ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP052

SIMULATION STUDIES ON THE SATURATED EMISSION AT PITZ

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Abstract

In this paper we report our consideration and simulation on the space charge dominated emission in the L-band photocathode RF gun at the Photo Injector Test facility at DESY in Zeuthen (PITZ). It has been found that the emission curve, which relates the extracted and accelerated bunch charge after the gun to the laser energy, doesn't agree very well with Astra simulations when the emission is nearly or fully saturated. Previous studies with a core-halo model for a better fit of the experimentally measured laser transverse profile as well as with an improved transient emission model have resulted in a better agreement between experimental data and simulation. A 3D FFT space charge solver including mirror charge and binned energy/momentum has been built, which also allows more emission mechanisms to be included in the future. In this paper, the energy spread during emission was preliminarily analyzed. Experimentally measured emission curves were compared with simulation, showing the effect of the inhomogeneity of the laser on the emission and beam parameters.

INTRODUCTION

The space charge effect during photo emission in an RF photocathode gun is one of the key factors determining the quality of the accelerated electron beam. For a given bunch charge, it can be optimized, for instance, by tuning gun gradient, injection phase or by cathode laser pulse shaping. According to the magnitude of space charge, the photo emission can be either source dominated or space charge dominated. For the former, the emitted charge depends on the laser energy and the quantum efficiency (QE) of the cathode. For the latter, the space charge is comparable to the accelerating gradient, therefore suppressing the emission. At PITZ [1], the measurement of the emission curve, which gives the relation between the incoming laser energy and the outgoing bunch charge, is a routine task. The modeling of the emission using a particle tracking code such as Astra [2] does not always give satisfying agreement, especially for the space charge dominated emission or saturated emission. Along with the investigation of cathode physics such as Schottky effect [3], a 3D space charge solver has been developed for considerations of effects such as the inhomogeneity of the laser transverse profile and the quantum efficiency over the cathode and the large energy spread of the electron bunch during the emission. Further development will also take into account the physics behind the emission process. In this paper, we report about our 3D space charge solver based on fast Fourier transformation (FFT) [4] and the application of the solver to study the energy spread effect and to simulate the emission under experimental conditions. The measured laser profile was used to modify a homogeneous distribution generated by Astra for the 3D solver. The simulation results are compared and discussed.

3D SPACE CHARGE SOLVER

In order to calculate the space charge forces, the whole electron bunch of a given distribution is transformed into its rest frame, which turns the problem of space charge into solving the Poisson's equation. The method of solving it in 3D using FFT has been described in detail in Ref. [4]. In this method, the solution of Poisson's equation (or the static potential ϕ) is given by

$$\phi(\vec{r}) = \frac{1}{4\pi\epsilon_0} \times \int G(\vec{r}, \vec{r}')\rho(\vec{r}')d\vec{r}', \tag{1}$$

where $\vec{r} = (x, y, z)$, ρ is the charge density and G is Green's function defined as

$$G(\vec{r}, \vec{r}') = \frac{1}{|\vec{r} - \vec{r}'|}. \tag{2}$$

In Eq. (1) the static potential is written as the convolution of Green's function and the charge density and therefore can be solved efficiently using FFT [5]. After knowing the static potential, the electric fields in the rest frame can be derived by $\vec{E} = -\nabla\phi$ and the fields in the laboratory frame can be obtained by Lorentz transformation.

The mirror charge effect during emission is not negligible and is solved in a similar way by using the shifted Green's function method [4]. In the above, it has been assumed that the bunch has a very small energy spread which makes the bunch static in the Lorentz transformed rest frame. In the case of large energy spread, the bunch should be treated specially, for example, by binning the bunch according to the kinetic energies or momenta of individual electrons or by slicing them longitudinally, if a strong correlation between the kinetic energy and position exists. The fields solved from each bin or slice are then summed together.

EFFECTS OF ENERGY SPREAD ON SPACE CHARGE CALCULATION

As mentioned above, the transformation of the bunch into its rest frame for calculating the static potential is valid when the beam has a small energy spread. In fact, the energy spread during emission is large. For instance, the longitudinal phase space shown in Fig. 1 (left) gives an RMS energy spread ($\Delta E/E$) as high as 140%, when half of the bunch was emitted.

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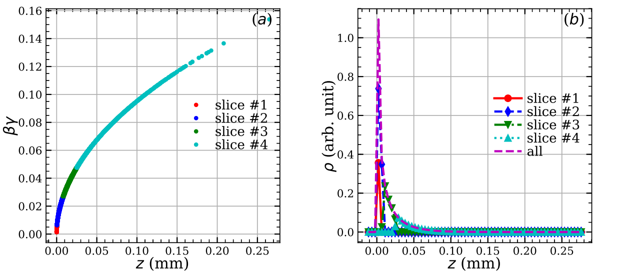

Figure 1: Longitudinal phase space grouped by momentum (a) and charge density profile of each group (b).

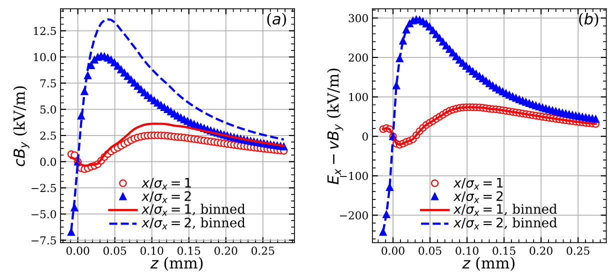

Figure 2: Vertical magnetic field (a) and effective focusing field (b) along the bunch in the laboratory frame.

In the laboratory frame, the effective transverse space charge field in the horizontal plane is given by $E_x^{\mathrm{eff}} = E_x - vB_y$, where E_x and B_y are the horizontal electric field and vertical magnetic field, respectively, v is the speed of the electron. The components E_x, E_z and B_y are obtained from the static electric field $E_x^{'}$ in the rest frame by Lorentz transformation,

$$E_x = \gamma E_x^{'},\ E_z = \gamma E_z^{'},\ B_y = \beta\gamma E_x^{'}, \qquad (3)$$

where γ is the Lorentz factor. Since $\gamma \sim 1$ during the emission, a large energy spread will affect B_y. In Fig. 2 (a) the B_y fields along the bunch as given in Fig. 1 are plotted. For comparison the space charge forces were solved by either taking the bunch as a whole or by grouping the beam into four slices according to the electrons' momenta (as denoted by colors in Fig. 1 (a)). The longitudinal charge density profile of each bin is shown in Fig. 1 (b). Although the slice #4 has much larger momentum spread, it takes up a much smaller fraction of the whole bunch charge.

In Fig. 2 (a), the difference in B_y between unbinned and binned methods became prominent towards the bunch head (right side) or in the outer part (e.g., $x/\sigma_x = 2$). However, as the B_y component is much smaller than the E_x component (by a factor of β as given in Eq. (3)), the effective focusing field E_x^{eff} turned out to be very insensitive to the momentum spread. As illustrated in Fig. 2 (b), one can hardly see the difference between fields calculated from unbinned and binned methods. The contribution of B_y to the focusing field can be written as $vB_y \sim \beta^2 E_x$. In the case shown here, $\beta \leq 0.14$, thus $vB_y/Ex \ll 1$. As more detailed investigation is still to be performed to study the effect of energy spread on the emission and on the beam dynamics with particle tracking, the unbinned method will be used in the following section to simulate the emission in the RF gun.

EXPERIMENTAL STUDY ON EMISSION

At PITZ, an L-band normal conducting 1.6 cell RF gun with a Cs_2Te photocathode is in operation. A bucking coil and a main solenoid are around the gun cavity for emittance compensation. The gun can provide a gradient as high as 60 MV/m on the cathode [1] for the generation of high-brightness electron bunches for X-ray free-electron lasers. The axial field profile in the gun and the accompanying solenoid field profile are given in Fig. 3. In this study, we consider the emission experiments performed at a lower gun gradient of 40 MV/m, which is dedicated to study the emittance optimization for a possible future continuous wave (CW) mode operation condition of the European X-ray Free-Electron Laser (XFEL) with a superconducting RF gun (SCRF) [6].

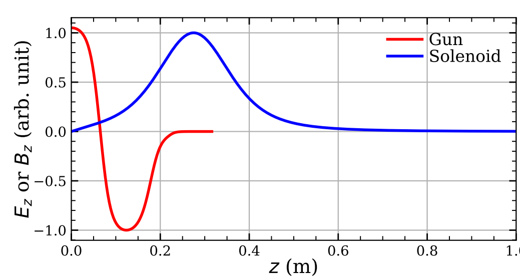

Figure 3: Axial electric and solenoid field profiles in the gun.

The cathode laser passes through a tunable beam shaping aperture (BSA) before hitting the photocathode. By overfilling the BSA with a transversely Gaussian laser, a uniform transverse laser, hence a uniform electron distribution can be generated. The laser can be imaged at a virtual cathode (VC) camera, located at the equivalent distance from the incoming laser as the real cathode inside the RF gun. The measured laser beam deviates from uniform distributions due to optics alignment imperfections or crystal defects, which leaves a core inhomogeneity and non-negligible outer halo surrounding the core. Figure 4 (a) shows the VC image of the laser pulse with a BSA diameter of 1.3 mm. Its radial profile was fitted with a core-halo model [7] in Fig. 4 (b), showing a good uniform core and an apparent tail.

To measure the emission curve, the laser energy was scanned for various BSA diameters. As shown in Fig. 5 (a), the extracted bunch charge increased proportionally with the laser energy when the laser energy was small. As the laser energy increased, the space charge began to dominate the emission, known as emission saturation. When the BSA was

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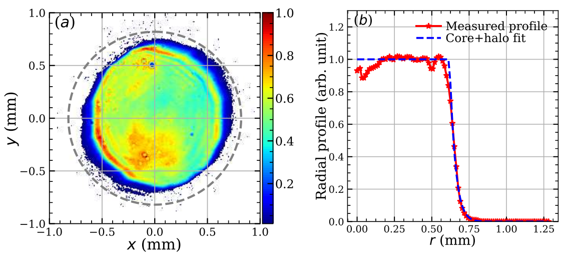

Figure 4: Measured laser transverse profile (a) and core-halo fit (b).

small, the saturation came earlier with respect to the laser energy, as stronger space charge was present.

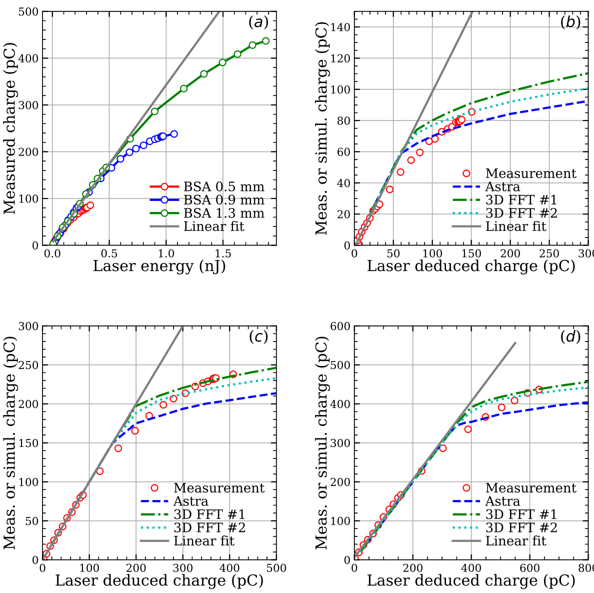

Figure 5: Measurements and simulations on emission curves at various BSA diameters: (a) measurement; (b)-(d) simulations for BSA diameter of 0.5, 0.9 and 1.3 mm.

SIMULATIONS ON EMISSION CURVES

For the simulations, the measured radial profile of the laser pulse was used to modify the initial transverse distribution with 200 k macroparticles generated by Astra for particle tracking using the cylindrical space charge model in Astra. A similar distribution with 10^6 macroparticles was generated for simulations using the 3D space charge solver (referred as 3D FFT #1 later) for comparison with Astra. The 2D laser transverse distribution was also used to generate non-cylindrically symmetric transverse distribution (referred as 3D FFT #2 later) to study the effect of the inhomogeneity on the emission. For the Astra simulation, it has 40 grid cells in radial direction and 50 along the bunch; for the 3D solver, the meshing grids are $N_x \times N_y \times N_z = 32 \times 32 \times 128$.

For three BSA diameters, the input bunch charge was scanned and the extracted bunch charge was collected at the gun exit. The results are shown in Fig. 5 (b) to (d), where initial transverse distributions are cylindrically symmetric for Astra and 3D FFT #1 and inhomogeneous for #2. For initially cylindrically symmetric distributions, Astra simulations give a lower emission curve in the saturation regime for all the three cases, which may be resulted by the meshing resolution for space charge calculation and will be studied later. For the 3D solver, the inhomogeneity of the initial distribution was found to suppress the emission charge slightly for all the three cases. Still the measured emission curves were not well reproduced. Thus future studies will consider more cathode physics behind the emission process.

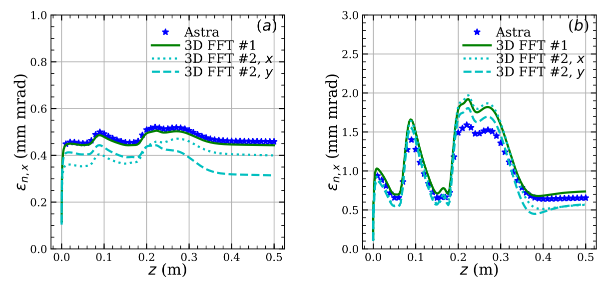

Figure 6: Comparison of simulated RMS emittance in the gun with input charge of 20 pC (a) and 100 pC (b).

In addition, the beam emittance along the gun has been compared for bunch charges of 20 pC and 100 pC at BSA = 0.5 mm, as shown in Fig. 6. For the linear regime (20 pC), good agreement with Astra was found, given the same initial distribution. Meanwhile, the inhomogeneity introduced non-negligible changes to both x and y emittances. For the saturated emission (100 pC), discrepancies appeared after the emission between Astra and the other two, mainly due to the difference in the extracted charges (70 pC for Astra and ~80 pC for the others). The discrepancy implies that the simulated beam parameters in the saturated regime could be unreliable if the emission is not well modelled.

CONCLUSION

A 3D space charge solver using the FFT method has been developed at PITZ for the simulation of the emission curves in the normal conducting RF gun. The large energy spread of the bunch during the emission was analyzed preliminarily and it was found insensitive for space charge calculation. Emission curves were simulated with Astra and tracked with the 3D solver. Discrepancy was found between Astra simulation and the space charge solver, probably due to the meshing solution in the 3D solver. The inhomogeneity of the transverse laser beam distribution could suppress the emission charge slightly. The particle tracking with the 3D solver was also crosschecked with Astra and good agreement was found for the linear regime. The deviation for the saturated regime shows the importance of well modeling the emission.

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