THE CYCLOTRON COMPLEX FOR THE DAEDALUS EXPERIMENT

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Abstract

The cyclotron complex for the DAEδALUS CP-violation neutrino experiment consists of a compact cyclotron able to accelerate high-current (5 electrical milliamps) H_2^+ beams up to an energy of 60 MeV/amu, cleanly extract this beam with two electrostatic deflectors, and transport it to a superconducting ring cyclotron (D-SRC) able to accelerate the beam up to 800 MeV/amu. H_2^+ is dissociated with thin stripping foils for efficient extraction as protons then the beam impinges on a megawatt-class target for neutrino production. The D-SRC is similar in size and engineering concept to the SRC at RIKEN. Space-charge dominated beam dynamics simulations using OPAL have been performed for an eight-sector geometry, and indicate acceptable transmission and low beam losses. Subsequent engineering magnet-design studies [1] pointed to a six-sector configuration as more practical. Results of the studies conducted to date are presented.

INTRODUCTION

The goal of DAEδALUS is the search for a nonzero CP-violation parameter δ [2,3]. This experiment needs three neutrino sources produced by a proton beam with energy of about 800 MeV/amu. In this paper we discuss one of the DAEδALUS Superconducting Ring Cyclotrons, D-SRC, which has to be driven with a proton beam power of 1.6 MW. Further information on the scheme to produce decay-at-rest sources driven by such cyclotrons can be found in [2,3], as well as all constraints discussion, the R&D successes, including construction of a beam-line test-stand [4], and future plans.

Significant changes have been made to the previous eight-sector-design of the D-SRC [5], which did not allow four PSI-like RF cavities to be hosted. The new six-sector-design solves this problem. The new magnetic sector is described in this report, as well as evaluating the other solution, and the reasons that drove the DAEδALUS collaboration together with the Technology and Engineering Division (T&ED) of the MIT Plasma Science and Fusion group to the final choice. T&ED developed the magnet conceptual design to provide very preliminary cost estimates to fabricate a single magnet sector [1]. The conceptual design includes solid modelling and analyses for the conductor and winding pack design, high temperature superconductor and copper current leads for the magnet, structural design of the magnet cold mass, cryostat and warm-to-cold supports, cryogenic design of the magnet cooling system, and magnet power supply sizing. Injection system preliminary study is reported in [6].

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Here we present the features of the new design and the results of beam dynamics simulation achieved without space-charge effects.

THE SECTOR MAGNET EVOLUTION

In the design presented in [5] there were three major blocking points:

- the variable coil cross section, which could cause complications to the cooling system and the natural flow of the LHe. Moreover, arrangements with tilted coils are acceptable but add complexity to the wounding process;
- there wasn't enough room to host PSI-like RF cavities;
- the residual radial force was too high.

We studied two very different options. The first solution, option A, is an eight-sector machine, Fig. 1. The difference with [5] is based on the consideration that even if we have an eight-sector machine we don't need symmetry eight at energies below 400 MeV/amu. First, we shaped the iron to free the space up to radii smaller than 400 cm, and then we designed a new coil that has symmetry four at the lower radii and symmetry eight at the outer radii. The optimization process led us to reach almost the same precision in the field isochronism and for the vertical focusing (maybe a little bit better) than in the previous design.

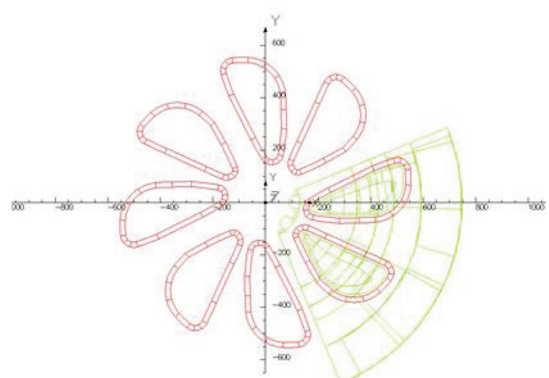

Figure 1: Option A layout.

Improvements are:

- we have four valleys in which the space between coils is 95 cm, large enough to install RF cavities;
- the current density has been decreased from 34A/mm^2 to 28.33 A/mm^2. We could stress again the current density parameter up to 34 A/mm^2 and adapt the coil. In this way we could gain more space for the cavities or the injection tools;
- cross-section is constant and it is 20x30 cm^2, without any negative curvature.

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However, this solution has some drawbacks. Although the outer geometry has a perfect eight symmetry, the magnetic field up to radii of 500 cm has a component of harmonic 4, which is small, but not zero. Moreover, the space for the injection has been severely reduced and the stray field in the valley has risen to almost 7 kGauss.

To overcome these issues we developed option B, which is a six-sector-cyclotron. Basically, the sector was scaled by a factor 6/8 and so was the coil, than the optimization process started shaping the iron to get a good isochronism (now fixed in the order of +/-0.05%) and the evolution of beam parameters during the acceleration. For sake of completeness, the stop band resonance for a six sector machine is for γ=3 that means about E=1900 MeV/amu, which is very far from our final energy. This solution does not have the issue for the installation of the PSI-like RF cavities, even if the maximum number of cavities allowed is four. The new design implies a simpler injection system since the space separation between valleys is larger than in an eight-sector machine. Also in option B, the cross section of the coil is constant and it is 31x16 cm^2. The current density is 34 A/mm^2. As it was in option A, the distance between the iron and the internal face of the coil has been increased to 10 cm. Moreover, the coil is parallel to the median plane, from which the distance is 12 cm.

The optimization process led us to results better than the eight-sector machine. Since we have more space, we can have more spiraled coils, and this really helps the vertical focusing. The T&ED study reports both solutions are feasible. However, option B, with six sectors, which is shown in Fig. 4, is the favorite. There are many arguments in favour of this decision:

- lower cost of building a smaller number of magnets (~6/8=75%);
- more space around the winding to accommodate the structural coil case and the cryostat;
- easier beam injection and extraction;
- smaller residual radial magnetic force on the coils.

THE NEW MAGNETIC SECTOR

A view of half cyclotron with all the coils and the RF cavities is shown in Fig. 4. Table 1 summarizes the parameters of the D-SRC comparing them with the RIKEN's ones. The iron is spiralled at the outer radii to assure the vertical focusing and the big hole in the centre of the hill is maintained. The valley will host four PSI-like cavities, which are able to achieve 1 MV of acceleration voltage and are the best performing among the existing ones. The possibility of adding two additional cavities is under evaluation, see the next section.

Although the optimization process is still going on, a good isochronism, on the order of +/-0.5‰ (Fig. 2a) has been reached. The phase of the isochronous particle oscillates between +/-30°RF.

The q-graph, together with the coupled most dangerous resonances are plotted in Fig. 2b.

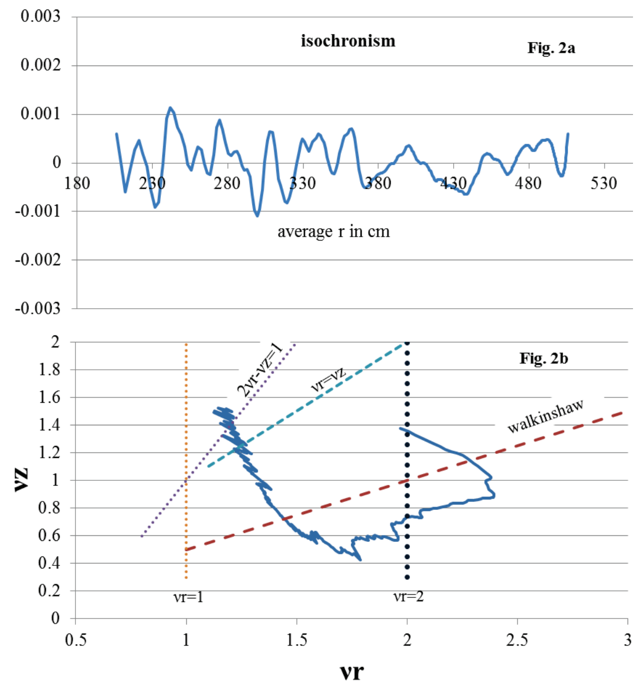

Figure 2a: Field isochronism for the new six-sector-cyclotron. Figure 2b: Tune plot of the six-sector cyclotron

BEAM DYNAMICS

A compact cyclotron similar to the one proposed in [7] for IsoDAR experiment will provide the beam to inject in the D-SRC. The main difference between DAEδALUS-injection cyclotron and IsoDAR cyclotron will be the harmonic number, in DAEδALUS set to 3. The preliminary study of the injection system in the D-SRC is reported in [6]. The acceleration and extraction have been evaluated with the code SPIRAL GAP, which does not take into account the space-charge effects. Simulations done with SPIRAL GAP pointed out an issue we need to overcome. Our configuration forecasts four PSI-like RF-cavities working in 6th harmonic; this means that the acceleration has symmetry two. The coupling effect of this symmetry when the resonance ν_r=2 is crossed at 670 MeV broadens the beam radially. Consequently, when the beam crosses the Walkinshaw resonance at 780 MeV, we see a vertical beam explosion. Simulations of the beam acceleration assuming the six-sector-cyclotron and six acceleration cavities, with the same the gain of energy per turn than in the case with four cavities, show the problem disappears, see Fig. 3. Unfortunately, it won't be possible to install more than four PSI-like cavities, because two valleys must be free to host the electrostatic deflector for the beam injection and the correcting magnet along the extraction trajectory, both located in the central region of the D-SRC. We are evaluating installing two additional double-gap resonators starting at the average radius of 320 cm. These two additional cavities could be similar to the new double-gap cavities designed by PSI for the upgrading of the injector II [8]. Alternative solution to solve this problem is to change the magnetic field configuration at outer radius to move the Walkinshaw resonance out of the acceleration region. Fig. 4 shows the magnetic field on a patch on the median plane. The last closed orbit and the extraction orbit are drawn, too. There is enough space to insert a magnet at the inner radii to optimize the focusing of extracted beam (see Fig. 4).

Table 1: Main Parameters of Proposed DSRC Compared to Riken-SRC

Basic	DSRC	Riken-SRC	units
Max field in the hill	4.72	3.8	T
Max field on the coil	4.27	4.2	T
Stored Energy	303	235	MJ
Coil size	31x16	21x28	cm^2
Coil circumference	10.85	10.86	m
Current density	34	34	A/mm^2
Height	6	6	m
Length	7.3	7.2	m
Weight/sector	830	800	tons
SC trim	No	4	Sets
Valley field	0.6	0.4	T
Extraction method	Stripper foil	Electrostatic channel	

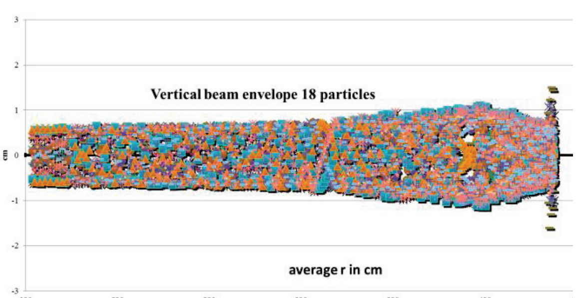

Figure 3: Vertical beam envelope with six-sector-cyclotron and six acceleration cavities, normalized emittance 6.75 π.mm.mrad.

CONCLUSIONS

The present study demonstrates that it is possible to achieve the required isochronous field with good focusing properties, even if some parameters have to be modified to achieve a more reliable solution. In the next future simulations using the OPAL code will be performed. According to the previous simulations made using the magnetic field map of the previous eight-sector D-SRC [9] we don't expect a significant difference with respect to the result already achieved. The six-sector solution looks good, and we will look into it.

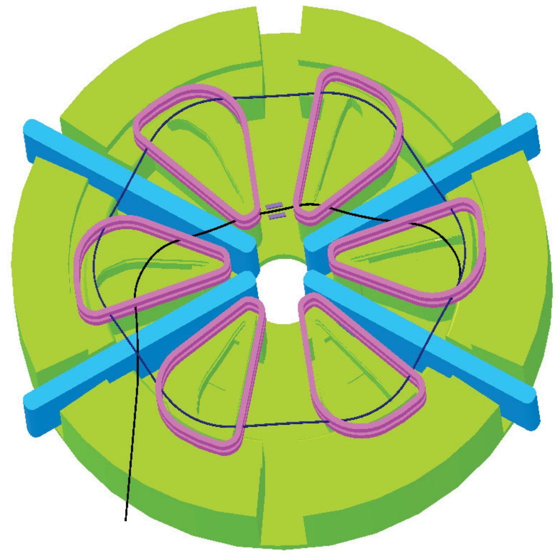

Figure 4: Half cyclotron, option B, with coils. RF cavities, last closed orbits, and extraction orbit with the correction magnet are drawn, too.

AKNOWLEDGEMENTS

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