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Kicker Thyratron Experience from SLC*

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Abstract

The SLAC Linear Collider has five fast kickers for the damping ring injectors, extractors, and the electron extractor for the positron target that use multi-gap Deuterium-filled thyratrons. The thyratrons operate with 30 to 70 kV anode voltages and 1 to 5 kA currents, to deliver pulses to kicker magnets with ≈ 30 ns rise times, up to ≈ 150 ns pulse widths, at 120 Hz. Operating and lifetime experience with several types of thyratrons and support electronics are discussed. Floating driver and power supply electronics were replaced by a ferrite choke isolator to allow grounding of the cathode support electronics with a commensurate increase in operating reliability. The construction of a 100 ns Blumlein enabled detailed measurements of the switching times for all SLC thyratrons under similar conditions. In the final focus area, the kickers dump the SLC beams after the $e^+ e^-$ collisions. These thyratrons function with 15 kV anode voltages and up to 2 kA currents to produce 1/2 sine pulses with ≈ 300 ns rise times, ≈ 550 ns FWHM, at 120 Hz. Operating experience with these thyratrons will also be presented.

I. SINGLE BUNCH KICKER EXPERIENCE

The first kicker thyratron combination to operate in the SLC consisted of Blumlein configured triaxially, Z = 16.7 Ω, using castor oil as a dielectric and cooling medium for the thyratron. The first thyratron used in 1981 was an EG&G HY5333, a very compact three gap tube, rated for 50 kV and high di/dt ≈ 17 kA/µs operation. Early SLC operation required five of these pulsers. The Blumlein pulser system is still in use today in three SLC areas [1]. The thyratron is still an EG&G unit, but was upgraded in 1983 to a HY5353 which is usually operated at 35 kV, switching ≈ 4 kA with ≈ 30 ns for the 0 to 100% rise time.

The Blumlein was limited in length/height because of the intended application to about 80 ns across the base line, since the e^+ damping ring revolution time is 120 ns. These parameters dictate thyratron rise time to << 30 ns for an flattop pulse. Unfortunately, rise times were ≥ 30 ns resulting in a parabolic pulse shape, which then forces the jitter performance to << 1 ns. The HY5353's are being pushed to their limit in terms of required rise time, di/dt, and jitter performance. They were operated at high reservoir voltages in the days of resonant charging, and required frequent attention to avoid SLC down time. The typical approach was to nurse the tube until SLC Operations said, "OK, replace it." This they were reluctant to do because it could take four or five hours to accomplish. To date, HY5353 installed lifetimes are ≈ 1000 hours rather than a reasonable value, e.g., ≈ 5000 hours.

Currently a command charger [2] is used on the Blumlein, which charges the line in 50 µs and holds the charge for 50 µs before the thyratron is triggered. It allows a higher reservoir voltage, for a rise time of ≈ 25 ns, and the pulse to pulse jitter is < 1 ns. Command charging has resulted in better kicker performance with a modest increase in thyratron lifetime. The long term timing drift is canceled via a feedback system [3].

A jump increase in jitter is the first indication of a thyratron problem. Normally, jitter instability can be stopped with dc reservoir voltage adjustments, or in rare situations the dc heater voltage is increased. Decreasing the anode voltage does stop the jitter, but that also decreases the kick angle and impairs SLC operation. When the thyratron reaches the > 1000 hour stage of operation and a big jump of jitter occurs, it is more difficult to reduce or stop with heater or reservoir voltage adjustments. The HY5353 has a pre-ionization electrode or keep-alive (K-A) grid that is usually operated at ≈ 50 mA. In this regime the voltage on the electrode measures ≈ 20 V, and when a new thyratron is first installed, jitter is << 1 ns, but as the tube ages the jitter increases, and to reduce it the K-A current is removed by grounding the K-A grid through a low impedance. This improves the jitter performance for weeks and sometime months, but eventually the >>1 ns jitter reappears and forces another application of current to the K-A grid. It generally takes two or three episodes of K-A on and off before we are convinced that tube replacement is necessary. Replacement with a new or rebuilt device seems the only solution. The old unit is installed in the test Blumlein. The rejuvenation period takes about 100 hours, the anode voltage, heater, reservoir, and K-A current are varied until the thyratron stabilizes.

Occasionally the HY5353 will fire-through and can after a spate of arcing destroy the output stage of the trigger driver, which indicates operation in the spark gap mode. The trigger driver has been protected from the effects of fire-through with series diode and L-C filter. The drawback of this protection is a slower trigger rise time and consequent increase in jitter. A new output stage for the trigger generator using pulse compression has been designed and is undergoing testing. It offers a five fold speed up in the rise time from the generator while preventing reverse current from blasting the output SCR. The compressor drives the control grid with a sharper pulse to further reduce the jitter from the HY5353.

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A thyratron engineer at EG&G had proposed a theory that implicated cathode hot spotting, which caused the HY5353 to exhaust an area of the cathode. It then could operate in an unstable mode until a new cathode emitting area was established [4]. Another HY5353 researcher [5] theorized that the instability was caused by grid hot spotting because of supporting evidence discovered in disassembled HY5353's. He had taken several apart and noticed bluing on the circumferences of certain control grid penetrations as if the plasma were following a specific path, which remained fixed for a period of operation until the beginning of jitter instability. He had disassembled thyratrons that had three bouts of instability and had found three different blued grid circumferences and matching polished areas on the anode. The two explanations are similar, and serve to indicate what has been observed with the HY5353's in the SLC Blumleins. However in a recent autopsy by EG&G no definite evidence for either phenomena was reported. The EG&G official version reads [6], "Gas clean-up is not evident. Cathode deterioration is causing time jitter increase with life. Cathode deterioration after 10^9 shots is normal life in our estimation." For 120 Hz operation, this translates to a 2300 hour lifetime. Fortunately, we have managed to wrest $\approx 2\times10^9$ shots based on operating hours, by nursing the thyratrons back to usability on the Blumlein test stand. Considering the total number of thyratrons consumed, the lifetime is ≈ 5000 hours, but since every unit has to be pulled out at ≈ 1000 hours for rehabilitation, once or twice, the confidence level for the HY5353 is < 50%.

II. TWO BUNCH KICKER EXPERIENCE

The Blumlein pulser with its narrow pulse specifically for e^+ single bunch injection and extraction was ineffective for two bunch kicking in the e^- damping ring. In this ring SLC needed a kicker magnet pulse with a long flattop width for the two bunches with a 60 ns separation, and rise and fall times of ≤ 30 ns. The kicker uses two parallel thyratrons with each discharging a pair of 50 Ω coaxial cables [7]. Each thyratron is coaxially enclosed. Both coaxial enclosures are housed in a tank that has a mineral oil circulation system providing a filtered dielectric and thermal transfer. The thyratrons are EEV CX1671D's which when properly used are capable of ≤ 30 ns rise times for 10 to 90%. The anodes work at up to 70 kV, normally 60 kV and each thyratron switches 1.2 kA for a ≈ 150 ns pulse. These kickers are also command charged to allow high gas pressure operation for fast switching.

In the early version of this kicker (1986), the trigger driver, reservoir, heater, and prebias supplies were at the cathode potential during the pulse. The cathode electronics package was trigger and power connected to the control racks via fiber-optic cable and high frequency transformer isolation respectively. They were not reliable, hard to diagnose, and difficult to maintain without replacing the package and thyratron as an ensemble. Our early operating experience of the CX1671D is masked by the numerous false alarms caused by the triggering and supply stability problems with the electronics package.

In 1989 an isolation choke was designed so that the trigger driver, reservoir, heater, and prebias supplies could be located at ground. This choke was designed for a 5.6×10^{-3} V-sec flux swing. It consists of two stacked toroids of CMD5005 material with 2 sq. in. of area. All of the thyratron trigger, supply, and diagnostic wires and coaxial cables are bundled together with an overall jacket diameter of 1/2 inch, and then nine turns of this composite cable are wound onto the stacked toroids. The choke presents an impedance approximately 50 to 100 times the 25 Ω load on the thyratron cathode, or ≈ 20 A pulsed path to ground compared to the 1200 A load current. Turn to turn voltage can be as high as 4.4 kV in the circulating oil dielectric, hence a special nine holed nylon guide is placed into the toroid hole so that each turn is always physically isolated from adjacent turns. The choke is biased via an air core inductor of 100 μH connected from the cathode to ground. The core bias is ≈ 3.5 A, determined by the R_{dc} of the air core coil, and supplied parasitically from the dc heater supply. The resistance of the air coil was kept low to insure this 3.5 A bias. Eliminating the fiber-optic triggering reduced the jitter dramatically. The reliability of the commercial heater and reservoir supplies with hard wired diagnostics resulted in a major reduction of kicker downtime. These isolation chokes have been in use for almost two years, finally offering a true idea of the CX1671D's performance and lifetime.

Combining the early CX1671D experience with the latest data indicates the nominal is lifetime is 5500 hours with a confidence level of 70% and increasing.

Figure 1. Comparison of the floating electronics package (left) with the isolation choke package (right).

III. LONG BLUMLEIN RESULTS

SLC obviously needs fast and reliable thyratrons for kickers. An investigation into the suitability of our present thyratrons and a quest for better types led to the construction of a 100 ns Blumlein using water (LCW) as a dielectric to keep the physical length to a reasonable size. The Blumlein had two sets of internal electrodes, so that with a modest effort the impedance could be changed from 12.5 Ω to 25 Ω for switching point impedances of 6.25 Ω and 12.5 Ω. This would allow variation of the R in the L/R time constant. It could also offer an idea of whether the L, or the ionization time of the thyratron dominated the fall time. The thyratron was mounted externally and coaxially beneath the line with forced air cooling to allow quick replacement and measurement access. The anode voltages were typically 25 kV, somewhat less than the actual operating voltages. The line was tested using various spark gap configurations, and then reworked to reduce the lead inductance from the center conductor to anode to 40 nH.

The data in Table 1 was taken by discharging the line into a resistive load of either 25 Ω or 12.5 Ω, and measuring the fall time (10 to 90%) at the anode of the switching device. In a few cases, no measurements were taken. The thyratrons tested were or had been used in other applications at SLAC and except for the new CX2025X, may have been previously used.

The CX1574C is the thyratron for the final focus kicker and has a 5100 hour average lifetime. It was selected for testing because of good lifetime experience, compact size (one gap), and a 15 kA current rating. The CX1536A had been used with some success in the klystron modulators on the linear accelerator where they had averaged ≈ 8000 hours. The tube is a rather compact two gap device with a 10 kA rating.

Z_{Line} =			25 Ω	12.5 Ω
SWITCH	ht."	gaps	t_{fall} in ns	t_{fall} in ns
Spark Gap	<1	1	–	12
CX1574C	8.4	1	–	42
CX1536A	12.6	2	–	60
CX1671D	13.5	3	–	60
HY5353	5.8	3	14	15 to 20
CX2025X	8.7	4	18	20

Table 1. Comparison of fall times using the Long Blumlein.

Since the CX1671D was being applied in the two bunch kicker, it could be considered a candidate for Blumlein use as well. It is a somewhat long tube with three gaps and a modest 3 kA rating, probably marginal for a 12.5 Ω Blumlein and 4 kA switching point current.

For the HY5353, we needed actual validation, since it had been in use for six years as the Blumlein thyratron. It is the shortest three gap and most compact of the thyratrons tested with a 5 kA rating for μs width pulses, and conceivably capable of 10 kA at the 100 ns width. The Blumlein was changed from 12.5 Ω to 25 Ω and the fall times for the thyratrons decreased by only 10%. This discovery indicated the fall is not L/R dominated but is mainly determined by the thyratron ionization time. Data in Table 1 implies this, since the one gap CX1574C has a two times longer fall time than the three gap HY5353. Data below in Table 2 for the HY5353 offers the same implication, i.e., increase the gas pressure and decrease the ionization time. Furthermore, the K-A grid could be prepulsed with additional reductions in fall time.

Reservoir Voltage (V)	4.0	4.5	5.0	5.5
HY5353 $t_{fall\ 10\text{-}90}$ (ns)	16	14	12	10

Table 2. Comparison of fall times vs reservoir voltage.

The CX2025X is a recent (1988) thyratron design from EEV intended as very fast, high di/dt switch, with 100 kV and 15 kA specifications. The results show it as the only serious competition for the HY5353. A redesigned thyratron housing for the SLC Blumlein with a CX2025X will permit additional testing and an eventual reliability run.

IV. SUMMARY AND PROSPECTS

The long Blumlein tests offered a validation that the HY5353 was the only production thyratron for the single bunch kicker applications. Which unfortunately is still an SLC handicap, since it is a short lived and cranky thyratron once past the 1000 hour stage. The possible replacement a CX2025X could possibly exhibit better total performance without the eccentricities of the HY5353, once the mechanical changes to the thyratron housing on the Blumlein are accomplished. The double bunch kickers use a thyratron pair, which are far more reliable especially after the replacement of the floating electronics package, since the tubes are quite suited to kicker parameters. The final focus kickers are also correctly tubed for the present with additional work planned to reduce the reverse voltage and current for even longer lifetime.

KICKER	Units	1 bunch	2 bunch	FF 1/2 sine
Thyratron	ea	HY5353	CX1671D	CX1574C
t_{PW}	ns	80	150	540
pulse/p'lse jitter	ns	≤ 1	≤ 0.5	≤ 5
V_{Anode}	kV	35	70	+12 & -2
I_{Anode}	kA	4	1.4	+2 & - 0.4
$t_{fall\ 10\text{-}90}$	ns	25	30	300
PRR	Hz	120	120	120
Average Life	hr	5000	5500	5100
Confidence	%	< 50	70	80

Table 3. Comparison of thyratron parameters and lifetimes.

Table 3 summarizes our operating experience with the three kicker thyratrons. Based on the tests done with the long Blumlein, SLC does have the right thyratrons in the right locations. It is also possible that the Blumlein pulser can be improved by using the CX2025X in place of the HY5353.

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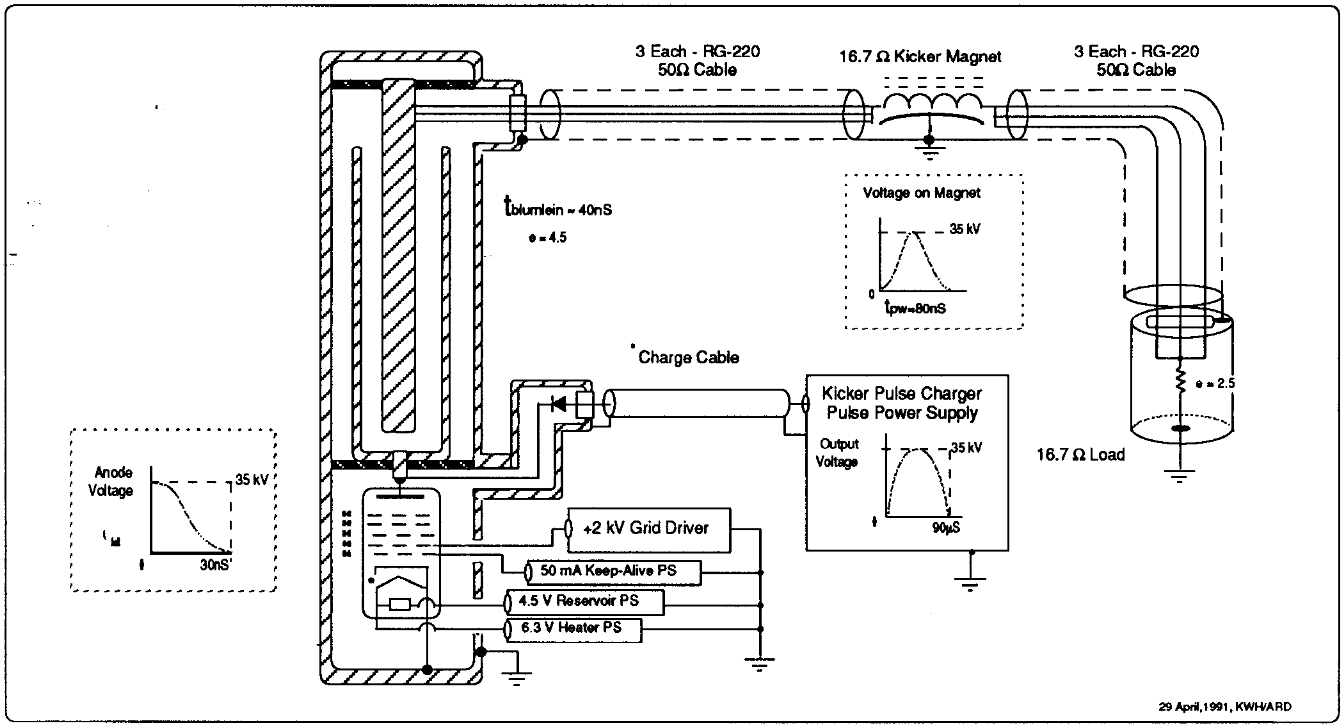
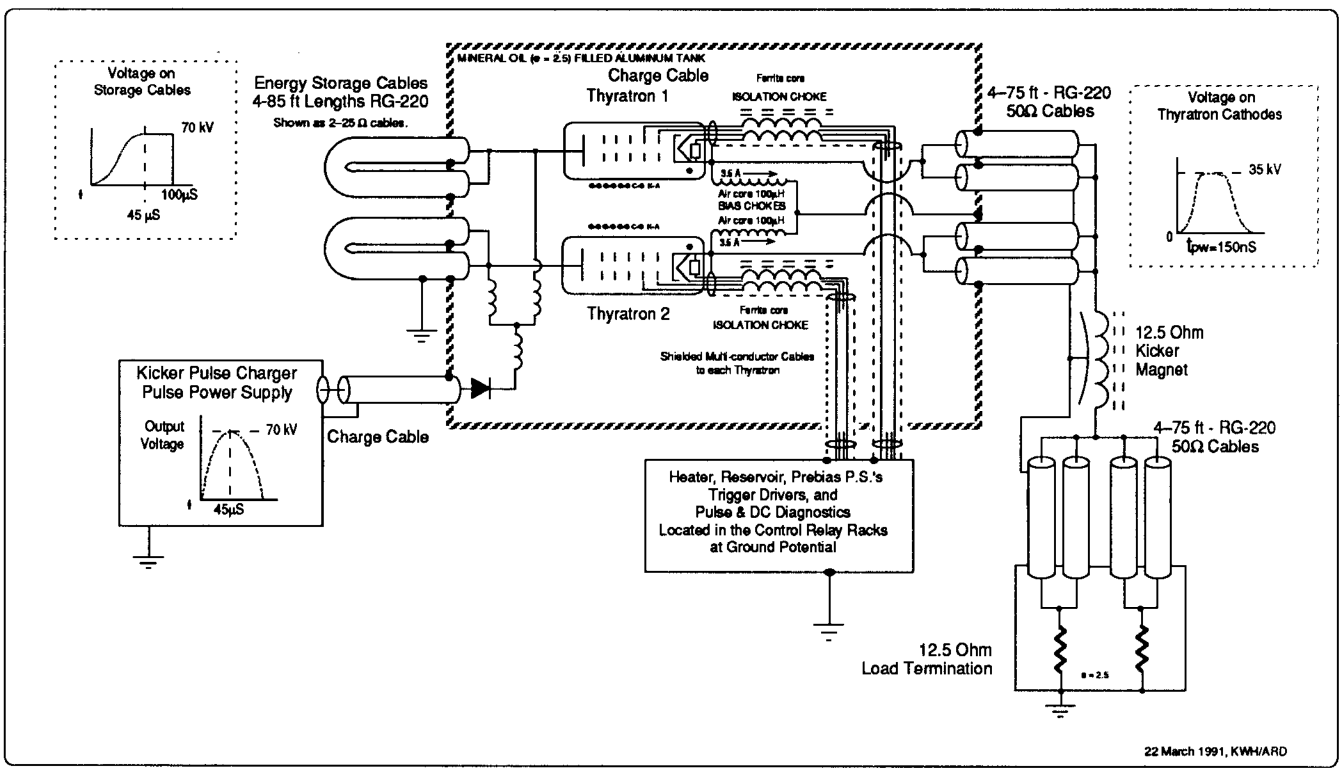


Simplified Schematic of SLC Single Bunch Blumlein Kicker System



Simplified Schematic of SLC Two Bunch Kicker System