ISBN: 978-3-95450-253-0 ISSN: 2673-5571 doi:10.18429/JACoW-HB2023-THBP52

A PYTHON PACKAGE TO COMPUTE BEAM-INDUCED HEATING IN PARTICLE ACCELERATORS AND APPLICATIONS

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Abstract

High-energy particle beams interact electromagnetically with their surroundings when they travel inside an accelerator. These interactions may cause beam-induced heating of the accelerator's components, which could eventually lead to outgassing, equipment degradation and physical damage. The expected beam-induced heating can be related to the beam coupling impedance, an electromagnetic property of every accelerator device. Accounting for beam-induced heating is crucial both at the design phase of an accelerator component and for gaining an understanding of devices' failures. In this paper, an in-house developed Python tool to compute beam-induced heating due to impedance is introduced. The different features and capabilities will be showcased and applied to real devices in the LHC and the injector chain.

INTRODUCTION

A high-energy beam of charged particles traveling inside an accelerator component will generate electromagnetic wake-fields in the vacuum chamber that hosts it. This electromagnetic interaction can be described, in the frequency domain, through the concept of beam-coupling impedance: a complex quantity that is function of the beam chamber's geometry and material properties [1]. Wake-fields, and hence the impedance, other than affecting beam dynamics can be the source of energy deposited on accelerator components. This last phenomenon is impedance-related beam-induced heating (BIH) and may lead to a number of issues: outgassing, pressure spikes, unwanted beam dumps, and, potentially, permanent damage to the devices [2]. Thus, in many cases a good understanding of BIH is mandatory to push the performance of the machine.

In this proceeding, a python package that allows to easily compute the dissipated power due to BIH is presented [3]. The package named BIHC collects various methods to do this computation. More specifically, it is tailored for usage in the LHC and in the injector chain with two main applications:

1. During feasibility studies in the design phase of accelerator components.

2. To understand impedance-related issues that can occur during machine operation and investigate potential mitigation solutions.

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Following the introduction of the analytical formalism, two applications to the central beam pipe of the CMS experiment in the LHC and the beam wire scanners in the SPS will be shown to demonstrate the code's capabilities.

BEAM-INDUCED HEATING

The tool implements the equations for computing impedance related BIH for two scenarios: a single beam traveling in the vacuum chamber and two counter-rotating beams traveling through the same vacuum chamber.

Single Beam Scenario

The power dissipated due to a circulating beam into an accelerator component can be expressed as [1]:

$$P = 2(f_0 e M N_b)^2 \cdot \sum_{p=0}^{+\infty} |\Lambda(p\omega_0)|^2 \mathrm{Re}[Z_z(p\omega_0)]. \quad (1)$$

To compute Eq. (1), one characteristic quantity of the accelerator component (the real part of the longitudinal beam-coupling impedance $\mathrm{Re}[Z_z]$) and several characteristic quantities of the particle beam are needed.

The beam considered in the formalism is composed of a repetition of M bunches of N_b charged particles, each with charge e, that are circulating in the accelerator with revolution frequency f_0. The bunches have a certain longitudinal charge profile (for instance Gaussian or q-Gaussian) and they are spaced in time following a predetermined filling scheme. This is shown in Fig. 1 for a real fill of the LHC machine.

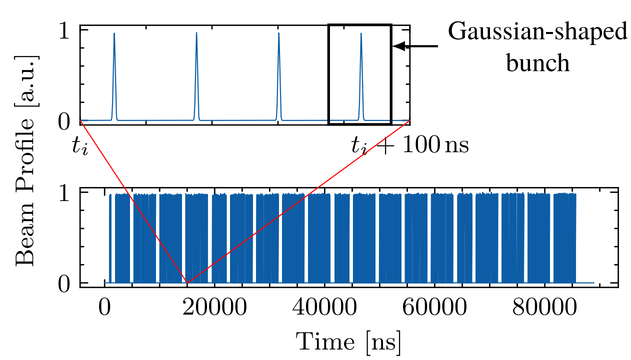

Figure 1: Normalized longitudinal beam profile of one 25 ns LHC fill with Gaussian bunch shape. The code allows to define as bunch shapes also q-Gaussian, binomial and cosine squared.

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Ultimately, the filling scheme defines the sequence of bunches, and together with the bunch shape, it defines the longitudinal beam profile (i.e. the evolution of the beam charge in time at a fixed location). The Fourier-transform of the normalized longitudinal beam profile (so that the area under the signal is unity) is the normalized beam spectrum $\Lambda(\omega)$.

Two Counter Rotating Beams Scenario

In the scenario where two beams are circulating in the same vacuum chamber in opposite directions (counter-rotating) some interference phenomena occur. These are related to the arrival delay of bunches of the two beams at the location of interest. In a vacuum chamber that presents top/bottom or left/right symmetry, the power loss is given by [4]:

$$P(s) = (2f_0 eMN_b)^2 \cdot \sum_{p=0}^{+\infty} |\Lambda(p\omega_0)|^2 \Bigg(\mathrm{Re}\Big[Z_z^0(p\omega_0)\Big] + \Big(\Delta y_1(s) + \Delta y_2(s)\Big)\mathrm{Re}\Big[Z_z^1(p\omega_0)\Big]\Bigg) \cdot \Big(1-\cos(p\omega_0\tau_s)\Big), \qquad (2)$$

where s is the distance from the interaction point (IP) of the two beams at which the power loss is being computed, Z_z^0 and Z_z^1 are the longitudinal impedances of order 0 and 1, Δy_1 and Δy_2 are the offsets from the geometrical center of the chamber of respectively beam 1 and beam 2, $\tau_s = 2s/c$, with c the speed of light, is the relative time delay of arrival at s of the two beams. It is worth noting that, in Eq. (2), for both beams, the same longitudinal beam profile, hence the same beam spectrum, is assumed.

APPLICATIONS

The code has been successfully utilised (and bench-marked) in a number of scenarios. Two examples, one application in the LHC with counter-rotating beams and one application in the SPS, are presented to demonstrate some of the code's capabilities and features.

The Central Beam Pipe of CMS

The vacuum chamber of the CMS experiment that hosts both beams near the collision point is known as the Central Beam Pipe (CBP). During the Run2 of LHC (2015-2018) it was made of a central cylindrical segment of beryllium, with an external diameter of 45 mm, a thickness of 0.8 mm and a length of almost 3 m. A 3D CAD model of this structure, which also includes two conical terminating sections, can be seen in Fig. 2. This device represents a unique case study in terms of impedance-related BIH for a number of reasons: a) it hosts the two counter rotating beams, b) because it is centered in the IP, it is possible to study many peculiarities of interference phenomena predicted by the model in Eq. (2), and c) the resulting temperature increase is monitored by a set of optical fiber thermal sensors, placed directly on the object, allowing for benchmarking the results [5].

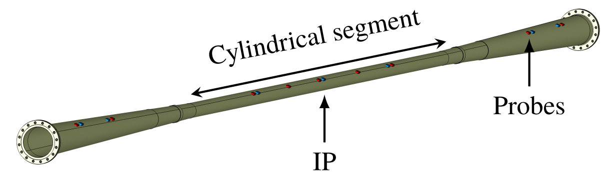

Figure 2: 3D CAD model of the CBP of CMS during the Run2 of LHC. The device is centered in the IP. Schematically, on top of the CBP, the thermal probes' positions are reported.

The dissipated power distribution along the pipe during certain fills of the LHC machine has been computed from the beam coupling impedances and beam parameters automatically retrieved by the tool using pyTimber [6]. Figure 3 shows the power loss density distribution (green curve) along the CBP as a function of the distance from the IP (top x-axis) or, equivalently, the phase shift (bottom x-axis) for fill 6675 (12-13 May 2018). In addition, the plot also reports the power loss value for a single beam (red curve) and for a single beam multiplied by two (blue curve). This underlines the impact of interference phenomena due to the presence of the two beams on the power loss.

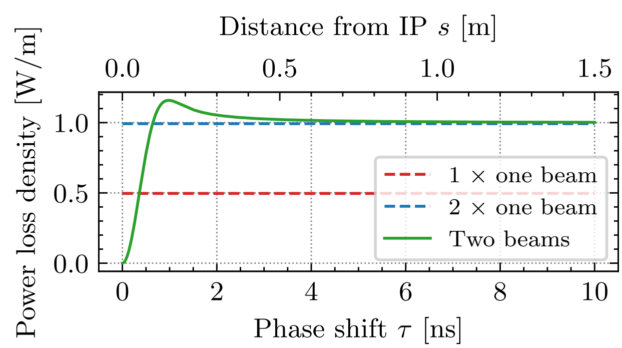

Figure 3: Power loss distribution along one half of the CBP. The behaviour is symmetrical in the other half of the pipe.

Finally, a comparison between the temperature increase measured by one of the thermal probes and the one estimated from the computations performed with BIHC is presented for various fill in Fig. 4. The agreement is excellent and provides a successful benchmark of the tool [5].

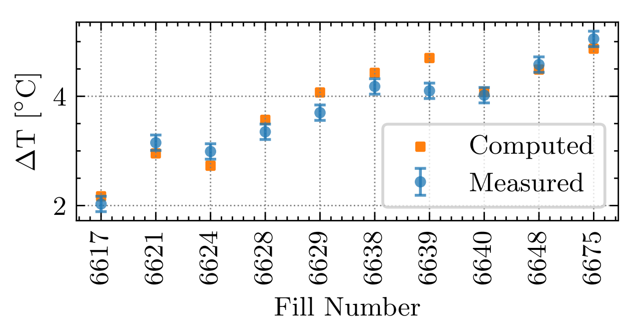

Figure 4: Thermal excursion measured by the probe located at 50 mm from the IP and the simulated thermal excursion.

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The SPS Beam Wire Scanners

Beam wire scanners (BWS) are instruments that measure the transverse beam profile [7, 8]. A thin carbon wire moves across the beam, and the interaction between wire and beam generates a cascade of secondary particles that are detected by a scintillator. From the signal acquired, it is possible to reconstruct the transverse profile. On the 12th of April 2023, during the scrubbing run in the SPS machine, all four BWS' wires were found broken when in parking position (not scanning the beam). The 3D CAD model can be seen in Fig. 5. The investigation of the wire breakage condition, in terms of power deposited on the wire, was performed thanks to the tool presented here. Furthermore, several mitigation solutions proposed were studied with the quantitative analysis allowed by the code.

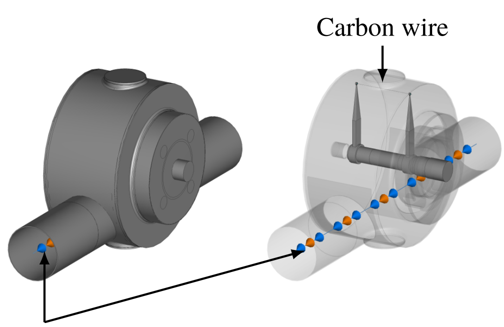

Figure 5: 3D CAD model of the SPS beam wire scanners.

The power loss evolution was evaluated during the beam ramp. Several longitudinal beam profiles measured at different time steps in the SPS cycle were imported to compute the beam spectrum evolution in time. Figure 6 displays the mean bunch length (black curve) and the expected power loss evolution along the ramp computed with BIHC. The results refer to one of the possible mitigation solutions explored that consisted in the introduction of 6 ferrite tiles in the BWS tank.

In the case of impedance curves with several peaks (as for the BWS), the power loss computation is highly sensitive to the frequency of the peaks. More specifically, if the impedance peak overlaps with one of the beam's spectral lines, the power loss contribution will significantly rise. The frequency of the peaks in an impedance curve (obtained from simulations or measurements) has some inherent uncertainty. To account for this, the code allows to perform a statistical study: the considered impedance curve gets shifted rigidly in frequency within a certain interval in steps of f_0. In this way it is possible to get an average, minimum and maximum power loss estimation, reported on the left side of Fig. 6. Moreover, the statistical occurrence of the power loss values computed when applying the frequency shift can be obtained. This is shown, for the last time step (flat top), on the right side of Fig. 6.

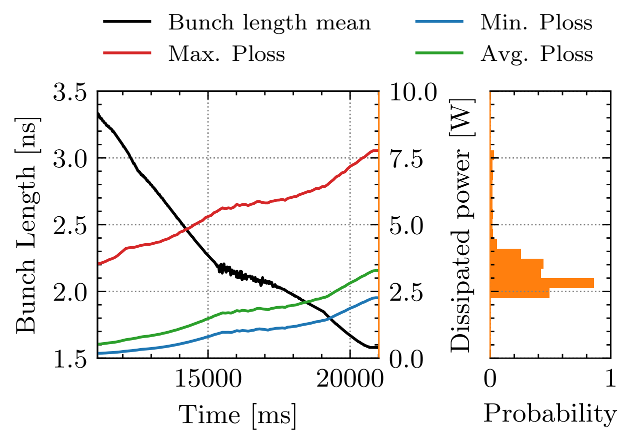

Figure 6: Power loss evolution in time during the ramp (second y-axis). The bunch length evolution in time is reported on the first y-axis. A histogram reporting the probability of having a certain dissipated power value, for the last time step of the computation, is shown on the right side. The number of protons per bunch is the LIU target intensity of $N_b = 2.3 \cdot 10^{11}$. The filling pattern consists of 4 trains of 72 bunches with 25 ns spacing (SPS standard).

CONCLUSION

In this paper a python package to compute impedance related beam-induced heating for single beam and two beams cases was presented. Some of the main features were showcased, together with their application to power loss computations of real accelerator devices.

The code is optimized for the LHC and its injector chain, but is general enough to be used in other machines. Special care was given to the possibility to define the beam parameters accurately. For the two real applications shown, the parameters were retrieved automatically from pyTimber [6] or assigned manually after performing measurements of the beam profile. However, it is also possible to import filling schemes obtained from the LPC web tools [9]. Additionally, a method to shift rigidly the impedance curve to make statistical considerations on possible errors or uncertainties of the resonant frequency of the impedance peaks is presented as one of the code's capabilities.

The code has proven to be an helpful tool for feasibility studies and reverse engineering applications. It is a documented and benchmarked tool that can be constantly expanded for future specific needs.

ACKNOWLEDGEMENTS

The authors wish to thank the CMS iPipe team, the SPS BWS Task Force, and the SY-RF-BR section for the beam profile measurements.

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