SPACE CHARGE COMPENSATED RF GUN: A NEW WAY TO ULTRA HIGH BRIGHTNESS ELECTRON BEAMS

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Abstract

A preliminary study to achieve space charge field compensation in a laser driven RF gun is presented: first order evaluations of the electron beam brightness and emittance are given, together with an estimation of the bremsstrahlung effects produced by the compensating positron beam.

Introduction

The RF laser driven electron guns have pushed up, in the last years, the capability to generate high brightness electron beams[1], allowing to produce high currents (≈100 A) associated to low transverse normalized emittances ($\approx 1\cdot 10^{-5}$ m·rad).

The success of these devices, with respect to the conventional thermoionic guns, is due both to the higher current densities delivered by semiconductor photoemitters, which constitutes the cathode surface, and to the lower emittance increase produced by the space charge forces. In fact, the possibility to apply to the photocathode surface strong electric RF fields minimizes the momentum transfer from the space charge field to the beam electrons, which is the basic process causing an emittance deterioration[2,3].

However, the minimum emittance attainable is still limited at high current levels by the space charge effects. In this paper we analyze a tentative scheme to compensate for such effects and to achieve the theoretical brightness available from a photoemitter injector, which depends only on the delivered current density and on the equivalent photocathode temperature.

Space charge compensation

Since the space charge forces are produced by the negative charge and current densities associated to the photoelectrons, one can envisage to superimpose a positive charge and current onto the electron bunch just in the first acceleration step, where the photoelectrons are still not relativistic and the space charge forces (scaling like I/γ^2) are dominant.

A possible scheme is shown in Fig.1: while a laser pulse of proper frequency hits the photocathode and ejects photoelectrons, a positron bunch is injected from the rear, through the thin photocathode support, into the RF cavity. As a result, the current densities of the photoelectron bunch and of the positron bunch superpose during the acceleration through the cavity: a burst of X-rays is also produced by the bremsstrahlung process of the positrons inside the photocathode support. The problems related to the radiation damage and to the positron scattering in the support will be studied in the next section: let us now examine what are the requirements on the positron bunch and on the laser pulse to achieve space charge compensation.

First of all, we consider a fully relativistic positron bunch of high kinetic energy, whose transverse dynamics inside the RF cavity is scarcely influenced by the RF field (considerations based on the radiation damage suggest a positron energy around 100 MeV): that allows to consider as constant the associated current density along the gun cavity.

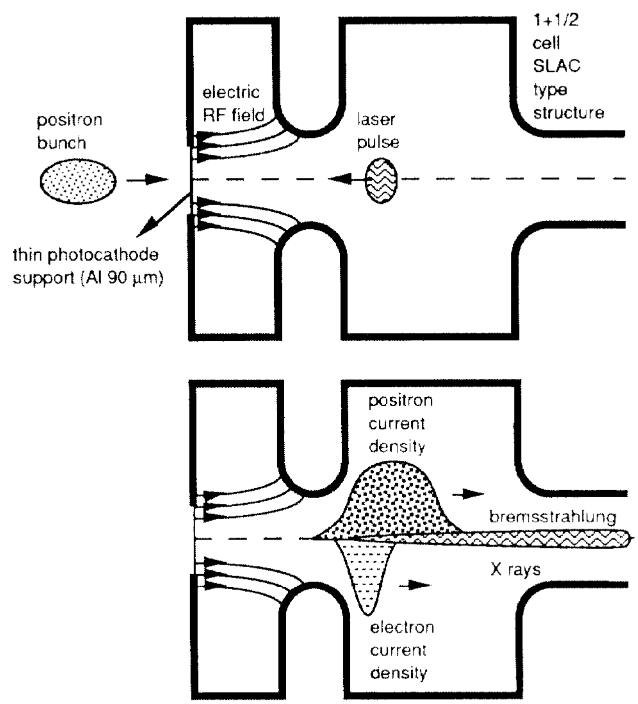

Fig.1 - Space charge compensation scheme: before the photoemission (top diagram) and during the acceleration of the compensated photoelectron bunch (bottom diagram). See text for details.

Following K.J.Kim[3], and taking $\beta\approx 1$ for the positron bunch, the transverse momentum transfer Δp_r produced on an off axis electron (per unitary displacement off axis) by the total space charge field of the two superposed current and charge densities is given by

$$\Delta p_r = \int_0^T F_r\, dt = \frac{-e}{2\varepsilon_0 c} \int_0^L dz \left[\rho_p \frac{(1-\beta)}{\beta} - \frac{\rho_e}{\beta\gamma^2} \right] \qquad 1)$$

assuming that the off axis electron moves along the gun at a constant radius, and taking uniformly charged and long bunches with density ρ_p (positron) and ρ_e (electron). Here β and γ are referred to the electrons and L is the RF gun cavity length. From the integral in eq.1) it can be seen that the total force applied to the electron cannot be reduced to zero all along the acceleration: in the case of a positron density equal to the electron density the total force comes out to be always defocussing, due to the magnetic field produce by the positron current (which is larger than the focussing force applied by the magnetic field of the electron bunch). Therefore the space charge field cannot be indeed neutralized all over the acceleration through the rf gun cavity if only one positive charge and current density is applied.

Taking an RF field of the type $E=E_0\cos(kz)\sin(\omega t+\phi_0)$ (ϕ_0 is the injection phase of the photoelectrons at the cathode surface z=0), we can apply the substitution $d\gamma/dz=eE_0\sin\phi_0/mc^2$, under the assumption that the integrand in 1) is relevant near the cathode surface (at z«1): hence, we get

$$\Delta p_r = \frac{-mc}{2\varepsilon_0 E_0 \sin\phi_0}\left[\rho_p \int_1^{\gamma_f} \frac{(1-\beta)}{\beta} d\gamma - \rho_e \int_1^{\gamma_f} \frac{(1-\beta^2)}{\beta} d\gamma\right] \qquad 2)$$

where γ_f is the final gamma value at the gun exit.

The total momentum transfer comes out to be:

$$\Delta p_r = \left(1-\sqrt{\frac{1-\beta_f}{1+\beta_f}}\right)\rho_p - \frac{\pi}{2}\rho_e \qquad 3)$$

Assuming $\beta_f\approx 1$ at the gun exit (which is usually the case for a RF gun) the total momentum transfer caused by the space charge field (electron +positron) can be zeroed taking $\rho_p=(\pi/2)\rho_e$. The effect of the space charge force can be then compensated globally taking a positron current which is $\pi/2$ times the electron current.

Radiation damage

The positron bunch, hitting the photocathode support, looses energy by emitting bremsstrahlung radiation and because of ionization produced by the collisions inside the target. Both the processes cause an energy deposition inside the photocathode support which must be evaluated and kept low in order to avoid cathode damages.

The energy loss due to radiation emission can be evaluated by[4]:

$$\Delta E_{rad} = E\left[1+\frac{1}{18\ln(183Z^{-1/3})}\right]\frac{s}{X_0} \qquad 4)$$

where E is the positron energy, Z the atomic number of the element in the target, s the target thickness (g/cm^2) and X_0 the radiation length of the Z-element. While the radiation loss scales like the incident energy (the approximate formula given above is valid for high energy positrons and light elements) the collision (ionization) loss scales roughly invariant with respect to the incident energy E. For positrons at 100-500 MeV in Aluminum (whose radiation length is 25 g/cm^2) a good scaling law for the ionization energy loss is given by[5]: ΔE_{col} [MeV] $\approx 48(s/X_0)$.

To estimate the power dissipated into the photocathode support we assume that the ionization loss is completely deposited and thermalized inside the target, whilst the radiation loss, which is largely constituted by high energy photons, escapes from the target if the thickness is small with respect to the radiation length, as for the present case (a 90 μm Al support for the photocathode means a thickness of 25 mg/cm^2, which is 0.1% of the radiation length). Defining η as the fraction of radiation loss deposited into the support (usually η«1 for s/X_0«1), we can estimate the average dissipated power P_d in the support by:

$$P_d[\mathrm{mW}] = f[\mathrm{Hz}]Q_b[\mathrm{nC}]\left(\Delta E_{col}+\eta\Delta E_{rad}\right)[\mathrm{MeV}] \qquad 5)$$

where f is the repetition rate of the positron bunches and Q_b the charge per bunch.

The bremsstrahlung photons are emitted within a root mean square angle given approximately by

$$\theta^{v}_{rms} \approx \frac{\ln\gamma}{\gamma} \qquad 6)$$

while the secondary electrons generated in the e.m. shower are confined within the same angle.

The last relevant quantity to be evaluated is the mean angle of scattering of the positrons after the passage through the photocathode support:

$$\Theta^{e}_{rms} \approx \frac{10.5}{E(\mathrm{MeV})}\sqrt{\frac{s}{X_0}} \qquad 7)$$

Both the angles (expressed in rad) can be kept small by using high energy positron beams: a good energy seems to be around 100 MeV, which keeps low the total energy loss at about 0.15 MeV , giving at the same time a photon emission mean angle $\theta^{v}_{rms}\approx 27$ mrad and a positron scattering angle $\Theta^{e}_{rms}\approx 3$ mrad (with $s/X_0=1\cdot10^{-3}$).

Brightness enhancement with space charge compensation

Assuming a complete space charge compensation, the normalized emittance ε_n at the gun exit becomes a function of only the photocathode equivalent temperature W, i.e. the energy of the photoelectrons emerging from the cathode surface, and of the RF field induced emittance increase. A first order evaluation gives, for the normalized rms emittance[3]:

$$\varepsilon_n = 8.1\cdot10^{-7}\,\sigma_r\sqrt{W + 1.4\cdot10^{-7}\,E_0^2\,\nu_{RF}^4\,\sigma_z^4\,\sigma_r^2} \qquad 8)$$

where E_0 is the peak field on the cathode in MV/m, σ_r and σ_z the laser pulse gaussian widths in mm and ν_{rf} the RF field frequency in GHz (ε_n in m·rad). The emittance minimization requires therefore a cold cathode and a low level, low frequency RF field. The slippage of the electron bunch inside the positron bunch is instead minimized when a high peak field on the cathode is applied: if the superposition of the two bunches has to be assured up to the gun exit (i.e. up to $\beta\approx1$), the positron bunch length L_p (in mm) must be larger than the electron bunch length by a quantity $511/(E_0\sin\phi_0)$ (E_0 in MV/m), which gives an estimation of the slippage.The positron bunch charge Q_p required for the space charge compensation comes out to be (taking into account eq. 3):

$$Q_p = \frac{\pi}{2}\left(1 + \frac{511}{E_0\sin\phi_0 L_e}\right)Q_e \qquad 9)$$

where L_e is the electron bunch length in mm.

A trade off between a high peak field on the cathode, required for low positron bunch charge (hence low power dissipation inside the photocathode support), and a low peak field, required for the emittance minimization, must be therefore attained.

Finally, the maximum brightness achievable at the gun exit can be evaluated as a function of only the RF field frequency, the laser pulse shape and the cathode characteristics. Taking a normalized brightness defined as[6] $B_n=2I/(4\pi\varepsilon_n)^2$, where I is the electron bunch current, and substituting for ε_n the expression given in 8), we get:

$$B_n^{max}[\mathrm{A/m^2rad^2}] = \frac{10^{12}\,J^{max}}{0.81\,W + 2\cdot10^{-4}\,\nu_{RF}^{23/4}\,\sigma_z^4\,\sigma_r^2} \qquad 10)$$

where J^{max} is the maximum current density delivered by the photocathode (units kA/cm^2, while ν_{RF} is given in GHz and σ_r,σ_z in mm). The peak RF field E_0 in eq.8) has been taken from the usual scaling law[7] $E_0[\mathrm{MV/m}]=42\nu_{RF}^{7/8}[\mathrm{GHz}]$.

Again, low frequency RF fields are preferable to minimize the brightness deterioration along the acceleration in the RF gun cavity: unless a RF field effects compensation scheme is used[8], a careful optimization of the operating frequency is needed to achieve the maximum brightness with the lowest positron current.

A 1.5 GHz compensated RF Gun

We enlist in this section a possible set of parameters for a space charge compensated RF gun: the selected RF frequency is 1.5 GHz, which is compatible with fairly high peak field, around 60 MV/m, allowing at the same time to keep low the RF induced emittance increase.

A bunch charge of interest is in the range of some nC: fixing that quantity at 5 nC, the required positron bunch charge becomes 30 nC (if a gaussian width σ_z=1.5 mm is used). The dissipated power in the photocathode support due to the radiative and collision losses is 3 mW per Hz of repetition rate (assuming η=.5, which is surely an over-estimating of the radiative energy deposited in the support). Since the gun length (whose geometry is shown in Fig.1) is about 200 mm and the extraction beam pipe is 40 mm in size, the root mean square divergence of the bremsstrahlung radiation (≈27 mrad) gives a safety margin to avoid that X-rays hit the beam pipe wall.

The root mean square angle of scattering for the positrons is also small enough (a few mrads) to avoid beam pipe hitting if the initial spot size on the cathode is kept small: since this requirement must be satisfied also to minimize the RF induced emittance increase, the laser spot on the cathode (which must be matched with the positron spot size) has to be kept as small as possible compatibly with the available maximum current density. Taking a value of 700 A/cm^2, which can be considered as the status of the art level for the maximum current density delivered by semiconductor photoemitters, a value of 3 mm for the gaussian radial width of the laser pulse has to be taken for 5 nC of extracted bunch.Assuming a transverse gaussian distribution for the bremsstrahlung radiation beam, its 99% ($3\sigma_r$) radius comes out to be 14,4 mm: a negligible amount of radiation will hit the cavity wall.The whole set of data is enlisted in Table1.

Table 1 - 1.5 GHz gun data (SLAC type 1+1/2 cell structure)

Peak field on the cathode	60 MV/m
Photocathode temperature (W)	0.2 eV
Laser pulse rms length ($2\sigma_z$)	10 ps
Laser pulse gaussian width σ_r	3 mm
Electron bunch charge	5 nC
Peak current	400 A
Positron bunch charge	30 nC
Positron bunch rms length	11.5 mm
Diss. power in the photocathode support (η=.5)	3 mW/Hz
Bremsstrahlung radiation beam 99% spot size at the gun exit	14.4 mm
Positron transverse size (rms) at the gun exit (*)	5.3 mm
Electron beam brightness at the gun exit [A/m^2·rad^2]	B_n=2.7·10^{12}

(*) (with a positron rms normalized emittance 5·10^{-3} m·rad)

The normalized rms transverse emittance of the electron bunch at the gun exit is plotted in Fig.2, according to 8), as a function of the laser pulse gaussian widths σ_z and σ_r (the upper scale gives the rms laser pulse length). The iso-emittance curves (units mm·mrad, solid lines) are shown, together with the current density threshold curves (dashed lines): at 1000 A/cm^2 of delivered current by the cathode all the plot region above the curve is permitted while the region below requires higher current densities.The emittance values range in the order of a few mm·mrads.

The brightness at the gun exit comes out to be (at σ_r=3,σ_z=1.5) B_n=2.7·10^{12} A/m^2·rad^2, largely determined by the cathode temperature (50% of brightness degradation produced by the RF field effects). In absence of space charge compensation the beam brightness would be lowered by a factor ≈500.

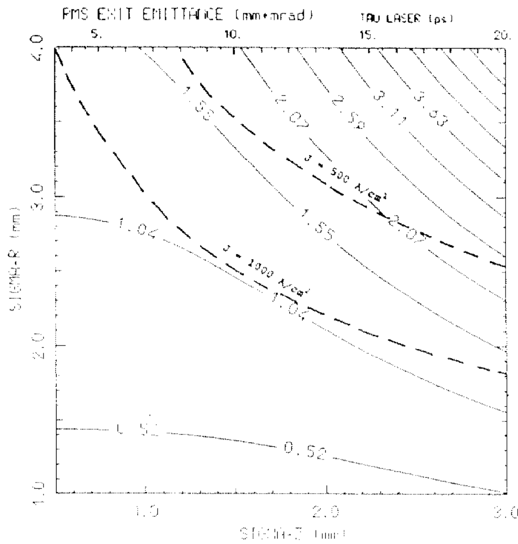

Fig.2 - Rms normalized iso-emittance curves at the gun exit. See text for details

Conclusions

We presented a preliminary study on a possible scheme to achieve space charge compensation in an RF gun: the main goal is the possibility to generate ultra high beam brightness, i.e. in the range of 10^{12} A/m^2·rad^2, avoiding the degradation of the beam brightness available at the photocathode surface, which is usually some orders of magnitude higher than the one obtained at the gun exit.

Accurate numerical simulations (of the PIC type) are needed to optimize the superposition of the positron bunch and the emitted photoelectrons, i.e. to find the best choice of the free parameters: the positron bunch charge, length and injection phase with respect to the laser pulse. In particular, for gaussian bunches a precise tuning of these parameters is mandatory.

MonteCarlo simulations are also needed to study the e.m. shower generated by the positron bunch inside the photocathode support: the fraction η of radiation loss absorbed by the support must be evaluated and, more relevant, the number of photons and secondary electrons stopped inside the photocathode layer has to be computed, in order to estimate the possible cathode damage.

We did not estimate another potential benefit produced by the compensating positron bunch: the field depletion at the cathode surface produced by the photoelectron extraction is counter-balanced by the wake field associated to the positron bunch, which may even enhance the peak electric field on the cathode, allowing to extract more charge. This effect has still to be evaluated.

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