A Python Package to Compute Beam-Induced Heating in Particle Accelerators and Applications

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Introduction

A high-energy beam of charged particles travelling 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. Wake-fields, and hence the impedance, other than affecting beam dynamics can cause heating of the accelerator components.

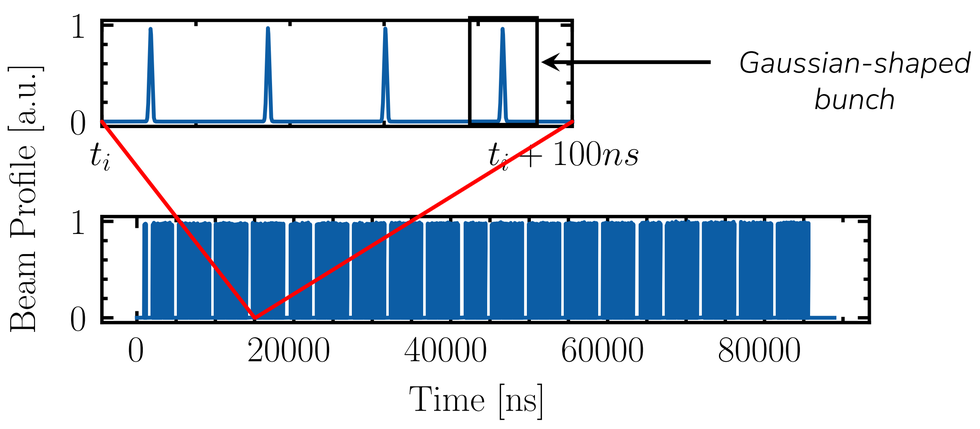
Beam-Induced Heating

Impedance-related beam-induced heating (BIH) may lead to several issues: outgassing, pressure spikes, beam dumps, and, potentially, permanent damages. A good understanding of BIH is mandatory to push the performance of the machine.
The package (BIHC) implements equations to compute the power loss in two scenarios:

1) Single beam power loss:

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

Revolution frequency, *Longitudinal impedance*, *Number of bunches*, *Number of particles per bunch*, *Normalized beam spectrum*, *Fourier-transform of the longitudinal beam-profile*



2) Two counter-rotating beams power loss:

$$P(s) = (2f_0 e M N_b)^2 \cdot \sum_{p=0}^{+\infty} |\Lambda(p\omega_0)|^2 \left(Re\left[Z_z^0(p\omega_0) + \left(\Delta y_1(s) + \Delta y_2(s)\right) Re\left[Z_z^1(p\omega_0) \right] \right) \cdot \left(1 - cos(p\omega_0 \tau_s)\right) \right)$$

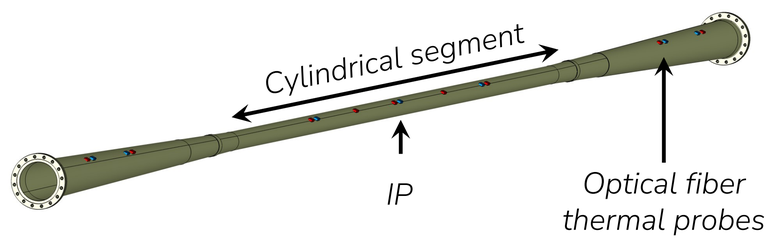
Distance from IP, *Impedance of order 0*, *Offset of the beams from the geometrical center*, *Impedance of order 1*, *Phase shift of the beams at the location:* $\tau_s = 2s/c$

Package tailored for usage in the LHC and in the injector chain with two main applications:
1. During feasibility studies (design phase).
2. Study of impedance-related issues (operation).

Two examples to demonstrate some of the code's capabilities and features:
1. In the LHC with counter-rotating beams (Central Beam Pipe of CMS)
2. In the SPS, are presented (Beam Wire Scanners)

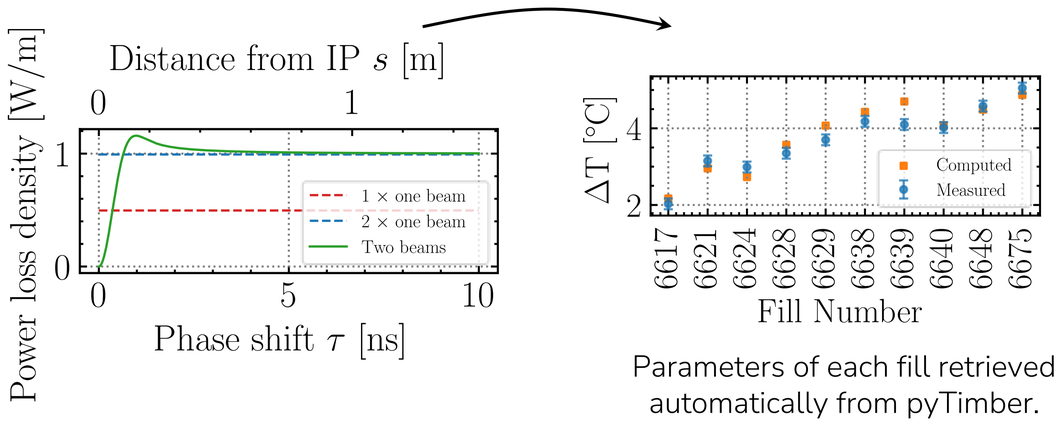
Central Beam Pipe of CMS

The vacuum chamber of the CMS experiment that hosts both beams near the collision point is known as the Central Beam Pipe (CBP).



LHC Run 2 (2015-2018)

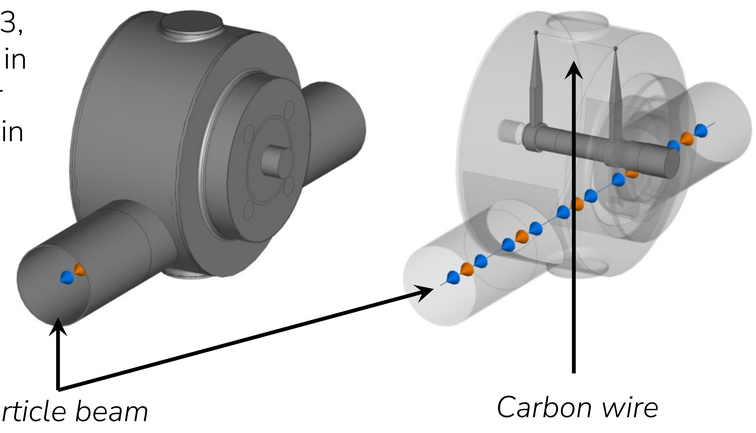
Benchmark between simulations and thermal data from the probes



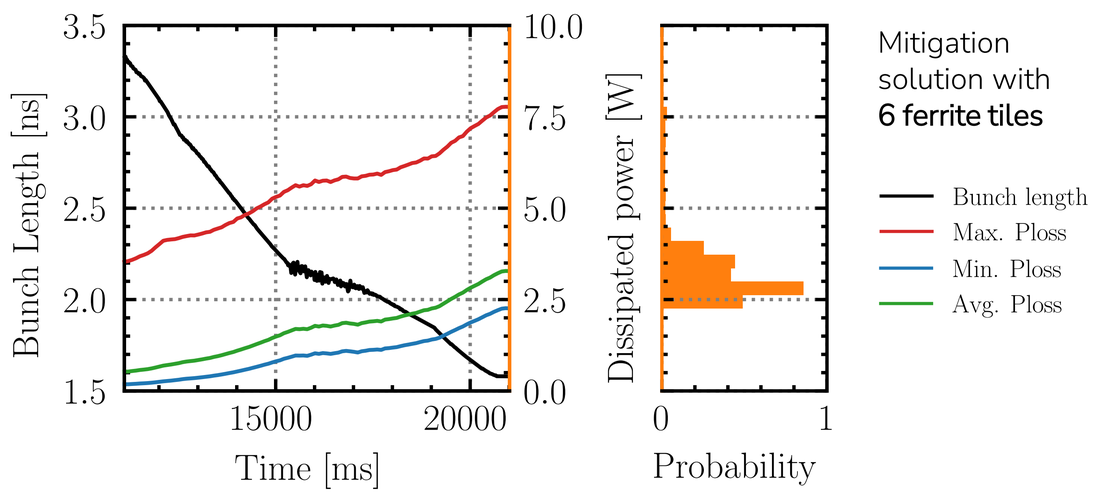
Parameters of each fill retrieved automatically from pyTimber.

Beam Wire Scanners

On the 12th of April 2023, during the scrubbing run in the SPS machine, all four BWS' wires broke when in parking position



Analysis of power dissipated on the wire was performed with BIHC. Allowing for statistical considerations as well.



Mitigation solution with **6 ferrite tiles**

Number of protons per bunch is the LIU target intensity of $Nb = 2.3 \cdot 10^{11}$. The filling pattern has 4 trains of 72 bunches with 25 ns spacing (SPS standard).

Conclusions

BIHC is a python package to **compute impedance related beam-induced heating** for single beam and two beams cases:
- 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.

The code has proven to be a 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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