FAST KICKER MAGNETS FOR THE 200-GeV ACCELERATOR *

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Summary

Several fast-transfer systems using kicker magnets are needed for the proposed 200-GeV Accelerator. A possible system for transfer from the injector synchrotron to the main ring using stationary, full-aperture kicker magnets presents the most stringent requirements. The extraction kicker for the injector synchrotron will be about 4 m in length, have a 4-by-14-cm aperture, and require a field of 300 G. For 100% efficient transfer the rise time of the magnetic field must be shorter than 17 ns, which is the time between beam bunches, and which is nearly an order of magnitude less than the rise times achieved in existing kicker magnets. Because of the required rise time and the limited length, each magnet is divided into 48 modules operated as 24 push-pull pairs. Each module is analyzed as a short-circuited ferrite-and dielectric-loaded transmission line. The short-circuited mode of operation ensures that voltage on the magnet is applied for only about 12 ns, thus reducing HV problems, and at the same time produces a kick twice as great as can be obtained from terminated magnets. Each module is energized by a tapered coaxial pulse line and switched on with a triggered spark gap.

Introduction

Kicker magnets will be used to transfer beam from the linac to the booster synchrotron, from the booster to the main ring, and at times from the booster and main ring to the experimental areas. The beam from the linac is injected into the booster with four separate magnets, which are turned on relatively slowly before beam enters the booster and which are turned off together rapidly after the beam has completed four revolutions. The booster and main-ring kicker magnets must provide fields that are turned on rapidly, have constant amplitudes for several microseconds, and unspecified fall times. Tentative specifications for two of the kickers are given in Table I. The booster extraction magnet is followed by a magnet with similar aperture and timing requirements which inflects the beam into the main ring, but which has only one third the average field requirement, making it somewhat easier to build. Extraction of all or part of the beam from the main ring is the least difficult of the kicker-magnet problems because length for magnets is available and because the size of the beam is small. An alternate scheme for the booster extraction magnet using a mechanically resonant plunged magnet system was investigated by Mr. C. E. McDonald; the electrical analysis and magnet configuration for this plunged system are identical to those used for full-aperture extraction, with the dimensions of the magnet being reduced, enabling fewer sections of higher impedance to be used.

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Table I. Kicker magnet specifications

	Booster Injection	Booster Extraction
Magnet length (m)	1	4
Gap height (cm)	4.5	4
Gap width (cm)	12	14
Good field height (cm)	4.5	1
Good field width (cm)	12	4
Average field (G)	700	350
Kick tolerance (%)	1	1
Rise time (ns)	any	17
Flat top (μs)	16	2
Fall time (ns)	130	any
Max. repetition rate (s^{-1})	18	18

Booster Injection

Magnet systems that must provide a field with a fast rise time are quite different from those that must provide a fast fall time. The difference is due largely to the transient responses of available high-power pulse-forming networks. If we examine the current wave form obtained when a coaxial line is discharged, we get a very fast rise time, an almost flat pulse with a small amount of pulse droop given by

$$\frac{\Delta I}{I_o} = -\left[\frac{(1/a)+(1/b)}{l_n(b/a)(\pi\mu\sigma)^{\frac{1}{2}}}\right](t)^{\frac{1}{2}}$$

and a long fall time at the end of the pulse, with the asymptotic form

$$\frac{I}{I_o} = \frac{\ell}{2Z_o}\left(\frac{1}{a}+\frac{1}{b}\right)\frac{\mu^{\frac{1}{2}}\, u_{-1}\,(t-T_o)}{[\pi^3\sigma(t-T_o)]^{\frac{1}{2}}}$$

for a coaxial line of radii a and b, length l, conductivity σ, and impedance Z_o. From the second equation, the time required for a 16 μs pulse to fall to 1% of its initial value is of the order of 50 μs for even the largest diameter cables available. A lumped-element line is not better in this respect; and example obtained with a computer program is shown in Fig. 1. This lumped-element line uses 12 sections and produces a current within 0.5% of the flat-top level in 4 μs, when $L_1 = 1.75\,L$.

To achieve a fast-fall-time magnet, the circuit shown in Fig. 2 was chosen for the booster injection system. At the end of the pulse, switch S_2 is triggered, giving an exponential field fall-time, delayed by the length of cable between the magnet and the switch. The 130-ns fall-time constant is long enough to allow this magnet to be analyzed as a lumped inductance and to use a high permeability ferrite for the return path. The calculation is not difficult.

Booster Extraction

Magnet

After the beam has been accelerated to 8-GeV in the booster, it has a structure in time consisting of 2-ns-wide bunches spaced 17-ns apart. For 100% efficient transfer of the beam to the main ring, the field of the kicker must rise from 0 to its final value in 17 ns. The available time is allocated among the jitter and rise time of the spark gap, junction mismatches, and the magnetization time of the ferrite--all of which are lumped under τ in the subsequent analysis--as well as the propagation time through the magnet. For ferrites an approximate relation between μ and the ferromagnetic resonance frequency is $(\mu-1)f_r \propto \gamma M_s$, where M_s is the saturation magnetization and γ is the gyromagnetic ratio. In practice this works out to give $\mu > 100$ for the 130-ns fall-time magnets and $\mu \approx 10$ for the 17-ns rise time magnets. From the way the μ of the return path enters into the expression for the average μ, a μ of 100 is approximately as good as $\mu = \infty$, but $\mu = 10$ is not. The small value of μ for suitable ferrites is a handicap because the drop in magnetomotive force in the return path is comparable to that across the gap. Therefore the gap field is very sensitive to magnetization changes with time in the ferrite. Phenomenologically, the relation of M for an applied step function of H is given as an exponential, but the actual increase of magnetization with time is more complicated.

The circuit evolved as most satisfactory for the booster extraction magnets is shown in Fig. 3. Analysis of this magnet is considerably simplified by approximating the magnet by two coaxial lines of radii a and b with a radial wedge of angle θ_1 cut out of it to form the gap, as shown in Fig. 4. For equal and opposite excitation of the two coaxes, a plane of symmetry exists through the midplane of the gap. Each half of this simplified geometry has a capacitance and inductance per unit length given by $C' = (\theta_1\varepsilon_1 + \theta_2\varepsilon_2)/\ln(b/a) = 2\pi\varepsilon/\ln(b/a)$ and

$L' = \ln(b/a)/[(\theta_1/\mu_1) + (\theta_2/\mu_2)] = \mu\ln(b/a)/2\pi$, respectively, which also define average μ and ε for the TEM-like mode of propagation. For this mode $Z_0 = [\ln(b/a)/2\pi](\mu/\varepsilon)^{\frac{1}{2}}$ and $v = (\mu\varepsilon)^{-\frac{1}{2}}$ are respectively the characteristic impedance and velocity of propagation. The minimum field in the gap is $B = \mu i/2\pi b$. The length of a section of magnet or module is determined by the *time it takes the incident pulse to travel twice* through the magnet and for all of the ripples on the current waveform (caused by input mismatches, spark gap jitter and rise time, and the bandpass characteristics of the structure) to pass out of the magnet. If we define the time between bunches as T and lump all of the above rise times as τ, the length of a module is $l_n = \frac{v}{2}(T-\tau)$.

The current as a function of the distance along the beam axis at the time the first bunch to be deflected arrives at the magnet is shown in Fig. 3. If we use $I = V_{p\ell}/Z_0$ for the current going through a short-circuited magnet from a matched pulse line of impedance Z_0 and charging voltage $V_{p\ell}$ the kick per module $K_n = V_{p\ell}[T-\tau]/2[b\ln(b/a)]$ is independent of μ and ε as long as the maximum kick is desired. The number of sections required in the direction of the beam to provide a total kick K is $n = K/K_n$. As each of these sections is made up of a pair of modules operated in a push-pull mode, the magnet is made up of 2n modules, each of which is independently excited at the proper time through its own spark gap and pulse line. The fixed available total length L for the magnet can be related to the length of an individual module ℓ_n and the length ℓ_o of the junction for one module as $L = n[\ell_n + (\ell_o/2)]$. As only the voltage $V_{p\ell}/2$ reaches this junction and is applied to it for twice the propagation time through the magnet, about 12-ns, the junction can be made much shorter than would be required if it had to withhold this voltage for the entire 2.1-μs pulse.[2]

The junction length ℓ_o is determined by the reflections it produces on the current waveform: the reflection from the incident pulse causes a small degradation in rise time, but the reflection caused by the pulse as it leaves the module is reflected back into the module and is present there at the same time as the beam. This second reflection is minimized by making the average impedance of the junction equal to Z_0.

The required kick of 0.13 W/m can be achieved with n = 24 sections, using $V_{p\ell}$ = 65 kV, a = 3 cm, b = 7 cm, and $(T-\tau)$ = 10 ns; taking 2 and 3 ns respectively for spark gap jitter and rise time and 2 ns for junction mismatches. With total length L of 4.1 m, the length per module is given as 15 cm. The required propagation velocity v = (2)(15)cm/10 ns = c/10 so that a $\mu\varepsilon$ product of 100 is necessary. From overall considerations of spark-gap erosion and power-supply problems, we want to use the highest μ compatible with the fast rise times, and then adjust the ε to reach the desired $\mu\varepsilon$ product. With a ferrite having $\mu = 10$, the effective permeability obtained by averaging azimuthally and longitudinally is only $\mu_{eff} = 3.3$, requiring an effective ε_{eff} of 30.

The required average ε can be obtained in a way that does not greatly distort field lines, by alternating dielectric and ferrite laminations and then taking suitable averages. The filter characterisitics of the magnet structure can be estimated by averaging over a cross section to get average μ and ε values for both the ferrite and dielectric pieces and working out the dispersion relation from the trace of the product of the transmission matrices of the laminae.[3] For a composite line made of length l_1 of μ_1 and ε_1 alternating with lengths l_2 of μ_2 and ε_2, the dispersion relation is

$$\cos\beta\ (\ell_1+\ell_2) = \cos\beta_1\ell_1 \cos\beta_2\ell_2 - \frac{1}{2}\left[\left(\frac{\mu_2}{\mu_1}\frac{\varepsilon_1}{\varepsilon_2}\right)^{\frac{1}{2}} + \left(\frac{\mu_1}{\mu_2}\frac{\varepsilon_2}{\varepsilon_1}\right)^{\frac{1}{2}}\right] \sin\beta_1\ell_1 \sin\beta_2\ell_2,$$

where $\beta = \omega/c$, and $\beta_i = \omega(\mu_i\varepsilon_i)^{\frac{1}{2}}$ As the first cut-off occurs at $\beta(\ell_1+\ell_2) = \pi$ when $\beta_1\ell_1$ and $\beta_2\ell_2$ are small angles, the dispersion relation simplifies approximately to $\omega = \omega_c \sin(\phi/2) = \omega_c \sin[\beta(\ell_1+\ell_2)/2]$, where ω_c is the cut-off frequency, and ϕ is the phase shift per section.

The approximations made in the calculation get better as the size of the aperture is reduced and the length of the return path gets shorter, so that a wavefront can propagate over the entire cross section with approximately the same velocity. While theoretically the cut-off frequency can be made as high as desired by subdividing the laminations, practically we have had to consider using dielectrics with an ε of only about 100, because of the fragility of very thin laminations. For a ferrite of $\mu = 10$ and thickness of 6 mm, and a dielectric of $\varepsilon = 100$ and a thickness of 2 mm. we obtain a structure with an impedance of 17 Ω and a first passband cut-off frequency of 575 MHz; a pulse with a 3-ns rise time should propagate through the structure without noticeable distortion or rise time degradation. A more exact description of the propagation through the magnet including the aperture involves the use of integral equations. The actual magnet configuration is shown in Fig. 5.

Spark Gaps

Because of the short interval between bunches, every nanosecond is valuable, and the spark gap is the major contributor to time losses. The jitter and rise time used in the calculation were 3 and 2 ns respectively, based on results obtained with a three-electrode gap pressurized to 10 atmospheres and on results reported in the literature. By using higher pressures, rise times under 2 ns can possibly obtained, and we are constructing a spark gap suitable for pressures up to 50 atmospheres. Typical jitter obtained so far with high-power spark gaps is reported to be around 5-ns,[4,5] however, with the tendency to increase after several 100 000 pulses of operation due to electrode erosion.

The jitter for the simultaneous firing of all 48 gaps can probably be reduced below 2 ns by the use of a pulsed electron beam from a small one-cavity microwave linac as proposed by Rudin Johnson of LRL. Preliminary experiments were carried out on a 3 electrode spark gap placed in the beam path of 7-MeV pulsed linac. When the beam was applied simultaneously with a trigger pulse on the center electrode, breakdown of the gap with a delay of about 6 ns and a jitter of 0.8 ns was observed, while triggering with either the voltage pulse or the electron beam alone gave delay time and jitter one order of magnitude higher. The energy loss with distance is nearly constant for energies above 100 keV in air, and equal to about 200 keV/m-atmosphere. If we assume a beam passing through 1 cm of air at 50 atmospheres and two 1-mil stainless steel windows per spark gap, the energy loss per gap is 160 keV. A 100-mA, 1-MeV beam could thus be split into eight parallel beams each going through approximately six gaps to provide a precisely timed source of electrons to initiate the discharge with low gap-to-gap total jitter.

Field Regulation

The droop in the current amplitude and the change of magnetization of the ferrite return path cause the magnetic field in the gap to vary in time. While both of these effects are small, they are outside of the 1% kick tolerance requirement and some sort of compensation must be provided. The short, 2 μs pulse width rules out active regulation from gain-bandwidth limitations, and the high currents required make programmed regulation using tubes unattractive. A satisfactory solution for obtaining a uniform kick is the use of a pulse line whose impedance may be adjusted as a function of length. However, it is not necessary that all pulse lines be adjustable, as the integral of the magnetic field rather than the value of the magnetic field must be kept constant. Lumped pulse lines or commercial HV cables may be used to supply power to most of the modules and a few adjustable pulse lines may be used to correct the kick. An adjustable pulse line has been tentatively set as a 6-in-OD, 4½-in-ID coax divided into 30 sections. Each section is filled with silicone oil, which is available with dielectric constants ranging continuously from 2.2 to 2.8 and which has excellent high-voltage and high-frequency properties An analysis of a transmission line into which a length of line of another impedance is inserted shows that, to first order in the difference in impedances, a pulse is transmitted through this line without distortion, and that such a line used as a pulse-forming network will produce a current $I = V/Z_o(z)[t-2(z/v)]$ through the short-circuited magnet, where z is distance along the pulse line. A convergent process for flattening out the kick is to integrate the magnetic field along the direction of the beam and then change the impedance of the section of line which corresponds to an error in the kick-versus-time picture.

Conclusion

The study of the kicker magnets has been one of feasiblity, and shows that an extraction system for 100% efficient beam transfer from the booster to the main ring is possible. One of the major problems is the simultaneous firing of a high number of spark gaps with time jitter under 2 ns. It is believed that this problem can be solved with the proposed trigger method. The required 1% kick tolerance can be obtained by using tapered pulse-forming networks.

The numbers used for the booster extraction magnet were given to illustrate the problem and might change with further investigations and the final layout of the injector synchrotron. A greater total length for the magnets and a reduced total kick would be desirable, leading to a higher impedance and a smaller number of modules.

Acknowledgments

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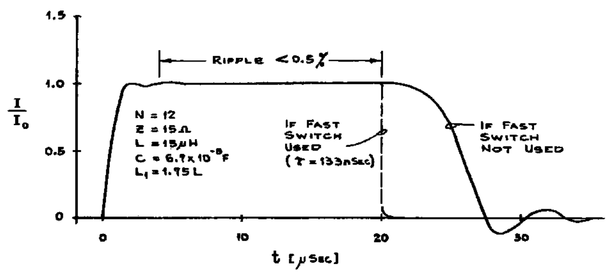

Fig. 1. Current pulse through magnet from 12-section lumped line.

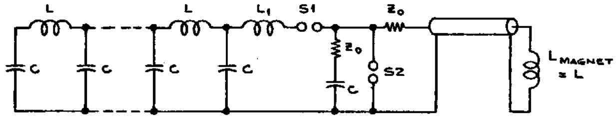

Fig. 2. Circuit diagram for booster injection kicker magnet.

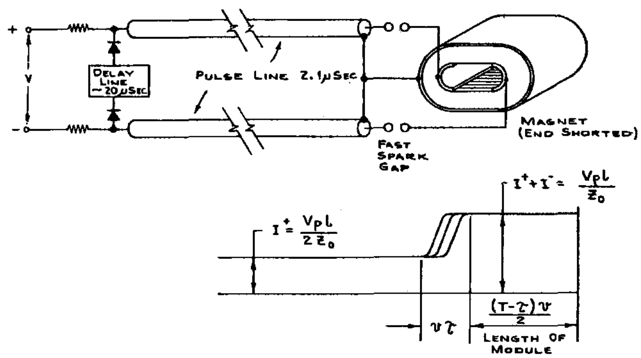

Fig. 3. Schematic circuit of booster extraction system.

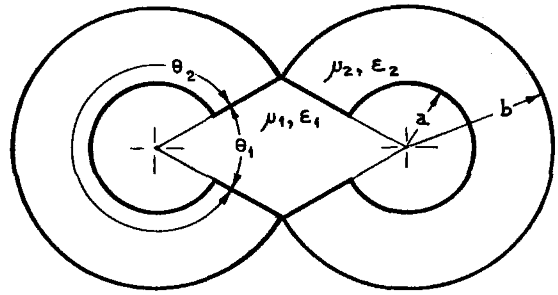

Fig. 4. Geometry of extraction magnet as used for calculations.

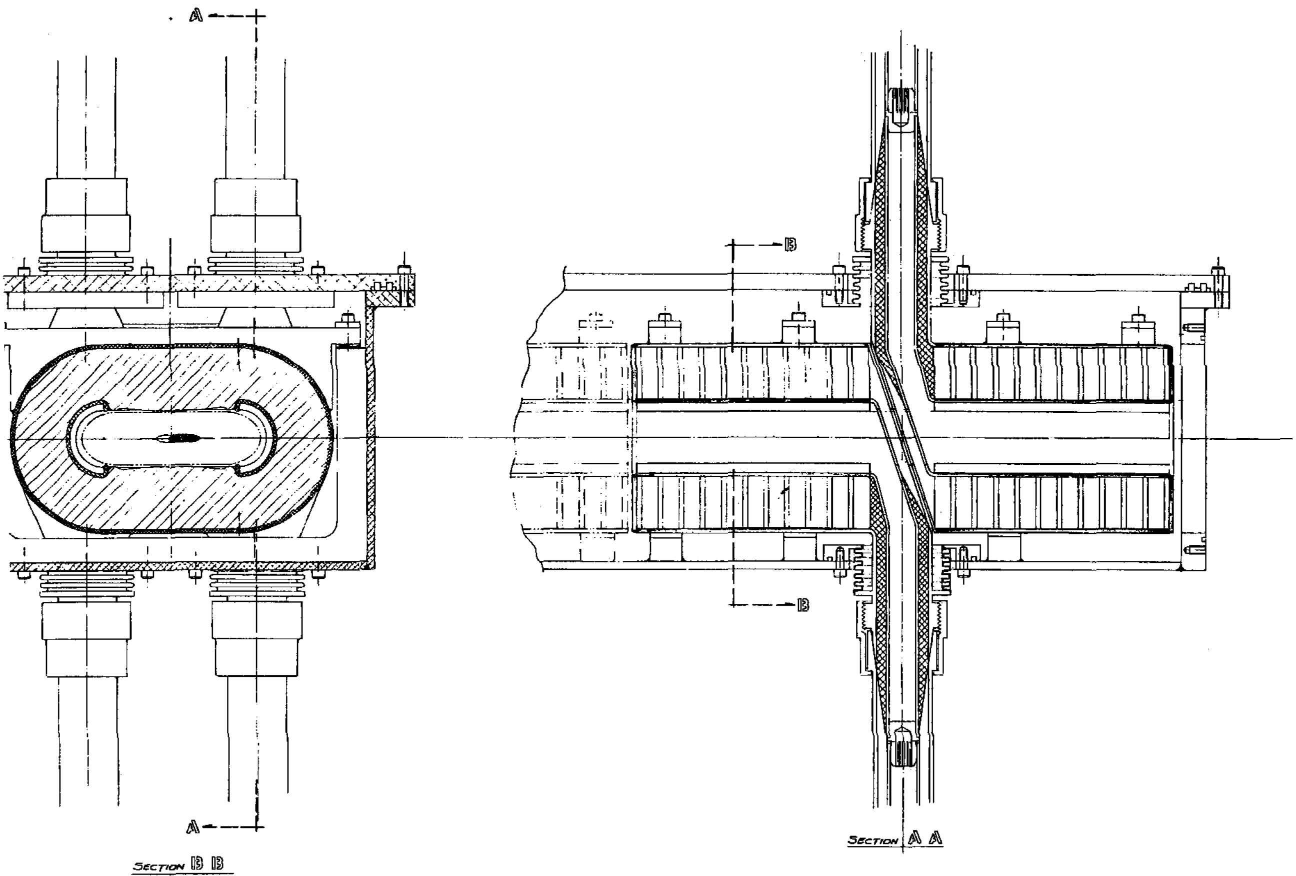

Fig. 5. Fast kicker magnet.