GENERATION OF A MULTIPULSE COMB BEAM AND A RELATIVE TWIN PULSE FEL

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Abstract

A radiofrequency electron gun driven by a train of laser pulses joined to a compressor generates trains of THz-subpicosecond e- pulses. Assuming a prompt electron emission, the laser train generates a train of electron disks at the cathode, then the disk train evolves towards a slug with a slight density modulation but also with a peculiar sawtooth energy modulation. This kind of energy modulation is transformed into a density modulation by a buncher recovering at a good extent the initial intensity beam profile. The THz electron beam formation and the FEL interaction are studied, from start-to-end, by simulations for the SPARC machine, with two electron pulses generated through that mechanism.

INTRODUCTION

Electron pulse trains of some hundreds pC charge, sub-picosecond length and repetition frequency of some THz can be useful to drive FEL experiments, plasma accelerators and efficient generation of THz radiation [1]. A radio-frequency (rf) electron gun whose photocathode is illuminated by a comb-like laser pulse generates at the cathode subpicosecond high charge disk trains.

It is well known in fact that a disk-like bunch, i.e. a bunch with longitudinal dimension γL (in the bunch moving frame) shorter than its transverse dimension R, corresponding to an aspect ratio: $A=(R/\gamma L)>>1$ has a longitudinal space charge field component linear along the bunch [2,3,4]. The normalized longitudinal space charge field as a function of the aspect ratio A for a uniform charge distribution of length L is given by [5]:

$$E_Z = \sqrt{A^2 + \left(1-\frac{z}{L}\right)^2} - \sqrt{A^2 + \left(\frac{z}{L}\right)^2} \ .$$

During acceleration the bunch aspect ratio scales like $1/\gamma$ while the longitudinal space charge force decreases like $1/\gamma^2$. It results that at the exit of the gun cavity the work done by the longitudinal space charge force along the bunch produces a linear correlation in the longitudinal phase space, if acceleration takes place fast enough to prevent transition at low energy from disk like bunch (A>1) to cigar like bunch (A<1). This is a very attractive feature for a subsequent bunch compression, since the final bunch length after any compressor device is limited by the longitudinal emittance resulting from non-linearities in the accelerating and longitudinal phase space fields. The work done by the space charge force produces an energy modulated electron beam, of about $\Delta E \sim 0.4$ MeV, with a sawtooth profile. Such an energy distribution can be exploited to restore the initial density profile either by means of an rf accelerating structure operating in the velocity bunching mode [6] or by a magnetic compressor [7,8,9] with negative R_{56}.

The amplitude of the energy modulation depends on the number and initial thickness of the electron micro-bunches. Given the charge per macrobunch, the thinner the microbunches the higher the resulting energy spread at the end of the rf-gun and, in turn, the tighter turns the current modulation after a compression. The beam dynamics inside the rf-gun and downstream inside a velocity-buncher is studied by simulations with the PARMELA [10] code and here we present the results relative to six and two microbunches train generation. In the latter case, the twin micropulses electron beam exiting the beamline is then transported and focused into the undulator for the FEL simulation with the GENESIS [11] code. These studies are carried out on the LNF-SPARC machine; the parameter set for the case under discussion is reported in Table 1.

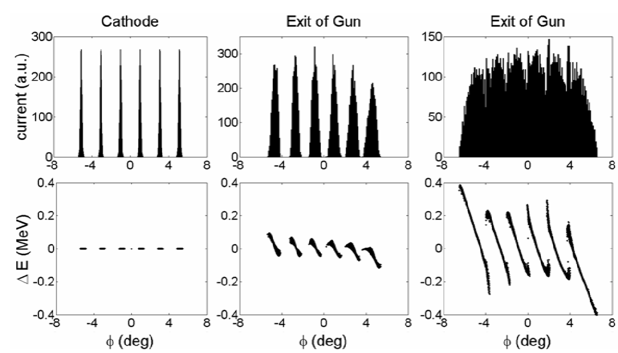

Fig. 1: Evolution of a six bunches train: at cathode, at exit of gun (left and middle plots) and at the entrance of the first linac section at z=1.5 m (right plots). Upper row: longitudinal profile, lower row: ΔE(MeV) versus length .

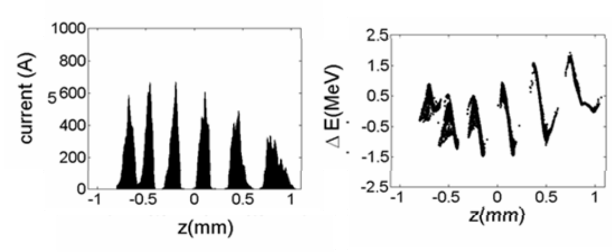

Fig. 2: Beam current and ΔE(MeV) at the end of three TW structures, that is at 12 m far from cathode, as a function of longitudinal coordinate z(mm), left and right plot respectively.

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Table 1. Parameters for the rf-gun (first column), velocity bunching cavity (second column) and two accelerating cavities (third and fourth column) used for the compressed twin pulse simulation in the SPARC accelerator.

	Rf-gun	I TW section	II TW section	III TW section
Gradient [MV/m[	120	25	25	21.3
Energy [MeV]	5.6	16.5	91.2	155.5
Phase ϕ [deg]	32	-93	0 (on crest)	0 (on crest)
Solenoid field [Gauss]	2730	1100	1100	0
length [cm]	15	300	300	300

BEAM SIMULATION RESULTS

We present the dynamics of a possible comb beam generation experiment at the SPARC photoinjector [12], under commissioning at the INFN national laboratories in Frascati. The SPARC photoinjector consists in a 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, the first two embedded in a solenoid field as foreseen for the velocity bunching experiments. The photocathode in 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) and delivering about 500 µJ energy per pulse. Electrons emitted by the cathode are accelerated in the gun up to 5.6 MeV. Then, they drift for about 1.5 m and afterwards they enter the three accelerating sections to reach the final energy of 150 MeV.

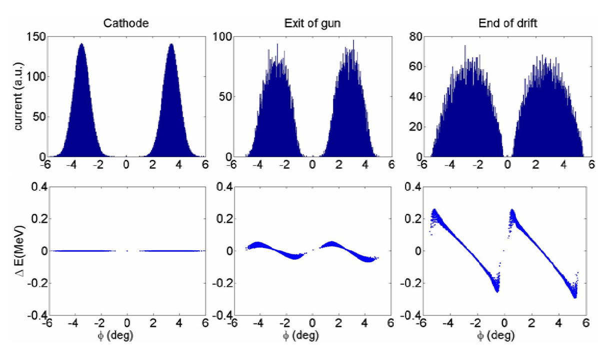

Fig. 3: Evolution of a 10 ps comb beam at cathode, at exit of gun (left and middle plots) and at the entrance of the first linac section at z=1.5 m (right plots). Upper row: longitudinal profile, lower row: ΔE [MeV] versus length.

An example of the results of PARMELA simulations is shown in Fig. 1: the features of initial density washing out and the sawtooth shape of the energy modulation are evident. Fig. 2 shows the restored density beam modulation after passing through a velocity buncher. The beam enters the first TW section at -101° off crest and beam energy at the end of beamline is about 90 MeV; the total charge of the six bunches train is the nominal SPARC bunch charge Q_{tot}= 1.1 nC.

An analogous study for a twin pulse generated at the cathode is shown in Fig. 3; each one of the two Gaussians has a longitudinal sigma of σ_t=0.6 ps and they are far from each other ~2 mm. The radial spot has been decreased accordingly to the charge reduction. In fact, emittance has been optimized at expenses of the two microbunches charge, being the total charge halved with respect to nominal value. Nevertheless, two peaks with current of the order of I_{peak}~400 A are obtained at the end of the three accelerating cavities (as shown in the upper left plot of Fig. 4). The corresponding beam emittance and envelope evolution along the beamline are shown in Fig. 5, in red and blue are shown the rf compressed and uncompressed cases, respectively. The projected rms emittance results $\varepsilon_{x,rms}$=1.4 µm and rms energy spread $(\Delta E/E)_{rms}$=0.14 % without rf compression at 12 m, while $\varepsilon_{x,rms}$=3.3 µm and $(\Delta E/E)_{rms}$=0.3 % with rf compression (with the parameter set reported in table 1).

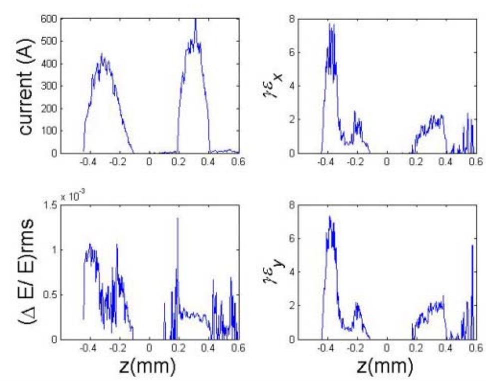

Fig. 4: Beam current (upper left) of a twin compressed pulse beam at the end of three TW structures, rms radial and vertical projected emittance (upper and lower right, respectively) and rms energy spread (lower left).

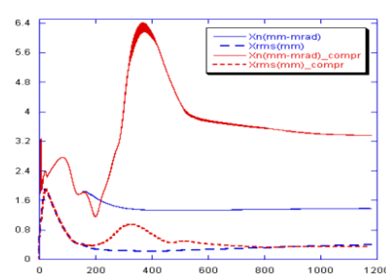

Fig. 5: Evolution of beam emittance (full line) and envelope (dotted line) with rf compression (red) and uncompressed case (blue) for the twin pulse beam case.

This twin pulse beam, exiting the three accelerating cavities with a slice emittance of about $\varepsilon_{slice}\leq 2$ µm and energy spread $(\Delta E/E)_{slice}\leq 0.1\%$ (see Fig. 4), is then focussed and sent though the undulator with the goal of producing two separated but close radiation spikes, useful for pulse-probe experiment.

FEL SIMULATIONS

The FEL radiation emitted by the twin pulse comb beam has been computed by means of the code GENESIS. The undulator parameters assumed in the simulations are the wiggler period λ_w=2.8 cm and the wiggler parameter A_w=1.47, according to the nominal values of the SPARC project.

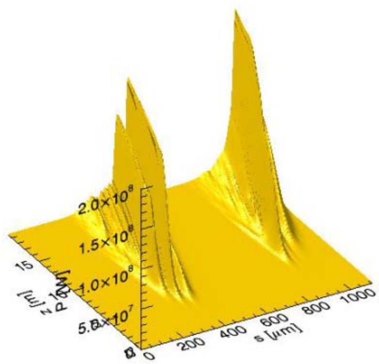

Fig. 6: Radiation power along the undulator (z) and along the bunch (s).

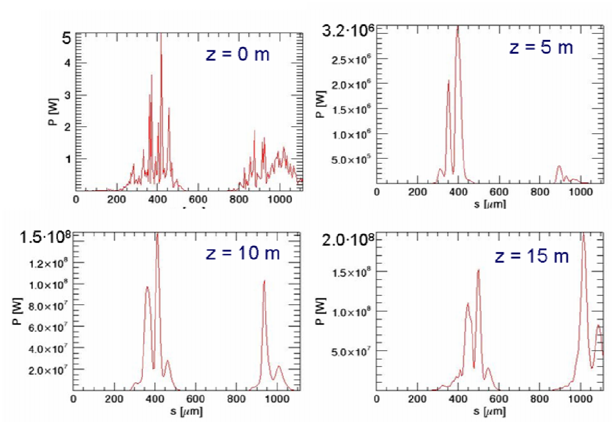

Fig. 7: Radiation power P in Watts versus the coordinate s along the bunch in μm at z=0, 5, 10 and 15 m.

The beam given by PARMELA has been focussed and matched to the undulator, the r.m.s. value of x at the entrance of the undulator being 87 μm. The simulation has been followed up to saturation (wiggler length L_w= 19 m) in the undulator. Fig. 6 shows a plot of the radiation power versus both the coordinate z along the undulator and the coordinate s on the bunch. In Fig. 7 four snapshots of the radiation pulses at z=0, z=5 m, z=10 m and z=15 m are presented. As appears from Fig. 7 the radiation produced by the trailing bunch (the structure on the right of the figures) saturates before 10 m, reaching a power peak value of P_{peak}=1.5 10^8 W, while the leading bunch produces P_{peak}=2 10^8 W in about 14 m.

The radiation wavelength is around 0.48 μm, and the parameter ρ calculated for each single bunch is of the order of $\rho \approx 10^{-2}$. The three dimensional gain length L_g is about 0.35 m. The slippage length is of the order of 100 μm, resulting smaller than the distance between the two peaks of the radiation; hence the two pulses do not overlap. We notice that the two radiation bunches have different values of $<\gamma>$, in fact for the leading bunch it is $<\gamma>$=305.74 while the trailing bunch $<\gamma>$=304.96, so they have two slightly different values of the radiation wavelengths.

CONCLUSIONS

Simulations show that an rf-gun driven by a laser subpicosecond pulse train in connection with a buncher can transform that laser pulse train into a subpicosecond electron beam pulse train. The beam features in terms of peak current, energy spread and emittance are very sensitive to the injection phase into the rf-cavity, to the charge of the macro-pulse and to the compensating solenoidal fields. The injection phase into the velocity buncher cavity has to be around -100° because a phase space rotation of 270° is required in order to obtain the whole compression.

The exploitation of the presented technique for the generation of two high current peaks in SPARC machine has shown that the energy spread and emittance of the two 0.6 ps long electron pulses are good enough for the FEL interaction in the SPARC undulator. The FEL simulation of the twin peaks shows that they do not interfere, thus leading to two neatly separated powerful radiation pulses useful for pump-probe experiments.

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