MULTIPOLE EFFECTS IN THE RF GUN FOR THE PSI INJECTOR

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Abstract

For the 250 MeV test injector at PSI, it is planned to use a 2.6 cell RF gun originally developed for high charge operation in the CLIC test facility CTF-2. First start-to-end simulations assuming perfect field symmetries show, that this gun should be able to generate bunches at 200 pC with an emittance of below 400 nm rad, which would be compatible with the requirements for the SwissFEL. This gun uses double side coupled RF feeds in the last cell as well a asymmetrical tuners in the last two cells, which lead to transverse multipole effects in the field and phase space distribution and may lead to a deteriorated emittance. Since the beam in the last cells is already relativistic at energies between 4 and 6.4 MeV, this effect can be computed in a clean way by looking at the distributions of the integrated beam voltage at the cavity iris and deriving any transverse kicks via the Panovsky-Wenzel theorem. Doing this approach for the various operation modes planned for the SwissFEL shows an emittance dilution well below critical thresholds.

INTRODUCTION

Within the framework of the SwissFEL project at PSI, a 250 MeV test injector facility (see fig. 1 on the next page) is under construction, which will be used to develop test techniques to create and transport high brilliance electron beams suitable for short wave length free electron lasers.

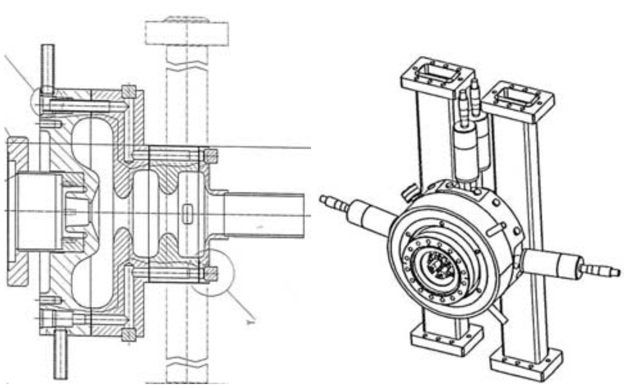

Figure 2: Geometry of the RF gun

Initially it will operate as a stand-alone machine. It must produce the ultra-high brightness electron beam and permit an objective assesment of the technological risks, which are associated with the construction of a low-energy XFEL user facilty. Later it is intended to use it as the injector for the main linac of the future SwissFEL free electron laser facility.

Table 1: Baseline operation modes of the SwissFEL

	High	Small
Bunch charge Q (pC)	200	10
Laserspot σ_r (μm)	270	100
Pulse length FWHM (ps)	9.9	3.7
Acc. gradient (MV/m)	100	100
$\epsilon_{N,slice}$ @ 150 MeV (nm rad)	320	80
$\epsilon_{N,proj}$ @ 150 MeV (nm rad)	330	96

For the electron source itself, two options are forseen. The first uses a pulsed DC gun in combination with a two-frequency cavity; the high initial gradient in the gun is supposed to give a high brilliance beam at a reduced current of 5.5 Amperes, which is compressed ballistically by the subsequent two-frequency RF cavity in combination with a drift to approximately 20 A[1]. The alternative consists in using a more convential S-band RF gun running at 100 MV/m and to generate this 20 A beam current directly at the exit of the gun[2]. Recent results from LCLS[3] make this option look rather promising.

For first tests, it is planned to use a 2.6 cell gun originally developed for high current operation in the CLIC test facility CTF-2. The general geometry of this gun[4] is shown in fig. 2. The specialty compared to other design is the large diameter first half cell, where the TM_{02} resonance is used for the main accelerating mode. The original reason for this choice is, that this resonance is particularly well suited for the operation with extremely high beam charges and currents. For the operation at the modest currents of the SwissFEL (Tab. 1), this feature has no influence.

The structure is rotationally symmetric, with perturbations introduced by tuners, field sensors and the holes of the power couplers. These introduce field asymmetries in the monopole type accelerating mode, the main effect of these being transverse kicks on the beam. Small dipole and quadrupole corrector magnets after the gun can easily compensate the integral average kick over the bunch length. What remains, is the transient, time varying part, which leads to emittance growth. More recent designs[5] avoid these problems by obviating the need for tuners all together through more precise manufacturing and by compensating the field perturbation coming from the power coupler with a more complicated race track geometry of the cells.

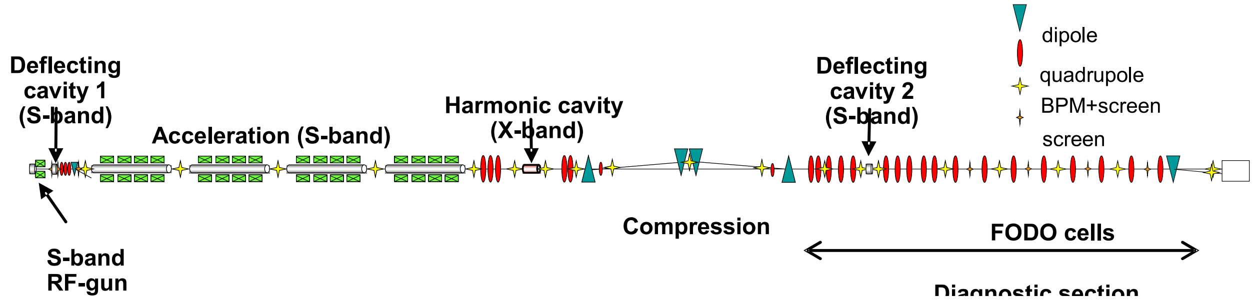

Figure 1: Layout of 250 MeV test injector

METHODOLOGY

Apart from minor perturbations from tuners and field sensors, the first cell is rotationally symmetric in a very good approximation and standard 2 1/2 D beam dynamics simulations will predict the beam dynamics in a relatively precise manner. In cells two and three, we have piston tuners and in cell three, the power coupler with its double holes, which are placed at a 90^o angle to the tuners. Cell one also has two, symmetrically placed tuners, but their influence is negligible and was omitted in the analysis.

The input coupler feeds RF power into the gun via a U-turn shaped waveguide, which is side coupled via two symmetric coupling slots (Fig. 3) to the last cell. Due to symmetry, all odd number multipole fields as dipoles, sextupoles etc. cancel out. What is left, are even number multipoles as quadrupoles, which affect the beam transversally. An interesting fact is, that the main contribution to the field distortion is not due to the real power flux through the slots filling the gun and compensating for internal losses, but caused by the perturbation of the cell geometry which would correspond to a reactive power flux.

We have only one tuner of 6.5 mm diameter per cell, so all multipoles are present, the strongest one being the dipole. In this case, the beam will see a transverse kick due to the tuners.

The average kicks and focusing experienced by the beam can be easily compensated by small corrector magnets following the gun. The problem is the amplitude variation over the bunch length giving an uncorrigible increase in the transverse momentum spread and emittance.

Computing the effect directly using a 3D particle-in-cell code becomes challenging – the effect of the coupler needs to be cleanly separated from the emittance dilution due to RF fields, wakes and numerical noise. So an indirect approach was employed here, which, while being approximative, gives a clean picture of the multipolar contribution.

As can be seen in figure 4, the beam in the second and third cells has already a relativistic energy of roughly $\gamma = 9$ and 11 respectively. If, in addition, we approximate the particle trajectories to be parallel to the cavity axis, we can use two techniques to accurately compute the kick distribution coming from the coupler.

The first is a algorithm[7] used for the computation of wake potentials. Essentially, it states, that the transverse distribution of the accelerating voltage seen by a relativistic beam at an offset (r, ϕ)

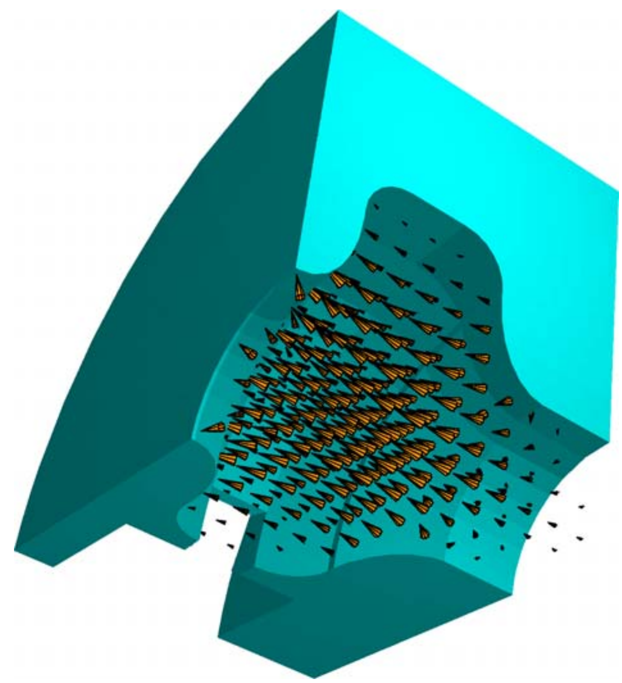

Figure 3: Symmetric quarter of the third cell with coupling slot showing the fundamental mode.

$$V_{\|}(r, \phi, t) = \int E_z(r, \phi, z - ct, t)dz$$

follows a potential distribution in two dimensions:

$$\Delta_{r,\phi} V_{\|}(r, \phi) = 0 \tag{1}$$

This means in practice, that we just need to integrate the voltages in a numerically advantageous way at the beam pipe radius itself. The values inside the beam pipe are obtained from solving eq. 1 with the given boundary values at the beam pipe. With a cylindrical beam pipe, this is done by computing the Fourier series of the boundary values over the angle ϕ. Given the Fourier coefficients A_n and B_n, the

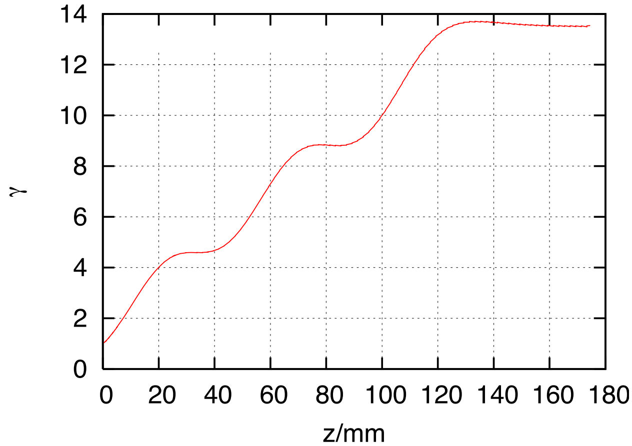

Figure 4: Evolution of beam energy γ during acceleration in the gun. The third cell extends from $z = 78\,mm$ to $z = 125\,mm$.

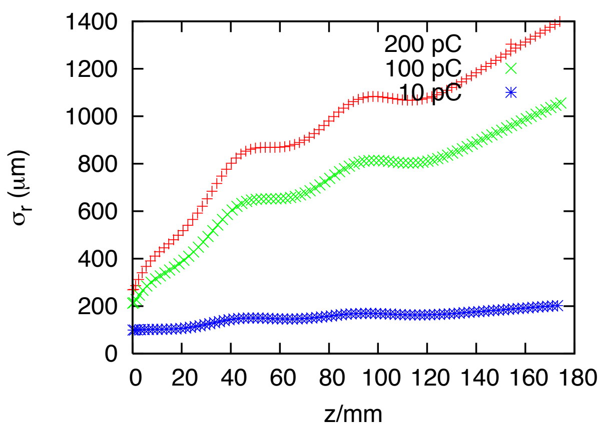

Figure 5: Rms beam radius σ_r during acceleration in the gun. The third cell extends from $z = 78\,mm$ to $z = 125\,mm$.

voltage inside the beam pipe is given as:

$$V_{\|}(r,\phi) = \sum_{n=0}^{\infty} \frac{r^n}{r_0^n} \left(A_n \sin n\phi + B_n \cos n\phi \right)$$

As the second tool, the Panovsky Wenzel theorem [6] relates the transverse kick voltage to the longitudinal one as:

$$\vec{V}_{\perp} = \int \nabla_{r,\phi} V_{\|}(r,\phi) dt \qquad (2)$$

For the case of a quadrupole kick, the resultant emittance dilution is obtained by calculating the standard deviation of the transverse kick over the whole bunch (transversally and longitudinally) and weighting it with the rms transverse size. Dipoles kicks don't vary with the radial offset, so one only has to compute the transverse kick using the longitudinal distribution.

SIMULATION RESULTS

Power couplers

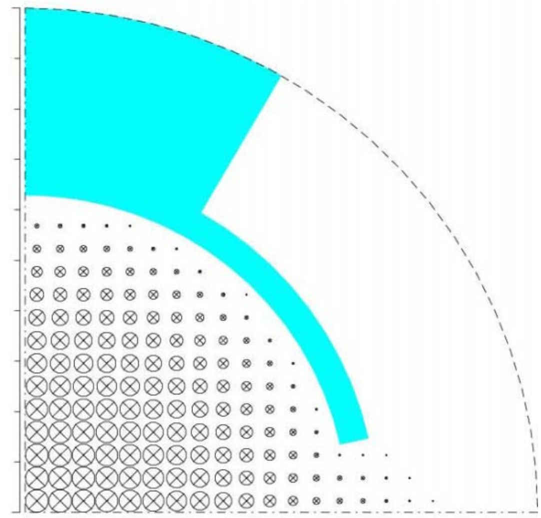

Figure 6: Cut through third cell with coupling hole showing accelerating mode

For the numerical simulations, a quarter of the last cell was modeled, which included the coupling slot and a segment of the U-type waveguide. The modeling was done using a three dimensional cylindrical grid (mesh lines in r, ϕ and z direction). The big advantage of this type of grid is, that the field solution for a completely rotational symmetric cell without coupling slots shows a perfect symmetry. We do not have to worry about numerical artifacts creeping into the field resulting in artificial multipolar kicks. Figure 6 shows the electric field in the equatorial plane of the cell.

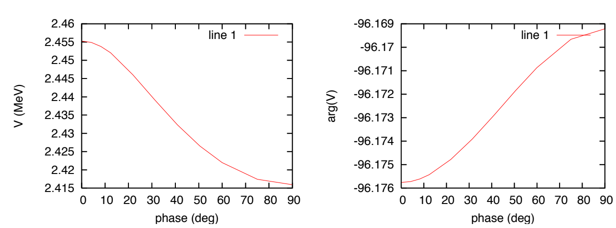

Figure 7: Amplitude and complex phase of integrated beam voltage at the beam pipe wall versus phase ($0 < \phi < 90$).

Figure 7 shows the variation of the integrated beam voltage at the beam pipe wall. Decomposing it into multipole components give the following dependency at $r = 20$ mm:

$$V_{\|}(\phi) = 2.466\text{MeV} + 21.48\text{keV} \cdot \cos(2\phi) \ldots .$$

The solution is dominated by monopole and quadrupole fields, higher multipoles can be safely ignored. The phasors of the monopole and quadrupole voltages are aligned better than 0.2 degrees, which via the Panovsky Wenzel theorem means, that the bunch traverses the cavity in the

Table 2: Emittance dilution ϵ_N due to coupling slots for the two operation modes. For comparison, the initial thermal emittance ϵ_{th} is also included.

	High	Small
Bunch charge Q (pC)	200	10
Beam radius in cell 3 (μm)	1530	240
Beam energy in cell 3 (γ)	11	11
Bunch length (ps)	10	4
$\sigma_{V_\perp}$ (eV/c)	50.5	3.2
ϵ_N (nm rad)	13	0.3
ϵ_{th} (nm rad)	195	72

zero crossing of the transverse kick. The kick distribution within the beam pipe comes out to be

$$V_\perp(r, \phi, t) = 1.7\text{keV/c/mm} \cdot r \cdot \cos(2\phi) \cdot \sin(\omega t)$$

with $\omega = 2\pi\, 3$ GHz as the resonance frequency.

For simplicity, we assume a bunch with homogeneous charge distribution of radius r_0 and length Δt. For the variance of the transverse kick we solve

$$\sigma_{V_\perp}^2 = \frac{1}{\pi r_0^2 \Delta t} \int_{-\Delta t/2}^{\Delta t/2} \int_0^{2\pi} \int_0^{r_0} V_\perp^2(r, \phi, t) r\, dr\, d\phi\, dt$$

to obtain:

$$\sigma_{V_\perp} = 3.3 \frac{\text{eV}}{\text{c pC mm}} r_0 \Delta t$$

The resulting emittance dilution comes out as:

$$\epsilon_N = \frac{1}{mc} \sigma_r e \sigma_{V_\perp}$$

Table 2 summarizes the results for the different operation modes.

Tuners

All cells contain stub like piston tuner to adjust the resonant frequency and the field balance within the structure. In the TM_{02} half cell, two pistons of 9.2 millimeter diameter are needed to give the required tuning range. These are placed symmetrically at opposite locations on the cell diameter, the resultant perturbation contains only even-order multipoles (quadrupoles etc.) and was omitted in the following calculation due to their small amplitude.

The following two cells each contain one piston of 6.5 millimeter diameter at the cell diameter. From the theoretical design, they should reach into the cavities by two millimeters. The real, actual values have not been measured. So, to be on the safe side, they were assumed to be positioned three millimeters in for the calculation. With only one tuner per cell, we have asymmetry and the effect will be a dipole kick to the beam. Also, both tuners are aligned, so that both contributions will add up linearly.

The calculation follows essentially the same approach as that for the coupling holes, the difference being, that one does it for a dipole kick instead of a quadrupolar distribution. So the intermediate results are omitted and only the final results are listed in table 3.

Table 3: Kicks and emittance dilution ϵ_N due to the cell tuners in cell 2 and 3 (tuner position at 3 mm) for the two operation modes. For comparison, the initial thermal emittance ϵ_{th} is also included.

	High		Small	
Bunch charge Q (pC)	200		10	
Tuner in cell	2	3	2	3
Beam radius (μm)	790	142	790	142
Beam energy (γ)	9	9	9	9
Bunch length (ps)	10	10	4	4
$\sigma_{V_\perp}$ (eV/c)	137	100	55	40
ϵ_N (nm rad)	24	28	1.7	1.8
ϵ_{th} (nm rad)	195	72	195	72

CONCLUSION

A concern for using CERN gun 5 in the PSI 250 MeV injector was a possible emittance dilution due to transient multipole kicks coming from the RF input coupler. The effect has been computed approximatively via a combination of indirect techniques. The additional dilution due to the coupler geometry is well below the initial thermal emittance to be expected from the cathode and will fulfill the specifications of the machine. Also the transverse kicks coming from the tuners in the last two cells create dipole kicks within the required tolerances.

REFERENCES

[1] A. Oppelt et al., “Towards a low emittance X-ray FEL at PSI”, Proc. of the 2007 Free-Electron Laser Conference (FEL2007), Novosibirsk (Russia)

[2] Y. Kim et al., “Linear Accelerator for the PSI-XFEL FEL3 Beamline”, Proc. of the LINAC 2008, Vancouver, Canada (2008)

[3] Y. Ding et al., “Measurement and Simulations of Ultra-Low Emittance and Ultra-Short Electron Beams in the Linac Coherent Light Source”, Phys. Rev. Lett. 102, 254801 (2009), SLAC-PUB-13525

[4] R. Bossart and M. Dehler, “Design of a RF Gun for Heavy Beam Loading”, proc. of the European Particle Accelerator Conference EPAC, June 10-14 1996, Barcelona, Spain, pp. 1544-1546.

[5] Z. Li et al., “Coupler design for the LCLS injector S-band structure”, proc. of the Particle Accelerator Conference (PAC05), 16-20 May 2005, Knoxville, TN, USA (2005), SLAC-PUB-11728

[6] W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instr. 27 (1956), p. 967.

[7] T. Weiland, NIM 216 (1983), 31-34