



Comparison of two hybrid magnet designs

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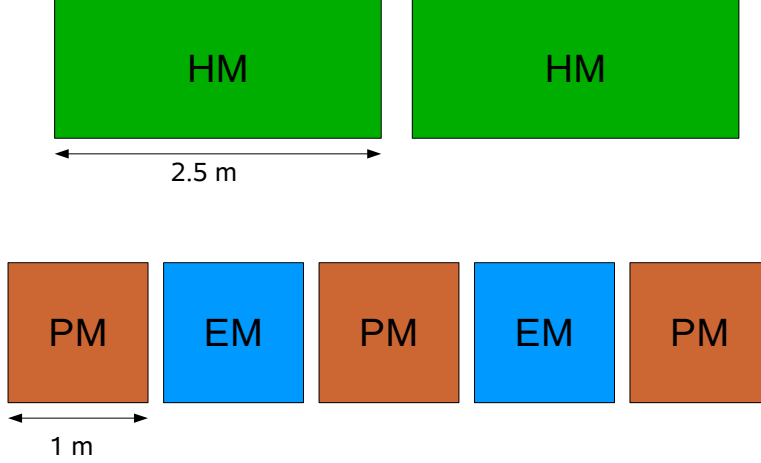


Figure 1: A electro/permanent hybrid dipole magnet (HM) and a segmented dipole configuration (PM-permanent magnet, EM-electromagnet).

1 Introduction

There are different ways of bending an electron beam other than with electromagnets. Two types will be compared here, an electro/permanent hybrid dipole magnet and a dipole magnet made from adjacent segments of electromagnets and permanent magnets. The best configuration is the one that consumes the least power and contains the lowest amount of permanent magnet material (PMM). The total length of the dipole is 5 meter and it has to bend $1^\circ/\text{m}$ on average. The two configurations to be discussed here are shown in figure 1. The parameters used to optimize the magnet are shown in table 1 and the magnetic field strength for a number of energies is shown in table 2.

E [GeV]	Nom. E [GeV]	Pole gap [cm]	Pole width* [cm]
10-20	17.5	3	10

Table 1: Parameters used to optimize the dipole magnet. (* under the condition that the magnet is C-shaped.)

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 2: Magnetic field strength as function of electron energy.

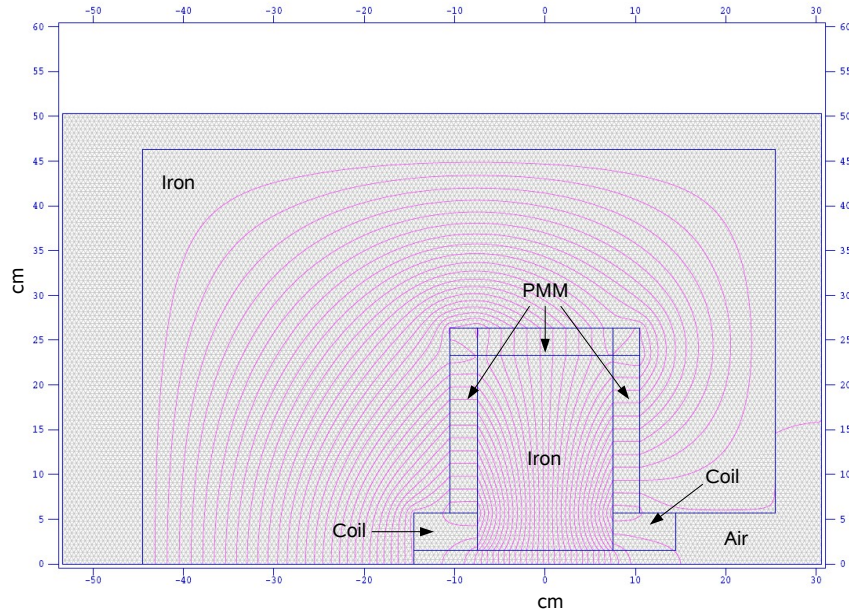


Figure 2: A electro/permanent hybrid dipole made from rectangular blocks of permanent magnet material.

In section 2 the hybrid magnet (HM) and the permanent magnet (PM) are optimized. A comparison of the hybrid magnet and the segmented dipole is presented in section 3, and finally some conclusions are made in section 4.

2 Hybrid magnet

In a previous report [1] several types of hybrid dipoles were discussed. Since then the parameters of the magnet have changed (table 1). Both the pole gap and pole width have decreased to reduce the amount of permanent magnet material in the magnets. The pole width has been reduced under the condition that the magnet is open on one side so the photons can escape the electron trajectory.

Two types of hybrid magnets are discussed here and schematics are shown in figure 2 and 3. The amount of iron, pole shape and size of the coils have not been optimized, but this will not influence the conclusions made in this report. In order to evaluate what size and geometry the blocks should have to minimize the amount of PMM, a number of geometries were used as input in the Pandira program [2]. VACOMAX 225 [4] ($\text{Sm}_2\text{Co}_{17}$) with remanent field $B_r=1.03$ T and $H_c=720$ kA/m (minimum values taken from table 2 in Vacuumschmelze's product catalogue [4]) was used as input in Pandira and B as function of H was assumed linear in the second quadrant. Results from the calculations are shown in figure 4. For a certain magnetic field strength there is a clear limit for the minimum amount of PMM. Comparing the two different configurations it is no particular advantage of using the more complex configuration (figure 3).

The second important property for the dipole magnet is the efficiency of

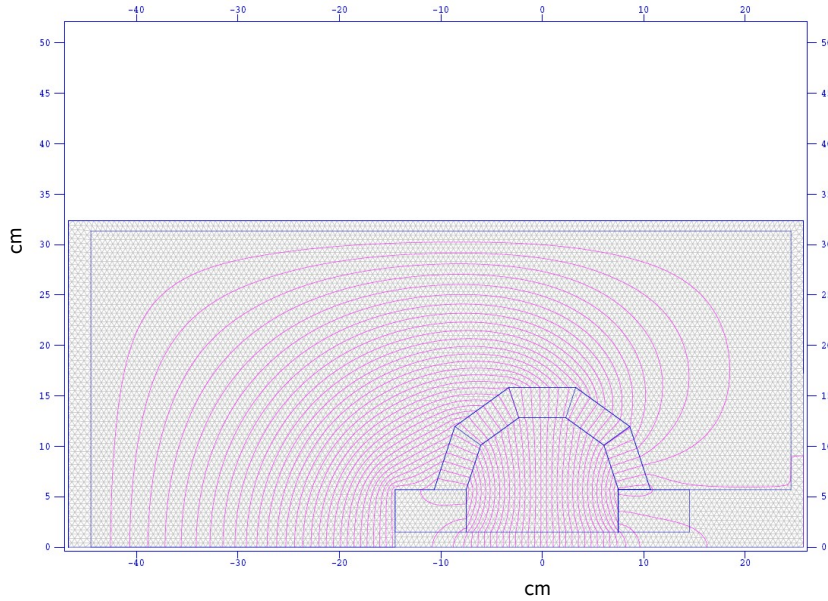


Figure 3: A electro/permanent hybrid dipole made from 10 non-rectangular blocks of permanent magnet material.

the coils. The field strength was therefore also calculated for 87 A (10% of the maximum current). The dimensions of the conductors were taken from the technical proposal for the electromagnet [3] and the number of conductors was 2×15 . From the calculations at 0 A and 87 A the derivative of the field was calculated for all configurations. The magnetic field strength B at zero current was plotted as function of (dB/dI) . The goal is to find a magnet with a small volume of PMM and with high dB/dI . Therefore a selection was made including all configurations positioned left to the green curve in figure 4. B and dB/dI for those configurations are plotted in figure 5 (green). From investigating the configurations with bias field close to 1.02 T (17.5 GeV) it is concluded that one possible alternative is made from rectangular blocks where the blocks are ≈ 3 cm thick (red * in figure 4 and 5).

Figure 7 and 8 show results from calculations when the volume of PMM was kept constant (same as optimized configuration red *). In the first simulation (red) $a=d$ (see figure 6) were varied between 1 cm and 7 cm. The volume PMM remained constant by adjusting c . The maximum field was obtained for $a=d=3.5$ cm. Two more simulations were done in a similar way adjusting only one parameter (a or d) while the other one was fixed at 3.5 cm. The results show that for $a=d=3.5$ cm the field strength in the gap is maximized. Reducing the thickness of the blocks to $a=d=3$ cm the B field is reduced only by 1.5%, but dB/dI is increased by 12%. Reducing a and b to 2.5 cm the loss in field strength would be (6%). By using even thinner blocks, a lot less flux go through the pole gap. Instead the field go through the PMM, since that path include a shorter distance through material with similar permeability as air.

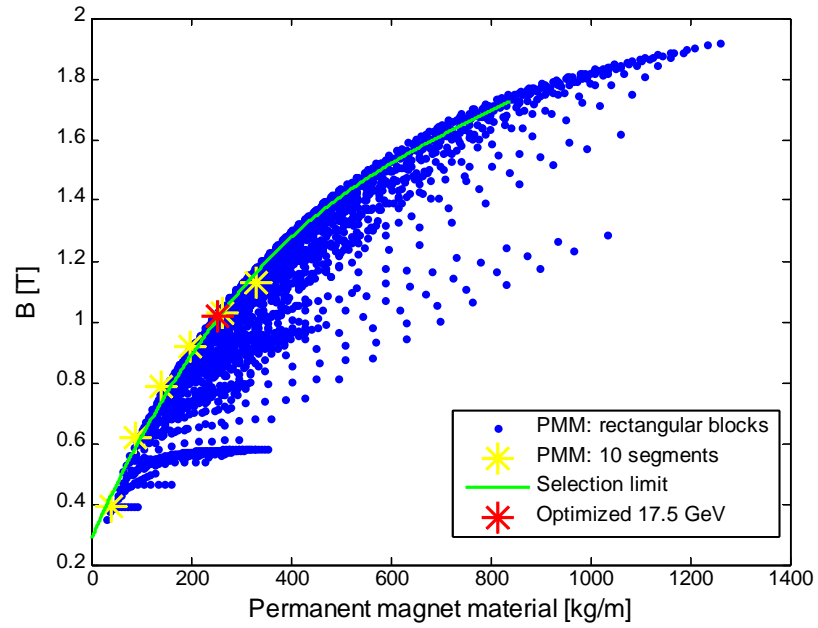


Figure 4: Field strength and volume of PMM plotted for different hybrid configurations.

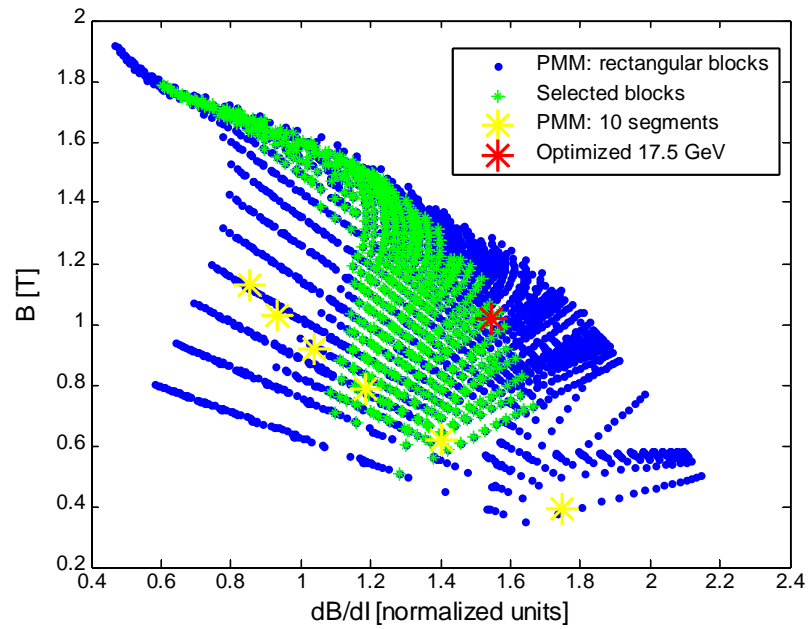


Figure 5: Field strength B and dB/dI for different hybrid configurations (same as in figure 4).

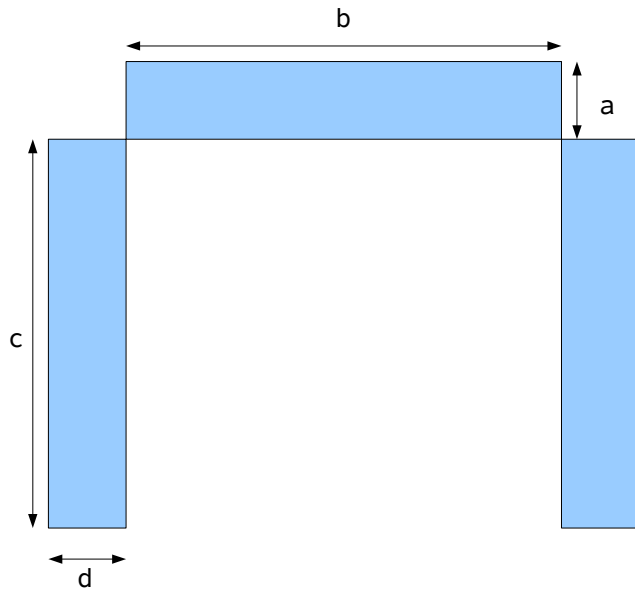


Figure 6: Parameters adjusted in the calculations presented in figure 4,5 and 9.

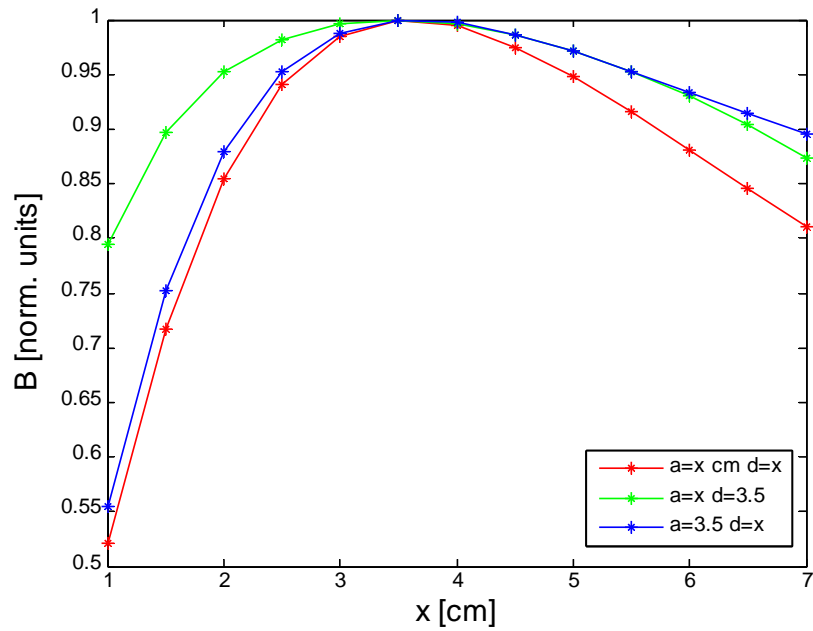


Figure 7: B from calculations changing the dimension of the blocks while the volume of PMM was constant. c was adjusted to maintain constant volume of PMM and $b=15$ cm in all simulations.

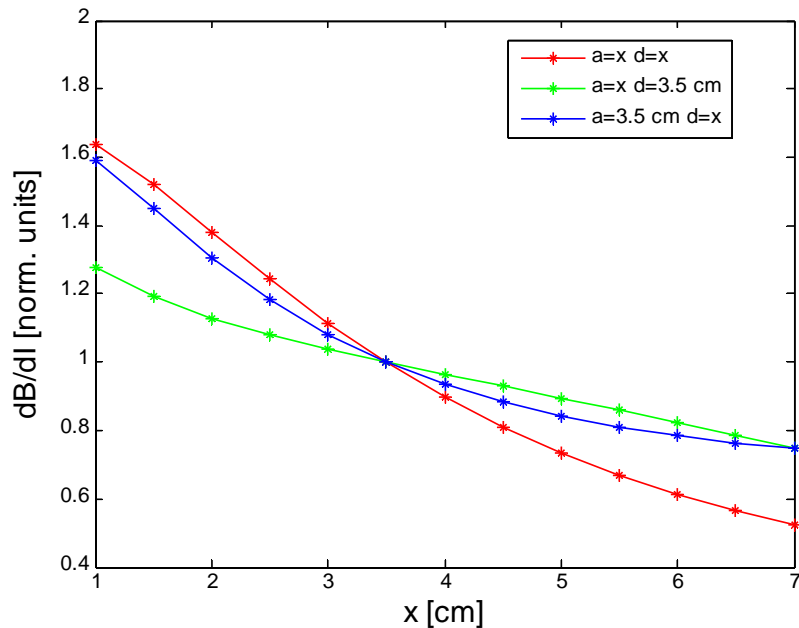


Figure 8: dB/dI from calculations changing the dimension of the blocks while the volume of PMM was constant. c was adjusted to maintain constant volume of PMM and $b=15$ cm in all simulations.

If it is no need for adjusting the field in the gap, coils are not needed. By removing the coils and moving the PMM closer to the gap more flux pass through the gap. The increases of the flux is less than 10% after removing the coils and moving the permanent magnets closer to the gap. Calculations were performed to present a similar plot to figure 4 and the results are shown in figure 9. These results are used in section 3 for the segmented dipole.

3 Hybrid vs segmented dipole

In order to compare the two dipole configurations presented in figure 1 an optimized hybrid magnet and an optimized permanent magnet configuration are needed. In the calculations the segmented dipole will be treated as a 3 m long permanent magnet next to a 2 m long electromagnet. In practice the magnets are split into 1 m sections and placed next to each other to minimize the pole widths (see figure 1).

The bias field for the two configurations was calculated with equation 1,

$$B = \frac{2E \cdot \sin(\theta/2)}{c \cdot q \cdot l}, \quad (1)$$

where θ is the deflection angle (5°), c the speed of light, q the electron charge and l is the length of the magnet. A 5 m hybrid magnet needs 1.02 T field and a 3 m permanent magnet needs 1.70 T field to bend a 17.5 GeV electron beam

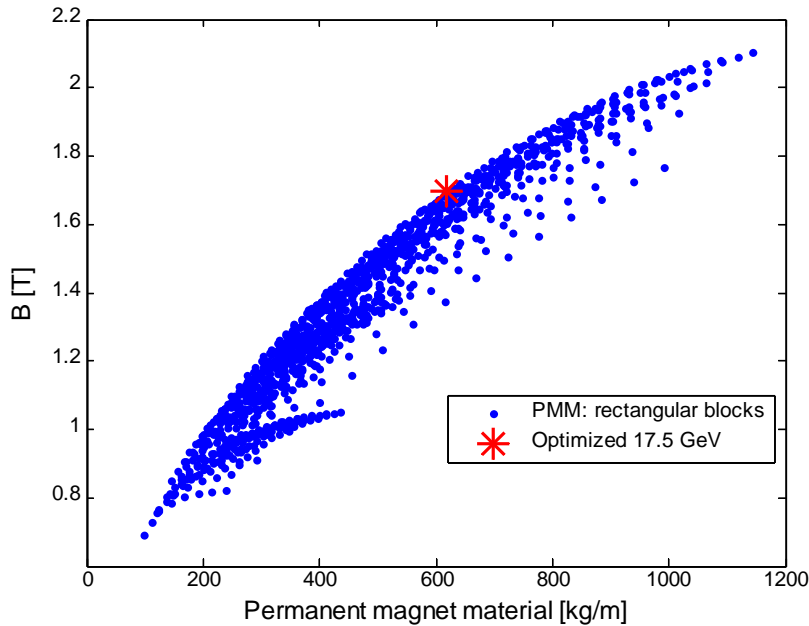


Figure 9: Field strength B and volume PMM plotted for a permanent magnet made from rectangular blocks of PMM and iron. Configuration optimized to bend 5° in 3 m (red *). This configuration is discussed in section 3.

5° . The results presented in figures 4-9 were used to characterize these magnets and the results are presented in table 3.

	a [cm]	b [cm]	c [cm]	d [cm]	B [T]	PMM [dm^3/m]	total PMM [dm^3]
Hybrid	3	15	17.62	3	1.02	30.1	151
PM	6	15	23.2	6	1.70	73.7	221

Table 3: Geometry and field strength for the hybrid magnet and the permanent magnet (red * in figure 4 and 9). See figure 6 for the labels $a-d$.

In order to compare the two configurations in terms of energy consumption, B as function of coil current, I , was calculated for the hybrid magnet and the electromagnet. The field for the hybrid magnet was calculated using Pandira and for the electromagnet the standard text book formula was used (electromagnet with infinite permeability of iron),

$$NI = \frac{B}{\mu_0} l_g, \quad (2)$$

where N is the number of turns of the coil, μ_0 is the permeability of air and l_g is the pole gap. The results are shown in figure 10. The coil current as function of beam energy was then calculated for the 2 m electromagnet. All steps how this was done are explained below and the results are presented in table 4.

Column 1: Energy of the electron beam.

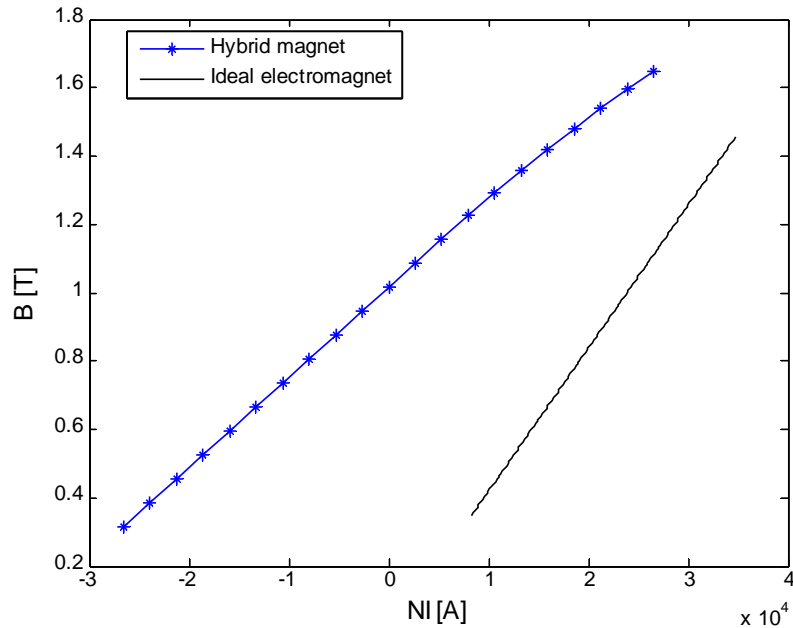


Figure 10: Characteristics for the hybrid magnet and an ideal electromagnet with 3 cm pole gap.

Column 2: The deflexion by a 3 m 1.70 T permanent magnet as function of electron beam energy (calculated using 1).

Column 3: Correction by the 2 m long electromagnet to deflect the beam 5° over 5 m (5° subtracted by column 2).

Column 4: Magnetic field needed for the electromagnet to make the correction (column 3). It was calculated using equation 1.

Column 5: Current needed to obtain the correction field (column 4) was calculated using equation 2.

Column 6: Current for a 5 m hybrid magnet (see figure 10).

Column 7: Current for a 5 m electromagnet (see figure 10).

The interesting information is the difference in power consumption between the hybrid magnet and the segmented dipole. The power, P , for the magnets can be written as,

$$P = RI^2 = \frac{\rho L}{A}(NI)^2, \quad (3)$$

where ρ is the resistivity of copper, L is the average length of the coil, and A is the gross coil area. If we disregard the pole widths and assume that resistivity and the area of the coils are the same for both the electromagnet and the hybrid magnet,

$$P_{hybrid} = CL_h(NI_h)^2 = 5C(NI_h)^2, \quad (4)$$

$$P_{segmented} = CL_s(NI_s)^2 = 2C(NI_s)^2, \quad (5)$$

where C is a constant. The results are presented in figure 11. In the electron beam energy range 10-20 GeV the power consumption of the segmented dipole

E [GeV]	θ_{3m} [°]	θ_{2m} [°]	B_{2m} [T]	NI_{2m} [kA]	NI_{hyb} [kA]	NI_{em} [kA]
5.5	16.0	-11	-1.75	-41.8	-26.4	8.6
7.5	11.7	-6.7	-1.46	-34.8	-22.0	1.0
9.5	9.2	-4.2	-1.17	-27.8	-17.7	13.2
11.5	7.6	-2.6	-0.87	-20.9	-13.2	16.0
13.5	6.5	-1.5	-0.58	-13.9	-8.8	18.7
15.5	5.6	-0.6	-0.29	-8.0	-4.4	21.5
17.5	5	0	0	0	0	24.2
19.5	4.5	0.5	0.29	6.9	4.4	27.1
21.5	4.1	0.9	0.58	13.9	9.0	29.9
23.5	3.7	1.3	0.87	20.8	13.7	32.6
25.5	3.4	1.6	1.16	27.7	18.7	35.4

Table 4: The current for the hybrid magnet and the segmented dipole magnet. See text for explanation of the different columns.

is 3% lower than for the hybrid dipole. Taking into account the total length of the coils assuming the pole width and size of the coil in figure 2,

$$P_{hybrid} = CL_h(NI_h)^2 = (5 + 2 \times 0.54)C(NI_h)^2, \quad (6)$$

$$P_{segmented} = CL_s(NI_s)^2 = (2 + 2 \times 0.54)C(NI_s)^2. \quad (7)$$

This assumption results in that the hybrid dipole is about 25% better than the segmented dipole.

A general expression to compare the power consumption of the two configurations can be derived using equation 3 together with an expression for the current. For a certain beam energy both configurations use a magnetic field induced by the coils to bend the same number of degrees (θ_{2m} in table 4). The conventional magnets have to use more current to bend θ_{2m} over two meters compared with the hybrid magnet that bends θ_{2m} over 5 meters. The current in the coils can be expressed as,

$$I = \frac{dI}{dB}B(\theta_{2m}) = \frac{dI}{dB} \frac{2E \cdot \sin(\theta_{2m}/2)}{c \cdot q \cdot l}. \quad (8)$$

The slopes of the magnetization curves (figure 10) can be used to determine the power consumption,

$$P = RI^2 = \frac{\rho LN^2}{A} \left(\frac{dI}{dB} \frac{2E \cdot \sin(\theta_{2m}/2)}{c \cdot q \cdot l} \right)^2. \quad (9)$$

In order to find a hybrid configuration that consumes less power than the segmented dipole configuration ($P_h < P_s$),

$$\left(\frac{dI}{dB} \right)_h < \sqrt{\frac{L_s l_h}{L_h l_s}} \sqrt{\frac{A_h N_s}{A_s N_h}} \left(\frac{dI}{dB} \right)_s, \quad (10)$$

where s and h stand for segmented- and hybrid dipole, respectively. It is here assumed that the coils are made from the same material.

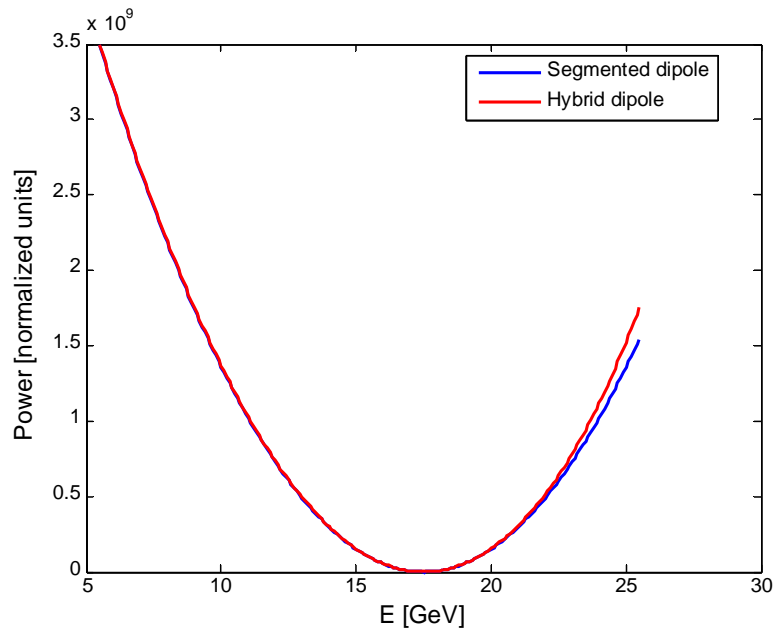


Figure 11: Comparison of the power consumption between the segmented dipole and the hybrid dipole.

In order to compare these both alternative solution with a conventional electromagnet the ratio between the power of the hybrid magnet over the electromagnet (obtained from NI_{em} in table 4) is presented in figure 12. The hybrid magnet has lower energy consumption compared with an electromagnet for beam energies larger than 11 GeV.

Another important aspect is the pole width, W , of the magnets. A schematic explaining W is shown in figure 13. For a 2.5 m hybrid magnet bending an electron beam 2.5° , $W=14$ mm. Note that this is the minimum pole width, since the beam spread is not taken into account. For the segmented dipole the bending angles are not the same for each segment. The trajectories of electrons with kinetic energies 6-25 GeV (see table 5) moving through a segmented dipole are shown in figure 14. A 20 cm separation between the magnets was included. If only 10-20 GeV beams are considered the pole widths of the first and last permanent magnet are similar to the pole width of hybrid magnet. The permanent magnet in the middle is slightly larger. An alternative is to move the magnet according to the beam energy. That results in a smaller pole width than the hybrid magnet. Unless the magnet has to be designed for lower energies than 10 GeV there is no big difference in pole width between the hybrid magnet and the segmented dipole magnet.

4 Conclusions

Two alternatives to conventional dipole electromagnets have been compared. The first is a hybrid magnet formed by attaching coils to a permanent magnet

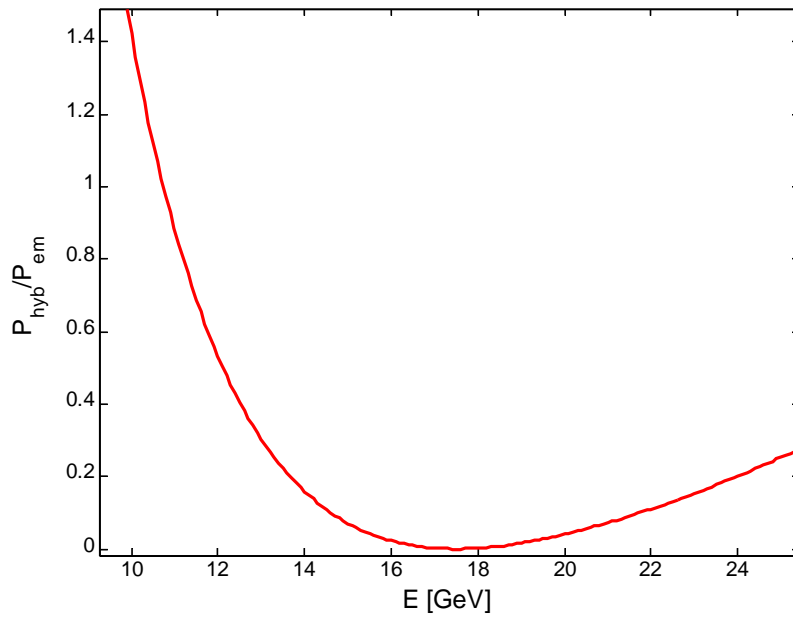


Figure 12: The hybrid magnet compared with a conventional electromagnet. The hybrid magnet is favored for ratios lower than 1.

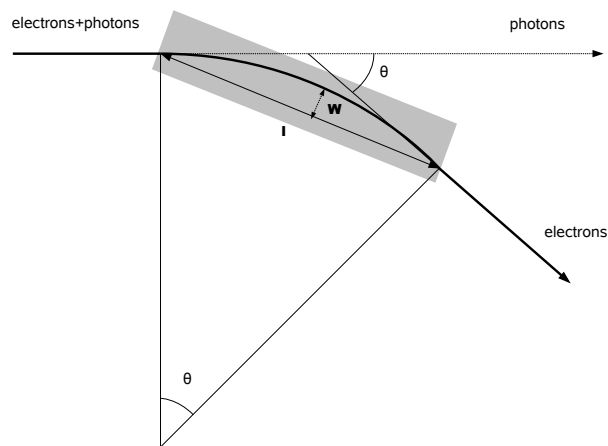


Figure 13: Schematic of an electron beam moving through a dipole magnet.

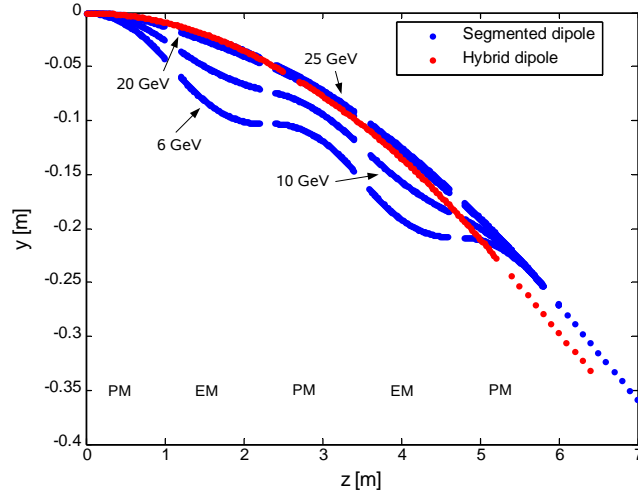


Figure 14: Trajectories of electron beams moving through a segmented dipole magnet. The trajectory for electrons moving through the hybrid magnet is also shown (red curve) for comparison.

E [GeV]	θ_{PM} [$^{\circ}/m$]	θ_{EM} [$^{\circ}/m$]
6	4.87	-4.81
10	2.92	-1.88
20	1.46	0.31
25	1.17	0.75

Table 5: Beam energies and bending angles used to calculate the beam trajectories in figure 14.

and in the other configuration the permanent magnet and the electromagnet are separated. The power consumption seems to be equal or less for the hybrid magnet and the segmented dipole consumes about 50% more permanent magnet material than the hybrid dipole magnet. The reason is that the increase of PMM is not linear with respect to the field strength, it appears to be faster. Allowing the hybrid magnet to use an extra 50% of permanent magnet material the power consumption can be reduced by making the blocks thinner (b and d in figure 6). To sum up the hybrid magnet seems to be a better choice.

In order to have a simple hybrid configuration and to minimize the amount of permanent magnet material it is concluded that using rectangular blocks with same thickness (or slightly thicker) than the pole gap is a good choice. In order to reduce the power consumption thinner blocks can be used, but for such a configuration the amount of permanent magnet material in the magnet increases.

References

- [1] F. Hellberg, Investigating the possibility of a hybrid magnet design for BV/BW dipole magnets at the XFEL, MSL-06-1, 2006.
- [2] POISSON/SUPERFISH group of codes, Los Alamos National Laboratory.
- [3] S. Ananjev *et. al.*, Technical proposal for a batch of electromagnets for the XFEL project, September 2005.
- [4] Rare earth permanent magnets Vacodym vacomax, <http://www.vacuumschmelze.de>.