INDUCTANCE CALCULATIONS AND MEASUREMENTS FOR THE CERN LHC INJECTION PULSE FORMING NETWORK

M.J. Barnes, G.D. Wait, TRIUMF, Vancouver, B.C., Canada.
L. Ducimetière, CERN, SL Division, Switzerland

Abstract

The injection kicker systems for the two LHC beams will each consist of four travelling wave magnets, four pulse forming networks (PFNs), and two resonant charging power supplies (RCPS). Each system must produce a kick of 1.3 Tm with a flattop duration adjustable between 4.25 µs and 7.8 µs, and rise and fall times of less than 900 ns and 3 µs respectively. Ripple in the field flattop must be less than ±0.5%. To achieve this stringent requirement, the PFN inductances are made of a continuous straight and rigid coil with constant and high precision pitch. Frequency dependence of the inductance and resistance of the PFN coil, as well as the effect of distortion during winding, are main issues and have been assessed via electromagnetic simulations. Component selection for the PFN was made on the basis of these theoretical models. A prototype PFN was built at CERN, without trimming of any component values. A system including the PFN, thyratron switches, terminating resistors, and the prototype RCPS built at TRIUMF has been set up. The system has been extensively tested and performs to specification. This paper describes 2D and 3D electromagnetic simulations of the PFN coil and compares the predictions with measurements.

1 INTRODUCTION

The European Laboratory for Particle Physics (CERN) is constructing the Large Hadron Collider (LHC). The LHC will be equipped with kicker systems for the injection of the incoming particle beams onto the accelerator's circular trajectory. Two pulsed systems, of 4 magnets and 4 PFNs each, are required for this purpose.

The 5 Ω PFN consists of two lumped element delay lines, each of 10 Ω, connected in parallel. There are two thyratron switches connected to the PFN, referred to as a main switch (MS) and a dump switch (DS). For the prototype PFN each 10 Ω line consists of 23 seven-turn cells, plus two end cells. A cell consists of a series inductor, a resistor connected in parallel, and a capacitor connected to ground. The capacitance values are graded linearly from the MS to the DS[1, 2]. The two coils are 3.85 m long, with 175 turns and a pitch of 22 mm. The conductor is a copper tube of 8 mm outside diameter and a wall thickness of 1 mm, wound on a rigid fibreglass coil former. The coils are not adjustable and therefore must be defined with high precision. Each coil is surrounded by a 3 mm thick Omega shaped aluminium screen that has an inner radius of 140 mm (Fig. 1). Both lines are mounted in a rectangular tank with mild steel walls.

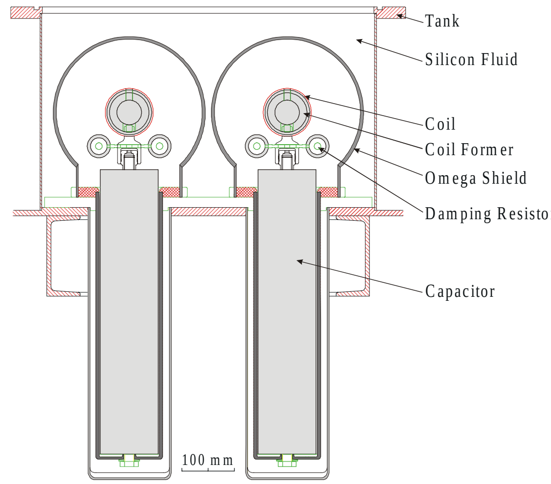

Figure 1: Schematic cross section of 5 PFN

2 PROTOTYPE PFN COIL DESIGN

Opera2D[3] simulations have been carried out to assess the frequency dependence of inductance and resistance of the coil[2]. The Omega shield and steel tanks are both modelled as circular. Fig. 2 shows the inductance of a 7-turn cell versus frequency for a mean radius of the coil of 41.5 mm. The "*Grover limits*" refer to values calculated from equations and are discussed in section 4.3.

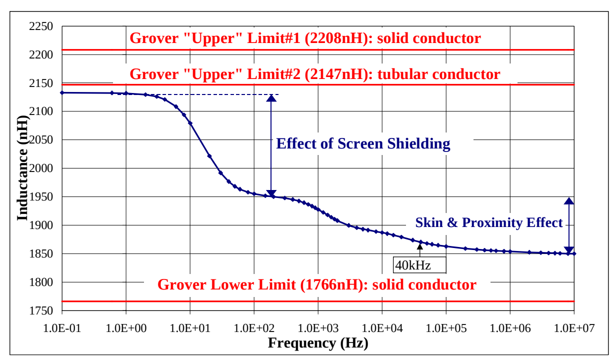

Figure 2: Inductance versus frequency for a 7 turn cell

The reduction in inductance as frequency is increased from DC to a few hundred Hertz is mainly due to screen shielding. The reaction field from the eddy currents induced in the Omega shield reduces the flux density along the axis of the coil from 0.343 T near DC to 0.315 T, for a current of 6 kA. As the frequency is increased beyond a few hundred Hertz the inductance decreases, mainly due to skin and proximity effect.

Conduction losses along the coil result in droop of the pulse of approximately 0.5% in the kicker magnet. PSpice[4] simulations show that constant loss in an (idealized) PFN coil can be compensated for by grading the capacitor values linearly from the MS end to the DS end. The required grading per cell (ΔC) is given by[5]:

$$\Delta C = R \times \frac{(2 \times Z - R)}{(Z - R)^2}, \text{ with } \quad Z = \sqrt{\frac{L}{C}},$$

where Z is the impedance of the PFN, and R, C and L are respectively the equivalent series resistance, capacitance and inductance per cell. This grading eliminates the droop resulting in a PFN of the correct impedance. Further PSpice simulations with a frequency dependent model for both conduction losses and inductance[1, 6] show that a linear grading of the capacitance by +0.08% per cell is required for eliminating the droop. From the above equation, 0.08% corresponds to a series resistance of 2 mΩ per cell, which is the calculated value at 25 kHz. However the predicted magnitude of the flattop is correct if the inductance of the coil is chosen at 63 kHz. As a compromise the mean radius of the coil is chosen such that the nominal inductance is stated at 40 kHz; this inductance is 5 nH per cell greater than at 63 kHz.

For the prototype PFN, the capacitors were purchased and, based on the actual measured values, the nominal mean radius of both coils was chosen to be 41.5 mm[1].

3 MEASUREMENTS & PREDICTIONS

The predicted kick pulse flattop ripple, of the prototype PFN with a nominal coil, was ±0.1%, and the duration of the PFN voltage pulse (without turning on the DS), at 90% of the flattop, 8.88 µs. The PFN was tested at voltages up to 60 kV[7]. A calibration procedure was developed to provide measurements on the ripple of a 30 kV pulse to a precision of ±0.1%[8]. Fig. 3 shows a measured pulse, which was obtained after compensation for the Tektronix 6015 probe[9] and the oscilloscope amplifier. The top of the measured pulse is flat to within ±0.3%, 600 ns after the end of a rise time of approximately 60 ns, without any adjustments of the PFN. The pulse duration, at 90% of the flat top (Fig. 3), is 9.06 µs, i.e. 2% greater than predicted. This error corresponds to approximately 4% error in the product LC of the PFN. The capacitance values are known to the ±0.1% level, and have negligible voltage dependence[10]. In addition measured parasitic capacitance, between each PFN capacitor and its coaxial housing, is modelled. Therefore the majority of the difference in the predicted delay is attributable to an error in the inductance value.

Detailed measurements of the outside diameter of the PFN coils show that the average mean coil radius is 42.1 mm, which is 1.4% greater than nominal. This results in an average increase in inductance of 2.7% (see Table 1). The average radius near the centre of the PFN is 1.5% and 0.8% greater than at the MS and DS ends, respectively. Further measurements show that the copper tube from which the coil is made is no longer round. The outside diameter, measured on the axis parallel to the axis of the coil, is between 0.15 mm and 0.30 mm larger than the nominal 8 mm. Since the former has grooves to fit the theoretical 8 mm circular cross section, it explains why the coil mean radius is slightly too large.

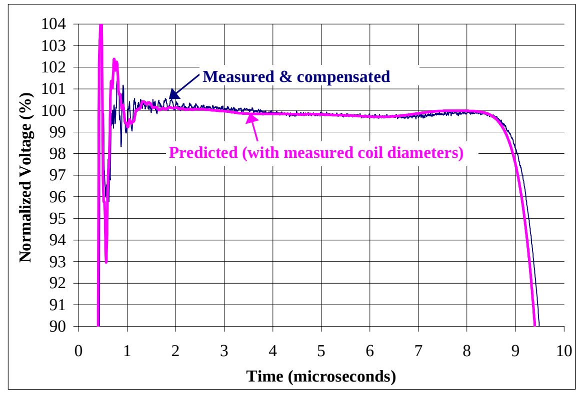

Figure 3: Measured and ‘predicted’ flattop portion of PFN voltage pulse each normalised to 100%

The ‘prediction’ in Fig. 3 is from PSpice with the PFN cell self-inductance and mutual coupling scaled with measured coil diameters. The variation in the coil radius explains the small dip in the waveform around 6 µs. The predicted pulse duration is then 9.00 µs, i.e. 0.65% less than measured. Therefore the simulated inductance is 1.3% less than that of the actual PFN coil. Further electromagnetic analyses of the coil have been carried out to identify this remaining 1.3% error.

4 ELECTROMAGNETIC ANALYSES

4.1 Effect of “Keystoning”

An Opera2D model has been used to assess the effect of the cross section of the conductor that is no longer circular after winding. The “keystoned” conductor has an outside “diameter” of 8.15 mm to 8.3 mm, measured longitudinally relative to the coil axis, and 7.7 mm to 7.8 mm measured radially. The coil model was modified to be two semicircular tubes joined by two straights, the straights being parallel to the axis of the coil. Simulations were run, at 40 kHz, to determine both self and mutual inductances. The results are shown in Table 1.

Table 1: Predicted Inductance for Various Geometries of Conductor, at 40 kHz

Mean Radius (mm)	Outside diameter of semicircular tube (mm)	Length of straights (mm)	Predicted Inductance (nH/cell)
41.5	8.0	0.04	1869
41.5	7.8	0.04	1882
41.5	7.8	0.4	1870
42.1	7.8	0.4	1921

Reducing the outside diameter of the tube by 0.2 mm, with negligible length (0.04 mm) of straight, increases the predicted inductance from 1869 nH to 1882 nH (+0.7%). However introducing straights of length 0.4 mm reduces the inductance back to close to the original value.

Opera2D has also been used to assess the effect of an error in the inside radius of the Omega shield: an increase in the average inside radius by 1 mm (0.71%) increases the predicted inductance, at 40 kHz, by 0.12%.

4.2 *Effect of the Helix*

All the 2D simulations are axisymmetrical. This means that each turn of the coil is modelled as a tubular ring around the central axis of the coil. Hence the 2D model neglects the effect of the helix of the coil. Therefore, a Tosca[3] 3D simulation has been carried out with the winding modelled as a helix: a five cell (35 turn) helix was modelled. Three cylinders, each of length 154 mm, the cell length, and with a radius of 140 mm (the shield radius) are meshed to simulate three cells. The inductance of the central cell is calculated from its predicted stored energy. For comparison, the 3D simulation was repeated with a purely axisymmetrical conductor. In both cases a tangential magnetic boundary condition was specified at a radius of 140 mm in an attempt to simulate the effect of screen shielding. The 3D simulations show that the helix has an inductance 0.7% greater than the purely axisymmetrical winding. However Tosca only weakly imposes the specified boundary condition, and hence a 3D eddy current simulation would be required to properly assess the effect of the helix.

4.3 Cross Check of Magnetic Predictions

As a crosscheck on the Opera2D predictions, the publication of F.W. Grover[11] has been used. Equation 118 on page 143 was used to calculate the low frequency inductance of a current sheet of mean radius 41.5 mm. The result is 2163 nH per cell. Equation 135 on page 163 was then used to correct the inductance calculated from equation 118 for insulation space for a coil of 175 turns. The correction per cell is 45 nH, giving a total inductance of 2208 nH/cell. This value is shown on Fig. 2 as "Grover Upper Limit#1". The Grover limits assume that the flux return path can be out to a radius of infinity, and that there is uniform current distribution in a solid conductor.

Any long straight conductor, with uniform current distribution, has an internal inductance of 50 nH/m. A long straight tubular conductor with inside and outside diameters of 6 mm and 8 mm, with uniform current distribution, has an internal inductance of 16.5 nH/m. "Grover Upper Limit#2" on Fig 2 has been derived from Upper Limit#1 by subtracting a correction for the internal inductance of an equivalent length (1.8 m per cell) of straight conductor. "Grover Upper Limit#2" is 1% greater than the predicted inductance at 0.1 Hz; this is attributable to the current density towards the axis of the coil being 10% greater than the uniform distribution value.

At higher frequencies the equivalent mean radius of the coil is less than 41.5 mm because the current is further concentrated towards the axis of the coil. The minimum equivalent radius of the nominal coil is 37.5 mm which, according to the current sheet formula, would give an inductance of 1766 nH per cell cell (Fig. 2). This value is reduced by a further 175 nH, to 1591 nH, to account for internal inductance of an equivalent length of tubular straight conductor (55 nH), and screen shielding (120 nH). The 1591 nH is 260 nH less than the predicted inductance at 10 MHz; this difference is due to the current free regions. The current distribution in each turn, away from the ends of the coils, does not affect the effective pitch at high frequencies[11]. However the ratio of the effective cross sectional diameter to pitch is reduced, leading to a larger correction for "insulation" space[11].

5 CONCLUSIONS

Non-adjustable coils have been entirely designed using PSpice and magnetic simulations. A prototype PFN has been constructed and has been successfully tested. Differences between predicted and measured waveforms have been analysed and understood to be due to the inductance of the prototype coil being 4% greater than expected. The main difference, 2.7%, is due to the mean coil radius being greater than designed. "Keystoning" of the conductor does not account for any further significant error. Using an axisymmetrical model, as opposed to a 3D helix model, may account for a further 0.7% of the error. Analysis of the 2D results has shown that the inside radius, rather than the mean radius, mainly determines the high frequency inductance. Hence attention will be paid to this during the manufacture of the series of PFN coils.

ACKNOWLEDGEMENTS

The authors acknowledge the help of staff at Vector Fields for their assistance modelling the helical winding.

REFERENCES

[1] M.J. Barnes, G.D. Wait, L. Ducimetière, G.H. Schröder, E.B. Vossenberg, "Kick Sensitivity Analysis for the LHC Inflectors", 23rd Power Modulator Symposium, California, June 1998, pp96-99.

[2] M.J. Barnes, G.D. Wait, L. Ducimetière, U. Jansson, G.H. Schröder, E.B. Vossenberg, "Kick Stability Analysis of the LHC Inflectors", 5th European Particle Accelerator Conf., Barcelona, June 1996, pp2591-2593.

[3] Vector Fields Inc., Illinois 60505, USA

[4] Cadence Design Systems Inc., Oregon 97223 USA.

[5] Private communications with J. Uythoven, CERN.

[6] M.J. Barnes, "Optimize SPICE models to accurately simulate frequency-dependent impedances", PEIN, December 1996.

[7] M.J. Barnes, G.D. Wait, E. Carlier, L. Ducimetière, G. Schröder, E. Vossenberg, "High Voltage Measurements on a Prototype PFN for the LHC Injection Kickers", IEEE Particle Accelerator Conf., New York, 1999, pp1509-1511.

[8] M.J. Barnes, G.D. Wait, L. Ducimetière, G.H. Schröder, E.B. Vossenberg, "Construction and 60kV Tests of the Prototype Pulser for the LHC Injection Kicker System", 12th IEEE Int. Pulsed Power Conf., California, June 1999, pp777-780.

[9] Tektronix Inc., Oregon 97070-1000, USA.

[10] M.J. Barnes, G.D. Wait, "High Current 66 kV Tests on High Stability PFN Discharge Capacitors for CERN LHC", 12th IEEE Int. Pulsed Power Conf., California, June 1999, pp773-776.

[11] F.W. Grover, "Inductance Calculations: Working Formulas and Tables", Dover Publications Inc., 1973.