# Simulation Study of the RF Gun for the TTF Free Electron Laser

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ABSTRACT

An 1.3GHz photocathode rf gun injector is under study at DESY for the proposed TTF FEL. The injector, composed of the gun cavity, the solenoids and the booster cavity, is expected to deliver a 20MeV electron beam with a normalized transverse rms emittance of 1$\pi$mm-mrad and a longitudinal rms emittance of 20kev-mm at a charge of 1nC. Its performance has been studied by the space-charge tracking code PARMELA. The influence of the laser bunch dimensions on the beam emittances are studied. The parameters are optimized and the emittance compensation technique is employed. The effect of halo particles on the rms emittance is discussed.

## 1 Introduction

The free electron laser at the TESLA Test Facility (TTF FEL) [1] is based on the principle of the so-called self amplified spontaneous emission [2] [3]. In order to meet the requirements for an electron beam with high brightness and small energy spread an rf gun is currently under study at DESY. Table 1 presents the rf gun design parameters.

Table 1. TTF FEL rf gun design parameters

| | | |
|---|---|---|
| charge | nC | 1 |
| rms normalized emittance $\epsilon_n$ | $\pi$mm-mrad | 1 |
| rms longitudinal emittance $\epsilon_z$ | keV-mm | 20 |
| rms bunch length $\sigma_z$ | mm | 0.8 |
| rf pulse duration | ms | 1 |
| repetition rate | Hz | 10 |

The whole rf gun injector consists of an $1\frac{1}{2}$cell gun cavity operating at 1.3GHz, solenoids and a booster cavity which is a standand 9-cell superconducting TESLA cavity. The booster cavity is followed by a magnetic chicane, that acts as a bunch compressor. The design bunch length after the compressor is 0.8mm. Figure 1 shows the layout of the injector.

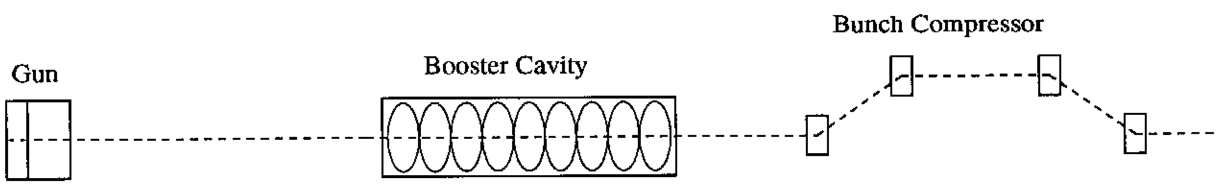


Figure 1: A schematic layout of the photocathode rf gun injector for TTF FEL.

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At the level of a few $\pi$mm-mrad the normalized emittance can be affected by a number of small contributions like field asymmetries or the thermal emittance of the electrons at the cathode, rather than being dominated by a single effect. In order to reduce field asymmetries an axis symmetric coaxial input coupler, as shown in Figure 2, is now being optimized. In this paper, we study only the contributions from the space charge and the rf field by means of PARMELA [4], thus assuming perfect rotational symmetry. In order to improve the transverse emittance the so-called emittance compensation scheme [5] is adopted. We optimize the beam dimensions as well as the solenoid field and position with respect to the lowest achievable transverse and longitudinal emittances. In section 2, we introduce the field map of the gun cavity and the solenoid magnet. In section 3, we describe the optimization of many parameters, such as the launch phase of the electron beam with respect to the rf, the laser beam spot and its bunch shape. The emittance compensation technique is described in cases with and without accleration in the booster cavity in section 4 and 5, respectively. In section 6, we discuss the problem of halo particles which lead to a significant overestimation of the relevant emittance parameters in our calculations.

The space charge force is handled with a mesh method. In most calculations we simulate 1000 particles, but for careful studies, 10,000 or even 50,000 particles have been simulated.

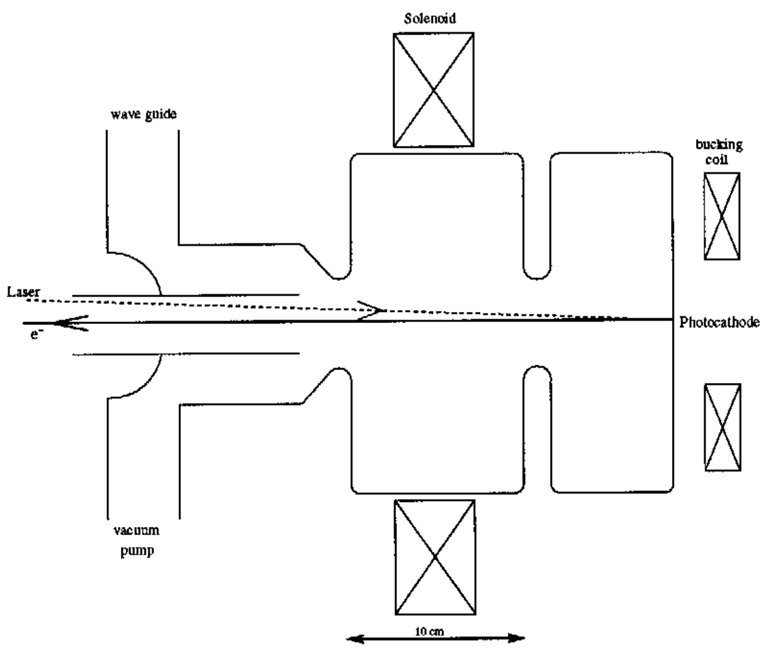


Figure 2: Schematic drawing of the TTF FEL rf gun with a coaxial input coupler.

## 2 Field Map of Gun Cavity and Solenoid Magnet

The geometrical dimensions of the gun cavity have been optimized in order to minimize the emittance growth caused by the rf field. The code SUPERFISH [6] is used to generate the 2D rf fields of the gun cavity in our simulation study. Figure 3 shows the SUPERFISH field map of the cavity. The maximum field at the cathode is 50MV/m which is limited by the rf power source right now. The coaxial input coupler scheme avoids field asymmetries and offers more flexibility in the positioning of the solenoid, which is very important as will be shown in section 4 because the optimum solenoid position is found to be close to the cathode.

We use a solenoid magnet similar to that designed for the SLAC/BNL/UCLA gun [7] in our simulations. Its field distribution is generated by the POISSON code [6]. To simplify the field calculation, we use Dirichlet's boundary condition to force the magnetic field strength to be zero at the position of the cathode. Figure 4 shows the field distribution of the solenoid magnet. In the gun a bucking coil will be used to compensate the field produced by the solenoid magnet at the cathode location. The solenoid has an iron york for the flux return, thus the field is condensed in a small region. This will facilitate the design of the required bucking coil.

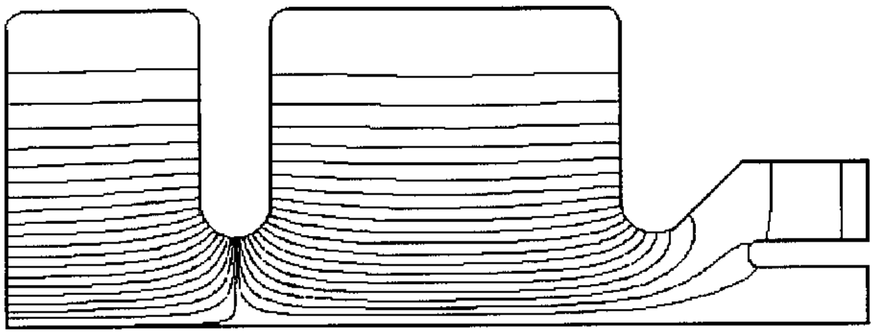

Figure 3: SUPERFISH field map of the gun cavity. The lines represent electric field lines. The field strength is propotional to the line density.

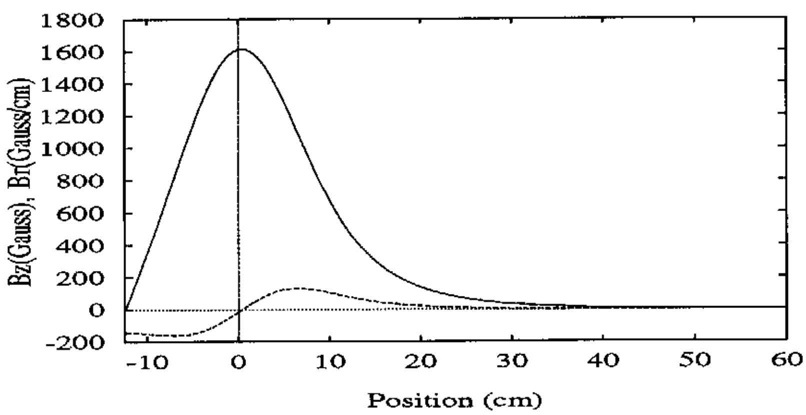


Figure 4: POISSON field distribution of the solenoid magnet. Inner radius is 12cm, outer radius 24cm, length 10cm, centered at 12.5cm from the cathode.

## 3 Effects of the Laser Dimensions and the RF Field on the Emittance

Due to the difference of the space charge forces in the middle and the tails of the bunch, both the longitudinal and the transverse emittance will increase primarily in the low energy part of the gun. For a constant bunch charge, different bunch radii and time structures cause different values of space charge induced emittance growth. In our simulations, we define the bunch charge density as uniform in radius. The laser bunch time structure is defined as a pulse with flat-top and Gaussian edges. This bunch can be treated with a number of short Gaussian pulses in the PARMELA input. The rise and falling time is simply taken as $2\sigma_z$, the flat-top is $\Delta_z$, where $\sigma_z$ is the rms width of each short Gaussian pulse. The FWHM value of the bunch is close to $\Delta_z + 2\sigma_z$. The present design specifications for the laser provide a minimum bunch length of 5ps FWHM with a rise time of 5ps. This bunch has a gaussian shape. It can be elongated by overlaying several gaussian bunches with a time delay, thus obtaining a more flat-topped pulse structure.

Sophisticated modelocking techniques allow the reduction of the laser pulse rise time to about 2ps [8]. This option will be investigated in more detail after we have gained the first experience with the laser.

Figure 5 shows both the longitudinal rms emittance and the normalized transverse rms emittance changing with the laser beam spot size. Without any solenoid fields, the simulations were just ended at the gun exit. Since the maximum gradient cannot be as high as in an S–band cavity, the beam radius has to be larger to reduce the space charge density. On the other hand the rf fields of an L–band structure are more uniform in r and z, therefore a larger beam radius can be accepted. In our case, the optimum beam radius is about 1.5mm. The longitudinal emittance is very small at the gun exit, but it will grow up quickly along the drift space as a result of the space charge forces. At spot size radii of 2.0–2.4mm the calculations show fluctuations of about 15% in the transverse plane. Rather than being due to physical effects, these fluctuations seem to indicate problems of the simulations which are not understood yet.

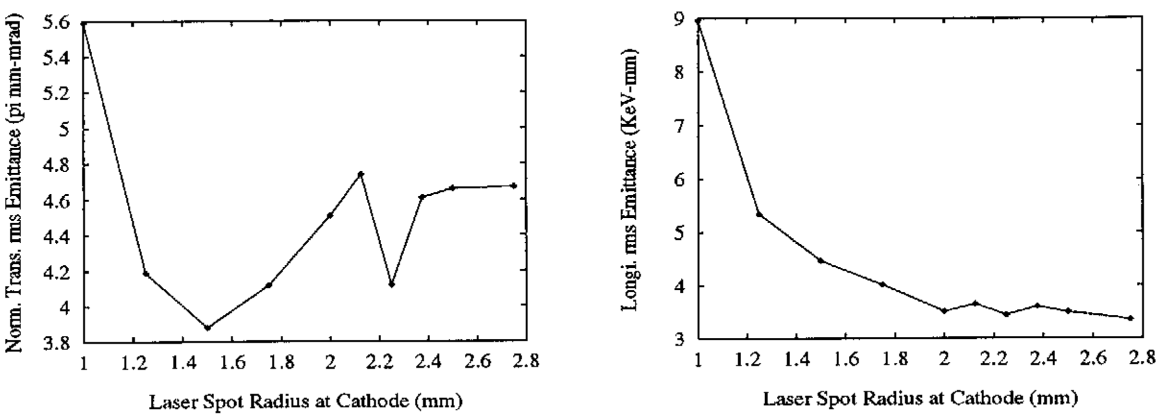


Figure 5: Emittances change with the beam radius. $E_0$=50MV/m, flat-top 5.8ps, rise time 2.3ps.

Figure 6 and Figure 7 plot emittances versus laser bunch structures. For the transverse emittance an optimum bunch length can be found at $\Delta_z$ ~7ps. This optimum is the result of a trade-off between the time varying rf field effect and the space charge effect. The longer bunch means less charge

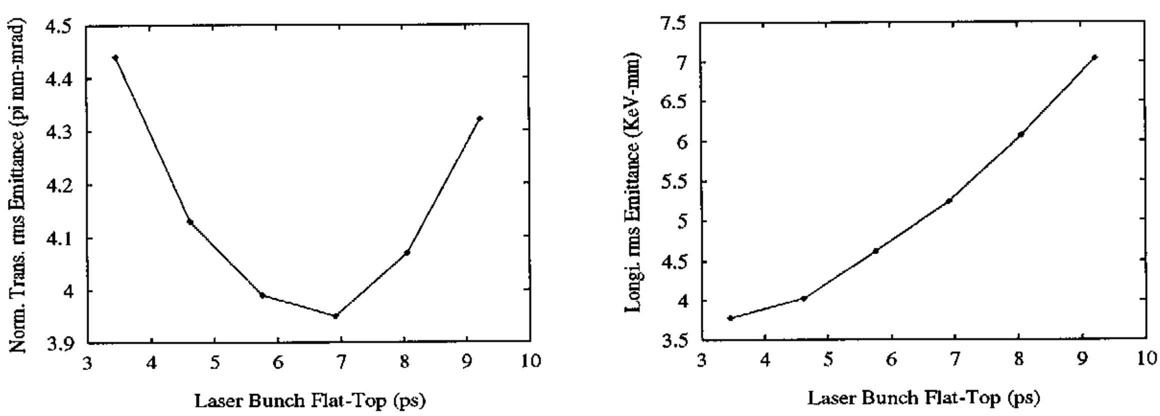


Figure 6: Emittances change with the laser pulse flat-top. $E_0$=50MV/m, rise time 2.3ps, spot radius 1.5mm.

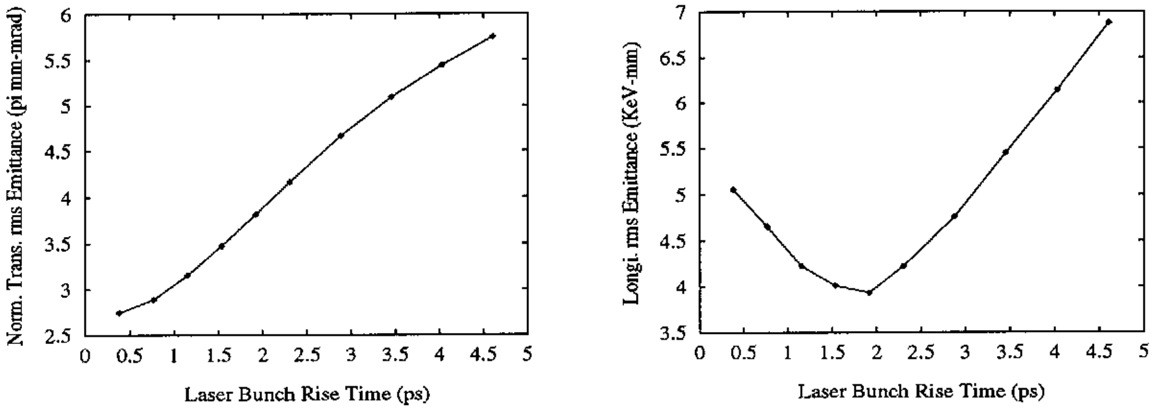


Figure 7: Emittances change with the laser pulse rise time. $E_0$=50MV/m, flat-top 5.8ps, spot radius 1.5mm.

density but a larger variation in time of the rf field. The longitudinal emittance is, within the range shown in Figure 6, steadily increasing with the pulse length. This indicates that the rf contribution to the longitudinal emittance dominates. However, the dependence of the longitudinal emittance on the laser spot size and on the rise time also shows a significant space charge contribution to the longitudinal emittance. In order to reduce the longitudinal emittance we will operate at a bunch length of $\Delta_z$ ~5.8ps. The transverse emittance is increased by only 1% as compared to the optimum, but the longitudinal emittance is reduced by about 12%. The shorter bunch helps also to relax the requirements for the bunch compressor.

Figure 7 shows the effect of the rise time on the transverse and longitudinal emittance. The increase of the transverse emittance with the rise time can be understood as an increasing difference of the space charge forces between the middle and the ends of the bunch when the rise time is getting larger. Note, that the longitudinal emittance is drastically increasing for rise times less than 1ps.

Figure 8 presents the emittances changing with the rf field gradient. The maximum gradient should not be less than 50MV/m in our case. Note, however, that a smaller emittance as shown in this calculation might be reached at lower or higher gradients if all parameters (spot radius etc.) are optimized for the new working point. The effect of the launch phase on the emittance is plotted in Figure 9. There is an optimum launch phase at around 32°. At about 27° again rather unphysical fluctuations of only 4% are found.

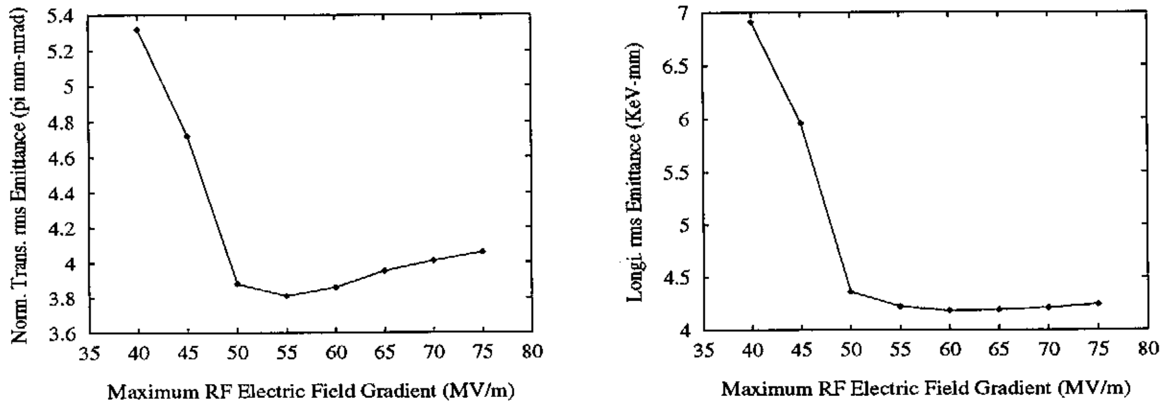


Figure 8: Emittances versus rf field gradient. flat-top is 5.8ps, rise time 2.3ps, spot radius 1.5mm.

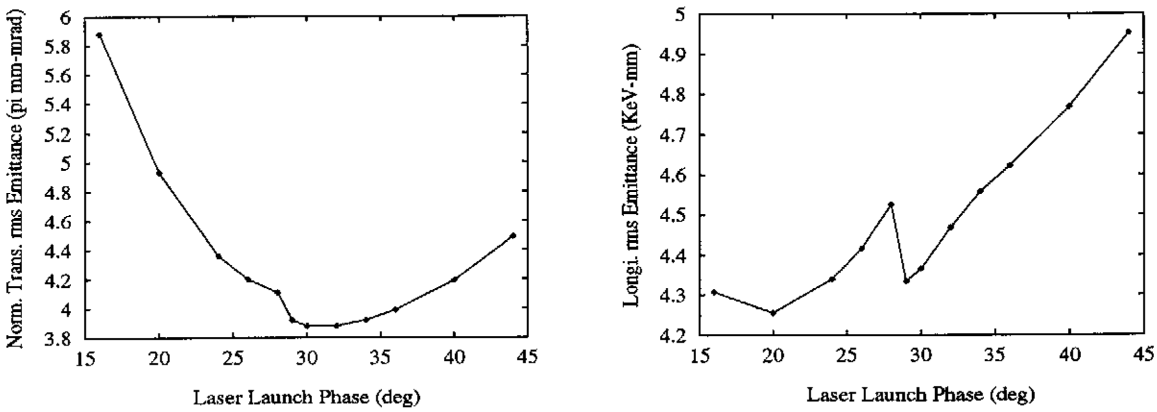


Figure 9: Emittances versus laser pulse launch phase. $E_0$=50MV/m, flat-top 5.8ps, rise time 2.3ps, spot radius 1.5mm.

After more calculations to optimize those parameters discussed before but including the downstream booster cavity and the solenoidal field, we have found that the optimum parameters are nearly the same as those obtained in this section. The optimum parameters are listed in Table 2. These parameters are kept unchanged in the following two sections.

Table 2. The PARMELA simulation parameters

| | |
|---|---|
| charge | 1nC |
| transverse profile | uniform, 1.5mm radius |
| longitudinal profile | flat-top 5.8ps, rise time 2.3ps |
| $E_0$ | 50MV/m |
| launch phase | 32° |
| $E_{halfcell}/E_{fullcell}$ | 1.0 |
| initial thermal emittance | 0.0 $\pi$mm-mrad |
| initial energy | 0.5eV |

# 4 Emittance Compensation without Booster Cavity

The previous section revealed the emittance at the gun cavity exit. The transverse emittance is too large to be used in the TTF FEL. It can be reduced by means of the space charge emittance compensation scheme [5] which effectively eliminates most of the correlated space charge induced emittance growth. If the charge distribution in the bunch is self similar during its motion, the space charge induced distortions are correlated with the position in the bunch. They can be removed by applying an appropriate focusing kick, thereby rotating the bunch in phase space. In the subsequent drift space, the space charge forces counteract the convergence of the beam and the correlated emittance growth is compensated. The minimum emittance one can obtain is sensitive to both, the location and the strength of the focusing solenoid.

The first calculations were done without booster cavity. The solenoid magnet is 10cm long. Figure 10 plots the minimum emittance versus the position of the center of the solenoid magnet. The optimum position is found to be close to the cathode at about 10cm. Note, that this position is accessible for the solenoid only due to the coaxial input coupler scheme. The minimum emittance versus the field strength when the solenoid magnet is at its optimum location is also plotted in Figure 10. It shows that the emittance is very sensitive to the solenoid strength. This is still true when the booster cavity is included.

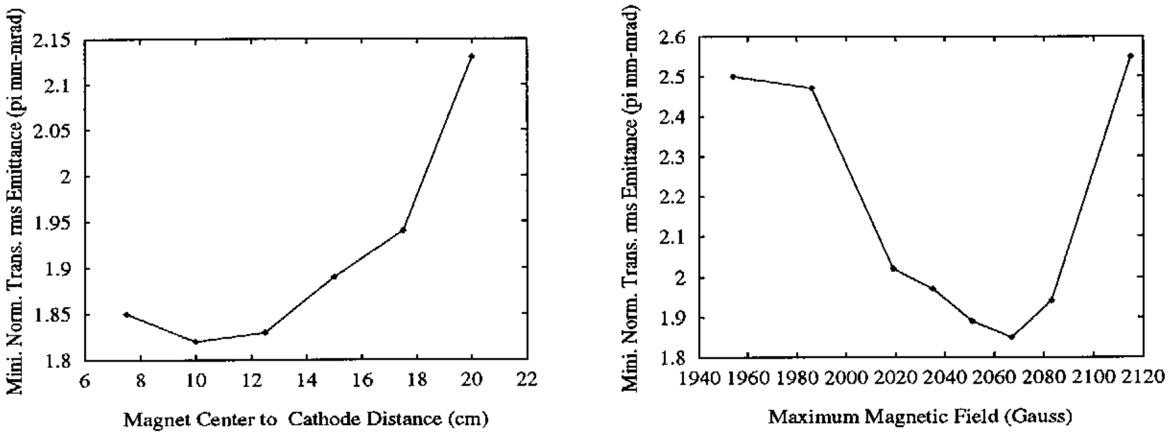


Figure 10: LEFT: Minimum transverse emittance versus magnet position. RIGHT: Minimum emittance versus magnetic field strength, center at 12.5cm.

In Figure 11 the resulting emittance growth along the beam line is plotted. At the minimum emittance location, the transverse emittance is 1.4$\pi$mm-mrad, the longitudinal emittance is 18keV-mm. The minimum emittance is at about 102cm behind the gun cavity.

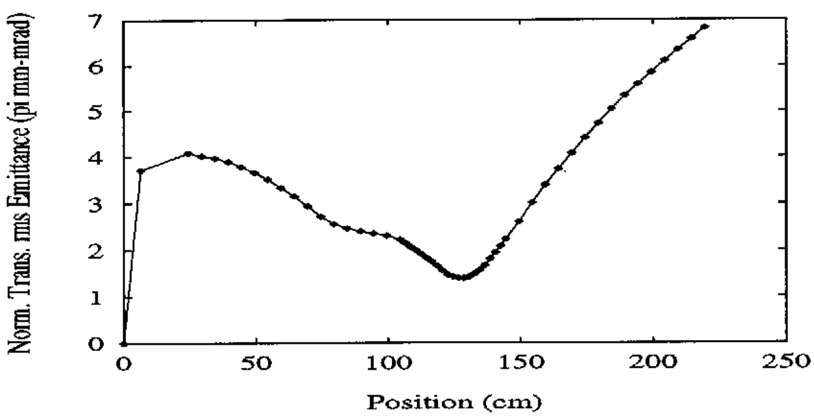


Figure 11: Transverse emittance versus beamline position without booster cavity.

## 5 Emittance Compensation with Booster Cavity

After reaching a minimum the emittance starts growing again due to the space charge forces. However, by locating the accelerator section around the minimum emittance location, the emittance can be further compensated down to a smaller value. In addition, the location of the minimum emittance can be pushed further away from the gun cavity, and at a sufficient high energy there is essentially no more emittance growth.

The booster cavity is a 9-cell superconducting TESLA cavity. As the booster cavity is operated in standing wave $\pi$−mode, it is easy to use SUPERFISH to calculate the fields of the middle cells and the end cells seperately. Then the field distributions are read by PARMELA. The total energy gain is assumed to be 15 MeV.

We have studied the effect of the distance between the gun exit and the first iris of the booster cavity on the emittance. The left picture of Figure 12 shows the minimum emittance versus this

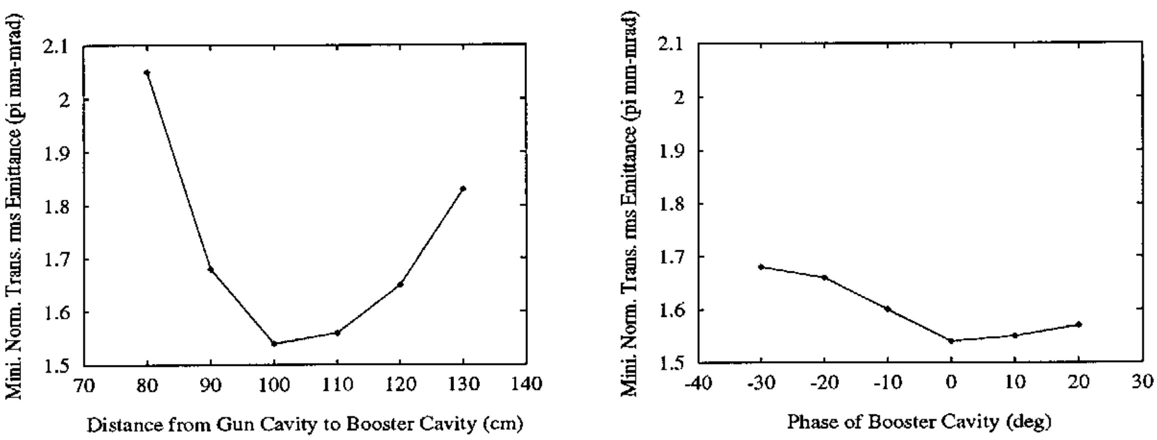


Figure 12: Left: Minimum transverse emittance versus the distance between the gun cavity and the booster cavity at a fixed solenoid strength. Right: Minimum transverse emittance versus the rf phase of the booster cavity. The energy gain is propotional to the cosine of the phase.

distance when the solenoid field strength is kept constant. It is found that the minimum emittance changes only slightly within a rather wide range. We should pointed out that this does not mean that the optimum distance is 100cm as shown in this figure. As we will see later, nearly the same minimum emittance can be reached by changing the solenoid field strength for different gun-booster cavity distances whithin some range.

The booster cavity is also required to produce a suitable energy-phase correlation of the bunch which is needed for the bunch compressor following the booster. This can be done by changing the rf phase of the booster cavity. The minimum emittance versus the rf phase of the booster cavity is plotted in Figure 12 on the right side. The emittance is not very sensitive to the booster cavity phase within some range. In order to have a suitable energy-phase correlation, the electron bunches should be injected into the booster cavity at a negtive phase. We estimate the bunch length behind the booster cavity to be $\sigma_z \leq 1.1$mm (see Figure 15). Hence it has to be compressed only by a factor of $\sim$1.4. According to the design specifications [9] a correlated energy spread of $\Delta E/E = 3 \times 10^{-3}$ is required to achieve this compression factor. The energy spread can be produced by running the booster cavity at $-20°$.

Figure 13 shows the emittance as a function of the beam line position with a gun-booster cavity distance of 100cm. The minimum rms emittance is $1.2\pi$mm-mrad and the longitudinal emittance is 21keV-mm. Unfortunately, the minimum emittance location is only about 100cm away from the booster cavity. It can be useful to push the location of the minimum emittance further away from the booster cavity in order to preserve the emittance in the bunch compressor. Figure 14 presents results where the distance between gun and booster cavity is 123cm. After adjusting the strength of the solenoid the minimum emittance is about $1.2\pi$mm-mrad, but the location of the minimum is shifted downward to about 250cm behind the booster cavity. At a distance of 150cm between booster cavity and gun the minimum emittance location is found at 270cm behind the booster cavity. The minimum emittance value is $1.2\pi$mm-mrad. Thus the gun–booster distance gives us some flexibility for the matching of the beam to the bunch compressor. We have not included the bunch compressor in our simulations yet.

## 6 The effect of halo particles on the rms emittance

Figure 15 shows various distributions like phase space plots, beam spot and energy-phase plots of the electron bunch at the exit of the gun cavity and near the emittance minimum.

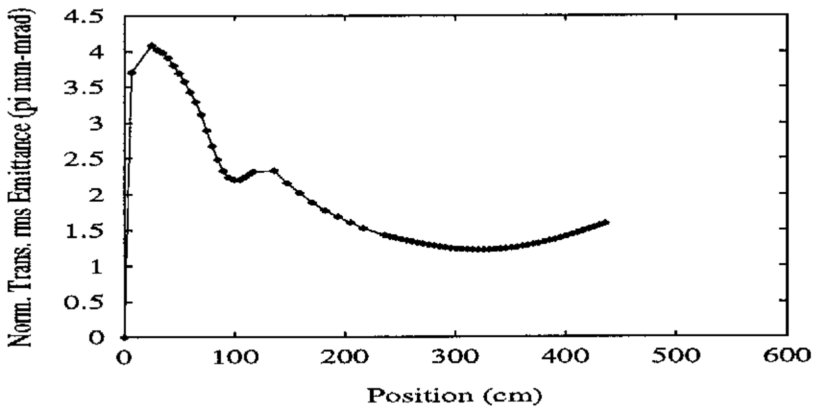


Figure 13: Transverse emittance plotted as a function of the beam line position. The distance between gun and booster is 100cm.

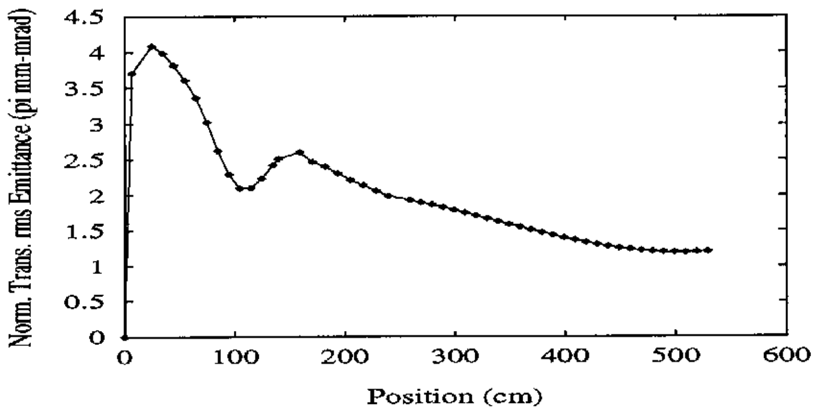


Figure 14: Transverse emittance plotted as a function of the beam line position. The distance between gun and booster is 123cm.

As can be seen the beam develops a halo of particles especially in the transverse distribution. This halo has a significant effect on the calculation of the rms emittance even though it contains only a small number of particles. While it is reasonable to assume that the beam develops a halo, it is doubtful that the predictions of a macro-particle code on the particle distribution in the halo are precise since it contains only so few particles. In addition the rms emittance might not be the relevant parameter for the FEL operation in case of a beam with a halo. One can argue that the emittance of the particles in the core of the beam is more relevant because the halo particles do not contribute to the FEL process. In practice it will be hard to scrape the halo particles from the beam due to wakefields produced by the scraper. However, introducing a scraper in the simulations seems to be an appropriate way to calculate an emittance that is relevant for the FEL process. Table 3 lists the transverse and longitudinal emittances of the beam for various collimator radii. The collimator is placed close to the emittance minimum. From Figure 15 it can be seen that it scrapes the halo efficiently in x'–x (and y'–y). By scaping off only 5% of the charge the transverse and longitudinal design emittances can be reached.

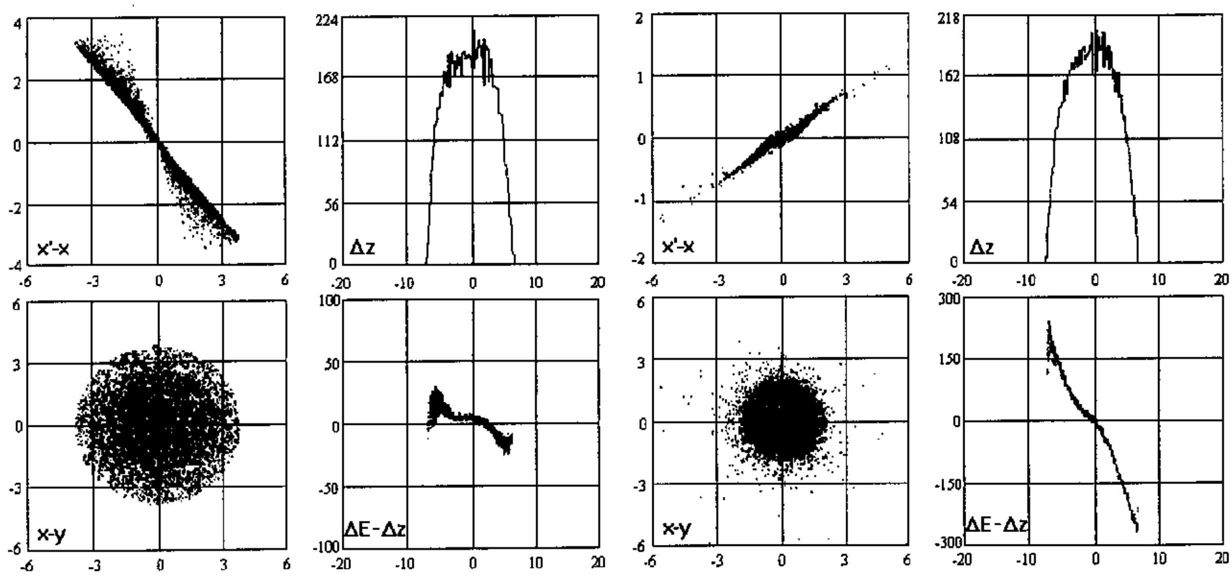


Figure 15: Various distributions of 10,000 particles. LEFT: at gun cavity exit; RIGHT: after the booster cavity (rf phase at 0°). x,y in mm, x' in mrad, ΔE in keV and $\Delta z$ in ps. Note, that the head of the bunch is on the left side in the $\Delta E$–$\Delta z$ plots.

Table 3. Beam emittances versus collimator setting

| Collimator radius (mm) | Percentage | $\epsilon_{nx}$(rms)($\pi$mm-mrad) | $\epsilon_z$(rms)(keV-mm) |
|---|---|---|---|
| | 100% | 1.20 | 20.7 |
| 3.5 | 99.2% | 1.11 | 20.5 |
| 3.0 | 98.5% | 1.09 | 20.2 |
| 2.5 | 97.2% | 1.07 | 19.8 |
| 2.4 | 96.8% | 1.06 | 19.7 |
| 2.3 | 96.0% | 1.06 | 19.5 |
| 2.2 | 94.4% | 1.05 | 19.2 |
| 2.1 | 91.8% | 1.04 | 18.8 |
| 2.0 | 88.8% | 1.03 | 18.1 |

# 7 Conclusion

In this paper we have presented a first set of simulation results for the parameter optimization for the TTF FEL gun. Various effects like field asymmetries, wakefields and thermal emittance of the electrons emerging from the cathode are not included. They have to be treated seperatly. By means of a careful design like e.g. the symmetric input coupler, the contributions of these effects can be kept small. The next steps to be worked out include a complete simulation of the gun with the bunch compressor and a cross-check of our results by means of independent programs like MAFIA and ATRAP.

A first test of the SASE principle will be performed at the TTF in 1998. The beam energy will be in the range of 300-500MeV and the required emittances are 3$\pi$mm-mrad transversely and ~50keV-mm longitudinaly. With a rise time of the laser pulse of 5ps a transverse emittance of 1.8$\pi$mm-mrad and a longitudinal emittance of 22keV-mm has been achieved in our simulations.

In order to achieve the parameters of Phase II the rise time of the laser has to be reduced to 2ps. The required additional modelocking techniques have already been discussed but are not worked out in detail yet. A reduction of the rise time below 2ps would allow smaller transverse emittances but at the expence of an increased longitudinal emittance. The design parameter of 1$\pi$mm-mrad and 20keV-mm have been achieved in our simulations with reasonable laser parameters, however, improvements are desirable in order to increase the safety margin. Beside a further careful optimization of all parameters increased gradients in the booster cavity and the gun have to be considered.

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