REDUCTION OF SURFACE FLASHOVER OF THE BEAM SCREEN OF THE LHC INJECTION KICKERS

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Abstract

The LHC injection kicker magnets include beam screens to shield the ferrite yokes against wake fields resulting from the high intensity beam. The screening is provided by conductors lodged in the inner wall of a ceramic support tube. LHC operation with increasingly higher bunch intensity and short bunch lengths, requires improved ferrite screening. This will be implemented by additional conductors; however these must not compromise the good high-voltage behaviour of the kicker magnets. Extensive studies have been carried out to better satisfy the often conflicting requirements for low beam coupling impedance, fast magnetic field rise-time, ultra-high vacuum and good high voltage behaviour. A new design is proposed which significantly reduces the electric field associated with the screen conductors. Results of high voltage tests are also 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 must be less than ±0.5 %.

KICKER MAGNET

General

A low impedance (Z) of 5 Ω and carefully matched high bandwidth system meets the stringent pulse response requirements. An MKI system consists of a multi-cell 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. The nominal PFN operating voltage is 54 kV. There are four MKI systems at each injection point.

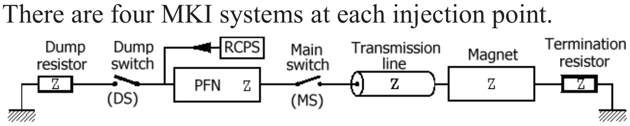

Figure 1: Schematic circuit of a MKI kicker system.

Design

Each cell of the kicker magnets consists of a U-core ferrite sandwiched between high voltage (HV) conducting plates: two ceramic capacitors are sandwiched between a HV plate and a plate connected to ground (Fig. 2).

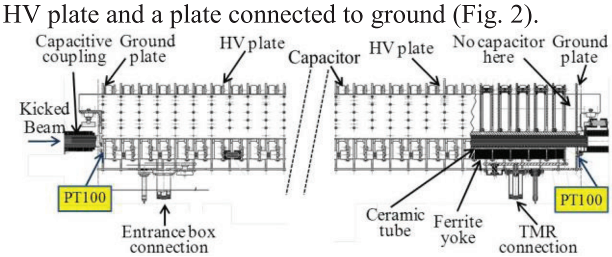

Figure 2: MKI kicker magnet.

The high LHC bunch intensity, well above the design intensity, causes significant heating of the magnet ferrite yoke due to its coupling impedance to the beam [2, 3]. To limit the longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, a ceramic tube (99.7 % alumina) with screen conductors on its inner wall is placed within the aperture of the magnet [1]. 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 (Fig. 2).

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 (max.) during field rise and a negative peak during field fall: the maximum is about twice the magnitude of the minimum. Figure 3 shows the predicted maximum voltage versus conductor number: conductors #1 and #24 are adjacent to the HV busbar, whereas #12 and #13 are adjacent to the ground (GND) busbar. The highest maximum voltage (~30 kV) occurs for conductors #1 and #24. Predicted maximum voltage between adjacent screen conductors is also shown in Fig. 3: the highest value is ~2.7 kV.

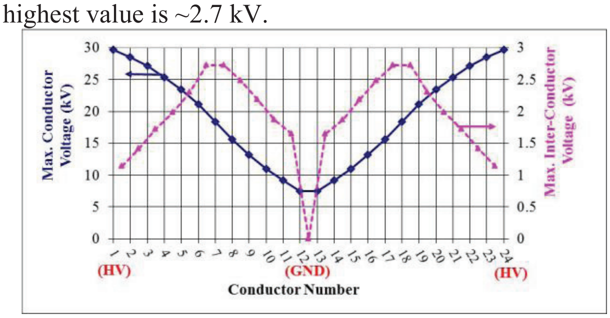

Figure 3: Conductor and inter-conductor voltages, for 24 screen conductors, for 60 kV PFN voltage.

In the original design the extruded ceramic tube had 24 nickel-chrome (80/20) conductors, each 0.7 mm x 2.7 mm with rounded corners, inserted into slots [1]. In the version installed in the LHC, nine conductors closest to the HV busbar were removed to reduce the maximum

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electric field by 20%. With this arrangement no surface flashover was observed up to 49 kV PFN voltage. However removing screen conductors had the effect of increasing beam impedance and thus heating of the ferrite yoke [2-4]. Improved ferrite screening will be achieved by installing all 24 conductors; however the good HV behaviour of the magnets must not be compromised.

A kicker magnet with a modified beam screen was installed in the LHC, for testing with beam, in Sept. 2012. This version (Fig. 4) had 19 screen conductors, instead of the so far installed 15, to reduce the beam induced ferrite heating by a factor of ~2 [3]. To reduce surface flashover the capacitively coupled end of each screen conductor had a sphere installed on it: hence 4 mm diameter holes, ~50 mm deep, were machined in one end of the ceramic tube (Fig. 4) – a difficult procedure. HV testing did not result in any surface flashover below 50 kV PFN voltage, but occasional surface flashover did occur above 50 kV PFN. Thus, to permit all 24 screen conductors to be installed, simulations have been carried out to study and optimize the design of the capacitively coupled end.

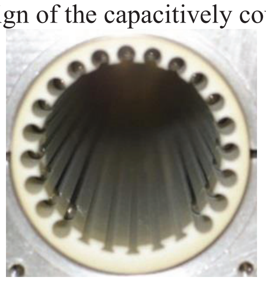

Figure 4: 19 beam screen conductors, each with a sphere.

3D ELECTROMAGNETIC SIMULATIONS

Extensive 3D electromagnetic simulations have been carried out, using the code TOSCA, to study electric fields on the surface of the ceramic. Two different 3D models were used, one with the circular geometry and a "flattened" model: they give very similar predictions, but the flat model is less prone to meshing errors. Each screen conductor is assigned the "Max." conductor voltage shown in Fig. 3. The metallization on the outside of the ceramic tube is modelled as being at 0 V.

The predictions show that, as a result of the high permittivity (9 to 10) of the alumina, equipotential lines penetrate into the ceramic "teeth" between adjacent screen conductors. This results in an increase in the radial surface electric field, between adjacent conductors, by a factor of almost 10 in comparison with what might otherwise be expected.

Table 1 shows the predicted axial and radial electric fields for various numbers of screen conductors and configurations. The axial and radial electric fields tabulated are the highest predicted values, on the inner surface of the ceramic, from the end of the screen conductors to the end of the ceramic tube and between adjacent screen conductors, respectively. The abbreviation "met." indicates that the outside of the ceramic tube is metallized at the capacitively coupled end [4]; "ofs. cyl." indicates that the metallization is removed over a distance of ~20 mm, before the ends of the screen conductors, and replaced by a stainless steel cylinder whose inside diameter is 4 mm greater than the outside of the ceramic tube: the axis of the cylinder is offset by 1 mm with respect to the axis of the ceramic tube such that there is 3 mm clearance, to the outside diameter (OD) of the ceramic tube, on the HV busbar side, and 1 mm clearance on the GND busbar side. "Stag." and "V" indicate non-optimized and optimized lengths for the capacitively coupled end of the conductors, respectively. In the "V" version conductors at lower voltage "shade" those at higher voltage [4].

Table 1: Predicted Electric-Field for 60kV PFN Voltage

No. cond.	Shape	Spheres	Image current path	Axial field (kV/mm)	Radial field (kV/mm)
15	V	no	met.	11.4	4.0
19	stag.	yes	met.	8.2	15.7
24	stag.	yes	met.	9.7	17.5
24	V	no	ofs. cyl.	6.9	2.1
24	V	yes	ofs. cyl.	3.9	7.5

The predictions, for 15 and 19 conductor versions, together with previous observations of the surface flashover inception voltage, have been used to determine the upper limits for the predicted electric field. For the 19 conductor case the observed surface flashover is probably initiated by the high radial electric field: at 50 kV PFN the predicted radial field is 13 kV/mm. Table 1 shows that the maximum electric field, for 24 conductors with spheres and metallization, is predicted to be 17.5 kV/mm: thus surface flashover might be expected to occur at ~45 kV PFN. Table 1 also shows that removing some metallization and replacing it with the offset cylinder, reduces the maximum electric field by a factor of more than 2, providing a safety margin for operation at the PFN design voltage of 60 kV.

HV LABORATORY TEST RESULTS

Tests have been carried out in the laboratory to validate the predictions. To permit HV testing at screen voltages well above those expected during normal LHC operation, without risking damage to a kicker 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. All screen conductors were connected to the main switch (MS in Fig. 1) of an LHC PFN. A ~12 Ω resistive terminator was connected in parallel to the output of the MS. Transmission line lengths were relatively short so as to minimize voltage oscillations. Table 2 shows predicted electrical field for the two tested geometries, using 63 kV equivalent LHC PFN voltage: this is the PFN voltage which gives 30 kV maximum on a screen conductor. During most of the tests a pulse of 1200 ns duration was applied, which is ~400 ns longer than the positive induced voltage during LHC operation.

Table 2: Predicted Electric-Field, for Laboratory Test Setup, with 63 kV Equivalent LHC PFN Voltage

No. cond.	Shape	Spheres	Image current path	Axial field (kV/mm)	Radial field (kV/mm)
24	stag.	no	met.	17.5	5.3
24	stag.	no	ofs. cyl.	11.6	3.9

A summary of the results from the laboratory tests is shown in Fig. 5. The metallized ceramic tube version was conditioned to ~47 kV equivalent PFN voltage, which corresponds to 13 kV/mm predicted axial electric field. This conditioning took considerably longer than for the version with the offset cylinder, which was tested to ~65 kV equivalent PFN voltage: this corresponds to 12 kV/mm predicted axial electric field. The 12 kV/mm is ~60 % greater than the maximum electric field predicted for 60 kV operation, in the LHC, with the offset cylinder (Table 1). A 56 mm OD ceramic tube will be tested – this is the diameter to be installed in the MKIs during LS1.

Both versions of the screen conductors were subsequently tested with pulses up to 8000 ns duration (Fig. 5). Further HV tests are planned in the laboratory with bipolar pulses applied to the screen conductors.

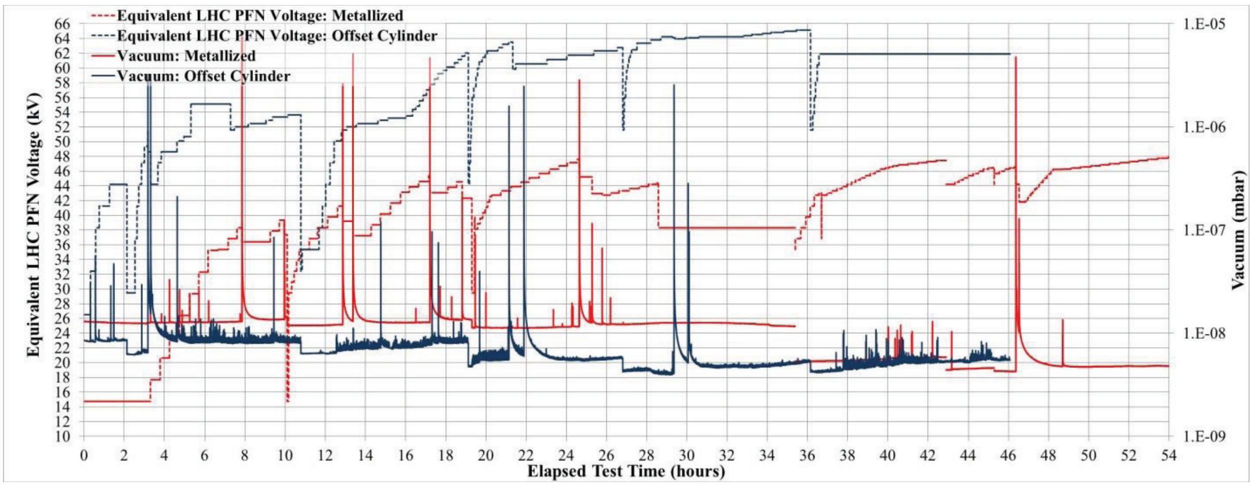

Figure 5: HV tests of beam screens, consisting of 24 screen conductors, for a ceramic tube of 53 mm OD: the plot shows vacuum level (solid line) and equivalent LHC PFN voltage (dashed line).

ONGOING RESEARCH

Following installation of the upgraded kicker magnet in the LHC, during Sept. 2012, the ceramic tube had to be conditioned to reduce vacuum activity, due to electron cloud, to an acceptable level [5]. An SEY of <1.4, for the ceramic tube and screen conductors, would prevent electron-cloud [6]. The NiCr screen conductors have a measured SEY of ~2.3. A SEY of ~6.4 for 95 % alumina has been measured: this can be reduced to ~1 by coating with Cr_2O_3 [7]. In addition the Cr_2O_3 increases the surface flashover voltage of the alumina by ~50 % [7]. R&D is on-going to develop a means of applying a suitable coating to the inside of the 3 m long ceramic MKI tube. The goal is to install one MKI magnet in the LHC, with a coated ceramic tube, for testing with beam.

CONCLUSIONS

Following extensive studies and simulations a new design has been developed, to permit the installation of the full complement of 24 screen conductors, which meets the often conflicting requirements for the beam screen. Initial testing, in the laboratory, shows excellent HV performance, in agreement with simulations.

ACKNOWLEDGMENT

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