THE BEAM SCREEN FOR THE LHC INJECTION KICKER MAGNETS

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Abstract

The two LHC injection kicker magnet systems must each produce a kick of 1.2 T.m with a flattop duration variable up to 7.86 µs, and rise and fall times of less than 0.9 µs and 3 µs, respectively. Each system is composed of four 5 Ω transmission line kicker magnets with matched terminating resistors and pulse forming networks (PFN). The LHC beam has a high intensity, hence a beam screen is required in the aperture of the magnets This screen consists of a ceramic tube with conducting “stripes” on the inner wall. The stripes provide a path for the image current of the beam and screen the magnet ferrites against Wake fields. The stripes initially used gave adequately low beam impedance however stripe discharges occured during pulsing of the magnet: hence further development of the beam screen was undertaken. This paper presents options considered to meet the often conflicting needs for low beam impedance, shielding of the ferrite, fast field rise time and good electrical and vacuum behaviour.

INTRODUCTION

CERN, the European Laboratory for Particle Physics, is constructing the Large Hadron Collider (LHC) which will bring protons into head-on collisions at 2 x 7 TeV. The LHC will be filled through a chain of injector machines. Two counter-rotating beams, which can collide in up to 4 interaction points, will circulate in two horizontally separated beam pipes. Each beam pipe will be filled by 12 batches of protons injected, at 450 GeV, successively on the machine circumference. Injection is carried out in the horizontal plane by a septum magnet followed by a vertical fast pulsed kicker system. Table 1 summarizes the main parameters of the LHC injection kicker system.

Table 1: LHC injection kicker system parameters

Number of magnets per system	4	
Kick strength per magnet	0.3	T.m
Characteristic impedance	5	Ω
Operating charging voltage (PFN)	54	kV
Field flat top ripple	< ±0.5	%
Field flat top duration	up to 7.86	µs
Field rise time 0.5% to 99.5%	0.9	µs
Field fall time 99.5% to 0.5%	3.0	µs
Magnet length	2.7	m

The beam to be injected approaches the kicker at an angle of 0.8 mrad, requiring a total kick of 1.2 T.m for deflection onto the central machine orbit. 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. The 12 batches of protons are each of either 5.84 µs or 7.86 µs duration, leaving 11 gaps of 0.94 µs and 1 gap of 3 µs for the kick rise and fall-time, respectively.

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KICKER MAGNET

General

A low impedance (Z = 5 Ω) and carefully matched high bandwidth system is needed to fulfil the stringent pulse response requirements. The system is therefore composed of a multi-cell PFN [1] and a multi-cell travelling wave kicker magnet [2], connected by a matched transmission line and terminated by a matched resistor. Fig. 1 gives the basic circuit diagram.

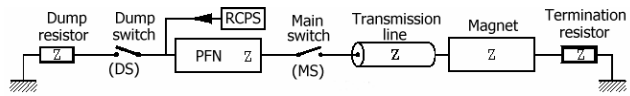

Figure 1: Schematic circuit of system.

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.

Design

The travelling wave magnet is composed of 33 cells [2]. The nominal inductance of the ferrite C-core is 101 nH per cell and the matching capacitance, obtained using ceramic capacitors, is 4.04 nF. The magnets are operated in vacuum of ~10^{-11} mbar. The complete magnet is baked out at 300°C before HV conditioning and tests.

With LHC beam, which has high peak current, the impedance of the ferrite yoke can provoke significant beam induced heating, even beyond the Curie temperature. To limit beam impedance, while allowing a fast field rise time, a ceramic pipe, of 50 mm outside diameter and with screen conductors on its inner wall, is placed within the aperture of the magnet. The conductors provide a path for the image current of the beam and screen the ferrite against beam induced heating [3]. At one end all the conductors are directly connected to the standard LHC vacuum chamber. At the other end all screen conductors are open circuit and were originally capacitively coupled to a metallization over the last 150 mm of the outside diameter of the ceramic beam pipe. The metallization is connected to the ground. Nine ferrite toroids, referred to here as Beam Impedance Reduction Ferrite (BIRF), are placed around the outside diameter of the ceramic beam pipe at both ends. The BIRF damps high-Q resonances which the beam may otherwise excite.

In the initial design the ceramic beam pipe had 24 straight etched resistive (silver) stripes on its inner wall. These stripes gave adequately low beam impedance but, due to very high electric field at their edges, resulted in discharges between stripes at the open-circuit end and vacuum rise during pulsing of the magnet at only 15 kV PFN voltage. Development was carried out to understand and rectify the discharge problem. Computer models have been extensively used to predict magnetic field and voltages induced on the screen conductors.

Modelling

The electrical circuit of the complete kicker system, including PFN, thyratrons, transmission line, magnet, beam screen conductors and terminators has previously been optimised. The mathematical model has been further developed and now includes the two sets of BIRFs: their inductive and resistive characteristics are derived from the toroids' effective magnetic parameters and the datasheet complex permeability. Capacitance between adjacent screen conductors and between each screen conductor and the magnet HV and return busbars is now also included. The PSpice model makes use of symmetry and thus only half of the screen conductors are explicitly represented. For each cell, the model includes coupling between the inductance of the individual magnet cell and the inductance of each screen conductor, as well as between the screen conductors. The resulting 156 coupling coefficients for each of the 33 magnet cells are calculated using two different codes: Faraday [4] for DC conditions and Opera2D [5] at 1 MHz. PSpice simulations show that the two sets of coupling coefficients result in very similar predictions for the magnetic field as well as the voltage induced on the screen conductors.

BEAM SCREEN

Tested options for improving the beam screen include: (a) 24 painted spiral stripes with 4 turns over their length. The stripe discharges started at 30 kV PFN voltage – a significant improvement over the straight stripes; (b) solid conductors, each 0.7 mm x 2.7 mm with radiused corners, inserted into slots on the inside of a newly developed extruded ceramic pipe. The slots are open over their full length to avoid charge build up on naked ceramic.

PSpice simulations show that the screen conductors must be capacitively coupled to the LHC vacuum pipe at the pulse input end of the magnet, so that absolute and inter-screen conductor voltages are both minimized.

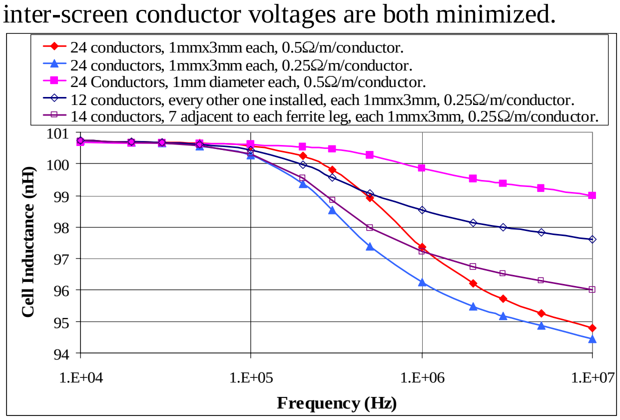

Figure 2: Frequency dependence of the cell inductance for various beam screen conductor configurations.

The screen conductors can result in a significant frequency dependence of the magnet inductance. Such dependence has been calculated using Opera2D and is subsequently modelled in the equivalent circuit of each magnet cell. Fig. 2 shows predicted cell inductance for various screen conductor configurations. In general the resistivity considered is such that the total DC resistance, for all screen conductors in parallel, is 2 mΩ/m.

The decrease in inductance, with increasing frequency, results in a reduction in the initial magnitude of the flat-top field. The minimum decrease in cell inductance occurs with evenly distributed conductors of minimum cross-sectional area (Fig. 2). However conductors of more rectangular cross-section are mechanically easier to hold in slots in the ceramic beam-pipe and hence are preferred.

The voltage on a screen conductor is mainly induced by mutual coupling with the cell inductance. Hence the induced voltage is a positive peak (Max.) during field rise and a negative peak (Min.) during field fall. In general the Max. is about twice the magnitude of the Min. Fig. 3 shows the predicted Max.−Min. conductor voltage as a function of conductor number: conductor #1 and #13 are adjacent to the HV and ground busbars, respectively. The largest value of Max.−Min. voltage (~42 kV) occurs for conductor #1: the voltage does not fall below 80% of 42 kV until conductor #5. Fig. 3 also shows the predicted Max.−Min. voltage between adjacent screen conductors: the largest value (~4.2 kV) occurs between conductors #6 & #7 and also between #7 & #8, which is where the conductors are closest to the legs of the C-core ferrite.

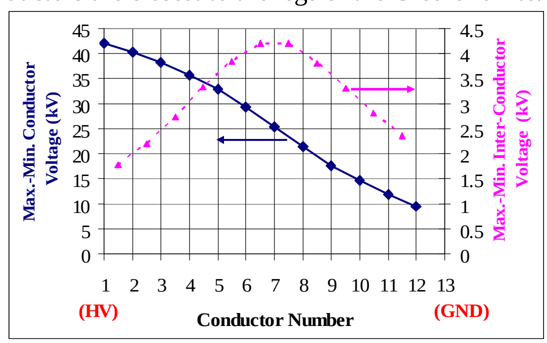

Figure 3: Predicted conductor voltage and inter-conductor voltage for 24 of 0.7 mm x 2.7 mm screen conductors for normal operation at 54 kV PFN voltage.

HV testing of a magnet with 24 screen conductors, each 0.7 mm x 2.7 mm, was quite successful: no discharge was observed until 30 kV PFN voltage. However during HV testing up to nominal voltage there was a discharge (HV to ground) within the magnet itself which resulted in a significant reduction of the discharge inception voltage of the screen conductors. Frequent distortion of the measured magnet pulse current was then observed. PSpice simulations of a breakdown from the HV to ground have been carried out. When it occurs at the pulse input end of the magnet, towards the end of magnet fill time, and with low loss (NiZn) BIRF installed, the induced voltage on screen conductor #1 has little damping and oscillates between +32 kV and −41 kV, i.e. an excursion of 73 kV. Such a voltage excursion may have caused a discharge of the screen conductors to ground and resulted in a metal deposition on the ceramic beam pipe: thereafter the screen conductors were more susceptible to further discharge. PSpice simulations of a discharge: (a) between the open-circuit end of all screen conductors; and (b) from the screen conductors to the ground; result in very similar distortion of the magnet pulse current. Hence magnet current and voltage signals cannot be used to determine the nature of the screen breakdown.

Voltage oscillations on the screen conductors, during a fault condition, can be damped by increasing losses associated with the BIRF at the end where the screen conductors are connected to the vacuum chamber, by: (a) connecting a 30 Ω resistor in parallel with a NiZn BIRF; (b) replacing 3 of the 9 BIRF toroids with a suitable lossy (MnZn) ferrite such as Ferroxcube 3E25. The resulting dissipation during normal operation is 0.25 J/pulse.

There are unavoidable vacuum gaps between the screen conductors and the slots of the ceramic beam pipe. Where the screen conductors are capacitively coupled to the metallization, these gaps will have a high electric field stress during pulsing of the magnet, which may result in plasma and hence a discharge of the screen conductors. The highest voltage is associated with the conductors closest to the HV busbar (Fig. 3): hence, to reduce the maximum field stress by 20%, the 9 conductors closest to the HV busbar were removed; this does not influence the predicted voltage on the remaining 15 screen conductors. Subsequent testing, without any BIRF damping, was very encouraging: no discharge was observed up to 49 kV PFN voltage. With a 30 Ω resistor in parallel with the BIRF, no discharge was observed below 54 kV: after further conditioning, testing was successfully completed at 57 kV and no significant discharge then occurred below 50 kV. However removing screen conductors has the undesirable effect of increasing beam impedance (see below). As a compromise 9 screen conductors, that end 77 mm before the start of the metallization, were re-inserted into the beam pipe. No discharge was observed up to 48 kV PFN voltage and, after further conditioning, testing was successfully completed at 57 kV: however conditioning was more problematic than for only 15 screen conductors.

BEAM IMPEDANCE MEASUREMENTS

Beam impedance measurements on the magnet, in its vacuum tank, were made using the one wire resonator method. Power deposition in the magnet is mainly in the ferrite and is calculated from the beam impedance and the spectrum of the beam, assuming a $\cos^2$ bunch profile at top energy (7 TeV), which is a pessimistic assumption. Table 2 gives the power deposition, per meter length.

Table 2: Power deposition in ferrite assuming a $\cos^2$ bunch profile for the nominal LHC beam at top energy.

Screen conductor configuration	Power (W/m)
No screen	~2400
24 painted, straight, stripes	41
24 painted stripes (4 twists)	~90
24 full-length wires each 0.7 mm x 2.7 mm	41
15 full-length wires each 0.7 mm x 2.7 mm	116
15 full-length wires and 9 reduced length wires, each 0.7 mm x 2.7 mm	87

The 24 initial painted straight stripes reduce power deposition by a factor of ~60 in comparison to no beam screen. Stripes with 4 twists result in ~2 times more power deposition than straight stripes. 15 full length conductors result in ~3 times the power deposition compared to 24 conductors. Re-inserting 9 conductors, of reduced length, together with the 15 full length conductors, reduces the power deposition by ~25%.

Fig. 4 shows the real part of measured impedance, of an LHC injection kicker, for various beam screens: without a screen the real part of impedance is ~450 Ω/m at 1 GHz.

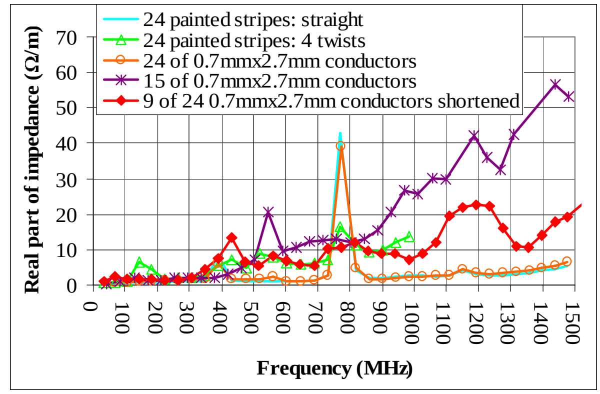

Figure 4: Real part of measured complex impedance, of an LHC injection kicker, for various beam screens.

Measurements show that a 30 Ω resistor in parallel with the NiZn BIRF also has the benefit of suppressing a high impedance beam resonance at ~2.6 MHz.

CONCLUSIONS

As a result of the high intensity of the LHC beam a screen is necessary in the aperture of the kicker magnets. Induced voltages on screen conductors and distortion of the magnetic field impose serious limitations. As a compromise the present screen consists of 15 full-length and 9 shorter conductors inserted into slots on the inside diameter of the ceramic beam-pipe. A mixture of low loss and lossy BIRF ferrites are used to damp high-Q resonances which the beam may excite and to damp voltage oscillations induced on the screen conductors during fault conditions. This results in a quite low beam impedance, shielding of the ferrite, fast field rise time and a discharge free beam screen. Optimisation studies continue to further reduce the beam impedance. Thermal modelling is to be carried out to estimate the heating and cool-down behaviour of the magnet.

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