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Calibration Measurements of the LHC Beam Dumping System Extraction Kicker Magnets

J. Uythoven, F. Castronuovo, L. Ducimetière, B. Goddard, G. Gräwer,
F. Olivieri, L. Pereira, E. Vossenberg
CERN, Geneva, Switzerland

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CALIBRATION MEASUREMENTS OF THE LHC BEAM DUMPING SYSTEM EXTRACTION KICKER MAGNETS

J. Uythoven*, F. Castronuovo, L. Ducimetière, B. Goddard, G. Gräwer, F. Olivieri, L. Pereira, E. Vossenberg, CERN, Geneva, Switzerland.

Abstract

The LHC beam dumping system must protect the LHC machine from damage by reliably and safely extracting and absorbing the circulating beams when requested. Two sets of 15 extraction kicker magnets form the main active part of this system. They have been produced, tested and calibrated by measuring the integrated magnetic field and the magnet current at different beam energies. The calibration data have been analysed, and the critical parameters are compared with the specifications. Implications for the configuration, control and operation of the beam dumping system are discussed.

INTRODUCTION

The LHC Beam Dumping System [1] consists per LHC ring of 15 horizontally deflecting extraction kicker magnets MKD, 15 vertically deflecting septum magnets and 10 dilution kicker magnets, followed by several hundred meters of beam transfer line before the extracted beam reaches the dump absorber block. The energy stored in one nominal LHC beam is 360 MJ, about a factor of 200 larger than at HERA or at the Tevatron.

The MKD kicker system [2] is the most safety critical and most complex element of the Beam Dumping System as a fault in the system can lead to significant damage of LHC equipment. The extraction of the beam from the LHC takes place under a fixed angle of 0.275 mrad by the MKD magnets; as a result the MKD system needs to track the beam energy (between 450 GeV and 7 TeV). The maximum operating voltage of the MKD system is 30 kV for a pulsed current of 19 kA. The yoke length is 1.35 m with a maximum integrated field strength of 0.43 Tm.

The most critical parameters of the MKD pulse are the rise time and the synchronisation. The LHC has a beam free gap of 3.0 μs into which the rise time of the kicker needs to fit. To allow for variations (synchronisation errors, measurement precision etc.), the rise time of the pulse has to be smaller than 2.85 μs. The delay between pulse trigger and the moment of reaching the 100 % field level should also be the same for all 15 MKD systems and for all beam energies.

The aperture of the downstream extraction channel allows for a variation of the extraction angle up to 10 %. Taking into account some system variations (error on the knowledge of the beam energy, pulse stability etc.) the kicker pulse 'overshoot' is specified to be within an amplitude window of 7.5 %. A measured magnetic field pulse is presented in Fig. 1. Both the measured current and the measured magnetic field pulse are characterised by 6 points: Lower Threshold (Low TH), two 100 % points, overshoots OS1 and OS2 and End point (End). The end point has been specified to be at least 91 μs after the 100 % field level has been reached for the first time (the revolution time is 89 μs).

The rise time of the pulse has been calculated from Low TH to the 100 % field value. Low TH corresponds to 0.5 σ, where σ is the beam size which varies with beam energy. As a result the rise time is calculated between 0.86 % and 100 % of the field level for the beam at injection energy and 0.22 % and 100 % at full energy. This definition has been chosen because the protection of the LHC ring from a sweep of the kicker magnets by the TCDQ collimator [1] is also expressed in σ of the beam size.

Calibration of the extraction kicker system is required to verify the correct functioning of all elements before installation in the LHC. The calibration procedure includes the measurement of the integrated magnetic field in the aperture [3]. The relationship with the measured magnet current is established. Once installed in the machine, the magnetic field can not any more be measured. The estimated absolute accuracy of the field measurements is 0.5 %, with a relative accuracy of 0.2 %.

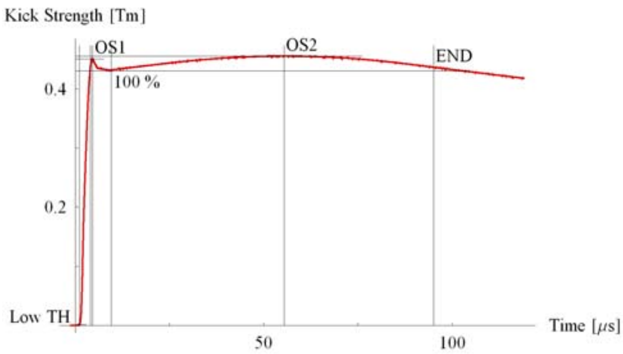

Figure 1: Measured integrated magnetic field for a 7 TeV beam.

CALIBRATION PROCEDURES

Detailed calibration procedures were published and agreed upon before the series measurements started [4]. All magnets have been calibrated using the same generator and the same metal coated ceramic chamber. The calibration of all generators is presently ongoing; here in turn the same magnet and ceramic chamber are used for the different generators. A calibration has also been performed for three different ceramic chambers, covering the span in resistances of the chambers which will be installed in the LHC.

*jan.uythoven@cern.ch

The magnet calibration has been carried out for 6 different kick strengths, relating to different beam energies. The generator and ceramic chamber have been calibrated for 18 different beam energies.

Field map and stability measurements have also been performed but are not discussed in this paper, as they comply with the requirements.

CALIBRATION OF THE MAGNETS

All magnets have been measured to be within specification, with the rise time remaining a critical parameter. The spread in rise time between the different magnets (at a given energy) is about 50 ns. The spread in measured integrated field strength is about 1 %, depending on the beam energy, see Fig. 2. Following this measurement the magnets will be installed in the machine with the strongest magnet the furthest away from the extraction septa, to optimise the lever arm.

The delay between the trigger time and the moment of reaching the 100 % current level was measured to vary by about 125 ns for the different magnets. This spread was not found back in the magnetic field measurements and the difference was explained by the different characteristics of the current transformers 'attached to the magnets' and will need to be taken into account during operation, see Fig. 3.

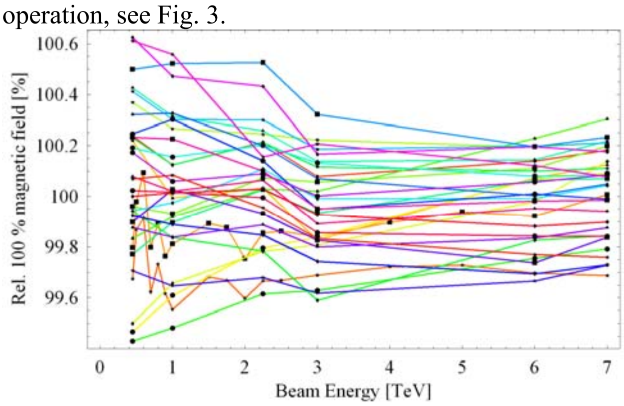

Figure 2: Relative field strength for all 32 calibrated magnets for the different LHC beam energies. The same generator settings were used for all magnets.

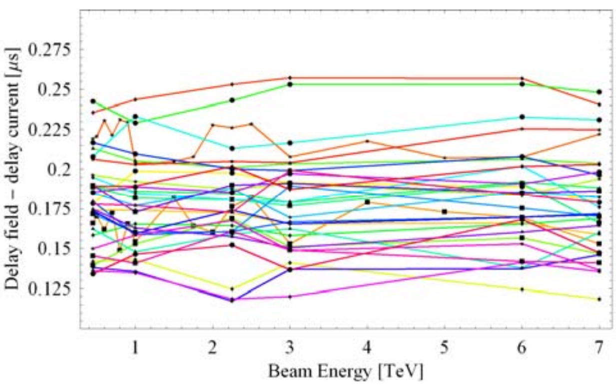

Figure 3: Difference in delay between the 100 % point of the magnet field and the 100 % point of the current for the 32 calibrated magnets.

CALIBRATION OF THE GENERATORS

The generator calibration has so far been performed for 14 out of the 32 generators. The trigger voltage has been optimised for each beam energy and for each generator to obtain a constant delay between the trigger and the first 100 % field point for all beam energies. Without this adjustment the variation for the different beam energies is about 150 ns (not seen in Fig. 3 as the dependence is the same for both field and current). The optimised trigger voltages are shown in Fig. 4; two different 'groups' can be identified for the two different switch manufacturers which have been used. The resulting synchronisation of the magnetic field is shown in Fig. 5 and has a remaining error of about 25 ns which is similar to the measurement error. The 'constant' difference between the generators (the current transformer being identical) will be compensated for at installation by using a different passive delay for each generator.

The measured rise time for the different beam energies is given in Fig. 6. It shows that the rise time is not within the specification of 2.85 μs for all generators and for all energies. As in Fig. 4, two groups can be identified, depending on the switch manufacturer. The effective extraction kick rise time of 15 MKD systems can be reduced by mixing "slow" and "fast" generators.

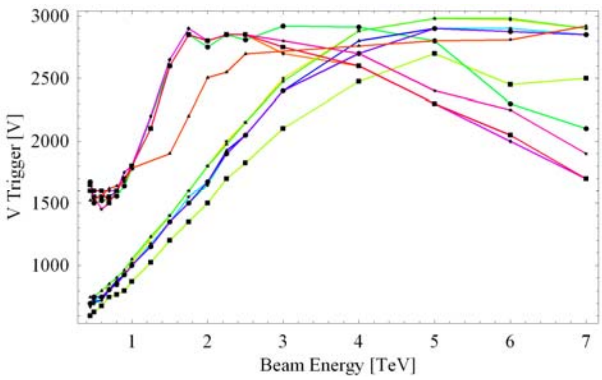

Figure 4: Optimised trigger voltages for the different generators.

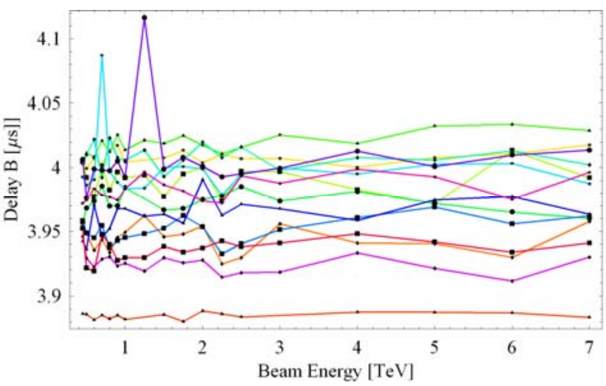

Figure 5: Synchronisation of the magnetic field for the different generators. The two 'spikes' have been tracked back to measurement errors.

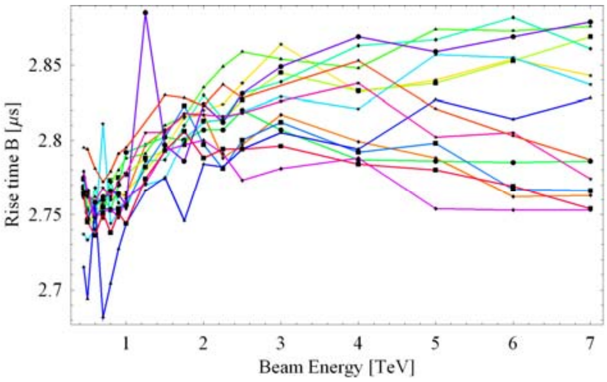

Figure 6: Measured rise time for the different generators.

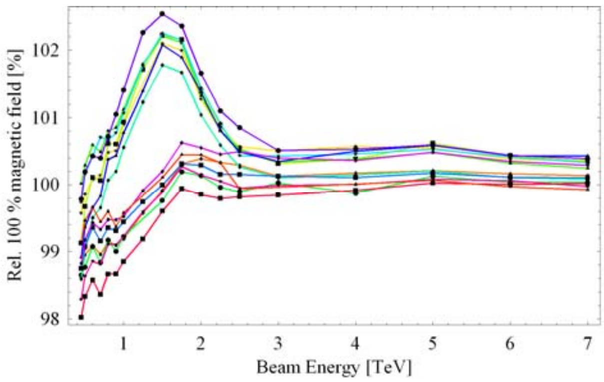

Figure 7: Measured relative kick strength for the different generators.

Both overshoots, OS1 and OS2, are within the specification of 7.5 % for all generators and all energies. The pulse length is also within specification, except for 1 so far rejected generator, for which the compensation voltage will need to be adjusted to be within specification. A significant spread in kick strength has been found, for the same generator settings (except for the trigger voltage), see Fig. 7. Also here the different switch types can be identified. These curves agree within about 0.5 % with the same plot made for the measured current. It can be concluded that for the same magnet and the same ceramic chamber, the magnetic field can be determined to within 0.5 % from the measured magnet current. From the magnet calibration procedures it can be concluded that for the different magnets there is an uncertainty between measured field and measured current of about 0.75 %. Applying the individual calibration results to the different magnets and generators can reduce these errors.

EFFECT OF THE CERAMIC CHAMBER

Calibration measurements have been made with three ceramic chambers, differing in chamber resistance (dc resistance measured over the chamber). The three chambers used for calibration had a measured resistance of 1.31 Ω, 1.50 Ω and 1.63 Ω. The thickest coating increases the delay between measured magnetic field and current by 40 ns. Therefore, it has been decided not to use the chambers with the thickest coating. The range of resistances of chambers installed in the machine will be between 1.41 Ω and 1.63 Ω, with delays varying by about 30 ns. This can be compensated for in the system (e.g. by cable length), which will give an effective gain in rise time of up to 30 ns.

The chamber coating also has an effect on the measured magnet current and kick strength. For the three chambers used in the calibration the measured magnet current decreases by 1.33 % for the thickest coating relative to the thinnest coating, while the measured integrated magnetic field strength decreases by 0.87 %. This effect should also be taken into account for operation.

CONCLUSIONS

During the calibration process of the MKD extraction kicker magnets, generators and a sample of the ceramic chambers several characteristics important for the future operation have been identified. The calibration results show that the system is well within specification on all parameters, with the exception of the system rise time, which is at the limit of the specification. The calibration results for the current transformer delays, delays due to the coating of the ceramic chamber and differences in delays between the different generators will be compensated for by hardware in the LHC installation. These corrections will reduce the effective system rise time by 275 ns. Variations of trigger voltages as a function of energy have been determined for each generator. This reduces the effective rise time by another 150 ns. The synchronisation between the different generators for the different energies has a residual error of about 25 ns, similar to the measurement error.

The calibration results were used to define the location of the individual equipment in the LHC. A relationship between the measured magnetic fields (not accessible in the machine) and currents has been established. This will accelerate the system commissioning with beam, as for safety reasons system settings can only be changed locally during a machine access.

REFERENCES

[1] LHC Design Report, Volume I, The LHC Main Ring, Chapter 17, “The Beam Dumping System” CERN-2004-003, 4 June 2004.

[2] E. Vossenberg et al., “Dual Branch High Voltage Pulse Generator for the Beam Extraction of the Large Hadron Collider”, Proc. 25th International Power Modulator Conf., Hollywood, California, 2002.

[3] J.H. Dieperink, J. Uythoven, “High Precision Magnetic Field Measurements of Fast Pulsed Magnets”, Proc. 12th IMMW, Grenoble, France, October 2001.

[4] J. Uythoven, B. Goddard, “MKD and MKB System Calibration Requirements”, CERN-LHC-MK-ES-0002.