20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

# Beam Diagnostics by Infrared Time Resolved Detectors

Alessandro Drago[1],Mariangela Cestelli Guidi[1],Antonio De Sio[2],Augusto Marcelli[1],Emanuele Pace[3]

[1] *Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, Via E. Fermi 40, Frascati,* alessandro.drago@lnf.infn.it, mariangela.cestelliguidi@lnf.infn.it, augusto.marcelli@lnf.infn.it
[2] *INAF, Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze,* desio@arcetri.astro.it
[3] *Universita' di Firenze, Largo E. Fermi 5, 50125 Firenze,* pace@arcetri.astro.it

***Abstract* – Last generation storage rings, both light sources and colliders, needs many different diagnostic systems to achieve specification goals. Many commercially available diagnostics are used to measure real-time accelerators performance. Nevertheless going towards higher luminosities or lower emittance, diagnostics need to be always more sophisticated. At DAFNE, the LNF e+/e- Φ-factory, colliding at 1.02 GeV energy in c.m., efforts are carrying on to achieve higher luminosities for the KLOE detector. Given that a ~20-25% discrepancy has been measured between the extrapolated 10 bunches peak luminosity and the standard fill pattern (~100 bunches) one, it is necessary to investigate what really happens and why. Letting apart the trivial case of measurement non-linearity or saturation in KLOE, used as precision luminosity monitor, new diagnostic techniques are needed. A new diagnostics tools, based on infrared time resolved multi-pixels detector and funded by CSNV of INFN is under test at LNF to help this analysis.**

## I. INTRODUCTION

Electron and positron beams stored in last generation circular accelerators, both used as light sources and as colliders, need power diagnostics systems to evaluate and to characterize the behaviour of the stored charges. These are gathered in bunches of the order of 10^9 – 10^13 particles showing usually shapes that in first approximation are Gaussian in the three dimensions. The bunches run through the vacuum chamber at light speed in h equilibrium points (called buckets) to maintain the synchronous phase with the strong RF (radio frequency) sinusoidal fields restoring every turn the lost beam energy. The h number is called harmonic and it is given by the ratio between the RF frequency and the ring revolution frequency.

Many diagnostics systems allow the accelerator physicists to check the beam performance driving the working conditions towards the desired goals in terms of e-/e+ total stored currents, beam shapes and dimensions, transverse and longitudinal positions. Toroidal magnetic tools, electrostatic pickups, electromagnetic striplines or cavities, and synchrotron light monitors are the usual and in large part commercial devices used to know how many charges are in the ring, how they are distributed in the buckets, how much the bunches are unstable or misshaped for coupled bunch oscillations due to Coulomb's force and ring vacuum chamber impedance.

The achievement of higher luminosity for the colliders or lower emittance for the synchrotron light source, needs to control at the best the beam characteristics and to identify any not foreseen behaviours. The diagnostics role is hence fundamental and always new tools need to be planned and put under investigations to follow the accelerator physicist requests. Furthermore it is important to note that while the beam diagnostics is based on turnkey and mature technologies, on the contrary the bunch-by-bunch diagnostics has state-of-art applications showing promising development perspective.

## II. E-CLOUD INSTABILITY

Charged particles passing through bending or wiggler magnets emit synchrotron light and the photons hitting the vacuum chamber can extract ions and electrons from the metal walls, made mostly by copper, aluminium, steel or other alloys used as coating. In general the extracted charged matter is harmful for the beams having opposite sign charge, i.e. the positive charged ions for the electron beams and the extracted electrons for positron or proton stored beams.

The free ions tend to be trapped in the negative charged bunches increasing the beam vertical size, that usually is much smaller than the longitudinal or horizontal ones by specifications. This effect is coped by using gaps (10-20% of contiguous empty buckets), vacuum pumps and clearing electrodes (that have the disadvantage to increase the ring impedance).

The effect on the beams of the electrons extracted from the metal walls is much more complicated and more difficult to cope. First of all every vacuum chamber surface type has a typical SEY (Secondary electron Emission Yields) value describing the production characteristics of the parasitic electron clouds that are formed in these regions of the ring. As said above, while for the negative charged stored particles the e-clouds are

ISBN-14: 978-92-990073-2-7

not a big issue because they produce repulsive forces, for the positive charged beam, like positrons or protons, instabilities can arise from the parasitic Coulomb's attractive fields producing severe limitations to maintain stored the particle beams. In order to limit and control the e-cloud effects, many techniques have been developed as well as many diagnostics tools to study the actual performance of each techniques. The mitigation techniques are mainly solenoidal fields, clearing electrodes and sophisticated vacuum chamber coatings. The diagnostics techniques are many and some of them are discussed in the next paragraph.

## III. THE DAFNE CASE

DAFNE is a Φ-factory, i.e. a circular accelerator composed by electron-positron double main rings, a LINAC, transfer lines and one accumulator ring. DAFNE is located at Frascati and colliding at 1.02 GeV energy in centre of mass [1]. See Fig. 1. below.

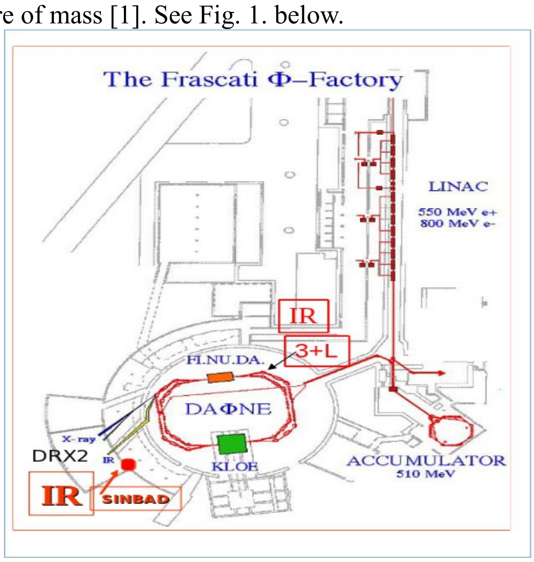



Fig. 1. DAFNE layout with the two IR beamlines

In DAFNE, powerful and extremely advanced bunch-by-bunch feedback systems are used to control destructive or harmful oscillations of the beams both in the longitudinal and in the two transverse planes. The feedback control is implemented by fast correction signals applied to power amplifiers feeding stripline-type or cavity-type kickers [2],[3].

It is interesting to note that the instability growth rate for each oscillation mode can be quickly evaluated by using the bunch-by-bunch feedback systems. In particular in DAFNE the more evident e-cloud effect is an extremely fast horizontal instability [4] with grow rates of the order of 20 microseconds or even less for the -1 mode (resistive wall instability) as confirmed also by simulations made by e-cloud models [5]. The feedback systems are so powerful and efficient to be able to damp in ~20 revolution turns, i.e. ~7 microseconds [6]. To get this result the power applied usually is 500 W but in some cases it has been 1000 W.

To limit the e-cloud effects in the positron ring, solenoids have been installed around the straight sections of the vacuum chamber and clearing electrodes have been inserted inside the 8 bending magnets and in the 4 wigglers where the synchrotron light hits stronger.

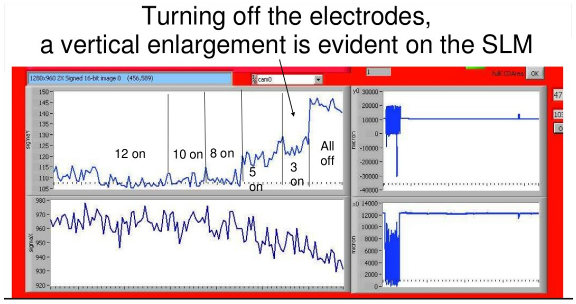



Fig. 2. Turning off the clearing electrodes a beam vertical enlargement is evident on the SLM.

Diagnostics systems are necessary to verify and evaluate the setup and the correct operation of solenoids and electrodes, for example checking the best voltage value to apply to the electrodes and with which polarity. The voltage has been progressively increased up to 500 V while the polarity, at the begin with attractive sign, is now changed to the repulsive one. This is to avoid to have too large parasitic currents towards the electrode power supplies causing faults.

At DAFNE, up to now, the diagnostics used to monitor solenoids and electrodes basically are [7],[8]:

a) standard SLM (synchrotron light monitor),

b) modal grow rate measurements,

c) bunch by bunch betatron tune spread along the pattern train.

For the first diagnostics the SLM gives only beam transverse sizes, enveloping all the bunch train, while the last two measurements are bunch-by-bunch techniques made by using the feedback capabilities.

The importance of these measurements is in the fact that a vertical enlargement can be also produced for the positron beam by the e-cloud effect (observed by the SLM turning off the clearing electrodes, see Fig. 2.). A beam vertical enlargement of course decreases the peak luminosity as intuitively and analytically it can be argued.

The betatron tune spread along the bunch train can be easily observed by using the feedback diagnostic capabilities in the two transverse planes of the positron beam, while it is negligible for the electron beam. See in the Fig.3 the horizontal tune spread with the clearing electrodes turned off, and in the Fig.4. the same measure with the electrodes turned on. Both measurements are done at about 600 mA beam current. In the first case the spread is 0.008 while in the second it is reduced to 0.004.

Given that the betatron tune are carefully chosen to get the higher peak luminosity it is clear that, larger is the tune spread, minor is the total peak luminosity.

## IV. DAFNE LUMINOSITY

Beyond the e-cloud issue and the other beam instabilities that can be classified as single beam behaviours, DAFNE needs to solve also other problems directly related to the luminosity, i.e. to the collision intensity. Indeed many efforts are carrying on to achieve higher peak luminosity for the KLOE detector, that takes data from collisions at 1.02 GeV energy. In the last years the crab-waist [9] technique has been implemented in the interaction region. Basically this is done by focussing the two beams by a couple of very strong sextupole magnets for each ring to obtain a higher peak luminosity. This technique has lead to very good results in the past for the Siddartha detector achieving >4*10^32 cm$^{-2}$s$^{-1}$ peak luminosity. The same result for KLOE detector still has not been gotten but the work is in progress.

Indeed not only the peak luminosity is lower by a factor >2, but there is also a 20-25% discrepancy that has been measured between the 10 bunches peak luminosity (extrapolated) and the standard fill pattern (~100 bunches) one, so it is necessary to investigate what really happens and why. More exactly the peak luminosity (July 2014) has been 2*10^31 cm$^{-2}$ s$^{-1}$ for 10 bunches and 1.7*10^32 cm$^{-2}$ s$^{-1}$ for 100 bunches.

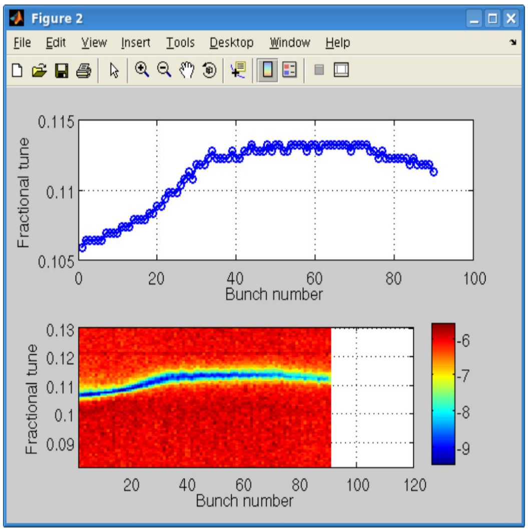



Fig. 3. Horizontal e+ tune spread versus bunch number with clearing electrodes turned off and ~600mA beam current.. The spread is 0.008

Letting apart the trivial case of a non-linearity or a saturation of KLOE detector measurement system, that however should carefully checked, new studies can be planned. Furthermore KLOE is used as precision luminosity monitor because this is the best that can be done at DAFNE but what really would be useful to understand the luminosity discrepancy should be a precision bunch-by-bunch luminosity monitor that unfortunately is not still available. Indeed if the luminosity lack could be correlated to the e-cloud effects as vertical enlargements or betatron tune spread, because distributed with the same tendency along the positron bunch train, this would be extremely useful to clarify the problem and to try to fix it.

Moreover also the vertical position for each bunch of the two beams need to be measured because it cannot be excluded that the vertical enveloped measured size has a component given by vertical position shift beyond shape variation along the bunch train.

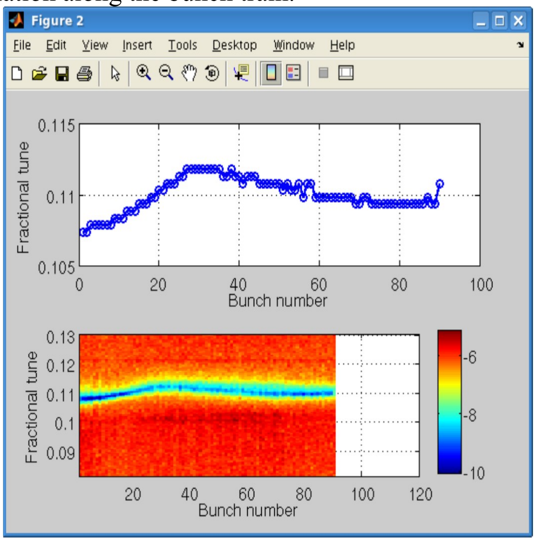



Fig. 4. Horizontal e+ tune spread versus bunch number with clearing electrodes turned on and ~600mA beam current. The spread is 0.004

The question is: how to discover these not foreseen behaviours?

In this paper an innovative diagnostic tool, working bunch-by-bunch and turn-by-turn is presented together with some preliminary measurements made at DAFNE by using it. In particular an experiment, called 3L_2D and including this innovative detection system, has been funded by the CSNV (Commissione Scientifica Nazionale V) of INFN for the years 2013-14. The 3L-2D experiment has the goal to study the beam behaviour in terms of position and size and especially but not only in presence of electron cloud effects.

The importance of this study is evident, as said above, from the DAFNE e+ SLM data showing that the e-cloud density increasing produces vertical enlargements of the bunches (Fig. 2.) and bringing, as consequence, to a luminosity decrease. What is not clear is how the enlargement is distributed along the bunch train and how it depends by the stored pattern. Furthermore it must be underlined that the 3L_2D detector can give vertical position information for each bunch that can be useful also for the electron beam. Indeed a partial bad overlap for only few bunches at the interaction point could be another source of luminosity lack. It can be noted that the regular DAFNE orbit monitor gives an average orbit with a refresh of only 7 Hz and cannot be used for the goal.

In conclusion the 3L_2D detector can hence help to explain the luminosity discrepancy found showing both vertical position and vertical enlargement for each bunch.

## V. INFRARED UNCOOLED DETECTORS

As well known, the synchrotron light is the most common radiation field applied to beam diagnostics. There are classic techniques to measure the dimensions of cross section of the beam from the image of SR emission as well as to measure the angular spread of the particles in the beam by direct emission observation [10]. From a longitudinal point of view it is possible to measure the bunch length by using a simple photo diode. Given that the synchrotron radiation is spread in a large frequency range, the light can be used for diagnostics by making observations in the IR, visible, UV and X-ray. While for high energy and ultra low emittance beams the X-ray and UV detection is preferred, for relatively low energy storage rings, like DAFNE rings, that are working at 510 MeV, with beam transverse dimensions and emittance that are not very small, infrared detectors can be used fruitfully offering from some points of view the most interesting choice.

The authors, in collaboration with the VIGO S.A., are carrying on a research line to use HgCdTe uncooled detectors working in the mid-infrared (~10 micron) with a rise time < 1ns. In particular the experiment wants to use HgCdTe semiconductors as diagnostics tool to make bunch-by-bunch and turn-by-turn measurements in the longitudinal [11,12] and transverse [13] plane.

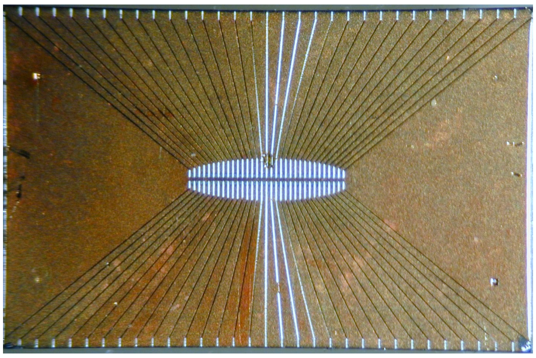


Fig. 5. The 2x32 pixel HgCdTe array detector by VIGO S.A. The total area is 2x4 mm.

This low cost approach have to cope, from a commercial point of view, with much more expensive streak cameras for the longitudinal bunch length and with synchrotron light monitors or gated cameras for transverse measurements. Commercial SLM devices, that work at frequencies around or below 100 Hz, can acquire only the envelope of the beam and not the bunch-by-bunch profile as for the 3L_2D experiment goal. However also the expensive commercial gated cameras still do not seem to have the needed capabilities in terms of sampling clock that for DAFNE is 368 MHz.

Another key point for the experiment is the interest about time resolved infrared detectors that is growing since the development of uncooled compact semiconductor devices with very fast response time that can be used in many different fields, from astrophysics to biomedical, from laser to particle beam diagnostics, as well as for space and military purposes.

In this particular case, the IR time resolved detection system of the 3L_2D experiment is designed for investigations about e-cloud effects on the bunch-by-bunch transverse dimensions in different filled patterns by using the 3+L positron infrared beamline of DAFNE and as consequence to study also the peak luminosity lack described above. Measurements are also carried on at SINBAD, the infrared beam line from the electron ring.

## VI. APPARATUS DESCRIPTION

To use the HgCdTe semiconductors with the goal to the beam data taking, a special dedicated apparatus has been designed and built at LNF with great amplification and large frequency range.

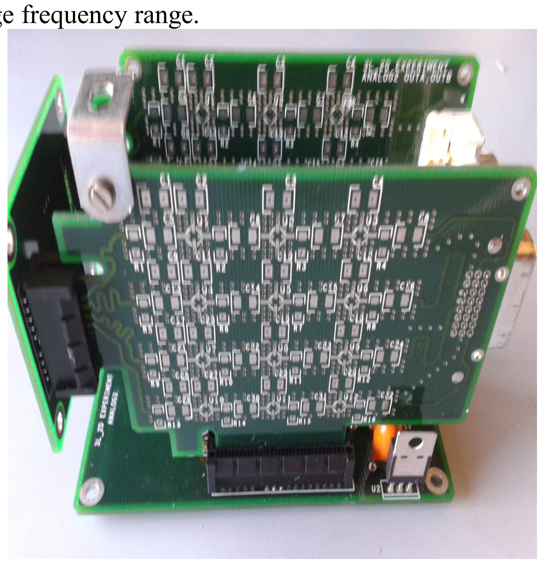
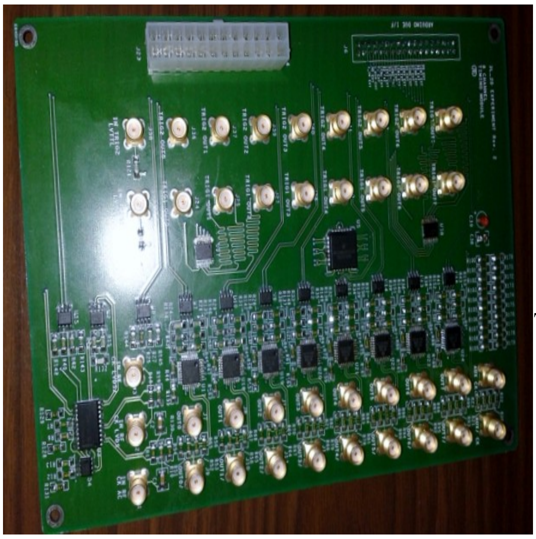


Fig. 6. The four analogue modules containing the array and 2x16 channels of 3-stage amplification. All boards are put inside a small box.

In particular the transverse bunch-by-bunch system is built around the small semiconductor with 2x32 pixel array producing very small signals of the order of tens of microVolts. See Fig. 5.

To acquire the signal a special and very compact camera has been built having 16 channels with 3-stage amplification that gives >40 dB gain, see in Fig. 6. Sixteen amplified analogue signals are connected to custom designed FPGA systems with 14 bit analogue to digital converter. To acquire each pixel a programmable modular timing board with 1 ps of rms jitter and 10 ps of minimum step has been designed with 8 channels. See in Fig. 7. The delay for each pixel is programmable by a low cost Arduino Due board interfacing a personal computer. The bunch-by-bunch and turn-by-turn data acquisition can arrive to 16 M contiguous values that are stored in real time on the FPGA and then sent to the server by using http protocol through a dedicated local area network.



To

Fig. 7. The precision timing module to deskew for each pixel the 368 MHz sampling clock with 1ps of rms jitter and 10 ps of minimum steps.

## VII. MEASUREMENTS

Preliminary data have been taken from SINBAD beamline at DAFNE in the last 13 June and are presented below in Fig. 8.

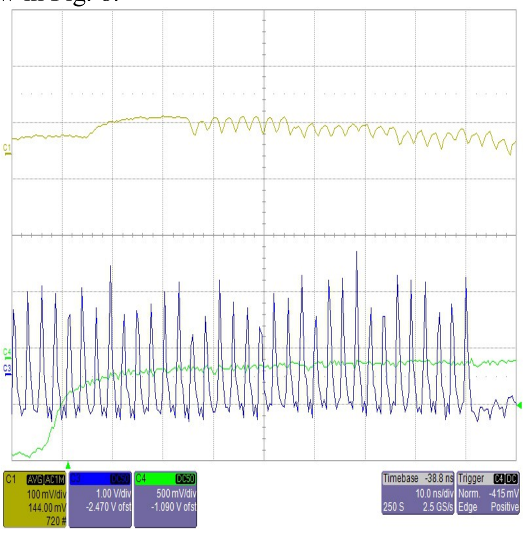


Fig. 8. DAFNE data taking from SINBAD on June 13, 2014. The green trace is the machine revolution trigger, the blue trace is the beam signal from an electromagnetic pickup, the yellow trace is the beam signal from one HgCdTe pixel amplified by 40 dB.

The green trace is the machine revolution trigger, the blue trace is the beam signal from an electromagnetic pickup, the yellow trace is the beam signal from a HgCdTe pixel amplified by 40 dB.

The experiment data taking will restart in the next October following the DAFNE runs after the summer 2014 shutdown.

## VIII. CONCLUSION

An innovative diagnostics system has been presented in this paper with some preliminary measurements done in the last June. DAFNE really needs in the next run answers and solutions to the not foreseen problems arisen in the last runs with KLOE detector and the 3L_2D experiment can help to solve them.

## IX. ACKNOWLEDGEMENT

This is to remember and to thank for the excellent work done many researchers and technicians involved: Alessio Bocci that has been the beginner of the IR detector research, Lisa Gambicorti that has designed the 3+L mirror beamline scheme, Rossano Sorchetti and Simone Bini that have many times realigned the 3+L beamline mirrors, Donato Pellegrini that has built the camera mechanics and and Umberto Frasacco that has assembled the timing boards.

## REFERENCES

[1] The DAΦNE Project Team presented by G.Vignola, "DAΦNE, The Frascati PHI-factory", 1993 Particle Accelerator Conference (PAC '93), Washington, May 1993, p.1993.

[2] S. Bartalucci, M. Bassetti, R. Boni, S. De Sanctis, A. Drago, A. Gallo, A. Ghigo. M. Migliorati, L. Palumbo, R. Parodi, M. Serio, B. Spataro, G. Vignola, M. Zobov: "Analysis of Methods for Controlling Multibunch Instabilities in DAFNE", Particle Accelerators, Amsterdam, Vol. 48, n. 4, Feb. 1995, p.213 -237. LNF-93/067 (P), 15/10/1993.

[3] A. Drago, et al., "Longitudinal Quadrupole Instability and Control in the Frascati DAFNE Electron Ring", published in Physical Review Special Topics - Accelerators and Beams, Vol. 6, pag. 052801-1, 052801-11, 2003. Also published in SLAC-PUB-9829, May 2003. 27 pp.

[4] Alessandro Drago, "Fast Horizontal e+ instability measurements in DAFNE", PAC'09-TH5RFP057, 3pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.

[5] Theo Demma, Alessandro Drago, Susanna Guiducci, Mikhail Zobov (INFN/LNF, Frascati (Roma)), Kazuhito Ohmi (KEK, Ibaraki), "A simulation study of the electron cloud instabilty at DAFNE", FR5RFP070, proceedings of PAC09, Vancouver, BC, Canada, 4-8 May 2009. 3 pp. PAC09-

FR5RFP070. Presented at Conference: C09-05-04.
[6] Alessandro Drago, “DAFNE horizontal feedback upgrade”, PAC’09-TH6REP072, 3pp. Presented at Particle Accelerator Conference (PAC 09), Vancouver, BC, Canada, 4-8 May 2009.
[7] A.Drago, D. Alesini, T. Demma, A. Gallo, S. Guiducci, C. Milardi, P. Raimondi, M. Zobov, INFN-LNF, 'Mitigation and control of instabilities in DAFNE positron ring'. e-Print: arXiv:1204.5016 [physics.acc-ph]. BIW’12, Newport News, VA, USA.
[8] D. Alesini, A. Drago, A. Gallo, S. Guiducci, C. Milardi, A. Stella, M. Zobov (Frascati), S. De Santis (LBNL, Berkeley), T. Demma (Orsay, LAL), P. Raimondi (ESRF, Grenoble). “DAFNE operation with electron-cloud-clearing electrodes”. 2013. 6 pp. Published in Phys.Rev.Lett. 110 (2013) 124801. DOI: 10.1103/PhysRevLett.110.124801.
[9] ] C.Milardi et al., “DAFNE setup and operation with the crab-waist collision scheme”. EPAC08-WEPP036, Jul 2008. 3pp. Proceedings of EPAC08,Genoa,Italy:2599-2601,2008
[10] Albert Hofmann, “The Physics of Synchrotron Radiation”, Cambridge University Press, 2004.
[11] A. Bocci, M. Cestelli Guidi, A. Clozza, A. Drago, A. Grilli, A. Marcelli, A. Raco, R. Sorchetti, M. Piccinini, M. Piccinini, E. Pace, J. Piotrowski. 'Bunch-by-Bunch Longitudinal Diagnostics at DAFNE by IR Light', DIPAC’07, Venezia.
[12] A. Bocci, A. Clozza, A. Drago, A. Grilli, A. Marcelli, M. Piccinini, A. Raco, R. Sorchetti (LNF), L. Gambicorti, (INOA-Firenze), A. De Sio, E. Pace, (Un. degli Studi di Firenze), J.Piotrowski, (VIGO, Poland), 'Beam Diagnostics of the positron beam at DAFNE by 3+L experiment', TH5RFP058, PAC'09.
[13] A. Bocci, M. Cestelli Guidi, A. Clozza, A. Drago, A. Grilli, A. Marcelli, A. Raco, R. Sorchetti, INFN-LNF, Frascati, L.Gambicorti,Istituto Nazionale di Ottica Applicata-CNR, Firenze, Italy, A. De Sio, E. Pace, Università degli Studi di Firenze, Firenze, Italy, J. Piotrowski, VIGO System SA, Poland, 'Fast IR array detector for transverse beam diagnostics at DAFNE'. MOPD098. IPAC'10.