# A low emittance, flat-beam electron source for linear colliders

R. Brinkmann, Y. Derbenev, and K. Flöttmann
*DESY, D-22603 Hamburg, Germany*
(Received 9 December 2000; published 18 May 2001)

We present a method to generate a flat (large horizontal to vertical emittance ratio) electron beam suitable for linear colliders. The concept is based on a round-beam rf photoinjector with finite solenoid field at the cathode together with a special beam optics adapter. Computer simulations of this new type of beam source show that the beam quality required for a linear collider may be obtainable without the need for an electron damping ring.

DOI: 10.1103/PhysRevSTAB.4.053501 PACS numbers: 29.17.+w, 41.75.Fr

## I. INTRODUCTION

The transverse phase space densities (ratio of bunch charge to emittance) required for the colliding bunches in different schemes for a next generation $e^+e^-$ linear collider exceed the possibilities of conventional electron guns by large factors. Photocathode rf guns designed for free electron lasers provide much smaller emittances, but the beam delivered by these devices is naturally "round," ($\varepsilon_x = \varepsilon_y$), in contrast to the "flat" beam ($\varepsilon_y \ll \varepsilon_x$) needed for a linear collider to suppress beamstrahlung [1] at the interaction point; see Table I. We developed a scheme in which a round low emittance beam is transformed into a flat beam and which is suitable to replace the electron damping ring for a linear collider facility by one or a combination of a few rf guns. The method is outlined in the following section and the complete setup and computer tracking simulation results are described in Section III of this paper.

TABLE I. Bunch parameters for linear collider projects in comparison with typical free electron laser (FEL) rf gun parameters. Here and in the following, $\varepsilon$ denotes the *normalized* emittance.

| | TESLA | $X$-band | FEL |
|---|---|---|---|
| Charge $Q$ (nC) | 3.2 | 1.5 | 1 |
| $\varepsilon_x$, $\varepsilon_y$ ($10^{-6}$ m) | 10, 0.03 | 4, 0.05 | $0.5, \ldots, 1$ |
| $Q_b/(\varepsilon_x \cdot \varepsilon_y)^{1/2}$ | 5.8 | 3 | $1, \ldots, 2$ |

## II. BEAM OPTICS ADAPTER

The beam optics "trick" used here was originally applied to match a flat electron beam to a round hadron beam in an electron cooling scheme [2]. For the case of an electron gun considered here, this transformation is possible in the presence of a longitudinal solenoid field at the position of the cathode where the beam is generated and can be constructed by combining the end field of the solenoid with a suitable skew quadrupole arrangement [3–5]. The effect of the skew quadrupoles is such as to remove the angular momentum of the beam due to the solenoid field and to break the symmetry between the $x$ and the $y$ plane of betatron motion. In detail, the construction of the desired 4-dimensional linear transformation, acting on the phase space vector $(x, x', y, y')$, proceeds in the following way.

Consider the transformation matrix $E$ of a solenoid end field (longitudinal field strength $B_z$, particle momentum $p_0$) in thin lens approximation:

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & -1/\beta & 0 \\ 0 & 0 & 1 & 0 \\ 1/\beta & 0 & 0 & 1 \end{bmatrix}, \quad \beta = 2p_0/eB_z\,. \quad (1)$$

Next, a skew block $4 \times 4$ matrix $C$ is constructed from $2 \times 2$ matrices $M, N$ in the following way:

$$C = \frac{1}{2}\begin{bmatrix} N + M & N - M \\ N - M & N + M \end{bmatrix}, \quad (2)$$

where $M, N$ have the form

$$M = \begin{bmatrix} \cos\mu & \beta\sin\mu \\ -\frac{1}{\beta}\sin\mu & \cos\mu \end{bmatrix}, \qquad N = M(\mu + \pi/2)\,. \quad (3)$$

The phase $\mu$ is a free parameter, the essential point is the 90° phase difference between matrices $M$ and $N$. The total transformation is given by ($c = \cos\mu,\ s = \sin\mu$)

$$T = CE = \begin{bmatrix} c - s & \beta(c + s)/2 & -(c + s) & \beta(c - s)/2 \\ -(c + s)/\beta & (c - s)/2 & (s - c)/\beta & -(c + s)/2 \\ 0 & \beta(c - s)/2 & 0 & \beta(c + s)/2 \\ 0 & -(c + s)/2 & 0 & (c - s)/2 \end{bmatrix}. \quad (4)$$

  

This transformation turns an initial round-beam distribution with rms size $\sigma_r$ and angular spread $\sigma_{r'}$ into one with emittances ($\gamma = p_0/mc$):

$$\varepsilon_y/\gamma = \frac{1}{2}\,\beta\sigma_{r'}^2, \qquad \varepsilon_x/\varepsilon_y = 1 + \frac{2\sigma_r^2}{\beta^2\sigma_{r'}^2}. \tag{5}$$

The final emittance ratio is thus simply variable by adjusting $\beta$ via the magnetic field $B_z$. The practical realization of the transformation matrix $C$ can easily be done by a triplet of skew quadrupoles; see Refs. [4,5]. It should be noted here that the above derivation assumed vanishing cross correlations in the initial particle distribution, i.e., a beam which is neither convergent nor divergent nor rotating at the position of the solenoid end field. This does not present a fundamental limitation of the method; in practice the matching conditions can be fulfilled by proper adjustment of the focusing elements in the beam line. One example is the tapering of the solenoid field in the setup described in the following section.

## III. SETUP OF THE FLAT-BEAM SOURCE AND SIMULATION RESULTS

A complete setup of a flat-beam source was first studied in Ref. [3]. A low emittance (round) electron beam is produced in an rf photoinjector very similar to the ones installed at the FNAL A0-experiment and at the TESLA Test Facility (TTF) at DESY. The phase space density achievable in these sources is limited by space charge effects, in particular, the variation of the defocusing force over the length of the bunch. Starting from this approach, we achieved a significant improvement of the transverse emittance by optimizing the beam and magnetic field parameters. In contrast to the TTF gun which is used for the FEL operation, the longitudinal emittance is of much less concern for the linear collider application. This permits one to drastically increase the bunch length and reduce space charge effects leading to emittance growth. Simultaneously, the beam radius at the cathode can be reduced and the magnetic field strength compatible with the required final horizontal emittance ($\varepsilon_x \propto B_z\sigma_r^2$ as described above) can be increased. The benefit of a strong solenoid focusing in the gun is the possibility to (partially) cancel the effect of the rf focusing spread (see below) which for long bunches would otherwise become the dominant source of emittance growth.

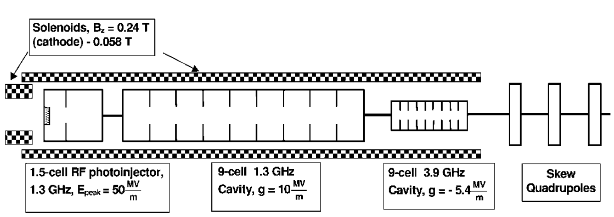


FIG. 1. Sketch of the electron beam source layout.

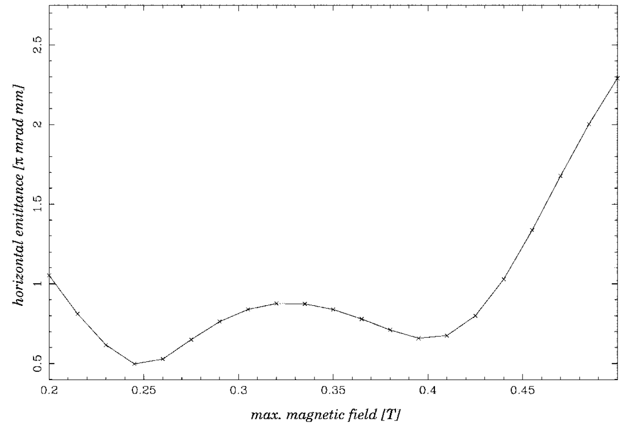


FIG. 2. Horizontal emittance obtained from ASTRA [6] simulations at the exit of the rf gun vs solenoid field at the cathode.

The complete setup, which has been investigated by computer simulation [6] is shown schematically in Fig. 1. It consists of a $1\frac{1}{2}$-cell 1.3 GHz rf gun followed by a 9-cell cavity used as an energy booster and a 9-cell third harmonic cavity used to remove the second order correlated energy spread in the bunch. For the sake of simplicity of the beam optics matching to the adapter triplet, a continuous solenoid field extending from the gun over the booster and third harmonic cavities has been assumed. In the cathode region, the field is enhanced by an additional coil (in the FEL gun, this "bucking coil" is normally used to adjust the magnetic field strength to zero).

We determined the optimum magnetic field over the length of the gun numerically by minimizing the emittance growth due to the rf focusing effect. The dependence of the emittance at the gun exit as a function of magnetic field at the cathode is shown in Fig. 2. For this calculation the emittance is calculated without the contribution of the rotational motion, in order to be sensitive to effects which determine the final vertical emittance. The solenoid field disturbs the cancellation of the effect of focusing and

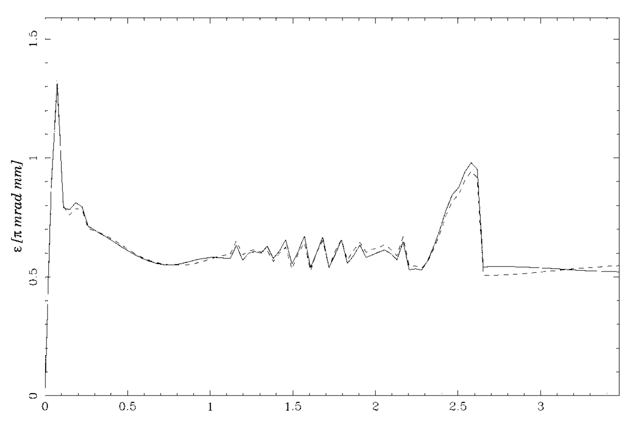


FIG. 3. Horizontal and vertical emittances obtained from ASTRA [6] simulations for the electron source up to position $z$ just before the end of the solenoid.

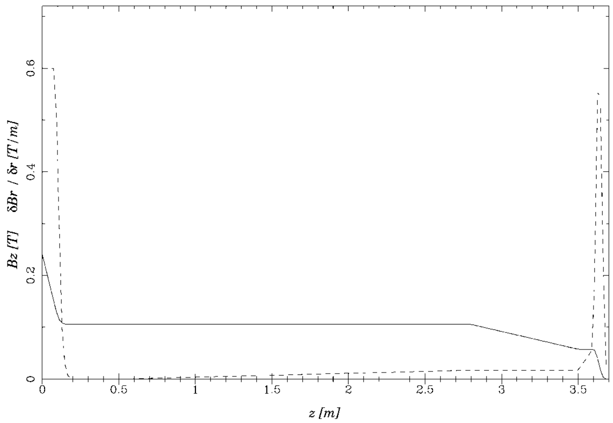


FIG. 4. Solenoid field strength $B_z$ (solid line) and radial derivative $dB_r/dr$ (dashed line) as a function of position along the beam line.

defocusing forces at the entrance and the exit of a cell, which reduces the emittance growth due to rf fields in other cases [7]. Since a radial kick leads to an angular motion of the electrons, the cancellation works only for specific phase advances of the Larmor angle over one cell. As compared to a complete cavity cell, traversed at higher energy, the situation in the rf gun is more complicated due to the 1.5-cell layout and the fact that the beam radius and the trajectory phase with respect to the rf field change during passage of the particles through the structure. We find that the total Larmor phase advance from the cathode to the exit of the gun amounts to 150° for the solenoid field strength at which the first emittance minimum occurs and to 250° at the second minimum. A detailed analysis of the effect is in progress.

The emittance of the round beam before exiting from the solenoid, including space charge but not taking into account the thermal contribution from the cathode, is about 0.5 mm mrad for a bunch charge of $Q_b = 0.8$ nC (Fig. 3). Because of the small rms spot size of only 0.26 mm on the cathode the contribution of the thermal emittance is estimated as $\varepsilon_{\mathrm{th}} \leq 0.15$ mm mrad [8]. The magnetic field is smoothly reduced along the beam line (Fig. 4) from 0.24 T at the cathode (corresponding to the first emittance minimum, see above) to 0.058 T in order to match the radial expansion of the beam (Fig. 5) and avoid any collective rotation, i.e., $\sigma_r^2 B_z$ has the same value at the cathode and at the end of the solenoid.

TABLE II. Electron source parameters.

| | |
|---|---|
| Laser pulse flat top | 100 ps |
| Bunch charge | 0.8 nC |
| rms radius at cathode | 0.26 mm |
| Solenoid field at cathode | 0.24 T |
| rf gun peak electric field | 50 MV/m |
| Booster cavity accelerating voltage | 10 MV |
| Third harmonic cavity decelerating voltage | 1.8 MV |
| Final beam momentum | 14.2 MeV/$c$ |
| rms bunch length | 8 mm |
| Relative energy spread | 0.2% |
| Transverse emittance | 0.5 mm mrad |
| Estimated thermal emittance | <0.15 mm mrad |

A summary of the electron source parameters and of the resulting beam parameters at the end of the beam line enclosed by the solenoid is given in Table II. We use the particle distribution obtained by the tracking code to simulate the transport through the final part of the beam line with the end field of the solenoid and the skew quadrupole triplet. Since the ASTRA code assumes cylindrically symmetric beams for space charge calculation, space charge effects are not taken into account for this part of the simulation. The evolution of the beam emittances through the flat-beam adapter is shown in Fig. 6. We finally obtain an emittance ratio of 370 with $\varepsilon_x = 1.1 \times 10^{-5}$ m, $\varepsilon_y = 3 \times 10^{-8}$ m.

We thus obtain an almost exact match with the TESLA design emittances, but it has to be noted that this was achieved with one-quarter of the design bunch charge. Going to higher bunch charge will require us to reoptimize

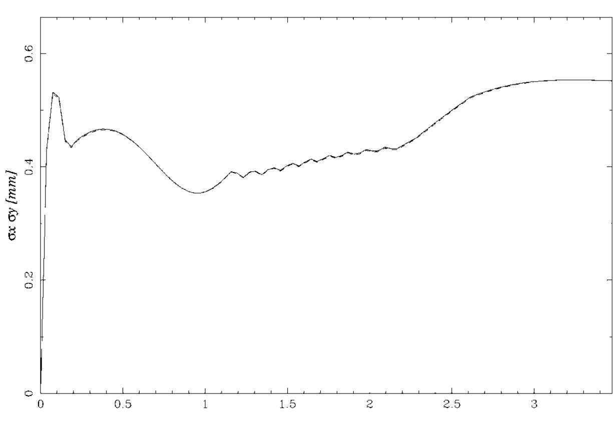


FIG. 5. Transverse beam size as a function of position along the beam line.

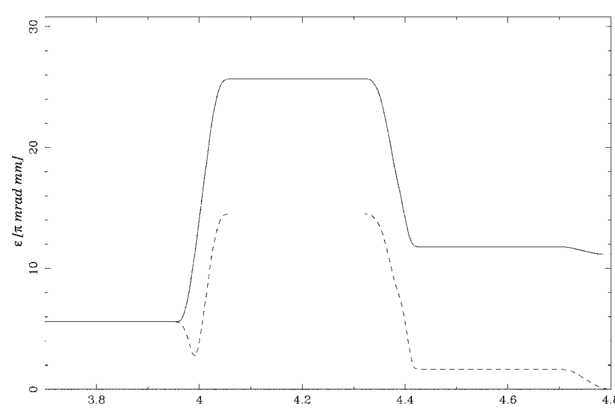


FIG. 6. Evolution of the horizontal (solid line) and vertical (dashed line) beam emittances in the skew quadrupole triplet.

the rf gun parameters. This has not yet been investigated in detail.

## IV. CONCLUSIONS

We have shown that a flat electron beam can be generated by a low emittance rf gun combined with a linear beam optics transformation. Computer simulations show that at low bunch charge ($<1$ nC) emittances comparable to the ones achievable in damping rings can be obtained. A higher bunch charge, such as required for TESLA, can be obtained by combining the beams from several guns. One way to achieve this is to merge bunches of slightly different energy in a bending section (so-called dispersive funneling). This method, as well as issues regarding space charge effects in the flat beam, needs further studies. Furthermore, emittance preservation in the low-energy part of the preaccelerator and bunch compressor section following the source must be investigated.

The first successful demonstration of a flat-beam source was recently achieved in an experiment performed at the A0 test stand at FNAL [9]. While the possibility of generating a beam with a large horizontal-to-vertical emittance ratio was clearly proven, the vertical emittance obtained was still about 1 order of magnitude larger than the design goal for a future linear collider. Further improvements of the rf gun parameters at A0, in particular, a reduction of the space charge effect by operating with longer bunches, are under discussion and may allow us in the future to push the performance to higher beam quality.

[1] P. Chen and K. Yokoya, KEK Report No. 91-2, 1991.
[2] Y. Derbenev, University of Michigan Report No. UM-HE-98-04, 1998.
[3] A. Burov and V. Danilov, FNAL Report No. TM-2040, 1998.
[4] R. Brinkmann, Y. Derbenev, and K. Flöttmann, DESY Report No. TESLA 99-09, 1999.
[5] A. Burov and S. Nagaitsev, FNAL Report No. TM-2114, 2000.
[6] K. Flöttmann, ASTRA user manual, available on the internet: http://www.desy.de/~mpyflo/Astra_dokumentation.
[7] J. Rosenzweig and L. Serafini, Phys. Rev. E **49**, 1599 (1994).
[8] K. Flöttmann, DESY Report No. TESLA-FEL 97-01, 1997.
[9] D. Edwards *et al.*, in Proceedings of the XXth International Linac Conference, Monterey, 2000 (to be published).