BEAM DYNAMICS SIMULATIONS OF SUB-PS ELECTRON BUNCH PRODUCED IN A PHOTO-INJECTOR

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Abstract

A growing number of experiments require low emittance ultra-short electron bunches in the 100 fs range (rms value) for the production of coherent light or the injection into a plasma for laser-plasma acceleration. Especially in the last case it is highly desirable to have a compact accelerator; hence a strong experimental activity is carried out to get such a beam directly from a photo-injector. We have performed beam dynamic simulations using the PARMELA code to study the performances of the alphaX photo-injector installed in the University of Strathclyde in UK*. This RF gun is aimed to produce electron bunches which have 100 pC of bunch charge, 100 fs bunch length and 1 π mmmrad transverse emittance. We will show the results of systematic parametric studies as a function of charge and laser pulse duration as well as the natural evolution of the beam phase space as a function of the distance from the photo-cathode.

INTRODUCTION

Up to now the preferred way to get very short bunch is to use a magnetic chicane but this could lead to a degradation of the emittance due to the emission of coherent synchrotron radiation. Moreover it is difficult to make a compact beamline in such a scheme. Some experiments as alphaX [1] in the University of Strathclyde strive to produce X ray in the SASE [2] regime with a very short accelerator which the length is roughly 7 meters. The idea is to inject a very short electron bunch coming from a photo-injector into a laser-plasma [3] accelerating cell to bring it at 1 GeV over few millimeters instead of ≈ 30 m in classical linear accelerators. In order to get an efficient acceleration in the plasma, the specification on the bunch length must be absolutely fulfilled. So the purpose of this study is to investigate the behaviour of sub-ps electron bunches directly issued from the photo-injector using numerical simulations.

PARMELA SIMULATIONS

PARMELA is a well-known code used for beam dynamics in linacs which takes into account the space charge force effect. It was created by Los Alamos National Laboratory and modified at LAL by B. Mouton to include, for instance, the photo-injectors.

AlphaX Photo-injector

The alphaX photo-injector is made of 2.5 cells at 3 GHz resonant frequency. This gun designed at the Eindhoven University of Technology [4] exhibits two noticeable features. First, the shape of irises is elliptical because, according to the RF simulations, the surface electrical field is reduced by a factor 2 with respect to the more usual cylindrical shape. So one hopes to operate the gun at gradient higher than 100 MV/m without electrical breakdowns. Secondly the RF power is sent to the gun via a coaxial “doorknob” antenna in a coupler at the output of the gun. In this way the gun keeps a perfect cylindrical symmetry in order to avoid possible degradation of the emittance rising in non-symmetric coupling.

Simulations in PARMELA are performed with the electrical field of alphaX calculated with the 2D RF code SUPERFISH. Results are shown in table 1 for 6000 macro-particles used in the simulation.

Table 1: Results of PARMELA simulations at the output of the gun, input parameters are (rms value): Q = 100 pC, laser has a Gaussian profile, radius = 1.4 mm cut at 10 mm and pulse duration = 100 fs cut at 500 fs. The peak electrical field is 92 MV/m and the phase is chosen to optimise the energy gain, rms value.

Beam radius (mm)	3.1
Bunch length (fs)	206
Energy (MeV)	6.2
Normalized Emittance (πmmmrad)	4.2
Energy spread (%)	0.172

In this case the specifications are not fulfilled, the emittance being 4 times higher and the bunch length 2 times bigger. About the emittance there is a way to significantly reduce the effect of the space charge forces thanks to a uniform transverse profile instead of a Gaussian shape for the laser. The same technique can be applied along the longitudinal axis. But before to show the results of the improvements with a square distribution, one may wonder about the validity of these calculations. Indeed most of simulations are usually performed with electron bunches which the length is in the picosecond range.

Test of PARMELA

Up to now there are no measurements of sub-ps bunches produced directly from the gun to compare with PARMELA simulations. But it is possible to check if the results of PARMELA are at least in agreement with the

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physics of charged beam. For instance the scaling of the emittance as a function of the bunch charge depends on the space charge forces. Normally the repulsive force applying on each electron is proportional to the total charge. In figure 1 we tested this scaling law for 2 bunch lengths, 10 ps and 100 fs.

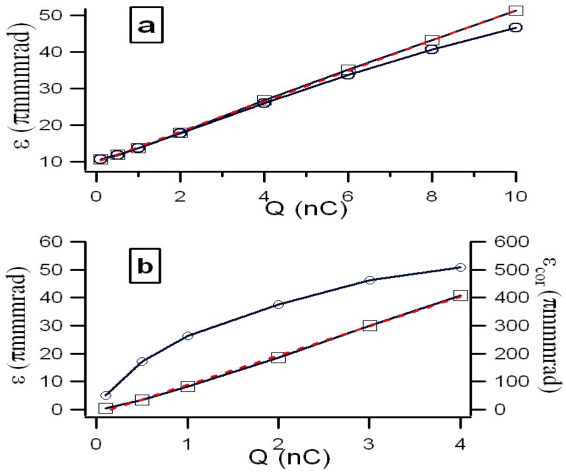

Figure 1: normalized emittance as a function of the total charge. In a), the laser pulse duration is 10 ps; in b), it is 100 fs. Lines with circle are raw PARMELA results, lines with squares are corrected data and dashed red line is a linear fit. In the case of b), the value of the corrected data is reported on the right axis.

In the case of the long bunches, 10 ps, the growth of the emittance becomes non-linear for charges above 4 nC and this change even occurs below 1 nC for the 100 fs bunches. This is due to the fact that the space charge force is proportional to the electronic density. So when it becomes stronger, the bunch length increases leading to a reduction of the space charge force and therefore the emittance growth is slowed down. To remove this effect, we multiplied the emittance by a corrective factor which is the ratio of the bunch length at the output of the gun over the bunch length at zero charge. The corrected data fit perfectly with a linear law for fs bunches as well as for ps bunches. So PARMELA seems to be still reliable for short bunches and we can look for better performances with 100 fs bunches.

EMITTANCE OPTIMISATION

It is now usual to make a flat shape of the laser distribution in order to decrease the space charge forces. After optimisation, the best parameters for the laser are: in transverse plane, σ_r = 4 mm, r_{max} = 1.2 mm and no change in the longitudinal axis, results are given in table 2. The emittance is reduced by 33 % with respect to the case of the laser with a Gaussian profile (table 1). However it was impossible to find a set of longitudinal laser parameters which allows one to further decrease the emittance. It is a first visible difference with respect to the ps bunches where using also a flat longitudinal pulse leads to a supplementary reduction of the emittance.

Table 2: Results of PARMELA simulations for Q = 100 pC in rms value (6000 macro-particles) for a laser flat transverse profile and 2 accelerating fields.

	92 MV/m	120 MV/m
Beam radius (mm)	1.6	1.5
Bunch length (fs)	283	196
Energy (MeV)	6.2	8
Normalized Emittance (πmmmrad)	2.8	2.4
Energy spread (%)	0.43	0.32

Moreover the bunch length and the energy spread are enhanced while it should be the opposite. One way to overcome these difficulties is to increase the accelerating gradient. But it seems to profit mainly to the bunch length which is reduced of 30 % while it is only 14 % for the emittance. Of course only the experiment can tell if the gun can be operated at such high gradient with a good stability. So unless to relax the specification on the bunch length it seems difficult to get the 1 πmmmrad for 100 pC and 100 fs bunch length.

LONGITUDINAL DYNAMICS

For some applications the bunch length is a parameter of a paramount importance and one must investigate how evolves a bunch with a length of 100 fs.

Natural Behavior

Plotting the evolution of the bunch length as a function of the longitudinal distance, a special feature of the short bunches appears, as illustrated in figure 2.

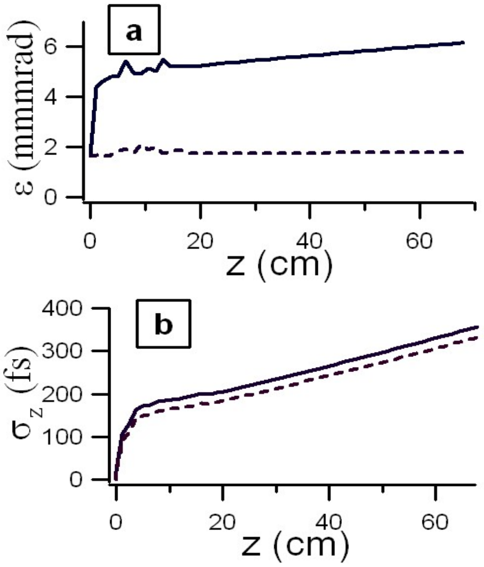

Figure 2: a), emittance as a function of the longitudinal distance z; b), bunch length as a function of z. Plain line is the simulation taking into account the space charge forces, dashed line is without space charge. Parameters of the simulations are the same as used in table 1 except number of macro-particles, 1000 in this case.

In the drift space after the gun, there is a slow increase of the emittance while the bunch is lengthened by a factor 2. In the case of the emittance it is clearly the consequence of the space charge forces. At the opposite the major part of the bunch lengthening even occurs without the inclusion of the space charge forces. The latter give a very weak contribution to the bunch length. This bunch lengthening was already investigated by previous studies [5] with the GPT code and is a pure geometrical effect. External electrons have higher divergence with respect to electrons on axis. Therefore they follow a longer path than electrons in the centre of the bunch and accumulate a time lag which means they go to the tail of the bunch. With longer bunch, 10 ps, a drift of the external electrons of 0.1 ps is completely absorbed in the overall bunch.

Behavior with Vertical Focussing

To transport the electron beam or to focus it for an experiment, the use of a solenoid or quadrupole is unavoidable. Usually the longitudinal dynamic is not coupled to the transverse motion, except in a dipole. But for fs bunches it is not true anymore. We performed a simulation with a quadrupole focussing in the horizontal plane, results are shown in figure 3.

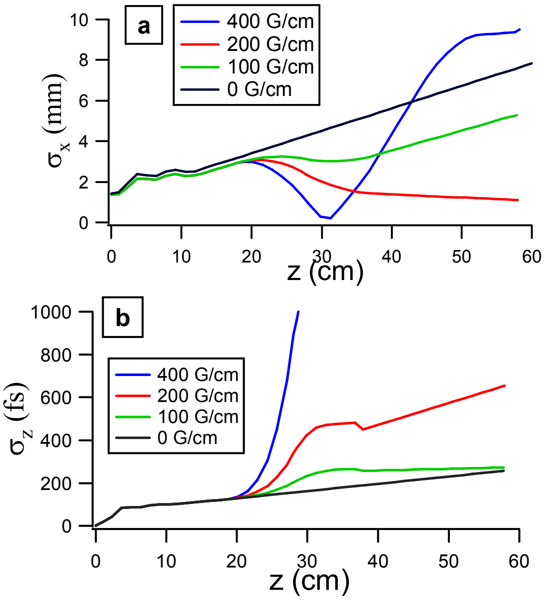

Figure 3: simulations without space charge, same parameters for the laser (see table 1), a horizontal quadrupole is placed at z = 20 cm; in a), horizontal sizes (rms) and in b) the bunch lengths (rms) for several values of the quadrupole gradient.

When one tries to focus the electron beam, the bunch length quickly increases. When the beam passes through the quadrupole, external electrons have a longer path to go to the focus point with respect to the on axis electron. It is a critical issue because if it is really required to focus the beam at a size below 0.2 mm (to inject in a capillary for instance) the bunch length inflates, from 130 fs up to 4 ps, 40 cm after the gun. Simulations performed with a solenoid give the same results as the quadrupole ones. So every time the beam is transported or focused with magnets the bunch length strongly increases.

The only way to compensate this bunch lengthening is to use a curved photo-cathode [6] made in such a way that external electrons are emitted in first with respect to on axis electrons.

With a Laser at Non-zero Incidence

Usually in the simulations, one neglects the angle of incidence of the laser onto the photo-cathode because it is very small, ≈ 3° in our case. In figure 4 is reported the result of a simulation with an incident angle of 3° and compared with the case at normal incidence.

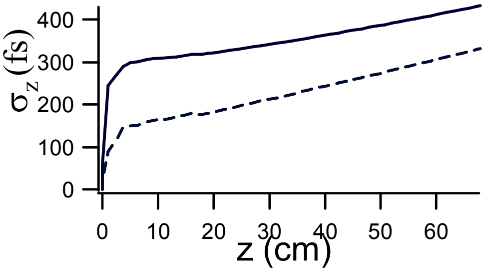

Figure 4: bunch length as a function of the longitudinal distance. The parameters of the simulations are those used in table 1; plain line: angle of laser incidence is 3°, dashed line: normal incidence on the photo-cathode.

The result is rather clear: for femtosecond bunches one must not neglect the angle of incidence anymore. Even with only 3° it induces a bunch lengthening of 120 fs.

CONCLUSION

A study of femtosecond bunches based on PARMELA simulations has been performed which shows that the handling of such beam produced from a photo-injector is rather difficult. External electrons have a longer path to travel than the core electron; a drift space or magnets used to transport or focus the beam induce inevitably a bunch lengthening. The minimization of the emittance thanks to a flat transverse profile of the laser is obtained at the expense of a degradation of the bunch length and energy spread.

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