NUMERICAL SIMULATION OF SYNCHROTRON RADIATION FOR BUNCH DIAGNOSTICS*

A. Paech†, W. Ackermann, T. Weiland, TEMF, TU Darmstadt, Germany
O. Grimm, DESY, Hamburg, Germany

Abstract

A technique to measure the bunch shape at the FLASH[1] facility at DESY, Hamburg, uses the synchrotron radiation (SR) generated at the first bunch compressor chicane. In this paper a new method is introduced to numerically calculate this radiation with the emphasis of including the effects of the chamber walls. As a first step towards the final aim of simulating a spacially extended charge distribution, the method, that is based on the uniform theory of diffraction (UTD), is described for a single point charge distribution. The calculated fields in front of the vacuum chamber exit are compared to measurements.

INTRODUCTION

For the operation of the FLASH at DESY, Hamburg, the longitudinal charge distribution of the electron bunches that drive the free electron laser is of high importance. One method [1, 2] to measure the bunch shape is to analyze the coherent far-infrared synchrotron radiation generated at the last dipole magnet of the first bunch compressor, which is schematically shown in Figure 1.

For the correct interpretation of the results it is mandatory to know how various parameters, like the bunch shape and path, the vacuum chamber walls, the optical beam line, etc., influence the observed spectrum. Since the characterization and investigation of these effects by measurement or analytical techniques is very difficult, numerical simulation is employed.

The aim of this work is to calculate the generation of synchrotron radiation inside the bunch compressor with the emphasis of including the effects of the vertical and horizontal vacuum chamber walls in the vicinity of the last dipole magnet. Challenging problems for the numerical simulations are the very short wavelength and the broad frequency range of interest ($\lambda = 10\,\mathrm{mm} \ldots 10\,\mu\mathrm{m}$).

As a first step, it is shown how the radiation leaving the vacuum chamber that is generated by a single point charge can be calculated with the help of the uniform theory of diffraction (UTD). Furthermore to test the simulation method some measurements of the radiation leaving the chamber (done at DESY) are compared to simulation results.

* This Project is supported by the Helmholtz Association under contract HGF-VH-FZ-006.

† paech@temf.tu-darmstadt.de

[1] Free electron LASer Hamburg, former VUV-FEL

SIMULATION METHOD

The simulation is basically conducted in two parts. First the electromagnetic fields inside the vacuum chamber are calculated. Knowing these fields the radiation from the waveguide exit can be calculated in a subsequent step.

Fields Inside the Chamber

Because the size of the metal chamber is much bigger than the wavelengths of interest, volume or surface discretizing methods, such as the finite integration technique, finite element methods or boundary element methods easily reach their limit and are difficult to apply to calculate the SR fields.

Methods based on geometric optics, like the uniform theory of diffraction [3, 4], in contrast do not require a discretization of the structure and are more suitable in such a high frequency regime. However, they face other problems. First, the structure is nearly closed and has a lot of walls, resulting in many reflections and making the ray tracing very time consuming. And second, the UTD usually is efficient only for point sources, but the deflected bunch is a continuous source much bigger than the wavelength.

Therefor the excitation by the moving charge is described by a large number of calculational point sources along the path, hence discretizing the path itself. Different formulations for these sources can be determined by discretizing integral formulations [5] of the fields generated along the path. However care has to be taken to choose the right formulation, because the calculational point sources need to fulfill Maxwell's equations and satisfy the far field condition at the edges of the chamber.

A suitable source formulation can be obtained by starting with the retarded potentials [6] Φ and $\vec{A}$. These are calculated for a point charge moving on a given path. The electric and magnetic fields are obtained by $\vec{E} = -\nabla\Phi - j\omega\vec{A}$ and $\vec{B} = \mathrm{rot}\,\vec{A}$. In a last step all terms proportional to R^{-2} and R^{-3} are neglected and for the electric field a partial integration is performed. This results in a formulation

$$\vec{E}(\vec{r}) \approx \int_{-\infty}^{\infty} \underbrace{\frac{-j\omega\mu_0 Q}{4\pi R}(\vec{v} - \hat{R}(\hat{R}\cdot\vec{v}))e^{-j\omega(t' + \frac{R}{c_0})}}_{\vec{E}'_d} \mathrm{d}t'$$

$$\vec{H}(\vec{r}) \approx \int_{-\infty}^{\infty} \frac{1}{Z_0}\hat{R} \times \vec{E}'_d \,\mathrm{d}t'$$

which can be interpreted as a summation of electric dipoles

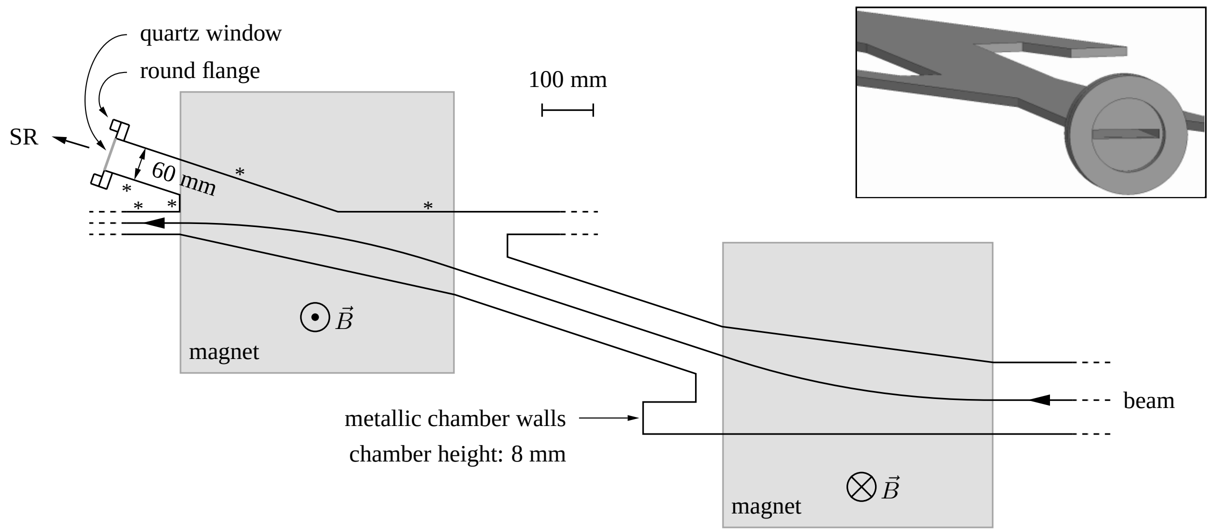

Figure 1: Top view of the beam path and the vacuum chamber it is passing through. The radiation leaving the quartz window is guided through an optical beam line to the diagnostic equipment. The symbol * indicates chamber walls which have been taken into account in the simulation. In the upper right a 3D model of the chamber, looking at the quartz window, is shown.

of length $v\mathrm{d}t'$ along the particle path, and represent suitable sources for the UTD calculation. It is stressed at this point, that although terms with higher powers in $1/R$ are neglected, the given formulation also includes the effects of the Coulomb or velocity term from the classical Liénard-Wiechert formulation. Furthermore it is emphasized that these terms essentially have to be included into the simulation to yield correct results for longer wavelengths in the vacuum chamber setup.

Finally it has to be mentioned, that the UTD simulation assumes an infinite waveguide preceding the quartz window. Diffractions at the waveguide exit are considered in a subsequent simulation.

Radiation from the Waveguide Exit

Once the fields are determined inside the vacuum chamber at the position of the waveguide exit, the propagation in free space is calculated by angular spectrum propagation (for close distances) or the Fresnel approximation (for big distances) [7]. Here it is assumed, that the fields at the aperture of the waveguide flange can be approximated by the results from the preceeding simulation, on the basis of an infinite waveguide. This assumption is justified as long as the wavelength is not to long [6, 8].

COMPARISON WITH MEASUREMENTS

As a test for the described method, the fields at a distance of $38\,$mm in front of the waveguide exit (quartz window), are calculated for three wavelengths ($1.4\,$mm, $350\,\mu$m and $155\,\mu$m) and compared to measurements performed at DESY. There the radiated energy density was measured with the help of a pyroelectric detector with three narrow optical band pass filters in a plane in front of waveguide exit. All measurements have been performed at $E = 130\,$MeV and $Q = 1\,$nC.

For the simulation of the fields in front of the quartz window, two simplifications have to be noted. First considering all the walls of the structure from Figure 1 would lead to a very high number of possible reflections for the UTD and to very long computation times. Investigations have shown, that only the walls labeled by a * in Figure 1 have to be considered in the simulation for the main effects inside the chamber. Secondly at present only a point charge with $Q = 1$nC has been considered in the simulations.

The results are shown in Figure 2 and it can be seen, that the radiation patterns from the simulation and measurement show a good agreement. The radiated energy per bunch in the $1.4\,$mm band, as a further test of plausibility, is also in basic agreement. The measurement gives a value of approximately $1.2\,\mu$J whereas the simulation gives a value of $0.77\,\mu$J. Differences are most likely due to uncertainties in the measurement and the approximation of the bunch shape by a point charge in the simulations.

It should be noted, that for the simulations at the short wavelengths, the incoherent radiation effects of the bunch are not considered because of the point charge model. So the amplitude of the radiation patterns is not realistic. But it can be seen, that the radiation patterns itself basically agrees between measurement and simulation.

OUTLOOK

After the promising results for the radiation patterns in front of the quartz window, the next steps are now to calculate the radiation through the optical beam line to the

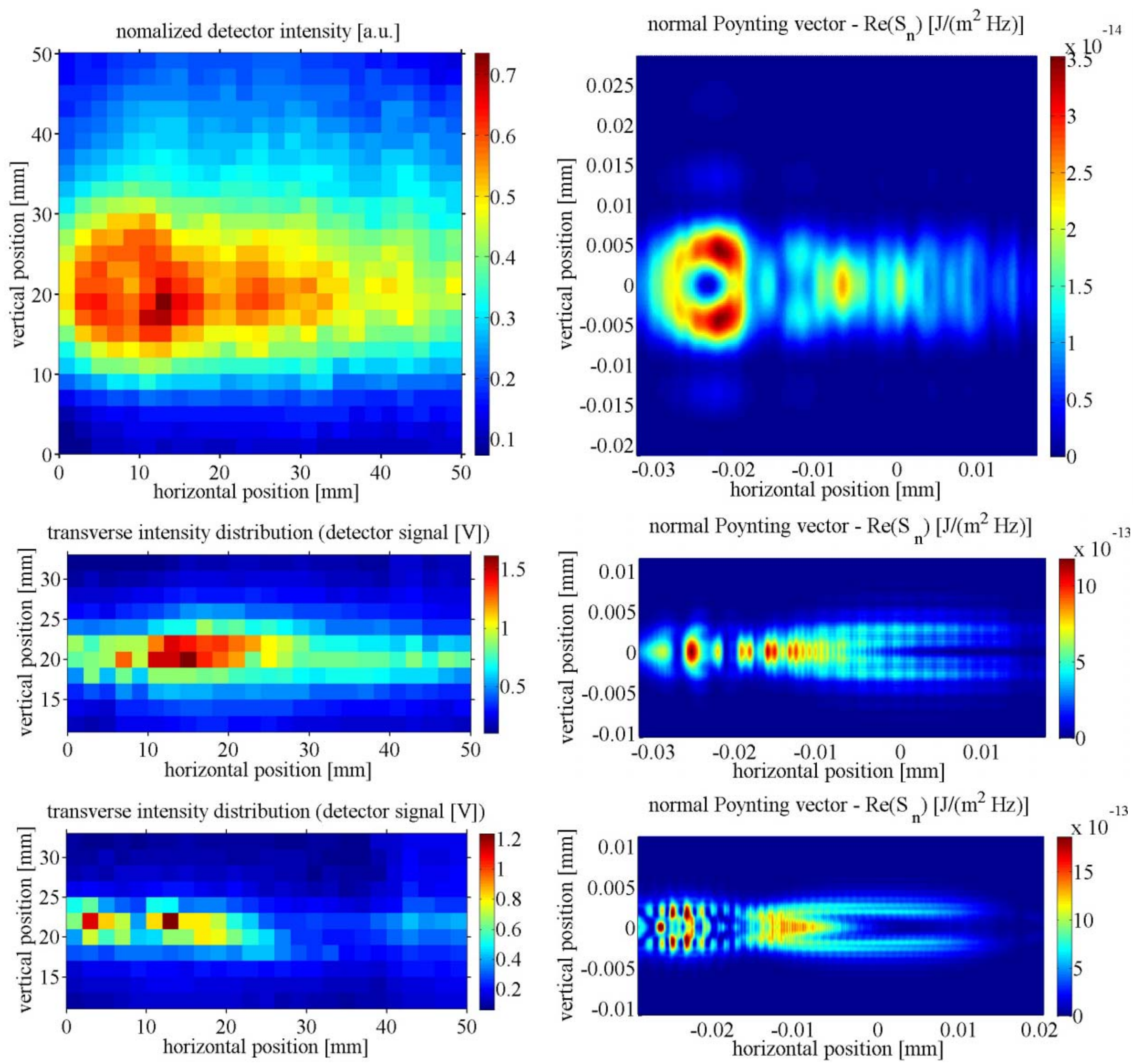

Figure 2: A comparison of measurement and simulation for the field intensity at a distance of 38mm in front of the waveguide exit (quartz window) as seen from inside the vacuum chamber. On the left the measurements with a pyroelectric detector are shown and on the right the simulations with the described method (using a point charge). From top to bottom the results are shown for four different wavelengths: $\lambda = 1.4$mm, 350μm, 155μm.

measurement lab (≈ 12 m distance) and to consider a more realistic charge distribution.

REFERENCES

[1] O. Grimm, P. Schmüser, “Principles of longitudinal beam diagnostics with coherent radiation”, TESLA FEL Report 2006-03, April 2006.

[2] L. Fröhlich, “Bunch Length Measurements Using a Martin-Puplett Interferometer at the VUV-FEL”, TESLA FEL Report 2005-02, June 2005.

[3] D.A. McNamara, C.W.I. Pistorius, J.A.G. Malherbe, Introduction to the Uniform Geometrical Theory of Diffraction, Artech House, Boston, 1990.

[4] C. A. Balanis, Advanced Engineering Electromagnetics, Wiley, 1989.

[5] G. Geloni, E. Saldin, E. Schneidmiller, M. Yurkov, “Paraxial Green’s functions in Synchrotron Radiation theory”, DESY Report 05-032, February 2005.

[6] G. S. Smith, An Introduction to Classical Electromagnetic Radiation, Cambridge University Press, 1997.

[7] J. W. Goodman, Introduction to Fourier Optics, Third Edition, Roberts & Company, 2005.

[8] C. A. Balanis, Antenna Theory, Third Edition, Wiley, Hoboken, 2005.