Detailed design report of the development of dipole magnets for MEBT application at MedAustron.

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Introduction

MedAustron is a proton therapy facility based in Austria. The development of this facility requires several beam manipulation devices such as Magnets, RF cavities, correctors, steerers, etc.

Dipole magnets allows medical professionals to selectively steer proton and other ions of specific energy to have a precise control over therapy. This selective control allows for radiation to be targeted at a specific spot and thus results in a highly effective treatment of diseases such as cancer.

The development of dipole magnets for changing the trajectory of ions such as Carbon C^{6+}, protons, etc for MEBT part of this facility is of interest in this detailed design report. Several other topics such as fabrication and cost estimation of such dipole magnets have also been discussed.

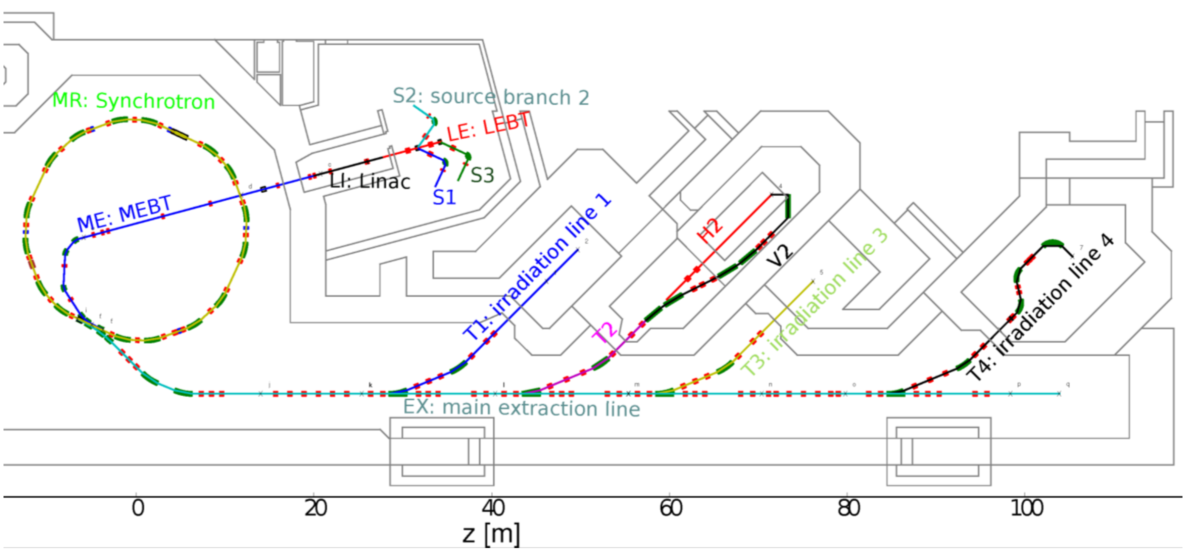


Figure 1: MedAustron facility

1 Physical requirements

At the time of the development, the most demanding species considered were the Carbon C^{6+} ions with a kinetic energy of T = 7 MeV/U (total T = 84 MeV). This allowed to define a maximum value of the B field that needs to be obtained by the dipole steerer system in the MEBT part of the facility. Protons were also considered but as the total momentum of proton is smaller compared to a carbon ion at a given value of kinetic energy, the following calculations and estimations are based on the assumption that facility operates at a maximum energy of 7MeV/U in the MEBT section.

The following table summarizes the required performance of the magnet.

Parameter	Value	Unit
Number of magnets	3	
Bending angle (per magnet)	36	deg
Horizontal good-field region	± 20	mm
Vertical good-field region	± 23	mm
Field quality inside GFR $\Delta B/B_0$	$< \pm 1 * 10^{-3}$	
Vacuum chamber thickness	2	mm
Max. available water pressure drop	0.7	MPa
Inlet water temperature	20	$^{\circ}C$
Max. converter current	600	A
Max. converter voltage (3 magnets in series)	80	V
Operation mode	DC	

Table 1: Magnet requirements

2 Detailed design and engineering

This section summarizes the design choices and calculations performed to determine the specifications of the magnet design.

2.1 Preliminary calculations

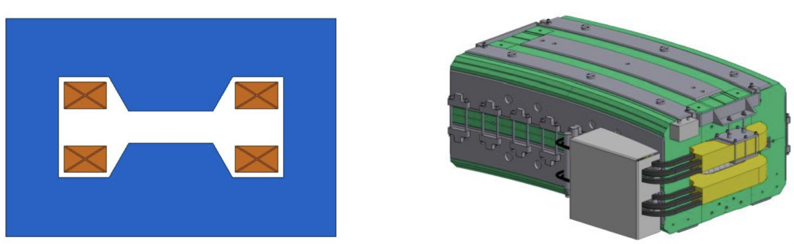


Figure 2: H shape configuration for dipole magnet.

Two types of magnet configuration are possible: C-type and H-type. Both can be used to bend the field. After several considerations, the H shaped yoke was preferred over the C type yoke.

The H-shaped yoke separates the flux into two portions on either side of the vacuum tank, and the coils' placement in the median plane.H type configuration allows to reduce the stray flux, and also the length of the lines of force in the iron is reduced, and a smaller pole piece can therefore be used. Also, the H shaped configuration is mechanically more rigid.

We compute the relevant parameters.

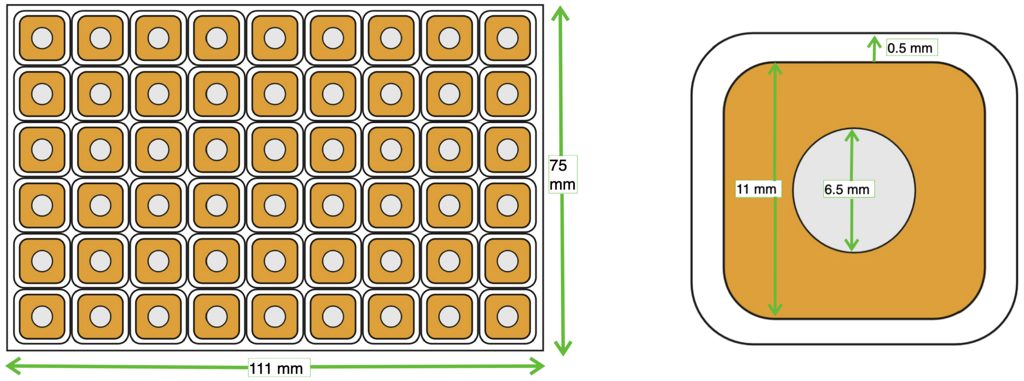


Figure 3: The conductor and coil total cross section.

- aperture height h : the vertical good-field region is $\pm 23\ mm$, the vacuum chamber thickness is $\pm 2\ mm$, the isolation thickness is $\pm 0.5\ mm$, and we chose a margin of $\pm 0.5\ mm$. By multiplying the total addition by 2, we obtain an aperture height : $h = 52\ mm$.
- magnetic length l_{mag} (using $k = 0.55$) : $l_{mag} = l_{iron} + 2 * h * k$ with $l_{iron} \leq 340\ mm$. We chose $l_{iron} = 340\ mm$, and we compute $l_{mag} = 397.20\ mm$.
- flux density B : $B\rho = \frac{p}{q}$ with $\rho = \frac{l_{iron}}{2 * \sin\frac{\alpha}{2}}$, and we find $B = 1.1909\ T$
- Pole width or yoke thickness : $w = 2 * GFR_H' + 2 * a$ where $GFR_H' = GFR_H + s$ with $s = \rho * (1 - \cos\frac{\alpha}{2})$. To compute the pole overhang a, we have two formulas :
  - the unoptimized one : $x_{unoptimized} = 2\frac{a}{h} = -0.36 \ln\frac{\Delta B}{B_0} - 0.90$
  - the optimized one : $x_{optimized} = 2\frac{a}{h} = -0.14 \ln\frac{\Delta B}{B_0} - 0.25$

  We computed a and we obtained with the first one 41.3 mm and 18.6 mm with the second one. We chose an arbitrary value between these two, closer to the optimized one. With $a = 25\ mm$. Finally, we get : $w = 192.91\ mm$
- Excitation current NI : the formula giving the excitation current is : $NI = \frac{B * h}{2 * \mu_0}$
  After the computation of the excitation current, we can not compute the number of turns, knowing the current. The maximal current is 600 A, we choose a margin of about 10 %, so the current is 540 A. With this value of the current, we obtain 46 turns. We need a good ratio between the width and the height of the wire. The ratio : $\frac{width}{height}$ has to be between 1 and 2. Hence, we chose a ratio of 9 over 6, which gives us 54 turns. The corresponding current is 469.99 A. We still are in the margin of 10 %, so it is coherent. Another reason to use higher number of turns than the minimum required was to lower the current density thus reducing the running cost of the magnet.
- As mentioned before, there are 9 "columns", and 6 "rows". The copper wire is a square of 11 mm side. We need an insulation of 1 mm between each wire, and half of this value for the extrem side (left and right), or a total insulation of 9 mm. And there is also an outer insulation of 1.5 mm in each side. We arrive to the following formula for the coil width horizontally: $9 * 11 + 9 + 2 * 1.5 = 111\ mm$. For the coil height (vertically), the similar computation gives 75 mm respectively..

The formula for the conductor length is : $l_{avg} = perimeter + 4 * b_w$. The perimeter of one pole is : $2 *$ (length of the magnet + gap + pole width + pole gap). The length of the magnet is 340 mm, the two gaps (gap of the magnet and the pole gap) are of 4 mm, and the pole width is 192.91 mm. $b_w = 111\ mm$ is the width of the coil. To have the total conductor length, we have to multiply these values by the number of turns. The final formula is : $l_{avg} = 54 * (2 * (340 + 4 + 192.91 + 4) + 4 * 111) = 82.394\ m$. For the conductor cross-section : we have to determined some parameters :

- $c = 11\ mm$ is the length of the square
- $r_b = 3.25\ mm$ is the cooling bore radius
- $r_{edge} = 1\ mm$ is the edge rounding radius
- A_{con} is the conductor cross-section

Hence, the formula is : $A_{con} = c^2 - \pi r_b^2 - 4 * (r_{edge}^2 - \frac{\pi r_{edge}^2}{4})$. We get $A = 86.96\ mm^2$

- Resistance $R_c = \frac{N_{turns} * l_{avg}}{A_{con} * \sigma_{Cu}} = 0.016\ \Omega$ where $\sigma_{Cu} = 5.8.10^7\ S/m$.
- Voltage $V_m = I * m * R_c = 14.963\ V$ where $m = 2$ is the number of coils per magnet.
- Dissipated power $P = V_m * I = 7.0325\ kW$.
- Current density $j = \frac{I_{nom}}{A_{con}} = 5.4048\ A/mm^2$.
- Coolant flow $Q = \frac{14.3 * P}{\Delta T_{max}} * 10^{-3} = 3.3522\ l/min$ where $\Delta T_{max} = 15°C$.
- Flow velocity $u = \frac{16.67 * Q}{Holesurface}$ where the hole surface is the surface of the cylinder where the water is moving through. So, $u = \frac{16.67 * Q}{\pi r_b^2} = 1.6838\ m/s$.
- Pressure drop $\Delta P = \frac{60 * Coolinglength * Q^{1.75}}{hydraulicdiameter^{4.75}} = \frac{60 * l_{avg} * Q^{1.75}}{r_b^{4.75}} = 5.6497\ bar$.
- Reynolds number $Re = \frac{u * hydraulicdiameter}{\nu}$ where the hydraulic diameter is the diameter of the hole where the water is cooling. So, $Re = \frac{u * 2 * r_b}{\nu} = 16633$.

Parameter	Value	Unit
Aperture height	52	mm
Magnetic length	397.20	mm
Flux density	1.1909	T
Pole width	192.91	mm
Excitation current	469.99	A
Conductor length	82.394	mm
Conductor cross section	86.96	mm^2
Resistance	0.016	Ω
Voltage	14.963	V
Dissipated power	7.0325	kW
Current density	5.4048	A/mm^2
Coolant flow	3.3522	l/min
Flow velocity	1.6838	m/s
Pressure drop	5.6497	bar
Reynolds number	16633	

Table 2: Magnet characteristics for a C^{6+} ion at 7 MeV/U

To remain below the limits and having a not to high pressure drop, we had to increase the cooling diameter. For the cooling diameter, we chose 6.5 mm instead of 6 mm. We change the characteristic of our conductor, and we saw that it changed all of the other parameters. Hence, it shows that in real life, changing one parameters influences many others parameters of the magnet.

2.2 Simulation for C^{6+} and Protons

An objective function has been developed in order to find a geometry that best satisfies the constraints, then the variables x_i, $i = 1, 2, 3, 4, 5, 6$, have been modified manualy in order to minimize $F(x_i)$.

$$\min F(x_i) = (B_{FEM,C_{6+}}(x,0) - B_{target,C_{6+}})^2 + (B_{FEM,leg}(x,0) - B_{target,sat})^2 + \\ (B_{FEM,tooth}(x,h) - B_{target,sat})^2 + TotalCost(x_1, x_2, x_3, x_4, x_5, x_6)$$

Where:
x_1 : Height of tooth
x_2 : Width of tooth
x_3 : Radius of tooth
x_4 : Width of the leg
x_5 : Radius in Yoke leg
x_6 : Current

In adition, the restriction for the $F(x_i)$ are, $B_{target,C6+} = 1.19$ T, $B_{target,sat} = 1.5$ T. Also, for a better understanding of these parameters, Figure 4 is presented.

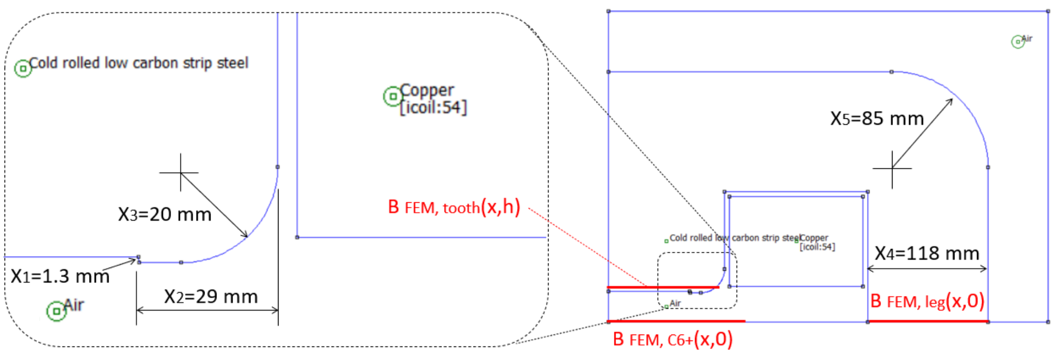


Figure 4: Parameters obtained from the optimisation process

The results of the magnetic field obtained with the variables presented in Figure 4 are shown in Figure 5. It can be seen that for most of the yoke the 1.5T constraint is met, while a maximum of 1.8T is allowed at the corners for the case of C_{6+}.

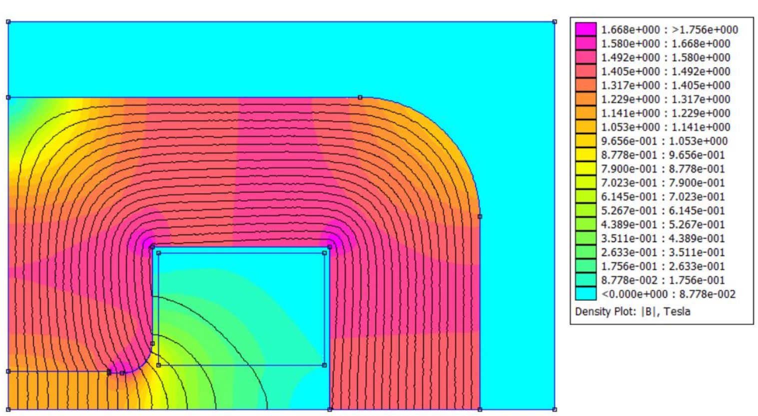


Figure 5: Magnetic flux simulations, T = 7 MeV/U, C^{6+}

It should be noted that we did not optimise for C_{6+} and protons at the same time, but optimised for C_{6+} first, and then by fixing this geometry and varying the current, we found that the magnetic field in the GFR also meets the objective for the protons (Figure 6).

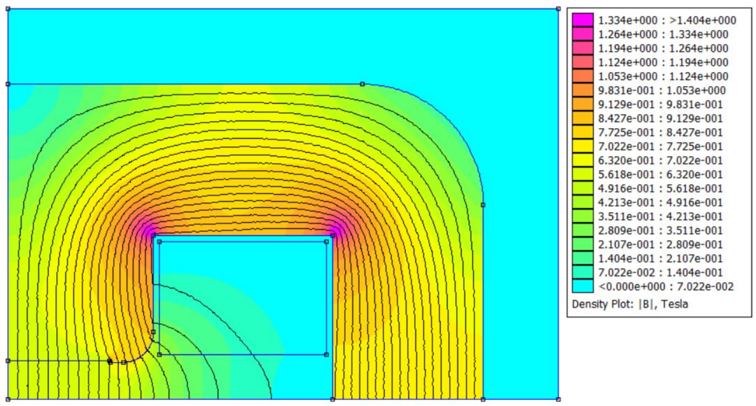
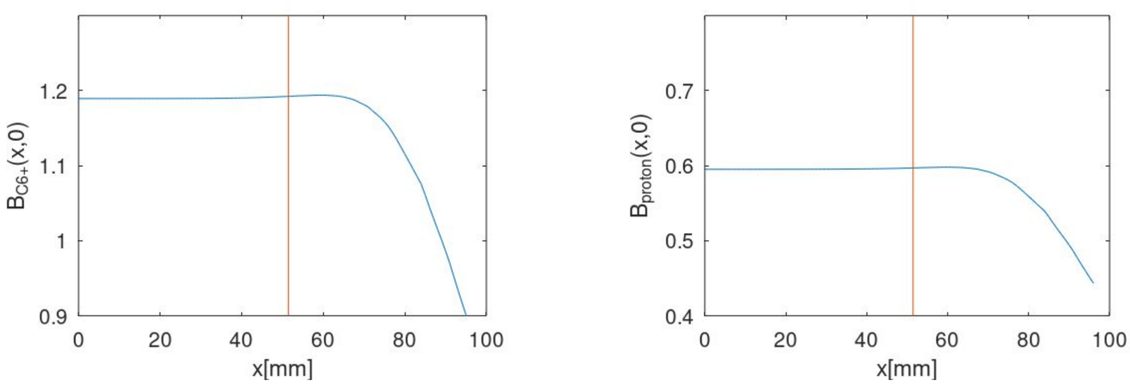


Figure 6: Magnetic flux simulations, T = 7 MeV/U, Proton

On the other hand, values for the magnetic field of the GFR zone (Vertical red line) are obtained for C_{6+} and for protons, Figure 7.



(a) C^{6+}

(b) Proton

Figure 7: Field quality simulations, T = 7 MeV/U

3 Fabrication

Magnets consist of ferromagnetic materials, i.e. a material that can be magnetized and then creates a magnetic field. We distinguish magnetically ”soft” materials like annealed iron, which looses its magnetization and magnetically ”hard” materials, such as alnico and ferrite, which stay magnetized and are hard to demagnetize.

In our case study, we considered an electromagnet, which is a structure consisting of a coil of wire that acts as a magnet as long as an electric current passes through it. In order to enhance the magnetic field of the coil, we combine it with a yoke of ”soft” ferromagnetic material, such as iron.

After having described our magnet design, we want to give a brief overview on the fabrication process of the magnets, based on the lecture slides by Thomas Zickler of the JUAS 2023. Once the design is completed and the prototype finalized, the magnet is brought to the series production. To this end, the materials and the tooling are procured and with these, the yokes, coils and accessories are produced. The accessories contain the electric and hydraulic connections, measurement devices and mounting aids. After the assembly and final tests and measurements, the magnet is installed for the operation.

3.1 Yoke

Yokes are typically produced in two different ways. They can either be produced from machining solid steel or as laminated yokes. We consider here a laminated yoke where the individual laminations are stamped from sheets. After the stamping, the laminations are stacked and glued or welded to form the yoke. Finally, they are machined to e.g. drill the some bores and assembled.
Advantages of laminated yokes are that steel sheets are cheaper in purchasing than massive steel blocks. Furthermore, producing yokes from laminated steel is less expensive when manufacturing them for a large series. Although the required specific tooling is more expensive in the beginning, the costs are lower for the overall series production. Furthermore, the properties of the steel can be tailored by rolling and annealing and are also consistent over the entire series.

Insulation The sheets are electrically insulated by a surface coating of several μm thickness, either on one or on both sides. Many different types of insulations are available, which e.g. are based on oxid, photosphate, organic or inorganic coatings and which result in different colors. A common choice is e.g. the colorless STABOLIT 70 which is an organic bonding lacquer and applied in a thickness that ranges between 5 μm to 8μm.

3.2 Coil

Coil design is generally based on experience and benefits from empirical data. For the coil manufacturing we define a conductor type and material, a conductor insulation, winding, ground insulation and use an epoxy impregnation. For the conductor, copper is a favourable choice due to its low resistivity. It is typically used in a tubular form to allow for easy application of water cooling and comes in a range of cross sections, e.g. round, square, and rectangular. Further criteria to consider for the coil design are the coupling and distribution of the flux lines in the coil, for example.

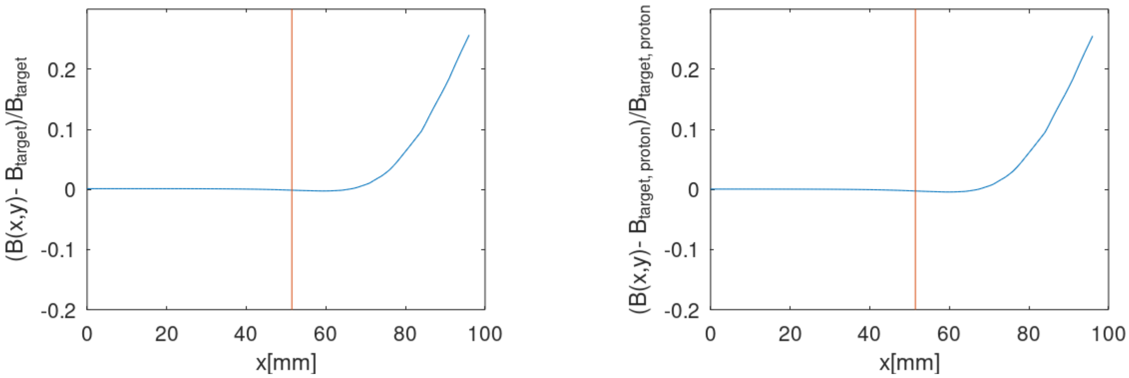
Coil insulation Since several conductors are arranged in the coil, insulation is required to ensure that current is only flowing in the desired circuit. Therefore, a thorough electric insulation is required to avoid local heating, damages or field distortions. A common choice is epoxy resin, where defects like bubbles, voids cracks and an uneven application need to be avoided for a safe operation.

4 Performance

Different ion species typically used in proton therapy were considered for simulation and testing of this magnet. This section is dedicated to the magnet performance at the peak value of the considered ion. The two species considered in the simulation were C^{6+} and proton at 7 MeV/U, the result are as follows

Parameter	C^{6+}	Proton	unit
Current	470	230	A
Current density	5.4	2.65	A/mm^2
Magnetic field	1.19	0.59	T

Table 3: Magnet performance



(a) C^+ (b) Proton

Figure 8: Field quality of both species.

As can be seen from the Fig 8, the results are within the requirements in the good field region. In other words, the selection of H type magnet and its associated supporting structures allows us to get a high field. $\Delta B/B < 10^{-3}$ in the good field region for both the species.

5 Cost estimation

5.1 Initial capital

In order to build the magnet, several costs have to been taken into consideration. Firstly, some costs are fixed such as Design cost: 10,000 euros, Stamping tool: 15,000 euros, Stacking tool: 12,000 euros, Winding tool: 10,000 euros, Impregnation mould: 20,0000 euros.

Those fixed costs are independent of the number of magnets built. Fixed costs are equal to 67 000 euros. Four magnets are required. From the design and for one magnet, are extracted:

- Volume of the yoke: 0.066805 cubic meters
- Volume of the coils: 0.025405 cubic meters

Expense	Cost (in kilo euros)	Fraction of capital (%)
Design	10	5.93
Stamping tool	15	8.89
Stacking tool	12	7.11
Winding tool	10	5.93
Impregnation mould	20	11.86
Magnets (4)	101.64	60.27

Table 4: Capital distribution

Knowing the volumic mass of steel and copper, the mass required is computed for a total mass of **734 kg** per dipole. Prices for steel and copper are 2 euros per kg and 22 euros per kg. Manufacturing costs have also to be taken into consideration. It represents 12 euros per kg for the yoke and 36 euros per kg for magnets. Auxiliary parts for one magnets are 5000 euros. All those values give a initial cost of 25,409 euros per magnet and so 101,640 euros for 4 required magnets.

5.2 Running costs

Three of the four magnets are running 4200 hours per year. The price of the MWh is 125 euros. By multiplying the voltage by the current by working hours, we have he MWh needed. We multiply this result by the price of the MWh and then we apply a formula that takes into consideration a 5% inflation of the price. Running cost is estimated to be 84,790 euros for 20 years for 3 magnets. To conclude, the estimated cost of the production and the use of the magnets is 253,430 euros.

Conclusion

Dipole magnets are important in the field of particle accelerator based facilities such as proton therapy devices. The design of the magnet was done in collaboration with MedAustron. Several methodologies were considered for the desing and development of such magnets keeping the requirements and restrictions in mind.

Several design choices were discussed from the shape of magnets to coil and yoke structures. Finally, the most optimum configuration satisfying all the parameters was selected and reported for further fabrication. The proposed design produces a good field in the good field region while keeping the current density and thus the power consumed under limit. This concludes the development of dipole magnet for the MedAustron facility.