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

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Abstract

Each of 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 matching terminating resistors, four 5 Ω Pulse Forming Networks (PFN) and two Resonant Charging Power Supplies (RCPS). Nine PFNs have been built at TRIUMF and all have been tested at low voltage (10 V) to ensure that the performance is within specification. High voltage tests (60 kV) will be carried out at TRIUMF following the manufacture of thyratron switch tanks. All of the PFNs were measured without damping resistors installed: the maximum peak-to-peak voltage ripple was less than 0.9% (i.e. ±0.45%). In addition, a few PFNs were measured with damping resistors: the ripple was better than ±0.1% for 87% of the flattop duration. The absolute average measured flattops of the 9 PFNs are all within ±0.1% of each other. This paper describes measurements and analyses of the pulse performance of the PFNs. The measurements are compared with PSpice predictions.

1 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, of four magnets, four PFNs and two RCPS each, are required for this purpose.

The combination of ripple and instability in the field from all kicker system components must be less than ±0.5%. The RCPS pulse stability measured over 46 hours is better than ±0.1% and the stability over 14 consecutive pulses is better than ±0.02% [1]. With similar results from the PFNs, thyratron switches and the kicker magnets, the overall ±0.5% field specification should be achieved.

The 5 Ω PFN consists of two lumped element delay lines, each of 10 Ω, connected in parallel. Two thyratron switches are connected to the PFN, referred to as a main switch (MS) and a dump switch (DS) [2]. For the production PFNs, each 10 Ω line consists of 26 central cells plus two end cells. A cell consists of a series inductor, a damping resistor connected in parallel, and a capacitor connected to ground. The inductors are part of a single continuous coil, 4.356 m long, with 198 turns and a pitch of 22 mm. The central cell inductors are made of 7 turns each. The nominal MS and DS end cell inductors have 9 turns and 5 turns respectively, but are built with one extra turn to allow some adjustment to compensate for end-effects. PSpice simulations show that a 1% decrease in the MS end inductance gives up to 0.17% increase in the kick for the first 400 ns of the flattop. The coil conductor is a copper tube with a nominal outside diameter of 7.94 mm and wall thickness of 1 mm, wound on a rigid fibreglass coil former. The 26 central cells of the coils are not adjustable and therefore must be defined with high precision. Both delay lines are mounted in a rectangular tank with mild steel walls (Fig. 1) that is filled with insulating silicone fluid. Each line is surrounded by a 3 mm thick, Ω shaped, aluminium screen, which has an inner radius of 140 mm (Fig. 1).

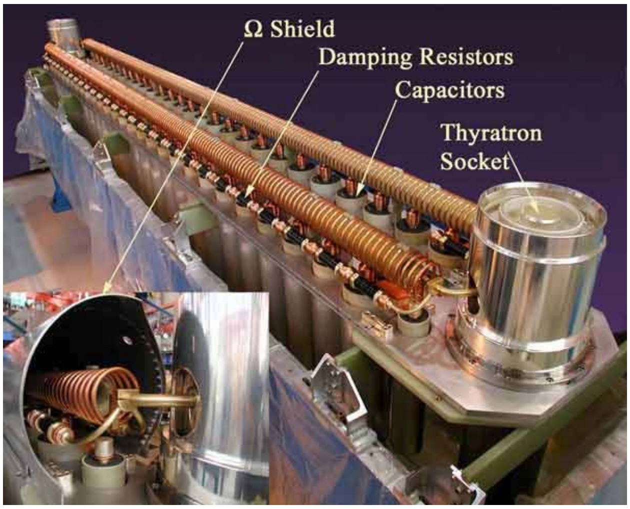

Figure 1: PFN during assembly showing capacitors in coaxial housings, damping resistors, precision coils and thyratron connection sockets. Ω shield at lower left.

2 CAPACITORS AND GRADING

The capacitors are manufactured with a tolerance of ±7% of a nominal 19 nF and are selected in pairs (1 capacitor per cell in a 10 Ω line). The sum of the pair of cell capacitor values is graded linearly, increasing in value from the MS to the DS end of the PFN by 0.08% per cell in order to compensate for conduction losses [2,3]. The selection of 520 capacitors to make up ten sets from a batch of 548 was carried out using a computer program. The values for PFN #2 are shown in Fig. 2.

The algorithm [2] works by constructing a 2D matrix containing every possible sum of pairs. A target value is calculated for each pair, allowing for grading, and assuming ideal PFN coils. The algorithm scans the matrix to identify the pair which sum to a value closest to the required target value. This pair is then eliminated from the matrix to prevent a capacitor being selected more than

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once. The target value is achieved to a precision of better than ±0.1%. If there is more than one pair whose values sum equally close to the target value, then the pair closest to the start of the matrix is chosen. This, combined with entering the 548 values into the algorithm in ascending order, had the unintentional effect of forcing the largest spread in the lower numbered PFNs. Hence the average spread of individual values is ±5% for PFN #2 (Fig. 2) and decreases to ±1.7% for PFN #10, thus flattop ripple is reduced for higher PFN numbers (Fig. 4). The measured flattop ripple, without damping resistors, is ±0.4% for the first 4 PFNs and ±0.2% for the last 5 PFNs.

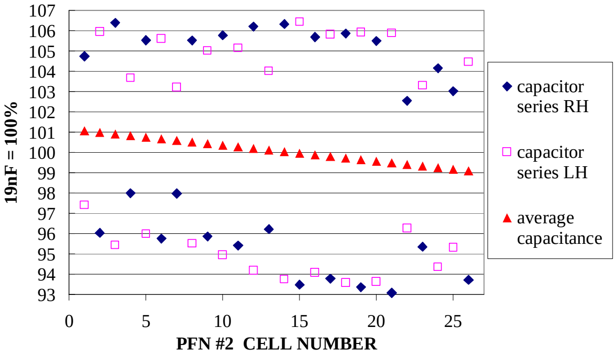

Figure 2: Graded capacitor values for cells 1 (DS end) to 26 (MS end) in PFN#2.

To assess the effect of sorting the capacitor values in ascending order, the values were re-entered into the algorithm in random order. The new selection of pairs was simulated using PSpice. Without damping resistors the calculated ripple was better than ±0.2% for all of the 9 PFNs; which is approximately twice as good as entering capacitor values in ascending order. However simulation results also show that the damping resistors are so efficient that the flattop ripple is independent of the order of entering the capacitor values into the algorithm.

The increase in effective capacitance of each capacitor due to the coaxial housing is 130 pF without silicone fluid, plus an additional 34 pF when silicone fluid is added. The pulse duration increases by 0.09% due to this 34 pF (0.18%) increase in effective capacitance.

The capacitance of two sample capacitors have previously been measured as a function of voltage up to 22 kV, and found to be constant to within ±0.01% [4].

3 DAMPING RESISTORS

There are four different nominal values of damping resistors in the PFN (33.4 Ω, 80 Ω, 100 Ω & 157 Ω). Ceramic-carbon resistors have been chosen because of their low inductance and high voltage and surge energy capabilities. Their main disadvantage is a drift in value with time, especially when stored or used in air. The predicted field is relatively insensitive to a 2.5% change in the value of any damping resistor except for the parallel MS resistors (33.4 Ω per resistor) [2]. In order to stabilize their long-term values, the MS end damping resistors have been vacuum impregnated at 100°C in silicone fluid. All the resistors have been stored in silicone fluid since receipt. The total change in the value of the MS end damping resistors was +1.2%, with +0.35% during the 7 months prior to heat treatment, +0.3% during heat treatment, and +0.5% during the 17 months since heat treatment. The change in value of the 80 Ω, 100 Ω & 157 Ω damping resistors, since receipt, is approximately +0.8 Ω (i.e. 1% to 0.5%). The voltage dependence of the MS end damping resistors is −1.32%/kV/cm and this is taken into account when specifying its nominal value.

4 INDUCTANCE PRECISION

The coils are wound on fibreglass coil-formers that have a groove machined with a pitch of 22±0.02 mm and inside diameter of 74.9±0.2 mm. The mean coil diameter was specified as 82.8±0.35 mm. The diameter of the finished coils was measured at one position for each of the 26 central cells. Fig. 3 shows the mean diameter of each pair of coils with error bars indicating the minimum and maximum diameters. The coil cell diameters are all within ±0.3 mm of 82.8 mm.

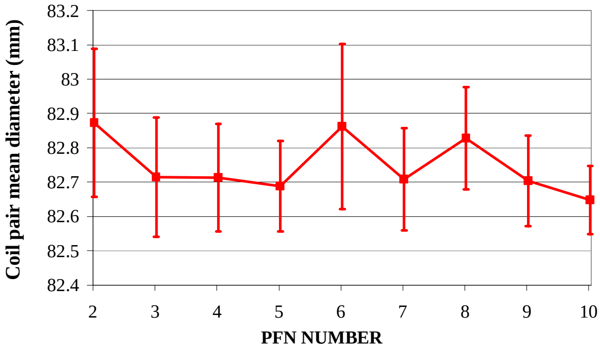

Figure 3: Mean diameter of a pair of coils for each PFN. Error bars represent the maximum and minimum mean diameter of each pair of coils.

The change in the voltage or field flattop for a step change in the coil diameter of 0.35 mm (0.42%) would be 0.21%. There is an incidental step in the coil diameter of PFN#2 at cell #19. This results in a step change of 0.15% in the measured pulse voltage at ~4.5 µs (Fig. 5).

The inductor coils for the prototype PFN built at CERN have a nominal mean diameter of 83 mm. The copper tubular conductor has a nominal outside diameter of 8.0 mm: the predicted inductance of a 7 turn cell, at 40 kHz, is 1869 nH [3]. For the series of PFNs built by TRIUMF the nominal outside diameter of the copper conductor is 7.94 mm, however the cross section is not circular after winding. The conductor has an outside "diameter" of 8.05±0.05 mm, measured longitudinally relative to the coil axis, and 7.75±0.05 mm measured radially. Ref [3] shows that the inductance of the PFN coil is dependent upon the average of these two dimensions with a 0.7% increase in inductance for a 0.2 mm decrease in average conductor outside diameter. The average is 7.9 mm for the TRIUMF coils, and therefore the cell inductance is 0.35% greater than for an 8 mm conductor.

5 PULSE MEASUREMENTS

The calibration of the oscilloscope was established for the voltage flattop (but not for the 50 ns rising edge) by replacing the PFN with a 5 mF capacitor bank with a low parasitic inductance and series resistance. In order to compensate for errors in the system these measurements were compared with PSpice simulations, in which the low voltage charging and switch circuit were also modeled.

The PFNs were charged to 10 V and discharged into a precision 5 Ω load using a fast switching MOSFET with very low (15 mΩ) on state resistance. All of the PFNs were measured without damping resistors installed. PFNs # 2, 4, and 10 were also measured with damping resistors. Fig. 4 shows the average flattop voltage and ripple (error bars) measured from 2 µs to 9 µs. The ripple on the 9 PFNs without damping resistors varies from ±0.15% on PFNs # 9 and 10 to ±0.44% on PFNs #3 and 4. The resultant voltage ripple, with damping resistors, is less than ±0.1% during the last 87% of the flattop. With 10.000 V charging voltage the average measured pulse flattop for the 9 PFNs was 5.004 V±0.1%, without silicone fluid, indicative of the quality control during manufacture of the PFNs. Based on the timing measurements with and without silicone fluid, this will become 5.007 V (cf. 5.000V), with silicone fluid.

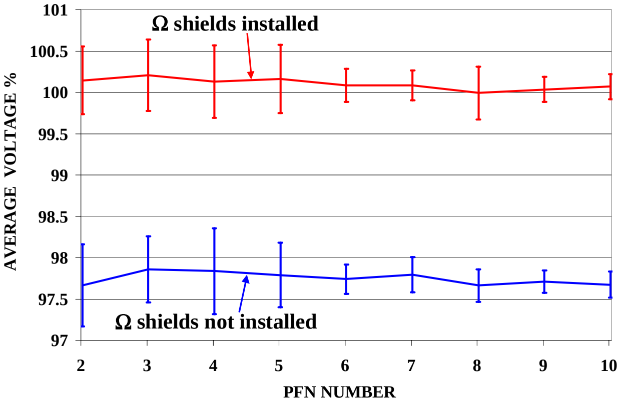

Figure 4: Measured average flattop voltage normalized to 200V charging voltage (2µs to 9µs): error bars represent ripple (no damping resistors).

PSpice simulations were performed which included the measured coil diameters and capacitance values for PFN#2 and all known parasitics. The value of the self-inductance for each cell is based upon that calculated for an 83 mm mean diameter of coil with an 8 mm diameter conductor. This value is scaled by both a factor $(D_m/83)^2$ for each cell, where D_m is the measured mean diameter of the cell, and by 1.0035 for an average conductor diameter of 7.9 mm as explained in section 4. Therefore the nominal total inductance of a 7 turn cell, at 40 kHz, is 1867 nH. The absolute difference between the measurements and the predictions for PFN#2 (Fig. 5) is 0.3%. The shapes of the measured and predicted waveforms are in excellent agreement.

The measured voltage pulse was used to predict the kick rise time and flattop for a model of the real kicker magnet [5]. The resulting kick rise time (0.2% to 99.8%) for PFNs with damping resistors is 850 ns and the flattop is at least 8.2 µs (c.f. required 7.86 µs duration).

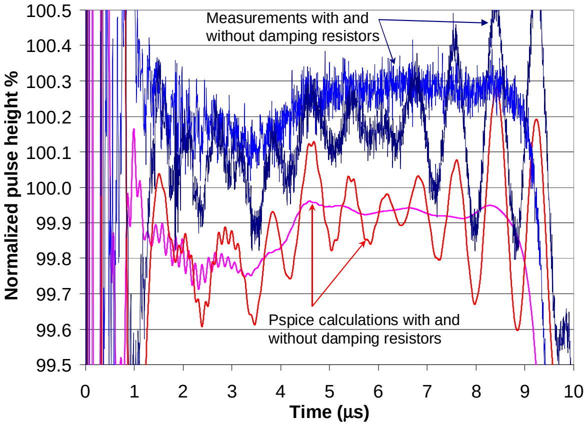

Figure 5: PFN#2 measured and predicted pulse voltage with and without damping resistors installed.

6 SUMMARY

The series of 9 PFNs has been built at TRIUMF. The low voltage pulse measurements are in excellent agreement with predictions. The measurements for 3 PFNs with damping resistors installed show that a flattop voltage ripple of less than ±0.1% has been achieved for the last 7 µs of the voltage pulse flattop. There is a 0.4% dip in the kick of PFN#2 during the first 100 ns of the pulse flattop (possible calibration error). If the dip is real it could be corrected by adjusting the inductance of the MS end cell. We expect all 9 PFNs will have low ripple once the damping resistors are installed. The HV results are expected to be consistent with the LV measurements.

7 REFERENCES

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