BEAM DYNAMICS STUDIES IN A LOW-FREQUENCY HIGH-PEAK POWER LASER-DRIVEN RF GUN

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Abstract

An IR-FEL experiment (ELSA) is under construction at Bruyères-le-Châtel. The injector consists of a laser-driven photocathode placed inside a 144 MHz RF cavity. A prototype has been built and operation is starting. Electron bunches 25 to 100 ps wide containing a charge up to 10 nC are expected to be delivered at an energy of 1 to 1.5 MeV. Extensive beam dynamics simulations have been made to predict the injector response. Beside the well-known PARMELA code, a locally developed code, ATHOS, as well as codes developed at Limeil (MATISSE and VLAMINCK), at Orsay (OAK, PRIAM) and Ecole Polytechnique were used. In spite of the specificity and limitations inherent to each code, an overall agreement within 20% is obtained for the main beam characteristics. It is shown that for intense short bunches, the space charge induced correlated emittance growth can be controlled by a magnetic lens.

Introduction

A linac is under construction at Bruyères-le-Châtel as part of an IR-FEL experiment (ELSA). It consists of a laser-driven photocathode placed inside a 144 MHz RF cavity and followed by three 433 MHz RF accelerating cavities. Electron bunches 50 ps wide containing a charge of 10 nC are expected to be delivered at an energy of 15 to 20 MeV. We will focus in the present paper on the beam dynamics in the photo-injector section [1]. The choice of a low frequency considerably reduces RF effects and permits extraction and acceleration of longer electron bunches. Magnetic compression after acceleration would be used to increase the peak current. On the other hand, such a low frequency limits the maximum electric field on the photocathode to 15-30 MV/m and space charge effects could be a limitation in performances. These problems are addressed in the present paper through dynamics calculations in the photo-injector.

Beam dynamics calculations

Most of the calculations have been made using the well known PARMELA code. However, a lot of calculations have also been made using other codes in order to better understand the injector response and to check the reliability of the results. These codes are : OAK developed at Orsay and the local code ATHOS in which the beam is represented by disks and rings ; a PIC code under development at Ecole Polytechnique (EM-LEL) ; PRIAM [2] developed at Orsay ; the Maxwell-Vlasov codes MATISSE and VLAMINCK under development at Limeil. As far as average beam parameters are concerned (transverse emittance, beam radius, energy spread), an overall agreement is obtained as shown in table 1 where the radius and the normalized emittance calculated by different codes at the injector exit are given for comparison when there is no focusing lens.

The experimental set-up is described elsewhere [1]. The photo-injector consists of a plane photocathode placed inside a 144 MHz RF cavity. A magnetic lens placed in the nose of the cavity and centered at 12.5 cm from the photocathode was used to control the emittance growth [3]. For simulations, the cavity was followed by a long drift section.

All the calculations have been done for a cylindrical extracted beam of uniform density, 1 cm^2 in section and 50 ps wide.

TABLE 1. Beam characteristics at 20 cm from the cathode

$B_z = 0$, $E_z = 15$ MV/m , $S = 1\ cm^2$, $T \sim 1$ MeV

ε_n(π mm mrad)	OAK	PARMELA	ATHOS	EM-LEL	PRIAM	VLAMINCK
10 nC - 100 ps				50	82	160
10 nC - 50 ps	110	116	235	64	82	180
10 nC - 25 ps	125	104		74	106	200
5 nC - 50 ps	93	86	142		55	100
R (mm)						
10 nC - 100 ps	16			18	16.5	16.5
10 nC - 50 ps	20	19.6		20	18.6	19.8
10 nC - 25 ps	24	22		> 20		> 20
5 nC - 50 ps	15	16.5		18	15	15.2

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1 - CEA/limeil
2 - THOMSON and LAL-ORSAY
3 - LAL-Orsay
4 - Ecole Polytechnique

The RF electric field on the photocathode was 15 MV/m and the electron energy gain in the cavity 1 MeV. We have used the usual normalized transverse emittance given by :

$$\varepsilon_n = 2\beta\gamma \left(\langle r^2 \rangle \langle r'^2 \rangle - \langle rr' \rangle^2\right)^{1/2}$$

Photo-injector beam emittance and focusing

Most of the calculations have been made for a charge of 10 nC in the bunch (200 A peak current). The evolution of the beam radius and the emittance in a drift space following the photo-injector is shown in fig.1 for different values of the lens magnetic field B. The beam radius is very sensitive to B. There is a waist for B between ~ 1100 and 1300 G and a cross-over for higher B values. There is a domain around 1300 G where the bunch undergoes partly a waist and partly a cross-over, due to the energy spread along the bunch. The emittance has a maximum value of ~ 160 π mm.mrad near the exit of the cavity and then decreases to a minimum in qualitative agreement with the analysis of ref.[3]. A minimum emittance of 60 π mm.mrad and a well focused beam are obtained at a distance of 60 cm from the photocathode for a lens strength B=1250 G, indicating that the lens is correctly positioned [3]. Further simulations in the downstream accelerating sections have shown that these beam qualities can be easily maintained and even improved until the energy is high enough for the space charge effects to be small. The minimum emittance depends smoothly on the lens strength. Our simulations systematically show that the best beam is obtained when the beam undergoes a minimum emittance and a waist of minimum radius at a same location. Increasing further the lens strength leads to a cross-over followed downstream by a rapid divergence and uncontrollable emittance growth.

Simulations for 5 nC bunches show a similar behaviour. The minimum emittance is obtained at about the same location for a slightly lower lens strength (1225 G).

For 1 nC bunches, the behaviour is totally different, as shown in fig.2. The beam can be very well focused but the emittance reduction is quite negligible, indicating that the space induced correlated transverse emittance is no more the main source of emittance growth.

Assuming that the different sources of emittance growth are not correlated, an estimate of the space charge induced correlated emittance, ε_L, can be obtained from a quadratic difference between the maximum emittance, as observed near the exit of the cavity, and the minimum emittance at the waist. Figure 3 shows that ε_L is approximately a linear function of the charge in the bunch and becomes the essential source of emittance growth for high-intensity beams. The removal of this component is of prime importance for obtaining good quality intense pulsed beams.

Similar dependences have been calculated by codes like TBCI-SF, MATISSE, PRIAM, EM-LEL and will not be discussed here due to lack of place and some results will be published at the FEL-90 meeting.

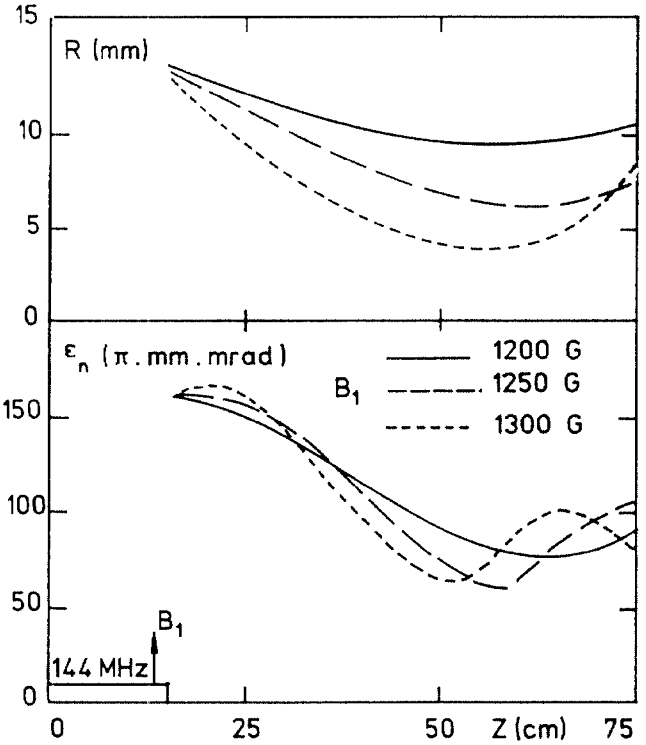

Fig.1 : Evolution of the beam radius and emittance in a drift space following the 144 MHz photo-injector for different strengths of the lens B1 and a beam current of 200 A.

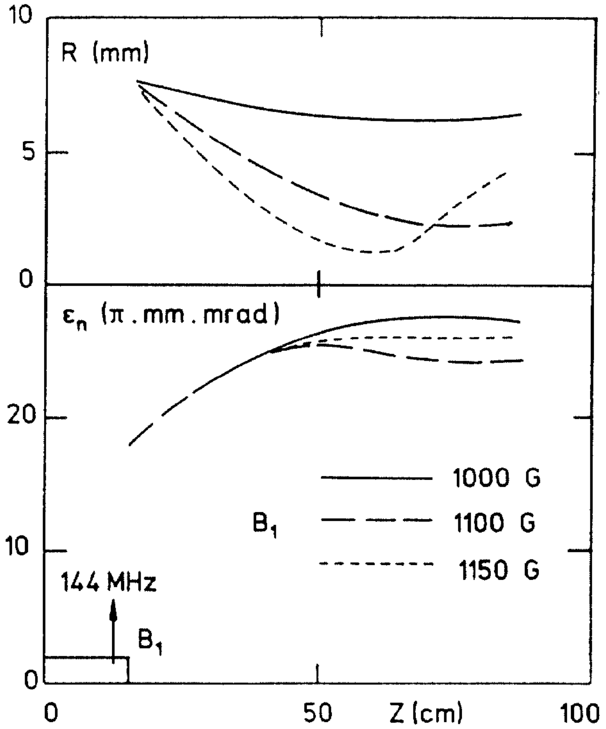

Fig.2 : Evolution of the beam radius and emittance in a drift space following the 144 MHz photo-injector for different strengths of the lens B1 and a beam current of 20 A.

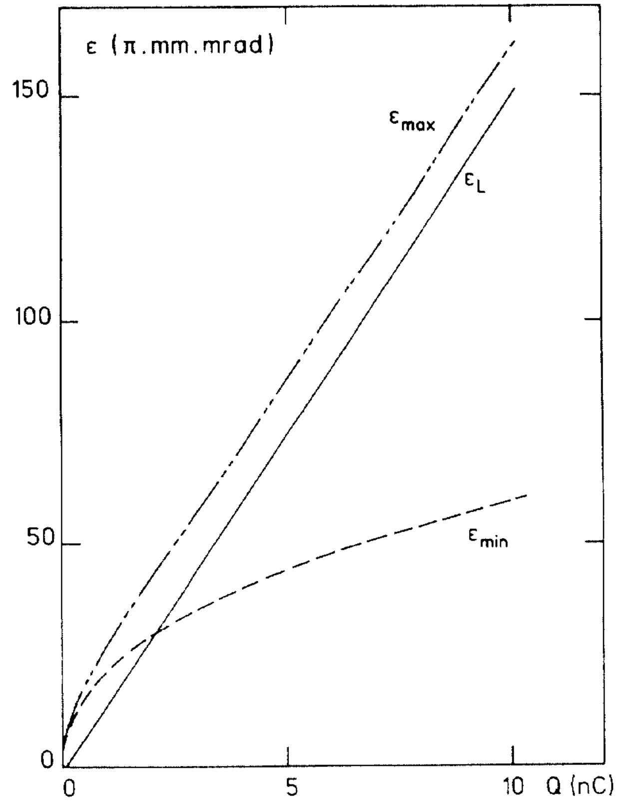

Fig.3 : Maximum and minimum emittances and their quadratic difference ε_L as a function of the charge in the bunch.

Energy spread

Because of the relatively low RF field strength on the photocathode, a quite large energy spread is observed at the waist for a 10 nC bunch under the influence of the space charge forces (fig.4). However, the energy distribution remains highly correlated to the position of the electrons in the bunch and a correction is therefore possible, for example, through a slight phase-shift of the accelerating cavities downstream. Nevertheless, because the average energy is only 1 MeV, the energy spread results in a velocity modulation and a widening of the bunch. For an initial rectangular bunch of 50 ps, the width is 65 ps at the output of the injector cavity and 85 ps at the beam waist. Preliminary experimental results [1] indicate that the output energy could be increased at least up to 1.5 MeV, reducing considerably the velocity modulation.

Because of the energy distribution along the bunch, the magnetic lens focuses each slice at a different position downstream. We obtain a waist on the average only. Thus, while removing a large part of the space charge induced correlated transverse emittance, we introduce at the same time a new kind of correlated transverse emittance which seems to represent a non negligible part of the minimum emittance at the waist.

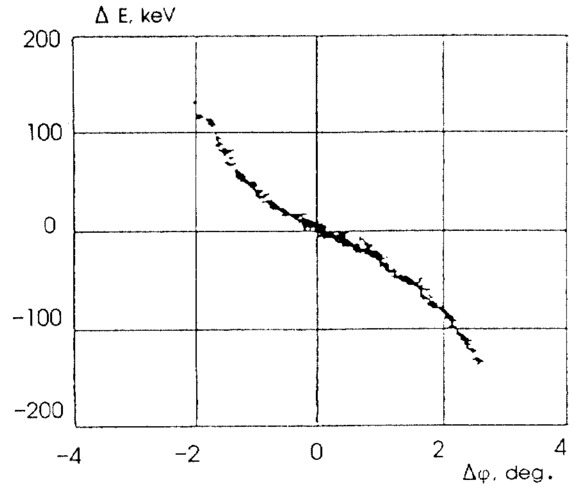

Fig.4 : Energy spread along the bunch at the beam waist for a peak current of 200 A (1° ~ 19.5 ps)

Conclusion

The response of the 144 MHz photo-injector installed at Bruyères-le-Châtel has been investigated numerically.

The beam characteristics have been evaluated consistently within 20% using different codes. It has been shown that a simple magnetic lens configuration is sufficient to remove a major part of the emittance growth from the dominant mechanism, the space charge in intense short bunches.

As a drawback, the energy distribution along the bunch induces chromatic effects in the lens affecting the residual emittance.

References

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