Development of a compact and fast trimmable FeCo magnet for medical gantries

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In the frame of the Tulip project, an application for accelerator technology to radiation therapy, supported by a CERN Knowledge Technology Fund, the design, manufacture and test of a compact, fast trimmable iron cobalt (FeCo) accelerator dipole magnet prototype has been performed and completed at CERN. The aim of this project is to illustrate the benefits of a FeCo magnet for medical gantries in which weight and size are critical. The prototype is a 250 mm long dipole providing a central field of up to 1.8 T, the field can be trimmed in the percent range at frequencies of up to 200 Hz. The experimental results clearly demonstrate that FeCo magnets can be interesting alternatives for medical gantries because of their linear behavior up to high fields and their compact nature.

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I. INTRODUCTION

The study for this magnet was tailored for the TULIP (turning linac for protontherapy) and the FASST (fast adaptive spot scanning therapy) machines designed by the TERA foundation [1,2] for cancer therapy. A 3D CAD model of the gantry is shown in Fig. 1, where the bending magnet is labeled as HEBT.

This paper describes the requirements, electromagnetic design, construction and magnetic measurements of an iron cobalt (FeCo) dipole prototype magnet. This compact FeCo prototype could be used for the feasibility studies of a new generation of compact medical gantries based on the work of Amaldi *et al.* [3,4]. These machines require compact magnets with a large field range and a fast response (up to 200 Hz of repetition range).

The solution for compactness and good dynamic behavior proposed in this paper is the use of FeCo laminations to make the magnet core. It has been decided to use a FeCo alloy, which has the property of having a very high saturation threshold, for the yoke for two main reasons: reducing the weight and size of the magnet in order to simplify the rotating structure, and achieving a fast response.

The saturation point of FeCo alloys is higher than in typical electrical steels, and therefore it is possible to design a more compact magnet because the yoke is less saturated

and can achieve higher fields in the aperture. For example, for a given bending angle a magnet with a FeCo yoke is shorter than a magnet with a common nongrain oriented FeSi yoke because the peak field of the FeSi magnet is lower due to saturation, assuming both yokes have the same cross section. To achieve a FeSi magnet of the same length as the FeCo magnet it would be necessary to increase the cross section of the yoke, which increases the mass significantly, and/or increase the current. In this type of hadron therapy machine these factors start to be significant, especially in the gantry where the weight has to be compensated with counter blocks, increasing the complexity and the total machine weight, and the magnet length

FIG. 1. Layout of the cyclotron and the accelerating structure placed in line with the gantry. The prototype described in this paper can provide guidelines for the design of the last two dipoles placed in the HEBT bending structure.

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FIG. 2. Typical treatment steps starting at the maximum energy, irradiating the distant part of the tumor, and decreasing in energy and in time for each closest tumor slices.

which will define the gantry radius and consequently the building size. Therefore, even though the FeCo laminations are more expensive, this additional cost could be compensated by the reduction of the costs of the building and the moving structures.

In addition, if the yoke is saturated, at high field steps it is necessary to change the current in a significant way, which produces not acceptable delays. Figure 2 shows the typical treatment steps.

Therefore, to illustrate the differences between a FeCo and FeSi steel, two prototypes have been built: one with a FeCo yoke and the other one with a FeSi yoke.

The paper starts with a general introduction to FeCo alloys. Then, the electrical, cooling and magnetic design is presented in detail. The following sections present the construction of the prototype, the experimental results, and finally the conclusions are drawn.

II. DESIGN REQUIREMENTS

The requirements for the model magnet are representative of the ones imposed by the beam dynamics calculated for TULIP [5]. The actual magnets are foreseen to be curved but the prototype has been simplified: it is straight without chamfers. These requirements are listed in Table I.

TABLE I. Magnet requirements.

Parameter	Units	Prototype	Final
Field at max. energy	T	1.8	1.8
Field at min. energy	T	1	1
Iron length	mm	250	1546
Gap height	mm	25	25
Vertical good field region	mm	21	21
Horizontal good field region	mm	80	110
Field homogeneity in the mid plane at 1.8 T	$\times 10^{-4}$	≤ 2	≤ 2

The following sections present the construction of the straight prototype but the final magnet will be curved with an angle of 75° .

III. IRON COBALT ALLOYS

Iron cobalt is a soft magnetic alloy showing a saturation polarization of up to 2.35 T (see Fig. 3) depending on its composition and state [6,7]. Usually this material is used in the construction of stator/rotor assemblies of aircraft power generators when either high magnetic field are required with as little weight as possible or when rotation frequencies are important (> 200 Hz). Due to its higher saturation, when compared to typical irons to get the same magnetization and performances, FeCo is the best choice for special requirements where size and weight are predominant factors.

Commercial iron-cobalt alloys suitable for magnets are Vacoflux 48 from Vacuumschmelze [8], AFK502R from Aperam [9] and Hiperco 50A from Carpenter [10]. These types of alloys exist with different cobalt amounts from 17% to 49%. Their prices are directly linked to the cobalt price and as a result proportional to cobalt content. The magnetization curves show a saturation field up to 0.8 T higher than the FeSi steel and 0.4 T higher than grain oriented steel see Fig. 3. These alloys need to be annealed typically to about $820\text{--}880^\circ\text{C}$ to achieve their best performance. After the treatment the relative magnetic permeability is large (> 20000 for an AFK502R 0.2 mm lamination) and the saturation polarization increases up to 2.35 T. The BH curve of the AFK502R sample measured at CERN using an Epstein frame is shown in Fig. 4. The insulation between sheets is typically given by a thin layer of magnesium oxide (MgO).

As the material expands during the annealing by about 1% in an anisotropic way, the machining process to achieve precise mechanical tolerances has to be performed afterwards.

In addition, cobalt gets activated by ionizing radiation. Therefore, this aspect has to be considered when designing

FIG. 3. Magnetization curves of standard FeSi, grain oriented and FeCo alloys.

FIG. 4. Relative permeability and induction curves of the AFK502R sample from Aperam [9] measured at CERN with an Epstein frame.

a magnet with a FeCo yoke to avoid exposing the personnel to high doses.

IV. PROTOTYPE LAYOUT

For reasons of cost, time and ease of manufacturing, a straight H-type dipole with a laminated iron length of 10 times the aperture is chosen, more details about the design of this prototype are reported in [11]. The magnetic excitation is obtained by water cooled coils. The overall dimensions of the prototype magnet are shown in Table II. A schematic CAD view of the magnet is shown in Fig. 5 and the cross section of the magnet is shown in Fig. 6.

A. Yoke

The yoke is made of laminated FeCo sheets (AFK502R from Aperam [9]) with stainless steel end plates. U shape stainless steel reinforcement bars are welded on the yoke and tie-rods are placed on each side of the pole and on the top of the half yoke without need of holes in the yoke. The end and side plates are made of nonmagnetic stainless steel to minimize the influence of the eddy currents induced by them on the magnetic field in the aperture.

A lamination thickness of 0.2 mm is selected due to the skin effect. At a given relative permeability of 20 000 and

FIG. 5. Laminated straight H type TULIP dipole magnet.

fast field variation rate the skin effect starts to decrease the average field inside the lamination.

At a frequency of 100 Hz, the penetration depth, calculated according to [12], is

$$\delta = \frac{1}{\sqrt{\pi\mu_0\mu_r f \sigma}} \simeq 0.22 \text{ mm},$$

$$\frac{\bar{B}}{B_0} \approx 1,$$

where B_0 is the field located at the edge of the lamination and $\bar{B}$ is the average field amplitude in the lamination.

At a frequency of 200 Hz:

$$\delta = \frac{1}{\sqrt{\pi\mu_0\mu_r f \sigma}} \simeq 0.16 \text{ mm},$$

$$\frac{\bar{B}}{B_0} \approx 0.94.$$

The frequency of operation is high but the amplitude of the variation of the field is very small, as shown in Fig. 2. Therefore, the iron losses due to hysteresis effect and eddy currents induced in the iron are very small in comparison to the ohmic losses of the coils. For this reason, the natural convection with the surrounding air is enough to avoid a temperature increase in the yoke.

Table III lists the yoke characteristics. The laminations are insulated by a layer MgO obtained by heat treatment.

B. Coils

Each coil is made of 48 turns (6×8). Such a coil requires, at nominal field, a total current of 37 695 A ($2 \times 48 \times 392$ A).

The conductor has a cross section of $10.6 \times 7 \text{ mm}^2$ and a 4 mm hole diameter. The cooling diameter is enough to allow winding the complete coil in one circuit for the prototype. However, for practical reason we wound each coil in three pancakes, as it would be for a full scale magnet.

TABLE II. Overall prototype dimensions.

Parameter	Units	Prototype magnet
Overall width	mm	761
Overall height	mm	448
Overall length	mm	512
Overall weight	kg	520

FIG. 6. Cross section of the H type dipole magnet.

The copper-section of this conductor is $A = 60.78 \text{ mm}^2$, yielding a current density:

$$J = \frac{I}{A} \simeq 6.4 \frac{\text{A}}{\text{mm}^2}.$$

The overall conductor length is 58.3 m or 19.43 m per pancake. This results in a resistance of:

$$R_{\text{magnet}} = \frac{\rho l}{A} \simeq 33 \text{ m}\Omega,$$

$$R_{\text{pancake}} = \frac{\rho l}{A} \simeq 5.4 \text{ m}\Omega,$$

where l is the length and ρ is the electrical resistivity of the conductor.

The voltage drop in steady state with a dc excitation is

$$U = IR \simeq 13.5 \text{ V}.$$

To estimate the value of the voltage during the ramp up it is necessary to calculate the value of the inductance, which can be estimated using the following expression [13]:

TABLE III. Yoke characteristics.

Parameter	Value	Units
Type	laminated	...
Material	FeCo	...
Lamination thickness	0.2	mm
Packing factor	$\geq 96\%$	...
Lamination surface	82440	mm^2
Lamination mass	334	kg
Complete assembly	~ 400	kg

$$L = \frac{\mu_0 (2N)^2 S}{g} \simeq 20 \text{ mH},$$

where N is the number of turns per pole, S is the surface of the dipole field and g is aperture length. Therefore, the maximum voltage drop with the maximum ramp rate of 600 A/s is

$$U = IR + L \frac{dI}{dt} \simeq 25 \text{ V}.$$

The coil is designed for DC operation at maximum current. The dissipated power per pancake at nominal current is

$$P_{\text{pan}} = \frac{\rho l}{A} I^2 \simeq 844 \text{ W},$$

and the total power dissipated in the magnet is

$$P_{\text{tot}} = \frac{6\rho l}{A} I^2 \simeq 5 \text{ kW}.$$

The minimum required water flow, Q , per pancake in l/min for a 10°C temperature increase can be calculated as follows:

$$Q = 14.3 \frac{P[\text{kW}]}{\Delta T[^\circ\text{C}]} \simeq 1.2 \frac{\text{l}}{\text{min}}.$$

The maximum pressure is limited to 15 bars, which is the value available in the different laboratories and machines. Furthermore, the water velocity should be kept below 3 m/s to avoid erosion in the conductor. The relationship between flow and pressure for a circular pipe of diameter d

is described by Blasius law [14]. Using this expression it was decided to chose a pressure drop of 6 bar, which produces a flow of:

$$Q = \left(\frac{\Delta P d^{4.75}}{60l} \right)^{\frac{1}{1.75}} = \left(\frac{6 \times 4^{4.75}}{60 \times 19.43} \right)^{\frac{1}{1.75}} \approx 2.12 \frac{1}{\text{min}}.$$

Therefore, the total water flow of the magnet is $6Q \approx 12.7$ l/min.

V. MAGNETIC DESIGN

This prototype magnet is manufactured to prove: (i) The assembly of a yoke with this high saturation electrical steel (ii) The linear magnetization curve until ~ 2 T (iii) The fast response to a current variation (few amperes by ms).

The design is done to have a linear transfer function until 1.8 T in the gap and, at the same field, a good horizontal homogeneity in the mid plane (80×21 mm). This homogeneity, due to the side shims, will be achieved only at top field and will not cover other condition from 1 to 1.8 T. No shims or chamfer are foreseen in the pole ends to improve the integrated field homogeneity.

The simulations have been performed using Cobham's Opera-2d [15] and Opera-3d [16] finite element analysis software. Even though the magnet will operate with a dynamic cycle, the simulations carried out are magneto-static. This is because dynamic time stepping finite element simulations are very time consuming and in most of the cases the accuracy of the results is not good enough. The dynamic behavior of the eddy currents induced in the iron is strongly related to the value of the magnetic permeability (which changes with saturation) and the electrical resistivity (which in many cases is unknown and difficult to measure). Therefore, the yoke has been designed to minimize the eddy current effects with thin laminations and nonmagnetic end plates, as described in previous sections.

A. 2D simulation with the FeCo alloy

The average flux density in the return yoke is kept between 1.6 and 2 T however the shim locally increases the field to more than 2.2 T.

Figure 7 shows a 2D view of the flux density in the yoke with a field of 1.8 T in the center.

The side shims, 6×1 mm, have been chosen to have the best center horizontal homogeneity at the maximum field within the good field region (GFR). We obtain an error $\Delta B/B$ of less than 1×10^{-4} per unit (pu), increasing up to 20×10^{-4} pu at 1 T.

B. 2D simulation with the standard FeSi alloy

With the same cross section, the maximum field intensity, still providing the required field quality of

FIG. 7. FeCo magnet 2D flux density simulation.

$\pm 2 \times 10^{-4}$ pu, has to be kept within 1.28 T, i.e., 0.52 T lower than the field with FeCo.

By powering the FeSi version at the same current as the FeCo at 1.8 T we reduce the field intensity to 1.68 T, however the homogeneity and the third harmonic degrade respectively to 130×10^{-4} and 4.6×10^{-4} pu.

Improving the design with the same current density, see Fig. 8, a center field of 1.8 T cannot be achieved due to the iron saturation. To provide 1.8 T, with $\pm 2 \times 10^{-4}$ pu of field accuracy, the cross section of the FeSi magnet shall be enlarged by 30% with respect to the FeCo magnet and the current shall be increased by a minimum of 5.5%.

C. 3D simulation with FeCo alloy

The choice to not add end shims results in an increased field in the pole ends, as you can see in Fig. 9, the light green colored pole part has a flux density higher than 2.2 T.

FIG. 8. FeSi magnet 2D flux density simulation with an increased yoke cross section to achieve a center field of 1.8 T.

FIG. 9. Opera 3D view of a FeCo yoke quarter.

Even if the magnet is short in comparison to the final one, the homogeneity in the mid plane remains the same as in the 2D simulations, below 1×10^{-4} pu. Resulting from the lack of chamfer or end shims, for a GFR of 80×21 mm, the B_0 integrated field homogeneity the error increase:

$$\frac{\Delta \int B_y \cdot dl}{\int B_0 \cdot dl} = -130 \times 10^{-4}.$$

The same effect affects the harmonics in particular the sextupolar field harmonic (B_3) with a value of -3.7×10^{-4} pu.

VI. CONSTRUCTION

The manufacture of the magnets is described in detail in [17]. Two prototypes have been manufactured for comparison purpose. The first one with normal FeSi steel (NO20) and the second with the FeCo alloy from Aperam, the AFK 502R grade which has the highest cobalt ratio of 49% [9].

Rectangular sheets of 205×600 mm have been cut and treated. The FeSi steel was coated with a C-5 inorganic varnish before cutting. On the other hand, the FeCo sheets

FIG. 10. FeSi and FeCo laminations. The FeCo laminations have a blue/purple color due to the magnesium oxide (MgO) layer.

FIG. 11. Geometrical measurement results of a FeCo pre-series lamination.

FIG. 12. Stacking of the yoke.

were treated after cutting by an annealing treatment at 850°C for six hours. A picture of FeSi and FeCo laminations is shown in Fig. 10.

As explained before, due to its anisotropic expansion, FeCo laminations have suffered an important deformation after the stamping. After several preseries laminations, the

FIG. 13. Coil winding performed in-house.

FIG. 14. Impregnated coil.

series ones have been precut with some millimeters of extra material to remove the deformation induced by the thermal treatment. Figure 11 shows schematically the geometrical measurements performed to a preseries lamination. The color red represents that the lamination is larger than the specification and blue represents that it is smaller.

The laminations are stacked and welded together using stainless steel side and end plates. In addition, each half-yoke has three M12 rods, insulated with polyimide and with G11 washers, used to ensure a good parallelism of the end plates before welding. The welding procedure in the stacking tool is shown in Fig. 12. The welding procedure used in this magnet is tungsten inert gas (TIG) welding without additional material along the laminations and with additional material between the laminations and the side plates.

FIG. 15. Assembled magnet.

The coil is wound using an appropriate mandrel under tension; insulation is made of polyimide and fiber glass tapes, and the coil is impregnated with epoxy resin as shown in Figs. 13 and 14.

The assembled prototype magnet with all the electrical and water connections, and protection covers is shown in Fig. 15.

VII. SATURATION EXPERIMENTAL RESULTS

After the prototypes manufacture was completed, magnetic measurements were performed to them to characterize their properties. The static B - I curve for both prototypes and the values calculated using a constant permeability of the iron are shown in Fig. 16. The measurements were carried out at the magnetic measurements laboratory at CERN using a Hall probe at the center of the magnet. It can be appreciated that the FeCo prototype has an almost linear behavior even at ~ 1.86 T. The FeSi prototype starts to saturate much earlier at ~ 1.18 T.

We define the transfer function at the center of the magnet, TF , as

$$TF = \frac{B}{I},$$

where B is the magnetic field at the center of the aperture and I is the exciting current. The transfer function for both prototypes obtained from magnetic measurements and from the 3D simulation model are shown in Fig. 17. It can be appreciated that the magnetic measurement data is consistent with the simulation results. As in the B - I curve, the early saturation of the FeSi prototype can also be appreciated.

Fig. 18 shows the current cycle used for the study of the dynamic performance of both prototypes. The beginning of the current cycle, $I \simeq 400$ A, simulates the treatment of a deep tumor with a beam of 230 MeV and the end of the current cycle, $I \simeq 170$ A, simulates the treatment of a tumor closer to the surface with a beam of 70 MeV. The zoom in

FIG. 16. Center magnetic field as a function of current.

FIG. 17. Center transfer function as a function of current.

Fig. 18 displays the difference in the current cycles with respect to the reference. The difference in shape of the currents was produced by an upgrade in the control algorithms of the power converter in between measurements. The current wave-forms have a delay with respect to the reference current due to the power converter, which has to be accounted for.

The integrated magnetic field for both prototypes is shown in Fig. 19, for the current cycle from Fig. 18. It can be appreciated that at high currents there is a significant difference between the FeSi prototype ($\int Bdz \simeq 0.469$ Tm) and the FeCo prototype ($\int Bdz \simeq 0.549$ Tm), around 15%.

FIG. 18. Top: current cycle used for the experiment. Bottom: zoom of the current step from 6.15 to 6.25 seconds.

One important requirement is that it should behave linearly up to ~ 1.8 T, i. e. this means that for a given variation of current there should be a similar variation of integrated field at low and at high field. This can be studied using the integrated transfer function, which is expressed in Tm/A and it is defined as follows:

$$TF_I = \frac{\int Bdz}{I}.$$

The transfer function of Fig. 19 shows clearly that there is a much larger variation in the integrated transfer function for the FeSi prototype ($\Delta TF_I^{\text{FeSi}} \simeq 16.99\%$) than for the FeCo prototype ($\Delta TF_I^{\text{FeCo}} \simeq 4.25\%$). In practice, this means that for a given step in current the field variation would be different at low currents from high currents for the FeSi prototype, which can produce problems in the control of the field.

Figure 20 shows the current and the integrated magnetic field normalized from 5.5 to 6.5 seconds and a zoom of a step of $\Delta I \simeq 1.14$ A ($\Delta I \simeq 0.3\%$) at high field. The step in the integrated field is 0.22% for the FeCo prototype. The step in field for the FeSi prototype is considerably smaller, 0.14%, because the yoke is saturated thus the magnet is operating in the nonlinear region.

Figure 21 shows the current and the integrated magnetic field normalized from 65.5 to 67 seconds and a zoom of a step of $\Delta I \simeq 1.76$ A ($\Delta I \simeq 1.02\%$) at low field. The step in

FIG. 19. Top: integrated magnetic field. Bottom: integrated transfer function.

FIG. 20. High current step. Top: current normalized and bottom: variation of the field normalized.

the integrated field is 1.02% for both prototypes. The step in field is similar in both cases because the iron is not saturated thus the magnet is operating in its linear region.

FIG. 21. Low current step. Top: current normalized and bottom: variation of the field normalized.

FIG. 22. High current step delay.

VIII. EDDY CURRENT EFFECTS

As it was mentioned in the introduction, it is important that this magnet can have a fast response, i. e. that after a step in current, the field must reach the new value quickly. This field delay is caused by the eddy currents induced inside the laminations of the yoke. Figure 22 shows the normalized fields and currents for a step at high current for the FeCo and FeSi prototypes. It is considered that the transient response is finished once the field settles inside $\pm 0.02\%$ of the new value, this is shown using boxes in the figure. The field delay of the FeCo prototype is 17.2 ms while the field delay for the FeSi prototype is 11.5 ms.

It is important to point out that for the same change of current, the drop of field for the FeSi prototype is smaller ($\Delta \int B_{\text{FeCo}} \approx 0.22\%$ against $\Delta \int B_{\text{FeSi}} \approx 0.14\%$), which means that to achieve the same drop in field it would be necessary to have a larger step of current that takes more time. Therefore, it can be concluded that in terms of field delay due to eddy currents both magnets behave in a similar way at high currents.

Figure 23 shows the normalized fields and currents for a step at low current. The field delay of the FeCo prototype is $\Delta t_{\text{FeCo}} \approx 26.9 \text{ ms}$ while the field delay for the FeSi

FIG. 23. Low current step delay.

prototype is $\Delta t_{\text{FeSi}} \simeq 25.9$ ms. In this case, when the FeSi prototype is not heavily saturated the change in magnetic field is similar in both magnets and therefore the field delay is almost identical.

IX. CONCLUSIONS

This paper has presented the design, construction, and measurement of a FeCo prototype magnet for medical gantries and compared it with the same prototype built using FeSi.

The experimental results show that the magnetization curve, the B - I curve, of the FeCo prototype is linear up to 1.8 T as expected. On the other hand, the FeSi prototype starts to show a nonlinear behavior much earlier at around 1.18 T.

The nonlinear behavior can also be appreciated from the variation of the integrated transfer function along the current cycle: the variation of the integrated transfer function of the FeCo prototype is $\sim 4.25\%$ while the variation of the FeSi prototype is $\sim 16.99\%$.

The dynamic behavior of the magnets in terms of delay due to eddy currents is similar in both prototypes.

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