Operational Experience with SLC Damping Ring Kicker Magnets*

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Abstract

The damping ring kickers for the SLAC Linear Collider must provide 7 mrad kicks to 1.2 GeV beams with 60 nsec rise and fall times and fit in a 50 cm length around a 21 mm diameter ceramic beam pipe. This requires that they operate at up to 40 KV. The construction and operation of two types of quasi-coaxial ferrite magnet potted with RTV silicone rubber is discussed. Production yield has been improved by changes in RTV degassing, transfer, and cure. Operation lifetime is dominated by voltage, radiation, and thermal cycling.

I. DESIGN CONSIDERATIONS

The SLAC Linear Collider (SLC) damping rings are small 1.2 GeV synchrotrons used to reduce the emittance of *e+* and *e-* bunches by radiation damping before they are accelerated in the main linac to 50 GeV and collided. The damping ring revolution time is only 120 nsec, and 2 bunches circulate in each ring, so the kicker rise and fall times must be less than 60 nsec. The injection and extraction straight sections provide no damping so their length was minimized, thus a 7 mrad kick is required to clear the injection and extraction septa. The kickers are located where ring bends were omitted for dispersion suppression. The energy, angle, aperture, and length requirements imply a current of order 2000 A, and the energy, angle, aperture, and time requirements determine a voltage of order 30 KV.

The kickers were intended to be terminated transmission lines with the beam in the gap of the ferrite flux return [1,2]. Ferrite-free current strip kickers would require nearly twice the current of ferrite kickers. Transmission line structures give the optimum pulse response. The magnet pulse is provided by several RG-220 coaxial cables in parallel, and another set of cables carries the pulse to a matched terminating load. The kickers are in the air outside an alumina ceramic beam pipe with a Kovar inner coating (about 1 ohm/square) that prevents the ferrite from being heated by beam image currents, and keeps the ferrite from loading the beam. The ceramic is 50 cm long, 21 mm diameter with 3 mm walls, with a capacitive choke joint at one end to prevent the coating from forming a shorted turn in the magnet, while still allowing beam image currents to pass. Several hundred watts can be dissipated in the coating by image currents and magnet eddy currents.

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II. SHORT PULSE MAGNETS

The first type of SLC damping ring kicker magnet (Fig. 1) uses ferrite both as flux return and as capacitor dielectric to form a continuous quasi-coaxial structure with a design impedance of 16.7 ohms. An aluminum slab center conductor is surrounded by ferrite tiles inside a rectangular aluminum outer conductor. The beam pipe lies in a gap in the ferrite parallel to the slab 23 mm square and 33 cm long. The flattened geometry is necessary to provide sufficient surface area for the capacitance through the 19 mm thick ferrite tiles to balance the inductance of the gap. High permeability ferrite must be used because the flux return path is so long compared to the gap height. TDK K6A and Ferroxcube 4C4 nickel-zinc ferrite have been used in the past, and Ceramic Magnetics CMD-5005 is presently used. Manganese-zinc ferrite has higher permeability but is too slow due to its conductivity.

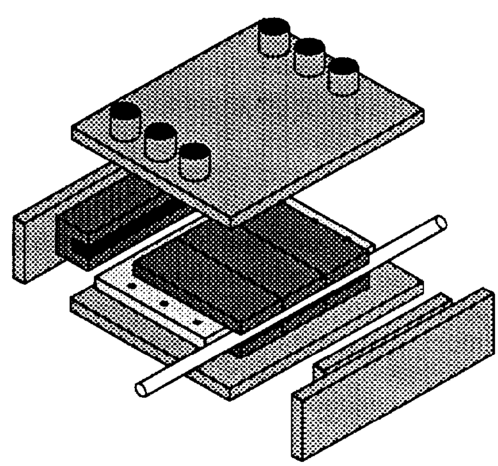

Figure 1. Exploded view of short pulse magnet

The largest feasible ferrite tiles are used to minimize the number of joints between tiles, where failures typically occur. The ferrite piece opposite the beam pipe (the spline) has a slot ground into it for the center conductor slab, to recess the high field corners of the slab away from the joints between ferrites. Silicone grease is applied on all sides of the ferrites before they are squeezed together during assembly to exclude air. The

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ferrite and slab dimensions must match well to prevent voids between parts or ferrite breakage. The ends of the magnet are potted with General Electric RTV-615 silicone rubber to exclude air. The RTV is vacuum degassed but poured at atmospheric pressure (there is ample opportunity for any bubbles to rise to the surface before cure). The aluminum surfaces are primed, but the ferrite is usually covered with excess grease and the RTV does not adhere well.

There have been no bulk dielectric failures in the thick RTV insulation of this type of magnet, but there have been many failures at the poorly bonded ferrite-RTV joint, and in joints between tiles. Air in the joints forms corona which erodes the ferrite and leads to breakdown. Failed magnets are disassembled, cleaned, reassembled, and repotted. The ferrite tile corners tend to chip, but the void fills with grease when the magnet is reassembled. The grooved spline ferrite often breaks during disassembly, but can be glued back together. Magnets have been rebuilt with a short spline with no significant change in performance.

Three cables connect to Hugin contact bands in the center conductor slab where it extends beyond the ferrite at both ends, with ground braids clamped to cylinders on the outer conductor surface. Originally the cable insulation was inserted without any preparation into a cavity formed in the RTV during potting, but these connections had a high failure rate. Delrin plastic inserts are now potted into the ends to accept the cable insulation, which is tapered and greased to form an air-free connection. There have been no Delrin insert failures although there has been some corona damage.

The ceramic beam pipe with its grounded ends is separated from the high voltage on the center slab by a plastic insulator machined to match the pipe diameter, with a minimum thickness of 1.5 mm minimum. It is nevertheless necessary to apply grease to the beam pipe to prevent corona between the slab and the grounded coating inside the beam pipe. This grease tends to polymerize when irradiated, and makes it difficult to separate a failed magnet from the somewhat fragile ceramic beam pipe.

Since the structure has no LC cell boundaries it was expected to behave as a transmission line with a 25 nsec transit time and 16.7 ohm impedance up to frequencies determined by ferrite properties. However the output current pulse and the magnet field pulse resemble much more strongly those of a simple lumped LC circuit rather than a transmission line [3]. This was initially blamed on the ferrite, but is now understood to be a subtle effect of the continuous geometry and the beam pipe gap, which allows flux to travel the length of the magnet faster than the naive expectation. Because of this distortion, this type of magnet is used in the *e+* ring where a flat top is not needed and a short pulse is desired, resulting in the term short-pulse magnet.

III. LONG PULSE MAGNETS

Another type of kicker magnet (Fig. 2) was designed to produce a long flat pulse [4]. This design has 15 LC cells with ferrite toroids (5" ID, 8" OD, 1" thick) potted into aluminum holders. A slice and a gap is cut from the toroids leaving an effective 22 mm square aperture for the beam pipe. Magnets with a design impedance of 12.5 and 16.7 ohms have been made with Stackpole 2285 and Toshiba M4D21A nickel-zinc ferrite respectively. The capacitance to balance the gap inductance is obtained in the 2 mm between the large diameter aluminum center conductor and an aluminum shielding ring milled into the ferrite holder, filled with GE RTV-615.

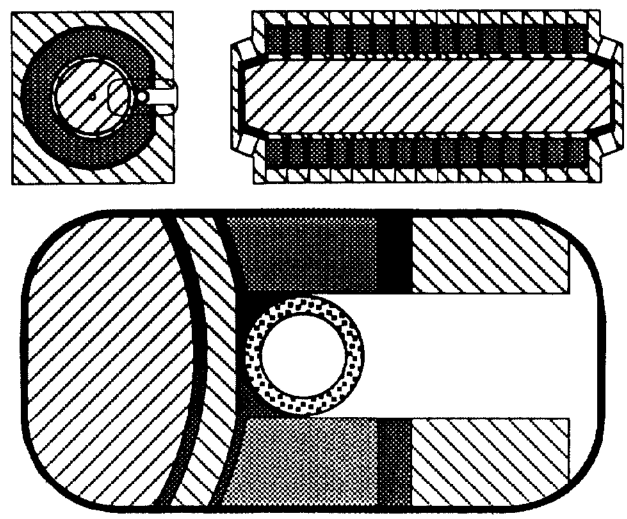

Figure 2. Cross sections of long pulse magnet with detail of region near beam pipe

The magnet stands on end in a vacuum vessel while RTV that has been vacuum degassed is introduced from the bottom. Bubbles were usually observed to rise into the overflow bowl. A significant fraction of the magnets failed initial testing, presumably because corona formed inside bubbles and eroded a path from high voltage to ground. The production yield has been improved greatly by several process improvements. The RTV is now agitated during vacuum degassing with an impeller on an O-ring sealed rotary feedthru, which promotes degassing by cavitation bubbling and bringing RTV from the bottom of the degassing vessel to the surface where gas can diffuse out. The magnet potting vessel is evacuated for transfer but pressurized to 5 atm during cure to compress and redissolve any bubbles. The RTV is cured at room temperature rather than in an oven so it will never be under tension from thermal contraction.

Failures in service are almost exclusively arcs through the thin RTV near the beam pipe near the upstream end of the magnet, and less often in the thick RTV in the upstream magnet end. The RTV is observed to become brittle and glassy after exposure to radiation, more so near the beam pipe. Failures are also more likely when turning back on after an interruption in SLC operations. The beam pipe coating is a source of heat, and RTV has a large thermal expansion coefficient, so we believe that thermal cycling of radiation damaged RTV causes cracking and failure. Radiation exposure is primarily from particle losses at injection rather than synchrotron radiation. The injector magnets receive a large dose from beam scraping on the septum upstream. The intervening bend magnet sprays particles with energy loss in one direction, and allows photons to escape from the pipe. The injector magnet was moved to the outside of the ring to protect the RTV near the beam pipe from beam spray, and the direct photon beam was absorbed by external shielding.

Magnet lifetime has been improved by magnet heaters with thermostats set somewhat above normal operating temperature. Changes in eddy current heating are minimized by keeping the pulse rate as constant as feasible, even during machine access periods. Failed magnets are disassembled using a special hole saw to cut the cells away from the center conductor. The ferrite is normally undamaged and left potted into its holder, although a few cells have had to be repotted or replaced. The center conductor, cells, and ends are cleaned, polished, primed, and repotted. Some magnets have been repotted over 6 times.

Direct electric fields from the center conductor are shielded from the beam pipe. However, dB/dt electric fields at the start and end of the pulse do appear between the coated ceramic and the grounded aluminum of the magnet, so grease must be used to prevent corona on the beam pipe, and polymerization of the grease complicates magnet replacement. The grease is now applied between a Kapton sheet and the beam pipe, but none between the pipe and the magnet. Instead there is a photoetched copper pattern on the Kapton that contacts the magnet which excludes air from high field regions and field from air regions, and also partially covers the ferrite. This reduces the magnet inductance and improves the pulse shape.

Four cables are connected at each magnet end, with tapered and greased insulation fitting into tapered cavities in the RTV. The cable center conductors angle in to the tapered ends of the magnet center conductor and are held by setscrews accessible through holes in the RTV that are later filled with grease. There have been some magnet failures associated with the setscrew arrangement. The cable ground braids are clamped to tubes at the magnet ends. The cables enter the magnet from awkward angles, and there have been cable failures from the tight bends, particularly since the cable polyethylene gets warm from the magnet heaters.

The aluminum ferrite holders prevent flux from travelling the length of the magnet, and the LC cell time constant is much shorter than the thyratron current pulse rise time, so long-pulse magnets made with Toshiba ferrite are transmission lines with very little current pulse distortion and an impedance close to 16.7 ohms [4]. The Stackpole ferrite has lower initial permeability, which was intended to reduce the magnet inductance at the expense of strength and produce a fast 12.5 ohm magnet. However the permeability increases with excitation (the magnets operate well below saturation), and the inductance approaches the gap-dominated value of 16.7 ohms. There is in fact little difference between Stackpole and Toshiba magnets at operating current. The increased transit time, and internal reflections from mismatch with the 12.5 ohm pulser and load, distort the field pulse and prevented 2 *e-* bunch SLC operation until the current pulse was shaped to compensate.

IV. Status and Prospects

Recent experience is consistent with a magnet lifetime at 120 Hz and increasing SLC beam intensity (and thus radiation levels) of about 8 running months. This still implies a failure on average every 2 months. Part of this improvement is due to operating at the minimum possible voltage, which requires the damping ring orbits to be displaced toward the septa. This tightens the tolerances for low-loss injection into the *e-* ring. It also reduces the aperture of the *e+* ring, with some loss of captured intensity. As the SLC beam intensity increases, the image current heating of the beam pipe is becoming important, and we are planning to stabilize the pipe temperature with a water-cooled metal bar to minimize thermal cycling of the RTV near the beam pipe.

A new magnet design is nearing production. It will use 1 cm thick epoxy as dielectric between large area plates to increase the voltage capability, no organic materials in high electric fields near the beam pipe, and small ferrite cores with metal separators and field shapers to reduce inductance for a fast transit time. Epoxy shrinks during cure (far more than does RTV) which has slowed progress. Potting tests have demonstrated that problems from epoxy shrinkage can be minimized by precasting cells in shrinkable molds, then potting cells together in a shrinkable structure. Tests of an electromagnetic mockup show good pulse performance. The goal of reliable operation at 40 KV will require careful attention to corona and electrical breakdown to the beampipe itself.

V. References

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