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AN RFQ DIRECT INJECTION SCHEME FOR THE ISODAR HIGH INTENSITY H_2^+ CYCLOTRON*

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Abstract

IsoDAR is a novel experiment designed to measure neutrino oscillations through $\bar{\nu}_e$ disappearance, thus providing a definitive search for sterile neutrinos. In order to generate the necessary anti-neutrino flux, a high intensity primary proton beam is needed. In IsoDAR, H_2^+ is accelerated and is stripped into protons just before the target, to overcome space charge issues at injection. As part of the design, we have refined an old proposal to use an RFQ to axially inject bunched H_2^+ ions into the driver cyclotron. This method has several advantages over a classical low energy beam transport (LEBT) design: (1) The bunching efficiency is higher than for the previously considered two-gap buncher and thus the overall injection efficiency is higher. This relaxes the constraints on the H_2^+ current required from the ion source. (2) The overall length of the LEBT can be reduced. (3) The RFQ can also accelerate the ions. This enables the ion source platform high voltage to be reduced from 70 kV to 30 kV, making underground installation easier. We are presenting the preliminary RFQ design parameters and first beam dynamics simulations from the ion source to the spiral inflector entrance.

INTRODUCTION

In the IsoDAR (Isotope Decay-At-Rest) experiment [1], H_2^+ ions will be delivered by a high performance ion source, accelerated to 60 MeV/amu in a compact cyclotron, and then stripped to protons and dumped on a beryllium target surrounded by a lithium sleeve. Neutrons generated by the protons hitting ^{9}Be will be captured on ^{7}Li, and the resulting ^{8}Li will then beta decay-at-rest, producing a very pure $\bar{\nu}_e$ beam. This accelerator and target system will be placed close (16 m from the center) to an existing neutrino detector (e.g. KamLAND) to measure $\bar{\nu}_e$ disappearance from neutrino oscillations via inverse beta decay. This process is depicted in Figure 1. The short baseline will allow tracing out more than a full period of the oscillation wave inside the detector, thus presenting a definitive search for proposed sterile neutrinos that may participate in the oscillation but not in the weak interaction. In order to get definitive results over the course of a few years, a high neutrino flux is necessary; hence a very high primary proton beam is desired.

In the summer months of 2013 and 2014, tests of high intensity H_2^+ production, transport, and injection into a cyclotron were conducted at Best Cyclotron Systems, Inc.

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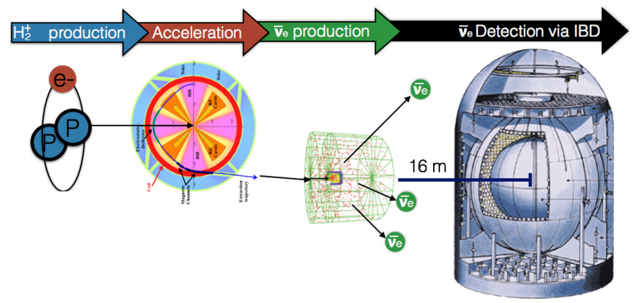

Figure 1: Cartoon of the IsoDAR experiment. Detector image courtesy of the KamLAND collaboration.

(BCS) in Vancouver, Canada. The ion source, borrowed from INFN Catania in Italy, was the "versatile ion source" (VIS), an off-resonance 2.45 GHz ECR ion source. From the VIS, it was possible to extract 12 mA of H_2^+. The main objective was to test the extent to which space charge will be a limiting factor in the low energy beam transport and the injection into the cyclotron through a spiral inflector. It was possible to show that the transmission through the spiral inflector at beam currents on the order of 10 mA was $\approx$ 95%. The typical acceptance of an unbunched beam into the cyclotron RF bucket is on the order of 5%, and with a 2-gap multiharmonic buncher, this acceptance can be increased to 10-20%. Considering the present performance of the VIS and suggested improvements to the source, the nominal 5 mA of H_2^+ extracted from the cyclotron is achievable, but pushing the limits. We are exploring two avenues to improve the situation: (1) We are constructing a new ion source (multicusp) dedicated to the production of H_2^+, and (2) we are investigating the use of an RFQ to replace the LEBT. The RFQ is a linear accelerator that can focus, bunch, and accelerate a continuous beam of charged particles at low energies with high bunching and transmission efficiencies. RFQs are very attractive for low energy ion accelerators, e.g. for applications with high current beams or in combination with sources such as an ECR, because the source can be close to ground potential and is easy to operate and to service. Because the basic RFQ concept can be implemented over a wide range of frequencies, voltages, and physical dimensions, it is an ideal structure to use for bunching an intense ion beam for injection into a cyclotron and has already been used in several cyclotron systems for radial injection of input beams [2]. It can also be used for axial injection at much lower energies as first proposed in 1981 [3]. However, to date, direct axial injection into a compact cyclotron using an RFQ has not yet been realized. For high acceptance into

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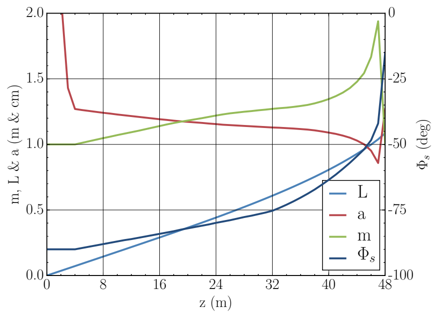

Figure 2: RFQ-Linac design parameters for IsoDAR direct injection.

the cyclotron, the injected beam should be bunched at the cyclotron frequency (33.2 MHz at 4th harmonic), resulting in the use of the four-rod RFQ structure [4].

RFQ DESIGN

Such an RFQ has been designed for axial injection into the IsoDAR cyclotron. The design parameters of this injector RFQ are listed in Table 1. This four-rod structure accelerates and bunches H_2^+ ions extracted from an ECR ion source for injection into the spiral inflector in the cyclotron. To minimize the RFQ's radial dimension, distributed spiral inductor resonators would be used.

PARMTEQ SIMULATIONS OF RFQ

This RFQ, which is used primarily for bunching the beam, has only 48 cells. The design parameters of the RFQ vanes are shown as a function of cell number in Figure 2. Figure 3 shows the calculated phase space projections at the output of the RFQ using 50,000 macroparticles in the beam dynamics code PARMTEQ [5]. The total phase width of the beam is 90°, but 60% of the beam is within ±10°. The energy spread of the beam at 80 keV has a FWHM value of 5 keV

Table 1: IsoDAR RFQ-Linac Injector Parameters

Parameter	Value
Operating frequency	33.2 MHz
Injection energy	15 keV
Final beam energy	80 keV
Design input current	10 mA
Current limit	22 mA
Transmission at 10 mA	99%
Inp. trans. emittance (6-rms, norm.)	0.5 π-mm-mrad
Nominal vane voltage	43 kV
Bore radius	1.27 cm
Maximum vane modulation	1.94
Structure length	1.09 m
Peak RF field surface gradient	4.66 MV/m
Structure RF power	0.82 kW
Beam power	0.64 kW
Total input RF power	1.46 kW

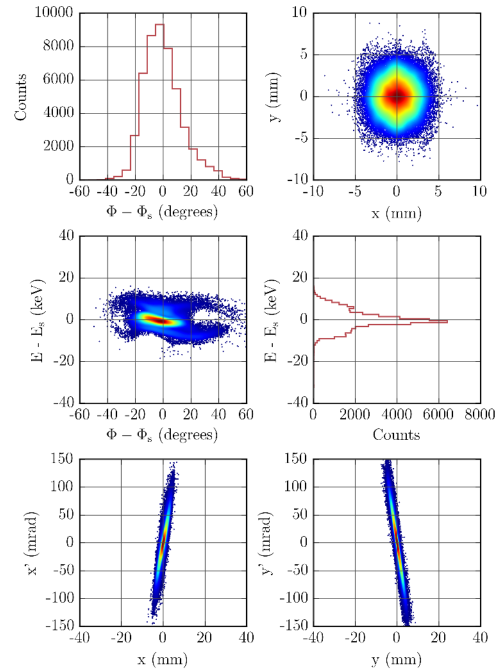

Figure 3: Phase Spaces of the RFQ output beam.

but has a "halo" that extends out to ±1.5%. Figure 3 shows the output phase spaces in all three planes. As seen in the figure, the beam in the transverse planes exiting the RFQ is almost circular with a diameter of ≈6mm. The transmission of protons is 0% showing very good H_2^+ beam purity

ION SOURCE AND MATCHING TO RFQ

Two types of ion sources are currently being considered for IsoDAR: A new 2.45 GHz off-resonance ion source comparable to the VIS and a multicusp ion source with a short plasma chamber (a prototype is currently being built at MIT). Both are plasma type ion sources, and the extraction can be simulated with the well known code IGUN [6]. For the IsoDAR cyclotron, the CW beam from the ion source can be extracted in an accel–decel extraction system, and focused into the RFQ using a segmented einzel lens. As an example, the optics for a 10 mA beam coming from a VIS-type source, calculated with IGUN, is shown in Figure 4.

CYCLOTRON INJECTION SIMULATIONS

In order to verify the feasibility of the RFQ injection scheme, careful investigation of the matching of the RFQ exit to the cyclotron is necessary. The particle-in-cell (PIC) code OPAL [7] was recently updated with routines to incorporate complicated electrode geometries as boundary conditions during the calculation of self-fields and for the termination of particles. In addition, OPAL-CYC, the subset of OPAL tailored to cyclotron simulations, was upgraded to manage axial injection through a spiral inflector. The first step in this simulation study was to transport the particles exiting the RFQ to the entrance of the spiral inflector in order to see how much of an effect the residual magnetic

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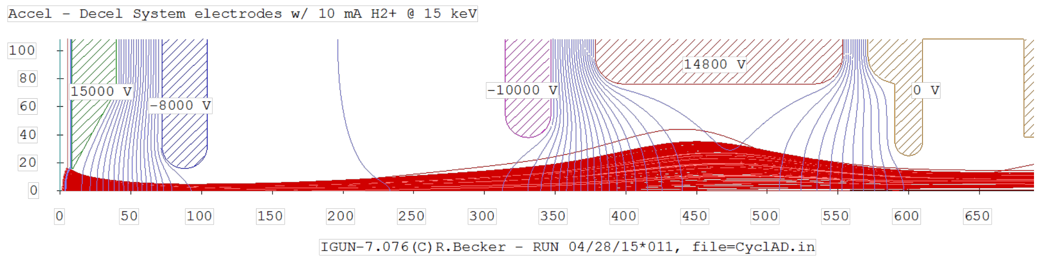

Figure 4: IGUN simulation of beam extraction and matching to RFQ.

field in the cyclotron plug would have. The resulting 1-rms beam radii as well as $B_z(z)$ on-axis are shown in Figure 5. It becomes immediately clear that even with the small focusing effect of the magentic field, the beam size increases significantly over the distance of ≈ 15cm. Transporting the beam through the spiral inflector, about 80% of the beam is lost before encountering the first acceleration gap. It is possible to change the divergence and size of the beam at the exit of the RFQ by shortening the last cell. However, tests with different beams exiting the RFQ yielded similarly unacceptable results. In order to improve this behaviour in the next design iteration, an additional focusing element and a one gap buncher will be placed inside the plug (between RFQ exit and spiral inflector entrance) to compensate for the divergence and energy spread of the bunch.

CONCLUSION

The IsoDAR proton driver aims to deliver 10 mA of protons to a high power beryllium target to produce a pure $\bar{\nu}_e$ beam for a conclusive search for the existence of sterile neutrinos. H_2^+ was chosen as primary ion to overcome space-charge issues. First tests with a 2.45 GHz ECR ion source (VIS) and a test beam line showed that achieving the necessary injection efficiencies to ultimately extract 5 mA of H_2^+ from the cyclotron is possible, but pushing the limits of classic LEBT design. An RFQ closely coupled to the ion source upstream and re-entrant to the cyclotron iron yoke can overcome the limitations experienced in the preliminary tests. In a design study, a 1.09 m long RFQ for 33.2 MHz operation was simulated using Parmteq. The results are very promising, showing an RFQ output emittance of 1.4 π-mm-mrad (4-rms, normalized). This is similar to the original LEBT design, but with transport efficiency increased to 99% and with 63% of the beam within ±10° RF phase angle and within ±2 keV energy spread at 80 keV beam energy. In addition the system is much more compact, making underground installation easier. Preliminary injection simulations using the OPAL code suggest that the increase in beam size from the exit of the RFQ to the entrance of the spiral inflector is inhibitively large and thus, the next design iteration will incorporate a focusing element and a re-buncher between RFQ and spiral inflector.

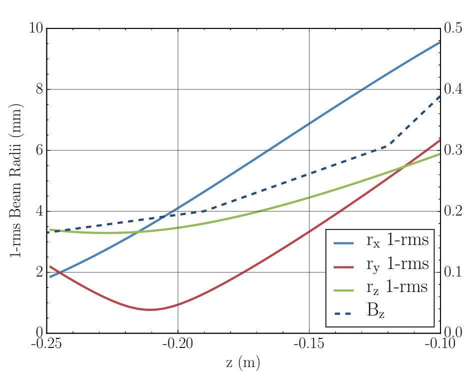

Figure 5: The 1-rms bunch radii for the beam traveling from the exit of the RFQ to the entrance of the spiral inflector. The residual axial magnetic field of the cyclotron is plotted on the secondary axis.

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