SIMULATIONS OF THE COHERENT GAP RADIATION FOR THE BUNCH LENGTH MONITOR OF FERMI@Elettra

R. Appio*, P. Craievich, M. Ferianis, M. Veronese, Sincrotrone Trieste, Trieste, Italy

Abstract

Non-destructive bunch length measurements after the magnetic compression is performed in Fermi@Elettra via the so-called Bunch Length Monitor (BLM) diagnostics. The BLM system is based on the diffraction radiation from a ceramic gap, captured by three millimeter-waves diodes, and the edge radiation from the last bending magnet of the bunch compressors, captured by a pyrodetector. In this paper we report on the study of the coherent radiation from a gap which we performed both applying the analytical theory and by means of simulations of the radiated electromagnetic field (CST Particle Studio). The study started from a simple gap in vacuum; time and frequency domain results were then investigated and compared with analytical theory. Finally in order to study a more realistic system, we investigated the effect of the dielectric and metallic holed shield used to assure the electric continuity.

INTRODUCTION

FERMI@Elettra is a single pass seeded FEL working at the Sincrotrone Trieste Laboratory. A description of the facility is presented in the FERMI Conceptual Design Report [1]. Two Bunch Length Monitors (BLM) are foreseen, one at the exit of each bunch compressor. The BLM provide the relative bunch length information required by the longitudinal feedback system, in order to stabilize the final output peak power of the FELs.
To allow for relative bunch length measurements in a wide range, the FERMI@Elettra BLM has been designed to use two coherent radiation sources. The first source is the coherent radiation from the bending magnets of the BC1 compressor. The second is coherent radiation from a ceramic gap. The diagnostics based on the first source covers the shorter bunches length, being its transfer function limited at low frequencies by angular acceptance of the transport system and by the sensitivity of the pyrodetectors. A more accurate description could be found in [2]. The diagnostics based on the gap system, performs the detection of coherent radiation, using mm-wave diodes with central frequencies around respectively 30, 100 and 300 GHz. The diodes are mounted on an optical breadboard by means of translation stages that allow to vary the distance of the diode from the gap. The system is very similar to the LCLS one.

SIMULATION RESULTS

Simulations of the coherent gap radiation have been done using CST-PS (*Computer Simulation Technology-Particle Studio*), an electromagnetic field simulation software [3].
The simulations have been performed using a gaussian bunch with a longitudinal FWHM of 10 ps, and a charge of 1 nC. The very first simulation has been done using a simple vacuum gap model, in order to perform a comparison with the theoretical radiation, obtained from [4] and [5]. The model used is shown in Figure 1. The electric field radiated from the gap is captured by a probe put in a point 45 mm far from the pipe axis. Figure 1 illustrates a conceptual model of the system, in which the gap dimensions, and the position of the electric field probes can be seen.

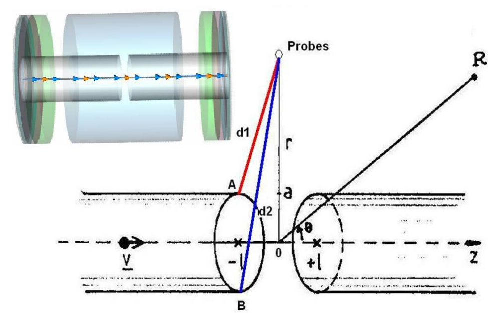

Figure 1: Model of the gap used in CST for the simulation of the energy radiated by the gap (left top) and scheme of the analytic model from [5]

Two perfect electric conductor tubes represent the vacuum pipe in which the electron beam travels, while the integration volume is limited by a vacuum material cylinder. At the edges of the tube, there are three cylinders of different materials, with increasing conductivity σ, until the most external layer, that is made of perfect electric conductor (infinite conductivity). This ensures the Perfect Matched Layer conditions, needed in order to avoid reflections of the radiated electromagnetic field from the pipe edges [6]. Both time and frequency domain have been investigated, and the results are shown in Figures 2 and 3. Simulations and analytical studies have been performed in order to optimize the system.
Figure 2 shows the energy radiated by a gap with radius $a = 17.4$ mm, and length $2\ell = 6.35$ mm. Two main structures are present, that could be attributed to the radiation from the upper, and lower edge of the first part of the structure. This hypothesis is confirmed by the temporal distance of the two structures, which corresponds to the time that the electric wave takes to cover the length difference of the two paths from the edges to the probe (that is between A and B, in Figure 1). Changing the gap size (2ℓ), the tem-

* roberto.appio@elettra.trieste.it

poral behavior of $|E_z|$ does not modify, confirming that the strongest radiation comes from the first waveguide, as provided by theoretical studies (see eq. 1). We also studied the dependence of radiation from the waveguide thickness (in Figure 2: in blue the radiation for 100 μm thickness waveguide, in green the radiation from a 2 mm thickness waveguide). In the 2 mm case, the time evolution is similar to 100 μm case, but there is an oscillation that could be generated from resonance between the gap edges.

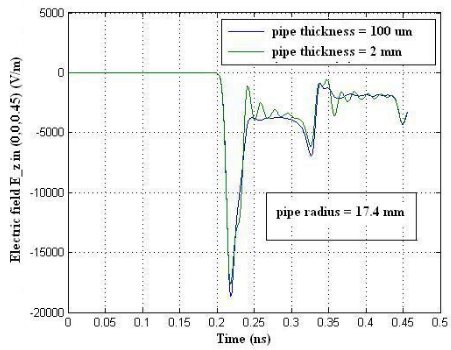

Figure 2: Temporal trend of the z_component of the electric field in the point (0.45,0.0,0.0), in which there is the probe.

Figure 3 shows 13 consecutive snapshots of the maximum values of the electric field along the sagittal plane and the pattern of the radiated field can be clearly seen.

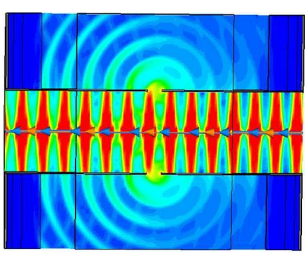

Figure 3: Maximum value of the electric field radiated in each point of the structure.

REALISTIC GAP MODEL

In order to have a realistic model of the installed vacuum break, a gap filled with alumina has been used, and a metal enclosure needed to provide the vacuum chamber electrical continuity has been considered. Figure 4 shows a comparison between results obtained with a gap in vacuum and the one with alumina. It is worthwhile to note that in time domain the behavior is the same, while in frequency domain, in the model with alumina, there is an energy absorption in range between 40 GHz and 50 GHz.

Furthermore, in order to evaluate the effect of a misalignment of the diodes, we have compared the radiation in $z = 0$ position (on-axis case), and $z > 0$ (off-axis) at the same distance from the waveguide axis. Figure 5 shows

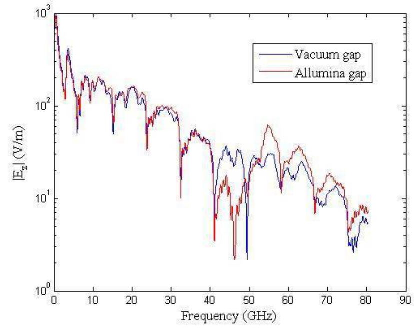

Figure 4: Comparison between vacuum gap and alumina filled gap model, in frequency domain.

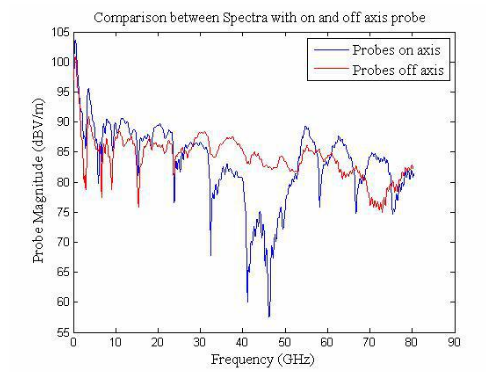

Figure 5: Comparison between field radiated in case of probe on x-axis.

the comparison between these simulations. Up to 55 GHz off-axis geometry can be preferable in terms of field magnitude, while above above 55 GHz, on-axis is better.

Finally, the holey shielding used in order to assure the electric continuity of the gap has been considered, including the flanges. The structure is shown in Figure 6, together with the frequency domain results. Three resonance peaks are present, due probably to the geometry of the structure, behaving like a resonant cavity. The frequencies of this peaks are closed, within 10%, to those of the coaxial cavity. These resonance frequencies, however, are out of the diodes ranges, in the BLM. In time domain, Figure 7 shows the typical inductive behavior of a holey structure.

THEORETICAL STUDIES

The problem of the radiation emission of an ultrarelativistic particle can be studied starting from Maxwell equations, with the introduction of boundary conditions. The expression for the spectrum-angular density of the radiated energy, in high frequency approximation is shown in eq. 1, as obtained in [5].

$$\frac{d^2W(\theta)}{d\omega d\Omega} = \beta q^2 \frac{\sin^2\theta J_0^2(ka\sin\theta)}{4\pi^2 c(1-\beta\cos\theta)^2 I_0^2(\frac{ka}{\beta\gamma})}$$

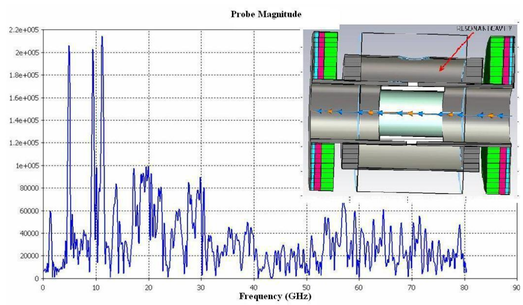

Figure 6: Complete gap model, and frequency domain simulation result.

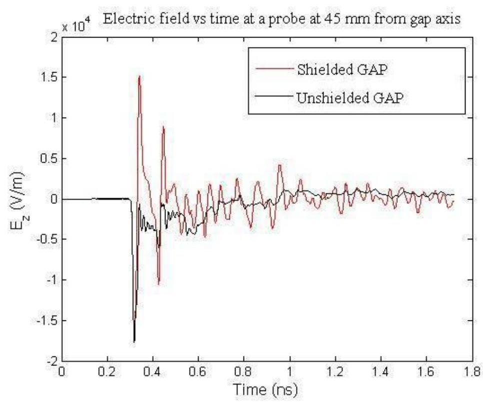

Figure 7: Comparison, in time domain, between the field radiated by the shielded and unshielded structures.

$$\left| \sqrt{\frac{1-\beta}{1-\cos\theta}} e^{jk\ell(1-\beta\cos\theta)/\beta} + j\sqrt{\frac{1+\beta}{1+\cos\theta}} e^{-jk\ell(1-\beta\cos\theta)/\beta} \right|^2 \quad (1)$$

where β is the ratio v/c, k is the wavenumber, a is the radius of the pipe and $J_0(x)$ is the first type, zero order Bessel function, and θ is the angle shown in Figure 1. In order to perform a comparison between theoretical formulation and simulation results, the spectrum-angular density of the energy radiated has to be calculated starting from the electric field obtained with simulations. From Poynting vector $\mathbf{S}(f)$, using the correlation between it and the electric field, the spectrum-angular radiation can be calculated as:

$$\frac{d^2W}{df\,d\Omega} = \frac{2r^2}{\eta}|E_z(f)^2| \quad (2)$$

where η is the free space impedance (377 Ω) and $E_z(f)$ is the Fourier Transform of the electric field obtained from simulation. It is worthwhile noting that the other two components ($E_x(f)$ and $E_y(f)$) are negligible if compared with $E_z(f)$. Figure 8 shows a comparison between the numerical simulation with CST-PS (eq. 2) and the analytical results from eq. 1. An excellent agreement is found between the two approaches.

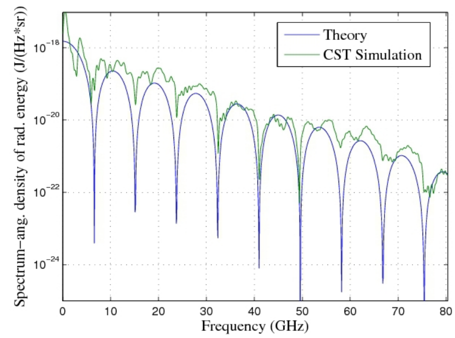

Figure 8: Comparison between simulation results and theoretical formulation of the spectrum-angular energy radiated by the gap.

CONCLUSIONS

Simulations of the electromagnetic field radiation have been done, with the help of CST Particle Studio on the coherent radiation emitted from a gap.
Time domain simulation provided useful information on the radiation, showing that the strongest field comes from the first part of the waveguide, and in particular from the edge diffraction. Furthermore, time domain simulations have shown to be important for the optimization of the structure and the diodes positioning.
From the time domain electric field, the spectrum-angular density of the radiated energy has been performed, and compared with the theoretical results, with high degree of match in results.

ACKNOWLEDGMENTS

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