The effect of the electron-beam parameter spread on microwave generation in a three-cavity axial vircator

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Abstract

The behavior of the generation efficiency and radiation spectrum of a three-cavity axial vircator versus the radius of the injected electron beam, its impedance and energy homogeneity is studied. This paper establishes that for each geometry of a three-cavity resonator, there exist the optimal (maximizing the generation efficiency) values of these parameters and determines the range within which they may vary without losing the efficiency of generation.

1 Introduction

Power sources of electromagnetic radiation with virtual cathodes (vircators) have become a subject of intense study [1, 2] lately. The capability to produce gigawatt power level microwave pulses makes the vircator-based sources promising devices for such applications as plasma physics and techniques, high energy density physics, accelerator physics and techniques, and radar and communication technologies. High-current electron accelerators demonstrate unique capabilities as seed sources for powering such microwave oscillators. The power of high-current electron beams achievable at present is $10 \div 100$ GW, while the corresponding radiation power of the vircator is as high as tens of gigawatts [2, 3].

The main advantages of vircator-based oscillators are high output power of microwaves, the possibility to generate without external guiding fields, and compactness. Their chief disadvantages lie in low efficiency, instability of the generation frequency during the pulse length and its poor reproducibility in experimental series. The typical generation efficiency achievable in experiments is only $1 \div 2\%$.

Resonant electrodynamic systems placed into the region of VC formation offer a means to increase the generation efficiency and stabilize the frequency of microwave radiation [4]. This approach is embodied in a three-cavity axial vircator (Fig. 1). Under the electron beam parameters (energy of 630-700 keV and current of about 21 kA) reported in [5], the three-cavity axial vircator realizes a steady single-frequency ($f = 4.1$ GHz) generation regime with output power as high as ~ 1 GW and generation efficiency of 6.6%.

The authors of [6] performed a PIC simulation of a similar three-cavity vircator with the generation frequency from 3 to 4 GHz in several geometries. It was demonstrated that the efficiency of such oscillators can be rather high (~ 5 % and higher) even at quite small beam energies (under 500 keV). But the simulation described in [6] was quite idealized: the parameters of the electron beam injected into the resonator were considered to be set rigorously, and the beam was assumed to be homogeneous and monochromatic. However, in actual experiments with three-cavity resonators, the electron beam is generated in a high-current diode with an explosive-emission cathode. In this case, the absolute values of the beam energy and current vary significantly during the voltage pulse, as well as their ratio, i.e., the beam impedance (due to the expansion of the cathode plasma); different dynamical effects cause the beam radius to vary (it does not always equal to the radius of the emitting surface of the cathode). Moreover a certain energy spread always exists in the initial beam (it is not monochromatic). Thus it is practical to know what effect the imperfection of the beam and/or the slight variation of its parameters may have on the efficiency and spectrum of generation. This paper studies how the generation efficiency and the radiation spectrum depend on the electron-beam radius, impedance, and energy spread in each of the three designs of a three-cavity vircator suggested in [6].

2 Simulation results

To simulate the electron beam dynamics in an axial vircator, we used the particle-in-cell method, realized in a free 2.5D PIC code XOOPIC [7]. The oscillator is shown schematically in Fig. 1, where 1 is the emitting cathode, 2 is the anode mesh, 3 are the resonator sections of the vircator, and 4 is the cylindrical output drift tube. The electron beam of specified configuration is injected into the first resonator cavity directly, and so all the processess occurring in the cathode-anode gap are neglected. For all vircator designs considered here, the electron beam energy was assumed to be constant and equal to E=450 keV [6] (generation in such vircators at various beam energies was studied in [8, 9]).

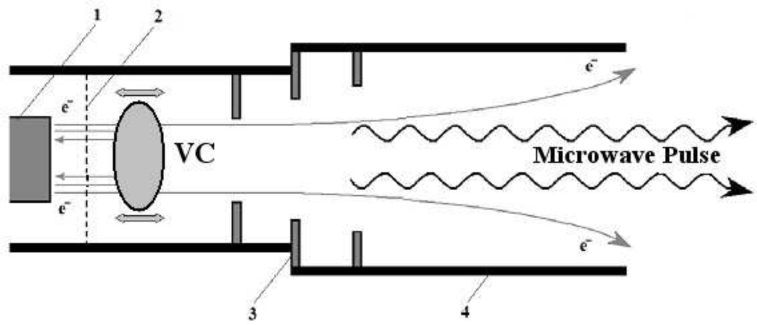

Figure 1: Scheme of a three-cavity vircator.

In the selected scheme of a three-cavity vircator, the virtual cathode oscillates in the first resonant cavity (where the beam-microwave energy conversion occurs), and we shall distinguish between the resonators by its dimensions L_1 and r_1 (length and radius). The parameters of the considered resonators [6] are listed in Table 1.

Resonator	L_1, mm	r_1, mm	Radiation frequency f, GHz
#1	60	50	3.2
#2	54	45	3.6
#3	48	45	3.7

Table 1: Resonator designs

We first study the generation characteristics as a function of the electron-beam radius at constant beam current of 15 kA, the same for all three designs. The simulation results are given in Figs. 2-4.

As is seen, there is an optimal radius of the electron beam for each design of the three-cavity vircator at which the maximum generation efficiency is achieved. Let us note that all three dependencies are similar, which is obvious from Fig. 3, and for this reason we can suppose that η will reveal a similar dependence on r_b in other possible designs of three-cavity resonators, too. It should also be mentioned that as the beam radius is increased (compared to its optimal value), the generation efficiency reduces slower than in the case when the beam radius diminishes. Thus a 10% increase in the beam radius leads to a 30% decrease in the generation efficiency, while a 10% decrease in the beam radius leads to a 50-80% drop in the radiation efficiency, approaching the radiation efficiency of a conventional axial vircator (without resonant cavities). This can be explained, in particular, by the fact that with decreasing radius of the beam (at constant current and energy) the major radiation frequency in the vircator increases sharply because the beam plasma frequency grows (the generation starts to occur at the second harmonic), which is accompanied by spectral broadening (Fig. 4). The drop in the efficiency with growing beam radius is related to the decrease in the beam-current supercriticality, and finally to the vanish of the conditions for VC formation.

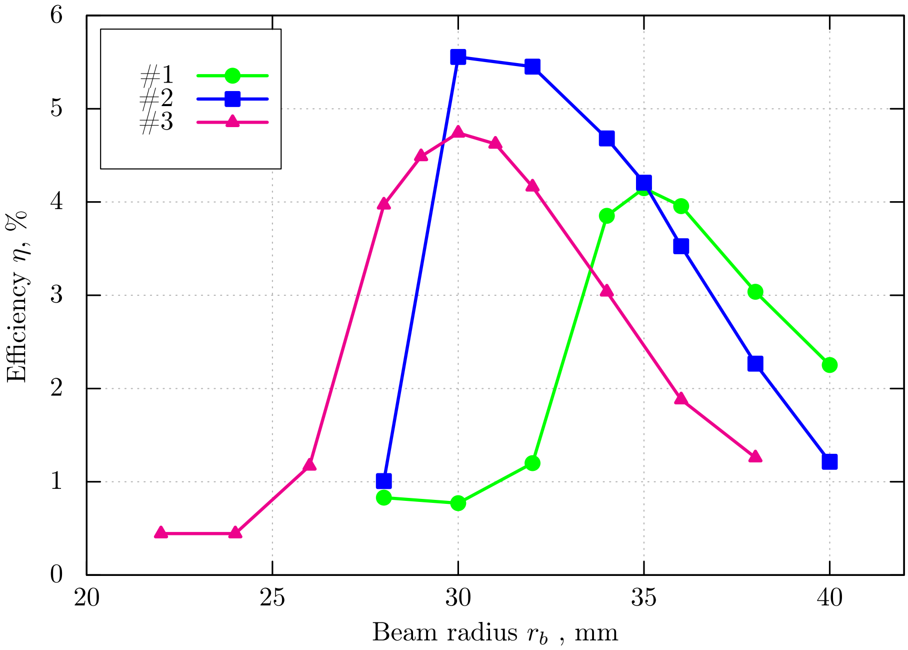

Figure 2: Generation efficiency as a function of the electron beam radius for three vircator designs. The beam energy and current are 450 keV and 15 kA, respectively.

The optimal values of the electron beam radius: $r_{b1} = 35$ mm, $r_{b2} = 32$ mm, and $r_{b3} = 30$ mm, obtained from the simulation results were used for further computations. The efficiency dependence on the beam impedance in three-cavity vircators was studied by simulating the system behavior at different currents of the injected beam (the energy was set to be 450 keV and did not vary). The maximum efficiency $\eta \sim 5$ % corresponds to the impedance $Z \sim 30 \div 35$ Ohm for all studied vircator designs and drops to 1% whenever the impedance changes by 10 Ohm (Fig. 5). This circumstance is crucial for practical realization of the three-cavity vircator, because in actual high-current diodes with explosive-emission cathodes, the impedance is constantly decreasing through cathode plasma expansion.

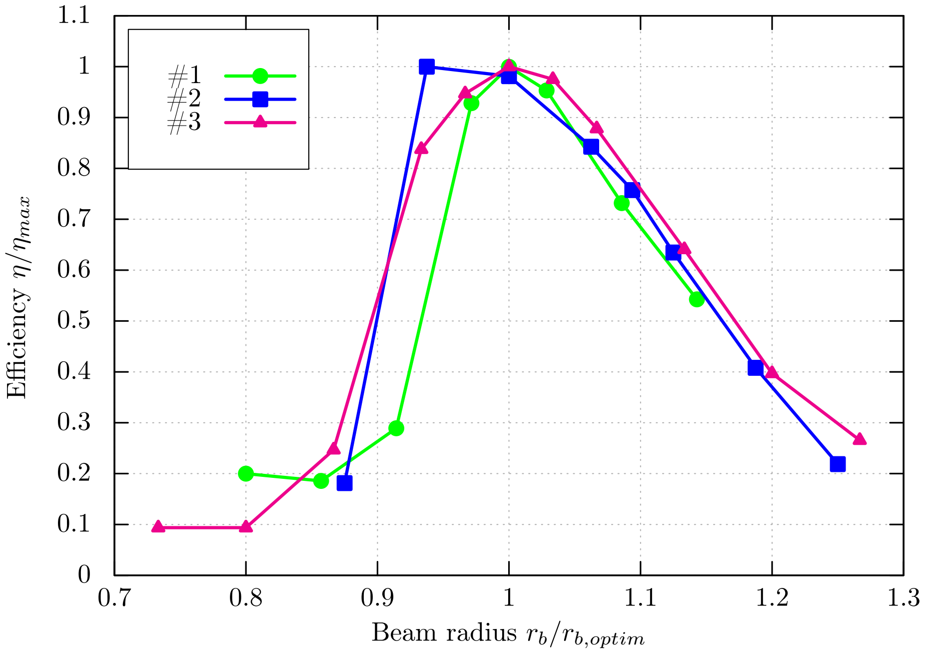

Figure 3: Generation efficiency as a function of electron-beam radius: r_b and η are normalized to their optimal values; the beam energy and current are 450 keV and 15 kA, respectively.

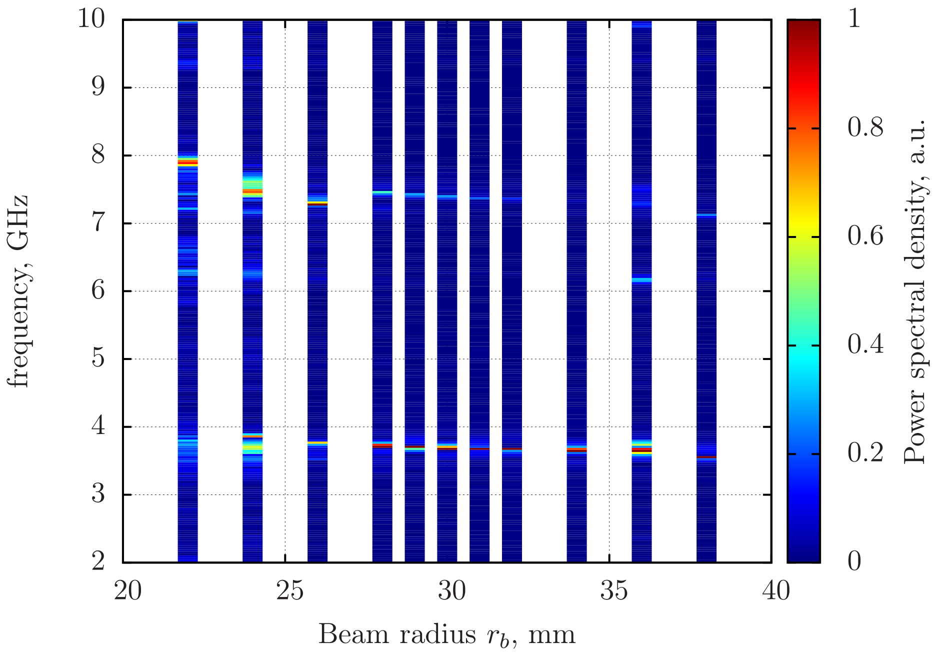

Figure 4: Radiation spectra for vircator #3 at different values of the beam radius.

Plasma frequency increases with diminishing beam impedance, as well as with decreasing beam radius, and the moment comes when the main generation frequency shifts to the range of higher harmonics (Fig. 6). In fact, with decreasing beam impedance (i.e., with increasing beam current) the radiation efficiency grows monotonously from the moment when the VC formation becomes possible until the generation is single-mode and occurs at the main working frequency of the resonator. The generation efficiency drops sharply as the generation shifts to the range of high frequencies.

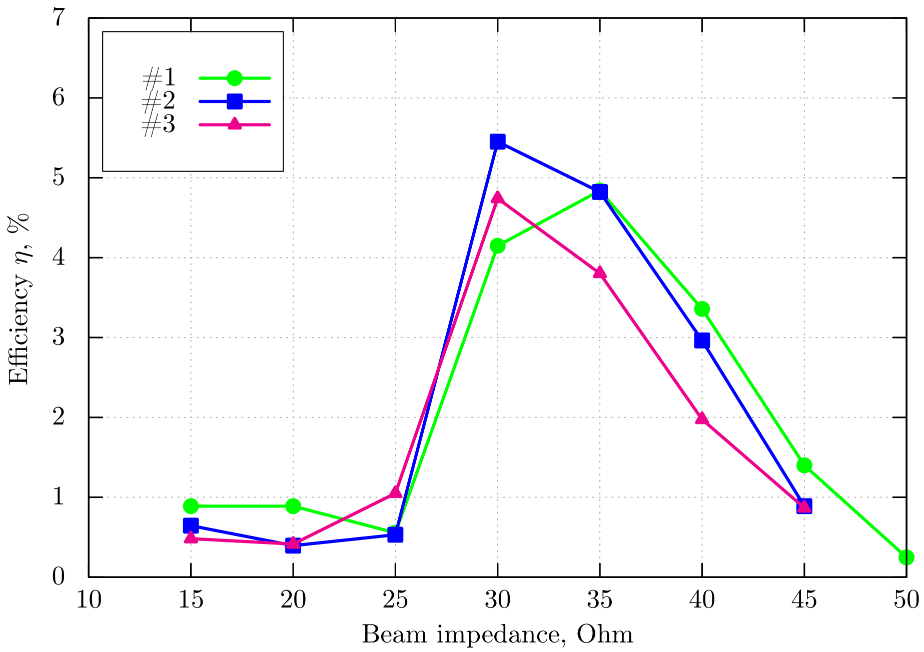

Figure 5: Generation efficiency as a function of electron beam impedance for three vircator designs; the energy of the beam electrons equals 450 keV.

Thermal spread in the energies of beam electrons can also noticeably diminish the generation efficiency η (see also [10, 11]). By way of example, Fig. 7 shows η vs dE_0/E_0, where $E_0 = 450$ keV and $dE_0 (= 3/2kT)$ is the average kinetic energy of thermal motion of beam electrons. When the spread is as small as 5% (or even 1.5% for vircator #1), the efficiency drops to ~ 1 %, which is typical of axial vircators without resonant cavities. Figures 8 and 9 show that in this case, the radiation spectra broaden, and the amplitudes of higher harmonics in them are increased.

3 Conclusion

This paper presents a numerical simulation of microwave generation in a three-cavity axial vircator with the electron beam energy of 450 keV and the frequency of $3 \div 4$ GHz. This paper also analyzes the dependence of the generation efficiency and spectrum on the radius of the injected beam, its impedance and the presence of the energy spread. The relations obtained here enable us to conclude that microwave generation in the considered vircator has a resonant character. It has been found that for each geometry of the three-cavity resonator, there is an optimal radius of the electron beam that provides maximum generation efficiency (as high as 5% and even more) that can drop dramatically (to 1%) when the beam radius differs by 10% from the optimal value. It is determined that the optimal values of the electron beam impedance for a three-cavity vircator lie in the range from 30 to 35 Ohm. It has also been established that as the electron beam energy spread is enhanced, the

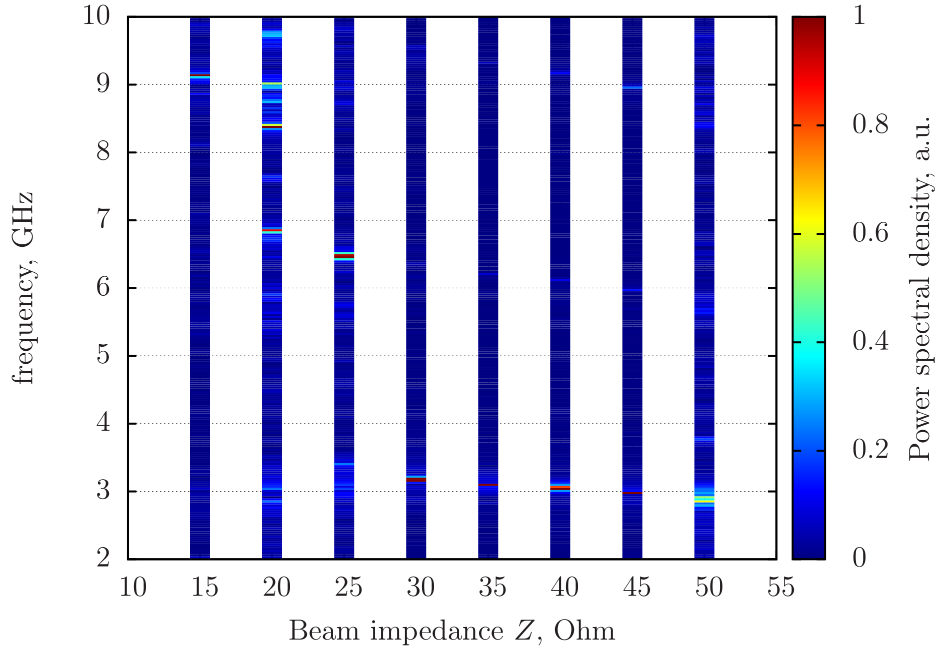

Figure 6: Radiation spectra for vircator #1 at different values of the beam impedance (the energy of the beam electrons equals 450 keV).

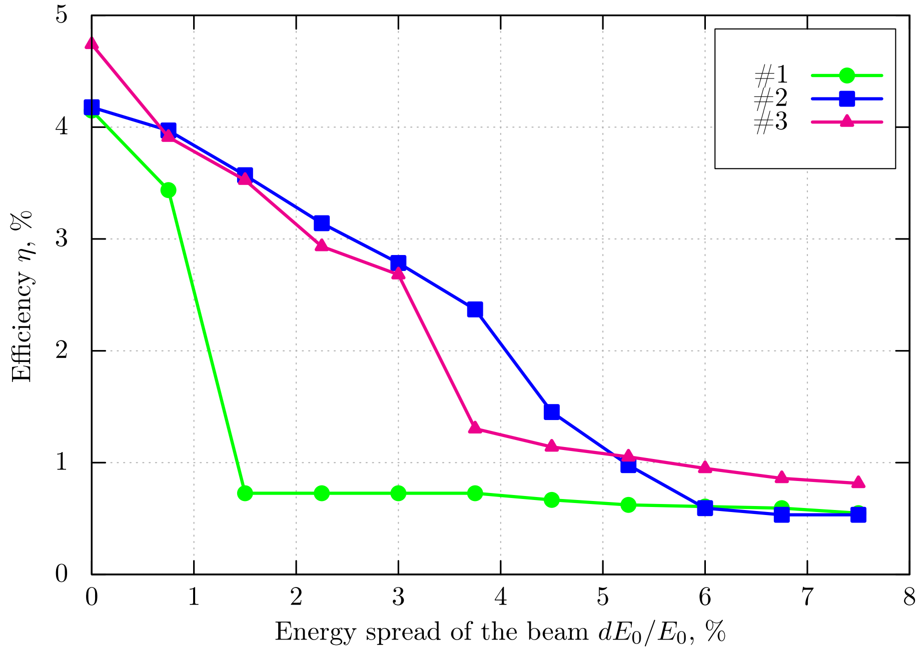

Figure 7: Generation efficiency as a function of thermal spread in energies of beam electrons for three vircator designs. The beam energy and current are 450 keV and 15 kA, respectively.

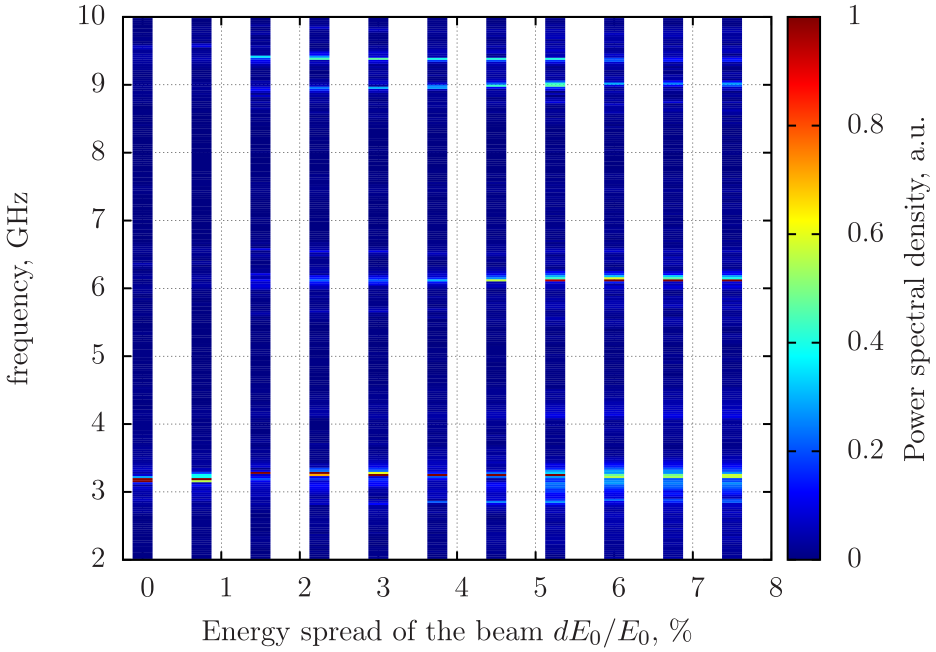

Figure 8: Radiation spectra for vircator #1 as a function of beam energy spread.

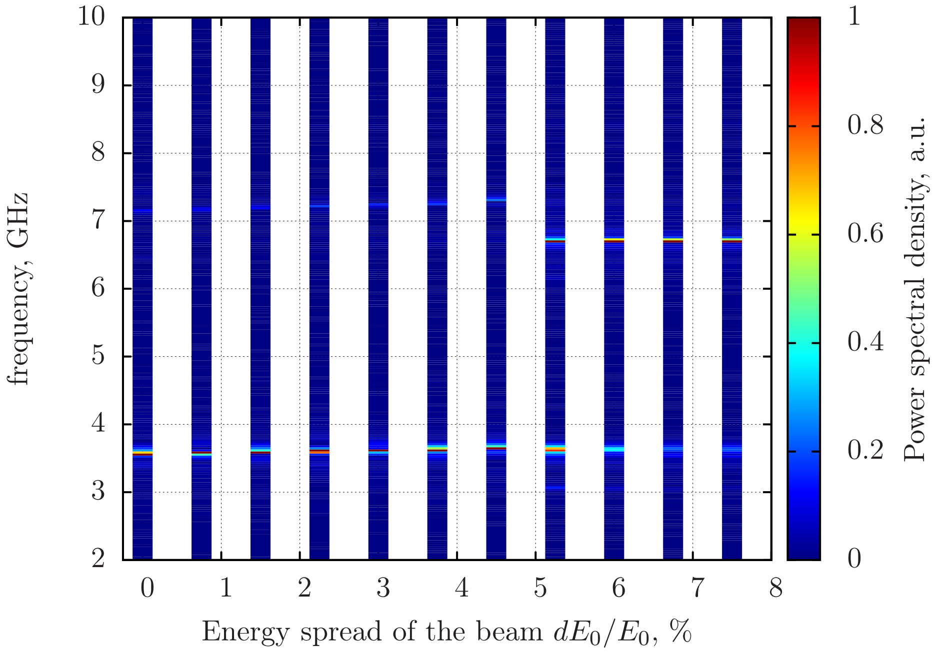

Figure 9: Radiation spectra for vircator #2 as a function of beam energy spread.

generation efficiency falls off fairly rapidly and drops to a fraction of the previous value even when the spread is as small as 5%.

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