BEAM-BASED MEASUREMENT OF THE WAVEFORM OF THE LHC INJECTION KICKERS

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Abstract

Proton and ion beams are injected into LHC at 450 GeV by two kicker magnet systems, producing magnetic field pulses of up to 7.8 μs flat top duration with rise and fall times of not more than 900 ns and 3 μs, respectively. Both systems are composed of four travelling wave kicker magnets, powered by pulse forming networks. One of the stringent design requirements of these systems is a field flat top and post-pulse ripple of less than ±0.5%. A carefully matched high bandwidth system is required to obtain the required pulse response. Screen conductors are placed in the aperture of the kicker magnet to provide a path for the image current of the, high intensity, LHC beam and screen the ferrite against wake fields. However, these conductors affect the field pulse response. Recent injection tests provided the opportunity to directly measure the shape of the kick field pulse, with high accuracy, using a pilot beam. This paper details the measurements and compares the results with predictions and laboratory measurements.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with kicker systems for injecting the incoming particle beams onto the accelerator's circular trajectory. The preservation of the transverse emittance of the proton beam, at injection into the LHC, is crucial for luminosity performance. The transfer and injection process is important in this respect, and injection errors (angular or displacement) are a well-known source of beam blow-up. Hence this led to a very tight specification for the injection kicker ripple. The maximum allowed injection error into the LHC was specified as 1.5σ (where σ is the equilibrium beam size) in either plane [1], which resulted in a specification of the maximum ripple of the SPS extraction and LHC injection kickers of ±0.5 %.

The ripple of some of the LHC injection kickers has previously been measured with an inductive probe, for different pulse durations [2]. High-frequency ripple was observed at the start of the pulse flat top on both MKI magnets that were measured. However it was not known whether the high-frequency ripple was real or introduced by the measurement system. Recent measurements have been carried out with beam to map out the deflection waveform.

MKI SYSTEM DESIGN

The two LHC injection kicker systems each consist of four magnets, four Pulse Forming Networks (PFNs) and two resonant charging power supplies. The two kicker systems (named MKI2 and MKI8) generate magnetic field pulses of approximately 900 ns rise time, 3 μs fall time and up to 7.86 μs flat top duration. Each kicker magnet is 2.7 m long [3]: conductive stripes in the aperture of the magnets limit the beam impedance and screen the ferrite [4].

The kicker systems have 5 Ω characteristic impedance: each PFN consists of two lumped element delay lines, each of 10 Ω, connected in parallel. Two thyratron switches are connected to the PFN, referred to as Main Switch (MS) and Dump Switch (DS). Each 10 Ω PFN line consists of 26 central cells plus two end cells. A cell consists of a series inductor, a damping resistor connected in parallel, and a capacitor connected to ground. The inductors are part of a single continuous coil, 4.356 m long, with 198 turns and a pitch of 22 mm. The 26 central cell inductors are made of 7 turns each: these central cells are not adjustable and therefore must be defined with high precision. The nominal MS and DS end cell inductors have 9 turns and 5 turns respectively, but are built with one extra turn to allow some adjustment to compensate for end effects [3]. Both delay lines are mounted in a rectangular tank with mild steel walls (Fig. 1) that is filled with insulating silicone fluid. Each line is surrounded by a 3 mm thick, Ω-shaped, aluminium screen, which has an inner radius of 140 mm (Fig. 1). The complete electrical circuit has been modelled with PSpice. The simulations show that a 1% decrease in the MS end cell inductance gives up to 0.17% increase in the kick for the first 400 ns of the flat top.

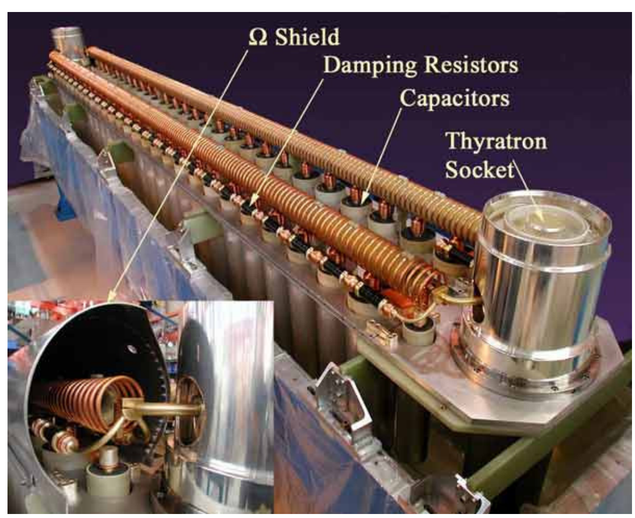

Figure 1: PFN during assembly showing capacitors in coaxial housings, damping resistors, precision coils and thyratron connection sockets; Ω shield at lower left.

MEASUREMENTS & PREDICTIONS

Initial Measurement with Beam

The waveform of the LHC injection kickers was measured accurately with an LHC-type single bunch pilot beam, by varying the kick delay for the injected bunch and recording the position of the single bunch on BTV displays. In order to obtain a calibration of the measurement, the PFN voltage was set to a known value, the kick delay set such that the injected beam was approximately in the centre of the (flat) field pulse, and the position on the BTV screen noted. This procedure was repeated for several values of PFN voltage.

A typical BTV display is shown in Fig. 2: the beam position is clearly seen, however there is some noise on the display. An online numerical analysis of this display gives the position of the beam, but this value can be affected by the noise. A more detailed analysis is carried out off-line in which the noise is removed before analysis, and a 3D fit is made to the beam central position, giving a more accurate value for the beam position.

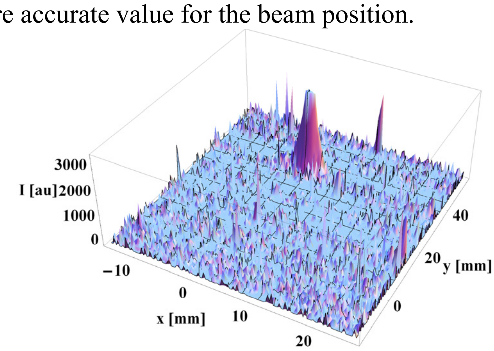

Figure 2: 3D display of beam position.

Fig. 3 shows the measured beam deflection waveform for the clockwise injection (MKI2) and the anti-clockwise injection (MKI8) of beam. Significantly more data was taken for MKI8 than for MKI2, however, as expected, the measured deflection waveforms are very similar. The estimated error bars, for the given measurements with beam, are ±0.3%. In general the deflection waveforms are within the specified tolerances, except for the front-end of the flat top which overshoots by ~2%, and is above the 0.5% specification for ~400 ns.

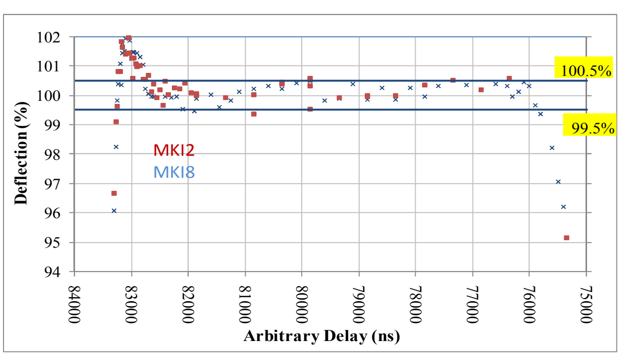

Figure 3: Measured deflection waveform for MKI2 and MKI8 (PFN MS end cells adjusted to 7.5 turns).

Comparison of Measurements and Predictions

Fig. 4 shows both a flat top magnetic field measured using an inductive probe [2], for a kicker magnet pulsed using a representative PFN, and also the deflection measured with beam for MKI8. The inductive probe measurement overshoots by approximately 1% and the first 2 µs of the flat top exhibits ~8 MHz damped ripple. The measured beam deflection, which has a time resolution of 25 ns from 1.25 µs to 1.7 µs, overshoots by almost 2.2%: this waveform does not exhibit the 8 MHz ripple. Hence the ~8 MHz ripple, measured with an inductive probe, is an artefact of the measurement.

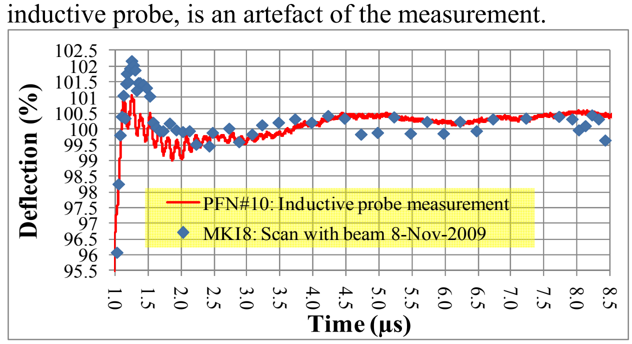

Figure 4: Flat top magnetic field measured for a kicker magnet pulsed using a representative PFN, and deflection measured with beam for MKI8; 7.5 turns for MS end cells.

Detailed PSpice simulations of a kicker magnet system, including the kicker magnet beam screen, measured diameters of PFN coils (for scaling nominal cell inductance), and measured PFN capacitor values, have been carried out. These simulations were run for MS end cells with 7.5, 8, 8.5 and 9 turns modelled. In each case the magnetic field was calculated by integrating, with respect to time, the difference between the predicted input and output voltage of the kicker magnet. Fig. 5 shows the first 2 µs of the flat top of the predicted field together with the deflection measured with beam, for MKI 8. The MS end cell affects the first 500 ns of the flat top. For the measured deflection the PFN MS end cells had 7.5 turns: the predicted field, with 7.5 turns, is very similar to that measured except that the measurement exhibits a more smoothed first peak.

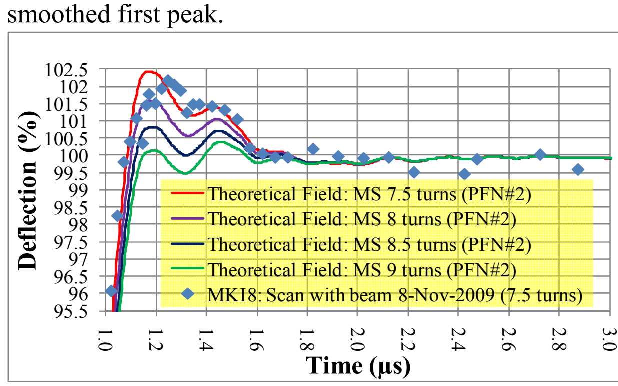

Figure 5: Predicted field together with the deflection measured with beam, for MKI8.

Re-measurement with Beam

During January 2010 the MS end cells of the 4 PFNs of both MKI2 and MKI8 were adjusted to 8.25 turns. From Fig. 5, 8.25 turns are expected to reduce the field overshoot from 2.2% to 1%. A new measurement with beam was carried out during March 2010. Fig. 6 shows the measured flat top deflection for MKI8, with beam, with 7.5 turns and 8.25 turns: 8.25 turns results in an overshoot of 1%. The good agreement in Fig. 5 between 7.5 turns theory and the measured waveform, confirmed by the recent measurements with 8.25 turns, shows that the PSpice predictions can be used to choose the optimum adjustment for the MS end cells. The measurements shown in Fig. 6 indicate that the flat top is extended by ~200 ns for the recent measurements with 8.25 turns: this is not due to the adjustment of the MS end cells.

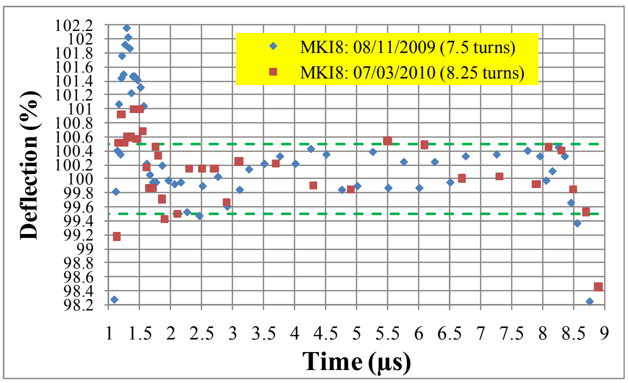

Figure 6: Measured flat top deflection for MKI8 for PFN MS end cells with 7.5 turns or 8.25 turns.

Fig. 7 shows the measured rising-edge of the deflection for MKI8, with beam, for 7.5 turns or 8.25 turns. The time resolution during the pre-pulse period and rising edge is generally 100 ns. The rise-time, 0.5% to 99.5%, is between 840 ns and 900 ns: however increased resolution of measurement data is required to determine the actual rise time. In addition more data is required in the pre-pulse period, to both better determine the zero-level and assess noise in the measurement.

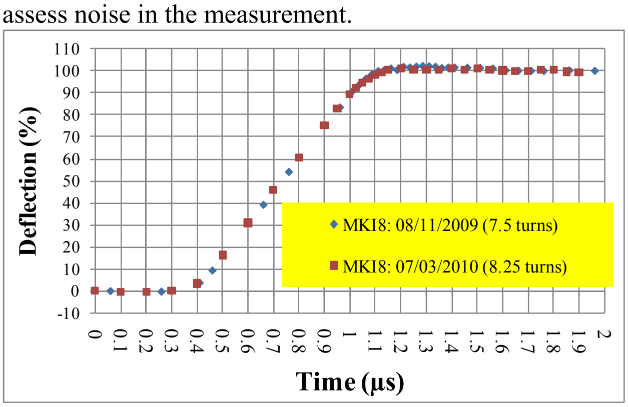

Figure 7: Measured rise of deflection for MKI8 for PFN MS end cells with 7.5 turns or 8.25 turns.

Fig. 8 shows the post-pulse deflection for MKI8, measured with beam, for 7.5 turns or 8.25 turns. The time resolution during the post-pulse period is 200 ns up to an elapsed time of 11.7 µs. There is only a single measurement point after 11.7 µs for the 8.25 turns: thus insufficient post-pulse data is available to confirm the deflection fall time. However, neglecting the "noise" in the 7.5 turn data at 16.4 µs, the fall time of the deflection, between 99.5% and 0.5%, is between 3 µs and 4 µs: the 4 µs is due to a single point at 12.4 µs exceeding 0.5%.

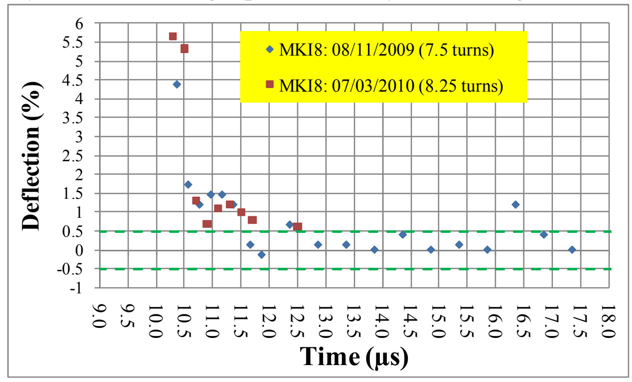

Figure 8: Measured post-pulse deflection for MKI8 for PFN MS end cells with 7.5 turns or 8.25 turns.

CONCLUSIONS

The flat top of the deflection waveforms for the LHC injection kickers has been measured with beam. With 7.5 turns, for the PFN MS end cells, the front-end of the deflection overshoots by 2.2%: this overshoot is reduced to 1% by changing the MS end cells to 8.25 turns. Further adjusting the MS end cells to 8.75 turns is expected to reduce the overshoot to 0.5%. The rise-time of the deflection is between 840 ns and 900 ns. However the pre-pulse period and the rising edge were generally measured with 100 ns resolution: higher resolution is required to determine the actual rise-time. Similarly the measurements need to be extended further into the post-pulse period, with a resolution of ~200 ns, to determine whether the fall-time meets the 3 µs specification and if the post-pulse ripple is less than 0.5%. Several sets of data are needed for each measurement to reduce the noise.

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