STUDY OF THE NEW RETURN YOKE FOR THE UPGRADED SUPERCONDUCTING CYCLOTRON OF INFN-LNS

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Abstract

The LNS Superconducting Cyclotron (CS) has been working for 20 years making a wide range of ions and energies available. Many experiments are performed each year. In the near future a major upgrade is planned. This will allow to overcome the major limitation of the CS, which is the beam power delivered to the users, that at present does not exceed 100 W. In the new version of the CS, the extracted beam power will be increased up to a factor 100. This improvement will be reached extracting by stripping a specific set of light ions and energies extracted by stripping. Nevertheless, the extraction through the two electrostatic deflectors, providing a beam power limited to 100 W, will be also maintained to fulfil the users' requests. The new design could strongly affect the beam dynamics. The iron yoke penetrations do not respect the three folds symmetry of our cyclotron and have a complex shape, due to the double extraction methods and all services' entrances. This inhomogeneity produces unwanted field harmonics, which have to be reduced as much as possible to avoid beam precession or second order effects. Here the study accomplished to minimize the perturbation of the non-three fold field symmetry using the current sheet approximation (CSA) is presented, along with the state-of-art configuration of the updated cyclotron.

INTRODUCTION

The INFN-LNS Superconducting Cyclotron ("Ciclotrone Superconduttore", CS) is an isochronous three-sector compact accelerator equipped with two pairs of superconducting coils and a RF system operating in the range of 15 to 48 MHz These features allow the acceleration of almost all ions up to uranium in a wide range of energies, between 10 to 80 AMeV.

The CS was designed for nuclear experiments with low intensity beams. The beam extraction is performed with through two electrostatic deflectors, which limits the maximum power delivered to the users. Indeed, due to the compactness, the last accelerated orbit is not completely separated from the previous one.

Then, the maximum extraction efficiency is limited to 60%. The non-extracted beam hits the septum on the first electrostatic deflector, causing issues due to thermal deformation of the septum, extra outgassing. The increased dark current on the deflector and the consequent discharges can cause mechanical damages. The present intensity is not sufficient for production of radioactive nuclei or for investigation of rare nuclear reaction, while it is not at all a limit for the exploitation of usual nuclear experiments.

The goal of this project is to add a new extraction system dedicated to a selected set of ions and energies, keeping the extraction the other ions and energies allowed by the operating diagram through the present extraction system. The selected ions will be extracted by stripping without the limitation described above and the beam power could reach 10 kW in some cases. See Table 1.

At first, the request of high beam power came from the experiment NUMEN [1] and from scientists interested to use the FRIBs facility at LNS [2], which is used to produce radioactive ions with the in-flight method. The selected ions for the extraction by stripping are ^{12}C, ^{18}O, ^{20}Ne at energies between 15 and 70 AMeV, see Table 1.

This extraction method is based on the sudden change of charge state and the consequently drop of the magnetic rigidity after the stripper foil crossing.

Table 1: List of the Ions to be Extracted by Stripping and Expected Power Extracted

Ion	Energy	I_{source}	$I_{accelerated}$	$I_{extracted}$	$P_{extracted}$
	AMeV	eμA	eμA	pps	Watt
$^{12}C^{4+}$	18	400	60 (4+)	$9.4 \cdot 10^{13}$	3240
$^{12}C^{5+}$	30	200	30 (4+)	$4.7 \cdot 10^{13}$	2700
$^{12}C^{4+}$	45	400	60 (4+)	$9.4 \cdot 10^{13}$	8100
$^{12}C^{4+}$	60	400	60 (4+)	$9.4 \cdot 10^{13}$	10800
$^{18}O^{6+}$	20	400	60 (6+)	$6.2 \cdot 10^{13}$	3600
$^{18}O^{6+}$	29	400	60 (6+)	$6.2 \cdot 10^{13}$	5220
$^{18}O^{6+}$	45	400	60 (6+)	$6.2 \cdot 10^{13}$	8100
$^{18}O^{6+}$	60	400	60 (6+)	$6.2 \cdot 10^{13}$	10800
$^{18}O^{7+}$	70	200	30 (7+)	$2.7 \cdot 10^{13}$	5400
$^{20}Ne^{4+}$	15	600	90 (4+)	$1.4 \cdot 10^{14}$	6690
$^{20}Ne^{7+}$	28	400	60 (7+)	$5.3 \cdot 10^{13}$	4800
$^{20}Ne^{7+}$	60	400	60 (7+)	$5.3 \cdot 10^{13}$	10280

According to data in ref [3], for the selected ions at energies bigger than 15 AMeV, the percentage of the particles with q=Z (where q and Z are charge state and atomic number of the ion respectively) after the stripping foils is > 99 %. That means that low losses are expected inside the machine if the extraction channel is carefully designed. Table 1 summarizes the expected results in term of beam power increase for the cases studied. In Table 1, the values of beam current delivered by the ion source and accelerated by the cyclotron are conservative.

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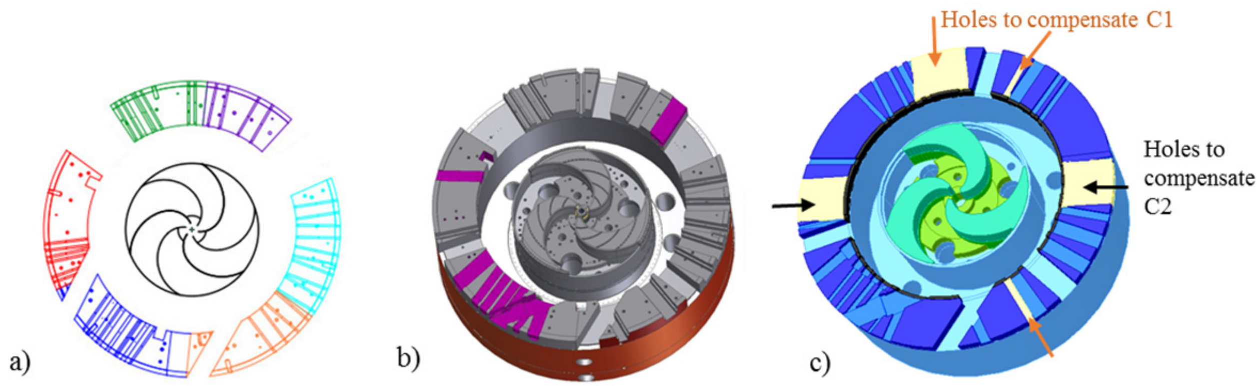

Figure 1: Views of the bottom half of the CS. The first ones, a) and b), are top views of the CS as it is today. In a), the existing extraction channel is in the orange sector. In b) the modifications needed to add the new extraction channel, which is almost 30 degrees away from the old one, are shown in magenta. Finally, c) shows the results of the optimization's process, see text. The arrows highlight the areas where the iron has been removed.

Indeed, the limit of 10 kW is posed mainly to maintain the beam losses inside the cyclotron below 100-200 W and to mitigate the problem of machine activation.

For each ion and energy of interest, the position of the stripper foil has been found, as well as the positions of the two magnetic channels needed to provide radial focusing and to slightly steer the beam after the pole radius. See Ref [4-6] for more details on the design of the extraction channels. Note that, since the stripping extraction is by definition a multi-turn extraction, an energy spread is introduced. The computations have been done considering an energy spread of +/-0.3% [7].

As showed in Ref [4-6] the new extraction system implies major mechanical modifications to the cyclotron.

Firstly, a new cryostat with new superconducting coils [8] is mandatory. The new extraction channel has a larger vertical gap than the existing one. Massachusetts Institute of Technology [8] has done a feasibility study of the cryostat and a call for tenders is at the moment open to select the supplier for the new magnet. Secondly, additional penetrations are necessary to host new magnetic channels and new compensation bars.

MECHANICAL MODIFICATIONS TO THE IRON YOKE

Since the CS has been designed and constructed more than 30 years ago, the engineering drawings of the machine are only on paper. 3D models were created reconstructing the cyclotron state-of-art.

The introduction of the new extraction channel implies the rotation of the penetrations for the horizontal tie-rods and the addition of new penetrations for the new magnetic channels, the new compensation bars [4-6] and the new stripper foil housing. Moreover, other few changes to the penetrations have been optimized. A detailed explanation of all the modifications done by the LNS engineering team working at this project is reported in [9].

The yoke modifications are done to a central ring of the yoke that has a height of 25 cm, ±12.5 cm around the median plane, which is the particle acceleration plane.

The drawing of Figure 1 a) shows the state-of-art of this ring. The existing extraction channel is in the orange sector. In the dark blue sector, there are all the penetrations for the first electrostatic deflector and the penetration for the radial injection, which today is not anymore used. The poles and the inner wall of the cryostat are designed as well.

The drawing in Figure 1 b) shows in magenta all the modifications needed in the yoke according to the engineering team to add the new extraction line and the necessary subsystems.

However, drilling new non-symmetric penetrations add new field harmonics components, which have to be decreased at least at the level of the existing, working, configuration, Figure 1 a). This step is mandatory since field harmonics components are responsible for a precession of the beam and for unwanted second order effects on the beam.

Therefore, the iron in the central ring of the yoke has to be redistributed, where possible, to guarantee good beam dynamics performance, and, at the same time, have stresses under control.

During the CS construction, the first and second harmonic field components optimization was done keeping off the iron at the right of the violet sector and at the left of the green sector of Figure 1 a). Today, to achieve a final optimized design, 3D simulations are useful. Note that, in the dark blue sector, there is also the penetration for the radial injection, which today is not anymore used since the beams are axially injected.

Then, as a starting point of the optimization process to get the final configuration of the upgraded CS, it is possible to add iron closing the old penetration for the radial injection and closing the holes at the right of the violet sector and at the left of the green sector (keeping only the needed penetrations).

USE OF CSA TO DECREASE THE UNWANTED HARMONICS

The method used to define the iron profile in the central ring of the return yoke is the Current Sheet Approximation (*CSA*), [10], which gives the possibility to study the iron shape using a coil of negligible thickness that occupies the same volume of the iron. This method has been used also to define the profile of the magnetic channels needed in the new extraction channels. The CSA is valid in the case of full-saturated iron and, as a first approximation; it is possible to consider it reliable for all values of the current flowing in the superconducting coils. Figure 2 shows the central ring after the modifications needed to add the new extraction channel. In blue, there is the outer wall of the cryostat, which is not a part of the return yoke, but it is iron-made and has not a three-fold symmetry. Then, it has an effect of the field harmonics components and it has been taken into account in these magnetostatic computations.

As a starting point, the first and second harmonic of the magnetic field has been evaluated for the configuration with the iron ring as in Figure 2, including only the needed penetrations for the CS and closing the old unused ones as explained above.

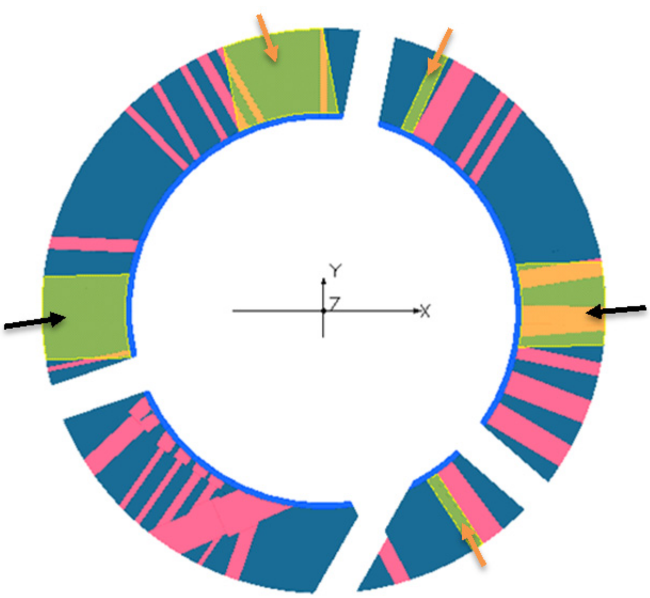

Figure 2: Central iron ring of the yoke of the CS. In navy, there is the iron with all the penetrations needed to guarantee both extraction methods. In translucent yellow, there are the profiles of the new penetrations to add to the central iron ring of the yoke to cancel the first (orange arrows) and second (black arrows) field harmonic components.

Using the FEM code OPERA (Cobham), it is possible to design a parametrized coil combining arc and straight conductors. In this way, it is possible to identify the size and position of iron to be removed to have the field harmonics compensated.

The yellow volumes in Figure 2 show the profiles of the holes needed for the corrections using the CSA. The two small iron penetrations and the big one centred at about 100 degrees are needed to cancel the first harmonic component, whose peak is in correspondence of the new extraction channel. The other two pieces to remove are also necessary to compensate the second harmonic component.

A 3D view of the iron yoke after the optimization process is reported in Figure 1 c).

The first and second harmonic of the magnetic field vs. radius for the initial and of the final configuration achieved by the optimization process, are shown in Figure 3. Along the entire acceleration path the first harmonic stays below 5 Gauss and the second does not reach 1 Gauss. This result is better than the present performance obtained with configuration in Figure 1 a).

Although the volume of the central iron ring is similar to the present case and the harmonic compensation is very satisfactory, other solutions are under investigation. The idea is to replace the big hole centred at 100 degrees, with other smaller ones opportunely placed around the ring.

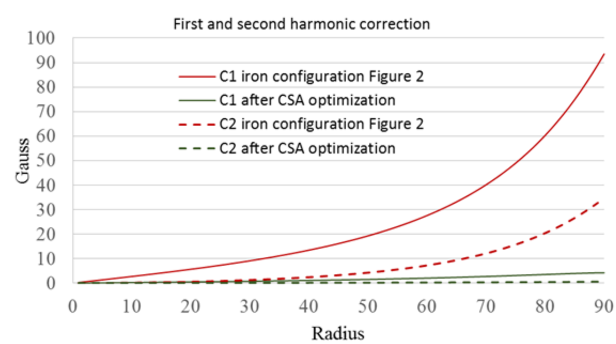

Figure 3: First and second harmonic before and after the optimization process using the CSA method.

This is done in the perspective to distribute as much as possible the compression stresses due to the lack of iron. For the same reason, to compensate the second harmonic component, simulations will help to understand if smaller pieces of iron closer to the acceleration path can avoid the drilling of the big holes in the iron. It worth mentioning, these results are important not only for the high intensity beams, but also for all the accelerated ions included the ones extracted through electrostatic deflectors.

CONCLUSIONS

The goodness of the optimization process to cancel the first and second field harmonic components through the use of parametrized coils and the CSA approximation has been proven. Further investigations are mandatory to try to reduce the volume of the iron to take off the central iron ring of the yoke of the CS. Moreover, the same calculations will be done for more values of current flowing in the superconducting coils.

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