Status of the SLC Damping Ring Kicker Systems*

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Abstract

The damping ring kickers for the SLAC Linear Collider must meet extreme requirements on rise and fall time, flatness, time and amplitude jitter and drift, voltage, repetition rate, and reliability. After several generations of improvements to the pulsers, magnets, and controls, and evolution in the understanding of the requirements, the kicker systems are no longer a serious constraint on SLC performance. Implications for future linear colliders are discussed.

I. EARLY KICKER EXPERIENCE

The SLAC Linear Collider (SLC) damping rings require injection and extraction kickers with rise and/or fall times of 60 nsec. The first generation SLAC-designed short-pulse kicker system [1] was adequate for commissioning the first damping ring with single bunches, but had problems with charge voltage regulation, thyratron risetime, thyratron time drift, magnet failures, load failures. Magnet pulse shape distortion would preclude kicking 2 *e-* bunches on a long flat pulse required for full SLC operation, and a group at Fermilab agreed to develop a second generation long-pulse kicker system [2]. In the meantime, more short-pulse kickers were produced for comissioning the second ring with single bunches for the first SLC beam collisions in 1987.

For the 1988 SLC physics run, the long-pulse kickers were installed in the *e-* ring, and many features of the Fermilab pulse charging system were incorporated into a SLAC pulse charging system used for all the kickers [3]. It soon became apparent that while the new magnet pulse shape was better, it was adequate for 2 *e-* bunch injection but not for extraction, which cost a factor of 2 in possible collision rate. The new magnet design seemed to have a poor lifetime, and magnet failures increased dramatically as the repetition rate was raised. Thyratron time drift required constant operator intervention. The long-pulse system thyratron controls and the pulse chargers failed frequently. The kicker systems were the largest single cause of downtime in the 1988 SLC run.

A kicker improvement program was launched, with the goals of reducing down time, improving stability, and operating with 2 *e-* bunches. Experts from laboratories around the world graciously lent their experience, but many of the SLC kicker problems were unique. Sufficient progress was made [4] to allow the first SLC physics results in 1989.

II. KICKER MAGNETS

The damping ring straight sections are short, requiring 7 mrad kick angles, which combined with the 60 nsec risetime requires voltages up to 40KV. The kicker surrounds a 50 cm long 21 mm diameter ceramic beam pipe with a metallic coating to shield the beam from the ferrite. The magnets were designed as terminated transmission lines for optimum pulse shape. Both generations of kicker magnet design produce distorted pulse shapes and have limited service lifetimes [5]. Production yield has been improved by agitating the RTV under vacuum during degassing, and curing under pressure to redissolve bubbles. Service lifetime has been increased by evolutionary improvements to about 8 running months at 120 Hz with increasing beam intensity (and losses) [6]. Much of the improvement stems from keeping beam orbits close to the septa to minimize the kicker voltage, at some expense to ring acceptance, particularly for *e+*.

Failures in service of the original magnet design seem to depend primarily on voltage and number of pulses. Failures of the long-pulse magnets are arcs through the silicone rubber (RTV) dielectric very close to the beam pipe, and frequently occur soon after interruptions in operation. The RTV becomes brittle when radiation damaged, and thermal cycles crack it, followed by arcs in the cracks. Lifetime has been improved by flipping the injector magnets over to avoid spray from beam loss in the septum, adding heaters to prevent thermal contraction, and curing the RTV at room temperature so it is never under tension in service. Water cooled metal bars will soon be installed in the magnets to control beam-induced heating of the ceramic pipes.

The causes of pulse shape distortion in both magnet types are now understood [7]. The short-pulse magnets behave more like single LC circuits than transmission lines because flux is not prevented from flowing down the magnet. The long-pulse magnets are mismatched due to ferrite nonlinearity. Risetime has been improved by reducing the inductance with copper-on-Kapton "flux gaskets," which also help confine the grease used to prevent corona near the beam pipe.

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Much effort has gone into designing a third generation magnet with improved pulse shape and higher voltage capability that still fits the available space. It will use thick alumina-loaded epoxy dielectric for higher voltages and magnetic field shaping to reduce inductance for fast transit time. Epoxy requires careful processing and mold design for large volume castings with no bubbles, cracks, or debonding despite large shrinkage [8]. Magnet cells will be prepotted in shrinkable molds then potted together in a shrinkable structure. Tests of an electromagnetic mockup show good pulse performance.

III. PULSERS

Much effort has gone into improving thyratron reliability, time drift and jitter [9]. The failure-prone floating electronics package in the long pulse system was replaced completely by ferrite choke isolated rack mounted electronics, possible due to the short (150 nsec) pulse length, which have been robust and easily maintained. The more benign EEV CX-1671D thyratrons in the long-pulse systems now operate with very fast FET pulsers [10], producing RMS time jitter of as little as 100 psec and long useful life. Some of the EG&G HY-5353 tubes in the short-pulse systems perform equally well for limited times with DC keep-alive, but eventually become erratic, destroying even slow robust grid pulsers and keep-alive supplies and displaying time jumps of up to 10 nsec. Without keep-alive, the risetime is significantly degraded.

A major improvement in diagnosis and repair time was obtained by moving the pulsers and loads from the ring housings to surface buildings. The 80 foot runs of RG-220 did not degrade the rise time significantly. A third kicker pulser, load, and control system was added in each damping ring surface building to serve as a hot spare. These have occasionally been used as complete systems, but more often as sources of hot spare parts, or for adiabatic installation of engineering improvements. The pulse chargers, thyratron tanks, and loads are oil-cooled, and the oil circulation and cooling systems have been largely rebuilt for reliability and standardization. High voltage connectors on the pulser outputs facilitate the switch between pulsers [11].

III. CONTROLS AND INSTRUMENTS

The kicker timing and monitoring system [12] has evolved considerably from the original DC supply and single trigger signal. A fixed trigger rate independent of beam conditions was OR'd in with the beam-dependent trigger to prevent drifts from dynamic beam rate changes imposed by SLC machine protection systems. A hardware timing feedback module was developed to adjust the timing continuously to keep the mean thyratron delays within 100 psec of a reference trigger, independent of voltage, reservoir, or age. The timing feedback correction is read remotely and stored in a history buffer, providing a valuable diagnostic about thyratron health and allowing failure diagnosis or even prediction. Commercial time interval counters with remote readout and history of both time drift and time jitter and local continuous display of time jitter provide equally valuable information.

The thyratron pulse shape and thus magnet field at beam time varies with many parameters other than the charging voltage. Fast samplers provide information on amplitude mean and RMS for all kicker thyratron and magnet pulses (at both beam times if relevant). A remote control multiplexed oscilloscope and video camera remains the best instrument for some diagnostics of pulse to pulse variations. Each kicker installation now has a dedicated 'scope with computer assisted setup, so a single button press will display any important signal in a familar and labelled format within seconds. There is also pulse by pulse time and amplitude data for each thyratron and magnet pulse, which can be synchronized with beam position monitor information.

IV. MULTIBUNCH OPERATION

Making optimum use of the linac repetition rate requires that 2 short *e-* bunches 60 nsec apart in the north damping ring and 1 of the 2 *e+* bunches 60 nsec apart in the south ring be injected and extracted by the kickers each machine cycle. One *e-* bunch collides with the *e+* bunch, the other *e-* bunch makes *e+* for collisions 2 cycles later, and the second circulating *e+* bunch continues to damp before extraction the next cycle. The damping rings have loose injection kicker tolerances because errors damp out, but emittance growth from linac wakefields imposes tight (10^{-3} to 10^{-4}) tolerances on the extraction kicker. For a single bunch this is a jitter tolerance, and is fairly easy to meet by putting the beam on the peak of the pulse. For 2 bunches the tolerance applies to the difference between the kicks of the 2 *e-* bunches, as well as the jitter in either kick. Until 1989, the SLC operated in a mode requiring 4 linac pulses per collision, in part because the kickers could not meet the multibunch tolerences. The SLC has run with 2 *e+* bunches in the south damping ring since 1989 in a 2 pulse per collision mode, and with 2 *e-* bunches in the north ring since 1990 in full 1 pulse per collision mode.

The 2 *e-* bunch extraction tolerances were met by distorting the long current pulse to compensate for the magnet imperfections [13]. This was first done with a droop inductor to produce a flatter magnet pulse, and a peaking capacitor to produce a faster rise time. The shaping was adjustable only by stopping the pulser, was done by trial and error, and was not precise enough for high beam intensity operation. The lumped pulse shaping components have now been supplemented by fine tuning devices that can be adjusted under remote control. One device is a charge line tuner that changes the second bunch kick without altering that of the first. Another is a small pulser that sends an adjustable pulse backward through the magnet to cancel the small kick received by the second bunch on the previous turn by thyratron prepulse or early risetime [14]. Further pulse shaping devices presently constructed and ready to commission are a saturating ferrite line to filter out thyratron prepulse and sharpen the risetime, and a remotely controlled LC tuner to control the slope of the field pulse for the first bunch.

V. LESSONS FOR FUTURE COLLIDERS

Linear collider damping ring kickers are subject to far more serious constraints than most other accelerator kickers. They must run at high rates continuously and will likely be exposed to continuous beam losses. The need for fast damping leads to small rings which require fast risetimes and thus large voltages. Linac wakefields impose much tighter tolerances on extraction kicker jitter than most kicker applications, and operation with multiple bunches imposes additional difficult constraints on pulse shape.

The component in the SLC kicker systems that fell the farthest short of design performance was the magnet (both generations). The very fast risetimes require careful electromagnetic design, and the high voltages require careful electrostatic and mechanical design. For the SLC, the very short available length has made improvements very difficult, although very little damping ring performance would have been sacrificed if more space had been allocated for kickers. More length reduces the total power requirement, which can be used to lower current, voltage, or both. Multiple magnets fed in parallel would have a more favorable tradeoff between voltage and risetime, which is the basic kicker dilemma for SLC. The constraints of operating the magnet in the air outside the coated ceramic beam pipe are also large, particularly radiation damage to insulation exposed to air. It is worth re-examining the possibility of kickers inside the machine vacuum.

It has been possible to make thyratrons operate with 30 nsec risetime to 40KV and 2000A and 100 psec jitter. Time drifts are very much larger but easily corrected by feedback for constant rate operation. Optimum performance requires pulse charging and fast high voltage grid drivers and multigap tubes. Series switched circuits give better performance than Blumlein circuits because they present a higher impedance to the tube,but the plasma formation time scale sets a limit to risetime improvements. Multigap thyratrons have prepulse which can be a problem for multibunch extraction, but saturating ferrite filters can eliminate it and perhaps improve risetime as well (although not falltime).

It is very difficult to produce a passively perfect multibunch extraction kicker system. Moderate magnet imperfections can be compensated by current pulse shaping, at least for small numbers of bunches. For future colliders with trains of many closely spaced bunches it is not clear this approach remains practical. It is also possible to add independent small correction pulses at the magnet, or at other locations, to put multiple bunches on the same trajectory. This latter scheme does not compensate for jitter. Adding a second kicker $n\pi$ away in betatron phase away that receives the same pulse in parallel with an appropriate delay can compensate for both amplitude differences and jitter. However it could not compensate for kicks from other ring turns, one of the SLC problems.

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