LOW-FREQUENCY TIME DOMAIN NUMERICAL STUDIES OF TRANSITION RADIATION IN A CYLINDRICAL WAVEGUIDE*

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Abstract

Transition radiation is frequently used to determine the time profile of a bunched relativistic particle beam. Emphasis is usually given to diagnostics sensitive to wavelengths in the infrared-to-optical portion of the spectrum. In this study, CST Particle Studio simulations are used to make quantitative statements regarding the low-frequency (DC to microwave) behavior of coherent transition radiation from a mirror inclined at 45 degrees relative to the particle beam trajectory. A moving Gaussian bunch confined within a cylindrical beam pipe is modeled. Simulation results are presented.

INTRODUCTION

When a relativistic particle traverses the boundary between two media with different dielectric constants, transition radiation, which was first predicted by I. Frank and V. Ginzburg, arises in a wide continuous spectrum [1], and it has been extensively studied theoretically [2]. Transition radiation has been one of the most promising tools for diagnostics of charged particle beams in the microwave [3,4], mm-wave [5], far-infrared [6,7] and optical [7] ranges of wavelength. It is frequently used to determine the position, size, energy, emittance, and time profile of a bunched relativistic particle beam.

In this paper, we simulate transition radiation in the structure shown in Figure 1 in the time domain by using a numerical solution. CST Particle Studio [8] is an electromagnetic field and particle tracking simulation software package applied to making quantitative statements regarding low frequencies (DC to microwave).

The particle beam is modeled as a line charge entering the beam pipe along the z axis and hitting a perfectly conducting metal mirror inclined at 45 degrees relative to the particle beam trajectory. The electromagnetic fields from the transition radiation are calculated and recorded by using CST Particle Studio. These fields are sensitive to the detailed structure of the beam, allowing the determination of bunch length. The results will help us to understand the transition radiation in time domain and design effective bunch length diagnostic monitors for the accelerators. The preliminary results are presented and analyzed.

STRUCTURE AND BUNCH

The top view and front view of the simulated structure are shown in Figure 2.

The beam pipe and coupler are modeled as semi-infinite cylinder waveguides with 34.80 mm diameter, representative of the APS linac beam pipe. The particle beam is a Gaussian-distributed line charge that moves at light speed. When the bunch hits the mirror, transition radiation is emitted. A few probes are set up in the structure to detect and record the electromagnetic fields as the beam passes through the beam pipe and the transition radiation occurs.

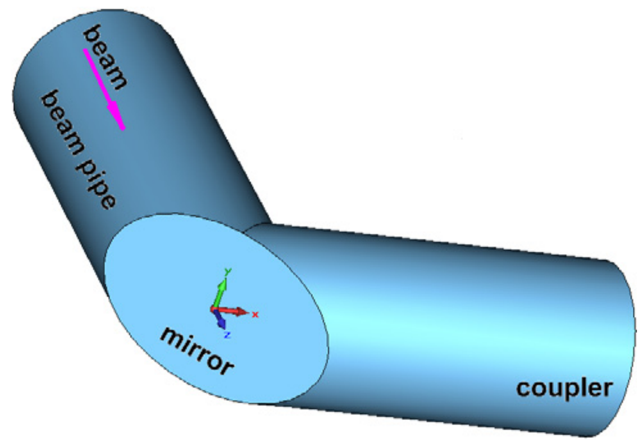

Figure 1: Structure for simulation of transition radiation using a moving Gaussian-distributed line charge.

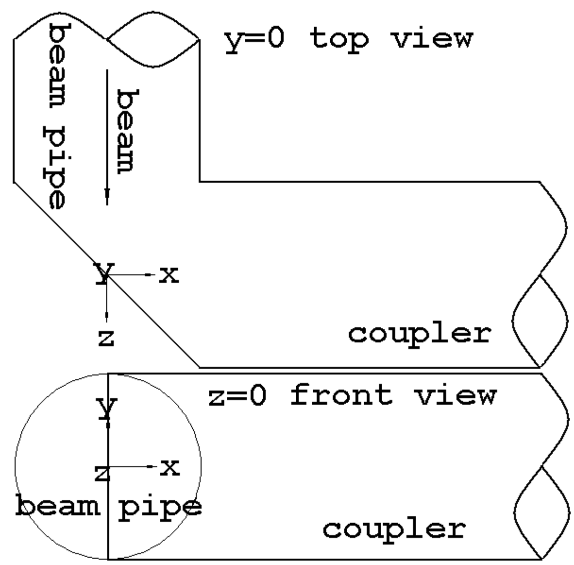

Figure 2: Diagram (top view on the top and front view on the bottom) of the simulated structure.

SIMULATION OF THE TRANSITION RADIATION

Initial Condition

Figure 3 illustrates the electric field in the beam pipe before the beam hits the mirror. There are three white

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strips in the 2-D contour (top graph in Figure 3). The middle strip represents the center of the Gaussian-distributed bunch, and the other two strips are at 3-sigma deviation from the center.

It also shows the electric field Ey at a point that is located in the middle of the beam pipe and offset along the y axis in time domain (middle graph in Figure 3) and frequency domain (bottom graph in Figure 3). The spectra in Figure 3 and the following Figures 4 – 6 are the FFT of the time-dependent signals over a 3-ns duration. Before the beam strikes the mirror, the electric field is mostly Gaussian with a peak at 8.7 GHz, which is related to the pipe diameter and arises from the reflections of the electromagnetic fields in the pipe.

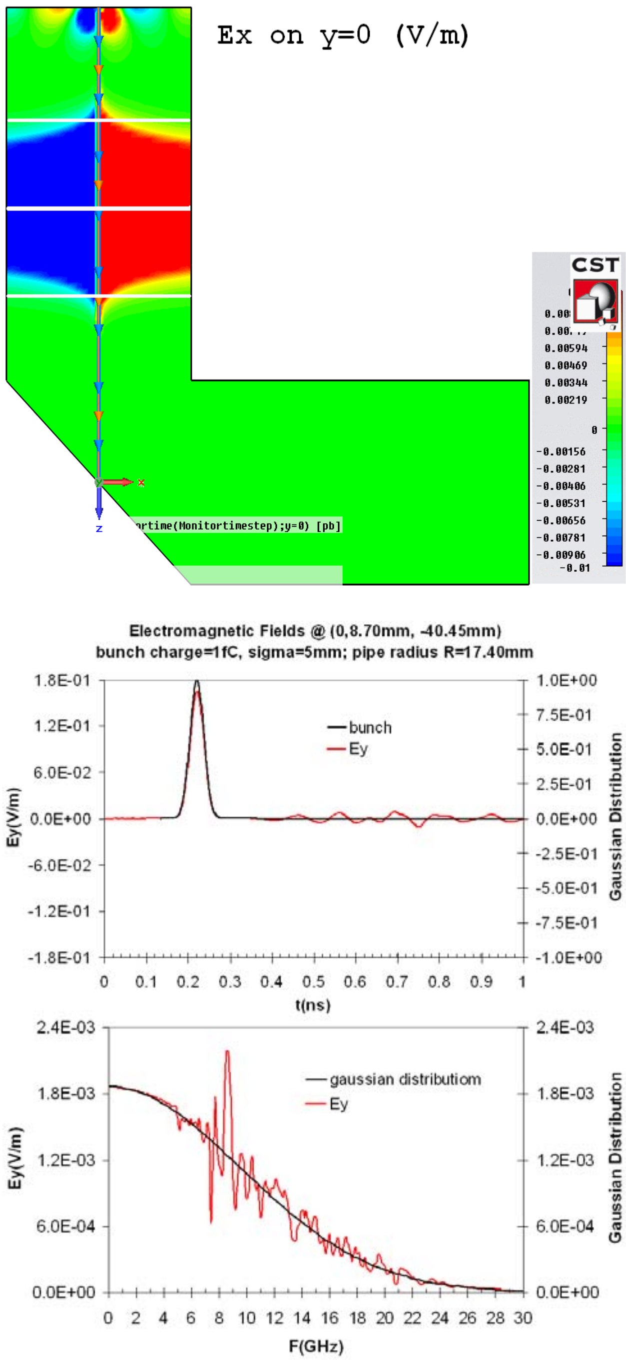

Figure 3: The electromagnetic field produced by a Gaussian bunch with 5-mm sigma. Top graph is the 2-D contour of Ex on the y=0 plane at 0.2 ns. Middle graph shows Ey and the line charge density in the time domain, and in the frequency domain in the bottom graph. Data correspond to the point (x, y, z) = (0 mm, 8.70 mm, -40.45 mm).

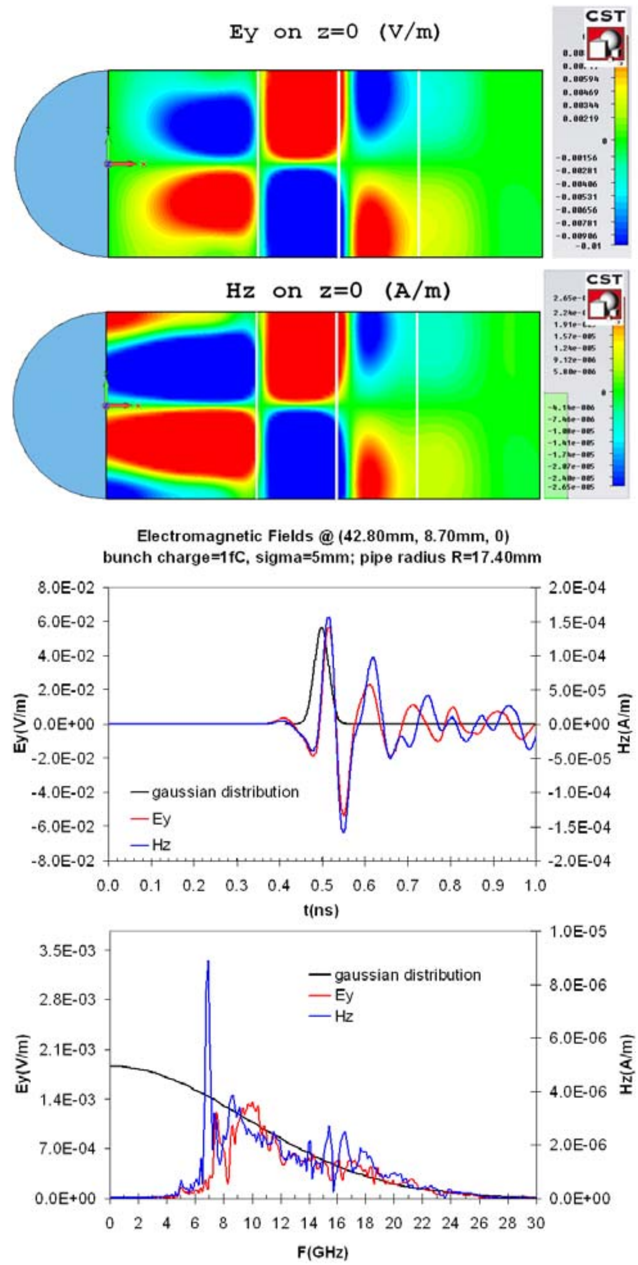

Figure 4: The electromagnetic field representing the transition radiation in the coupler. Top two graphs are the 2-D contours of Ey and Hz on the z=0 plane at 0.5 ns. The third graph shows Ey, Hz, and the assumed line charge at the light speed reflected by the mirror in the time domain, and in the frequency domain in the bottom graph. Data corresponds to the point (x, y, z) = (42.80 mm, 8.70 mm, 0 mm).

Transition Radiation

When the beam hits the mirror, it disappears and transition radiation is emitted. The radiation is shown in Figure 4. Similar to Figure 3, the white strip in the middle of the top two graphs represents a plane wave moving at the speed of light that was emitted at the time that the center of the distribution struck the mirror. The other two strips are three standard deviations from the center.

The precursor signal in the 2-D contour and 1-D time domain graphs are caused by interference from the corner. Beyond this interference effect, the first cycle in the time domain seems related to the bunch shape. The higher frequency portion in the frequency domain shows a similar pattern to the Gaussian bell curve except for some peaks. It is possible to reconstruct the bunch duration based on this result by Gaussian fitting at high frequencies.

DIFFERENT BUNCH LENGTHS AND PIPE SIZES

Comparison of the spectra for different bunch lengths and different pipe sizes were made.

Different Bunch Sizes

The spectra for different bunch sigma with beam pipe radius = 17.40 mm are shown in Figure 5. The higher-frequency portion fits the Gaussian bell curve well except for a few peaks. The transition radiation spectrum of the shorter bunch is better represented since a larger portion of the bunch spectrum lies above the beam pipe cutoff frequency.

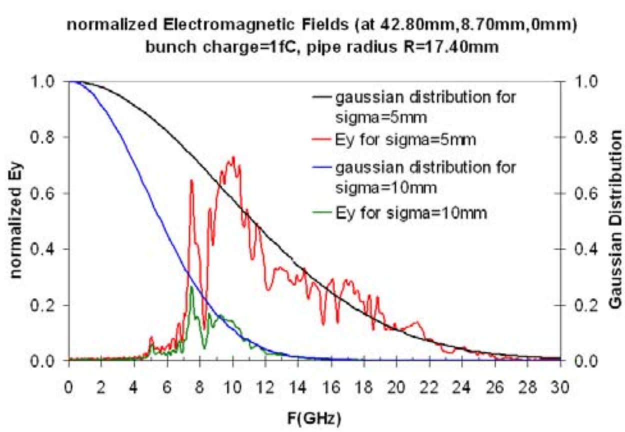

Figure 5: The spectra for different bunch sigma with beam pipe radius = 17.40 mm.

Different Beam Pipe Sizes

The spectra for different beam pipe sizes using the same bunch sigma = 10 mm are shown in Figure 6. Here one can also see the effect of moving the beam cutoff frequency in relation to the bunch spectrum.

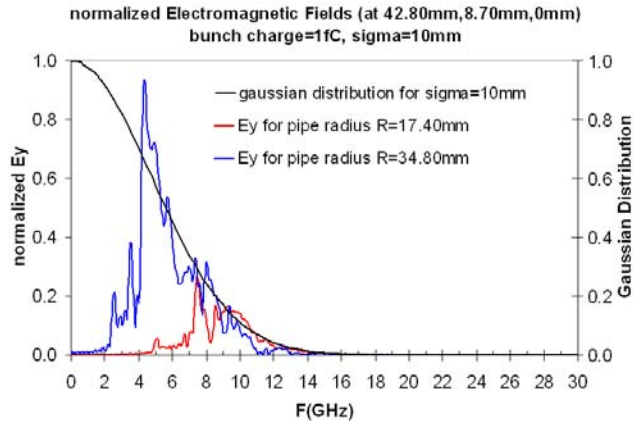

Figure 6: The spectra for different beam pipe sizes with bunch sigma = 10 mm.

SUMMARY

Numerical studies of coherent transition radiation in both time and frequency domain for Gaussian-distributed line charges traveling in cylindrical beam tubes have been performed. The radiation field is seen to be radially polarized, but with a low-frequency cutoff imposed by the beam pipe size. The time profile of the fields in the output coupler does not directly reflect the time structure of the bunch due to the low-frequency cutoff along with the effects of discreet circular waveguide modes. It is generally the case, however, that the bunch length / bunch duration can be inferred from inspection of the high-frequency content of the coherent radiated fields, for bunch lengths sufficiently small in comparison to the beam pipe radius.

Future investigations will include studies of non-Gaussian beam distributions and the design of a coaxial microwave probe for direct spectral analysis of the coherent radiation fields. Another area of interest is the fields associated with non-relativistic beams, for use as an electron gun diagnostic, for example.

ACKNOWLEDGEMENTS

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