Nuclear Instruments and Methods in Physics Research A 721 (2013) 1–9

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

S-Band RF photoinjector as a driver for coherent Cherenkov source

A.V. Smirnov [a],*, P. Musumeci [b]

[a] RadiaBeam Technologies, LLC, 1717 Stewart Street, Santa Monica, CA 90404, USA
[b] University of California at Los Angeles, Los Angeles, CA, 90095, USA

ARTICLE INFO

Article history:
Received 19 February 2013
Received in revised form
14 March 2013
Accepted 11 April 2013
Available online 24 April 2013

Keywords:
Photoemission
Wakefield
Shunt impedance
Phase velocity

ABSTRACT

Resonant Cherenkov radiation in capillary slow-wave structures driven by relativistic beams from a low-energy S-band photoelectron gun is considered. The generation of few megaelectron volt, sub-millimeter-sized, sub-ps microbunches is analyzed numerically. Different modes of operation of such an overfocused, high-current-density system with corresponding adaptation of RF photoinjector is discussed including some experimental measurements with beam on-cathode microbunching. Feasibility of generation of high peak power generation at terahertz frequencies is demonstrated with laser pulse multiplexing and photomixing.

1. Introduction

Electromagnetic waves at terahertz frequencies are only at the beginning of extensive exploration, because these waves are difficult to generate, handle, and analyze compared with other more explored regions of the electromagnetic spectrum. The terahertz range of the EM spectrum is energetically equivalent to photons of several milli-electronvolts (meVs), or temperatures of tens of degrees Kelvin, hence of relevance for many physical, chemical, and biological processes including superconducting gaps and protein dynamical processes. There is a wide mismatch between available sources and research or commercial needs in this frequency range. This gap is especially critical for a wide range of frontier and emerging applications demanding at least a fraction of a microjoule of energy within sub-nanosecond pulses [1].

So far the most powerful infrared (IR) and far infrared (FIR) sources in operation are Free Electron Lasers (FELs). Only very few facilities around the world operate specifically at terahertz frequencies and deliver substantial pulse power to users. A MW level of narrowband peak power has been produced in the FEL at Novosibirsk [2]. In terms of peak power, ultrashort, relativistic electron microbunches have shown even higher power using broadband transition radiation. According to the tests made in Brookhaven's Source Development Lab of BNL, 200 MeV, sub-ps, nanocoulomb bunches can produce up to 100 μJ pulse energy, and tens of watts of average power with special mirrors [3,4]. At Lawrence Berkeley Laboratory, 0.1 μJ THz energy has been produced from plasma-vacuum transition with some prospects of generating up to 100 μJ/pulse [5]. At the Stanford Linear Accelerator Center (SLAC) a terahertz radiation from sub-100 femtosecond compressed relativistic electrons has been demonstrated [6]. The Jefferson National Lab, Brookhaven National Lab, BESSY storage ring, and the Advanced Light Source at Berkeley, also have strong research programs to build a dedicated terahertz source.

For narrow bandwidth radiation generation, resonant Cherenkov radiation is an attractive alternative to undulator radiation due to the frequency being independency from the beam energy (for relativistic beams) and due to the much higher equivalent shunt impedance. Coherence is provided by the Cherenkov synchronism between the microbunch and fundamental (or one of the lowest) eigenmode along the interaction space having dozens to hundreds of wavelengths.

Interest in these kinds of structures dates back few years. Substantial damage threshold of several Gigavolts per meter in terahertz region for the metallized capillary quartz tubes was identified in the T-481 wakefield experiment [7] using 28 GeV electron beam. Lower energy electron beam was used in UCLA to produce ~150 kW peak intra-structure power from a 10–11 MeV, 200 pC charge [8].

It was also found that even lower beam energy can be used while producing higher power if the beam is on-cathode microbunched with, e.g., beatwave, properly overfocused, and the radiator is designed with higher shunt impedance and outcoupling efficiency [9,10]. Such a novel configuration makes the source much more compact and attractive for broad applications compared to FELs, synchrotron or broadband transient radiation sources.

---

* Corresponding author. Tel.: +1 31 082 258 45; fax: +1 215 392 5535.
E-mail address: asmirnov@radiabeam.com (A.V. Smirnov).

0168-9002/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nima.2013.04.024

However, low beam energy and custom mode of operation of the photoinjector require special attention to the beam dynamics and radiation. In this paper we consider some features of such a terahertz source performance using both single bunch and optically-multiplexed (microbunched) modes of operation.

2. Photoinjector-driven terahertz source scheme

Here we consider a 2.856 GHz conventional BNL/SLAC/UCLA type photoinjector [11] as a driver for the source depicted schematically in Fig. 1. The RF electric and magnetostatic longitudinal field profiles are given in Fig. 2.

The radiator is shown schematically in Fig. 3. In general it can be represented by any slow-wave structure (not necessarily dielectric-loaded) having substantial shunt impedance for one of the lowest eigenmodes synchronous with the relativistic electron beam at terahertz frequency of interest. Various capillary radiators loaded with different materials are characterized in Ref. [9] at ~1 THz. Here we use a square $0.6 \times 0.6\ \mathrm{mm}^2$, 1-cm long channel with about 16 μm thick diamond coating which is sustainable to electron bombardment. With analytical or numerical eigenmode modeling one can routinely estimate that at 0.96 THz the structure has about r/Q=8 kΩ/m waveguide shunt impedance over Q, as high as ~0.83 group velocity, and ~1000 Q-factor (dependently on hydrogen presence in CVD diamond). One can expect satisfactory lifetime of the radiator even if it is dielectric loaded (especially for thin diamond coating): the beam interception with the structure is not dangerous because the average beam power of the low-energy, laser-driven beam is low.

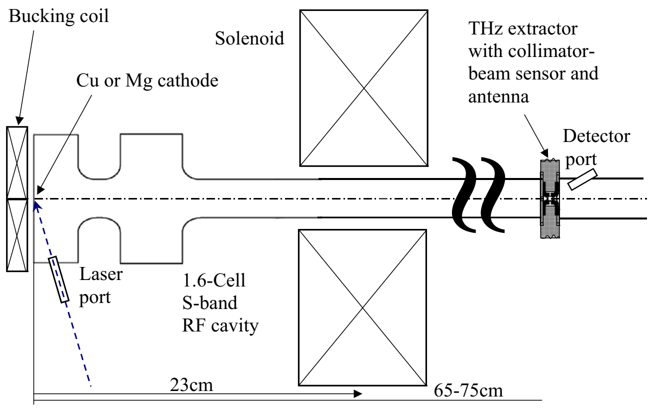

Fig. 1. Schematic layout of a pulse terahertz source based on S-band 1.6 cell BNL/SLAC/UCLA type photoinjector. Cooling, RF, diagnostics, terahertz outcoupling, and laser systems are not shown.

Note such a high group velocity has certain specifics known as "compression" [12] imposed on calculation of wakefields including attenuation and magnitude.

Energy radiated by a single microbunch can be calculated analytically with the eigenmode excitation theory applied in time domain [12] as follows:

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

where $\Phi \approx \frac{1}{q}\int_q \frac{dq}{dz}(z')\exp\ (-i(kz'/\beta))\ dz'$is the bunch formfactor, q is the bunch charge, $\omega = 2\pi f = h(\omega)/v$ is the resonant frequency, $\beta = v/c$, $k = \omega/c$, Q is the Q-factor, $Q|\beta - \beta_{gr}| > > 1$, and $\alpha = \pi f/Q\ v_{gr}$ is the attenuation.

For a long train of microbunches the saturated power can be estimated from superposition as follows [12]:

$$P = \frac{\omega}{4}\frac{r}{Q}\frac{1}{|v_{gr}|}\left| I\ \Phi L \frac{1-e^{-\alpha L(1+ia_s)}}{\alpha L(1+ia_s)}\right|^2 \tag{2}$$

where $Q|\beta - \beta_{gr}| > > 1 \quad [L(\beta_{gr}{}^{-1} - \beta^{-1})f/c]\ ^2 > > 1,\ a_s = 2Q(f/f_b - 1)(1-\beta_{gr}/\beta)$ is the generalized detuning, f_b is the frequency of the microbunched train (or its resonant subharmonic).

Formulae (1,2) are verified numerically and experimentally in different frequency bands [13,14].

Saturation occurs when the macropulse duration exceeds the so called drain time $T_D = L(v_{gr}{}^{-1} - v^{-1})$. Note if the bunch separation T_b exceeds the drain time the power is calculated instead of Eq. (2) as follows: $P = W_{1b}/T_b$.

To accurately calculate the wakefields induced in the structure by the beam ensemble with dynamically changing density profile and number particles caused by losses we will use here the same technique developed earlier [9] based on time domain analytical theory [12], field superposition, and importing of many the

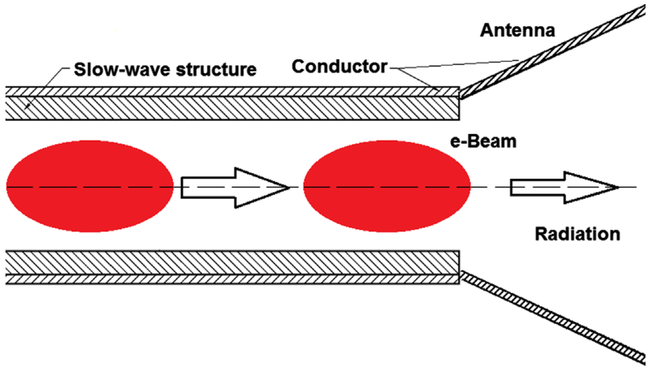

Fig. 3. Schematics of extractor-radiator integrated with antenna.

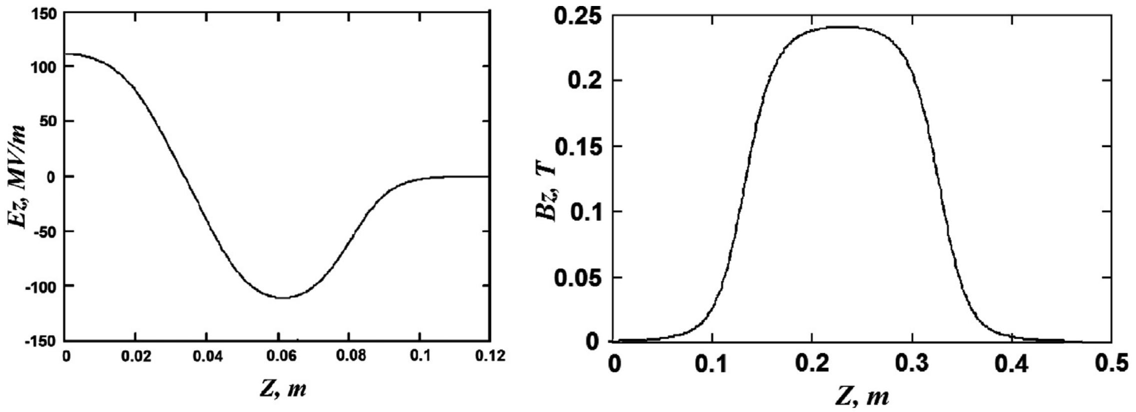

Fig. 2. Longitudinal RF electric and magnetostatic field profiles used in simulations of the 1.6-cell S-band BNL/SLAC/UCLA RF photoelectron gun.