HIGH POWER CYCLOTRONS FOR NEUTRINO EXPERIMENTS

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Abstract

The study of the neutrino properties using decay-at-rest beam requires high intensity proton beams able to produce optimal reaction channels. In particular, the MIT experiments named DAEδALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) and IsoDAR (Isotope Decay At Rest) require a proton beam current up to 10 mA each. High power cyclotrons able to produce proton beams at the maximum energies of 60 MeV (IsoDAR) and 800 MeV (DAEδALUS) are under investigation: the critical points and the proposed solutions are discussed here.

INTRODUCTION

The aim of the DAEδALUS experiment is the observation of the neutrino oscillation characteristics, which can give information about the CP violation [1]. The optimal channel to produce the neutrino fluxes is a 800 MeV proton beam on a low Z target. The experiment requires three different neutrino sources, located at 1.5, 8.0 and 20 km from the detector, which have to operate with 20% duty cycle, in order to allow the identification of the source that produced the neutrino measured at the detector and to allow for measuring the background. The requested beam power for each source is 1, 2 and 5 MW respectively.

A cyclotron complex is proposed to drive each of the three neutrino sources. Each complex consists of a DAEδALUS Injector Cyclotron (DIC) to reach the intermediate energy of 60 MeV/amu and of the DAEδALUS Superconducting Ring Cyclotron (DSRC) to

accelerate the beam up to 800 MeV/amu [2].

To mitigate the strong space charge effects at 10 mA, we accelerate H_2^+ molecules instead of protons. With electrostatic deflectors the beam is extracted from the DIC. The beam from the DSRC is extracted by a carbon stripper foil [3].

The DIC, if operated with a 100% duty cycle is an ideal accelerator to drive IsoDAR, an experiment to investigate the existence of the sterile neutrinos [4]. This experiment requires the machine to be placed near an underground detector.

THE INJECTOR CYCLOTRON

The DIC is a four sector compact machine. Its main features were presented at previous conferences [5,6] and will be not described here. It is equipped with 4 RF double-gap cavities. To allow a better capture efficiency of the injected beam, the working frequency has been significantly reduced with respect to the 6th harmonic of the previous design. To achieve the coupling with the DSRC, the DIC will work by using harmonic 3rd (24.6 MHz), while for the IsoDAR experiment the machine will work in harmonic 4th (32.8 MHz). The configuration of the magnetic circuit guarantees both the condition of optimum isochronism and a slow crossing of the $v_r = 1$ resonance at the extraction region. This feature allows to increase the inter turns orbit separation of the final two turns to 20 mm and obtain an extraction efficiency close to 100% by using electrostatic deflectors. Beam dynamic simulation including space charge effects along the full acceleration path were performed by using OPAL code [7].

To install the DIC underground, for the IsoDAR experiment, each component of cyclotron has to meet serious constraints to allow access through the small existing tunnel. The machine will be built in several parts in a way similar to the TRIUMF cyclotron. A critical part is the vacuum chamber, because pressure lower than $5 \cdot 10^{-6}$ Pa is mandatory to minimize the beam losses. The vacuum chamber consists of three main components: the upper and lower liner and the cylinder wall. These components have to be cut into two parts and welded in situ. A similar solution is proposed for the coil.

The cyclotron iron was also divided taking into account both size and weight of each element. It includes the 4 independent poles, which have to be embedded over the yoke. Similarly the yoke is divided into 4 symmetric parts (see Fig. 2).
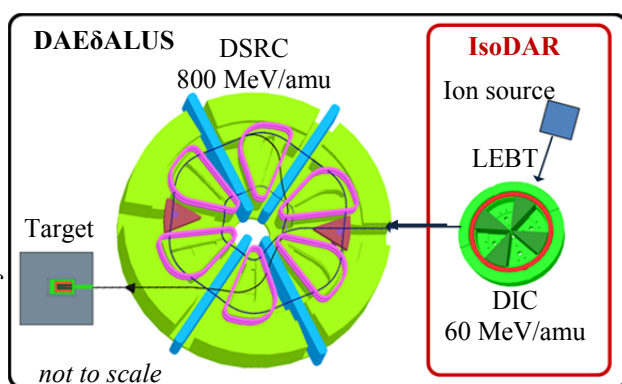

Figure 1: The DAEδALUS accelerator complex consists of a high intensity source and LEBT, of the injector cyclotron and of a Ring superconducting cyclotron booster.
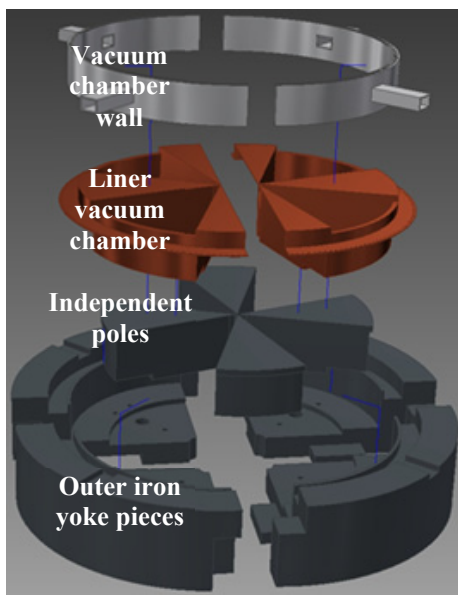
Figure 2: Magnet assembling. The vacuum chamber wall and the liner vacuum chamber are both divided into two parts.

BEAM INJECTION AT LOW ENERGY

A critical issue concerning the high intensity beam is the beam injection. Into compact cyclotrons, like the proposed DIC, the beam is usually injected by a spiral inflector, which bends the beam into the median plane.

The spiral inflector of the DIC has a large electrode gap of 15 mm, to avoid beam halo striking the electrodes. But the larger gap means also a higher vertical size of the device, hence there is a need to include the variation of the magnetic field along the injection. Moreover, in order to limit the space occupied by the device itself, the tilt angle of electrodes and the applied voltage have high values.

To verify the design method accuracy, the reliability of the simulation and to perform a true test, a prototype device will be tested in the coming months at Best Cyclotron Systems, Inc. (BSCI) in Vancouver, Canada, where a small 1 MeV cyclotron prototype has been built for high-intensity injection and beam dynamics studies.

The spiral inflector applies an electric field on the order of 15 kV/cm that prohibits space charge neutralization in this region and may be even upstream in the beam line. It also limits the maximum size of the useful space for the beam.

An alternative solution to the usual spiral inflector is under study. It is a magnetic inflector based on the so called Halbach magic ring, an array of permanent magnets able to produce a high uniform magnetic field inside the ring and a low stray field outside. A set of 6 modified Halbach rings has been modelled in order to guide the beam from the injection line to the cyclotron median plane. In order to minimize the cost, the rings have all the same geometry.

The inner aperture of our modified Halbach ring has a radius of 1 cm, while the maximum external radius is around 2.5 cm. These dimensions guarantee enough space for the beam and also fit the space available in the central region of the DIC. The first results concerning the beam transport simulation show a high transport efficiency (see Fig. 3). The study of the technical solutions for a correct assembling of the permanent magnets and of the tuning of the whole system is in progress.
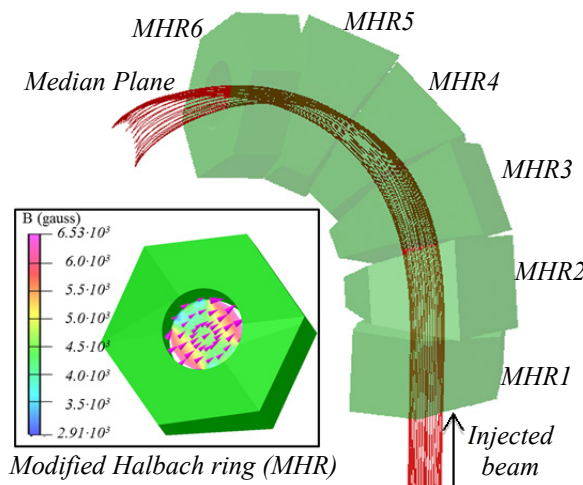

Figure 3: View of the magnetic inflector, which consists of 6 modified Halbach rings, that bend the beam into the median plane.

THE BOOSTER RING CYCLOTRON

The DAEδALUS Superconducting Ring Cyclotron (DSRC) is the last module of the accelerator complex and provides the acceleration of the H_2^+ beam up to 800MeV/amu. The design has significantly changed since the first feasibility study [3, 8]. Reducing the number of the magnetic sectors to six, both the iron and cryostat complexity drops, as well as the costs. Moreover, the beam injection and extraction systems become simpler. The maximum magnetic field was reduced from the early value of 6 T to 4.5 T and consequently, the radial magnetic forces on the sectors are significantly decreased. Further details are published in [9].

A current density of 34 A/mm^2 feeds the six superconducting sector magnets. This value is creditable since it is the used value for the RIKEN SRC. The long straight sections of the superconducting coils of the DSRC are connected by stainless steel plates installed inside the cryostat to contain the large structural forces. Magnetostatic studies and the optimization process have been done using the OPERA-3D code (Cobham). The study of the conductor, the winding pack design and the cryostat study, as well as the evaluation of the warm-to-cold supports have been presented in [10].

Four single-gap copper cavities are used to accelerate the beam. The operating frequency is the 6th harmonic (49.2 MHz), the acceleration voltage at injection radius is 0.5 MV while it grows up to 1 MV at extraction radius. These cavities are almost similar to those used at PSI.

Unfortunately, studies on the beam dynamics, pointed out that at position where the resonances $v_r = 2$ is crossed, the combined effects of the 6 sectors and of 4 RF cavities produce a growing of the beam size in the vertical direction.

Adding two additional double gap cavities in the two empty valleys is enough to avoid this effect. In Fig. 1, the magnetic structure, the coil and the 4 PSI-like cavities are shown. An isochronicity in the order of ±0.05% and a phase shift between ±10° RF were achieved. The Walkinshaw resonance is crossed once very rapidly, and no beam loss was observed. The extraction trajectory that crosses the inner part of the DSRC, and the correction magnet is also drawn in Fig. 1. Extraction is achieved by means of a thin (2 mg/cm^2) pyrolitic graphite foil.

The DSRC will be operate with a duty cycle of 20% and a pulse width around 1 - 2 ms to ensure the foil temperature is kept below 2500 K. Based on the experience of SNS we anticipate foil lifetime of several months.
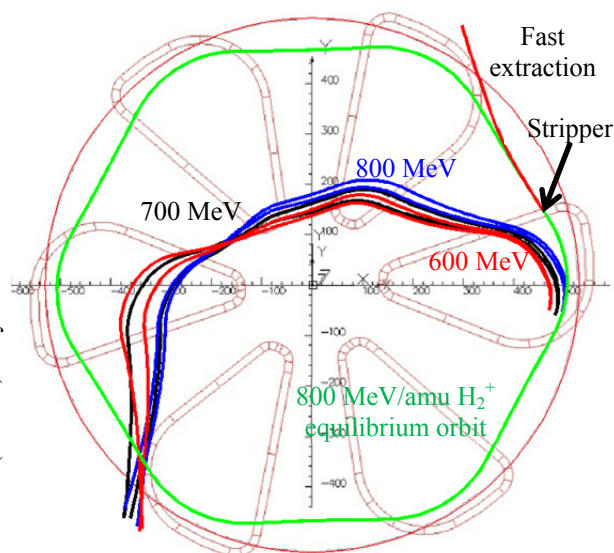

Figure 4: Trajectories of proton produced by H_2^+ dissociation in a localized position go away from the booster cyclotron.

FUTURE DEVELOPMENTS

Despite the fact that acceleration of H_2^+ offers the advantages mentioned before, there is a problem related to the exis tence of many vibrational states that have binding energy lower than the fundamental states. We plan to dissociate the majority of these vibrational states both at the source level and along the matching line between the DIC and the DSRC. But if H_2^+ molecules in the vibrational states higher than 7 - 8 with respect to the fundamental state are injected inside the DSRC, they will be dissociated by Lorentz stripping due to the high magnetic field and lost inside the vacuum chamber.

To avoid this problem we plan to build up a local magnetic field bump, of 3 - 5 kGauss, inside each hill and having an angular width of about 2°. These magnetic bumps can be produced using permanent magnets placed inside the vacuum chamber. This solution allows producing the electromagnetic stripping just at the proper position and not everywhere along the orbit trajectory. A proper location of this bump will allow us to dump the dissociated proton outside of the DSRC vacuum chamber.

According to the trajectories shown in Fig. 4, the particles with energies higher than 650 MeV/amu bend away from the cyclotron. Unfortunately, for beam energy as low as 600 MeV or lower the trajectory strikes the inner part of the cryostat. Despite this, the presented solution is very promising and will be studied further.

To avoid the beam crossing the inner part of the DSRC, see Fig. 1, a study to achieve a fast extraction was performed. In particular, if the stripper foil is placed at the exit edge of the hill, instead of the entrance of the hill, the stripped protons cross the following valley where they find a reverse field that bends them towards the outer radii with respect to the accelerated H_2^+ beam. In the simulated magnetic configuration at the end of the valley the separation between the stripped beam and the last accelerated orbit increases up to 20 mm. Unfortunately, this value is not enough to push away the proton beams.

We performed simulation increasing the reversed magnetic field along the extraction path by 5 kGauss and the separation between the accelerated orbit and extracted proton beam grows up to 18 cm and the beam can escape the cyclotron region, see Fig. 4. The fast extraction could be done in the valley where we plan to install the double gap cavities. The higher magnetic field can be achieved by permanent magnets. Further simulations of the full magnetic configuration of DSRC are necessary to verify the isochronism of the magnetic field and the stability of the beam dynamics.

REFERENCES

[1] J.M. Conrad and M.H. Shaevitz, Phys.Rev.Lett. 104, 141802 (2010).

[2] J. Alonso et al., "Expression of Interest for a Novel Search for CP Violation in the Neutrino Sector: DAEδALUS", Jun 2010. e-Print: arXiv:1006.0260.

[3] L. Calabretta et al., Int. Conf. on Cycl. and their App. Lanzhou 2010; TUA1CIO01.

[4] A. Bungau, et al, Phys. Rev. Lett. 109, 141802 (2012).

[5] D. Campo et al., IPAC'12, New Orleans (USA) 2012, MOPPD026.

[6] D. Campo et al, Int. Cycl. Conf. App., Vancouver (C) 2013, to be published.

[7] J.J. Yang et al.; Nucl. Inst. & Meth. in Phys. Res.; section A; vol. 704; (2013) p.84-91; ISSN: 0168-9002.

[8] A. Calanna et al., PAC New York (USA) 2011,

[9] A. Calanna et al, Int. Cycl. Conf. App., Vancouver (C) 2013, to be published.

[10] J. Minervini et al., "Engineering Study of Sector Magnet for the DAEδALUS Experiment", arXiv:1209.4886.