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DETECTION OF THE SR INFRARED EMISSION OF THE ELECTRON BUNCHES AT DAΦNE

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Abstract

The synchrotron light emission is a radiation source covering a large energy domain from IR to x-ray energies, with an accurate sub-nanosecond time structure determined by the temporal and the physical structure of the stored electron bunches. With proper detectors, the synchrotron radiation emission can be used to perform spectroscopic experiments with very high time and spatial resolution but also to investigate the physical structure of the bunches. We present here the first characterization of the synchrotron light emission of DAΦNE in the midIR domain with a resolution time of few ns. Experiments have been performed using the SINBAD beamline, characterizing the emission of 105 bunches stored in the electron ring of the DAΦNE collider. With a small uncooled infrared detector optimized to work at a wavelength of 10.6 μm we observed the gap between individual bunches separated by about 8 ns, a time equivalent to a frequency of 125 MHz.

INTRODUCTION

In recent years both technological advances in the development of infrared detectors and their declassification for civil use made available to scientists new powerful systems for many industrial and scientific applications. Nowadays, many research areas: Astronomy, Biology, Geology, Space Applications etc., need these devices to perform many fundamental experiments unrealistic with the previous infrared technology [1)].

Infrared detectors are sensitive to a large wavelength range: from approximately 1 μm to about 1000 μm, a region that is divided in four main energy domains: nIR (1 – 5 μm), midIR (5 – 20 μm), farIR (20 – 200 μm) and sub-millimeter and millimiter wavelengths (200 – 1000 μm). Infrared detectors are classified as quantum and thermal detectors: the quantum detectors can detect single photons and can be realized with intrinsic or extrinsic semiconductors with variable band gap to select the cut-off wavelengths and the band of detection. They utilize photoconductor or photovoltaic effect inside the semiconductor to detect IR photons. Thermal detectors can detect also photons with very low energy from UV (0.1μm) up to extreme IR (1000 μm). These latter are i.e. bolometers that consist of an absorber and a semiconductor or superconductor thermometer. One of the main characteristics of infrared detectors is their operation at cryogenic temperatures (i.e., 4.2 K or 77 K) that depend on the cut-off wavelength of the detector, in order to suppress the thermal generation noise that limits performances and to achieve the highest allowed sensitivity. Recently new technological capabilities allowed the development of infrared detectors working at room temperature, optimized to detect nIR and midIR wavelengths [2)]. These uncooled detectors may efficiently work with brilliant sources as quantum cascade lasers or synchrotron light source (SR) such as SR dedicated machines or colliders like DAΦNE.

The DAΦNE (Double Annular Φ-factory for Nice Experiments) Φ-factory is an e^+/e^- collider, with center of mass energy 1.02 GeV that has been designed to run high-energy physics experiments at the Laboratori Nazionali di Frascati (LNF) of the INFN [3)]. Owing to the high current for each of 120 storable bunches (i.e. ~20 mA), this collider is characterized by a high accumulated current (> 2 A). Presently, DAΦNE operates by filling 105 consecutive buckets out of the available 120, with a gap of 15 bunches to avoid ion trapping in the electron beam. In this configuration, the minimum bunch distance is 2.7 ns and the maximum single-bunch current is ~20 mA. The emitted light has a pulsed structure: each single electron beam emits a pulse of radiation and the time structure of the emission depends on the bunch filling scheme which modulates the gap between two consecutive bunches; each bunch has a quasi-Gaussian shape and its length is in the range 100 - 300 ps FWHM.

SINBAD (Synchrotron Infrared Beamline At DAΦNE), a beam line dedicated to the IRSR (InfraRed Synchrotron Radiation), has been operating at DAΦNE since 2001[4)]. SINBAD collects the radiation emitted by one of the DAΦNE bending magnets at wavelengths from about 10 to 10000 cm^{-1} (1-100 μm). At the end of the beamline, a microscope and a Rock-solid^{PM} interferometer, working in a customized vacuum chamber, have been available since autumn 2002 for spectroscopy and micro-spectroscopy experiments.

As discussed above, the IR range is a very large energy domain and different detectors are used to cover the nIR, midIR and farIR. Typically, nIR and midIR interferometers are

equipped with single element cooled HgCdTe or InSb detectors. However, the continuous advances in infrared detectors manufacturing, pushed by military applications, have recently made new infrared array detectors available to scientific applications, allowing very high spatial resolution at fast rate. Actually, they allow the acquisition of many spectra with a single exposition of hundreds or thousands of pixels reducing the acquisition time with respect to that required by a single element detector [5]. However, the time resolution of these detectors is still low (~ 1 ms) considering the dynamics of many physical systems so that, the availability of fast infrared detectors with ns or sub-ns response time and with faster readout time (i.e. ~μs) is strategic for spectroscopic applications. Time-resolved experiments carried out using FTIR (Fourier Transform Infrared) interferometers allow to study the rich molecular structure in the midIR spectra and the fast time scale of vibrational motions with the use of Rapid and ultrarapid Scan ($1 - 10^{-3}$ s) or Step Scan methods ($1 - 10^{-9}$ s). These tools can probe and characterize protein folding, photo-cycles, reaction kinematics, excited electronic-state, electronic structures, as well as many dynamic chemical phenomena[6].

The pulsed structure of synchrotron radiation allows in principle to perform time-resolved experiments in the midIR with resolution smaller than μs down to ps. The actual limit is the insufficient detectivity of currently available fast IR detector. These detectors should be also used to monitor light emission of storage ring bunches, an application that typically requires time resolution in the ns range. A single element or – even better – an array of a few elements sensitive to midIR and characterized by a ns time resolution is apparently the most appropriate device to monitor the source stability and the bunch dynamics.

2 THE INFRARED EMISSION OF THE DAΦNE ELECTRON BUNCHES

We present the first experiments carried out to resolve the time structure of the IRSR emission at DAΦNE with a maximum bunch frequency of about 125 MHz. Data have been collected measuring the IR emission of 105 bunches at the end of the SINBAD beamline, using a single element uncooled detector manufactured by VIGO System. This photovoltaic detector [7] – series *PVMI-10.6* – (photovoltaic multiple junction detectors optically immersed) – is operated at room temperature and characterized by a ns response time in the 8 to 12 μm range with optimized sensitivity at 10.6 μm. Its multiple heterojunction photovoltaic structure is constituted by a variable gap (Hg,Cd,Zn)Te semiconductor optically immersed in a high refractive index GaAs (or CdZnTe) hyperhemispherical or hemispherical lens. The specifications of the detector are summarized in Tab. 1 and its spectral response, as available from the data sheet, is reported in Fig. 1. The main advantage of this fast detector is the capability to operate at room temperature that contributes also to reduce the overall size of the device because of unneeded cooling systems. The main drawback being the Detectivity[1] may be reduced typically by two orders of magnitude or more with respect to standard cooled

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[1] D^* is the normalized detectivity definited as $D^* = \sqrt{\frac{A_d \cdot \Delta f}{NEP}}$, where A_d is the optically active detector area, Δf the Noise-equivalent electrical bandwidth and NEP the noise-equivalent power. D^* can be interpreted as the S/N ratio out of a detector when 1W of radiant power is incident on the detector, given an area to 1 cm^2 and noise-equivalent bandwidth of 1 Hz. The units of D* are defined as [cm $Hz^{1/2}$ W^{-1}] [Jones].

HgCdTe photodiodes taking into account its generation-recombination noise at room temperature [8].

The experimental setup used to monitor the DAΦNE emission is briefly described below. The 1 mm^2 *VIGO – PVMI-10.6* detector was placed at the focus of the last toroidal mirror of the SINBAD beamline after the diamond window separating the high vacuum inside the beamline from the interferometer station working at higher or atmospheric pressure. The SINBAD optical system demagnifies the source image by a factor 2.3 at the final focus and its size is about 1×2 mm at midIR wavelengths [9]. The IR detector output voltage was amplified by a Mini-Circuits ZFL500 linear amplifier with an input impedance of 50 Ω, bandwidth of 0.05 - 500 MHz, Voltage gain (A_v) of 20 db, Noise-Figure (NF) of 5.3 dB. The amplified signal was analyzed by an oscilloscope, model LeCroy WaveSurfer 454 with an acquisition time of 2 Gsamples/s and a bandwidth of 500 MHz. The electrical connection between the detector, the preamplifier and the scope was realized by double shielded RG223 cable with a BNC connector interface. The use of RG223 cables has been necessary for eliminating an extraneous signal, a high frequency background signal noise instead detected with single-shield RG58.

TAB. 1: Technical characteristics of the IR detector [7].

Detector Type	*VIGO – PVMI-10.6*
Working Temperature	300 K
Responsivity (@10.6 μm)	0.27 V W^{-1}
Noise Density	1.3 nV $Hz^{-1/2}$
Detectivity	$(2.1 \pm 0.4)\cdot 10^7$ $W^{-1}cm\ Hz^{1/2}$
Detector Resistence	105 Ω
Response Time	≤1 ns
Optical Area	1 mm × 1 mm
Bandwidth	DC to VHF

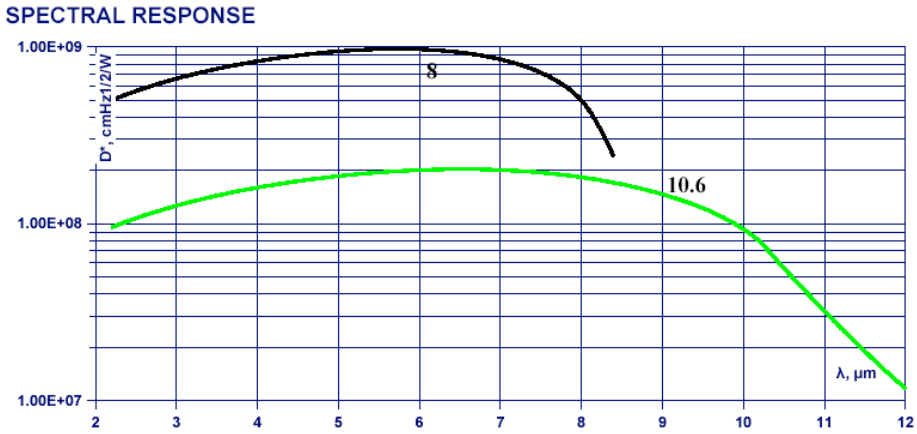

FIG. 1: Spectral response of the *PVMI-10.6* detector optimized at 10.6 μm (green line) [7].

This experimental setup was used to collect firstly a series of data during the normal operation of DAΦNE and later the specific structure of the electron bunches. In the standard configuration, DAΦNE is operated with a structure of 105 electron bunches equally spaced and a gap of 15 bunches. The radio-frequency (RF) system of each DAΦNE ring consists of a normal conducting single cell cavity running at 368 MHz on the 120th harmonic of the revolution period. Therefore, the gap between two bunches is ~2.7 ns. The IRSR emission of the electron bunches during standard operation is shown in Fig. 2.

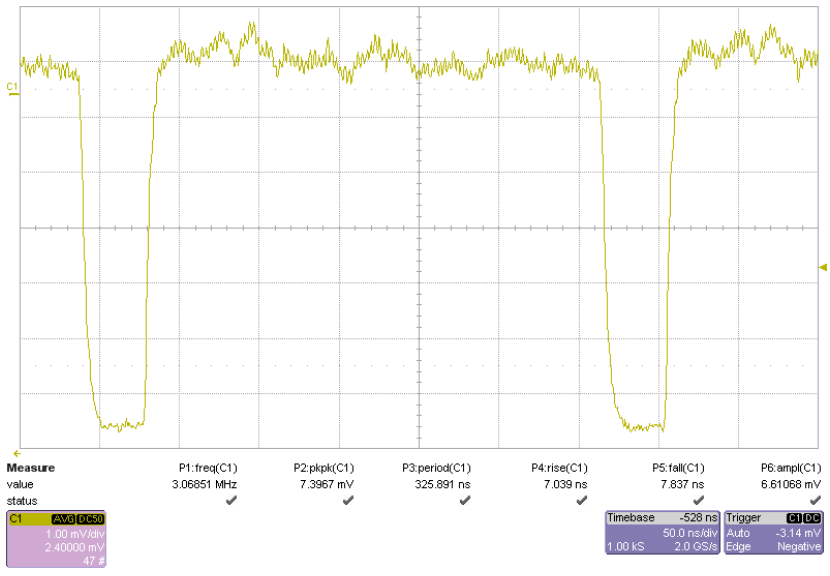

FIG. 2: The signal corresponding to the radiation emitted by 105 electron bunches of the total 120 buckets of DAΦNE measured by the amplified VIGO IR detector.

As reported in Fig. 2, the output voltage of the IR detector amplified by a 20 dB voltage amplifier exhibits amplitude of ~6.5 mV with an average stored electron current of ~1 A. The signal duration is about 285 ns that correspond exactly to the emission length of 105 bunches, while the time gap is about 40 ns, just the length of 15 equivalent bunches. The time scale of the signal in Fig. 2 is 325 ns, i.e., the frequency of 3.07 MHz corresponding to 120 bunches. Fig. 2 shows also a background, mainly in the part of the signal with the buckets carrying current, while for the empty buckets, the signal does not seem to show this noise.

Fig. 2 clearly highlights that the VIGO IR detector is not able to resolve the emission of bunches separated by 2.7 ns, but it measures only an average signal of the light emission of the electron bunches.

In order to test the detector speed and trying to distinguish the emission of a single bunch, a particular bunch structure was selected and stored in DAΦNE. This structure is shown in Fig. 3 for the second set of measurements. Each box in the table stands for an electron bunch (1 to 120); the red boxes allow the bunch injection (and the storing) of the selected structure, while the white boxes correspond to empty bunch positions. Selecting in this way the electron bunch configuration to be filled, it is possible to investigate different bunch gaps and also to resolve the emission of a single bunch investigating the time response of the detector.

Fig. 4 shows the IR signal measured by the detector. The overall structure of the IR emission is well resolved according to the bunch scheme described in Fig. 3.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120

FIG. 3: Configuration of the DAΦNE bunches selected to characterize the detector speed attempting to resolve the IR emission of a single electron bunch.

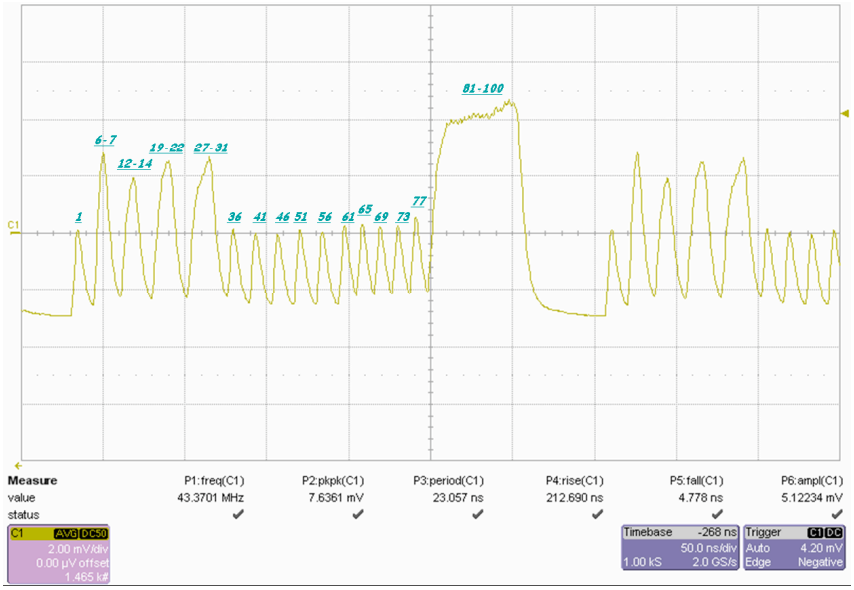

FIG. 4: IR signal of the DAΦNE bunches described in Fig. 3.

Each electron bunch was filled with a current of about 10 mA providing a stored current total value of 415 mA. As shown in Fig. 4, the signal related to the emission of a single bunch is lower by a factor of 2 or more than the signal corresponding to the emission of more than 2 consecutive bunches separated by 2.7 ns. This is apparently due to the detector time resolution that is not able to discriminate each emission peak of two bunches separated by 2.7 ns, providing only the average signal. The IR detector allows to separate the emission of individual bunches only when the gap is equivalent to – or more than – the length of 3 bunches (all bunches from 31 to 81 in Fig. 3), that is 10.8 ns or 13.5 ns.

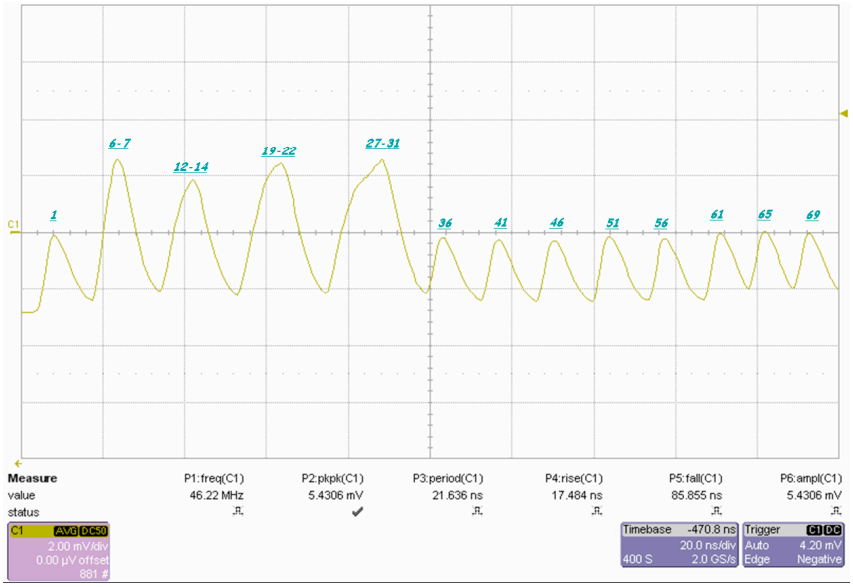

FIG. 5: An enlarged view of the IR emission related to the bunch structure described in Fig. 3.

The separation of the electron bunch emission is more evident in Fig. 5 where the bunch structure is shown in a wider time scale, up to the bunch number 69. The gap between the emission of stored electron bunches ranging from 36 to 61 is ~13 ns while that of those ranging from 61 to 69 is ~10 ns, as expected by the adopted bunch scheme.

Data clearly indicate that the frequency response of the VIGO detector is RF/4 that is equivalent to a frequency of 92 MHz in full agreement with the specifications of the detector (see Tab.1). In a second test, using the same optical configuration, we have been able to measure also the IRSR emission of two bunches separated by a gap of 8.1 ns equivalent to only two bunches gap. The observed signal is shown in Fig. 6 where the gap between the emission of the bunch number 101 and that of the number 104 is clearly recognized.

In another experiment not reported here, we attempted without success to detect the emission of two bunches separated by smaller gap – up to 5.4 ns – that is equivalent to a separation time of one single bunch gap. Summarizing the results, the maximum frequency response ν_m of the PVMI-10.6 VIGO detector is estimated between RF/3 and RF/2:

$$125 \text{ MHz} < \nu_m < 184 \text{ MHz}$$

In fact, looking at Tab. 1 the VIGO detector is characterized by a response time $\tau \leq 1$ns that, considering the definition of bandwidth BW:

$$BW = \frac{1}{2\pi \cdot \tau} \qquad (1)$$

that corresponds to a value of 159 MHz, in agreement with the value estimated by this experiment.

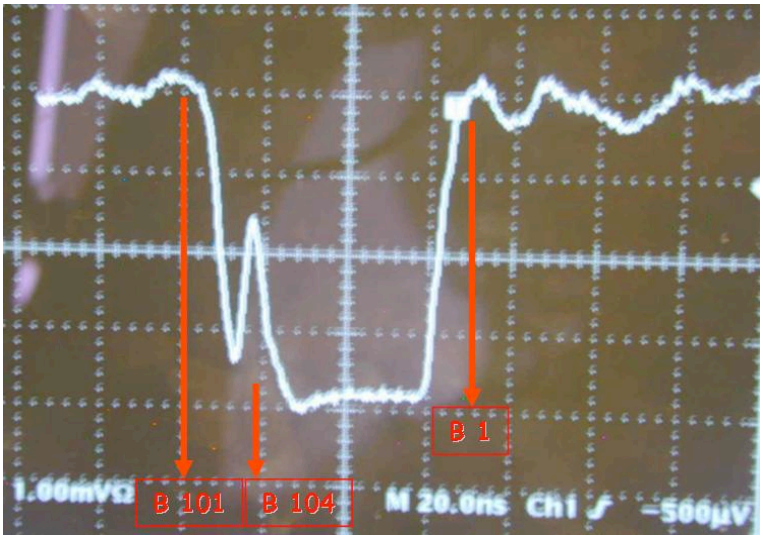

FIG. 6: IR emission of two bunches separated by a time equivalent to two bunches gap (~ 8.1 ns).

Finally, we measured the IRSR emission of a single pulse, by storing in DAΦNE only one bunch with a current of 9 mA, and the result is reported in Figs. 7 and 8.

Fig. 7 shows the time structure of the emission when only one electron bunch of 120 is stored, a scenario corresponding exactly to an emission frequency of 3.07 MHz.

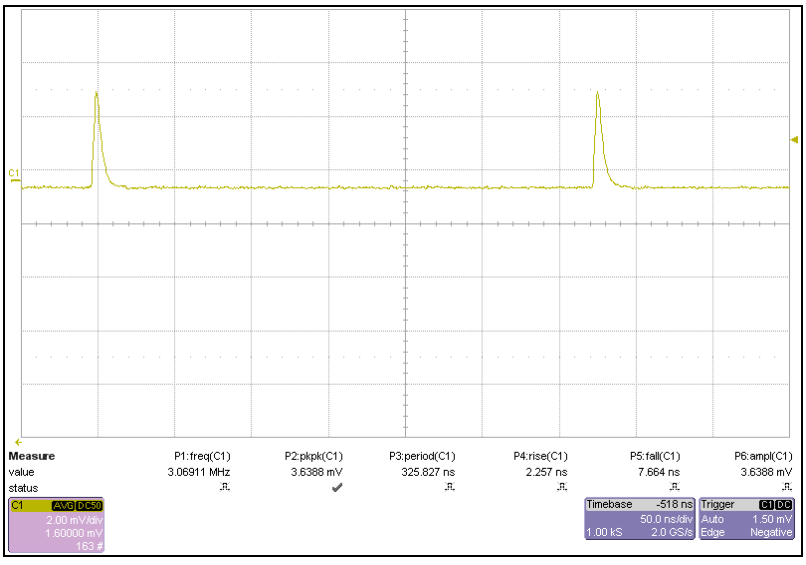

FIG. 7: Time structure of the emission when only a single bunch is stored at DAΦNE.

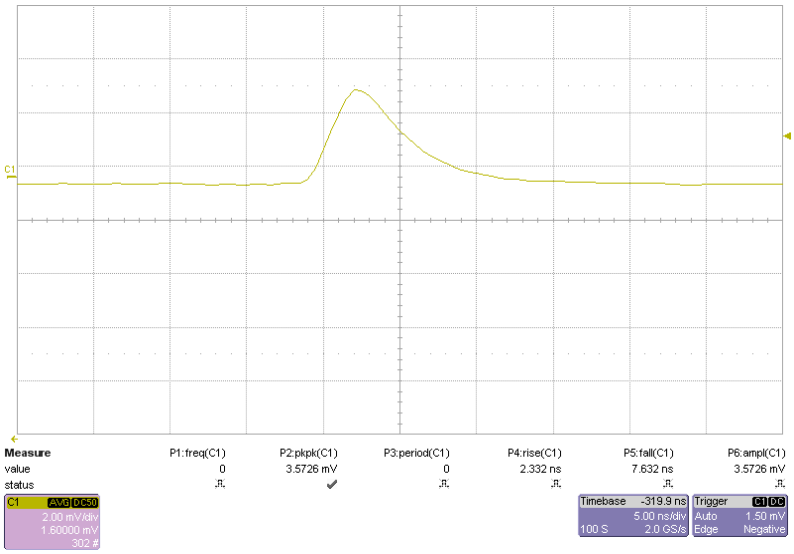

FIG. 8: Signal emitted by a single bunch of DAΦNE measured by the IR VIGO detector.

The emission structure of one single bunch as measured by the VIGO detector is shown in Fig. 8. Using this signal, it is possible to evaluate the rise time (t_r), definited as the time that the output signal of the detector goes from 10% to 90% of its final value, and the fall time (t_f) of the detector, definited as the time that the output signal of the detector goes from 90% to 10% of its final value, that we measured as 2.3 ns and 7.6 ns respectively.
The response time τ of the detector, defined as the time that the output signal of the detector reach a value of ~ 63 % of its final value, can be evaluated using the equation[10]:

$$t_r^{10-90} = 2.19\,\tau \qquad (2)$$

where actually t_r is the measured rise time of the detector. As a consequence, the response time of the detector τ ~1 ns, that corresponds to a bandwidth of 159 MHz, is in agreement with the specifications of the VIGO detector.

The same formula can be used to evaluate the fall time t_f of the detector along with the response time, if the fall time replaces the rise time in the previous formula. In this way the response time is the time that the detector takes to reach the 1/e value of the initial one after the irradiation is switched off. The estimated response time τ during the fall down is ~3.5 ns, e.g., equivalent to a cut-off frequency of 45 MHz. The response time in this case is more that 3 times slower so that, we are able to detect only the emission of two electron bunches separated by more than ~5 ns, a time gap equivalent in our filling scheme to the length of two bunches separated by ~8 ns. Therefore, we need a faster detector to detect such pulses. While these experiments allow a complete characterization of the VIGO detector, they also show that the detection of one single bunch emission is feasible. Actually, in the next future, the investigation of the intrinsic emission structure of a single bunch will be possible using new IR detectors with response time of a few hundreds of ps [11].

3 CONCLUSIONS

These experimental data are the first direct measurement of the midIR light emission of electron bunches using an uncooled fast IR detector having time resolution of few ns. This detector is fast enough to follow the bunch structure of DAΦNE, a total bunch frame of ~ 300 ns, and to observe, using a specific bunch filling, the emission of two consecutive electron bunches separated by about 8 ns. Actually, only faster detectors, e.g., with response time < 1 ns, are suitable to fully characterize the bunch emission of the standard DAΦNE operation which is based on a bunch distance of 2.7 ns. Detectors with similar characteristics can be manufactured and short response time, as 50 ps, are achievable in devices optimized for high frequency operation, with little expense in responsivity (see pag. 122 ref. 12).

The results obtained shown that these detectors are suitable for fast imaging applications in order to investigate the characteristics and the dynamics of electron bunches at IR wavelengths.

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