Determination of the field balance of the rf gun cavity at PITZ

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The main challenge of the **P***hoto* **I***njector* **T***est Facility at DESY* **Z***euthen (PITZ) is optimizing an electron source for* **F***ree* **E***lectron* **L***asers and future colliders. Fast acceleration of the photo-electrons in the rf gun cavity reduces space charge effects. In this way a better electron beam quality can be achieved. That is why the rf field properties are of great importance for better electron source performance i.e. smaller beam emittance which is needed for future linear accelerators. The field balance inside the rf cavity is one of the main rf gun characteristics, responsible for the beam dynamics in photo injectors. Since no direct diagnostics of the field balance is forseen at PITZ, a method to obtain the field balance from longitudinal beam momentum measurements has been proposed. Beam momentum measurements have been performed at PITZ for various rf gradients and different rf phases. A procedure to fit simulated results to measured data has been elaborated, resulting in best congruity for the field balance of 1.07. Method features and results are discussed in this paper.*

1 Introduction

1.1 *PITZ - The* **P***hoto* **I***njector* **T***est Facility at DESY* **Z***euthen*

PITZ is a test facility at DESY Zeuthen for research and development on laser driven electron sources for FELs and linear colliders. The **T**ESLA **T**est **F**acility at DESY Hamburg is already running using a PITZ gun in preparation for the **T**eV-**E**nergy **S**uperconducting **L**inear **A**ccelerator (TESLA) [1] which is supposed to be built in the near future.
TESLA's two main projects are the High Energy Linear Electron Positron Accelerator, optimized for center-of-mass energies between $90GeV$ and approximately $800GeV$, and the X-FEL, an FEL in the X-ray regime. The TTF will then be utilized as a second generation test facility and as a **V**acuum **U**ltra **V**iolet-FEL [2].
One of the main goals of PITZ is to optimize the electron beam source. The electron beam cannot be enhanced once it has left the **r**adio **f**requency gun. Thus, in contrast to storage rings the beam has to fulfill the needed requisites at the time of ejection.
This optimization is only possible if all the physical characteristics of PITZ are well defined. This includes the knowledge about solenoid and cavity fields inside the rf gun.

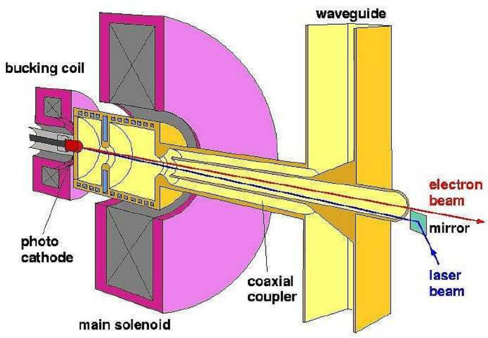

Fig. 1: *Schematic view of the PITZ rf gun*

1.2 *The rf gun at PITZ*

In Fig.1 a schematic view of the rf gun is shown. Reflected by a mirror a laser beam ($\lambda = 262nm$, pulse energy $E_{pulse} \approx 200\mu J$) is guided to the Ce_2Te cathode where the electrons are released via the photoelectric effect. The electrons are now accelerated in the 1.5 cell copper cavity where an electromagnetic field oscillates at $1.3GHz$. This rf field is fed over a coaxial coupler by the waveguide that is connected to the klystron. The main solenoid is used to focus the beam transversally. The bucking coil compensates the magnetic field at the cathode. Optimization of the beam properties is mainly done to lower its emittance . For this the different parts of the rf gun need to be well characterized.

1.3 The 1.5 Cell Copper Cavity

The 1.5 cell copper cavity is operated in π-mode. The electric field in the half cell always points to the opposite direction as it does in the full cell (see Fig.2 and Fig.3). The field balance is defined as the absolute value of the ratio between the electric field amplitudes at the cathode and in the full cell of the cavity.

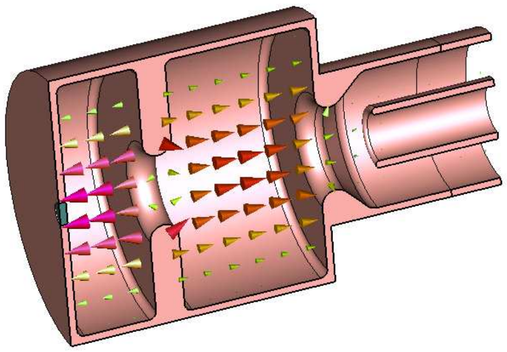

Fig. 2: *Electric field inside the cavity*

$$FB = \left| \frac{E_z^{cathode}}{E_z^{fullcell}} \right| \tag{1}$$

Knowledge about the field balance is of great importance for understanding the processes in the photo injector and for further optimization in order to fulfill the requirements for future projects like the X-FEL.
Directly measuring the field balance is not possible without inserting any detecting probes into the cavity. This could disturb the field symmetry. In October 2001 before installation a tuning procedure was carried out. Measurements with a dummy cathode which was realized by a metal plate resulted to a longitudinal electric field balance of ~1 at a frequency of $1299.977MHz$[3]. Unfortunately after the installation of the gun cavity, the field balance cannot be controlled directly.

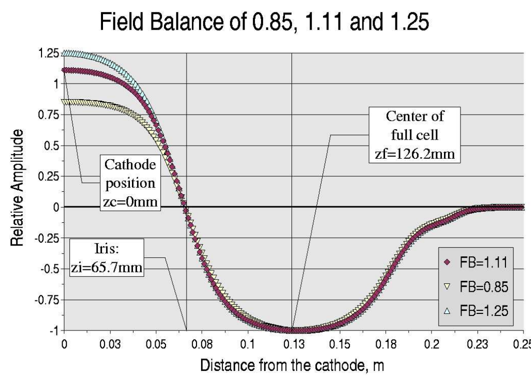

Fig. 3: *Cavity E_z-field axial distributions for field balances of 0.85, 1.11 and 1.25*

1.3.1 Modeling field balances

Although it is not known on which actual field balance the cavity works the amplitudes for different possible field balances can be calculated. For these calculations a standard amplitude distribution (FB=1.00) is used to model other field balances.
Hence the following ansatz is used.

$$E(z) = E_0(z) \cdot f(z) \tag{2}$$

Here E_0 is the standard field distribution with FB=1.00 and z is the longitudinal position measured from the cathode ($z = 0$).
To formulate an expression for the correction factor $f(z)$ one has to consider requirements for the electric field in the cavity.

- Continuity for the distribution and the first derivative
- No longitudinal electric field at the position of the iris $z_i = 65.7mm$:
  $E_z(z_i) = 0$
- Local extremum of the electric field in the center of the full cell $z_f = 126.2mm$:
  $\left.\frac{\partial E_z(z)}{\partial z}\right|_{z=z_f}$

Using these restrictions the following equations are deduced.

For a field balance $FB \geq 1.00$:

$$f(z) = \begin{cases} FB + (1-FB) \cdot \left(\frac{z}{z_i}\right)^2 & \text{if } z \leq z_i \\ 1 & \text{else} \end{cases} \tag{3}$$

For a field balance $FB \leq 1.00$:

$$f(z) = \begin{cases} FB & \text{if } z \leq z_i \\ \frac{FB}{\left(a_0 + a_1 \cdot (z - z_f) - \frac{a_{-1}}{z}\right)} & \text{else} \end{cases} \quad (4)$$

with:

$$a_0 = FB + \frac{(FB - 1) \cdot z_f \cdot z_i}{(z_f - z_i)^2} \quad (5)$$

$$a_1 = \frac{z_i \cdot (1 - FB)}{(z_f - z_i)^2} \quad (6)$$

$$a_{-1} = \frac{(FB - 1) \cdot z_f^2 \cdot z_i}{(z_f - z_i)^2} \quad (7)$$

An example of field distributions with field balances of 0.85, 1.11 and 1.25 is shown in Fig.3.

2 Determining the field balance

The approach that was chosen to determine the current field balance is based on simulations with the defined theoretical field balances (see Fig.4), introduced in the last section. These simulations were compared to the measured data to identify the actual field balance. In both cases phase scans of the mean kinetic energy respectively the mean momentum were performed.

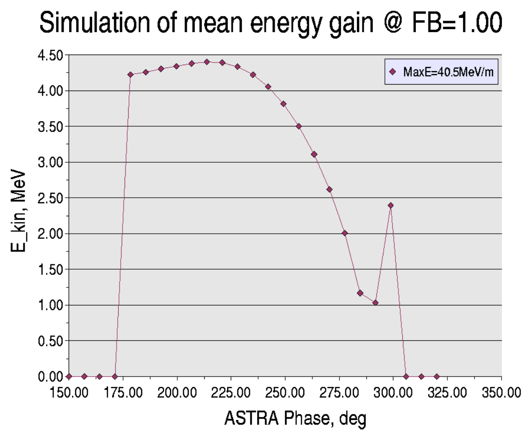

Fig. 4: *Simulation of mean energy gain*

2.1 *Experimental and simulated parameters*

ASTRA is **A** **S**pace Charge **Tr**acking **A**lgorithm[4] to simulate the dynamics of electron bunches in the rf gun under the influence of cavity, solenoid and space charge fields. For most of the simulations used here the mean kinetic energy was scanned over the ASTRA phase of the oscillating rf-field. In order to compare the measurements with the ASTRA simulations transformations of physical parameters are necessary.

The measured mean momentum needs to be converted into the mean kinetic energy which is used by ASTRA. This transformation is done by the following formula which can be deducted from the mass-energy-relation.

$$E_{kin} = \sqrt{p^2c^2 + m_e^2c^4} - m_ec^2 \quad (8)$$

where $m_ec^2 = 0.511MeV$ is the rest mass of the electrons.

Furthermore the **S**et **P**oint phase used in the experiment needs to be converted to the ASTRA phase. This is done by picking the phase of maximum momentum ϕ_0 and transforming the SP phases ϕ with

$$\phi_{ASTRA} = \phi_0 - \phi \quad (9)$$

In addition the SP voltage (SPV) that steers the field amplitude and thus the energy gain in the cavity has to be converted to the maximum amplitude of the E_z component (MaxE). For this conversion a maximum energy gain scan over the field amplitude was done. This scan leads to an almost linear dependency and thus allows to calculate the corresponding MaxE for a given maximum energy gain by interpolation. This was done for each individual field balance with sufficient accuracy.

2.2 *Measurements*

For the measurements the mean electron beam momentum was measured in the dispersive arm into which the beam is bend by a dipole magnet. Since the angle of deflection depends on the momentum of the electron bunch one can calculate the momentum by measuring the position of the beam on the screen in the dispersive arm at a given dipole current. Higher momentum leads to a lower angle of deflection.

The momentum spread of the electron bunches due to space charge forces and rf field influence might cause this image in the dispersive arm to stretch over the whole screen. In cases where the screen size was too small for the momentum distribution a **M**omentum **A**nd **M**omentum spread **A**nalysis was done using the MAMA tool (see [5]). This is an automated tool that scans the

momentum distribution using different dipole currents to merge various images into one. With this method a wider momentum range can be scanned.
The electron beam momentum distribution was measured for SP voltages of 33, 30, 25, 20 and 15. The phases ranged from $\phi_0 - 40deg$ to $\phi_0 + 40deg$, where ϕ_0 is the phase of maximum momentum gain (see Fig.5). The charge of the electron bunch was about $300pC$. The solenoid current to focus the beam was varied between $240A$ and $270A$ in order to get best focussing conditions at the screen in the dispersive arm.

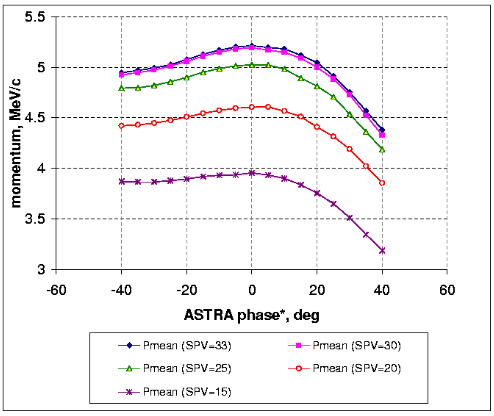

Fig. 5: *Measurement of mean momentum as a function of rf phase for different SPV*

2.3 Simulating the kinetic energy gain with ASTRA

To simulate the measured data with ASTRA the conversions of the mean momentum, the SP phase and the SP voltage have to be done according to section 2.1. Since the SP phase was only varied in steps of 5 degrees there is an uncertainty of the phase of maximum energy gain ϕ_0. So for each curve the phase was corrected to fit to the corresponding data. This was done with the "PhaseShifter" tool that minimizes the expression:

$$\Delta E = \sum_i |M_i - S_i| \tag{10}$$

where M_i is the measured data and S_i the simulated data.
The simulations were performed with varying field balances which were created using the "FieldGen" tool which is based on the algorithm explained in section 1.3.1. As an example of simulation results, a fit to the measured data using a field balance of 1.07 can be seen in Fig.6.

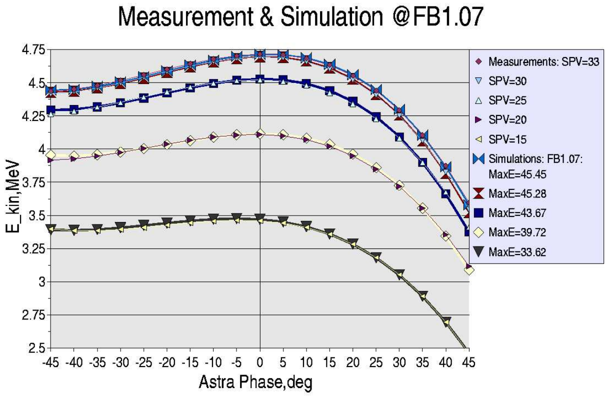

Fig. 6: *Measurement and Simulation for FB=1.07*

2.4 Defining the criteria for the simulations of the measurements

To decide which of the simulations with different field balances fits the real conditions of the rf gun a quantitative criteria of the fit has to be defined. Basically there were two different methods taken into consideration. The first is to compare the curvatures in the maximum of the curves of the measurement and simulation. The second one is fitting a cubic function to the curves to calculate the deviation between measured and simulated data.

2.4.1 Calculating the curvature in the maximum

From previous simulations it is seen that curves with an equal maximum kinetic energy gain have different curvatures depending on the field balance. The curvature C is defined as the second derivative of a curve at the phase of the maximum energy gain:

$$C = \left.\frac{\partial^2 E_{kin}(\phi)}{\partial \phi^2}\right|_{\phi_0} \tag{11}$$

In order to calculate the curvature of a simulated curve as shown in Fig.4 a parabolic fit was chosen using the χ^2-method [6]. Parameters a, b and c with

$$E_{kin}(\phi_{ASTRA}) \approx a \cdot \phi_{ASTRA}^2 + b \cdot \phi_{ASTRA} + c \tag{12}$$

were calculated to minimize the χ^2 where:

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i} \tag{13}$$

O_i: observed data, E_i: expected data

These fits were created with the "Scan" tool

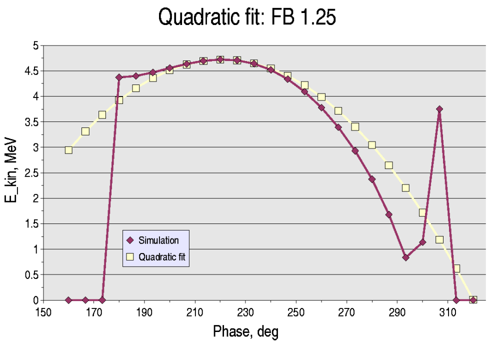

Fig. 7: *Quadratic fit to the simulated data at maximum energy gain* $\pm 20deg$*. FB=1.25*

which is a simple data analyzing tool implemented for ASTRA Scan-files (see Fig.7). So for each curve the parameters a, b and c were calculated.

For a given parabola the curvature is constant and defined through:

$$C = \frac{\partial^2(ax^2 + bx + c)}{\partial x^2} = 2a \tag{14}$$

This was done for field balances of 0.75, 1.00 and 1.25 and maximum energy gains ranging from 3.0 up to 5.0 in steps of 0.2. The result was an almost linear dependency between the curvature and the maximum energy gain for each field balance (see Fig.8). The measure of quality of a simulation would be defined as the difference of the curvatures from the simulation and the measurement (in their maximum). The problem of this method is that the quadratic fit is only an acceptable approximation in a small interval around the maximum. For larger intervals the curves cannot be approximated by a parabola. This is why a second method was thought of.

2.4.2 Cubic fit of the phase scans

For wider ranges of phase intervals a cubic fit is a more accurate approximation than the quadratic fit introduced before. Fitting the same curve (see Fig.7) with a cubic function the χ^2 is reduced clearly (see Fig.9).

To compare the simulated data with the conducted measurements cubic fits were chosen

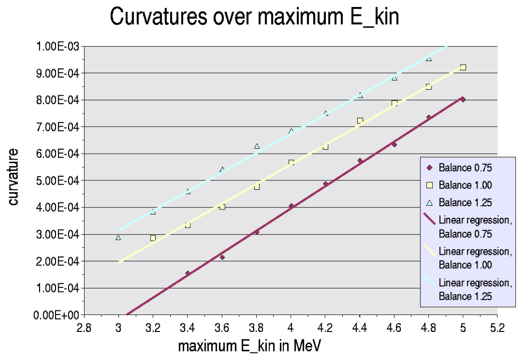

Fig. 8: *Characteristic dependency between the curvature and the maximum energy gain*

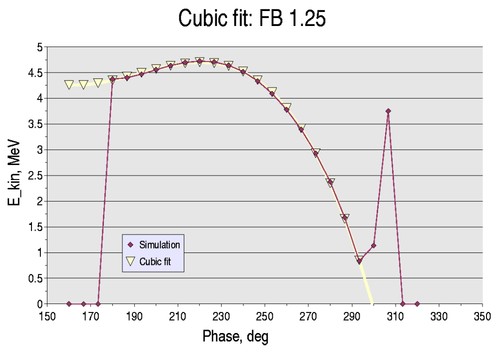

Fig. 9: *Cubic fit to the simulated data. FB=1.25*

since the interval of $\phi_0 \pm 40deg$ is too wide for an acceptable quadratic fit.

For field balances of 1.00, 1.05, 1.06, 1.07, 1.08, 1.09 and 1.11 simulations were done to fit the data. Again the phases were shifted by the "PhaseShifter" tool to reduce eventual phase offsets. The new parameters of the fits are automatically recalculated.

Each curve was shifted separately. The reason for this is that during the measurements of the five curves each one has its own phase offset. For each curve a different phase of maximum energy gain was obtained.

For constant SP voltages and varying field balances one cannot decide which offset is the correct one without assuming a certain field balance to begin with. The latter ones are more or less negligible since their differences are only tenth or hundredth of a degree.

Comparing the fits of measurements and simulations instead of the actual data provides the ability that the number of data points does not have to be consistent. Furthermore, the phase shifting operations would not be possible without interpolating the data between the mea-

	SP voltage					
FB	33	30	25	20	15	total
1.00	0.154	0.208	0.284	0.278	0.199	1.123
1.05	0.133	0.133	0.229	0.208	0.150	0.853
1.06	0.137	0.128	0.226	0.199	0.144	0.833
1.07	0.144	0.124	0.223	0.193	0.138	0.823
1.08	0.155	0.127	0.220	0.187	0.133	0.823
1.09	0.167	0.132	0.222	0.183	0.129	0.834
1.11	0.213	0.159	0.230	0.179	0.127	0.907

Tab. 1: *Deviations for different field balances and SP voltages*

sured and simulated data.
The measure of quality of the simulation is evaluated by calculating the area between a fit to a measured curve and its corresponding fit to a simulation. This deviation gets smaller for better simulations.

2.5 Determination of the field balance

For every mentioned field balance simulations were done to fit the data in phase and maximum kinetic energy gain. The visible difference between the simulations and the measurements is again the curvature (see Fig.10 and 11). On

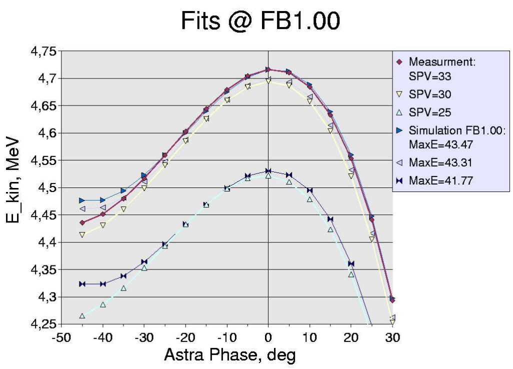

Fig. 10: *Comparing simulation and measurement. FB=1.00*

the left side of both diagrams it can be observed that the overall curvature for the field balance of 1.00 is smaller than the overall curvature of the curve with FB=1.11.
The measure of quality of the simulations is calculated as described in section 2.4.2 via determining the deviations between the cubic fits of simulated results and measured data. The deviations for each curve and for each field balance are shown in Fig.12.

These deviations are minimized for a field balance of 1.07. Taking into account only the total deviations a parabola fit is used to find the field balance of minimum deviation (see Fig.13). Again the field balance of 1.07 yields to the smallest discrepancy.

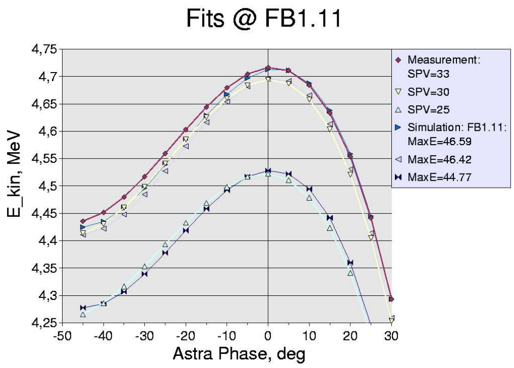

Fig. 11: *Comparing simulation and measurement. FB=1.11*

	SP voltage				
FB V	33	30	25	20	15
1.00	43.47	43.31	41.77	37.99	32.15
1.05	44.90	44.73	43.14	39.24	33.21
1.06	45.18	45.01	43.41	39.48	33.41
1.07	**45.45**	45.28	43.67	39.72	33.62
1.08	45.73	45.56	43.94	39.96	33.82
1.09	46.00	45.83	44.20	40.20	34.02
1.11	46.59	46.42	44.77	40.72	34.46

Tab. 2: *Maximum electric field (MV/m)*

Analyzing the deviations for each curve (see Fig.14 and Tab.1) again minimum deviations can be seen for a field balance of 1.07. In Tab.2 the corresponding maxima of the electric field are listed. For a field balance greater than 1.00 they correspond to an electric field on the photocathode.

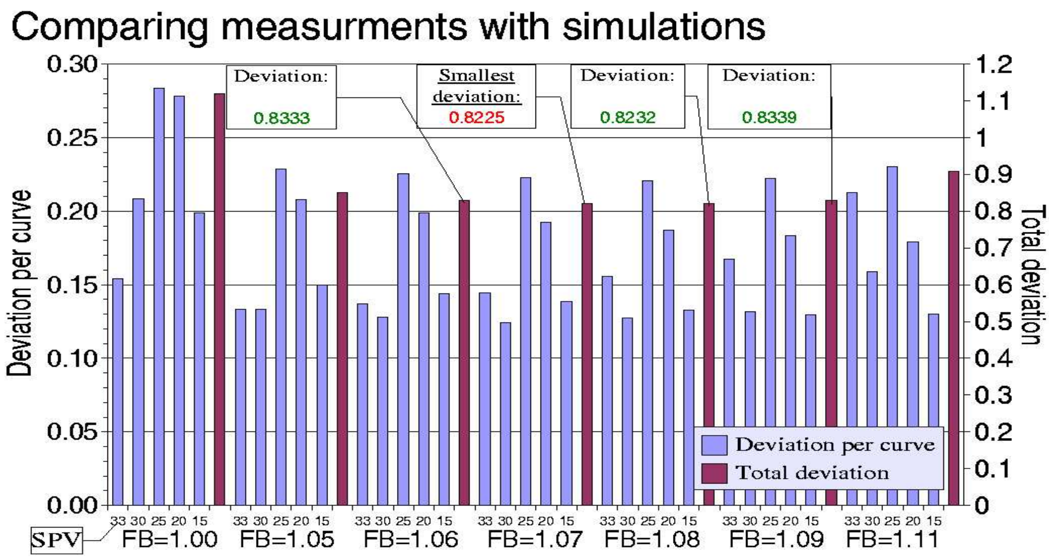

Fig. 12: *Comparing deviations for different field balances*

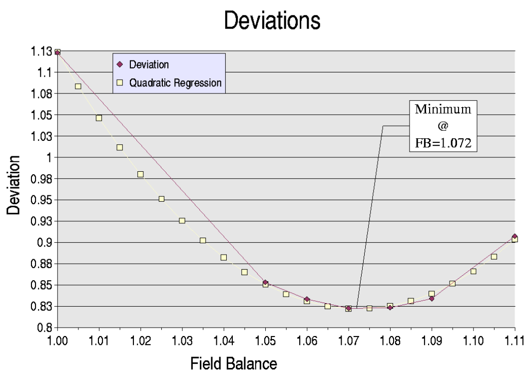

Fig. 13: *Determination of the field balance*

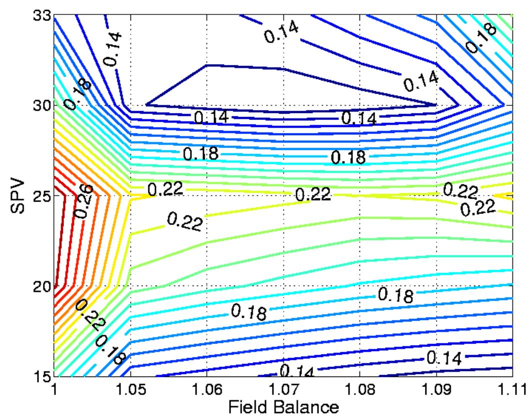

Fig. 14: *Contour plot of the deviations*

3 Conclusion

The field balance of the rf gun cavity is of great importance for the understanding of the processes in the photo injector and further optimization in order to fulfill the challenging requirements of X-FEL. A method of beam based determination of the field balance was proposed. Using this method the fits to measurements and simulations can be quantitatively compared to determine which field balance leads to the smallest deviations. With this method the field balanced is estimated to be 1.07.
Further improvements of this method could include the consideration of the solenoid field which was handled as being constant and the cathode position which might not be exactly at $z = 0$ as assumed.

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