Characterization of coherent Cherenkov Radiation Source

A.V. Smirnov,
RadiaBeam Technologies, LLC, 1717 Stewart St., Santa Monica, CA 90404, USA

Engineering formulae for calculation of peak, and spectral brightness of resonant long-range wakefield extractor are given. It is shown that the brightness is dominated by beam density in the slow wave structure and antenna gain of the outcoupling. Far field radiation patterns and brightness of circular and high aspect ratio planar radiators are compared. A possibility to approach diffraction limited brightness is demonstrated. The role of group velocity in designing of the Cherenkov source is analyzed. The approach can be applied for design and characterization of various structure-dominated sources (e.g., wakefield extractors with gratings or dielectrics, or FEL-Cherenkov combined sources) radiating into a free space using an antenna (in microwave to sub-mm wave regions). The high group velocity structures can be also effective as energy dechirpers and for diagnostics of microbunched relativistic electron beams.

PACS Numbers: 29.27.-a, 41.75.Ht, 41.75.Fr, 84.40.Az, 42.72.Ai, 07.57.Hm

1. Introduction

A growing number of national scale facilities such as synchrotron radiation sources, free electron lasers (FELs) and free-electron masers (FEMs) around the world are dedicated specifically to the THz-sub-THz range to deliver substantial power to users. However, to cover the rapidly growing demand in THz science and technology [1], more flexible, preferably in-house access to dedicated THz sources is required. The number of applications of THz radiation is very large. We give here only a several areas:

- Broad range research in material science, molecular biology, fast chemistry, solid state and nuclear physics. Excitation of low-energy states: plasmons, phonons, polarons, magnons, spin resonances, charge orders, superconducting gaps.
- Development of new medical tools for clinics for skin cancer diagnostics and dental imaging.
- Measuring drug concentration in pharmaceutical industry.
- High-throughput imaging of microchips at higher dynamic range for early detection of defective units.
- Non-destructive testing of dielectric composite materials. THz waves offer the best way to test graphite fibers used in aircraft as well as thermal insulation foam for space shuttles.
- Environmental monitoring of pollution, green house gases, and ozone destruction by tracing corresponding pointers in the earth's atmosphere, stratosphere and upper troposphere with THz waves.

- Remote (standoff) detection of concealed weapons, hidden objects/threats, chemical agents, traces of explosives, and hazardous materials.

Most of these applications are still remain potential or undeveloped. Very often the reason is limited access to the high power, high brightness sources and limited capabilities of existing, usually laser-based, laboratory sources. For example, in stand-off spectroscopy increasing of peak power and spectral brightness just by an order of magnitude would result in two orders improvement in detection. However, the cost per unit of THz power (or pulse energy, or spectral brightness - dependently on application) remains too high to develop rapidly the significant potential of the “THz market”. Conventional radiation facilities based on FELs, electron storage rings, and/or energy recovery linacs (ERLs) are too large, expensive, and not always readily available for a broader community of researchers, investigators, scientists and commercial users to operate it on a flexibly customized, on-demand, independent base.

For narrow bandwidth radiation generation, resonant Cherenkov radiation can be an attractive alternative to undulator radiation due to the frequency 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 GV/m in THz region for the metallized capillary quartz tubes was identified in the T-481 wakefield experiment [2] 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 [3].

66 It was also found that even lower beam energy can be used while producing higher power if the
67 beam is on-cathode microbunched with, e.g., beat-wave or multiplexing techniques, properly
68 overfocused, and the radiator is designed with higher shunt impedance and outcoupling
69 efficiency [4,5,6].

70 RadiaBeam Technologies have recently conceived [7] and experimentally tested [8] a laser-free
71 concept of a high rep rate, long-train-pulse, T-ray source. A 5 MeV electron beam produced by a
72 thermionic L-band injector and momentum-modulated is longitudinally compressed in a
73 magnetic chicane and focused onto a slow-wave radiating structure to produce a sub-THz
74 generation [9].

75 Such low energy resonant Cherenkov radiators (or wakefield extractors) can make the source
76 compact and attractive for broad applications compared to FELs, synchrotron or broadband
77 transient radiation sources provided the source characteristics are competitive or at least
78 sufficient. Dependently on application these characteristics are not always limited by radiated
79 energy per pulse, peak or average power.

80 Though the mechanism of Coherent Cherenkov Radiation (CCR) employed in such devices is
81 well-known, characterization of these sources very often remains insufficient. That makes
82 difficult to evaluate the source value for different applications or compare it with other sources
83 (e.g., based on undulators, molecular lasers, or laser-driven photoconductive antennas). Also
84 optimization of the source design is impossible without proper characterization and well-defined
85 goal functions. Besides, the CCR mechanism can be employed for beam characterization (e.g.,
86 measuring of bunch length). But this requires simple, reliable, accurate, and straightforward
87 characterization of the radiation.

Up to $0.2 \text{ GW/sr}\cdot\text{cm}^2$ brightness has recently been achieved at $\sim 2.25 \text{ THz}$ and 50 kW peak power with a broadband optical rectification technique using a tilted optical pulse front [10]. The brightness reported is about 70% of the diffraction limit (which is $B = P/\lambda^2$ at this frequency). However, it is incorrectly claimed as exceeding the brightness of existing far infra-red (FIR) FELs. FEL radiation brightness can be evaluated as $B = P/(4\pi^2\epsilon_x\epsilon_y)$, where ϵ_x , ϵ_y are the transverse emittances, $\sqrt{\epsilon_x\epsilon_y} > \lambda/2\pi$, and $B \approx B_{\text{limit}} = P/\lambda^2$ when $\sqrt{\epsilon_x\epsilon_y} < \lambda/2\pi$ (i.e. in diffraction-limited case [11]). Most of FIR FEL sources operate in a diffraction limited mode due to attainability of low beam emittance (i.e. lower than the emittance of diffraction limited photon beam $\lambda/2\pi$), but at comparable or much higher peak power. Besides, spectral brightness of FIR FELs remains superior among existing sources due to long undulators being available. The most powerful, 0.6 MW FIR FEL in Novosibirsk [12] operates in a deep diffraction limit which is $B \approx B_{\text{limit}} = 1.9 \text{ GW/sr}\cdot\text{cm}^2$ (at $\lambda=180 \text{ }\mu\text{m}$, normalized emittance $\epsilon_{nx,y}=\beta\gamma\epsilon_{x,y}=15 \text{ }\mu\text{m}$, and $\sim 13 \text{ MeV}$ beam energy). Peak broadband brightness for the most powerful 1 MW mm-sub-mm wave synchrotron radiation source at Thomas Jefferson Laboratory is about $0.6 \text{ GW/sr}\cdot\text{cm}^2$ ($\sim 54\%$ of the diffraction limit B_{limit}). However, brightness per cost or per footprint can be indeed exceeded in non-FEL FIR sources.

Below we attempted to pave an engineering path for characterization of structure-dominated sources employing radiators (or extractors). The sources comprising an antenna are not limited by CCR mechanism but may also include undulator with fast or slow-wave structure (e.g., mm-wave Bragg resonator and waveguide), or Cherenkov-FEM combined sources [13].

2. Antenna gain and brightness.

111 Unlike short wavelength FELs and undulator sources that to first order can be considered as
 112 unbounded, our sources of interest are bounded with a structure (metallized capillary tube,
 113 cladding dielectric structure, metal gratings, plasma channel etc.). That structure can be
 114 represented by a piece of closed, open or “leaky” waveguide usually supplied by (or serving
 115 itself as) a device matching the impedance of the waveguide with a free space impedance for
 116 better outcoupling of the radiation. Thus in the far-field region the radiation is actually formed
 117 by the antenna, whereas the beam serves only as a launcher for the structure (unlike FEL). Note,
 118 dependently of particular interaction mechanism of the beam with external static fields and/or
 119 internal wakefields the structure type can be fast or slow wave.

120 Once an antenna is used for outcoupling it can be characterized by directivity and gain [14] for
 121 the modes launched upstream the interaction structure (serving as virtual antenna port). It is very
 122 convenient to express the power density and brightness via the antenna gain (or directivity)
 123 assuming nearly normal orientation of the detector with respect to incident rays:

$$124 \quad S = \frac{dP_{ff}}{dA} = \frac{1}{4\pi R_d^2} \sum_n G_n P_n, \quad \text{and} \quad B = \frac{d^2 P_{ff}}{dA d\Omega} \approx \frac{1}{A_A} \cdot \frac{1}{4\pi} \sum_n P_n G_n, \quad (1)$$

125 where P_{ff} is the power of far-field radiation, R_d is the distance between the source and the
 126 detector (object), $R_d \gg W_A$, $R_d \gg W_A^2/\lambda$, W_A is the maximum antenna dimension, λ is the
 127 wavelength, S is the power density (determined by Poynting vector flux), $d\Omega$ and dA are the
 128 infinitesimal small solid angle and area, A_A is the antenna aperture area; P_n is the modal power
 129 on the transition from the slow-wave structure to the antenna, and G_n is the generalized antenna
 130 gain.

131 In general the summation in Eqn. (1) may also include different polarizations and geometric
132 wakefields induced by the beam in the opening of the antenna. Interesting to note the low-
133 frequency part of the wake induced in the antenna itself was effectively used in the experiment
134 for pre-tuning of the beam microbunching system based on RF energy modulation and chicane
135 [9,15].

136 Not all the power on the waveguide exit is outcoupled and radiated. The power can be partially
137 reflected back because of mismatch of the antenna and the waveguide. Besides, the antenna itself
138 has ohmic and radiation losses. These effects are taken into account in the generalized antenna
139 gain:

$$140 \quad G = (1 - |I|^2)\eta D,$$

141 where I is the reflection from the transition to the antenna, η is the radiation efficiency of the
142 antenna, and D is the antenna directivity defined as the power density in particular direction
143 (where it is maximum) related to the power density averaged over total solid angle 4π :

$$144 \quad D = 4\pi P_{ff}^{-1} dP_{ff} / d\Omega.$$

145 The power of coherent Cherenkov radiation in (1) may be interpreted as peak power or averaged
146 power. The averaged power is determined by total energy radiated per a microbunch or train of
147 microbunches. To calculate the CCR power let us assume that only a single (dominant) structure
148 mode interacts effectively with a single microbunch. This is typically provided in effective
149 designs (even if the structure is overmoded [15]).

In case of a single microbunch the energy and power radiated into the structure (at the waveguide exit for positive group velocity $v_{gr} > 0$) can be calculated as follows:

$$W_{lb} = \frac{\omega}{4} \frac{rL}{Q} \frac{(q\Phi)^2}{|1 - \beta_{gr}/\beta|} \left(\frac{1 - \exp(-\alpha L)}{\alpha L} \right)^2, \quad P_{lb} = \frac{\omega}{4} \frac{r}{Q} |v_{gr}| \cdot \left(\frac{q\Phi}{1 - \beta_{gr}/\beta} \frac{1 - \exp(-\alpha L)}{\alpha L} \right)^2, \quad (2)$$

where $\Phi = \frac{1}{q} \int_q \frac{dq}{dz}(z') \exp\left(-i \frac{kz'}{\beta}\right) dz'$ is the bunch formfactor, L is the structure length, q is the bunch charge, $\omega = 2\pi f$ is the resonant frequency defined from the Cherenkov resonant condition: $\omega = h(\omega)/v$, $\beta = v/c$ is the normalized velocity of the beam, $k = \omega/c$, Q is the structure Q-factor, $Q|\beta - \beta_{gr}| \gg 1$, r is the waveguide shunt impedance (per unit length), and $\alpha = \pi f / Q v_{gr}$ is the attenuation.

The formulae (2) have been originally derived using rigorous techniques of inverse Fourier transformation and residues [16] and also for a closed corrugated structure in a ultra-relativistic approximation of loss factor [24]. The same result can be easily obtained from simple circuit theory corrected with a group velocity effect. Indeed, the energy lost by a bunch in a resonant cavity having zero group velocity is $W_{lb} = \omega q^2 R / 2Q$, where $R = r T^2 L_{eff}$ is the cavity shunt impedance including transit time factor. To make transition to a waveguide with a non-zero group velocity the following corrections to be made: a) the frequency to be taken at Cherenkov synchronism with the modal phase velocity; b) the transit time factor to be replaced by the bunching factor; c) only a forward wave is excited leading to another factor of two in the denominator; d) attenuation of the wakefield excited and propagating along the waveguide leads to the factor $(1 - \exp(-\alpha L)) / \alpha L$; and e) the front and trailing edges of the wakefield moving at velocities v_{gr} and v lead to compression (expansion at negative group velocity) effect (for the

170 wake length [17]) similar to the Doppler effect (for the wavelength). That results in the following
 171 effective length L_{eff} of the resonant circuit: $L_{eff} \rightarrow L/(1 - v_{gr}/v)$ at non-zero group velocity.

172 These corrections lead us exactly to the expression of energy given in Eqn. (2). To get the peak
 173 power we have to divide the energy by the difference between filling time and time of flight - so
 174 called drain time $T_d = L(v_{gr}^{-1} - v^{-1})$. Experimental data obtained in different frequency bands by
 175 different research groups [3,9,18,19] confirm formulae (2) very well.

176 Important to emphasize that design of a CCR source with relatively high* group velocity offers a
 177 number of advantages: a) dramatically reduced sensitivity to fabrication errors [15]; b) reduced
 178 losses due to reduced attenuation; c) larger beam aperture allowing higher current; and d)
 179 radiation enhancement for given shunt impedance (see Eqn. (2)). Though shunt impedance
 180 usually reduces with group velocity, nevertheless the total benefit at higher group velocity can be
 181 still significant (see the next section).

182 On the other hand high group velocity broadens the spectral width determined by the inverse
 183 drain time: $\Delta f = 1/T_d$ (which is nearly FWHM). The spectral brightness of a CCR source
 184 operating in single bunch mode can be evaluated as follows:

$$185 \quad \frac{\Delta B_{lb_Peak}}{\Delta f} = \frac{\omega}{4} \frac{r}{Q} \frac{L}{1 - \beta_{gr}/\beta} \cdot \left(q\Phi \frac{1 - \exp(-\alpha L)}{\alpha L} \right)^2 \quad (3)$$

186 Averaged spectral brightness for pulses having repetition rate f_{rate} can be calculated as follows:

* High group velocity” means here approaching to the beam velocity. Some travelling wave tubes are designed to operate in this mode.

$$\frac{\Delta B_{lb_Aver}}{\Delta f} = \frac{\omega}{4} \frac{r}{Q} \frac{L^2}{|v_{gr}|} f_{rate} \left(q\Phi \frac{1 - \exp(-\alpha L)}{\alpha L} \right)^2, \quad (4)$$

Thus as it can be seen from (3) and (4) high group velocity can be still beneficial for the peak brightness unlike averaged spectral brightness. However, since low group velocity is impractical for FIR CCR source, much stronger effect on maximizing of averaged spectral brightness have structure length, repetition rate and duty factor. Note, the repetition rate and duty factor can be made higher by orders of magnitude in laser-free injectors (thermionic, field emission, and secondary electron emission).

Note unlike microwave region the wakefield energy at short wavelengths and zero group velocity (i.e. operating π -n mode) cannot be effectively induced and extracted for a number of reasons: a) below cm wavelengths it is not possible to fabricate and tune close to optimal coupling for such a tiny but electrically long resonant structure; b) structure detuning caused by phase shift effect of diffused power flow propagation [20,21] cannot be controlled leading to desynchronism between the structure and the beam; c) the closer the group velocity to zero the more critical are tolerances to maintain the resonant interaction; and d) forming of long microbunched trains to launch the resonator structure (fraction of nanosecond at THz frequency) is not possible at high coherency within the train.

For a long ($t > L/v_{gr}$) train of microbunches with interval less than the drain time ($T_b < T_d$) the wakefield power induced within the structure can be calculated as steady-state excitation (or, alternatively, as a superposition of the long train in time domain [16]):

$$P_{train} = \frac{\omega}{4} \frac{r}{Q} \frac{1}{|v_{gr}|} \left| I \Phi L \frac{1 - e^{-\alpha L(1+ia_s)}}{\alpha L(1+ia_s)} \right|^2, \quad (5)$$

207 where I is the beam current within the train, $Q|\beta - \beta_{gr}| \gg 1$, $[L(\beta_{gr}^{-1} - \beta^{-1})f/c]^2 \gg 1$,

208 $a_s = 2Q(f/f_b - 1)(1 - \beta_{gr}/\beta)$ is the generalized detuning, and $f_b = 1/T_b$ is the frequency of the
209 microbunched train (or its resonant sub-harmonic).

210 As it can be seen from Eqn. (5) for a long bunch train the low group velocity is preferable.
211 However, unlike microwave region for the short (mm-sub-mm) wavelengths of our interest it is
212 very difficult to provide a low detuning factor between the train period and the Cherenkov
213 resonant frequency (that may limit the jitter to femtoseconds) and simultaneously provide
214 extremely tight tolerances implied by low group velocity.

215 The spectral bandwidth of the radiation of the long train in a steady state mode at $t > L/v_{gr}$ and
216 $T_b \ll T_d$ is determined entirely by the spectrum of the Fourier transform of the bunch sequence.

217 We omit here the case when the group velocity is negative as it is neither advantageous nor
218 practical in a mm-sub-mm wave region. Although a number of microwave structures used in
219 some linacs and travelling wave tubes have been designed to operate at $v_{gr} < 0$ (starting from
220 60's), such a structure (with magnetic inter-cell coupling to get $v_{gr} < 0$) applied hypothetically to
221 mm-sub-mm region would have too small a beam aperture.

222 Note the single bunch CCR mode described by Eqns. (2-4) occurs also for a train of
223 microbunches being much shorter than the filling time or when the interval within the train is
224 longer than then the drain time. In the last case the wakefields induced by the bunches do not do
225 not overlap. Additional advantage of this mode of radiation is that the interval between
226 microbunches can be made non-equidistant without any effect on the performance at $T_b > T_d$ or
227 moderate effect at $T_b < T_d$ (as long as the total bunching formfactor for the train is still substantial

[6]). In the intermediate case when the train length is approaching to the filling time L/v_{gr} a simple superposition can be applied for the analytical calculation of the wakefields with taking into account group delays [16].

As it can be seen from the simple analysis above the single bunch mode operation of CCR source designed with high group velocity appears to be much more practical. This is valid for both laser driven ps-sub-ps photoinjectors (including those operating in beatwave or multiplexed modes) and laser-free systems (based on energy chirping followed by magnetic compression).

The reciprocity principle also implies that this conclusion to be applicable to novel short-wavelength accelerating concepts based on slow-wave accelerating structures (e.g., micro- and nano-scale) and media (including collinear wakefield accelerators).

3. Comparison of circular and planar configurations for single bunch mode of CCR source operation

Let us assume that slow-wave structures to be compared have the same resonant frequency and the same fixed length short enough to neglect differences in attenuation. Assume also that the beam charge density and formfactor (bunching factor) are the same. And finally assume that filling time is always less than the bunch interval (i.e., single bunch CCR mode). Then the beam shape and structure-dependent part of the power is the following (see Eqn. (2)):

$$P_{peak}^{factor} = \frac{r}{Q} \frac{\beta_{gr} S_{beam}^2}{(1 - \beta_{gr}/\beta)^2} \quad \text{for peak power and} \quad P_{averaged}^{factor} = \frac{r}{Q} \frac{S_{beam}^2}{1 - \beta_{gr}/\beta} \quad \text{for averaged power.}$$

Therefore to compare the brightness for different configurations under the conditions above it is sufficient to compare the following brightness factors:

$$B_{peak}^{factor} = \frac{r}{Q} \frac{\beta_{gr} A_{beam}^2}{(1 - \beta_{gr}/\beta)^2} \frac{G}{A_A} \quad \text{for peak brightness, and } B_{averaged}^{factor} = \frac{r}{Q} \frac{A_{beam}^2}{1 - \beta_{gr}/\beta} \frac{G}{A_A} \quad \text{for averaged brightness.}$$

We can roughly assume that similarly to sheet beam klystron the shunt impedance r/Q is roughly inversely proportional to the beam area A_{beam} that occupies the structure aperture (see also Fig. 4). Then in terms of total flux and manufacturability a planar structure is preferable (e.g., for applications where high throughput and/or area of illumination are required such as simultaneous imaging of large volumes or areas - semiconductor chips inspection, or environment monitoring).

In the hypothetical ‘‘FEL approximation’’ when $A_A \Rightarrow A_{beam}$ and for the same group velocity, gain and antenna aperture, there is no obvious advantage of the planar configuration over the circular one in terms of brightness. Note, for given beam current density the FEL brightness is proportional to product of beam beta functions $\beta_x \beta_y$, whereas for given beam brightness it is proportional to product of beam transverse emittances $\epsilon_x \epsilon_y$. So in the last case, which is more relevant to a FEL having relatively long interaction distances (in beta function scale), using of high aspect ratio flat beams is not useful in terms of radiation brightness.

However, the situation in a short, structure-dominated radiating system such as CCR source is different. As an example we compare here two realistic configurations of 1 cm wide planar and conventional circular periodic structures with rectangular wall corrugations ended with antenna. Both are designed for the $f=500$ GHz frequency, have the same 0.8 mm minimal dimension of the bore aperture, phase velocity $\beta_{ph}=0.98-0.99$, iris thickness 50.8 μm and 0.13-0.15 mm period.

In Fig. 1 we show part of these structures with only a few periods shown and attached to high gain antenna. Dispersion curves as well as shunt and wakefield impedances of a “closed variant” of such structures (i.e. with side walls for planar structure) can be calculated analytically using classical matched field approach [22,23,24]. Here we consider an oversized side-open planar structure. A similar rectangular structure, but not oversized, has been characterized analytically [25]. Useful feature of the side-open oversized structure is essentially single mode operation [15] in spite of large group velocity, electrically large width, and gap ($0.8c$, 17λ and 1.33λ correspondingly).

Note a monopole TM-like mode employed in CCR source is unique for an antenna technique. Antennas usually use dipole modes including cell phones, radars, photoconductive THz sources, and waveguide FEMs. This difference results in different antenna geometries. To our knowledge the analytical theory and design for antennas launched with monopole TM modes are not developed. Therefore numerical full-wave simulations in time or frequency domains are performed to determine the antenna directivity and gain [4,5,15]. On the other hand conversion from monopole TM mode to the dipole TE mode within the antenna (or its feeder) seems to be difficult to implement efficiently at THz frequencies.

We modeled here simple antenna shapes shown in Fig. 1 using the monopole mode launched in the port that corresponds to the same mode induced by the wakefield [15] (simulated numerically with GdfidL code [28]). We found that for the circular configuration the gain is limited by the field distribution over the donut-shaped pattern (see below) which cannot be as sharp as the two beams produced by the planar configuration.

Fig. 1.

As it can be seen from Fig. 2 considerable gains as high as 21 dB for circular and 26 dB for planar configurations can be attained. Such high gain values can be useful for applications where high flux density is required on substantial areas at limited distances such as scaled radar modeling [26], high throughput screening, fast chemistry, material sciences and high-field physics [27].

Fig. 2

Since the antenna opening angle is limited by a narrow range of angles where reflections are low, we plotted in Fig. 3 gain and ratio of the gain to the antenna aperture area vs. antenna length for fixed angle antenna openings. One can see from Fig. 3 that optimum length for maximum gain (or radiator flux density) is much longer than that for maximum G/A_A ratio (or radiator brightness).

Fig. 3

In Table 1 we have compared the planar and circular radiators at moderate charge density 6.25 pC/mm² within the radiator apertures. The radiators are partially optimized for maximum flux

density and maximum brightness using the plots given in Fig. 3. Note that the shunt impedance is calculated for 2.6 MeV beam using an eigenmode model of a single period and averaged over beam aperture (which is uniform for circular configuration and not uniform across the beam 10mmx0.8mm area for the planar configuration). The radiators are characterized for two different antenna variants: maximum gain (and flux density) and maximum gain per antenna aperture (and hence brightness). For comparison in Table 1 we also give the parameters of USCB FIR FEL operating at approximately the same frequency and beam energy.

Table 1

In-depth optimization of CCR radiator system in terms of brightness is a more complicated task as it includes not only optimal widths of both beam and the structure (for planar configuration) but also 3D beam dynamics starting from the very cathode. In Fig. 4 we plotted power as a function of beam width for fixed charge and charge density for 1 cm wide planar structure. The wakefield power at ~500 GHz is calculated in Fig. 4 numerically with the GdfidL code [28] in a time domain for 130 μm rms bunch length. One can see that due to the coherency (see Eqn. (2)) power at fixed charge density grows almost linearly with the beam width.

Fig. 4.

Thus the planar configuration can give more than 2 orders higher brightness at the same current density in spite of about twice less product of shunt impedance and interaction cross-section. The main contributors in the brightness enhancement are almost one order higher product of shunt impedance and interaction cross-section squared as well as higher ratio of antenna gain per antenna area (see Fig. 3). Besides, the group velocity factor $1/(1 - \beta_{gr}/\beta)$ is twice higher for the planar design in this example.

In practice it is difficult to realize a uniform beam density of the beam across such a high aspect ratio planar structure. A more realistic distribution of a longitudinally-microbunched beam is quasi-flat, but still with substantial aspect ratio (exceeding ten, [7]). That can make the dependence of power vs. width given in Fig. 4 non-linear. Nevertheless one can see from the example above that CCR source brightness may approach diffraction limit at least at sub-THz frequencies especially in planar variant.

Acknowledgements

This paper would be impossible without the question raised by Dr. Alexander Zholents about brightness of this type of sources and his stimulating interest, remarks, and discussions. The author is grateful to Karl Bane for discussion of the analytical calculation of the CCR effects and Warner Bruns for the opportunity to use the GdfidL code. The author appreciates earlier discussions with Prof. Claudio Pellegrini and more recently with Dr. Alexander Murokh as well as their supportive interest to the compact high power CCR THz sources and its characterization. This work is supported by the US Department of Energy under the contract DE- SC-FOA-0000760.

-
- [1] S. Chattopadhyay, S. T. Corneliussen, G. P. Williams, “Emerging Concepts, Technologies and Opportunities for Mezzo-Scale Terahertz and Infrared Facilities”, THPKF084, EPAC’04, Lucerne, Switzerland p. 2454 (2004).
- [2] H. Badakov , M. Berry , I. Blumenfeld , A. Cook , F.-J. Decker, M. J. Hogan, R. Ischebeck, R. Iverson, A. Kanareykin, N. Kirby, P. Muggli, J.B. Rosenzweig, R. Siemann, M.C. Thompson, R. Tikhoplov, G. Travish, D. WalzE-169: Wakefield Acceleration in Dielectric Structures. URL: <http://www.slac.stanford.edu/grp/rd/epac/Proposal/E169.pdf>
- [3] A.M. Cook, R. Tikhoplov, S.Y. Tochitsky, G. Travish, O.B. Williams, J. B. Rosenzweig, in Physical Review Letters PRL 103 (2009) 095003
- [4] A.V. Smirnov. A High Performance, FIR Radiator Based on a Laser Driven E-Gun. Photonics Research Developments, Editors: Viktor P. Nilsson, Nova Science Publishers (2008) 247
- [5] A.V. Smirnov, in Proceedings of Russian Particle Accelerator Conference (RUPAC) 2012, Saint-Petersburg (2012) 430
- [6] A.V. Smirnov, P. Musumeci. Nuclear Instruments and Methods in Physics Research A 721 (2013) 1
- [7] A. V. Smirnov. Proceedings of PAC2013. Pasadena, CA, USA (2013) 1421
- [8] Y. Kim et al. Proceedings of PAC2013. Pasadena, CA, USA (2013) 282
- [9] R. Agustsson, S. Boucher, T. Grandsaert, J. Hartzell, A. Smirnov et al. Proceedings of IPAC2013, Shanghai, China (2013) 2295
- [10] S. Hayashi, K. Nawata, T. Taira, J. Shikata, K. Kawase, H. Minamide. Scientific Reports 4, Article number: 5045 (2014) 1

-
- [11] R. Hettel, M. Borland. In Proceedings of PAC2013, Pasadena, CA USA (2013) 19
- [12] S. V. Miginsky, N.A. Vinokurov et al., in Proc. of Asian Particle Accelerator Conference (APAC) 2007, Indore, India (2007) 616
- [13] M. Einat, E. Jerby, A. Shahadi. Nuclear Instruments and Methods in Phys. Res. A 375 (1996) 21
- [14] R. S. Elliott. Antenna Theory and Design. IEEE Press, A John Wiley & Sons, Inc., Hoboken. New Jersey, 2003.
- [15] A. V. Smirnov et al. Proceedings of PAC2013. Pasadena, CA, USA (2013) 925
- [16] A.V. Smirnov, Nucl. Instrum. and Meth. NIM A, 480 (2-3) (2002) 387
- [17] E.S. Masunov, A. V. Smirnov, in Nucl. Instrum. and Meth. In Phys. Res. Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, V. 508, Issue 3, 11 (2003) 245
- [18] W.Gai, M.E. Conde, R. Konecny, J.G. Power, P. Shoessow, X. Sun, P. Zou, in Proc. of the Advanced Accelerator Concepts, AAC2000, AIP Conf. Proc. 569 (2000) 287
- [19] D. Yu, D. Newsham, A. Smirnov, Proc. 10th Advanced Accelerator Workshop, AIP 547 (2002) 484-505.
- [20] T. P. Wangler. RF Linear Accelerators. Wiley publishing. 2008
- [21] A.V. Smirnov, in Nucl. Instrum. and Meth. In Phys. Res. NIMA 489 N 1-3 (2002) 75
- [22] L. Lewin. Theory of Waveguides. Butterworths and Co. Publishers. 1975
- [23] N.P. Sobenin, B.V. Zverev, I.S. Shedrin. Handbook on iris loaded waveguides. Atomizdat 1977 (in Russian).
- [24] K. L. F. Bane and G. Stupakov. Physical Review Special Topics - Accelerators and Beams, V. 6, 024401 (2003)

-
- [25] M. Filtz. IEEE Proceedings of 1996 Particle Accelerator Conference. Sweden (1996) 2373.
- [26] T. M. Goyette, C. Dickinson, J. Waidman, W. E. Nixon. In Algorithms for Synthetic Aperture Radar Imagery VII, Edmund G. Zelnio, Editor, Proceedings of SPIE Vol. 4053 (2000) 615 <http://proceedings.spiedigitallibrary.org/>
- [27] M. C. Hoffmann, J. A. Fülöp. Journal of Physics D: Applied Physics 44, 8 (2011) 83001
- [28] W. Bruns, “The GdfidL Electromagnetic Field simulator,” <http://www.gdfidl.de/>

Figure 1

a)

b)

c)

Figure 2

Figure 3

Figure 4

Table 1.

Configuration	β_{gr}	r/Q , k Ω /m	P_{Peak} , kW	B_{limit} , MW/sr·cm ²	B_{Peak}/B_{limit}	dB_{Peak}/df μ J/sr·cm ²	B_{Aver} , W/sr·cm ²
Circular (S=max)	0.61	34.4	0.1	0.028	4.4%	0.11	0.025
Circular (B=max)					26%	0.66	0.15
Planar(S=max)	0.82	0.8	8.5	2.4	31%	22	4.7
Planar (B=max)					54%	40	8.4
UCSB FIR FEL	1	N/A	3	0.83	100%	250	67