Requirements for the LHC Collimators

associated to Impedance/Heating aspects

- Thick insulators $\Longrightarrow$ thin metallic coating
- How thick is a 'thick insulator'?
- Bad conductors $\Longrightarrow$ beam induced heating
- Naked and 'hidden' metallic layers
- General impedance-related guidelines for the collimator design

Inductance and Resonances for Thick Insulators

In case of collimator jaws consisting of thick insulators, such as Boron-Nitride as for the TDI or other ceramic materials, a thin metallic coating is very important:

- to reduce the broad-band inductive impedance seen by the beam
- to avoid resonances $\Longrightarrow$ beam instabilities
- to avoid charging-up the insulator surface $\Longrightarrow$ sparking

How thick is a 'thick insulator'?

The surface inductance of an insulator block of thickness t with large relative dielectric permittivity $\varepsilon_{\rm r} \gg 1$ is independent of $\varepsilon_{\rm r}$ and proportional to the thickness

$$L_{\Box} = \mu_o \sqrt{\frac{\varepsilon_{\rm r} - 1}{\varepsilon_{\rm r}}} \times t \sim \mu_o \times t .$$

This corresponds to an inductive longitudinal coupling impedance

$$\frac{Z}{n} \simeq \frac{\omega_o L_{\Box}}{2\pi b} \times \ell$$

where ℓ is the total collimator length, b the collimator distance from the beam, and ω_o the ring angular revolution frequency ($\omega_o = 2\pi \times 11\,\mathrm{kHz}$ for the LHC).

How thick is a 'thick insulator'? (continued)

For a thickness $t = 1\,\mathrm{mm}$ the surface inductance is $L_\square \simeq 1.25\,\mathrm{nHenry}$ and, assuming a collimator half-aperture $b = 1.25\,\mathrm{mm}$ and a total collimator length $\ell = 20\,\mathrm{m}$, we arrive at a coupling impedance $Z/n \simeq 220\,\mathrm{mOhm}$ comparable to the total LHC impedance budget of about $250\,\mathrm{mOhm}$.

For a thick naked insulator block with $t = 5\,\mathrm{cm}$, $b = 5\,\mathrm{mm}$ and $\ell = 3\,\mathrm{m}$, such as the TDI absorber, the impedance would be $Z/n \simeq 415\,\mathrm{mOhm}$, i.e. nearly twice the total LHC impedance budget!

Metallic Coating of Thick Insulators

To reduce the large broad-band inductive impedance seen by the beam in case of collimator jaws consisting of thick insulators, we recommend a thin metallic coating. The coating should avoid em field penetration over most of the bunch spectrum and, in view of possible low-impedance paths for the beam image currents associated with metallic structures located outside of the collimator blocks, this implies a coating thickness comparable to the skin depth $\delta_{\rm skin}(\omega) = \sqrt{\frac{2\rho}{\mu_o \omega}}$ at the relevant frequency ω.

The skin depths at 600 MHz (corresponding to the rms frequency of the 7 TeV LHC bunches) for Cu, Be and Ti are $2.6\,\mu$m, $4\,\mu$m and $20\,\mu$m, respectively. Since the resistivity of deposited metallic layers is always significantly larger than the theoretical value, it is prudent to take a few skin depths (to include also lower frequencies).

Metallic Coating of Thick Insulators (continued)

We therefore propose metallic coatings of 10 μm, 20 μm and 100 μm, respectively:

metallic coating	recommended thickness [μm]
Cu	10
Be	20
Ti	100

Resonances in a thick dielectric pipe (or collimator jaw)

For circular geometry, the first resonance appears when the thickness of the dielectric equals one quarter of the reduced wavelength

$$\frac{\lambda/\sqrt{\varepsilon_{\mathrm{r}}}}{4} = t$$

and higher resonances at odd multiples thereof. See B. Zotter, *Longitudinal instabilities of charged particle beams inside cylindrical walls of finite thickness*, Part. Acc. **1**, 311-326 (1970).

For example: $\varepsilon_{\mathrm{r}} \sim 12$ and $t = 1\,\mathrm{cm} \quad \Longrightarrow \quad \lambda = 4t\sqrt{12} \simeq 14\,\mathrm{cm}$

and the wavelength of the first resonance is comparable to the LHC bunch length. Since typical ceramic materials have small dielectric losses ($\tan\delta \sim 10^{-4} \ll 1$), these are high-Q resonances and can be dangerous for beam stability. A thin metallic coating would also drastically reduce such narrow band impedance.

Naked and 'hidden' metallic layers

Will a thin metallic coating resist to beam impact/losses and for how long? This is an important and difficult question that may have to be addressed by beam tests. Also impedance/heating implications of small scratches caused by the beam in the metallic coating for ceramic or graphite collimator jaws will require further studies.

In case a thick ceramic or other dielectric material is chosen for the collimator jaws, an interesting idea ca be to have a thin dielectric layer, say 0.1 mm thick, visible to the beam and an underlying metallic layer that will shield the bulk of the collimator jaw. The impedance associated with very high frequency resonances in the naked thin dielectric layer may require further studies.

Graphite collimator jaws: estimated power deposition

In case of graphite collimator jaws, the resistive impedance would have modest implications for beam stability, but there would be some heating. We estimate a beam induced heating of 240 W/m, for ultimate LHC beam intensity and collimators around $6\,\sigma$ at injection. A $10 - 20\,\mu$m Cu coating of the graphite would reduce the beam induced heating to about 8 W/m.

This power scales with the square of the bunch intensity and approximately with the inverse of the collimator aperture. Therefore in collision the above figures are multiplied by a factor 4.

Depending on the heat deposition, the uncoated graphite may outgas and create vacuum problems, in addition to dust.

Graphite collimator jaws (continued)

The heat deposition in collimator jaws consisting of ‘naked’ graphite or some other bad conductor can in principle be substantially reduced by metallic structures running parallel to the beam direction and homogeneously distributed along or just below the collimator surface (‘loaded graphite’?). Note that over most of the bunch spectrum the image currents are determined only by the collimator geometry and not by the local conductivity, i.e. they do not redistribute to follow paths of lower impedance.

Is there a material worse than graphite from the point of view of power dissipation in a collimator? The answer is yes: ferrite would dissipate in the same geometry in the order of 10 kW!

General impedance-related guidelines for the collimator design

To reduce broad-band impedance and trapped modes associated with geometric discontinuities of the LHC vacuum chamber, we recommend a minimum tapering angle of about 15° at all transitions. For a 20 mm depth of the collimator jaws, this corresponds to a tapering transition of about 75 mm.

Sliding contacts should be envisaged also to shield possible cavity-like structures created in the collimator tanks when the collimators jaws are near the beam.

To allow a smooth conduction of the beam image currents, a good RF contact is needed between the vacuum chamber and any metallic coating, hidden metallic layer or sliding contact associated with the collimator jaws.