A MULTI-MODE RF PHOTOCATHODE GUN

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Abstract

A photocathode injection gun based on standard emittance compensating techniques and driven by several ($N \geq 2$) harmonically related RF sources is considered. Multi-harmonic excitation can provide high-quality flatness in time of the field at the cathode when a bunch is being injected. This allows one to obtain ≥1 nC, 20–40 ps electron bunches with preservation of low emittance. Another advantage is a reduction of Ohmic losses and the required input RF power for a given cathode field. Preliminary calculations show that input power in a three-mode cavity (0.65 GHz, 1.3 GHz, 2.6 GHz) is nearly half the power needed to feed a single mode with the same cathode field. A further appealing property is the predicted increase of a breakdown threshold due to a reduction of surface exposure time to high fields in the symmetric cavity, and due to a so-called anode-cathode effect in the longitudinally asymmetric cavity. These properties may help one to reach bunch energies as high as 3–5 MeV after the first half cell.

INTRODUCTION

An injection gun produces compact bunches of electrons by means of the synchronized, high repetition rate laser light and high-power RF field. A schematic view of the 1.5 cell RF gun is shown in Fig. 1. Modern injection guns also use transverse emittance compensating techniques based on two-solenoid system [1, 2]. Typically RF gun is able to release electron bunches of 1–10 nC charge and 10–20 ps length with the normalized emittance ε_{rms}=1–10 μm [4].

It has been known that addition of a harmonic to the rf fundamental field would reduce the rf emittance, allowing complete freedom of beam size and length to control the space charge forces [2, 3]. As it will be shown the use of many modes ($N \geq 2$) in RF gun is appealing due to several additional reasons. These include a reduction of Ohmic power losses and input RF power, an increase of accelerating gradient due to breakdown threshold increase, a reduction of a dark current due to smaller idle fields in comparison with such fields in a single mode gun cavity. The mentioned goals can be reached in a multi-mode, room temperature accelerating structure [5–7]. High accelerating fields at the axis of such a structure exist only during the narrow time intervals when a bunch traverses this structure. During time intervals between bunches fields near the axis is zero or small enough. This principle automatically requires that structure should contain equidistant spectrum of modes with harmonically related frequencies. The multi-mode accelerating structures operating in several resonant, equidistantly-spaced, axisymmetric, TM-like eigenmodes allows reduction of the exposure time to surface fields. Additionally, there are two complementary effects (that is reduction of high-field areas and reduction of those fields which are responsible for electron emission) which also help to increase accelerating gradient [6, 7].

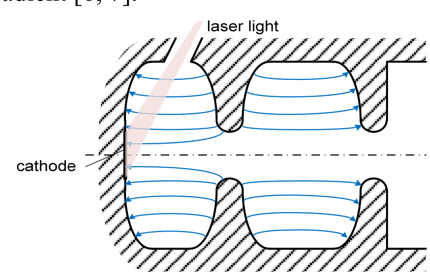

Figure 1: Schematic view of 1.5 cell RF injection gun driven by laser.

CONCEPTS OF A MULTI-MODE RF GUN

First of all, in order to provide best emittance, a high-quality flatness in time of the accelerating field at the cathode is necessary so that each portion of the electrons in the injected bunch starts in the same field magnitude. This is important because ideally inevitable difference in energies of the injected electrons should not be accompanied by position difference. In order to satisfy this condition, whole electrons should be injected in the constant field and be accelerated up to a relativistic energy in this field. In Fig. 2 one can see that several f+2f, f+3f, f+4f, or f+6f mode combinations are able to provide such ideal flat field distribution near field maximum. Three modes naturally allow more freedom in obtaining flatness quality and duration of the flat pulse part. This idea allows in principle reducing longitudinal bunch emittance. Another potential advantage is associated with the fact that multi-harmonic field, resulted by several coherent RF sources, reaches maxima to be proportional a number N of these sources. This leads to reduction of overall Ohmic losses and the input RF power (for a given peak cathode field).

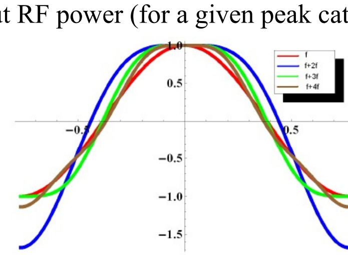

Figure 2: Field behaviour at bi-modal RF gun cavity.

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Preliminary calculations show that input power in a symmetric three-mode cavity (f = 0.65 GHz, 2f = 1.3 GHz, 4f = 2.6 GHz) is 30% less in a single mode with the same cathode field (Table 1). Field structures of the used modes are shown in Fig. 3 (cathode at bottom). The input power in a symmetric three-mode cavity with frequencies f = 0.65 GHz, 2f = 1.3 GHz, 6f = 3.9 GHz is nearly half the power needed to feed the single first mode. A further appealing property is the predicted increase of breakdown threshold due to a reduction of the surface exposure time to high fields. The carried out calculations show that breakdown threshold can be increased in the three-mode cavity by factor 10–30%. A possible feeding scheme for the mentioned multi-mode RF gun is shown in Fig. 4.

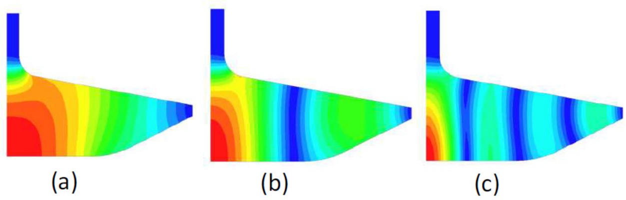

Figure 3: E-field structures of modes in three-mode RF gun cavity: a) 0.65 GHz, b) 1.3 GHz, c) 2.6 GHz.

Table 1: Powers for different field amplitude ratios between three modes with the total peak surface field at cathode 100 MV/m.

a_1 P_1 (MW)	a_2 P_2 (MW)	a_4 P_4 (MW)	Total Power (MW)
1 28.1281	0 0	0 0	 28.1281
0.820836 18.9519	0.314011 2.49813	–0.134847 0.201089	 21.6511
0.684617 13.1837	0.485832 5.97995	–0.170449 0.32129	 19.4849

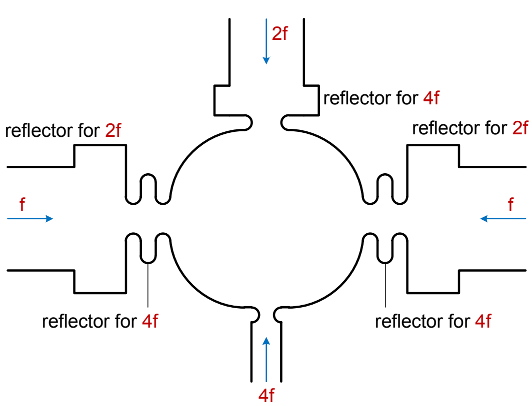

Figure 4: Feeding of injection gun by external RF sources.

The output electron energy in RF gun cavities is limited by breakdown and dark current phenomena (if to assume that as high as necessary RF power is available, and cooling is enough to accommodate wall losses). In order to increase bunch energy the "anode-cathode" effect can also be used [7]. This effect occurs in longitudinally asymmetric cavity so that emission fields at cathode surface takes place when all modes are in-phase condition. Fields on the right iris of the first cell at this time are even more than fields on cathode, but these fields do not allow electron emission (this is a virtual "anode" in that time). For a half of a period of the lowest mode these modes becomes out-phased, that is why, an instant "cathode" field at the first iris are less than breakdown threshold. Time-dependent field dynamics on cathode and on the iris surface are shown in Figs. 6, 7 where injection gun frequencies were f = 0.65 GHz, 2f = 1.3 GHz, 4f = 2.6 GHz. Mode structures are shown in Fig. 5. As one can see in the Fig. 6, possible injection time interval lies between t_1 = –100 ps and t_2 = 100 ps. Calculations show (Fig. 8) that one can reach bunch energies as high as 3–6 MeV even after the first half cell. In the next cell the mutual phase of RF field and electrons is to be chosen to compensate energy difference caused by the first cell. Mode powers are summarized in the Table 2.

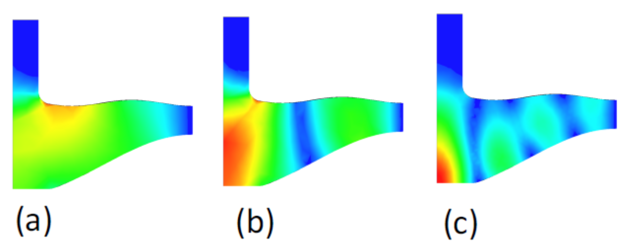

Figure 5: E-field structures of modes in three-mode asymmetric RF gun cavity: a) 0.65 GHz, b) 1.3 GHz, c) 2.6 GHz.

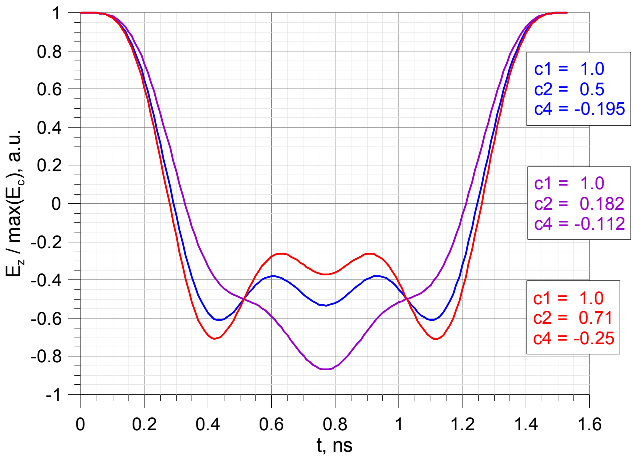

Figure 6: Time dependence of RF fields at physical cathode for different mode ratios(all fields are normalized by maximum of field at cathode).

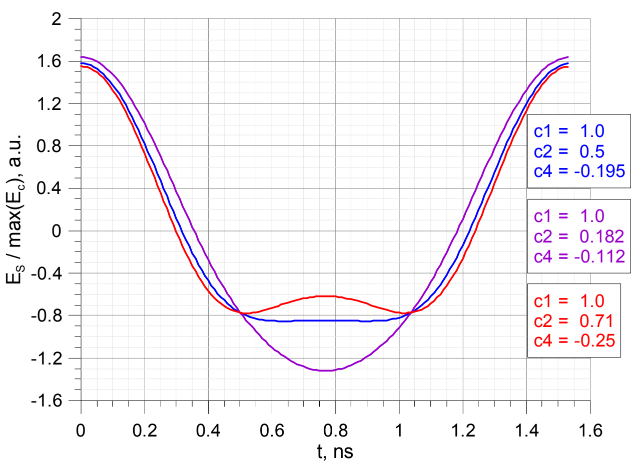

Figure 7: Maxima of surface E-fields at iris wall for different mode ratios as function of time.

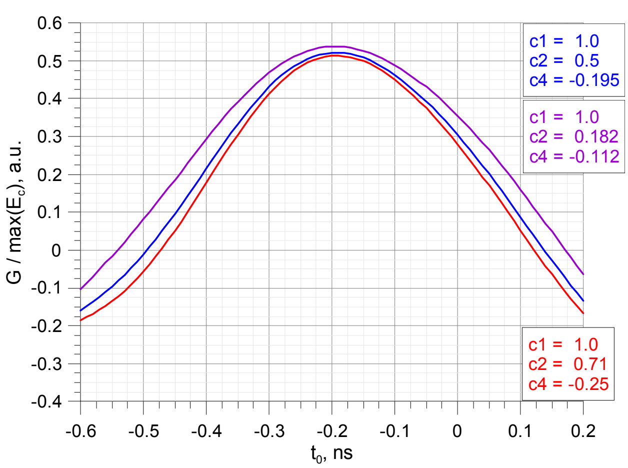

Figure 8: Gradients of different mode combinations as function of injection starting time.

Table 2. Powers of different mode combinations.

Combination	P (MW) / max E_c^2 (MV/cm)^2			
	Mode 1	Mode 2	Mode 4	Total
$c_1 = 1$ $c_2 = 0.5$ $c_4 = -0.195$	37.2	15.5	5.76	58.5
$c_1 = 1$ $c_2 = 0.182$ $c_4 = -0.112$	55.3	23.1	8.58	87
$c_1 = 1$ $c_2 = 0.71$ $c_4 = -0.25$	29.7	12.4	4.61	46.7

CONCLUSION

Application of several harmonically related modes in the first RF injection gun cell promises less loss and less input power in comparison with traditional single mode gun of the same bunch charge and beam emittance. In a cavity of the asymmetric design one can obtain faster acceleration (higher acceleration gradient) and less dark current.

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