Effect of Saturating Ferrite on the Field in a Prototype Kicker Magnet

M.J. Barnes, G.D. Wait
TRIUMF
4004 Wesbrook Mall, Vancouver, B.C., Canada

Abstract

The field rise for kicker magnets is often specified between 1% and 99% of full strength. Three-gap thyratrons are frequently used as switches for kicker magnet systems. These thyratrons turn on in three stages: the collapse of voltage across one gap causes a displacement current to flow in the parasitic capacitance of off-state gap(s). The displacement current flows in the external circuit and can thus increase the effective rise-time of the field in the kicker magnet. One promising method of decreasing the effect of the displacement current involves the use of saturating ferrites. Another method for achieving the specified rise-time and 'flatness' for the kick strength is to utilize speed-up networks in the electrical circuit. Measurements have been carried out on a prototype kicker magnet with a speed-up network and various geometries of saturating ferrite. Measurements and PSpice calculations are presented.

1 INTRODUCTION

Many of the kicker magnets for the now defunct KAON factory required kick rise/fall times of less than 82ns[1]. In order to achieve the required kick rise/fall times in the available space pulse forming network (PFN) voltages of approximately 50kV would have typically been required[1].

The design of the pulse generator proposed for the injection and extraction kicker magnets was based on that of the CERN PS division[2]: three gap deuterium filled thyratrons would have been used for the high voltage switching. The individual gaps in a three gap thyratron break down in sequence[3,4]. Initially the gap closest to the cathode conducts and the full PFN voltage is shared between the centre and anode gaps. Approximately 50ns later the centre gap starts to conduct and the full PFN voltage builds up across the anode gap[3]. The voltage redistribution between the parasitic capacitance of each of the gaps is associated with a flow of displacement current[4]. The displacement current also flows in the external circuit[4], and hence through the kicker magnet, and thus can increase the effective rise-time of the kick. Time-domain mathematical simulations[1,5,6,7], using PSpice[8] circuit analysis software, confirmed that connecting saturating ferrites on the input to the kicker magnet (Fig. 1) is a promising method of decreasing the effect of the displacement current. These ferrites have the additional advantage of removing resonances due to the input cable from the longitudinal beam impedance spectrum[9].

As part of the KAON factory project definition study a 10 cell, 30Ω, prototype transmission line kicker magnet was built at TRIUMF[10]. This kicker magnet is based on the design of those of the CERN PS division[2]. Measurements have been carried out on the prototype magnet with various geometries of saturating ferrites connected on the input to the kicker magnet. The kicker magnet was housed in a vacuum tank and connected to a 30Ω pulse generator borrowed from CERN PS Division. This pulse generator has been modified at TRIUMF to operate at up to 50Hz with a PFN pre-charge of 80kV[1].

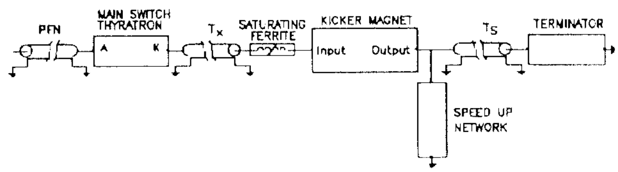

Figure 1: Block diagram of kicker magnet system

2 MEASUREMENTS

2.1 *Measurement System*

In order to determine the field in the kicker magnet, capacitive pickups were installed on the high voltage capacitance plates at the input and output of the magnet. Each pickup is connected to the central conductor of 50Ω coaxial cable. To provide a path for image current in the coaxial cable, a 50Ω resistor is connected, adjacent to the pickup, from the ground conductor of each coaxial cable to the corresponding central conductor. The capacitance of each pickup is approximately 2pF.

A Tektronix 11401 digital oscilloscope was used in Enhanced Accuracy mode[11]. The oscilloscope was also set-up to stop acquisition when the complete record was filled with data[11]. An analogue integrator was connected on the input of one of the oscilloscope amplifiers. The amplifier input impedance was set to 1MΩ. The input to the integrator is terminated in 50Ω. The integrator resistance is 2.64kΩ, and the capacitor value is 948pF. The resultant time constant is a compromise between too small a value, which results in considerable droop of a flat-top voltage, and too large a value which results in parasitic inductance of the integrator affecting the measured signal.

In order to minimize digitization errors associated with the resolution of the oscilloscope amplifiers, the integrated signal was fed into two channels of an 11A34[11] amplifier: one channel had a vertical resolution of 100mV/div, and the second channel had a vertical resolution of 5mV/div. 100mV/div permitted the full magnitude of the pulse to be displayed, whereas 5mV/div was used to measure the effect of pre-pulse displacement current. The time constant of the integrator is dependent upon the input capacitance of the oscilloscope. With the integrator connected to only one channel, the measured time-constants are 2.606μs, 2.594μs, and 2.578μs, at elapsed times of 100ns, 300ns and 1μs, respectively, after a transient. When the integrator is also connected to a second channel, via 50Ω coaxial cable with a 1ns delay, the corresponding time-constants are 2.724μs, 2.698μs and 2.674μs.

Measured data is downloaded to a PC for processing. In-house software reads in the data, and provides data manipulation functions which include: correction for droop of the analogue integrator; normalization; phase advance/delay; and output in Common Simulation Data Format (CSDF). The CSDF files are then edited and the high and low resolution waveforms are spliced together. The CSDF file is then read into Probe[8] for further processing.

The total voltage droop ($V_{d(n)}$) associated with measurement point number 'n', attributable to the analogue integrator, is calculated from the following equation:

$$V_{d(n)} = \left(1 - e^{\left(\frac{-\Delta t}{\tau}\right)}\right) V_{(n-1)} + \sum_{m=x+1}^{m=n} V_{d(m-1)} \qquad (1)$$

where: Δt is the time increment between waveform records; τ is the time-constant of the integrator (non-linearities are neglected); $V_{(n-1)}$ is the recorded voltage associated with the (n-1)th measurement point; and x is the user specified start point for droop correction ($V_{d(x)} = 0$). The voltage ($V_{c(n)}$) of the n^{th} measurement point corrected for droop is given by $V_{(n)} + V_{d(n)}$. Hence:

$$V_{c(n)} = V_{(n)} + \left(1 - e^{\left(\frac{-\Delta t}{\tau}\right)}\right) \sum_{m=x+1}^{m=n} V_{d(m-1)} \qquad (2)$$

Eqs. 1 and 2 have been validated using PSpice. PSpice analysis shows that an error of 5% in the time-constant results in an error of almost 1%, over a 600ns time interval, in the magnitude of the 'flat-top' of the field.

Following correction for integrator droop, using the measured 300ns time-constant, the waveform is averaged over a user specified interval of time, and then normalized to this average. The input voltage is normalized in a time window centered approximately 300 ns after the rising edge of the pulse. The output voltage is normalized in a time window centered approximately 300ns plus the low frequency delay of the magnet after the rising edge of the pulse. The low frequency delay through the kicker magnet is dependent upon the equivalent, low frequency, impedance connected to the output of the kicker magnet. This normalization procedure corrects for differences in the values of the capacitive pickups at the magnet input and output. The field in the magnet is then computed from the integral, with respect to time, of the difference of the magnet input and output voltages. In order to preserve relative timing between magnet input and output voltages, the trigger for the oscilloscope is, in each case, the terminator voltage.

2.2 Results

Fig. 1 shows a block diagram of the kicker magnet system used for the tests reported in this paper. The one-way delay of T_x and T_s (see Fig. 1) are 220ns and 27ns, respectively: thus the low frequency delay of the kicker magnet, to the 'flat-top' of the voltage, is given approximately by the inductance of the kicker magnet (891nH[10]) divided by the corresponding resistance of the main-switch terminating resistor. If the coaxial cables were reversed, the low frequency delay of the magnet would be given approximately by the inductance of the kicker magnet divided by the impedance of the longer coaxial cable (30.6Ω).

The trigger thyratron used to turn-on the dump switch thyratron, located at the remote end of the PFN, behaved erratically. Thus the dump switch trigger was disconnected for the measurements reported in this paper: this has the effect of permitting a significant tail to form on the current pulse, preventing any current reversal, thus increasing the remanent field in the saturating ferrites. The resulting pulse has a 'flat-top' of approximately 660ns.

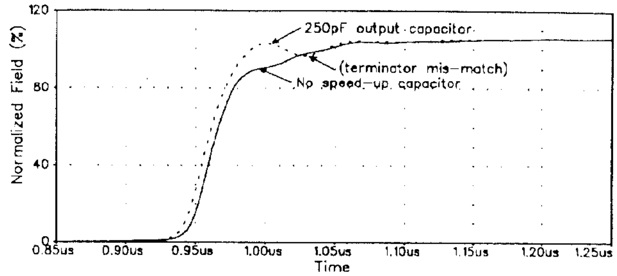

Figure 2: Measured field, normalized, with and without an output speed-up capacitor

Fig. 2 shows the field in the prototype kicker magnet, with and without a speed-up capacitor on the output of the kicker magnet, for operation with a PFN pre-charge of about 50kV. Without a speed-up network there is undershoot at the front-end of the flat-top of the pulse. The undershoot is partially compensated for by connecting a 250pF capacitor at the output of the magnet. With the 250pF speed-up capacitor present there is a trough in the field which occurs approximately 28ns after the first peak. This trough is attributable to the terminator resistance being low (26.9Ω) for the frequency components and voltage (25kV) magnitude associated with the flat-top of the pulse. Hence two 2.2Ω resistor disks were added to the terminator, so that its resistance value would be closer to that of the coaxial cables (30.6Ω). The modified terminator (31.5Ω) and the 250pF output speed-up capacitor were used for the remainder of the measurements reported in this paper.

Fig. 3 shows the pre-pulse field in the prototype kicker magnet when various geometries of toroidal saturating ferrites, manufactured from CMD5005[12], are connected on the input to the magnet. Two geometries of CMD5005 were used: 'fat' ferrite had inner and outer diameters of 40mm and 60mm, respectively; 'thin' ferrite had an inner diameter of 40mm and an outer diameter of 45mm. Several fat toroidal ferrites were purchased as two halves, while others were purchased unsplit. Unless stated otherwise the fat ferrite used for the tests consisted of one split ferrite with a cross-sectional area (CSA) of $2cm^2$, assembled without any spacer in the gaps, and several unsplit cores. All the thin ferrites were purchased unsplit. Without saturating ferrite present, pre-pulse cathode displacement current creates a pre-pulse field which is almost 4% of the flat-top field (Fig. 3): the 1% to 99% field rise-time is 151ns. Adding fat ferrite reduces the pre-pulse field, but the reduction, for a given increment in CSA, gets progressively smaller. The pre-pulse field has a sharper knee point when a CSA of $12cm^2$ of thin ferrite, rather than $12cm^2$ of fat ferrite is used: the 1% to 99% field rise-times with fat and thin ferrite are 99ns and 79ns, respectively.

As a result of the geometry of the housing used for the thin ferrites, it was not possible to test a CSA of $16cm^2$ of thin ferrite; instead $12cm^2$ of thin and $4cm^2$ of unsplit fat ferrite were combined. The result of this measurement is shown in Fig. 3: the 1% to 99% field rise-time is 62ns.

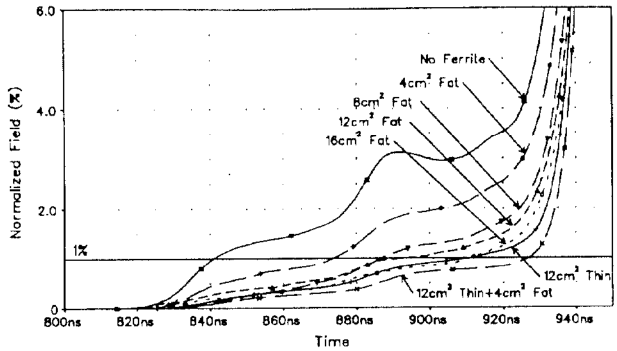

Figure 3: Measured normalized pre-pulse field for various geometries of saturating ferrite

3 MATHEMATICAL SIMULATIONS

Fig. 4 shows the predicted and measured pre-pulse field with and without saturating ferrites. A three gap thyratron with drift spaces modelled[7], and a time delay between consecutive gaps of 45ns, is simulated for the PSpice studies. Without any saturating ferrites present, the measurement and prediction are in good agreement. However when 12cm^2 of thin and 4cm^2 of fat ferrite are used, the predicted pre-pulse field is considerably better than the measured field. This indicates that the core parameters simulated (LEVEL=2, MS=267E3, A=47.46, C=0.2061, K=24.11, GAMMA=0) for the ferrite result in a higher initial incremental inductance than in reality.

The geometric parameters simulated for the CMD5005 are the effective CSA (A_e) and effective magnetic path length (l_e), both calculated in accordance with specification IEC205. The equations in IEC205 assume uniform field distribution over the cross section. Similarly PSpice assumes that the magnetic field is equal everywhere inside a magnetic core, except at an air-gap (gap>0)[13].

In order to determine whether non-uniform field distribution explains discrepancies between measurements and predictions, the fat saturating ferrites were modelled in two ways. Firstly the saturating ferrites were modelled as one lumped piece. Secondly the saturating ferrites were modelled as four series connected cores: each core represents one of four concentric annular rings of 2.5mm radial thickness. The resulting PSpice predictions for the pre-pulse field were virtually identical, indicating that non-uniform field distribution does not account either for the discrepancies, or for the difference in saturation characteristics between the thin and fat ferrites. PSpice analysis of the same CSA of thin and fat saturating ferrites shows that

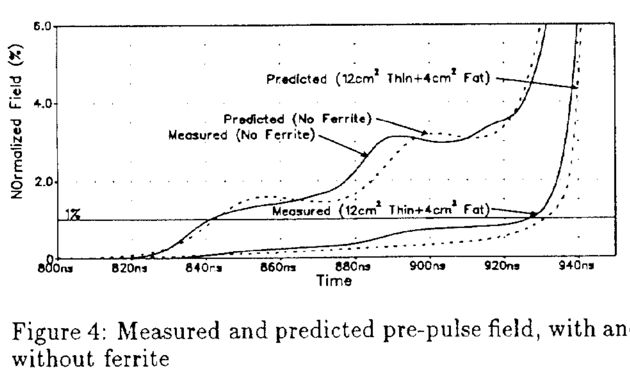

Figure 4: Measured and predicted pre-pulse field, with and without ferrite

the thin ferrite reduces the pre-pulse field by about 10% in comparison with the fat ferrites ($\frac{A_e}{l_e}$ is approximately 17% larger for the thin ferrite): this prediction partially explains the improvement in pre-pulse field obtained using thin saturating ferrites (see Fig. 3).

4 CONCLUSION

Measurements on the prototype kicker magnet show that a 1% to 99% field rise-time of 62ns has been achieved by using saturating ferrites to suppress the effect of pre-pulse displacement current. A speed-up capacitor on the output of the kicker magnet is effective at improving the flat-top of the field.

Discrepancies between theory and measurement could be attributable to a number of reasons, for example: remanent field in the cores, which is not taken into account in the simulation as PSpice is only run for a single pulse; and/or differences between CMD5005 databook characteristics and actual characteristics. Further investigations are required to identify the discrepancies.

5 ACKNOWLEDGEMENT

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