EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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**CERN-AB-2008-057**

# UPGRADING THE FAST EXTRACTION KICKER SYSTEM IN SPS LSS6

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## Abstract

A fast extraction system, located in the LSS6 region of the CERN SPS accelerator, transfers 450 GeV/c protons, as well as ions, via the TI 2 transfer line towards the LHC. The system includes three travelling wave kicker magnets, all powered in series, energised by a single Pulse Forming Network (PFN) and terminated by a short circuit. The specification for the system requires a kick flattop of 7.8 μs with a ripple of not more than ±0.5%. Recent measurements with beam show that the ±0.5% kick specification is achieved over 7.1 μs of the kick flattop; however the ripple over 7.8 μs is ±0.75%. Initial electrical measurements have been carried out on each of the three magnets; more detailed comparisons of the beam measurements and the contribution of each magnet to the detailed shape of the flattop kick will be carried out. This paper reports the results of initial measurements and plans for future measurements to permit modifications to the PFN for reducing flattop ripple.

Presented at
EPAC'08, 11th European Particle Accelerator Conference, Genoa, Italy - June 23-27, 2008

*Geneva, Switzerland*
*August 2008*

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### *Abstract*

A fast extraction system, located in the LSS6 region of the CERN SPS accelerator, transfers 450 GeV/c protons, as well as ions, via the TI 2 transfer line towards the LHC. The system includes three travelling wave kicker magnets, all powered in series, energised by a single Pulse Forming Network (PFN) and terminated by a short circuit. The specification for the system requires a kick flattop of 7.8 μs with a ripple of not more than ±0.5%. Recent measurements with beam show that the ±0.5% kick specification is achieved over 7.1 μs of the kick flattop; however the ripple over 7.8 μs is ±0.75%. Initial electrical measurements have been carried out on each of the three magnets; more detailed comparisons of the beam measurements and the contribution of each magnet to the detailed shape of the flattop kick will be carried out. This paper reports the results of initial measurements and plans for future measurements to permit modifications to the PFN for reducing flattop ripple.

## INTRODUCTION

CERN, the European Laboratory for Particle Physics, is constructing the Large Hadron Collider (LHC) which will bring protons into head-on collisions at 2 x 7 TeV [1]. The LHC will be filled through a chain of injector machines. Two counter-rotating beams, which can collide in up to 4 interaction points, will circulate in two horizontally separated beam pipes. Each beam pipe will be filled by 12 batches of protons injected, at 450 GeV, successively on the machine circumference. An extraction kicker system installed in long straight section 6 (LSS6) of the Super Proton Synchrotron (SPS) will be used to provide a deflection, in the horizontal plane, in order to transfer protons as well as ions to the clockwise ring of the LHC. Table 1 summarizes the main parameters of the SPS extraction kicker system. Flattop ripple of the field pulse must be less than ±0.5%, a demanding requirement.

Table 1: SPS LSS6 extraction kicker system parameters

| | | |
|---|---|---|
| Beam momentum | 450 | GeV/c |
| Total system deflection angle θ | 37 | mrad |
| Number of magnets per system | 3 | |
| Characteristic impedance | 10 | Ω |
| PFN operating voltage | 33.1 | kV |
| Length per magnet | 1.674 | m |
| Specified 2-98% rise and fall time | ≤8.8 | μs |
| Specified kick flattop duration | 7.8 | μs |
| Specified kick flattop ripple | ≤±0.5 | % |

## KICKER SYSTEM

The three kicker magnets installed at LSS6 are travelling-wave type magnets, each consisting of 7 ferrite cells. There are 2 types of kicker magnet, referred to here as "L-type" and "S-type". The two L-type magnets have apertures of 147.7 mm by 35 mm: the S-type magnet has an aperture of 135 mm by 32 mm.

Prior to 2006 the LSS6 kicker system used two L-type and two S-type magnets [2], with individual PFNs, characteristically terminated in 10 Ω. During 2006 one S-type magnet was removed, providing a spare, and the output of the three series magnets was short-circuited. Compared with a characteristically terminated system, an otherwise identical short-circuit system has twice the rise and fall time, but only half the PFN voltage is required. The negative reflection generated by the short circuit travels through the magnets, PFN and an inverse solid state diode stack, and is absorbed by a matched dump resistor. The PFN capacitors are designed to withstand repetitive negative voltages. As a result of the negative reflection there is only significant voltage on the magnets during field rise and fall times. However the magnet voltage reverses during the field fall, hence the magnet closest to the PFN experiences a total voltage swing equal to the PFN voltage.

The 10 Ω PFN utilized is a 17 cell, single line, L-C network. A cell consists of a series inductor and a capacitor connected to ground. The inductors are ~105 mm diameter, 10 turns per cell, with a pitch of ~15 mm. The coil is not straight and continuous but rather has four 90° turns and a straight section above each capacitor: thus self-inductance of a cell and mutual inductance between cells are not well defined.

A thyratron switch, referred to as a Main Switch (MS), connects the PFN to 5 parallel 50 Ω coaxial transmission lines, each 175 m long, which go to the first kicker magnet (named L10). Coax cables connect from the output of L10 to the input of the second magnet (L9) and from the output of L9 to the third magnet (S6), whose output is short-circuited.

### *Measurements with Beam*

During 2007 the MKE kick waveform for LSS6 was measured with beam (Fig. 1), by changing the kicker timing and measuring the beam position. Fig. 1 shows that the 'ripple' is ±0.75% over the specified 7.8 μs, which exceeds the specification of ±0.5%. The field overshoot, which occurs prior to the 7.8 μs flattop specification, is within the specified rise-time of 8.8 μs.

The total beam deflection at a given downstream location depends on the field in the aperture, phase advance and beta functions between the kicker and point of observation. Hence the location of the kicker has an influence on its relative strength. The beam passes through the aperture of magnet L10 before passing through the aperture of magnets L9 and then S6. Magnet L10, L9 and S6 provide approximately 35.2%, 33.3% and 31.5%, respectively, of the kick shown in Fig. 1.

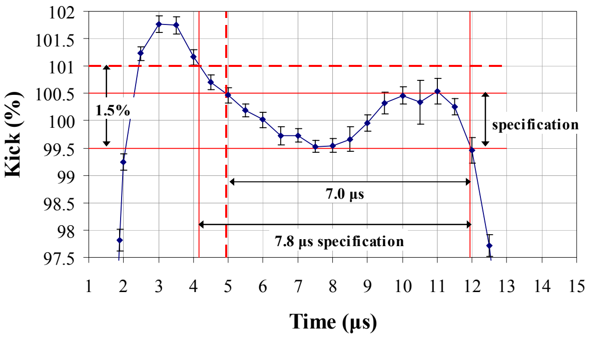

Figure 1: LSS6 kick, measured with beam.

## *Electrical Measurements of Field Pulse*

To reduce the flattop 'ripple' it is proposed to adjust individual cells of the 17 cell PFN. The shape of the pulse is tuned, at 50 V, while discharging the PFN into a 10 Ω resistive load, by adjusting the appropriate cells of the coil. Hence, to properly carry out the adjustments, it is necessary to be able to accurately relate electrical measurements to the measured beam deflection.

The LSS6 installation includes a high precision Bergoz Current Transformer (CT) mounted on the short-circuit output of magnet S6; unfortunately no other CTs are installed adjacent to the three magnets. Since the single-way delay of each magnet is ~1.1 µs, the instantaneous CT current does not accurately reflect the instantaneous current flow at the input or output of the other two magnets. Thus the measured current cannot be used to calculate the field in each of the magnets.

Pulsed field measurements are typically carried out on an individual magnet by two different methods:

- with an inductive probe in the magnet aperture as an absolute field reference; this method cannot be used after the magnet is installed in the accelerator;
- with a magnet's Capacitive Pick-Ups (CPUs), which still permit measurements once the magnet is installed in the accelerator.

There is a CPU installed on the input and output of each magnet [3]. The CPU consists of a Class 2 ceramic capacitor with one electrode connected to ground. The other electrode of the ceramic capacitor, which is connected to a coaxial feedthrough, faces towards the HV end plate of the magnet; there is stray capacitance, typically of a few tens of femto-Farads, between the HV end plate and the ceramic capacitor. The stray capacitance and ceramic capacitor form a divider. A low-inductance 50 Ω resistor is series connected between the output of the feedthrough and a low loss coaxial cable; the resistor helps to terminate reflections on the coax. The coax is connected to a high impedance input of the measurement equipment. However the measured voltage droops due to the non-infinite input impedance; the measured flattop of a 10 µs pulse typically droops by 0.4%. Provided that the value of the ceramic pick-up capacitor, the capacitance of the coaxial cable and the input impedance of the measurement equipment is known, this droop can mostly be mathematically compensated for. However, it has recently been shown, on a different kicker system, that the value of the Class 2 ceramic capacitors typically used exhibit frequency dependence and reduces in value by ~8% between 100 Hz and 1 MHz. The effect of the frequency dependence should be compensated for, so as to avoid both underestimating the droop associated with the higher frequency components and introducing an unrealistic offset in the interpreted post pulse field.

The field in a kicker magnet can, from Faraday's law, be determined by the integral with respect to time of the difference of magnet input and magnet output voltage. The value of stray capacitance, between a magnet HV plate and one an electrode of the ceramic capacitor, is not well defined and hence the ratio of magnet voltage to the magnitude of measured voltage is not precisely known. Hence the CPU technique is ideally suited to a magnet resistively terminated in its characteristic impedance; in this case the magnitude of the input pulse, at an elapsed time chosen to correspond to a "ripple free" flattop part of the pulse, and the magnitude of the output pulse, at a later time corresponding to the single-way delay of the magnet, can be normalized to the same value. Thus, when the input and output voltages, measured via the CPUs, are subtracted there is not a "residual offset voltage" attributable to a difference in the divider ratio of the two CPUs. The normalization also compensates for small differences in calibration of the channels of the oscilloscope (assuming the calibration does not change during the measured pulse). If this normalization is not carried out, the resulting residual voltage is integrated and wrongly interpreted as a slope of the flattop field. A residual voltage can result in a significant error: a residual voltage of 1% during the flattop results in an artificial field flattop slope of 10% over a 10 µs interval.

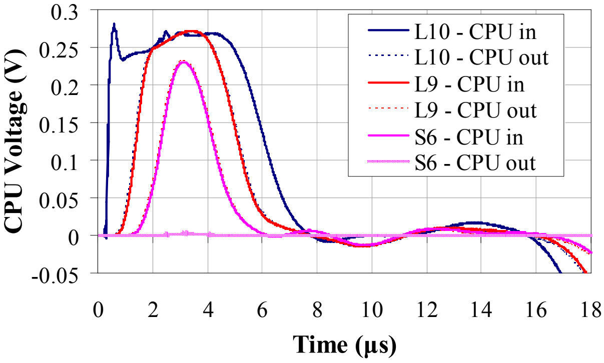

Figure 2: Measured voltage (magnets in accelerator), via CPUs, during field rise and flattop.

For a magnet terminated in a short-circuit there is only voltage present transiently, during the rising and falling edges of the field pulse; thus it is not possible to normalize the measured input and output signals. Hence recent CPU measurements, on each of the 3 magnets in LSS6 (Fig. 2), could not be reliably interpreted to provide the field shape. Investigations are currently underway, in the HV laboratory, to develop a measurement technique, for the CPU, for use with short-circuited magnets.

### *Measurement Plan*

The preliminary plan is to make measurements firstly on a resistively terminated magnet and subsequently on the same magnet terminated in a short-circuit. The measurements for both magnet terminations will include: input and output current; voltage induced in an inductive probe placed in the aperture of the magnet; voltage of the input and output CPUs. The CPU measurements on the resistively terminated magnet will allow the relative normalization factors to be determined; these factors will then be used to interpret the CPU measurements on the short-circuited magnet. However the factors include an allowance for both the divider ratio of the CPUs and the calibration of the two channels of the oscilloscope. Thus special care will be taken to ensure that each CPU is always sampled via the same channel and the sensitivity of each channel is the same for both sets of measurements.

### *Magnet Current*

A spare L-type magnet in the laboratory has been connected with five parallel, 200 m long, 50 Ω coax cables on the input: a metal box, containing a Bergoz CT, is connected on the magnet end of one of the 200 m cables. The metal box forms a "coaxial" return for the current through the CT. A 2.98 m long cable initially connected the output of the metal box containing the CT to the input of the magnet. Similarly a 2.9 m coax cable was used to connect each of the other four 200 m long cables to the magnet; thus the overall lengths of all five cable lengths, between MS and magnet input, were initially 202.9 m to 202.98 m.

For the measurements on the resistively terminated magnet four 4.9 m long, 50 Ω, coax cables are connected from the output of the magnet to the terminator. The fifth connection from the magnet output to the terminator is made with a 1.8 m coax from the magnet output to a 2nd metal box, containing a CT; a 2.2 m and a series 2.35 m coax connect from the CT box output to the terminator.

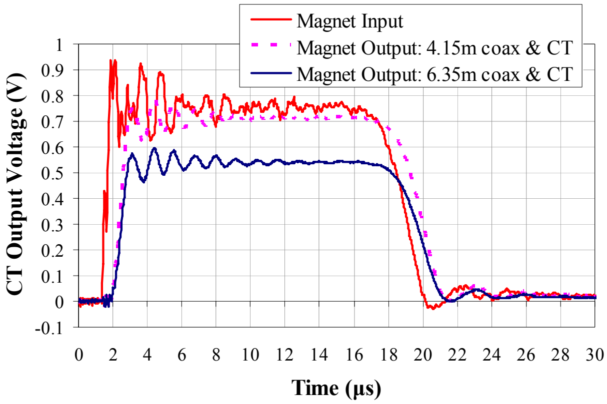

Figure 3: Measured CT output voltage, for magnet output cable lengths of 4.15 m and 6.35 m.

It was initially assumed that the CTs would measure one-fifth of the input and output currents. However the first measurements indicated that the magnet output current was almost 30% less than the magnet input current (Fig. 3). Measurements confirmed that the metal box housing the CTs was not directly influencing the current measurement and that, in a bench test, the flattop current from the two CTs agreed to better than 1.2%. The 30% difference between input and output CTs was partly due to the fact that the presence of the CT box introduces an additional delay of ~4 ns. PSpice simulations, of lossless transmission lines, show that to obtain current sharing to within ±1% of the mean current, the overall delay between the magnet output and the terminator has to be within 0.3 ns (6 cm) for each of the five parallel paths. Removing the 2.2 m cable, in series with the output CT, reduced the difference between the measured input and output currents to 6% (Fig. 3).

PSpice simulations of the 200 m coax cables on the input of the magnet show that sharing of the pulse current is not substantially influenced by the additional delay of the path containing the input CT box. However, an extra 4 ns delay, of the path containing the CT, results in ~30 ns duration (i.e. similar to the rise-time modelled) current transients of −13% of the flattop current; these transients are not necessarily present in the magnet current. In order that any transients introduced by differences in delays are ≤0.25% of the pulse current, the relative delays of the 5 parallel paths have to be within 80 ps.

## CONCLUSIONS

CPU measurements have been carried out on the, short-circuited, LSS6 magnets in the accelerator. Due to limitations in the measurement technique the voltage data cannot be reliably translated into field. Hence, to further develop the technique, detailed measurements of a resistively terminated magnet have commenced. Problems associated with the measurement of the pulsed current are now understood and are being corrected. The field will be carefully measured using both the inductive and capacitive probes. Subsequently detailed measurements will be carried out on the magnet terminated in a short-circuit. If the proposed method of "calibrating" the CPUs proves to be effective, this procedure will be carried out on each of the three magnets installed at LSS6.

## ACKNOWLEDGEMENTS

The work described in this paper is the result of the efforts of many people. Of special note are the contributions of P. Burkel, N. Depotex and Y. Sillanoli.

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