A COMPACT HIGH INTENSITY CYCLOTRON INJECTOR FOR DAEDALUS EXPERIMENT

D. Campo[1,*], A. Calanna[1,*], MIT, Boston, USA
L. Calabretta, D. Rifuggiato, INFN-LNS, Catania, Italy
A. Adelmann, J. Yang, PSI, Villigen, Switzerland & MIT, Boston, USA
M. Maggiore, L.A.C. Piazza, INFN-LNL, Legnaro, Italy

Abstract

DAEδALUS (Decay At rest Experiment for δ_{cp} At Laboratory for Underground Science) is a new approach to search for CP violation in the neutrino sector. The experiment needs three sources of high intensity neutrino fluxes driven by high intensity accelerator able to deliver proton beam with energy of 800 MeV and average power of some MW. To reduce the accelerators cost a cyclotron complex consisting of an injector cyclotron and of a superconducting ring cyclotron has been proposed. The injector cyclotron has to accelerate a H_2^+ beam with maximum current of 5 mA. Moreover the beam extraction has to be performed by electrostatic deflector to preserve the H_2^+ for the further acceleration into the ring cyclotron, so an extraction efficiency of 99.9% is mandatory. Although the high beam current, our simulations, including space charge effects, shown that this ambitious goal is achievable. The main characteristics of the injector cyclotron, its special features and the extraction process are here presented.

INTRODUCTION

The DAEδALUS experiment plans to observe oscillation characteristics of neutrinos from nearby sources, located at 1.5, 8 and 20 km from the detector [1]. The neutrino fluxes are produced by a high power proton beam with an energy around 800 MeV on a low Z target. The requested beam power for the three sites are 1, 2 and 5 MW respectively. A strong constraint imposed by the experiment to the accelerators complex is to operate with 20% duty cycle, to allow the identification of the neutrino sources and also to measure the background of the experiment. Additional constraints to the accelerators experiment are compactness and cost-effectiveness.

In order to deliver a proton beam at 800 MeV with an average power of about 1.6 MW, we proposed an accelerator complex composed by one DAEδALUS injector cyclotron (DIC) and a superconducting ring cyclotron (DSRC), able to accelerate H_2^+ molecule beam [2]. The cyclotrons operate with a duty cycle of 20% (1 ms beam on and 4 ms beam off), hence the beam current and the peak power are 5 times higher than the average power. In particular, the DIC will accelerate a peak current of 5 mA up to 60 MeV/n, while the DSRC must be able to accelerate the beam up to 800 MeV/n and handle 8 MW of peak power.

[1] Present address: LNS-INFN, Catania, Italy
[*] on leave from CSFNSM, Catania, Italy

Table 1: Main Parameters of the DIC

E_{inj}	35 keV/n	E_{max}	61.7 MeV/n
B_0	1.075 T	<B> at R_{ext}	1.166 T
$\langle R_{inj} \rangle$	51.58 mm	$\langle R_{ext} \rangle$	2000 mm
N. Sectors	4	Hill width	25.5° ÷ 36.5°
Valley gap	1800 mm	Hill gap	100 mm
Diameter	6240 mm	Full height	2700 mm
N. Cavities	4	Cavities λ/2	Double gap
RF Harmonic	6th	RF frequency	49.2 MHz
Acc. Voltage	70 ÷ 250 kV	Power/cavity	<160 kW
Coil size mm²	200x250	Current density	3.17 A/mm²

One of the main challenges of this accelerator complex concerns the space charge effects in the DIC and beam losses at the extraction from the DIC and from the DSRC. The choice to accelerate the H_2^+ instead of protons has the advantage to reduce significantly the perveance value of the beam, while the beam losses at extraction in the DSRC will be relaxed, because of stripping extraction.

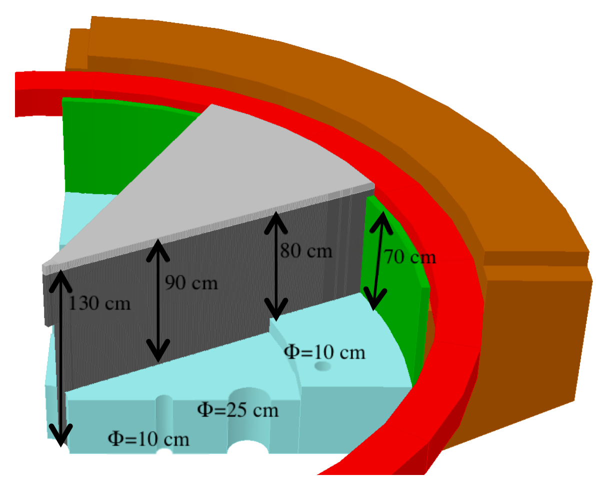

Figure 1: Layout of 1/8 of the DIC magnet.

Two Electrostatic Deflectors (ED) will extract the beam from the DIC. To minimize the beam losses at the ED, it is mandatory to increase the orbit separation at the extraction radius. This goal was achieved using the orbit precession of the beam centre, when the beam cross the

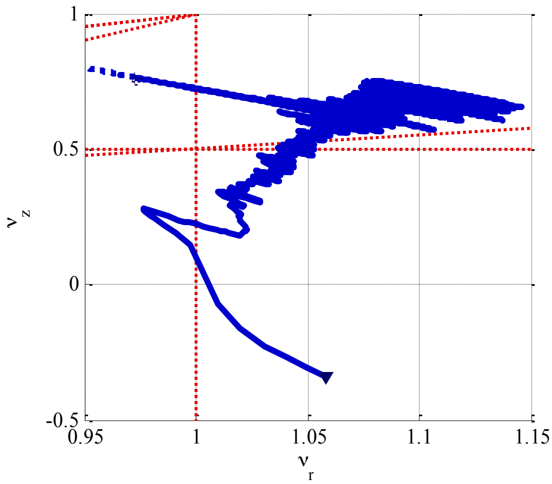

Figure 2: The tune diagram of the DIC. The ν_r=1 crossing occurs 2 MeV before the beam extraction.

ν_r=1 resonance. The extraction energy from the DIC has been upgraded up to 60 MeV/n, respect to the former proposal [3]. This choice was made to simplify the beam injection into the DSRC and improves the acceleration process [4]. In consequence, the size of the DIC was increased and all the main parameters were revised.

MAGNET DESIGN

To achieve the extraction energy of 60 MeV/n, in the DIC, we proposed a 4 sector compact cyclotron energized by a pair of room temperature coils, which was inspired both by the experience of the Injector II of PSI and by the commercial compact cyclotrons designed by EBCO, IBA and SHI. The DIC main parameters are shown in Table 1. The final configuration is obtained from an iterative process, in order to achieve an optimal balance between the conditions of optimum isochronism along the acceleration and the need for crossing of the resonance ν_r=1 just before the extraction.

To minimize the beam losses due to the interaction with the residual gases a good vacuum, in the order of 1÷2 10^{-8} Torr is requested. We plan to cover the whole cyclotron pole, including the hill, with a liner differential vacuum system. To achieve a good vacuum conductance, a large vertical gap of 10 cm was chosen.

Only for radii smaller than 13 cm the gap height was decreased at 80 mm, to improve the vertical focusing in the central region. The pole radius is 220 cm and the angular width of the hill varies between 25.5° in the inner region up to 36.5° in the extraction region. The width of the hill was optimized to achieve the ν_r=1 resonance crossing just 1 MeV/n before the extraction.

Room temperature coils are placed symmetrically at 10 cm from the median plane. The inner radius of the coils is 223 cm, the coil size measures 200 x 250 mm^2 with a current density of 3.167 A/mm^2. The weight of each coil is about 5 Tons and the total electrical power consumption for both the two coils is around 330 kW.

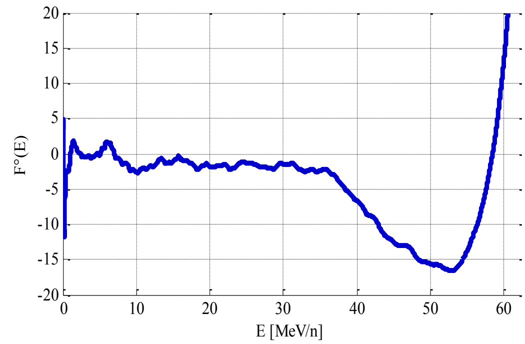

Figure 3: Phase of the accelerated equilibrium orbit.

Although the power consumption is not very high, a superconducting solution, using the MgB_2, a high Tc superconducting cable, could be a more convenient and safer solution.

OPERA Vector Field was used to create the magnetic models and to simulate the magnetic field. Due to the symmetry of the DIC, only 1/16 of the volume was simulated.

BEAM DYNAMIC

The magnetic field of the final configuration for the DIC varies between 0.28 tesla (inside the valley) and 2.11 tesla (in the hill), with an average value in the range of 1.05 ÷ 1.2 tesla. The accelerating system consists of 4

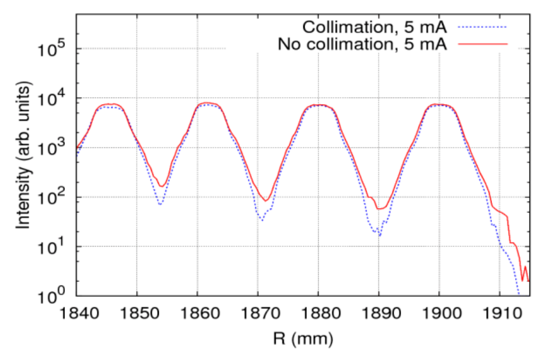

Figure 4: Radial density distribution along the last 4 turns of the DIC.

double-gap RF cavities placed inside the cyclotron valleys. Each cavity resonates at the frequency of 49.2 MHz, with harmonic 6^{th}. The cavity shape was optimized in order to guarantee an accelerating voltage increasing from 70 kV at the inner radii up to 250 kV at outer radius.

The tune diagram in Fig. 2 shows that the beam crosses the ν_r=1 resonance at the end of the acceleration process, while other critical resonances were crossed at low energy only. Our simulations shown that the necessary beam quality is preserved. The isochronism was evaluated with GENSPE, and the phase slip shown in Fig. 3 demonstrates that it does not exceed the ±15 deg.

The beam dynamic along the DIC is space charge dominated. OPAL was used to evaluate space charge effects by means of large-scale simulations similar to a

ISBN 978-3-95450-115-1

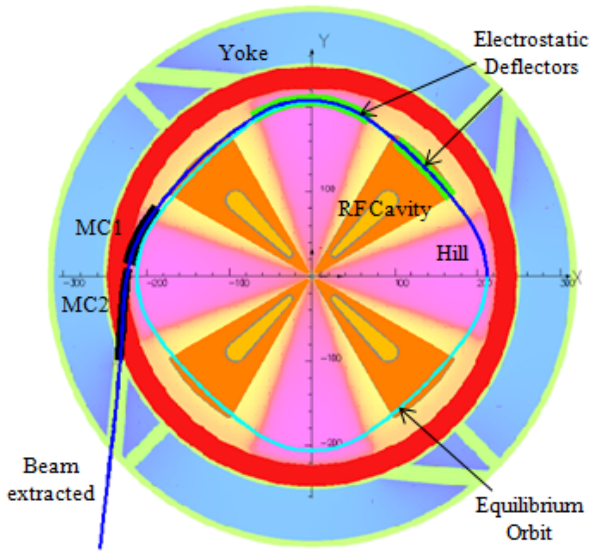

Figure 5: Layout of DIC magnetic field. The extraction trajectory, with the magnetic channels, the electrostatic deflector and RF Cavities are also shown.

study reported in [5]. So far up to 10^6 particles throughout the whole DIC where used in order to obtain statistical meaningful results, mainly w.r.t. beam losses. The radial distribution around the extraction septum is shown in Fig. 4. The turn separation, about 14 mm, at the last orbit is mainly due to the large energy gain per turn. Due to the effects of the first harmonic precession, introduced by crossing the resonance v_r=1, this separation increases up to 20 mm. The use of a 4 collimators scheme around 1 MeV/n allows us to increase the turn separation even further, as shown in Fig. 4. We evaluate the beam loss at the ED to an acceptable level of about 120 W.

BEAM EXTRACTION

According to the Fig. 5, the beam is extracted using two electrostatic deflectors (ED), placed inside one RF Dee and in a hill. The use of two ED instead of just one was chosen to maintain the maximum voltage lower than 60 kV, and at the same time, to have a large gap inside the ED for the extracted beam. The electric field and the gap of ED1 are 30 kV/cm and 20 mm, while the values for ED2 are 25 kV/cm and 24 mm. The use of the two ED produce a well separated extracted trajectory that at the position of the first magnetic channel MC1 is about 8 cm separated from the last accelerated orbit. This separation is conservative, and probably a lower separation of 5 - 6 cm could be acceptable. The beam envelopes for the extraction trajectories are presented in Fig. 6. For all the beam simulations we assume a normalized emittance of 13.4 π mm.mrad. This value again is very conservative,

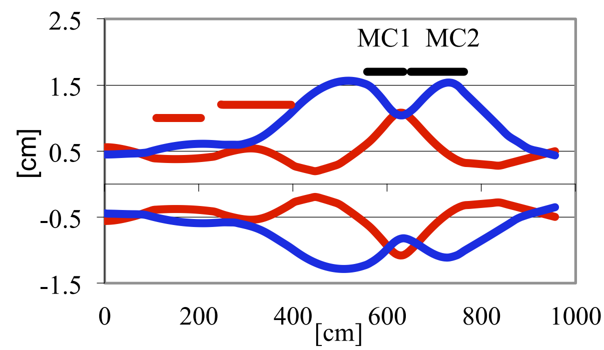

Figure 6: Beam envelope in radial (blue line) and axial plane (red line) along the extraction trajectory.

about 40 times the beam emittance of the ion source [6], taking into account non linear effects along the inflector which will increase the emittance.

The beam envelope in Fig. 6 represents 90% of the beam intensity. The beam envelope along the extraction path is small in both the radial and axial plane. An initial energy spread of ± 0.2% is assumed in the simulation.

FINAL REMARKS

The injection system studies are in progress. The axial injection will consist of a spiral inflector with a gap between the two electrodes larger than 1 cm. This is a reasonable value taking into account space charge that is the most critical aspect at low energy.

ACKNOWLEDGMENT

It is a pleasure to acknowledge that A. Calanna, D. Campo and partially J. Yang are supported through funding from MIT.

REFERENCES

[1] 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.
[2] L. Calabretta et al., Int. Conf. on Cycl. and their App. Lanzhou 2010, http://www.JACoW.org.
[3] D. Campo et al., “A low energy cyclotron injector for DAEδALUS experiment”, IPAC San Sebastiàn 2011, WEPS073 http://www.JACoW.org.
[4] A. Calanna et al., “A superconducting ring cyclotron for the DAEδALUS experiment”, IPAC New Orleans 2012, MOPPD026 http://www.JACoW.org.
[5] Bi, Y. J. and A. Adelmann, et al., Phys. Rev. ST Accel. Beams 5, 054402,Dio:10.1103/PhysRevSTAB.14.054402 http://www.JACoW.org.
[6] S. Gammino et Al., XIX ECR ion Source Workshop, Grenoble, 2010, MOPOT012 http://www.JACoW.org.