TESLA FEL-Report 1996-08

Multi bunch effects in a $1^1/_2$ cell rf gun

Klaus Flöttmann, Christoph Stolzenburg
DESY, Notkestr. 85, 22603 Hamburg, Germany

Introduction

The rf gun currently under construction for the VUV Free Electron Laser at the TESLA Test Facility (TTF) [1] at DESY is supposed to run in a multi bunch mode with bunch repetition frequencies of up to 9MHz and up to 8000 bunches in one pulse train. The gun is being built as a normal conducting 1½ cell cavity. The fundamental mode is a π-mode at 1.3GHz. The pulse train structure is primarily determined by rf and efficiency considerations for the test linac which is built in superconducting technology. In the following it will be shown that the performance of the rf gun will not be limited by multi bunch effects. In addition the case of much higher bunch repetition frequencies (~100MHz) will be discussed. These frequencies are typical for normal conducting linacs, but might in a later stage also be desired at the TTF FEL for pump and probe experiments.

Mode spectrum and loss parameters

Table 1 gives a listing of mode frequencies and longitudinal loss parameters $k_{//}$ for the first 10 monopole modes of the gun cavity calculated with MAFIA [2]. The calculations were performed for ultrarelativistic particles (β=1). Taking the variation of the velocity into account increases the loss parameter of the first mode (0-mode) by ~25%.

mode number n	frequency ν GHz	Q-value Q	loss parameter $k_{//}$ V/pC	$V_{n\,max}$ at 9MHz kV	$V_{n\,max}$ at 100MHz kV
0	1.3031	20881	0.0575	5.4	58.7
fun	1.3076	22768	0.5825	-	-
1	2.0146	21729	0.2425	15.2	166.8
2	2.5743	15916	0.1650	6.0	65.1
3	2.9658	21799	0.1525	6.6	71.5
4	2.9951	36060	0.0450	3.2	34.5
5	3.0258	26168	0.0400	2.0	22.1
6	3.3092	27818	0.0650	3.2	34.9
7	3.4112	32096	0.0438	2.4	26.3
8	4.0390	22353	0.1350	4.4	47.7

Table 1: Frequencies, longitudinal loss parameters $k_{//}$ and induced voltage at bunch repetition frequencies of 9MHz and 100MHz for the first 10 monopole modes of the gun cavity at a charge of 1nC per bunch.

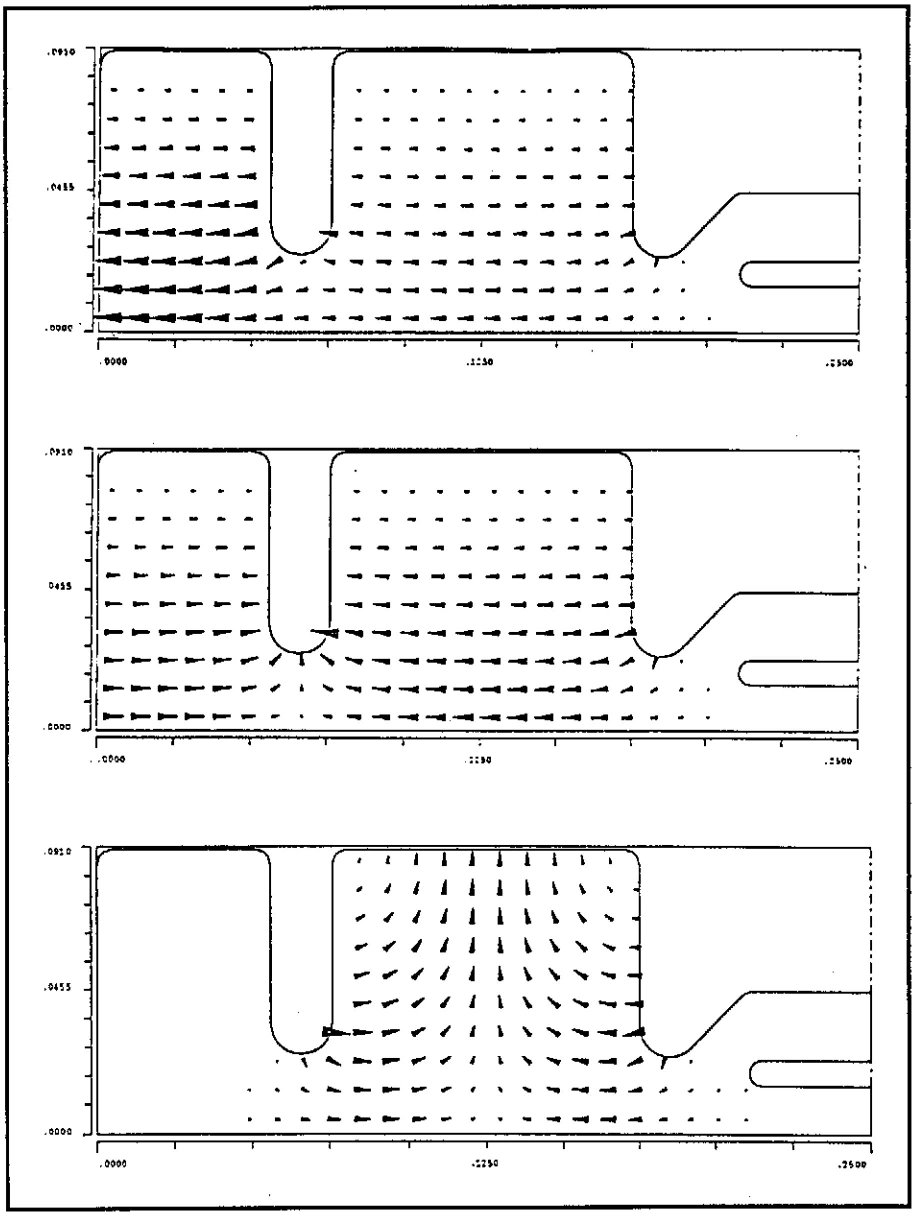

Fig. 1: Field pattern of the 0-mode (top), the fundamental mode (middle) and the first higher order mode (bottom) of the gun cavity.

Fig. 1 shows field patterns of the 0-mode, the fundamental mode and the first higher order mode which has the highest loss parameter of all higher order modes. The 0-mode is suspected to have a negative influence on the emittance due to the field gradient extending through the iris hole. This mode may disturb the balance of focusing and defocusing forces occurring on both sides of the cavity iris since the energy of the bunch is changing while passing the iris hole.

The field distribution and the loss parameter of the 0-mode depend on the field balance E_l/E_2 of the fundamental mode. (E_l and E_2 denote the field amplitudes of the accelerating mode in the half cell and the full cell, respectively.) For $E_l/E_2=0.5$ - 1.5 a maximum loss parameter of $k_{// \text{0-mode}}=0.115$ V/pC was found, i.e. about a factor of 2 higher as in the case of a balanced field ($E_l/E_2=1$).

Resonant mode excitation

The injection of the bunches has to be synchronized to the frequency of the fundamental mode, so that the bunches are emitted at a fixed phase of the rf. Hence a phase shift $\Delta\Phi_n$ occurs for all other modes. The phase shift is given by:

$$\Delta\Phi_n = 2\pi \frac{\nu_n - \nu_{fun}}{\nu_b} \tag{1}$$

ν_{fun}=frequency of the fundamental mode
ν_n=frequency of the parasitic mode
ν_b= bunch repetition frequency

Only if the phase shift is a multiple of 2π the mode is excited at resonance. Thus the resonance condition is:

$$\nu_b = \frac{\nu_n - \nu_{fun}}{m} \tag{2}$$

where m is an integer number.

Since the mode is damped between successive bunches due to wall losses, the maximum voltage $V_{n\,max}$ that can be excited at resonance of mode n is given by:

$$V_{n\,\max} = \frac{V_{n\,0}}{1 - e^{-\frac{\pi\nu_n}{Q_n\nu_b}}} \tag{3}$$

$V_{n\,0}$ is the voltage excited by a single bunch passage in the mode n, i.e.:

$$V_{n\,0} = 2 \cdot q \cdot k_{//\,\mathrm{n}} \tag{4}$$

q = charge per bunch =1nC

The resonance excitation is worst for low frequencies and high Q-values. A listing of induced voltages $V_{n\,max}$ at a bunch repetition rate of 9MHz is given in Table 1. The first higher order mode reaches the highest voltage of 15kV corresponding to 0.25% of the accelerating voltage of 6MV. At a bunch repetition rate of 100MHz a voltage of 167kV corresponding to 2.8% is reached.

If the difference frequency $|\nu_n - \nu_{fun}|$ is large compared to typical bunch repetition frequencies, it is reasonable to assume that the mode is excited with the maximum voltage $V_{n\,max}$ irrespective of the actual phase shift.

If, however, the difference frequency is comparable to the bunch repetition rate, the resonance lines are well separated and one could easily operate between the resonance lines if this turns out to be necessary. Fig. 2 shows the excitation of the 0-mode for bunch repetition frequencies of 1-9MHz. In this simulation the correct phase shift according to equation 1 and the damping of the mode has been taken into account. The figures show the maximum amplitude that is reached during the transient excitation process. Except for the resonance lines this maximum occurs within the first 10-15 bunches. The first resonance line at 4.5MHz has a relative amplitude of 20 corresponding to 2.7kV.

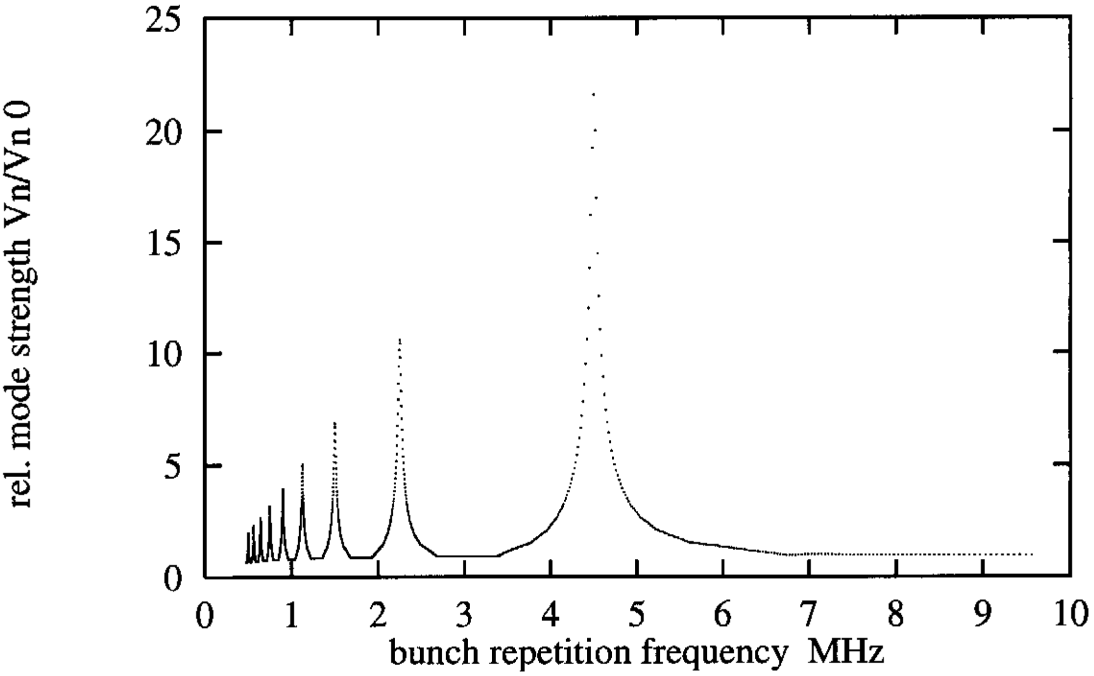

Fig. 2: Excitation of the 0-mode for bunch repetition frequencies of 1-9MHz.

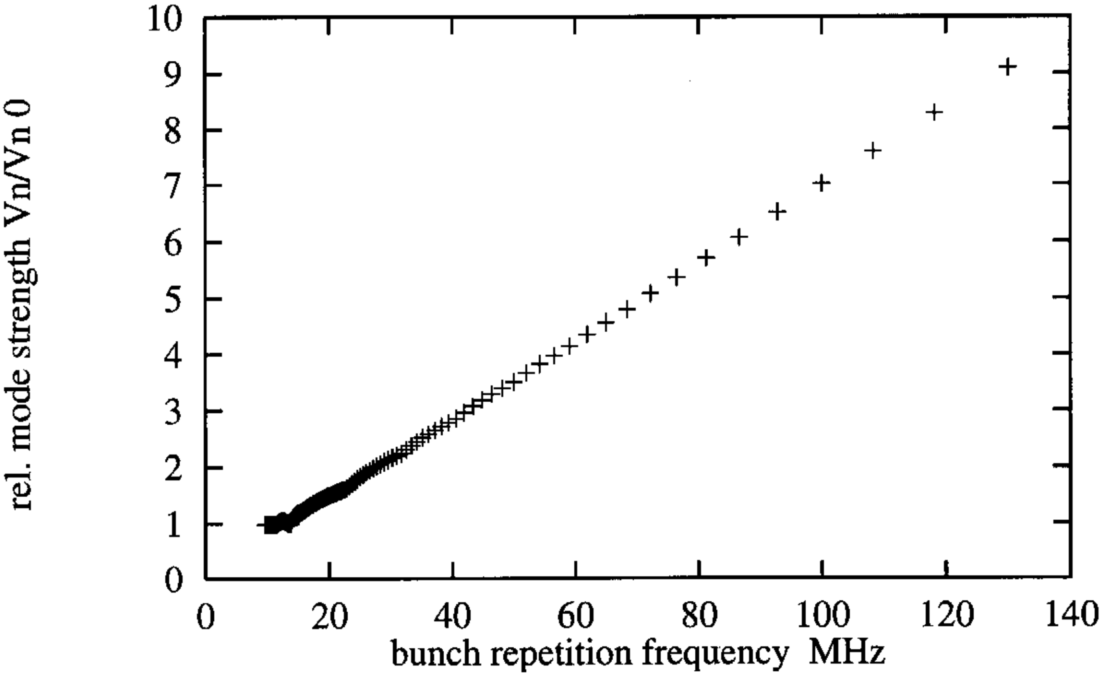

Fig. 3: Excitation of the 0-mode for bunch repetition frequencies of 9-140MHz.

A normal conducting linac would typically operate at bunch repetition frequencies above the first resonance line. Fig. 3 shows the excitation of the 0-mode for a frequency range of 9-140MHz. The induced voltage increases with increasing bunch repetition frequency, but stays far below the induced voltage as given by equation 3. At 100MHz a relative mode strength of 7 is reached, i.e. still lower as the excitation on the first resonance line at 4.5MHz.

It should be noted that the mode separation $\nu_{fun} - \nu_0$ is related to the cell-to-cell coupling κ by the relation:

$$\nu_{fun} - \nu_0 = \nu_{fun}\kappa \tag{5}$$

(This relation is strictly valid only for the case of $E_1 = \sqrt{2}E_2$, for details see [3].)

Thus the mode separation can be changed in the design phase of the gun by adjusting the cell-to-cell coupling, i.e. the iris hole and thickness. A high coupling increases the field stability on the cost of a somewhat reduced shunt impedance. In addition resonance lines occur at higher frequencies and with higher amplitudes.

Emittance degradation due to parasitic modes

In order to calculate the effect of the parasitic modes on the transverse and longitudinal emittance of the electron bunches a tracking code was modified, so that it could track particles through a cavity which is excited with two modes of different frequency, amplitude and phase. The space charge forces have been calculated with a point-by-point method. The emittance was calculated directly at the gun exit and no additional focusing was included. The electron bunch had a uniform transverse and longitudinal profile, a radius of 1.5mm and a length of 2.6mm (8.5ps). These parameters are close to the optimum parameters found for the gun in simulations that included the compensation scheme for space charge induced emittance growth [4].

Besides slightly increased longitudinal and transverse emittances parasitic modes can induce an energy jitter. It has been found that both effects scale roughly linearly with the amplitude of the parasitic mode. In the simulations the parasitic mode has been excited with a high voltage (1-10MV/m) in order to have a significant effect. The emittance degradation and the energy jitter depend also on the relative phase of the parasitic mode and the fundamental mode. Table 2 lists the worst results for the 0-mode and the first higher order mode scaled to the voltage excited at a bunch repetition frequency of 9MHz. The results have to be compared with the design parameters of 1π mrad mm and 20keVmm for the transverse and longitudinal emittance, respectively. In the calculations the pessimistic assumption of a resonant excitation of the 0-mode according to equation 3 has been made.

	unit	0-mode	first higher order mode
transverse emittance	π mrad mm	$6.3 \cdot 10^{-3}$	$14.4 \cdot 10^{-3}$
longitudinal emittance	keVmm	0.27	0.75
energy jitter	%	±0.3	±0.9

Table 2: Emittance contribution of parasitic modes at a bunch repetition frequency of 9MHz.

The most significant contribution is the energy jitter which, however, is reduced by a factor of ~4 in the subsequent capture cavity before the beam enters the first bunch compressor. At a bunch repetition rate of 100MHz all contributions are about an order of magnitude higher. While the transverse emittance growth is still tolerable, the contribution to the longitudinal emittance is becoming significant and the energy jitter will produce major problems in the subsequent bunch compressor.

Beam loading of the fundamental mode

The voltage drop of the fundamental mode due to the passage of a single bunch is given by:

$$\Delta V = 2 \cdot q \cdot k_{//\,\mathrm{fun}} \tag{6}$$

For q=1nC:

$$\Delta V = 1165\ V \tag{7}$$

The filling of the cavity is given by:

$$V_{(t)} = V_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \tag{8}$$

with a maximum cavity voltage of $V_0 \cong 6 \cdot 10^6\ V$ and a filling time τ of:

$$\tau = \frac{2 \cdot Q}{\omega} = 5.6 \cdot 10^{-6} s \tag{9}$$

The beam loading may lead to an energy variation of the bunches. It is, however, exactly compensated by the filling of the cavity if the first bunch is injected after the cavity has been filled during a time t_i, determined by:

$$e^{-\frac{t_i}{\tau}} = \frac{\Delta V / V_0}{1 - e^{-\frac{t_b}{\tau}}} \geq \frac{\Delta V}{V_0} \tag{10}$$

t_b= bunch spacing

t_i is large compared to the filling time τ since the voltage drop is small and the bunch spacing is rather long. However, it is still small compared to the total length of the rf pulse of $1 \cdot 10^{-3}$s. Table 3 lists t_i/τ for typical operation parameters.

bunch rep. frequency	bunch distance t_b [s]	t_i/τ	t_i [s]
$\rightarrow 0$	$\rightarrow \infty$	8.5	$48 \cdot 10^{-6}$
1 MHz	$1.0 \cdot 10^{-6}$	6.7	$38 \cdot 10^{-6}$
9 MHz	$1.1 \cdot 10^{-7}$	4.6	$26 \cdot 10^{-6}$

Table 3: Time t_i spent to fill the cavity before the first bunch is injected in order to minimize the energy spread due to beam loading for different bunch repetition frequencies.

Transverse dipole modes

Electron bunches that the cavity on axes excite transverse deflecting dipole modes that can kick subsequent bunches. The kick strength is different for all modes in a bunch train, hence it cannot be compensated by a static corrector. Table 4 lists normalized loss factors and related parameters for the first 10 transverse dipole modes. The spectrum is dominated by the second and fourth mode. The amplitude of the third and the fifth mode are about 25% of the fourth mode, while the voltage of all other modes is only small.

mode number n	frequency ν GHz	Q-value Q	norm. loss parameter $k_{//}$ V/nC mm	$V_{n\,max}$ at 9MHz V	$V_{n\,max}$ at 100MHz V
1	1.6812	14093	0.35	17.2	187.2
2	1.7533	28647	10.31	975.7	10736.3
3	1.9928	24871	3.55	257.5	2824.6
4	2.0190	27209	13.69	1071.0	11760.1
5	2.4377	21941	4.6	241.9	2641.0
6	2.6952	23421	0.29	14.7	160.8
7	2.9544	31159	1.22	75.0	820.5
8	3.1425	35484	0.0	0.0	0.0
9	3.2339	23410	2.1	89.2	970.1
10	3.2918	21331	1.8	68.7	744.5

Table 4: Frequencies, transverse loss parameters $k_\perp$ and induced voltage at bunch repetition frequencies of 9MHz and 100MHz for the first 10 dipole modes of the gun cavity at a charge of 1nC per bunch.

In order to estimate the transverse kick due to the dipole modes it has been assumed that all bunches in a bunch train pass trough the cavity with the same initial offset and that the first ten modes add up coherently.

A transverse deflection of ~0.5mrad for 1mm offset is found. For a bunch repetition rate of 100MHz the transverse deflection is a factor of 10 stronger, thus the requirements for the alignment would be much tighter in this case.

The initial offset of a bunch train is determined by the position of the emission area of the electrons. The FEL gun will be equipped with Cs_2Te cathodes that allow two different modes of operation. In the first mode the active area of the cathode is larger than the spot size of the laser. (This is the usual operation mode for guns with a metallic cathode.) Thus the offset of the electron emission area and the spot size can be corrected with adjustments of the laser optics. On the other hand the offset is not constant due to positioning fluctuations of the laser beam. In the second operation mode the active area of the cathode is smaller than the spot size of the laser beam. The offset of the cathode is constant and determined by mechanical tolerances of the cathode plug. The spot size cannot be changed with the laser beam but it has a well defined radial boundary. Thus a beam with a radially uniform distribution can be produced if the spot size of the laser beam is larger than the cathode radius and the laser beam is homogeneous.

We intend to start the operation in the first operation mode, so that the spot size can be adjusted with the laser optics. After empirical optimization of the spot size a cathode with the correct size will be included and operation in the second mode will be tested.

The mechanics of the cathode plug should allow an alignment accuracy of ≤ 0.2mm. Thus the beam jitter induced by parasitic modes will be below 0.4mm at a distance of 4m (i.e. behind the capture cavity).

While the initial offset of the bunch train is given by the position of the emission area, the trajectory of the electron bunches is additionally influenced by the alignment of the focusing solenoid that is located around the second cell of the gun. Since the solenoid is rather strong (0.2T) and the electron energy is low the alignment requirements for the solenoid are tight. The kick strength of the solenoid amounts to 3mrad per mm relative offset of the electrons with respect to the solenoid axis. The solenoid will be mounted on a mover system that will allow a precise alignment of the magnet on a 10micron scale based on beam observations. The movers will be a slightly modified version of the movers already under development for the S-band test facility.

Conclusion

It has been shown that longitudinal monopoles in the TTF FEL gun will have only a negligible effect on the transverse and longitudinal emittance at the design bunch repetition frequency of 9MHz. The induced energy jitter is also very small. At bunch repetition frequencies as high as 100MHz the contribution to the longitudinal emittance would not be negligible and the energy jitter would produce significant problems in the bunch compressor.

In order to minimize energy variations due to the beam loading of the fundamental mode the cavity has to be filled for 4-7 filling times (~20-40μs) before injection of the first bunch. This is still small compared to the total length of the rf pulse of ~1ms.

Transverse dipole modes set alignment tolerances of the emission area of the electrons with respect to the cavity axis of about 0.2mm. The focusing solenoid will be mounted on a mover. Thus it will be possible to move the solenoid axis close to the cavity axis as determined by beam observations.

Acknowledgment

We would like to thank Jacek Sekutowicz and Zhang Min for the calculation of loss parameters and field patterns.

References

1 'A VUV Free Electron Laser at the TESLA Test Facility at DESY-Conceptual Design Report', TESLA-FEL 95-03, DESY, June 1995.

2 The MAFIA Collaboration 'Users's Guide MAFIA Version 3.2' CST GmbH, Lauteschlägerstr. 38, 64289 Darmstadt, Germany.

3 R. Bossart, et al 'RF-Gun Construction, Tuning and High Power Tests' European Particle Accelerator Conference, Berlin 1992.

4 Y. Huang, K. Flöttmann 'Simulation Study of the RF Gun for the TTF Free Electron Laser' TESLA-FEL 96-01, DESY, January 1996.