DEVELOPMENT OF A SOURCE OF A THz RADIATION BASED ON A 3-MeV ELECTRON BEAM AND FUTURE PLANS*

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Abstract

Design features and some past experimental results are presented for a sub-THz wave source employing the Advanced Photon Source's RF thermionic electron gun. The setup includes a compact alpha-magnet, four quadrupoles, a novel radiator, a THz transport line, and THz diagnostics. The radiator is composed of a dielectric-free, planar, over-sized structure with gratings. The gratings are integrated into a combined horn antenna and ~90° permanent bending magnet. The magnetic lattice enables operation in different modes, including conversion to a flat beam for efficient interaction with the radiating structure. The experiment described demonstrated the generation of narrow bandwidth THz radiation from a compact, laser and undulator-free, table-top system. This concept could be scaled to create a THz-sub-THz source capable of operating in long-pulse, multi-bunch, and CW modes. Additionally, the system can be used to remove unwanted time-dependent energy variations in longitudinally compressed electron bunches or for various time-dependent beam diagnostics. Plans for future experiments and upgrades are also discussed.

INTRODUCTION

For narrow bandwidth radiation generation, resonant Cherenkov radiation can be an attractive alternative to coherent undulator radiation. The radiation's coherence is provided by the Cherenkov synchronism in the radiation producing device between the electron microbunch and fundamental eigenmode along the device's interaction region of hundreds of radiation wavelengths. In the UCLA experiment [1], an 11 MeV electron beam from a laser-driven radio frequency (RF) photoinjector produced up to 10 µJ per RF macropulse at about mm wavelength, a fixed frequency radiation using a magnetic chicane for electron bunch compression and a 1-cm long quartz capillary tube.

In the experiment presented here a thermionic electron RF gun generates a long train of momentum-chirped electron bunches which are compressed in an alpha-magnet. Coherent Vavilov–Cherenkov radiation is produced downstream of the magnet in a planar, partially open, slow-wave structure. It comprises a pair of electrically large, dielectric-free, high aspect ratio, metal gratings.

To the best of our knowledge, an intense, tuneable, coherent radiation with a sub-mm wavelength was not produced to date using a completely laser-free and undulator-free table-top system with a few MeV electron beam.

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EXPERIMENTAL SETUP

The experiment was jointly developed by RadiaBeam Technologies, LLC and the Accelerator Systems Division of Advanced Photon Source (APS) at Argonne National Laboratory (ANL) and conducted in the Injector Test Stand (ITS) of the APS. Figure 1 shows a schematic of the experimental setup. To obtain short electron bunches, low energy electrons are scrapped off inside the alpha-magnet vacuum chamber via a remotely controlled copper insertion aperture.

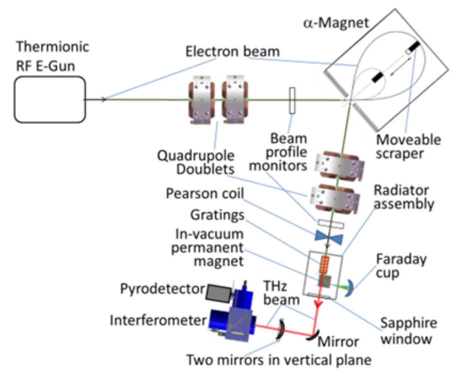

Figure 1: Schematic layout of the experimental setup. Five beam steering correctors are not shown. The layout footprint is about (1×1.5) m^2.

A set of four quadrupole lenses is used to control vertical and horizontal beam envelops in the beamline to obtain a quasi-flat beam transverse profile in the THz radiator. The 2.5 cm short in-vacuum permanent magnet after the radiator directs the electron beam into a Faraday cup at the end of the beamline. The Cherenkov radiation exits to the air through a 3.7 cm diameter sapphire window and is transported to the interferometer by off-axis parabolic mirrors.

The alpha-magnet has a maximum trajectory depth of 16 cm, minimum magnetic gap of 2.2 cm, and a maximum gradient of the magnetic field of 4 T/m. The alpha-magnet vacuum chamber includes a scraper to collimate low energy portion of the beam.

The electron beam and beamline parameters are given in Table 1. The quadrupole gradients were pre-set using the values defined from beam transport simulations and

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the beam transverse profiles were taken with YAG-screens and matched to the simulated profiles in two locations (see Fig. 1).

Table 1: Beam Parameters of the RBT-ANL Experimental Setup at APS/ITS

Averaged beam kinetic energy	E	2.5-3 MeV
E-gun macropulse beam current	I	up to 400 mA
RF pulse repetition rate	ν	6-15 Hz
Beam macropulse duration FWHM	t_r	~250 ns
Bunch charge on the Faraday cup	q	up to 30 pC
Minimum rms bunch duration	σ_t	<1ps

RADIATOR ASSEMBLY

The THz radiator assembly and the grating are illustrated in Fig. 2. The side-open pair of oversized planar copper gratings are combined with a horn antenna followed by a ~90° permanent bending magnet. The magnet poles gradually open to avoid interception of the near field sub-mm wave. A remotely controlled mechanical system is employed for fine adjustment of the vertical position of the entire assembly and pitch angle of the structure.

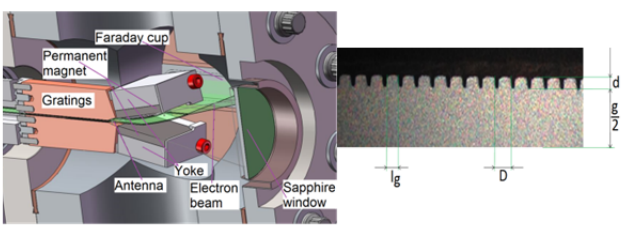

Figure 2: Rendering of the radiator assembly (left), and a magnified photo of a 2 mm long fragment of the grating structure (right).

Unlike mm- and sub-mm-wave tubes [2] and dielectric-loaded slow-wave structures, the grating structure used in this experiment has exceptionally high group velocity, v_{gr}=0.82c, where c is the speed of light. This results in several consequences: significant shortening of the wakefield length, reduction of the wake attenuation rate, broadening of the spectrum, and enhancement of the radiated field (at a given shunt impedance [3,4,5]). It also results in significantly relaxed tolerances to fabrication errors and surface roughness for the gratings [6]. Another benefit is dispersion-enhanced sensitivity of the resonant Cherenkov frequency to the particle velocity. That allowed us to extend the electronic frequency tuning to relativistic beams.

Table 2: Electrodynamic and Geometric Parameters of the Periodic Slow-Wave Structure Design

Operating mode frequency	f	500 GHz
Q-factor	Q	~1000
Averaged shunt impedance over Q	r/Q	1.2 kΩ/m
Normalized group velocity	β_{gr}	0.8
Interaction gap	g	0.8 mm
Structure width	w	10 mm
Interaction length	L	44.5 mm
Period	D	127 μm
Groove depth	d	51 μm
Groove width	l_g	76 μm

MEASUREMENT RESULTS

The microbunching and coherency effects are clearly manifested by the presence of substantial quadratic component of the pyro signal plotted vs. the Faraday cup current (see Fig. 3). The optimum compression of the electron bunches, obtained by changing the alpha-magnet current to maximize the pyrodetector signal, was found to be at (10.5±0.5) A, which is in a good agreement with the value of 10.2 A simulated without space charge effects. Note that for a circular beam of a 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 [7]).

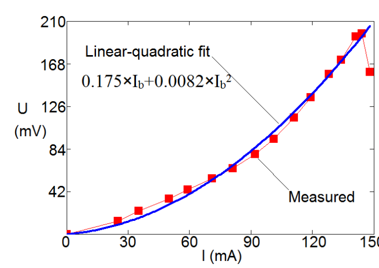

Figure 3: Pyrodetector signal magnitude plotted as a function of the Faraday cup current.

Figure 4 and Figure 5 show two spectra of the CCR radiation measured by a Michelson type interferometer [8]. The 7.3% minimum bandwidth we measured slightly exceeds the theoretical value of ~6% determined by the drain time, i.e. difference between the filling time and the time of flight.

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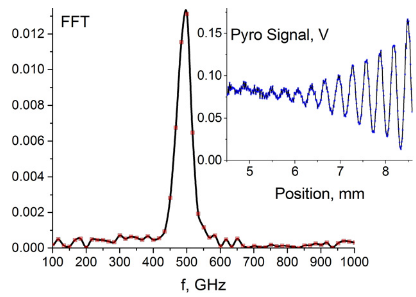

Figure 4: FFT of the raw experimental interferogram (inset) obtained at 0.96° pitch angle of the radiator, 2.5 MeV beam kinetic energy and 11.3 A current in the alpha-magnet.

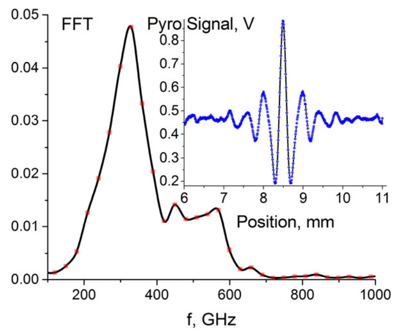

Figure 5: FFT of the raw experimental interferogram (inset) obtained at 2.5 MeV beam kinetic energy, 0.96° pitch angle of the radiator and 8.8 A current in the alpha-magnet.

Dozens of collected interferograms indicate that the two spectral components are tuneable smoothly and reproducible within (476-584) GHz (i.e. 20%) and (311-334) GHz ranges (i.e. 7%).

The maximum energy density of the radiation impinging on the detector's sensitive area was found to be ≥50 µJ/cm2 per macropulse. This density is consistent with the (18-121) µJ energy per RF macropulse power evaluated with analytical means [3].

DISCUSSION

The experiment described above has demonstrated good potential for a compact, robust, laser and undulator-free, table-top system for the generation of a narrow bandwidth THz radiation. This setup can be considered as a prototype of a highly efficient THz-sub-THz source capable to operate in a long-pulse multi-bunch (or even continuous) mode driven by a CW injector.

A similar structure can be efficiently used for other applications, i.e., to remove unwanted time-depend energy variations in longitudinally compressed electron bunches [9,10] or for time-dependent beam diagnostics.

FUTURE PLANS

RadiaBeam is working to make the system a commercially available product by decreasing the overall size and complexity through the use of permanent magnet quadrupoles (see Fig. 6) and a permanent magnet alpha-magnet.

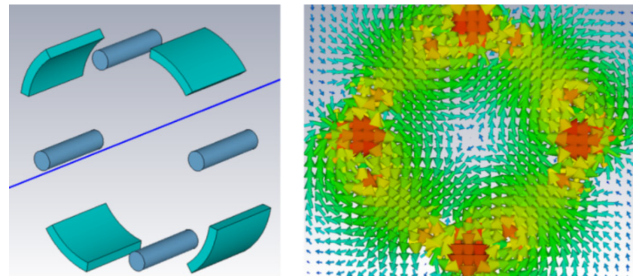

Figure 6: Iron-free adjustable permanent magnet quadrupole design. [LEFT] shows CST model of the quadrupole magnet and [RIGHT] shows the resulting magnetic field map.

Additionally, RadiaBeam has designed an application-specific high-current RF gun (see Fig. 7) based on conventional thermionic dispenser cathodes requiring modest RF power.

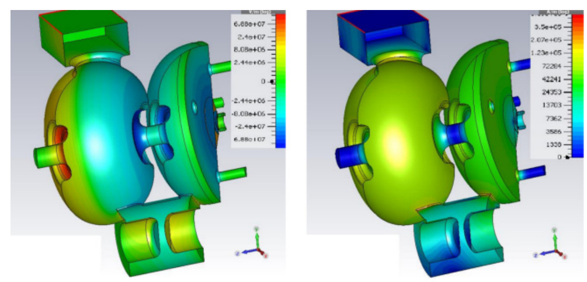

Figure 7: 1.5-cell RF gun, S-Band, 2 MeV, 1 A peak, 3 MW input power. [LEFT] shows surface electric field intensity and [RIGHT] shows surface magnetic fields.

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