Nuclear Inst. and Methods in Physics Research, A 1033 (2022) 166661

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Method for measuring positron number in high intensity nanosecond positron bunches based on Poisson statistic

B. Rienäcker [a], S. Mariazzi [b,c,*], L. Povolo [b,c], F. Guatieri [d,b], R. Caravita [c], L. Penasa [b,c], F. Pino [e], G. Nebbia [f], R.S. Brusa [b,c]

[a] Physics Department, CERN, 1211 Geneva 23, Switzerland
[b] Department of Physics, University of Trento, via Sommarive 14, 38123 Povo, Trento, Italy
[c] TIFPA/INFN Trento, via Sommarive 14, 38123 Povo, Trento, Italy
[d] Tech Univ Munich, FRM 2, D-85747 Garching, Germany
[e] Department of Physics and Astronomy "Galileo Galilei" University of Padova, Via Marzolo 8, 35131 Padova, Italy
[f] INFN Padova, via Marzolo 8, 35131 Padova, Italy

ARTICLE INFO

Keywords:
Positron
Positron beam
Gamma radiation detection

ABSTRACT

A novel method for the measurement of the number of positrons contained in intense positron bunches is presented. The technique is based on the Poisson distribution of the number of gamma rays emitted by many simultaneous positron–electron annihilations in a small solid angle. The results have been found in good agreement with those achieved with a calibrated CsI(Tl) detector coupled to a photodiode. The small dimension of the required equipment and the reduced constraints of the technique open the possibility of monitoring, in complex positrons systems, the number of positrons at different positions that are too difficult to reach with other devices.

1. Introduction

The recent development of an efficient positron (e^+) trapping and storage technology [1] has allowed the production of intense positron bunches opening the possibility of a series of new experiments. The use of positron trapping and storage was at the basis of the first anti-hydrogen formation [2,3] and the production of molecular di-positronium (Ps_2) [4]. Other fields that have benefited from this technique are positronium (Ps) spectroscopy [5–9] and Ps–Ps interaction studies [10] thanks to the high yield of positronium in vacuum that can be obtained by implantation of positrons into positron/positronium converters [11–13]. The production of dense Ps clouds is also critical to perform many other fundamental experiments such as the production of anti-hydrogen through charge exchange reactions between Ps excited into Rydberg states and antiprotons [14–16], precise spectroscopy experiments for QED tests [17–20], tests of gravity on matter–antimatter systems [21,22], high resolution tests for the existence of mirror matter [23] and laser cooling tests on ultra-light atoms [24].

The number of positrons contained in these intense bunches has been so far estimated by using a calibrated CsI detector coupled to a photodiode or Faraday cups [25–27]. These methods are fast and can therefore be used for online monitoring of the e^+ beam intensity in fixed points of a positron apparatus. However this kind of measure involves the simultaneous annihilation (within 10–20 ns) of up to 10^8 positrons; as a consequence, nonlinearity effects of the detection chain and/or saturation of the signal could affect the estimation. In the present work the results of such measures have been verified with a totally different technique based on the Poisson distribution of gamma rays emitted by many simultaneous positron–electron annihilations in a solid angle covering only a small fraction of the full 4π sphere. This novel method is immune to all effects of detector nonlinearity and furthermore allows to monitor the number of positrons annihilating in all the positions of the positron systems where the installation and the calibration of dedicated devices might be difficult to achieve.

2. Experimental method

AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is an experiment based at CERN that aims at the direct measurement of the Earth's gravitational acceleration on antihydrogen [16]. The AEgIS positron system, used for the measurement reported in the present work (see Fig. 1), is described in detail in Ref. [26]. Briefly, positrons are produced via β^+ decay by a 7 mCi ^{22}Na source. Fast positrons from the radioactive source are slowed down to an energy of a few eV by using a solid Ne moderator [28]. The slow e^+ are magnetically guided into a three-stage Surko trap (First Point

* Corresponding author at: Department of Physics, University of Trento, via Sommarive 14, 38123 Povo, Trento, Italy.
E-mail address: sebastiano.mariazzi@unitn.it (S. Mariazzi).

https://doi.org/10.1016/j.nima.2022.166661
Received 13 January 2022; Received in revised form 18 March 2022; Accepted 21 March 2022
Available online 11 April 2022

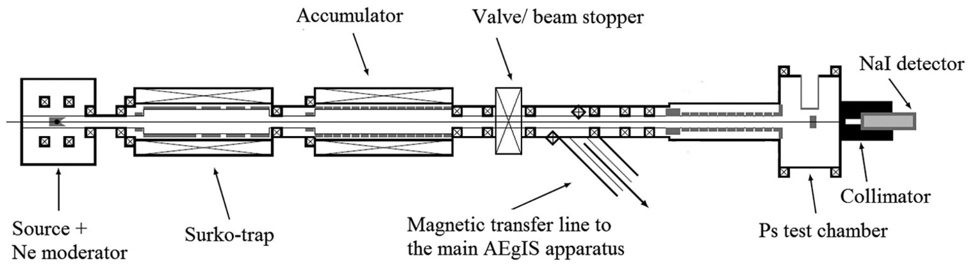

Fig. 1. Sketch of the employed positron system.

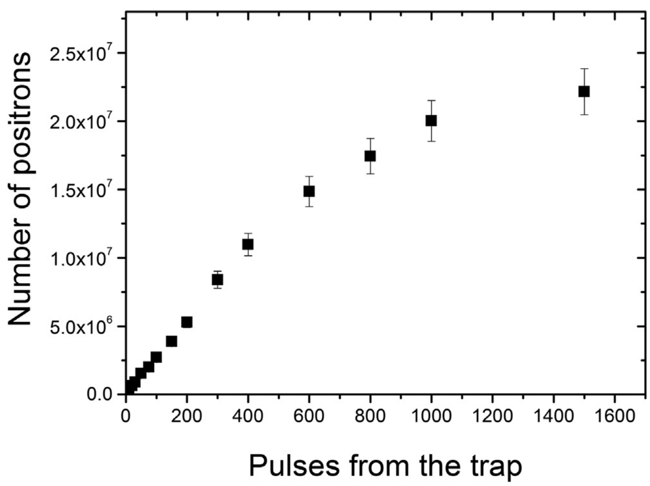

Fig. 2. Number of positrons in the accumulator plotted against the number of pulses from the Surko trap as measured with a calibrated CsI detector coupled to a photodiode (black squares). The asymptotic value of $\sim 2 \cdot 10^7$ is determined by the positron lifetime in the accumulator. The source activity was 7 mCi. Statistical errors are shown.

scientific technology) [1]. In the Surko trap the positrons are cooled by interacting with N_2 and SF_6 gas and released after trapping every 0.15 s with an energy of ~17 eV. Positrons released from the trap are transported by magnetic fields towards the accumulator where many positron pulses can be stored. Thanks to the absence of contaminants (base pressure in the low 10^{-10} mbar range) and the optimization of the cooling gas pressure (N_2 pressure around $6 \cdot 10^{-8}$ mbar), the positron lifetime in the accumulator exceeds hundred seconds. The e^+ radial confinement in the accumulator is provided by a 0.1 T magnetic field.

Longitudinal confinement of the positrons is ensured by a harmonic potential well of approximately 14 V generated by 23 electrodes of 2.54 cm in diameter. Positrons dumped from the accumulator can be magnetically transported to the main magnets of the AEgIS experiment [16,29] or to the secondary chamber for Ps experiments [26,30]. Extraction of the positron bunch from the accumulator and following magnetic transport result in a transport efficiency close to 100 %. Fig. 2 shows the number of positrons stored in the accumulator as a function of the number of pulses from the trap (and thus as a function of time).

The measurement was performed by storing positrons for a given time and then dumping them with an energy of around 300 eV. Dumped positrons were annihilating on a valve, used as stopper, placed in the proximity of the accumulator exit (see Fig. 1). The spot diameter of positrons in this region has been measured by a MicroChannel Plate (MCP) coupled to a phosphor screen, the FWHM turns out to be smaller than 3 mm. Positrons annihilated with the electrons of the medium yielding two gamma rays of 511 keV from each e^+ annihilation. The emitted gamma rays were detected by a calibrated CsI(Tl) detector (40×50 mm) coupled to a photodiode (Scionix assembly 40 P 50/18-E2-Cs-X, photodiode Hamamatsu Si PIN S3204) placed in the proximity of the valve, in order to determine the absolute positron number. In this test, up to $\sim 2 \cdot 10^7$ positrons were stored in around 225 s (corresponding to roughly 1500 pulses from the trap. See Fig. 2). The calibration of the CsI(Tl)+photodiode detector was performed by using a phosphor screen (Kimball Physics PHOS-UP22GL-B7x7-R750) coupled to a CCD camera (Hamamatsu, Orca R2). A continuous beam with a known number of positrons[1] was allowed to annihilate on the phosphor screen to record the related image intensity. Then, positrons were pulsed and dumped on the same phosphor screen. The number of positrons contained in the bunch was estimated on the basis of the comparison of the first and latter image intensity produced on the phosphor (for the linearity of phosphor screen with the number of impinging particles see, for example, Ref. [27]). The signal annihilation given by the positron bunch was simultaneously acquired with the CsI(Tl)+photodiode. The signal amplitude of the CsI(Tl) detector was finally correlated to the image intensity of the phosphor and thus to the number of positrons in the bunch. The effort to calibrate the CsI(Tl) detector instead of directly using the phosphor screen coupled to the CCD camera is justified by the flexibility of the CsI(Tl) detector. Indeed, it is a small and external detector that is not bound to the position where it has been calibrated and can be used in different positions of the system (provided that the variation of solid angle and attenuation of the surrounding materials are taken into account). However, the described calibration could introduce some error in the determination of the positron number contained in the bunch mainly due, as previously mentioned, to nonlinearities and/or saturation effects that could affect the outcome [25,31]. This made desirable a cross check of the number with an alternative technique.

The method here investigated to determine the intensity of the positron bunch is based on the Poisson distribution of emitted gamma rays in a small solid angle. The number of photons emitted by the annihilation of a bunch of e^+ is distributed isotropically and in a small solid angle their distribution is expected to be Poissonian, namely following the probability mass function given by Eq. (1):

$$P(n) = \frac{\lambda^n}{n!} \cdot e^{-\lambda} \tag{1}$$

where n is the number of gammas measured for each event in the fraction of solid angle $\delta\Omega/\Omega$ defined by the detector and λ is the mean value of such number, that is $\lambda = N \cdot \delta\Omega/\Omega$, where N is the total flux of gamma rays emitted by positron annihilation for each accumulator spill.

For the present measurements we have used a $2'' \times 4''$ NaI crystal coupled to a spectroscopy photomultiplier tube (PMT) (Scionix Hollande, 51 B 102/2M-E1 assembly), the detector being placed inside a 5 cm thick lead collimator with an entrance hole of 2 cm diameter. In such way only the central part of the detector is irradiated in order to optimize the full energy peak efficiency. The detector has been calibrated, at first, with single photons emitted from a ^{22}Na source so

[1] A calibrated NaI+PMT detector has been used to estimate the intensity of the continuous beam. The NaI detector has been calibrated by using a calibrated ^{22}Na radioactive source placed at different distances from the detector. The threshold of the pulse amplitude discriminator has been set in order to acquire only 511 keV excluding Compton and 1274 keV gammas.

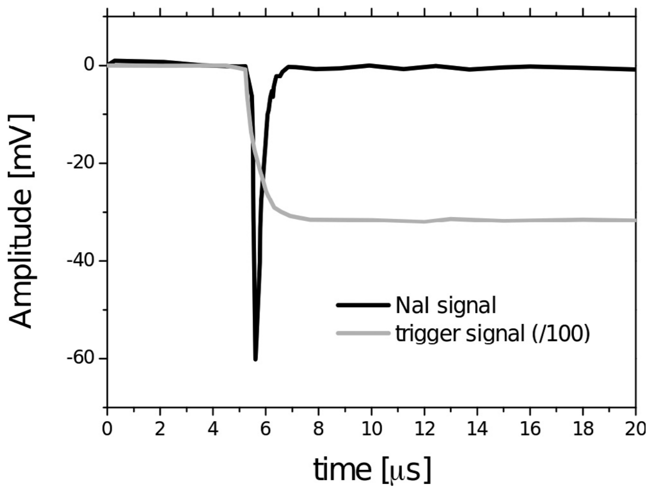

Fig. 3. Signal detected with the NaI detector (black curve). The amplitude of 60 mV corresponds to the detection of 3 gamma rays of 511 keV. The gray curve is the trigger signal (divided by a factor 100) used to dump positrons from the accumulator.

that it would deliver a 20 mV signal for a gamma ray of 511 keV. The detector has been then set at a distance of 145 cm from the closed gate valve at the exit of the accumulator, defining a geometrical acceptance of $\delta\Omega/\Omega = 1.18 \cdot 10^{-5}$ (see Fig. 1). The alignment has been done with a laser pointer. A series of test runs were made with the AEgIS positron system in order to verify the presence of signals multiple of 20 mV. Signals of 20, 40, 60, 80 mV amplitude were observed and ascribed to the detection of 1, 2, 3, 4 gammas, respectively. Only a few events with amplitude not being a multiple of 20 mV were recorded. They were excluded from the statistic when their amplitude was more than ±10% out of the closest multiple of 20 mV. A signal corresponding to the detection of 3 gammas with energy of 511 keV is reported in Fig. 3.

Complete GEANT 4 simulations have been run to better interpret the experimental tests. PENELOPE physics (G4EmPenelopePhysics Class Reference) has been used to simulate two different geometries: the full geometry of our apparatus and the case of detector + lead collimator without other structures around (see Fig. 4a). For each simulation, 5 10^9 gamma rays at 511 keV have been generated at a distance of 145 cm from the detector front surface. The energy spectra simulated using the two geometries are reported in Fig. 4b. In both the configurations, the signal of the 511 keV events is predominant explaining why many measured signals were multiple of 20 mV. In the case of the simulation in the detector + lead collimator configuration, the ratio between the counts in the full energy peak and the number of 511 keV gammas in the solid angle determined by the collimator gives a direct estimation of the full energy peak efficiency at 511 keV of our detector (0.64, in agreement with the indication given by tests with the ^{22}Na radioactive source).

The introduction of the full geometry in the simulation produces a decrease of the 511 keV photopeak amplitude due to the attenuation given by the material interposed between the detector and the positron annihilation spot. By comparing the number of counts in the photopeaks in the two simulated geometries, the gamma attenuation factor results $\mu_\gamma = 0.137$. This value is in good agreement with a cross check estimation done considering the materials placed between the accumulator exit and the detector (a stainless steel flange of 2 cm, the steel valve plate of about 1 cm, and about 3 mm of steel which is the phosphor holder installed in the Ps test chamber) and their attenuation coefficients at 511 keV [32]. The introduction of the full geometry also results in the increase of the counts on the left of the 511 keV photopeak. This effect is ascribable to the presence of Compton gamma rays scattered towards the detector from the surrounding materials [33,34]. As in the experimental tests we counted in the photopeak all the signals with an amplitude multiple of 20 mV ± 10%, even Comptons with an energy above 460 keV (corresponding to an amplitude of 18 mV) were recorded. From the simulation, one can observe that, of all the events with energy above 460 keV, 15% belong to scattered Comptons and 85% are in the 511 keV photopeak. Taking into account this effect, the simulations indicate that the effective detection efficiency at 511 keV in our experimental tests is 0.75 = 0.64/0.85.

At this point, measurements of amplitude distribution were performed and compared with the Poisson distributions of Eq. (1) in order to extract the average number of gammas emitted per spill of the accumulator.

3. Results and discussion

A first run of 100 measurements has been performed storing for each measurement 100 pulses in the accumulator and spilling them.

The results of such measurements are shown in Fig. 5 (plotted in % probability). The experimental distribution well represents a Poisson one and is compatible with an average number of photons between 3 and 4. The best fit according to Eq. (1) gives $\lambda = 3.4 \pm 0.2$ (reduced χ^2 = 0.31).

Taking into account the correction factors for attenuation (μ_γ = 0.137), geometrical acceptance ($\delta\Omega/\Omega = 1.18 \cdot 10^{-5}$), folding the experimental results with the values of detection efficiency and Compton contribution yielded by the GEANT4 calculation ($\epsilon_{511\ \mathrm{keV}} = 0.75$, see previous section) and considering that an e^+ annihilation produces 2 gammas (gamma multiplicity = $\epsilon_\gamma = 2$), the number of positrons at the exit of the accumulator can be calculated as:

$$N_{e^+} = \frac{\lambda}{\mu_\gamma \cdot \delta\Omega/\Omega \cdot \epsilon_\gamma \cdot \epsilon_{511\ \mathrm{keV}}} \tag{2}$$

that turns out to be $N_{e^+} = (1.4 \pm 0.2) \cdot 10^6$. The reported error takes into account also the probability of detecting simultaneously 2 Compton whose sum of energy coincidentally is exactly (511 ± 50) keV and that can be confused with a real 511 keV event. According to the GEANT4 calculation, this contribution is less than 3% of the detected events.

A second set of measurements accumulating 1000 trap pulses for each spill has been performed. Also in this case 100 measurements were carried out. We performed some tests in exactly the same conditions as the preceding run obtaining signal amplitudes compatible with more than 20 gammas. During these test runs it was noticed that:

1. The Poisson distribution for mean values larger than 10 is very broad.
2. The preliminary tests showed that the detector response is not linear for a flash of gammas larger than 15.
3. Repositioning and re-aligning the detection system, in order to reduce the geometrical acceptance, would be a rather challenging task.

Therefore we decided to keep the original geometrical acceptance and introduce an additional absorber made of thin calibrated sheets of lead in order to attenuate the flash of gamma rays reaching the detector at each spill. A lead absorber of 14.8 mm was then placed at the end of the Ps test chamber (see Fig. 1) equivalent to 4 halving lengths for 511 keV gammas, thus giving an attenuation factor of 1/16 = 0.0625 [32]. In this way the number of gammas reaching the detector at each accumulator spill was again of a few units. The experimental distribution for 1000 trap pulses is shown in Fig. 6.

The experimental distribution fits a Poisson with a mean value $\lambda = 3.7 \pm 0.1$ (reduced $\chi^2 = 0.07$). Applying Eq. (2) with proper correction factors (μ_γ = original attenuation · additional attenuation = 0.137 · 0.0625, $\delta\Omega/\Omega = 1.18 \cdot 10^{-5}$, $\epsilon_\gamma = 2$ and $\epsilon_{511\ \mathrm{keV}} = 0.75$) we obtain that at each spill of 1000 trap pulses the accumulator delivers $(2.4 \pm 0.2) \cdot 10^7$ positrons. In Fig. 7, the two values of positron number estimated at 100 and 1000 pulses with the Poisson method are compared to the

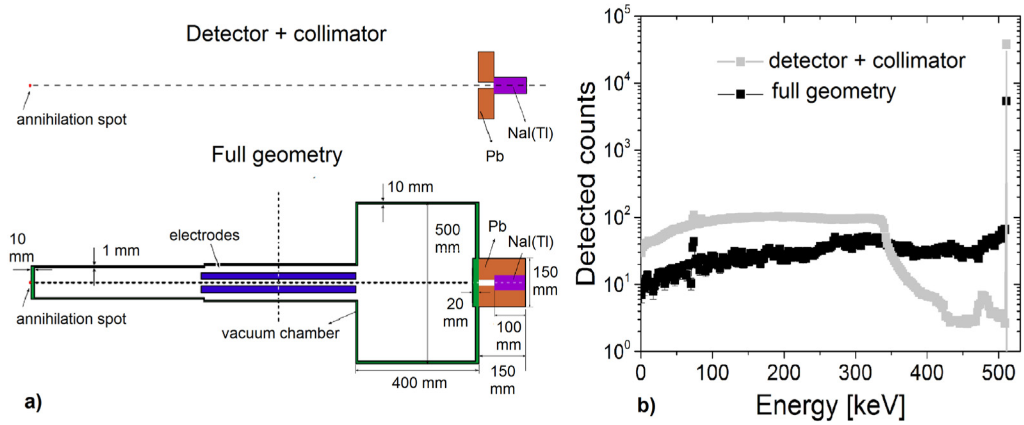

Fig. 4. Panel a shows the geometries used for the GEANT 4 simulations. The geometry of the detector + collimator configuration is reported in the upper part while the full geometry is shown in the bottom one. The simulated energy distribution of the detected gamma rays in the two geometries is reported in panel b. For each simulation, 5 10^9 gamma rays at 511 keV have been generated in the annihilation spot indicated in panel a.

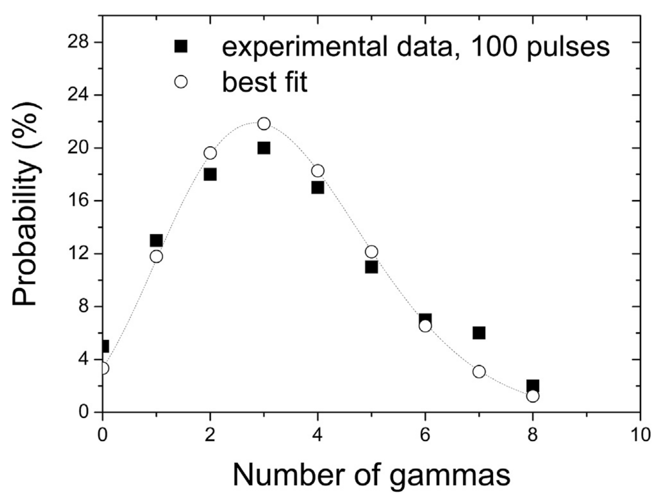

Fig. 5. Measured distribution of the number of detected gamma rays for 100 trap pulses (black squares) compared with the best fit according to Eq. (1) ($\lambda = 3.4 \pm 0.2$) (open cycles). The dashed line is an eye-guide. The fit has been performed taking into account the statistical error $N/\sqrt{N}$, where N is the number of events in each experimental point.

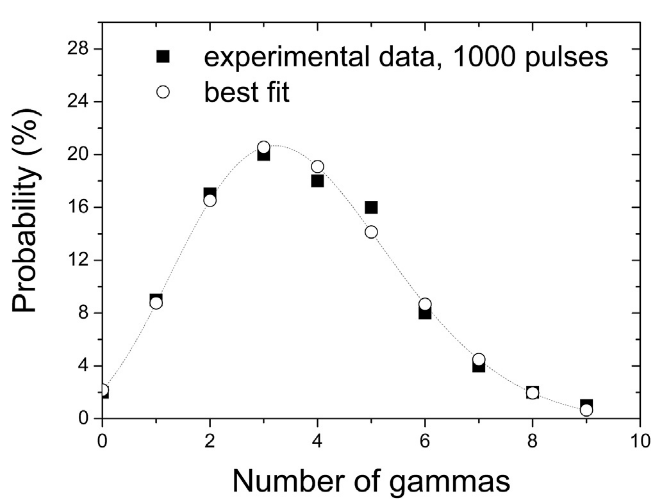

Fig. 6. Measured distribution of the number of detected gamma rays for 1000 trap pulses (black squares) compared with the best fit according to Eq. (1) ($\lambda = 3.7 \pm 0.1$) (open cycles). The dashed line is an eye-guide. The fit has been performed taking into account the statistical error $N/\sqrt{N}$, where N is the number of events in each experimental point.

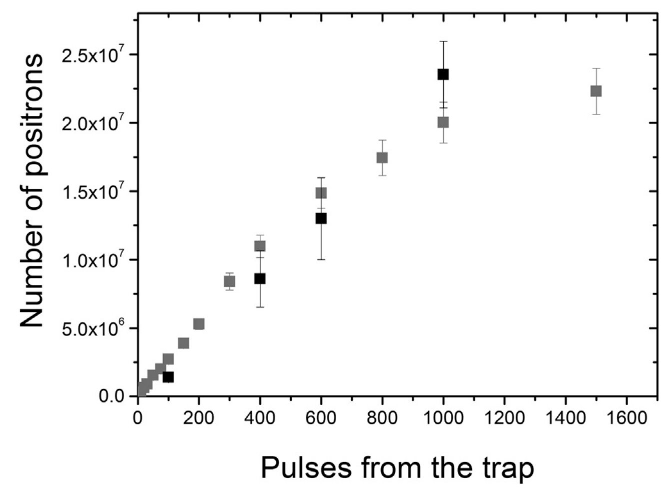

Fig. 7. The e^+ number estimated with the Poissonian method detailed in the text for 100, 400, 600 and 1000 trap pulses (black squares) compared to the values (reported in Fig. 2) measured with the calibrated CsI(Tl) detector + photodiode (gray squares). Statistical errors are reported.

results obtained with the CsI(Tl)+photodiode method. Two more values estimated with the Poisson method at 400 and 600 pulses are reported in the plot.[2] A reasonable agreement between the results achieved with Poisson and the CsI(Tl)+photodiode method has been found.

4. Conclusions

The intensity of positron bunches produced by the AEgIS positron system has been measured with a technique based on the Poisson distribution that characterizes the number of emitted gamma rays into

[2] Due to the impossibility to place the NaI(Tl) detector exactly in the same position as during the previous two measurements, three Poisson distributions have been acquired in a different position at 100, 400 and 600 pulses and the relative λ values have been extracted. The new position resulted in a value of λ <1 for 100 pulses. This allowed to appreciate the Poisson distribution even at 400 and 600 pulses without the introduction of any further attenuator. The found value of λ at 100 pulses in the new position has then been normalized to the positron number values at 100 pulses of the previous set of measurements. The values of positron number for 400 and 600 pulses have been rescaled accordingly. The obtained values for 400 and 600 pulses are reported in Fig. 7 with the relative propagated errors.

a solid angle covering a small fraction of the 4π sphere. The measurements have been performed with a $2'' \times 4''$ NaI crystal + PMT. The detector was placed inside a lead collimator with an entrance hole of 2 cm diameter in order to maximize the full energy response of the system to 511 keV gamma rays. The number of positrons estimated with this technique is in reasonable agreement with the results of measurements carried out with a calibrated CsI(Tl) detector giving a valid cross check of previous estimations.

The described Poissonian method requires many spills from the accumulator and thus a rather lengthy measurement. However this is compensated by the possibility of monitoring the number of positrons annihilating in different positions of a complex apparatus like the one of AEgIS that are too difficult to reach with other devices. Thanks to the small dimension of the needed equipment and reduced constraints of the Poissonian technique the intensity of bunches can be evaluated in practically all the positron annihilation sites such as valves, degraders and surfaces of inner devices and actuators. As the described Poissonian method works in the low gamma density regime, it can be applied also in presence of thick layers of attenuating materials interposed between the source of the burst and the detector where other methods working in the regime of many simultaneous gammas (like the one based on Cs(Tl) + photodiode) fail. This is, for example, the case of the external monitoring of the number of positrons in a burst annihilating inside superconducting magnets like the ones used in the experiments dealing with antihydrogen formation [16,35–37].

CRediT authorship contribution statement

B. Rienäcker: Investigation, Formal analysis, Writing – original draft, Validation. **S. Mariazzi:** Investigation, Formal analysis, Data curation, Writing – original draft. **L. Povolo:** Data curation, Validation. **F. Guatieri:** Software, Validation. **R. Caravita:** Validation. **L. Penasa:** Validation. **F. Pino:** Software, Validation. **G. Nebbia:** Conceptualization, Methodology, Writing – original draft. **R.S. Brusa:** Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by Q@TN, the joint lab between University of Trento, FBK- Fondazione Bruno Kessler, INFN- National Institute for Nuclear Physics and CNR- National Research Council and by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No. 754496 – FELLINI.

References

[1] J.R. Danielson, D.H.E. Dubin, R.G. Greaves, C.M. Surko, Rev. Modern Phys. 87 (2015) 247.
[2] M. Amoretti, C. Amsler, G. Bonomi, A. Bouchta, P. Bowe, C. Carraro, C.L. Cesar, M. Charlton, M. Collier, M. Doser, V. Filippini, K.S. Fine, M.C. Fontana, R. Funakoshi, P. Genova, J.S. Hangst, R.S. Hayano, M.H. Holzscheiter, L.V. Jørgensen, V. Lagomarsino, D. Landua, E. Lodi Rizzini, M. Macri, N. Madsen, G. Manuzio, M. Marchesotti, P. Montagna, H.S. Pruys, C. Regenfus, P. Riedler, J. Rochet, A. Rotondi, G. Rouleau, G. Testera, D.P. Van der Werf, A. Variola, T.L. Watson, Nature 419 (2002) 465.
[3] G. Gabrielse, N.S. Bowden, P. Oxley, A. Speck, C.H. Storry, J.N. Tan, M. Wessels, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Hänsch, E.A. Hessels, Phys. Rev. Lett. 89 (2002) 213401.
[4] D.B. Cassidy, A.P. Mills, Nature 449 (2007) 195.
[5] D.B. Cassidy, T.H. Hisakado, H.W.K. Tom, A.P. Mills, Phys. Rev. Lett. 108 (2012) 043401.
[6] D.B. Cassidy, T.H. Hisakado, H.W.K. Tom, A.P. Mills, Phys. Rev. Lett. 108 (2012) 133402.
[7] A.M. Alonso, B.S. Cooper, A. Deller, S.D. Hogan, D.B. Cassidy, Phys. Rev. A 93 (2016) 012506.
[8] S. Aghion, C. Amsler, A. Ariga, T. Ariga, G. Bonomi, P. Bräunig, J. Bremer, R.S. Brusa, L. Cabaret, M. Caccia, R. Caravita, F. Castelli, G. Cerchiari, et al., AEgIS Collaboration, Phys. Rev. A 94 (2016) 012507.
[9] D.B. Cassidy, Eur. Phys. J. D 72 (2018) 53.
[10] D.B. Cassidy, A.P. Mills, Phys. Rev. Lett. 107 (2011) 213401.
[11] S. Mariazzi, P. Bettotti, S. Larcheri, L. Toniutti, R.S. Brusa, Phys. Rev. B 81 (2010) 235418.
[12] D.B. Cassidy, P. Crivelli, T.H. Hisakado, L. Liszkay, V.E. Meligne, P. Perez, H.W.K. Tom, A.P. Mills, Phys. Rev. A 81 (2010) 012715.
[13] D.B. Cassidy, T.H. Hisakado, H.W.K. Tom, A.P. Mills, Phys. Rev. B 84 (2011) 195312.
[14] M. Charlton, Phys. Lett. A 143 (1990) 143.
[15] P. Pérez, D. Banerjee, F. Biraben, D. Brook-Roberge, M. Charlton, P. Cladé, P. Comini, P. Crivelli, O. Dalkarov, P. Debu, A. Douillet, G. Dufour, P.. Dupré, et al., Hyperfine Interact. 233 (2015) 21.
[16] C. Amsler, M. Antonello, A. Belov, G. Bonomi, R.S. Brusa, M. Caccia, A. Camper, R. Caravita, F. Castelli, P. Cheinet, D. Comparat, G. Consolati, A. Demetrio, et al., AEgIS Collaboration, Comm. Phys. 4 (2021) 19.
[17] M.S. Fee, S. Chu, A.P. Mills, R.J. Chichester, D.M. Zuckerman, E.D. Shaw, K. Danzmann, Phys. Rev. A 48 (1993) 192.
[18] F. Castelli, I. Boscolo, S. Cialdi, M.G. Giammarchi, D. Comparat, Phys. Rev. A 78 (2008) 052512.
[19] D.B. Cassidy, T.H. Hisakado, H.W.K. Tom, A.P. Mills, Phys. Rev. Lett. 109 (2012) 073401.
[20] L. Gurung, T.J. Babij, J. Pérez-Ríos, S.D. Hogan, D.B. Cassidy, Phys. Rev. A 103 (2021) 042805.
[21] D.B. Cassidy, S.D. Hogan, Int. J. Mod. Phys.: Conf. Ser. 30 (2014) 1460259.
[22] S. Mariazzi, R. Caravita, M. Doser, G. Nebbia, R.S. Brusa, Europ. Phys. J. D 74 (2020) 79.
[23] P. Crivelli, A. Belov, U. Gendotti, S. Gninenko, A. Rubbia, J. Instrum. 5 (2010) P08001.
[24] T. Kumita, T. Hirose, M. Irako, K. Kadoya, B. Matsumoto, K. Wada, N. Mondal, H. Yabu, K. Kobayashi, M. Kajita, Nucl. Instrum. Methods Phys. Res. B 192 (2002) 171.
[25] T.L. Watson, Accumulation and Manipulation of Positron Plasmas for Antihydrogen Production, (Ph.D. thesis), University of Wales Swansea, 2003.
[26] S. Aghion, C. Amsler, A. Ariga, T. Ariga, A. Belov, G. Bonomi, P. Bräunig, J. Bremer, R. Brusa, L. Cabaret, M. Caccia, R. Caravita, F. Castelli, et al., AEgIS Collaboration, Nucl. Instrum. Methods Phys. Res. B 362 (2015) 86.
[27] G.B. Andresen, W. Bertsche, P.D. Bowe, C.C. Bray, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, S.S. El Nasr, J. Fajans, M.C. Fujiwara, D.R. Gill, J.S.. Hangst, et al., ALPHA Collaboration, Rev. Sci. Instrum. 80 (2009) 123701.
[28] A.P. Mills, E.M. Gullikson, Appl. Phys. Lett. 49 (1986) 1121.
[29] D. Krasnicky, S. Aghion, C. Amsler, A. Ariga, T. Ariga, A.S. Belov, G. Bonomi, P. Bräunig, R.S. Brusa, J. Bremer, G. Burghart, L. Cabaret, M.. Caccia, et al., AEgIS Collaboration, AIP Conf. Proc. 1521 (2013) 144.
[30] C. Amsler, M. Antonello, A. Belov, G. Bonomi, R.S. Brusa, M. Caccia, A. Camper, R. Caravita, F. Castelli, G. Cerchiari, D. Comparat, G. Consolati, A. Demetrio, et al., AEgIS Collaboration, Phys. Rev. A 99 (2019) 033405.
[31] Hamamatsu Website (2020) URL https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/si_pd_kspd9001e.pdf.
[32] Nist Website (2004) URL http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html.
[33] B.Y. Wang, P. Kuang, F.Y. Liu, Z.J. Han, X.Z. Cao, P. Zhang, Nucl. Instrum. Methods Phys. Res. A 885 (2018) 119.
[34] F.Y. Liu, P. Kuang, X.Z. Cao, P. Zhang, Y.J. Wang, Z.M. Zhang, H.H. Tang, B.Y. Wang, Nucl. Instrum. Methods Phys. Res. A 966 (2020) 163830.
[35] Y. Enomoto, N. Kuroda, K. Michishio, C.H. Kim, H. Higaki, Y. Nagata, Y. Kanai, H.A. Torii, M. Corradini, M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli, N. Zurlo, ASACUSA collaboration, et al., Phys. Rev. Lett. 105 (2010) 243401.
[36] P. Perez, Y. Sacquin, Classical Quantum Gravity 29 (18) (2012) 184008.
[37] C. Amole, G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, E. Butler, A. Capra, P.T. Carpenter, C.L. Cesar, S. Chapman, M. Charlton, A.. Deller, et al., ALPHA Collaboration, Nucl. Instrum. Methods Phys. Res. A 735 (2014) 319.