device with respect to the central region electrodes.
6) Evaluation of the present injection efficiency by beam tracking from the axial bore entrance, through the spiral inflector up to the central region exit of the CS.
7) Optimization of the position of the pillars to increase the clearance reserved to the ions for their escape from the central region.
8) Increase of the dee voltage to reduce the radial hits of the ions with the electrodes intersecting the median plane.

The injection efficiency is determined by the losses on the whole inflector assembly and on the central region electrodes. It has been evaluated considering three different models of the CS central region, that we named model I, II and III respectively [11]. The first model is the existing design and the other ones have been obtained from the existing design changing slightly the position of the pillars of 1-2 mm.

Figure 2 shows the differences between the models. Only the pillars, that have been moved, are shown. On the left, the differences between model I and II are shown and on the right the ones between model II and III.

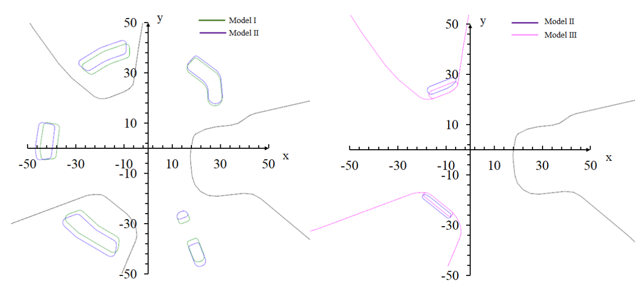

Figure 2: On the left differences between the models I and II and on the right the ones relative to the model II and III of the CS central region.

For each of the models of the CS central region, the injection efficiency has been evaluated for four values of the dee voltage: 86 kV (the nominal value for acceleration of the chosen reference ion), 90 kV, 95 kV and 100 kV.

Table 1 reports the values of the injection efficiency in percentage for the above-mentioned cases. It supposes particle RF-phases on a interval of 30° at the starting tracking position corresponding to the axial bore entrance.

Simulations show that, when the nominal dee voltage is applied to the existing electrodes of the central region, the ion losses are especially radial and concentrated on the pillars. The use of dee voltages higher than the nominal one has the effect to help a high number of ions to move away from the pillars reducing the hits, as shown in Fig. 3. When the model III and 100 kV dee voltage are considered, the increase of injection efficiency is really relevant and it is

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Table 1: 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 %

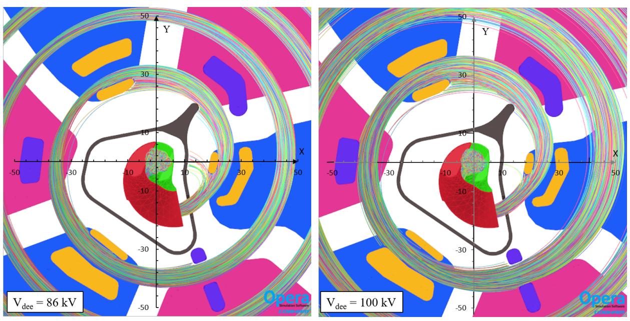

Figure 3: Beam particles in the existing CS central region, when the voltage applied to the dees is equal to 86 kV (on the left) and 100 kV (on the right).

almost 78% with respect to the present situation. Supposing to inject a DC beam into the CS and considering 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 of 15%.

The current maximum voltage applicable to the dees is about 82 kV. Although the simulations on the injection efficiency have been carried out for dee voltages higher than this value, the obtained results are valid for all the ion species accelerated at low and medium energies because they require a dee voltage less than or equal to this value, according to Eq. (1).

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

The expected beam energy resolution at the extraction for all the ion beams to be extracted by stripping is about 0.3 - 0.4%, according to the analytical formula in Ref. [12]. Simulations have confirmed this value, that is higher than the NUMEN requirement of about a factor 4 [11].

Simulations of beam tracking starting at 120 mm from the CS centre up to the extraction system have been carried out for the evaluation of the beam energy spread at the extraction. Figure 4 shows the energy distribution at the extraction of a beam of 5000 particles with 10° RF phase width at the starting position. In order to reduce the energy spread of the extracted beams, an energy selection process is foreseen outside the CS. FRAISE, the new FRAgment In-flight SEparator at INFN-LNS, will be also used as a beam energy selector [13]. This implies that only a portion of the accelerated beams could be transported to the NUMEN experimental hall. It is clear that the improvement of the injection efficiency, described in the previous section, can be a solution to avoid a relevant reduction of the total efficiency due to the beam energy selection process after the beam extraction.

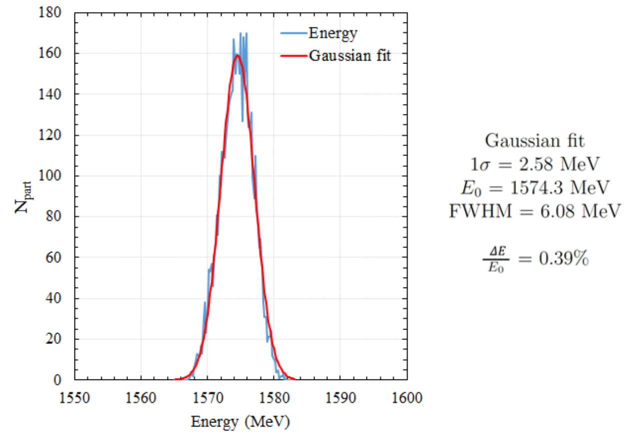

Figure 4: Beam energy distribution at the extraction of a sample of 5000 particles accelerated from 120 mm from the CS centre up to the extraction system.

Alternative solutions to the improvement of the beam energy resolution are under investigation at INFN-LNS. A solution could be the use of a wedged degrader, placed in the FRAISE beam line. It would allow to reduce the beam energy spread without significant loss of beam intensity. Other possible solutions could be the use of phase-slits installed within the CS, just outside the central region, for reducing the RF-phase width of the beam and the use of the existing harmonic coils installed at outer radii in the cyclotron to produce a first harmonic precession able to increase the separation between last turns at the stripper foil position. However, simulations have demonstrated that the energy gain per turn contributes only partially to the energy spread at the extraction and the main contribution to it is the large emittance injected in the central region of the LNS cyclotron. Also a good quality of the accelerated beam is necessary because an initial beam offset in the central region implies a further increase of the beam energy spread at the extraction. More details about all these aspects can be found in Ref. [11].

CONCLUSION

The project of the CS and the INFN-LNS facility upgrade (POTLNS PON Ricerca e innovazione 2014-2020) is funded by MIUR (Italian Ministry of Instruction, University and Research). The present study has allowed to establish a roadmap to be followed for the improvement of the CS performance.

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