IL NUOVO CIMENTO Vol. 37 C, N. 4 Luglio-Agosto 2014
DOI 10.1393/ncc/i2014-11816-1

Communications: SIF Congress 2013

The SPARC_LAB THz source driven by high-brightness electron beams

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ricevuto il 31 Gennaio 2014; approvato l'1 Aprile 2014

Summary. — The THz source produced at the SPARC_LAB test facility is able to deliver radiation pulses with time duration of few hundreds of femtoseconds and energy per pulse larger than 10 micro-Joule, corresponding to electric and magnetic fields of the order of 1 MV/cm and 0.5 T, respectively. The linac-driven THz radiation is produced as coherent radiation emitted by ultra-short high-brightness electron bunches. Depending on the electron bunch shaping, the THz radiation is characterized by a tunable spectral bandwidth suitable for electron beam longitudinal diagnostics, characterization of novel materials, pump-probe experiments.

PACS 41.60.Dk – Transition radiation.
PACS 41.85.Ja – Particle beam transport.
PACS 29.20.Ej – Linear accelerators.
PACS 29.27.Bd – Beam dynamics; collective effects and instabilities.

1. – Introduction

The motivation for developing a linac-based THz source stays in the ever growing interest of filling the so-called THz gap [1] with high peak power radiation sources, *i.e.* of the order of hundreds of MW.

THz radiation is electromagnetic (EM) radiation whose frequency lies between 0.1 e 10 THz, therefore in the region of spectrum between microwaves and infrared (IR). Being in between these two bands, THz radiation shares with them several properties, *e.g.* it is non-ionizing, it is highly penetrating in a large variety of insulating materials, but not in liquids and metals. In addition, the THz part of the spectrum is energetically equivalent to many important physical, chemical and biological processes.

The linac-based THz radiation source developed at the SPARC_LAB test facility [2] opens the possibility to perform experiments in different fields of research [3]. Indeed,

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since THz pulses produced at SPARC_LAB are intense, peak power of the order of 100 MW, and as short as 100 fs, they are suitable for investigating ultra-fast and non-linear phenomena and performing THz pump-THz probe spectroscopy.

In order to be considered a powerful pump source, THz radiation should have energy per pulse higher than few tens of microjoule, pulse duration of sub-ps scale, since an excitation starts to exist after half a cycle ($T \approx 100$ fs–10 ps), tunable frequency, electric and magnetic fields of the order of MV/cm and T, respectively.

Beyond application purposes, coherent THz radiation is also used as powerful longitudinal diagnostic [4] of high-brightness electron beams that drive, for example, Free-Electron Lasers (FELs) [5], plasma-based accelerators [6, 7] and advanced radiation sources [8].

2. – The SPARC_LAB THz radiation source

The SPARC photo-injector delivers high current, low emittance electron beams, which are usually referred as high-brightness beams. Electrons are generated by a UV laser pulse hitting a copper photocathode embedded in the S-band gun. Afterwards, the few MeV electrons enter in the 3 traveling wave (TW) S-band Linac, which boost their energy up to 170 MeV when injected on the crest of the RF field. At the end of the linac a diagnostics and matching section allows to characterize the 6D electron beam phase space and to match the beam to the four beamlines. The diagnostic section consists of two quadrupole triplets, the first one used for emittance measurements, an RF deflecting cavity to measure the longitudinal beam profile and, when combined with the dipole, to measure the longitudianl phase space.

The high-brightness electron beams so produced and characterized serve as active medium in the single pass FEL in different schemes, *e.g.* SASE and SEEDED, serve as source for THz radiation generation, for testing advanced electron beam diagnostics, such as Electro-Optic Sampling and cavity beam position monitors, as source for gamma rays, and for novel acceleration concepts based on laser and electron beam plasma interactions.

The linac-driven THz radiation [9, 10] is produced at the SPARC_LAB through radiative phenomena based on relativistic electron bunches.

Transition (TR) and Diffraction Radiation (DR) can be considered as two aspects of the same phenomenon: when a charged particle crosses the interface between two media with different refraction indexes, TR is emitted both in forward and backward direction; when the emitted radiation is produced by only a part of the particle field, because of a slit cut on the screen, it is called DR, in full correspondence with the wave optics in which only a part of a wave front is allowed to propagate. Depending on the extension of the EM field of the relativistic particle, *i.e.* $\gamma\lambda/2\pi$, with γ the electron Lorentz factor and λ the emitted radiation wavelength, DR is emitted if the slit width is comparable with $\gamma\lambda/2\pi$, while TR is produced in the limit of zero slit width.

Currently, both Coherent Transition Radiation (CTR) and Coherent Diffraction Radiation, from both 3 and 5 mm slit apertures, are generated from ultra-short (sub-ps, down to 100 fs) electron bunches produced and manipulated at the SPARC high-brightness photo-injector.

The technique used at SPARC to manipulate the high-brightness electron beams relies on low energy RF compression (the velocity bunching) [11, 12] and on the use of properly shaped trains of UV laser pulses with THz repetition rate hitting the photo-cathode (comb laser beam) [13]. Each laser pulse produces at the photocathode a disk of electrons with the same time spacing. While the longitudinal density modulation is mixed up at

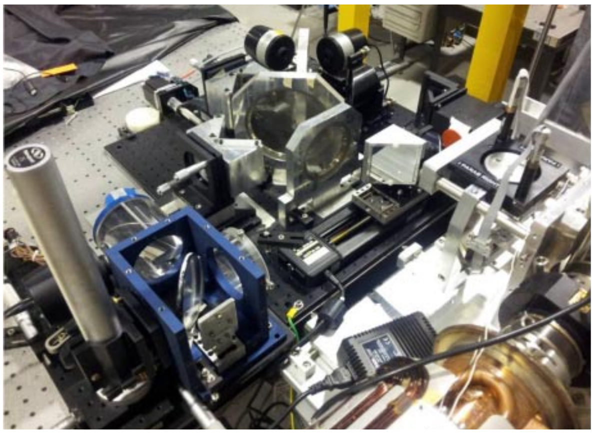

Fig. 1. – Experimental apparatus. The Michelson interferometer is the blue box on the left; the Martin-Puplett interferometer is in the upper center and a Golay cell can be also inserted moving the flat mirror on the left end of the linear stage.

the gun exit due to longitudinal space charge forces, a sawtooth distribution shows up in energy. Therefore, a dispersive system is needed to turn the energy modulation back into a density modulation, thus restoring the original comb-like longitudinal distribution. In the SPARC photo-injector the dispersive system is represented by the first linear accelerating section, operated far from the crest of the RF field, in the so-called velocity bunching regime.

The coherent radiation spectrum, generated by a longitudinally modulated electron beam, is a single line at frequencies corresponding to the comb repetition rate and higher harmonics, whose intensity is the same as all the electrons were confined in the single μ-bunch. The bandwidth narrows with increasing the number of μ-bunches in the train. This technique represents a way to reduce the space-charge force, proportional to Q/γ^2, which limits the charge, *i.e.* the number of electrons, that can be contained in a short bunch.

Taking advantage of advanced electron beam manipulation techniques, well-established at SPARC_LAB [14], both broadband and quasi-narrow band THz radiation is produced.

Two stations at SPARC_LAB are dedicated to THz applications and electron beam longitudinal diagnostics. Both CTR and CDR sources are currently characterized by measuring the radiation spectrum in air both through a set of discrete custom THz filters, placed in front of a Golay cell detector, and an interferometer, either Martin-Puplett, with wire grids to select polarizations, or Michelson, with a 12 μm Mylar beam splitter. Pyrodetectors are used in this case.

A picture of the complete detecting apparatus is shown in fig. 1.

The energy per pulse of the coherent THz radiation as produced by means of an electron beam with 120 MeV energy, 300 pC charge and 160 fs pulse duration is shown in fig. 2 for different slit apertures (CTR corresponds to a closed slit).

A calibrated Golay cell detector, with diamond window, has been used to estimate the energy per pulse of the THz radiation reported in fig. 2. Cut-off frequencies are estimated to be 150 GHz and 5 THz, due to screen finite size, optics acceptance etc. and quartz window transmission, respectively.

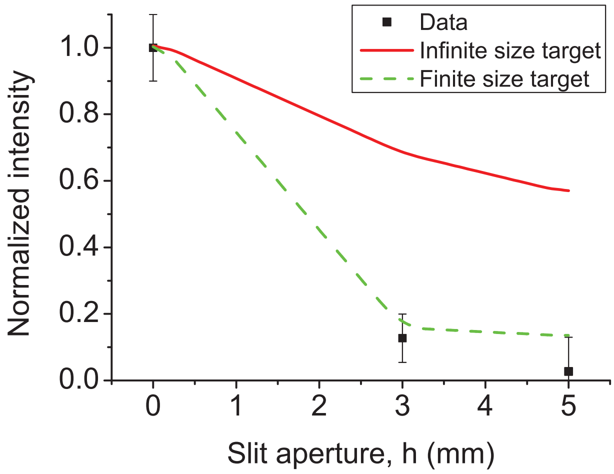

Fig. 2. – Energy per pulse of THz radiation as produced by a 300 pC, 160 fs, 120 MeV electron beam. The plot is function of the slit aperture (0 mm slit aperture correspond to the CTR emission).

From the point of view of narrowband THz emission, the first accelerating section is operated at a compression phase corresponding to the so-called over-compression regime, where the two bunches are well separated in time, *i.e.* at a distance of the order of ps.

Experimentally a beam composed by two Gaussian bunches of duration smaller than 200 fs (FWHM), separated by 4.3 ps, and total charge of 160 pC was extracted from the cathode. In order to select the CTR emission at THz frequencies and enhance its intensity, the pulse inter-distance has been reduced down to 0.8 ps by means of RF compression in velocity bunching. The longitudinal phase space of this working point is shown in fig. 3.

For such a longitudinal distribution, the interferogram is multi-peaked (fig. 4), whose time distance corresponds to the separation of the bunches in the train.

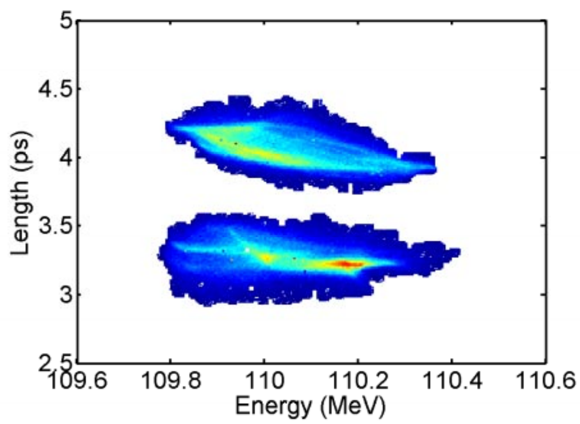

Fig. 3. – Measured longitudinal phase space for a two μ-bunches comb beam, 80 pC/bunch, in the over-compression regime. The bunch inter-distance is 0.8 ps.

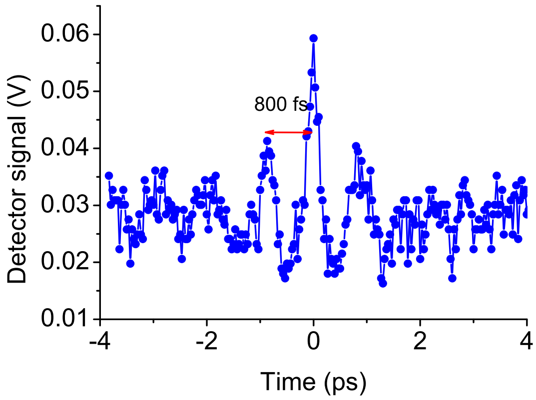

Fig. 4. – Autocorrelation function of the CTR spectrum as generated by a two μ-bunches train. The interferogram is measured by means of a Michelson interferometer.

The retrieved form factor (fig. 5) is then peaked at the comb repetition frequency, *i.e.* 1.2 THz, whose bandwidth depends on both the modulation of the bunches in the train and their length. In the case shown in fig. 5, the large bandwidth depends on the multi-shot nature of the technique.

The advanced THz radiation, produced at the SPARC_LAB test facility, is characterized by 100 fs duration pulses, few hundreds of MW peak power, several tens of micro-Joule energy per pulse, broad and narrow bandwidth. Beyond the use of THz radiation for electron beam longitudinal diagnostics, all the features mentioned make the SPARC_LAB THz radiation strongly competitive with respect to conventional THz sources and extremely suitable for investigating non-linear THz spectroscopy and for testing novel detectors and materials.

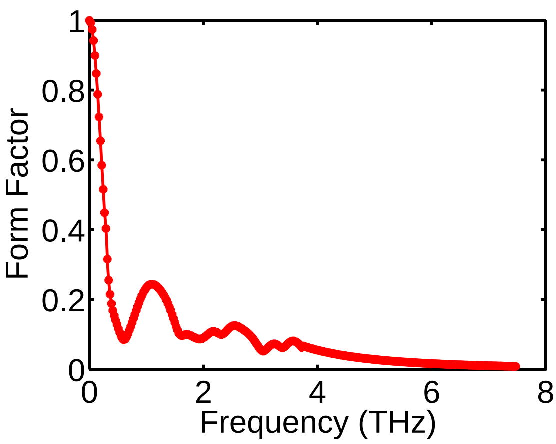

Fig. 5. – Retrieved form factor, peaked at the comb repetition frequency, *i.e.* 1.2 THz.

3. – Conclusions

Coherent THz radiation is currently produced and optimized at SPARC_LAB through ultra-short relativistic electron bunches as both transition and diffraction radiation. Different THz emission regimes, both broad band and narrow band, have been achieved by properly control electron beam shaping, length and charge, therefore by properly set the photo-injector parameters.

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The author would like to thank all the people which contributed to this work, in particular the whole SPARC team and the TeraLab group (Phys. Dept., University of Rome La Sapienza). This work has been partially supported by the EU Commission in the Seventh Framework Program, Grant Agreement 312453 - EuCARD-2, Contract n.283745-CRISP and by the Italian Ministry of Research in the framework of FIRB-Fondo per gli Investimenti della Ricerca di Base, Project no.RBFR12NK5K.

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