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HIGH POWER CYCLOTRONS FOR THE NEUTRINO EXPERIMENTS DAE δ DALUS AND ISODAR

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Abstract

DAE δ DALUS (Decay At rest Experiment for δ_{cp} At a Laboratory for Underground Science) has been proposed to measure the value of the CP violating phase δ through the oscillation of low energy muon antineutrinos to electron antineutrinos. With a single large detector, three accelerators at different distances enable the oscillation to be measured with sufficient accuracy. We have proposed the multi-megawatt DAE δ DALUS Superconducting Ring Cyclotron (DSRC) as the means of producing the 800 MeV 12 mA protons required, through the acceleration of H_2^+ ions with highly efficient stripping extraction. The system comprises an ion source, a LEBT, and an injector cyclotron which feeds into the main ring. The injector cyclotron can also be used for a separate experiment, IsoDAR (Isotropic Decay At Rest) in which low energy protons produce 8Li . This gives a very pure electron antineutrino source which can be used to measure, or rule out, short range oscillation to a sterile neutrino. We describe recent developments in the designs of the injector and the booster, and the prospects for the two experiments.

INTRODUCTION: THE CONCEPTS

The DAE δ DALUS collaboration [1, 2] proposes to determine the value of the weak CP violating phase δ through measurements of the oscillation $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at different distances. Due to the size and cost of suitable neutrino detectors, this is achieved though having multiple low-energy neutrino sources. The current design has 800 MeV proton accelerators at distances of 1.5, 8 and 20 km, with powers of 1.0, 1.6 and 4.8 MW. Each accelerator operates on a 20% duty cycle.

A suitable high current proton cyclotron design has been reported previously[3, 4, 5]. This paper reports on recent progress[6, 7].

CHOICE OF BEAM PARTICLE: H_2^+

We propose to use H_2^+ ions, accelerated to a total energy of 1.6 GeV (800 MeV per proton). This ion is chosen to enable extraction from the cyclotron, where the orbits are

too close to easily accommodate a septum, using a foil to strip the electron.

A second advantage over protons is the reduction in the effects of space charge, which plays a pivotal role in the injector. Large-scale particle simulations [8] show that the injector cyclotron is space charge dominated but that a 5 mA beam current can be extracted with tolerable beam losses on the septum. (By contrast, in the ring cyclotron, no space charge induced beam loss is observed during acceleration and extraction.) Space charge effects can be quantified using the generalised perveance, $K = \frac{qI}{2\pi\epsilon_0 m\gamma^3\beta^3}$ showing that H_2^+ has half the effect compared to protons.

The use of H_2^+ imposes more stringent vacuum requirements: below 10^{-8} rather than 10^{-7} torr, to reduce losses from dissociation due to gas collisions. Also the high rigidity of the high energy, high mass particle means that high field strengths are needed, requiring a superconducting magnet.

Lorentz stripping should not be a problem even in these high fields, as the H_2^+ ion is considerably more tightly bound than the alternative H^- ion (2.8 eV rather than 0.7 eV). However not all H_2^+ molecules produced by the ion source are in their ground state, and dissociation from an excited state requires appropriately less energy. Some states are long lived (compared to the time spent in the accelerator) and could be Lorentz stripped in the 6T magnetic field, which would produce unacceptable beam losses. We do not know what mixture of states is produced by the ion source, and we are starting an experimental programme to measure this. If there is a problem then the H_2^+ can be cooled by mixing with molecules of an inert neutral gas, such as Helium. This is being investigated using the ORNL facility.

There is also a possibility that when the H_2^+ interacts in the foil it produces H^0 - neutral hydrogen atoms, which would also result in losses.

Assuming a phase acceptance of $\pm 10^\circ$, and a factor of 2 due to bunching in the LEBT, the source is required to deliver 50 mA of H_2^+ . The Versatile Ion Source (VIS), designed and built at INFN-LNS (Catania) should achieve this. It is an off-resonance 2.45 GHz microwave discharge source[9] and can produce beams with emittance of order

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0.1 π mm mrad. We have currently extracted 20 mA of H_2^+ from this source in early tests, and work is ongoing to increase this number.

The LEBT that takes the beam from the ion source comprises two solenoids, separated by a Wien filter and a collimator slit to select the H_2^+ ions, and focussing quadrupoles. This section also includes an RF buncher for longitudinal compression, to increase capture efficiency. Experimental tests with the source, and the matching of the beams from it, are currently under way at BEST cyclotrons, in Vancouver.

THE INJECTOR

The DAE δ DALUS Injector Cyclotron (DIC) will accelerate 5 mA of H_2^+ ions up to 60 MeV/amu. This is an order of magnitude more than current commercial cyclotrons, giving it a potential application as a productive source of medical isotopes.

It has 4 sectors, an outer diameter of 6.2 m, is 2.7 m high and weighs 450 tons. The field, from a conventional magnet, increases from 1.075 to 1.16 T.

Injection will be done using a spiral inflector. Bunches can be extracted conventionally, as the turn by turn separation at extraction is 2 cm, using two electrostatic deflectors and two magnetic channels. Four 49.2 MHz (6th harmonic) double-gap RF cavities accelerate the bunches in 107 turns. The isochronism is better than 5×10^{-4} .

The effect of space charge has been studied using the OPAL code[10]. Because of these issues, we have increased the proposed injection energy from 30 to 70 keV (35 keV/amu), giving the same generalised perveance as commercial cyclotrons.

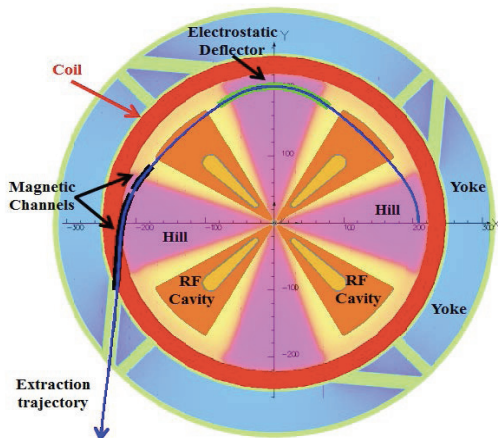


Figure 1: The Injector

THE MAIN CYCLOTRON

The DAE δ DALUS Superconducting Ring Cyclotron (DSRC), is the main component of the accelerator system.

04 Hadron Accelerators

A13 Cyclotrons

Details of the design have changed considerably since previous studies[3, 4, 5] and may change further as the design is optimised.

Eight superconducting sector magnets are used, with current densities of 3400A/cm². The enormous structural forces have been analysed in detail using OPERA, and stainless steel plates are used to connect opposite segments. The cryostat is made of iron and stainless steel, with walls of varying thickness. The magnetic is similar to the existing RIKEN SRC, hence the parameters are in general creditable.

Four single-gap copper cavities are used, 3m high and 8.8m long, operating at 49.2 MHz (6th harmonic) with a Q value of 37,500, giving an acceleration from 2.0 to 4.0 MV per turn. These cavities are similar to those of the PSI cyclotron and their parameters are hence also creditable. It may be possible to supplement these by two double-gap cavities, and this option is being considered. These are included in the design shown in Figure 2. Injection uses five magnetic channels and an electrostatic deflector. Extraction is by means of a thin (2mg/cm²) pyrolytic graphite foil, a few cm² in size. Electrons are stopped on a copper shield. Any neutral hydrogen produced can be extracted safely. The pulse width has to be kept below 1 ms to ensure the foil temperature is kept below 2500 K. Based on the experience of SNS we anticipate foil lifetimes of several months.

Isochronicity of the design is adequate, and focussing is sufficient in both planes. The Walkinshaw resonance is crossed rapidly, and only once, and should not lead to beam losses.

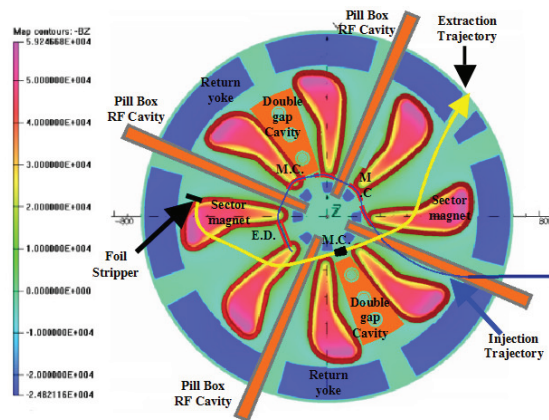


Figure 2: The main cyclotron

The requirements for this machine are similar to those for ADS systems, and thus have a very large potential application.

ISODAR

In addition to the main DAE δ ALUS experiment, the low energy injector cyclotron could be used for some interesting neutrino experiments [11, 12]. With careful target

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design and optimisation, low energy protons can produce short lived isotopes which rapidly β decay, producing an electron antineutrino. As the isotope has time to stop in the target, the decay occurs at rest in the lab and the distribution produced is isotropic. We propose a 60 MeV, 5mA, 600 kW H_2^+ accelerator, which is about a factor of 10 more intense than cyclotrons currently used for medical isotope production. A ^9Be target produces neutrons, which are moderated by D_2O and interact in a ^7Li sleeve, which will produce ^8Li , giving $2.6 \cdot 10^{22} \bar{\nu}_e$ per year with an average energy of 6.4 MeV. 14.6 antineutrinos are produced per 1000 protons. 90% of these are produced in the sleeve, and 10% in the beryllium target. Production of neutrinos, and antineutrinos from other isotopes, is negligible.

A specific package for low energy proton interactions is necessary and we have used the QGSP-BIC-HP physics package in GEANT4[13]. Further details are presented in another contribution to this conference[14]

The neutrinos can be measured up to 20m away using the clean and characteristic inverse beta decay signal, and provide a definitive answer on the existence or otherwise of sterile neutrinos which have been proposed as a possible solution to the 'reactor anomaly'. It would also provide a large sample of $\bar{\nu}_e e^-$ scattering events, which could provide a signature for dark matter candidates. The experiment needs a detector of size of order 1 kton. This could be KAMLAND, and the accelerator could be installed in the Kamioka mine. Access through the existing tunnel requires the cyclotron to be taken in parts, and the enclosing copper liner will have to be cut in two and welded in situ, which is problematic but possible. The SNO+ detector is also under consideration.

PROSPECTS FOR DAE δ DALUS

The investigation of CP violation in the neutrino sector is one of today's greatest issues in particle physics, as a key to big bang cosmology. DAE δ DALUS presents a unique way to probe this question, and we are vigorously arguing its case with our colleagues, with presentations at many workshops, conferences and seminars.

We see development in four stages, of which the first, testing of the Ion Source, is already under way. The second is the construction of the injector. We would then construct one DSRC, and finally another two. Each step would not merely be a technical development, but would bring a full physics programme.

The developments in accelerator technology would also bring strong industrial benefits, through improved medical isotope production and by building the accelerators needed for ADSR/Thorium fuelled nuclear power.

The design is still evolving as our understanding grows, with many possibilities not discussed here also being considered. The DAE δ DALUS collaboration is a vigorous international and cross-disciplinary team: great progress is being made, and is set to continue.

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