HIGH VOLTAGE PERFORMANCE OF SURFACE COATINGS ON ALUMINA INSULATORS

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Abstract

Alumina insulators and dielectrics are required for a variety of applications in particle accelerators. Their use in high voltage devices, both pulsed and DC, is well established as both insulation and mechanical support. In accelerator equipment the alumina is usually used in ultra-high vacuum and hence charge accumulation can be an issue, especially when the alumina is near to the beam. To address challenges regarding surface flashover and high secondary electron yield in high intensity accelerators, surface treatments and coatings are being considered. This paper presents predictions of the influence of surface coatings, on alumina insulators, upon electric field.

INTRODUCTION

Kicker magnets are used for fast injection and extraction of beam from particle accelerators. These systems typically operate at relatively high voltage and current to produce a pulsed magnetic field with fast rise and fall times. At CERN, kicker magnets are generally installed within the vacuum system, both to limit the dimensions of the magnet aperture and to use the vacuum as a good insulator. Kicker systems for high intensity beam, e.g. for the Large Hadron Collider (LHC), must operate reliably as miskicked beam can damage downstream equipment. One cause of miskicked beam can be electrical breakdown in the kicker magnet during the pulse. To ensure reliable operation electric field must be limited to within safe values, especially at triple junctions, i.e. the interface between a dielectric, conductor and vacuum. Software such as Opera2D and Opera3D are frequently used to predict electric field strength in complex geometries: a "lossy dielectric" solver module has recently been used to study the influence of a resistive surface coating, also known as a semi-conducting dielectric, upon electric field. Predictions are presented for the injection kickers of both the LHC (MKI) and Super Proton Synchrotron (MKP).

MKI SYSTEM

General

Each MKI system has a high bandwidth and is impedance (Z=5 Ω) matched to meet the stringent pulse response requirements. A system consists of a multi-cell Pulse Forming Network (PFN) and a travelling wave kicker magnet [1], connected by a matched transmission line and terminated by a matched resistor: Figure 1 gives the basic schematic. The PFN design voltage is 60 kV and, allowing for overshoot, the magnet design voltage is 35 kV.

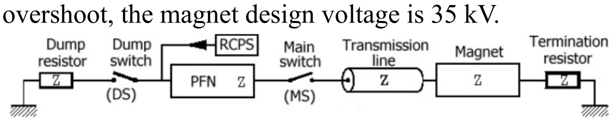

Figure 1: Schematic circuit of a MKI kicker system.

Design

Each cell of the kicker magnets consists of a U-core ferrite between two high voltage (HV) metallic plates: 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 beam coupling impedance [2], during LHC Run 1. To limit the longitudinal beam coupling impedance, while allowing a fast magnetic field rise-time, an extruded alumina tube, with screen conductors lodged in its inner wall, is placed within the aperture of the magnet. 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 each screen conductor, during the rise and fall of the magnetic field, via 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 2 shows the predicted maximum voltage versus conductor number: conductors #1 and #24 are adjacent to the HV busbar (which is at the bottom of the aperture), whereas #12 and #13 are adjacent to the ground (GND) busbar. The highest maximum voltage (~30 kV) occurs for conductors #1 and #24.

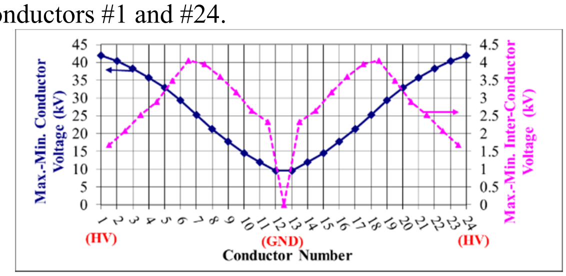

Figure 2: Conductor and inter-conductor voltages, for 24 screen conductors, for 60 kV PFN voltage.

The MKI magnets initially installed in the LHC had only 15, of a possible 24, screen conductors: it was necessary to omit 9 to limit high voltage breakdown [3]. However the missing screen conductors contributed to significant heating of the ferrite yoke by the high intensity LHC beam [4, 5]. In order to reduce the beam induced heating, while achieving good high voltage performance, the design of the beam screen was extensively analysed [3-5]. Although the resulting beam induced power deposition and high voltage performance are adequate for operation during Run 2 of the LHC [6], the alumina has a high Secondary Electron Yield (SEY). An SEY of greater than 1.4 can result in multipacting and hence a rise in pressure [7], which can be detrimental to the HV performance of the kicker magnet. In order to reduce the SEY of the inner surface of the alumina

ISBN 978-3-95450-147-2

tube, surface treatments or surface coatings are under consideration. A surface coating such as Amorphous Carbon (aC) can reduce the SEY to below 1.4: however aC is resistive and thus it is necessary to study its influence upon rise and fall times of the magnetic field, electric field strength and power dissipation in the thin coating. The following gives the effect of aC, simulated on the inside surface of the alumina tube, upon predicted electric field.

Model

In the dielectric solver modules of both Opera2D and Opera3D, two dimensional current flow and electric field equations are simultaneously solved to model the electric field in applications containing semi-conducting dielectrics [8]. Simulations of the electric field, associated with the alumina tube with a thin resistive coating on the inner surfaces, were carried out in 2D. As a result of the left-right symmetry of the beam screen it is only necessary to model half of the geometry: a cross-section is shown in Fig. 3, left. The slots of the 3 m long alumina tube are not perfectly flat – hence there are likely to be small gaps between a screen conductor and the alumina, which can result in a high electric field in this region. A vacuum gap of 0.1 mm is modelled between each screen conductor and the alumina (Fig. 3, right). At the capacitively coupled end of the screen conductors, there is a stainless steel cylinder with a clearance of 3 mm/1 mm to the OD of the alumina tube, on the HV/ground busbar side, respectively: this gap is chosen so as limit the maximum electric field [2, 3].

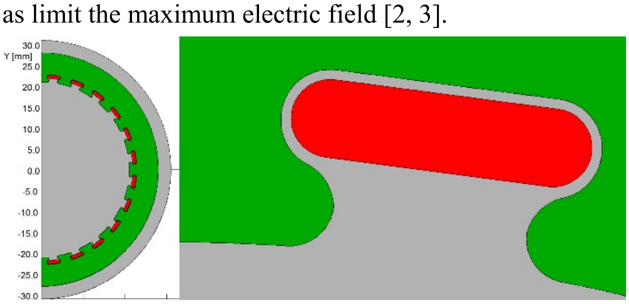

Figure 3: left - 2D section of MKI beam screen and right zoom of a screen conductor in a slot (green - alumina; red - screen conductors, grey - vacuum).

The resistive coating applied to the inner surface of the alumina tube may have a thickness of ~100 nm: however, in order to avoid meshing problems, a thickness of 1 µm is modelled. Nevertheless the coating thickness and the conductivity of the thin layer are simulated such that the d.c. sheet resistance is the required value.

Figure 4 shows the input voltage of the MKI magnet and the resulting voltage induced, at the capacitively coupled end, on the screen conductor adjacent to the HV busbar. During the rising/falling edge of the field the voltage induced on this screen conductor is 29.7 kV/-17 kV: the corresponding induced voltage for the screen conductor adjacent to the return busbar side is 7.5 kV/-4.3 kV. In the Opera simulation the voltage drive applied to each screen conductor is a simplified, piece-wise linear, version of the actual voltage (Fig. 4). For the simulations reported in this paper the coating is assumed to be aC: a relative permittivity of 5 is modelled [9]. For the alumina tube, a relative permittivity of 10 and a conductivity of 10^{-15} S/m are used.

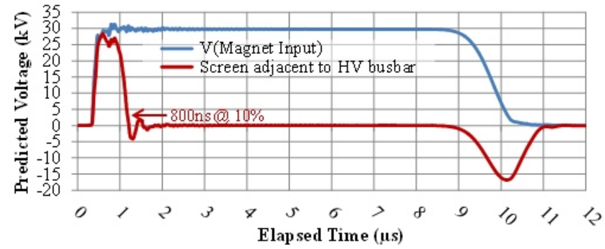

Figure 4: Magnet voltage and voltage of screen conductor adjacent to HV busbar, for 60 kV PFN voltage.

Predictions

Figure 5 shows the predicted maximum electric field without a coating and for coatings with various values of resistance per square (also known as sheet resistance), at the end of the flattop (600 ns) of the induced voltage pulses. The predicted potential within the alumina tube without a coating and with a coating with a sheet resistance of 10 kΩ/□ (i.e. 10 kΩ/square) are shown in Fig. 6.

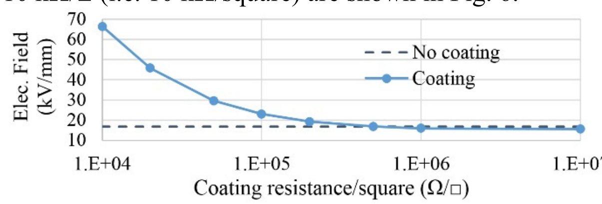

Figure 5: Electric field versus sheet resistance for MKI.

Figure 5 shows that a coating with a resistance of less than ~500 kΩ/□ increases the maximum electric field, in comparison with no coating. The high electric field occurs in the 0.1 mm gap between the alumina and the screen conductor. Without a coating the inner surface of the alumina tube has a predicted potential (Fig. 6, left) which is within 1.5 kV of that of the adjacent screen conductor. With a coating of 10kΩ/□ the inner surface of the alumina tube has a predicted potential (Fig. 6, right) which differs from that of the adjacent screen conductor by up to 6.5 kV: thus the electric field in this region is significantly higher than without the coating. Modelling the stainless steel cylinder as having a clearance of 3 mm to the OD of the alumina tube results in very similar predictions as shown in Fig. 5.

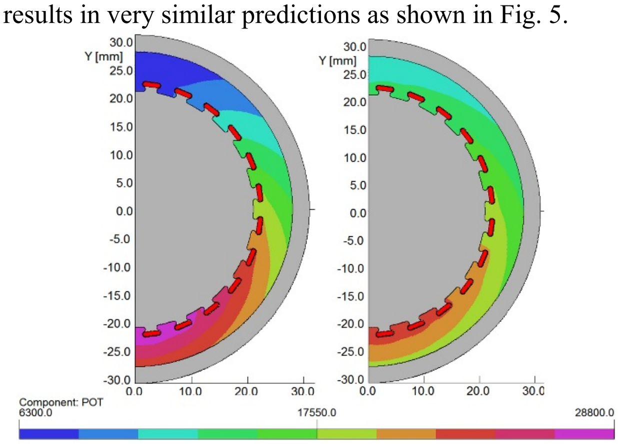

Figure 6: Predicted potential of alumina cylinder without any coating, at 600 ns (left). Potential of alumina cylinder with a coating of 10 kΩ/□ at 600 ns (right).

The resistive coating results in the predicted inner surface potential of the alumina tube converging towards the average potential of all the screen conductors: the time constant is dependent upon both the sheet resistance and parasitic capacitances. However, even for 10kΩ/□, the time constants are long compared with the duration of induced voltages, and thus the local coating potential is determined by capacitive coupling to the adjacent screen conductor.

Transient simulations have also been carried out with, as a worst-case, only the screen conductor at the lowest potential touching the coating, and all others with a 0.1 mm gap. Again, even for 10kΩ/□, the time constants are long compared with the duration of induced voltages, and hence the maximum electric field is not influenced by the contact.

MKP SERIGRAPHY STUDIES

The MKP is an impedance matched (Z=12.5 Ω) kicker system: the PFN design voltage is 55 kV. The high beam intensity and the large number of bunches can cause significant beam induced power deposition in the ferrite yoke of the MKP-L magnet [10], and hence an important temperature rise of the yoke. There is a total of 10 mm of available vertical space in the aperture of the MKP-L magnet [11]; hence to reduce the power deposition a beam screen has been proposed. The screen could consist of an alumina plate with 5 interleaved serigraphed silver fingers over the full length (~0.7 m) of the magnet aperture (Fig. 7): three of these fingers would be connected to beam-pipe ground at one end and the other two connected to beam-pipe ground at the other end. During the field rise and fall time voltage would be induced on the serigraphy: the magnitude of the induced voltage depends upon both the horizontal position in the aperture, relative to the HV and ground busbars, and also the longitudinal position in the magnet. Opera2D simulations have been carried out to predict the electric field. These studies include the influence of a thin aC coating to reduce SEY of the alumina.

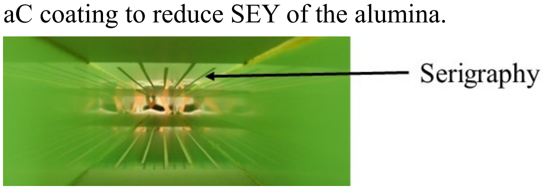

Figure 7: Serigraphed PCB, for impedance measurements.

Design & Model

The aperture of the MKP-L magnet is 141.5 mm wide x 54 mm high. The driving voltage of the HV conductor is modelled as half of the PFN voltage, i.e. 27.5 kV. The model includes a 2 mm thick alumina plate in the aperture with a gap of 2 mm to the ferrite leg (Fig. 8): on the beam side of the plate, there are five equally spaced silver fingers. The middle finger is aligned with the nominal orbit of the beam, i.e. the centre of the aperture, and there is a spacing of 12 mm between adjacent fingers. Maximum electric field is at either end of the aperture, where 2 or 3 fingers are physically close to beam pipe ground and are thus assumed to be at ground potential: the other 3 or 2 fingers are simulated as having an induced voltage proportional to the position between the HV and ground busbars, i.e. 19.3 kV/8.3 kV for the fingers closest to the HV/ground busbars, respectively. A thin resistive layer of aC is simulated over the surface of the alumina and serigraphy, with a relative permittivity of 5. The alumina plate has a relative permittivity of 10 and conductivity of 10^{-15} S/m. The HV pulse in the busbar has a 30 ns rise time and 3 μs flat top: the field in the magnet has a 225 ns rise-time, and hence the voltages induced on the serigraphy have 225 ns flattop.

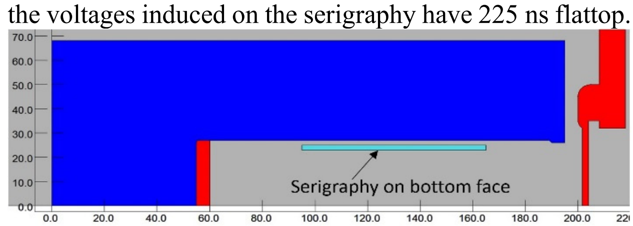

Figure 8: Cross-section of MKP-L magnet: symmetry is utilized so only half the magnet is simulated (dark blue – ferrite; cyan – alumina plate; red – busbars).

Predictions

Figure 9 shows the maximum electric field predicted without a resistive coating and for coatings with various values of sheet resistance. These values are predicted at the start of the flattop of the induced voltage pulses.

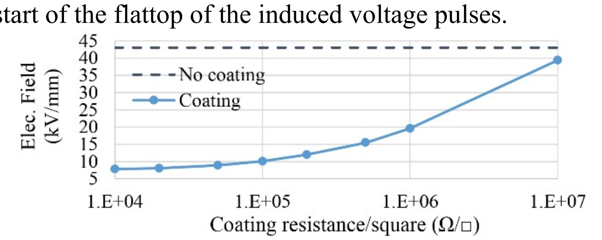

Figure 9: Electric field versus sheet resistance for MKP-L.

The addition of a conductive layer over the serigraphy greatly reduces the maximum predicted electric field: the lower the sheet resistance the lower the electric field. However the sheet resistance must be sufficiently high to limit instantaneous power dissipation during field rise and fall.

CONCLUSION

For the MKI, for a given geometry of the screen conductors, the highest possible sheet resistance should be chosen: this implies a very thin layer of aC – but the minimum thickness must be compatible with achieving a SEY of less than 1.4. A high sheet resistance is also consistent with low instantaneous power dissipation, within the aC. An alumina tube will be internally coated with a thin layer of aC and high voltage tests carried out: the coating will subsequently be carefully inspected for damage.

For the MKP-L the serigraphy in the aperture creates high electric fields and may lead to surface flashover. The application of an aC coating over the serigraphy reduces SEY and decreases the predicted electric field. High voltage tests of an alumina plate with serigraphy and with and without an aC coating are planned. A study to determine the feasibility of installing two 2 mm thick alumina plates in the MKP-L aperture will shortly commence. In addition studies to determine whether serigraphy and an aC coating would degrade the field rise-time have commenced.

ISBN 978-3-95450-147-2

REFERENCES

[1] M.J. Barnes, L. Ducimetière, N. Garrel, G.D. Wait, "The LHC Injection Kicker Magnet", in *Proc PAC'03*, Portland, USA, May 2003, p.1162.

[2] H. Day, M.J. Barnes, F. Caspers, E. Metral, B. Salvant, "Beam Coupling Impedance of the New Beam Screen of the LHC Injection Kicker Magnets", in *Proc. IPAC'14*, Dresden, Germany, June 2014, paper TUPRI030.

[3] M.J. Barnes et al., "High Voltage Performance of the beam Screen of the LHC Injection Kicker Magnets", in *Proc. IPAC'14*, Dresden, Germany, June 2014, paper MOPME074.

[4] H. Day, M.J. Barnes, F. Caspers, E. Métral, B. Salvant, "Impedance Studies of Improved Beam Screens for the LHC Injection Kickers", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPME033.

[5] PhD Thesis, H. Day, 2013.

[6] M.J. Barnes et al., "Operational Experience of the Upgraded LHC Injection Kicker Magnets", presented at IPAC'16, Busan, Korea, May 2016, paper THPMW033.

[7] M.J. Barnes et al., "Upgrade of the LHC Injection Kicker Magnets", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOPWA030.

[8] *http://www.cobham.com/communications-and-connectivity/antenna-systems/specialist-technical-services-and-software/design-simulation-software/*

[9] S. Calatroni, Private communication, 27/10/2015.

[10] M.J. Barnes et al., "Studies of impedance-related improvements to the SPS Injection Kicker System", presented at IPAC'16, Busan, Korea, May 2016, paper THPMW030.

[11] M.J. Barnes, L. Sermeus, "MKP: Considerations on MKP improvements", ABT LIU Project Review 2015, 20 Nov. 2015, *https://indico.cern.ch/event/460131/*