A Multi-Frequency RF Photocathode Gun

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Abstract. The concept of a photocathode injection gun driven by several harmonically related phase-locked RF sources is considered. This concept is aimed at providing electron bunches with parameters as follows: charge/bunch \( \geq 1 \ \text{nC} \), bunch energy 5-10 MeV, bunch width 20-40 ps, and fundamental frequency \( = 1.3 \ \text{GHz} \). In comparison with a conventional single mode 1.5 cell injection gun, multi-harmonic excitation can allow operation with lower RF power input, lower Ohmic losses, and lower beam emittance (for a given cathode field).

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INTRODUCTION

An injection gun forms compact bunches of electrons by synchronizing high repetition rate laser pulses and high-power RF fields applied to a photocathode. A conventional injection gun consists of a 1.5 cell cavity and uses transverse emittance compensating techniques based on a two-solenoid system [1,2]. Typically an RF gun is able to release electron bunches of 1-10 nC charge and 10-50 ps length with a normalized rms emittance \( \varepsilon_{\text{rms}}=1-10 \ \mu \text{m} \) [4]. It has been known that addition of a field harmonic of the fundamental rf field could reduce the emittance, allowing improved freedom to manipulate beam size and length to control space charge forces [2,3]. As was shown recently, the use of many modes \( (N \geq 2) \) in an RF gun is appealing due to several additional reasons [8], described below.

In a cavity excited simultaneously by several harmonically related modes, electrons are accelerated by a field which is a sum of partial mode contributions. The acceleration field is proportional to a total number \( N \) of modes, because an accelerated bunch sees all modes in phase. The necessary RF power to provide a given gradient is asymptotically reduced by a factor of \( N \) in comparison with a single mode gun [5,6]. An application of several harmonically related modes in RF injection gun cell thus promises less loss and less input power in comparison with traditional single mode gun of the same bunch energy, length, charge, and emittance.

In a multi-frequency cavity there are effects of exposure time reduction and a so-called “anode-cathode” phenomenon [7] that may mitigate against RF breakdown. On a cavity surface, cathode fields (fields pointed out so that electron auto-emission is possible) and anode fields (such fields prohibit auto-electron emission) are not equal to one another. Therefore, acceleration of a bunch might be at higher field than the usual breakdown threshold, if one postulates that auto-electron emission is responsible for the onset of breakdown. The anode-cathode principle may allow one to obtain acceleration at a higher acceleration gradient and less dark current in comparison with a single mode gun. High acceleration gradient in addition allows one to obtain lower transverse emittance, because the initial time interval when particle energies are not yet relativistic (Coulomb space-charge force is dominant), becomes smaller.

Several modes of different frequencies and different spatial structures allow optimization of the space-time structure of fields by manipulations of amplitudes and phases of these modes. An optimization of field structure promises to obtain improved longitudinal emittance in comparison with classical design.

RF GUN BASED ON A TM\textsubscript{010}-TM\textsubscript{011} F+2F CAVITY

Let us consider a two-frequency half-cell RF gun cavity, fed by two harmonically related and phased klystrons (see Figure 1). The total rf electric field on the axis of the cavity as a function of time \( t \) and longitudinal coordinate \( z \) can be written in a form:
where $a_1$ and $a_2$ are amplitudes of modes $TM_{010}$ and $TM_{011}$ respectively, $F_1(z)$ and $F_2(z)$ are functions describing field distributions of these modes, $f_1$ and $f_2$ are frequencies, and $\phi_1$ and $\phi_2$ are phases. In our case $f_1=1.3$ GHz, and $f_2=2f_1$. The parameters $a_1$, $a_2$, $\phi_1$, $\phi_2$, and cavity length were optimized in order to provide the highest output bunch energy and the lowest longitudinal emittance. Electric field distributions of modes, $F_1(z)$ and $F_2(z)$ along the axis of an 8 cm long cavity, which were found after an optimization procedure; resulting field patterns are shown in Figure 2. The optimal fields on left and right sides of the cavity are shown in Figures 3a, b. Note that there is an essential difference between so-called cathode-like and anode-like fields. The first mentioned fields pull electrons out of metal bulk and are able to initiate fast breakdown, and the anode-like fields push electrons in a metal and are less dangerous. In calculations the maximum of the cathode-like surface field was restricted to a level $\sim 100$ MV/m in order to prevent breakdown. Electrons are emitted due to laser pulses with RF field of magnitude $\sim 60$ MV/m.

The bunch of 40 ps length, started at $z = 0$ on the cathode, crosses the cavity in approximately 0.3 ns. During this time the bunch sees the accelerating field in the range between 60 MV/m and about 180 MV/m (see Figure 4). Finally the bunch reaches about 9 MeV energy, and its longitudinal emittance ($\sim 2$ keV-radian) is two times less than emittance in the classical 1.5 cell single-mode RF gun of the same bunch length and the same maximum cathode field. Of course, there is a tradeoff between energy and emittance. For example, about 10 MeV can be obtained in our 0.5 cell gun, but emittance in this case equals that of a conventional 1.5 cell gun. If one prefers to have lower emittance, like $\sim 3$ times less than in the 1.5 cell gun, the energy falls to 6 MeV.

Note that the transverse emittance in our 0.5 cell gun should be less than in a 1.5 cell gun, because the accelerated bunch spends less time in the presence of the dominant radial Coulomb forces. Rough estimations show that a minimum of the transverse emittance is proportional to time, which is necessary for electron bunches to reach relativistic energies. Thus the emittance in our case could be approximately 3 times less than in a conventional 1.5 cell RF gun.

The feeding system of the gun includes 4 rectangular cross-section waveguides, one pair of face-to-face waveguides for each frequency, as shown in Figure 5. Each mode is easily excited and does not leak into the port of the other mode. In order to provide accurate tuning of eigenmode frequencies, a technique based on frequency control in a cavity with flexible walls could be applied [6].
FIGURE 3. E-field of TM$_{010}$ and TM$_{011}$ mode superposition at the left wall on axis of the cavity (a); and at the field amplitude maximum at the right cavity wall (b).

FIGURE 4. Field distribution at cavity axis (a) in times corresponded to positions of bunch center: 1 - $z_c=0$ cm (start position), 2 - $z_c=2$ cm, 3 - $z_c=4$ cm, 4 - $z_c=6$ cm, 5 - $z_c=8$ cm (end of the cavity) and particle trajectories (b). Red corresponds to the central particle, blue is the first particle of bunch, green is the last particle.
RF GUN BASED ON TM$_{010}$-TM$_{030}$ F+3F CAVITY

In order to obtain a low longitudinal emittance in an RF gun which is necessary, for example, for production of high-power coherent radiation in XFELs [9], all electrons of a bunch should see similar and constant accelerating fields during their flight from the cathode to the output.

A cavity, operating with TM$_{010}$ and TM$_{030}$ modes at $f$ and $3f$ frequencies, was designed as a 1.5 cell cavity as shown in Figure 6. However, in contrast to the conventional design, the cells are independent, i.e. fields of one cell do not penetrate into the neighboring cell.

Because cells do not couple to one another, let us start with studies of the first cell (see Figure 7). Design of this cell was found using an optimization procedure similar to that described in the previous section. In accordance with the idea to provide similar acceleration conditions for all electrons the full field, written in the form of Eqn. (1) with $f_1 = 1.3$ GHz and $f_2 = 3f_1$, the parameters were optimized to obtain a flat top in dependence of the accelerating field on time (see Figure 9a). The first cell length was about 5 cm. On-axis fields of the first cell are shown in Figure 8 (cathode field again was limited to a level 100 MV/m). The fields do provide similar conditions for all electrons in a bunch (see Figure 9b). Calculations show that after the first cell, the energy of electrons could be as high as 3.7 MeV, but the longitudinal emittance is at least 100 times less than in a classical single frequency gun. To provide such an acceleration gradient one needs about 16 MW of power at frequency $f$ and 0.35 MW at frequency $3f$ in case of normal conducting copper cavity. In the case of a superconducting cavity, the powers reduce down to 2.53 MW and 0.06 MW, respectively.

In order to feed the cavity, the scheme of the previous gun version was used (two face-to-face pairs of rectangular waveguides). In order to avoid leaking of high-frequency power into a port of the low-power radiation, an additional low-$Q$ cavity to be transparent for frequency $f$ was used. The cavity consisted of a cell iris, a waveguide section and a small additional iris. Figure 10 shows that both operating modes might be effectively excited.

The second cell with field magnitudes similar to fields in the first cell allows an increase in electron energy by a factor-of-two without an increase of longitudinal emittance. That is why the power which is necessary in order to feed the second cell is close to that needed for the first cell. Unlike the previous gun version the transverse emittance is not less than that of a conventional gun.
FIGURE 6. $E$-fields of TM$_{010}$ eigenmode (a); and TM$_{011}$ eigenmode (b); in a 1.5 cell cavity.

FIGURE 7. $E$-fields of TM$_{010}$ eigenmode ($f = 1.3$ GHz, $Q = 20,715$) (a); and TM$_{030}$ eigenmode ($f = 3.9$ GHz, $Q = 18,496$) (b).

FIGURE 8. Fields of TM$_{010}$ eigen mode (red solid) and TM$_{030}$ eigen mode (blue dashed) at cavity axis.
FIGURE 9. $E$-field of $\text{TM}_{010}$ and $\text{TM}_{031}$ mode superposition at axis of cathode (a) and particle trajectories (b).

FIGURE 10. Excitation of $\text{TM}_{030}$ mode at frequency $f$ (a) and excitation of $\text{TM}_{300}$ mode at frequency $3f$ (b).

REFERENCES