LASER COMB: SIMULATIONS OF PRE-MODULATED E$^-$ BEAMS AT THE PHOTOCATHODE OF A HIGH BRIGHTNESS RF PHOTOINJECTOR

M. Boscolo, M.Ferrario, C. Vaccarezza, LNF-INFN, Frascati, Italy
I. Boscolo, F. Castelli, S.Cialdi, Mi-INFN, Milano, Italy

Abstract

A density modulated electron beam generated at the photocathode of a radio-frequency electron gun evolves within an accelerator towards a homogenous beam but with an energy modulation. The density modulation is changed into energy modulation. This energy distribution can be exploited to restore the initial density profile, called *comb beam*, with a proper rf phase of the accelerating cavities and by adding a proper compressor. The comb beam at the cathode is generated driving the photocathode by the relative laser pulse train. This laser pulse is obtained with a shaping device inserted into the laser system. The dynamics is studied within the SPARC system with the PARMELA code.

INTRODUCTION

Short electron bunches with high charge, low-emittance, and low-energy spread are generated by radio-frequency (rf) e$^-$ gun driven by laser pulses. Applications of this kind of electron source cover free-electron lasers [1], plasma acceleration experiments and Compton scattering [2] and high brilliance linear collider [3]. The wide spectrum of applications is due to the capability of these electron sources of producing target electron beams. This feature is mostly due to the possibility of a proper modulation of the driving laser beam [4].

In this paper we study the generation of a multipulse e$^-$ beam in the SPARC accelerator [5], aiming to produce high peak current (higher than nominal working point) and train of pulses. We investigate the dynamics of the e$^-$ beam with PARMELA [6] simulations.

SPARC parameters of interest to our study are (see also Table 1): 10 ps pulse length, 1.1 nC bunch charge, projected emittance less than 2 μm and electrons energy of 5.6 MeV at the exit of the rf gun. The important geometrical parameters (see Fig. 1) are: 1.6 cell rf gun operated at S-band with a peak field on the cathode of 120 MV/m followed by an emittance compensating solenoid and three accelerating cavities 3 m long of the SLAC type (2856 MHz traveling wave), the first one is embedded in a solenoid. The first traveling wave (TW) structure is set at the relative maximum of the normalized emittance oscillation and to the relative minimum of the beam envelope, according to the Ferrario's working point [7]. This position is at 1.5 m from cathode for the nominal SPARC parameters.

The photocathode of the rf electron gun is illuminated by a Ti:Sa laser providing, in the standard operation, 10 ps long rectangular (1 ps rise time) light pulses at 266 nm (third harmonic) delivering about 500 μJ energy per pulse. Electrons emitted by cathode are accelerated in the gun. Then, they drift within a focusing magnetic field for about 1.5 m and afterwards, they enter the three accelerating sections.

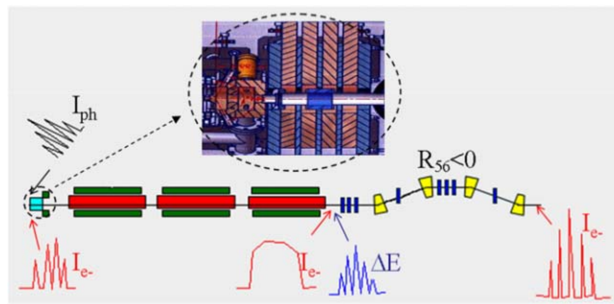


Figure 1: Experimental scheme. In the dotted circle the exploded view of the rf gun and compensating solenoid.

In this paper we study the effect of a train modulation of the 10 ps laser pulse. A train of sinusoidal oscillations modulated by a Gaussian can be created splitting the laser pulse at the exit of the third-harmonic crystal, introducing a proper time delay between the two splitted beams and then recombining them. Afterwards, the two beams have to be extended by a stretcher that brings the spectrum in time again. The two beams interfere generating a train.

The generation of a train with pulses of non-sinusoidal shape, for instance much thinner peaks (as discussed below), requires a shaping system inserted just after the amplifier system or inside the amplifier system after the multipass amplifier and before the compressor. The shaping system is a 4-f system, whose core is the liquid-crystal-spatial-light-modulator (LC-SLM) [4].

We will term the train of pulses as *comb beam*.

Table 1: SPARC beam and gun nominal parameters.

L(ps)	10
Q(nC)	1.1
Energy(MeV)	5.6
Projected Emittance(μm)	<2
B_{gun}(T)	0.273
E_{peak}(MV/m)	120
φ_{inj}(deg)	32

COMB E$^-$ BEAM PHYSICS IN AN ACCELERATOR SECTION

The beam and machine parameters used for PARMELA beam dynamics studies are those presented in the

*Work partly supported by Ministero Istruzione Università Ricerca, *Progetti Strategici*, DD 1834, Dec.4, 2002 and European Contract RII3-CT-PHI506395CARE.

introduction. An example of the results of these studies is shown in Fig. 3. We can remark the following:

- the initial electron bunches of equal charge wash out in such a way that the initial 100% intensity modulation is reduced to ~85% at the exit of the rf gun (Fig. 3(b) upper) and to ~25% at the exit of the drift section (Fig. 3(c) upper). The density modulation almost disappears already at the end of the first accelerating structure (Fig. 3(d) upper) and the profile starts to assume a slight pancake shape;
- an energy modulation with the periodicity of the intensity grows until the end of the drift space. Notably, the energy modulation has a saw-tooth fashion;
- the amplitude of the energy modulation ΔE depends both on the number of the e^- beam pulses and on the initial width, as shown in left and right plots of Fig. 2, respectively;
- the beam energy structure does not change so much up to about 40 MeV, but since then it starts to evolve and it results strongly distorted after the whole accelerating section. The density beam profile at the end of the beamline shows the well-known pancake shape.

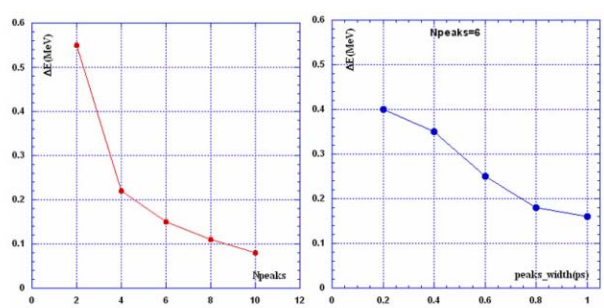


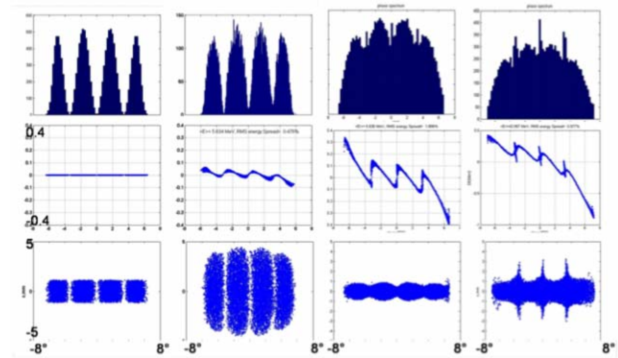
Figure 2: Energy modulation ΔE(MeV) at 1.5 m for a 10 ps comb beam: as a function of the number of sinusoidal peaks (left); and as a function of the FWHM for N_{peaks}=6 (right).

Density modulation is transformed into energy modulation. The periodic beam profile evolves towards a homogeneous one with small undulations and finally the peaks and valleys are interchanged.

The beam dynamics shown by simulations is explained by the action of the longitudinal space charge force. The internal electric field generated at the surfaces of the charge thin disks induces a either positive or negative velocity variation of the electrons, depending on the disk sides. The accelerated particles move through the inter-disk space washing out the longitudinal spatial modulation and, in the meanwhile, changing their energy. The longitudinal space charge force vanishes when particles become ultra-relativistic. In fact, from the simulations it is clear that the intensity and the energy profiles evolve within the gun and within the drift space because the beam energy is relatively low. Once electrons enter the cavities they become very soon ultra relativistic and both the energy and intensity profiles are determined by the rf field only in conjunction with the rf phase.

The very short spikes shown in the intensity profile and in the x-ϕ beam section (column (d) Fig. 3, 4 and 5) are low density regions.

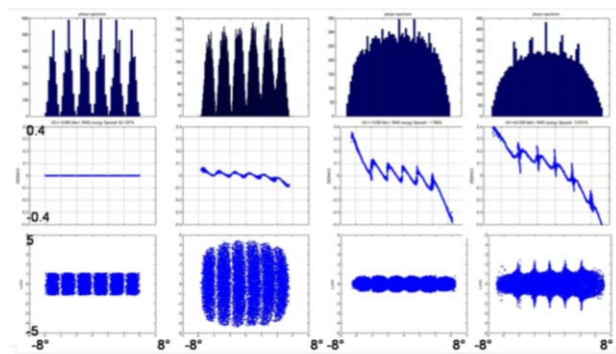
This 'multibunch' beam ends up having a worse projected emittance (up to a factor 3) compared to the well known homogeneous cylindrical e^- beam.



(a) (b) (c) (d)

Figure 3: Evolution of a 10 ps comb beam with 4 bunches at cathode (a); at exit of gun (b); at 1.5 m (c); at z=4.57 m with E=43 MeV(d). Upper: longitudinal profile, middle: ΔE(MeV)-ϕ(°), lower: x(mm)-ϕ(°).

Energy modulation as a function of frequency sinusoidal modulation



(a) (b) (c) (d)

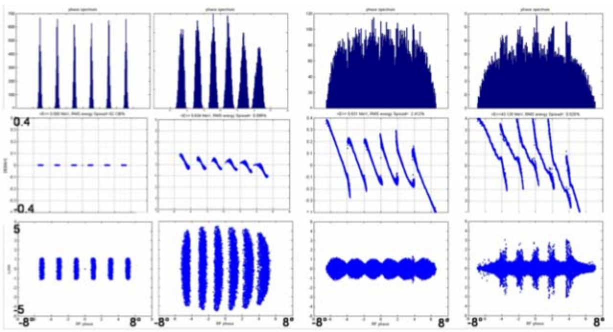
Figure 4: Evolution of a 10 ps comb beam with 6 bunches at cathode (a); at exit of gun (b); at 1.5 m (c); at z=4.57 m with E=43 MeV(d). Upper: longitudinal profile, middle: ΔE(MeV)-ϕ(°), lower: x(mm)-ϕ(°).

The amplitude of the energy modulation for a sinusoidal beam decreases with the number of the peaks. As shown in left of Fig. 2 at z=1.5 m ΔE goes from ~0.22 MeV for a comb beam of 4 sinusoidal peaks to ~0.11 MeV for the 6 case and to ~0.08 MeV for the 10 peaks one. This behaviour complies with the reduction of the charge per disk, in fact: $Q_{disk}=Q_{beam}/N_{peaks}$.

Energy modulation as function of the bunch widths

From Figs. 4 and 5 we may see that the thinner the disks the wider the energy modulation. In Fig. 5 is plotted a comb beam of 6 Gaussians with a FWHM of 0.2 ps, to be compared to the case of Fig. 4 where the 6 sinusoidal peaks have FWHM of 1 ps.

The behaviour complies with the fact that the thinner the charge density the higher is the charge density and, in turn, the surface electric field. In addition, the inter-disk distance increases.



(a) (b) (c) (d)

Figure 5: Evolution of a 10 ps comb beam with N_{peaks}=6 and FWHM=0.2 ps at cathode (a); at exit of gun (b); at 1.5 m (c); at z=4.57 m with E=43 MeV(d). Upper: longitudinal profile, middle: ΔE(MeV)-ϕ(°),lower: x(mm)-ϕ(°).

Comb beam compression

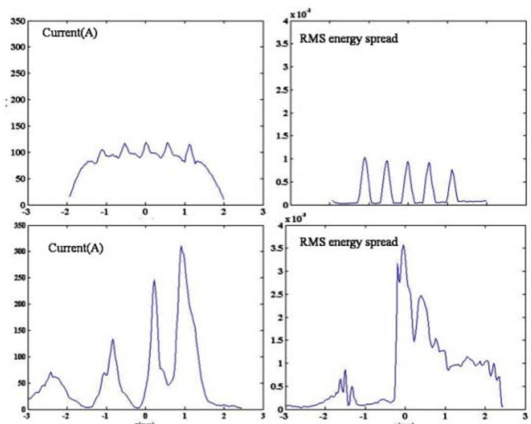


Figure 6: Comb beam before magnetic compression (upper) and after magnetic compression (lower).

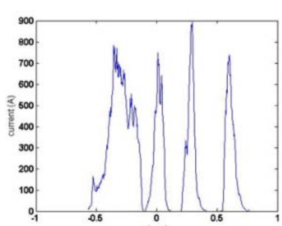


Figure 7: Beam current at the end of three TW structures in the rf compression case. The comb beam at cathode has 6 bunches and FWHM=0.2ps in 10 ps.

The comb beam with 6 bunches and FWHM=0.2 ps has been compressed in order to convert the energy modulation into density modulation. Both techniques of magnetic and rf compression have been analyzed.

A magnetic compressor with R_{56} = -0.1 m after the three TW sections at 155 MeV has been studied. The result of the PARMELA simulation is reported in Fig. 6: at the entrance of the magnetic compressor the density distribution (upper left) has lost almost completely the initial comb shape, which has been converted into energy distribution (upper right); at the compressor exit high peaks current of the order of ~300 A (lower left) are produced.

Rf compression [8] has been achieved with PARMELA simulations accelerating the beam in the first TW section -96º off crest. The beam density at the end of the three accelerating structures is reported in Fig. 7: there are four peaks of current of about 750 A. Moreover, further optimizations of both compression techniques are underway.

DISCUSSION

The space charge force, which is considered a destructive force, in this case is turned into a constructive force.

The intensity and energy evolution of a pulse train created at the photocathode of the SPARC injector is well explained by the action of the longitudinal space charge force connected to the charge of the disks. The density modulation is changed by the space charge force into energy modulation. The higher the charge density the higher is the energy amplitude. The profile evolution stops once the beam becomes almost homogeneous.

The profile of the energy modulation constructed before the rf cavities is completely distorted by the acceleration process. The energy modulation can be usefully exploited to generate a high energy comb beam with very high peak current, re-designing the accelerating sections in such a way that the energy profile is maintained, and then inserting a proper beam compressor. Within the technology of this machine the velocity bunching mechanism seems essential for obtaining good electron bunches in terms of phase space quality.

A comb beam accelerator relies on the capability of the laser which drives the rf gun to provide target light profiles by means of a versatile shaping system inserted in the laser system. We would like to stress that the realization of a laser pulse train in the UV band is a real challenge.

REFERENCES

[1] C. Vaccarezza at al., "Status of the SPARX FEL Project", this Conf.
[2] L. Serafini et al, "The PLASMONX Project for advanced beam physics experiments @ LNF", this Conf.
[3] http://www.linearcollider.org
[4] I. Boscolo, S. Cialdi, F. Castelli, D. Cipriani, Report1-PHIN-CARE-JRA2-WP3, Second Task Pulse Shaping http://www.infn.it/phin/docs_files/19_Deliverable_INFN_Mi.pdf and references therein.
[5] L. Serafini et al, 'Status of the SPARC Project', this Conf.
[6] J.Billen, "PARMELA", LA-UR-96-1835, 1996.
[7] M. Ferrario et al., "Homdyn study for the LCLS Photoinjector", SLAC-PUB-8400, Mar 2000.
[8] M. Ferrario et al. "Beam dynamics study of an RF bunch compressor for High Brightness beam injectors", Proc. of EPAC02, p. 1762, June 2002 Paris.