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KICKER SYSTEMS FOR THE STANFORD LINEAR COLLIDER*

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ABSTRACT The Stanford Linear Collider requires kicker magnet systems for damping ring injection and extraction, positron prodution, and final focus extraction. The design, construction, monitoring, and operation of high stability pulse chargers, fast thyratron pulsers and matched magnets are discussed. Progress on kicker system upgrades for SLC luminosity improvement is reported.

1. INTRODUCTION

The Stanford Linear Collider (SLC) produces intense ≈50 GeV e^- and e^+ bunches which are focussed to small spots and collided. Small synchrotrons (damping rings) are used to reduce the bunch emittances before final acceleration in a common linac. Fast kicker magnets are used for damping ring injection and extraction. An e^- bunch for e^+ production is accelerated in the same linac then diverted to the e^+ source by another fast kicker. After colliding, the e^- and e^+ bunches are directed out of the common final focus to dumps by other kickers.

To maximize the synchrotron radiation damping rate, the damping ring period is only 120 nsec. Ideally, the e^- ring contains two bunches 60 nsec apart, injected and extracted by a single magnet pulse. This requires a 60 nsec rise time for the extractor, a 60 nsec fall time for the extractor, and a 60 nsec flat top for both. In the e^+ ring, only one bunch at a time is injected or extracted, but to allow two bunches to damp at once, both injector and extractor must have both 60 nsec rise and fall times. The e^+ production system kicker also requires a 60 nsec rise time. The final focus kickers have much looser requirements on risetime and stability. They are similar to storage ring kicker systems, have proven rather reliable, and will not be further discussed here.

A short-pulse kicker system was designed at SLAC and used for early damping ring commissioning.[1] Another system to make long pulses for the e^- ring was developed for the SLC at Fermilab.[2] During the first attempts at physics running in 1988, it became clear that even the Fermilab system did not produce sufficiently flat pulses for two bunch extraction from the e^- ring. There were also severe reliability problems with the damping ring kicker magnets and pulsers, such that

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kickers were the largest single source of SLC downtime in 1988. There has been a large effort to understand and solve the reliability and quality difficulties.[3]

2. MAGNETS

The short-pulse kicker magnets are continuous transmission-line structures with ferrite used as both magnetic flux return and capacitor dielectric. This dual role of the ferrite requires a large area and volume, so separate slabs of ferrite are grouted together with silicone grease. Failures tend to be from tracks through the silicone grease between ferrite slabs, or arcs at the connectors, or along surfaces where the silicone rubber potting in the magnet ends has pulled away from the ferrite.

The magnets designed for long pulses (although sometimes used for short pulses as well) are 15-cell LC lines. A 10 cm diameter center conductor is potted into a stack of ferrite toroids in milled aluminum holders. The 2 mm gap between the center conductor and the holders, filled with GE 615 RTV silicone rubber potting, provides the capacitance. About half the long-pulse magnets fail in testing before reaching 40 KV. Even though the RTV is vacuum degassed and transferred under vacuum, sharp points are still observed to nucleate bubbles, and bubbles emerge from the magnet during the transfer process. There is a continuing effort to improve the degassing and potting procedures.

The long-pulse magnets typically have shorter service lifetimes than the short-pulse magnets, with failures typically due to arcs in the high radiation region near the beam pipe, where the RTV becomes very brittle and weak. The radiation is dominated by beam electrons that have lost energy by scraping the beam pipe (especially the injection septum) and are then bent into the kicker by the DC bend magnet upstream. Synchrotron radiation is not significant by comparison. The extractor magnet is upstream of its septum, receives much less radiation, and has a much longer lifetime. The radiation dose to the injector magnets has been greatly reduced by lead and tungsten shielding upstream. Since many magnet failures have occurred after shutdowns when the magnet temperature dropped, which may have cracked the brittle radiation-damaged RTV, the magnets are now kept at operating temperature by heaters during shutdowns.

Measurements of reflection, transmission, and magnetic field pulse shape indicate that the short-pulse magnets do not behave like transmission lines. The output voltage and current begin to rise with almost no delay relative to the input, but with poorer rise time. The field rises almost uniformly along the magnet length, rather than propagating as a wave. The azimuthal gap in the ferrite for the beam pipe causes the magnetic field to propagate longitudinally at the speed of light. The magnet has no significant longitudinal gaps in the ferrite and thus behaves more like a single inductor and capacitor than a transmission line.

Magnetic field propagates through long-pulse magnets in a wave, and the output pulse is delayed but not degraded. Presumably the better pulse behavior is due to the ferrites being separated by the aluminum holders. However, measurements indicate that at full voltage, the magnetic field continues to rise for longer than the delay time of the magnet. The long-pulse magnets appear to have a nonlinear (amplitude-dependent) impedance. The ferrite permeability increases with excitation, so the magnet becomes mismatched at full voltage. A reflection from the mismatch at the magnet output causes the field to increase for a constant input current. The effect of the permeability change is enhanced because the ferrite used has low initial permeability and the ferrite path is long compared to the gap.

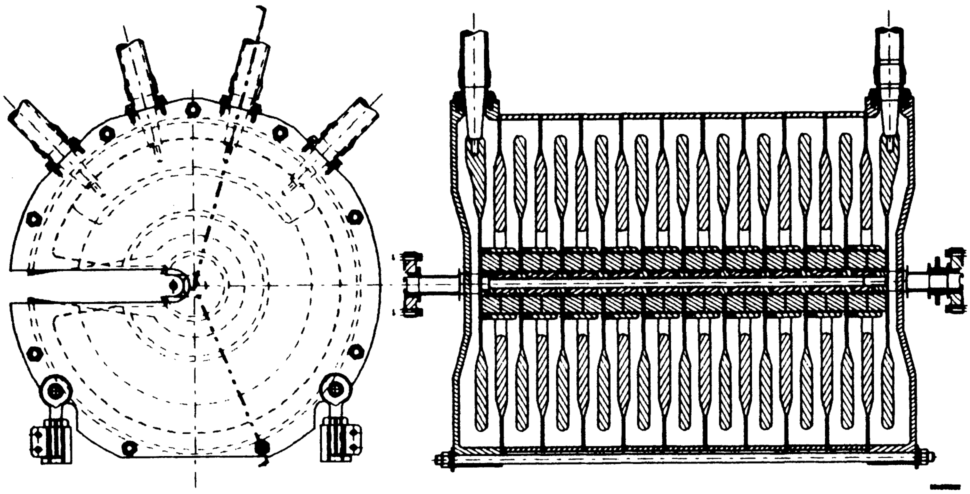

FIGURE 1. New Kicker Magnet Design

A new magnet type (Figure 1) is presently being designed to help solve magnet lifetime and pulse quality problems. To avoid breakdown, the insulation is 1 cm thick epoxy. Capacitance is provided by radial plates on the center conductor interleaved with ground plates. The complex electrode profiles ensure that electric field enhancement at the plate edges is less than 10%. The electric field is low in the irradiated region near the beam pipe. The capacitor plates separate the ferrite longitudinally. Nonlinearity is minimized and the magnet strength is maximized by using small ferrite toroids of high initial permeability. A slot allows the magnet to be slipped over the existing ceramic beam pipe without breaking vacuum, and the magnet will be compatible with present pulsers.

3. PULSERS

The short-pulse modulators are 16.7Ω output impedance triaxial castor oil Blumleins using single EGG HY5353 thyratrons in the oil. The Blumleins use rack-mounted DC heater, reservoir, and keep-alive supplies and grid pulsers, and have been quite reliable. Time jitter of 100-200 psec and current jitter of $\approx 10^{-4}$ are commonly obtained. However, the thyratron does not become fully conducting during the 38 nsec pulse width, so there is no true current flat top, and the amplitude varies a few percent with the reservoir setting.

The long-pulse modulators are 12.5Ω output impedance line-type (39 mm Felten & Guilleaume polyethylene coax) pulsers using pairs of EEV CX1671D thyratrons in a tank of transformer oil as series switches. They have superior rise time and show a good current flattop, but time jitter is somewhat worse than the Blumleins (typically 300-500 psec). The heater, reservoir, and grid pulser electronics are attached to the thyratron cathodes, and thus pulse up to 40 KV. They are powered through isolation transformers, and the trigger is sent through an optical fiber. The floating electronics package is difficult to maintain or monitor, and has been a serious reliability problem, primarily due to failures of the SCR stack and charging electronics in the grid pulser circuit. Since the thyratron pulse is only 100 nsec long, it is feasible to control the thyratron directly from rack mounted supplies, isolated by a ferrite common mode choke, with the heater current used to bias the choke. Two such systems have been built and operated, and will be installed during the next SLC shutdown.

Presently, all the fast pulsers are pulse-charged about 100 μsec before being discharged, which allows higher thyratron reservoir settings without breakdown, and thus better rise time. A 1 KV DC supply charges a capacitor bank, which a FET chopper regulates to a precision voltage. An SCR switches a half sinusoid pulse into a stepup transformer, whose secondary is "grounded" to the capacitor bank. The FET is used to pull down the secondary before the pulse voltage overshoots the desired level, producing regulation to the 10^{-4} level. The SCRs were often damaged if a thyratron broke down spontaneously soon after the charge pulse peak (a common occurance), when the SCR was neither fully on nor off. The problem was solved by detecting the breakdown and retriggering the SCR before it could be damaged.

The thyratron pulses travel through parallel RG-220 coaxial cables to the magnets, and through more cables to oil-cooled resistive loads. The peak current is of order 2 KA per magnet, with peak power of order 50 MW, and average power of order 500 W. Originally, all the pulse chargers, pulsers, and loads were located in the damping ring vaults. This complicated maintenance and repair enormously, and during January 1989 they were moved to new above-ground service buildings. This move provided the unexpected bonus of almost eliminating floating electronics package failures. Apparently when one thyratron fired early, the pulse travelled to the magnet and back to the other tube, damaging its electronics package unless it had fired before the pulse arrived. The new longer cables allow more time for the tubes to fire before reflections arrive.

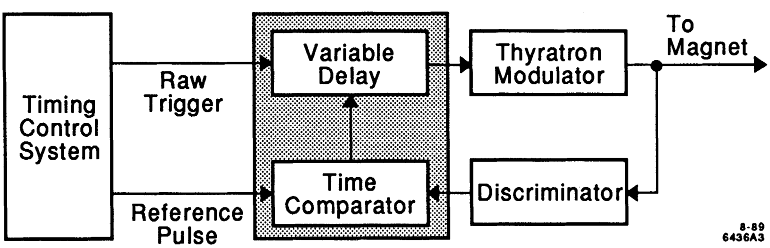

FIGURE 2. Timing Feedback System

Damping ring kicker pulse times must be reproducible to a fraction of a nanosecond. Thyratron internal delays are sensitive to charge voltage, heater and reservoir settings, and temperature. The grid pulser delay is also temperature sensitive. Until recently, the various timing drifts had to be manually corrected by the operators continuously, and mistakes often proved destructive. A timing feedback system has now been implemented for each thyratron (Figure 2). The SLC timing system provides a raw trigger pulse to the timing feedback module. After a variable delay, the module sends a trigger to the thyratron pulser. The thyratron output pulse time is sensed by a discriminator. The feedback module compares the discriminator time to a reference pulse and either increases or decreases the variable delay by 100 psec for the next pulse, with a range of ±200 nsec. The delay value is read out continuously and provides a valuable monitor of thyratron status.

4. MULTIPLE-BUNCH OPERATION

The e^+ ring is presently operating with two bunches damping simultaneously but injected and extracted singly. Even though the stored orbit is disturbed by injecting or extracting while the other bunch is damping, the coherent damping time is short enough that the emittance is not measurable increased. The SLC is not yet operating in the design mode with one e^+ and two e^- bunches on each linac cycle, although efficient injection and extraction of two e^- bunches has been demonstrated.

As noted, neither short- nor long-pulse magnets give flat magnetic field pulses from flat current pulses. It is possible to adjust the timing so two bunches would receive equal kicks even from a non-flat pulse, but this requires the pulse to come so early that one bunch receives a significant kick from the leading edge of the pulse on the previous damping ring turn. This kick is not at the same betatron phase as the final turn kick, and therefore cannot be cancelled by adjusting the timing. This is irrelevant for injection because even with unequal kicks, the two bunches rapidly damp to a common ring orbit. However, linac wakefields dilute the emittance of the bunches unless both are extracted onto the same linac orbit to high precision, requiring the two extraction kick amplitudes to be equal within 10^{-3} to 10^{-4}.

The new magnet design should produce a flatter field pulse given a flat current pulse, so the equal-kick timing should not result in a significant leading-edge kick on the previous turn. However, equalizing the kicks via timing results in the bunches being on sloping parts of the magnet waveform, so the adjustment varies both amplitudes simultaneously, and thyratron time jitter results in amplitude jitter. It is preferable for both bunches to be on locally flat parts of the pulse, and to be able to adjust the amplitudes separately. Figure 3 illustrates the general principle of pulse shaping by variable mismatch in a pulse forming line, and the mechanical implementation.

The discharge wave in the pulse forming cable initiated by the thyratron produces opposite and nearly equal reflections from both ends of a variable impedance region inserted near the end of the cable. This produces a variable current, and therefore a variable magnetic field, near the end of the magnet pulse. The variable impedance is provided by a rotor and stator in a tank of transformer oil with cable connections at both ends. The stator is a hollow half-cylinder high voltage electrode, and the rotor is a grounded hollow half-cylinder which turns on a shaft. The impedance of the rotor-stator transmission line is varied by turning the rotor with a stepping motor on the tank end. The tuner tank has been designed, and a scale model has been sucessfully tested.

An additional obstacle to two e^- bunch operation is prepulse. Multigap

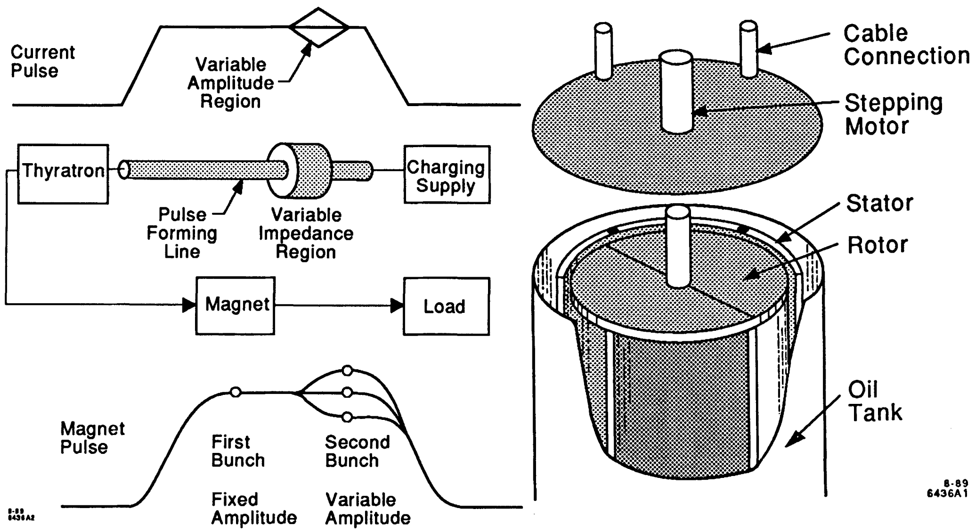

FIGURE 3. Pulse Shape Tuning Device.

thyratrons produce narrow precursor pulses of about 10^{-2} amplitude for about 100 nsec before the main current pulse as the internal gaps break down. These cause a small but still unacceptable kick on the turn before extraction. Saturable ferrite toroids at the pulser output have been shown to attenuate (but not eliminate) the prepulses without degrading the main pulse rise time. Another active control is being designed to cancel the prepulse completely. A small pulse will be injected at the load with amplitude and time adjusted such that the net magnetic field from the prepulse and the additional pulse will cancel.

5. STATUS AND CONCLUSIONS

The SLC kicker systems present unique challenges. The reliability and operability problems of 1988 have largely been solved, so kickers are no longer the most significant single cause of downtime, and require virtually no operator attention. Damping ring extraction amplitude jitter is adequate ($< 10^{-3}$) to avoid wakefield problems at present intensities. A new magnet design is expected to improve lifetime and produce a flatter pulse. The new magnets, in combination with pulse shape control, should allow acceleration of e^+, e^- for collisions, and e^- for e^+ production simultaneously on each linac pulse, which will double the SLC luminosity.

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