LAL (ORSAY) RF GUN PROJECT

C. Travier
Laboratoire de l'Accélérateur Linéaire
Bât. 200, Centre d'Orsay
91405 ORSAY Cedex, FRANCE

J. Gao
visitor from IHEP
P.O. Box 2732, Beijing 100080, CHINA

Abstract

A two-cavity RF gun basic design is presented. The electric field distribution along the beam axis is chosen to minimize emittance growth. Independent phasing of the cavities allows to minimize energy spread. Simulations with the codes PARMELA [1] and PRIAM [2] are presented. According to this design, a low-level model cavity was launched.

Introduction

As part of the LAL/Orsay R & D program on future e^+e^- linear colliders [3], an RF gun design was started at the beginning of 1990.

Originally proposed by G.A. Westenkow and J.M.J. Madey [4], the RF gun concept is now widely studied and experienced. Both thermionic [4-6] and laser-driven [7-15] RF guns are now under construction, test or operation around the world.

The cathode being located in a high-gradient RF cavity, the electrons experience a high accelerating field and are thus less sensitive to space charge forces. In case of laser-driven RF guns, very short pulses can be produced by illuminating high-current density photocathodes with picosecond lasers. These properties result in high-brightness electron sources well suited for e^+e^- linear colliders, FEL injectors and synchrotron radiation storage ring linear injectors.

At Orsay, the goal of this development on RF gun is to gain some experience in this field while providing a possible high-brightness gun for the accelerator test-facility NEPAL [16]. The chosen operating frequency is thus 3 GHz. A dispenser cathode will be used, therefore allowing both thermionic and laser-driven operation [17].

Theoretical investigations showed that two-cavities independently powered and phased would allow to minimize both emittance and energy spread. Longitudinal electric field profile with RF focusing was chosen for the first cavity.

Beam dynamic simulations were conducted using both PARMELA and PRIAM codes. Many parameters can be varied: accelerating field in both cavities, RF phase for laser pulse, phasing of the cavities, pulse length, current, laser spot size, laser profile. Results presented here are partial and do not cover all the possible range of investigations.

Theoretical investigation

In an RF gun, electron beam is subject to several effects that contribute to energy spread and emittance growth [18]: space charge forces both linear and nonlinear, nonlinear time-independent field effects and linear time-dependent RF field effects which are characteristic of RF guns when compared to DC guns. To minimize emittance growth, there are at least two criteria: one is to minimize nonlinear field effects [19,9] (by designing a cavity with linear radial fields and by taking a beam diameter small enough), the other is to minimize linear time-dependent RF field effects [20].

Assuming that a cavity has a cylindrical symmetry, the electric field $E_z(r,z,\varphi,t)$ can be written $E_z(r,z)\sin(\omega t+\phi_0)$. Maxwell equations allow then to express the electromagnetic fields off axis $(E_z(r,z),\ E_r(r,z), H_\varphi(r,z))$ as a function of the longitudinal on axis electric field $E_z(0,z)$. The transverse force F_{rrf} applied to a particle of charge q and velocity v_z is expressed by $F_{rrf}=qE_r-q\mu_0 v_z H_\varphi$. It can then be written as:

$$F_{rrf}=-\frac{qr}{2}\left(\frac{dE_z(0,z)}{dz}\sin(\omega t+\phi_0)+\epsilon_0\omega v_z E_z(0,z)\cos(\omega t+\phi_0)\right)$$
$$+\frac{qr^3}{16}\left(\left(\frac{d^3E_z(0,z)}{dz^3}+k^2\frac{dE_z(0,z)}{dz}\right)\sin(\omega t+\phi_0)+\right.$$
$$\left.\mu_0\epsilon_0\omega v_z\left(\frac{d^2E_z(0,z)}{dz^2}+k^2E_z(0,z)\right)\cos(\omega t+\phi_0)\right)+h(r^5)+\cdots \quad (1)$$

where $\omega=kc$. If space charge forces F_{rsc} are considered, then

$$F_r=F_{rrf}+F_{rsc} \quad (2)$$

The two criteria mentioned above can be mathematically expressed as follows:

$$[F_{rrf}]_{nonlinear\ part}=0 \quad (3)$$

$$\frac{\partial}{\partial\phi_0}\int_0^{t_f}F_r dt=0 \quad (4)$$

where t_f is the time when the particle exits the cavity of length L and ϕ_0 represents the phase of the RF when it leaves the cathode at $t=0$. Which criterion to choose depends on which effect is dominant. In our case, because of relatively long bunches, we used the second criteria to design our cavities. We consider only the linear term in equation (2) which is dominant and regard the partial derivatives $\frac{\partial\beta_z}{\partial\phi_0}$, $\frac{\partial r}{\partial\phi_0}$ and $\frac{\partial t_f}{\partial\phi_0}$ as negligible. The following boundary conditions are assumed:

$$E_z(0,0)=E_0,\quad E_z(0,L)=0,\quad \beta_0\approx 0,\quad \omega t_f+\phi_0=\pi \quad (5)$$

When trying to solve equation (4), it is natural to introduce some RF focusing near the cathode to help control the space charge effects. This can be expressed mathematically by writing:

$$\left.\frac{dE_z(0,z)}{dz}\right|_{z=0}=\frac{2m_0c^2k\cos\phi_0}{e^2rE_0\sin^3\phi_0}\int_1^{\gamma_f}\frac{F_{rsc}}{\beta_z}d\gamma \quad (6)$$

A sufficient condition to satisfy equation (4) is then:

$$\frac{d^2E_z(0,z)}{dz^2}=-k\cot(\omega t+\phi_0)\left(\frac{d\beta_z}{dz}E_z(0,z)+\beta_z\frac{dE_z(0,z)}{dz}\right) \quad (7)$$

where

$$\frac{d\beta_z}{dz} = \frac{(1-\beta_z^2)^{\frac{3}{2}}}{\beta_z}\frac{eE_z(0,z)}{m_0c^2}\sin(\omega t+\phi_0), \quad t = \frac{1}{c}\int_0^z \frac{dz}{\beta_z} \tag{8}$$

Equation (7) together with conditions (5) and (6) can be solved numerically for given E_0, ϕ_0, current and cathode radius, provided that a simple linear expression is assumed for F_{rsc}. For the parameters of interest in our case, the resulting field distribution is shown in figure 1.

In the previous discussion, longitudinal emittance which is due to energy spread caused by time dependent RF forces was not minimized. By using a second cavity, it is possible to reduce energy spread while preserving emittance. For almost relativistic electrons, a cavity of length $L = \lambda/2$ having a field distribution $E_z(0,z) = E_1\sin(kz)$ satisfies both criteria [20]. It is then possible to almost cancel the energy spread by adjusting the maximum field E_1 and/or the phase shift between the two cavities ϕ_{12}. If $\phi_{12} = \pi - \Delta\phi/2$, then the field strength necessary to cancel the energy spread ΔW is:

$$E_1 = \frac{4k\Delta W}{e\pi\Delta\phi^2} \tag{9}$$

If for other reasons, E_1 is set to a given value, then:

$$\phi_{12} = 2\pi - \phi_{1av} - \arcsin\left(\frac{2\Delta W}{E_1\lambda\sin(\frac{\Delta\phi}{2})}\right) \tag{10}$$

where ϕ_{1av} is the average phase of the particles at the exit of the first cavity and λ is the RF wavelength.

Simulations

The two cavities shown on figure 2 were designed with SUPERFISH [21]. Being decoupled, each cell was calculated separately. The field profile as used for PARMELA simulations is shown on figure 1. After a slight modification of the PARMELA particle generation, it was shown that results obtained for 100 particles were reliable when compared to those corresponding to a much higher number. Therefore, all the simulations presented here were done with 100 particles. As the bunch is quite long and the current not too high, the mesh grid method is used for space charge calculations in order to save computer time. The effect of image charges in the cathode plane is not included in these simulations. A few parameters are not varied and their value are compiled in table 1. Electrons are assumed to leave the cathode with no energy and no emittance. The laser pulse is taken uniform in both transverse and longitudinal directions.

For given accelerating field and charge in the bunch the optimization procedure is as follows. The RF phase for laser pulse is varied to find the smallest emittance at the first cell exit. This phase is then frozen and the phase shift between the two cavities is varied to minimize the energy spread at the gun exit.

Figures 3 and 4 show the emittance at the exit of the first cavity, as a function of ϕ_0 for different field levels, with and without space charge forces respectively. ϕ_0 is the emitting RF phase of the "reference particle" which is taken at the center of the bunch. These pictures show that unlike for short bunches [22], the minimum of emittance is obtained for low ϕ_0 due to a strong bunching of the particles as shown on figure 5.

Figure 6 shows the dependence of emittance on peak accelerating gradient while figure 7 shows that the minimum emittance is quasi-linear with the bunch charge.

For a maximum electric field of 70 MV/m in both cavities, figure 8 shows the variation of both emittance and energy spread as a function of the phase shift between the two cavities.

A complete set of parameters for a typical run is given in table 2. Figure 1 shows the bunch evolution in this case as obtained from PRIAM. Both programs give consistent results.

In all these simulations, the emittance is taken as the normalized r.m.s. emittance defined as $\epsilon_N = 4[< x^2 >< (p_x/mc)^2 > - < x(p_x/mc) >^2]^{1/2}$ where x is the coordinate of a particle in the beam, p_x is the particle's momentum component in the x direction and $< \ >$ indicates averaging over the entire beam.

Project Status

Started in February 1990, the simulations with PARMELA and PRIAM will be continued. Different parameters will be scanned (shorter bunch length, magnetic field,...). Simulations in the case of a thermionic cathode are also in progress.

In order to check RF properties of the cavities and determine the two coupling holes, their influence on field symmetry and to check that cavities are effectively decoupled, a low-level model cavity was launched. Measurements will be done during the summer 1990.

Acknowledgement

We would like to thank Y. Thiery who performed all the simulation runs and B. Mouton who diligently modified PARMELA according to our wishes. Many thanks to Dr. J. Le Duff for his constant support.

References

[1] Version from K. Crandall and L. Young at LANL, with modifications from K.T. McDonald (BNL) and B. Mouton (LAL). User's manual from B. Mouton, LAL/SERA 89-356, 1989.

[2] G. Le Meur, these proceedings.

[3] J. Le Duff, in Proc. of the 1988 Linear Acc. Conf., Williamsburg, VA, October 3-7, 1988, pp. 285-287.

[4] G.A. Westenkow, J.M.J. Madey, Laser and Particle Beams (1984), Vol 2, Part 2, pp. 223-225.

[5] J. Gao, Beijing IHEP/FEL/89-04-(A,B,C,D),in chin., 1989.

[6] E. Tanabe et al., SLAC-PUB 5054, August 1989.

[7] R.L. Sheffield et al., Proc. of the 1988 Linear Acc. Conf., Williamsburg, VA, October 3-7, 1988, pp. 520-522.

[8] S. Joly, Proc. of the 1988 European Part. Acc. Conf., Rome, 1988.

[9] K.T. McDonald, DOE/ER/3072-43, Princeton University, 1988.

[10] M. Curtin et al., to be published in Proc. of the 1989 FEL Conf., 1989.

[11] S. Chattopadhyay et al., LBL-25699, ESG Note-55, 1988.

[12] Y. Baconnier et al., CLIC Note 65, 1988.

[13] W. Gai et al., Proc. of the 1989 Part. Acc. Conf., Chicago, 1989.

[14] H. Chaloupka et al., Nucl. Inst. and Methods in Phys. Res. A285 (1989), pp. 327-332.

[15] R. Bonifacio et al., Nucl. Inst. and Methods in Phys. Res. A289 (1990), pp. 1-13.

[16] G. Bienvenu, these proceedings.

[17] H. Bergeret, M. Boussoukaya, R. Chehab, B. Leblond, J. LeDuff, LAL/RT 90-04, 1990.

[18] B.E. Carlsten, R.L. Sheffield, Proc. of the 1988 Linear Acc. Conf., Williamsburg VA, October 3-7, 1988, pp. 365-369.

[19] M.E. Jones, W.K. Peter, IEEE Trans. on Nucl. Sci., Vol NS-32, No 5, p. 1794, 1985.

[20] J. Gao, LAL/SERA 89-291, Orsay, August 1989.
[21] K. Halbach, R.F. Holsinger, Proc. of the 1976 Part. Acc. Conf., pp. 213-222
[22] K.J. Kim, Y.J. Chen, Proc. of the 1988 European Part. Acc. Conf., Rome, 1988.

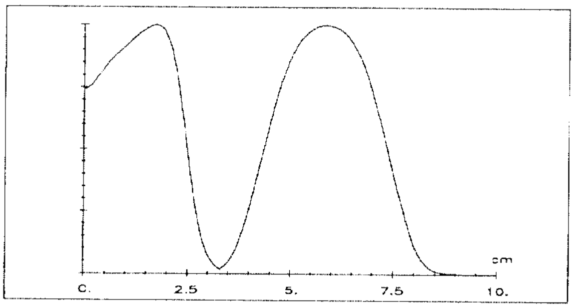

Fig. 1: Longitudinal on-axis electric field

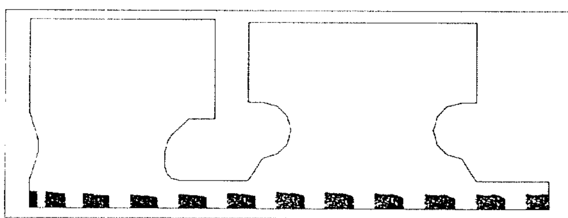

Fig. 2: Cavity contour

Table 1
Fixed parameters during simulations

Laser pulse length (ps)	30.
Laser spot radius (mm)	3.
RF Frequency (GHz)	3.
First cell length (cm)	3.325
Second cell length (cm)	5.835
Cell aperture radius (mm)	5.
Emittance at cathode (mm.mrd)	0.
Magnetic field (T)	0.

Table 2
Parameters for a typical run

Number of particles	100
Charge in a bunch (nC)	2.
RF phase for laser pulse (deg.)	22.
Phase shift between cavities (deg.)	150.

	1^{st} cell	2^{nd} cell
Max. electric field (MV/m)	70.	70.
Kinetic energy (MeV)	1.326	2.867
Bunch length (ps)	17.	17.
Peak current (A)	118.	118.
Bunch radius (r_{max}) (mm)	3.1	3.9
Energy spread (KeV)	186.	33.
Energy spread (%)	14	1.1
Emittance (mm.mrd)	27.3	34.2
Emittance (RF) (mm.mrd)	18.7	15.5
Angular divergence (mrd)	44.7	24.2

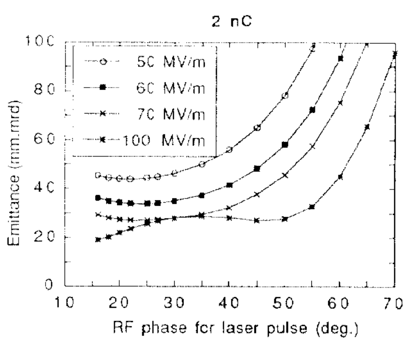

Fig. 3: Emittance after the first cell vs. ϕ_0 for a 2 nC bunch

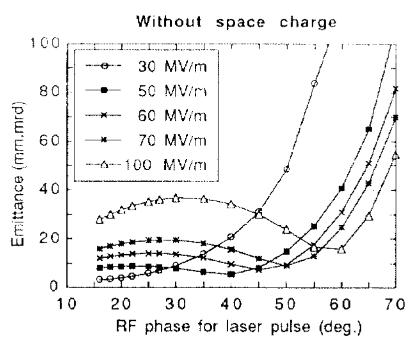

Fig. 4: Emittance after the first cell vs. ϕ_0 when space charge effect is not included

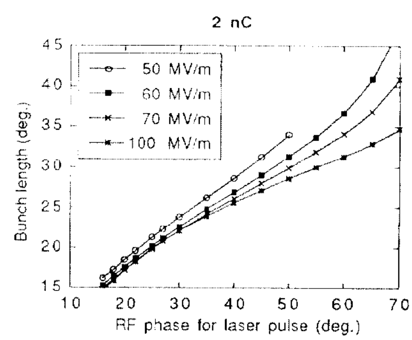

Fig. 5: Bunch length after the first cell vs. ϕ_0

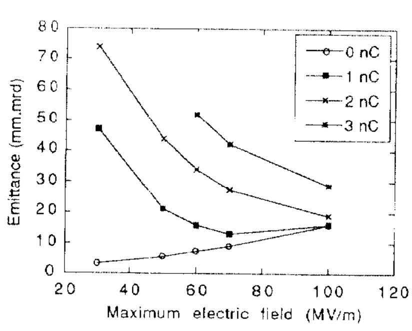

Fig. 6: Emittance after the first cell vs. the maximum electric field

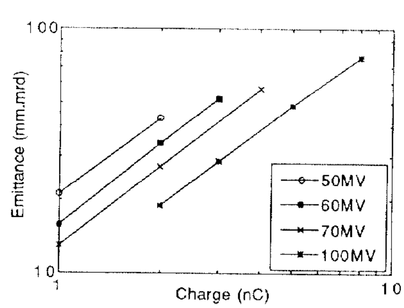

Fig. 7: Emittance after the first cell vs. bunch charge

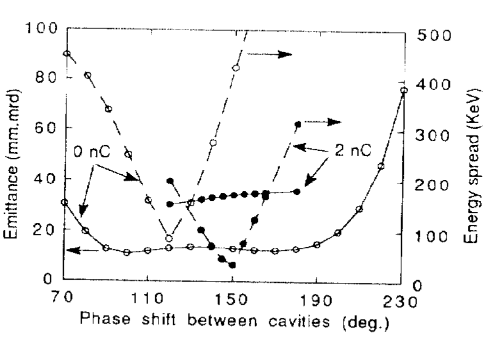

Fig. 8: Emittance and energy spread after the second cell vs. the phase shift between the two cavities