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THE TIME RESOLVED POSITRON LIGHT EMISSION (3+L) EXPERIMENT: A NOVEL DIAGNOSTICS TOOL FOR THE DAΦNE POSITRON RING

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Abstract

At the Laboratori Nazionali di Frascati, a novel diagnostics experiment named 3+L (**T**ime **R**esolved **e⁺** **L**ight), funded by the Vth National Scientific Committee of the Istituto Nazionale di Fisica Nucleare, has been set-up on one of the positron ring bending magnet to monitor in real time e+ bunch shape and behavior in DAΦNE lepton collider. The system represents a novel fast diagnostic instrument that allows monitoring of bunch-by-bunch and turn-by-turn positron infrared (IR) emission with the goal to improve the DAΦNE diagnostics. Indeed, the main aim is to identify and characterize both longitudinal and transverse bunch instabilities to understand better the limits to the DAΦNE performances in terms of positron beam current and collider luminosity.

The front-end of the experiment consists of an ultra high vacuum (UHV) chamber where a gold-coated plane mirror deflects the radiation through a ZnSe window. In addition, a compact optical layout in air focuses the radiation on uncooled HgCdTe photodetectors used to measure the synchrotron radiation emission at mid-IR wavelengths. At present, all experimental installations of the project have been completed and a characterization of the radiation emitted by the positron beam is available.

In this technical note we present the actual status of the experiment and a description of the experimental set-up. Moreover, wave optics simulations of the photon emission, measurements of the visible beam spot collected with a CCD camera and measurements of the IR optical power at the focus spot will be presented and discussed. Data in the time domain acquired with different fast IR photo-detectors from both electron and positron bunches at DAΦNE and at the Hefei synchrotron radiation facility from the electron beam will be also presented. Finally preliminary measurements obtained with a fast IR array detector will be presented.

1 – INTRODUCTION

In order to improve the diagnostics of the e^+ ring of the DAΦNE collider, a novel beam diagnostics experiment: the 3+L (Time Resolved Positron Light Emission) has been proposed and funded by the V^{th} National Scientific Committee of the INFN in the year 2007-2009 [1,2]. The main goal of the proposal was to perform bunch-by-bunch and turn-by-turn longitudinal and transverse beam diagnostics of positrons in order to investigate bunch instabilities and in particular to study the limits to DAΦNE performances. A compact optical system collecting the IR synchrotron radiation emission from one of the bending magnet of the positron ring have been assembled and tested and is now in operation in the DAΦNE hall. It allows focusing the radiation on compact fast IR photo-detectors to perform real-time bunch diagnostics. During 2009 first measurements of the e^+ bunches were performed and the experiment, thanks to a remote control via Ethernet, may collect data using different fast photon detectors [3-5].

The recent availability of room temperature IR devices based on HgCdTe alloy semiconductors has allowed obtaining sub-ns response times [6]. These detectors typically optimized in the mid-IR range are capable to detect the brilliant synchrotron radiation IR emission also of high current storage rings and for these characteristics have been considered suitable also for beam diagnostics. At DAΦNE, measurements of the time structure of the synchrotron light emission of both electrons and positrons have been performed with uncooled IR photo-conductive detectors achieving a time resolution of about few hundreds of picoseconds [7-9]. The first experimental tests have been performed at SINBAD (Synchrotron Infrared Beamline At DAΦNE) the IR beamline operational at Frascati since 2001 [10].

The devices we used are based on HgCdTe multilayer hetero-structures grown by MOCVD technology on oriented GaAs (211) and (111) substrates. They have been optimized to work at 10.6 μm and their best response time may reach 100 ps or lower when cooled at 205 K with a 3-stage Peltier cooler [11].

The response time of the 3+L experiment using these IR photodiodes allows the separation of the emission signals between two consecutive bunches of e^+ or e^- DAΦNE beam and allows to measure the Gaussian profile of each bunch of the train with a resolution in the range of σ~200-250 ps. These signals are suitable for real time longitudinal bunch-by-bunch and turn-by-turn diagnostics. Diagnostic systems based on such IR devices could be reasonably used in many other accelerators. In fact the spectral angular power distribution extracted from a bending magnet at small frequencies for $\omega<<\omega_c$, where ω_c is the critical frequency does not depend by the energy of the accelerator but only by the radius of curvature of the bending magnet and by the current stored in the ring [12]. Consequently, at IR wavelengths, the power of the synchrotron radiation (SR) extracted from a bending magnet is comparable for all the circular accelerators, mainly depending by the current and the collection angle. As a consequence, in principle, a diagnostics based on fast IR devices could be considered for all the storage rings.

Tests of this IR diagnostics have been also performed at the Hefei Light Source (HLS), the synchrotron radiation facility of the National Synchrotron Radiation Laboratory (NSRL) in China. A few IR photodiodes have been tested during a campaign of

measurement at Hefei and data have been compared with those available from the diagnostics beamline of the synchrotron source. We collected data simultaneously from the same bunches using the IR set-up and that of the diagnostic beam line of HLS working at shorter wavelengths. The experiments demonstrate that diagnostics in the sub-ns time domain at IR wavelengths is possible using HgCdTe uncooled photodiodes. However, results are limited and work is in progress to improve the HLS set-up for simultaneous data acquisitions of IR, NIR/visible and streak camera data.
Nevertheless, the collected data allow claiming that IR photodiodes satisfy all the requirements of an ideal device for beam diagnostics compatible with almost all accelerators. They are compact and robust, easy to manage, vacuum compatible and have a significantly lower cost with respect to a streak camera, a much more expensive device used for a similar beam diagnostics. Indeed, diagnostics based on fast IR photon devices may represent an effective, reliable and cheap alternative for photon beam diagnostics.
Moreover a first prototype of a fast bi-dimensional IR detector constituted by 2 linear arrays with 32 pixels has been built and assembled for the first time. This device composed by two linear arrays each with 32 pixels also optimized to work at mid-IR wavelengths is characterized by a response time of each single pixel of ~1 ns. A 64 channels analog electronics board has been built to receive and amplify the signals of this array made by the VIGO System. The detector allows separating the IR emission of each bunch of the stored charge train and has been thought to allow real time imaging of the DAΦNE IR synchrotron light and a turn-by-turn and a bunch-by-bunch diagnostics of the transverse dimensions of each individual stored bunch. Such diagnostics may open new opportunities, in particular the possibility to investigate bunch-by-bunch transverse beam instabilities, correlating in a real time bunch positions along the accumulated train of stored particles.

2 – EXPERIMENTAL SET-UP

As well known, DAΦNE is an e^+/e^- collider, with center of mass energy at 1.02 GeV, designed to operate at high current (~2 A) and with up to 120 stored bunches [13]. DAΦNE may operate with different bunch patterns. The present typical operation mode is 105 consecutive electron buckets out of the available 120 with a gap of 15 bunches to avoid ion trapping in the electron beam. With this configuration, the minimum bunch distance is 2.7 ns. In standard conditions, a bunch has a Gaussian shape along the three axes of symmetry with a FWHM bunch length ranging from 150 to 300 ps depending by the bunch current.

The front-end of the experiment extract the IR radiation from the bending magnet of the positron ring. It is characterized by a critical energy of 273 eV and positioned in the long section after the IP2, one of the two interaction points of DAΦNE, where FI.NU.DA. detector is located. Figure 1 shows the layout of the DAΦNE accelerator (left) and the top view of the bending magnet chamber of the positron ring where the radiation is extracted for the 3+L experiment (right).

The project is based on a compact front-end with a high vacuum (HV) chamber that hosts a gold-coated plane mirror. At a distance of ~0.9 m from the light source a slit of 18 mm x 58 mm (VxH) is set along the path of the light. Its acceptance angle is 20 x 64 mrad (VxH). At 10 μm of wavelength, i.e., the optimized operational wavelength of the IR photodetectors we used for beam diagnostics, the rms opening angle of the source is Ψ_σ ~8.64 mrad [12] so that in vertical direction the clear aperture of the slit allows collecting almost all emitted radiation. Along the extraction line and before the HV chamber a beam-stopper remotely controlled by the DAΦNE control room is installed to absorb all emitted radiation when diagnostics is turned off and w.

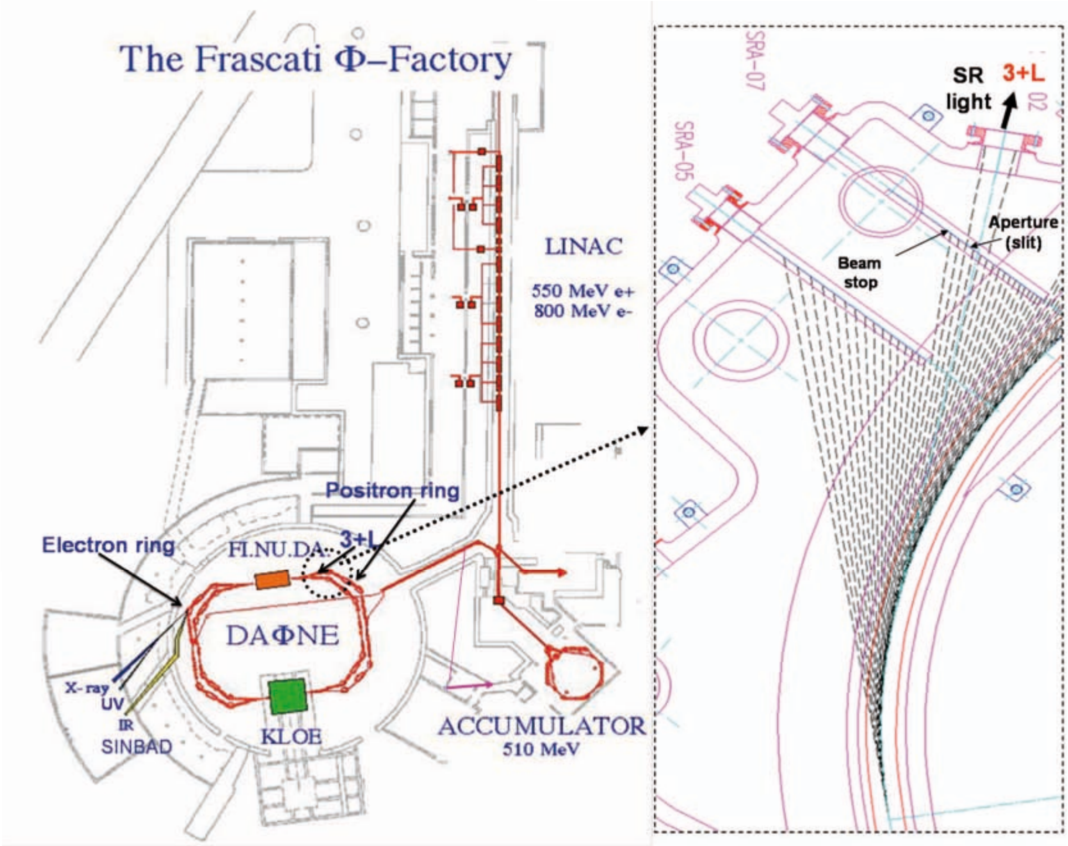

FIG. 1 – Layout of the DAΦNE storage ring complex with the main high energy experiments installed in the two interaction regions and SR beamlines (left). On the right a magnified top view of the UHV chamber of the positron ring where the synchrotron radiation is extracted for the 3+L experiment.

The first gold-coated plane mirror inside the HV chamber is placed at a distance of ~0.84 m from the slit and collects in horizontal an angle of ~41 mrad. It deflects the radiation by 90° through a ZnSe window that transmits radiations in the range 0.6-12 μm (800-17000 cm^{-1}). In order to collimate and focus the bending magnet emission we designed a compact optical system composed by five mirrors working in air, installed in the DAΦNE hall after the ZnSe window. The optical system focuses radiation on a small spot of about 0.1 mm^2. A schematic optical layout of the 3+L exit port and of the optical system is showed in Figure 2.

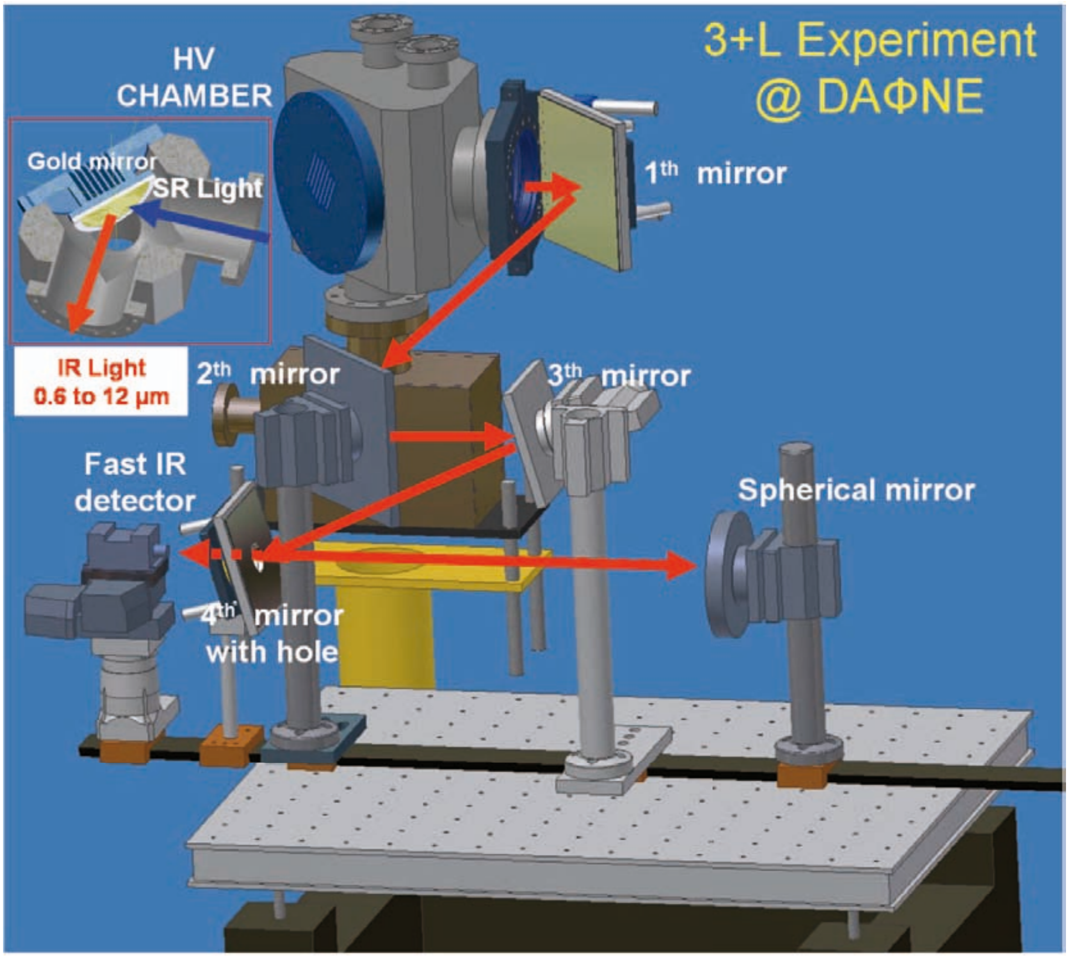

***FIG. 2** – View of the optical layout of the 3+L experiment with the front end, the optical table, the mirrors and the IR detector. The ideal path of the IR radiation, focused at the end on a small spot where the detector is installed, is showed with red lines.*

The mirrors were mounted on an optical table as showed in Figure 2. Looking at the optical layout, all mirrors are plane mirrors except one, the spherical focusing mirror. This optical layout demagnifies the source of a factor ~5 and, in principle, allows performing also the imaging of the source. To maintain the layout as compact as possible, the 4^{th} plane mirror has a centre hole to allow radiation focused by the spherical mirror to have its focus behind it. Detectors are mounted on a motorized xyz micrometer stage to align them to the light spot located behind the 4^{th} mirror.

A PC installed in the DAΦNE hall allows the remote control of the experiment. In particular a PCI-COM bridge RS-232 board controls motors and the xyz stage. Two webcams and a camera monitor the detector position and mirrors positioning. A scope model Tektronics TDS 820 with 6 GHz of bandwidth is connected to the PC by a USB-GPIB interface for data collection. A power supply connected to the PC by a GPIB I/O controller is used to supply amplifiers and detectors. Dedicated software packages have been developed under the LabVIEW platform for data acquisition, to control the power supply of detectors and amplifiers and to control the xyz stage. The acquisition system is however temporary and we plan in the future to replace it with a better dedicated set up.

3 – EXPERIMENTAL DATA

A first characterization of the diagnostics has been carried out during DAΦNE operations in different experimental runs performed in 2008 and 2009 with the 3+L experimental setup using several fast IR detectors. Moreover, wave optics simulations and calculations of the SR source with the SRW software package, measurements of the spot with a CCD camera during the first alignment of the optical mirrors and measurements of the optical power of the beam at the focus of the experimental setup have been performed. The single bunch signal acquisitions carried out with different fast IR photodetectors and the results of their data analysis are described in detail in the section 3.4.

3.1 Simulations with the SRW software

In order to optimize the optical system of the experiment and to characterize the photon source at IR wavelengths both ray tracing simulations with the ZEMAX™ software and the wave optics SRW package [14] have been performed. The latter code allowed computing in the far field approximation of the wave-front produced by the DAΦNE relativistic particle beam generated in the bending magnet. Then, the computed radiation wave-front has been propagated through drift spaces, mirrors and apertures according to the 3+L optical layout.

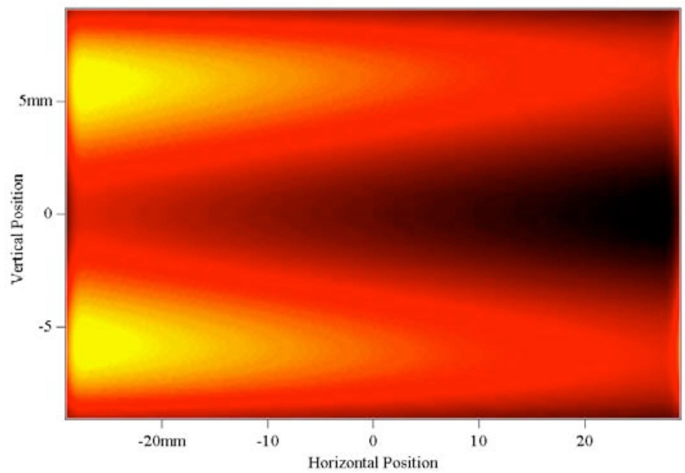

***FIG. 3** – Spatial distribution of the SR intensity at the slit position of the 3+L line calculated at 10 μm with the SRW package.*

In Figure 3 is reported the spatial distribution of the light extracted from the bending magnet at 10 μm with a total degree of polarization calculated with SRW at the entrance slit. The simulation at 10 μm shows that in the vertical direction more than 70 % of the radiation is collected by the slit.

In order to evaluate the fraction of the power transported at the focus spot and its dimension, we simulated the propagation of the SR wavefront through the entire optical path. In the SRW calculations we replaced the spherical focusing mirror by an ideal thin lens. Simulations show that about 50% of the flux (photon/s) at 10 μm collected by the first mirror inside the HV chamber is focused to the final spot. The source image at 10 μm obtained by SRW at the focus of the 3+L optical system is showed in Figure 4. At this wavelength the size of the spot is characterized by a FWHM of 340 x 110 μm^2 (see Figure

4) that matches quite well the area of a typical single element photodetector that ranges between 250x250 μm^2 and 1x1 mm^2. Actually, the optical system allows concentrating the most intense part of the power onto the photodetector allowing an optimized data acquisition. As discussed in the next section, simulations were also performed at visible wavelengths (0.6 μm) to compare data with CCD acquisitions. The analysis returns a vertical FWHM of the spot of ~80 μm, in good agreement with source dimensions observed with a visible CCD camera.

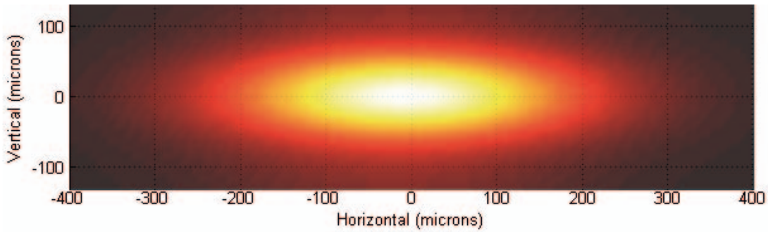

FIG. 4 *– Distribution of the IR beam calculated by the SRW software at 10 μm.*

3.2 Measurements with a CCD camera

The first characterization of the 3+L optical system was performed at short wavelengths observing the spot with the visible CCD camera Model Elmo TDP-322D (1/3'' CCD camera). We monitored the visible spot size along the optical path around the focus to obtain a preliminary alignment of the optical system and a characterization of its performance. A contour plot of the focal image collected by the CCD camera is showed in Figure 5. Later the CCD camera was replaced by the fast IR detectors placed at the focus of the optical system.

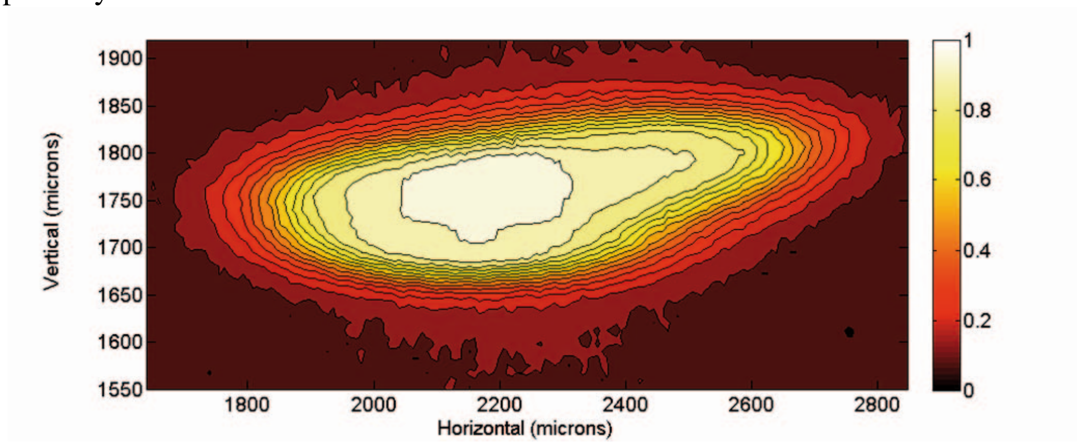

FIG. 5 *– The contour plot of the visible focal spot of the optical system measured with the CCD camera.*

The estimated FWHM of the visible spot is 750x150 μm^2 (HxV), a value slightly larger than data obtained by SRW simulations, i.e., ~2 times larger both in the vertical and the horizontal directions. However, we have to underline that, due to the intense photon flux at visible wavelengths, the evaluation may be certainly affected by the saturation of the central pixels of the CCD. Moreover, a non-perfect alignment of the mirrors and the unavoidable presence of spherical aberrations affected the early tests. Nevertheless, measurements with the CCD camera confirm the performance of the optical system and data are in a reasonable agreement with simulations. In order to improve the mirrors alignment, in the future a remote control of the spherical mirror and of one of the plane mirrors is foreseen.

3.3 The source power at IR wavelengths

To characterize the power of the SR IR source we performed measurements using a calibrated NIST power meter Melles Griot 13 PEM 001/J with filters in the range 5-20 μm. In Figure 6 we showed the measured power after a filter with a cut-off of 5 μm as a function of the circulating current in the positron ring. From the linear fit of the curve of the Figure 6, we estimated at the focus of the optical system with ~1 A of stored positrons a power of ~4.4 mW.

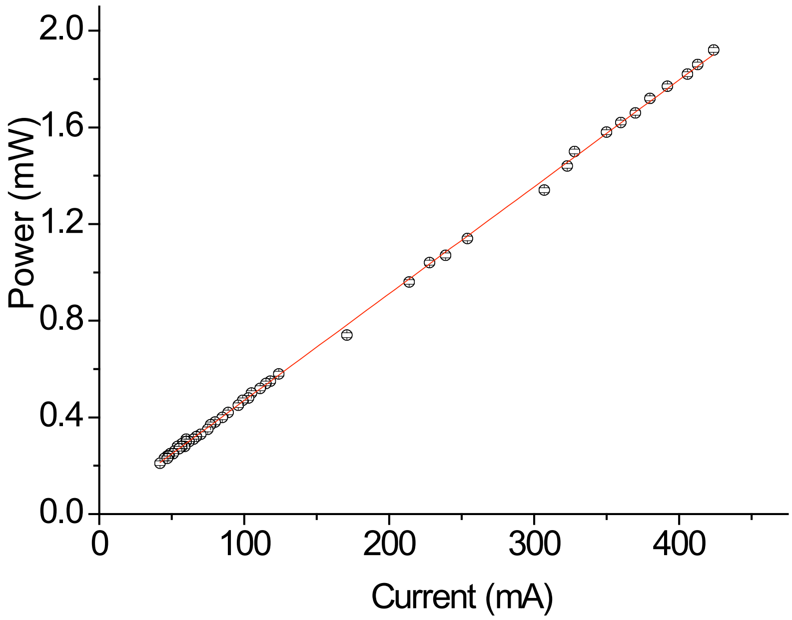

FIG. 6 – The SR power measured at the focus of the optical system of 3+L (black dots) vs. positron current. The red line is the linear fit of the experimental data.

In order to compare measurements with the calculated power emitted by the stored beam, we estimated the power of the radiation collected by the 3+L line between 5 and 20 μm. The total radiated power emitted by the positron beam from the bending magnet can be written as [15]:

$$P = \frac{9.91 \cdot 10^{-16} \tilde{a}^4 \vartheta I}{\tilde{n}} \left[\frac{\mathrm{W}}{\mathrm{mA\ mrad}} \right] \qquad (1)$$

Using the DAΦNE parameters: $\gamma=1\cdot10^3$, the bending magnet radius $\varrho=1.4$ m, a current of I=1 A and an horizontal collection angle of $\theta=40$ mrad, i.e., the angle collected by the first mirror inside the UHV chamber, the value of the total power collected by the 1st plane mirror is ~28 W. From Ref. 16 we also know that the source power in the wavelength range 5-20 μm is ~0.05 % of the total power integrated over the entire wavelength range (~28 W).

This rough evaluation addresses a total power of ~14 mW, about three times higher of data measured by the power meter in the wavelength range determined with the filter at the focus of the 3+L set up. However, taking into account the indetermination of the efficiency of the filter and that a fraction of the radiation is lost along the optical path of the optical system, in particular due the hole at the center of the 4th mirror, the power we measured at the focus of 3+L has to be lower than the estimated value. However, the power at the focus of the optical system with a beam current in the range 500-1000 mA, corresponding to ~5 -10 mA/bunch is enough to operate with the fast IR detectors with a signal ≥1 V at the output of the amplifier and a very good S/N ratio.

3.4 Measurements with fast IR photodiodes

During experimental runs at DAΦNE different fast IR devices were characterized using the 3+L set up and the SINBAD IR beamline. Different measurements have been performed, in particular to improve response times and S/N ratios of these devices. The results achieved are associated both to improvements of the detectors and to the use of a faster electronics.

The first devices (photo-conductive detectors) we tested, were characterized by a fall time of the signal of a single bunche of ~1.2 ns [7-9]. Additional tests performed with a better amplifier characterized by a higher gain and a larger bandwidth, showed improvements by a factor 2, i.e., a fall time of ~600 ps [1-3]. Actually the improved performances of the last generation of devices allows monitoring bunches with a Gaussian shape characterized by a fall time detection of ~ 400 ps, a factor three better with respect to the first detectors.

During normal DAΦNE operations different fast IR photon detectors have been tested at the focus of the optical system of 3+L. In particular, measurements were carried out using fast PVMI 3-stages detectors from VIGO System S.A. These detectors are based on HgCdTe multilayer hetero-structures grown by the MOCVD technology on oriented GaAs (211) and (111) substrates. They have been optimized to work in the mid-IR at 10.6 μm and their best response time may reach 100 ps or lower when cooled at 205 K with a 3-stage Peltier cooler [11].

Photodiodes were inverse polarized varying bias voltages in order to obtain best performances, i.e. faster response times and an optimized S/N ratio. All systems are very sensitive and during measurements we detected also noises associated to the two radio cavities of the DAΦNE rings (see Par. 3.5).

In the following are summarized the main results obtained with these IR devices. The best time responses were obtained with the PVMI 3-stages detector SN 5003. The schematic layout of the electronics circuit used to polarize the device is showed in Figure 7. For such device all measurements were carried out at room temperature. The output of the device was connected to a broadband preamplifier to enhance the signal of the photodiode. The amplifier was characterized by 50 Ohm input/output impedance, ~46 dB gain and 0.01-2500 MHz of bandwidth. Because the 3+L experiment is installed inside the storage ring hall, the circuit, the PV-5003 detector and the amplifier were all placed inside a metal box to shield the RF signal of the klystrons installed in the DAΦNE hall. Coaxial cables and *SMA* connectors were used to connect the output of the amplifier to two channel oscilloscope for data collection. The scope was the digital sampling scope Tektronics TDS 820 with a 6 GHz bandwidth.

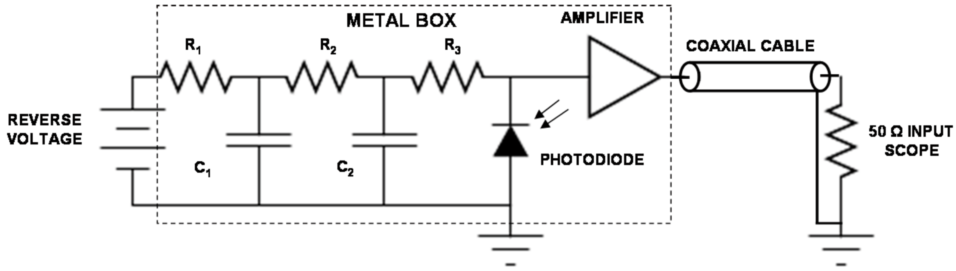

FIG. 7 *– The layout of the electronic circuit used to polarize the detector, to shield the detector from the RF signals present in the DAΦNE hall, and to read-out the signal.*

Different measurements were performed both during standard DAΦNE operations and in a few dedicated shifts with single bunch configuration. In Figure 8, we report the signal of a few positron bunches measured with 650 mA of an accumulated current.

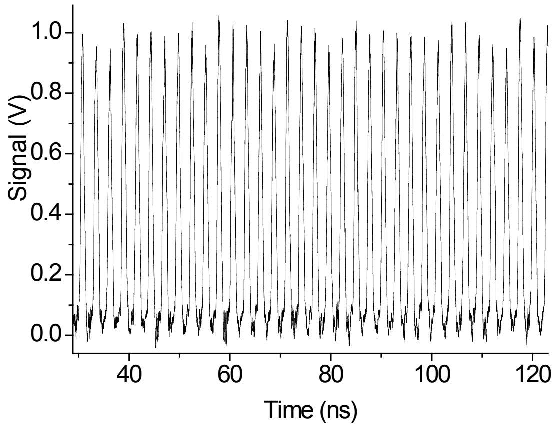

FIG. 8 *– The e^+ bunch pattern. The response time of the 3+L experimental set-up may resolve the separation between consecutive bunches up to 2.7 ns.*

As well showed in Figure 8, the time resolution of the system allows the separation of the emission between two consecutive bunches of the positron beam and addresses the possibility of a real time longitudinal bunch-by-bunch and turn-by-turn diagnostics.

From these experimental data we may obtain different bunch parameters, information regarding detector characteristics and evaluate electronic performances. As an example, in Figure 9 we show the shape of a single positron bunch measured with the uncooled IR photodiode. Data show that with a bunch current of ~5 mA the bunch profile is Gaussian with a length of σ~240 ps while both the rise time and the fall time measured by this detector are ~ 400 ps.

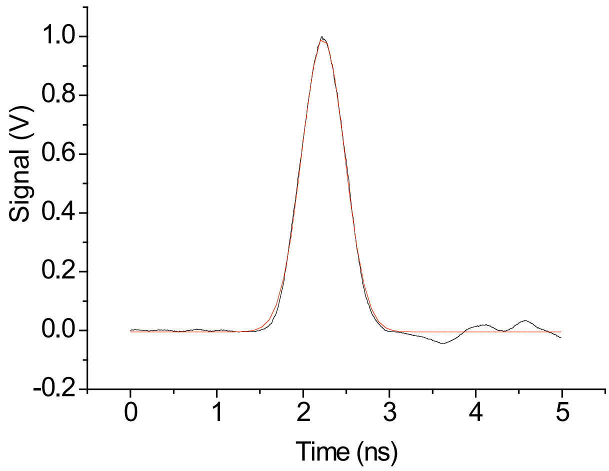

***FIG. 9** – The shape of a typical positron bunch (black) measured at IR wavelengths and its Gaussian fit (red).*

Data have been collected also vs. the positron current in order to characterize the bunch length behaviour. In Figure 10 is reported the rms bunch length of the Gaussian distribution used to fit data as a function of the bunch current.

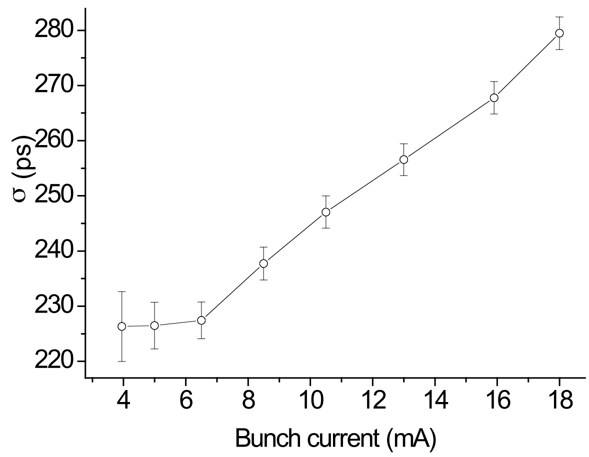

***FIG. 10** – Behaviour of the rms bunch length vs. the bunch current measured with IR uncooled photodiode.*

The σ of the Gaussian distribution increases as function of the bunch current, exhibiting a linear behavior for currents higher than ~7 mA, while, for lower currents, the σ has a constant value of ~225 ps. The behavior is probably due to the actual limit of the response time of the photodiode (and of the electronics) at room temperature. Indeed, data collected with a streak camera installed at DAΦNE devoted to the measure of the bunch lengths of the positron ring measures a σ of ~66 ps [13]. Comparing data collected by the IR detector with those of the streak camera at the same bunch current the σ measured at IR wavelengths is from 3 to 4 times larger. At present the streak camera performance is better but improvements in the IR experimental set-up are foreseen with an optimized electronics and more performing detectors. Moreover, it is important to address that the streak camera installed at DAΦNE can also work in the multi-bunch mode but allowing only the measurement of the envelope of all bunches. On the contrary, a detection system based on fast photodiodes may return information about the longitudinal dynamics of the stored beam e.g., bunch-by-bunch and turn-by-turn.

3.4.1 *Signal vs. bunch current: linearity.*

In order to measure the amplitude signal of the fast IR photodiode and to characterize its linearity, acquisitions of a single bunch as a function of the current were performed. Data are showed in Figure 11. Both the peak signals of the bunch (black dots) and the integrated bunch signal vs. time (red dots) as a function of the bunch current are plotted in Figure 11. Linear fits of experimental points are also showed (red lines). Both the peak and the integrated signals of the bunch vs. the single bunch current exhibit a clear linear behaviour. Data confirm that the photodiode has an excellent linearity suitable to obtain information about the bunch-by-bunch beam current.

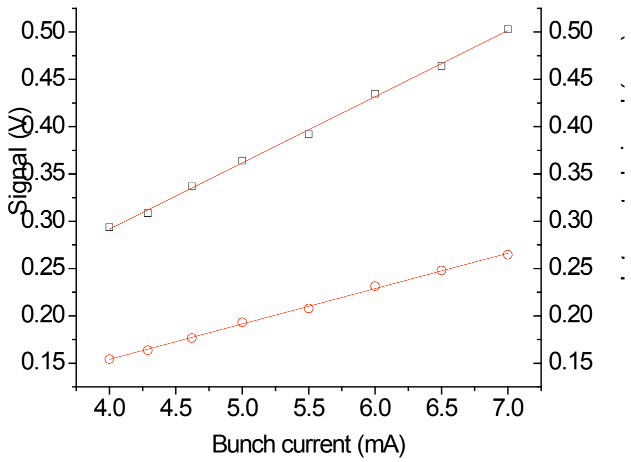

***FIG. 11** – Peak signals of a single bunch (black) and the integrated signal (red) vs. bunch current. Red lines represent the linear fits of the data.*

3.5 RF signal noise

During the characterization of both detector and electronic of the IR devices, we measured at the output of the photodiodes the noise induced by the RF klystrons of the rings spatially close to the experimental set up. The noise is characterized by a power spectrum composed by the frequency of the DAΦNE RF cavity and its harmonics. Actually, measurements performed outside the DAΦNE hall, in particular at the IR beamline SINBAD, located outside the DAΦNE hall in a laboratory well shielded by the signals of the RF klystrons, present the same power spectrum although its intensity is attenuated by more then one order of magnitude.

A similar noise was also detected at the Hefei Light Source (HLS) in China during a campaign of measurements performed with the same IR devices [16]. In this case the noise is characterized by the power spectrum of the RF of the HLS ring.

In order to reduce the RF noise a well shielded dedicated electronics was used to amplify the photodiode signal. A photograph of the detector with its compact electronics, mounted at the focus of the 3+L experiment is showed in Figure 12.

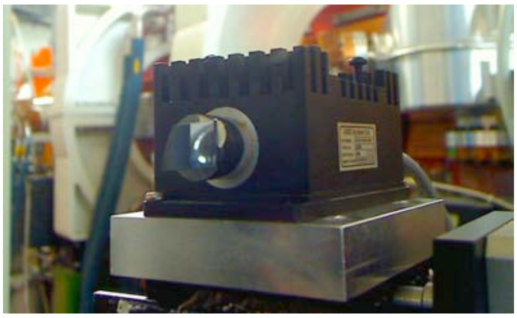

FIG. 12 *– The amplifier, the IR photodiode with its mid-IR filter installed at the focus of the 3+L optical system inside the DAΦNE experimental hall.*

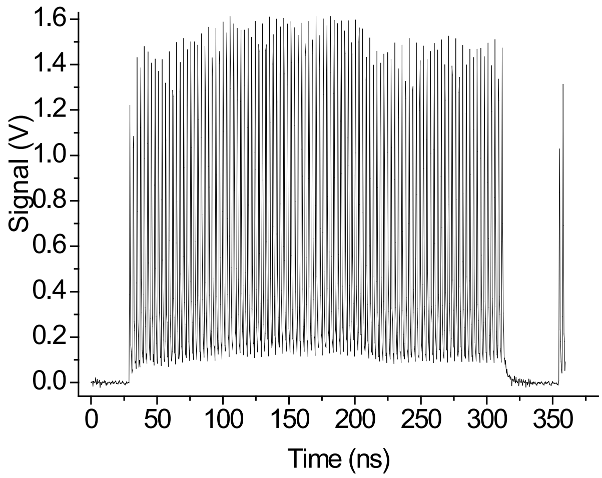

FIG. 13 *– The typical bunch pattern with the 105 e^+ bunches and the gap (on the right) measured with the shielded electronics of the cooled PVMI 3-stages VIGO detector.*

The authors have experimentally found that the noise level increases as function of the positron and of the electron currents. With this set-up the peak-to-peak voltage associated to the RF noise ranges from 10 to 30 mV and allows obtaining a S/N ratio > 100, a factor 10 time higher with respect to the other electronics previously used.

As an example the signal of the e^+ bunch pattern with separation of 2.7 ns measured by the PVI-3TE-10.6, SN 5986 device is showed in Figure 13. In order to optimize the response time of the detector, in these measurements also a mid-IR filter with a cut-off at 5 μm was used (see Figure 12) to cut the power associated to wavelengths lower than 10.6 μm for which the photodiode was optimized. The electronics system is composed by a transimpedance amplifier with a high bandwidth in the range 0.0001-1000 MHz and with a gain of 3900 V/A (~37 dB). It allows to bias the device at a fixed voltage and to cool down at 205 K to optimize its performances.

Although an optimization of the voltage value was not possible with the new electronics set-up, to obtain similar response times as those achieved with the previous electronics set-up, a reverse bias voltage was applied to the photodiode. Actually the response time of this latter device, that in principle may reach ~100 ps or lower, was only ~500 ps, a factor ~2 slower than the best previous device. Nevertheless, its compact electronics set-up exhibited a much better shielding of the RF signal and a much lower noise level. In the future, this electronics configuration should allow to achieve response times down to ≤100ps actually improving the longitudinal diagnostics of the 3+L experiment.

3.6 Measurements at Hefei Light Source

At Hefei Light Source (HLS) a series of experiments has been set up to evaluate the response of the fast IR photodiodes with another SR source with different power, bunch length and bunch pattern. Moreover, experimental data have been compared with those collected at the diagnostics line of the synchrotron source of the National Synchrotron Radiation Laboratory (NSRL). In this case the experimental set-up, i.e., electronics and photodiodes were the same that at DAΦNE measured bunch lengths of ~ 200-250 ps.

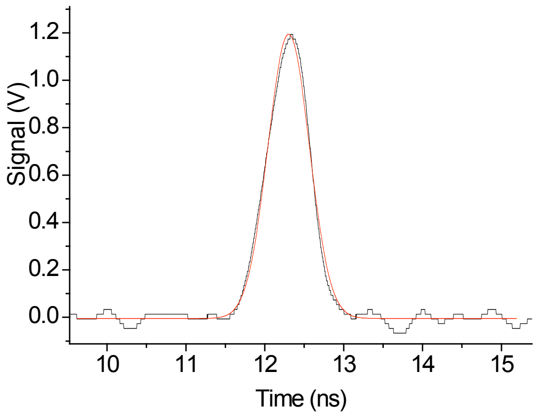

FIG. 14 *– Measurement of a single bunch of the electron beam (black) with its Gaussian fit (red).*

At Hefei photodiodes were installed inside the HV chamber that hosts the final optical element of the IR beamline. The optical system of the HLS IR beamline is composed by a set of gold coated reflecting mirrors that collects and focuses the beam to the entrance of a BRUKER v60 interferometer. For the experimental set-up we used a small elliptical mirror after the existing optical system to deflect and focus the IR beam onto the IR detector [16].

At HLS bunch lengths are in the range ~240-300 ps with a RF of 204.016 MHz and a revolution frequency of 4.534 MHz. With a full fill pattern of 45 bunches, the separation is 4.9 ns and the total beam current is in the range 100-300 mA. [17]. We monitored the longitudinal bunch lengths of the electron beam in the time domain with our uncooled IR photodiode. With such full-fill pattern the IR photodiode resolved both the time structure of the electron bunches and the pattern of each individual bunch. As an example in Figure 14 we report one single bunch measurement at a beam current of 118 mA. The bunch length estimated by a Gaussian fit is σ ~ 262 ps.

At Hefei we had the possibility to compare measurements at IR wavelengths with a different methods, i.e., collecting data of the same bunches simultaneously using the experimental set-up of the diagnostics beamline operative at HLS. This dedicated beamline monitors the longitudinal lengths of e^- bunches using a fast InGaAs photodiode optimized in the

NIR/visible range (750-1700 nm). A streak camera is also available for purpose of diagnostics at the same beamline. In particular, for the first time, data at IR wavelengths using a HgCdTe photodiode were simultaneously collected and compared with data obtained at NIR/visible wavelengths with a commercial InGaAs photodiode. In Figure 15 are compared data of four consecutive bunches collected with both the IR (red) and the NIR/visible (black) photodiodes. An impressive agreement can be observed, i.e., the same signal amplitudes between signals is acquired with the two photon-detectors working at different wavelengths.

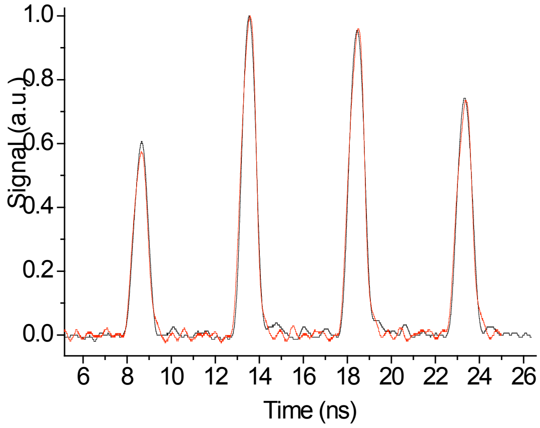

FIG. 15 *– Comparison among signals of four consecutive bunches collected at IR (red) and NIR/visible (black) wavelengths with the two photodiodes.*

Finally in order to have information about the longitudinal beam dynamics we performed bunch length measurements of the electron beam vs. current at the IR exit port comparing data available at the HLS diagnostics station during one filling run of the electron storage ring. In particular, after the bunch re-filling we collected the signal of each bunch with both the IR and the NIR/visible photodiodes monitoring the length vs. the beam current behaviour. The FWHM of the bunch as a function of the current is reported in Figure 16 where the red line refers to data of the HgCdTe photodiode (IR) and the black one to data collected with the InGaAs detector.

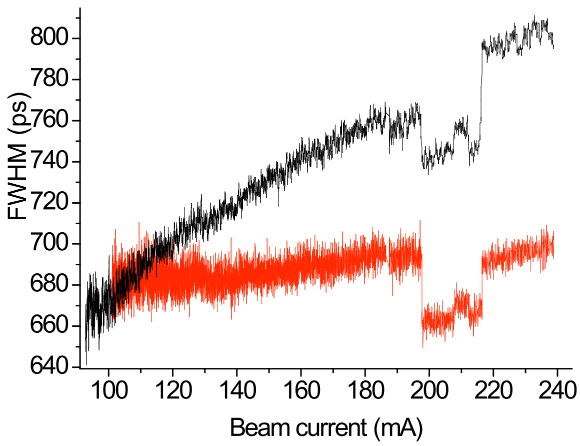

FIG. 16 *– Comparison of the bunch length vs. current measured at IR (red) and NIR/visible (black) wavelengths.*

As showed in Figure 16 the FWHM of the bunch length measured by the two detectors exhibits a similar behaviour and in particular the same bunch longitudinal dynamic, e.g., the sudden unexpected change observed during the run above 190 mA. However, while the NIR/visible photodiode addressed a total variation of about 140 ps between the min. and the max. value of the current, for a current > 110 mA the FWHM bunch length collected by the IR photodiode is almost constant and its total variation exhibits a moderate increase. Nevertheless, during the run described in Figure 16 in the range 190-220 mA both detectors monitored the same sudden change of the beam emission. However, both data do not allow understanding the origin of the observed phenomenon we associated to a change of the RF voltage of the cavity.

It is important to underline also that the S/N ratio of IR photodiode data allowed acquisition with the scope in the single shot mode while due its lower S/N ratio, data at NIR/visible wavelengths are the result of the average of at least 15 individual acquisitions.

Although preliminary, the results achieved clearly demonstrate that diagnostics at IR wavelengths is possible in the sub-ns time domain using HgCdTe uncooled photodiodes and the latter may be successfully used in different accelerators. Better results could be certainly obtained using cooled and faster IR photodiodes coupled to a dedicated electronics pushing the present time resolution limits. To improve the actual results the design of an improved setup is in progress at HLS to perform IR, NIR/visible and streak camera simultaneous data acquisitions.

3.7 Preliminary data using a fast IR array detector

A new device in collaboration with the VIGO System company has been also designed and built. It was recently assembled with an interface board to attempt the first transverse diagnostics of the positron bunches of DAΦNE at IR wavelengths. The device consists of a fast array detector with 2x32 pixels each characterized by a size of ~50x50 μm^2 and a response time of ~1 ns. Two prototypes of the imaging device with its electronics board have been set up for preliminary tests at the IR SINBAD beamline. Photos of one of the two devices are showed in Figure 17.

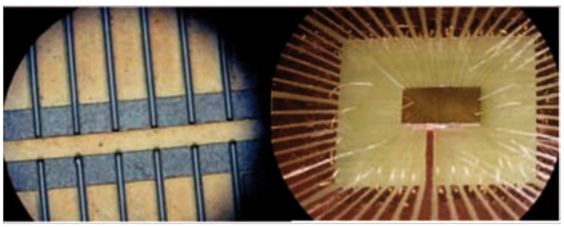

FIG. 17 *- Magnified view of a few pixels of the photoconductive IR array (left). The interface board and the detector with the connection between pixels (right).*

First preliminary tests have been performed with some pixels of the array illuminated by the IRSR emission [18]. For these preliminary measurements we built an interface board with pixels of the array connected by gold bonding wires to the board and to the input of an analog electronics board. The dedicated electronics has 64 channels with a bandwidth ≥1 GHz/channel and it has designed to amplify signals with a gain of ~50-55 dB as a function of the power supply voltage. To characterize each pixel a four channels scope has been used to collect and analyze signals. In the future to collect and store simultaneously signals from all channels we plan to use a fast digital electronics now under design.

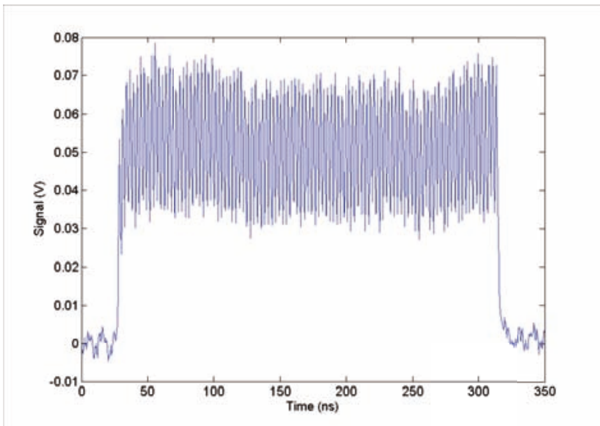

FIG. 18 – *The IR signal of the 105 electron bunches as collected by one of the pixel of the IR array detector.*

For the tests the array has been aligned at the focus spot of the optical system placed after the last toroidal mirror of the SINBAD beamline. The SINBAD optical system de-magnifies the source image by a factor 2.3 and at mid-IR wavelengths its size is ~ 2.0x1.5 mm. The array has been placed in the vertical plane in front to the IR spot. Only four pixels with size is 50x50 μm^2 were connected to the electronics of the board so that only a portion of the spot have been monitored. However, the signals of the four pixels have been simultaneously collected with a bandwidth of 600 MHz and at a rate of 2.5 Gsample/s by the four input channels of the scope. An example of the acquisitions obtained by one single pixel of the array is showed in Figure 18. It shows the IR emission of each of the 105 bunches and also the gap is clearly resolved.

To reduce the noise level and to obtain a high S/N ratio the acquisition has been performed averaging 32 sweeps of the waveform. A maximum S/N~36 has been achieved with a beam current of ~1550 mA. As also showed in Figure 18 the bandwidth of the detector is large enough to separate signals between bunches separated by ~2.7 ns although the response time is higher and the next bunches do not reach the same offset level of the first one. With an exponential fit of the signal of the last bunch, an evaluation of the response time of each pixel may be obtained. In Figure 19 we compared the IR signal of the last bunch with its fit (blue and red lines, respectively) that yields to an evaluation of the response time of the pixel of ~1 ns. Comparing data from different pixels, the response time ranges between ~1 and ~1.3 ns. In this configuration, the response time is also affected by the bandwidth of the scope and also the sample rate (600 MHz and 2.5 Gsamples/s, respectively) limits the resolution of the device.

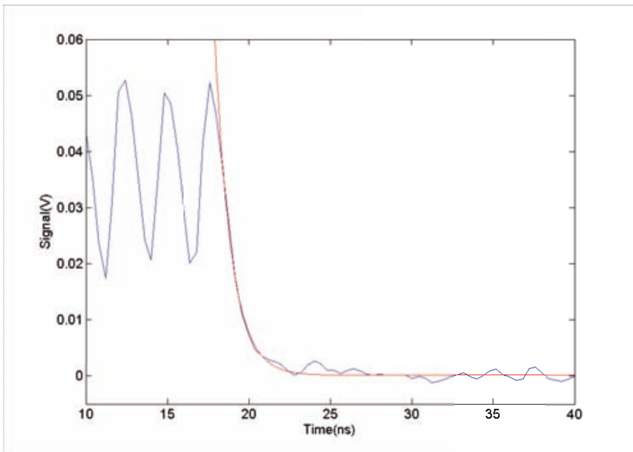

FIG. 19 *– Comparison of the signal of the last electron bunches (blue) with its fit (red) to evaluate the pixel response time.*

Unfortunately, these preliminary measurements are limited to only a few pixels of the array connected to the electronics board and collected by the scope. Actually, the four pixels belong to the two different lines of the array as showed in Figure 20.

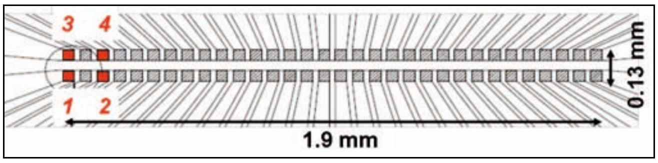

FIG. 20 *- Layout of the IR array detector with its dimensions and the pixels (red squares) used for the experimental tests.*

Two data sets obtained collecting simultaneously the signals of the four pixels of the detector with an electron beam current of 2000 mA and 1700 mA are compared in Figure 21 and 22, respectively. The upper panel in both Figure 21 and Figure 22 shows the signals of the pixels 1 and 2 (black and red lines, respectively) while the lower panel reports the signals of the pixels 3 and 4. The curves in Figure 21 and in Figure 22 refer to the first and the last 22 bunches of the train, respectively. Actually, the four pixels collect data from two different portions of the IR spot so that the pixels 1 and 2 are characterized by different amplitudes with the signal of the pixel 1 always higher than that of the pixel 2. Similar results characterize the response of the pixels 3 and 4, with the signal of the pixel 3 similar to that of the pixel 1 and always higher than the pixel 4. Data are compatible with an shaped illumination and in particular with the upper pixels, i.e., 1 and 3, collecting the brightest portion of the spot.

Work is in progress to extract the bunch-by-bunch transverse size of the source collecting data from more than four pixels of the array.

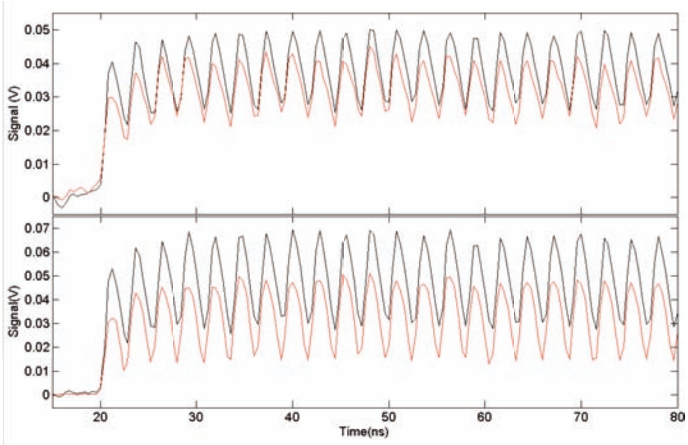

***FIG. 21** - Data from the four pixels of the IR array detector showing the first 22 bunches of the electron beam with an accumulated current of ~2000 mA.*

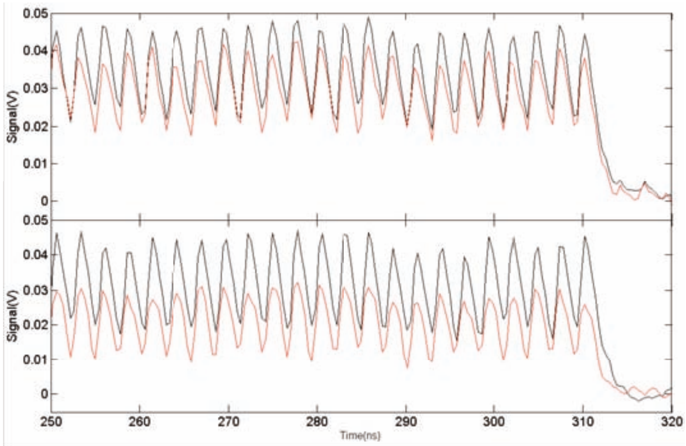

***FIG. 22** - Data from the four pixels of the IR array detector showing the last 22 bunches of the electron beam with an accumulated current of ~1700 mA.*

CONCLUSIONS

A new IR experimental station dedicated to the bunch-by-bunch diagnostics of the e^+ beam in the DAΦNE collider, has been installed and commissioned. The 3+L experiment is based on compact and fast photon IR detectors that allow to measure beam parameters such as longitudinal and transverse sizes, collecting the synchrotron radiation extracted by a bending magnet of the positron ring.

This experiment used, for the first time, fast IR detectors with sub-ns response times recently available on the market, to monitor in real time electron and positron bunches. Improvements in the performances of these compact IR photo-detectors i.e., faster response times and higher S/N ratio, allowed us to observe response times of ~ 225 ps.

The devices we tested in the framework of the 3+L experiment allow the separation of the emission between consecutive bunches of both e^-/e^+ beams addressing the challenging possibility of a real time longitudinal bunch-by-bunch and turn-by-turn diagnostic. In particular data showed that, with a bunch current of ~5 mA, the bunch profile is Gaussian with a length of σ~240 ps. The best estimated rise time and fall time of these IR detectors are ~ 400 ps. Moreover, for currents lower than ~7 mA/bunch, we measured a σ value substantially constant of ~225 ps, that at room temperature is probably the lower limit in the

time response of such photodiodes and their associated electronics.
From a comparison with data collected with the streak camera installed at DAΦNE [13], the σ measured at IR wavelengths is 3 to 4 times larger but improvements are foreseen with a better electronics and with most performing detectors. However, already now the diagnostics based on fast IR photodiodes may return information about the longitudinal dynamics of the beam in the multi-bunch mode that are not achievable with the streak camera available at DAΦNE with the present set up.

Similar experiments have been performed also at the Hefei Light Source (HLS) with the same IR photodiodes. In this case data have been compared with the information collected at the diagnostics beamline of this synchrotron radiation facility of the National Synchrotron Radiation Laboratory (NSRL). We performed simultaneous measurements at IR wavelengths of electron bunches using the experimental set-up of the diagnostics beamline, i.e., with a fast InGaAs photodiode optimized in the NIR/visible range (750-1700 nm) and a streak camera. Comparable results have been obtained with the two diagnostics, resolving in the full-fill pattern mode both the time structure of the electron bunches and the profiles of each individual bunch demonstrating that IR photon-beam diagnostic is suitable for almost all accelerators.

In the next future improvements should be obtained using faster (cooled) IR photodiodes with a better time resolution, e.g., response times ≤100 ps. With this improved technology better results monitoring bunch lengths should be obtained both for DAΦNE and for almost all circular accelerators, working at high and at medium-low energies.

In collaboration with the VIGO Company we developed also a first prototype of a fast bi-dimensional IR detector made by two linear arrays with 32 pixels. This device has been optimized to work at mid-IR wavelengths with a response time of each single pixel of ~ 1 ns although, in principle, new devices may be assembled and characterized by faster response times. We also showed for the first time that an array device can be successfully used to perform real time imaging of a synchrotron source at IR wavelengths. Indeed, an optimized device should be used for a turn-by-turn and a bunch-by-bunch diagnostics of the transverse dimensions of the particle beam.

The array with the electronics board is at present under installation at the 3+L experiment with the goal to monitor the transverse size of the positron bunches. In the last months we also started data acquisition from a few pixels of the IR array detector monitoring the e^- beam at the SINBAD IR beamline at DAΦNE. Analysis of the data shows that the pixels signals exhibit different amplitudes that can be correlated to the intensity of the source. Work is also in progress to characterize all pixels of the array and to store a fast transverse IR image of the circulating bunches with an optimized fast digital electronics. With such new diagnostic, thanks to the possibility to correlate in a real time the position of the bunch and the instabilities of each packet in the train, it appears feasible to collect bunch-by-bunch data that can be successfully used to extract information regarding beam instabilities. In conclusion, the 3+L experiment really represents an important step forward to improve bunch-by-bunch diagnostics at DAΦNE as well as to achieve a more accurate knowledge in many accelerators of the beam behaviour in terms of dynamics and shape.

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