LOW POWER CONSUMING HYBRID BENDING MAGNET AT THE XFEL BEAM DUMP

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Abstract

At the end of the European XFEL the electron beam is separated from the photon beam and directed towards the beam dump with a bending magnet. This dipole magnet is designed to bend 10-25 GeV electrons by 1°/m and is 10 meter long in total. By integrating permanent magnet material into a conventional electromagnet, this so-called hybrid magnet with a 1 T bias magnetic field consumes no power at the nominal energy of the XFEL, 17.5 GeV. The magnetic field can be increased or decreased by magnet coils to obtain 1°/m deflection for all energies between 10 and 25 GeV. Here a proposal for such a hybrid configuration is presented together with its characteristics.

INTRODUCTION

In a free electron laser the electrons are bent away from the laser light with electromagnets and stopped in a beam dump situated away from the experimental hall. At the European XFEL the electrons are bent vertically 10° in a 10 m long double bending achromat magnet [1]. Each beam line ends with such a magnet. It is the largest electromagnet of the XFEL and it consumes a significant amount of power. It is therefore desirable to find a way to lower the power consumption of these magnets. This report presents a feasibility study of the use of a permanent magnet/electromagnet hybrid for this purpose [2, 3]. At the nominal energy of the XFEL, 17.5 GeV, the electrons require a magnetic dipole field of 1 T in order to bend 1°/m. Integrating permanent magnet material (PMM) into an electromagnet to produce a 1 T bias field in the pole gap results in a bending magnet that consumes no power at the nominal energy. Magnet coils can then be used to increase or decrease the magnetic field in the pole gap. The aim has been to design a hybrid magnet that uses less power than a conventional electromagnet between 10 and 25 GeV (0.58 and 1.46 T).

A passive safety system must exist in order to prevent the electron beam from reaching the experimental hall in case of component failure. With conventional electromagnets in the bending unit it is necessary to place an additional permanent magnet further down the photon beam line for safety. The advantage of a hybrid magnet is that the bias magnetic field of the permanent magnet also works as an integrated safety system.

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MAGNETIC FIELD CALCULATIONS

In a conventional dipole electromagnet the magnetic field is confined in a steel yoke ($\mu_{\rm rel} \approx 1000$) and a small air gap ($\mu_{\rm rel} \approx 1$). If the air gap is increased more current is needed to maintain the field strength (the slope of the magnetization curve dB/dI becomes smaller). Because the permeability of PMM is similar to the permeability of air, the insertion of PMM in the yoke results in lower dB/dI. Despite this it can be favourable to use a hybrid magnet under certain conditions.

Consider a C-shaped dipole electromagnet and assume that the magnitude of the field in the gap is the same as in the yoke. The Maxwell equation important in this case can be presented in integral form by applying Stokes' theorem:

$$\oint \frac{\vec{B}}{\mu\mu_0} \cdot d\vec{l} = \int_S \vec{J} \cdot d\vec{S} = NI, \tag{1}$$

where I is the current and N the number of turns. For an electromagnet equation 1 can be written as,

$$NI = \frac{B}{\mu_0} l_g + \frac{B}{\mu_s \mu_0} l_s, \tag{2}$$

where l_g the size of the gap, l_s the average length of the steel yoke, μ_s permeability of steel, and μ_0 is permeability of air. By replacing part of the steel yoke with PMM a bias magnetic field passes through the yoke and the gap. The relationship between B and H in the direction parallel to the easy axis (the main axis of magnetization) of a PMM is linear in a wide range with slope $\mu_p \approx 1$. The magnetization curve can therefore be written as,

$$B_p = \mu_0 \mu_p H_p + B_r, \tag{3}$$

where B_p is the magnetic field, H_p is the magnetic field intensity, and B_r is the remanent field of the PMM. The magnetic equation for the hybrid magnet can written, similar to equation (1), as

$$NI = \frac{B}{\mu_0} l_g + \frac{B - B_r}{\mu_0 \mu_p} l_p + \frac{B}{\mu_0 \mu_s} l_s, \tag{4}$$

where l_p is the length of the permanent magnet material along the easy axis. Equations (2) and (4) show that the more PMM is added to increase the bias field the more current needs to go through the coils for a specific correction of the magnetic field. This is illustrated in figure 1 where the ratio of the power consumption of the two types of magnets is plotted as function of beam energy. It is clear that this simple type of hybrid magnet is not a good option for 10-25 GeV electrons.

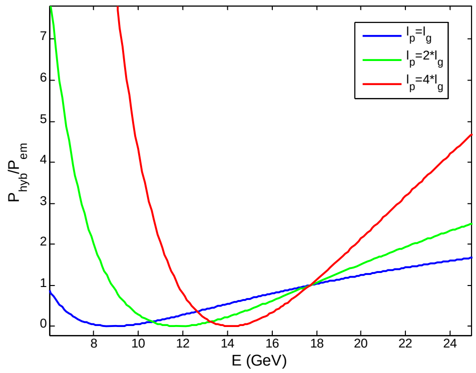

Figure 1: The ratio of the power of a conventional electromagnet and a hybrid magnet with the same geometry as function of beam energy. The hybrid magnet is favoured for ratios lower than 1.

A better alternative is to concentrate the magnetic field with several blocks of PMM. Here an alternative design made of rectangular blocks of PMM is presented, similar to one presented by K. Halbach [4]. The configuration of the blocks is shown figure 2. Calculations were performed

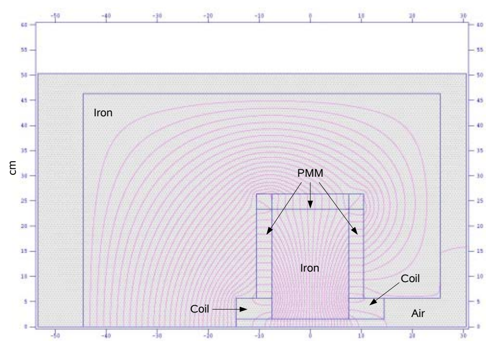

Figure 2: A 2D view of a hybrid dipole made from rectangular blocks of permanent magnets.

using the Pandira program [5] to optimize the magnet with respect to the amount of PMM and dB/dI. Vacomax 225 ($\mathrm{Sm_2Co_{17}}$) with remanent field B_{r}=1.03 T and H_{c}=720 kA/m was used as input in Pandira and B as function of H was assumed to be linear in the second quadrant of the magnetization curve. In order to determine the size of the blocks to minimize the amount of PMM a number of geometries were used as input in Pandira. Figure 3 shows the parameters a, c and d that were changed in the simulation. The pole width b was fixed. Results of the calculations are shown in figure 4 and it shows a distinct limit for the minimum amount of PMM for a certain bias field. The second important parameter is the efficiency of the coils of the hybrid magnet. The magnetic field derivative (dB/dI) is approximately constant in the working range of the magnet and was calculated for all configurations. Figure 5 shows the magnetic field strength B at zero current versus dB/dI. To highlight the configurations using a low

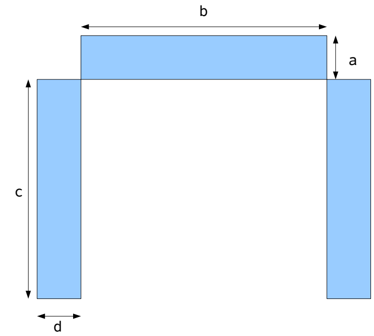

Figure 3: Parameters adjusted in the calculations to optimize the hybrid magnet.

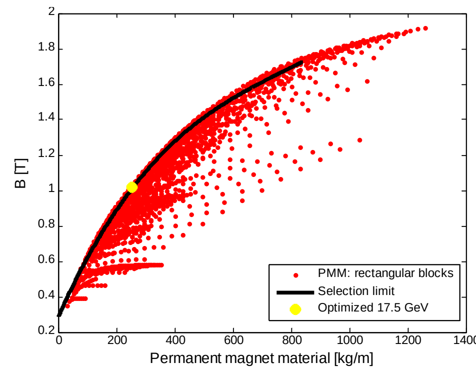

Figure 4: Field strength and mass of PMM per unit length plotted for different hybrid configurations.

amount of PMM the points left of black curve in figure 4 were plotted as black rings in figure 5. From investigating

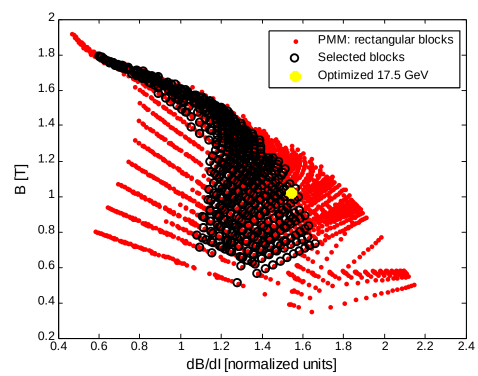

Figure 5: Field strength B and dB/dI for different hybrid configurations.

configurations with bias field close to 1.02 T (17.5 GeV) it is concluded that a possible design is made from blocks with the same thickness as the pole gap (3 cm). Having a,d<3 cm enhances dB/dI, but more of the field from the PMM leaks through the block of PMM instead of passing through the pole gap. This can be compensated for example by increasing c, but results in an increase of the total amount of PMM. On the other hand a configuration of blocks slightly thicker than 3 cm uses less PMM, but has a lower dB/dI.

Figure 6 shows the characteristics for the optimized hybrid magnet in the interval important for the XFEL bending magnet together with an ideal electromagnet (infinite permeability of iron). The difference in power consumption

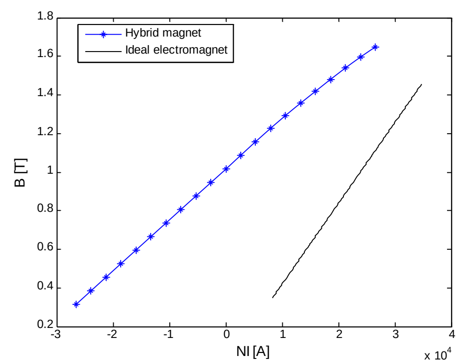

Figure 6: Characteristics for an optimized hybrid magnet and an ideal electromagnet.

between a hybrid magnet and a conventional magnet can be illustrated by plotting the ratio of the power of the hybrid magnet over the power of an electromagnet as function of electron beam energy. Figure 7 shows that this particular hybrid configuration using Vacomax 225 is better than a conventional electromagnet for beam energies larger than 11 GeV.

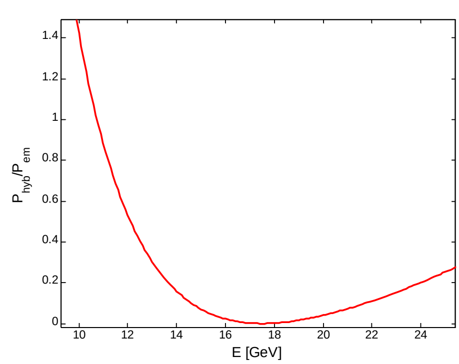

Figure 7: The optimized hybrid magnet compared with a conventional electromagnet. The hybrid magnet is favoured for ratios lower than 1.

SUMMARY

Here a proposal for a permanent magnet/electromagnet hybrid for the XFEL beam dump magnet has been presented. The hybrid magnet has a 1 T bias field and consumes no power at the nominal energy of the XFEL. Magnet coils are used to change the magnetic field when changing the beam energy. The hybrid magnet consumes less power than a conventional electromagnet for electron energies $>$11 GeV. The hybrid magnet can be optimized even further by using permanent magnet material with higher B_r and reducing the bias field in order to make the magnet power efficient between 10 and 25 GeV. The issue whether the hybrid magnet represents a better choice than the conventional electromagnet still needs to be addressed. The hybrid magnet include PMM, is more complicated to manufacture and therefore more expensive than an electromagnet. The higher cost to manufacture the hybrid magnet must be returned by a lower power consumption. Additionally, the hybrid magnet is situated close to the electron beam dump region and is therefore exposed to neutron radiation backscattered from the dump. The permanent magnet material must be able to withstand this [6]. Any loss of bias field due to demagnetization by radiation must be compensated for by the coils and the hybrid will loose its advantage.

If the hybrid magnet can be made cost efficient and radiation resistent it represents an interesting solution for the bending magnet unit as well as the passive safety system of the European XFEL.

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