A SUPERCONDUCTING RING CYCLOTRON FOR THE DAEδALUS EXPERIMENT

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Abstract

DAEδALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) provides a new approach to the search for CP violation in the neutrino sector. High-power, continuous wave proton cyclotrons provide efficiently the necessary proton beams and energy to create the neutrinos from pion and muon decay-at-rest.

In this paper the most challenging question regarding a cyclotron based high-power proton driver in the range of 1 to 8MW with a kinetic energy of 800MeV is addressed. The required cyclotrons must exceed the performance of the world's best performing cyclotron, at PSI, in both energy and power, while, at the same time, maintaining cost effectiveness. The selected accelerated particle for DAEδALUS is H_2^+ to reduce the space charge effects and to easily extract the beam by a stripper foil, which converts the H_2^+ into two protons.

The features of the proposed magnetic sector and superconducting coils are compared with the RIKEN Superconducting Cyclotron design, which is the most similar accelerator existing. TOSCA module of OPERA3D by Cobham has been used to compute magnetic field and GENSPE to work out beam dynamics studies. Both results are here presented.

INTRODUCTION

The goal of DAEδALUS is the search for a nonzero CP violation parameter δ [1]. This experiment needs three neutrino sources produced by a proton beam with energy of about 800 MeV/n. The three sites are located at 1.5, 8 and 20 km far from the underground detector. Each site has to be driven with a proton beam power of 1, 2 and 5 MW respectively. A further constraint requested to the accelerators is to operate with a duty cycle of 20%, typically 1ms beam on, 4ms beam off properly synchronised. Due to this duty cycle the beam peak power is 5 times higher than the average power. The accelerator complex consisting of two cyclotrons, one injector cyclotron [2] and a main ring cyclotron booster, has already been proposed as drivers for energy amplifier or waste transmutation plants [3]. According to our proposal [4,5], a superconducting ring cyclotron able to accelerate a beam of H_2^+ up to 800 MeV/n with a peak current of 5 mA, average power 1.6 MW, is here presented.

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The acceleration of H_2^+ molecule allows extracting the beam by insertion of a thin carbon foil at the radius where the beam reaches the maximum energy. The stripper foil breaks the H_2^+ molecule and produces two free protons. Extraction by stripping does not require well-separated turns at the extraction radius and allows using lower energy gain per turn during the acceleration process and/or lower radius for the magnetic sectors. This means a significant reduction both of the construction cost of accelerator and of power consumption for the RF cavities. The efficiency of extraction by stripper is not sensitive to the beam bunch length or to the energy spread of the beam. Moreover, in cyclotron where the beam dynamic is dominated by space charge effect, the beam bunches are self bunched and flattopping cavities are unnecessary [private communication, J. Yang and A. Adelmann, PSI]. The layout of the proposed DAEδALUS Superconducting Ring Cyclotron (DSRC) is shown in Fig. 1. The injection trajectory with the four magnetic channels (MC) and an electrostatic deflector (ED) necessary to perform the beam injection are also shown. The beam extraction is quite straightforward and only one magnetic channel (MC) is requested to steer a little the trajectory and to produce a gentle axial focusing on the beam. A comparison between the main parameters of DSRC, and the RIKEN SRC is presented in table 1.

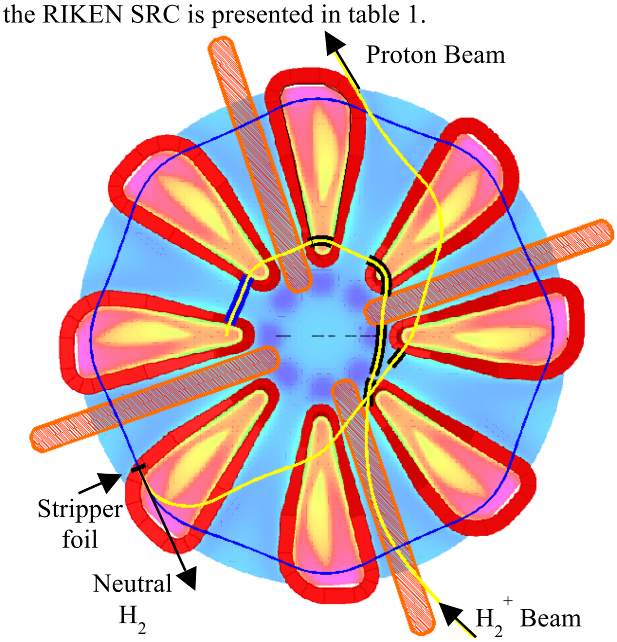

Figure 1: DSRC Layout, with the injection and extraction trajectory. Coils and cavities are also shown.

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Table 1: Main Parameters of Proposed DSRC compared to RIKEN-SRC

Basic	**DSRC**	**Riken-SRC**	**units**
Max field in the hill	6.05	3.8	T
Max field on the coil	6.18	4.2	T
Stored Energy	280	235	MJ
Coil size	30x24 and 15x48	21x28	cm^2
Coil circumference	9.8	10.86	M
Magnetomotive force	4.9	4	MA/sct
Current density	34	34	A/mm^2
Height	5.6	6	m
Length	6.9	7.2	m
Weight/sector	<450	800	tons
Extra magnetic shield	0	3000	Tons
SC trim	No	4	Sets
Valley field	0.6	0.4	T
Extraction method	Stripper foil	Electrostatic channel	
Magnetic Forces			
Expansion	1.87	2.6	MN/m
Vertical	3.7	3.3	MN
Radial Shifting	2.7	0.36	MN
Azimuthal Shifting	0.2	0	MN

THE SECTOR MAGNET

The isochronous field is produced by 8 magnet sectors; a couple of superconducting coils powers each sector.

The coils shape is shown in Fig. 2. Each coil is NbTi made. The coils do not stay on a plane but they are tilted as shown in Fig. 2. The 8 superconducting sector magnets generate the bending and focusing fields of the DSRC.

The iron of the sector and mainly the hill were designed to achieve a proper magnetic field with the desired isochronism and focusing properties. Fig. 2 shows a 3D view of the magnetic sector together with the superconducting coils. The big hole in the centre of the hill has been introduced for many different reasons: field isochronism, vertical focusing, insertion of cryogenic panels for the vacuum system, and to host a cold plate that connects the two longest arms of the coil.

The updated configuration of the magnetic sector produces an isochronous magnetic field with an accuracy of ±0.4%, with good focusing properties in both the radial and vertical planes and with reliable shape, as shown in Fig. 3. The values of ν_z and ν_r were evaluated by the code GENSPE, which uses the magnetic field map produced by the sector of Fig. 2 as input and evaluates the static orbit of the particles.

However, in the present baseline design several technical constraints exist, which may require modifications of the layout and are here listed. The space between the magnets is possibly insufficient for the installation of the cavities. Indeed the minimum distance between two contiguous coils, at a radius of 1700 mm, is about 600 mm. This value is critical for the installation of both single gap RF cavities (PSI like) and also for the installation and maintenance of the devices necessary for the injection. The free space in the cyclotron centre is rather limited and this results in difficulties with the injection scheme. The proposed solution to build a coil with constant cross section but variable shape of the conductor bundle is critical if a Rutherford type cable in a helium bath is chosen (as in the RIKEN magnets). The shape variation occurs when the arrangement of conductors is reshaped or the cable is tilted. In both cases the flow of the liquid helium is seriously disturbed and the outflow of helium gas produced by local heating is hindered. If we have to maintain this configuration, an indirect cooling system becomes mandatory.

The forces on the coils are important, as shown in Table 1. There is one big force that pushes outward the coils; this force is about 5 times the residual radial force developed in the Riken's coil. A huge force acts on the two radial sides of the coils trying to make them round. This force is in the same order of the Riken's one and to balance it and to reinforce the structure of the liquid helium [LHe] vessel a connecting plate (2.2 m long and 9 cm thick) to join together the longest arms of the coil has been forecasted. This solution has already been used in the Riken SRC [6]. The connecting plate will be part of the LHe vessel. To have a robust LHe vessel a thickness of 4 cm for the inner wall and for the plate near the median plane was assumed, while for the outer wall and plate far from the median plane a thickness of 7 cm was fixed. If this structure should be not strong enough to support also the vertical attractive force between the pair of coils a stiffening box along the longest arms of the coils, inside the cryostat and far from the median plane is foreseen [private communication, J. Minervini the coil to sustain the huge vertical attractive force. To balance the total residual forces F_x and F_y has been foreseen a tie rods

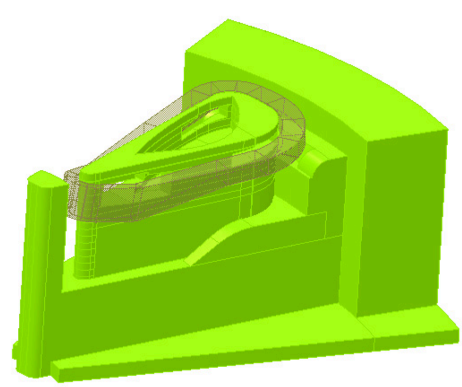

Figure 2: 3D view of the magnetic sector and of one of the pair of NbTi superconducting coils.

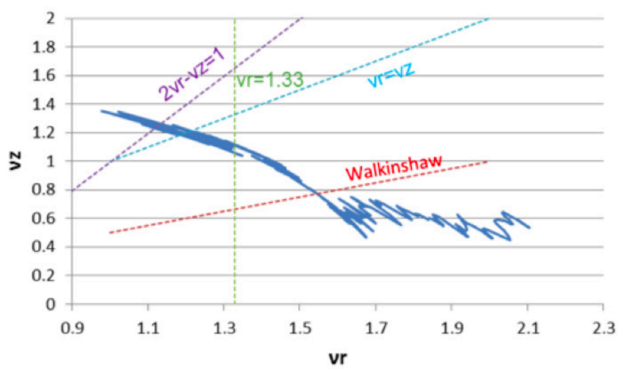

Figure 3: Tune plot of the 8-sector cyclotron.

set that maintain the LHe vessel in the right position.

A six-sector cyclotron has been evaluating to achieve the required isochronous field needed, too. This solution relaxes many of the critical parameters described above. A wider hill allows a different modulation of the angular width of the iron pole and consequently of the coils, which can have a more spiralled shape. These changes could help to achieve a stronger vertical focalization.

Nevertheless, more computations and simulations are mandatory before accepting this important change in the design of the cyclotron.

BEAM DYNAMIC

The iron of the 8-sector hill was shaped to match the required ideal isochronous field with an accuracy of ±0.4%. Although this value is not enough to guarantee the acceleration of the beam, we expect that the further small corrections on the magnetic field, to achieve the good isochronisms with precision better than 10^{-4}, do not change significantly the focusing properties of the field. A serious effort was necessary to maintain the ν_z higher than 0.5. In Fig. 3 both the ν_z and ν_r are presented. These results are quite satisfactory. Despite the fact that some resonances are crossed this is done quite fast and none serious problem is expected. J. Yang and A. Adelmann of PSI simulated the beam dynamic using the computer code OPAL [7] that takes into account also of the space charge effects. Their simulations demonstrate that the beam size does not show significant increase along the acceleration path. The energy gain per turn used in the simulations takes account of the proper voltage profile of our cavities [8].

The beam envelopes for the extraction trajectory are presented in Fig. 4. The normalized beam emittance used in this simulation was 3.35 π mm. mrad. This large value, about 30 times the emittance of the ion source [5], takes into account the non linear effects along the injection, acceleration and extraction from the cyclotron injector and space charge effects which produces a serious broadening of the initial beam emittance. Despite the large emittance, the beam envelope across the injection and extraction path is quite small in both the radial and axial plane. In particular the beam envelope along the extraction path takes account also of the energy spread of ±1%. The preliminary simulations run at PSI by J. Yang and A. Adelmann by the code OPAL, modified to take account of the stripper extraction, achieved this value.

Further beam dynamic analysis have been undertaken by F. Méot [9] using different tools, aiming to show that the magnetic field produced by the magnet sector here presented allows the proper acceleration of the beam.

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. The six-sector solution looks appealing and needs to be deeply investigated.

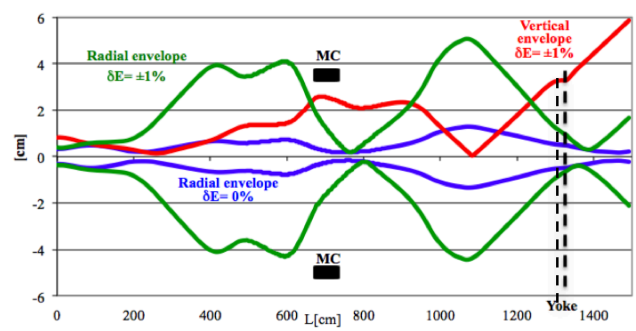

Figure 4: Radial and axial beam envelope along the extraction trajectory. Effects due to the energy spread (±1%) are also shown.

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