

LOW POWER MEASUREMENTS ON AN AGS INJECTION KICKER MAGNET

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Abstract

The present AGS injection kickers at A5 location were designed for 1.5 GeV proton injection. Recent high intensity runs have pushed the transfer kinetic energy to 1.94 GeV, but with an imperfect matching in transverse phase space. Space charge forces result in both fast and slow beam size growth and beam loss as the size exceeds the AGS aperture. An increase in the AGS injection energy to 2 GeV with adequate kick strength would greatly reduce the beam losses, making it possible to increase the intensity from 70 TP ($70 \cdot 10^{12}$ protons/s) to 100 TP. R&D studies have been undertaken by TRIUMF, in collaboration with BNL, to design two new kicker magnets for the AGS A10 location to provide an additional kick of 1.5 mrad to 2 GeV protons. TRIUMF has designed a 12.5Ω transmission line kicker magnet with rise and fall times of 100 ns, 3% to 97%, and field uniformity of $\pm 1\%$ over 85% of the aperture, powered by matched 12.5Ω pulse-forming lines. This paper describes the results of detailed capacitance and inductance measurements, on the prototype magnet, and compares these with predictions from electromagnetic simulations.

INTRODUCTION

The design for the Alternating Gradient Synchrotron (AGS) A10, 11 cell, transmission line kicker magnets [1], is based on a TRIUMF prototype 10-cell kicker magnet [2, 3], which was itself based on designs originated at CERN [4]. The transmission line type kicker (Fig. 1) consists of ferrite C-core sections sandwiched between high voltage (HV) capacitance plates. One C-core ferrite, together with its ground and HV capacitance plates, is termed a cell. Each cell conceptually begins and ends in the middle of the HV capacitance plates. Striplines, at the input and output of the kicker, have an impedance as close as possible to that of the kicker magnet.

Table 1: Existing A5 and proposed A10 kicker system parameters for 2 GeV protons

Parameter	Existing A5	Proposed A10
Deflection angle	2.48 mrad	1.5 mrad
Gap height	57.15 mm	81 mm
Gap width	127 mm	137 mm
Rise-time 3% to 97%	140 ns	100 ns
Fall time 97% to 3%	140 ns	100 ns
Flat-top Duration	0 to 2250 ns	0 to 1650 ns
Number of magnets	3	2
Magnetic field	24.2 mT	19.1 mT
Current	1100 A	1235 A
PFL Voltage	32.5 kV	30.9 kV
Magnet type	Lumped	Transmission line

[#] Now employed at CERN, Switzerland.

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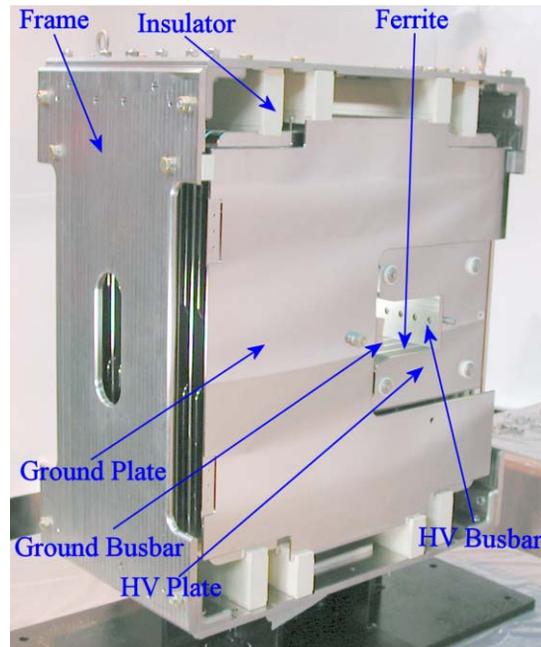


Figure 1: Prototype AGS A10 kicker magnet.

DESIGN CONSIDERATIONS

General

The rise-time of the magnetic field is dependent upon the rise-time of the input pulse, the delay of each cell (\sqrt{LC}), where L and C are the inductance and capacitance per cell of the kicker magnet, respectively, and the number of cells. To achieve rise and fall times of 100 ns (Table 1) two 11 cell kicker magnets are used, rather than one 22 cell magnet, each driven by its own pulse generator. The characteristic impedance (Z) of a cell is given by Eq. 1.

$$Z = \sqrt{L/C} \quad (1)$$

Impedance mismatches result in reflections which cause field ripple and potentially reduce the life of the thyatron switches. Therefore a carefully matched high bandwidth system is needed to obtain the required pulse response. Hence each of the two proposed A10 systems is composed of a Pulse Forming Line (PFL) and a travelling wave magnet, connected by a matched transmission line and terminated by a matched resistor (Fig. 2).

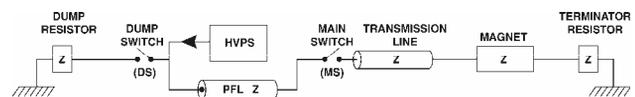


Figure 2: Schematic circuit of one kicker magnet system.

To obtain a compact and cost efficient design a low system impedance of 12.5Ω is chosen. Fig. 2 gives a circuit schematic for one of the kicker systems.

Simulations

The magnetic and electric fields associated with the aperture of the prototype A10 kicker magnet have been studied using 2D and 3D electromagnetic codes: the magnetic field simulations included the effect of eddy currents [5]. The shape of the aperture was optimized to achieve a design goal of $\pm 3\%$ deflection uniformity, for protons, throughout 90% of the aperture cross-sectional area. The predicted inductance of a central cell of the optimized geometry is 62.4 nH [5]. To achieve 12.5 Ω characteristic impedance, the required capacitance is therefore 399.2 pF per cell.

The capacitance of each cell is determined by the geometries of both the HV and ground plates. However edge effects of the plate result in a reasonable fraction of the capacitance of a cell, and thus the 3D code Coulomb [6] was used to predict the cell capacitance and finalize the geometry of the plates. The cell length is 30.06 mm and the thickness of each plate is modelled as 4.763 mm, which results in a plate separation of 10.267 mm. The selected geometry of the HV and ground plates gave a predicted central cell capacitance of 396.3 pF [7], which is within 0.73% of the 399.2 pF required for 12.5 Ω . The predicted edge effect capacitance for this plate geometry is 6.5 pF/m.

Fringe fields result in an appreciable increase in inductance per cell towards the ends of a kicker [3, 5]. Hence in order to obtain realistic inductance predictions the 3D eddy current code Elektra has been used to simulate the kicker magnet [5]. Elektra has successfully been applied, previously, to accurately predict the cell inductance of a transmission line type kicker magnet [3].

MEASUREMENTS

Capacitance

The thickness of the capacitor plates is less than expected: the measured thickness is between 4.56 mm and 4.59 mm, which gives an average plate separation of 10.455 mm, for a cell length of 30.06 mm. Scaling the cell capacitance, from the predicted value of 396.3 pF, with plate separation (10.455 mm, rather than the expected 10.267 mm), gives a cell capacitance of 389.2 pF.

The measured capacitance of the AGS magnet, using a Fluke PM6306 LCR meter [8], is in the range 4711.0pF to 4711.3pF: this is the capacitance for 12 sets of capacitor plates (11 cells). A frequency of 50 kHz was chosen for this capacitance measurement because the specified basic measurement accuracy of the PM6306 meter is best and is $\pm 0.1\% \pm 1$ digit (i.e. ± 4.7 pF ± 0.1 pF $\Rightarrow \pm 4.8$ pF) at this frequency [8]: this corresponds to ± 0.4 pF per cell.

The Coulomb 3D simulations predict that an end cell has a capacitance 9 pF greater than a central cell. Hence, correcting the measured capacitance for predicted end effects, results in an average capacitance of 391.1 pF ± 0.4 pF per central cell. This is within 0.5% of the theoretical value of 389.2 pF.

Inductance

To determine inductance per cell of the A10 kicker magnet, it was driven with a low voltage pulse with a 7 ns rise-time. Fig. 3 shows the propagation of the pulse through each of the 11 cells of the kicker. A high impedance low-capacitance probe was used for measuring voltage on each of the HV capacitance plates: the kicker was driven from a ~ 12.5 Ω source and terminated with a 12.67 Ω resistor. The ‘flat-top’ oscillations in Fig. 3 are damped out by an elapsed time of ~ 450 ns. These oscillations are excited by the fast (7 ns) rise-time of the input pulse; the rise-time of the actual HV pulse (~ 30 ns) would not excite such severe oscillations.

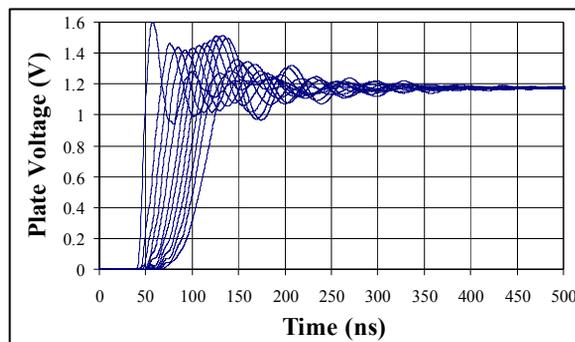


Figure 3: Pulse propagation through the prototype kicker.

The inductance of a cell was determined from the measured pulse propagation, by the following procedure:

- Calculate flux by integrating, up to 1150 ns, the potential difference between the two HV capacitance plates which sandwich the ferrite of the cell of interest;
- Divide the flux by the current flowing through the terminating resistor at ~ 1150 ns; the current is calculated from the voltage drop across the resistor.

The same probe was used to measure the voltage of each capacitance plate and the voltage across the terminating resistor. The measurement data was processed to remove the DC offset of the channel of the oscilloscope, and then normalized to the average of the voltage values in the time range of 1000 ns to 1150 ns: this normalization corrects for any drift in the output voltage of the pulse generator. Fig. 4 shows both measured and predicted cell inductance.

The measured and predicted cell inductances are in good agreement for all the central cells (#2 to #10) of the kicker magnet: the average of the measured inductance, for 7 central cells (#3 to #9), is 62.2 nH, only 0.3% less than the predicted value. However the measured inductance of the end cells is approximately 30% greater than the predicted inductance. CERN have used the above procedure to measure the cell inductance of many kicker magnets and have developed an equation for end cell inductance: namely the effective length of the end cell is increased by an amount approximately equal to one-quarter of the aperture height [9] (for the prototype KAON magnet the additional length was 21% of the aperture height and the measurement and predictions were

in good agreement [3]). For the AGS magnet the additional effective cell length would be 20.25 mm (81 mm/4) i.e. 67% of the physical cell length: this gives an end cell inductance of 104 nH, which is close to the predicted inductance of 99.3 nH. The discrepancy between the measured and predicted end-cell inductance is not yet understood, but may be due to the prototype AGS magnet being tested without striplines (Fig. 1): further tests are needed to determine if this is the reason.

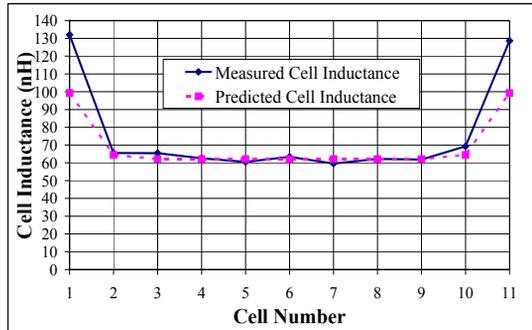


Figure 4: Measured and predicted cell inductance.

The measured propagation delay through the prototype A10 kicker magnet, at the 50% level, is 63 ns: the predicted propagation delay, for an end cell inductance of: (a) 99.3 nH is 64.5 ns, and (b) 130 nH is 67.0 ns. Thus the agreement between measured and predicted propagation delay indicates that the prototype A10 kicker end cell inductance is close to the theoretical value of 99.3 nH.

Magnetic Field

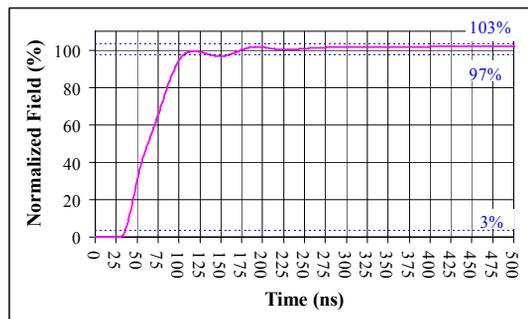


Figure 5: Measured magnetic field for prototype A10 kicker magnet (no peaking capacitors).

Fig. 5 shows the normalized field for the prototype A10 kicker magnet. The field is calculated from the integral, with respect to time, of the magnet input voltage minus the magnet output voltage normalized to the input voltage. Normalizing the output to the input voltage, before subtracting, compensates for losses in the busbars and also drift of the pulse generator. For the measurements the prototype kicker was not equipped with peaking capacitors, and hence there is no compensation for the end cell inductance being higher than that of a central cell. The rise-time of the magnetic field (Fig. 5), between 3% and the first 97% crossing, is 69.5 ns. The predicted 3% to 97% magnetic field rise-time is:

- 68.3 ns: no striplines or peaking capacitors, quality factor of 10 for cell inductance, 99.3 nH end cell

inductance;

- 65.1 ns: no striplines or peaking capacitors, quality factor of 10 for cell inductance, 130 nH end cell inductance;
- 95 ns: simulated A10 circuit, quality factor of 10 for cell inductance and 99.3nH end cell inductance.

The measured magnetic field rise-time is between 1.2 ns and 4.4 ns longer than predicted, however the rise-time is within the 100 ns specification.

CONCLUSIONS

Capacitance measurements carried out on the prototype A10 kicker magnet are in excellent agreement with predictions. The measured and predicted cell inductances are in good agreement for all the central cells (#2 to #10) of the 11-cell kicker magnet. The average characteristic impedance of a central cell is 12.61 Ω , 0.9% higher than the 12.5 Ω goal: almost 0.4 percentage points of this error is due to the design value of the cell capacitance being 0.73% below the theoretical ideal value. The measured inductance of the A10 kicker end cells is approximately 30% greater than the predicted inductance. The 3D code used for the prediction of cell inductance has previously been shown to agree well with measurements [3]. In addition the predicted end cell inductance, for the prototype A10 kicker magnet, is in reasonable agreement with a rule of thumb, which is itself based on many measurements, developed at CERN. The magnetic field rise-time is within the 100 ns specification.

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