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High Current Cyclotrons for Neutrino Experiments

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DAEδALUS is a program which seeks to produce a number of high current cyclotrons for providing intense sources of neutrinos. These sources will be employed for sensitivity to sterile neutrinos and non-standard neutrino interactions through the IsoDAR experiment, as well coherent neutrino scattering, and a measurement of CP violation in the neutrino sector, among other things. DAEδALUS and IsoDAR require accelerators able to deliver 10 mA proton beams at 800 MeV and 60 MeV, respectively. The solution to providing such a high current is to accelerate 5 mA beams of H_2^+ ions to 800 MeV/n by a superconducting separated sector ring cyclotron, fed by a 60 MeV/n injector cyclotron. The DAEδALUS injector cyclotron can be used as a driver for the IsoDAR experiment as well. Using H_2^+ ions rather than protons offers two advantages: firstly, the space-charge effects are halved for the same number of protons delivered, and secondly, they can be extracted with essentially 100% efficiency by stripping in a thin foil. The physics goals of the project are presented along with a discussion of some technical aspects of the machines including the results of a number of design studies.

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1. Introduction

The DAEδALUS project will produce advanced cyclotrons in order to create pion and muon decay-at-rest sources of neutrinos for a CP violation search in the neutrino sector and a number of other physics measurements. The cost-effective cyclotrons will be designed to outmatch, in energy and power, the current world-leading device at the Paul Scherrer Institut (PSI).

In the first section, we discuss the ultimate goal of DAEδALUS, a measurement of CP violation in neutrinos, and a number of other interesting physics possibilities in each phase of the project, including a set of sterile neutrino probes, a non-standard neutrino interaction search, and a measurement of as-yet-unseen coherent neutrino-nucleus scattering. Industrial applications of these machines, while quite interesting and important, are not discussed at length. With the physics goals of the experiment presented, the requirements of the cyclotron machines are then discussed. Then, the challenges and issues associated with all phases of the program in the context of accelerator design are presented and a number of design study results are shown. Further, alternative designs are considered and the question of risk is addressed in a number of places, with existing accelerator facilities used for comparison and extrapolation purposes. While there are a number of significant technical challenges associated with designing and constructing high power target and shield systems, here we focus on the design of the cyclotron machines that will meet the physics goals presented.

2. The DAEδALUS goal

The ultimate goal of the DAEδALUS project is to measure CP violation in the neutrino sector [1]. This piece of physics has been identified as one of the most important future measurements in the field [2, 3, 4]. A discernible difference between neutrino oscillations and antineutrino oscillations would be an indication of this effect. CP violation is one of the requisites for producing a matter dominated universe. Although CP violation has been observed in the quark sector, it is not enough to produce the asymmetry that we see today. Observation of the effect in neutrinos may give us important information with regard to quark-lepton unification, the theory of leptogenesis [5, 6] and, in general, may provide a hint as to why we live in such a universe.

The neutrino CP violating parameter, δ_{CP}, can be measured by looking at $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillations. With DAEδALUS, the antineutrino flux comes from 800 MeV protons hitting a carbon target to produce charged pions. The positively charged pions come to rest quickly in the target and subsequently decay to produce a muon and a muon neutrino $\pi^+ \to \mu^+\nu_\mu$. The muon then comes to rest itself to produce an electron neutrino and a muon antineutrino $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$. The $\overline{\nu}_\mu$ flux goes up to 52.8 MeV, as shown in Fig. 1. The three flavors of neutrinos and antineutrinos from the target are emitted isotropically with a well know energy shape. The intrinsic contamination of $\overline{\nu}_e$, from creation at the target, rather than from oscillations, is at the $\sim 4\times10^{-4}$ level because almost all of the (grand)parent π^- capture before they can decay.

By measuring the oscillation wave as a function of distance travelled (L) and energy (E), the value of δ_{CP} can be measured. DAEδALUS will probe the oscillation wave at three different distances with three similar accelerator facilities located at L=1.5 km, 8 km, and 20 km from an

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ultra-large, kiloton-scale detector composed of Gd-doped water or scintillator. The concept and configuration are shown in Fig. 2.

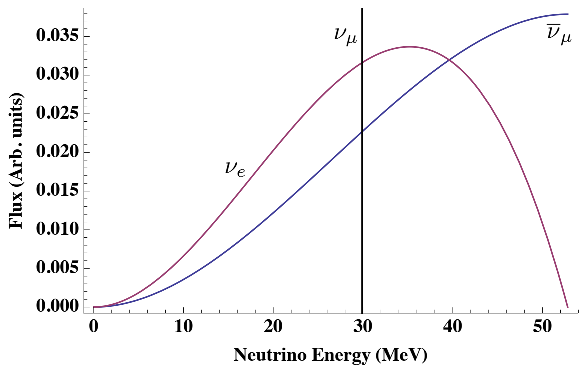

Figure 1: The neutrino and antineutrino energy distributions for a pion and muon decay-at-rest source.

The sources at each of the three accelerator facilities will need to be run at different times in order to be able match a neutrino event to a facility and distance travelled. Further, all accelerators will need to be off for about half of the time so that steady-state backgrounds in the detector can be measured. The DAEδALUS power requirements at each site are 0.8, 1.6 and 4.8 MW, respectively. These requirements have been determined so that DAEδALUS can match the sensitivity of the Long Baseline Neutrino Experiment (LBNE) 2011 design [7]. LBNE is a conventional long baseline neutrino oscillation experiment. The combination of such an experiment's data, especially in neutrino-mode, with DAEδALUS can provide sensitivity that is even better than a conventional beam experiment in combination with an intensity upgrade, such as Project-X for LBNE [8]. Further, the combination of DAEδALUS and a long baseline oscillation experiment can provide two independent measurements of neutrino CP violation with almost completely orthogonal sources of systematic errors.

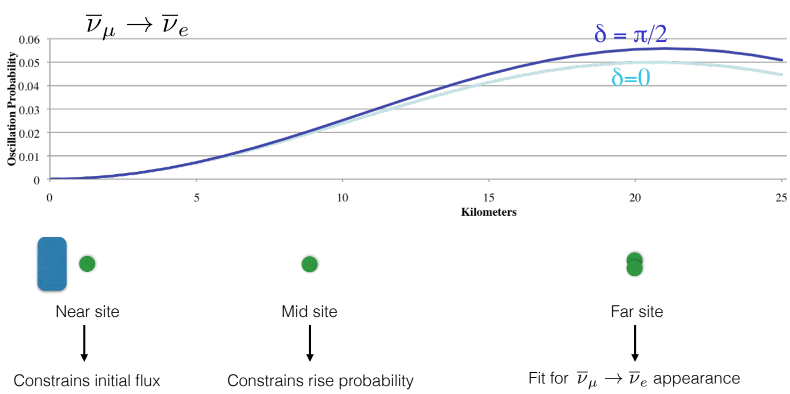

Figure 2: The layout of the DAEδALUS experiment, showing the accelerator locations with respect to an ultra-large detector, and the corresponding oscillation probability for two different values of δ_{CP}.

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2.1 Physics with DAEδALUS

DAEδALUS has developed a phased program for addressing the technological issues associated with constructing these cyclotrons and establishing their viability. Phase 1, which is well underway, aims to construct and test the ion source; Phase 2 is a full-scale trial of the injector cyclotron and low energy beam transport system with the possibility of an interesting physics opportunity, called IsoDAR; Phase 3 will proceed with the creation of the first full accelerator module; and Phase 4 involves the implementation of the full DAEδALUS experiment with cyclotrons at the three sites discussed above.

The DAEδALUS Injector Cyclotron (D-IC) will produce 5 mA of H_2^+ at 60 MeV. Along with a number of physics opportunities associated with this source, the D-IC has applications in the production of medical isotopes.

The IsoDAR concept will rely on the injector cyclotron to produce an intense source of electron antineutrinos. The 60 MeV protons from the D-IC will be directed onto an ^{8}Be target. The interaction will create a large neutron flux coming off of the target. A surrounding 99.99% isotopically pure ^{7}Li sleeve will be used to capture thermal neutrons. The resulting ^{8}Li beta decays to produce an electron antineutrino with energy in the range 3-14 MeV. This source can be located within tens of meters of an existing scintillator based detector [9], such as KamLAND, for detecting inverse beta decay (IBD) interactions $\overline{\nu}_e p \rightarrow e^+ n$ and $\overline{\nu}_e$-electron elastic scatters.

There are a number of physics possibilities available with these electron antineutrino events. IsoDAR will provide sensitivity to neutrino oscillations at high-Δm^2, where a positive result would be indicative of a sterile neutrino. In fact, IsoDAR can reach a sensitivity of $>10\sigma$ to electron antineutrino disappearance at $\Delta m^2 \sim 1$ eV^2 and even has the ability to distinguish between the existence of one or two sterile neutrinos in many mixing scenarios. Further, the $\overline{\nu}_e$-electron scatter sample would provide a unique sample for probing beyond the Standard Model [10].

The first accelerator module will be used to create a source of neutrinos from stopped pion and muon decay and will nominally act as the "near" accelerator for the CP violation measurement. This source can also be used to accomplish a number of short-baseline neutrino measurements, especially when considered in combination with a number of smaller detectors located proximally to the accelerator. First, the source can be used, in combination with an experiment such as LENA [11], to search for high Δm^2 $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance as well as ν_e disappearance indicative of a sterile neutrino [12], which are both complementary measurements to IsoDAR. Indeed, if the sterile neutrino exists, we will want to describe its properties and mixing behavior as precisely as possible. Studying the sterile neutrino with both neutrino and antineutrino oscillations can also allow for stringent tests of both CP and CPT violation. Notably, the electron antineutrino appearance search will also be a direct test of the LSND and MiniBooNE anomalies [13, 14]. The near accelerator can also be used to perform a coherent neutrino scattering experiment with a dark-matter-style detector sensitive to nuclear recoils at the keV-scale [15]. Such a detector could be placed within tens of meters of the source in order to search for the well-predicted but as-yet-unseen process of a neutrino coherently interacting with an entire nucleus. Further, in case the accelerator is located at a deep underground lab, a dedicated dark matter detector will likely be able to make the discovery as well. A multi-detector or multi-target setup can also provide a unique neutral current based sterile neutrino oscillation search using coherent neutrino-nucleus scattering [16]. If there is a sterile

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neutrino or neutrinos, the neutral current will be uniquely sensitive to the sterile flavor composition of the fourth neutrino mass eigenstate.

3. The DAEδALUS accelerator complex

The beam power at each neutrino source station will be supplied by a DAEδALUS Injector Cyclotron, delivering beam at 60 MeV/amu which is then accelerated by the DAEδALUS Superconducting Ring Cyclotron (D-SRC) up to 800 MeV/amu.

This accelerator complex delivers a peak proton current of 10 mA and, when operated with a duty cycle of 20%, its average beam power is 1.6 MW. To deliver the 0.8 MW power required at the first location, the accelerator will be driven at 10% duty cycle, while for the second site the duty cycle will be increased to 25% for achieving 2 MW. For the far site we have two options: the first option is to install three 25% duty cycle accelerators, which all together could deliver up to 6 MW; the second and cheaper option is to inject the beams delivered by two D-IC into one D-SRC. This accelerator configuration seems feasible and allows the delivery of 3.2 MW when operated with a duty cycle of 20%. In this scenario, two accelerator complexes at the far site should be able to deliver a beam power up to 6.4 MW. The D-IC in operation with a 100% duty cycle is also a proper driver for the IsoDAR experiment.

Today, the PSI cyclotron is the world's most powerful proton driver. It is able to deliver a beam current of about 2.4 mA at 590 MeV (1.4 MW) and there is a plan to increase the beam current up to 3 mA and more. Clearly, meeting the DAEδALUS goal to inject and extract a 10 mA proton beam is challenging. One of the main strategies for overcoming this issue is to inject and accelerate H_2^+ ions instead of bare protons.

The use of an H_2^+ beam has the disadvantage of a beam magnetic rigidity that is twice that of a proton beam of the same energy. However, the strategy has two great advantages: (1) The beam extraction from the D-SRC can be accomplished with the use of a stripping foil, avoiding the need for a clean separation between turns that is mandatory for bare protons; and (2) the beam space charge effects are significantly reduced. At higher beam currents the space charge of the particle beam produces a repulsive force among the particles that broadens the beam size. A measure of the strength of the space charge effect is the so-called "generalized perveance", defined by

$K = \frac{qI}{2\pi\varepsilon_O m\gamma^3\beta^3}$, where q, I, m, γ and β are the charge, current, rest mass and the relativistic parameters of the particle beam, respectively [17]. The higher the value of K, the stronger the space-charge detuning effects. The space-charge effects for 5 mA of H_2^+ beam are equivalent to a 2.5 mA proton beam with the same γ. We expect that the 5 mA H_2^+ of beam accelerated along the D-SRC will have similar space-charge effects present in the 2.4 mA proton beam being accelerated currently at PSI. Similarly, the characteristics of the beam along acceleration through the D-IC will be quite similar to the acceleration of PSI's "Injector 2". To save money and space, we will use the a compact cyclotron design for the D-IC instead of a separated sector cyclotron like the "Injector 2" of PSI. For this reason, the central region and the characteristics of the injected beam are quite similar to commercial cyclotrons used for radioisotope production. The beam injected into commercial cyclotrons is provided by external sources of H^- with energies in the range 25-30 keV. These cyclotrons are routinely able to accelerate up to 1 mA and have gone up to 2 mA of H^- beam. If we compare the space charge effects of 2 mA H^- injected at 25-30 keV with the

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space charge effect of 5 mA H_2^+ at 70 keV the perveance K values are very similar. An additional advantage for H_2^+ vs. H^- ion sources is the lower value of the normalized emittance of the delivered beam, typically 1.5-2 times smaller.

The space charge effects and beam dynamics in the DAEδALUS cyclotrons have been studied quantitatively by numerical methods implemented in the parallel code OPAL [18], developed at PSI. Some results of the beam dynamic simulations are presented in the following section.

4. The DAEδALUS Superconducting Ring Cyclotron

The initial design of the D-SRC was based on an 8 sector machine. For reducing the size and cost of the device, a superconducting separated sector design is the most convenient solution. Using the OPERA3D code by Cobham we simulated the magnetic field of the cyclotron and the beam dynamics features investigated using the OPAL code. In the D-SRC, the beam loss at extraction is relaxed by using stripping extraction that has an efficiency very close to 100%, even if the beam orbits at the extraction radius are not well separated. The two main problems that we investigated are: (1) the vertical focusing at higher energies, which is usually weak in a superconducting cyclotron, and (2) the relatively large energy spread of the extracted proton beam, due to the multi-turn extraction. Distributions of the H_2^+ beam in the vertical/radial plane, at a fixed azimuthal position, for 0 mA and a 5 mA are shown in Fig. 3. Beam halos extend vertically $\pm$20 mm, although they clear the vacuum chamber, which has a 70 mm gap. It is quite evident from the simulation that, in the D-SRC, space charge and neighboring bunch effects introduce vertical beam halo, but these effects have a negligible impact on the beam losses. The previous 8 sector D-SRC

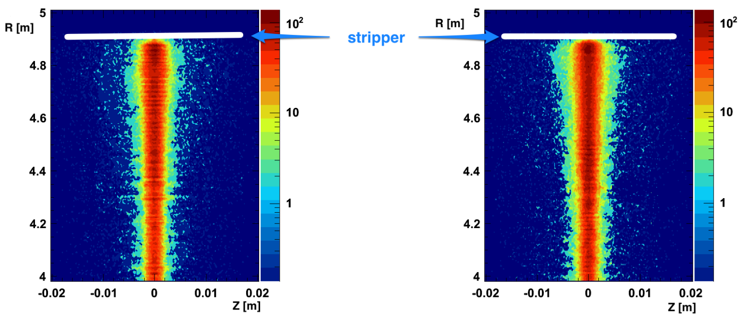

Figure 3: The simulated particle projection distribution for a H_2^+ beam in the vertical (Z) - radial (R) plane, at a fixed azimuthal position, for a 0 mA (left) and a 5 mA (right) plane.

design was unsatisfactory because the space between the sectors was not large enough to install the coil's cryostat and the RF cavities. Moreover, the proposed coil had a challenging configuration shape [19]. The updated design of the D-SRC consists of a new 6 sector machine. Among other things, the new design allows more room for installation of the PSI-like RF cavities and reduces the cost. The design of the new 6 sector D-SRC has been developed together with the Technology and Engineering Division (T&ED) of the MIT Plasma Science and Fusion group. T&ED developed the magnet conceptual design to provide a realistic solution both for the magnetic coils and for the cryostat. In particular, the cryostat design satisfies the cryogenic request and, at the same time, is robust enough to balance the enormous magnetic forces [20]. This new configuration allows the

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Table 1: The main parameters of the proposed D-SRC in comparison to the Riken-SRC.

Properties	D-SCRC	Riken-SRC	Properties	D-SRC	Riken-SRC
Max field in the hill	4.72 T	3.8 T	Max field on the coil	4.27 T	4.2 T
Valley field	0.65 T	0.04 T	Extraction method	Stripper	El. deflector
Coil size	31x16 cm^2	21x28 cm^2	Coil circumference	10.85 m	10.86 m
Current density	34 A/cm^2	34 A/cm^2	Stored energy	303 MJ	235 MJ
Height	6 m	6 m	Outer Radius	7.3 m	7.2 m
Weight/sector	830 tons	800 tons	Number of trim coils	0	22 + 4 S.C.

installation of 4 PSI-like RF cavities. These cavities are able to achieve 1 MV of acceleration voltage and are useful to minimize the length of the acceleration path and reduce the losses due to the interaction of beam particles with the residual gases. The electrostatic inflector occupies a valley for the injection, and two magnets in another valley allow the proper adjustment of the injection and extraction trajectories. Moreover, the new 6 sector design allows a simpler injection system since the valleys are larger than in the 8 sector machine.

Table 1 summarizes the parameters of the new D-SRC and compares them with RIKEN's SRC [21]. The iron shape has been optimized to maintain a vertical tune higher than 0.5. A further optimization of the boundary of the iron pole is in progress to achieve an isochronism better than 10^{-3} and a phase shift lower than $\pm 20^\circ$ RF. This procedure consists of shimming the boundary of the cyclotron pole sectors carefully in both the design and construction phases.

5. The IsoDAR cyclotron

The design of the IsoDAR cyclotron is simply based on the DAEδALUS injector cyclotron [22] design, but it takes into account solutions for transport and assembly of the machine through the constricted access apertures of the Kamioka mine. Moreover, the required beam intensity is about 10 times higher than the maximum intensity delivered by the 30 MeV compact cyclotrons used for radioisotope production. In particular, during the beam injection, the space-charge effects are a crucial issue. This effect is mitigated by injecting H_2^+ beam at an energy of 70 keV or higher, but not avoided.

In order to investigate the problems related to the injection of this high current beam and to check the critical issues, a collaboration between MIT, INFN-LNS, and Best Cyclotron Systems Inc. (BCSI) [23] has installed a test stand at the BCSI laboratory in Vancouver. The IsoDAR cyclotron, like the D-IC, is a four-sector machine, with a pole radius of 220 cm and a large vertical gap of 10 cm. Four RF double-gap cavities, with an accelerating voltage that rises from 70 kV at the inner radii to 250 kV at the outer radius, are placed in the four magnet valleys. The large accelerating voltage at outer radius allows achieving an inter-turn separation of about 13 mm. The beam power extracted from IsoDAR will be 600 kW. This huge power poses a serious constraint on the efficiency of the extraction process, which must be close to 100%. To increase the inter-turn separation, the outer region of the pole is designed to allow the beam to cross the νr=1 resonance in the extraction region. So, driving a small off-center in the beam orbit, the first harmonic precession increases the inter-turn separation to 20 mm and an extraction efficiency of 99.98% (with electro-

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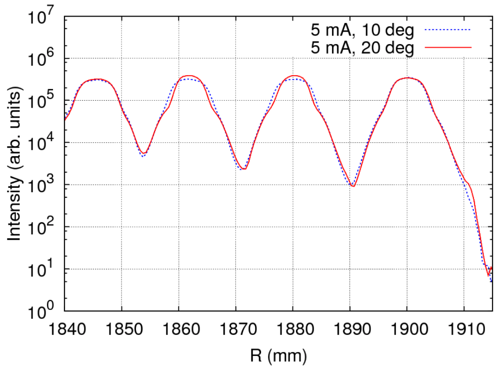

Figure 4: The radial profile of the last four turns at the center of the valley for a 5 mA H_2^+ beam with an initial phase width of 10° and 20° RF.

static deflectors) is expected. The result of the beam acceleration, including space charge effects, as performed by the OPAL code [18], is shown in Fig. 4.

5.1 The injection line

The H_2^+ molecule beam has to be injected at the highest energy possible. Ion sources like VIS [24] can work with an extraction voltage of 70 kV and deliver H_2^+ beam with an energy of 35 keV/amu. An axial injection system based on a Spiral Inflector (S.I.) will be used to bend the beam from the axial direction to the median plane. The S.I. of IsoDAR has a 15 mm gap between the electrodes, instead of the usual value of 6-10 mm used in cyclotrons for nuclear physics research or radioisotope production. The entire system, including the S.I. and central region, is designed by using the back/forward integration method starting from an accelerated equilibrium orbit (AEO). The shape and the position of the tips in the central region are modified in order to guarantee a suitable energy gain and an optimal vertical focusing during the beam transport from the S.I. to the AEO. As concerns the S.I., several models are under study. The voltage difference between the electrodes is in the range 20-22 kV, and a large tilt angle is used to achieve the matching between the S.I. particle path and the median plane path. An alternative to the electrostatic S.I. is to use a dipole magnetic inflector made by a set of permanent magnets. The main advantage of using a magnetic inflector is that we avoid the insertion of an electrostatic device that destroys locally the neutralization effect of space charge compensation due to the ionization of the residual gas. Studies on the feasibility of this option are in progress.

5.2 Technical solutions for installation in the mine

The IsoDAR cyclotron has to be installed underground near an appropriate neutrino detector, a possible option being KamLAND at the Kamioka mine in Japan. As the experimental site has a small access area, both transport and assembly pose critical constraints to the cyclotron design. The IsoDAR cyclotron will not be the first case of cyclotron "cutting-in-pieces". The most famous example is the TRIUMF 500 MeV cyclotron. A tentative solution for constructing the coils, magnet circuit, and vacuum chamber has been evaluated. The aluminum coil is divided into 13 layers parallel to the median plane with an angular width of 180°. This solution allow that all the pieces

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are the same, but the machining of the coil plate is complicated and expensive. An alternative solution consists of concentric layers with an angular width of 180° . This solution is easier and cheaper than the former case, but the welding and the cooling water system might be challenging. As concerns the iron, a tentative solution would be to divide each pole into four independent sector poles with a weight of 13 tons each. Also, the yoke is cut into four symmetric pieces with an angular width of 90° and a weight of 45 tons; each yoke part has a radius of 3.2 m and a height of 1.2 m. The vacuum chamber consists of an upper and lower region that is just the RF liner of the four cavities plus an additional cylinder wall around the median plane. These three vacuum chamber components have to be welded on-site (see Fig. 5). This is a critical part of the machine assembling, because a vacuum lower than 5×10^{-6} Pa is needed to minimize the beam power losses along the acceleration path.

The IsoDAR cyclotron design is still in progress. Moreover, the possibility of using deuterons with a maximum energy of 40 MeV/amu, instead of H_2^+ with 60 MeV/amu, is under evaluation to reduce the cyclotron pole radius down to 180 cm. This possibility makes the transport and installation of the cyclotron inside the Kamioka cavern simpler and comes with a cost reduction as well.

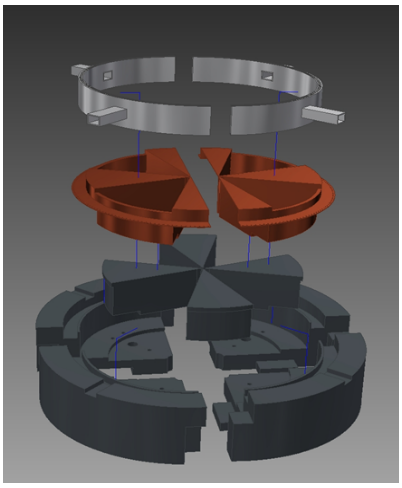

Figure 5: The layout of the IsoDAR magnet and vacuum chamber divided in smaller parts.

6. Conclusion

High current cyclotrons offer an attractive opportunity for advancing neutrino physics by enabling compact sources that can be deployed in close proximity to large detectors. In this paper we have shown the compelling physics case for these devices, have presented an attractive conceptual solution for these cyclotrons, and have addressed some of the technical challenges to be overcome, from beam dynamics simulations of the highly-space-charge-dominated beams to installation in confined underground environments. In all, we are confident that the cyclotrons can indeed be built and deployed, and can perform to the required specifications.

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