A POSSIBLE THz RADIATION SOURCE WITH A TRAIN OF SHORT PULSES IN THE SPARC HIGH BRIGHTNESS PHOTOINJECTOR

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Abstract

A radiofrequency electron gun followed by a compressor can generate trains of terahertz sub-picosecond electron pulses by illuminating the photocathode with a comb laser pulse. Any radiation process which does not change the electron distribution can be used to study the coherent spectrum of radiation emitted by a comb electron bunch. The coherent part of the spectrum is strongly enhanced by its N^2 dependence, where N is the number of particles in the bunch, being interesting both as possible source of Far-Infrared Radiation (FIR) and as diagnostic tool of the bunch structure.

A feasibility study for a possible experiment at SPARC to be realized with the addition of a dedicated magnetic chicane is discussed. An optimization study of a magnetic chicane with a negative and variable R_{56} is studied, together with a set of parameters relative to the SPARC machine with the intent of demonstrating the feasibility of this experiment. The dynamics is studied within the SPARC system with the PARMELA code.

INTRODUCTION

Electron pulse trains of some hundreds pC charge, sub-picosecond (sub-ps) length and repetition frequency of some terahertz can be useful to drive FEL experiments, plasma accelerators and efficient generation of terahertz (THz) radiation [1]. A radio-frequency (rf) electron gun whose photocathode is illuminated by a comb-like laser pulse generates at the cathode sub-ps high charge disk trains. The work done by the space charge force produces a negative linear energy chirp that can be exploited to restore the initial density profile either by means of an rf accelerating structure operating in the velocity bunching mode [2] or by a magnetic compressor with negative R_{56} [3,4,5].

The intent of the work is to study both the electron beam dynamics and THz radiation generated by a train of micro-bunches, produced by the comb beam feature through a magnetic compressor. The obtainable radiation power is compared to the one emitted by a single bunch. We present the feasibility study of a THz generation source at the high brightness SPARC [6] photoinjector that could be situated downstream the dogleg and magnetic compressor, as in the layout of Fig. 1.

The dogleg consists of two bending magnets with bend angles of equal magnitude but opposite sign separated by a straight section hosting three quadrupoles. After a straight line with three more quadrupoles necessary for matching conditions there is a magnetic compressor, consisting of four bending magnets and five quadrupoles, necessary for reaching highly negative R_{56} values. Downstream the magnetic compressor THz radiation could be generated as coherent transition radiation (CTR) emitted by the beam crossing a metal foil oriented at 45º incidence and autocorrelated using a Martin-Puplett-type interferometer.

The beam dynamics inside the rf-gun, accelerating cavities and downstream inside a magnetic compressor is studied by simulations with the PARMELA [7] code. We first discuss the results obtained with one short electron bunch and its coherent spectrum of radiation, then a train of two, three and five micro-pulses with an analysis of their coherent radiation spectrum.

SINGLE BUNCH SIMULATIONS

The intensity distribution of the radiation emitted by a bunch with longitudinal profile g(x) is the one emitted by a single electron multiplied by $[N+N(N-1)f(\omega)]$, where N is the number of particles in the bunch and $f(\omega)$ is the form factor, that is a number between 0 and 1 related to the bunch geometry, being defined by

$$f(\omega)=\left|\int_{-\infty}^{\infty} g(x)\cdot e^{-j\frac{\omega}{c}x}dx\right|^2$$

In our case $N\sim10^9$ and the coherent part of the spectrum is strongly enhanced by its N^2 dependence, interesting both as possible source of FIR radiation and as diagnostic tool of the bunch structure. We can assume that the radiation process does not modify the bunch

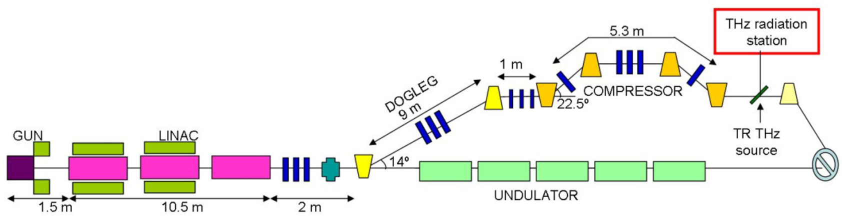

Fig. 1. Cartoon of the SPARC photoinjector with a THz radiation station downstream a dogleg and compressor, where bending and quadrupole magnets are marked by yellow wedges and blue lenses, respectively.

Table 1. Parameters for the rf-gun (first column), and three accelerating cavities (second, third and fourth column) used for comb beam simulation in the SPARC accelerator compressed in a magnetic chicane to be installed after the dogleg.

	Rf-gun	I TW section	II TW section	III TW section
Gradient [MV/m[	120	10	10	6
Energy [MeV]	5.6	35.5	65.6	83.7
Phase ϕ [deg]	32	0 (on crest)	0 (on crest)	0 (on crest)
Solenoid field [Gauss]	2730	400	0	0

case for the chosen process for THz radiation generation, i.e. CTR. The goal was to find an optimized parameter set first for a single bunch and afterwards for a bunch train suitable to produce THz radiation, that is with a spectral content in this range.

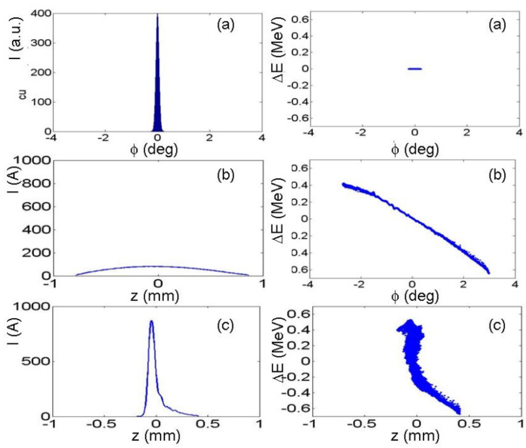

Fig. 2. Bunch (a) at cathode, (b) at exit of linac and (c). at the exit of the compressor. Left and right frames, respectively: longitudinal profile and ΔE(MeV) vs length.

To produce the theoretical curve of the spectrum content of the electron bunch at the TR foil, the creation and transport of the beam in the accelerating sections were first simulated using the tracking code PARMELA. This detailed simulation employed 50000 macroparticles. The beam obtained from PARMELA at the end of the linac was matched with MAD through the transfer line and dogleg up to the compressor entrance. With MAD we also found the right quadrupoles strength values in the chicane for the desired R_{56}, and used these values for tracking the electron beam with PARMELA from the linac exit up to the THz radiation source (see layout of Fig. 1). The longitudinal profile at this position is then used to calculate with a dedicated algorithm its form factor, for the prediction of the expected spectral content of its emitted radiation.

Dedicated simulations have shown that the chosen area of parameters corresponds to a non space charge dominated beam. 3-D space charge effects in the magnetic chicane can therefore be neglected.

The single bunch optimized for our purpose has Q=300 pC, full length at cathode L=200 fs and 1 mm of transverse radius (left (a) plot of Fig. 2). The beam enters the three accelerating sections on crest and beam energy at the end of beamline is about 83.7 MeV. The parameter set for the case under discussion is reported in Table 1. The results of PARMELA simulation are shown in Fig. 2: (b) plots show the beam at the end of the linac with a negative linear chirp of about ΔE~1 MeV induced by the space charge force and (c) plots show the compressed beam at the exit of chicane. The maximum compression, about a factor 7, is obtained with R_{56}=-70 mm and the final bunch has σ_z=55 μm and peak current I_p=800 A. The full evolution of the beam emittance and envelope in the two transverse planes is shown from the cathode to the exit of the compressor in the left and right plots of Fig. 3, respectively. Such short pulse is suitable for THz radiation generation, as appears from the corresponding form factor shown in Fig. 7. However, being the form factor sensitive to the bunch length and charge, the optimal radiated power can be tuned experimentally with careful pulse shaping studies at cathode.

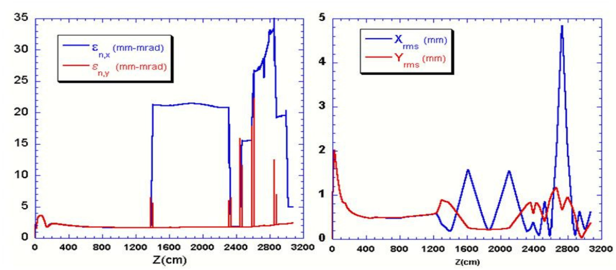

Fig. 3 Left and right frames, respectively show the beam emittance and envelope evolution for the single pulse case from cathode to the magnetic compressor exit

BUNCH TRAIN SIMULATIONS

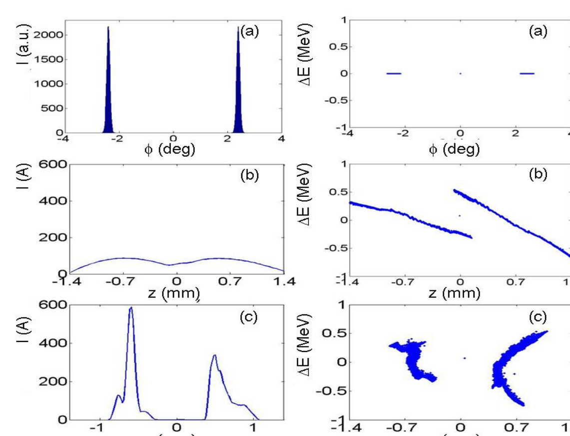

Fig. 4. Two pulses comb beam (a) at cathode; (b) at exit of linac and (c) at the exit of the magnetic compressor (R_{56}=-100 mm). Left and right frames: longitudinal profile and ΔE(MeV) versus length, respectively.

With a train of micro-pulses with a separation of the order of λ or some multiples the form factor approaches 1 at that wavelength. The form factor provides a useful description of the micro-bunches inter-distance, being very sensitive to this parameter. So, in our case, in order to enhance the emitted power of THz radiation, the micro-pulses inter-distance must be a multiple of 300 μm. Unfortunately, the initial micro-bunches inter-distance at cathode is slightly distorted both during acceleration and compression. Consequently, using the comb technique it is not trivial to obtain perfectly equally spaced micro-bunches, parameter that is crucial for the application under discussion. However, the solution can be overcome both experimentally and with simulation by finely tuning the inter-distance of bunches at cathode in order to obtain a form factor as close to 1 as possible at a desired THz frequency. Moreover, also the capability of the magnetic chicane to compress the micro-bunches by the same factor is important to produce a clean spectrum. This parameter could be adjusted at cathode, experimentally, as well.

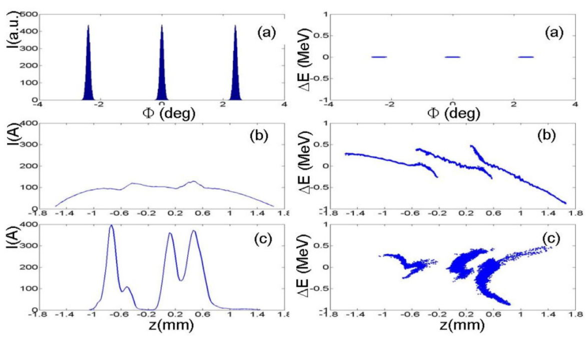

Fig. 5 Three pulses comb beam (a) at cathode; (b) at exit of linac and (c) at the exit of the magnetic compressor (R_{56}=-120 mm). Left and right frames: longitudinal profile and ΔE(MeV) versus length, respectively.

Examples of our studies are shown in Figs. 4, 5 and 6, for the two, three and five micro-bunches train, respectively. The charge for two and three pulses is 300pC/peak and is 120/peak for the five micro-pulses train.

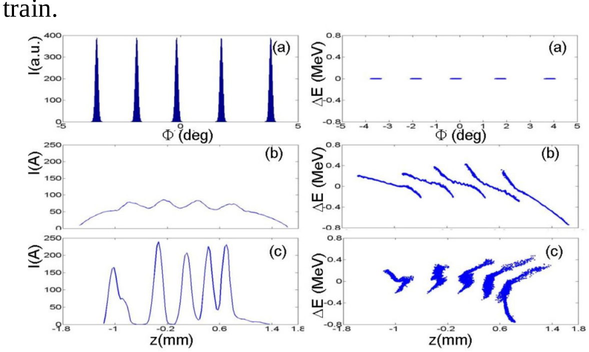

Fig. 6 Five micro-pulses comb beam (a) at cathode; (b) at exit of linac and (c) at the exit of the magnetic compressor (R_{56}=-120 mm). Left and right frames: longitudinal profile and ΔE(MeV) versus length, respectively.

The corresponding form factors are plotted in upper plot of Fig. 7. A realistic comparison of the different structures can be done only taking into account the total number of electrons involved in the process together with the single particle white frequency distribution of Transition Radiation. Lower plot of Fig 7 shows the form factor multiplied by the number of particles N^2 for the different cases of comb beams.

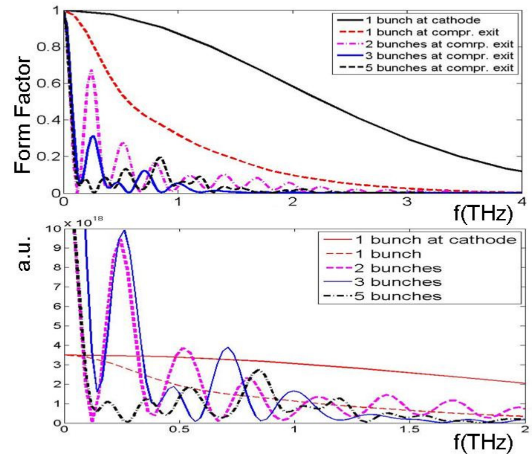

Fig.7 Form factor and (N^2·form factor) by for two (pink), three (blue) and five (black) micro-bunches compared to one bunch.

CONCLUSIONS

Simulations show that an rf-gun driven by a laser sub-ps pulse train in connection with a magnetic compressor can transform that laser pulse train into a sub-ps electron beam pulse train. The beam features in terms of peak current, energy spread and emittance are very sensitive to the charge of the macro-pulse, to the compensating solenoidal fields and to the R_{56} value of the magnetic chicane. In fact, R_{56} has to be around -100 mm to compress the beam using the negative linear chirp induced by the space-charge force.

The exploitation of the presented technique for the generation of THz radiation in SPARC machine has shown the feasibility of this experiment. We showed that the quality of the coherent spectrum emitted by a comb beam is tightly connected to the electron micro-bunches lengths and to micro-pulses inter-distance. To this regard, we think there is still margin of improvement and work is in progress to further optimize all the electron beam parameters to maximize the THz emitted power.

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