Beam Coupling Impedance Simulations of the LHC TCTP Collimators

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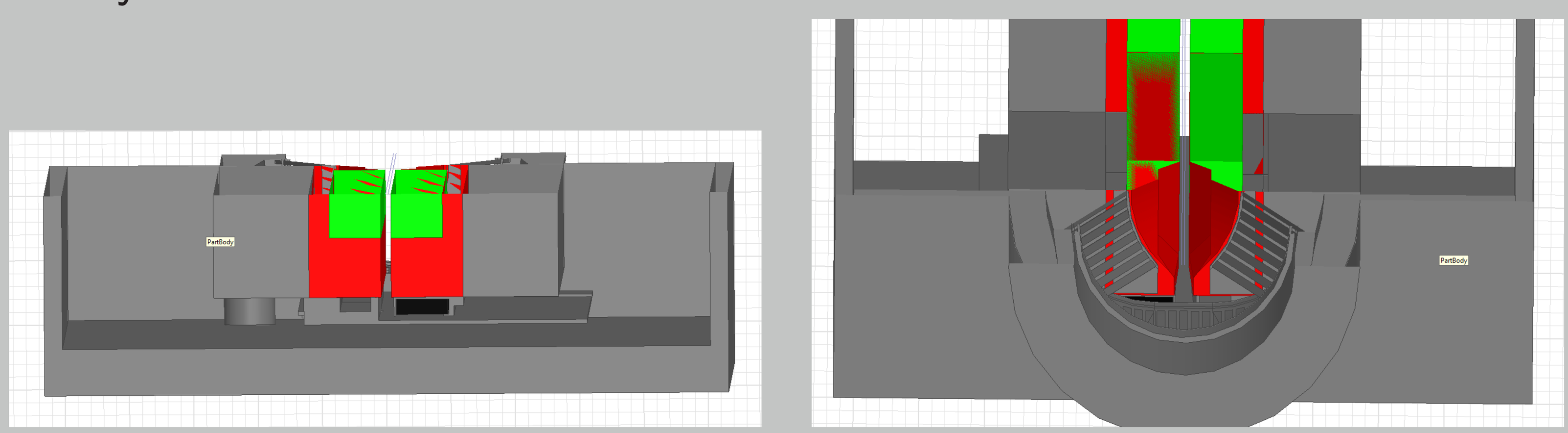
Abstract

As part of an upgrade to the LHC collimation system, 8 TCTP and 1 TCSG collimators are proposed to replace existing collimators in the collimation system. In an effort to review all equipment placed in the accelerator complex for potential side effects due to collective effects and beam-equipment interactions, beam coupling impedance simulations are carried out in both the time-domain and frequency-domain of the full TCTP design. Particular attention is paid to trapped modes that may induce beam instabilities and beam-induced heating due to cavity modes of the device.

Introduction - TCTP Design

- The TCTP is a collimator design intended to replace a number of existing teritary collimators in the LHC.
- It has two new design features
  1. Built in BPMs, to give accurate beam position data to speed up collimator setup
  2. A new RF screeen design, whereby the cavity of the vacuum tank is no longer directly screened, and ferrite tiles are used to damp the resulting cavity modes.



(a) (b)

Figure 1: The design of the TCTP structure illustrating 1(a) the ferrite damping circuit and 1(b) the RF fingers from the vacuum to the collimator jaw. Ferrite is in black, copper in red, tungsten in green and stainless steel in grey.

- The phase 1 RF system uses sliding RF contacts to isolate the vacuum tank from the cavity seen by the beam, thereby moving the cavity modes to high frequencies where the beam power spectrum is small.
  - ▷ This produces secondary problems with the production of dust and fears that over time the RF contacts may lose contact.
- The phase 2 RF system allows the vacuum tank to be visible to the beam via a narrow longitudinal gap, but uses ferrites to greatly reduce the Q of the resulting cavity modes.

Using Lossy Materials to Damp Cavity Resonances

- Any given cavity in a beam pipe will have a set of resonant cavity modes determined by it's dimensions
  - ▷ The frequencies of the modes are determined by the dimensions of the cavity, larger dimensions give rise to modes at lower frequencies
  - ▷ The **R/Q** of a mode is strictly a function of the geometry of the cavity. It is independent of the material the cavity is made from.
  - ▷ The Q of the cavity is a function of the materials in the cavity. This we can change.

$$P_{loss} = I_b^2 \frac{R_s}{Q} Q S(\omega_r) \tag{1}$$

- where I_b is the beam current, R_s is the shunt impedance of the resonance and $S(\omega_r)$ is the magnitude of the beam power spectrum at the resonant frequency ω_r.
- If we can reduce Q we can reduce the power loss. Adding ferrites to locations with high magnetic fields does exactly this.

Simulations Parameters

- To identify the eigenmodes of the TCTP, we use the eigenmode solver of the frequency domain solver HFSS [1]. We model realistic surface materials as seen in Fig. 1 and characterise the cavity mode properties using a postprocessing evaluation of the modal fields. We then produce a sum impedance due to all modess at a angular frequency ω from

$$Z_{total}(\omega) = \sum_{i=1}^{n} \frac{R_{s,i}}{1 + jQ_i\left(\frac{\omega}{\omega_{res,i}} - \frac{\omega_{res,i}}{\omega}\right)} \tag{2}$$

- where $R_{s,i}$ is the shunt impedance, $\omega_{res,i} = 2\pi f_{res,i}$, $f_{res,i}$ is the eigenfrequency of the resonance, and Q_i is the quality factor of the resonance, i is the i-th eigenmode of the cavity, and n is the number of eigenmodes to be considered.

Beam Coupling Impedance Results

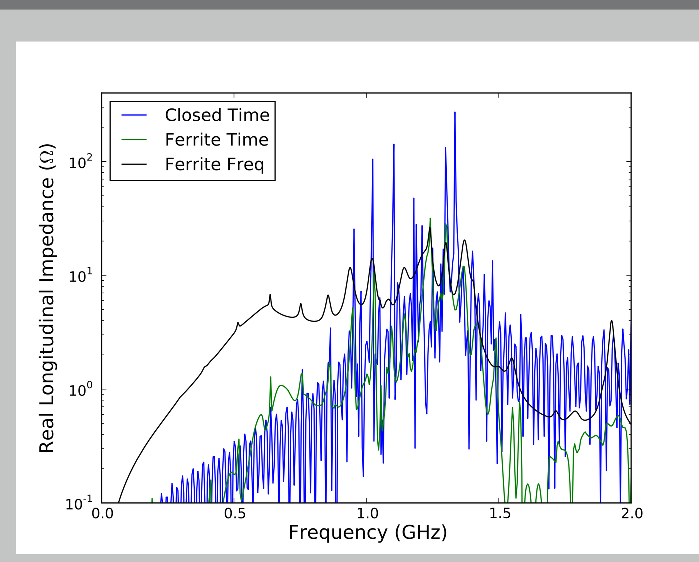


Figure 2: The beam coupling impedance of the TCTP from both time domain and frequency domain simulations, compared to that of a simple closed collimator.

- It can see from Fig. 2 that we have reasonable agreement between the time domain and frequency domain results for the ferrite damped case.
- Comparing the impedance of the closed case (phase 1 type design) and the ferrite case (phase 2 type design), we see the predicted impedance profile is present.
  - ▷ The closed structure has a number of cavity modes, predominantly occurring at frequencies greater than 1GHz. The peak value of the impedance of these modes is seen to be comparatively high when compared to the ferrite case, due to the higher Q of the resonances.
  - ▷ The cavity modes of the ferrite damped structure occur at lower frequencies than those of the closed case. However we can see that the peak values of the high frequency (i.e. greater that 800MHz) resonances is substantially (on the order of 10%) lower than that of the closed structure.
- *NOTE:* The time domain simulations were terminated before the complete decay of the wakepotential. This means that the peak height of the resonances is not indicative of the realistic value. This is due to the long computational time necessary to evaluate the wakepotential completely.

Beam-Induced Heating Estimates

Table 1: Beam parameters for different operation modes of the LHC and future upgrades

Operation Mode	$N_b(10^{11})$	No. of bunches
LHC, τ_b=50ns	1.45	1380
LHC, τ_b=25ns	1.15	2808
HL-LHC, τ_b=50ns	3.3	1380
HL-LHC, τ_b=25ns	2.2	2808

- Due to future upgrades planned for the LHC, we must consider the potential heat load on the TCTP due to a number of different beam parameters, summarised in Tab. 1.
- The power loss P_{loss} due to a longitudinal impedance $Z_{\parallel}$ in a storage ring can be given by [1]

$$P_{loss} = (f_{rev} e N_b n_{bunch})^2 \sum_{n=0}^{\infty} \left(2\left|\lambda(\omega_0)\right|^2 \Re e\left(Z_{\parallel}(\omega_0)\right)\right) \tag{3}$$

- where f_{rev} is the revolution frequency, e is the electron charge, N_b is the bunch population, n_{bunch} the number of bunches in the storage ring $\lambda(\omega)$ is the bunch current spectrum is the frequency domain, $\omega_0 = 2\pi f_0$ and $f_0 = \frac{1}{\tau_b}$, and τ_b is the bunch spacing.
- To ensure that the damping ferrites do not cross their Curie temperature, we also calculate the heat load directly on the ferrites.

Table 2: Heating Estimates for the TCTP collimator for different beam modes. P_{loss} is the total power loss and $P_{loss,ferr}$ the power lost in the ferrite tiles.

Operation Mode	t_b (ns)	P_{loss} (W)	$P_{loss,ferr}$ (W)
LHC, τ_b=50ns	1	27	1
LHC, τ_b=25ns	1	34	2
HL-LHC, τ_b=50ns	1	140	7
HL-LHC, τ_b=25ns	1	104	5
HL-LHC, τ_b=50ns	0.5	374	19
HL-LHC, τ_b=25ns	0.5	279	14

Summary

- We have verified the effectiveness of using a damping system to reduce the expected beam induced heating due to cavity impedances in a collimator.
- Providing heat loads on the collimator and the ferrite tiles for a number of LHC and LHC upgrade plans, determined whether the damping system remains effective even for very high intensity beams.

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