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Modeling and simulation of RF photoinjectors for coherent light sources

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ABSTRACT

We propose a three-dimensional fully electromagnetic numerical approach for the simulation of RF photoinjectors for coherent light sources. The basic idea consists in incorporating a self-consistent photoemission model within a particle tracking code. The generation of electron beams in the injector is determined by the quantum efficiency (QE) of the cathode, the intensity profile of the driving laser as well as by the accelerating field and magnetic focusing conditions in the gun. The total charge emitted during an emission cycle can be limited by the space charge field at the cathode. Furthermore, the time and space dependent electromagnetic field at the cathode may induce a transient modulation of the QE due to surface barrier reduction of the emitting layer. In our modeling approach, all these effects are taken into account. The beam particles are generated dynamically according to the local QE of the cathode and the time dependent laser intensity profile. For the beam dynamics, a tracking code based on the Lienard–Wiechert retarded field formalism is employed. This code provides the single particle trajectories as well as the transient space charge field distribution at the cathode. As an application, the PITZ injector is considered. Extensive electron bunch emission simulations are carried out for different operation conditions of the injector, in the source limited as well as in the space charge limited emission regime. In both cases, fairly good agreement between measurements and simulations is obtained.

1. Introduction

RF photoinjectors can provide highly charged electron beams with very low transverse emittance [1–8]. This is a crucial property, in particular, for coherent light sources since the radiated light intensity tends to grow near-quadratically with decreasing beam emittance [9]. Therefore, the optimization of injector operation in terms of increasing beam current while at the same time reducing its transverse emittance is an important task in linear accelerator design. This task includes, in the first place, the characterization of the electron beam with respect to a large number of machine parameters such as photocathode material, spot size and intensity of the cathode-illuminating laser pulse, longitudinal beam profile, accelerating field strength, solenoid current and many others.

Photoinjector characterization studies are typically done by numerical simulations. Several particle tracking tools are available and are commonly used for this purpose (cf. [5,10–19]). However, so far no suitable numerical model can incorporate the photoemission process with sufficient accuracy to resolve the complex beam dynamics in the close vicinity of the cathode. In other words, it is not possible to predict from first principles the beam current produced by the photocathode for different injector operation conditions. The knowledge of this current is, however, the first prerequisite for all beam tracking and space charge field simulations in the injector and further down in the accelerator chain. A common assumption used in conventional simulations is that the emission current profile is identical with the intensity profile of the laser pulse applied at the cathode. However, the QE of the photocathode, and thus the emission current depends also on the local space charge and RF fields at the cathode (see details in Section 4). This is due to the modulation of the effective work function of the emitting layer by the electric fields applied on the cathode (Schottky-like effect). The space charge field at the cathode is determined itself by the emission current and, furthermore, by the dynamics of the emitted particles in the vicinity of the photocathode. In photoinjectors, the particle dynamics immediately after their emission is characterized by an extremely fast transition from the non-relativistic to the highly relativistic regime. This makes space charge and beam tracking simulations in this region particularly difficult. The problem is, thus, multifaceted and it requires a numerical model which is able to cope with all of these effects. In the following, we will introduce a simulation approach dealing with these beam dynamics and particle emission issues for RF photoinjectors

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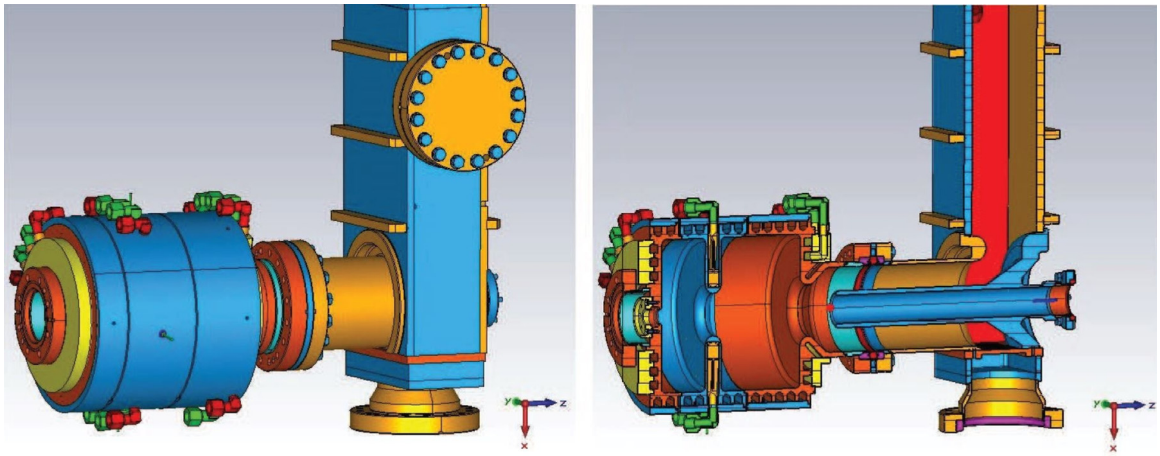

Fig. 1. Sketch of the PITZ RF gun. Left: Exterior view. Right: Cut-plane view depicting the 1.6-cell cavity and the RF waveguide system.

operated in the source limited as well as in the space charge limited emission regime. We will refer primarily to the PITZ photoinjector of DESY [1–3]. For this injector, a large database of measurements exists which can be used to assess the validity of our simulations.

The paper is organized as follows. In Section 2, a motivation for this work is given by describing the discrepancies arising between conventional beam dynamic simulations and measurements for the PITZ photoinjector at DESY in Zeuthen [20,21]. In Section 3, the particle tracking codes used in the photoemission studies are described. These include a Lienard–Wiechert (LW) based tracking code [13,22] and a fully electromagnetic Particle-In-Cell (PIC) code [14]. The photoemission models used in the simulations are introduced in Section 4. In Section 5, simulation results are presented. These results are compared with corresponding measurements for different operation conditions of the PITZ photoinjector.

2. The PITZ photoinjector

The main motivation for this investigation is a number of discrepancies between simulations and measurements, which were observed for the photoinjector of the European XFEL at the Photo Injector Test Facility at DESY in Zeuthen (PITZ) [20–24]. A sketch of the RF photogun employed at PITZ is shown in Fig. 1. Its main components are a 1.6-cell copper cavity operated at 1.3 GHz and a magnetic focusing system. The electron beam is generated at the back-plane of the gun cavity by illuminating a cesium-telluride photocathode with short laser pulses. A peak accelerating field of up to 60 MV/m is applied in the cavity. As a result, electron bunches are accelerated immediately after their emission up to nearly the speed of light within a distance of a few millimeters from the cathode. We will not go into further details on the PITZ gun and its operation parameters. For a thorough description, the interested reader is referred to [1–3].

For the characterization of injector current, two typical measurements are performed. One is the measurement of the emitted bunch charge (Q_{tot}) as a function of the cathode laser launch phase (ϕ_l) for a given laser pulse energy (W_l). The other one is the bunch charge measurement for different laser pulse energies while keeping the laser launch phase constant. In the measurements, Faraday cups (FCs) and integrating current transformers (ICTs) are used. These are located at about 0.78 and 0.935 m downstream of the cathode, respectively. The ICTs can measure the total charge in the electron bunch with a precision of about 30 pC whereas the FCs have a charge resolution of up to 2 pC.

A typical phase scan for the PITZ gun is shown in Fig. 2 (see also [20,21]). The gun phase is measured with respect to the maximum mean momentum gain (MMMG) phase. Thus, each gun phase corresponds to a different accelerating field strength applied on the cathode during the bunch emission phase. At the nominal phase (0° w.r.t. MMMG) and for a RMS laser spot size (XYrms) of 0.3 mm the charge of the emitted bunch amounts to 1 nC. The phase scan measurements are performed for two different laser pulse intensities. For a laser transmission (LT) of 100%, the emitted charge depends mainly on the accelerating electric field gradient at the cathode plane, where the laser intensity is no longer a limiting factor. Thus, the bunch charge measured in this case (top black curve) represents the space charge saturation limit of the gun at the corresponding accelerating field strength. In comparison, a laser transmission of 62% is defined such in the experiments that a nominal bunch charge of 1 nC can be extracted at 6° w.r.t. MMMG phase of the gun. For the lower laser intensity with LT = 62% (green curve) and for gun phases between 0 and 50° the bunch charge is nearly constant with respect to the gun phase. In this region, the injector is apparently operated in the source limited regime. In this case, the emitted charge depends only on the laser intensity and on the QE of the cathode, but not on the accelerating field strength at the cathode.

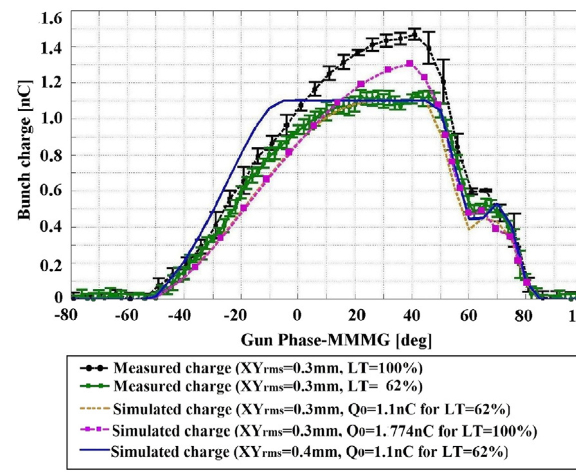

Fig. 2. Measured and simulated bunch charges for different gun phases of the PITZ injector. A flat-top laser pulse of 20 ps length and a RMS spot size of 0.3 mm are applied. Two laser pulse intensities are considered, denoted by LT = 100% and LT = 62%, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Also in Fig. 2, conventional beam dynamics simulation results obtained from ASTRA [15] (pink, yellow and blue curves) are compared with the measurement data (black and green curves). Since the photoemission process is not explicitly modeled, the charge produced by