CHARACTERIZATION OF THE THz SOURCE AT SPARC

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Abstract

The region of the spectrum from 0.1 to 10 THz is of great interest for several experiments in different areas of research. A THz radiation source can be produced at SPARC as coherent transition radiation emitted by both a compressed and longitudinally modulated beam intercepting a metal foil placed at 45^o with respect to the beam propagation. The status of the THz source at SPARC and results on its characterization are described in the paper.

INTRODUCTION

In the last decade, big efforts have been done in exploiting radiation in the so-called THz gap. This spectral interval, which is roughly located between the microwave and the far infrared region (0.1-10 THz), has been poorly investigated so far mainly because of the lack of intense and stable radiation sources.

A linac-driven THz radiation source can be produced at SPARC as Coherent Transition Radiation (CTR) emitted by both an ultra-short high-brightness electron beam (HBEB) and a longitudinally modulated one [1], [2].

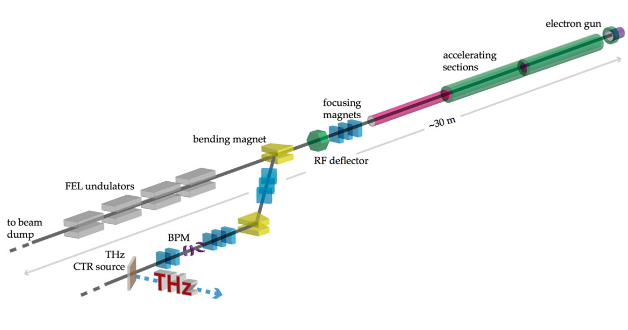

Figure 1: Layout of the SPARC accelerator.

THEORETICAL BACKGROUND

THz radiation from CTR is generated when a bunch of relativistic electrons travels through a vacuum-metal interface. Each electron in the bunch emits radiation, whose spectrum depends on the bunch longitudinal dimension through the form factor $F(\lambda)$ [3], defined as the Fourier transform of the bunch longitudinal profile, λ being the emitted wavelength. Indeed, the total radiation intensity, $I(\lambda) = I_{sp}[N + N(N-1)F(\lambda)]$, with I_{sp} the single particle radiation intensity (e.g. transition radiation, synchrotron radiation,...), is dominated by incoherent emission, proportional to the number of particles in the bunch, N, in case of bunch length larger than the emitted wavelength. In case of short bunches, the emission of radiation is coherent, and proportional to N^2, at wavelengths of the order, or longer than the bunch length, thus the shorter the bunch length the higher and the more broadband the spectrum is.

The velocity bunching technique, based on the longitudinal phase space rotation due to a correlated time-velocity chirp in the electron bunch, can be used to compress the bunch down to sub-ps duration using rectilinear trajectories at relatively low energy [4], [5].

High power, narrow-band, i.e. monochromatic, THz radiation can be also generated by means of a longitudinally modulated beam, the so-called comb beam [1], [2], [6]. A comb beam is a train of n electron sub-ps, hundreds of pC bunches, obtained by illuminating the photocathode with a train of very short laser pulses with THz repetition rate. Assuming a prompt emission at the photocathode, each laser pulse will produce a disk of electrons which, modulated by the longitudinal space charge forces, will show a sawtooth energy distribution along the propagation direction. In presence of a dispersive system, the energy modulation will turn back into a density modulation, thus restoring the comb-like longitudinal distribution presented at the photocathode. If such a beam impinges on a transition radiation (TR) screen, CTR emission at the THz frequencies is observed at SPARC. The longitudinal form factor of such a distribution, for n μ-pulses equally spaced, is a single line at the comb repetition rate, whose intensity is the same as all the electrons are confined in the single μ-bunch, the spectrum being strongly suppressed outside the comb repetition frequency.

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EXPERIMENTAL APPARATUS

The THz radiation detection set-up is shown in Fig. 2. CTR is generated at the interface between the vacuum and an Aluminated Silicon screen placed at 45^o with respect to the beam axis. The backward CTR radiation, reflected normally to the beam direction, is extracted from the vacuum pipe through a z-cut quartz window and collected by means of two 90^o off-axis parabolic mirrors in order to be focused onto the THz detector. Either pyroelectric or Golay cell detectors can be used, in an operating spectral range of 0.1 - 3 THz and 0.04 - 10 THz, respectively. Cut-off frequencies are estimated to be about 150 GHz and 5 THz, due to screen finite size, optics acceptance, etc. and quartz window transmission, respectively. Three remotely controlled linear stages can adjust the position of detector along the x, y and z axes, thus allowing mapping of the detector area (x, y) and optimization of the longitudinal position (z) with respect to the focal plane.

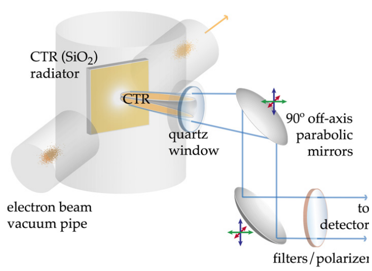


Figure 2: Drawing of the THz source set-up.

In order to fully characterize the THz spectrum several band-pass filters with characteristic frequency of 0.38 - 1.5 - 2.5 - 3.4 - 4.3 - 4.8 THz [7], can be inserted between the THz source and the detector. In addition a wire grid polarizer can be also used to select the polarization.

RESULTS

The SPARC THz source has been characterized under different beam conditions, e.g. different beam charge, RF compression factors and laser pulse shapes, in order to exploit a wider range of coherent emission regimes. In all the cases the beam energy was around 100 MeV.

During the first run the high charge regime (500 pC) has been investigated to underline the importance of the beam longitudinal compression to both extend the frequency range and gain the intensity of THz radiation generated by CTR. By comparing in Fig. 3 the THz radiation signal, as detected by a pyrodetector, we can estimate a gain of a factor of 25 when a 2 ps beam was compressed by a factor 4 down to 500 fs; the effect of a shorter pulse duration is even more evident in the peak power and energy. The peak of the blue curve corresponds to an average power of 120 μW.

Shot-to-shot electron beam fluctuations affecting the THz pulse stability have been investigated, being of around 10%, and mostly due to charge, i.e. number of electrons, instability.

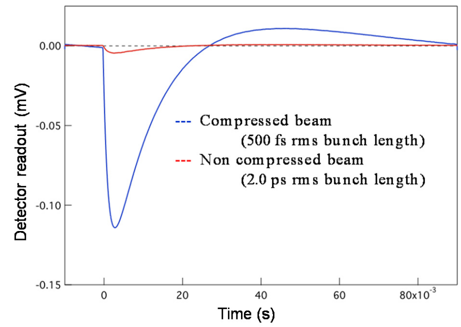


Figure 3: Pyrodetector readout corresponding to the THz radiation emission in case of 2 ps RMS (red curve) and 500 fs RMS (blue curve) pulse duration with 500 pC charge.

High Peak Power THz Source with HBEBs

A detailed study of the CTR spectral emission has been performed under velocity bunching regime with a beam compressed down to a factor of 14 (260 fs RMS duration length after compression) and emittance compensated. Figure 4 reports the CTR average power as function of the frequencies selected by the band-pass filters used [7], showing the extension of the CTR spectrum to frequencies as high as 5 THz.

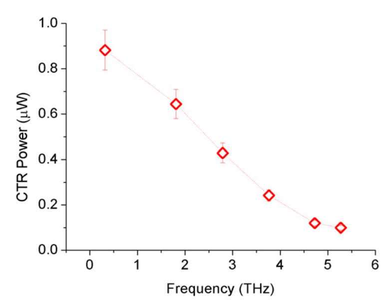


Figure 4: CTR average power measured with a Golay cell detector at SPARC in case of a 260 fs bunch (260 pC).

Since intensity and extension to higher frequency is limited by the quartz window transmission, we planned to replace it with a diamond window. It would allow extending up to 10 THz the achievable frequency range, paving the way to a wide panorama of applications.

Readout signals from detector (both the pyroelectric and the Golay cell) allowed estimating the peak power for the THz source. These data are represented in the cartoons of Fig. 5 (solid symbols) superimposed to the expected values from simulations. The same figures of merit for the existing THz sources are also reported, together with the expected performance for the future SPARX [8] and FERMI [9] sources.

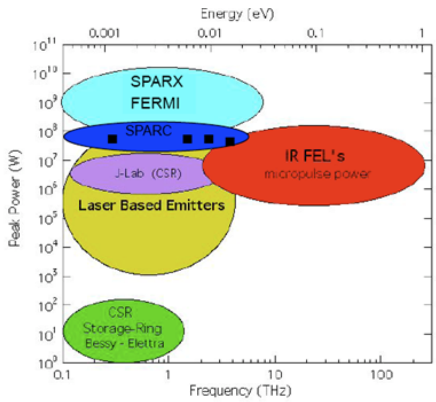
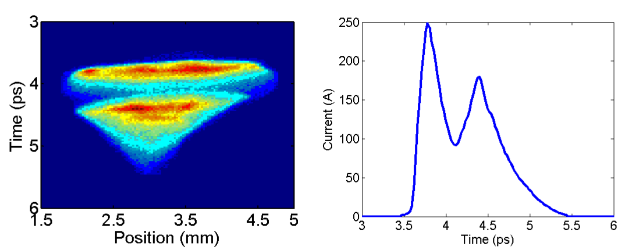


Figure 5: Figure of merit for existing THz sources compared to simulation and data (black squares) measured at SPARC.

Narrow-band THz Source with a Comb Beam

First measurements dedicated to the production and optimization of electron pulse trains for THz radiation generation have been performed [6], [10] for n=2.

We have been operating with two Gaussian longitudinal profiles, 0.18 ps rms long and separated by 4.3 ps. The total extracted charge was 180 pC. In order to select the CTR emission at the THz frequency and enhance its intensity, the pulse inter-distance has been reduced and the pulse profile shrunk by RF compression, i.e. velocity bunching regime. Although the two pulses are not clearly separated, the desired comb distance of 0.7 ps (Fig. 6) has been obtained, operating with the injection phase of the first accelerating section at -99^o from the on-crest acceleration (overcompression regime).

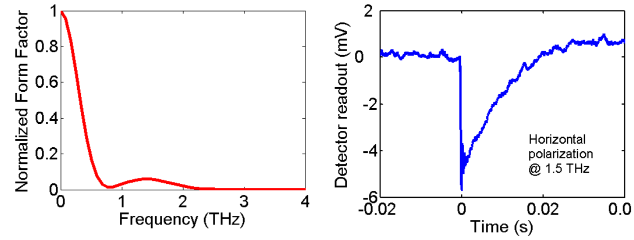


(a) (b)

Figure 6: Comb image (a) and temporal profile (b) obtained by streaking the beam by means of the RF deflector.

The form factor of such a distribution is represented in Fig. 7a), showing a slight modulation centered at the comb frequency, i.e. 1.5 THz, which is expected to be enhanced in case of clearly separated pulses. The CTR average power for the horizontal polarization component and at the comb frequency has been measured at SPARC by means of a Golay cell detector and shown in Fig. 7b). A band pass filter with central frequency at 1.5 THz and a wire grid polarizer to select the desired polarization have been used.

Further measurements are foreseen in order to better



(a) (b)

Figure 7: Form factor of the two pulses electron train (a) and detector readout (b) for the horizontal component of the THz radiation field at the comb frequency. The peak of the curve corresponds to an average power of 0.5 μW. The decay time is characteristic of the Golay cell detector.

control pulses inter-distance and duration length to select both comb frequency and emission intensity.

CONCLUSIONS

A linac-driven high intensity THz radiation source is under characterization at SPARC taking advantage of the high brightness electron beams. Both standard, i.e. ultra-short beams, and novel schemes, i.e. comb beams, can be used to generate respectively high power broadband or monochromatic and tunable THz radiation which is interesting for several applications.

Experimental results confirm the very good performances of the SPARC THz source as compared to worldwide existing sources, like the coherent synchrotron radiation emitted at the 3rd generation light sources, as well as those at dedicated FELs and energy recovery linac. More remarkable is the gain of about two orders of magnitude with respect to laser based table-top emitters. In particular, the Peak Power measured values suggest the possibility of performing pump-probe THz spectroscopy.

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