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Efficient Extraction of High Power THz Radiation Generated by an Ultra-Relativistic Electron Beam in a Dielectric Loaded Waveguide

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Abstract:

We have measured an intense THz radiation produced by a sub-picosecond, relativistic electron bunch in a dielectric loaded waveguide. For efficient THz pulse extraction the dielectric loaded waveguide end was cut at an angle. For an appropriate choice of angle cut such antenna converts the TM_{01} mode excited in the waveguide into a free-space fundamental Gauss-Hermite mode propagating at an angle with respect to the electron beam trajectory. Simulations show that more than 95% of energy can be extracted using such a simple approach. More than 40 oscillations of about 170 picosecond long 0.48 THz signal were explicitly measured with an interferometer and 10 micro Joules of energy per pulse, as determined with a calorimetric energy meter, were delivered outside the electron beamline to an area suitable for THz experiments.

With the recent advances in X-ray free electron lasers (X-FEL) it is now possible to produce transversely coherent hard X-rays with high peak power and short pulse duration, 10 - 100 femtoseconds (1). With such time structures, X-ray techniques can be used to probe dynamics induced by an external pump signal in various samples at the timescale of atomic motions. Most such time resolved studies to date have made use of readily available visible and near-visible pump sources to trigger the events and, thus were able to study only a small subset of phenomena accessible to photons with eV energies. However, a number of recent experiments have investigated the dynamics stimulated by THz and mid-infrared pulses that have led to advances like the selective control of an insulator metal transition (2), discovery of light induced superconductivity in a stripe-ordered cuprate (3), observation of coherent nonlinear photonic effects that can be used for ultrafast control of materials (4) and manipulation of orbital order in manganites by THz radiation (5). For these types of experiment, narrow band, tunable and high peak field (300 kV/cm and higher) THz pulses are required.

Due to the availability of high quality ultra-relativistic electron beams at light source facilities beam driven methods for THz production, based on transition (6), Cherenkov (7-11), synchrotron (12) and undulator radiation (13), are entertained for a THz pump. In this

paper we focus on THz generation by means of Cherenkov radiation by an ultrarelativistic electron beam. Compared to all other methods of THz generation, Cherenkov radiation in a slow wave structure provides high peak power THz pulses with typical bandwidth of 1 – 10%. Recently several experiments have demonstrated the generation of THz radiation in dielectric loaded structures (7, 8, 10). An all-metal corrugated structure can also be used for THz generation (9, 11). In the most impressive THz generation experiment a 20 GeV, 50 micron long, 3nC FACET beam was transported through a 15 cm long capillary generating hundreds of milli-joules of pulse energy with GW peak power (14). Such a strong signal can be used as a THz pump at x-ray free electron laser facilities. This requires however, finding a practical way to radiate this signal out of the dielectric loaded waveguide into a convenient free-space mode. In the case of dielectric loaded structures in the microwave range it is possible, though cumbersome, to create a horn similar to a traditional horn antennas (15). For THz sub-mm dimension wakefield structures a simpler solution is required. In this paper we present a simple approach for power extraction from the dielectric loaded waveguide: an angled cut of the waveguide. This approach is an extension of Vlasov antenna (16) to dielectric loaded waveguides. We resort to the angle cut due to fabrication simplicity. Finite difference time domain simulations show that extraction efficiency is very high (more than 95%). We performed an experiment to extract the 0.48 THz pulse generated by an ultra-relativistic beam. The extracted signal had been characterized and total energy in a pulse delivered to the user area outside the electron beam line was measured to be 10 uJ by calorimetric detector (17). The signal to noise ratio of the interferometer scan was improved by an order of magnitude compared to standard measurements (7, 11).

Figure 1. Left: Simulation of THz radiation from the cut end, showing electric field arrows. Cut angle and radiation angle defined. Right: Experiment setup: THz signal is extracted into the interferometer.

A relativistic electron bunch generates Cherenkov radiation when passing through a slow wave structure like a corrugated or dielectric loaded waveguide. It excites only modes with phase

velocity equal to the velocity of beam, i.e. close to the speed of light. In simulations and experiment reported here we use a metallized quartz capillary with a dielectric constant of 3.8, metallized on the outside with inner diameter, 400 μm and outer diameter, 550 μm . The ultra-relativistic beam excites a TM_{01} mode in such a waveguide at 483 GHz. A typical dimensional tolerance of a quartz capillary manufacturing process is few percent. It is important therefore to have a robust with respect to manufacturing errors radiator design for practical power extraction. We designed the end of the tube to be cut at an angle in order to provide efficient power extraction from the waveguide in a wide frequency range (Figure 1). We denote cut angle, α , as an angle between the cut plane and a plane perpendicular to the waveguide axis (Figure 1, left), i.e. $\alpha=0$ is the standard waveguide end. The radiation angle γ is an angle between electron trajectory and THz pulse wave vector k (Figure 1, left).

Figure 2. Left: Antenna performance metric: mode reflection as a function of frequency on decibel scale (-15 dB is equivalent to >96% of power radiated) for various values of the angle cut, α . Right: Radiation intensity as a function of angle for various values of the angle cut.

CST Microwave Studio (18)], the Maxwell's equations solver, was used to simulate the radiation extraction. The simulation was set up such that the TM_{01} mode was launched from one end of the tube towards the angle cut at various frequencies (Figure 1, left). At the end of the waveguide the mode is partially reflected back and partially radiates out. The goal of the radiator design process is to maximize mode extraction and to convert radiation into a directed wave beam. The reflection (S_{11} parameter) of the mode is calculated as a function of frequency and measured in decibels, $[dB] = 10 \log_{10}(P_r/P_i)$, where P_r and P_i is reflected and incident power correspondingly. Minimized reflection of the mode from the waveguide end signifies efficient power extraction. We performed a parametric scan of angle cut varying the cut angle, α , and observe that the extraction efficiency stays high over a wide range of angles (Figure 2, left). Thus the design is robust with respect to capillary dimensions and the angle of the cut. The radiation angle, γ , strongly depends on the cut angle, α (Figure 2, right), however this does not create problems in the experiment. A large aperture off-axis paraboloid mirror is used to intercept the radiation and direct it towards the diagnostics setup (Figure 1, right).

Figure 3. A) Standard measurement scheme and C) raw signal from interferometer corresponding to A) dominated by transition radiation. B) Measurement scheme with angle cut and D) raw signal free of transition radiation influence.

We performed a THz generation and extraction experiment at the Brookhaven National Laboratory Accelerator Test Facility (ATF) (21). An electron beam with ~ 60 MeV energy, focused to a $100\text{ }\mu\text{m}$ round spot is transported through the $400\text{ }\mu\text{m}$ round aperture of a quartz-loaded waveguide. The beam has a quasi-rectangular current profile, $300\text{ }\mu\text{m}$ long (1 ps) with a 100 pC bunch charge. Such beam drives strong wakes in a slow wave structure inserted into the beamline. This signal is transported into an interferometer and detected by a liquid helium cooled bolometer (Figure 1, right). In previous experiments (7, 11) the wake, partially exiting the slow wave structure at the end of the waveguide, was collected by an off-axis parabolic mirror. The mirror had an aperture to transmit the electron beam (Figure 3A). Passing through the hole in the mirror, the beam generates coherent transition radiation (CTR) and so we actually measure a mixture of CTR (coherent transition radiation) and Cherenkov radiation (Figure 3A, 3C). While nominally there is sufficient peak power generated by the beam in the wakefield structure, only a tiny fraction is actually transmitted to the measurement setup. When mixed with a strong CTR signal, the signal to noise ratio for the Cherenkov radiation measurement is low (Figure 3C). Figure 3C depicts an interferometer measurement of the signal produced by an electron bunch train consisting of 4 bunches. These bunches produce a CTR signal with the same periodic time structure as the current in a bunch train, hence the 4 strong oscillations near the zero-crossing point of the interferometer (0 mm mirror offset) in figure 3C.

In the case when the dielectric loaded waveguide has an angle cut end for efficient wakefield radiation, the experimental setup allows us to avoid unnecessary transition radiation generation because the wakefield is radiated at an angle to the electron beam trajectory (Figure 3B). Hence the THz signal can be transported into the interferometer by a parabolic mirror placed away from

the electron beam (Figure 1B). In this case there is no transition radiation produced; the interferometer measures only the Cherenkov radiation signal. The signal to noise ratio is improved by an order of magnitude compared to the setup in figure 3A. Variations in the signal amplitude of the interferometer measurement (seen in figure 3D) are due to electron beam charge fluctuations in the accelerator. The measurement shown in figure 3D is a direct measurement of 40 oscillations of a 480 ± 20 GHz signal generated by electron beam exciting the TM_{01} mode passing through a metallized quartz capillary, “tube 1” (dielectric constant 3.8, ID=400 μm , OD = 550 μm , L = 3 cm, group velocity = 37% of speed of light, shunt impedance = 167 kOhm/m). The spectrum of this narrowband signal is shown in figure 4, right in red.

Figure 4. Left: Autocorrelation function from signal produced by electron beam passing through tube 1. Right: Fourier transform of autocorrelation functions of signals produced by tube 1 (red) and tube 2 (blue).

In an identical experiment with a different quartz capillary, “tube 2” (dielectric constant 3.8, ID=600 μm , OD = 1400 μm , L = 3 cm, group velocity = 27% of speed of light, shunt impedance = 111 kOhm/m) a TM_{01} mode at 115 ± 5 GHz signal was generated, extracted and characterized by the interferometer (Figure 4, left, and right in blue). Note that the measured signal is narrowband. In reality the bandwidth measurement is limited by the scan length of the interferometer. The actual bandwidth of the signal, which can be calculated based on the group velocity of the mode and structure length, is even lower, about 1%. Based on the calorimetric pulse energy measurement for tube 1 (10 μJ) we estimate that 480 GHz signal with almost 60 kW of peak power was delivered outside vacuum to the bolometer in a 170 picosecond pulse.

The demand for high brightness X-ray light sources stimulates the development of high quality electron beams. Such beams can now be used also to produce high power THz radiation in dielectric loaded waveguides with sub-mm apertures. Here we presented a simple and practical method to extract THz radiation from these structure without having to build a sub-mm scale impedance matching horn antennas and mode converters. In the experiment performed at ATF we extracted a 170 ps long 480 THz signal, generated by an ultra-relativistic electron beam, from a dielectric loaded waveguide with 400 μm aperture and delivered 10 μJ of energy per pulse to the user area for signal characterization. This power level can be used as a THz pump for X-ray probe experiments at light source facilities.

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