TESTS OF A HIGH VOLTAGE PULSER FOR ILC DAMPING RING KICKERS*

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Abstract

The baseline configuration for the International Linear Collider (ILC) damping rings specifies a single 6.6 km damping ring for electrons and two 6.6 km rings for positrons. Kicker requirements are determined by the damping ring circumference and the train structure in the main linac. The nominal bunch train parameters in the ILC main linac are trains of 2820 bunches with 308 ns spacing and a train repetition rate of 5 Hz. The pulsers for the damping ring kickers must have rise and fall times suitable for bunch spacings of ~ 3 ns, must be able to operate with 3.25 MHz bursts, and must support an average pulse rate of 14.1 kHz. We describe bench and beam tests of a pulser from FID Technology whose specifications roughly meet these requirements. We then discuss the implications of our results for the ILC damping ring kickers.

INTRODUCTION

The large number of bunches per train (2820) and the relatively large main linac inter-bunch spacing (308 ns) in the International Linear Collider baseline design [1] result in a bunch train that is more than 200 km long. A damping ring of this size would be very costly so the bunch train is damped in compressed form. In the 6.6 km electron damping ring of the ILC baseline, mini-trains spaced at 308 ns intervals with an inter-bunch spacing of 3.08 ns are specified. An alternate mode of operation for the main linac has been proposed which would roughly double the number of bunches, while halving both the bunch charge and the inter-bunch spacing. This would require that the damping ring mini-trains be spaced at 154 ns intervals. The damping ring injection and extraction systems are expected to be able to handle either operating scenario.

A system of stripline kickers has been chosen as the default technology for injection into and extraction from the damping rings. Very fast pulsers with a few nanosecond pulse width and operating in the multi-kV regime are required in order to inject and extract the beams with a reasonable total number of kickers.

PULSER REQUIREMENTS

In order to maintain constant beam loading in each damping ring, the injection and extraction cycles will be synchronized. Extraction will proceed from the tail to the head of a train, with each damped bunch that is extracted being replaced by a "hot" injected bunch. In order not to perturb the neighboring bunches in the train, in particular the damped bunch just in front of a bunch undergoing injection or extraction, this means that the energy in the kicker structure must be zero when the preceding bunch exits the structure and must return to zero before the trailing bunch enters the structure. If we treat the bunch as a δ-function, this requirement can be expressed as:

$$t_p \leq 2t_b - 2t_k \tag{1}$$

where t_p is the duration of the pulse driving the kicker, t_b is the bunch spacing, and t_k is the length of the kicker structure. Thus, for a 30 cm stripline kicker, and the specified ILC damping ring bunch spacing, this means that the total width of the pulse must be ≤ 4.16 ns. Note that, for a flat-top pulse with negligible rise and fall times, we would ideally want the pulse width to be twice the kicker length for the kicker to be fully efficient. Furthermore, in this limit, we would want to make the kicker length be one-half of the bunch spacing in order to maximize the available kick to each bunch.

Extraction (and injection) of the bunches from (into) the damping ring takes place in a burst with a repetition period given by the bunch spacing in the main linac. Thus, the driver for the kicker structure must be able to sustain a peak repetition rate of roughly 3.25 MHz for short periods of time (≤ 1 ms). Trains in the ILC main linac are injected in a 5 Hz cycle. This means that the driver must be able to handle the power requirements of an average repetition rate of approximately 14 kHz. If we also consider the possibility of main linac bunch spacings as short as 154 ns and longer bunch trains, up to 5640, we must double the peak and average repetition rate requirements for pulsers.

The overall requirement for the system of fast kickers is to deliver a kick of 0.6 mrad to a 5 GeV electron beam. The kick angle is related to the kicker parameters by:

$$\theta = \frac{2eV_0 l}{Eh} \tanh\left(\frac{\pi w}{2h}\right) \tag{2}$$

where V_0 is the kicker voltage (per electrode), l is the kicker length, h is the kicker half-gap, w is the half-width of the electrodes, and E is the beam energy. As can be seen from Eqn. 1, the length of a single kicker module is constrained due to the requirement for a rapid rise time. For plausible pulser voltages, this implies that large arrays of stripline kickers are required for injection and extraction. The baseline damping ring lattice specifies an array of 22 10 kV extraction kickers and 42 equivalent injection kickers. The pulse stability requirement for the array of extraction kickers is determined by the necessary kick angle repeatability

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Table 1: FID Technology Pulser Specifications[2]

Pulser	FPG2-3000-MC2	FPG1-3000	FPG3-3000	FPG10-3000
Output impedance [Ω]	50	100	100	100
Maximum output per channel [kV]	±1	1	3	10
Number of channels	2	1	1	1
Rise time 10-90% of amplitude [ns]	0.6-0.7	0.6-0.7	0.6-0.7	0.6-0.7
Pulse duration at 90% of maximum [ns]	2-2.5	2.5-3	2.5-3	2.5-3
Fall time 90-10% of amplitude [ns]	1-1.5	1-1.5	1-1.5	1.2-1.7
Maximum PRF in burst mode [MHz]	3	3	3	3
Maximum PRF in continuous mode [kHz]	15	15	15	15
Triggering - internal, external 5-10 v [ns]	20	20	100	100
Amplitude stability in burst mode [%]	0.5-0.7			
Pre- and after-pulses [%]	1.5			
Timing jitter, relative to trigger [ps]	20			

of 7×10^{-4}. For an array of kickers, this means that the tolerance on the voltage fluctuations in individual kickers is given by

$$\sigma_V \leq \sqrt{N_k} \times 7 \times 10^{-4} \tag{3}$$

where N_k is the number of kickers. For the case of 22 extraction kickers this becomes $\sigma_V \leq 0.33\%$.

We have investigated the availability of a commercial device, suitable for driving a stripline kicker, that can meet the baseline requirements. FID Technology, Ltd., a manufacturer of pulse generators, provided several sets of pulser specifications that they feel they can meet. These are presented in Table 1. Note that one possibility for the increased pulse rates required in the case of 5640 bunches would be to allow for alternating pairs of units to be fired. We have purchased an FPG2-3000-MC2 unit for our initial testing on the bench and with a linac beam.

PULSER TESTS

We have carried out tests on two versions of the FPG2-3000-MC2 pulser. Experience with our first unit was somewhat disappointing. Initial tests at low duty cycle showed reasonable output from the unit. However, we soon encountered serious degradation in the output of all but the first pulse when operating the pulser in burst mode at high duty cycle. The problem first appeared in the negative channel with the positive channel quickly following. The failure was traced to a bad resistor in the charging circuit of each channel and the unit was repaired by FID. In order to validate the fix, we set the repaired unit up to run at high duty cycle for several weeks. After just under a month, the unit began to show the same symptoms as in the original failure. Shortly thereafter, FID Technology provided us with a second unit that had significantly improved cooling. The results in the remainder of this paper describe tests carried out with the second unit which has performed without significant problems.

Figure 1 shows the waveforms of the two channels of the FPG2-3000-MC2 as obtained with a LeCroy LC574AL oscilloscope (1 GHz input bandwidth) using 46 dB of attenuation. From these waveforms we infer the peak voltage at the outputs of the pulser to be approximately 1.08 kV. Fea-

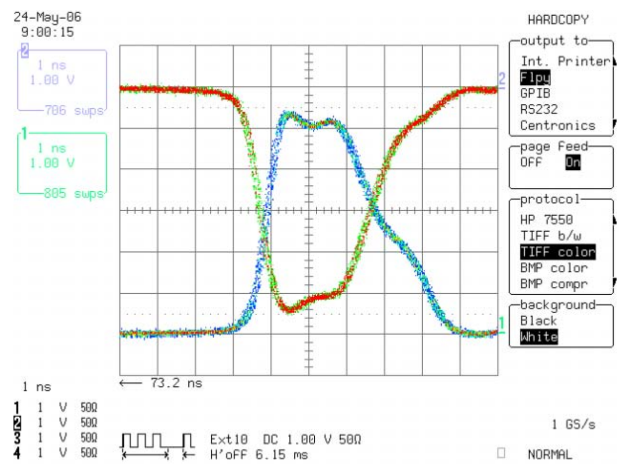

Figure 1: Waveform obtained from the FPG2-3000-MC2 pulser with 46 dB attenuation. The waveform shown is for the first pulse in a burst and is the accumulation of several hundred sweeps.

tures of the scope traces to note are: a small voltage, associated with the charging of the device, is discernible prior to the main pulse; the rise-time and top of the pulse appear consistent with the specifications given in Table 1; and the fall-time of the pulse is somewhat longer than the specifications given in Table 1. If we define the full width of the pulse to be the period between the 10% points of the waveform, we see that the pulse is ~ 5 ns in duration, which is somewhat wider than desirable for use with bunch spacings of 3.08 ns and a 1 ns long stripline. A large portion of this width is due to the approximately 2.4 ns fall-time of the pulse. Since this will only impact the trailing "hot" bunch, it may be acceptable. The voltage induced in the kicker due to device charging prior to the main pulse will be seen by the damped bunch which precedes the bunch being extracted or injected. As has been suggested elsewhere, this feature can potentially be dealt with by a suitable feed forward system using an extra kicker.

Although not shown, we have also investigated variations in amplitude from pulse to pulse within bursts of pulses. Comparisons of the oscilloscope waveforms for the different pulses show equivalent pulse heights to within approximately 2% for all of the pulses examined.

Digitized output from the pulser has been used to simulate the response of a stripline kicker to the pulser. Figure 2 shows the expected kicks to the beam for a 1 ns stripline (red) corresponding to the ILC baseline and a 2.1 ns stripline (black) corresponding to the test kicker at the A0 Photoinjector (A0PI) at Fermilab. For the nominal 15 MeV A0 beam and a 1.05 kV kicker, this implies a kick of roughly 14 mrad to the beam.

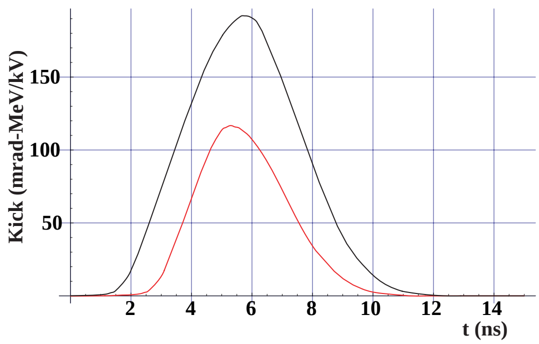

Figure 2: Simulation of the expected kick from a 1 ns stripline (red) and a 2.1 ns stripline (black) based on scope data taken with the FPG2-3000-MC2 pulser.

The kicker diagnostic line at the A0PI provides a pair of BPMs, with 1.46 m moment arm, upstream of the 2.1 ns kicker. A dipole corrector is located 0.79 m after the center of the kicker and allows approximate nulling of the beam trajectory before it passes through a pair of downstream BPMs spaced by 1.39 m. Figure 3 shows data that was obtained by scanning the trigger time of the pulser relative to the arrival time of the bunch in the A0 kicker. The points are determined by measuring the difference in angles between the two sets of BPMs and subtracting the contribution of the nulling corrector. The maximum kick amplitude recorded in Figure 3 is just under 14 mrad and the width of the pulse at the 10% points is slightly under 8.0 ns, both in good agreement with our simulation prediction. The error bars on the points represent the sigma of the angle distribution as obtained over many pulses in the accelerator. When the pulser is triggered out of time with the bunch, the scatter is approximately 0.06 mrad and represents our resolution limit using the A0PI as presently configured. On the top of the peak, the scatter is approximately 0.12 mrad. If we subtract the measurement resolution in quadrature from this value, we obtain a measure of the short term stability which includes the effects of both timing jitter and pulser amplitude stability. This value is 0.75% of the kick and is reasonably consistent with the pulser amplitude stability specification shown in Table 1. It is approximately twice as large as the value desired for the damping ring extraction kickers.

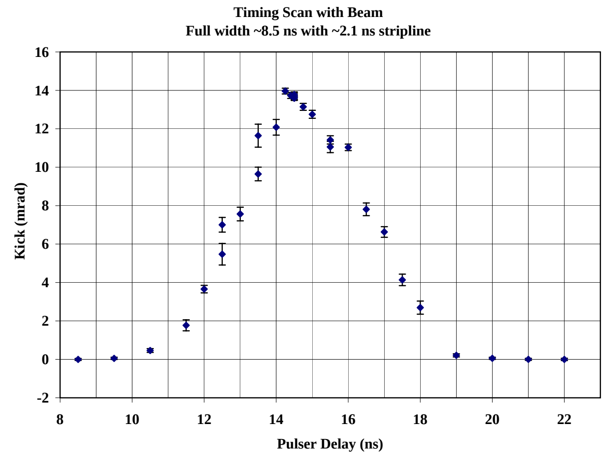

Figure 3: Beam kick obtained by scanning the pulser trigger relative to the beam arrival time taken at the A0 Photoinjector.

CONCLUSION

The measured parameters of the FPG2-3000-MC2 pulser approach the timing specifications desired for the ILC damping ring kickers. If it is found acceptable to have some perturbation of the "hot" bunch trailing the extracted/injected, it is possible that the a pulser with the observed time structure would be acceptable for damping ring applications. At the same time, there are several issues that require further research: first and foremost, the performance of a unit operating at 10 kV must be demonstrated; we also need to verify that the amplitude stability can be improved by roughly a factor of 2 in comparison to the present unit; a more detailed characterization of the performance of pulses throughout the pulse train is required; and, for the option of 154 ns spaced bunches it must be demonstrated that a unit can be built and operated with 6.5 MHz bursts and 28 kHz average pulse rate.

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REFERENCES

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[2] V. M. Efanaov, B. O'Meara, private communication.