TESLA 99-09

A Flat Beam Electron Source for Linear Colliders

R. Brinkmann, Ya. Derbenev and K. Flöttmann, DESY

April 1999

Abstract

We discuss the possibility of generating a low-emittance "flat" ($\varepsilon_y \ll \varepsilon_x$) electron beam by combining an RF-laser gun with a special beam-optical transformation. The achievable beam quality corresponds to a normalized transverse emittance of about $(\varepsilon_x \cdot \varepsilon_y)^{1/2} = 10^{-6}$ m per nC of bunch charge with ratio $\varepsilon_x/\varepsilon_y$ of the order of 10^2. In a scheme with a combination of a small number of such devices, it may become possible to replace the electron damping ring for a Linear Collider facility.

1. Introduction

The 4-D transverse phase space densities foreseen for the colliding bunches in different Linear Collider facilities presently under study exceed the possibilities of conventional electron guns considerably. With modern designs of laser-driven RF-guns for Free Electron Laser projects, the situation is much improved, but the remaining problem is that such devices produce round beams not useful for e+e- Linear Colliders (flat beams are needed to suppress the beamstrahlung at the Interaction Point). Attempts to design RF-guns with flat cathode have so far not been successful, the predicted beam quality misses the requirements for the 4-D emittance by about two orders of magnitude. Improvements using the so-called space charge emittance compensation are possible, but more difficult than for a cylindrically symmetric beam (J. Rosenzweig and co-workers, see Section 3.4.4 in ref. [1] for a discussion of this issue for the case of the TESLA project).

	TESLA CDR	TESLA high L.	NLC/JLC	CLIC	FEL
Q_b [nC]	5.8	3.2	1.5	0.6	1
Norm. ε_x, ε_y [10^{-6} m]	15, 0.25	10, 0.03	4.5, 0.1	1.9, 0.1	1…1.5
$\varepsilon_x \cdot \varepsilon_y / Q_b$ [10^{-12}m/nC]	0.65	0.094	0.30	0.32	1…2

Table 1: Bunch parameters at the IP for different Linear Collider projects [1-3] in comparison with typical FEL RF-gun parameters [4]. Here and in the following, $\varepsilon_{x,y}$ denote the *normalised* emittances.

As one can infer from Table 1, the combination of bunches (merging different orbits by dispersive "funneling") from a small number of RF-guns can yield the desired 4-D phase space density (except for the more ambitious parameters of the TESLA high luminosity version) and thus replace the electron damping ring, provided that a way to convert the round electron beam from the gun into a flat one can be found.

2. The Flat Beam Adapter

We use a beam optics "trick" here which was originally proposed in the context of cooling high-energy hadron beams with an electron beam circulating in a storage ring [5]. In that case the idea is to transform the naturally flat electron beam into a round shape with small angular spread (low temperature) in the cooling section. This transformation is possible if a longitudinal solenoid field is present and can in practice be provided by the combination of a triplet of skew quadrupoles and the end-field of the solenoid [6]. For the application considered here, we reverse the transformation: starting with a low-emittance round beam from an RF-gun with finite solenoid field at the cathode, the beam passes through the end-field and the skew-triplet. By suitable choice of parameters, an arbitrary ratio of final emittances $\varepsilon_x/\varepsilon_y$ can be achieved, whereas the geometric mean $(\varepsilon_x \cdot \varepsilon_y)^{1/2}$ is conserved and equal to the transverse emittance of the gun. In detail, the transformation is constructed in the following way (see ref [6]):

We start from a 2x2 Matrix

$$M = \begin{bmatrix} \cos(\mu) & \beta \sin \mu \\ -\sin(\mu)/\beta & \cos(\mu) \end{bmatrix}$$

and define a 2nd matrix N = -F·M, where

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

Here, $\beta = -2pc/eB_z$ (p is the beam momentum, B_z the solenoid field) and μ is a free parameter.

The uncoupled 4x4 matrix $U = \begin{bmatrix} M & 0 \\ 0 & N \end{bmatrix}$ is transformed into a skew block by means of a 45 deg. rotation:

$$C = R_{45}^{-1} U R_{45} = 1/2 \begin{bmatrix} M+N & N-M \\ N-M & M+N \end{bmatrix}$$

The complete 4x4 Matrix T = C·E, where E is the matrix for the solenoid end-field in thin lens approximation, is then given by:

$$T = \begin{bmatrix} \cos\mu - \sin\mu & \beta(\cos\mu + \sin\mu)/2 & -\cos\mu - \sin\mu & \beta(\cos\mu - \sin\mu)/2 \\ -(\cos\mu + \sin\mu)/\beta & (\cos\mu - \sin\mu)/2 & (\sin\mu - \cos\mu)/\beta & -(\sin\mu + \cos\mu)/2 \\ 0 & \beta(\cos\mu - \sin\mu)/2 & 0 & \beta(\cos\mu + \sin\mu)/2 \\ 0 & -(\sin\mu + \cos\mu)/2 & 0 & (\cos\mu - \sin\mu)/2 \end{bmatrix}$$

Note that the transformation is non-symplectic (the canonical transverse momentum inside the solenoid includes the transverse vector potential). For the initial 4-D phase space (x_0, x_0', y_0, y_0') distribution we assume a round beam with $\sigma_{x0} = \sigma_{y0} = \sigma_r/2^{1/2}$, $\sigma_{x0'} = \sigma_{y0'} = \sigma_{r'}$ and vanishing cross-correlations $<x_0\, x_0'> = 0$, etc. (beam neither convergent nor divergent nor rotating). The matrix T transforms this into a distribution in (x, x', y, y') with the following properties:

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

$$\beta_x = \beta_y = \beta \quad , \quad \alpha_x = \alpha_y = 0$$

By adjusting the solenoid field and thus the parameter β, in principle any (large) emittance ratio $\varepsilon_x/\varepsilon_y \propto B_s^2$ can be realized.

The simplest practical solution for the transformations M and N is a symmetric skew quadrupole triplet. In order to demonstrate the method we give an example, not related to a particular RF-gun design, but with "typical" parameters. The adapter lattice is sketched in Fig. 1 and the beam and magnet parameters are listed in Table 2. The development of the horizontal and vertical emittances through the beam line are shown in Figs. 2a,b and the phase space distributions in Figs. 3a-c. A final emittance ratio of about 60:1 is achieved. The numerical simulations were done with the GPT tracking code [7], space charge forces were neglected. The beam transformation through the adapter is not sensitive to chromatic aberrations, inclusion of a 0.5% energy spread did not change the results significantly.

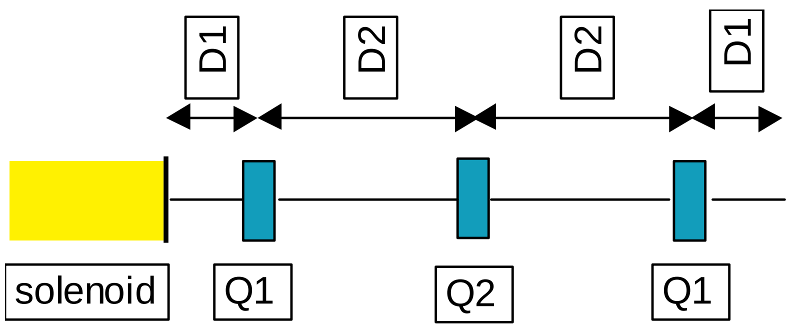

Fig. 1: Magnet lattice for the round-to-flat beam adapter. Note that the quadrupoles are of *skew* type, i.e. rotated by 45 deg. about the beam axis.

Beam momentum p [MeV/c]	20
Initial beam size $\sigma_{x0} = \sigma_{y0}$ [mm]	0.5
Initial norm. emittance $\varepsilon_{x0} = \varepsilon_{y0}$ [10^{-6} m]	1.0
Solenoid field B_s [T]	0.041
Parameter β [m]	3.33
Final emittances ε_x, ε_y [10^{-6} m]	8.0, 0.13
Quad lengths $l_{Q1,2}$ [m]	0.02
Quad gradient g_1 [T/m]	2.43
Quad gradient g_2 [T/m]	-2.85
Drift length D1 [m]	0.035
Drift length D2 [m]	1.052

Table 2: Parameters for the adapter beam optics example.

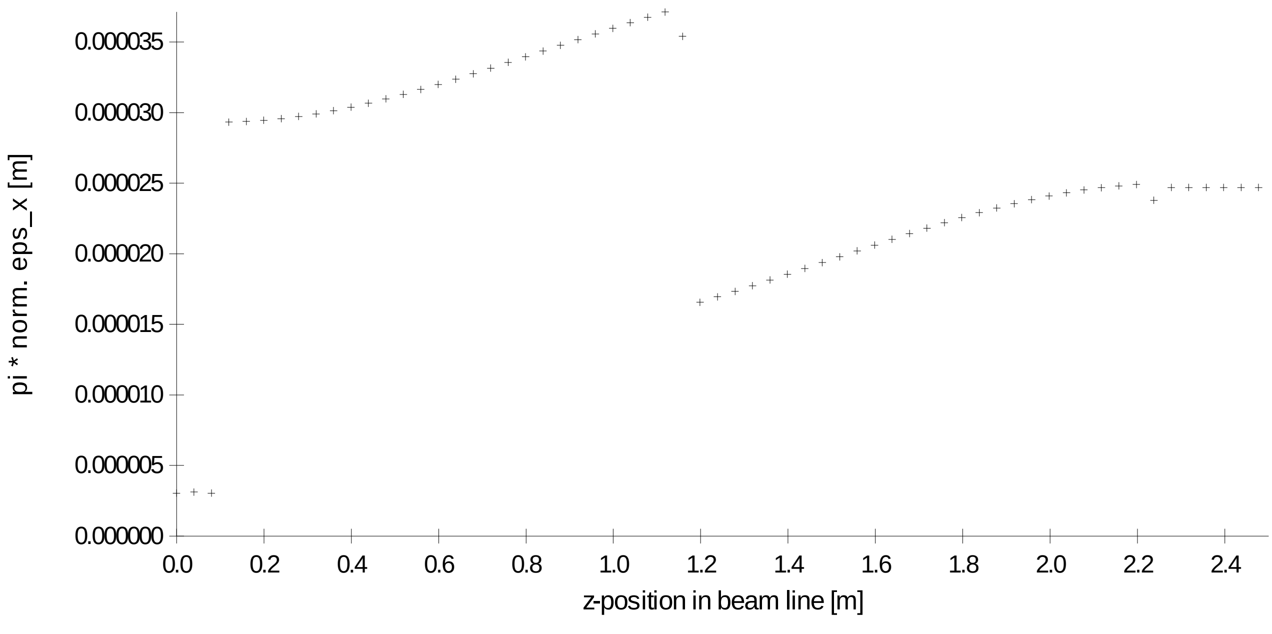

Fig. 2a: Evolution of the horizontal beam emittance through the adapter beam line. The solenoid ends at z = 0.05m.

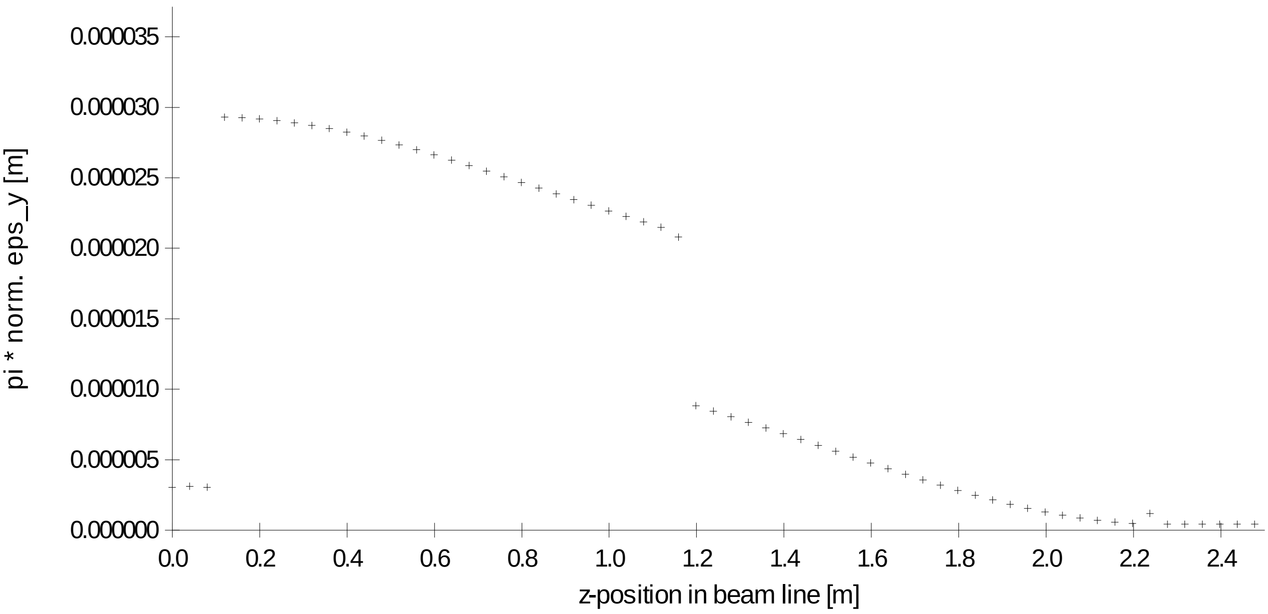

Fig. 2b: Evolution of the vertical beam emittance through the adapter beam line.

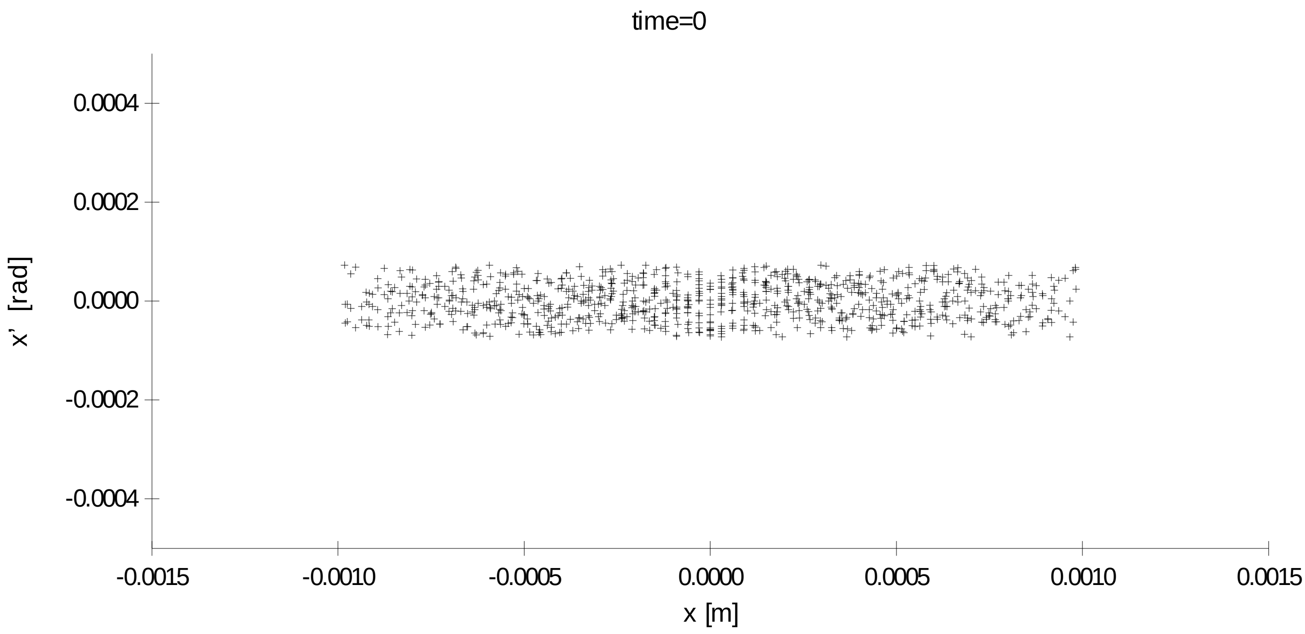

Fig. 3a: Initial transverse phase space distribution (equal in x and y) for the adapter beam line example.

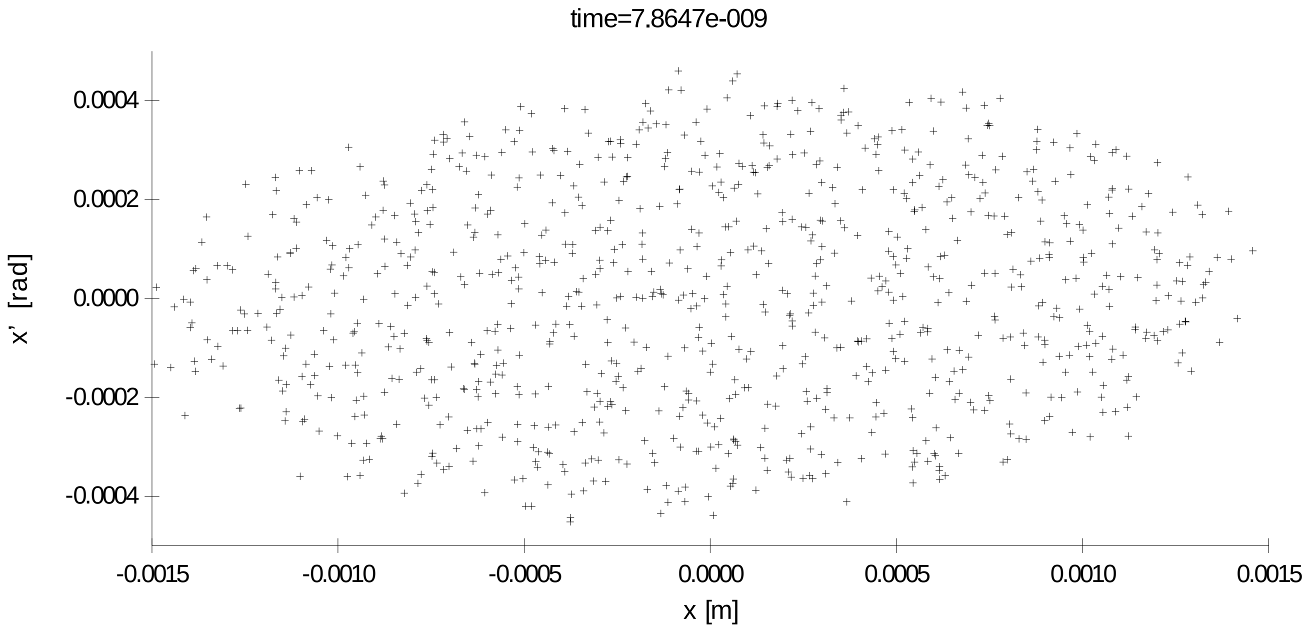

Fig. 3b: Final horizontal phase space distribution for the adapter beam line example.

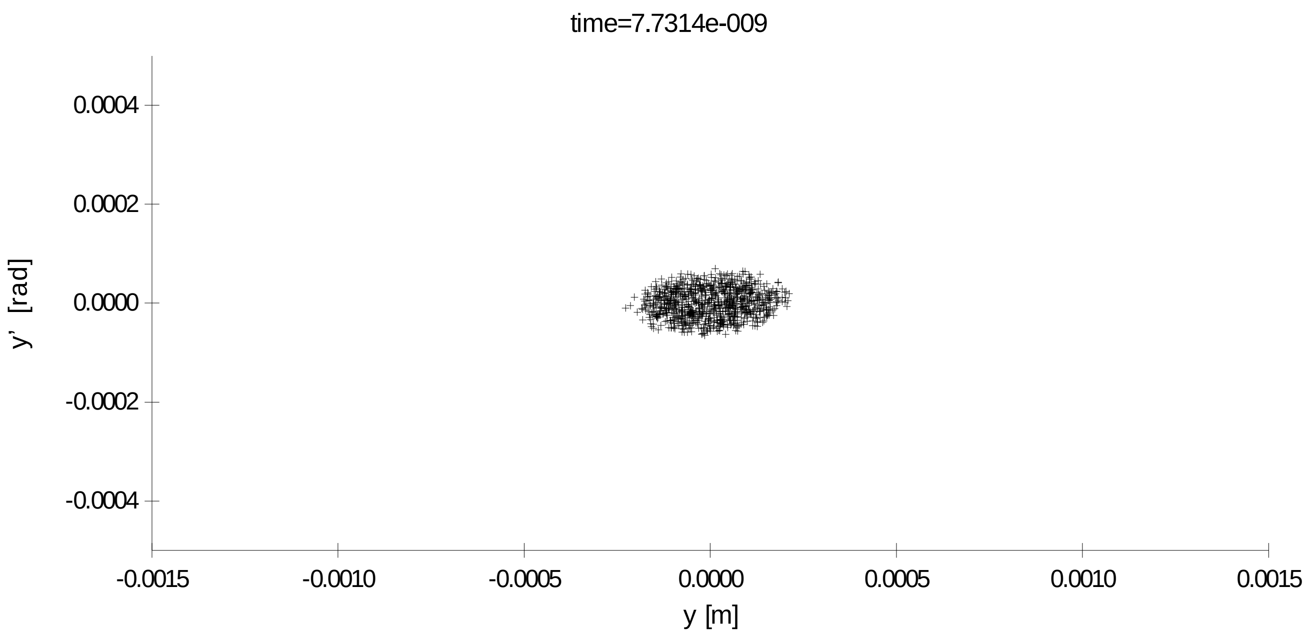

Fig. 3c: Final vertical phase space distribution for the adapter beam line example.

3. RF-Laser Gun

The design of the low-emittance electron beam source can be based on the concept developed for the TESLA Test Facility FEL RF-gun [4]. The layout of the 1 ½ cell L-Band TTF-FEL gun is shown in Fig. 4.

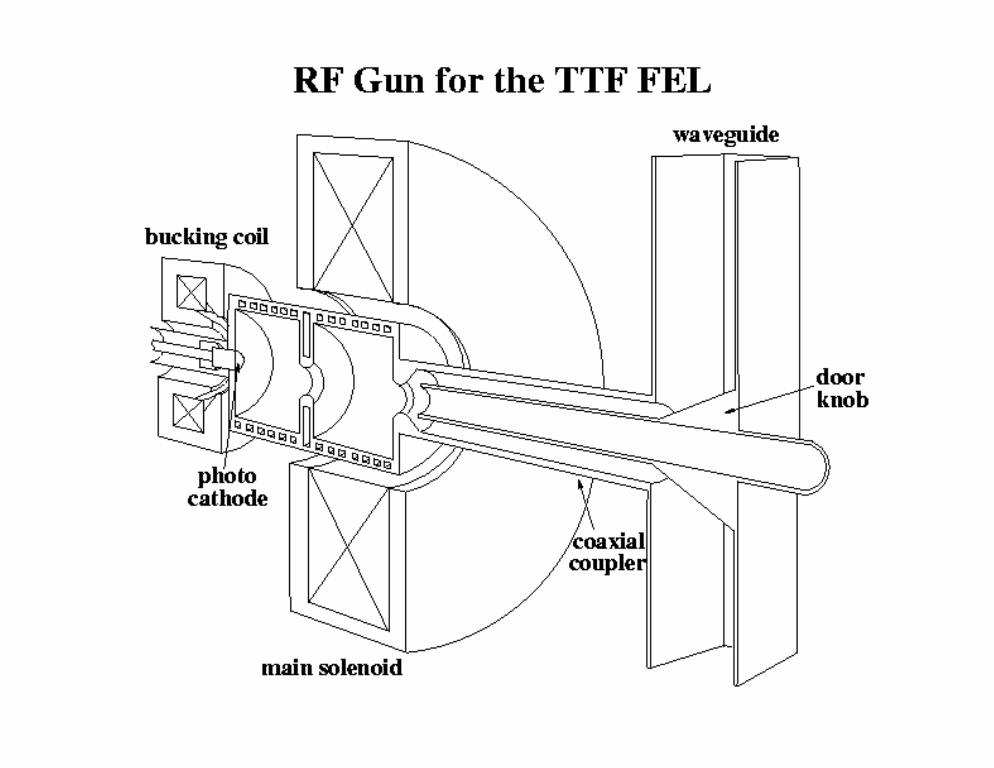

Fig. 4: Layout of the TTF-FEL Laser RF-gun.

The complete beam line studied here includes a 9-cell 1.3 GHz accelerating section starting at a distance of 1.6m downstream from the gun cathode and operating at an accelerating gradient of 15MV/m. The required finite longitudinal magnetic field B_c at the cathode can simply be achieved by adjusting the bucking coil strength. The beam emittance is calculated using the newly developed computer code ASTRA [8]. The optimization for minimum space charge limited emittance at the end of the beam line is done by adjusting the beam radius at the cathode, the length of the laser pulse flat top, the launch phase of the RF-gun (defined w.r.t. the beginning of particle emission from the cathode) and the peak field of the main solenoid and makes use of the so-called emittance compensation method. The optimization is done for two different bunch charges, 0.8 nC and 1.6 nC. In the simulation, we subtract the average angular momentum in order to remove the contribution to the calculated emittance from the collective rotation of the beam in the field-free region after it has exited from the gun.

Peak acc. field	50 MV/m
Launch phase	-40 deg.
Bunch charge	0.8 nC
Laser pulse flat top	8 ps
Laser pulse rise/fall time	2ps
Cathode radius	1.2 mm
Rms beam radius (homogeneous distr.)	0.6 mm
Main solenoid B_{peak} (at z = 0.11 m)	0.199 T
Field at cathode B_c	0.032 T
Beam energy after gun	5.3 MeV
Beam energy after acc. section	20.8 MeV
Norm. emittance (rms) @ 20.8 MeV	1.6 mm×mrad
Norm. emittance (95% of beam)	1.2 mm×mrad
Norm. emittance (rms), $B_c = 0$	*1.2 mm×mrad*
Norm. emittance (95%), $B_c = 0$	*0.9 mm×mrad*
Bunch length σ_z	1.3 mm
Rel. energy spread σ_E/E	0.2 %

Table 3: Parameters of the L-band RF-gun for 0.8nC bunch charge.

Peak acc. field	50 MV/m
Launch phase	-37 deg.
Bunch charge	1.6 nC
Laser pulse flat top	14 ps
Laser pulse rise/fall time	2ps
Cathode radius	1.8 mm
Rms beam size (homogeneous distr.)	0.9 mm
Main solenoid B_{peak} (at z = 0.11 m)	0.188 T
Field at cathode B_c	0.032 T
Beam energy after gun	5.3 MeV
Beam energy after acc. section	20.8 MeV
Norm. emittance (rms) @ 20.8 MeV	2.7 mm×mrad
Norm. emittance (95% of beam)	2.0 mm×mrad
Norm. emittance (rms), $B_c = 0$	*2.1 mm×mrad*
Norm. emittance (95%), $B_c = 0$	*1.6 mm×mrad*
Bunch length σ_z	2.3 mm
Rel. energy spread σ_E/E	0.5 %

Table 4: Parameters of the L-band RF-gun for 1.6nC bunch charge.

The resulting beam emittance (note that any initial, i.e. thermal emittance is neglected) contains an appreciable contribution from a small number of large amplitude and angle halo particles. Thus the emittance for 95% of the bunch is already considerably smaller than the rms value for the full distribution. An overview of the RF-gun parameters and resulting beam properties is given in Tables 3 and 4. In Fig. 5 the beam size as a function of position in the beam line is shown. As shown in Tables 3 and 4, the emittances with non-zero B_c are somewhat larger than for $B_c = 0$, apparently as a result of the combined action of the strong space charge forces and a higher magnetic field in the region near the cathode. This effect needs further investigations.

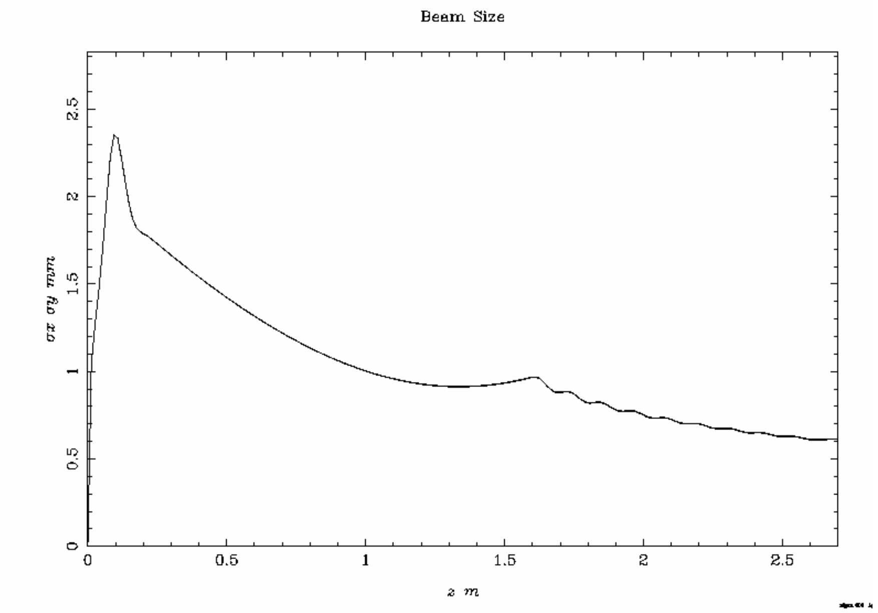

Fig. 5: Transverse beam size as a function of position in the L-band RF-gun beam line.

In contrast to beam sources for FEL applications, the bunch length and longitudinal emittance are not very critical parameters for the linear collider. We therefore consider the possibility to further reduce the space charge emittance dilution by increasing the bunch length. At L-band RF-wavelength a reasonable upper limit for the bunch length is reached for the parameters of the 1.6nC case described above, so that longer bunches should be accompanied by going to smaller operation frequencies of the RF-gun. We investigate a specific example at f_{RF} = 650MHz, assuming that the gun design can be derived by simple geometric scaling from the L-Band gun. Concerning the maximum achievable accelerating field at this frequency, we make the assumption to keep the power losses in the cavity walls constant per unit length of structure. Since the shunt impedance scales like $R_s' \sim f_{RF}^{1/2}$,this implies $g_{acc} \sim f_{RF}^{1/4}$. This scaling is somewhat arbitrary and needs to be more carefully investigated. The low-frequency RF-gun of the ELSA project [9] has a peak gradient of about 25 MV/m at f_{RF} = 144 MHz, in accord with the above scaling, but in that case only over a short accelerating gap.

The results obtained for a 1.6 nC bunch produced in a 650 MHz RF-gun with a peak accelerating field of 40 MV/m are encouraging (see Table 5 for beam and gun parameters).

Peak acc. field	40 MV/m
Launch phase	-43 deg.
Bunch charge	1.6 nC
Laser pulse flat top	30 ps
Laser pulse rise/fall time	2ps
Cathode radius	1.2 mm
Rms beam size (homogeneous distr.)	0.6 mm
Main solenoid B_{peak} (at z = 0.13 m)	0.151 T
Field at cathode B_c	0.036 T
Beam energy after gun	9.4 MeV
Beam energy after acc. section	28 MeV
Norm. emittance (rms) @ 20.8 MeV	1.85 mm×mrad
Norm. emittance (95% of beam)	1.35 mm×mrad
Norm. emittance (rms), $B_c = 0$	*1.3 mm×mrad*
Norm. emittance (95%), $B_c = 0$	*0.9 mm×mrad*
Bunch length σ_z	3.1 mm
Rel. energy spread σ_E/E	0.13 %

Table 5: Parameters of the 650 Mhz RF-gun for 1.6nC bunch charge.

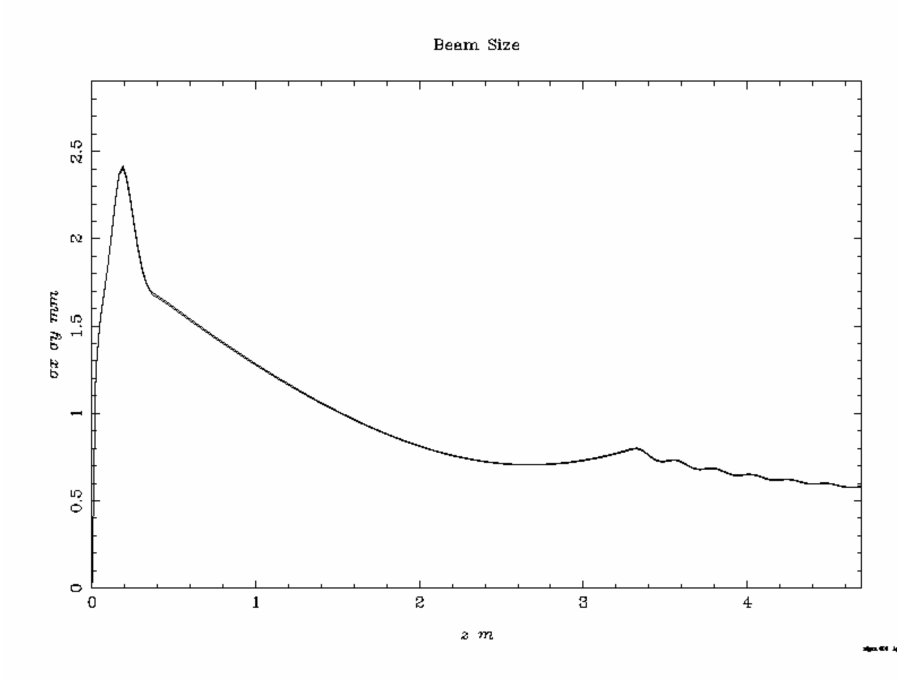

Fig. 6: Transverse beam size as a function of position in the 650MHz RF-gun beam line.

Beam momentum p [MeV/c]	28
Initial beam size $\sigma_{x0} = \sigma_{y0}$ [mm]	~0.6
Initial norm. emittance $\varepsilon_{x0} = \varepsilon_{y0}$ [10^{-6} m]	See Table 5
Final emittances ε_x, ε_y [10^{-6} m]	7.2, 0.57
Vert. Emittance (90% of beam) ε_y [10^{-6} m]	0.23
Quad lengths $l_{Q1,2}$ [m]	0.02
Quad gradient g_1 [T/m]	1.15
Quad gradient g_2 [T/m]	-1.35
Drift D1 (after end of acc. section) [m]	0.2
Drift length D2 [m]	1.10

Table 6: Parameters of the skew triplet adapter added to the 650MHz RF-gun beam line. The resulting beam emittances were calculated with the ASTRA simulation code (space charge switched off), using the phase space distribution from the previous simulation run (including space charge) with 1,200 particles as initial condition.

We used the particle distribution at the end of the beam line to test the adapter optics with a "real" RF-gun beam. The skew triplet parameters and resulting beam emittances are listed in Table 6. The vertical emittance is strongly enlarged by the halo related to the non-linear spread of the space charge force (see Fig. 7). Collimation of 10% of the vertical distribution leads to an emittance of $\varepsilon_y = 0.2 \cdot 10^{-6}$ m, which matches the requirements of the (relaxed) TESLA CDR parameters.

4. Conclusions

The results presented above show that a flat beam electron source for linear colliders is a realistic possibility. Our study of a complete system with 650MHz RF-gun and skew triplet should be viewed as a 1st proof-of-principle, from which one can start further optimizations. For instance, it is not clear which the optimum frequency for the RF-gun should be. For TESLA, a low frequency appears to be advantageous with respect to the achievable space-charge limited emittance, but a closer look at the technical realization (layout of the gun, focusing solenoids, availability of pulsed high power klystrons, etc.) is necessary. For other linear colliders, going to higher frequencies where very high accelerating gradients with short RF-pulse may be possible could be a better solution. In general one may point out that our electron beam source concept will profit from further optimization of RF-gun designs in general, driven by the developments for X-ray Free Electron Lasers. It should also be possible to test the flat beam transformation at existing or planned low-emittance RF-gun test facilities.

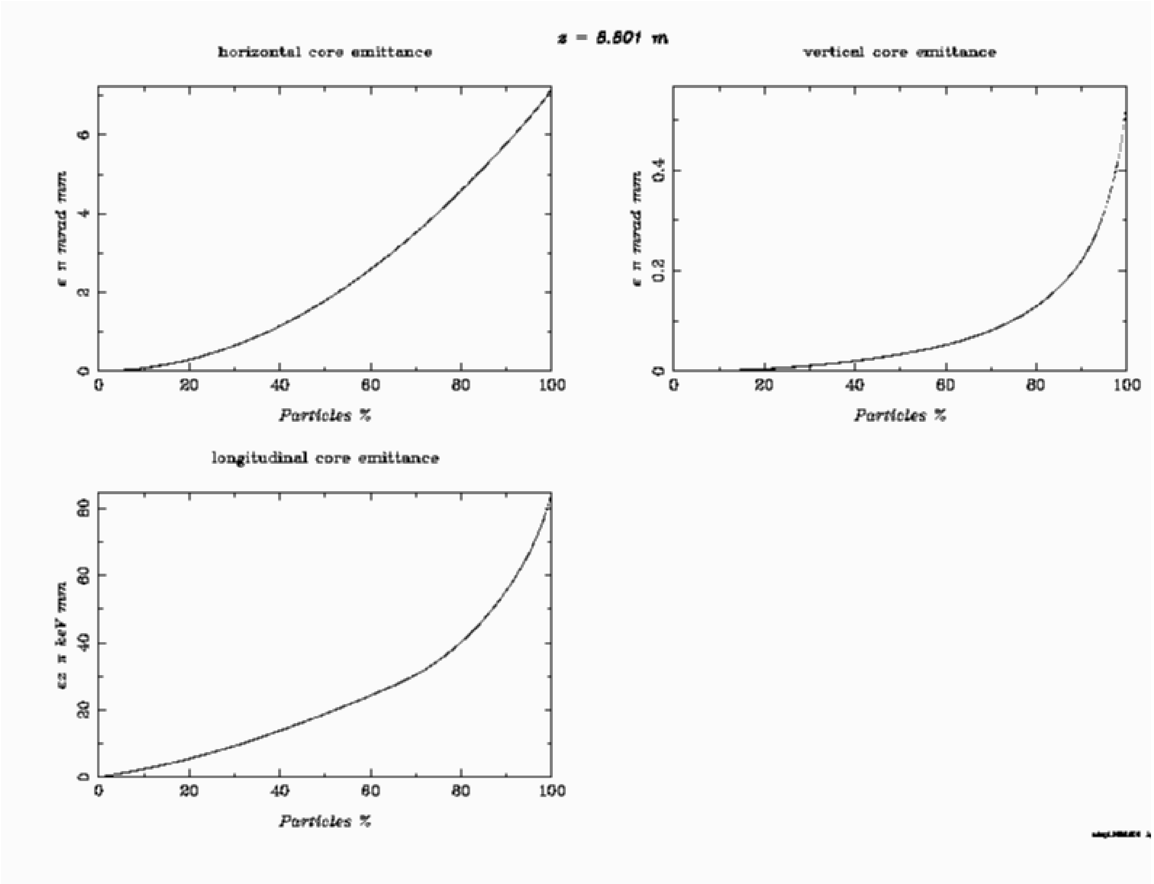

Fig. 7: The rms beam emittances (top figures: hor. and vert. planes, lower figure: long. plane) at the end of the 650MHz RF-gun beam line & skew triplet adapter optics as a function of the fractional part of the distribution for Q_b = 1.6nC.

The mechanism, which increases the beam emittance for non-zero B-field on the cathode, should be analyzed with the goal to possibly reduce or eliminate this effect.

The dispersive funneling to combine the beams from, say, two flat-beam sources must be worked out in detail[1]. Furthermore, it must be shown that, once a low vertical emittance is obtained, it can be preserved in the low-energy part of the main linear accelerator which follows (note that the injection energy into the linac for a beam from a damping ring is typically several GeV, in our case a few tens of MeV). Finally, at this point in time it is an open question whether the low-emittance RF-gun concept can be realized with a GaAs cathode, which would then allow obtaining a polarized electron beam.

[1] We estimate that a 1% energy difference between the two beams would be sufficient to merge the bunches on a common orbit in a scheme with 100mrad bend angle and an electrostatic wire septum.

References

[1] R. Brinkmann, G. Materlik, J. Roßbach and A. Wagner (eds.), *Conceptual Design of a 500GeV e+e- Linear Collider with Integrated X-ray Laser Facility*, DESY-97-048.

[2] R. Brinkmann, *Linear Collider Projects at DESY*, Proc. EPAC98 Stockholm, p. 53.

[3] G. A. Loew (ed.), updated parameter list for the *International Linear Collider Technical Review Committee Report*, http://www.slac.stanford.edu/xorg/ilc-trc/Table1_1/table1_.html.

[4] Y. Huang and K. Flöttmann, TESLA-FEL-96-01.

[5] Ya. Derbenev, *Adapting Optics for High Energy Electron Cooling*, University of Michigan, UM-HE-98-04, Feb. 1998.

[6] A. Burov and V. Danilov, *An Insertion to Eliminate Horizontal Temperature of High Energy Electron Beam*, FNAL TM-2040, March 1998.

[7] *GPT User Manual V.2.31*, Pulsar Physics, Utrecht, Netherlands.

[8] K. Flöttmann, *A Space Charge Tracking Algorithm*, to be published.

[9] S. Joly et al., *Progress Report on BRC Photo-Injector*, Proc. EPAC90 Nice, p. 140.