PROPOSAL FOR A HIGH POWER DEUTERON CYCLOTRON AT RISP

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Abstract

We are proposing a compact isochronous cyclotron able to accelerate a high intensity beam with q/A 0.5 up to the final energy of 60 MeV/A. When accelerating H_2^+, it can be used as a driver for a high-intensity anti-neutrino source, as in the IsoDAR experiment. We believe that this type of cyclotron source placed near a neutrino detector, like Reno_50 or KamLAND would give impressive sensitivity to sterile neutrino searches and to electroweak measurements using neutrino-electron scattering. Here we present the idea of a modified IsoDAR cyclotron as the primary accelerator to drive the ISOL system of Rare Isotope Science Project (RISP) at Daejeon (Korea). The IsoDAR cyclotron is able to accelerate any ion with charge to mass ratio q/A=0.5 so deuterons or fully stripped light ions can be accelerated with high beam current and delivered to the production target for radioactive ions of RISP.

INTRODUCTION

The IsoDAR neutrino source [1] consists of a (q/A=0.5) cyclotron delivering 60 MeV protons to a ^{9}Be target. IsoDAR can use the same cyclotron design as the injector cyclotron for the two-cyclotron system for the 800 MeV DAEδALUS experiment [1, 2].

This paper describes a design study of the IsoDAR cyclotron [3], the features of this accelerator and the possible uses in other research fields. In particular, we are exploring the use of the IsoDAR cyclotron to accelerate a deuteron beam up to an energy of 40 MeV/A to fulfill the requests of RISP (the Rare Isotope Science Project) in Daejon, Korea. In particular, RISP is evaluating the advantage of using a high power deuteron beam to strike a target converter producing an intense neutron flux to irradiate a target of ^{238}U. The rare isotopes produced by the neutron-induced fission are then analyzed and reaccelerated. A modified IsoDAR cyclotron could not only deliver a proton beam through the acceleration of the H_2^+, but also fully-stripped light ions like carbon and oxygen. These different projectiles allow the use of the most convenient target-beam combination to produce different radioactive species. Here we focus on how the IsoDAR cyclotron can satisfy the needs of RISP.

ISODAR CYCLOTRON FEATURES

The cyclotron designed for the IsoDAR experiment is very similar to the one designed for DAEδALUS injector. It is a 4 sector normal conducting machine able to provide H_2^+ beams, and more generally, beams with q/A=0.5 up to an energy of 60 MeV/A. Several reasons have convinced the IsoDAR collaboration that H_2^+ was the right ion to accelerate.

The binding energy of the electron in H_2^+ is 2.75 eV, this eliminates the Lorentz stripping problem. The acceleration of a molecular beam like H_2^+ needs a better vacuum, of the order of 10^{-5} Pa, to minimize the interaction with the residual gas. This vacuum level is within the range of existing machines.

Furthermore, H_2^+ acceleration reduces space-charge effects. A simple way to see this is to note that for every two protons injected at the center, there is only +1 electric charge. Thus, we have 5 mA of H_2^+ while we provide 10 mA of protons to the target.

Table 1: Details of the IsoDAR Cyclotron Design

Design element	Design value	Design element	Design value
E_{max}	60 MeV/A	E_{inj}	35A keV
R_{ext}	1.99m	R_{inj}	55 mm
$\langle B\rangle$ @R_{ext}	1.16 T	$\langle B\rangle$ @R_{inj}	0.97 T
Sectors	4	Hill width	25.5° - 36.5°
Valley gap	1.8 m	Pole gap	80-100 mm
Outer diameter	6.2 m	Full height	2.7 m
Cavities	4	Cavity type	λ/2 double gap
Harmonic	4th	frequency	32.8 MHz
Acc. Voltage	70 – 240 kV	Power /cavity	310 kW
ΔE/turn	1.7 MeV	Turns	95
ΔE/turn @R_{ext}	<20 mm	ΔR/turn @R_{inj}	>56 mm
Coil size	200x250 mm^2	Current density	3.617 A/mm^2
Iron weight	450 tons	Vacuum	<10^{-7} mbar
Beam Injection	By spiral inflector	Beam Extraction	electrostatic deflector

A measure of the space charge effect is the generalized perveance K [4]:

$$K = \frac{qI}{2\pi\epsilon_0 m\gamma^3\beta^3}$$

where: q and m are the charge and mass of the particle, β and γ are the usual relativistic parameters, ε_0 is the vacuum permittivity, and I is the beam current.

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The K value of a 5 mA H^{2+} beam injected at 70 keV (35 keV/amu) is quite similar to that of 2 mA of protons (or H-) injected at 30 keV. As this H- performance has been demonstrated in commercial cyclotrons today, we expect that the required H2+ current should be achievable.

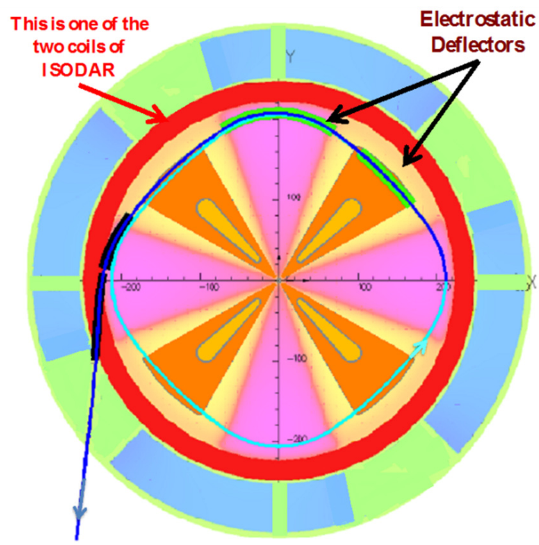

Figure 1: Sketch of IsoDAR cyclotron median plane.

On the other hand, high intensity ion sources of H_2^+ are still under development. A summary of the machine parameters is reported on Table 1.

Figure 1 shows a schematic cut at the median plane. In particular, the coils are in red, the hills in pink, the return yoke in blue and the RF cavities in orange.

Also shown is the last closed orbit in cyan and the extracted one in blue. Two electrostatic deflectors (ED) give a radial kick to the beam to reach the extraction channel. In black are sketched the two magnetic channels, whose function is to focus and slightly steer the beam locally correcting the magnetic field.

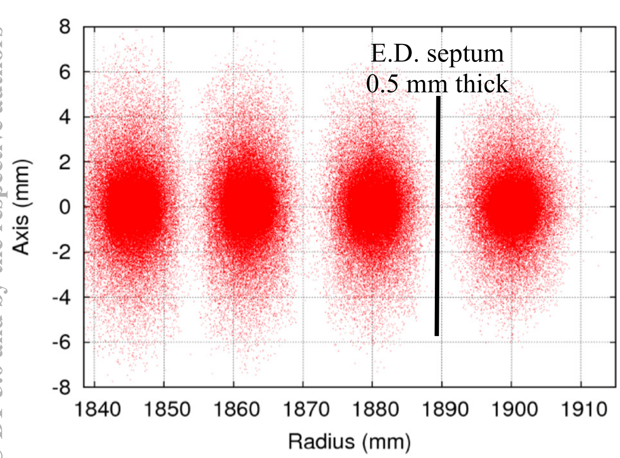

Figure 2: Snapshot of the last 4 accelerated turns of a 60 MeV/A IsoDAR cyclotron in front the E.D. entrance. The separation between the turns increases from 14 mm up to 20 mm.

The key point of a high current cyclotron is the extraction efficiency of the beam that must be about 99.98%. In Fig. 2 shows the particle distribution on the last 4 orbits accelerated in the IsoDAR cyclotron. This simulation was performed using the OPAL code [5] and takes into account of the space charge effects.

Although the beam halo size is of about 15 mm the inter-turn separation between the last two turns is 20 mm. So it is expected that the septum of the electrostatic deflector placed at R=1890 mm and having thickness of 0.5 mm should intercept only 0.02% of the beam particle that correspond to a beam power of 120 W for a 5 mA of H_2^+ at 60 MeV/A. The large inter-turn separation is due to the high energy-gain at the end of acceleration, about 1.9 MeV/turn, that gives about 14 mm of separation. The additional 6 mm produced by the orbit precession induced by a slow crossing of the ν_r=1 resonance, see fig. 3. This is achieved by a careful design of the cyclotron pole boundary, see Fig.3.

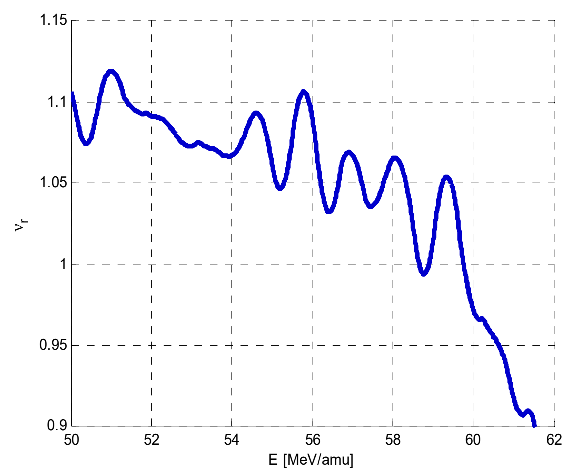

Figure 3: Plot of ν_r vs E showing the crossing of the resonance ν_r =1 around 60 MeV/A.

HOW ISODAR CYCLOTRON SUITS RISP NECESSITIES

The use of the IsoDAR cyclotron to accelerate and deliver a 1 mA D^+ beam is quite straightforward and much easier than the acceleration of the 5 mA of H_2^+. Indeed the space charge effects are smaller, ion sources able to produce a deuteron beam in excess of 10 mA already exist and last but not least, the acceleration of a bare nucleus like the D^+ instead of the molecular beam as the H_2^+ allows operation at a relaxed vacuum level. The expected beam power losses for 1 mA of H_2^+ beam along the acceleration path from 0.5 MeV/A up to 40 MeV/A will be below 30 W, see Fig.4, if the working vacuum stays around $5*10^{-6}$ Pa and the cyclotron is equipped with 4 RF cavities. The cavity voltage used in the simulation is assumed to be equal to the average value of 140 kV, a pessimistic value compared to the expected real voltage profile that should

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rise from 70 kV at inner radii up to 240 kV at the extraction radius of R=1.9 m. The beam power losses are about 30 W and 60 W, respectively at 40 and 60 A MeV. The corresponding beam intensity losses are respectively 1.4 μA and 1.6 μA.

It is important to emphasize that when comparing IsoDAR to RISP, several parameters are relaxed and that makes the extraction easier. Firstly, at 40 MeV/A the turn separation is naturally larger for the same voltage versus radius profile. Secondly, the maximum accelerating voltage can be reduced to 200 kV instead of the 240 kV used for IsoDAR. Moreover, the same number of microamps lost on the septum translates into less power. This has even more impact due to the fact the beam current is less (1 mA vs 5 mA).

In the case of the acceleration of the bare deuteron the expected working vacuum pressure can be relaxed to $(0.5\text{-} 1)*10^{-4}$ Pa. The interaction of the beam with the residual gas is the main source of the beam losses. The ED's are the other source of beam loss. From the previous considerations, if we scale the beam power intercepted by the septum of the ED at of 1 mA a deuteron beam at 40 MeV/A, the expected power lost should be in the order of 16 W.

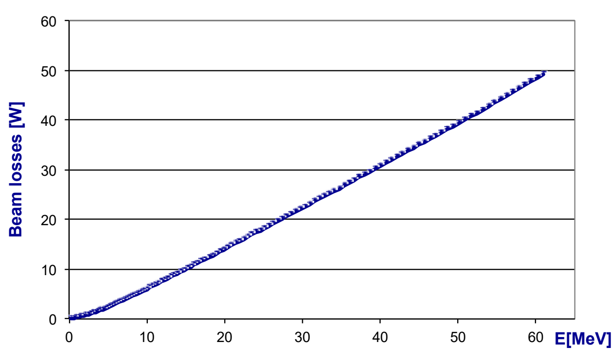

Figure 4: Beam losses of H_2^+ along the acceleration up to 60 MeV/A. The gas pressure is $5*10^{-6}$ Pa and the energy gain-per-turn about 1.4 MeV.

The radial size of an IsoDAR-like cyclotron to deliver the deuteron beam for the RISP at 40 MeV/A will be 15% smaller than IsoDAR cyclotron. The extraction radius will be reduced to 1.63 m. The acceleration of a deuteron nucleus avoids any problem of electromagnetic dissociation due to the high magnetic field and also reduces the interaction with the residual gas. Assuming a working vacuum of 10^{-4}-10^{-5} Pa the expected amount of particle losses is about 30 W for a 1 mA deuteron beam at 40 MeV/A.

Despite the fact that the expected beam full power losses will stay below 50 W, the flux of neutrons produced will still be quite high. For this reason, it is desirable to find solutions to mitigate the activation of the machine. In particular, the dees of the cavities made of copper, can be a major source of activation. To mitigate this problem the dees of the cavities could be made out of aluminum, or alternatively, a 5 mm thick layer of aluminum could cover the surfaces of the dees in the vicinity of the median plane.

CONCLUSIONS

The study performed for the IsoDar cyclotron is very useful to evaluate the possibility of a smaller version dedicated mainly to the acceleration of a deuteron beam at 40 MeV/A, with a beam current of 1 mA. Existing ion sources [6,7] are able to produce sufficient beam current of deuteron or of H_2^+ to satisfy the required beam current of RISP. If one wished to achieve currents of about 50 particle μAmp (pμA) for light ions it is mandatory to start with a new-generation ECR ion source that could produce beam currents of about 50-100 pμA for fully stripped light ions such as C^{6+} and O^{8+}. However, the typical injection efficiency into a Cyclotron is about 10% of the continuous beam, which could be increased up to 30% using a well-designed Buncher. The injection efficiency could be further increased up to 80-90% using an RFQ pre-accelerator to couple the ion source to the cyclotron. The RFQ could be installed in the injection central hole of the cyclotron. A interesting investigation of this option has been presented recently [8].

Contacts are in progress with the main cyclotron-building companies to determine the interest and costs to build this cyclotron.

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