HIGH INTENSITY COMPACT CYCLOTRON FOR ISODAR EXPERIMENT

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Abstract

The scientific international community in recent years has focused an increasing interest on the neutrino properties. The aim of the IsoDAR (Isotope Decay At Rest) experiment is to look for the existence of sterile neutrinos. To perform this experiment, a cyclotron able to deliver proton beam current up to 10 mA is proposed. This cyclotron is very similar to the DAEδALUS injector cyclotron (DIC), but, due to the required higher average beam current and the experimental underground site, it poses a new ambitious goal in terms of technical solutions.

INTRODUCTION

The existence of the neutrino states beyond the "standard" 3ν paradigm was predicted to explain some anomalies that were experimentally observed. The IsoDAR experiment's aim is the observation of the "so-called" sterile neutrinos by studying the oscillation of electron antineutrinos [1, 2, 3].

In the IsoDAR experiment, the electron antineutrinos are produced by ^{8}Li decay. A high-current proton beam strikes a beryllium target in order to produce a high flux of neutrons. Moreover, the interaction between the neutrons and the ultra-pure ^{7}Li sleeve surrounding the target produce a lot of ^{8}Li. The target is ~15 meters from a kiloton-scale detector and the produced antineutrinos would oscillate into and out of the sterile state within the volume of the detector. It will be possible to observe this sinusoidal event rate, which is a function of the distance from the target.

The whole experimental setup has to be installed underground, inside KamLAND, so a compact cyclotron able to accelerate a 5 mA beam of H_2^+ molecules up to the final energy of 60 MeV/amu is an optimal solution.

The design of this accelerator arises from the DAEδALUS injector cyclotron [4], but it takes into account solutions for transport and assembly of the machine through the constricted access apertures of the Kamioka mine. Moreover, the required beam intensity is about six times higher than the maximum intensity delivered by the 30 MeV compact cyclotrons used in the medical isotope production centers. In particular, during the beam injection, the space-charge effects are a crucial issue. To mitigate this effect, we propose to inject an H_2^+ beam at an energy of 70 keV, which has a generalized perveance value comparable to the value of existing high-intensity proton commercial cyclotron. The test stand, installed by a collaboration between MIT, INFN-LNS, and Best Cyclotron Systems Inc. (BCSI) [5] at the BCSI laboratory in Vancouver, will produce useful information in order to verify the feasibility of the beam injection and to check the critical issue.

THE ISODAR CYCLOTRON

The IsoDAR cyclotron has the same magnetic circuit as the DIC, while the acceleration system and the central region are different in order to improve the high-intensity beam production. It is a four-sector machine, with a pole radius of 220 cm and a large vertical gap of 10 cm; the hill angular width is 25.5° in the central region and increases up to 36.5° in the extraction region. A couple of coils at room temperature complete the system. Each coil has an inner radius of 223 cm and a size of 200 x 250 mm^2; the current density is 3.167 A/mm^2. The average magnetic field varies between 1.05 ÷ 1.2 Tesla, while the minimum and maximum values are 0.28 Tesla in the valley and 2.11 Tesla in the hill. The outer part of the pole has a special design to allow the ν_r=1 resonance crossing at the end of the acceleration. Introducing a small off-center in the beam orbit, the first harmonic precession produces a growing of the inter-turns orbit separation at the extraction region. A large inter-turn separation is mandatory to achieve an extraction efficiency of 100% using electrostatic deflectors.

Four RF double-gap cavities are placed in the four magnet valleys. The design of the λ/2 cavities allows production of an accelerating voltage that rises from 70 kV at the inner radii to 250 kV at the outer radius. A main difference of the IsoDAR cyclotron with respect to the DIC is the harmonic operation mode, harmonic 4th and 6th, respectively. Using a lower harmonic mode will allow improvements to the beam capture in the injection region and achievement of the required high-intensity transmission. Moreover, the thermal power losses of the cavities will be a little lower. Another huge difference vs. the DIC is the duty cycle: the IsoDAR cyclotron will work in continuous-wave mode, while the duty cycle of the DIC is only 20%. The higher beam power poses a serious constraint on the amount of the beam losses.

INJECTION SYSTEM

The injection system design is a crucial component to achieve the highest beam current. The H_2^+ molecule beam has to be injected at the highest energy possible, but at the same time we like to drive the ion source without the use of complex high-voltage platform.

The energy of 35 keV/amu was selected because an ion source like VIS or other similar source can work with an extraction voltage of 70 kV [6]. As in commercial cyclotrons, an axial injection system based on a Spiral Inflector (SI) will be used to bend the beam from the axial direction to the median plane.

The main characteristic of the IsoDAR SI is its size: in fact, the gap between the electrodes is set equal to 15 mm, instead of the value of 6÷10 mm used for the SI of compact cyclotrons for medical applications or nuclear physics research. This large value takes into account the high beam current and the large beam size that the device has to transport. Due to the large distance between the electrodes, the SI occupies a volume in which the magnetic field components' variation is not negligible, as it is supposed in the analytical treatment of the SI. This effect has to be carefully taken into account in order to shape correctly the SI electrodes and to avoid the introduction of a high-energy spread during the beam transport through the device.

The whole system is designed by using the back/forward integration method. The shape and the position of the tips in the central region are modified in order to guarantee a suitable energy gain and an optimal vertical focusing during the beam transport from the SI to the accelerated equilibrium orbit.

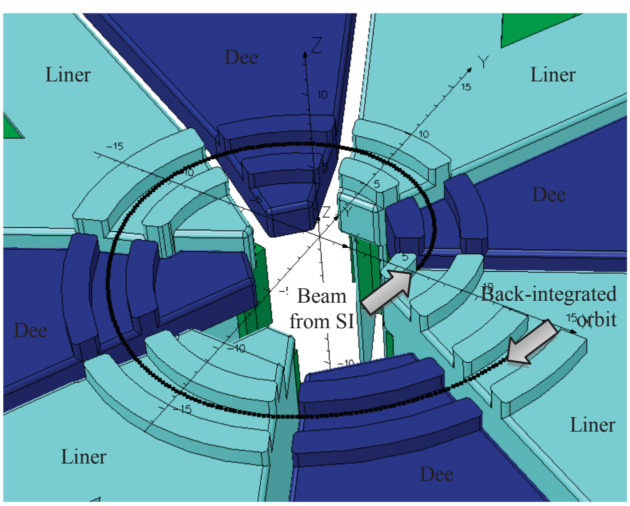

Figure 1: Schematic view of the IsoDAR central region. The back/forward path integration is used to placing the tips on dees and liners.

In the preliminary model, the vertical gap between the tips of the dee in the central region is set equal to 2 cm, but it could be necessary to increase this value. Despite the good vertical focusing achievable by using the 4th harmonics and four RF cavities, the central region has to transport high-current beam, so a conservative solution with larger vertical gap is preferable in order to take into account the space-charge effect.

The simulation results concerning the test stand central region realized at BCSI which uses two RF cavities in the 6th harmonic indicate a beam transmission efficiency around 50% of particles injected with a phase of ±10° RF around the central particle. Considering the harmonic mode variation and the use of four RF cavities, it is likely that the IsoDAR injection system will be able to transport 100% of a beam with a normalized emittance around 3 π mm.mrad. In Fig. 1 a view of the preliminary design of the central region is shown.

As concerns the SI, several models are under study. The voltage difference between the electrodes is in the range 20 - 22 kV, and large tilt angle is required to achieve the matching between the SI particle path and the median plane path.

An alternative to the standard SI, in order to reduce the beam properties worsening due to the electrostatic field effects, is to use a dipole magnetic inflector made by a permanent magnet. In fact, a permanent magnet system could be employed in the center of the machine to produce a magnetic field able to bend the beam onto the median plane. The direction of the magnetic field produced by the permanent magnets has to be perpendicular to the main magnetic field of the cyclotron, as in the case of permanent magnets used in some ion source systems. We are investigating this option.

PRELIMINARY SOLUTIONS FOR INSTALLATION IN MINE

The IsoDAR cyclotron has to be installed underground, in the Kamioka mine. The experimental site has a small access with horizontal and vertical aperture size of about 2.4 m and 3.2 m, respectively. So both transport and assembly pose critical constraints to the cyclotron design, because all the machine components must be limited in size and weight, but the machine features like the optimum vacuum of 10^{-6} Pa have to be preserved. The IsoDAR cyclotron is not the first case of cyclotron "cutting-in-piece." The most famous example is the TRIUMF 500 MeV cyclotron. Here, tentative solutions for the coils, for the magnet circuit, and for the vacuum chamber are presented.

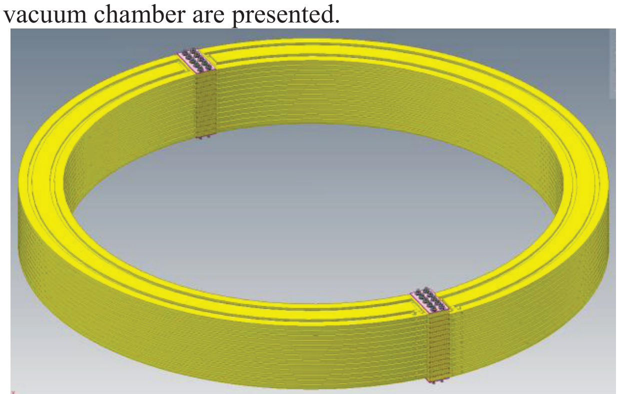

Figure 2: First solution for the coil assembling consists of 13 aluminum plates parallel to the median plane.

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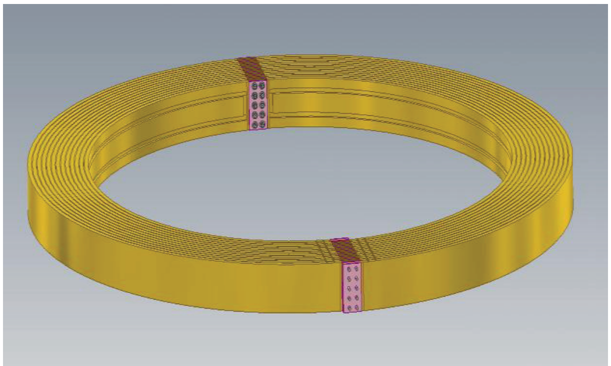

Figure 3: Second solution for the coil assembling. The coil is made up of concentric layers.

Two options were found out for the coils. In the first case, as shown in Fig. 2, the coil is divided into 13 layers parallel to the median plane with an angular width of 180°. This solution guarantees a good sealing of the cooling network, and all the pieces are equals, but the machining of the aluminium coil plate is complicated and expensive. The second solution consists of concentric layers with an angular width of 180° (see Fig. 3). The machining of the coil plate is easier and cheaper than the former case, but the welding and the cooling water system might be challenging. As concerns the iron, each half cyclotron is separated into four independent poles. Each pole has a weight of 13 tons and a height of 0.8 m, and has to be placed over the yoke elements. Also, the yoke is cut into four symmetric pieces with an angular width of 90° and a weight of 45 tons each yoke part has a radius of 3.2 m and a height of 1.2 m. These are the biggest components of the cyclotron. Both the wall and the liner of the vacuum chamber are divided into two parts that have to be welded. This is a critical part of the machine assembling, because a vacuum lower than $5 \cdot 10^{-6}$ Pa has to be guaranteed to minimize the beam power losses along the acceleration path of the high-intensity beam. These beam losses are due to interaction of the particle beam with the molecules of the residual gas.

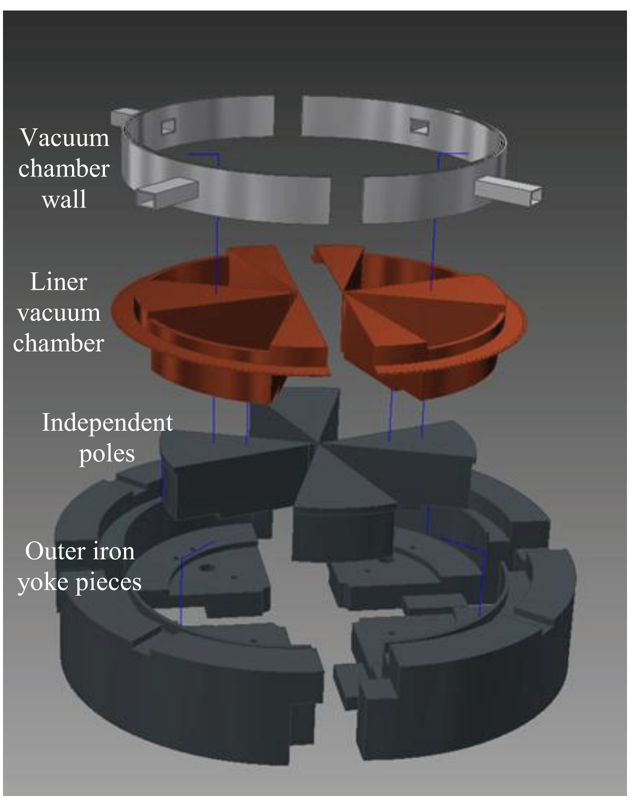

Figure 4: Magnet assembling. The vacuum chamber wall and the liner vacuum chamber are both divided into two parts.

NEXT STEPS

The IsoDAR cyclotron design is still in progress. The results of the test stand at BCSI will produce useful data to check the injection feasibility and to verify the design procedure. Moreover, the possibility of using deuteron with maximum energy of 40 MeV/amu instead of H_2^+ molecules with 60 MeV/amu is under evaluation. In this perspective, the design of the cyclotron will be simplified just due to the significant reduction of the pole radius, which will reduce to 180 cm, and of its weight. The transport of the cyclotron pieces to inside the Kamioka cavern will be simplified and cost a little reduced. Unfortunately, the deuteron beam poses a serious problem due to the activation of the cavern rock. The final decision will be taken in the following months.

Anyway, from point of view of the cyclotron no significant difficulties are involved because both cases concern the acceleration of particles with charge-mass ratio equal to 0.5. So, apart from a small variation in the magnetic field configuration due to a small change in the isochronous field, the conceptual design of the machine is the same.

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