KICKER MAGNETS FOR THE ADVANCED LIGHT SOURCE*

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INTRODUCTION

Fast pulsed kicker magnets will be used in the Advanced Light Source (ALS) Booster to accept injected 50 Mev electrons from the Source Linac and then eject the full energy 1.5 Gev beam into the Storage Ring. Their design has incorporated a number of unique elements to achieve the tight requirements for efficient beam transfer.

The booster orbit time of 250 ns and a maximum of 12 electron bunches, spaced 8 ns apart, defines the minimum required injection and extraction kicker magnet flat top time. A 100 ns injection fall time and extraction rise time were selected, with the 50 ns balance left for pulse settling and timing errors. The injected beam is deflected 59 mrad and the extracted beam 4 mrad. This can be accomplished with a 0.5 meter 200 gauss magnet for injection and a 1 meter 200 gauss magnet for extraction. A uniformity of +/- 0.5% temporally and spatially is required of the nominal 200 gauss flat top field to maintain a low loss/dispersion system.

Design goals

The main design goal for the kicker magnets is to produce the desired beam deflection without introducing any other beam perturbations. The magnets should also be low cost, reliable, and easily maintained. Meeting those goals required that 1) The magnet be outside the vacuum system, ie, a ceramic beam pipe be used, 2) The design of the magnets be identical except for their lengths. 3) The drivers be identical, with a minimum number of required parameter adjustments, and 4) The driving high voltage be kept below 20 kV.

SYSTEM DESIGN

Design considerations

The prevalent design for kicker magnets uses a terminated transmission line scheme. A high voltage pulse from a delay line is applied to a matching magnet impedance which in turn is terminated resistively with the characteristic value [1-4]. This requires that twice the voltage required by the risetime constraint be applied to the pulse forming network (PFN). Using a lumped LC magnet with a matching capacitor eliminates the magnet terminating resistor [5]. Further, splitting the magnet magnetically longitudinally, such that each half of the magnet is independent, reduces the inductance by a factor of 4, reduces the beam coupling [6], and provides a more uniform central magnetic field.

Ideally, all of the magnetic energy should reside in the air gap of the magnet. A high permeability ferrite return path makes this ideal condition true within 5%. The inductance of the magnet per unit length is given by,

$$L = n^2 u\, w/h$$

Where
L = Henry per meter
u = 1.257e-6
w = Width of gap in meters
h = Height of gap in meters
n = Number of turns

The half magnet gives 970 nH/m.

The maximum permissible system time constant is determined by the total required risetime divided by the settling accuracy time constant. 4.6 system time constants are required to settle to +/- 0.5% accuracy. The system time constant (T) must be less than or equal to 22 ns.

The magnet's time constant is given by

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

Where
L = magnet inductance in Henrys
C = magnet capacitance in Farads

A 0.5 m magnet has 490 nH which permits 1.0 nF of capacitance. A 200 gauss field requires 700 amps and a 15.5 kV initial pulse amplitude to rise in 100 ns. These values are just fine for the extractor kicker magnet. However, the fall time is a minimum of 1.414 times the risetime, but is reduced depending on the reflection coefficient of the pulse forming network. The falltime of the injector kicker magnet is its important time parameter. Dividing it into 0.25 m sections would give it a falltime less than 100 ns.

Magnets

Both the injection and extraction kickers consist of two magnets, each pair 0.25 m and 0.5 m long respectively. The magnets are identical, except for their length, with 44 mm by 68 mm apertures. Magnetically, the magnets are divided in two with a conductive septum down their length, top and bottom. This effectively reduces the inductive coupling between the driving conductors as well as reducing beam coupling and losses.

Heavy copper walls make up the outside housing, providing an image current return, shielding, and mechanical support for the return path ferrite and insulation [Fig.(1)]. The conductors are held in position by polystyrene slabs, which rest against the ferrite. The low dielectric constant polystyrene sheets also reduce the conductor to ground capacitance while being resistant to radiation damage. The ferrite has a relative dielectric constant of 13, while the styrene's is 2.1. Using a thick section between the ferrite and conductor reduces the capacitance approximately by half.

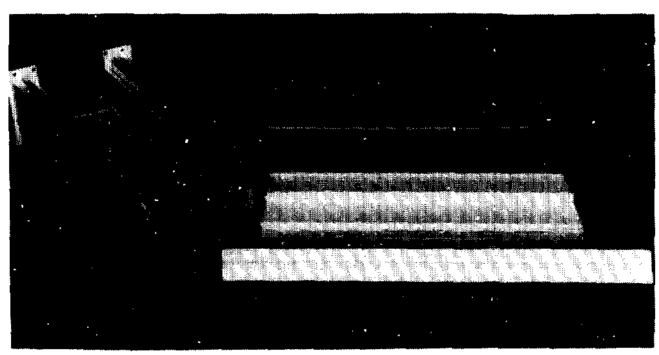

Fig.(1) Injector magnet test model with the top removed. The top ferrite is at the rear with the polystyrene spacers and copper top forward.

A ferrite was chosen to meet three requirements, 1) provide a minimum return path reluctance for a given section, ie, high permeability, 2) have a maximum flux density of > 3000 gauss, and 3) have a steeply increasing loss tangent beyond the peak frequency region to provide good damping properties. Computer modeling of the magnet showed that a 5 mm thick ferrite with 6.5 mm thick polystyrene spacer would meet the field uniformity requirement of 0.5% and minimize the conductor capacitance. The flux density at the corners however exceeded 2800 gauss.

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Testing the model by varying the permeability of the ferrite indicated a permeability of > 800 would be required to give > 95% of the field achieved with an infinite permeable ferrite. CMD5005 ferrite [7] which has an initial permeability of 1500, a maximum permeability of 4500 gauss and a .01 loss factor at 10 Mhz was selected.

Mechanically the magnets have three very different materials. (1) Copper, ductile, with a linear expansion coefficient(T.C.) of 1.6e-5/deg.C. (2) Ferrite, brittle, with a T.C. of 8.0e-6/deg.C. and (3) polystyrene, ductile, with a T.C. of 7.0e-5/deg.C. To alleviate fracturing the ferrite due to thermal expansion or over-tightening during assembly, constant force plunger pins are used to hold the ferrite firmly away from the outer copper shell. The two halves of the magnet push against the two septums in the top and bottom shell plates thereby giving a well defined mechanical center.

Driver

A hydrogen thyratron is used to switch a charged coaxial delay line to a one to one dual secondary bifilar transformer which drives each side of the magnet with opposite signed current [Fig.(2)]. An adjustable peaking capacitance is used to trim the flattop and provide an impedance match to the transformer.

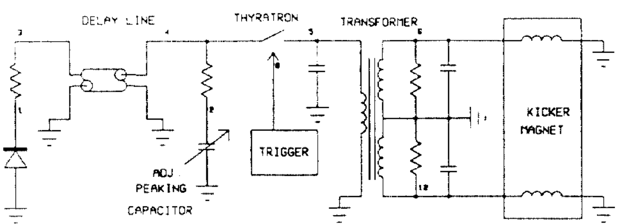

Fig. (2) Driver block diagram.

The flattop current is provided by a PFN made of six RG-213 coaxial cables which were individually cut to 150 ns electrical length, connected in parallel. One end of the cable bundle connects to a termination box which houses the charging current limiting resistors and the back terminating network. Adjusting the value of the back terminating resistance to be greater than the coax characteristic impedance provides the means to sweep out the thyratron plasma charge via a negative pulse. This strategy permits turning off the tube's conduction in 10's of nanoseconds.

The opposite end of the coax bundle is attached to the tube anode and a peaking network consisting of a resistance in series with an adjustable capacitor. This network supplies the initial additional charge to the stray capacitances of the tube cathode and transformer to provide a rapid current risetime.

The transformer is a tightly coupled 1:1:1, with a ferrite window core. The ferrite only provides sufficient inductance to minimize the droop of the flattop pulse to less than 0.25%. It is insulated with 3 mm polystyrene sheet then vacuum impregnated to eliminate any between winding air spaces.

The thyratron trigger pulse, first grid bias, filament and reservoir leads are multiturn wrapped through a ferrite toroid. This isolates the high voltage drive pulse from the supply circuits.

Mechanical layout

The mechanical layout of the interface between the driver, transformer, and magnet is crucial to the systems performance. Any additional series inductance and resistance or parallel capacitance will degrade the system risetime. The skin effect increases a conductors resistance. Wide conductors are used for all connections and in the transformer windings to reduce the skin effect while lowering series inductance. All conductors will be gold plated to prevent oxidation. Short leads further reduce the risetime effects.

Minimizing the leads gave a compact design [Fig.(3)] with the thyatron sitting with the transformer on top of the magnet. The tube is above the plane of the beam, so false triggering should be absent.

The tube housing is a coaxial pipe, with the delay lines and peaking network passing through an end cap and attaching to the anode. A vertical tube is attached to a cooling fan.

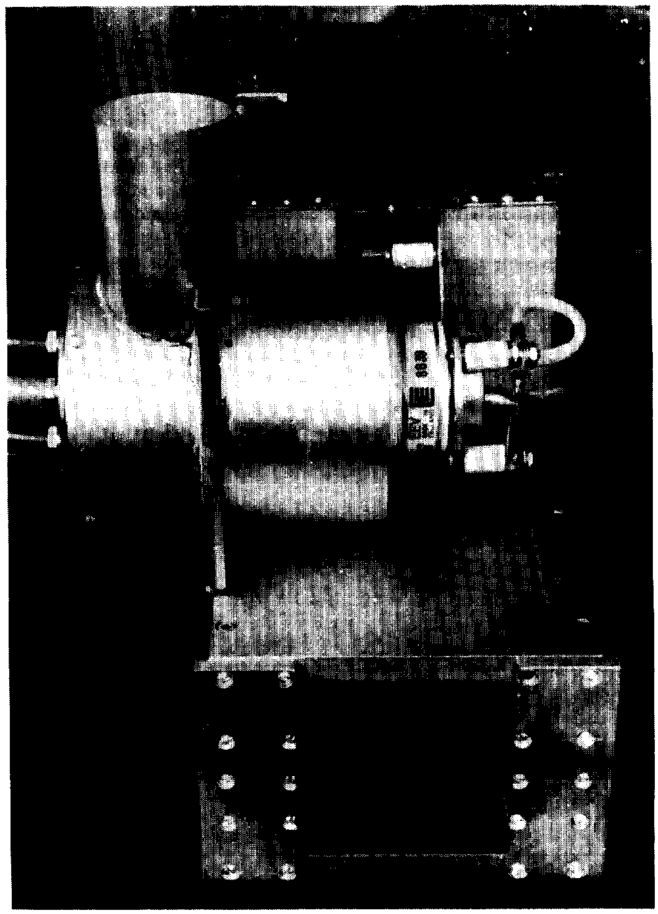

Fig.(3) End of magnet with delay lines, thyratron and transformer. Conductor current return shorting blocks and conductive septums at magnet midline are visible on magnet end.

EXPERIMENTAL SETUP

Magnet configuration

Test magnets for both the injection and extraction have been built. Network analyzer measurements of the magnet alone and the transformer coupled to the magnet indicate the inductances are above the calculated values, but the parallel capacitance is below the maximum allowable value. The measured values are 250 pF for the extractor magnet and 150 pF for the injector magnet. This is the result of placing the polystryene spacers in the magnet.

The transformer used on the extractor adds about 500 pF and 200 nH to the circuit. Combining the tube turn-on time (approx.10 ns) and the transformer contributions, a 0 to 99% risetime of 120+ ns is expected. The measurements shown are for this extractor magnet configuration.

The thyratron is a 20 kV rated ceramic tetrode with the smallest anode volume capable of carrying 2.4 kA. A plasma is maintained between grid 1 and the cathode. A reverse bias of -160 Vdc between grid 2 and 1 prevents the tube from firing. A +600 volt 10 ns risetime pulse, 50 ns wide triggers the tube. The measured anode delay varies for different tubes between 120 to 180 ns, but is constant for a given tube. The anode delay jitter is < 2 ns. This grid 2 biasing arrangement combined with the negative reflected anode pulse effectively turns off the tube in 10 to 20 ns. The expected plasma life time according to the manufacturer's data is in the microsecond range.

Measurement equipment

A lucite insert was made to fit into the magnet gap with three horizontal slots, spaced 12 mm above and below and on the center line. Lucite plates which held a probe coil where used to repeatedly position the probe at the slot center line and at +/- 12 mm and +/- 24 mm. A mapping of the field strength was performed by inserting the probe to fixed index marks on the rigid coax output line the coil was attached to.

B dot was measured using a 6mm diameter 4 turn coil. The coil has a 6 ns time constant into 50 ohms. The coil output was sampled at a 1 Ghz rate for 1024 samples with a 10 bit digitizer. The magnetic field strength was calculated by integrating the sampled data and scaling from the magnetic field calibration factor of the probe coil.

TEST RESULTS

Field risetime and flattop

The first extractor magnet tests gave a 0-99% risetime of 130 ns [Fig. (4)]. This is within the calculated value, but slightly longer than the desired value. The added risetime is dominantly due to the high transformer inductance and capacitance values. A second transformer was built which reduces in half the inductance and capacitance. The new transformer was installed on the injector magnet model. With the new transformer the extractor magnet field should rise in < 115 ns. The measured 0-99% risetime for the injector magnet was < 80 ns.

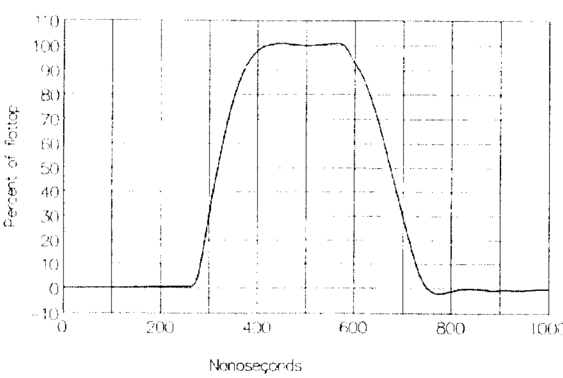

Fig.(4) Magnetic field waveform for extractor magnet model. Waveform is an average of 8 pulses with a 13 kV charging voltage.

Figure (5) is an expansion of the flattop region of the figure (4) field waveform. The effect of the peaking ring is evident, but the field temporally is within +/- 0.5%. Achieving this field accuracy requires careful attention to stray inductances and capacitances. The coupling effects of the adjacent sister magnet firing have yet to be determined.

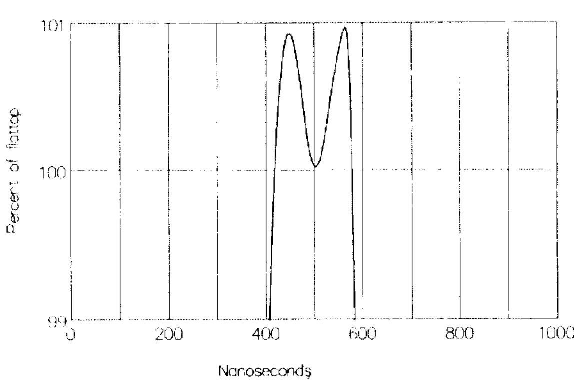

Fig.(5) Magnetic field during flattop time. Waveform is an expanded view of fig.(4).

Field uniformity

Fig.(6) is the plots of the normalize magnetic field values measured 75 ns after reaching flattop conditions. The time the sample value was taken is reference to the system trigger time zero.

The probe coil was located in the volume of the magnet by the lucite fixture previously described. Values were measured in three horizontal planes. The magnet midline and +/- 12 mm. The horizontal planes were sampled at their midline, +20 mm and +40 mm across the aperture at 5 point along its length. The length locations where the edge, 38 mm , 76 mm , 152 mm, and 267 mm into the magnet. The 267 mm point is the center of the magnet.

The uniformity of the field is better than the +/- 0.5% required over the central volume of the magnet.

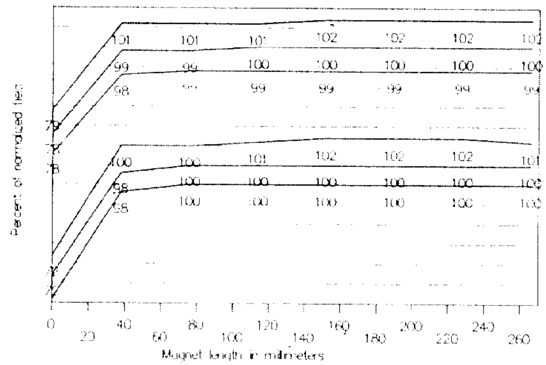

Fig. (6) Field uniformity for the middle and top planes in extractor magnet model. The lower three traces are the middle plane, starting with the center line, 20 mm and 40 mm toward the conductor. The top three traces are the top plane starting at the center line. The field rises as the conductor is approched. Pulse amplitude was like fig. (4). Values used where the flattop temporal midpoint.

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