HIGH VOLTAGE MEASUREMENTS ON NINE PFNS FOR THE LHC INJECTION KICKER SYSTEMS*

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Abstract

Each of the two LHC injection kicker magnet systems must produce a kick of 1.3 T.m with a flattop duration variable up to 7.86 µs, and rise and fall times of less than 900 ns and 3 µs, respectively. A kicker magnet system consists of four 5 Ω transmission line magnets with matched terminating resistors, four 5Ω Pulse Forming Networks (PFNs) and two Resonant Charging Power Supplies (RCPSs). Six RCPSs and nine PFNs, together with associated switch tanks and dump switch terminating resistors, have been built at TRIUMF and all have been tested at up to 60 kV PFN voltage to ensure that the performance is within specification. This paper describes the HV measurements, compares these results with low voltage measurements and analyses the pulse performance of the PFNs. The measurements are compared with results from PSpice simulations.

INTRODUCTION

The Large Hadron Collider (LHC) under construction at the European Laboratory for Particle Physics (CERN) will be equipped with kicker systems for injecting the incoming particle beams onto the accelerator's circular trajectory. Two pulsed systems, each consisting of four 2.7 m long magnets [1], four PFNs [2,3] and two RCPS [4], are required.

The combination of ripple and instability in the field from all kicker system components must be less than ±0.5%. The RCPS pulse-to-pulse stability is better than ±0.02% [4]. A description of the 9 PFNs and previous low voltage measurements is given in [2,3].

HIGH VOLTAGE TEST SETUP

All 9 PFNs, 20 thyratron switch tanks, and 10 dump switch (DS) terminators were tested to 60 kV PFN voltage at TRIUMF. The expected operating condition for LHC is 54 kV and 0.06 Hz. Each PFN and associated thyratron switch tanks were tested at 54 kV and 0.1 Hz for more than 24hrs. Detailed measurements were also carried out at 54 kV. Pulses of magnitude 27 kV are produced when a PFN is charged to 54 kV and discharged into a matched load. CERN provided a water-cooled terminating resistor and 10 RG220 cables to connect the terminator to the main switch (MS) CX2003 thyratron [5] (Fig. 1). The pulse length in the kicker magnet is, during LHC operation, controlled by a DS CX2503 hollow anode thyratron [5]. A water-cooled DS terminating resistor is mounted on the top of each DS tank. The optimum value of the DS terminator from PSpice simulations is 4.8 Ω±0.05 Ω, with a 27 kV pulse. A total of 10 precision DS terminating resistors were built and tested at TRIUMF with a measured resistance of 4.74Ω±0.01 Ω at 25°C and low voltage. The MS terminating resistor was measured to be 4.96 Ω at 25°C and low voltage. The voltage dependence of both terminators is –1.33%/kV/cm [6]: each consists of a stack of ten, 1" thick, resistor discs. Hence the value of the MS and DS terminating resistors at 27 kV is 4.89 Ω, and 4.68 Ω, respectively.

Each PFN system was tested at TRIUMF under the control of a CERN digital control system consisting of 4 racks of electronics. Thus during each test the PFN, thyratron switches and RCPS were controlled in a realistic manner.

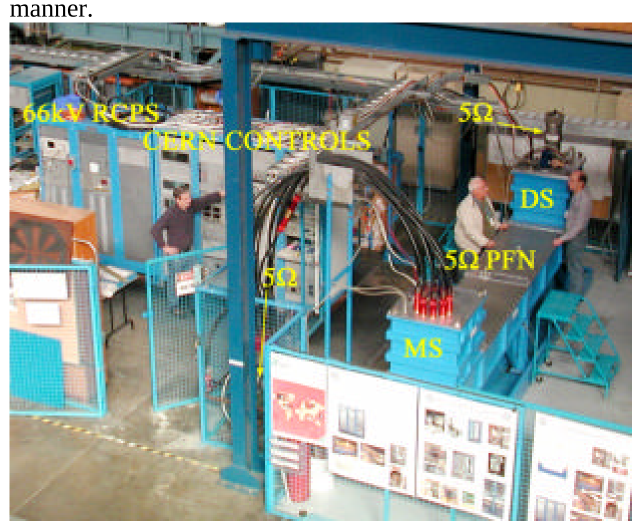

Figure 1: High Voltage Test Setup at TRIUMF.

Calibration

The calibration for the 10 V measurements was described in [2]. For the HV measurements a Tektronix 6015A 1000x probe was compensated as follows:

- the flattop from a 600 V pulse [7] with a 10 µs duration ("fast" in Table 1) was flat in the region between 4 µs and 8 µs after the start of the pulse;
- a 3 ms duration pulse was flat in the region between 2 ms and 3 ms ("slow" in Table 1) after the start of the pulse.

Table 1: Summary of 1000x probe calibration

Calibration Voltage	Measurement window	Calibration factor
Fast 600 V pulse (10µs)	4 µs to 8 µs	1010.3
Slow 600 V pulse (3ms)	2 ms to 3 ms	1015.4
DC 600 V to 18 kV		1006.0 ±6.0

The 1000x probe was also calibrated with DC voltages from 600 V to 18 kV and compared with the output of a

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precision (±0.1%) 2000.105 Metallux 6000:1 voltage divider [8]. All of the 1000x calibration data was taken in channel 1 of a Tektronix TDS 7104 digital oscilloscope with a voltage sensitivity of 5 V per division. The MS and DS terminators each consist of a stack of ten, 1" thick, resistor discs. This configuration is used to produce a 10:1 voltage divider. An additional CERN built ~40:1 voltage divider is connected to the output of the 10:1 MS terminator voltage divider. At 54 kV, the measured pulse shape from the CERN voltage divider was in excellent agreement with the 10 V pulse shape that was obtained after exhaustive measurements and calculations [2]. Since the CERN voltage divider has such a good response to the pulse shape, the calibration consisted of determining the amplitude normalization.

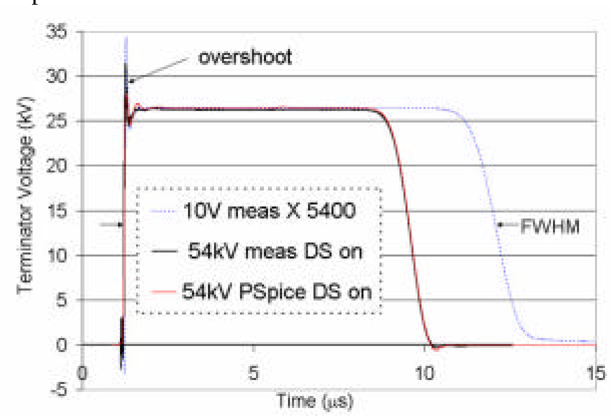

Figure 2: Measurements with 54kV on PFN#2 compared with 10V measurements and PSpice predictions.

The total voltage divider ratio for the ~10:1 and ~40:1 divider was measured by connecting the calibrated 1000x probe to the HV input of the MS terminating resistor. The 1000x probe signal was measured for an average of 10 pulses in a window between 4μs and 8μs from the start of the flattop, as per Table 1, without the DS operating. The output of the CERN voltage divider was terminated in a precision 50 Ω resistor and connected to channel 3 of the oscilloscope, which was used for all of the 10 V and HV measurements. The total voltage divider ratio for 18 kV and 54 kV, on the PFN, was 422.4 and 421.7, respectively.

The PFN voltage was measured by mounting the 1000x probe on the center of the PFN in a port that is normally used to ground the PFN when it is not in operation. The thyratron trigger timing was delayed so that a PFN charging voltage pulse could be measured in the 2 ms to 3 ms window (Table 1), as per the slow calibration pulse. The 1000x probe cannot be operated at 54 kV so instead the 18 kV measurement at the center of the PFN was normalized to the ratio of the voltage measured at the DS, using a Metallux precision voltage divider, at 54 kV and 18 kV: the nominal 54 kV control voltage was determined to be 53.996 kV. The absolute calibration of the 1000x probe varied by approximately ±1%, during the measurements. This magnitude of calibration variation was also reported in [9] for a P6015A probe.

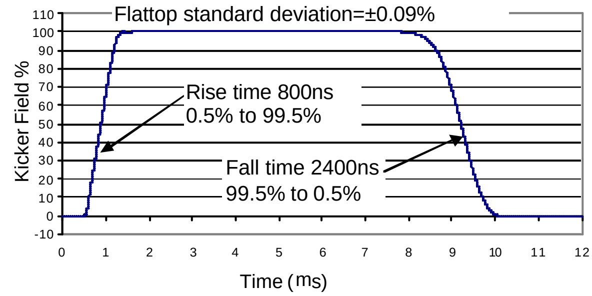

Figure 3: Kicker magnet field calculated for PFN#2 from voltage data in Fig. 2.

MEASUREMENTS

The PFNs were charged to 54 kV and discharged into a MS terminating resistor via a MS thyratron with and without operation of the DS. Fig. 2 shows the 10 V PFN measurement [2], for a precision 5 Ω terminator, multiplied by 5400 & 0.988: the 0.988 accounts for the value of the MS terminator at 27 kV. Fig. 2 also shows 54 kV PFN measurements for PFN#2. There is a 0.76% difference in absolute magnitude but the pulse shapes are in excellent agreement. The scaled up measurements for 10 V PFN voltage are ~0.44% high because they do not account for the full ~200 V drop across the thyratron [10]. Thus the 10 V and 54 kV measurements differ by only 0.3%. Fig. 2 also shows the effect of the DS operation on the voltage pulse duration and fall time.

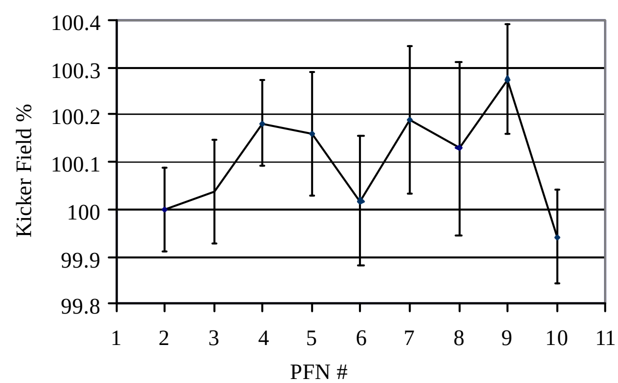

Figure 4: PFN#2 to #9 kicker fields normalized to PFN#2.

The measured pulse waveforms, at the MS terminator, were used as the input to a realistic PSpice model of the LHC injection kicker magnet. The resultant 0.5% to 99.5% field rise time for PFN#2 (see Fig. 3) is 800 ns (c.f. 900 ns specification) and the 99.5% to 0.5% fall time is 2.4 μs (c.f. 3.0 μs specification). The fall time is 1.99 μs if the 0.6% undershoot is not included. The overshoot shown in Fig. 2 charges an R-C filter at the entrance of the magnet and is not observed in the field (Fig. 3). Residual voltage ripple is integrated over the magnet fill time of 668 ns. The standard deviation of the flatness of the magnetic field for PFN#2, during the flattop, is 0.09%. The standard deviation of the flattop for each PFN is shown in Fig. 4 as an error bar. The largest flat top standard deviation is 0.16% (for PFN#8).

An important design consideration was the absolute precision of the PFN construction so that they are interchangeable with a minimum change in the relative calibration. All 9 PFNs were checked at nominal voltage: 54 kV was set by the CERN control system. Measurements of the individual MS terminator voltage were made in 2-month intervals over an 18-month period: these measurements were used as the input to the realistic PSpice model of the LHC injection kicker magnet. The resultant relative magnitudes of the field pulses are shown in Fig. 4. The field on PFN#2 is normalized to 100% as reference and the fields of the other PFNs are normalized to this reference. The standard deviation from the average field magnitude for all 9 PFNs is 0.11%. The maximum spread in the relative field calibration is 0.33%. This is a good indication of the precision of the PFN fabrication and the long-term stability of the system.

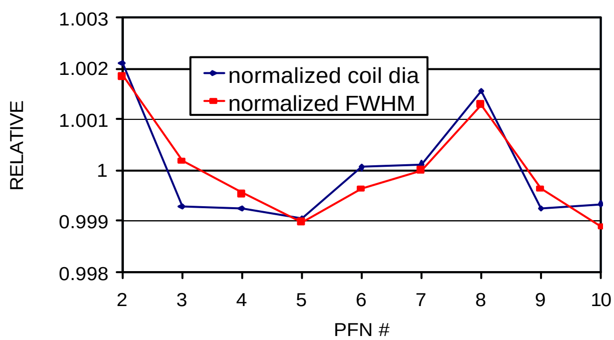

Figure 5: Coil diameter and FWHM normalized to unity.

The full width half maximum (FWHM), excluding overshoot and without the DS operating (see Fig. 2), of the PFN pulse width for 54 kV for all of the PFNs is 10.812 µs with a standard deviation of 11 ns. Fig. 5 shows both the relative FWHM for each PFN and the relative coil diameter for each PFN. The coil cell diameters are all within ±0.3 mm of 82.8 mm [2]. The FWHM is proportional to coil diameter: the total capacitance installed in each PFN is 1072.29 nF with a spread from maximum to minimum of 0.022% [11].

PSPICE

A full PSpice model was set up for PFN#2, including thyratrons, kicker magnet, metallization of the beam pipe, measured values of MS and DS resistor, PFN capacitor values and coil diameters. The full PSpice model gives a flattop 26.54 kV (Fig. 2): this is 1.1% higher than the measured 26.25 kV. The FWHM of the voltage pulse for PFN#2, without DS operation, was measured as 10.832 µs compared with 10.842 µs for the PSpice prediction. The excellent agreement in the FWHM indicates that the modeled PFN inductance and capacitance values are accurate, and that the small discrepancy in the magnitude of terminator voltage is probably due to losses not accounted for in the model. The measured voltage undershoot at the end of the pulse for PFN#2 is 350 V (0.6% field) and the predicted undershoot is 640 V (1.2% field). Displacement current, due to turn-on of thyratron gaps, integrated through the kicker magnet, is measured as a 100 ns ramp with a magnitude of 0.2%, whereas the PSpice prediction is 0.12%. However the measurement is noisy at this level.

SUMMARY

The series of 9 PFNs has been built to a high precision and successfully tested at TRIUMF. The high voltage pulse measurements are in excellent agreement with both the low voltage measurements and with PSpice predictions. The standard deviation in the relative field for the 9 PFNs, measured over 18 months, is 0.11%, indicative of the long-term stability as well as the precision of the fabrication. The measurements for PFN#8 shows a flattop field ripple with a standard deviation of less than 0.16%, over the full flattop of the pulse. The measurements for all other PFNs show a flattop field ripple with a standard deviation of less than this. Thus the overall system is within the specification of ±0.5%.

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