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NEW METHOD TO DESIGN MAGNETIC CHANNELS WITH 2D OPTIMIZATION TOOLS AND USING PERMENDUR VANADIUM

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Abstract

Magnetic channels are used in almost all cyclotrons to focus radially the beam along the extraction path through the coils and yoke region, where the rapid fall off of the magnetic field produces a strong vertical focusing and radial defocusing of the beam. These magnetic channels consist generally of three iron bars. The current sheet approximation has been generally used to evaluate quickly the performance of magnetic channels.

For the new magnetic channels to be used in the upgrade of the LNS-INFN k800 Superconducting Cyclotron, a new method was developed to investigate complex configurations and to achieve higher magnetic gradients in a larger area. The optimization procedure is based on a genetic algorithm implemented on MATLAB code and using the COMSOL code to perform the 2D magnetic field simulations.

Moreover, the use of permendur vanadium in alternative to iron allows to reduce the volume of the bars and mainly the magnetic force.

The results of our simulations are here presented.

INTRODUCTION

The LNS-INFN Superconducting Cyclotron (CS), Catania, has been working for 25 years delivering almost all ion beams in the mass range 2÷200 amu and energy range 10÷80 AMeV [1].

The CS was designed to perform nuclear physics experiments that generally use low intensity beams. Indeed, due to the compactness of the CS, the last accelerated orbit is not fully separated from the previous one, and the extraction efficiency is under 60%. The beam power dissipated on the septum of the first electrostatic deflector (E.D.) causes issues due to thermal deformation of the septum, extra outgassing, high dark current and E.D. discharges. For these problems the maximum beam power extracted from the cyclotron up to now stays below 100 W.

In 2016 the scientific community and the management of LNS-INFN approved a project to upgrade the CS to allow the extraction of beam power up to 10 kW for the ions with mass below 50 amu [2]. These high power beams are useful to perform the NUMEN experiment and also to drive the facility FRAISE (FRAgment In-flight SEparator) [3,4].

To achieve this goal, the beam will be extracted by stripping. This extraction method is based on the sudden change of charge state produced by the crossing of the beam through a thin carbon foil, so called stripper. The consequent decrease of the magnetic rigidity after the stripper produce a strong perturbation of the beam trajectory that naturally escapes from the cyclotron pole [5].

Although extraction by stripping is very convenient to achieve high extraction efficiency, its application is not trivial when extracting ions with a wide range of masses and/or energies. Indeed, the extraction trajectories are quite different for each different ion type, therefore a large Extraction Channel (Ex.Ch.) is mandatory, by far larger than the one used for electrostatic extraction. A new extraction system for a selected set of ions and energies has been designed [2].

In particular, two big Magnetic Channels (MC1, MC2) are mandatory to focus the beam along the extraction channel, see Fig.1. Moreover, these two channels have to provide large gradient, up to 2 kGauss/cm, over a large area (4 x 3 cm) to allow for an efficient transmission of the beams that have relatively large transversal sizes [6]. These MC were simulated using the so-called Current Sheet Approximation (CSA) [7]. The size of these channels are quite large and one of the problems, which appeared during the design of these magnetic channels was the magnetic force. As MC’s have wide range of positions, according to the ion trajectory, it is very challenging from the mechanical point of view to offset these magnetic forces. In particular, the

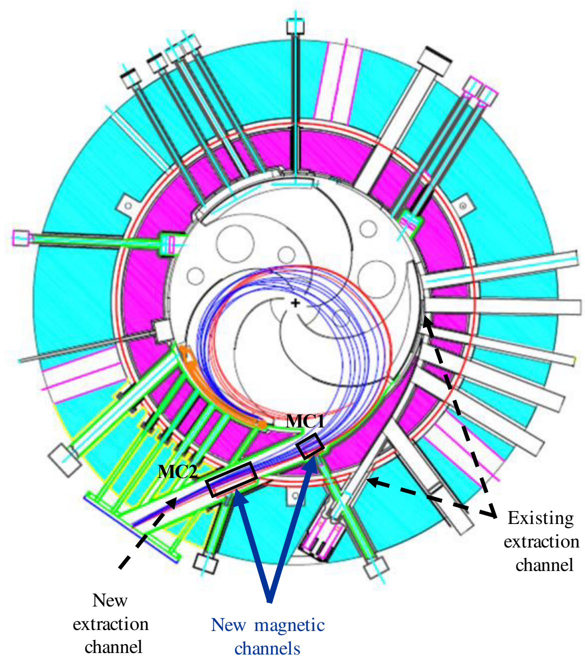

Figure 1: Layout of the two extractions channels from the CS. A set of new extraction trajectories achieved by stripping and the positions of the two new magnetic channels are also shown.

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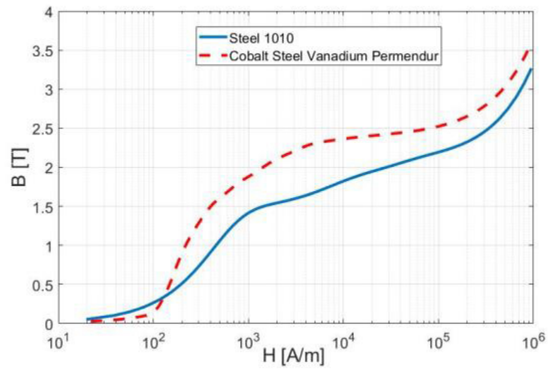

Figure 2: BH chart for Cobalt Steel Vanadium Permendur and Low Carbon Steel 1010.

force acting on MC1 could reach up to 1 ton. For this reason, we investigated the option to build these MC using permendur vanadium material that has a magnetization curve much higher than the pure iron, Fig. 2. Despite the permendur vanadium cost is quite high, it allows to reduce the cross section of the MC of about 10% and accordingly also the magnetic force. The results of these simulations are presented in the next section.

Moreover, we investigated also the option to optimize both the performance and the size of these channel. This method is based on a genetic algorithm which is described in the dedicated section. The results achieved with this optimization method are also presented in the last section.

MAGNETIC CHANNEL PERMENDUR VANADIUM MADE

One way to reduce the size of the MC, while keeping the same gradient, is to replace some parts of the MC's material from "conventional" Low Carbon Steel 1010 (LCS1010), which is widely used in cyclotrons, with Cobalt Steel Vanadium Permendur (CSVP). The magnetic properties of these materials are introduced in the simulation by using Comsol Material Library BH curves. The different magnetic properties of these two materials are shown in Fig 2.

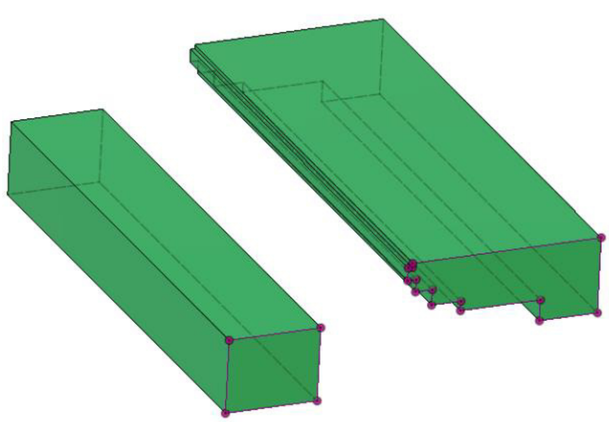

Figure 3: 3D model of magnetic channel, top half.

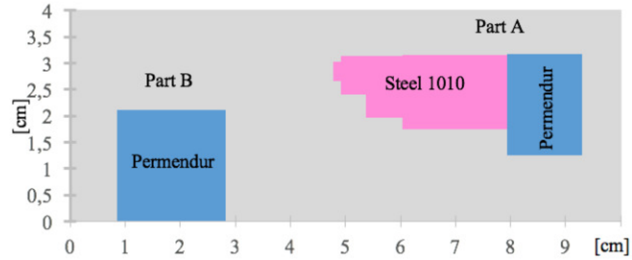

Figure 4: Parts of MC2 replaced with Cobalt Steel Vanadium Permendur (blue) and part kept with Low Carbon Steel 1010 (pink). Only top half part of MC2 is shown.

The preliminary design of the MC, developed by using the current sheet approximation is shown in Fig. 3. Half part is presented as inserted in the simulation that allows to use the middle plane symmetry to simplify the calculation.

As a first step of introducing CSVP in the design of MC we replaced two parts of the conventional MC, made from LCS1010, with CSVP, see Fig. 4. Part B was totally replaced with CSVP while only the right side of Part A was replaced with CSVP. The rationale of this partially material substitution is to preserve the easy manufacturing of a complex part by using LCS100.

The MCs design was studied in the magnetic field produced by the 3D model of the cyclotron. The 3D geometry of the cyclotron was imported in CST Studio software and the magnetic conditions were implemented to evaluate the magnetic field map. Middle plain magnetic field distribution is shown in Fig. 5.

We have adjusted the sizes of CSVP parts in order to maintain the same gradient as the fully LCS1010 magnetic channel. In order to do so, the width of the CSPV elements has been decreased by approximately 20%. The achieved gradients are presented in Fig. 6.

The force, applied on the MC's has been calculated using COMSOL Multiphysics software, as integration of the Maxwell's stress tensor over the surfaces of the MC.

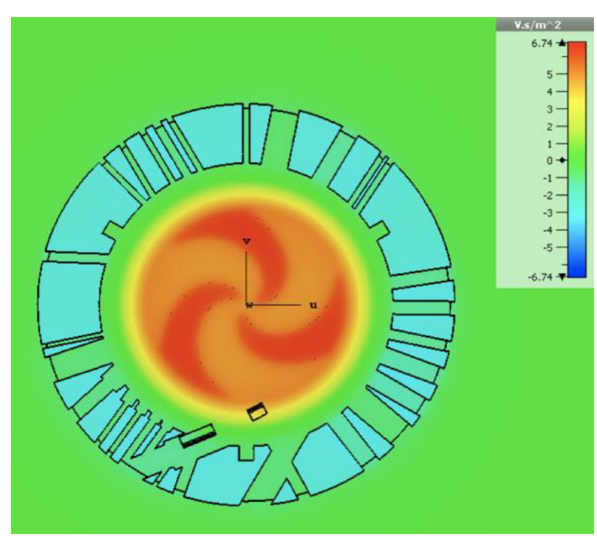

Figure 5: Middle plane magnetic field map achieved by CST Studio 3D model of the cyclotron. MC 1 and MC2 are in the most inner position.

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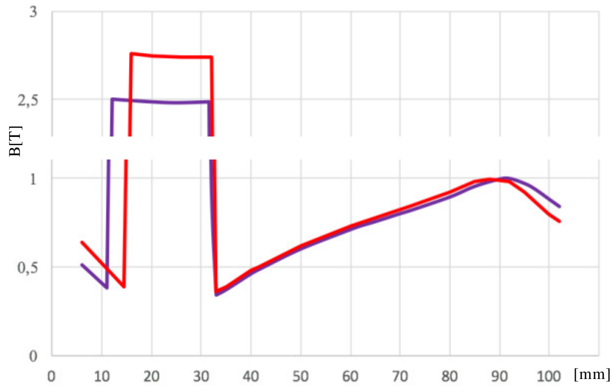

Figure 6: Magnetic field in MC2. Blue line, Low Carbon Steel 1010 made. Red line, partially made with Cobalt Steel Vanadium Permendur.

The positions of the MCs can be adjusted in or out to fit the different trajectories of each different ion beam. The two extreme allowed positions were taken into account for the evaluation of the force calculation and the results are shown in Table 1.

Use of Cobalt Steel Vanadium Permendur can reduce the size and the force on MC1 and MC2 by approximately of 10% and 7.5% respectively, compared to Steel1010. Similar reduction of force was found for both positions, inner

Table 1: Magnetic Forces on MC1 and MC2

MC1	Position	Steel 1010	Steel 1010 + Permendur
Fx Part B	in	-319 N	-294 N
Fy Part B	in	2753 N	2545 N
Fx Part A	in	-192 N	-176 N
Fy Part A	in	2316 N	2109 N
Fz Part A	in	775 N	720 N
Fx Part B	out	-525 N	-488 N
Fy Part B	out	3865 N	3578 N
Fx Part A	out	-268 N	-245 N
Fy Part A	out	2568 N	2362 N
Fz Part A	out	1087 N	1008 N
MC2			
Fx Part B	in	-372 N	-347 N
Fy Part B	in	-2172 N	-2020 N
Fx Part A	in	-317N	-293 N
Fy Part A	in	-3233 N	-3054 N
Fz Part A	in	1560 N	1470N
Fx Part B	out	-265 N	-245 N
Fy Part B	out	-1093 N	-1022 N
Fx Part A	out	-386 N	-349 N
Fy Part A	out	-270 N	-231 N
Fz Part A	out	700 N	712 N

and outer, as result of our simulation, see Table 1. Higher force reduction could be achieved if the full part A is permendur vanadium made.

OPTIMIZATION BASED ON GENETIC ALGORITHM

Genetic algorithm strategy is today a common and well developed method for optimization problems [8]. There are optimization strategies that suffer from high dependence upon the starting conditions and are able to find only local minima around it. Genetic algorithm automatically selects several starting conditions randomly chosen in the full space of the allowed solutions. This procedure deletes the dependency from the user selected starting point and allows the search in the full space of possible solutions.

The optimization procedure based on a genetic algorithm is implemented on MATLAB code [9]. An important variant that we adopted for the optimization of the MC was to use discrete variables instead of continuous. All variables, as it will be described in the following, are related to the geometric parameters of the design. An accuracy of one millimeter was set because solutions that differ of fractions of millimeter do not produce significant changes. In such a way we drastically reduced the space of the possible solutions moving from a continuous to discrete space of solution values. With this choice the computational time was reduced a lot and the capability to search in the whole space of possible solutions was more guaranteed.

The geometry is parametrized with 24 variables, the meaning of 20 of them is shown in Fig. 7. Six variables, identified by blue arrows, are able to change the height of the top part of the rod A. Other six variables, indicated by violet arrows, describe the bottom part. Four variables are used to identify the transverse position of the left side of the rod B and other four the right side. Two more variables are used to wrap and stretch the rod A, and the last two, to do the same for the rod B. Additional different constraints were applied to obtain a geometry compatible with the maximum allowed extension and to preserve the space needed for the beam. To produce a homogenous magnetic field gradient, we decided to remove the corners contribution by applying a rounding shape of all corners.

The genetic algorithm starts with a random selection of one hundred of possible solutions that constitute what is

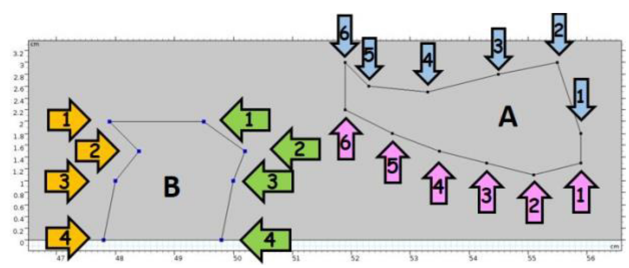

Figure 7: Parametrized design of MC with the identification of almost all variables that define the geometry.

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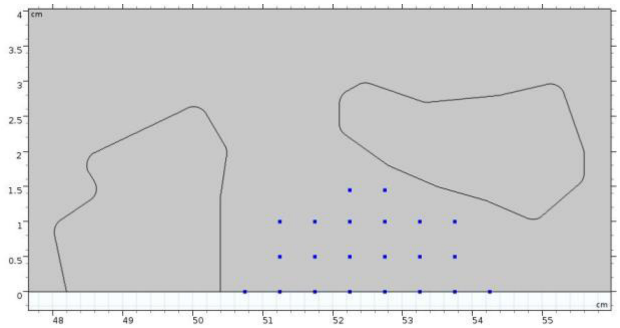

Figure 8: Map of points (blue marked) where the penalty function is evaluated.

commonly called a population.

The goodness function is evaluated for each individual, and good and bad individuals are identified. After the first step the genome constituted by the value of the variables of each individual are mixed between individuals to find the new population to be tested.

Only the best 30 individuals are allowed to share genome between them and 5 of randomly selected worst individuals. The new population is generated with a random mix of genome plus a small possible random variation. After few hundreds of populations, the global minimum is found when no more improvements are found and the goodness of the best individual shows a convergence trend.

The most important requirement that enable the use of a genetic algorithm is the computational time needed for the evaluation of the goodness function. A lot of work was done to identify the computational environment that allowed to compute the goodness function in few second. The geometry was tested by solving a 2D problem with Comsol Multiphysics instead of the 3D problem. This choice reduces the complexity of the problem introducing differences with small impact on the final 3D solution. In the real case we have a linear MC with a defined length inside a magnetic field. The simulated setup is equivalent to a MC of infinite length subjected to a constant external magnetic field. This will give a good agreement for the evaluation of the magnetic field at the center of the MC while will not take into account the fringing field at the two end of the MC. The need to have a fast goodness function evaluation imposed this simplification that will be removed in the last check of the design. The goal of the goodness

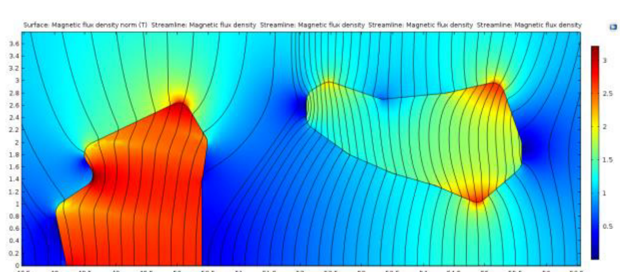
Figure 9: Colour-map and streamlines showing magnetic field value around MC2 after genetic algorithm geometry optimization.

function is the production of a uniform magnetic field gradient in all the beam region. A set of 22 points were taken into account for the calculation of the root mean square deviation. These points of interest are distributed in the area crossed by the beam and are shown in Fig. 8.

The area of the MC surfaces was taken into account to minimize the use of metal. In such a way we minimized the envelope of the MC but more important we reduced the magnetic force acting on the MC. The higher gradient obtained with this optimization procedure allow to use shorter MC that are subject to lower magnetic force.

OPTIMIZATION PROCEDURE RESULTS

The result shown in Fig. 9 was found after several iterations of the optimization procedure that help us to identify the most convenient degrees of freedom to be inserted in the design. Even if a big number of variables can be used with genetic algorithm, this number needs to be always limited to a value corresponding to one day of computational time. With this limitation the set of allowed geometries corresponding to all possible combinations of variables values represent a huge number of different geometries. Nevertheless, they are not comparable to the infinite number of possible geometries. Different tries were needed to identify the most crucial area where to insert higher freedom in the parametrized design. For the final configuration

Table 2: Margin Specifications

r	Z	$\frac{\partial B}{\partial r}$ [mT/cm]	Error [%]
50.75	0	246.2	-1.5
51.25	0	256.8	2.7
51.75	0	254.9	2.0
52.25	0	255.6	2.2
52.75	0	258.4	3.4
53.25	0	261.9	4.8
53.75	0	262.3	4.9
54.25	0	210.2	-15.9
51.25	0.5	248.8	-0.5
51.75	0.5	247.6	-1.0
52.25	0.5	251.6	0.6
52.75	0.5	256.0	2.4
53.25	0.5	259.2	3.7
53.75	0.5	275.1	10.0
51.25	1	218.0	-12.8
51.75	1	224.3	-10.3
52.25	1	242.8	-2.9
52.75	1	252.1	0.8
53.25	1	247.0	-1.2
53.75	1	232.8	-6.9
52.25	1.45	245.0	-2.0
52.75	1.45	249.3	-0.3

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shown in Fig.9, 14 parameters for the piece A and 10 for the piece B were used.

The convergence was found after 356 generations in approximated 20 hours of computational time with an Intel I7-3970X CPU.

An average gradient of 250 mT/cm with a mean error of 4.2% was obtained. The evaluated gradients for the set of points in the beam area and shown in Fig. 8, are presented in Table 2.

Each point, identified with its radial and vertical coordinates, its gradient and error are presented in Table 2.

To identify the contribution of different materials, the optimization procedure, using the same parametrized degree of freedom, was tested both with CSVP and LCS1010. Choosing a magnetic field gradient of 250 mT/cm for the two cases, different optimized geometries were found for the two materials. The average deviation over the twenty-two points in the beam area was significant, 4.2% in the case of CSVP and 8.0% for LCS1010.

CONCLUSION

According to our simulations the use of permendur vanadium instead of pure iron steel 1010 allows to reduce the magnetic force applied on the magnetic channel of at least 7%. Moreover, we investigated also complex shapes for the three bars magnetic channels. Using a genetic algorithm, it was possible to optimize the region of uniformity of the gradient and also to maximize the gradient values. Using MCs with higher gradient allows to reduce the length of the channels and consequently the magnetic forces acting on them. This greatly simplifies the handling mechanics of these magnetic channels.

During 2019 a prototype of MC1 and MC2 with the shape achieved by the new optimization procedure will be built. A comparison between the simulations and the experimental measurements will be made.

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