Comparison of Field Quality in Lumped Inductance versus Transmission Line Kicker Magnets

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Abstract

The choice between a transmission-line and a lumped inductance kicker magnet is generally based upon kick-strength rise-time requirements: the kick-strength rise-time in a lumped inductance kicker magnet is greater than for a transmission line kicker magnet. This disadvantage can be overcome by adding shunt capacitance to the lumped magnet. A lumped inductance kicker magnet may present a transient mis-match to the pulse generator: the reflections may shorten the life of the thyratron switches and transmission cables, unless other measures are taken. Circuit analysis code PSpice has been utilized to mathematically model a kicker magnet which is simulated as being broken up into various numbers of sections. In each case the values of shunt capacitors have been optimized. This paper presents the results of theoretical simulations to determine an optimum number of sections and optimum capacitor values for a kicker magnet. A field quality comparable to that of a transmission line kicker magnet can be obtained with a 3 cell lumped inductance magnet.

1 INTRODUCTION

Specifications for kicker magnets for particle accelerators typically require large deflection angles, fast rise-times and good field uniformity[1,2,3]. For example the specifications for the kicker magnets at the now defunct KAON factory required deflection angles in the range of 2 mrad to 12 mrad, and rise/fall time from 1 % to 99 % of full strength in the range of 80 ns to 160 ns. In addition the uniformity and stability of the kick strength were individually required to satisfy a ±1 % accuracy criterion[1].

Kicker magnets are either designed as lumped inductance or transmission line devices. Lumped inductance magnets typically consist of a section of magnetic material and a shunt capacitor to steepen the final stage of the field rise[4]. In transmission line magnets the series inductance is divided into discrete cells: the magnetic material of each cell is either sandwiched between plates which are capacitively coupled to the return conductor, or discrete capacitors are used. All cells are nominally identical, thus approximating a uniform impedance transmission line.

As part of the KAON factory project definition study a 10 cell prototype transmission line kicker magnet was built at TRIUMF[5]. Recent measurements on this prototype magnet show that a field rise-time of 62 ns (1 % to 99 %) has been achieved[6]. However a transmission line type magnet is mechanically complex, and therefore more difficult and expensive to assemble than a lumped inductance kicker magnet. Hence a theoretical investigation was undertaken to determine whether the field quality of a multi-cell transmission line kicker magnet could be achieved with a magnet consisting of a few cells.

Figure 1: Simplified schematic of circuit used for optimization

2 PROCEDURE

2.1 Equivalent Circuit

Fig. 1 shows part of the equivalent circuit simulated for the investigations. The circuit stimulus is a trapezoidal voltage pulse of positive polarity with rise and fall times of 20 ns and a flat-top of 660 ns: this approximates a positively charged Pulse Forming Network (PFN) and the associated thyratron switches. The circuit external to the kicker magnet is ideal; similarly losses, mutual coupling and series capacitance associated with the cells of the magnet are neglected. The total self-inductance (L_t) of the kicker magnet is assumed to be 1.8 μH, connected in an external circuit whose characteristic impedance (Z) is 25Ω. Thus the nominal value of the total shunt capacitance (C_t) of the magnet is 2.88 nF $\left(C_t = \frac{L_t}{Z^2}\right)$.

The process of determining an optimum design for a kicker magnet was undertaken in several stages. The initial studies considered 'N' cell transmission line type magnets, for $1 \leq N \leq 24$. For $N \geq 4$ the N-2 inner cells of the magnet were considered identical. For $N \geq 3$, in order to account for end-effects, the end cell inductance is 100 nH larger than the inner cell inductance. The values of the shunt capacitors associated with the kicker magnet were optimized to provide the best Figures of Merit (FOMs) for the field quality. A 3 cell magnet was then studied further. Several sets of seeds and bounds for the capacitor values were used for the optimization process.

The rise-time definition used for determining FOMs is 72 ns, which is the nominal transit time $\left(\sqrt{L_t C_t}\right)$ through the 25 Ω transmission line magnet. In order to minimize field rise/fall time an additional allowance is not made for the rise/fall time of the trapezoidal voltage pulse.

2.2 Optimizer Program

The optimizer used in these studies was the Paragon program from MicroSim Corporation[7]. Paragon takes as input the parameterized schematic diagram of an analog circuit or system, together with a description of the goals and constraints of the optimization. Paragon implements both least-squares and minimization algorithms. In both cases the problem may be unconstrained or may be subject to arbitrary nonlinear constraints. Simple bounds on the parameters are also handled. The optimizer calculates parameter values, uses PSpice[7] to simulate the circuit with these parameters, and then uses Probe[7] to evaluate circuit performance.

The optimization algorithm used is a quasi-Newton Least Squares minimization subject to simple limits on the parameter values. A number of performance goals are defined. The optimization process then computes the residuals of these goals and the partial derivative of each goal with respect to the parameters. This information plus history from previous iterations is used to determine a search direction which minimizes the sum of squares of the residuals. The process is repeated until the specification criteria have all been met or until no further measurable progress can be made.

2.3 *Performance Goals*

Three FOMs are used to assess the quality of the kick; one for each of the pre-pulse, flat-top, and post-pulse period. The FOMs are proportional to the integral, with respect to time, of the deviation of the kick-strength outside of specified limits[8]: the integrals are each normalized to the nominal value of the kick-strength flat-top. Limits of ±1 % are utilized for these investigations.

Negative reflected charge is calculated and used to assess the severity of reverse current that a thyratron switch may conduct, as a conventional thyratron may arc back in metal-arc mode[9]. However a saturating inductor may be connected at the input to the kicker magnet to reduce the effect of thyratron displacement current upon the pre-pulse field[6] and/or remove the resonances attributable to the input cable from the longitudinal beam impedance spectrum[10]. During the post-pulse period magnetically stored energy is released from the saturating inductor which creates a 'tail' on the current pulse. This tail tends to oppose the effect of the negative reflected charge, therefore reducing its severity. Positive reflected charge would normally be terminated by a dump switch at the remote end of the PFN, so is not necessarily a problem. In this paper reflected charge is normalized to the equivalent PFN pre-charge.

Unless stated otherwise, the performance goals for optimization are the three FOMs.

3 RESULTS

3.1 *'N' cell kicker magnet*

In general the sum of the optimized capacitor values fell into one of two categories, which are termed the 'low' and 'nominal' capacitance solutions. The total capacitance for the low and nominal capacitance solutions asymptotically approach 1.44 nF and 2.88 nF, respectively, as the number of cells is increased (Fig. 2).

Fig. 2 shows the rms value of the three FOMs, the integral of the absolute value of reflected charge (total reflected charge), and the negative reflected charge during the post pulse period, as a function of the number of cells in the kicker magnet and total capacitance. The rms value of the FOMs for both an optimum 3 cell magnet (section 3.2) and an ideal transmission line kicker magnet are also shown on Fig. 2. For each point plotted Paragon has been used to optimize three values of shunt capacitance, namely the input capacitance (C_{input}), output capacitance (C_{output}) and, for N ≥ 2, the inner cell(s) capacitance (C_{inner}).

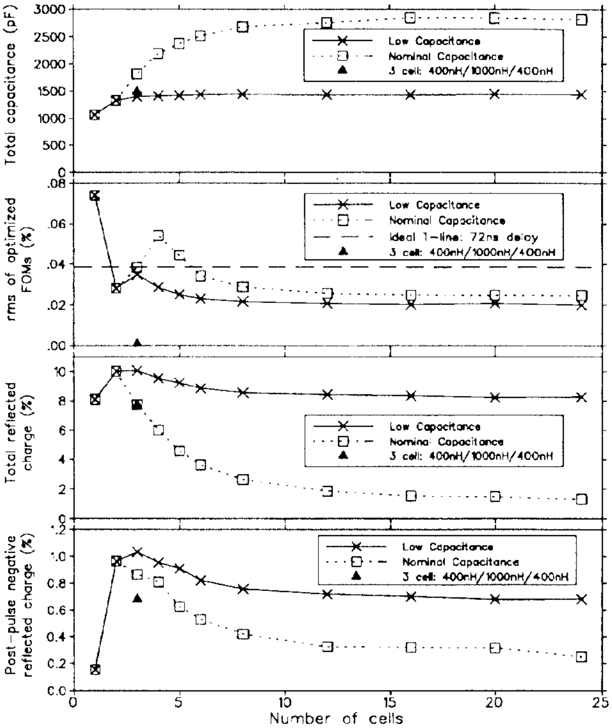

Figure 2: Dependence of various quantities upon both total capacitance and the number of cells

There is little benefit, from the perspective of field quality, from increasing the number of cells beyond 8 (Fig. 2). The rms value of the optimized FOMS for the low capacitance solution is better than for the nominal capacitance solution. However for N > 2 the reflected charge for the nominal capacitance solution is considerably better than for the low capacitance solution: in both cases there is little benefit obtained by increasing the number of cells beyond 8 (Fig. 2).

3.2 *3 cell kicker magnet*

A 3 cell magnet was investigated further. The two end cells were assumed to have an identical value of inductance. Several values of end cell inductance were considered: the central inductance value was such that L_t=1.8 μH. Paragon was then used to optimize C_{input}, C_{output} and C_{inner}. In general only one solution was identified for each value of end-cell inductance: the exceptions to this are for an inductance in the range of 600 nH to 700 nH (Fig. 3).

Fig. 3 shows the rms value of the three FOMs, the total reflected charge, and the negative reflected charge during the post pulse period, as a function of end-cell inductance. Fig. 3 also shows the rms value for the three FOMs for two 24 cell magnets and an ideal transmission line.

The end cell inductance which results in the best rms

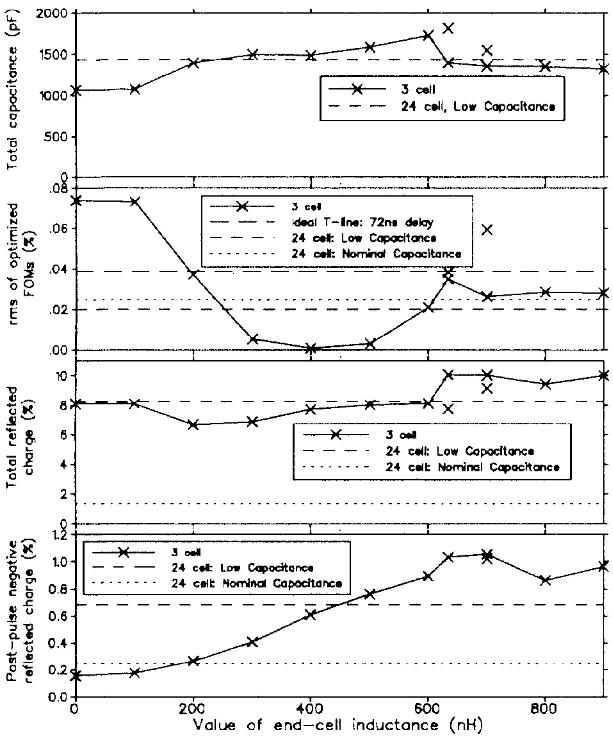

Figure 3: Dependence of various quantities upon the value of the end-cell inductance of a 3 cell magnet

value for the three FOMs is 400 nH. The rms value of the three FOMs is better for this optimized 3 cell magnet than for either 24 cell magnet or the ideal transmission-line.

The total reflected charge for a 3 cell magnet is in the region of 6.7 % to 10.1 % (Fig. 3). For an end-cell inductance up to 700 nH the post-pulse negative reflected charge increases with increasing end-cell inductance (Fig. 3), and is 0.6 % for an end cell inductance of 400 nH.

The 3 cell magnet optimization was rerun with an additional performance goal of minimizing post-pulse negative reflected charge: the value of each of the 3 inductors were allowed to vary, but the total inductance was constrained to be 1.8 μH. The optimum gives a rms value of the three FOMs (0.018 %), and a post-pulse negative reflected charge (0.22 %) which are better than the corresponding figures (0.025 % and 0.25 %, respectively) for the 24 cell, nominal capacitance, magnet. However the total reflected charge (5.7 %) is worse than for the 24 cell magnet (1.2 %).

3.3 Comparison and Comments

Fig. 4 shows the front-end of the predicted kick-strength, normalized to its flat-top value, for a 24 cell nominal capacitance magnet, an optimized 3 cell magnet with an end-cell inductance of 400 nH, and a 3 cell magnet whose capacitance values are each 720 pF (2.88 nF/4). The optimized 3 cell kicker magnet has a shorter rise-time than, and similar flat-top ripple to, the 24 cell magnet. The 3 cell magnet creates a large pulse of positive current through the thyratron, during the post-pulse period, but this is not necessarily a problem. If reflections do prove to cause reliability problems, an alternative option would be to consider the nominal capacitance version of a 5 or 6 cell kicker magnet: these magnets result in a significantly lower reflected charge than the 3 cell magnet (Fig. 2). If the value of end cell inductance for a 5 or 6 cell magnet were also optimized, an improvement similar to that obtained for the 3 cell magnet (section 3.2) would be expected.

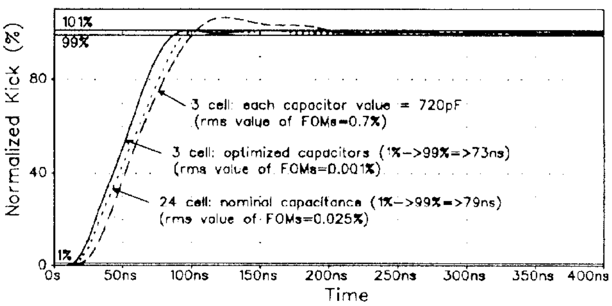

Figure 4: Predicted kick-strength for several kicker magnets

4 CONCLUSION

Paragon[7] has been utilized to determine optimum capacitor values for kicker magnets which have various numbers of cells. Various distributions of inductance for a 3 cell magnet have also been studied and the corresponding capacitor values optimized. An optimum 3 cell lumped inductance kicker magnet can give a field quality and post-pulse negative reflected charge which are better than those of a 24 cell transmission line magnet.

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