IMPACT OF THE RF-GUN POWER COUPLER ON BEAM DYNAMICS*

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Abstract

A production of high brightness electron beams is necessary for FEL operation. Since the beam quality degrades as the beam propagates along the beam line, every perturbation factor has to be studied. The electron beam dynamics in the TESLA Test Facility (TTF DESY) rf-gun has been investigated with the on-line simulation tool V-Code. While some of the rf-gun misalignments can be corrected by an earlier developed alignment procedure, the aside power coupler causes a field asymmetry resulting in unavoidable steering forces. The dependence of the accelerating mode offset on the longitudinal coordinate, calculated with CST Microwave Studio (MWS), has been implemented in the V-Code. Assuming a possible laser beam offset on the cathode additionally to the given rf field asymmetry one can explain the dependence of the electron beam offset measured by the first beam position monitor (BPM1) on rf phase. The measured data as well as simulation results are presented.

1 INTRODUCTION

To produce high quality electron beams needed for short wavelength FEL, a photocathode rf gun with emittance compensation is required [1]. The TTF injector includes a 1½-cell photogun cavity, operated at 1.3 GHz and a set of solenoids (primary, secondary solenoids and trim coil). A sketch of the TTF rf gun is shown in Fig.1. The beam diagnostics near the gun is presented by a button type beam position monitor BPM1.

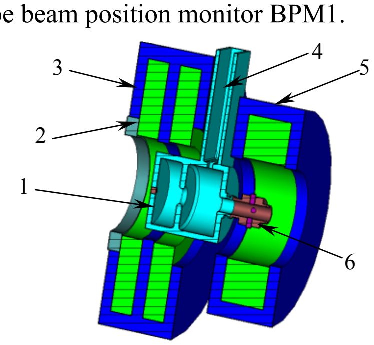

Figure 1: TTF rf gun layout: 1–rf cavity, 2–trim coil, 3-primary solenoid, 4-power coupler, 5-secondary solenoid, 6-beam position monitor BPM1 .

The rf cavity is fed by the aside input coupler 4. The coupler asymmetry results in rf field asymmetries (accelerating, dipole and higher order modes), which can lead to a significant emittance growth. Vertical offset of the accelerating mode from the cavity axis has been simulated with Microwave Studio [2]. The rf field asymmetry effect has been incorporated in the V-code [3], which has been used for the on-line simulations. To simulate beam offsets, measured by BPM1, the laser offset at the photocathode should be taken into account. Beam positions as functions of gun parameters, simulated with V-Code Alignment Utility [3,4], have been fitted to measured ones, resulting in a set of misalignment parameters. These parameters have been used for TTF gun alignment as well as for the beam dynamics simulations. The beam dynamics aspects of the power coupler and laser offset have been simulated with code ASTRA [5].

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2 MODE OFFSET SIMULATIONS

The rf field of the gun cavity can be directly calculated with Microwave Studio [2]. MWS eigenmode solver has been used for the rf mode offset calculations. Dependence of the mode offset on rf power can be determined from the eigenmode field map. Then the offset amplitude can be found from fitting of the simulated transverse kick on a beam to a measured one.

The electric field of the accelerating π-mode is shown in Fig.2a. The coupler hole dimensions are much smaller than cavity sizes and the field perturbation can be determined using magnetic field centre offset from the cavity geometrical axis. The magnetic field isolines in the coupler cross section shown in Fig.2b illustrate the rf field perturbation due to the input coupler.

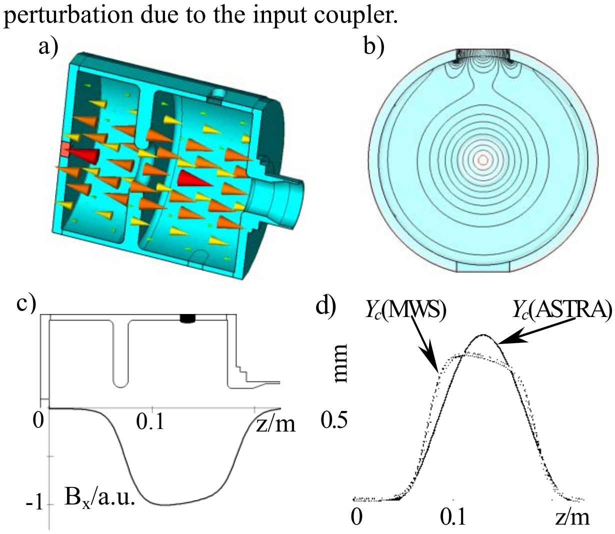

Figure 2: a) Electric field of the E_{01}-π mode; b) E_{01}-π mode magnetic field isolines in the coupler cross section; c) Horizontal component of magnetic field on the cavity axis; d) E_{01}-π mode offset.

Longitudinal dependence of the mode offset can be obtained from the $H_x(x=0, y=0, z)$ (Fig.2c). The spatial dependence of rf field near the cavity axis can be approximated by following functions:

$$\vec{E} = \left(-\frac{x}{2}F'; \quad -\frac{y - Y_c}{2}F'; \quad F \right) \cdot \cos(\omega t + \varphi_0) \qquad (1)$$
$$\vec{B} = \left(\frac{y - Y_c}{2}\kappa F; \quad -\frac{x}{2}\kappa F; \quad 0 \right) \cdot \sin(\omega t + \varphi_0),$$

where $F(z)$ is axial distribution of the electric field, $\kappa = \omega / c$ is the wave number, $Y_c(z)$ is the mode offset, shown in Fig.2d (Y_c(MWS) obtained from the field map and Y_c (ASTRA) is a cosine-like analytical approximation used for beam dynamics simulations).

3 BPM1 MEASUREMENTS AND SIMULATIONS

The electron beam dynamics in the TTF rf-gun has been investigated with the on-line simulation tool V-Code [3]. Some of the rf-gun misalignments, namely primary and secondary solenoid transverse offsets, have been significantly reduced after beam based alignment (BBA) [4]. The method of correction is based on the beam position measurements as function of solenoid currents. But for the more detailed study the coupler effect should be taken into account. For the coupler impact study the solenoids should be switched off. The measured dependence of the beam position on rf phase at the BPM1 location is shown in Fig.3a (the points with error bars).

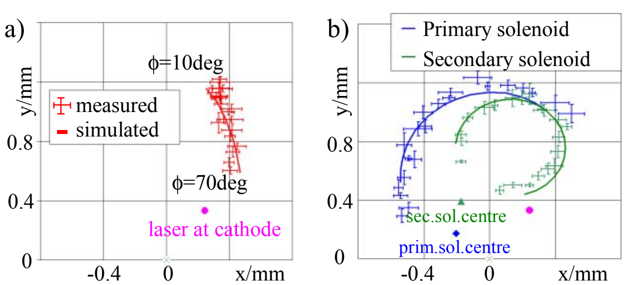

Figure 3: Beam position as a function of: a) rf phase; b) primary and secondary solenoid current.

One of the possible reason of electron beam offset can be a laser offset at the photocathode. In this case nonzero transverse rf field acting on the beam centre causes the transverse beam motion in radial direction, however the measurement demonstrates other dependence. Supposing correspondent BPM mechanical offset does not explain beam position dependencies on solenoid currents. We neglect high order modes contribution and apply the above mentioned analytical model for the perturbation of the π-mode for the beam offset simulations. The V-Code Alignment Utility yields mode offset amplitude 0.88mm and laser beam offsets at the cathode X=0.24mm, Y=0.33mm. Simulated fitted dependence is shown in Fig.3a with a solid line. Fig.3b illustrates measured (error bars) and simulated (solid curves) beam positions as function of current of primary (blue curves) and secondary (green curves) solenoid.

The alignment procedure, being applied to the TTF rf gun, yielded the beam alignment in one order better than it was before BBA. However it is impossible to avoid the impact of the aside power coupler within present cavity geometry. But by choosing proper misalignments set one can possible to minimize this effect.

4 BEAM DYNAMICS SIMULATIONS

The electron beam dynamics in the TTF rf-gun has been simulated with the macroparticle code ASTRA [5], which incorporates a space charge algorithm on a rotational symmetric mesh. ASTRA can simulate the mode offset by applying longitudinal cosine-like field centre dependence (Fig.2d). The offset parameters were taken from BPM1 simulations.

RF field asymmetry due to vertical power coupler does not itself cause the cross-plane coupling in the beam phase space, but together with solenoidal magnetic field (used in the emittance compensation scheme [6]) can result in strong coupling between X and Y phase spaces as well as between transverse and longitudinal phase spaces. One of the possible consequences of coupled motion in a beam transport system is an increase in the emittance projected onto the transverse planes at positions downstream.

Transverse emittance can be defined by determinant of the matrix:

$$\varepsilon_{tr} = \sqrt[4]{\det[\hat{\mathbf{M}}_{4\times4}]}, \qquad (2)$$

where matrix $(\hat{\mathbf{M}}_{4\times4})_{\xi\nu} = \langle \Delta\xi\Delta\nu \rangle$ $(\Delta\xi = \xi - \langle\xi\rangle$, $(\xi,\nu) = x, y, p_x, p_y$). In the case of the decoupled X and Y phase planes matrix

$$\hat{\mathbf{M}}_{4\times4} = \begin{pmatrix} \hat{\mathbf{M}}^x & 0 \\ 0 & \hat{\mathbf{M}}^y \end{pmatrix}, \qquad (3)$$

where $\hat{\mathbf{M}}^x$ and $\hat{\mathbf{M}}^y$ are 2×2 submatrices, and the transverse emittance

$$\varepsilon_{tr} = \sqrt{\varepsilon_x\varepsilon_y} = \sqrt[4]{\det[\hat{\mathbf{M}}^x]\cdot\det[\hat{\mathbf{M}}^y]}\,. \qquad (4)$$

The transverse emittance development for perfectly aligned gun without rf asymmetry with applied emittance compensation scheme is shown in Fig.4.

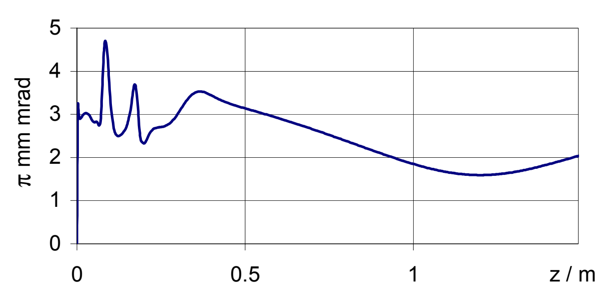

Figure 4: Emittance development in the photoinjector.

The rf field influence on the emittance is illustrated by Fig.5, where the emittance of the electron beam, tracked without space charge and with solenoids off, is depicted. For the comparison the case without rf kick from the power coupler is plotted with red squares.

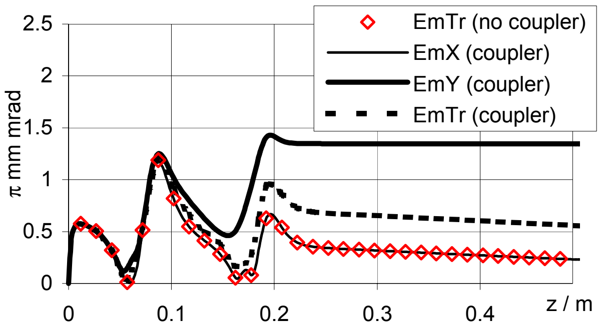

Figure 5: RF induced beam emittance.

Space charge forces, involved into consideration, significantly increase the electron beam emittance. As it is expected for the case without magnetic field (solenoids off) the vertical power coupler affect only the vertical phase space of the beam, i.e. we have decoupled motion but X and Y emittances are different (Fig.6).

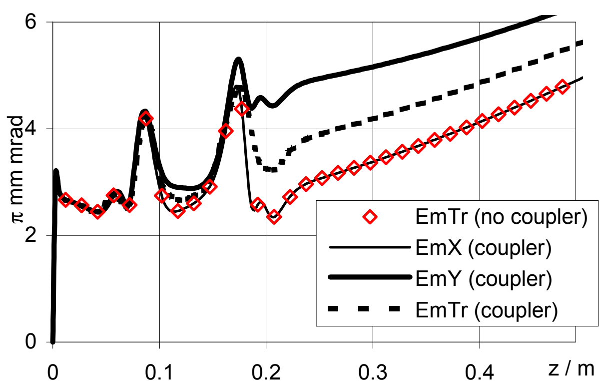

Figure 6: Space charge induced emittance.

Technique for the space charge induced emittance growth in high brightness electron beams implies solenoidal focusing near the photocathode [6]. Introducing a magnetic field in the gun with rf asymmetry causes strong coupling between X and Y phase spaces.

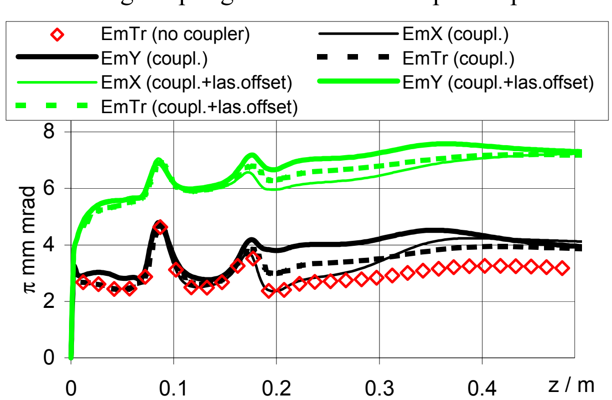

Figure 7: Emittance development for different factors.

The emittance development for the rf gun with focusing solenoids without rf field asymmetry is shown in Fig.4 and Fig.7 (red squares). Applying rf kick from coupler results in emittance growth (blue curves in Fig.7).

Even small laser beam offset at the photocathode can produce significant additional phase space coupling and emittance growth. Fig.7 Illustrates the electron beam emittance development in the case of 0.5mm horizontal laser beam offset, applied additionally to the rf kick.

The summary of the emittance growth at the point z=1.5m for different factors is shown in Table 1.

Table 1

Case	1	2	3	4
Space Charge	-	+	+	+
Solenoids	off	off	on	on
Laser offset X/Y,mm	0/0	0/0	0/0	0.5/0
$\varepsilon_{tr}, \pi \cdot mm \cdot mrad$, no coupler / coupler	0.39 / 0.75	15.6 / 15.9	2.03 / 3.94	5.91 / 7.07

Applying rf kick from the power coupler impacts significantly the transverse phase space. Transverse phase space of the electron beam at the position z=1.5 m for the cases 2, 3, 4 from Table 1 are shown in Fig.8.

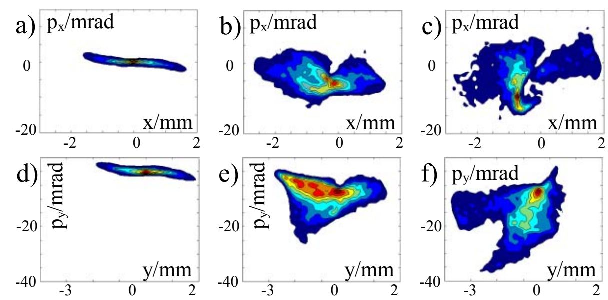

Figure 8: Transverse phase spaces (x,p_x) and (y,p_y) at longitudinal position z=1.5m: a),d) -case 3 (no rf kick) from the Table1; b),e) -case 3 (with rf kick); c),f) -case 4.

5 CONCLUSIONS

RF field asymmetry, produced by an aside power coupler, has an impact on the beam dynamics in the TTF rf gun, resulting in transverse kick and emittance growth by a factor 2. Additional laser offset at the photocathode causes more dramatic emittance growth emphasizing the kick from power coupler.

6 REFERENCES

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