

HIGH VOLTAGE PERFORMANCE OF THE BEAM SCREEN OF THE LHC INJECTION KICKER MAGNETS

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Abstract

The LHC injection kicker magnets include beam screens to shield the ferrite yokes against wakefields resulting from the high intensity beam. The screening is provided by conductors lodged in the inner wall of a ceramic support tube. The design of the beam screen has been upgraded to overcome limitations and permit LHC operation with increasingly higher bunch intensity and short bunch lengths: the new design also significantly reduces the electric field associated with the screen conductors, decreasing the probability of electrical breakdown. The high voltage conditioning process for the upgraded kicker magnets is presented and discussed. In addition a test setup has been utilized to study flashover, on the inner wall of the ceramic tube, as a function of both applied voltage and vacuum pressure: results from the test setup are presented.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerator's equilibrium orbits. Two counter-rotating beams circulate in two horizontally separated beam pipes. Each beam pipe is filled by 12 consecutive injections, at 450 GeV. The total deflection provided by the four MKI kicker systems, per injection point, is 0.85 mrad, requiring an integrated field strength of 1.3 T·m. Reflections and flat top ripple of the field pulse is less than $\pm 0.5\%$.

KICKER MAGNET

General

Each MKI system has a high bandwidth and is impedance ($Z=5\ \Omega$) matched to meet the stringent pulse response requirements. A system consists of a multi-cell Pulse Forming Network (PFN) and a 33-cell travelling wave kicker magnet [1], connected by a matched transmission line and terminated by a matched resistor (TMR): Fig. 1 gives the basic schematic. The PFN design voltage is 60 kV and, allowing for overshoot, the magnet design voltage is 35 kV. There are four MKI systems at each injection point, called P2 and P8. The operating PFN voltage for injection is 49.6 kV at P2 and 51.3 kV at P8.

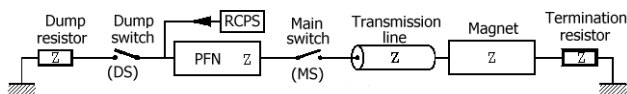


Figure 1: Schematic circuit of a MKI kicker system.

Design

Each cell of the kicker magnets consists of a U-core ferrite between two high voltage (HV) conducting plates: two ceramic capacitors are sandwiched between the HV plate and a plate connected to ground [1].

The LHC bunch intensity, together with the large number of bunches, caused significant heating of the magnet ferrite yoke due to its coupling impedance to the beam [2]. To limit the longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an extruded ceramic tube (99.7% alumina) with screen conductors lodged in its inner wall is placed within the aperture of the magnet [3]. The conductors, which provide a path for the image current of the beam, are connected to the standard LHC vacuum chamber at one end and are capacitively coupled to it at the other end.

Voltage is induced on a screen conductor mainly by mutual coupling with the cell inductance. Hence the voltages, at the open end of the screen conductors, show a positive peak during field rise and a negative peak during field fall: the positive peak is about twice the magnitude of the negative peak (Fig. 2). The maximum voltage (~ 30 kV) occurs for conductors adjacent to the HV busbar. The predicted maximum voltage between adjacent screen conductors is ~ 2.7 kV [3].

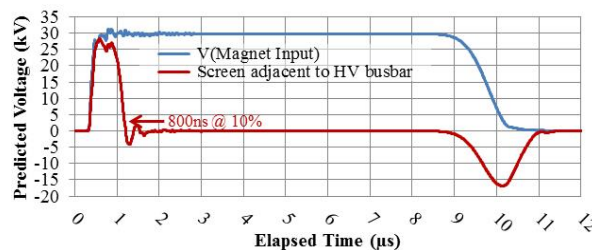


Figure 2: Magnet voltage and voltage of one screen conductor, for 60 kV PFN voltage.

In the original design the ceramic tube had 24 nickel-chrome (80/20) conductors, each $0.7\text{ mm} \times 2.7\text{ mm}$ with rounded corners, inserted into slots [1]. In the original version installed in the LHC, nine conductors closest to the HV busbar were removed to reduce the maximum electric field by 20%. With this arrangement no surface flashover was observed up to 49 kV PFN voltage [3]. However removing screen conductors increased beam impedance and thus heating of the ferrite yoke [2].

Operation in the LHC

In addition to normal operation of the MKI kicker systems, during which beam is injected into the LHC, there is a "SoftStart" (SS) mode: a SS is used when there is no beam in the LHC and no beam is being injected. SS

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was originally foreseen to ensure the kicker magnets are properly HV reconditioned, prior to injection: during a normal/extended SS, the PFN voltage is ramped to 3 kV/4 kV above the injection value. The SS mode was also used as a diagnostic, following a long fill of the LHC, to determine whether the MKI ferrite yoke was approaching its Curie temperature [4].

The average number of HV pulses per MKI magnet, during 2012, was $\sim 7.5 \times 10^4$: thus the total number of HV pulses for the 8 MKIs installed in the LHC was $\sim 6 \times 10^5$ for the year. Up until the third Technical Stop of 2012 (TS3), during September 2012, 7 of the 8 MKIs installed had 15 screen conductors. The eighth MKI had 24 screen conductors but only 15 of these, at the lowest voltage, extended past the ferrite yoke at the capacitively coupled end. During 2012 there were 3 electrical breakdowns in these 8 MKIs, two of which were in one MKI. The third breakdown occurred during a machine development study: anti-electron-cloud coils were deliberately turned-off and pressure, close to the capacitively coupled end of the MKI, increased from $\sim 1 \times 10^{-10}$ mbar to 7×10^{-9} mbar: within 10 pulses the electrical breakdown occurred and is thus attributed to the relatively high pressure.

During TS3 the MKI which had experienced two electrical breakdowns was exchanged for a version with 19 screen conductors: each conductor had a 3.8 mm sphere on its end. During the last 3 months of 2012 this newly exchanged MKI had four electrical breakdowns in $\sim 2 \times 10^4$ pulses – a relatively high rate.

Electric Field Simulations

Extensive 3D electromagnetic simulations have been carried out, using the code TOSCA, to study electric fields on the surface of the ceramic tube for 51.3 kV PFN voltage. The predictions, for 15 and 19 conductor versions, have been used to determine safe upper operating limits for the electric field. For 15 conductors, which gave a breakdown rate in the LHC of $\sim 5 \times 10^{-6}$ per magnet pulse, the nominal predicted axial field (in the range 9.8 kV/mm to 11.3 kV/mm) is a factor of ~ 3 higher than the azimuthal field. For the 19 conductor version, installed during TS3, which gave a breakdown rate in the LHC of $\sim 2 \times 10^{-4}$ per magnet pulse, the predicted azimuthal field increases to 13.4 kV/mm, and the axial field to 7 kV/mm. Studies of breakdowns in a test tank give a limit of ~ 13 kV/mm for surface flashover [3].

A new design, at the capacitively coupled end of the beam screen, allows 24 screen conductors to be used. This is achieved by removing metallization from the outside diameter (OD) of the ceramic tube, over a distance of ~ 20 mm before the ends of the screen conductors, and replacing it by a stainless steel cylinder with an inside diameter 4 mm greater than the OD of the ceramic tube. The axis of the cylinder is offset by 1 mm with respect to the axis of the ceramic tube [3]: there is $3_{-0.2}^{+0.3}$ mm clearance, to the OD of the ceramic tube, on the HV busbar side, and $1_{-0.2}^{+0.3}$ mm clearance on the “ground” busbar side. The nominal predicted axial and azimuthal

fields are then 5.9 kV/mm and 1.8 kV/mm, respectively: 5.9 kV/mm is $\sim 40\%$ less than the maximum field predicted for the 15 conductor beam screen, and 45% of the 13 kV/mm limit. Thus the new design is expected to have a low breakdown rate, while ensuring low longitudinal beam coupling impedance, in the LHC.

HV CONDITIONING AND TESTING

HV Conditioning

HV conditioning of an MKI magnet allows both the magnet and beam screen to be conditioned and their integrity validated. The process is carried out in two stages: (i) after an oven bake-out, HV pre-conditioning allows any issues to be identified at an early stage: (ii) the MKI is vented with dry nitrogen and vacuum valves, ion pumps and Penning gauges are installed; a jacket bake-out is carried out followed by HV conditioning. Experience shows that the magnet and beam screen do not significantly lose their HV conditioning between the two stages. The second HV conditioning is followed by a micro-discharge test (see below) for assessing the HV state of the magnet and beam screen.

The processes, which are carried out under computer control, are designed to achieve HV conditioning of an MKI while keeping to a reasonable minimum the number of electrical breakdowns and thus the risk of damage. Hence the duration of the HV pulse is initially limited to 1500 ns: this is a compromise between a very short value to limit the available energy in the event of a breakdown, and a sufficiently long value so that the voltage induced on the screen conductors returns to zero before being driven negative by the falling edge of the magnet input pulse (Fig. 1). The PFN voltage is increased to a maximum value of 56.4 kV, i.e. 10% above the nominal injection voltage for P8: Fig. 3 shows the programmed PFN voltage, versus minimum (i.e. without sparks) pulse count. The shape of the conditioning curves, shown in Fig. 3, are very similar to the optimized conditioning curves derived for CLIC RF structures [5].

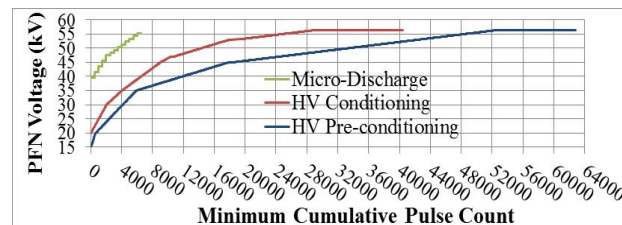


Figure 3: Programmed voltage, versus minimum pulse count, during conditioning and the micro-discharge test.

Subsequently, during both conditioning cycles, the PFN voltage is reduced to 55.4 kV and the pulse length, in the magnet, is increased at a rate of 20 ns per 26 pulses to 9000 ns – which is the two-way delay of the PFN.

The vacuum is a good indicator of both low level electrical activity and an electrical breakdown in the magnet or beam screen. If a breakdown occurs, accompanied by a reasonably high level of energy

dissipation, there is normally significant out-gassing: the pressure can take several tens of minutes to a few hours to recover to its pre-breakdown level. Based on experience during conditioning, vacuum thresholds of 5×10^{-9} mbar and 2×10^{-8} mbar are chosen for detecting “weak sparks” and “strong sparks”, respectively. In the event of a weak/strong spark the PFN voltage is decreased by 0.5%/12%, respectively, and the conditioning continues from the reduced voltage, increasing the total pulse count. If the pressure exceeds 4×10^{-8} mbar the conditioning process is paused for 1 hour to allow the vacuum to recover. The 12% reduction is based on observations that a smaller decrease often results in clusters of breakdowns, e.g. a 4% reduction in PFN voltage, following a strong spark, will frequently result in 2 or 3 consecutive strong sparks, thus increasing the risk of damage.

Capacitive pickups, one at each of the magnet input and output, give the relative timing of the edges of the input and output voltage waveform. If a breakdown occurs, the delay between the rapidly falling edges allows its longitudinal position in the magnet to be determined.

Micro-discharge Test

Following completion of the two stage HV conditioning process, a micro-discharge test is carried out for validating the MKI magnet and beam screen. Given the pumping speed with the 2 ion pumps, a pressure rise is considered a micro-discharge (energy dissipated in the magnet or beam screen is relatively low) when the pressure takes a few minutes to recover to its pre-breakdown level: a duration of 3 minutes has been defined [6], as this duration eliminates occasional spikes due to the Penning gauge from being interpreted as micro-discharges. Thus a micro-discharge is defined only by the duration of the pressure rise recovery time.

The micro-discharge test is carried out with a pulse duration of 8600 ns in the magnet, i.e. $\sim 10\%$ greater than nominal, from a PFN voltage of 40 kV up to 55.3 kV, i.e. 4 kV above the P8 PFN voltage. Of the 7 MKIs upgraded to date, during LS1, there has been only one micro-discharge in an MKI: this MKI will be installed at P2.

HV Testing of Beam Screen in a Test Setup

Separate tests have been carried to permit HV pulsing at screen voltages well above those expected during normal LHC operation, without risking damage to an MKI magnet: the setup did not use a magnet. Instead 24 screen conductors were installed in a 48 cm long ceramic tube, placed within a vacuum tank (called a Simi-tank). All screen conductors were connected to the main switch (MS in Fig. 1) of an LHC PFN. These tests validated the new design of the beam screen [3]. As a result of the Simi-tank setup (TMR of 13 Ω and all screen conductors driven to the same voltage), for a given PFN voltage, the electric field on the surface of the ceramic tube is $\sim 90\%$ higher than when installed in an MKI magnet.

A typical natural background pressure in the Simi-tank is $\sim 5 \times 10^{-10}$ mbar. The Simi-tank tests have been extended to study the influence of hydrogen pressure upon

electrical breakdown. Hydrogen was chosen as it is the main gas associated with electron-cloud. Gas pressures of 10^{-9} , 10^{-8} and 10^{-7} mbar have been investigated. The tests have given good results: there were no strong sparks for pressures up to 10^{-8} mbar, for an electric field of 8.6 kV/mm (corresponds to an equivalent PFN voltage of 75 kV during operation). There were a few strong sparks at 10^{-7} mbar, for a field of 11.5 kV/mm (corresponds to an equivalent PFN voltage of 100 kV during operation). These results were not as expected, based on experience of breakdown in the LHC following a smaller increase in pressure (see above). However a significant difference between the Simi-tank test and operation in the LHC is the absence of beam in the former – the beam may ionize the gas and thus provoke breakdown. Hence the Simi-tank will be modified such that the injected hydrogen can be ionized during the tests. The possibility of ionized gas provoking a breakdown is important to check: the vacuum is common to the four MKIs at each injection point, hence it could contribute to a common mode of breakdown in all four MKIs, simultaneously.

In order to reduce electron-cloud in the ceramic tube, a coating of either amorphous carbon (aC) or Cr_2O_3 is under investigation [7]. An aC coating, of ~ 200 nm thickness, has been successfully applied to the inside diameter of a 48 cm long ceramic tube: this will soon be installed in the Simi-tank for HV tests.

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