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Design of a High Duty Cycle, Asymmetric Emittance RF Photocathode Injector for Linear Collider Applications

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Abstract

One of the attractive features of the superconducting approach to linear collider design is that the transverse emittances demanded are much larger than in normal conducting schemes. For TESLA design parameters, the damping rings appear to be relatively large and expensive, and it is therefore of some interest to look into alternative sources. For electrons, a promising source candidate is an rf photocathode. In this paper, we present conceptual design work towards development of an asymmetric emittance rf photocathode source which can operate at the TESLA repetition rates and duty cycle, and is capable of emitting beams with the required emittances and charge per pulse.

1. INTRODUCTION

In linear colliders, the transverse emittances are generally asymmetric, for a variety of reasons. The most compelling have to do with ameliorating the effects of the beam-beam interaction by colliding "flat" beams ($\sigma_x >> \sigma_y$). This allows the beamstrahlung energy loss and spurious pair creation to be minimized, while at the same time loosening the constraints on the final focus system and allowing the beams to collide at a small angle, easing the task of disposing the beam exhaust. In addition, the standard way of obtaining low emittance $e^{\pm}$ beams is through the use of damping rings, which naturally give horizontal emittances which are much larger than vertical ($\varepsilon_x >> \varepsilon_y$).

For the TESLA design parameters, however, the higher average current allows for relaxation of the beam sizes at the final focus. This in turn implies that the emittances can be substantial larger in an SRF linear collider. In fact the TESLA parameter sets usually specify horizontal and vertical normalized emittances of 25-50 and 1 mm-mrad, respectively. These numbers are nearly two orders of magnitude larger than the corresponding normal conducting linear collider designs specify. These numbers are, in fact, near the present state of the art in rf photo-cathode technology. This state of affairs naturally has prompted the suggestion that the electron beam in an SRF collider might be created by an rf photocathode source, doing away with the electron damping ring.

II. ASYMMETRIC EMITTANCE RF PHOTOCATHODE GUNS

There is considerable experience in prod-using symmetric high brightness photocathode sources, whose charge per bunch and product of transverse emittances $\varepsilon_x\varepsilon_y$ are near that demanded by TESLA designs. Unfortunately, it is not possible to produce an asymmetric emittance beam from a symmetric beam which has a smaller emittance in one plane than the original symmetric emittance (see discussion in the Appendix). Thus one must start with an asymmetric beam, $\sigma_x >> \sigma_y$.

The scaling of the emittances with beam and rf parameters rf photocathode sources has been examined in previous work.[1] The emittances arise from three sources: the effective temperature of the photoelectrons (which is usually ignorable), the time-dependence of the transverse rf fields, and space charge.

The rf contribution to the rms emittances is, following Kim[2]

$$\varepsilon_{x,y}^{rf} = \tfrac{1}{\sqrt{2}} W k_{rf}^2 \sigma_z^2 \sigma_{x,y}^2$$

where $W = eE_{rf} / m_e c^2$, and E_{rf} and k_{rf} are the rf electric field amplitude and wave-number, respectively. This scaling pushes one to longer rf wavelength and impacts the large dimension (x in our case) emittance much more severely than the small dimension.

The space charge contribution has been estimated from simulations and model calculations to be, with laser injection phase φ_0,

$$\varepsilon_{n(x,y)}^{sc} = \frac{2N_b r_e}{7\sigma_{x,y} W \sin(\varphi_0)} \exp(-3\sqrt{W\sigma_y})\sqrt{\frac{\sigma_y}{\sigma_z}}.$$

It is also interesting to note that the product of the emittances takes the form

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$$\varepsilon_x^{sc}\varepsilon_y^{sc} \cong \left[\frac{2N_b r_e}{7W}\right]^2 \frac{\exp(-3\sqrt{W\sigma_y})}{\sigma_x\sigma_z}.$$

The exponential term is on the order of unity, and so, at first glance, it would seem that one can make the emittances arbitrarily small by raising $\sigma_x\sigma_y$, but this option is suppressed by the scaling of the rf component to the emittance. In addition, the minimizing of ε_y is ultimately constrained by the longitudinal space charge limit on minimum beam spot size[1], which is

$$\sigma_x\sigma_y \geq \frac{2N_b r_e}{W\sin(\varphi_0)}.$$

This limit has been verified experimentally[3]. Use of a beam at this limit allows us to rewrite the emittance product as

$$\varepsilon_x^{sc}\varepsilon_y^{sc} \cong 0.04\left[\frac{N_b r_e}{W}\right]\frac{\sigma_y}{\sigma_z}.$$

This points out the need to maximize the beam length, which can be exploited if one can circumvent the scaling of $\varepsilon_{n(x,y)}^{rf}$. This point will be returned to below.

III. DESIGN: BEAM DYNAMICS

It is clear that we would like to design a source at as low a frequency as possible since we are pushed towards large σ_z. We also need, however, large accelerating gradients (large W), which implies higher frequencies. A good optimum appears to be at 1300 MHz, which is conveniently the TESLA rf frequency. We have examined the behavior of an asymmetric beam in a 1.5 cell 1300 MHz standing wave π-mode gun, with parameters as listed in Table 1, by inputting an asymmetric beam profile into a form of PARMELA which uses a point-by-point space charge calculation algorithm.

Beam sizes ($\sigma_x,\sigma_y,\sigma_z$)	8, 0.25, 2 mm
Beam population N_b	5×10^{10}
Accelerating field E_{rf}	90 MV/m
Final energy E_b	8 MeV
Final emittances $\varepsilon_{nx},\varepsilon_{ny}$	95,4.5 mm-mrad

Table 1. parameters for PARMELA design calculation of asymmetric emittance rf photocathode source.

For the input beam charge and dimensions given, our final scaling law gives $\varepsilon_x^{sc}\varepsilon_y^{sc} \cong 400$ $(\text{mm - mrad})^2$ which is in fact very close to what is obtained by the simulation. We have fallen short of the TESLA design goals ($\varepsilon_x\varepsilon_y \leq 50$ $(\text{mm - mrad})^2$) by a factor of 2 to 4 in both transverse dimensions. This is not as discouraging as it may seem, since both the rf and space charge contributions to the emittance can be mitigated. Dynamical correction of the space-charge derived emittance is practiced at LANL and preliminary calculations[4] indicate that it may allow TESLA design emittances to be obtained in a 1300 MHz photoinjector. In addition, we are presently examining the effects of using an asymmetric cavity, using the 3-D electromagnetic code ARGUS, to minimize ε_x^{rf}.

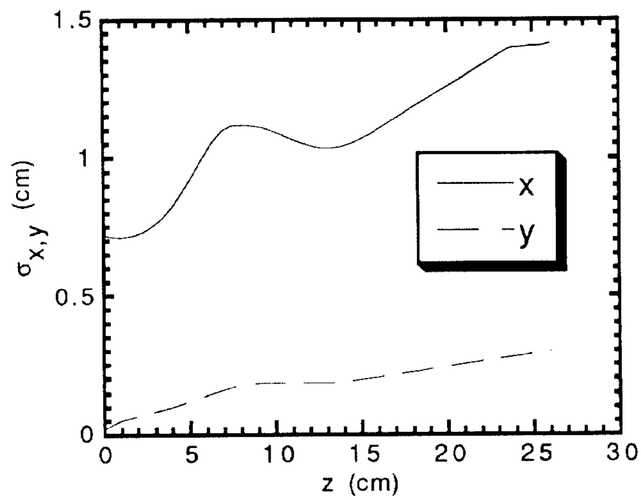

Figure 1: Evolution of the rms beam envelopes in 1.5 cell gun.

The beam dynamics in the gun are dominated by the alternating gradient rf focusing[5], as is shown in Figure 2. Beam transport after the gun must also be optimized to produce no emittance degradation. One common focusing element which is not allowed is the solenoid. Even if one achieves a linear nπ rotation to uncouple the beam, chromatic focusing (and rotation) effects, as well as space-charge effects (even at 8 MeV, the transverse electric field will produce an $\vec{E}\times\vec{B}$ rotation dependent on position in the beam), will destroy the smaller emittance ε_y.

IV. DESIGN: DUTY CYCLE EFFECTS

The TESLA duty cycle presents some difficult challenges to rf photocathode source design. The most obvious is in rf power, both average and peak. The shunt impedance of our gun design is $ZT^2 = 27\ \text{M}\Omega/\text{m}$, and thus the peak power is 15 MW. This peak power must be applied for about 1 msec, with a one percent duty cycle. During each pulse 800 bunches are extracted at a one MHz rate.

This is problematic in terms of both obtaining and dissipating the rf power. A thermal and structural analysis was performed, in which the average power (150 kW) was not found to be difficult to handle. This is not surprising, as the Grumman/BNL gun[6] has a similar average power, with a smaller mass. The peak power and the long rf pulse, may be more serious an issue. Fig. 2 shows the maximum temperature in the structure for the transient case, and we see that the peak temperature rise per pulse is only 15 degrees. The structural analysis is not complete, however, and so the issue of the effect of the heating on rf performance is not resolved. Also of impact on this design is the lack of a commercial klystron with the required specifications; the closest models in performance are presently the Thomson TH 2115 and TD2104U.

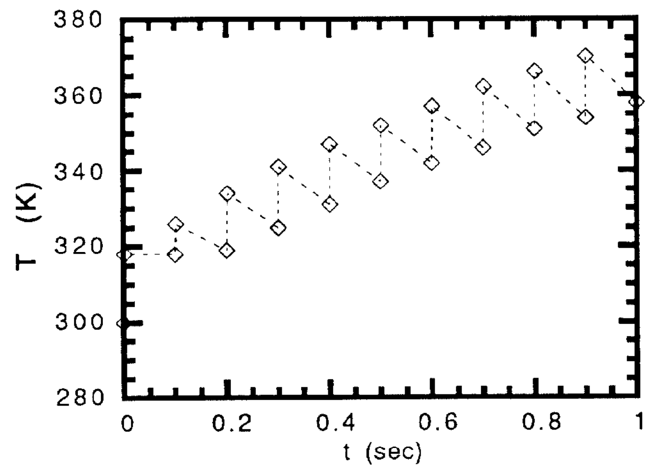

Figure 2. Transient profile of maximum temperature in rf photocathode gun structure.

The other major problem associated the TESLA time structure is that of obtaining a uniform (in laser energy) 800 pulse train at a 1 MHz rate during the rf pulse. This subject is still under study.

Appendix: Impossibility of reducing the minimum emittance in a transverse phase plane

The normalized rms emittances are constrained to evolve in certain ways. In particular the invariance of the determinant of the beam σ matrix under linear transport gives the condition

$$\varepsilon_x \varepsilon_y = \text{constant} \equiv \varepsilon_0^2.$$

where the rms emittances are defined by

$$\varepsilon_x^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

$$\varepsilon_y^2 = \langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2.$$

There are also many invariants associated with higher moments of the Vlasov equation, as discussed by Rangajaran, et al.[7] Of particular interest is a second order moment, which considering only transverse phase space is

$$\varepsilon_2^2 = \varepsilon_x^2 + \varepsilon_y^2 + 2\langle xy \rangle \langle x' y' \rangle - 2\langle xy' \rangle \langle x' y \rangle.$$

This invariant moment is a constant of the motion even if the x and y phase space planes become coupled. Note that if one introduces an infinitesimal coupling to a previously uncoupled system, it must be by applying a skew quadrupole kick, which only changes the last term in the above equation. In that case, it is easy to show that a kick of this form causes this additional term to be positive, $\langle xy' \rangle \langle x' y \rangle > 0$. Thus the rms emittances must grow if one couples the phase space planes, in order to preserve the invariance of ε_2.

Because of this, if one begins with uncoupled phase space planes, one must always completely uncouple the phase space planes in order to obtain a minimum sum of squares of the emittances. Now we have a second constraint on the emittances, derived from the second order invariant,

$$\varepsilon_2^2 = \text{constant} = \varepsilon_x^2 + \varepsilon_y^2.$$

If we now apply both constraints on the emittances, we can derive a condition for the final state emittances in terms of the initial emittances ε_x and ε_y, as follows. We have

$$\varepsilon_2^2 = \varepsilon_{x0}^2 + \varepsilon_{y0}^2 \quad \text{and} \quad \varepsilon_0^2 = \varepsilon_{x0}\varepsilon_{y0}.$$

Solving this system for the final emittances, we have

$$\varepsilon_{x,y}^2 = \frac{\varepsilon_2^2 \pm \sqrt{\varepsilon_2^4 - 4\varepsilon_0^4}}{2} = \varepsilon_{x0}^2 \text{ or } \varepsilon_{y0}^2.$$

The final emittances, under this uncoupled condition, can take on only the value of either of the initial emittances. Leaving the emittances unchanged is obtained by any total transformation which contains a rotation of $n\pi$, and exchange of the two emittances by any transformation containing a rotation of $(n+\frac{1}{2})\pi$ (n integer).

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