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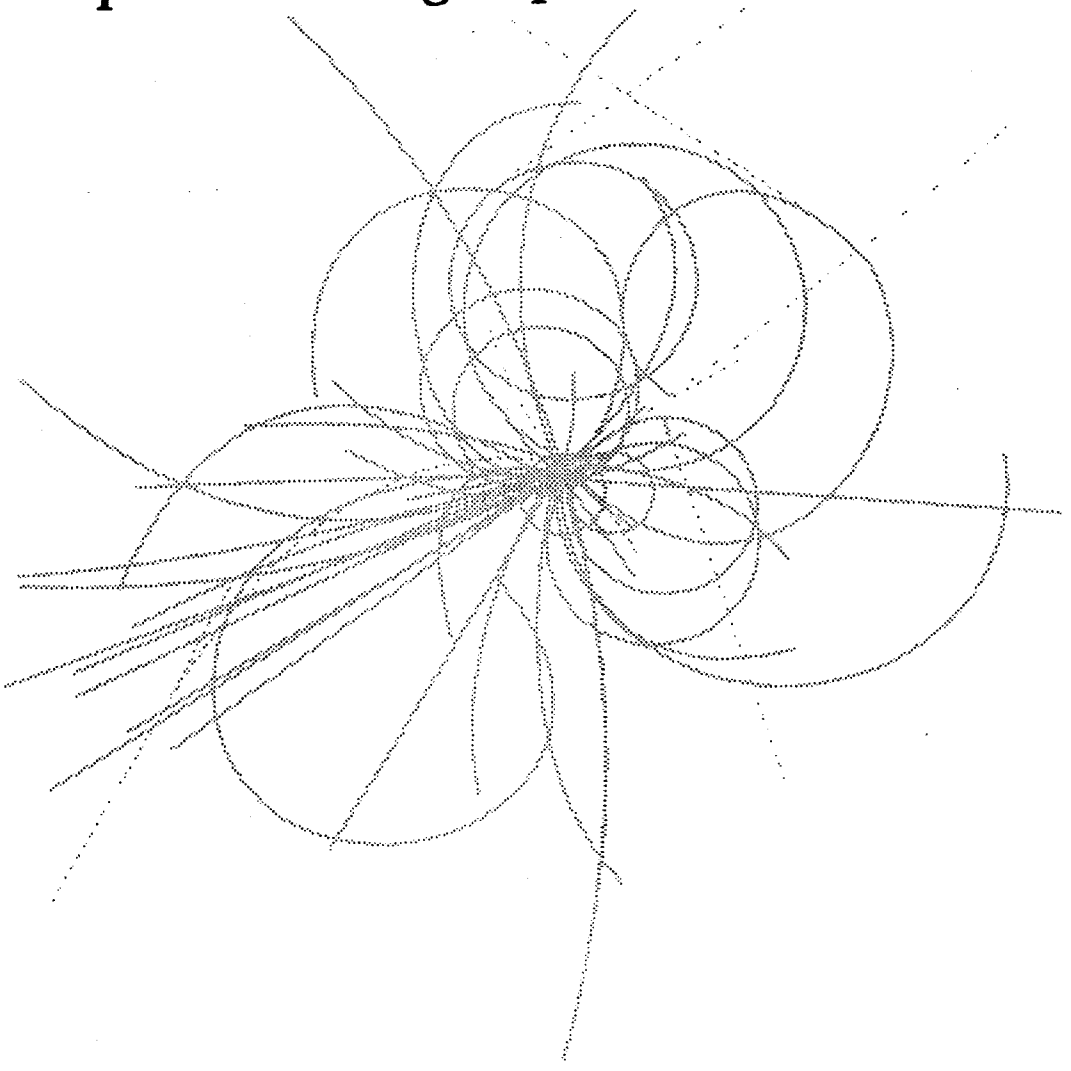

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KICKER MAGNET SYSTEMS FOR THE INJECTOR SYNCHROTRONS

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Abstract: A kicker magnet is a device capable of producing a pulsed magnetic field for the purpose of deflecting charged particle beams out of their defined orbit. The kicker magnets at the Superconducting Super Collider (SSC) Laboratory are designed to transfer beam bunches from a series of three booster stages into a counter-rotating 20 TeV collider ring. The required kicker magnetic field is the result of factors such as bunch spacing, maximum allowable lost bunches, required angular deflection, and other characteristics of synchrotron operation.

An overview of the injection synchrotron kicker magnet systems to be used in the SSC is presented. System design includes magnet and modulator design for each of the kicker systems addressed. Design issues for each subsystem are presented, including magnet geometry, magnetic material selection, feed topologies, switch selection, and other key considerations. An overview of system requirements, as well as a brief statement of design status, is also presented.

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INTRODUCTION

A block diagram of a typical kicker system is shown in Figure 1. The system is made up of a control system, a high voltage charging supply, a trigger generator, a pulse-forming line and switch, the magnet assembly, and a matching load. System charging and firing commands, generated in the main accelerator control room, synchronize all of the kicker magnets to achieve the sequential filling of the injection synchrotrons and main collider rings. Filling of the Medium Energy Booster (MEB) from the Low Energy Booster (LEB) occurs in seven cycles at 10 Hz; the High Energy Booster (HEB) is filled from the MEB in three cycles at 0.3 Hz; each collider ring is filled from the HEB in eight cycles at 0.01 Hz.

Two geometries, depicted in Figure 2, are under consideration for the SSC kicker magnets. The C-magnet (Figure 2(a)) uses a toroid or a C-core with a large air gap to accommodate the beam tube. Current driven through a single-turn busbar surrounding the magnetic

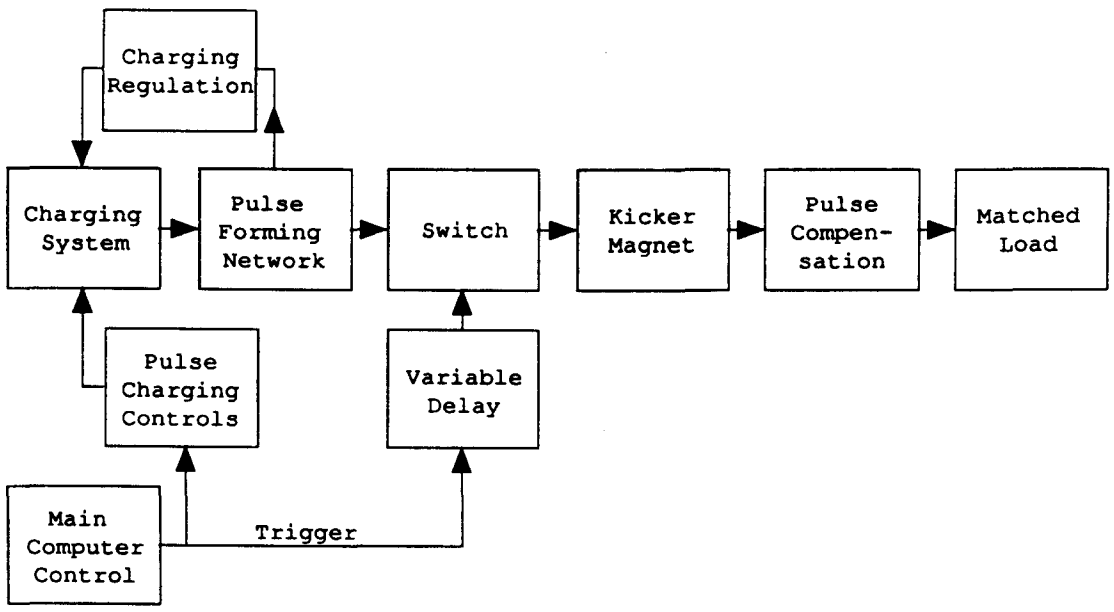

Figure 1. Block Diagram of Typical Kicker Magnet Systems.

material produces vertical flux in the air gap, resulting in horizontal deflection of the proton beam. The H-magnet (Figures 2(b) or 2(c)) employs either an H-core or a toroid with pole pieces to form a closed magnetic path with a large air gap in the middle. The H-magnet uses two equal driving currents of opposite direction on either side of the air gap to produce flux in the air gap. Since the current in each H-magnet bus is half that required in a C-magnet bus, the H-magnet is in many ways analogous to two parallel C-magnets.

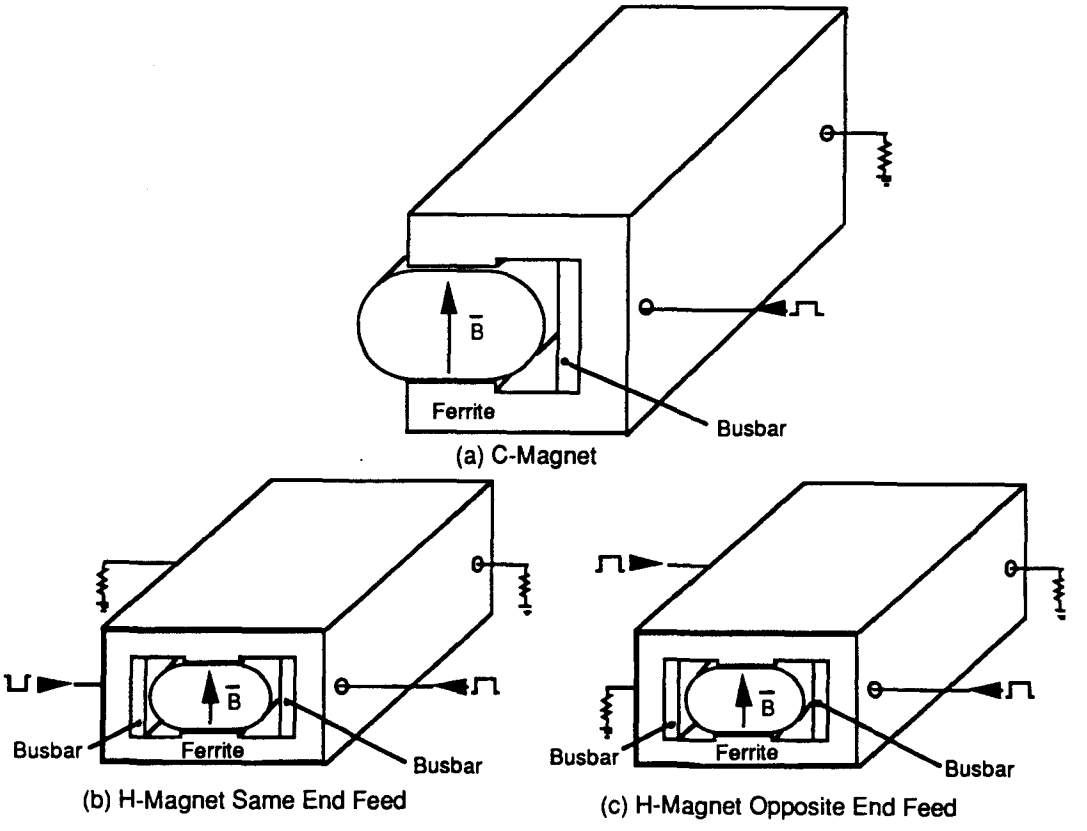

Figure 2. Comparison of H- and C-magnets.

Magnetic material selection depends primarily on the frequency of the drive pulse and the required magnetic field intensity. Generally, ferrite cores can be operated into the 100 MHz range with manageable core losses, but at the expense of lower saturation flux densities and small initial permeabilities. Laminated steel (or Metglas) cores offer much higher saturation flux densities and initial permeabilities, but with significant core loss above approximately 1 MHz (higher for Metglas).

Modulator choices depend on pulsewidth, risetime, and falltime requirements. Typically, for pulse widths of less than 2 μs, a charged-cable pulse-forming line is used. Risetimes, which are dominated by switch turn-on time, switch inductance, and stray capacitance, can be made lower than a few tens of nanoseconds, and flattop ripple is essentially zero. Droop due to cable losses can be compensated by passive correction circuits. Lumped LC pulse-forming networks (PFNs) are traditionally used for longer pulses. Both flattop ripple and rise/falltimes are functions of the number of elements in the network. Most of the SSC kicker systems will employ lumped-element PFNs.

Pulse parameters such as peak current, charge transfer, voltage, and jitter also determine the types of modulator switches. For many of the SSC kicker modulators, hydrogen thyratrons will be used. They are reliable, low-loss, low-jitter devices which, with careful design, can produce the required switching speeds and perform with long lifetimes. For the fastest kicker systems, alternative switches include the back-lighted thyratron (BLT) and spark gap. The BLT is advertised as being faster than a traditional thyratron, but since

BLTs are still in the development stage, very little lifetime data is available on any single device.[1] Triggered spark gaps, which are more compact and generally less inductive than thyratrons, are generally discounted in such high-reliability applications because of limited lifetime and/or excessive longterm jitter due to electrode erosion. Silicon-controlled rectifiers (SCRs) are under consideration for some of the slower kicker modulators, where high currents, long pulse widths, and less-demanding switching speeds are required. Series/parallel arrays of SCRs will be required because single devices capable of operating reliably at the voltages and currents of the kicker systems do not currently exist.

There are many other modulator issues which must be addressed in the design of individual systems. These include pulse-sharpening, load matching, and compensation circuitry. Pulse-sharpening may be necessary on some of the faster kickers if a switch cannot be found which meets all the pulse requirements. Matched loading is required when stringent flattop and falltime requirements demand no reflections or transients in the magnetic field. Finally, cable dispersion, cable attenuation, PFN droop, and other effects can result in flattop degradation outside acceptable limits. In these cases, compensation networks will be required within the system.

KICKER MAGNET REQUIREMENTS

The SSC requires six transfer kicker magnet systems, one at each end of the three transfer lines. The pulse parameters of the six systems are summarized in Table 1, where E or I after the booster name denotes the ejection or injection system.

Table 1. Kicker Magnet Parameters.

System	B_{max}	Aperture	Rise-time[a]	Pulse length	Jitter (rms)	Flat-top	Number magnet
LEBE	0.015T	5 × 9 cm	47ns	1.8μs	1ns	≤0.5%	4
MEBI	0.010T	5 × 10 cm	47ns	1.8μs	1ns	≤1%	4
MEBE	0.065T	5 × 10 cm	400ns	12.7μs	5ns	≤1%	2 × 6
HEBI	0.112T	4 × 4 cm	400ns	12.7μs	10ns	≤1%	2 × 6
HEBE	0.125T	4 × 4 cm	1.7μs	36.3μs	10ns	≤0.5%	2 × 6
ColI	0.060T	6 × 6 cm	1.7μs	36.3μs	10ns	≤1%	2 × 10

[a]0-99% risetime

MAGNET DESIGN ISSUES

Magnet design follows a logical approach based on three parameters. These parameters, set by the beam physics and material limitations, are peak magnetic field, aperture size, and peak operating voltage.

The approximate current required to establish a given magnetic field in the kicker magnet can be determined from Ampere's Law:

$$I \approx (B/\mu_o)[g+(l_m/\mu_r)] ,$$

where B is the desired magnetic field intensity, g is the air gap spacing (aperture height) across which the field is to be established, l_m is the mean length of magnetic material, and μ_r is the relative permeability of the magnetic material. In all the kicker magnets discussed in this paper, $g >> (l_m/\mu_r)$, giving rise to the following simplification:

$$I \approx Bg/\mu_o .$$

Material considerations limit the peak and charge voltages at which the kicker magnet system can operate. These limitations exist primarily on the modulator cables and switching devices, but may also exist on the pulse compensator, pulse-forming network capacitors (where required), and elsewhere. This voltage limit, when divided by the current required to establish the field, sets an upper limit on the operating impedance of the kicker magnet. For a distributed-element transmission line system, the operating impedance is given as

$$Z_o = (L/C)^{1/2} ,$$

where L and C are the inductance and capacitance per unit length of the transmission line system, respectively.

The distributed inductance for a kicker magnet system can be calculated based primarily on the aperture size. From Faraday's law, we obtain

$$L = \Phi/I = [\mathcal{R}_a+\mathcal{R}_m]^{-1} ,$$

where $\mathcal{R}_a$ and $\mathcal{R}_m$ are the air and magnetic material reluctances, respectively. Substituting the geometrical representation of the reluctances on a per unit length basis leads to

$$L = [l_m/(\mu_r\mu_o t)+g/(\mu_o W)]^{-1} ,$$

where t is the thickness of the magnetic material and W is the width of the aperture. If the thickness of the magnetic material is comparable to the width of the aperture, the following approximation can be made:

$$L \approx \mu_o W/[g+(l_m/\mu_r)] .$$

Furthermore, $g >> l_m/\mu_r$, and, therefore,

$$L \approx \mu_o W/g .$$

With the above expressions for the inductances per unit length and the maximum value of the magnet impedance, the minimum required capacitance per unit length of the kicker magnet can be calculated to be

$$C = \mu_o W/(Z_o^2 g) .$$

The per unit length propagation time (τ) for the kicker magnet is just the square root of the product of the inductance and capacitance per unit length. Substituting the above expressions for L and C gives

$$\tau = \mu_o W/(Z_o g) .$$

The magnetic field risetime at any point in the magnet depends on three effects. The first effect, the risetime of the applied pulse, depends on the speed of the switch as well as the stray modulator inductance and capacitance. The second effect is due to the finite electrical length of the kicker magnet and is described by the propagation time given above. Finally, second-order effects include 1) B-field penetration time through the resistively-coated beampipe, 2) variations in propagation speeds due to non-linear effects in the magnetic material, 3) hysteresis losses, 4) skin effect losses, and 5) eddy current losses in the beampipe coating. The net effect is a smoothing of the B-field risetime.

LEB-TO-MEB TRANSFER KICKER DESIGN STATUS

These kicker magnets must deflect the 9-12 GeV beam into and out of the LEB-to-MEB transfer line. Both C- and H-magnet geometries have been considered for this magnet set, and the H-magnet has been adopted as the baseline design.

Non-electrical advantages of the C-magnet include the ability to be designed to slide over the accelerator beampipe without breaking the vacuum and the fact that there are fewer parts to the C-magnet, thus making high tolerance machining and assembly easier.In addition, there is considerable experience with kicker magnets of the C-geometry within the high-energy physics community.[2,3] Disadvantages include the requirement for higher current in a single busbar and longer propagation times through the magnet for a given magnet impedance.

The H-magnet is more difficult to construct to tight tolerances, and replacement of the magnet requires either partial disassembly of the magnet or extraction of a section of accelerator beampipe with the magnet. However, for a given impedance, the H-magnet exhibits one-half the fill time of its C-magnet counterpart.

In the H-magnet, there are two feed configurations that can be used to produce currents of opposite directions in the two busbars. These are shown in Figures 2(b) and 2(c). In Figure 2(b), currents of opposite direction are generated by driving the two busbars from the same end with opposite-polarity voltage pulses. Current travels through the magnet to matching resistive loads. Figure 2(c) depicts another possible feed configuration, with the two busbars fed from opposite ends of the magnet with voltage pulses of the same polarity. Determining which feed system results in optimum performance of the magnet system is a major goal of future experiments at the SSCL. Other experiments, in either the design or procurement phase, include thyratron development, BLT characterization, and cable testing.

MEB-TO-HEB TRANSFER KICKER DESIGN STATUS

This set of kicker magnets transfers the beam from the MEB to the HEB at an energy of 200 GeV. The total current required to drive the necessary magnetic field is approximately 3500 A for the MEBE and 5000 A for the HEBI. Half of these current values are required for each busbar in a dual-bus H-magnet configuration. For the HEBI kicker, the inductance per unit length for a rectangular H-magnet surrounding the specified beampipe can be calculated as approximately 1.2 μH/m for each busbar. For the higher current magnet (HEBI), staying below a pulsed voltage limit of 50 kV requires that magnet impedance be less than 20 Ω. Selecting 16.7 Ω as the design impedance implies a busbar-to-ground capacitance of L/Z^2 = 4nF/m. This high capacitance cannot be achieved by relying strictly on the natural geometry of the magnet. Discrete capacitors, consisting of "pads" of copper-coated Kapton sheets, can be added along the magnet's length to realize an effective magnet impedance of the required 16.7 Ω.

Due to the longer pulse width and slower risetime for this set of magnets, a lumped-element pulse-forming network can be used instead of excessively long pieces of charged cable. If it is assumed that only the risetime is important in the case of ejection kicker magnets (since the MEB will be empty after the pulse), and both the rise and falltimes are important for the injection kicker magnets, then the HEBI again represents the worst case. The PFN must be designed so that the rise and falltimes are faster than 3% of the pulse width. For a PFN tuned to be flat to within ≤1%, this requires a minimum of 46 sections.[4] Switching in this set of kicker magnets will employ standard hydrogen thyratrons, since the pulse requirements are well within the operating range of existing devices.

HEB-TO-COLLIDER TRANSFER KICKER DESIGN STATUS

The final set of transfer kicker magnets is required to move the 2 TeV beam from the HEB to the Collider rings. Due to the high currents involved and long pulse widths necessary to empty the large HEB, a low-impedance C-magnet fed by a SCR-switched PFN is being considered. Again, the inclusion of discrete capacitors within the magnet will be required to achieve low magnet impedance.

The required total current for the HEBE kicker magnet is approximately 5500 A. To maintain pulse voltages below 50 kV requires impedances of less than 9 Ω. An impedance of 8.33 Ω equates to six 50 Ω cables in parallel and is certainly possible in a C-magnet configuration. If discrete capacitor "pads" are added, this value is achievable. If an H-magnet is chosen, the impedance per busbar can increase by a factor of 2, resulting in a possible operating impedance of 16.7 Ω. This will still require the addition of discrete capacitors.

The relatively slow risetime allows for investigation of solid-state switch arrays. SCRs have demonstrated extremely long lifetimes when operated conservatively, and they are capable of conducting several kiloamperes per device. Their voltage holdoff capability, however, is limited to approximately 3500 V. Therefore, series arrays would have to be used and properly biased to allow for operation at tens of kilovolts.

CONCLUSION

A wide variety of pulsed transfer kicker magnets and associated modulators will be developed for use at the SSC. Due to stringent risetime and flattop requirements for the LEB-to-MEB transfer kickers, several magnet and switching options are being investigated. The H-magnet geometry looks very attractive for this particular application. Essentially two tightly coupled C-magnets in parallel, the H-magnet can be designed for shorter fill times when compared against a C-magnet of identical impedance. Though thyratrons are the traditional switch of choice, investigations into BLTs and spark gaps are also underway.

The other kicker systems require a different design approach. The longer pulse widths and risetimes, combined with the large coulomb transfer, allow for the use of pulse-forming networks and slower thyratrons or SCR switches. Matching of magnet to modulator at the low values of impedance necessary, design and tuning of fast, ripple-free pulse-forming networks, and creation of large arrays of SCR switches are important design issues which must be addressed.

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