THz AND SUB-THz CAPABILITIES OF A TABLE-TOP RADIATION SOURCE DRIVEN BY AN RF THERMIONIC ELECTRON GUN*

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Abstract

Design features and experimental results are presented for a sub-mm wave source [1] based on APS RF thermionic electron gun. The setup includes compact alpha-magnet, quadrupoles, sub-mm-wave radiators, and THz optics. The sub-THz radiator is a planar, oversized structure with gratings. Source upgrade for generation frequencies above 1 THz is discussed. The THz radiator will use a short-period undulator having 1 T field amplitude, ~20 cm length, and integrated with a low-loss oversized waveguide. Both radiators are integrated with a miniature horn antenna and a small ~90°-degree in-vacuum bending magnet. The electron beamline is designed to operate different modes including conversion to a flat beam interacting efficiently with the radiator. The source can be used for cancer diagnostics, surface defectoscopy, and non-destructive testing. Sub-THz experiment demonstrated a good potential of a robust, table-top system for generation of a narrow bandwidth THz radiation. This setup can be considered as a prototype of a compact, laser-free, flexible source capable of generation of long trains of Sub-THz and THz pulses with repetition rates not available with laser-driven sources.

INTRODUCTION

To generate narrow bandwidth, sub-THz beams a resonant Cherenkov radiation is proved can be effective and compact alternative to coherent undulator radiation especially at beam energies as low as few MeVs produced by a thermionic RF Gun followed by a magnetic compression [1]. Classical coherent Cherenkov radiation is usually produced [2] in rather dispersive (low group velocity), closed resonant structures having electrically small (in wavelength scale) apertures. The radiation is usually driven by a monopole, essentially single mode, long-range wakefields. The coherent radiation frequency is determined by the resonant synchronism between phase and electron beam velocities. Therefore, for relativistic electron beams frequency adjustment is very limited to be practical for such a "resonant Cherenkov" source. We overcome this issue by using an overmoded, high group velocity, slow-wave structure employed as a radiator. Performance specifics of such a tuneable, oversized, side-open, planar experimental structure are discussed below.

Another fundamental problem related to Coherent Vavilov–Cherenkov radiation is limited maximum frequency when using low-energy, low-brightness driving electron beams. Since the interaction gap is still proportional to wavelength even for oversized, overmoded structures, the transmitted beam current drops dramatically. Besides, micro-bunching capabilities of magnetic compression remain limited resulting in rapid reduction of bunching factor at higher frequencies. These issues make such a source impractical above ~1 THz. Therefore, for 1 THz frequency and above we consider below a compact undulator instead of Cherenkov radiator using basically the same beamline.

RBT-APS EXPERIMENT OUTLINES

Experimental setup of the sub-THz source [1] was developed jointly by RadiaBeam Technologies, LLC and the Accelerator Systems Division of Advanced Photon Source (APS) at Argonne National Laboratory (ANL). It is deployed on the Injector Test Stand (ITS) of the APS. We briefly outline here three novel features of the source: a) rather wide tunability of the frequency and the radiation spectrum; b) capability to determine effective microbunch length from the spectra taken; and c) relatively low α-magnet extra strength required to make up the microbunch space charge.

Originally the side-open, oversized, planar radiator was designed for ~504 GHz frequency (at 0.986c phase velocity). Nevertheless we have produced spectra tuned across two frequency ranges: (476–584) GHz with close to theoretical 7% instantaneous FWHM (see Figure 1a), and also (311–334) GHz with 38% instantaneous bandwidth. Both single line (for each band) and two-line spectra (see Figure 1) are producible in a well controllable way. Tuning has been accomplished with the following means: a) kinetic beam energy variation (2.5-2.9) MeV; and b) alpha-magnet gradient (2.15-2.71) T/m. Additional, fine tuning was done by varying pitch angle related to aligning of the radiator assembly with respect to the beamline axis. The spectrum peak frequency was tuned mostly with beam energy, whereas the intensity of each of these frequency components was controlled relatively independently from zero to maximum by fine tuning of the beam transport (steering) within the structure. The interferometric results indicate that at higher electron beam energies the spectrum peak frequency is lower. This

*Supported by the U.S. Department of Energy (award No. DE-SC-FOA-0007702).
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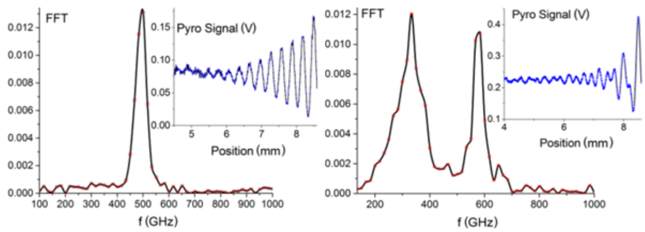
is expected from the dispersion of the resonant mode of the slow wave structure and also consistent with high group velocity exceeding 0.8*c*, which determines the enhanced frequency sensitivity to the beam voltage.



a) b)

Figure 1: Spectra Fourier-transformed from the raw experimental interferograms (on the insets) measured at (2.71, 2.15) T/m (a, b) α-magnet gradients and (2.9, 2.5) MeV (a, b) beam kinetic energies.

In the previous experiment [2] beam energy have also been varied by ~1 MeV. However, the electronic tuning did not take noticeable effect, because the beam was strongly relativistic (around 10.5 MeV energy), whereas the group velocity was lower ($\beta_{gr}\approx0.3$).

Appearance of two frequency components from a relativistic beam as seen in Figure 1b presents a new phenomenon. It results from wakefield excitation features in the side-open overmoded structure supporting also lower frequency synchronous modes (including dipole-like asymmetric modes). A similar effect is observed in simulations with longer bunches (see Figure 2): Generation of lower than the fundamental frequency (~300 GHz versus ~500 GHz) occurs at longer bunch lengths (>200 μm) when the beam is displaced horizontally by a few mm from the axis of symmetry. This correlates with our experimental observation of Figure 1b, where the alpha-magnet gradient is only 2.15 T/m vs. the 2.71 T/m gradient for Figure 1a, and also vs. the ~2.5 T/m optimal gradient found in simulations. This means that the bunch length for Figure 1b is certainly longer than that one in Figure 1a.

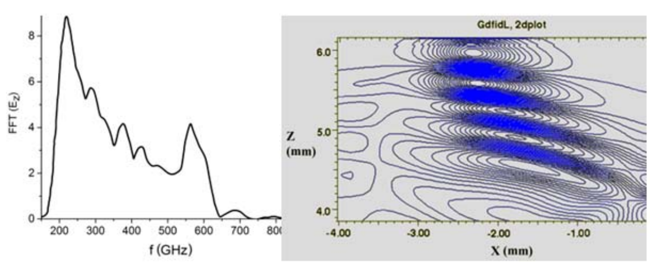


Figure 2: GdfidL [3] asymmetric wakefield simulation in gratings structure [4]: FFT for longitudinal field Ez at z=L and Ez contour plot in the median plane at t=24 ps. Filament microbunch with Gaussian distribution has δz=250 μm rms length and x=-2.5 mm horizontal offset. Structure axis of symmetry is located at x=0.

One can distinguish homogeneous spectrum broadening related to higher attenuation, larger gap, and reduced effective interaction length (vs. theoretical) caused by the beam misalignment and the beam losses inside the structure. Inhomogeneous broadening is related to pulse-to-pulse and intra-macropulse variations of the peak current and the electron beam energy.

Set of the interferograms taken allows also characterizing beam microbunching (relevant to the source wavelengths). We have selected interferograms that correspond to the same pitch angle and filtered them out to ensure that the spectral peak magnitudes are decreasing monotonously with frequency. For peaks having nearly coinciding frequencies we applied averaging. And finally we performed a fit of the plot obtained (see Figure 3) to the Gaussian bunching factor squared: $\exp\left(-(\omega\sigma_t)^2\right)$, where $\omega=2\pi f$, and σ_t is the r.m.s. bunch length. As a result we found σ_t=231 fs, (i.e. σ_z=69 μm) at standard deviation error of 4.1%. Other selections (e.g., for the same ~0.5 THz band or without filtering applied) give even shorter r.m.s. bunch durations (down to 200 fs at error ≤9%).

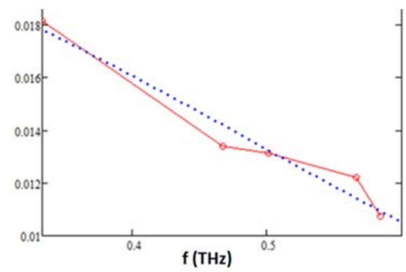


Figure 3: Radiation intensity (interferogram FFT units) as a function of spectrum peak frequency (solid) and fit to the formfactor squared for a Gaussian shape (dotted).

This result is very close to the bunch length measured in a very similar setup [5]. GPT [6] simulations performed with 20 pC charge (typically transmitted through the 1.75” long, 0.8 mm gap radiator) resulted in σ_t=205 fs (vs. ~90 fs without space charge effect in GPT or ELEGANT [7]). At much higher frequencies the r.m.s. bunch length cannot be applied reliably as the beam is generally not Gaussian (finer bunch structure may impact the formfactor).

From the experimental data taken at different flat beam currents transmitted through the planar radiator [1] we have also determined relative enhancement of the α-magnet gradient required to compensate space charge effect: ~0.65%/pC vs. 0.6%/pC found from GPT simulations. Note, for a circular beam at comparable energy, charge, and RF injector frequency, the increase of the optimum alpha-magnet gradient caused by the space charge effect appears to be more significant: ~20% for 20 pC charge and 80% for 100 pC charge [8]. That suggests flat beam configuration can be advantageous for enhanced microbunching to generate higher frequencies.

UNDULATOR-BASED RADIATOR

To extend the source capabilities beyond 1 THz frequencies and to enhance frequency tuning flexibility we are going to replace the Cherenkov radiator by an undulator (see Figure 4) to produce coherent spontaneous emission.

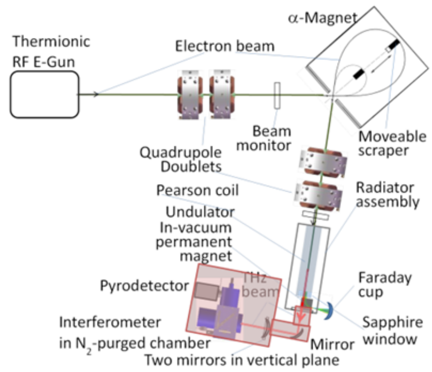


Figure 4: Beamline schematic for (~0.7-1.23) THz source.

The undulator design of classic Halbach type is shown in Figure 5. The 1st and 2nd integrals are matched. Undulator factor is 0.87 (r.m.s.), magnetic aperture 3.5×25.4 mm^2, and period 13.15 mm. These parameters enable generation of up to 1.23 THz frequency with 3 MeV beam.

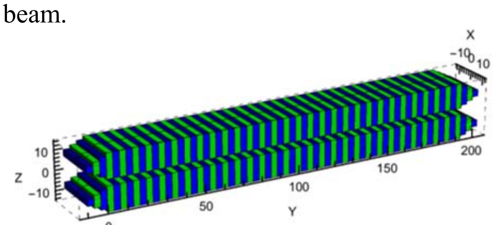


Figure 5: Radia [9] design of PM undulator.

Larger interaction gap (by factor of ~3) and longer length (~14 periods) would allow compensating the formfactor drop at these higher frequencies (at comparable relative spectral width). One important parameter is a product of transmitted bunch charge and formfactor at given frequency. GPT simulations are given in Figure 6 for this parameter at 1.23 THz and plotted along optimized beamline. For the undulator setup of Figure 4 this parameter achieved (>30 pC) is higher than that in previous setup (<30 pC at 0.5 THz).

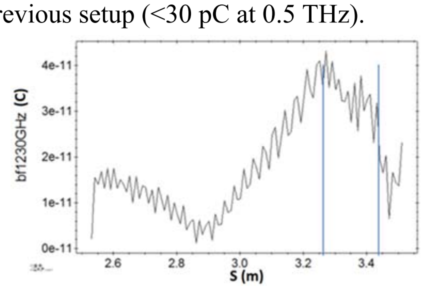


Figure 6: GPT simulation for equivalent point charge [C] capable of radiation at 1.23 THz plotted along the beamline downstream the alpha-magnet. The blue vertical lines indicate positions of undulator entrance and exit at 2.1 mm vacuum gap.

The radiator assembly with the built-in bending magnet is shown in Figure 7. The assembly has been designed to maximize THz and electron beams outcoupling while allowing longer engineering distance required between the undulator chamber opening (serving as an antenna) and Sapphire THz window as well as larger magnetic gaps (for both the undulator and bending magnets). That was enabled by substantially higher antenna directivity (37 dBi vs. 25 dBi for 0.5 THz Cherenkov radiator) using the same 2.5” cube. Calculations of the spontaneous THz undulator radiation indicate comparable and even higher peak power vs. that for the sub-THz setup [1].

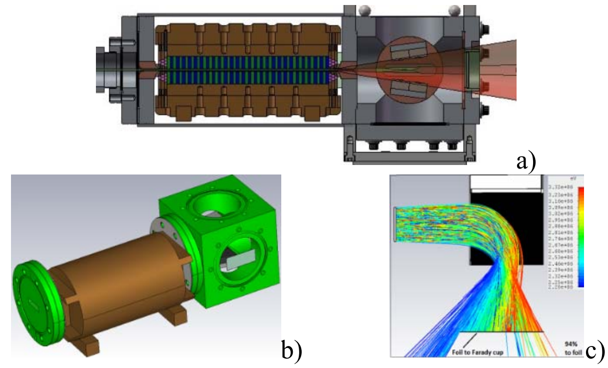


Figure 7: Radiator assembly vertical cut view (a), general rendering (b), and horizontal cut view (c) of the bending magnet sub-assembly with beam trajectories hitting Faraday cup screen.

ACKNOWLEDGMENTS

The authors are grateful to Don Dooley and Sid Levingston for the data on pyrodetector calibration and performance in the sub-THz region, Albert Hillman, Shifu Xu and Steven Shoaf for their help with magnet power supplies & controls, and Emma Curry for recalibration of the pyrodetectors at UCLA.

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