Flat-Beam Rf Photocathode Sources for Linear Collider Applications

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Abstract

Laser driven rf photocathodes represent a recent advance in high-brightness electron beam sources. We investigate here a variation on these devices, that obtained by using a ribbon laser pulse to illuminate the cathode, yielding a flat beam ($\sigma_x \gg \sigma_y$) which has asymmetric emittances at the cathode proportional to the beam size each transverse dimension. The flat-beam geometry mitigates space charge forces which lead to intensity dependent transverse and longitudinal emittance growth, thus limiting the beam brightness. The fundamental limit on achievable emittance and brightness is set by the transverse momentum distribution and peak current density of the photoelectrons (photon energy and cathode material dependent effects) and appears to allow, taking into account space charge and rf effects, normalized emittances $\epsilon_x < 5 \times 10^{-5}$ m-rad and $\epsilon_y < 10^{-6}$ m-rad, with $Q = 5$ nC and $\sigma_z = 1$ mm. These source emittances are adequate for superconducting linear collider applications, and could preclude the use of a damping ring for the electrons in these schemes.

Introduction

The rapid development of rf photocathodes as high-brightness, low emittance electron sources has been spurred on by their potential for use as injectors for linacs which drive free-electron lasers (FELs) and linear colliders[1]. For linear collider applications it is natural to consider sources which give asymmetric ($\epsilon_x \gg \epsilon_y$) emittances, as this asymmetry is necessary for the final focus, which must produce flat beams ($\sigma_x^* \gg \sigma_y^*$). Collisions of flat beams is an almost universal feature of current linear collider designs, as beam flatness can be used to diminish the effects of the coherent beam-beam focusing, or disruption[2]. The strength of the beam-beam interaction can cause the colliding beam particles to radiate photons (beamstrahlung), which induces an undesirable spread in collision energies. Coherent production of e^+e^- pairs by beamstrahlung photons in the intense electromagnetic fields of the oncoming beam is another source of beam-beam related problems[2].

At the lowest energies, as the electron beam leaves the cathode, it is the self-fields of the beam (space-charge fields) which are problematic, as they can give rise to non-uniform defocusing of the beam, which produces transverse emittance growth. The same scheme can be applied for mitigating the strength of the beam's fields here as is applied at the final focus – flattening the beam profile while keeping the cross-sectional area of the beam constant. This not only reduces the effects of space-charge, but also naturally produces an asymmetric emittance.

A cursory analysis of the prospects for this scheme are presented here. It appears that the demands for the electron emittances of a superconducting linear collider[3], which does not utilize such small beams at collision as a normal-conducting machine, can be met using a flat-beam rf photocathode, thus eliminating the need for an electron damping ring. This device can also be considered for supplying the electron beam emittances demanded by the CLIC design[4], which are not too different than those of a superconducting machine. In addition, a recently proposed far infrared FEL scheme[5], which uses a wave-guide with a few mm height to eliminate slippage between the beam and optical pulse, requires very small beam heights (a few mm) at low energy (< 20 MeV), due to the aperture restriction of the wave-guide. Asymmetric emittances from an rf photocathode source may allow the small beam height combined with high peak current needed for this application.

Emittances from Photocathodes

The inherent spread in transverse energy of photoelectrons emitted from the cathode is a complicated function of the photon energy, the applied electric fields, and the electronic structure and work function of the cathode material. It is best to take a characteristic energy, typically the difference between the photon energy and the work function, as the transverse temperature of the beam at emission. We take this temperature to be approximately $kT_\perp = 0.5$ eV for the purposes of this paper. The normalized rms horizontal and vertical thermal emittances of the

beam at the cathode are simply[6]

$$\epsilon_{n(x,y)}^{th} = \sqrt{\frac{kT_\perp}{mc^2}}\sigma_{x,y} \simeq \sigma_{x,y}(mm) \times 10^{-6} \; m \cdot rad.$$

Thus, to take the example of a superconducting linear collider design, to achieve emittances of $\sigma_{y,x} \leq 1,50$ mm-mrad respectively (with a number of particles in a bunch $N_b = 3 \times 10^{10}$), one would illuminate the cathode with a ribbon laser pulse of dimensions less than or equal to $\sigma_{y,x} = 1,50$ mm. Since σ_x is not small compared to typical L or S-band cavity dimensions, it would be better to make σ_x smaller by a factor of at least two. The peak current density derived from the cathode is probably not limited by physics of the laser-surface interaction, but by the longitudinal space charge effects near the cathode. Since short pulse beams can be considered to be infinitesimally thin at very low energy ($\sigma_z \simeq v_z\sigma_t \ll \sigma_{x,y}$), the decelerating electric force at the trailing end of the beam pulse is approximately, including the contribution from image charges

$$eE_z \simeq 4\pi e^2\Sigma_b = \frac{2N_b r_e m_e c^2}{\sigma_x\sigma_y}$$

where N_b is the number of electrons per pulse. If this field is as large as the rf accelerating field eE_{rf}, then one has a completely space-charge limited flow, analogous to the Child-Langmuir limit for gaps. In practice, the decelerating force must be kept much smaller than the applied accelerating field. We take the practical limit here to be a factor 10 times smaller than given above, as even at longitudinal space-charge fields much lower than the limit the bunch may lengthen significantly due to differential acceleration of the front and back of the beam, and we are interested in preserving short pulses. Thus the peak surface density allowed is

$$\frac{N_b}{\sigma_x\sigma_y} \leq \frac{eE_{rf}}{5r_e m_e c^2}$$

and for $eE_{rf} = 80$ MeV/m, $N_b \simeq 1.1 \times 10^{10}\sigma_x\sigma_y(mm^2)$. For the present example we have $N_b \leq 5.5 \times 10^{11}$, and we can afford to make our initial beam sizes, and thus emittances, smaller by large factors in each plane and still run at the desired N_b; the constraint due to longitudinal space charge can be restated as $\sigma_x\sigma_y \geq 2.7$ mm^2.

Transverse Emittance Growth

The blowup of transverse emittance by phase dependent rf focusing and by transverse space-charge forces has been analyzed by K.J. Kim for round beams[7]. The emittance increase due to rf effects in a flat beam can be written as a simple extension of these results

$$\epsilon_{n(x,y)}^{rf} = \frac{eE_{rf}}{\sqrt{2}m_e c^2}(\Delta\phi)^2\sigma_{x,y}^2,$$

where $\Delta\phi = 2\pi\sigma_z/\lambda_{rf}$. It is apparent from this expression that the larger of the two emittances will be affected by

this limit first. For our example, with a pulse length of 1 mm, peak accelerating field of 80 MeV/m and a 1.3 GHz rf gun, the emittance is rf limited when $\sigma_x \geq 12$ mm ($\epsilon_x \geq 12$ mm-mrad), which is smaller than our maximum beam size due to thermal effects. The rf focusing effects can be ameliorated by running at a lower rf frequency, or by shortening the bunch. In addition, it has been proposed by Serafini et al. to remove the phase space correlations by use of an independent rf cavity after the gun[8]. This scheme may allow total cancellation of the rf derived emittance growth.

Calculation of space-charge driven emittance growth is properly done by by self-consistent simulations. This is a very difficult and computationally time-consuming in three-dimensions, and for now we shall only present calculations based on extrapolation of Kim's two-dimensional round beam result to flat, three-dimensional beams. If we require that an expression for the emittance growth reduce to Kim's result in the round beam limit, and have the correct scaling of geometrical factors if the beam is long in its own rest frame ($\gamma\sigma_z \gg \sigma_{x,y}$), then we find

$$\epsilon_{n(x,y)}^{sc} \simeq \frac{\pi I}{4I_A}\frac{mc^2}{cE_{rf}\sin(\phi_0)}\frac{1}{3\sqrt{\frac{\sigma_x\sigma_y}{\sigma_z^2}}+5}\frac{2\sigma_{x,y}}{\sigma_x+\sigma_y},$$

where I is the peak beam current, $I_A \simeq 1.7 \times 10^4$ A is the Alfven current, and ϕ_0 is the initial phase of the bunch on the rf wave, which in practice is often near 70 degrees. For our superconducting linear collider example, we now take beam sizes smaller than the thermally limited maximum by a factor of four, $\sigma_x = 12.5$ mm – approximately the size where the rf contribution asserts itself – and $\sigma_y = 0.25$ mm (note the constraint $\sigma_x\sigma_y \geq 2.7$ mm is satisfied). The horizontal and vertical emittances due to space charge are $\epsilon_{nx}^{sc} = 23$ mm-mrad and $\epsilon_{ny}^{sc} = 0.46$ mm-mrad, respectively. The total emittances for this example are now $\epsilon_{nx} \leq \sqrt{(\epsilon_{nx}^{th})^2 + (\epsilon_{nx}^{rf})^2 + (\epsilon_{nx}^{sc})^2} = 29$ mm-mrad, and $\epsilon_{ny} \leq \sqrt{(\epsilon_{ny}^{th})^2 + (\epsilon_{ny}^{rf})^2 + (\epsilon_{ny}^{sc})^2} = 0.52$ mm-mrad, both slightly over half the design tolerances. The $\leq$ sign is used to indicate that the space-charge and rf derived emittance growth is not independent – correlations should make the total emittance smaller than the sum of squares.

Some Practical Considerations

The model we have used thus far ignores many dynamical aspects of the problem which can only be calculated accurately by computer simulation, a task will be undertaken in the future to assess more completely the physics of this device. For example, should be noted that our model for space charge driven emittance growth is based on the assumption that the beam size does not grow significantly after leaving the cathode – this growth will aggravate the space-charge driven emittance blowup. This assumption may not be justified when a thermal beam is quite small,

as the beam's 'depth of focus' is approximately proportional to the beam size at the cathode. Thus it may be necessary to provide transverse focusing in such a device.

The most common scheme for focusing low energy electron beams is by use of a magnetic solenoid. This is probably unacceptable for our purposes because of the mixing between horizontal and vertical motion due to the angular momentum induced at the entrance to the solenoid. The rotational velocity given to the electrons is caused by a transverse fringe-field which is purely radial. On the other hand, if the transverse is controlled by shaping a flux return yoke to give only a vertical component to the fringe field, then, in the approximation that the fringe field effects act as an impulse, the rotational motion is about the point $(x = x_0, y = 0)$, with radius y_0. In other words, vertical focusing is provided in this scheme, while the horizontal motion can be considered to be 'frozen'. Thus it is possible to provide focusing in using a solenoidal magnetic field without introducing unnecessary correlation of the two transverse phase planes.

Electrons which are created off-axis also traverse longer path lengths after encountering a transverse focusing element. It is possible to eliminate the pulse lengthening associated with this effect by shaping the laser pulse to liberate the off-axis electrons at slightly earlier times[9]. Since the beam in our scheme is wide in the horizontal dimension, it may be necessary to employ this technique to preserve pico-second pulse lengths.

Conclusions

Further theoretical and computational modelling of rf photocathodes in the flat-beam limit must be done to improve the level of understanding of this scheme. In addition, it is necessary to undertake experimental development of these devices. Tests which are scaled to smaller beam sizes and a shorter rf wavelength can be done at the UCLA compact linac source[10]. Also, it should be noted that the parameters given for the superconducting linear collider source is almost identical to the rf photocathode presently under development at for the Argonne Wake-field Accelerator injector[11]. Further tests at that facility would be valuable for judging the suitability of this electron source for linear colliders.

References

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