SIMULATION OF HIGH CURRENT EXTRACTION FROM THE ELSA RF PHOTO-INJECTOR

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Abstract

Extracting a high-charge bunch from a photo injector is a real challenge, because of space charge effects. Our goal is to extract a 100-nC bunch from our 144-MHz photo-injector, and to keep it a low emittance. The effect of HOM excitations has also to be considered for our a long term goal, which is to extract a burst of ten consecutive such bunches. This paper presents some simulations of basic phenomena (image charges, space charge limitation, RF mode excitation ...), that we carried out to validate the tool that we use (the MAFIA-TS2 2D PIC solver), and the results of global simulations.

INTRODUCTION

The intensity of electron emission is a critical issue in flash X-ray machines like AIRIX [1]. The ELSA unique low frequency (144 MHz) photoinjector [2] is a good tool to explore the domain of space charge limited emission. Such experiment requires improvements on the photo-injector, components (photo cathode, drive-laser, RF power...). An important work on the drive laser stabilization is underway. Boosting the RF power by +50% is also considered. We present here some simulations validating the principle of high charge emission. We use the MAFIA time-domain particle-in-cell (PIC) solver TS2 in a 2D axisymetrical simulation (r,z). Next subsections shows some of the simple tests that we made in order to check if basic phenomena were treated correctly by this code.

Image charge

Unlike the classical code PARMELA working with image charges, MAFIA-TS2 solves the Maxwell equations directly with the limit condition (metallic wall). We first checked the equivalence of the two formalisms.

A single particle is emitted at low speed (β_0<<1) from a metallic cathode without external field. In the non relativistic limit, the limit condition on the cathode is equivalent to an image charge moving backward from the cathode, symmetrically with the real particle. This image charge acts on the real particle by decelerating it along its trajectory. As the total energy of the real particle (kinetic plus potential) remains constant, we have:

$$\frac{mc^2}{2}\beta(z)^2-\frac{qe}{16\pi\varepsilon_0}\frac{1}{z}=cte\,,$$

the second term on the left hand side being the potential energy created by the image charge on the real particle.

With MAFIA, we simulated such a case, and computed the particle speed along its trajectory. As expected, the total energy (from MAFIA's speed and position) is indeed constant, after the first half mesh step (fig.1). The energy drop ΔE between initial and asymptotic-final kinetic energy is about the potential energy of the particle at the distance of one mesh step. We conclude that the so-called "image charge" effects are correctly simulated (as long as the initial energy is higher than ΔE).

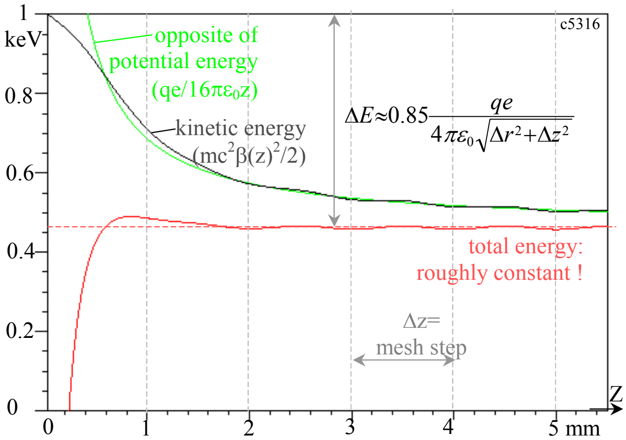

Fig. 1. A single particle decelerated by its image charge.

Space charge limitation

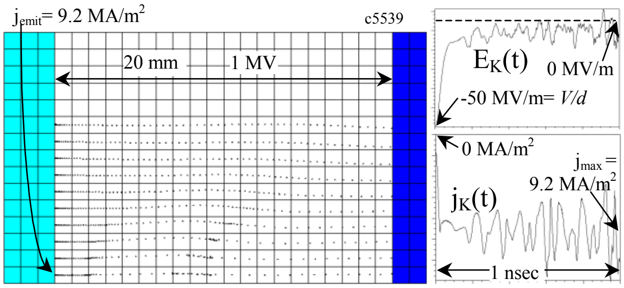

Fig. 2. Transient behaviour at the space charge limit value: electron motion gets turbulent.

In a planar diode with a uniform external field, the density of emitted electrons cannot exceed the value for which the external field is cancelled by the space-charge field. When this occurs, the particle motion becomes turbulent (fig. 2). If an attempt is made to emit a higher density current, the turbulence grows and some particles roll back to the cathode. Simulations show that the current limitation indeed coincides with the cancellation of the cathode field (fig. 3). The density limit, according to Child Langmuir's (CL) law, is proportional to $U^{3/2}/d^2$:

$$\hat{j}_{cl}=\frac{4}{9}\varepsilon_0\sqrt{\frac{2e}{m}}\frac{U^{3/2}}{d^2}=\frac{\varepsilon_0 mc^3}{e}\frac{1}{d^2}\frac{4\sqrt{2}}{3}u^{3/2}\,,\quad\text{with}\quad u=\frac{Ue}{mc^2}\,.$$

For voltages U>0.5 MV, the agreement is still good with the relativistic CL law [3] (fig. 4):

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$$\hat{j}_{clr} \approx \frac{\varepsilon_0 m c^3}{e} \frac{1}{d^2} 2(\sqrt{u+1}-0.85)^2$$

But the absolute MAFIA current limit is higher than CL's value by a factor (about 1.8 here) decreasing with mesh size. The residual discrepancy factor (which tends to 1.4 as mesh size tends to zero) results from the finite radial extension of the beam that permits a higher current density than in the CL's 1D model.

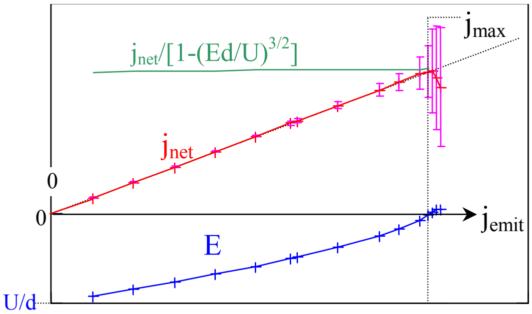

Fig. 3. For given voltage and distance, the cathode field (E_K) drops as the current density (j_{emit}) increases.

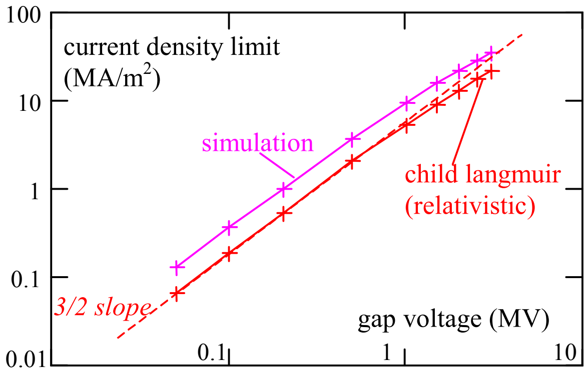

Fig. 4. Despite a 1.8 discrepancy factor, the voltage dependence of the density limit is OK.

Immersed cathode

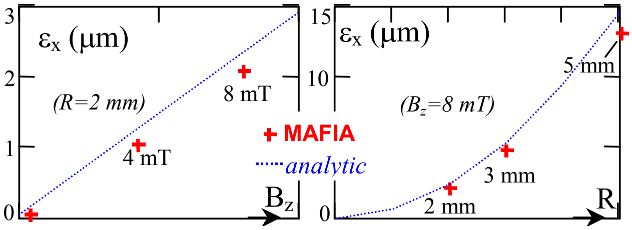

Fig. 5. Emittances with an immersed cathod .

Immerging a cathode in magnetic field B_z creates some azimuthal emittance. For a short bunch of radius R [4]:

$$\varepsilon_x = \frac{e}{mc^2} \frac{B_z c R^2}{8}.$$

A 1-pC bunch, 25-ps rms (gaussian) long, was simulated in the geometry of the ELSA photoinjector (see below). An additional coil in the cathode nose creates a longitudinal magnetic field on the cathode. From r, $r'=v_r/v_z$, *and* $\theta'=v_\theta/v_z$, MAFIA/TS2 computes the normalized rms emittance:

$$\varepsilon_x = \beta\gamma(<x^2><x'^2>-<xx'>^2)^{1/2}$$
$$=(\beta\gamma/2)(<r^2><r'^2+\theta'^2>-<rr'>^2)^{1/2}.$$

Results are in good agreement with the analytical value (fig 5).

ELSA PHOTO INJECTOR

RF Modes

Excitation of the photoinjector cavity by a short bunch of charge q has been simulated in time domain with the TS2 solver. After a Fourier transform, the spectrum shows the same frequencies than the modes computed by the eigenmode solver in frequency domain (fig. 6). Moreover, at 144 MHz, the amplitude of the accelerating mode is within 1% of the expected value: $U=q\omega R/Q$.

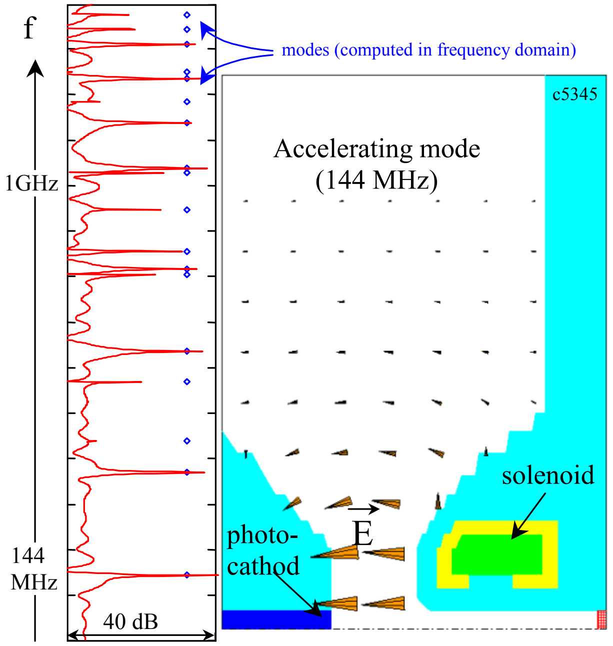

Fig. 6 Response of the ELSA photoinjector cavity computed in time and frequency domains.

Charge extraction

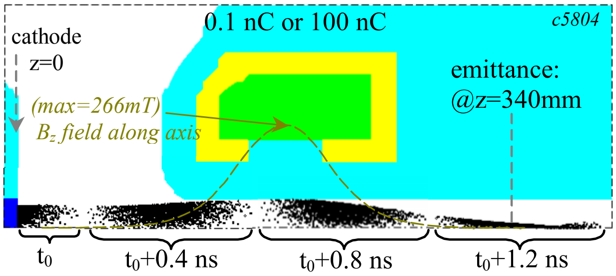

Fig. 7. 0.1 or 100 nC extracted from ELSA's photoinjector. The middle of the bunch is extracted at t_0.

A gaussian bunch (65 ps-rms) of 100 nC is extracted uniformly from a 15-mm radius photocathode. The RF voltage is U=2.7 MV, the gap length is d=100 mm.

According to MAFIA, such a bunch can be accelerated without major perturbation on the particle dynamics (fig. 7): the plots look exactly the same either for a low charge (0.1 nC) or a 100 nC charge. However, at 100 nC, a few particles (5.5 %) are lost on the wall tube: the photoinjector parameters (cathode radius, focusing magnetic field...) have not been optimized yet. As the emittance is dominated by non-linear radial effects due to the wide extraction area, the charge has only a slight influence on it: ε_x is 174 µm at 0.1 nC, and 181 µm at 100 nC (fig. 8).

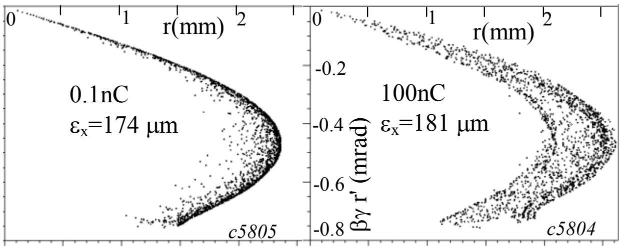

Fig. 8. Phase plane (r r') and emittance @z=340 mm.

Wakefields effects

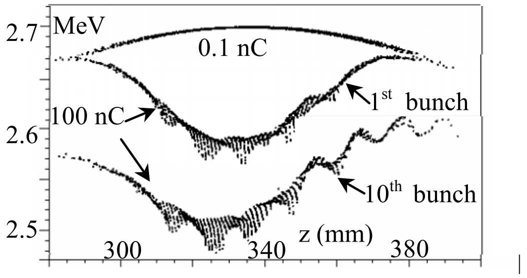

Fig. 9 Energy dispersion for different bunches.

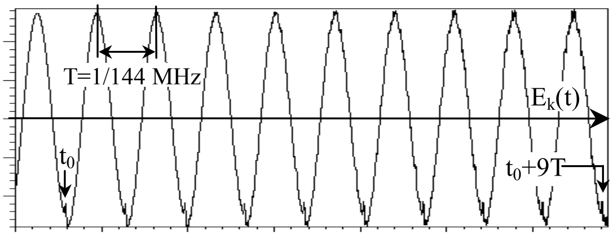

Fig. 10. Photocathode E-field for a 10×100nC bunch train.

The charge has also some influence on the output energy of the bunch (fig. 9). Wheras a low charge bunch is almost uniform in energy (apart from the top curvature due to the RF sine dependence of the fields), the wakefield of a 100-nC charge causes an energy drop in the bunch center. In addition, the global energy further decreases in case of multibunch operation because of cavity filling out: -0.27 Joule at each bunch out of 45 Joules initial energy. Each successive pulse emission causes a bump on the photocathode field, and some higher frequency noise gradually emerges (fig. 10).

Overloading

As no major consequence was observed so long, we tried to push the charge until bunch explosion: it occurred above 500 nC. As an example, an attempt to extract a charge of 1000 nC is displayed (fig. 11). This simulation clearly shows a particle lack on axis in the bunch center, a high number of lost particles (caused by radial excursion), and eventually, a split residual bunch coming out from the cavity. The number of particle is 1000, and the mesh step is 0.9 mm in the gap. Other mesh size and number of particle were tried: results were qualitatively equivalent.

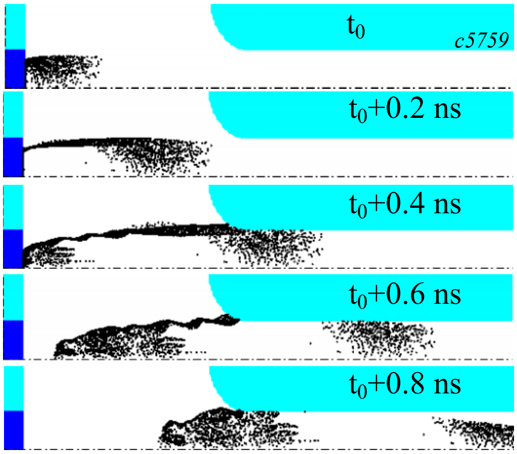

Fig. 11. At 1000 nC, the bunch explodes.

CONCLUSION

According to MAFIA simulations, a bunch charge of 100-nC can be extracted and correctly accelerated in the ELSA photoinjector. Apart from an acceptable energy degradation, no major consequence was observed on the beam dynamics. Multibunch operation can be considered for a few bunches.

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