A LOW EMITTANCE, FLAT-BEAM ELECTRON SOURCE FOR LINEAR COLLIDERS

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Abstract

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-laser gun 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.

1 INTRODUCTION

The 4-D transverse phase space densities 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", (ε_x = ε_y), in contrast to the "flat" beam ($\varepsilon_y << \varepsilon_x$) needed for a Linear Collider to suppress beamstrahlung at the interaction point, see Table 1. 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 set-up and computer tracking simulation results are described in section 3 of this paper.

Table 1: Bunch parameters for Linear Collider projects in comparison with typical FEL rf-gun parameters. Here and in the following, ε denotes the *normalised* emittance.

	TESLA	X-band	FEL
charge Q_b [nC]	3.2	1.5	1
ε_x, ε_y [10^{-6} m]	10, 0.03	4, 0.05	0.5…1
$Q_b/(\varepsilon_x \cdot \varepsilon_y)^{1/2}$	5.8	3	1…2

2 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 [1]. This transformation is possible in the presence of a longitudinal solenoid field and can be constructed by combining the end field of the solenoid (matrix *E* in thins lens approximation) with a suitable skew block matrix *C* (see refs. [2,3,4]). The 4×4 matrix *C* can be constructed from 2×2 matrices *M*, *N* in the following way:

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

where *M*, *N* have the form

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

The phase μ is a free parameter, the essential point is the 90° phase difference between matrices *M* and *N*. The beta-function is determined by the solenoid field and beam momentum, $\beta=2p_0/eB_z$. Together with the solenoid end field matrix

$$E = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 1/\beta & 0 \\ 0 & 0 & 1 & 0 \\ -1/\beta & 0 & 0 & 1 \end{bmatrix},$$

the total transformation is given by: ($c=\cos\mu$, $s=\sin\mu$)

$$T = C \cdot E =$$

$$\begin{bmatrix} c-s & \beta(c+s)/2 & -(c+s) & \beta(c-s)/2 \\ -(c+s)/\beta & (c-s)/2 & (s-c)/\beta & -(c+s)/2 \\ 0 & \beta(c-s)/2 & 0 & \beta(c+s)/2 \\ 0 & -(c+s)/2 & 0 & (c-s)/2 \end{bmatrix}$$

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

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

The final emittance ratio is thus simply variable by adjusting β via the magnetic field B_z. The practical realisation of the transformation matrix *C* can easily be done by a triplet of skew quadrupoles, see refs. [2,3].

3 SET-UP OF THE FLAT BEAM SOURCE AND SIMULATION RESULTS

A complete set-up of a flat beam source was first studied in ref. [3]. A low-emittance (round) electron beam is produced in an rf-laser gun very similar to the ones installed at the FNAL A0-experiment and at the TESLA Test Facility (TTF) at DESY. Starting from this approach, we achieved a significant improvement of the transverse emittance by optimising the beam and magnetic field parameters. In contrast to the TTF gun which is used for FEL operation, the longitudinal emittance is of much less concern for the Linear Collider application. This permits 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 ($\varepsilon_x \propto \sigma_r^2 \cdot B_z^2$ 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 rf-focusing spread which for long bunches would otherwise become the dominant source of emittance growth.

The complete set-up, which has been investigated by computer simulations [5] is shown schematically in Figure 1. It consists of a 1½-cell 1.3 GHz rf-gun followed by a 9-cell cavity used as energy booster and a 9-cell 3rd harmonic cavity used to remove the 2nd order correlated energy spread in the bunch. For the sake of simplicity of the beam optics matching to the adapter triplet, a continues solenoid field extending from the gun over the booster and 3rd harmonic cavities has been assumed. In the cathode region, the field is enhanced by an additional coil.

We determined the optimum field strength numerically by minimising the emittance growth due to the rf-focusing effect in the gun. It is found that for the chosen value the angle of Larmor rotation per cell length of the gun is about 90°. This supports the interpretation that the emittance optimum coincides with a partial cancellation of rf-focusing effects.

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 0.5mm·mrad for a bunch charge of Q_b=0.8nC (Figure 2). We note that this good beam quality is achieved here without applying the so-called space charge emittance compensation scheme. The magnetic field is smoothly reduced along the beam line from 0.24T at the cathode to 0.058T in order to match the radial expansion of the beam (Figure 3) and avoid any collective rotation, i.e. $\sigma_r^2 \cdot B_z$ has the same value at the cathode and at the end of the solenoid.

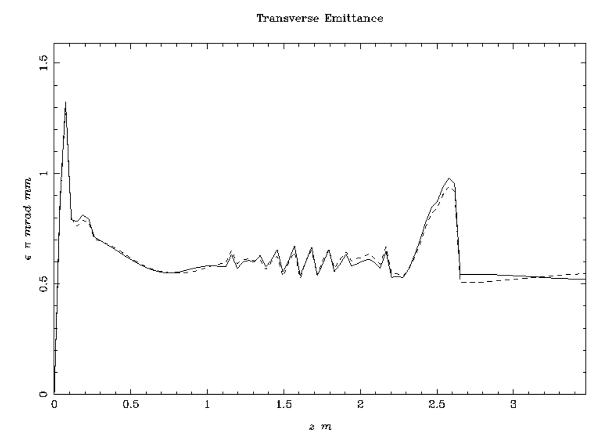

Fig. 2: Horizontal and vertical emittance obtained from ASTRA [5] simulations for the electron source up to position *z* just before the end of the solenoid.

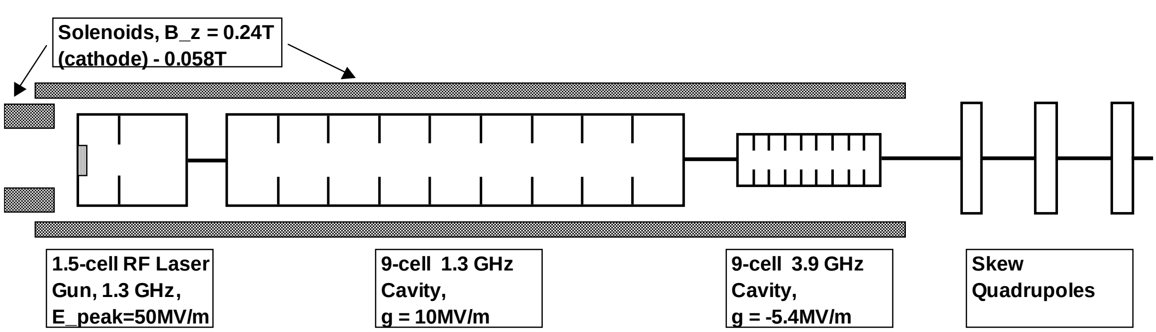

Figure 1: Sketch of the electron beam source layout.

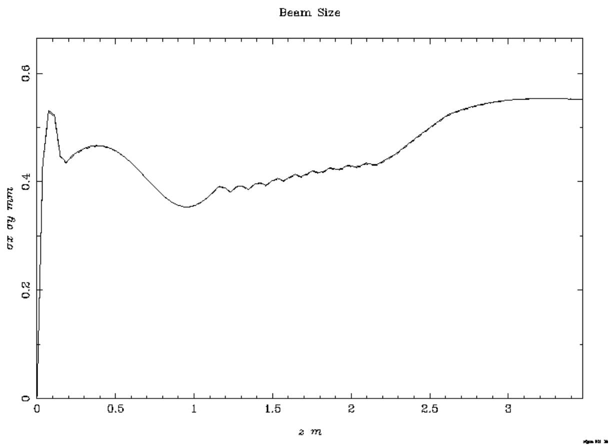

Fig. 3: Transverse beam size in the electron source beam line up to the end of the solenoid.

Table 2: Electron source parameters

laser pulse flat top	100ps
rise/fall time	4ps
bunch charge	0.8nC
rms radius at cathode (homogeneous distribution)	0.26mm
solenoid field at cathode	0.24T
rf-gun peak electric field	50MV/m
launch rf-phase	43 deg.
booster cavity accelerating voltage	10MV
3rd harmonic cavity decelerating voltage	1.8MV
final beam momentum	14.2MeV/c
rms bunch length	8mm
rel. energy spread	0.2%
transverse emittance	0.5mm·mrad
estimated thermal emittance	< 0.2mm·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 are given in Table 2. We use the particle distribution obtained by the tracking code to simulate the transport through the final part of the beam line with 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 Figure 4. We finally obtain an emittance ratio of about 370 with:

$$\boldsymbol{\varepsilon_x = 1.1\cdot10^{-5}\ \mathrm{m},\ \varepsilon_y = 3\cdot10^{-8}\ \mathrm{m}}$$

This matches the required parameters for TESLA almost exactly, 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 to re-optimise the rf-gun parameters. This has not yet been investigated in detail. Very roughly, we expect an increase of the round-beam emittance linearly proportional to the charge.

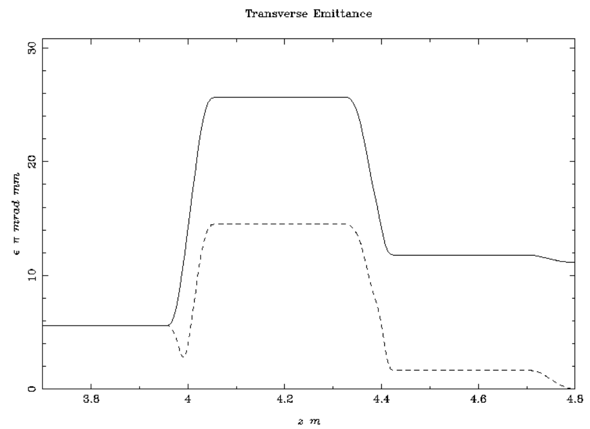

Fig. 4: Evolution of horizontal (full line) and vertical (dashed line) beam emittance through the adapter section.

4 CONCLUSIONS

We have shown that a flat electron beam can be generated by a low-emittance rf-gun combined with a simple beam optics transformation. The first successful demonstration of this method was recently (May 2000) achieved at the A0 experiment at FNAL [6]. Simulations show that at low bunch charge (< 1nC) emittances comparable to the ones achievable in damping rings can be obtained. A higher bunch charge, such as required for TESLA, can be obtained from combining several beams with e.g. 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 pre-accelerator and bunch compressor section following the source must be investigated.

REFERENCES

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