FAST AND RELIABLE KICKER MAGNETS
FOR THE SLC DAMPING RINGS*

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ABSTRACT

The design, construction, and operation of a kicker magnet with superior electromagnetic performance and greatly improved radiation tolerance is described. A short flux return of high mu ferrite improves the field strength and linearity with current, and novel metallic field-confining structures minimize the inductance. An 8-cell structure with capacitance integrated into each cell makes the magnet a nearly perfect transmission line. The capacitor dielectric is 1 cm thick alumina-loaded epoxy, processed to eliminate air voids, and cast in a multiple step procedure developed to circumvent epoxy shrinkage. The magnet operates with pulses of up to 40 kV and 3.2 kA at 120 Hz, with magnet transit times of less than 35 nsec and field rise and fall times of less than 60 nsec.

I. OLD AND NEW MAGNET DESIGNS

The Stanford Linear Collider (SLC) uses two 1.2 GeV damping rings to reduce the emittance of the e^+ and e^- bunches before acceleration in the main linac. Each damping ring requires an injection and extraction kicker magnet with rise and fall times of less than 60 nsec. The thyratron pulsers have rise/fall times of at best 25 nsec, so the magnet contribution must not exceed 35 nsec. The e^- kickers must inject or extract both bunches on a single pulse, requiring a 60 nsec flat top and two e^- extraction kicks must be different by less than 10^{-3}. These requirements are best met by a matched and terminated transmission line magnet. The kickers are outside of 21 mm diameter ceramic beam pipes, and the space allocated is less than 50 cm long. Voltages of up to 40 kV are required. There are substantial beam losses near the kicker magnets, with localized radiation levels of order 10^8 rads.

There have been two generations of SLC kicker magnets [1,2]. The first generation of SLC kicker magnets suffered from high voltage breakdown through the joints between the ferrite tiles used for both flux return and capacitor dielectric. They also had poor pulse quality, behaving more like LC elements than transmission lines, and were not suitable for extracting two e^- bunches on a single pulse. In the second generation of SLC kicker

magnets, the capacitance was provided by a 2 mm thick layer of RTV silicone rubber between the center conductor and grounded aluminum segments containing large slotted ferrite flux return cores. The RTV also became brittle upon exposure to radiation, then cracked when thermally cycled. In some locations the lifetime averaged as low as 10 days. There was substantial stray inductance due to the distance between the center conductor and the beam pipe. A ferrite advertised as low-mu was used, for low inductance (but low kick per ampere) but the mu at operating current levels was substantially higher, leading to a higher inductance and mismatch. The second generation could be used for extracting two e^- bunches on a single pulse, but only by shaping the current pulse to compensate for the mismatch of the magnet.

A new kicker magnet has been designed to overcome these shortcomings. It retains the segmented LC circuit and separation between flux return and capacitance functions of the second generation magnet, but eliminates the nonlinearity and subsequent impedance mismatch by using a short flux return path of high mu ferrite. It improves the HV breakdown and radiation damage performance by using thicker dielectric of alumina-loaded epoxy. The required capacitor surface area is obtained by radial plates. The stray inductance is reduced by extending the center conductor to one side of the beam pipe, forcing all the flux to enter the beam pipe. The magnet has 8 LC cells, with 6.5 cm diameter, 4 cm long ferrite cores in each cell. The center conductor is 1.9 cm diameter, with 25 cm diameter, 1.2 cm thick radial capacitor plates. There is a 5 mm thick aluminum cup attached to each HV plate that surrounds the ferrite core. The ground plates are 29 cm diameter, 1.2 cm thick, and have an 11.5 cm hole providing clearance from the ferrite cup. The ground plates are attached to the cylindrical outer conductor. The capacitor dielectric is 1 cm thick alumina-loaded epoxy. The plates have rounded edges, and are thinned elsewhere to increase the clearance at the edges of the other plates. There is a 30° wedge removed from the magnet to allow it to be installed over the beam pipe. The field enhancement from the resulting plate edges is ameliorated by making the cut in the HV plate at a larger angle and the cut in the ground plate a wider slot, so the enhancements only reinforce in a limited region. After the magnet is attached to the beam pipe, a wedge is inserted to fill the gap. The wedge contains a ground electrode that forces stray magnetic field to go through the beam pipe. See Figure 1.
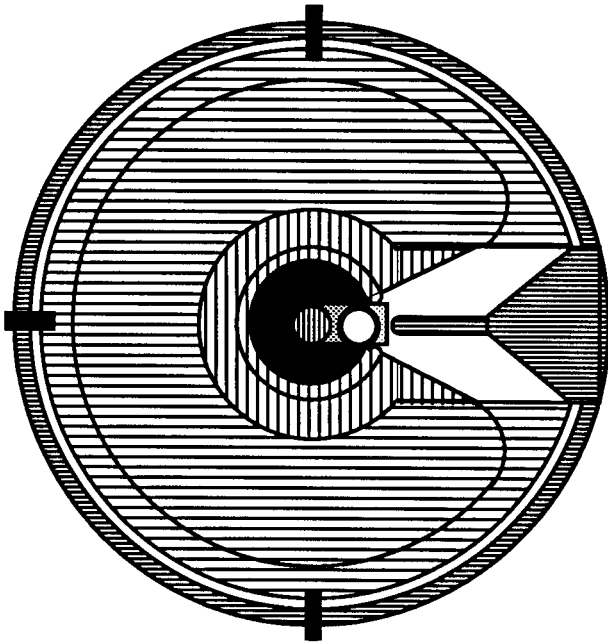

Figure 1: Cross-section end view of epoxy kicker magnet. HV plate is vertically hatched, and is largely hidden behind the horizontally hatched ground plate. The beam pipe is just to the right of center. The wedge insert is farther right.

II. EPOXY DIELECTRIC TECHNOLOGY

Several mineral-loaded epoxies were chosen for evaluation [3]. They have higher viscosity than unfilled epoxies, but have higher dielectric constants, are less brittle, and have greater radiation tolerance. A pot life of a few hours is required. The curing reaction is exothermic and accelerates with temperature so epoxies with cure times of less than a day tend to suffer thermal runaway.

Vacuum degassing is required not only to remove the bubbles introduced during mixing, but also dissolved gas that may come out of solution during shrinkage. Not all of the dissolved gas comes out during the initial froth stage, and agitation under vacuum is necessary [4].

The products of the epoxy curing reaction have a volume 3-5% less than the reactants. If a rigid hollow mold is filled with epoxy, the epoxy will not fill the volume after it is cured. Bubbles will grow as the epoxy shrinks. Shrinkage reduces the internal pressure, which can form spontaneous bubbles, or suck air into the mold. Epoxy may pull away from concave surfaces as it cures, or debond or crack later. Any of the above problems would be fatal in our high-voltage dielectric application. Epoxies with high filler content shrink less by total volume. Some epoxy chemistries remain liquid through a larger fraction (but not all) of the shrinkage.

Epoxy cured in a shallow open mold displays few pathologies because the shrinkage takes place by motion of the surface. Adhesion to the mold is good, particularly if the surface is sandblasted. Adhesion inside closed molds can be good if the mold is designed to accommodate the shrinkage by deforming. Epoxy can also be cast in stages. Each stage of the cure can shrink separately, which allows much better control of the results of shrinkage.

III. MAGNET CONSTRUCTION

The flux return cores are CMD-5005 nickel-zinc ferrite. The HV capacitor plates with center conductor stalk and ferrite cup, and the ground plates, are each machined from single pieces of aluminum. The plates are sandblasted for adhesion, then degreased. A cell consisting of a ferrite core, an HV plate, and a ground plate is cast in a closed mold. The top plate of the mold slides on an O-ring seal to allow for shrinkage. The mold is polished and treated with mold-release compound. A wedge-shaped mold-insert keeps epoxy out of the beam pipe region. The scars from fill and overflow hose fittings occur on the epoxy that is removed in the wedge region.

The epoxy used is Conapoxy FR-1727, which is 50% aluminum oxide powder by weight, and matches the thermal expansion coefficient of aluminum. It bonds well and is very resistant to fracture. However it is quite viscous, and will suffer thermal runaway if the mixing temperature is too high. The epoxy is mixed, degassed to a few Torr while being agitated, then transferred by air pressure on the epoxy surface into two molds per epoxy batch. The molds are at 10 Torr during transfer, and are pressurized to 5 atmospheres during cure. Finished magnet cells have both plates and the ferrite encapsulated in epoxy, with only the stalk ends of the HV plate and the edge of the ground plate exposed.

The magnet end-cells are aluminum dishes with 3 cm thick high voltage plates for the cable connections. Polished and tapered aluminum mold inserts form cavities where the cable dielectrics plug in. The cable ground braids attach to the dish. A polished metal wedge keeps epoxy out of the beam pipe region. The end-cell dishes and plates are sandblasted, degreased, and filled with epoxy, then cured with a free surface. One end-cell is also has a ferrite core and ground plate, and requires a larger epoxy volume, so it is filled partially, cured, then filled the rest of the way.

Before being assembled into a complete magnet, the cells and end-cells are high-voltage tested, sandblasted, and degreased. One end-cell is placed on a flat surface, and a metal rod is inserted vertically in its center conductor. Magnet cells are then slid onto the rod, which provides electrical contact between the cells. There are small O-rings on the center conductor stalks, which both seal epoxy away from the rod, and allow the cells to slide along the rod without touching as the epoxy shrinks. An aluminum

cylinder jacket (with a 30° wedge missing) is slid over the outside of the stack, then the other end-cell is added to the top. The jacket is held away from the end-cells by small rubber bumpers, and sealed to them by tape. There is about 2 mm of clearance between the jacket and the edges of the ground plates, and more between the edge of the cell epoxy and the jacket. This allows the cells to move during shrinkage without binding. As the epoxy in this volume shrinks, the radius of the jacket can decrease by narrowing the 30° slightly.

The aluminum electrode that forces flux to go through the beam pipe is inserted into the stack, with inorganic Mycalex insulators on each end. A full-length metal wedge is inserted into the stack, to align the cells and to exclude epoxy from the beam pipe region. An overflow well is caulked onto the jacket over the wedge region. The magnet is turned on its side with the wedge facing up for final potting. The epoxy is introduced through a fitting in the jacket and opposite the wedge. A notch in the ground plates allows the epoxy to flow from cell to cell. The epoxy used is Epic Resins R-1055/H-5039, which is 50% silica filled, has low viscosity and long pot life, and remains liquid for most of its shrinkage. The magnet is filled under vacuum, and cured under pressure.

After the epoxy has cured, screws are inserted through the jacket to make contact with the ground plates. An aluminum strap makes electrical contact between the end-cells and the jacket. The piece that fills the wedge is cast epoxy with a Mycalex insulating tip touching the beam pipe and an aluminum field-confining conductor.

VI. MAGNET PERFORMANCE

The performance of the epoxy kicker magnets themselves has been excellent. After the width of the flux-excluding conductor was adjusted, the magnets behaved like matched transmission lines, with negligible ringing or other imperfection. The transit time is less than 35 nsec. No magnet has ever developed internal HV breakdown or radiation damage during an SLC running year. In building over 20 magnets, only a few cells have been rejected due to potting mishaps, and a few more have failed HV testing before final potting. Two magnets have had minor final potting mishaps; both were repairable.

There have been a number of serious compatibility problems with the ceramic beam pipes. A thin metallic coating inside provides high frequency isolation between the beam and the magnet. This coating is grounded at one end, with a ceramic insulator disk at the other end so the coating is not a shorted turn through the magnet. These beam pipes survived many years and many old-type kicker magnet replacements, although in some cases the coating was no longer grounded.

After several months of operation in 1992 with the first two epoxy magnets, both beam pipes developed pinhole leaks due to corrosion near the ceramic gap, caused by ozone from corona discharge. New beam pipes were made, with better grounding of the internal coating to reduce the voltage on the gap, and epoxy encapsulation of the gap to exclude air from the high-field region. The 1993 SLC run was started with all epoxy magnets and some of the new beam pipes. After only a few weeks, one of the new beam pipes fractured at the ground end due to arcing from the magnet to ground along the ceramic. A few weeks later, another new pipe not only fractured at the grounded end, but the epoxy encapsulation of the ceramic gap end caught fire! In response to the fracturing, beam pipes were tested under vacuum along with magnets, and were installed without being removed from their magnets. Also, the coating was disconnected from the ground end of the pipes by abrading a short length of it away. These pipes survived the rest of the 1993 run without fracturing. Another pipe did fracture in 1993, but with a second-generation magnet. There was also another ceramic gap leak in 1993 when the epoxy encapsulation melted.

The present beam pipes have ceramic gaps at both ends, and the gap has been redesigned to withstand the voltage without epoxy encapsulation. There were no more pinhole leaks during the long 1994-5 SLC run. There was a beam pipe fracture, which appears to have been caused by arcing inside the beam pipe at the sliding metal fingers of a bellows shield near the ceramic gap. Since other bellows shields failed elsewhere in the damping rings in 1994-5, an improved shield is being designed, which will be integrated into the kicker beam pipes when it is available.

V. REFERENCES

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