INVESTIGATIONS OF THE SPACE-CHARGE-LIMITED EMISSION IN THE L-BAND E-XFEL PHOTOINJECTOR AT PITZ*

Y. Chen[†], E. Gjonaj, A. Tsakanian, H. De Gersem, T. Weiland
TEMF, Technische Universitaet Darmstadt, Schlossgartenstrasse 8, 64289 Darmstadt, Germany
C. Hernandez-Garcia, M. Krasilnikov, F. Stephan
Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany

Abstract

This paper discusses the numerical modelling of electron bunch emission for an L-band normal conducting RF photogun. The main objective is clarifying the discrepancies between measurements and simulations performed for the European X-ray Free Electron Laser (E-XFEL) injector at the Photo Injector Test Facility at DESY in Zeuthen, PITZ. An iterative beam dynamics simulation procedure is proposed for the calculation of the total extracted bunch charge under the assumption that the emission source operates at the space-charge limit of the gun. This algorithm has been implemented in the three-dimensional full electromagnetic PIC Solver of the CST Particle Studio ® (CST-PS) [1]. Simulation results are in good agreements with measurements for a series of operation parameters. Further comparisons with a conventional Poisson-solver-based (PSB) tracking algorithm demonstrates the great significance of transient electromagnetic field effects for the beam dynamics in high brightness electron sources.

INTRODUCTION

For the operation of Free Electron Lasers (FELs), high quality electron beams characterized by high brightness and extremely low transverse emittance, are required. An L-band normal conducting (copper) RF photoinjector was particularly designed and optimized at PITZ for the generation of such high quality electron beams for the European X-ray Free Electron Laser (E-XFEL) and the Free Electron Laser in Hamburg (FLASH) [2, 3]. Hereby, a crucial role plays the modelling of electron bunch emission as well as the simulation of the space-charge dominated beam dynamics in the gun.

It has been previously reported [4] that for specific machine conditions, comparatively large discrepancies between simulations and measurements are found. In particular, the total extracted bunch charge at an RMS beam size of 0.3 mm is much higher than predicted in the simulations. One source of discrepancy was identified in [5]. It was shown that in conventional Poisson-solver-based (PSB) tracking codes, the magnetic space-charge field contribution is neglected. For high current beams, this contribution becomes important due to the fast electron bunch expansion during emission. In order to take into account the impact of these magnetic space-charge fields, beam dynamics simulations based on the solution of the full set of Maxwell equations are necessary. Yet another important modelling issue, however, is the computation of the total charge extracted from the cathode when the injector is operated close to or at the space-charge limit. This quantity depending on various machine parameters is not a priori known. In this paper we propose a self-consistent simulation procedure which is able to predict very accurately space-charge field dominated photoemission in RF electron sources.

Investigations of the space-charge-limited emission will be performed specifically with parameters of significance experimentally obtained for the PITZ photoinjector project. The main components of the PITZ injector are a 1.6 cell copper RF gun cavity with a cesium-telluride photocathode, CDS booster cavity, cathode laser system, and multiple beam diagnostic systems. The electron beam is extracted as the photocathode is illuminated by the UV laser pulse at the wavelength of 257 nm, and then accelerated by a 1.3 GHz RF field excited in the gun cavity. A main solenoid and a bucking solenoid are additionally applied for beam focusing and space-charge emittance compensation. A detailed description of this setup can be found in [2, 3].

BUNCH EMISSION MODELLING AT THE SPACE-CHARGE LIMIT

A sketch of the total bunch charge extraction based on experimental observations [4] is shown in Fig. 1. The top curve shows the total space-charge-limited bunch charge at each gun launch phase when operating the emission source exactly at the space-charge limit. As for below the space-charge limit, the emission becomes a combination of two emission regimes, the space-charge-limited (SCL) and the quantum-efficiency-limited (QEL). The QEL regime in the combined emission case is marked out by the trapezoid area. The total charge in this regime depends on conditions of the emission source instead of the applied RF field at the cathode. As shown, the maximum extracted charge is apparently given by the flat-top region in the gun phase range. However, the charge extraction below this flat level (i.e., the rise / fall edge) is still limited by the space-charge field. This is because the space charge limits there are lower than the maximum total charge produced by the emission source.

In the following we propose a self-consistent simula-

---

* Work supported by DESY Hamburg and Zeuthen sites. PITZ: the Photo Injector Test Facility at DESY in Zeuthen, Berlin, Germany

[†] chen@temf.tu-darmstadt.de

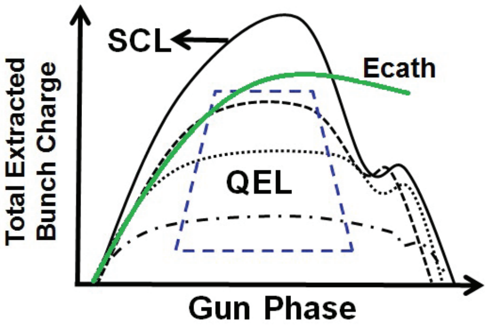

Figure 1: Sketch of the total bunch charge extraction as a function of the gun launch phase based on experimental observations. SCL: space-charge-limited. QEL: quantum-efficiency-limited. Ecath: the RF field at the cathode.

tion procedure specifically to calculate the total SCL bunch charge extracted from the cathode. Using a set of gun launch phases, the bunch emission simulation is performed initially with a sufficiently large total bunch charge depending on specific machine parameters (e.g., 2 nC in this paper). After emission, the number of particles used in the simulation is checked to see if any particle gets lost in the cathode region. If this is the case, then the calculation is repeated, by progressively decreasing the initial bunch charge that was injected in the previous simulation, until the maximum initial bunch charge is found such that the whole bunch can be emitted from the cathode without particle loss. This maximum bunch charge at a certain resolution of the iteration process is then interpreted as the SCL bunch charge. The same procedure is performed at each gun launch phase to find the corresponding SCL charge.

In order to precisely predict the total bunch charge in the space-charge dominated case based on the proposed simulation procedure, the magnetic space-charge field during emission also needs to be correctly modelled. Because of Coulomb repulsion (space-charge forces) for high current beams the electron bunch fast expands dramatically in all dimensions during emission, the impact of the magnetic space-charge fields on the beam dynamics becomes very significant. Thus, the full EM PIC solver of the CST-PS ® is used to model the bunch emission process. As the solver for the full set of Maxwell equations, it takes all transient electromagnetic effects into account.

The initial distribution of the emitted electron bunch at the cathode is reproducing the distributions of the cathode laser pulse. All particles are generated with the same longitudinal position, and with an appropriate spread in time. The bunch distribution is implemented by using the Particle Import Interface (PII) of the CST-PS ®. The accelerating RF fields and the focusing magnetostatic fields of solenoids are respectively calculated with the CST Microwave Studio ® and the CST EM Studio ® [1], and then all loaded into the PIC solver as external fields. Full 3-D space charge fields and external fields are thus included in the simulations. As for simulation parameters, an RMS bunch transverse size of 0.3 mm is considered. The bunch transverse distribution is uniform. A flat-top temporal profile of about 21 ps (FWHM) is applied. The maximum field strength of 45 and 60 MV/m at the cathode surface will be used for simulations respectively.

RESULTS

In order to exclude numerical problems of convergence, extensive full EM CST-PS simulations are firstly performed in regard to the enhancing mesh resolutions and the increasing number of macro particles. Fig. 2 shows the very good convergence of the total bunch charge extracted from the cathode as a function of time and the longitudinal position. The best resolution in space for PIC simulations is about 5 micrometers, and the number of macro particles varies from 5×10^5 up to 1 million. All CST-PS simulations have shown that the 1-nC bunch is, in fact, extractable with the RMS bunch size of 0.3 mm, which is consistent with the experimental results [4]. As shown, this result is also compared with the total charge predicted by the conventional PSB tracking approach (see pink and yellow curves). The latter shows the extractable bunch charge less than 1 nC, indicating the charge extraction is already limited by the space-charge field at this bunch size. This discrepancy in the prediction of the space-charge limit shows the significance of the magnetic space-charge field in the beam dynamics modelling for the space-charge dominated case.

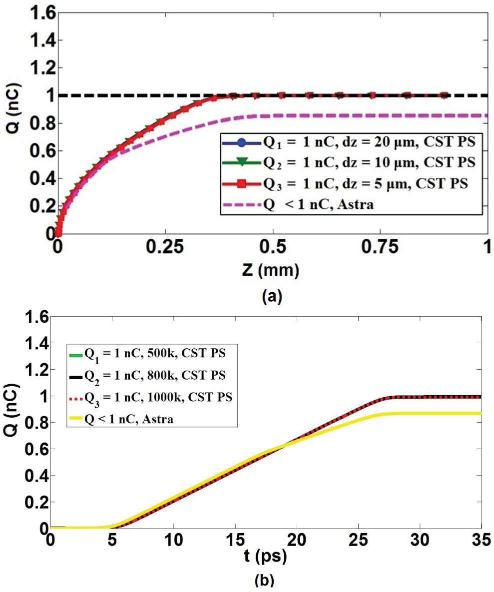

Figure 2: Total bunch charge extraction close to the space-charge limit at an RMS bunch transverse size of 0.3 mm by full EM approach in regard to the mesh resolution (a) and the number of macro particles (b), and the comparisons with the PSB tracking approach.

To validate the bunch emission model, the total SCL bunch charge has been calculated under different operation conditions of the gun. Fig. 3 shows the comparisons on the total SCL bunch charge over different gun phases between simulations and measurements for two laser transmissions, using two maximum accelerating field strengths of 60 and

45 MV/m, respectively. A flat-top temporal profile of 21 ps with 2 ps rise/fall time is applied. The laser transmission (LT) of 100% corresponds to the maximum available laser pulse energy for the indicated RMS beam size. In the 60 MV/m case, the black and red curves on top indicate a good agreement between simulation and measurement for LT = 100% . In the 45 MV/m case (blue curve), the simulated total bunch charges also agree well with the measured charges (dotted black curve) in the SCL regime (within the green circle) for a much lower laser transmission. The SCL total charge in this case is smaller than in the 60 MV/m case, due to the lower field strength at the cathode. Additionally, the flat-top part of the dotted black curve for the gun phases between 0 and 40 degrees shows the measured QEL charge, where the extraction does no longer depend on the cathode field because the set laser pulse energy is lower. Hence, the average of the measured charges (in the gun phase range within the flat-top region) is calculated as the initial total charge which is then injected into the iterative simulation procedure. An estimation of the total charge in the QEL regime is given by the pink curve. Hereby, the SCL emission model and the proposed beam dynamics simulation procedure still work well for very different operation conditions of the gun.

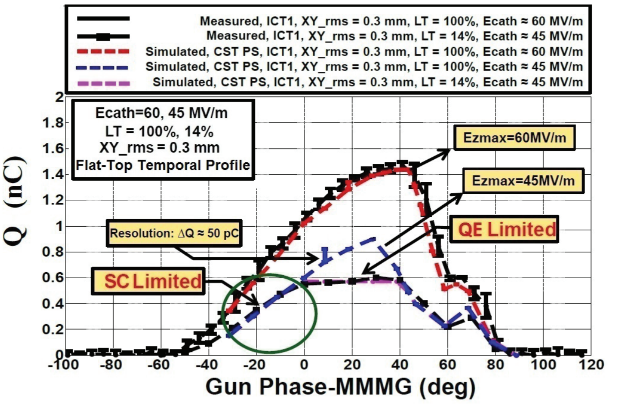

Figure 3: Comparisons between simulation and measurement of the total SCL bunch charge as a function of the gun phase w.r.t. Maximum Mean Momentum Gain Phase (MMMG). XYrms = 0.3mm, LT = 100% and 14%, Ecath = 60 and 45MV/m. The charge iteration resolution is 50 pC.

The SCL emission is further investigated by using a 2.7 ps (FWHM) short Gaussian temporal profile of the electron bunch. The RF power of the gun is fixed at 4 MW and the laser pulse energy is approximately 37 nJ. In Fig. 4, the red curve shows the space-charge-limited bunch charge as a function of gun phase simulated with the full EM approach. The violet curve represents the corresponding measured bunch charge. As shown, the measured curve is very close to the simulation results. It means the gun is nearly operated at the space-charge limit. The total SCL bunch charge predicted by simulations is able to fit the measured charge using this short Gaussian temporal profile. For gun phases higher than about 83 degrees, a significant number of particles are lost far away from the cathode. This is the reason why there are some deviations for higher gun phases. However, this effect should be excluded from photoemission studies, because it does not occur during emission. If one considers this, then the agreement between simulation and measurement is still good.

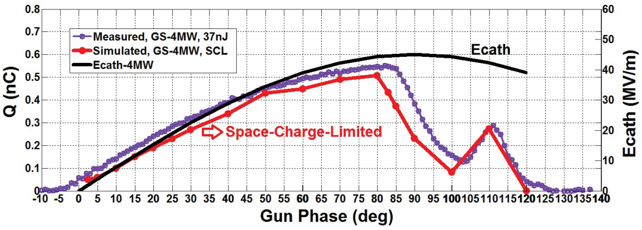

Figure 4: Total SCL bunch charge as a function of gun phase for a temporal short Gaussian bunch: the comparison between measurement and simulation. The charge was collected using integrating current transformers (ICT) at about 1 meter away from the cathode. Ecath: RF field at the cathode. The charge iteration resolution is 50 pC.

CONCLUSIONS

The numerical modelling of the space-charge dominated emission in the PITZ photoinjector has been performed by the full EM appraoch. The total space-charge-limited bunch charge extracted from the cathode is calculated based on the proposed self-consistent beam dynamics simulation procedure and found to well fit the measured charge. Its dependencies on various operation condtions of the gun are investigated. The obtained full EM simulation results have shown good agreements with measurements for different machine setting and laser parameters. It is demonstrated through multiple comparisons bwtween measurements, full EM simualtions, and PSB tracking simulations, that the contribution of the magnetic space-charge field is necessary to be taken into account for the beam dynamics modelling of the bunch emission process. This contribution becomes more significant as the beam current density increases. At or close to the space-charge limit, the neglect of this effect leads to large discrepancies in the total extracted bunch charge between measurement and simulation. Thus, the contributions of transient electromagnetic effects during the space-charge-limited photoemission are of great significance, and should be included in the beam dynamics modelling for the high brightness electron sources.

REFERENCES

[1] Computer Simulation Technology AG, CST Studio Suite ®, Darmstadt, `http://www.cst.com/`.

[2] M. Krasilnikov et al., PRST-AB 15, 100701 (2012).

[3] F. Stephan et al., PRST-AB 13, 020704 (2010).

[4] M. Krasilnikov, PITZ: Simulations versus Experiments, DESY-TEMF Collaboration Meeting, Darmstadt (2013).

[5] Y. Chen et al., “3D Full Electromagnetic Beam Dynamics Simulations of the PITZ Photoinjector,” IPAC’14, Dresden, 2014, MOPME008, p. 391 (2014).