Investigating the possibility of a hybrid magnet design for BV/BW dipole magnets at the XFEL

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Contents

Chapter 1

Introduction

This rapport concerns the design of vertical bending magnets deflecting the electrons away from the photon beam path toward the beam absorber at the European X-ray Free-Electron Laser (XFEL). In the technical design report [1] a 10/15 degree bend is provided by electromagnetic dipole magnets in a double-bend achromat (BV/BW). Proposals for the design of these electromagnets have been carried out by the Efremov Institute, St. Petersburg [2, 3]. Each magnet yoke is H-shaped, 2.5 m long and has a 6 cm pole gap. BV and BW consist of two and three magnets, respectively. The XFEL has been designed for a maximum electron energy of 25 GeV, but the nominal beam energy is 17.5 GeV [4]. It is possible that the machine will operate in CW mode in a far future. That can only be done at a lower energy (7 GeV) [4]. The energy range is therefore 6-25 GeV [1]. For electrons to be deflected 10° after moving through 2×BV and 15° after 2×BW they have to be bent 1°/m. Electrons with momentum p moving in a plane perpendicular to a uniform magnetic field, B, move in a circle with radius,

$$R = \frac{p}{qB}, \tag{1.1}$$

where q is the electron charge. The length of each magnet,l (see figure 1.1), can be written as function of the deflected angle θ as

$$l = 2R \cdot sin(\theta/2). \tag{1.2}$$

Using the approximate expression for the kinetic energy of a relativistic electron, $E = pc$, and equation 1.1 and 1.2, we obtain the following expression:

$$B = \frac{2E \cdot sin(\theta/2)}{c \cdot q \cdot l}. \tag{1.3}$$

Table 1.1 shows the calculated magnetic field for a number of beam energies. In order to estimate the minimum pole width, W, needed for BV and BW the

E [GeV]	**6**	**10**	**14**	**17.5**	**20**	**22**	**25**
B [T]	0.35	0.58	0.82	1.02	1.16	1.28	1.46

Table 1.1: Magnetic field strength as function of electron energy.

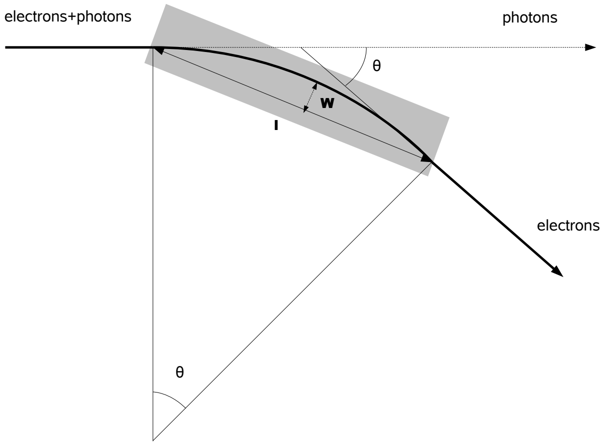

Figure 1.1: Schematic of an electron beam moving through a dipole magnet.

following expression was used:

$$W = R(1 - cos(\theta/2)). \tag{1.4}$$

The minimum width for a single magnet, BV and BW is shown in table 1.2. The pole has been designed to be approximately 20 cm wide for both BV and BW [2]. The main parameters for dipoles designed for the XFEL are presented in table 1.3.

Dipole length [m]	**2.5**	**5**	**7.5**
Minimum pole width [cm]	1.4	5.5	12.3

Table 1.2: The minimum pole width (W) calculated using equation 1.4 for dipoles of length l. BV/BW are designed to be 5/7.5 m and consist of 2.5 m segments.

Name	Length [m]	Gap [m]	B [T]	I [A]	Winding	E_{min} [GeV]	E_{max} [GeV]
BV	2x2.5	0.06	1.456	887	2x42	6	25
BW	3x2.5	0.06	1.455	886	2x42	6	25

Table 1.3: Main parameters for dipoles designed for the XFEL [2].

In connection to BV, a permanent magnet, situated further down the photon beam line is needed as a precaution, in case of power breakdown, to prevent the electron beam to reach the experimental hall. Another possibility is to combine a permanent magnet and an electromagnet. For example, permanent magnet material strong enough to deflect 17.5 GeV electrons 10 degrees is combined with an iron yoke and coils. The coils are powered by bipolar powers supplies to increase or decrease the magnitude of the field. This hybrid magnet would ideally consume less power than a conventional electromagnet, work as safety, and also make the beam line more compact. This report investigates the possibility of such a design.

Chapter 2 contains an introduction to magnetic circuits and permanent magnet materials. It also illustrates how a simple hybrid magnet can be constructed just by replacing all or part of the iron yoke in an ordinary electromagnet by permanent magnet material. As will be seen, however, such a configuration is not optimal. Instead, chapter 3 shows a design which allows a higher field strength and less current in the coils.

The magnetic field calculations carried out in this report have all been calculated with the commercial program Opera-3D from Vectorfields.

Chapter 2

Introduction to magnetic circuits and permanent magnet material

2.1 Conventional electromagnet

Before introducing the hybrid magnet the basic theory of a conventional H-shaped dipole magnet made from an iron yoke and conducting coils is discussed to clarify further arguments. A model of an H-shaped magnet based on the drawing of BV/BW in the technical proposal for a batch of electromagnets for the XFEL project [2] is presented in Figure 2.1.

The Maxwell equation important in this case can be written in terms of the magnetic field (B) as

$$\vec{\nabla} \times \vec{B} = \mu\mu_0 \vec{J} \tag{2.1}$$

where μ_0 is the permeability of air, μ is the permeability relative to air and $\vec{J}$ is the current density vector. Equation 2.1 can be written in integral form by applying Stokes' theorem and results in this useful expression,

$$\oint \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \int_S \vec{J} \cdot \vec{dS} = NI, \tag{2.2}$$

where I is the current and N the number of turns. Consider the closed path shown in figure 2.1 and assume that the magnetic flux lies inside and follows the yoke, is normal to the pole faces and is continuous across the gap ($B_i \approx B_g = B$). Subscript g and i is used for properties connected to the air gap and iron, respectively. Equation 2.2 can then be written as

$$NI = \oint_{gap} \frac{\vec{B}}{\mu_0} \cdot d\vec{l_g} + \oint_{iron} \frac{\vec{B}}{\mu_i\mu_0} \cdot d\vec{l_i} = \frac{B}{\mu_0} l_g + \frac{B}{\mu_i\mu_0} l_i. \tag{2.3}$$

Since $\mu_i > 1000$ and $l_i \approx 20 l_g$ the contribution from the second term in equation 2.3 is less than a few percent and therefore

$$NI \approx \frac{B}{\mu_0} l_g. \tag{2.4}$$

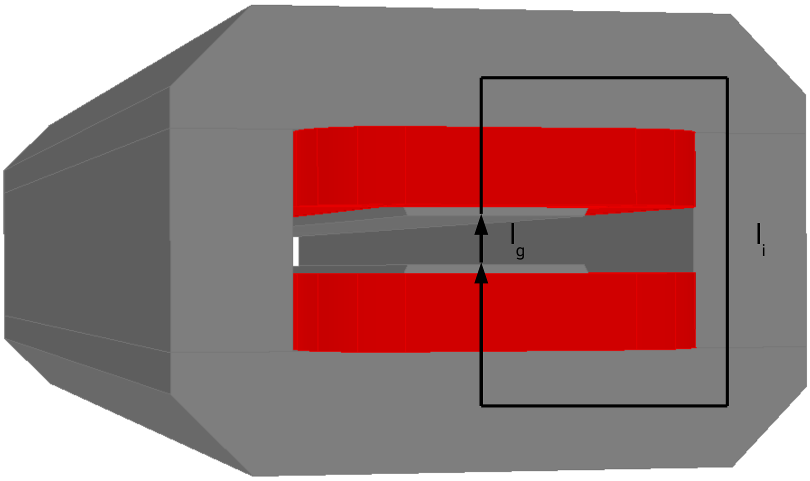

Figure 2.1: H-shaped dipol magnet. Iron yoke is grey and coils are red.

Applying the value of the maximum current, number of coils and size of the gap given in table 1.3 to equation 2.4 yields $B = 1.55$ T, which is slightly higher than the maximum field (1.46 T) calculated from more accurate calculations using Opera-2D [2] and Opera-3D [this report, see figure 3.7].

2.2 Introducing permanent magnet material

The most important properties of permanent magnet materials has been reviewed in a paper by Halbach [5]. The relationship between B and H in the direction parallel to the easy axis of permanent magnet material (PMM) is linear in a wide range (see figure 2.2) with slope $\mu_p \approx 1$. The offset of the curves from the origin, the remanent field, $B_r \approx 1$ T. The point where the slope becomes nonlinear can be well within the second quadrant, but as long as the working point is on the straight part of the curve, this linear dependence will not change.

Let us work out the field in the gap of an H-shaped dipole magnet entirely made by PMM, the same way we did for the electromagnet in section 2.1. The same assumptions are made here, the magnetic flux follows the PMM and in the air gap $B_g \approx B_p = B$. If we assume that the magnetization curve is linear for the PMM, it can be expressed as

$$B_p = \mu_0 \mu_p H_p + B_r, \tag{2.5}$$

where B_p is the magnetic field and H_p is the magnetic field intensity of the PMM, respectively. Applying equation 2.3 to a dipole magnet with yoke made of PMM gives

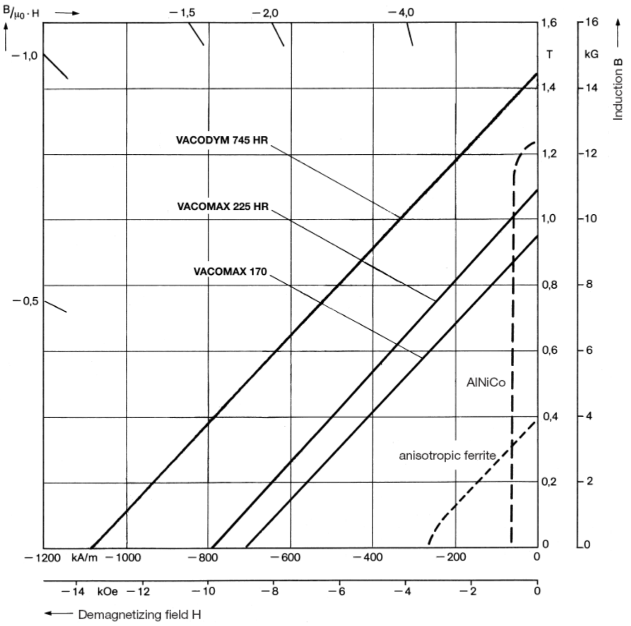

Figure 2.2: Typical demagnetization curves of some permanent magnetic materials. The figure is taken from Vacuumschmeltze's product catalogue [6]. The curve for VACOMAX 225 was used in all calculations.

$$0 = \frac{B}{\mu_0} l_g + \frac{B - B_r}{\mu_0 \mu_p} l_p. \tag{2.6}$$

Since there is no free current flowing, the line integral must be zero. Equation 2.6 can also be written as

$$B = B_r \frac{\frac{l_p}{\mu_p}}{l_g + \frac{l_p}{\mu_p}}. \tag{2.7}$$

This suggests that it is not possible to obtain a stronger field in the gap for such a dipole configuration than the remanent field B_r, which normally is close to 1.

2.3 H-shaped hybrid dipole magnet

In order to reach higher magnetic fields than the remanent field of the permanent magnet material in the dipole magnet described in section 2.2, it is necessary to introduce iron in the yoke and conducting coils. Figure 2.3 shows such a hybrid. The magnetic equation, similar to 2.3 and 2.6, for this configuration can be written as

$$NI = \frac{B}{\mu_0} l_g + \frac{B - B_r}{\mu_0 \mu_p} l_p + \frac{B}{\mu_0 \mu_i} l_i, \tag{2.8}$$

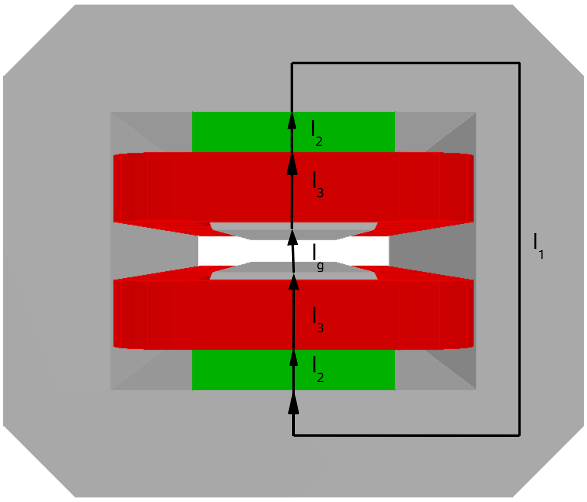

Figure 2.3: Hybrid dipole magnet made from iron (grey) and permanent magnet material (green). Coils are red.

where $l_i = l_1 + 2l_3$ and $l_p = 2l_2$ in figure 2.3. If we make the assumption that the last term in equation 2.8 is negligible the magnetic field can be written as

$$B = \frac{\mu_0 NI + B_r \frac{l_p}{\mu_p}}{\frac{l_p}{\mu_p} + l_g}. \tag{2.9}$$

To evaluate if this hybrid dipole is a better alternative than the electromagnet the ratio between the currents, calculated from equation 2.9 and 2.4, was plotted as function of B (μ_p=1 was assumed). Figure 2.4 shows this ratio as function of B for different length of PMM. It is clear that the hybrid magnet is not efficient for magnetic fields larger than B_r. The gap length has to be small compared to the length of PMM to reach high fields in the air gap at zero coil current. On the other hand, since $\mu \approx 1$ for the PMM, a large amount of PMM is just adding to the gap length, when the current is turned on to increase the field further.

2.4 Conclusions from the H-shaped hybrid magnet

The nominal energy of the XFEL is 17.5 GeV, which corresponds to ~ 1 T for an electron beam bending 1°/m. For the construction of a hybrid magnet to be justified, the magnet has to consume less power than a conventional electromagnet both at this energy and at a wide energy range around it. Here follow a few points that have to be taken into account when constructing a hybrid magnet:

1. An iron yoke in a closed path is needed for the coils to be efficient.
2. The PMM has to be placed so iron does not short circuit the field.

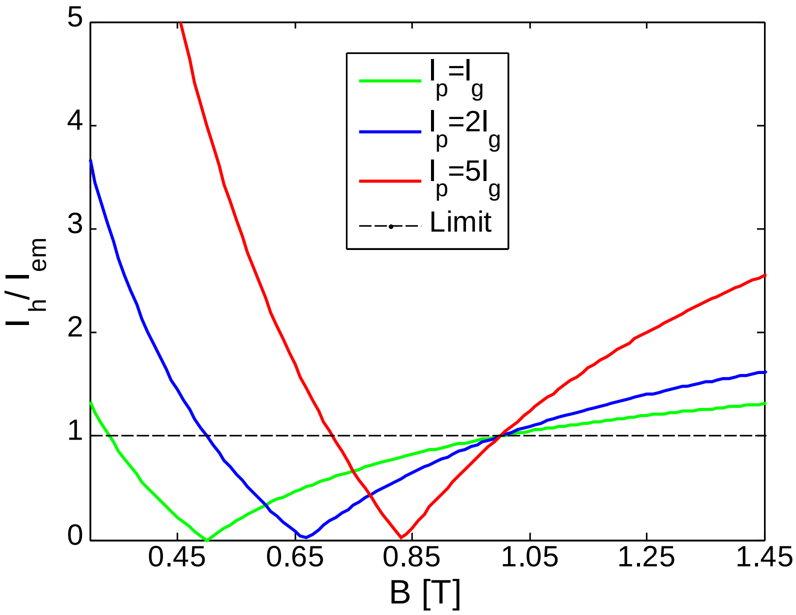

Figure 2.4: The ratio of the currents of the hybrid magnet and the electromagnet as function of B. The dashed line is there to "guide the eye". The hybrid configuration is preferred for ratios smaller than 1.

3. The contribution of magnetic flux from the PMM might need to be as high as B_r.

Point 1 and 2 are important and related. PMM has to be part of the closed path of the yoke to prevent short circuit of the permanent magnetic field. Simultaneously, PMM included in the closed path result in a lower contribution to the magnetic field from the coil current in the air gap, due to the much lower permeability ($\mu \approx 1$) of PMM.

In order to meet criteria 1-3, different types of configurations are introduced to form a permanent dipole magnet producing a field close to the remanent field of the PMM and to reduce the amount of PMM in the closed path of the electromagnet.

Chapter 3

Hybrid magnets made from Halbach designs

3.1 Halbach segmented permanent dipole

Figure 3.1 shows two types of permanent dipole magnet configurations proposed by Halbach in a paper from 1985 [7]. The dipole magnet in figure 3.1a consists of eight identical pieces placed in 45 degree intervals forming a circular shape. The advantage of this configuration is that, in principle, there is no upper limit for the field strength in the gap. The field strength only depends on the amount of permanent magnet material defined by r_1 and r_2 (see figure 3.1).

A hybrid dipole implementing an eight segment permanent magnet is shown in figure 3.2. Two of the segments have been modified to obtain a 20 cm pole width. To increase the contribution to the field in the air gap from the coils part of these two segments were also replaced by iron. The advantage of this design is the possibility of having strong dipole field in a compact configuration. The disadvantage is that coils can not be mounted close to the air gap, which results in less contribution from the coils to the field in the gap.

3.2 Block hybrid dipole

Constructing a dipole from the hybrid magnet shown in figure 3.1b is another alternative. There are a few similar designs described in articles, all of them without correction coils. Here the permanent magnets are rectangular blocks and the coils can easily be placed close to the air gap. A schematic of such a design is shown in figure 3.3. The main principle is to adjust the width and height of the PMM blocks to obtain as high field as possible without any current and to optimize the efficiency of the coils.

To illustrate the advantages and disadvantages of this type of dipole magnet, calculations were done for different configurations using identical blocks of PMM. The blocks had the same width as the pole (28.4 cm) and height as the pole gap (6 cm). VACOMAX 225 [6] (Sm_2Co_{17}) with remanent field B_r=1.03 T and H_c=720 kA/m (minimum values taken from table 2 in Vacuumschmeltze's product catalogue [6]) was used and B as function of H was assumed linear in

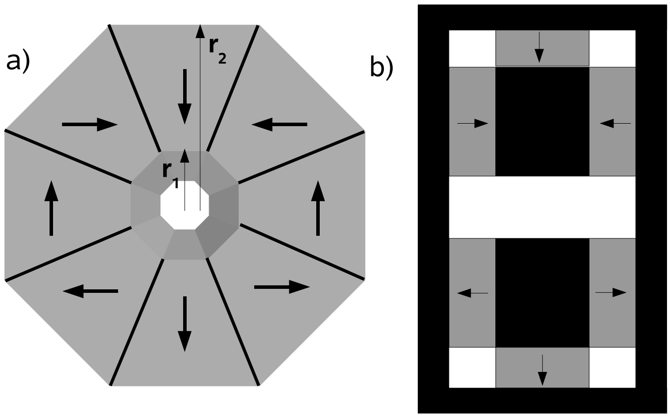

Figure 3.1: Two types of permanent dipoles. a) is made only with PMM (grey) and b) is in a hybrid configuration with iron (black). The arrows point in the direction of magnetization for each block.

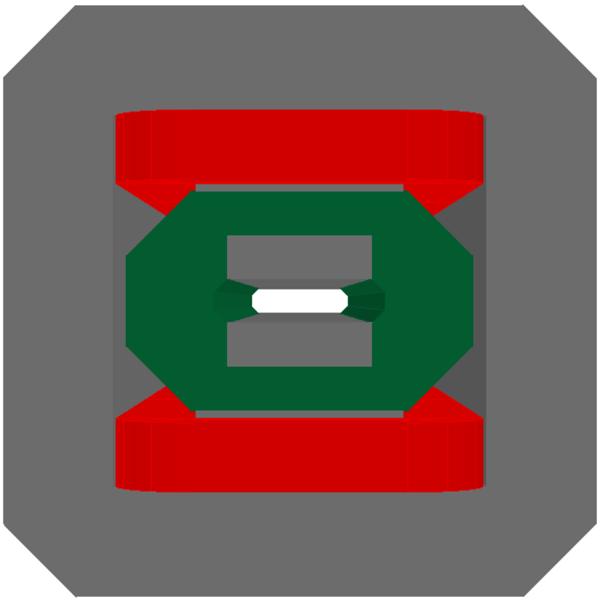

Figure 3.2: An eight segmented permanent dipole (green) in combination with a conventional H-shaped electromagnet (iron is grey and coils are red).

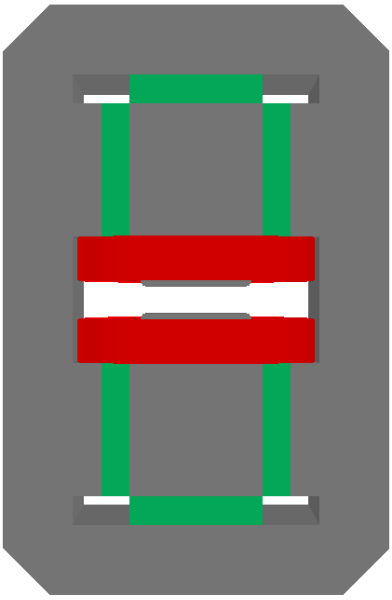

Figure 3.3: Hybrid dipole configuration made from rectangular blocks of PMM (green) together with an iron yoke (grey). Coils are red.

the second quadrant. The default BH-curve in OPERA-3D was used to define the properties of the yoke (see figure 3.4). Only the linear dependence at low currents was used to make the calculations less time consuming. The magnets were also made shorter for the same reason. Therefore trends concluded from the results are discussed rather than the exact values. The results are presented in table 3.1 and can be interpreted as follows: Configuration III has both the highest B_0 and highest dB/dI, and the conclusion is that it is preferred to make a high magnet using thin blocks. For a more compact configuration, IV is preferred compared to II, if a strong field at zero current has priority. If the efficiency of the coils has a higher priority, II is the better choice. Configurations II-IV consist of almost 70% more PMM than I. Good quality PMM can cost $\sim$500 €/kg [8] and the density of VACOMAX 225 is 8.4 g/cm^3. This suggests that a 2.5 m dipole magnet of configuration I would cost 1×10^6 € extra just for PMM. Reducing the amount of PMM is therefore a key factor. The different hybrid configurations I-IV are compared in figure 3.5.

The magnetic field for a 2.5 m long magnet of configuration I was calculated for a number coil currents. This was also done for the electromagnet (figure 2.1) and the eight segmented hybrid (figure 3.2). B as function of excitation current is shown in figure 3.7 and the ratio of the currents as function of B is presented in figure 3.8.

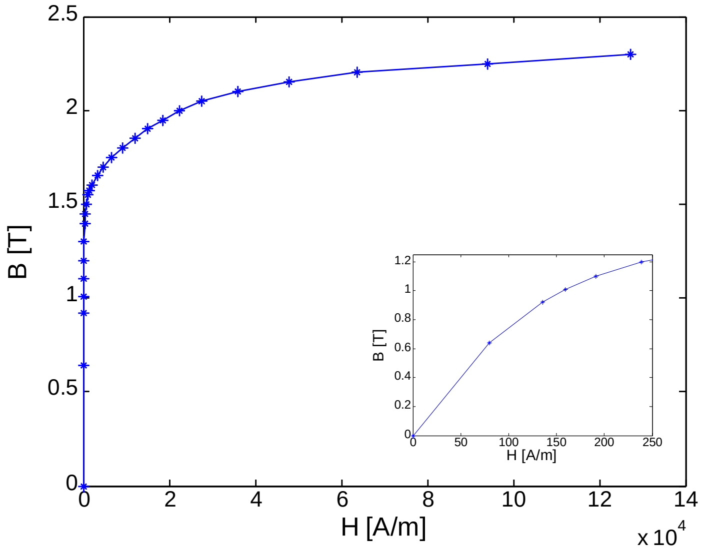

Figure 3.4: The BH-curve for the yoke used in all magnetic field calculations in OPERA-3D.

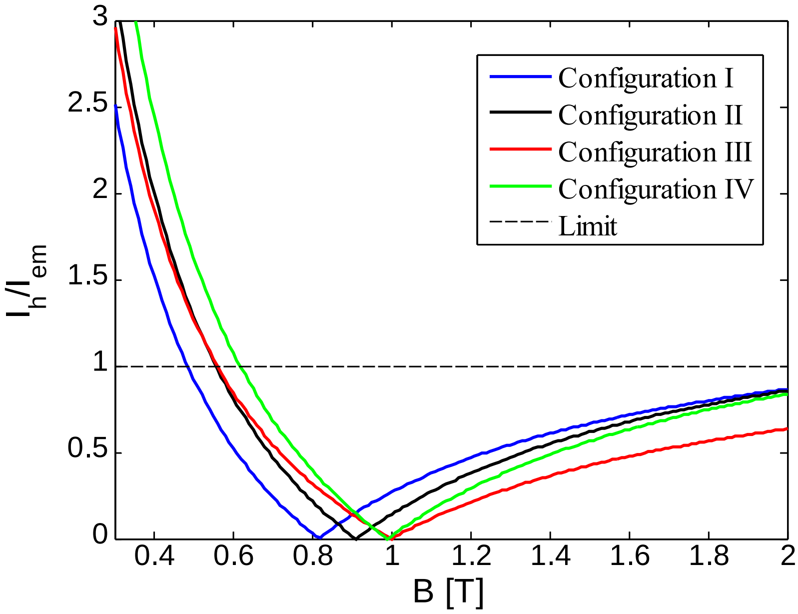

Figure 3.5: Comparison of the ratio of the currents of the hybrid magnet and the electromagnet as function of B. The hybrid magnet is the preferred design for ratios smaller than 1.

Configuration	B_0[T]	dB/dI	PMM [m^3]
I	0.82	1.00	0.26
II	0.91	0.93	0.43
III	1.00	1.15	0.43
IV	0.99	0.88	0.43
EM	0	1.46	0

Table 3.1: Comparison between four configurations of PMM in a hybrid configuration (see figure 3.6). dB/dI is normalized such that the current I is a number between 0 and 1, the last corresponding to the maximum current of the electromagnet in ref. [2]. The volume of PMM was calculated for a 2.5 m long dipole magnet.

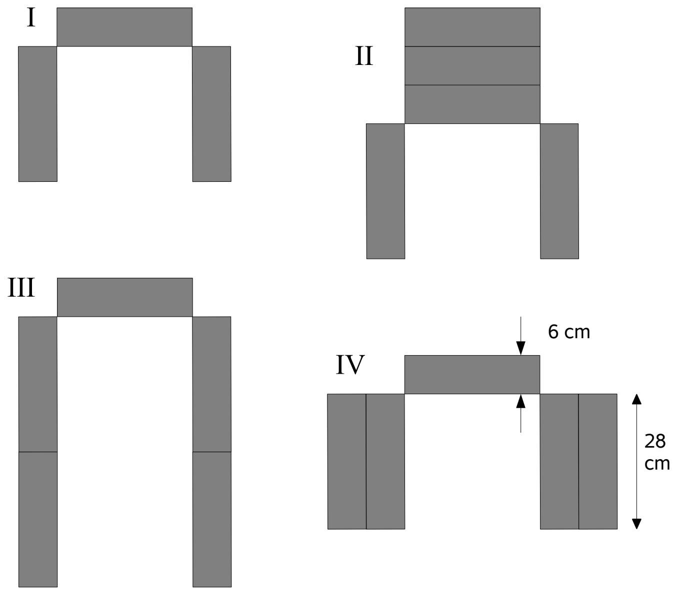

Figure 3.6: Four different configurations of PMM blocks in a dipole. Only upper half of the magnet is shown. See figure 3.3 for the whole hybrid magnet configuration.

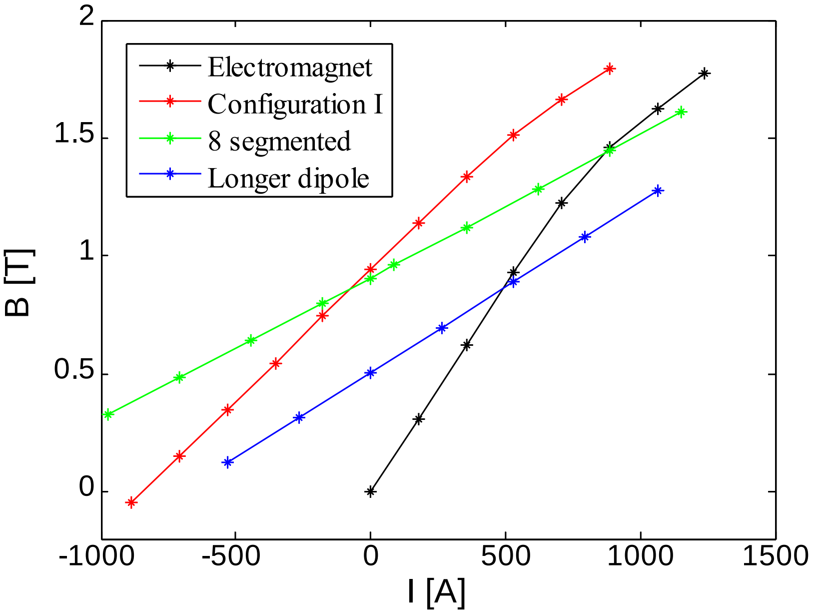

Figure 3.7: B as function of coil current for different hybrid configurations calculated with OPERA-3D.

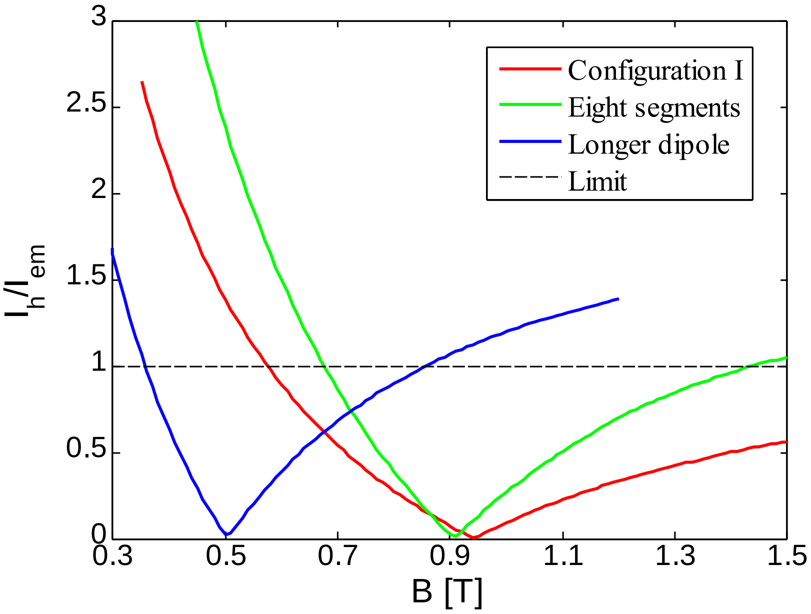

Figure 3.8: The ratio between the currents of the electromagnet and different hybrid magnets as function of B. The hybrid configuration is preferred for ratios smaller than 1.

Chapter 4

Discussion

The results presented in figure 3.5 and 3.8 show that it is possible to construct a dipole in a hybrid configuration that has a bias permanent field close the field needed for 17.5 GeV electrons. The magnet also saves energy in the energy range, approximately, 10-25 GeV. One drawback is that a magnet optimized for 17.5 GeV can probably not be power efficient at 7 GeV, which is the energy running in CW-mode. Also, these magnets are big and demand a large amount of PMM. The question is if, over a number of years with low energy consumption, investing in an expensive magnet in the end will save money. The power dissipated in an electromagnetic dipole can be calculated using [9],

$$P = 2\rho \frac{B l_g}{\eta \mu_0} j l_{av}, \tag{4.1}$$

where ρ is the resistivity of copper $1.86 \cdot 10^{-8} \Omega\text{m}$, l_{av} is the average turn length $\sim$6.14 m, $\eta \approx 0.99$ is the efficiency of the magnet related to the characteristic of the yoke, and j is the current density (maximum 7.6 A/mm^2 [2]). The power dissipated in each 2.5 m dipole is 56 kW, exclusive water cooling, at 1 T which corresponds to 17.5 GeV. If we assume that the magnet is turned on all the time, and that the price for electricity is 0.1 €/kWh, the power consumption is 5×10^5 kWh/yr. Assuming that a hybrid magnet will give an extra cost of 500 €/kg of PMM, a 2.5 m long magnet of configuration I results in an extra cost of $\sim 10^6$ €. It will then take more than 20 years before the money turned out to be well spent. On the other hand, if the price of electricity becomes much more expensive it might be a good investment. It may be worth noticing that the eight segmented hybrid design in figure 3.2 contains approximately 60% of the PMM in I, but the coils are less efficient (see figure 3.8) and it might also be more difficult to manufacture.

In this report we have restricted the design to the parameters given in the technical design report [1]. If the magnet instead is made twice as long the magnetic field strength can be halved. That corresponds to 0.5 T at the nominal energy and 0.75 T at the maximum energy. It is then possible to use the design shown in figure 2.3 instead. The four side blocks in design I are removed and even though the magnet is twice as long, it contains 2/3 of PMM of the previously discussed design (I). Its characteristics are shown in figure 3.8 (see also figure 2.4). Table 1.2 shows the minimum pole widths for BV and BW. Dipole magnet BV is 5 m long and its pole width can be made smaller by a factor of two compared to the current design [2, 3] according to the numbers presented in table 1.2. Dipole BW is 7.5 m and if it is possible to use short bends in between each 2.5 m dipole segment half the pole width can be used also here. This modification would result in a further reduction of PMM with a factor of two. In general it would be possible to optimize the magnet configurations somewhat further if more specific criteria for the optimization can be determined.

We conclude that it would be possible to use hybrid magnet dipoles for the beam dumps at the XFEL. To find out whether the higher production cost of hybrid magnets is offset by a lower cost of operation, a more detailed study on what permanent magnet material to use is needed as well as a more accurate knowledge about the manufacturing cost. It is also necessary to make an assumption how the machine will run, and to have an assuption about future energy prices.

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