DEVELOPMENT OF A COMPACT INSERTION DEVICE FOR COHERENT SUB-MM GENERATION*

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Abstract

A novel design of resonant Cherenkov wakefield extractor that produced a ~0.9 mm wavelength radiation is presented. The experiment was performed at Idaho Accelerator Center (IAC) using specially upgraded 1.3 GHz 44 MeV linac facility. Specifics of the radiator performance and design are outlined including low-energy beam interaction with non-circular geometry. Some elements of the design may have certain potential for future compact mm-sub-mm-wave sources.

INTRODUCTION

For narrow bandwidth radiation generation, resonant Cherenkov radiation is an attractive alternative to undulator radiation due to the frequency independency from the beam energy (for relativistic beams) and due to higher equivalent shunt impedance. Coherence is provided by the Cherenkov synchronism between the microbunch and fundamental (or the lowest) eigenmode(s) along the interaction space having dozens to hundreds of wavelengths. Relatively low ~11 MeV energy electron beam was used in UCLA to produce up to 10 μJ energy per laser pulse (or RF macropulse) from a 200 pC charge at sub-THz frequency (~270 GHz or ~370 GHz dependently on the capillary structure used [1]) with a multi-ps electron beam produced in a laser photoinjector was accelerated and magnetically compressed. Even lower beam energy can be sufficient with on-cathode microbunching and beam overfocusing within the radiator [2,3].

Here we consider another possibility of a low energy source that does not require any laser and/or undulator.

THE EXPERIMEMTAL SETUP

The experiment has been conducted at Idaho Accelerator Center (IAC) using a beam produced from a pulsed DC gun with thermionic cathode. The beam is pre-bunched, bunched and accelerated in the 1.3 GHz, 44 MeV nominal energy linac and then microbunched in a magnetic chicane. The experimental setup is described in Ref. [4]. The linac facility has been substantially upgraded [4,5,6,7] to address the experiment requirements. The IAC beamline was tuned with the parameters given in Table 1.

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Table 1: Beam Parameters in the Experiment

Beam energy	E	5 MeV
RF pulse rep rate	ν	30 Hz
Beam macropulse duration	t_{RF}	2 μs
Number of bunches in the train	N_b	2600
Transported bunch charge	q	30 pC
Rms bunch duration	σ_t	>500 fs

THE INSETION DEVICE

The slow wave system is presented by a pair of planar, side-open, copper gratings with symmetrical meander profile. The main structure parameters are given in Table 2 .Internal view of the radiator is presented in Fig. 1.

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

Resonant frequency	f	~316 GHz
Phase advance per period	θ	~88°
Q-factor	Q	2150
Gap-averaged shunt impedance	r	~4.3MΩ/m
Normalized group velocity	β_{gr}	0.8
Interaction gap	g	1.256 mm
Structure width	w	6.3 mm
Interaction length	L	30.4 mm
Period	D	234 μm
Groove depth	d	80.86 μm

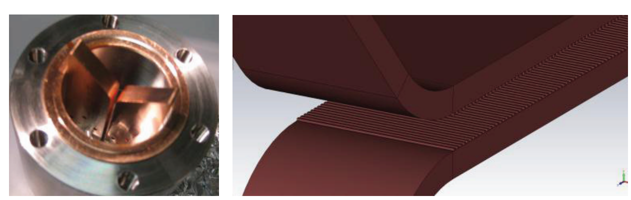

Figure 1: The insertion device interior (left) and magnified 3D rendering of the structure opening with planar horn antenna (right).

The structure was designed to operate at a substantial gap. Corresponding reduction of shunt impedance is partially compensated by some enhancement of the radiation at high group velocity [8]. A high-Q mode well-confined in the middle of the gap without spatial variations has been identified as fundamental (see Table 2 and Fig. 2) and capable to effectively interact with the beam propagating in the gap.

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For matched outcoupling without trapped modes we calculate below the energy radiated by a single microbunch using the modal energy loss found analytically with the eigenmode excitation theory applied in time domain [8] as follows:

$$W_{1b} \approx \frac{\omega}{4} \frac{rL}{Q} \frac{(q|\Phi|)^2}{|1-\beta_{gr}/\beta|} \left(\frac{1-\exp(-\alpha L)}{\alpha L} \right)^2, \quad (1)$$

where $\omega = 2\pi f = h(\omega) v$ is the circular frequency of the resonant Cherenkov radiation, $h(\omega)$ the wavenumber defined by the structure dispersion, q is the bunch charge, $r = E_z^2 / dP/dz$ is the shunt impedance, $\beta = v/c$, Q is the Q-factor, $Q|\beta - \beta_{gr}| >> 1$, $\alpha = \pi f / Q v_{gr}$ is the attenuation, and $\Phi = \exp(-(\omega\sigma_t)^2/2)$ is the formfactor for a Gaussian bunch having r.m.s. duration σ_t.

Note Eq. (1) applied to the setup [1] added with analytical calculation of shunt impedance gives 9 μJ energy which is the same as measured (at ~270 GHz [1]).

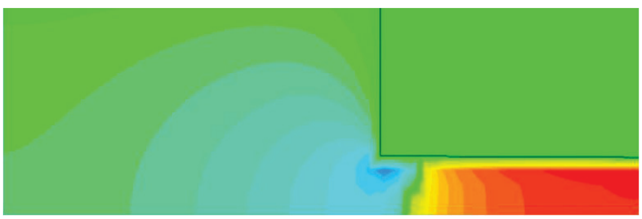


Figure 2: Contour plot of longitudinal electric field across one quarter of the periodic, side-open stricture for the lowest confined mode at ~316 GHz.

A single microbunch radiates during so-called drain time, defined as a difference between the filling time and the time-of-flight: $T_D = L(v_{gr}^{-1} - v^{-1})$. For our ~3 cm structure length we obtain T_D=21 ps, which also determines the radiation spectrum linewidth. More accurate calculations with time-domain model [8] show the radiation bandwidth ~31 GHz (~10%). A single bunch radiated power is W_{1b}/T_D.

The radiator (insertion) device is supplied by two Sapphire windows and cooling system (see Fig. 3).

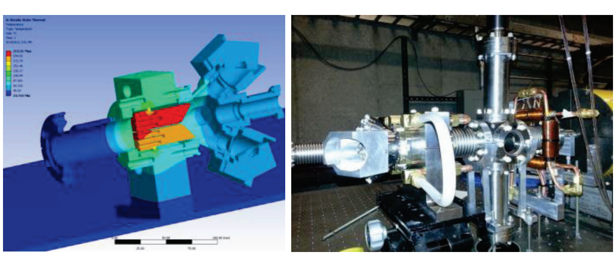


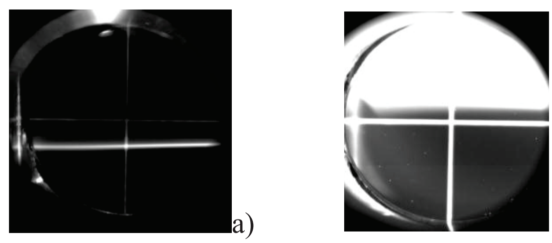
Figure 3: LEFT: ANSYS simulations of temperature distribution in the radiator at 160W power deposition on the molybdenum collimator (no water cooling). The maximum local temperature is 215.3°C. RIGHT: Radiator mounted in IAC beamline.

THE MEASUREMENTS

The wakefield radiation have been registered with two detectors: a GenTec QS-I-TEST SDX-1065 pyrodetector and a small custom made antenna connected to fast oscilloscope. The detectors were attached to the two ports of the radiator correspondingly.

In the experiment the linac beamline (including RF system, chicane and beam optics) have been carefully tuned in three steps: initial beam transport through the device (see Fig. 4(a)), registering cm-wave radiation with antenna only (see Fig. 5), and finally registration of the THz signal from the pyrodetector (see Fig. 6). Note conventional linac tuning even with fine flat beam (see Fig. 4(a)) does not produce any radiation at the absence of optimum energy modulation (chirping) at the entrance of the chicane.

The THz radiation was produced only after finer tuning of the compression system (including RF tuning) when the beam was energy-modulated to get sufficient compression while maintaining the stable generation at longer wavelength.



a) b)

Figure 4: Transverse profiles of a flat-tined beam as seen on the YAG screen upstream the radiator without chirping (a) and with chirping (b) when the radiation was initially registered.

The longer wavelength radiation is contributed by the wakefield induced by the horn antenna opening having about 2 cm length of the metal surface of the each side (and ~1 cm in projection on the beam axis). For bunches much longer than the structure period but much shorter than the horn length only geometric wake is induced and registered in the cm-wave region. For bunches comparable with the period or shorter both wakes are present and registered with two different detectors.

The power produced within the structure is calculated as follows. From recent calibration of the QS-I-TEST detector test box done at UCSB [9] we find that the responsivity for ν=15 Hz is 16 V/mW (neglecting responsivity dependency on higher rep rates and radiation frequency). The average voltage induced on the pyrodetector is 40 mV (see Fig. 6, right), therefore the average power incident on the detector is at least 2.5 μW.

Note fraction of power incident on the 5×5 mm crystal located at ~11 cm from the structure end is ~0.25 % as defined from 3D far-field simulations of the radiator design. That gives ~1 mW average power produced within the structure, or ~17 W power in a macropulse. Note this calculation does not take into account reduction of sensitivity at higher rep rate [9] (that is about counterbalances the increase of responsivity with respect to calibration frequency).

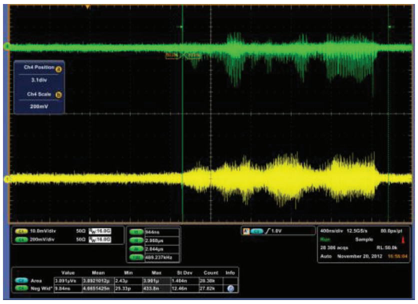


Figure 5: Fast oscilloscope traces for the signals taken from the Faraday cup downstream (on the top, green) and from a small antenna placed on the sapphire window (bottom, yellow). Animation is available [10].

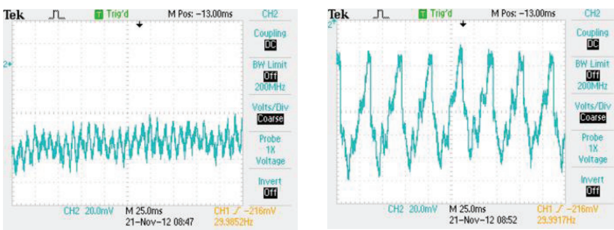


Figure 6: Oscilloscope signal from the pyrodetector when the electron beam is blocked (left) and when the beam is present, i.e., compressed and transported through the radiator (right).

From Eq. (1), Table 1 and Table 2 one can find that the formfactor Φ is about 0.37 that corresponds to ~210 μm r.m.s. bunch length. As expected it is larger than that was evaluated in the experiment with S-band linac [1]. Thus about 33 μJ per RF pulse have been produced at about two orders higher average power than that was available in low-energy experiments with laser photoinjector.

OUTLINE

A sub-THz Cherenkov radiation was produced at as low as 5 MeV beam energy using L-band linac with thermionic cathode and magnetic chicane without undulator and/or laser. A planar, side-open, dielectric-free, structure was fabricated with conventional CNC milling. Such a robust slow-wave structure is capable to radiate at as high as 0.8 group velocity, and aperture gap exceeding wavelength at substantial efficiency with respect to RF power consumed.

Inspection made upon disassembling showed the extractor does not have any sign of damage or degradation for ~2 weeks of operation at substantial beam loading (up to hundreds watt of average beam power).

Such slow-wave inserts can be used downstream chicane bunch compressors to passively remove energy modulation (as the “Dechirper” [11]). They can also be applied as diagnostics means for bunch length measurement. Unlike diagnostics based on transient radiation and interferometer such a tool can be easier in application, may operate at lower energies and wider range of bunch lengths.

The setup can be considered as a prototype of a robust and efficient THz-sub-THz source capable to operate in pulsed multi-bunch or even continuous mode of operation when driven by a superconducting RF injector [12]. Absence of laser system along with ruggedized design of the radiator-extractor allow producing higher average power than that with conventional photoinjectors and simultaneously may make the system more compact and available for small labs, businesses, and other facilities used in medicine, industry, and homeland security.

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