UPGRADE OF THE LHC INJECTION KICKER MAGNETS

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Abstract

Two LHC injection kicker systems, each comprising 4 magnets per ring, produce a kick of 1.3 T·m with a rise-time of less than 900 ns and a flattop ripple of less than ±0.5 %. A beam screen is placed in the aperture of each magnet, to provide a path for the image current of the LHC beam and screen the ferrite yoke against wake fields. The screen consists of a ceramic tube with conductors in the inner wall. The initially implemented beam screen ensured a low rate of electrical breakdowns and an adequately low beam coupling impedance. Operation with increasingly higher intensity beams, stable for many hours at a time, has resulted in substantial heating of the ferrite yoke, sometimes requiring cool-down over several hours before the LHC can be refilled. During the long shutdown in 2013/2014 all eight kicker magnets will be upgraded with an improved beam screen and an increased emissivity of the vacuum tank. In addition equipment adjacent to the injection kickers and various vacuum components will be modified to reduce the vacuum pressure near to the kickers during high-intensity operation. This paper discusses the upgrades.

INTRODUCTION

The Large Hadron Collider (LHC) is equipped with injection kicker (MKI) systems for deflecting the incoming particle beams onto the accelerators 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 injected beam is first deflected in the horizontal plane by a series of septum magnets followed by a vertical deflection by four MKI magnets [1]. The four magnets are named D, C, B and A: D is the first to see injected beam. The total vertical deflection by the four MKI magnets 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 %, a demanding requirement, to limit the beam emittance blow-up due to injection oscillations.

KICKER MAGNET

General

A low impedance (5 Ω) and carefully matched high bandwidth system meets the stringent pulse response requirements. Each MKI system consists of a PFN and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched termination resistor. Each travelling wave MKI magnet has 33 cells. A cell consists of a U-core ferrite sandwiched between HV conducting plates, and two ceramic capacitors sandwiched between a HV plate and a plate connected to ground.

After an MKI is installed in a vacuum tank (Fig. 1), and prior to mounting vacuum valves, the complete magnet is baked out, in an oven, to 300 °C: the bake-out permits the MKIs to achieve vacuum of ~10^{-11} mbar. Following cool-down the MKI is HV pre-conditioned to a PFN voltage of ~56 kV. Subsequently the MKI is returned to the clean-room, vacuum valve actuators are installed, and bake-out jackets are mounted on each vacuum tank. The jackets are used to re-bake the MKI before a final HV conditioning. The jackets remain on the tank such that a bake-out of the MKI can be carried out in the LHC tunnel, if required.

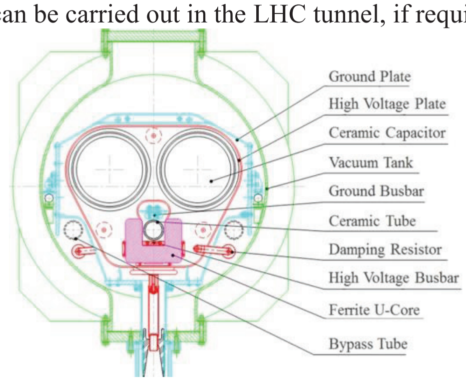

Figure 1: MKI kicker magnet cross-section.

Vacuum Tank and System

The 3414 mm long, 540 mm diameter, tanks housing the MKI magnets are reused from the LEP accelerator: they were used for 300 kV electrostatic separators and thus were electro-polished. Each vacuum tank requires a "bypass tube" for the counter-rotating beam: high conductivity copper is used. Figure 1 shows two bypass tubes – this allows an MKI to be used at either LHC injection point. Small longitudinal slots, in the copper, connect the vacuum of the tank and the bypass tube.

Each MKI tank has two ion pumps (~250 l/s each for N_2 @ ~10^{-7} mbar), two titanium sublimation pumps (1000 l/s each for H_2), a Penning gauge and two ionization gauges. Vacuum valves are mounted on each beam port of the MKI tank: these allow a magnet to maintain its HV conditioning, e.g. during transport.

The ports of adjacent MKI tanks are separated by ~550 mm: appropriate ports are interconnected by a beam pipe – these beam pipes are not NEG coated. Each interconnection has two bellows, each with a copper insert, for beam coupling impedance reasons, and an ion pump (~35 l/s for N_2 @ ~10^{-7} mbar). On either side of an installation of four MKIs, there is a beam observation system (called BTVSI), which is used for machine setup. During normal operation of the LHC the BTVSI is retracted, and the beam image current sees a continuous

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copper surface. In addition there is a beam position timing module (called BPTX), at one end of the installation of four MKIs, which has a copper insert.

EXPERIENCE IN THE LHC

Heating

During 2012 the LHC has been operated with 1380 bunches per beam and bunch intensities of ~$1.5 \cdot 10^{11}$ protons per bunch. The high bunch intensities have resulted in significant beam induced heating of the MKI magnets. To limit longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, a ceramic tube with screen conductors in its inner wall is placed in the aperture of the magnet [3-5]. 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.

When the temperature of the MKI ferrite yoke approaches the Curie point (~120˚C) the strength of the kick reduces and the mis-kicked injected beam could result in quenches of several superconducting magnets. Hence there is an interlock to inhibit injection if the measured yoke temperature is above specified thresholds. On about ten occasions, during 2012, after a series of long fills, it was required to wait longer than one hour before injecting to allow the cool-down of the MKI8D yoke. An upgraded MKI, equipped with an increased number of screen conductors (19 instead of 15), was installed during Technical Stop 3 (TS3), during Sept. 2012, to reduce the heating [3-5]. Subsequently the yoke of the upgraded MKI8D had amongst the lowest measured temperatures.

After TS3, magnet MKI8C occasionally delayed injection, due to a high temperature (up to 190°C) measured for ferrite toroids outside of the magnet yoke. Analysis of rise-time and magnet delay shows that the MKI performance was not affected by the increase of this temperature. The cause of occasional high heating of the ferrite toroids is still under investigation: one hypothesis is that it is attributable to a resonance (~500 MHz) of the overlap of the screen conductors with the external metallization of the ceramic tube [4, 5].

High Voltage Behaviour

During 2012 operation, a total of six MKI magnet flashovers occurred: these are thought to have been on the surface of the ceramic tube used to support the beam screen conductors. One of the flashovers occurred during a machine development test, when anti-electron-cloud coils were deliberately turned off, and is thus attributed to the relatively high vacuum pressure close to the MKIs. Three of the flashovers were associated with the MKI8D installed during TS3: this MKI has 3.8 mm balls installed on the end of the screen conductors but, as a result of metallization on the outside of the end of the ceramic tube, a high radial field (13.4 kV/mm at 51.2 kV PFN) occurs when the MKI is pulsed [6]. This field is ~40 % greater than the maximum electric field that occurs in the installed MKIs which have 15 screen conductors [6].

Electron-Cloud

Significant pressure rise, due to electron-cloud, occurs in and nearby the MKIs: the predominant gas desorbed from surfaces is H_2. Pressure rise increases the number of unidentified falling objects (UFOs) [7] and may augment the probability of electrical breakdown in the magnet and surface flashover on the ceramic tube. Conditioning of surfaces reduces electron-cloud, and thus pressure rise, but further conditioning is often required when beam parameters (e.g. bunch spacing, bunch length and bunch intensity) are pushed.

The ceramic tube of the replaced MKI8D magnet had a high secondary electron yield (6 to 7) when installed and required conditioning with beam, together with metallic surfaces facing the beam (e.g. screen conductors): Fig. 2 shows pressure, measured both in the upgraded MKI8D tank and nearby interconnects, normalized to the number of protons (p). The highest normalized pressure occurred in interconnect MKI8D-Q5, followed by interconnect MKI8C-MKI8D. Initially the beam current was kept low to maintain the pressure below the interlock thresholds. The ceramic tube conditioned relatively quickly but required ~250 hours, with beam, to achieve a normalized pressure similar to the pre TS3 (~4E-24 mbar/p) level.

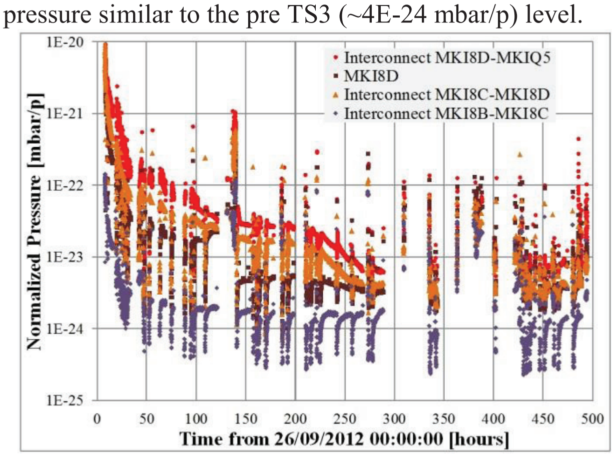

Figure 2: Pressure, measured both in and nearby tank MKI8D, normalized to the number of protons, after TS3.

UFOs

There have been a total of 58 protection dumps of LHC beam since 2010, of which 21 are due to UFOs at the MKIs: the UFO activity around MKI2 generally exceeded that around the MKI8s [7]. The beam suffering from MKI UFOs is clearly identified by the direction of the shower: the MKI UFOs are associated with the injected beam, thus MKI vacuum valves can be excluded as a source of the UFOs. After a comprehensive study program in 2011, the MKI UFOs were identified as macro particles originating from the ceramic tube inside the MKI magnets [8]. Thus the MKI8D installed during TS3 had improved cleaning of the ceramic tube, which included iterations of flushing the inside of the tube with Nitrogen at 15 bar and dust sampling, until no significant reduction of macro particles was noted. Before TS3, MKI8D had the highest UFO activity of the MKIs in Point 8; the replacement MKI8D had the lowest UFO activity [7].

MKI UPGRADES

During LS1

All eight MKI magnets will be equipped with 24 screen conductors: this will substantially reduce the longitudinal beam coupling impedance and hence the beam induced heating of the ferrite yoke [3-5]. However, to retain and even enhance the good HV behaviour, the electric field associated with the capacitively coupled end of the beam screen conductors must be substantially reduced. Extensive studies have been carried out to reduce the electric field and several modifications are proposed for the beam screen. The most significant benefit is obtained by removing the external metallization, from the outside of the ceramic tube, from a distance of ~20 mm behind the end of the screen conductors. Instead the path, for the beam image current, is provided by a stainless steel cylinder at a distance of between 1 mm and 3 mm from the outer surface of the ceramic tube [6]. The effectiveness of this has been demonstrated by HV tests in the laboratory and the procurement of the cylinders, for the series of the MKIs, has been launched.

In addition 4 mm diameter balls, on the capacitively coupled end of the screen conductors, further reduce the axial electric field but at the expense of increased radial electric field [6]. However the balls require holes to be machined, to a maximum depth of 60 mm, in the end of the ceramic tube – a difficult and delicate process. Ten ceramic tubes have been ordered and, to date, two have had suitable holes machined. To ensure the breakdown strength of the ceramic tube, especially where the holes are machined, the outside diameter of the tube is increased from 53 mm to 56 mm.

To improve cooling of the ferrite yoke the emissivity of the tank will be increased by pre-treatment with ion bombardment [3]. Tests will be carried out to ensure that the treatment does not degrade the excellent ultra-high vacuum performance of the vacuum tanks.

An improved cleaning procedure will be applied to all MKI ceramic tubes to reduce the number of UFOs (see above). The effectiveness of the proposed procedure has been demonstrated for the MKI8D installed during TS3: the number of UFOs per fill at MKI8D is significantly reduced [7]. With 15 screen conductors installed, macro particles could be detached and accelerated towards the beam by the high electric field when the kicker is pulsed [8]. The 24 screen conductors reduce the electrical field during most of the MKI pulse hence decreasing the probability of a particle being detached from the ceramic.

In order to mitigate electron multipacting the following will be NEG coated: copper insert of both the cold-warm transitions and the bellows close to the MKIs, MKI interconnects, bypass tubes (Fig. 3), BTVSIs and BPTXs. In addition NEG cartridges will be installed, on the cold-warm transition, to supplement existing ion pumps. On the MKI interconnects the ion pump will be exchanged for a version which also includes a NEG cartridge. The NEG coating of the various pieces has been launched. These modifications are expected to significantly reduce the pressure excursions which currently occur in and close to the MKIs during high-intensity operation.

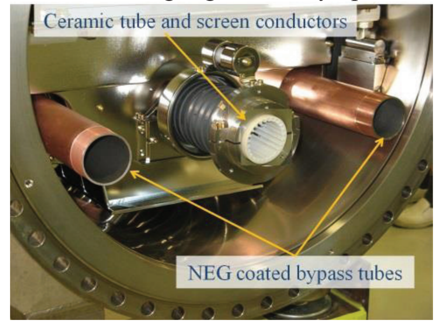

Figure 3: MKI with NEG coated bypass tubes and ceramic tube installed.

In order to increase the surface flashover voltage of the ceramic tube and reduce electron-cloud in the ceramic tube, a coating of either carbon or Cr_2O_3 is under investigation [6]. If successful this coating will be applied to the ceramic tube of one MKI for evaluation with beam.

Long Term

Other upgrades are being studied for the MKIs in view of HL-LHC: these include a high Curie temperature ferrite, an even higher emissivity coating for the tank, and active cooling of the outside of the vacuum tank.

CONCLUSION

During the long shutdown in 2013/2014 all eight MKI kicker magnets will be upgraded with an improved beam screen and an increased emissivity of the vacuum tank. In addition equipment adjacent to the injection kickers and various vacuum components will also be modified to help reduce the vacuum pressure near to the kickers during high-intensity operation. Furthermore improved cleaning of the ceramic tube is expected to reduce the number of MKI UFOs.

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