A High-Current Micro-Pulse Electron Gun*

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Abstract

A novel concept for a high-current-density micro-pulse electron gun has been studied. The concept employs the resonant amplification of an electron current by secondary electron emission in an rf cavity. We have studied this "multipacting" process in detail, including space charge, and have found the parameters necessary to make use of the phenomenon to produce a micro-pulsed electron beam. One wall of the cavity is made partially transparent to electrons but opaque to the input rf electric field. It is shown from self-consistent analytic theory and two-dimensional, fully relativistic, electromagnetic particle-in-cell (PIC) simulations that the current density scales with frequency cubed. The natural "bunching", or resonant phase selection of the particles gives rise to high current densities (20-5600 A/cm^2), high charge bunches (up to 100 nC/bunch for a solid beam and up to 1000 nC for a hollow beam), and short pulses (36-3.5 ps) for frequencies from 1.3 to 8 GHz. The beam pulse width is found to be typically 4.6% of the rf period. Beam extraction through the transparent wall was studied using a 2-1/2 dimensional PIC code. Good beam transmission (52-85%) with low normalized emittance (9-18 mm-mrad) could be achieved. The best normalized emittance per charge is 3 mm-mrad/nC. Tuning to the resonant parameters has been shown to be very tolerant. Electrical breakdown is not a problem, and materials are available to satisfy the secondary emission yield requirements for this device. Applications are accelerator injectors and rf generation at a high harmonic of the fundamental frequency.

I. INTRODUCTION

The development of high-current, short-duration pulses of electrons has been a challenging problem for many years. High-current pulses are widely used in injector systems for electron accelerators, both for industrial linacs as well as high-energy accelerators for linear colliders. Short-duration pulses are also used for microwave generation, in klystrons and related devices, for research on advanced methods of particle acceleration, and for injectors used for free-electron laser (FEL) drivers.

During the last few years considerable effort has been applied to the development of high power linac injectors [1-2] and particularly to laser-initiated photocathode injectors [3-8]. The best of these have somewhat higher brightness than the injector in reference [1], but the reliability depends on the choice of photocathode material, with the more reliable materials requiring intense laser illumination.

Summarizing, the methods used to date are rather complex, cumbersome, expensive, and have very definite limits on performance. The method to be described appears to be promising in large part because of a natural bunching process.

II. CHARACTERISTICS OF THE HIGH CURRENT MICRO-PULSE GUN (MPG)

Micro-pulses or bunches are produced by resonantly amplifying a current of secondary electrons in an rf cavity. Bunching occurs rapidly and is followed by saturation of the current density within ten rf periods. The "bunching" process is not the conventional method of compressing a long beam into a short one, but results by selecting particles that are in phase with the rf electric field, i.e., resonant. One wall of the cavity is highly transparent to electrons but opaque to the input rf field. The transparent wall allows for the transmission of the energetic electron bunches and serves as the cathode of a high-voltage injector. Axial and radial expansion of the pulse is minimized outside the cavity by using rapid acceleration and a combination of electrostatic and magnetic focusing. Inside the cavity, radial expansion is controlled by electric and/or magnetic fields. Both analytic theory and PIC simulation provide verification of this concept. This micro-pulse electron gun should provide a high peak power, multi-kiloampere, picosecond-long electron source which is suitable for many applications.

III. RESONANCE AND CURRENT DENSITY GAIN

In Fig. 1 is shown an rf cavity operating in a TM_{010} mode. Now assume at one of the electrode walls (the screen or grid) of the cavity there is a single electron at rest near the axis. This electron is then accelerated across the cavity and strikes the surface S. A number δ of secondary electrons are emitted off this electrode. Provided the average transit time of an electron in the cavity is one-half the rf period, and that the secondary electrons are in the proper phase with the rf field, these electrons will be accelerated towards the screen. If δ is also the secondary electron yield per primary electron of the screen, then upon reaching the screen, δT electrons will be

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transmitted, where T is the transmission factor. The number of electrons which are not transmitted is then $\delta(1-T)$. This is the number of electrons which are stopped by the screen, and can thus produce $\delta^2(1-T)$ secondary electrons. In order to have a gain of electrons, the number of secondaries produced must be greater than unity, that is, $\delta^2(1-T)>1$. The gain of electrons at time t after a number of transits is derived to be $G=[\delta(1-T)^{1/2}]^{(\omega t/\pi)}$, where π/ω is the half-period of the radian rf frequency ω. If there is a "seed" current density J_s in the cavity at t=0, then at time t the current density will be given by $J=GJ_s=J_s[\delta(1-T)^{1/2}]^{(\omega t/\pi)}$ until space-charge and saturation limit the current. The current density limit will be shown in later sections. The seed current density can be created by any of several sources including cosmic rays. For a very low seed current density a high current density can be achieved in a very short time. For example, if $\delta=8$, T=0.75, and J_s=14 x 10^{-10} amps/cm^2, at ten rf periods then J=1500 amps/cm^2.

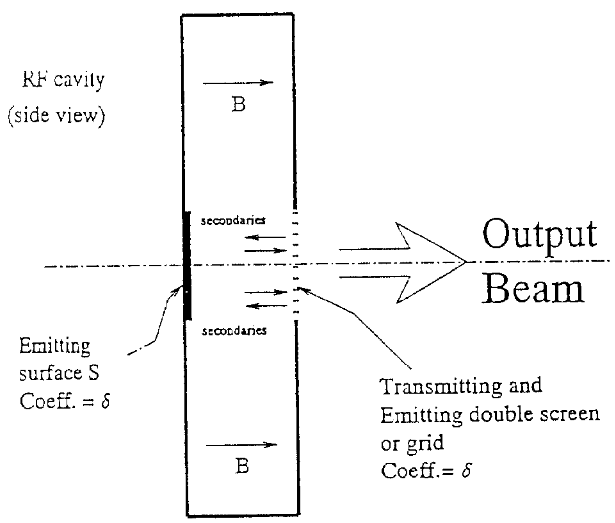

Figure 1: Schematic of micropulse gun for solid beam (TM_{010}) mode. A coaxial feed is used for rf input (not shown).

IV. STEADY-STATE PARALLEL-PLATE MODEL WITH BEAM (Theory)

In this section we will solve self-consistently for the steady state or saturation current density for a beam (charge slab) that is already "bunched". The axial bunch length or charge slab thickness is Δ, the axial gap spacing between the parallel plates or electrodes is d, and the beam density is n. We evaluate the equations of motion for electrons "attached" to the front ("f") and back ("b") of the charge slab. The equations of motion are

$$\frac{d^2x_{f,b}}{dt^2}=(e/m)[E_0\sin\omega t\pm E_{sc}] \qquad (1)$$

with initial conditions $v_{f0}(t=t_{f0}), v_{b0}(t=t_{b0}), x_{f0}(t=t_{f0})$, and $x_{b0}(t=t_{b0})=0$. The subscripts f and b refer to the front and back electrons and the top and bottom sign, respectively. The quantities E_0 and E_{sc} are the magnitudes of the rf and space charge electric fields, respectively.

At resonance when $\theta=\theta_{f,b}+\pi$, where $\theta=\omega t, \theta_f=\omega t_{f0}$, and $\theta_b=\omega t_{b0}$, the particles must cross the gap, or $x_f=d$ and $x_b=d-x_{f0}$. Assume that $v_{f0}=v_{b0}=0$. The following expression is obtained from the solution of the equation of motion (1),

$$\theta_{f,b}=\phi-\arccos\left[\frac{1\mp\alpha_s(\pi^2/2)-(x_{f0}/d)}{\alpha_0(\pi^2+2^2)^{1/2}}\right] \qquad (2)$$

where ϕ = arctan$(2/\pi)$, $\alpha_0=\dfrac{eE_0}{m\omega^2 d}$, $\alpha_s=\dfrac{eE_{sc}}{m\omega^2 d}$ $E_{sc}=ne\Delta/2\epsilon_0$ and ϵ_0 is the permittivity of free space.

Consider θ_b and therefore the positive quantity in brackets in Eq. (2). If we increase the space charge parameter α_s with all other parameters fixed, the back electrons will go out of resonance when the quantity in brackets exceeds one. Thus to maintain resonance and the maximum space charge we must satisfy the following equation

$$\alpha_{s,\max}=\frac{2}{\pi^2}\left[\alpha_0(\pi^2+2^2)^{1/2}-1+\frac{x_{f0}}{d}\right] \qquad (3)$$

The peak steady-state current density can be calculated from the expression J = nev and the above results,

$$\frac{J}{J_0}=\alpha_s\frac{2\alpha_0\cos\theta_f+\pi\alpha_s}{(\Delta/d)} \qquad (4)$$

where

$$J_0=\epsilon_0\frac{m}{e}\omega^3 d \qquad (5)$$

From the solution of Eq. (1) we can calculate

$$\left(\frac{\Delta}{d}\right)=\frac{\alpha_0}{2}\left[\sin\theta_f-\sin\theta_b+\frac{1}{2}(\theta_b-\theta_f+\pi)\cos\theta_f-\frac{1}{2}(\theta_f-\theta_b+\pi)\cos\theta_b\right]$$
$$+\frac{\alpha_s}{12}\left[(\theta_f-\theta_b+\pi)^2+\frac{\pi^3+(\theta_f-\theta_b)^3}{\theta_f-\theta_b+\pi}\right]+\frac{x_{f0}}{2d} \qquad (6)$$

As will be seen in the section describing the PIC simulations, the ω^3 scaling of the saturated current derived above is an important scaling law for the micro-pulse gun. This scaling is also derivable from the time-dependent current-voltage relation in a diode first derived by Kadish, Peter, and Jones [9].

V. CURRENT DENSITY AS A FUNCTION OF TIME (PIC Simulation)

Figure 2 shows a plot of the current density J_x across the gap (d=0.5 cm) as a function of time for a simulation with an rf frequency of 6.4 GHz and a voltage of 105.2 kV. The current density is measured near the second (right-hand) electrode which, in an actual experiment, would be the exit screen or grid. Hence, this is the current pulse which will exit the device. The top trace, corresponding to a positive current density, is that current which is emitted from the second (right-hand) electrode and propagates back to the first electrode. The bottom trace (negative current density) describes the beam that would leave the cavity. The curves are not symmetric about J_x=0 because the beam pulses have substantially different charge densities and velocities when they cross the position of the probe. In the case for which the current density is positive (i.e., electrons are propagating in the negative x direction), the electrons have just been emitted from the electrode and form a high-density bunch at a relatively low energy. In the case for which the current density is negative (i.e., electrons are propagating in the positive x direction), the electrons have already crossed the gap and are at a relatively high energy, and have spread somewhat due to space charge effects. The simulation ran out to a total of 2 ns and reached a peak amplitude of 2.8 kA/cm^2 for d=0.5 cm. At a gap length of 1.0 cm, the resulting current density increased to 7 kA/cm^2. Both cases use α_0=0.453.

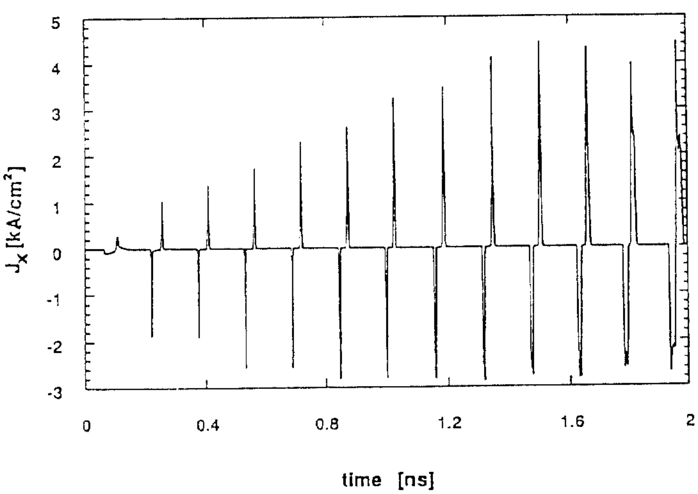

Figure 2: Plot of current density vs. time for simulation with rf frequency 6.4 GHz, voltage amplitude 105 kV, d=0.5 cm, and α_0=0.453.

VI. CURRENT DENSITY VS. FREQUENCY

In Fig. 3 we plot simulation results for the peak current density (at saturation) J_x (kA/cm^2) vs. frequency for a series of simulations with gap length 0.5 cm and drive parameter α_0=0.453. For comparison, we also plot the theoretical curve for J_x vs. frequency from the theory described in Section IV. Note the excellent agreement between theory and simulation. The ω^3 scaling for the MPG provides an important characterization of the proposed device. Note that the rf voltage must increase in proportion to ω^2 to maintain a fixed α_0.

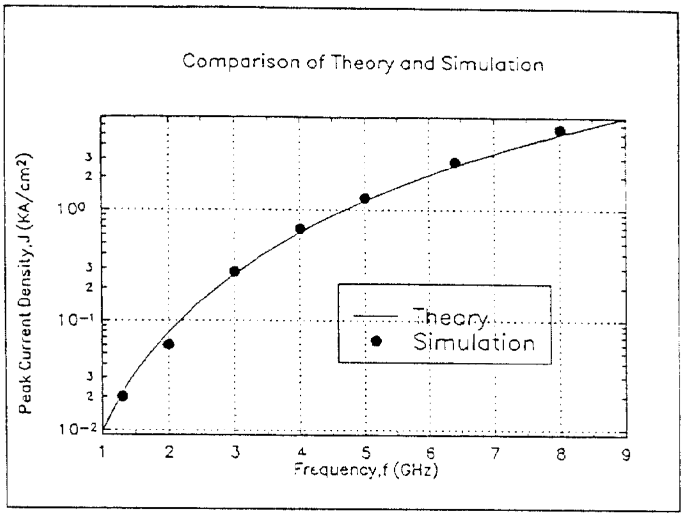

Figure 3: Comparison of peak current density in kA/cm^2 versus frequency for simulation and theory for a gap length of 0.5 cm and drive parameter α_0=0.453.

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