ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPME008

# 3D FULL ELECTROMAGNETIC BEAM DYNAMICS SIMULATIONS OF THE PITZ PHOTOINJECTOR*

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*Abstract*

The electromagnetic (EM) simulation software CST STUDIO SUITE® [1] has been applied to investigate the beam dynamics for the electron gun of the Photo Injector Test facility at DESY, Zeuthen site (PITZ). A series of 3D beam dynamics simulations are performed to study the bunch injection process at PITZ with the objective of clarifying the discrepancies between measurements and simulations. Multiple comparisons are presented for the transverse emittance and the total emitted charge between the measurement data and simulation results using CST STUDIO SUITE®and Astra [2].

## INTRODUCTION

The Photo Injector Test facility at DESY, Zeuthen site (PITZ) was built to develop and optimize electron sources for linac based free-electron lasers like the Free-Electron Laser (FLASH) and the European X-ray Free-Electron Laser (E-XFEL) in Hamburg. The PITZ setup consists of a photocathode RF gun, a booster cavity, and various systems for beam diagnostics. The electrons are generated from a $Cs_2Te$ photocathode and accelerated by a 1.3 GHz RF field excited in a 1.6 cell copper cavity. A focussing magnetic field is additionally applied by a pair of solenoids. A detailed description of the PITZ setup can be found in [3].

The space charge fields in the gun contribute significantly to the photoemission process as well as to emittance growth. In order to understand better the effect of space charge fields, detailed beam dynamics studies using fully 3D realistic bunch distributions are performed. As simulation tools, we use the following modules of CST STUDIO SUITE®: CST MICROWAVE STUDIO® (CST MWS), CST EM STUDIO® (CST EMS), and CST PARTICLE STUDIO® (CST PS). With CST STUDIO SUITE®, one can solve full set of Maxwell equations on the grid, which is able to handle arbitrary geometries and take all EM effects into account.

## METHOD OF SIMULATIONS

A complete 3D simulation model including the RF cavity, external solenoids, and subsequent beam tubes down to one meter total length from the cathode has been set up in CST PS. The simulations with CST STUDIO SUITE® consist of the field simulations and the Particle-in-Cell (PIC) simulations. A basic workflow is shown in Fig. 1. For comparison purposes, the initial particle distribution is generated by the Astra-Generator and then loaded into the Particle Import Interface at the cathode in CST PS. Thus, identical particle distributions are used in corresponding Astra and CST PS simulations, respectively. The main simulation parameters which are applied throughout the following simulations are listed in Table 1.

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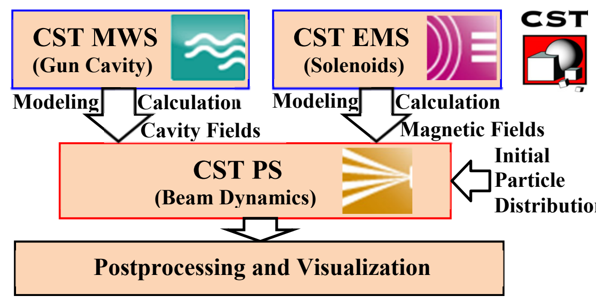


Figure 1: Simplified workflow of simulations

Table 1: Main Simulation Parameters

| Parameters | Units | Value |
|---|---|---|
| Laser Temporal Profile | ps | 2/21.5(flat top) |
| Initial Kinetic Energy | eV | 0.55 |
| Maximum Gradient $E_z$ | MV/m | -60.58 |
| Maximum $B_z$ | T | -0.2279 |

## EMITTANCE STUDIES

### *Short-Distance Beam Dynamics*

Beam dynamics simulations over a bunch propagation distance of about 20 mm from the cathode are performed in CST PS to observe possible issues at emission time, estimate space charge limitation, analyze numerical convergence, and identify numerical parameters for full-scale simulations.

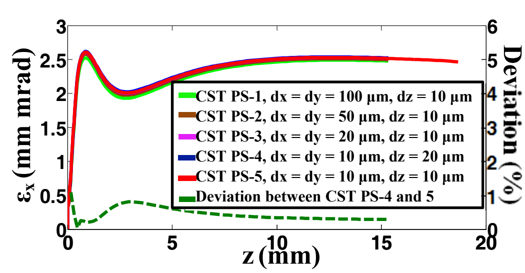


Figure 2: Numerical convergence of the bunch transverse emittance as a function of the longitudinal position for different transverse and longitudinal mesh resolutions, dx, dy, and dz, respectively. The rms laser spot size is $XY_{rms}$ = 0.4 mm and the total bunch charge is $Q_b$ = 1 nC.

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Figure 2 shows the good convergence of CST PS simulations in terms of the transverse bunch emittance. The numerical accuracy at the finest resolution is better than 0.5%. The number of particles used in the simulations, varies between $10^5$ and $2\times10^6$.

A comparison between the CST PS simulation and the Astra simulation is shown in Fig. 3. For illustration purposes the same bunch as before ($XY_{rms}$ = 0.4 mm) at the nominal gun operation phase is used. The discrepancy between the two simulation tools is about 20% at 20 mm behind the cathode. This is because the beam uniformity assumption adopted by Astra is violated at a few millimetres away from the cathode where the bunch emission is already completed. It indicates that the relative particle motion within the bunch due to space charge forces at emission time is important and it cannot be neglected in simulations.

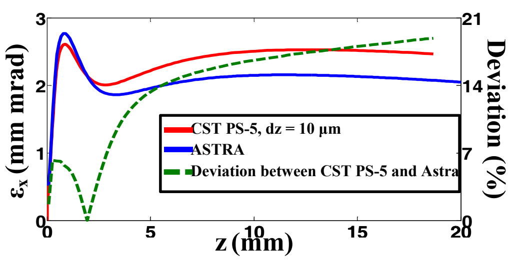


Figure 3: Transverse emittance as a function of the longitudinal position: comparison between Astra and CST PS.

Another drawback resulting from the numerical approximation used in Astra is that the emission space charge limitation cannot be properly predicted. As shown in Fig. 4, the total emitted charge in the Astra simulation is limited at below 1 nC for an rms laser spot size of 0.3 mm. However, no such space charge limitation is observed in CST PS simulations as the full nominal bunch charge of 1 nC can be extracted from the cathode. The later is in agreement with the experimental findings reported in [3], [4].

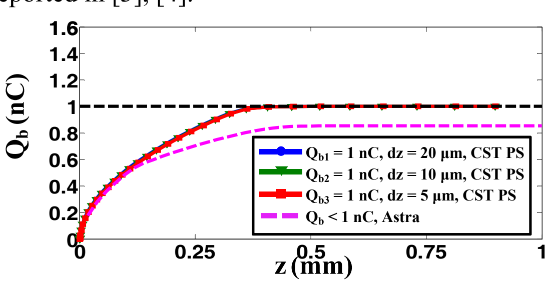


Figure 4: The total emitted charge ($Q_b$) as a function of the longitudinal position for an rms laser spot size $XY_{rms}$ = 0.3 mm and the initial charge at the cathode $Q_0$ = 1 nC.

## *Emittance Results at EMSY1*

The inaccuracies observed in short distance Astra simulations may propagate along the beam line and thus affect simulation results in later sections of the injector. In order to further investigate this effect, we perform full-scale simulations for the PITZ beam line up to a distance of 7 m behind the cathode. At z = 5.74 m, the first emittance measurement station (EMSY1) is located, so that simulation results can be compared with measurements. The numerical procedure consists in the simulation of the emission process using CST PS up to 3 cm behind the cathode, then restarting simulations in Astra using the particle distributions obtained in CST PS.

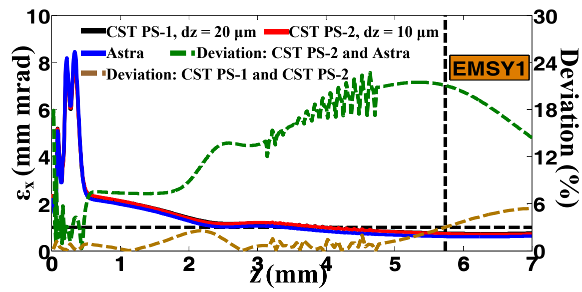


Figure 5: The transverse emittance in the longitudinal direction for the rms laser spot size $XY_{rms}$ = 0.4 mm and the total bunch charge $Q_b$ = 1 nC.

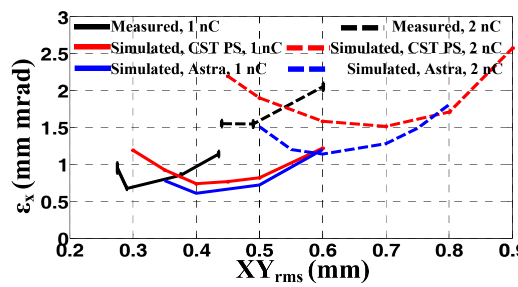


Figure 6: The transverse emittance at EMSY1 as a function of the rms laser spot size for the total bunch charge $Q_b$ = 1 nC (left) and 2 nC (right).

Fig. 5 shows the transverse emittance along the beam line for the rms laser spot size of 0.4 mm and the total bunch charge of 1 nC. Compared to a 'standard' Astra simulation including particle emission at the cathode, the transverse bunch emittance at EMSY1 resulting from our simulations is about 20% higher. This is the same figure as observed in Fig. 3. Thus, the space charge modelling error at the cathode in Astra simulations cannot be recovered in long distance simulations. As expected the emittance error remains nearly conserved as it propagates along the beam line downstream to the EMSY1.

Fig. 6 shows the transverse emittance as a function of the laser spot size for bunch charges of 1 nC and 2 nC, respectively. In the 1 nC case, the estimated laser spot size corresponding to the emittance minimum obtained by both types of simulations is the same (~ 0.4 mm). However, in CST PS simulations, the emittance values are higher and a full charge extraction at the rms spot size of 0.3 mm is attainable. Compared to measurements, all simulations indicate a systematical shift with respect to the laser spot size. The reason for this shift cannot be explained numerically. A probable cause is that the actual laser spot sizes are actually smaller than reported in the literature. Alternatively the bunch transverse size

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generated at the cathode may not coincide with the laser spot size as it is assumed in the present simulations. In the 2 nC case, the differences between CST PS and Astra simulations are even larger.

## PHOTOEMISSION STUDIES

### *Motivation and Simulation Scheme*

In the following, the problem of space charge limitation in the RF gun is investigated. The motivation is that, as mentioned above, Astra simulations predict space charge limitation at less than 1 nC for an rms transverse bunch size of 0.3 mm, whereas 1 nC and even higher bunch charges were detected experimentally.

To calculate the total emitted bunch charge $Q_b$, a scenario is proposed in which the laser produces just the maximum charge that can be emitted at the cathode without space-charge limitation. Using different gun phases, we start the simulation with a large initial bunch charge at the cathode $Q_0$ (e.g., 2 nC), and check if any particles get lost at the cathode when the emission is completed. If this is the case, then we repeat the simulation with a lower initial $Q_0$ at the cathode. This procedure is repeated until the full charge injected at the cathode can be emitted ($Q_0 = Q_b$). In this regime, the gun is operated exactly at the space charge limit.

### *Comparisons with Measurements*

Fig. 7 shows the total emitted bunch charge simulated in CST PS for different gun phases (w.r.t. MMMG: Maximum Mean Momentum Gain). The result agrees perfectly with the measurement data [4] at the first Integrating Current Transformer (ICT1) for a laser transmission (LT) coefficient of 100%. The pink curve shows the total emitted bunch charge simulated in CST PS at 2 mm behind the cathode where the bunch emission is already completed. Obviously, for gun phases higher than 40 degrees (rectangular region in Fig. 7), most particles get lost on the beam tube rather than at the cathode. If one considers this effect (red curve), the agreement between simulation and measurement for the maximum emitted total bunch charge is excellent. The emitted bunch charge simulated with Astra based on the same scenario is much lower than the one obtained in CST PS.

Fig. 8 shows the calculation of the total emitted bunch charge for a laser transmission (LT) coefficient of 62%. In this case, the gun is operated below the space charge limit for RF phases between 0 and 50 degrees (see green curve). The total emitted charge should therefore depend on the maximum charge produced by the laser at the cathode. This value is obviously given by the flat region in the measured curve where the emission charge does no longer depend on the gun phase. Based on this assumption, we calculated the total charges for LT = 62% by averaging the measured charges in the flat region and applying this value in simulations as the initial bunch charge, $Q_0$, to be injected at the cathode. The result is shown by the pink curve in Fig. 8.

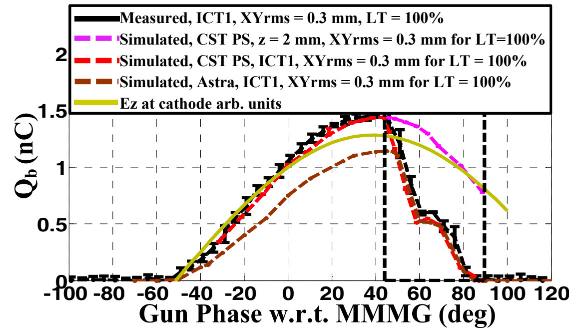


Figure 7: The total emitted bunch charge as a function of the gun phase w.r.t. MMMG for an rms laser spot size of 0.3 mm. The charge resolution of CST PS simulations is 50 pC for each gun phase. ICT1 locates at about 0.935 m.

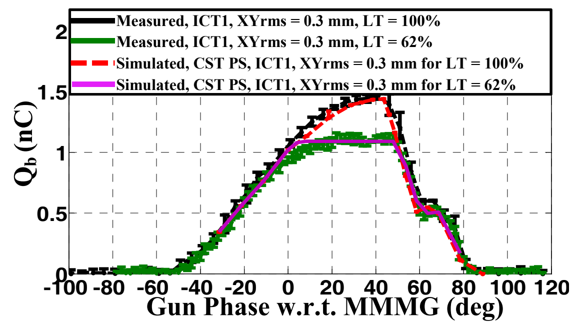


Figure 8: The total emitted bunch charge as a function of the gun phase w.r.t. MMMG for an rms laser spot size of 0.3 mm with the laser transmissions of 100% and 62%.

## CONCLUSION

We have simulated the beam dynamics in full 3D geometry of the RF electron gun at PITZ using the CST STUDIO SUITE® and Astra. The same optimum laser spot size corresponding to emittance minimum at EMSY1 was obtained in both types of simulations for a flat-top bunch with $Q_b$ = 1 nC and $XY_{rms}$ = 0.4 mm. However, the CST PS simulations showed higher emittance values than Astra (about 20% for $XY_{rms}$ = 0.4 mm). This is due to the space charge model used in Astra which may not be able to properly describe a space charge field dominated emission process. On the other hand, the total emitted bunch charges calculated with CST PS coincided well with the measurement data for a bunch with $XY_{rms}$ = 0.3 mm at the space charge limit (LT = 100%) as well as below it (LT = 62%).

## REFERENCES

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[4] J. Li, et al., "Emission Studies of Photocathode RF Gun at PITZ", ICAP'12, Rostock, p. 242, 2012.