A KICKER DESIGN FOR THE RAPID TRANSFER OF THE ELECTRON BEAM BETWEEN RADIATOR BEAMLINES IN LUX*

G. Stover#, LBNL, 1 Cyclotron Rd. Berkeley, California 94720, USA

Abstract

I present in this paper preliminary design concepts for a fast kicker magnet and driver for the rapid transfer of the electron beam between radiator beam lines in LUX. This paper presents a feasibility study to find a roughly optimized subset of engineering parameters that would satisfy the initial design specifications of: Pulse width < 30us, rise / fall time < 10 µs, time jitter < 1ns, magnetic length < 0.5meter, gap height = 15mm, gap width = 25mm, peak field = 0.6Tesla, bend angle = 1.7 deg. for beam energy of 3.1 Gev, repetition rate = 10KHz. An H magnet core configuration was chosen. Through an iterative mathematical process employing Mathcad 11 [1] a realizable design was chosen. Peak current, Peak voltage across the coils, conductor losses due to proximity and skin effects, and basic circuit topology were investigated. Types and losses of core material were only briefly discussed. The final topology consists of two magnets in series running at 10KHz, .3Tesla, 630 amp peak current, 10us pulse width, 693 Watts per coil section, driven by fast solid state switch with an energy recovery inductor.

INTRODUCTION

LUX is an R&D project in accelerator and laser-based ultrafast x-ray production based on a recirculating superconducting linac topology. High-brightness electron bunches of 2-3 mm-mrad emittance at 1nC charge in 30ps duration are produced in an rf photocathode gun and compressed to 3ps duration following an injector linac, and recirculated three times through a 1GeV main linac. The recirculating linac accelerates picosecond-duration electron bunches to 3GeV. Branching off from the third recirculation ring and the hard x-ray production line is harmonic-generation laser-seeded FEL in a cascaded series of undulators that will produce intense EUV and soft x-rays. A fast magnetic kicker may be advantageous for the rapid transfer of the electron beam between the harmonic cascade FEL and the hard x-ray radiator beamlines. Switching electron bunches between beam lines at a 10KHz rate dictates the implementation of a relatively fast pulsed system to drive the magnet load. For this analysis I chose a very simple L-C resonant discharge scheme (Fig. 1) used for a number of fast pulse magnets at the Advanced Light Source (ALS). See Fig.1.

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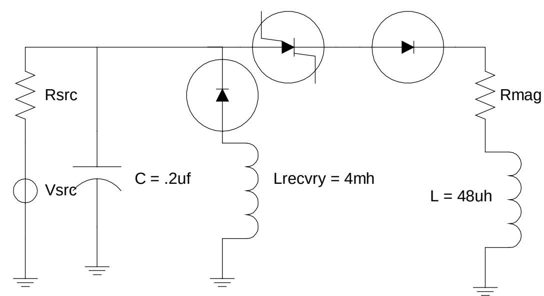
gdstover@lbl.gov



L-C resonant discharge scheme
Fig. 1

To minimize the power losses in the magnet the circuit is configured for a half sinusoidal discharge scheme using inductive energy recovery. Table I delineates the design goals for the magnet.

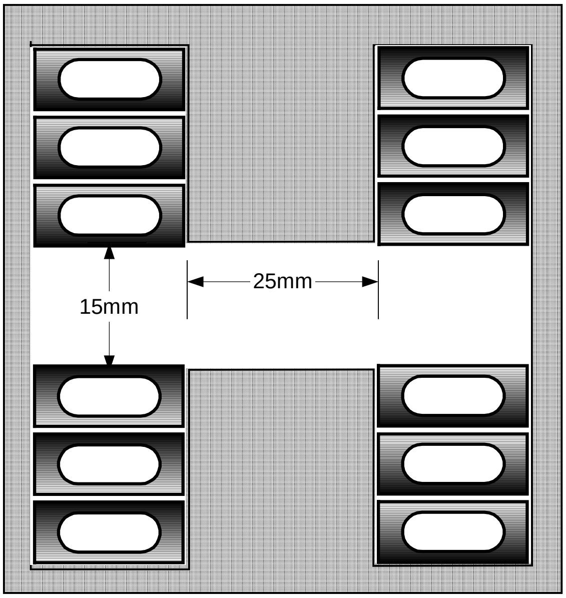
Table I – Initial design parameters for kicker magnet

Pulse width	≤30 µs
Timing jitter	< 1 ηs
Magnetic length	≅ .5 m
Gap height (entrance)	15 mm
Gap width (entrance)	25 mm
Gap width (exit)	25 mm
Peak field	0.6 tesla
Bend angle (3.1 Gev)	1.7 °
Repetition rate	10 KHz

MAGNET DESIGN

General design considerations

The initial magnet topology considered was a ferrite loaded C core septum magnet based on a design used at the Advanced Light Source [2]. Further discussions with J. Tanabe suggested that an H core 'window frame' (Fig. 2) would provide a more uniform gap field and a more effective containment of the pulsed field even at saturated core levels. In order to implement a quick study several parameters were restricted to design criteria used in the existing thin/thick septum magnets at ALS. These were: 1) The power loss per coil was kept below 500Watts. 2) The maximum voltage drop across individual coils is 4500volts or 1500volts per turn. This value is close to the nominal coil voltage (4200Volts) used in the ALS magnets. This insulation for these magnets is 2mm of epoxy glass as specified in [2].



Magnet profile – end view with six water cooled conductors. The full extent of ferrite core is not shown.
Fig. 2

Defining key magnet parameters:

From the cyclotron principle we can derive the equation and value for the $B\rho$ (beam stiffness) for E (the third re-circulation turn energy) = 3100Mev:

$$Bp = \frac{(E^2 + 2EE_0)^{1/2}}{300Z} = 10.335\_tesla - m \quad (1)$$

where Z (electron charge) = 1, E_0 = (electron rest energy) = 51. For large L_{eff} (effective magnetic length) to w (width) ratios the total flux is :

$$\int B \bullet ds \approx BL_{eff} = B\rho\theta \quad (2)$$

For a small angles $\theta = .85(\frac{\pi}{180})\_radians$ (3)

Solving for B we obtain a peak field of:

$$B_{pk} = \frac{(B\rho\theta)}{L_{eff}} = .307\_tesla \quad (4)$$

The smaller angle of $0.85°$ degrees is less than the specified design value of $1.7°$ but was chosen to keep the peak field on the ferrite pole tip face below the saturation of the typical high frequency ferrite (CMD3005) [3] used at the ALS. Other magnetic materials have higher saturation limits but may have higher losses at these frequencies. In order to achieve the total bending angle of $1.7°$ for the proscribed energy the magnetic length was extended into two sections of 0.5 meters each. The first magnet would have a window frame core as shown in Fig. 2. The second magnet would have a C core with an eddy current septum. For this study I chose to concentrate on the window frame design since most parameter values for the C core would be similar or smaller of the two magnets. From Ampere's law we obtain the current required to sustain the B field in the gap:

$$I_{pk} = \frac{Bg}{N\mu_0\eta} = 628\_amperes \quad (5)$$

Where the g (gap) = 15mm, N (the number of turns) = 6 and η (magnet efficiency) = .98. The variable η factors in the degree of saturation in the core. The gap height may change in future designs. Lowering this value would decrease coil power dissipation by the square of the ratio.

Defining magnet gap area and inductance:

For $\theta = .85°$ and $L._{eff} = .5meter$ the total beam deflection through the magnet d is:

$$d = L_{eff}\sin(\theta) = 7.4mm \quad (6)$$

Assuming the beam is centered at the entrance to the magnet the maximum exit gap required to safely clear the core is:

$$w = (\frac{w}{2} + d + \frac{b_{sc}}{2}) = 23.9mm \quad (7)$$

where b_{sc} (beam stay clear) = $\pm 4mm$. The shape of the gap is rectangular and:

$$A_{gap} = wL_{eff} = .013m^2 \quad (8)$$

And the flux in the gap is:

$$\Phi = B_{pk}A_{gap} = 4.98 * 10^{-3}\,webber \quad (9)$$

Consequently the inductance of the magnet is:

$$L = N\frac{\Phi}{I_{pk}} = 37\mu h \quad (10)$$

For $\omega = 50KHz$ which translates to a halfsine pulse period of $10\mu s$:

$$C = \frac{1}{\omega^2 L} = 0.274\mu f \quad (11)$$

The period of the half sine was iteratively chosen against the power loss in the coils. A shorter half period will decrease the power loss in a quasi-linear fashion. A limit of $10\mu s$ was set as reasonable operating point. Shorter periods would lead to increased core losses which were not modeled in this analysis.

With a fixed gap the number of turns on the magnet coil sets the total inductance which gives:

$$V_{pk} = I_{pk}\sqrt{\frac{L}{C}} = 7.3KV \tag{12}$$

N (the number of turns) was chosen to roughly maximize the voltage drop across the coils which is still below the 1500 V/turn limit. The total voltage drop is linearly proportional ratio of turns and can be tuned by the size of the capacitor. Conversely coil power dissipation is inversely proportional to square of the ratio $\frac{N_{new}}{N_{original}}$.

The skin depth is given by:

$$\delta_{cu} = \sqrt{\frac{2}{\omega\sigma_{cu}\mu_0}} = 0.295mm \tag{13}$$

where σ_{Cu} (conductivity of Cu) = $5.8*10^7 /\Omega m$. It is assumed that the majority of current flows in one skin depth. The resistance of one side of one conductor at one skin depth is:

$$R_{cond} = \frac{\rho_{cu}L_{eff}}{A_{cond}} = 9.42\times10^{-4}\,\Omega \tag{14}$$

where $\rho_{cu} = 5.8\times10^{-8}\,\Omega m$ and

$$A_{cond} = w_{cond}\delta_{cu} = 9.2\times10^{-6}\,m^2 \tag{15}$$

and $w_{cond} = 31mm$. The average power for a well formed half-sine wave form is:

$$P_{avg} = \frac{I_{pk}R_{cond}T_{1/2}F_{rep}}{2} \tag{16}$$

In addition to skin depth, conductor losses increase dramatically with frequency due to eddy-current "proximity" effects [5]. At higher currents the charge distribution in any one conductor is affected by the magnetic flux produced by the adjacent conductor. The conductor current flows; (into drawing ((-)dark) and out of drawing ((+)light)) are shown in Fig. 2. and illustrated in ref. [3]. These eddy loop currents are concentrated at the conductor boundaries and cumulatively add (turn by turn) to the normal excitation currents of the magnet. For example the current flows for the upper right hand coil at the interface of the first and second turns would be +/-628 amperes, at the second and third +/-1256 amperes and at the third outer surface +1884 amperes. Since there are two surfaces for each internal coil interface and two coil lengths per turn. The total power for either the upper or lower coil set is then is defined as:

$$P_{tot} = \frac{R_{cond}}{2}T_{1/2}\begin{bmatrix}2(3I_{pk})^2 + 4(2I_{pk})^2\\ +4(I_{pk})^2\end{bmatrix}F_{rep}$$

$$= 693\_Watts/coil \tag{17}$$

Where R_{cond} (resistance per conductor per single current sheet), $T_{1/2}$ (half sine period), F_{rep} (repetition frequency of the pulses). To keep the coil power dissipation close to the 500 Watt/coil limit the conductor cross-sectional areas of maximum current density were stretched resulting in flattened coils of width w_{cond} = 31mm. The coils are not to scale in drawing in Fig. 2. The current distributions are a very conservative estimate that needs to be verified by OPERA [6] or other 2D finite elements (FE) simulator.

CONCLUSIONS

The imposed limits of voltage drop, peak field, and power dissipation per coil are conservative. Increasing either of these would lead to a more compact magnet design. The choice of magnet core material will bound the peak field and higher frequency operation of the magnet. The key parameters that have the strongest effect on coil power dissipation are the number of turns (proportional to the square of the ratio), gap height (inversely proportional to the square of the ratio) and half-sine period (quasi-linear).

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