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High-intensity cyclotron for the IsoDAR experiment

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Summary. — The IsoDAR experiment is the MIT proposal to investigate about several neutrino properties, in order to explain some anomalies experimentally observed. It requires 10 mA of proton beam at the energy of 60 MeV to produce a high-intensity electron antineutrino flux from the production and the decay of ^{8}Li: it is an ambitious goal for the accelerator design, due also to the fact that the machine has to be placed near a neutrino detector, like KAMLAND or WATCHMAN, located in underground sites. A compact cyclotron able to accelerate H_2^+ molecule beam up to energy of 60 MeV/amu is under study. The critical issues of this machine concern the beam injection due to the effects of space charge, the efficiency of the beam extraction and the technical solutions needed to the machine assembly. Here, the innovative solutions and the preliminary results achieved by the IsoDAR team are discussed.

PACS `29.20` – Cyclotrons.
PACS `29.27` – Beam injection and extraction.
PACS `07.05` – Computer modeling and simulation.

1. – The IsoDAR experiment

IsoDAR (Isotope Decay At Rest) project poses the attention to the problem of the so-called sterile neutrino: the main goal, in fact, concerns the search of the existence of one or more states of sterile neutrinos by means of the observation of the electron-antineutrino disappearance [1, 2]. Another aim of the experiment is the search for non-standard interactions through antineutrino-electron scattering [3].

The IsoDAR experiment started as an intermediate phase of the DAEδALUS project (Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science) [4], but it has collected the interest of both the scientific community, interested in understanding if sterile neutrinos exist or not, and commercial companies, interested in the original items and the technologic innovations that it requires.

The experimental set-up is described in fig. 1. A 10 mA proton beam at the energy of 60 MeV strikes a Be target, which is surrounded by a volume of 99.99% pure ^{7}Li. The interaction of the proton beam with the Be target produces a high intense flux of

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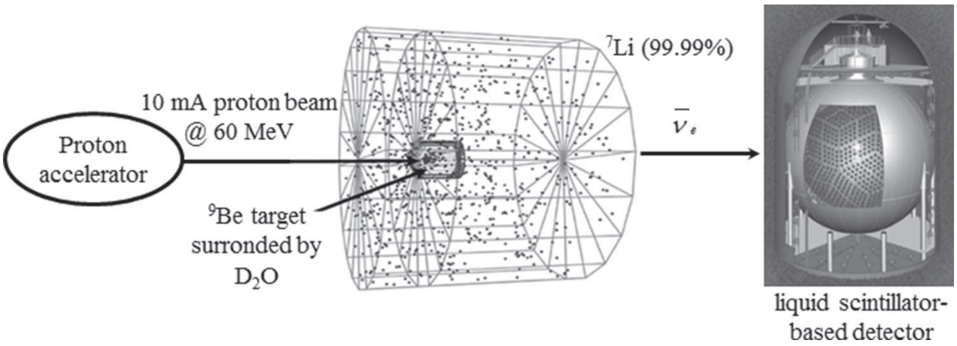

Fig. 1. – Schematic view (not in scale) of the IsoDAR experiment. A Be/Li target was designed in order to develop an electron anti neutrino flux by ^{8}Li decay. Note that the electron antineutrino source has to be placed few meters close to a liquid-scintillator–based detector to achieve a good distance/energy resolution.

neutrons, which, into ~ 50 kg pure ^{7}Li blanket, allows the ^{8}Li production. The ^{8}Li beta-decay produces electron-antineutrinos with a well-known energy spectrum, those have to be detected by a liquid scintillator detector such as KamLAND or WATCHMAN. The electron-antineutrino source has to be placed at a well-evaluated distance from the detector, because the sensibility of the experiment depends both on high event statistic and the good distance-energy resolution. For example, the optimal distance between the IsoDAR source and the KamLAND detector center is 16.5 m.

So, due to the experimental constrains, the main requirements for the proton accelerator are:

- the capability to produce a new record in intensity at the energy of 60 MeV/amu, that is a beam power of 600 kW;
- a compact design compatible to the installation, the commissioning and the maintenance in the underground site.

2. – The H_2^+ cyclotron

A compact cyclotron able to accelerate 5 mA of H_2^+ molecules up to 60 MeV/amu is the proposed solution in order to achieve the 10 mA current of protons. This choice allows to reduce the space charge effects, one of the main issues of high intensity beam at low energy. In fact, the space charge effects cause the beam emittance increase and then reduce the extraction efficiency. The beam perveance is a measure of the strength of the space charge effects: the perveance of 5 mA of H_2^+ beam at the energy of 35 keV/amu has the same value of the perveance of 2 mA of 30 keV protons, that is a current value achieved by commercial cyclotron produced by IBA (Ion Beam Applications S.A.) and Sumitomo HM-30 [5].

The IsoDAR cyclotron is very similar to the DAEδALUS injector cyclotron: the high-intensity beam production is the common goal, but while for the DAEδALUS experiment the injector duty cycle is about 20%, the IsoDAR machine has to work with a duty cycle of 100%. The final configuration of the DAEδALUS injector cyclotron has to guarantee a peak current of 5 mA of H_2^+, an average power of 120 kW and a peak power of 600 kW: a beam losses limit of 200 W is mandatory to guarantee the maintenance of the machine.

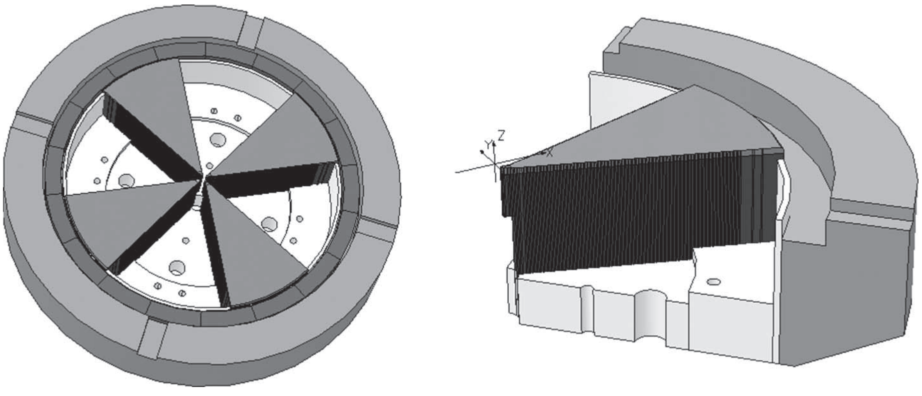

Fig. 2. – On the left, view of the IsoDAR cyclotron, able to accelerate the H_2^+ molecule beam up to 60 MeV/amu. It is a four-sector compact machine. On the right, view of one sector: the pole radius is 220 cm and the diameter is 624 cm. The coil inner radius is 223 cm.

A four-sector machine design is proposed (fig. 2) [6, 7] and the main parameters are reported in table I. It is a compact machine, with a pole radius of 220 cm and an outer diameter of 624 cm. A large gap of 10 cm is adopted, in order to have enough space for the beam transmission. Two room temperature coils are located 10 cm far from the machine median plane; the coil inner radius is 223 cm and the current density is 3.167 A/mm^2.

This configuration produces an average magnetic field in the range 1.05–1.2 Tesla, with a maximum value of 2.11 Tesla in the hill. The pole profile has been optimized in order to achieve the $\nu_r = 1$ resonance crossing at the end of the acceleration: in fact, the first harmonic precession is used to produce the growth of the inter-turn orbit separation in the extraction region and to reach an high extraction efficiency by using an electrostatic deflector, as it will be discussed in the next section.

Table I. – *IsoDAR cyclotron parameters.*

E_{inj}	35 keV	E_{max}	61.7 Mev
B_0	1.075 Tesla	$\langle B \rangle$ at R_{ext}	1.166 Tesla
$\langle R_{inj} \rangle$	51.58 mm	$\langle R_{ext} \rangle$	2000 mm
n. sectors	4	Hill width	25.5–36.5 deg
Valley gap	1800 mm	Hill gap	100 mm
Diameter	6240 mm	Full height	2700 mm
n. cavities	4	Cavity type	$\lambda/2$ double gap
RF harmonic	4th	RF frequency	32.8 MHz
Acc. voltage	70–240 kV	Power cavity	< 160 kW
Coil size	200×250 mm^2	Current density	3.17 A/mm^2

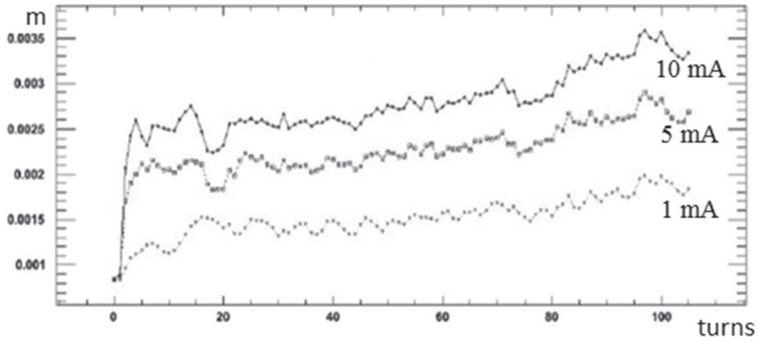

Fig. 3. – Vertical rms beam size of the accelerated beam as turn number function. The beam acceleration has been studied from the energy of 1 MeV/amu up to the extraction energy of 61.7 MeV/amu. Despite the space charge effects, the vertical rms beam size is few millimeters through the whole particle acceleration process.

The accelerating system includes four RF double gap cavities placed in the four magnet valleys and able to produce an accelerating voltage increasing from the value of 70 kV at the inner radii up to 240 kV at outer radii. The working frequency of the RF cavities is 32.8 MHz and the harmonic operation mode is 4^{th}. The harmonic mode 4^{th} for IsoDAR cyclotron is a lower value than the harmonic mode of the former DAEδALUS injector design, that was 6^{th}, and allows to improve the beam capture in the injection region.

Due to the space charge effects, the beam injection is a critical issue of the machine design: the axial injection by using spiral inflector is the usual method adopted in many compact machines, but, in the case of IsoDAR cyclotron, the feasibility was studied carefully and some experimental tests were performed.

3. – Beam dynamics results

The effectiveness of the proposed magnetic configuration has been tested by using the OPAL code. OPAL (Object Oriented Particle Accelerator Library) is able to simulate the space charge effects on large-scale particles [8]. The H_2^+ beam acceleration starting at the energy of 1 MeV has been simulated for current intensity values of 1 mA, 5 mA and 10 mA, and the simulations show that the magnetic configuration allows to transport the beam up to the extraction region with an acceptable beam size. In fig. 3, the vertical rms beam size as turn number function is reported: also in the case of 10 mA current, the beam spot size is few millimeters.

Another satisfactory goal is the proof of the efficacy of the first harmonic precession due to the $\nu_r = 1$ resonance crossing, close to the extraction region. The OPAL simulation (fig. 4) shows the radial separation among the last accelerated orbits: the separation is large enough for placing the electrostatic deflector septum and achieve an extraction efficiency of 99.9%. It easy to calculate that the power losses on the septum are less than 120 W, a value lower than the fixed constraint of 200 W.

4. – Beam injection

The beam injection in compact cyclotrons is realized by using an electrostatic device called spiral inflector. The spiral inflector consists of a couple of electrodes fed with

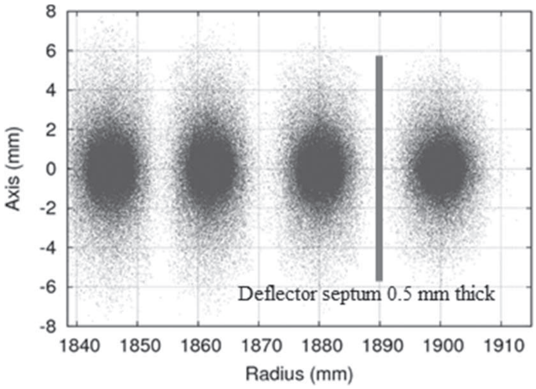

Fig. 4. – Inter-turn separation at the beam extraction. The effect of the first-harmonic precession, due to the $\nu_r = 1$ resonance crossing, allows to increase the orbit separation and to reduce the beam losses on the electrostatic deflector septum.

opposite voltage; the resultant electric field bends the particle beam from the axial line to the cyclotron median plane. The applied voltage at each electrode is usually few kV and the transmission efficiency is excellent.

The spiral inflector proposed for the IsoDAR cyclotron is very unusual, because of the large sizes compared to the usual spiral inflectors designed for other machines: for example, the electrode gap is 15 mm, instead of 5–8 mm gap adopted in compact cyclotrons. This large gap needs to feed the electrodes with a voltage of ± 11 kV.

Since no experimental proof of the high current beam injection feasibility exists, the IsoDAR collaboration moves to different plans of action, in order to achieve both data and experience to design accurately the cyclotron injection system.

The CAPEN (Ciclotroni Alta Potenza per Esperimenti sui Neutrini) experiment, approved by CSN 5∼INFN/LNS, is an injection feasibility test at the Best Cyclotron Systems Inc. (BCSI) site in Vancouver in collaboration with MIT. The aim was to test the capacity of the INFN Versatile Ion Source in the H_2^+ beam production, the properties of the beam transport line and the injection into a small cyclotron model designed by BCSI team [9-12]. The main components of the experimental set-up are shown in fig. 5.

INFN/LNS staff and BCSI staff designed the spiral inflector for the cyclotron model with the same properties required by the IsoDAR spiral inflector, in order to verify the device and to check the design method. The spiral inflector has a 15 mm gap and it works with an applied voltage of 10 kV on each electrode in the 1 Tesla magnetic field of the test stand magnet. The tests were completed in the summer 2014: 7.2 mA of H_2^+ were transmitted successfully through the spiral inflector, obtaining an efficiency higher than 85%. The resulting efficiency can be considered satisfactory: despite it was not possible to evaluate the space charge effects in the optimization of the spiral inflector, the adopted conservative choices have allowed the construction of an useful preliminary model. The electrodes were also tested with voltage up to ± 13.5 kV and this has not produced significant problems.

A new set of experimental tests could be realized by using a cyclotron designed by INFN/LNS team [13] to produce high current proton for radioisotope production. It will be built by BCSI and it will be used as prototype of a true IsoDAR cyclotron in order to verify both the beam injection and the acceleration of H_2^+ in the central region.

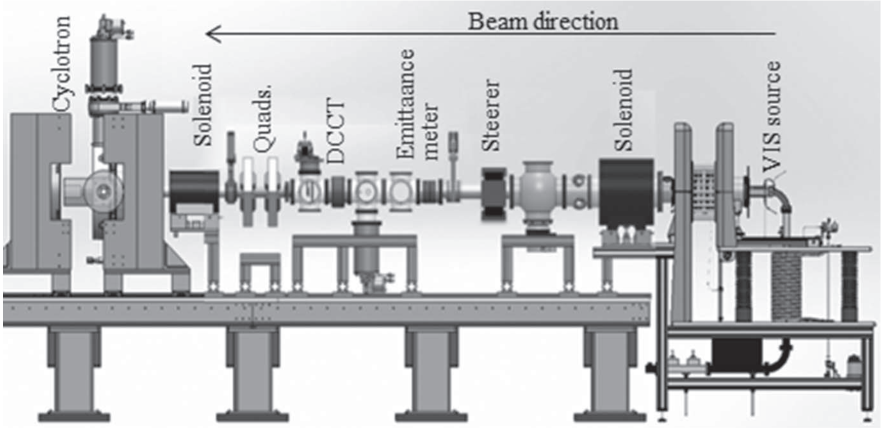

Fig. 5. – Beam line realized at Best Cyclotron Systems Inc. in Vancouver in collaboration with INFN/LNS and MIT for the injection feasibility tests.

An innovative alternative to the electrostatic spiral inflector was studied in the last year at INFN/LNS. It is a magnetic inflector, made of particular sets of permanent magnets and able to bend the particle beam from the injection line to the median plane of the cyclotron. In particular the device is based on the so called *Halbach ring*, an array of permanent magnets which are magnetized such as an high magnetic field arises in the inner volume of the ring.

The preliminary model of this device was designed in order to produce the same path of the spiral inflector designed for the test stand in Vancouver: H_2^+ molecules at the energy of 30 keV/amu in a magnetic field of 1 Tesla. Six sets of six permanent magnets were designed and placed in the centre of the magnet model and the size and the position of each element were optimized according to the results of the beam tracking through the whole model.

The first phase of the optimization work was based on the handling of numerical map representative of each Halbach ring, but, once a good configuration was found out, the whole model was verified by using Opera magnetic simulations.

To take into account also the cost of the device, the final configuration uses six modified Halbach rings all equal among them. Because the particle path has a spiral shape, the modified Halbach ring is an asymmetric device, with an inner aperture of 2 cm, as it is shown in fig. 6. The magnetic field at the centre of each modified Halbach ring is of 4.5 kgauss, while the outer field is too low to minimize the perturbation of the cyclotron properties. In fig. 7, an example of particle dynamics across the device is shown. The large inner gap is useful to achieve good transmission efficiency. This is a serious constrain to avoid beam halo striking permanent magnets and to guarantee the device reliability.

The study of the technical solutions needed for the assembling of the permanent magnets and for the tuning of the whole system is in progress.

5. – Technical issues

The IsoDAR experiment needs to stay near an underground big detector, so also the cyclotron has to be installed underground. Being the hall access to the cyclotron

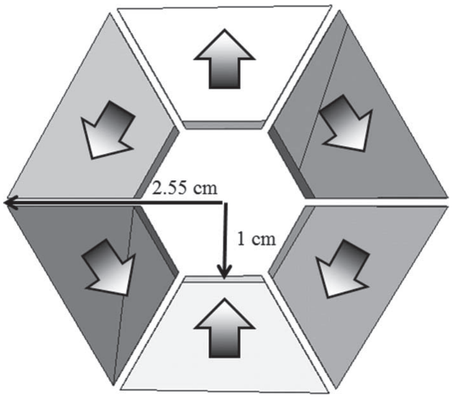

Fig. 6. – A schematic view of the modified Halbach ring. The arrows indicate the required magnetization direction of each permanent magnet, in order to have in the centre of the device a field directed along the y-axis.

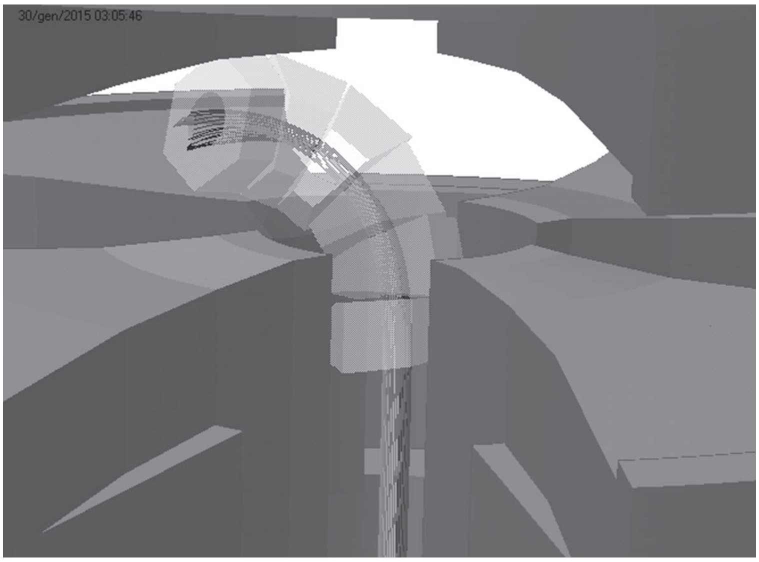

Fig. 7. – A view of the magnetic inflector model: the six modified Halbach rings bend the particles of 90 degrees, from the axial line to the machine median plane. The spiral shape of the device takes into account the bending effect due to the main cyclotron magnetic field.

installation limited to few meters, a particular attention has to be dedicated to the technical solutions for transportation and assembly of the different parts of the cyclotron: these constraints apply to all the elements, both in terms of size and weight.

The machine elements will be divided into several parts, as it is shown in fig. 8. The half-magnet will be separated into four poles (13 tons weight) and four yoke pieces (45 tons weight) with an angular width of 90 degrees. The vacuum chamber wall and the liner vacuum chamber will be divided into two parts. The welding of these elements will require a very careful work, in order to be able to reach a vacuum value lower than $5 \cdot 10^{-6}$ Pa: this constrain is required to minimize the beam power losses.

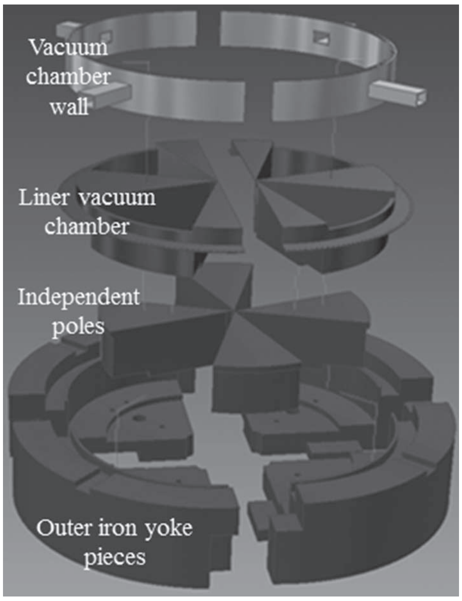

Fig. 8. – Magnet assembling to move the cyclotron into underground site.

Concerning the coil, the proposed solution is the separation into 13 alluminium plates parallel to the machine median plane. Each plate has an angular width of 180 degrees. It is a bit expensive solution, but it guarantees a good sealing of the cooling network.

6. – Final remarks

At this stage, the IsoDAR project makes the object of a dedicated R&D program with the involvement of numerous academic institutions listed hereafter:

- Amherst College,
- Cockcroft Institute for Accelerator Science and the University of Manchester,
- Columbia University,
- Duke University,
- Imperial College London,
- Lawrence Livermore National Laboratory,
- Laboratori Nazionali del Sud/INFN,
- Los Alamos National Laboratory,
- Massachusetts Institute of Technology,
- Michigan State University,
- New Mexico State University,

- Paul Scherrer Institut,
- RIKEN,
- Tohoku University,
- University of California, Berkeley,
- University of California, Irvine,
- University of California, Los Angeles,
- University of Hudderseld,
- University of Maryland,
- University of Tennessee,

together with commercial partners as AIMA (Accelerators for Industrial and Medical Applications), BCSI and IBA, which participate to the problem discussions and to R&D program.

The IsoDAR requirements need to find solutions to increase the research perspective of cyclotrons. In the recent years, the IsoDAR collaboration moved to study the feasibility of the facility by analyzing the critical points and searching the best solutions.

The most ambitious goal concerns the beam current value produced by the cyclotron: the beam injection test realized in collaboration with MIT, INFN-LNS and BCSI produced satisfactory results, it confirmed the design method and it gave useful data to design the final IsoDAR central region. Other validations came from the simulation work made by PSI colleagues: by using the OPAL code, tested on the data related to the PSI Injector ll cyclotron operations, the effectiveness of the magnetic configuration and, in particular, the possibility to achieved a satisfactory beam extraction by using electrostatic deflector were verified.

The IsoDAR cyclotron will be a powerful instrument to understand the neutrino physics problems and to explain the anomalies observed by short baseline experiments: the high sensitivity of the experiment could allow the definitive search for sterile neutrinos.

The high-intensity beams in the energy range expected for the IsoDAR experiment are required also for the production of therapeutic isotopes and tool set of diagnostic. The high-intensity beam facilities developed in the recent years often consider the use of the research accelerators for the production of conventional radionuclides and, also, of innovative radiopharmaceutical, as for example the new SPES (Selective Production of Exotic Species) project of Laboratori Nazionali di Legnaro of INFN.

The IsoDAR cyclotron with the innovative design and the limited cost is an interesting solution to satisfy the requests of the research community.

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