ARTICLE IN PRESS
Nuclear Inst. and Methods in Physics Research, A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

High intensity cyclotrons for neutrino physics

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ARTICLE INFO

Keywords:
Cyclotrons
High current
PIC
RFQ

ABSTRACT

In recent years, the interest in high intensity proton beams in excess of several milli-amperes has risen. Potential applications are in neutrino physics, materials and energy research, and isotope production. Continuous wave proton beams of five to ten milli-amperes are now in reach due to advances in accelerator technology and through improved understanding of the beam dynamics. As an example application, we present the proposed IsoDAR experiment, a search for so-called sterile neutrinos and non-standard interaction using the KamLAND detector located in Japan. We present updated sensitivities for this experiment and describe in detail the design of the high intensity proton driver that uses several novel ideas. These are: accelerating H_2^+ instead of protons, directly injecting beam into the cyclotron via a radio frequency quadrupole, and carefully matching the beam to achieve so-called vortex motion. The preliminary design holds up well in PIC simulation studies and the injector system is now being constructed, to be commissioned with a 1 MeV/amu test cyclotron.

1. Introduction

High intensity proton beams are used very successfully in spallation neutron sources like the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) [1], the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC) [2], and the Swiss spallation neutron source SINQ at the Paul Scherrer Institute (PSI) [3]. In addition to neutrons these spallation targets can also produce kaons, pions, muons, and neutrinos to be used in particle physics experiments (e.g. [4]). With the exception of PSI, these facilities use linear accelerators to produce high intensity proton beams, which are costly and require significant space. Recent developments in accelerator technology and improved understanding of the beam dynamics in high intensity cyclotrons have made these circular particle accelerators an attractive candidate for new high intensity proton drivers. Currently, PSI holds the record of highest power continuous wave (cw) proton beam from a cyclotron with 2.2 mA at 590 MeV energy, which amounts to ≈1.3 MW of beam power [5]. In this coupled cyclotron system, so-called *vortex motion* has been observed experimentally and been reproduced in Particle-In-Cell (PIC) simulations [6,7]. Here, the external focusing forces of the isochronous cyclotron combined with space-charge cause a spiraling of the bunch that can lead to longitudinal focusing. We can utilize this effect to accelerate even higher beam currents as will be discussed in this paper. Some proposed experiments and potential applications of high intensity proton beams are listed in Table 1 together with current and energy requirements.

After motivating the need for high intensity proton beams by using one of the given examples (the proposed neutrino experiment IsoDAR) in the following subsection, we will describe in detail the building blocks of a cyclotron-based proton driver in Section 2 together with the design choices that make such a system feasible. In Section 3 we will then present simulations of the individual parts, followed by a discussion of the next steps towards a running system in Section 4.

1.1. An example: The IsoDAR experiment

IsoDAR (Isotope Decay At Rest) is a novel, pure $\bar{\nu}_e$ source under development that makes use of a cyclotron-accelerated beam delivered to a decay-at-rest target. A high-intensity H_2^+ ion source feeds a 60 MeV/amu cyclotron. The beam is electron-stripped after extraction and transported to a ^{9}Be target, producing neutrons. The neutrons enter a ≥99.99% isotopically pure ^{7}Li sleeve, where neutron capture results in ^{8}Li. The ^{8}Li undergoes β decay-at-rest, producing an isotropic, pure $\bar{\nu}_e$ flux. Pairing this very high-intensity $\bar{\nu}_e$ source with a detector that

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https://doi.org/10.1016/j.nima.2018.07.036
Received 6 March 2018; Received in revised form 13 July 2018; Accepted 14 July 2018
Available online xxxx
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Please cite this article in press as: D. Winklehner, et al., High intensity cyclotrons for neutrino physics, Nuclear Inst. and Methods in Physics Research, A (2018), https://doi.org/10.1016/j.nima.2018.07.036.

Table 1
A few potential uses for high current proton beams. (ADSR — Accelerator Driven Sub-critical Reactors, ADS — Accelerator Driven Systems).

Experiments	Type	Current	Energy
IsoDAR [8,9]	Neutrino exp.	10 mA	60 MeV
DAEδALUS [10,11]	Neutrino exp.	10 mA	800 MeV
ADSR [12,13]	Energy	10 mA	<1.2 GeV
ADS [14,15]	Energy	4–120 mA	<1.2 GeV
Isotopes [16,17]	Medicine	<2 mA	3–70 MeV

contains hydrogen allows for the inverse beta decay (IBD) interaction, $\bar{\nu}_e + p \rightarrow e^+ + n$, and $\bar{\nu}_e$-e^- elastic scattering (ES) processes.

Our goal in developing IsoDAR was to "think outside of the box" on neutrino sources for underground science. We are producing a cheaper, more compact and purer source than existing neutrino sources, with flexibility to install the source underground at most laboratories.

Our initial proposal is to install IsoDAR near to the KamLAND detector. The first proposal for the layout of the IsoDAR facility placed the source at 16 m from the center of the KamLAND detector and assumed an energy resolution of $6.5\%/\sqrt{E}$ [9]. Recently, two potential improvements to this plan have been put forward. First, we have identified a new, potentially closer targeting site [18], at 12.5 m, increasing rates by ×1.6. Should this new location be employed, the additional statistics can allow us to either reach our physics goals more quickly or to run the cyclotron at 6 mA of protons (3 mA H_2^+) rather than 10 mA of protons (5 mA H_2^+) for the original time period. Running with 6 mA of protons is preferred to reduce operations cost and risk. Second, KamLAND is proposing an upgrade which will improve the resolution of the detector to $3\%/\sqrt{E}$, which benefits IsoDAR physics.

Because IsoDAR is relatively inexpensive, one can envision many such sources in the future. For example, the JUNO collaboration has worked with us on potentially bringing IsoDAR to their detector after reactor running [19].

1.2. Examples of the Physics of IsoDAR

In this section, we describe two examples of the IsoDAR physics program in detail. IsoDAR also makes other beyond Standard Model searches, nuclear physics measurements and provides calibration for KamLAND.

1.2.1. Sterile neutrino search

Interest in light sterile neutrinos has arisen from anomalies observed in a wide range of short-baseline (SBL) experiments employing neutrinos and antineutrinos of different flavors and different energies [20–26]. However, other experiments potentially sensitive to sterile neutrinos have observed null results [27–34]. This limits models that describe the anomalies. One such model that introduces one additional sterile neutrino ("3+1") depends on four BSM parameters, $\sin^2 2\theta_{ee}$, $\sin^2 2\theta_{\mu\mu}$, $\sin^2 2\theta_{\mu e}$, and Δm^2. The first three are the mixing angles measured in three types of oscillation experiments: ν_e disappearance, ν_μ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance. These are constructed of two matrix elements, $|U_{e4}|^2$ and $|U_{\mu 4}|^2$, hence they are interdependent. The fourth parameter, the squared mass splitting between the mostly sterile and mostly active states must be consistent for all three types of oscillations.

Global fits that include all of the SBL data sets show a marked improvement in $\Delta\chi^2_{null-min}/\Delta\text{dof}$ of 50.61/4 for a 3+1 model [35]. However, the appearance-only and disappearance-only allowed regions show poor overlap in allowed parameters [36]. This well-known tension is one of the primary reasons scientists question the sterile neutrino model.

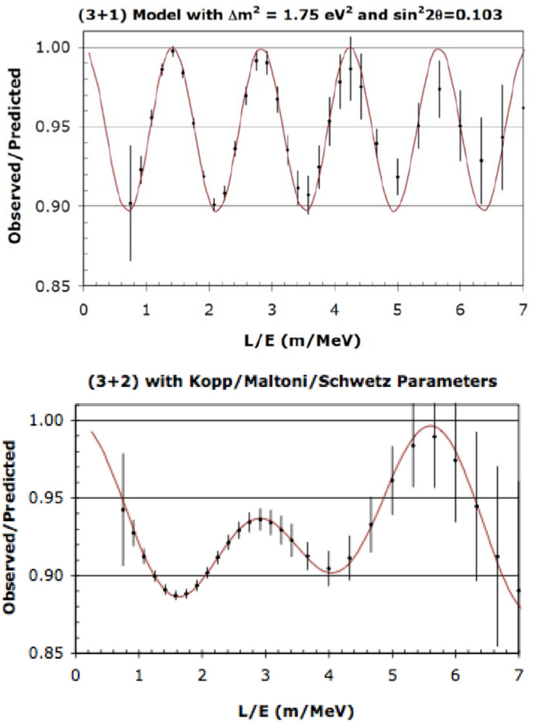

Fig. 1. IsoDAR@KamLAND L/E dependence, 5 years of running, for one (upper plot) and two (lower plot) sterile neutrinos. Solid curve is the oscillation probability with no smearing in the reconstructed position and energy and the data points with error bars are from simulated events including smearing from reconstruction for the original target location and detector (assumes present resolution, and target at 16 m).

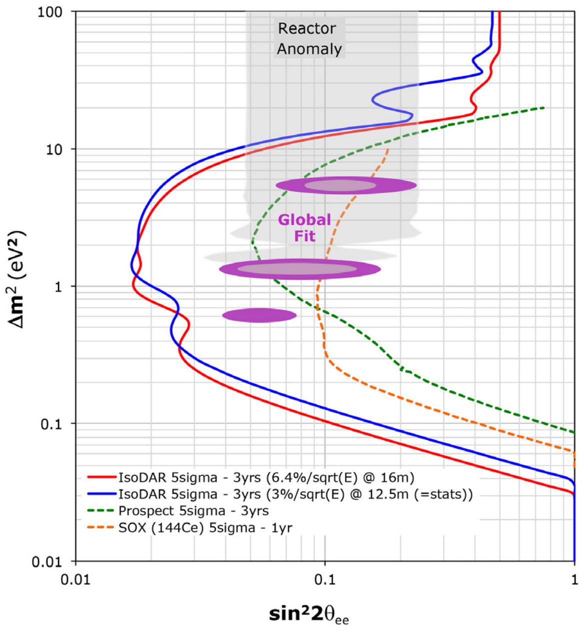

Fig. 2. Isodar@KamLAND at original site (red), new proposed site with equal statistics (blue), and in comparison to other experiments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

IsoDAR was developed to allow a sterile neutrino search that can resolve the confusing situation of anomalies in the electron-flavor sector. IsoDAR provides a very well-understood flux and a highly sensitive method to search for sterile neutrinos through reconstruction of the L/E dependence of the neutrino oscillation process, commonly referred to as an "oscillation wave", shown in Fig. 1.

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