Shielding of the VELO detectors from the LHC beam high-frequency fields: preliminary considerations

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Abstract

The sensitive area of the LHCb VELO silicon strip detectors will approach the LHC beams to a distance of 8 mm. The sensors will be encapsulated in a thin-walled box to separate the primary vacuum from the secondary vacuum. This encapsulation must be electrically conductive in order to provide adequate wake field suppression. In addition, it must shield the detectors from excessive high-frequency pick-up noise. Here, we present a simple estimation of the (absorptive) attenuation of the LHC high-frequency fields through the shield, and we draw some conclusions on the wall thickness proposed in the LHCb Technical Proposal.

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1 Introduction

The LHCb vertex detector is divided in two halves, each containing a number of silicon detector modules which must be shielded from the electromagnetic (EM) fields of the LHC beams. In the present design this is achieved by encapsulating all modules of one detector half in a thin-walled aluminium box [1]. The sensitive area of the silicon strip detectors will approach the LHC beams to a distance of 8 mm. The closest distance of approach of a strip to the aluminium wall is 1-2 mm. On the beam side of the aluminium walls the (radial) electric field component is expected to reach values close to 1 MV/m, while the peak (tangential) magnetic field component will be of the order of 1 kA/m. These EM fields clearly must be attenuated sufficiently as they propagate through the wall, so that the detectors are not excessively affected by high-frequency pick-up noise.

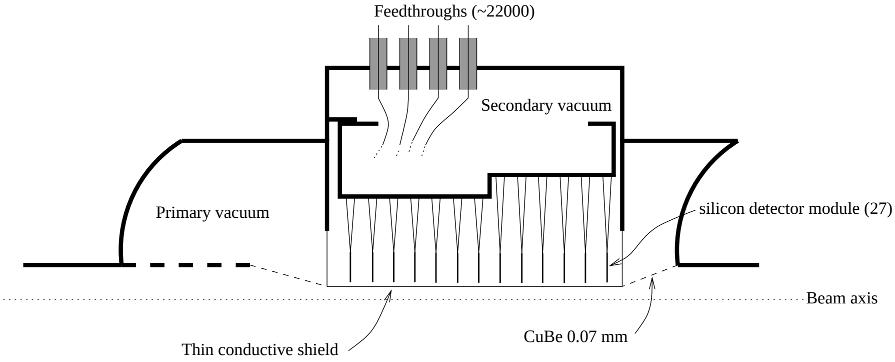

Figure 1: Sketch of the VELO shielding scheme. Dashed lines indicate shielding boundaries with holes.

A quantitative description of such effects is rather complex. Fig.1 shows a sketch of the current shielding scheme of the VELO detectors. The source of EM radiation is concentrated near the nominal beam axis. The most reliable way to assess the electro-magnetic compatibility (EMC) issues is by using an experimental test setup with a complete detector module. Such studies will be performed on a prototype detector module in the near future. Here, we argue that the thickness of the aluminium shield (100 μm) proposed in the Technical Proposal [2] sufficiently attenuates the high-frequency fields. Note that the wiring and grounding of the detector modules themselves, which can influence high-frequency pick-up, are not yet defined. Hence, we do not discuss other ways of RF field penetration, such as leakage via gaps or feedthroughs.

2 High-frequency fields of the LHC beams

The large field components of a charged cylinder of radius R moving at extreme relativistic velocity ($v \to c$) inside and on the axis of a prefectly conducting cylindrical pipe are the radial electric field E_r and the azimuthal magnetic field H_ϕ. They are given by [3]

$$\begin{aligned} E_r(r, z-vt) &= \frac{\lambda(z-vt)}{2\pi\varepsilon_0\, r} \\ H_\phi(r, z-vt) &= \frac{\lambda(z-vt)\, Z_0}{2\pi\mu_0\, r} \end{aligned} \tag{1}$$

at a distance $r \geq R$ from the axis. Here, $\lambda(z-vt)$ describes the longitudinal charge distribution on the moving cylinder (with total charge Q). $Z_0 = \sqrt{\mu_0/\varepsilon_0} \simeq 377\ \Omega$ is the vacuum impedance.

These expressions can be used to estimate the fields due to a sequence of bunches. For a gaussian bunch of length σ_z we replace $\lambda(z-vt)$ by $Q\,e^{-(z-vt)^2/2\sigma_z^2}/\sqrt{2\pi}\sigma_z$. Taking the example of an LHC bunch, $\sigma_z = 7.5$ cm and $Q = 18$ nC, the peak radial electric field near the pipe wall surface ($r = r_w$) amounts approximately to

$$E_r^{max} = \frac{Q}{(2\pi)^{3/2}\,\varepsilon_0\,\sigma_z\,r_w} \simeq 1.7\ \mathrm{kV}/r_w \simeq 0.3\ \mathrm{MV/m}\quad (\text{for } r_w = 6\ \mathrm{mm})\ . \tag{2}$$

(Alternatively, one expects a peak magnetic field $H_\phi^{max} = I^{max}/2\pi\,r_w \simeq 763$ A/m for a peak current $I^{max} \simeq 28.7$ A, and so a peak electric field $E_r^{max} = Z_0\,H_\phi^{max} \simeq 377\ \Omega \cdot 763$ A/m $\simeq$ 0.3 MV/m.)

In frequency space, the spectrum of such a gaussian bunch is continuous with each frequency having an amplitude $E(\nu) \sim e^{-(2\pi\nu\sigma)^2/2}$. In the case of a bunch sequence with bunch spacing c/ν_b the frequency spectrum is discretized. Here, ν_b is the bunch frequency (for LHC $\nu_\mathrm{b} =$ 40 MHz). The spectrum for the case of LHC (assuming a homogeneous sequence of gaussian bunches) is shown in Fig. 2. The peak electric field of the nth harmonic ($\nu_n = n\,\nu_\mathrm{b}$) is then

$$E_r^n \simeq 2\sqrt{\pi}\,\nu_\mathrm{b}\,\sigma\,E_r^{max} \cdot e^{-(2\pi n\nu_\mathrm{b}\sigma)^2/2} \simeq 10\ \mathrm{kV/m} \cdot e^{-(2\pi n\nu_\mathrm{b}\sigma)^2/2} \tag{3}$$

where $\sigma = \sigma_z/c$.

Similarly, for the magnetic fields

$$H_\phi^n \simeq 2\sqrt{\pi}\,\nu_\mathrm{b}\,\sigma\,H_\phi^{max} \cdot e^{-(2\pi n\nu_\mathrm{b}\sigma)^2/2} \simeq 27\ \mathrm{A/m} \cdot e^{-(2\pi n\nu_\mathrm{b}\sigma)^2/2}\ . \tag{4}$$

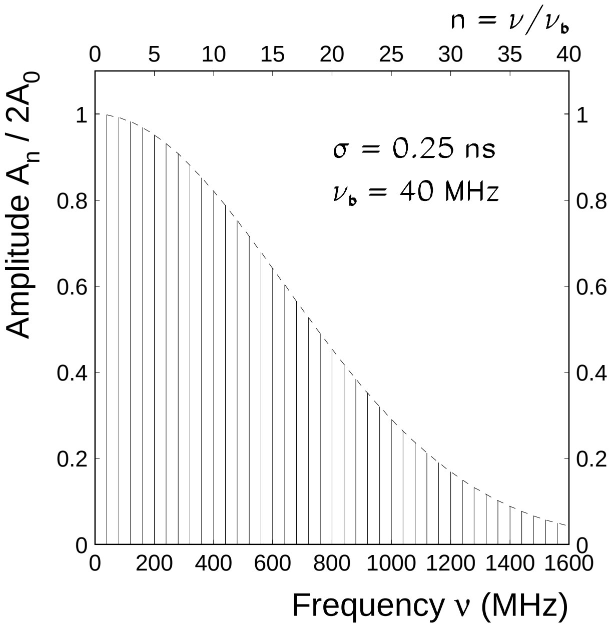

Figure 2: Fourier spectrum of LHC assuming a homogeneous sequence of gaussian bunches.

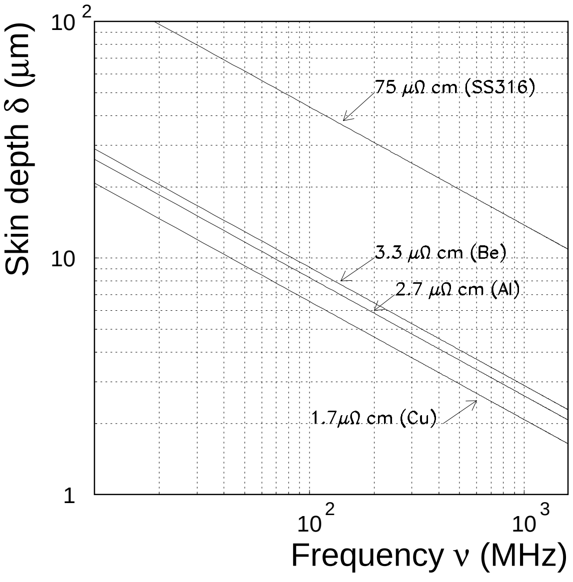

Figure 3: Skin depth as function of frequency for different materials (stainless steel 316, aluminium, beryllium and copper).

3 Shield thickness and attenuation

The EM fields drop to zero inside a perfectly conducting wall. For a quasi-perfect conductor one can derive [4], from the condition that the tangential component of the magnetic field be continuous and from Ohm's law, that the fields inside the wall material are predominantly tangential to the wall surface and that the magnetic field is dominating over the electric field. The tangential electric field is of order $\sqrt{\varepsilon_0 \omega \rho_c}\, Z_0$ times the magnetic field. Here, ε_0 is the permittivity of free space and ρ_c is the resistivity of the wall material. The unitless quantity $\sqrt{\varepsilon_0 \omega \rho_c}$ is small. Indeed, for $\rho_c = 2.7\ \mu\Omega\,\mathrm{cm}$ (aluminium) and $\omega = 2\pi\, 40$ MHz, $\sqrt{\varepsilon_0 \omega \rho_c}$ amounts to 10^{-5}. The normal component of the electric field is of second order in $\sqrt{\varepsilon_0 \omega \rho_c}$. Therefore, the relevant field component from the previous section is H_ϕ^n, from which we also can calculate the tangential electric field.

Both electric and magnetic fields propagate perpendicular to the wall surface and decay exponentially in the wall. The quantity characterizing this exponential fall-off, the so-called skin depth, is given as a function of frequency ν by

$$\delta(\nu) = \sqrt{\frac{\rho_c}{\pi \nu \mu}} \tag{5}$$

where μ is the (absolute) permeability. Here, we use $\mu = \mu_0$. The larger the frequency, the more the EM fields are attenuated radially throughout the wall material. Fig. 3 shows the skin depth as a function of frequency and for different values of the resistivity (corresponding to stainless steel 316, aluminium, beryllium and copper). For the frequency component n discussed in the previous section, the skin depth is $\delta_n = \sqrt{\frac{1}{n}}\, \delta_1$ with $\delta_1 = \sqrt{\frac{\rho_c}{\pi\, \nu_b\, \mu_0}}$. For an aluminium shield we expect a skin depth $\delta_1 \simeq 13\ \mu$m at $\nu_b = 40$ MHz. If we use a wall thickness of 100 μm, this corresponds to an attenuation by $e^{-100/13} \simeq 4.5 \times 10^{-4}$ at this frequency. Hence, the tangential magnetic field should be attenuated from 27 A/m down to 0.01 A/m, and the tangential electric field from $\approx 10^{-5}\, Z_0\, 27$ A/m ≈ 0.1 V/m down to 5×10^{-5} V/m.

If attenuation at the bunch frequency of 40 MHz is e^{-t/δ_1} for a wall thickness t, then at a higher harmonic frequency $\nu_n = n\nu_\mathrm{b}$ the attenuation will be $e^{-t/\delta_n} = e^{-t\sqrt{n}/\delta_1}$, i.e. the attenuation is stronger by the factor $e^{(1-\sqrt{n})t/\delta_1}$. For the above example and for $n = 2$, the extra attenuation is already substantial: $e^{(1-\sqrt{2})t/\delta_1} \simeq 0.075$.

4 Preliminary EMC studies of a VELO test module

We have tried to generate RF pick-up noise in a test detector module, with both electric and magnetic fields. For these tests we used a Hamamatsu prototype detector (R strips, n-on-n, 300 μm thick, 72 degrees coverage) connected to a 6-chip (SCTA128) hybrid via a fan-out. Pulses with rise time $\tau_\mathrm{rise} \simeq 0.8$ or 1.6 ns, width $\tau_\mathrm{width} \simeq 3$ ns and various repetition frequencies (1, 10, 21, 42 63, 84 MHz) were generated with an Agilent 81112 pulse generator (max 0.8 V output over 50 Ω) and amplified 10 times with a custom-made RF amplifier.

To test the sensitivity to electric fields we brought a 25 mm $\times$ 25 mm copper plate at a distance $d \simeq 4$ mm from the surface of the module, at various places (silicon, fan-out or hybrid area). The copper plate was connected to the signal wire of a coaxial cable with the shield left unconnected. Hence, when sending pulses into the copper plate, we expect a voltage U_C between the copper plate and any conducting wall facing it to be of the order of

$$U_C \approx 2\, U_\mathrm{gen}\ , \tag{6}$$

the pulse being reflected at the capacitor and reabsorded in the (50 Ω) pulse generator. Here, U_gen is the voltage sent out by the pulse generator (which includes the RF amplifier). The electric field E_C in this plate capacitor is then of the order of

$$E_C \approx 2\, \frac{U_\mathrm{gen}}{d}\ . \tag{7}$$

We started observing RF noise at voltages larger than or of the order of 1 V, *i.e.* electric fields of about 500 V/m. The field was predominantly perpendicular to the exposed surface.

To test the sensitivity to magnetic fields we brought a $\sim 50\ \Omega$ loop of diameter $D \simeq 28$ mm at a distance $d \simeq 4$ mm from the surface of the module, at various places (silicon, fan-out or hybrid area). The loop was made with a $50\ \Omega$ resistor terminating the signal wire of a coax cable to its shield. Hence, when sending pulses into the loop, we expect a current I_L through the loop of order

$$I_L \approx \frac{U_{\text{gen}}}{50\ \Omega}\ . \tag{8}$$

The magnetic field H_L in the center of this loop is then of the order of

$$H_L \approx \frac{I_L}{D} = \frac{U_{\text{gen}}}{D \cdot 50\ \Omega}\ . \tag{9}$$

In this case, we started observing RF noise at voltages larger than or of the order of 1 V, *i.e.* magnetic fields of about 5 A/m. Again the field was predominantly perpendicular to the exposed surface.

The above results are preliminary and coarse. The data are being analysed and the final results will be published elsewhere. However, when compared to the the RF field values discussed in section 3, they tend to indicate that attenuation through the shield is more than sufficient for any RF shield design candidate considered so far.

5 Remarks

In the above discussion, we have neglected possible reflections at the vacuum-wall boundaries. This is justified by the fact that reflections are negligible for frequencies which have a corresponding skin depth much smaller than the wall thickness [5]. Since we consider here frequencies $\nu \geq 40$ MHz and RF shield at least 100 μm thick and made of good conductive material, the fields have to penetrate at least 5-6 skin depths.

Further, we assumed a homogeneous sequence of bunches (*i.e.* identical bunches all spaced by the same distance). In the LHC bunches will have different charges and some buckets will be left empty. As a consequence, additionnal frequency lines will appear, *e.g.* multiples of the revolution frequency ($n \times 11.25$ kHz). These low frequency component will have a reduced amplitude, but also a much larger skin depth. For example, in the filling scheme of one LHC beam there will be gaps of 30 empty buckets between the 12 SPS trains of bunches. In addition, one of these SPS trains (which normally contain each three PS trains spaced by 8 empty buckets) will contain one empty PS train (*i.e.* 81 more empty buckets). This implies that frequency lines of 1, 12 and 36 × 11.25 kHz can be expected to be present with substantial amplitudes (about 35, 100 and 350 times smaller than that of the bunch frequency of 40 MHz). For these low frequencies attenuation by absorption is weak (typically $e^{-t/\delta}$ between 1 and 0.1), but reflection losses become important. These low frequencies should be taken into account in the shielding scheme.

Finally, our first tests were performed for the fields components perpendicular to the surface device under study. More extensive studies (also with a more realistic module prototype) will be carried out.

6 Conclusions

We presented an estimate of absorptive attenuation of the LHC high-frequency fields through the thin-walled encapsulation of the LHCb VELO. We argued that the (aluminium) wall thickness of 100 μm proposed in the Technical Proposal is sufficient to shield the detectors against high-frequency components of the LHC bunch spectrum when only considering RF attenuation in the shield. However, other ways of picking up RF noise (through gaps, feedthroughs, or low frequencies) should be considered and tested in a realistic environment.

References

[1] http://www.nikhef.nl/pub/departments/mt/projects/lhcb-vertex.

[2] LHCb Technical Proposal, CERN/LHCC 98-4.

[3] See *e.g.* in “Wake fields and impedance”, L. Palumbo, V.G. Vaccaro, M. Zobov, SCAN-9502084, LNF 94-041 P (5 Sep 1994).

[4] “Classical Electrodynamics”, J.D. jackson, second edition (1975), John Wiley & Sons.

[5] see *e.g.* in “Introduction to Electromagnetic Compatibility” by R.P. Clayton, John Wiley & Sons Inc., 1992, ISBN 0-471-54927-4.