ELECTRON DYNAMICS IN RF SOURCES WITH A LASER CONTROLLED EMISSION

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Photoemission radiofrequency (RF) electron sources are sources of electron beams with extremely high brightness. Beam bunching processes in such devices are well studied in case when laser pulse duration is much lower of rf oscillation period. At the same time photoemission RF guns have some merits when operating in 'long-pulse' mode. In this case the laser pulse duration is much higher of rf oscillation period but much lower of rise time of oscillations in a gun cavity. Beam parameters at the gun output are compared for photoemission and thermoemission cathode applications. The paper presents results of a beam dynamics simulation in such guns with different resonance structures. Questions connected with defining of the current pulse peak value that can be obtained in such guns are discussed.
PACS numbers: 29.25.Bx, 41.75.Lx

1 INTRODUCTION

Modern experimental investigations using relativistic electron beams require accelerators with high brightness beams to be applied. An injector system is paid great attention when designing such accelerators. Recently, injector systems based on radio frequency electron sources (RF guns) are researched highly [1, 2]. RF gun is realized by a pillbox supplied by RF power of ~10^6 W. A cathode is placed on the one of face walls. Its emitting surface is in RF field with strength of ~(10^7-10^8) V/m.

Current pulse duration in thermionic RF guns is approximately equal to RF power pulse duration. The second case is featured by wide application of RF guns with current pulse duration much lower than RF oscillation period ($\tau_p << c/f_0$), for instance, for S band ~10^{-11} sec. It's obviously that field strength in this case is not varied during the current pulse. This circumstance permits to obtain high brightness beams [3]. Beam shaping is more complicated when current pulse duration in RF guns is much higher of RF oscillation period but much lower of rise time of oscillations in a gun cavity ($c/f_0 << \tau_p << Q/\pi f_0$) [4]. Current density of the emission from a cathode in this case (the same as in thermionic case) is varied during current pulse time following the Schottky law. Besides, there are some limitations for generation intense electron beams. It is assumed here the finite stored RF energy value in the cavity. Oxide cathodes, that are good photoemitters, applied as a photocathode gives the possibility to design multipurpose electron sources. Electron dynamics in such RF guns is not enough researched in spite of their advantages when producing intense electron beam with microsecond and nanosecond current pulse duration.

The purpose of this work is the obtaining of information about particle dynamics features and electron bunch shaping in 'short-pulse' RF guns with photoemission oxide cathode. The main used method is the computer simulation of electron dynamics using PARMELA code [5].

2 CALCULATION RESULTS

Due to oxide photocathode can be applied in both thermoemission and photoemission mode, let's consider differences in electron dynamics in these cases. These differences are defined by the dependence of current density for photoemission and thermoemission on electric field strength (effect Schottky). The density of photoemission and thermoemission current in presence of external electric field on a cathode surface can be written respectively as [6]:

$$J_{\phi} = \frac{\vartheta A_0}{2k^2}\left[h\nu - h\nu_0 + e\sqrt{eE_k Sin\,\omega t/4\pi\varepsilon_0}\right]^2$$

$$J_T = \varsigma A_0 T_k^2 \exp\left(-\frac{\varphi_T - e\sqrt{eE_k Sin\,\omega t/4\pi\varepsilon_0}}{kT_k}\right)$$

where $E_к$ is maximum electric field strength on a cathode, V/m,
$T_к$ is cathode temperature,
hν is energy of quantum of laser radiation, eV,
$h\nu_0$ is minimum energy of quantum, corresponding to power ability of a single-photon photoemission (coincides with work function for metals), eV,
φ_T is work function, eV,
$\omega=2\pi f_0$,
κ is Boltzmann constant,
ε_0 is permittivity,
A_0 is Richardson constant,
e is electron charge,
ϑ and ς are dimensionless constants featuring cathode surface properties.

It follows from the analysis of given above expressions that time dependence of emission current density in these cases will be differed during accelerating half-period of RF oscillations. So, electric field increasing from 0 to 30 MV/m causes the emission current density increasing in 30% for the photoemission case ($h\nu$ = 3.49 eV, $h\nu_0$ = 2.0 eV). Such field increasing for the thermoemission Ba-Ni cathode (T_k = 1000K) causes the thermoemission density increasing in 11 times. It should be noted that given estimations are valid in absence of limitation by space charge ('3/2' law) and cathodes operate in saturation mode. However the difference in time dependence of current density can cause differences in phase-energy distributions of beams. In order to exam this statement we had computer simulation of beam dynamics for the single cavity RF gun described in [7]. Resonance system of the gun is the cylindric E_{010} cavity with fundamental frequency and quality factor of 2797 MHz and $1.3 \cdot 10^4$ respectively. The cavity is RF power supplied (up to 2 MW) through the coupling window in its element. It was assumed for the simulation that averaged over oscillation period current is equal for the photoemission and thermoemission (1.8 A). And it was supposed also that there is steady state for thermoemission and current pulse duration is $c/f_0 << \tau_p << Q/\pi f_0$ for photoemission. These conditions correspond to the given field approximation that is used in PARMELA code. Space charge limitation effect was taken into account in calculations because of it takes places during the part of oscillation period when the current value obtained after Langmuir formula is lower of photoemission (or thermoemission) saturation current. Electric field strength averaged over the cavity length was taken of 30 MV/m in both cases. Obviously it requires different RF power level to be supplied to obtain equal field strength in different gun operating modes. Fig. 1 and Fig. 2 show energy and phase particle distributions respectively.

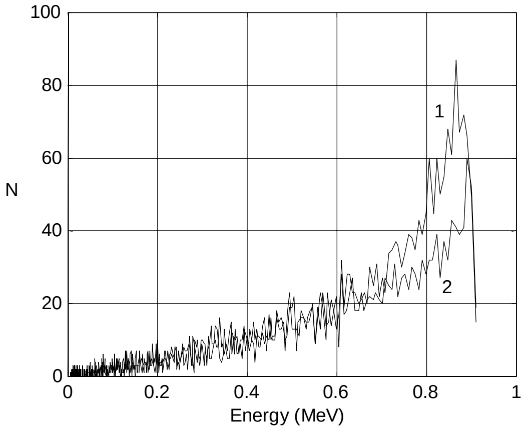

Fig. 1. Electron energy spread at the single-cavity RF gun output. 1 – photoemission, 2 – thermoemission.

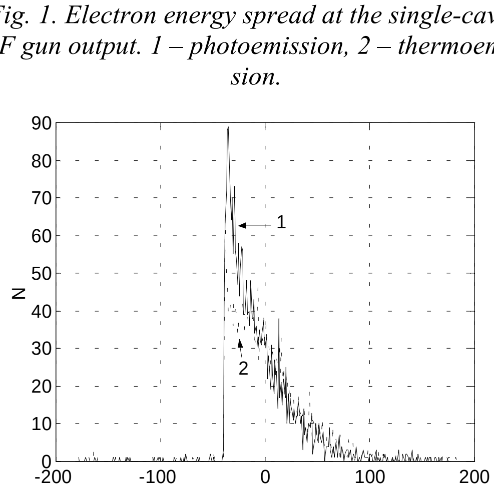

Fig. 2. Electron phase spread at the single-cavity RF gun output. 1 – photoemission, 2 – thermoemission.

Differences in particle energy distribution for different emission cases noted in simulation results were observed experimentally when the gun was researched being a part of the linac LU-60 injector system [8]. In particular, by the beam deflection in the injector deflecting system it was noted the electron energy distribution density is considerably higher of 'photo' electrons.

Main simulation results are summarized in Table 1. One can see that photoemission electron beam has the lower phase and energy spread comparatively with thermoemission electron beam. Hence, photoemission electron beam has lower longitudinal emittance Because of better angular performances it causes the considerable difference in the beam brightness. Pointed differences have influence primarily on particle phase-energy distributions (Fig. 3) that is important for the application of additional bunch phase compression systems based on the non-isochronism of particle motion, for instance, α-magnet.

Table 1

Parameter	Thermo	Photo
Supplied RF power, MW	1.3	0.570
Normalized emittance (rms), mm mrad	17.4	16.0
Maximum energy, MeV	0.91	0.91
Average energy, MeV	0.51	0.57
Energy spread width for 70% of particles, %	64	55
Bunch phase length for 70% of particles, degree	53	43
Output current averaged over period, A	1.19	1.3
Bunch peak current, A	11	15
Normalized brightness for 95% of particles, 10^9 A/м^2	4.5	7.3

It was noted during the simulation the strong dependence of output beam parameters on electric field strength and its distribution. It is obviously that these performances can't be changed actually due to hardware specialties in the single cavity gun. Therefor resonance system of multipurpose RF gun (capable to operate in both with thermoemission and photoemission cathode in broad supplying RF power range) has to have flexibly tuned resonance system. Two-cavity RF gun [9] can be taken as the example of such resonance system. The idea of multipurpose radiofrequency electron source was realized here for the first time. The gun has tools for tuning fundamental frequency in each cavity. It permits to vary amplitude ratio in cavities $\eta = E_{zmax1}/E_{zmax2}$ in range of 0.53…2.34 without changing fundamental frequency totally. We researched the dependence of output beam parameters on field strength and parameter η by computer simulation both in photoemission and thermoemission modes.

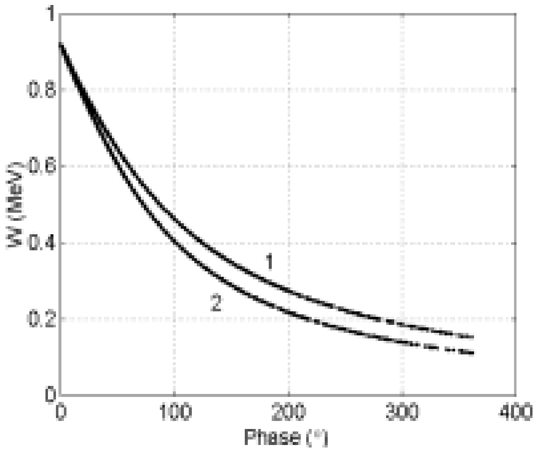

Fig. 3. Phase-energy electron distribution at the single-cavity RF gun output. 1 – thermoemission, 2 - photoemission.

Simulation results confirmed the main feature of the single-cavity gun that is expressed in follows: the photoemission electron beam has lower emittance, bunch phase length and particle energy spread and, hence, higher brightness. It was shown that the possibility to adjust field strength distribution along the cavity axis permits both to change particle energy and to optimize the system relatively the given beam parameter. For instance, to obtain minimum of beam normalized emittance (16 mm·mrad) under average field strength of 20 MV/m one should set $\eta = 1.25$. To obtain minimum of phase length (50° for 70 % of particles one should set $\eta = 0.82$ and to obtain minimum of energy spread (19 % for 70 % of particles one should set $\eta = 1.52$.

The finite value of electromagnetic field energy stored in resonance system of RF gun is the factor limiting maximum pulse charge in laser driven RF guns with current pulse duration that is significantly lower of time constant of the resonance system. It is obviously that energy of electron beam removed by particles out of the resonance system can't be higher of this value. Maximum charge value $q_{\max}$ at the gun output can be expressed as following:

$$q_{\max} \leq \frac{Q_0 \cdot P}{2\pi f_0 \cdot W_{aver}},$$

where Q is unloaded quality factor of the cavity;

P is power dissipated in cavity walls, W;

W_{aver} is average electron energy at the gun output, eV;

f_0 is operating frequency, Hz.

For typical values of $Q_0 = 10^4$, $P = 1$ MW, $f_0 = 3$ GHz, $W_{aver} = 0.5$ MeV peak pulse charge can reach 3 μC. This means that current pulse with duration of $\sim 10^{-8}$ sec can have amplitude of hundreds amperes. It should be noted that energy transferred to particles staying in the cavity is not taken into account here. This energy value, as a rule, is not higher of 20 % of energy transferred to electrons of main beam. Its value can be defined enough accurate using computer simulation of electron dynamics in a gun.

3 CONCLUSION

Analysis of computer simulation results permits to conclude the following:

1. Photoemission electron beam has higher brightness comparatively with thermoemission electron beam for equal field strength in the same gun.
2. Oxide cathode application in the same RF gun permits to realize thermoemission and photoemission modes simultaneously. This gives the possibility to obtain at RF gun output simultaneously two beams differed by current pulse duration and phase-energy distribution.

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