CERENKOV RADIATOR DRIVEN BY A SUPERCONDUCTING RF ELECTRON GUN*

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Abstract

The Naval Postgraduate School (NPS), Niowave, Inc., and Boeing have recently demonstrated operation of the first superconducting RF electron gun based on a quarter wave resonator structure. In preliminary tests, this gun has produced 10 ps long bunches with charge in excess of 78 pC, and with beam energy up to 396 keV. Initial testing occurred at Niowave's Lansing, MI facility, but the gun and diagnostic beam line are planned for installation in California in the near future. The design of the diagnostic beam line is conducive to the addition of a Cerenkov radiator without interfering with other beam line operations. Design and simulations of a Cerenkov radiator, consisting of a dielectric lined waveguide will be presented. The dispersion relation for the structure is determined and the beam interaction is studied using numerical simulations. The characteristics of the microwave radiation produced in both the short and long bunch regimes will be presented.

INTRODUCTION

Superconducting radiofrequency (SRF) electron guns are under development worldwide due to their potential for producing high quality, high average power electron beams. NPS, Niowave, and Boeing recently demonstrated operation of a new type of SRF gun based on a 500 MHz quarter wave resonator developed in support of the U.S. Navy's free-electron laser (FEL) program. Compared to conventional RF electron guns, quarter wave guns use highly re-entrant structures and relatively low frequency RF fields. Although initial testing was limited by the available RF power and radiation production due to field emission in the cavity, 78 pC bunches at 396 keV were extracted with a normalized RMS emittance of 4.5 µm [1]. No quenching events were observed. Further testing in a shielded facility is planned, with the objective of optimizing the emittance, and attempting operation closer to the gun's design parameters of 1.2 MeV and 1nC.

The characteristics of SRF guns that make them of interest for FELs also make them attractive for other light sources, but their use imposes important constraints, most notably in the electron beam's energy uniformity and bunch length. This paper considers the production of x-band radiation by a sequence of short electron bunches that are synchronous with the slow wave in a Cerenkov radiator, where each of the bunches can contribute coherently to the radiation field. Such bunch trains could be easily produced by photoemission in the NPS gun using a pulsed laser, beam splitters, and optical delay lines [2]. Particle-in-cell (PIC) simulations using the 2-D OOPIC code [3] are used to examine the characteristics of the microwave radiation.

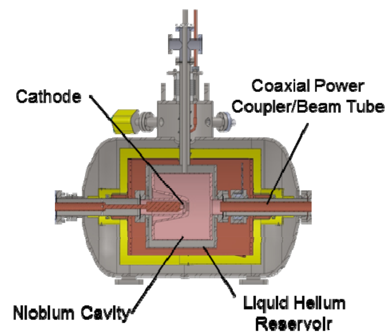

Figure 1: NPS/Niowave 500 MHz SRF electron gun.

THEORY AND SIMULATIONS

Cerenkov sources rely on the interaction of an electron beam with a slow wave structure, and are attractive sources of microwave and millimeter wave radiation. One approach to building such a source is to use a dielectric-lined cylindrical waveguide, as shown in Fig. 2. For these simulations, a cold beam of uniform radial profile fills the inside of the dielectric annulus, and is confined by an axial magnetic field so that the beam motion is purely longitudinal.

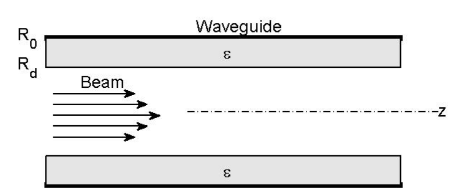

Figure 2: Simple Cerenkov radiator structure.

The dispersion relation for this structure is given by

$$\frac{\kappa_\varepsilon}{\varepsilon\kappa}\frac{J_1(\kappa R_d)}{J_0(\kappa R_d)}+ \frac{J_0(\kappa_\varepsilon R_0)Y_1(\kappa_\varepsilon R_d)-J_1(\kappa_\varepsilon R_d)Y_0(\kappa_\varepsilon R_0)}{J_0(\kappa_\varepsilon R_d)Y_0(\kappa_\varepsilon R_0)-J_0(\kappa_\varepsilon R_0)Y_0(\kappa_\varepsilon R_d)}=0 \quad (1)$$

where $\kappa^2 = \omega^2/c^2 - k_z^2$ and $\kappa_\varepsilon^2 = \varepsilon\,\omega^2/c^2 - k_z^2$ are

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the transverse wave numbers in the beam and dielectric regions respectively.

Here we assume a 2 meter long radiator with $R_0 = 2$ cm, $R_d = 1.5$ cm, and $\varepsilon = 4$. The dispersion curves for the three lowest order TM_{0n} modes are shown in Fig. 3 along with the beam mode for a 340 keV electron beam intersecting the TM_{01} and TM_{02} modes at 8.1 GHz and 26.3 GHz respectively.

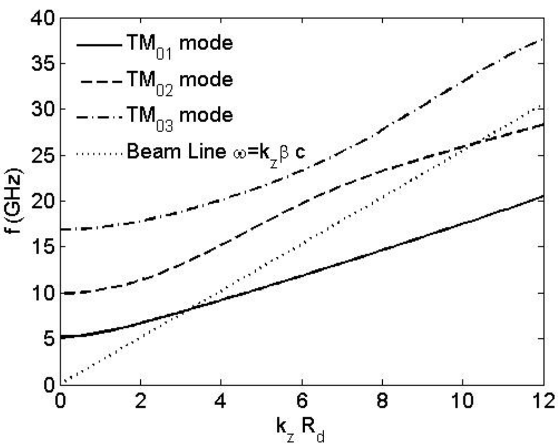

Figure 3: Dispersion curves for the Cerenkov radiator.

Cerenkov slow wave devices can operate in a number of regimes depending on the length of the electron bunch. With longer electron beams, they can be used as an amplifier where gain is achieved through coupling of the slow structure wave and the slow space chare wave on the beam [4]. Another regime of interest is transient radiation evolving from coherent spontaneous emission (CSE) arising from coherent density or velocity fluctuations on the beam [5]. In this case, the coherent fluctuations can be amplified as the RF wave packet slips backwards in the beam frame, allowing it to continually sample "fresh" beam, forming a short intense pulse of microwave radiation that can often exceed the maximum steady-state power associated with the amplifier regime. Fig. 4 shows an example of this process in a long pulse 340 keV 50 A beam seeded with a 20 ps FWHM, 50 A Gaussian perturbation.

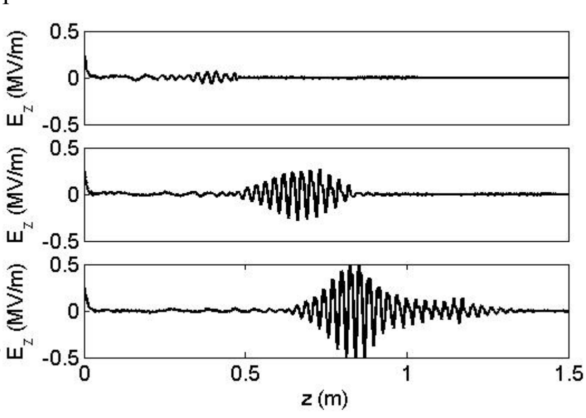

Figure 4: Amplified CSE for long pulse electron beam.

However, this process requires longer beams than can be generated in the NPS 500 MHz gun.

Coherent radiation will also result from short bunches or a pre-bunched beam that satisfies the synchronous condition defined by the waveguide mode and beam energy. For a bunch duration $\tau_b << 2\pi/\omega$, the radiation will scale as $N_b N_e^2$ where N_e is the number of electrons in each bunch and N_b is the number of bunches. For these simulations, monoenergetic 340 keV, 20 ps (FWHM) Gaussian bunches were used, and the scaling of the radiation was examined for peak bunch currents ranging from 5 A to 50 A. Fig. 5 shows a typical spectrum of the axial electric field for a 5 A peak current. The beam resonances at 8.1 GHz and 26.3 GHz are clearly seen, as well as oscillations near the first three TM_{0n} cut off frequencies of 5.2 GHz, 9.9 GHz, and 17 GHz.

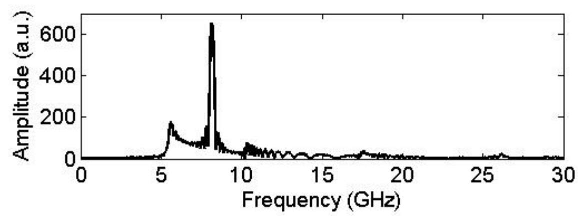

Figure 5: Single 5A bunch spectrum.

Fig. 6 shows that for low currents the radiation intensity scales approximately as the square of the beam current, as expected, but deviates from that scaling for larger currents. This is due to longitudinal defocusing of the bunch, as shown in Fig. 7. The spectral bandwidth increases linearly with peak current due to the space charge driven longitudinal momentum spread, which enables emission over a range of frequencies satisfying the synchronous condition.

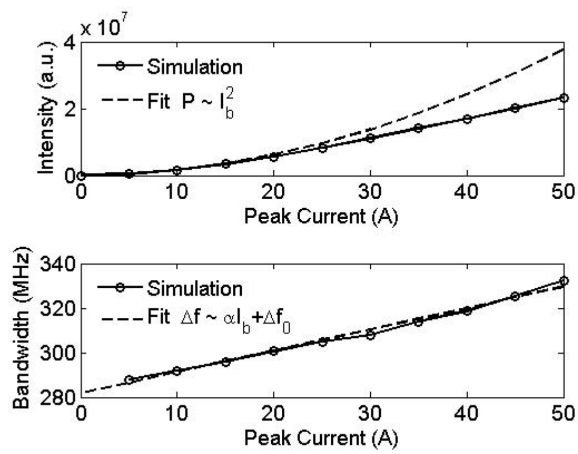

Figure 6: Scaling of radiation intensity and spectral bandwidth with peak current.

When a sequence of these monoenergetic, 340 keV bunches spaced at the 8.1 GHz wave period of 123 ps are injected into the Cerenkov radiator, the simulations show that the radiation intensity scales linearly with the number of bunches as expected (Fig. 8).

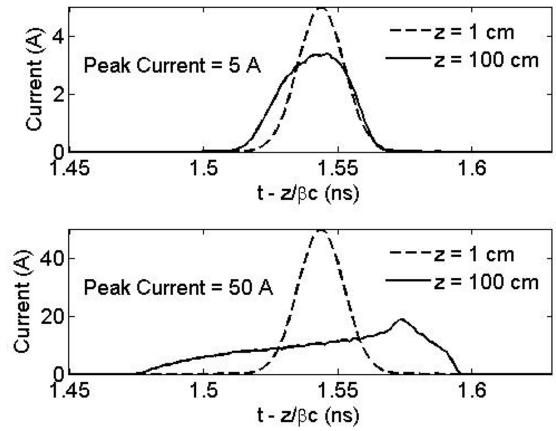

Figure 7: Longitudinal defocusing for 5 A and 50 A bunches.

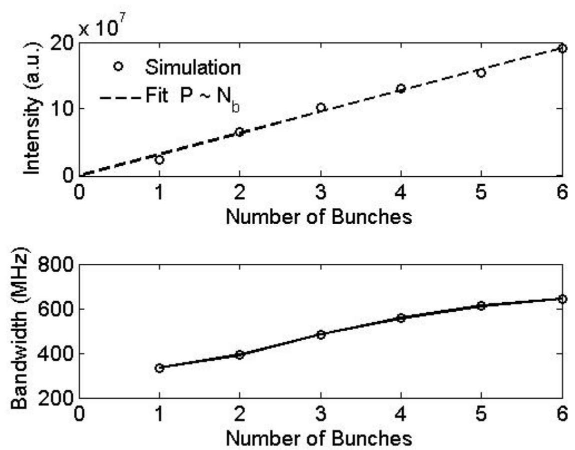

Figure 8: Scaling of radiation intensity and bandwidth with number of bunches for peak currents of 50 A.

Use of the SRF gun as a beam source imposes several constraints on the beam. First, the bunch train must be less than 1 ns, as beam is only extracted during half of the 500 MHz RF cycle. Second, bunches generated at different times in this RF cycle will have different mean energies and energy tilts. These effects are governed by the timing of the bunches with respect to the accelerating waveform. To investigate the effect of inter-bunch energy variation, we simulated a train of three 20 ps FWHM Gaussian bunches with 50 A peak currents. These bunches were assigned different energies corresponding to placement of the train on crest, after crest, and ahead of crest in the accelerating waveform as seen in Fig. 9. Energy variation within the bunches was neglected. The resultant spectra are shown in Fig. 10. In the on-crest case, the center bunch has an energy of 340 keV and the leading and trailing bunches have energies of 314 keV. Fig. 3 shows that these energies correspond to 8.16 GHz and 8.32 GHz respectively, and Fig. 10 shows peaks near those frequencies. In the off-crest cases, one bunch has an energy of 243 keV, corresponding to 8.97 GHz, and Fig. 10 shows that this frequency is only excited in the off-crest cases. The spectra are also influenced by longitudinal defocusing, variation in bunch spacing due to differing mean energies, differing beam interaction impedances, and the interaction bandwidth. Longitudinal defocusing may be offset by acceleration ahead of crest, although that was not considered in these simulations.

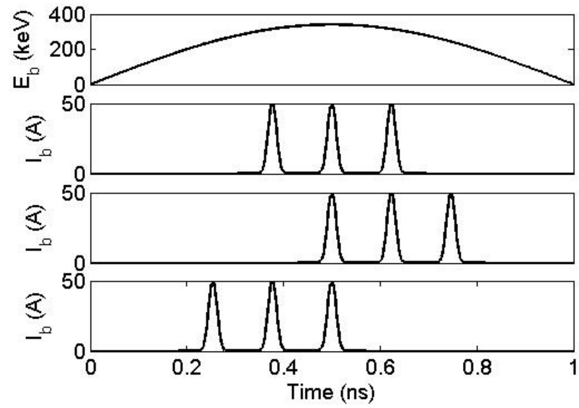

Figure 9: Relative phasing of bunch train within accelerating waveform for three simulated cases.

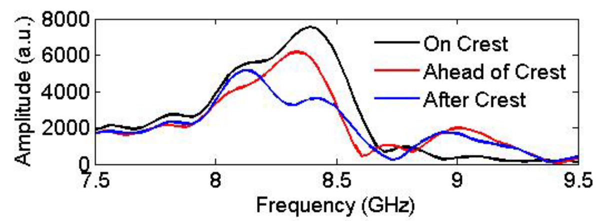

Figure 10: Spectra for the three-bunch sequences with different phasing relative to accelerating waveform.

SUMMARY

In this paper we considered the NPS SRF gun as a driver for a Cerenkov microwave source, using the PIC code, OOPIC to model the interaction. Single bunches and bunch trains exhibited the expected scaling of radiation intensity with the number of bunches. Scaling with peak current followed the expected trend at low current, but diverged at higher current due to longitudinal space charge forces. Relative phasing of the bunches in the accelerating waveform produced spectra consistent with the dispersion properties of the structure.

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