THE APPLICATION OF SATURATING INDUCTORS FOR IMPROVING THE PERFORMANCE OF THE CERN PS KICKER SYSTEMS

G.D. Wait, M.J. Barnes, TRIUMF, Vancouver, Canada,
K.D. Metzmacher, L. Sermeus, CERN, Geneva, Switzerland

Abstract

Kicker magnets are used for injection and extraction in the CERN PS. The addition of the LHC facility to the complex of accelerators at CERN requires an improved performance of the existing kicker magnet systems in the CERN PS. The injection kicker field must rise and fall from approximately 1% to 99% of full strength during the 96ns time interval between bunches, whereas the extraction kicker field must rise from approximately 0.5% to 99.5% of full strength during a gap of 121ns created in the beam. The kicker magnet systems require pulse forming network (PFN) voltages of up to 80kV. Displacement current arising from the turn-on of a multi-gap thyratron can significantly increase the effective rise-time of the kick. Saturating inductors can be used to reduce both the effect of the displacement current and the rise-time of the main current pulse. This paper describes the results of measurements on a system which includes saturating inductors. Some of the measurements are compared with theoretical predictions.

1 INTRODUCTION

Three gap deuterium filled thyratrons[1] are used as switches for the PS kicker magnet systems. The individual gaps in a three gap thyratron break down in sequence. Initially the gap closest to the cathode conducts and the full PFN voltage is shared between the centre and anode gaps. Approximately 40ns to 50ns later the centre gap starts to conduct and the full PFN voltage builds up across the anode gap. The collapse of voltage across one gap causes a displacement current to flow in the parasitic capacitance of off-state gaps. The displacement current flows in the external circuit and hence through the kicker magnet, and thus can increase the effective rise-time of the kick. One promising method of decreasing the effect of the displacement current involves the use of a "displacement current saturating inductor" (DISI) connected on (or near) the input of a kicker magnet. A "switching loss saturating inductor" (SLSI) may be connected adjacent to the thyratron anode to reduce the switching losses[2], so that thyratron life can be extended. This also improves the pulse voltage rise-time[3] and permits the adjustment of the thyratron reservoir voltage without any change in rise-time[4].

2 MEASUREMENTS

2.1 Circuit

Recent measurements have been carried out at TRIUMF in collaboration with CERN as part of the Canadian contribution to the LHC project. The test circuit consists of an 80kV pulse generator which can deliver 40kV pulses into a kicker magnet. The pulse generator is a 30Ω system, on loan to TRIUMF from CERN PS Division, and has been modified to permit testing with saturating inductors (SLSI) connected on the thyratron anodes (fig.1). The kicker magnet is a 10 cell, 31.5Ω prototype transmission line kicker magnet which was built at TRIUMF[5] as part of the KAON factory project definition study. This kicker magnet is based on the design of those of the CERN PS division[6]. The kicker magnet is housed in a vacuum tank and operated with PFN voltages of 60kV and 80kV for the tests described here. Measurements were performed with and without saturating inductors and with the kicker terminated in either a short-circuit or 30Ω. The circuit configuration is shown in figure 1. The one-way delay of τ_x and τ_m is 220ns and 26ns respectively. τ_s is 36ns for a resistive terminator and is 6ns when a short-circuit is placed at the output to the kicker magnet, at the Lemo connector that is at the base of the vacuum tank.

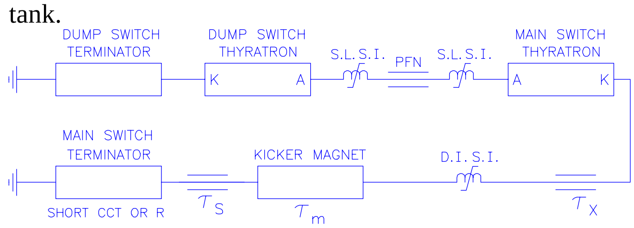

Figure 1. Block diagram of pulse generator and kicker magnet test system.

The inductance characteristics of the saturating inductor is related to the cross-sectional area (CSA) of the ferrite. Ferrite toroids, manufactured from CMD5005[7], were connected on the input to the kicker magnet. The DISI ferrite is quite thin (2.5mm), with an inner diameter of 40mm and a total CSA of $12cm^2$. Previous measurements[8] have shown that the pre-pulse field is improved when $12cm^2$ of thin ferrite is used, rather than $12cm^2$ of thick (10mm) ferrite. The SLSI consists of $60cm^2$ CMD5005 ferrite with an inner diameter of 1cm and an outer diameter of 7cm. The stray capacitance from the SLSI to ground enhances a 3rd pre-pulse displacement current peak in the voltage pulse[4].

2.2 Measurement System

Capacitive pickups were installed on the high voltage capacitance plates at the input and output of the magnet to measure the input (V_{in}) and output (V_{out}) voltages. The field in the kicker magnet is determined from $\int(V_{in}-V_{out})dt$. An analogue integrator was connected on a channel of a

0-7803-4376-X/98/$10.00 © 1998 IEEE

Tektronix TDS724A digital oscilloscope. The integrator time constant is approximately 2.6µs. This 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[8].

Signal averaging methods were employed in the TDS724A oscilloscope so that each waveform measured was the result of averaging 200 pulses. This improves the signal to noise ratio and permits accurate measurements of the pre-pulse displacement current. Measured data was transferred to a PC for processing. Software, which was developed at TRIUMF, reads in the data, and provides data manipulation functions which include: correction for droop of the analogue integrator; normalisation and phase advance/delay. The files are then read into Probe[9] for further processing.

The voltage droop associated with the analogue integrator is compensated for by analysis methods presented in a previous paper[8]. There is also a small portion of the signal (2%) which is due to inductive coupling in the signal cables situated inside the vacuum tank. The inductive coupling component was derived from measurements with the magnet terminated with a short circuit. This small correction was applied to the voltage waveforms from the capacitive pickups before calculating the field.

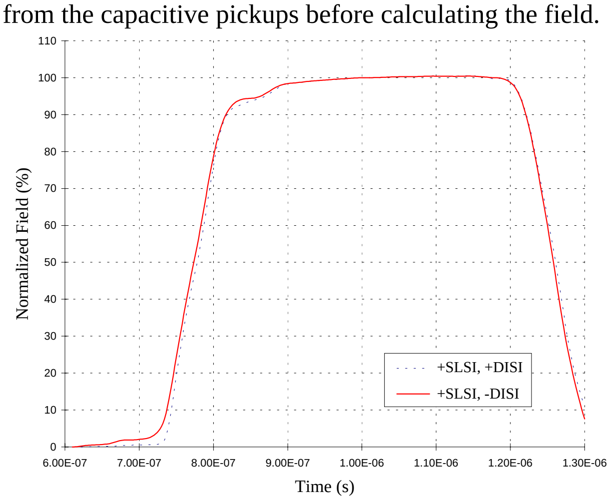

Figure 2. Magnet field at 80kV PFN with MS and DS SLSI, in a 31.5Ω kicker terminated with a short circuit, with and without a 12cm^2 DISI.

2.3 Measurement Results

Figure 2 shows the results of measurements with a PFN voltage of 80kV, a short-circuit terminator, a MS SLSI and a DS SLSI. The dashed line shows the kicker magnet field with 12cm^2 DISI. The solid line shows the field without a DISI. Note that there is a notch (undershoot) at the beginning of the flat-top of the field. This is due to a mismatch at the input to the magnet caused by the inductance of the housing for the DISI ferrite. The short-circuit is applied external to the vacuum tank and thus there is an inductance to ground at the output which also contributes a small amount to the notch in the pulse. PSpice calculations showed that this notch can be corrected by installing speed-up networks at the input and the output to the magnet each consisting of 200pF in series with 30Ω to ground.

PFN (kV)	MS SLSI	DISI	Term	0.5% rise-time (ns)	1.0% rise-time (ns)
60	no	no	R	152	144
60	yes	no	R	166	158
60	no	yes	R	105	76
60	**yes**	**yes**	**R**	**117**	**71**
60	no	no	SC	170	142
60	yes	no	SC	180	153
60	no	yes	SC	125	88
60	**yes**	**yes**	**SC**	**120**	**91**
80	no	no	R	156	148
80	yes	no	R	165	157
80	no	yes	R	111	81
80	**yes**	**yes**	**R**	**111**	**65**
80	no	no	SC	176	150
80	yes	no	SC	183	155
80	no	yes	SC	130	93
80	**yes**	**yes**	**SC**	**128**	**89**

Table 1. Measured field rise-times to 90% in the TRIUMF prototype kicker magnet under various conditions.

Rise-time measurements were performed without any speed-up networks. Since there is a notch in the flat-top of the pulses we present the data with rise-time definitions of 0.5% to 90% and 1% to 90%. This permits a consistent comparison of the effect that the ferrites have on the pre-pulse displacement current. Table 1 shows field rise-times for both 60kV and 80kV on the PFN, with and without ferrites, with a resistive terminator (R) and with a short-circuit (SC) terminator. In all cases there is a DS SLSI but this will not influence the front edge of the pulse. The DS SLSI reduces ripple at the trailing edge of the flat-top of the pulse which is caused by the DS anode displacement current.

In table 1 the rows in bold face are those in which there is both a DISI and a MS SLSI. The rise-times for 60kV and 80kV are the same. The short-circuit rise-times are longer than the resistively terminated rise-times as is expected since the fill-time is 64ns (52ns+12ns for the output strip-line) for the short-circuit case compared with 26ns for the resistively terminated case. There is a marked improvement in the rise-times if a DISI is used. The MS SLSI with no DISI causes an increase in the rise-time, due to a large 3rd displacement current peak; this shows up in the voltage waveforms but is not apparent in the integral, since the integration tends to blend the 3rd peak into the rising edge. The rise-time from 0% to 0.5% is 90ns when a DISI is installed for the short circuit case (fig. 3), so that a very small error in pre-pulse amplitude can introduce a large error in rise-time, depending on the rise-time

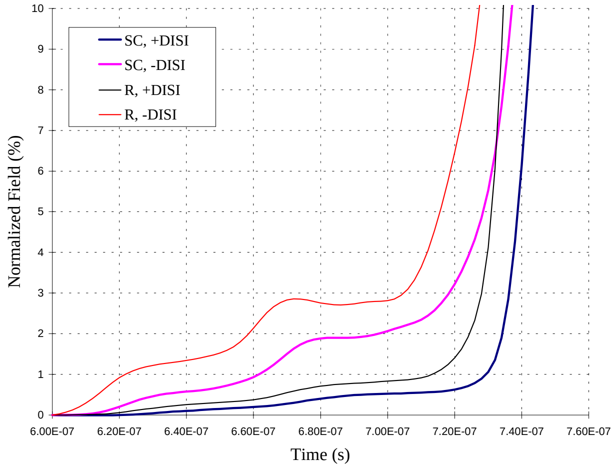

Figure 3. Pre-pulse kicker field with 80kV PFN, DS and MS DISI, with and without a 12cm^2 DISI, with a short-circuit terminator or a resistive terminator.

definition. This probably explains why for some of the cases, a slight improvement of rise-time occurs when there is a DISI with a MS SLSI, and in other cases it appears to improve without a MS SLSI.

Figure 3 shows the pre-pulse field for an 80kV PFN voltage with a MS SLSI installed. The magnitude of the pre-pulse field with no DISI is 2.8% (2%) of the full field with a resistive (short-circuit) terminator. The magnitude with a 12cm^2 DISI is 0.9% (0.6%) of the full field with a resistive (short-circuit) terminator. The measured pre-pulse field with a resistive terminator and without any ferrites is 3.2% of the full field (fig. 4)

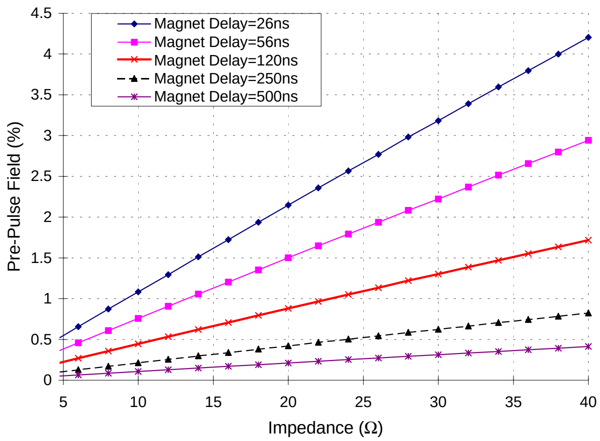

Figure 4 Calculated pre-pulse field amplitude as a function of magnet impedance and delay time without ferrites.

3 CALCULATIONS

The magnitude of the pre-pulse field, due to displacement current is dependent on the impedance of the kicker system. Fig 4 shows a plot obtained from PSpice calculations of the pre-pulse field versus magnet impedance for various magnet fill-times for the case without a SLSI or DISI in the circuit. The flat-top current in a kicker magnet, for a fixed PFN voltage increases as the magnet impedance reduces but the displacement current is almost constant. Therefore the amount of ferrite required to reduce the pre-pulse ripple is reduced for low impedance systems.

Theoretical calculations were performed to optimize the PS injection kicker (FAK) configuration, which is a 15Ω system operating at 80kV PFN voltage, using a PSpice model[9] of a thyratron[10]. The fill-time of the FAK with a resistive terminator is 56ns, which is to be compared with 64ns for the short-circuit TRIUMF magnet. The goal is to achieve a 0.5% to 99.5% field rise-time of 121ns. The simulation carried out includes a DISI where the CSA has been optimised to 3cm^2. However experience with the KAON prototype 30Ω kicker magnet at TRIUMF[8], operating at a PFN voltage of 50kV, showed that the DISI is slightly less effective at suppressing the effects of displacement current than predicted; thus 4cm^2 may be required for the FAK. Including a CSA of 3cm^2 reduces the theoretical field rise-time from 184ns to 134ns. In addition the values of four speed-up component networks have been optimized (with lossy transmission lines modelled). The resulting predicted field rise-time (0.5% to 99.5%) is 127ns.

4 CONCLUSION

The measurements show that there is considerable reduction in the field rise-time with the inclusion of a DISI in the circuit ahead of the kicker magnet. The use of a SLSI has only a slight benefit for the rise-time. However a MS SLSI will cause a reduction in thyratron switching losses and permits the reservoir voltage to be adjusted without affecting the rise-time. The measurements confirm calculations and thus show that the calculations for the PS kicker are quite realistic.

REFERENCES

[1] EEV, Chelmsford, Essex, U.K

[2] L. Ducimetière, D.C. Fiander "Commutation Losses of a Multi-gap High Voltage Thyratron". IEEE Conf. Record of the 1990 19th Power Modulator Symposium. pp248-253

[3] M.J. Barnes and G.D. Wait, "Improving the Performance of Kicker Magnet Systems" Proc. of XVth International Conference on High Energy Accelerators, Hamburg, July 1992, pp191-193.

[4] G.D. Wait and M.J. Barnes, "Thyratron Lifetimes, a Brief Review" presented at the Modulator-Klystron Workshop at SLAC for future Linear Colliders, SLAC Report 481, Oct, 1995.

[5] M.J. Barnes and G.D. Wait. "Comparison of Measured and Predicted Inductance per Cell for a Traveling Wave Kicker Magnet" Pres. at EPAC, Barcelona, June 1996, pp2588-2590.

[6] D.C. Fiander, K.D. Metzmacher, P. Pearce, "Proc. of the KAON PDS Magnet Design Workshop", Vancouver, Oct. 1988, pp71-79.

[7] Ceramic Magnetics Inc., New Jersey, USA

[8] M.J. Barnes and G.D. Wait, "Effect of Saturating Ferrites on the Field in a Prototype Kicker Magnet", Proc. of EPAC, London, June 1994, pp2544-2546.

[9] MicroSim Corporation, 20 Fairbanks, Irvine, California 92718. U.S.A.

[10] M.J. Barnes and G.D. Wait, "A Mathematical Model of a Three-Gap Thyratron Simulating Turn-On", Proc. of the 9th Int. Pulsed Power Conf., Albuquerque, June 1993, pp293-296.