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DESIGN, ANALYSIS AND MEASUREMENT OF VERY FAST KICKER MAGNETS AT SLAC*

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ABSTRACT

Recent experience with SLC has shown that very fast, ferrite-loaded, transmission-line, beam-kicker magnets can cause significant and undesirable distortion of a 1.5–2.5 kA, 20–40 kV pulse as it travels through the magnet. In general, there is a net lengthening of the pulse, with increases in its rise and fall times, a decrease in amplitude, and an unsymmetrical rounding of the flattop. In this partially tutorial treatise, a number of practical design considerations are discussed in terms of equivalent circuits, magnet circuit dispersion and dissipation, undesired circuit shunting and coupling, high-voltage breakdown problems and high-order-mode losses that lead to beam tube heating. These effects are linked to the properties of the materials, the presence of radiation and realizable magnet topologies. Measurements and calculations of some of these characteristics for several magnet designs are reviewed. The results presented come from a truly eclectic effort.

1. INTRODUCTION

In a nutshell, this paper discusses the current problems, successes and failures in trying to design inductors and capacitors to use with cables, power supplies, thyratrons and other untold circuitry to quickly deflect a bunched beam, then have the whole conglomeration become electrically transparent until needed for the next beam pulse. And for the desired kick to come with accuracy, speed and reliability is all that is asked! Two earlier papers[1,2] detailed the hardware and general circuit functions, and may be helpful in understanding this paper.

2. DESIGN CONSIDERATIONS

Very fast kickers are needed in accelerator beam transport lines to transfer the beam into and out of storage and damping rings, and to differently route individual bunches out of a chain of bunches. The case of whether one bunch out of one, one out of several, or several out of a number are being injected or ejected from a ring determines the required rise, fall and flattop time requirements for the kicking impulse. For the SLC, three of the above cases are required. They are listed in a reference[2] along with the extemely stringent tolerances (compared to most storage rings) on the magnitude of the kicks as required by the rest of the collider transport system. The jury is still out on whether such tolerances are possible with any magnets and pulsers currently being considered. Time jitter translates into amplitude jitter when the slope of the part of a pulse that actually deflects the bunches is not zero. So amplitude variations and slow rise or slow fall times also contribute to kick amplitude jitter, currently a most serious limiting factor for the SLC's luminosity.

Because high voltages break down easily in confined spaces, the trend in designing very fast pulsed kickers at CERN, CESR, FNAL and SLAC has been toward broadband transmission line types loaded with ferrites to enhance a magnetically induced deflection rather than an electric one. Therefore, hereafter in this paper, the term kicker magnet is used. If a magnet is well matched to its pulser and its energy-absorbing load, reflections during the pulse and ringing after the pulse are largely eliminated. Some attempts have been made to use a series of small, lumped-inductance, kicker magnets, individually resistively terminated and fed in parallel from individual pulsers with matching and/or de-Qing circuits to stop ringing.[3] These schemes have not yet been tried on SLC and are only referenced in this paper. The current, the ferrite material properties, and the geometry of the beam aperture contribute to set the magnitude of the magnetic field, and thus the kick. Some further general comments applying to a transmission-line-type magnet design are:[4]

(1) Stray inductance, stray capacitances, mutual inductances, and individual lumped elements within the magnet should be small enough or sized appropriately so that the bandpass and cutoff frequencies associated with them do not present significant dispersive effects to the harmonic frequency content of the desired kicking pulse and thus limit the rise and fall times and flattop shape.

(2) The imaginary and real parts of the permeability of the ferrite should be constant over the above-mentioned harmonic frequency range and over the magnet's operating current range. Since this is generally not at all true, the best that can be done is to choose a magnitude of permeability and circuit geometry that will minimize the effects of the ferrite's permeability variations. Unfortunately, ferrites with high permeability tend to be more lossy and have a poorer high-frequency response, which characteristics generally result in longer rise and fall times and possible heating problems within the ferrite.

(3) The pulse transit time through the magnet should be minimized since it directly increases the duration of the kicking impulse by convolution without increasing the flattop.

(4) High voltages result in shorter transit times, but require larger spacings, longer surface breakdown paths along insulators, and possibly design for corona suppression. Designs using thyratrons are usually limited to less than 100 kV at the tube, which means 50–100 kV at the magnet depending upon whether a PFL or a Blumlein line pulser, respectively, is used.

(5) Getting enough capacitance in the right places, so that it will hold off the voltage, is a challenge for any designer.

(6) High-order modes problems for the beam can be reduced by using an internally coated, ceramic, vacuum, beam tube through the magnet, but that may present additional corona, heating (cooling), and induced voltage breakdown problems. Also, the fast-changing magnetic fields in the kicker can induce voltages in unwanted places that can, in turn, present breakdown-related problems.

(7) Finally, material susceptibility to radiation damage must not be neglected.

3. DESIGN EQUATIONS

If a charged particle with momentum, p, is given a transverse momentum kick, Δp, it will be deflected by an angle Θ.

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Transverse, mutually perpendicular electric, E, and magnetic, B, fields of the right polarities are used to produce momentum kicks. If a particle of charge, e, travels at the speed of light, c, a total distance, ℓ, through such fields, a force, F, for a time, $\Delta t = \ell/c$, will result in $\Delta p = F\Delta t = e(E + cB)\ell/c$. Furthermore, a relativistic particle's momentum p can be related to its energy by $\mathbf{E} = pc/e$ and the electric field to a voltage, V, across a gap, g, by $E = V/g$. Combining these equations gives:

$$\frac{\Theta(\mathrm{mrad})\mathbf{E}(\mathrm{GeV})}{.03} = \frac{V(\mathrm{MV})\ell_T(\mathrm{m})}{.03g(\mathrm{m})} + B(\mathrm{G})\ell_T(\mathrm{m}) \quad . \qquad (1)$$

Equation (1) shows that a 473 kV voltage or a 720 G magnetic field or some combination of the two is required from a 45-cm-long magnet with a 2.2-cm gap to produce an 8-mrad kick of the 1.21 GeV beam pulses in the SLC damping rings. A field of 720 G is easier to switch than a voltage of 473 kV.

Of the two designs in use at SLAC, the FNAL kicker magnet was designed with distributed capacitance between a 10-cm diameter center conductor and a coaxial outer ground conductor. The characteristic impedance of this coaxial line is $\sim 1\Omega$, when the 0.2-cm gap is filled with GE 615 silicone rubber. The magnet's actual characteristic impedance, Z_o, is obtained when ferrite, C-shaped cores are inserted into the ground return circuit in such a way that the current must enclose each of the 15 cores separately. The FNAL magnet has almost complete shielding, from the electric field and its kick, of the ceramic beam tube, which is placed in the gap of the C-shaped cores.

The SLAC magnet is essentially a ferrite-filled, wide rectangular, coaxial line with some of the ferrite removed so that a beam tube can be inserted longitudinally in the ferrite's C-shaped cross section. The ferrite is placed in contiguous slabs without perodic, radial dividers along the direction of the beam pipe. The beam tube is located directly between the center and outer conductors, and sees an electric as well as a magnetic field.[1] The electric field's contribution to the kick in this case is only about 6%, but it is still worthwhile to connect and orient the magnet so that the electric kick adds to, rather than subtracts from, the magnetic kick. The coaxial space between the inner and outer conductors forms a distributed series inductance and a distributed shunt capacitance, whose values are determined by the dimensions, the permeability and the permittivity of the ferrite and the air gap.

The magnetic field of a magnet is related to a driving current, the geometry and the permeability of the ferrite. The ferrite is used to enhance and concentrate a magnetic field in the gap where a beam is to travel. From $\oint H \cdot ds = I$, $\int_s BdA = 0$ and $LI = BA$, the inductance, L, and the magentic field, B, can be calculated. For b as the average path length of the H field through the C-shaped ferrite, g as the distance across the gap, w as the gap width, t as the radial width of the C-shaped ferrite, ℓ_o as the length of an individual core (FNAL or CERN style) or ℓ_T as the total length of a continuous C-shaped ferrite (SLAC style):

$$L(\mathrm{H}) = \frac{\mu_o w(\mathrm{m})\ell(\mathrm{m})}{g(\mathrm{m})\left[1 + \frac{b(\mathrm{cm})w(\mathrm{cm})}{g(\mathrm{cm})t(\mathrm{cm})\mu_r}\right]} = \frac{\mu_o\mu_g w(\mathrm{m})\ell(\mathrm{m})}{g(\mathrm{m})} \quad , \qquad (2)$$

where μ_g is defined as a loaded-gap relative permeability and $\mu_o = 4\pi \times 10^{-7}$ F/m. The current needed to produce the magnetic field is given by:

$$\begin{aligned} I(\mathrm{A}) &= \frac{B(\mathrm{G})w(\mathrm{m})\ell(\mathrm{m})}{10^4 L(\mathrm{H})} \\ &= \frac{\Theta(\mathrm{mrad})\mathbf{E}(\mathrm{GeV})g(\mathrm{m})}{300\mu_o\ell_T(\mathrm{m})}\left[1 + \frac{b(\mathrm{cm})w(\mathrm{cm})}{g(\mathrm{cm})t(\mathrm{cm})\mu_r}\right] \quad . \end{aligned} \qquad (3)$$

The characteristic impedance, $Z_o = V/I$, give the ratio of the magnet voltage to its current. The Blumlein line pulser gets charged up to the opposite polarity of and to the same magnitude as the voltage that appears on the magnet. A PFN or PFL pulser discharges the same polarity voltage, but must be charged up to twice its output voltage. Note that in specifying thyratrons, and in calculating switching rates, a Blumlein line pulser switches twice the current that the magnet sees. Furthermore, a shunt capacitance, $C_o = L_o/Z_o^2$, is needed to make a transmission line out of the largely inductive ferrite magnet. The simplest model of a kicker magnet is of a lumped transmission line consisting of n series inductances, L_o, and shunt capacitances, C_o, which makes it a low pass filter with a cutoff frequency, $f_c = 1/(\pi\sqrt{L_oC_o})$. This means that a square pulse entering the magnet will pass out with rise and fall times[5] of $\tau = .805/f_c$ and have a ripple on the top of period $1/(2f_c)$. The transit time, or time that a pulse takes to get through the magnet, is given by: $t_t = \sqrt{L_TC_T} = L_T/Z_o$, where $L_T = nL_o$ and $C_T = nC_o$.

Therefore, the steps in designing or analyzing a magnet are: (1) choose a total length, ℓ_T; (2) calculate L_T or L_o and I from eqs. (2) and (3) and the desired ferrite and beam geometries and the relative permeability of the ferrite, μ_r; (3) choose a characteristic impedance based on what voltage and transit time can be tolerated; and (4) choose an n consistent with: realizable capacitances C_o and a desired f_c and τ. To achieve the above conditions, while also avoiding excessive dispersion, it may be necessary to choose a ferrite with a value of μ_r slightly lower than the optimum to make completely negligible the effects of its nonlinearities. Probably the real and the imaginary parts of the ferrite's permeability should be reasonably constant with frequency up to f_c. The absolute value of the imaginary part (attenuation or loss tangent) should be kept small. Thus, for a fixed aperture ($w \times g$) and with the magnet divided up into small lumped elements, with ℓ_T kept short and with the impedance kept high, the cutoff frequency will be relatively high and the rise, fall and transit times will be relatively short. If a moderate amount of fairly high permeability ferrite is used in a reasonably compact geometry so that μ_g is close to one, the properties of the ferrite should be less important. Still, unfortunately, a short high-impedance magnet requires high current and high voltage. In the end, several short, separately-driven magnets may be necessary. Gotcha — more power to the loads and from the pulsers for faster storage and kicking![3]

4. OPERATING EXPERIENCE

Operating the SLC damping rings and positron source with the SLAC and the FNAL kicker magnet systems has been difficult. On the bright side, the oil-cooled, resistive loads, which are used on both systems and are a derivative of a CERN design, have performed almost flawlessly. The charging power supplies for both the SLAC Blumlein line pulser and the FNAL PFL have had reliability and stability problems. They have now been replaced with more stable pulsed charging supplies. The SLAC Blumlein line pulsers are quite reliable, but they were designed with a 40 ns pulse line and with a thyratron switched current of up to 4000 A. At the rate of 100–200 A/ns, the switching time is 20–40 ns. Add to that a magnet transit time of 20 ns or more, some magnet impedance mismatches and some pulse distortion, and it is not surprising that there is no flattop and considerable post-pulse ringing. If the inductance, capacitance, loaded-gap relative permeability, characteristic impedance and transit time are calculated for the SLAC magnet, with an initial μ_r of over 1000, the following values result: 400 nH, 1100 pF, 1.04, 19 Ω, and 21 ns, respectively.

The FNAL pulsers have 120 ns PFL's and two paralleled thyratrons to switch only about 1000 A each. Two types of ferrites are used in the 15-cell FNAL magnets, one with a μ_r of 20 upwards and another with a μ_r of 50 upwards. The two magnet types have single-cell inductances, capacitances and loaded-gap relative permeabilities of: 21 nH, 114 pF and 1.75 and 28 nH, 114 pF and 1.3, respectively. The characteristic impedances and transit times are 13.5 Ω and 23 ns and 15.7 Ω and 27 ns, respectively. The above simplified equations do not give as good circuit values as hoped for. The permeability of the ferrites increases up to a factor of three over the operating range, as shown in manufacturer's literature and as determined from measurements on the FNAL magnets. Currently, all new designs envision using ferrites with an initial relative permeability of at least 100 and with short path lengths through the ferrite. Although the SLAC, continous-slab, ferrite magnet is not clearly understood as to whether or how the beam gap acts as a shunting and mutually-coupling, high-impedance strip-line, it is generally found to have slower rise and fall times with more ringing than the FNAL, segemented- and shielded-ferrite magnet as seen in fig. 1(a). Both magnets experience radiation damage to their silicone rubber insulation, with perhaps the SLAC magnet being slightly more durable. The current lifetime in service in the five SLC sockets is barely acceptable for either magnet. The rebuilding (repotting) rate for the 14 existing magnets is hard to keep up with. Most of the SLAC magnets have been rebuilt only once, but they have not seen much service either. The FNAL magnets have been rebuilt up to six times and currently are being recycled every few months. The rate will increase as radiation doses increase with higher machine running rates. An experiment to determine if powdered alumina loaded into the silicone rubber would improve the radiation resistance was disappointing. Air bubbles were even harder to get out of the more viscous potting compound. A great deal of recent effort has gone into trying to measure the details of the pulses from the various pulsers and magnets and to try to correlate the measurements with equivalent circuits, mismatches, thyratron characteristics and properties of the ferrites. Detailed correlation has not always been achieved, but parametric correctness is generally demonstrated. The thyratron prepulse phenomenon is understood as progressive avalanching of the multigrid thyratron during the switching process, and it can be as much as 1% peak, as seen in fig. 1(b). A long-pulse, water-filled, Blumlein line is being built and tested to see if it is an improvement over the FNAL PFL pulser. Presently, thyratron jitter is at best $\sim$ 500 ps. Soon, an accurate amplitude measurement circuit will be installed.[6] A new feedback circuit has reduced the long-term timing drift to less than 300 ns, making the effects of modest pulsetop ripple and slopes more manageable.

The pulsers and loads have been moved out of the damping ring vaults to a new surface building, where adjustments and measurements can be made during operation. The cathode and grid circuits for the thyratrons in the FNAL pulser are being redesigned for greater reliability and stability. Heat exchanger circuits for the SLAC Blumlein line pulsers are being installed as thermal drift from higher repetition rate operation now warrants them. Efforts to improve the repairability of the existing SLAC and FNAL magnet systems continue.

5. CONCLUSIONS

Work needs to be continued to understand all the causes of the pulse-shape pecularities. Designs for a more reliable and faster magnet are being looked into, especially ones involving segmented, shielded ferrite cores immersed in freon or in vacuum along with interleaved capacitor plates and the ceramic beam tube.[3,4,7,8] Feedforward schemes to cancel the thyratron-generated prepulse and efforts to tailor the pulse are being considered.[8] However, considerably more has to be learned to appreciably approach the original design specifications. So for now, BNS damping and other beam schemes will have to compensate for the kicker's weak performance in the SLC lineup. Finally, the resistance to radiation of a magnet's insulating material must be consistent with the desired service life.

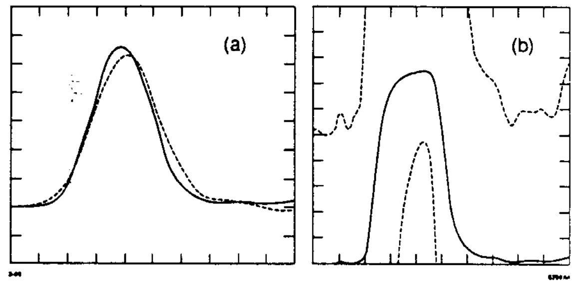

Figure 1: (a) Relative $\int B \cdot dl$ *vs. time* (20 ns/div.) *for* 17 Ω *SLAC (dash) and FNAL (solid) magnets and SLAC pulser. (b)* $\int B \cdot dl$ *vs. time* (50 ns/div.) *for a* 12.5 Ω *FNAL magnet and FNAL pulser (dash is* 10 X*).*

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