Development of detector and physics analysis tools for PANDA experiments at FAIR

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Abstract.
The PANDA collaboration at FAIR facility will address a rich variety of physics programs for studies of strong interaction and perturbative QCD. In India, initiatives have been taken up for the design and construction of some components of the PANDA detector. A silicon photo multiplier based scintillation detector is being planned to be built in India in collaboration with GSI, Darmstadt. Simulation studies and R&D work are being carried out in designing this detector which can provide a fast trigger signal for the PANDA experiments. The other component of the PANDA detector which the Indian group is interested to develop is luminosity monitor detector (LMD). Currently two possible solutions are being considered for LMD: (i) a double sided silicon micro strip detector and (ii) radiation hard Gallium Nitride (GaN)/Diamond sensors with a pitch of 50 µm. Simulations are being carried out. The analysis tools of vertex and kinematic fitting have been developed within the software framework of Pandaroot. The vertex fitting for the primary and secondary vertex based on kinematic constraints have been implemented for the full decay tree reconstruction. Simulation studies have been performed using a few benchmark channels to evaluate the performance of these methods.

1. Introduction
The PANDA experiment at FAIR is one of the key projects at FAIR (Facility for Anti proton and Ion Research), Darmstadt, Germany. The High Energy Storage Ring - HESR- at FAIR will provide intense anti proton beams of momentum in the range of 1 - 15 GeV/c. One of the main topics of study at PANDA[1] is charmonium spectroscopy and search for glueballs and hybrids in the charmonium mass region. Glueballs are excited state of pure gluons whereas hybrids are resonances consisting of a quark, an antiquark and excited gluons. These glueballs and hybrids, in contrast to normal mesons and other fermion - anti fermion systems, can have spin-exotic quantum numbers as the gluons carry additional degrees of freedom. Lattice QCD calculations predict a whole spectrum of bound gluon states and hybrids, whereas experimental information is scarce. Bound gluon systems offer a unique way to study one of the long standing problems in hadron physics- the origin of mass of strongly interacting particles. As we know, the Higgs
mechanism might be responsible for creation of mass of elementary particles. But for proton, the Higgs mechanism accounts for only a few percent of its mass while the rest of it, is believed to be, created by the strong interaction. The gluons which are massless carry color charge i.e., charges of strong interaction and thereby interact strongly between themselves. This mutual gluon attraction may allow formation of meson-like bound states of gluon even if no quarks are present. Thus glueballs acquire mass which arises solely from the strong interaction. At PANDA it should be possible to search for all glueballs and hybrids upto mass 5.5 GeV and make a high precision study by detecting both hadronic and electromagnetic decay modes revealing their true nature.

For the charmonium spectroscopy (both hidden and open charm), the goal at PANDA is to make a comprehensive measurement of spectroscopy of charmonium systems and hence to provide a detailed experimental information of the QCD confining forces in the charm region to complement theoretical investigation. It should be highlighted that most of the charmonium states have very narrow width and low production cross section, only in experiments like PANDA with its phase space cooled anti proton beam and high luminosity it is possible to obtain their mass, width and a systematic information of decay modes.

Investigation of medium modification of hadron mass in nuclear matter is another interesting topic that has been planned at PANDA. These studies, so far, have focused on the light quark sector eg., pion and kaon mesons due to the limitation in available energy. The in-medium pion mass is observed to shift as compared to its vacuum value and pion-nucleus potential has been deduced from experimental studies of deeply bound pionic atoms at GSI[2]. For kaons, repulsive mass shifts for K+ and attractive mass shifts for negative kaons are observed experimentally[3]. At PANDA, the medium modification of hadron mass studies can be extended to the charm sector. For example, experiments are being planned to study sub-threshold production of D-Dbar mesons in anti proton - nucleus collision. If the D meson mass gets reduced in the nuclear environment, the in-medium DDbars threshold would be lowered resulting in an enhancement of production cross section at sub-threshold energies.

The PANDA collaboration has an extensive program on single and double hyper nuclear physics. Such studies will provide us information on hyperon-nucleus and hyperon-hyperon interaction, the present knowledge of which is very limited. So far only few double hyper nuclear events have been observed. Hypernuclei are nuclear systems in which one or more nucleons are replaced by hyperons. A hyperon in a nucleus is not constrained by the Pauli exclusion principle, unlike a neutron or a proton. As a result it can populate all possible nuclear states which are not accessible otherwise. Certainly studies of hyper nuclei will provide a sensitive probe to the nuclear structure.

The PANDA detector is a complex detector designed to achieve 4π acceptance, high resolution for tracking, particle identification, calorimetry, and high rate capabilities (about 2 x 10⁷ annihilations / s). The details of the PANDA detector are described elsewhere[1]. The Indian group in the PANDA collaboration is involved [4] in detector construction, detector and physics simulation and development of analysis tools for PANDA experiments. In collaboration with the German group at GSI, Darmstadt and at FZ-Juelich, R&D work has been initiated. The present article reports on the initial simulation studies and R&D work towards the design and construction of i) silicon photomultiplier(SiPM) based fast scintillation detector known as SciTil detector and ii) luminosity monitor detector(LMD). The development of algorithm for vertex reconstruction that will be used in physics analysis has also been described.

2. The SciTil hodoscope detector
The detector, SciTil, will serve for precision time measurements for triggering and determination of time-of-flight. The detector, in the present design, consists of about 5700 scintillator tiles readout by Silicon Photomultiplier (SiPM) and will be mounted in the space between the elec-
tromagnetic calorimeter (EMC) and DIRC Cherenkov detector (DIRC stands for Detection of Internally Reflected Cherenkov light). The concept of SciTil provides the use of minimum material (so as not to deteriorate the performance of other surrounding detectors) and a good spatial resolution due to its granularity. The timing detector concept is based on 2.85 x 2.85 x 0.5 cm$^3$ scintillator tiles matching the front face of the calorimeter crystals. The scintillation photons produced in the scintillator tiles due to the passage of charged particles will be collected and readout by SiPMs. The number and size of the SiPMs and position of SiPM that will be coupled to the tile will be optimized based on a detailed simulation and R&D studies. In addition to timing and position information, the hodoscope will allow clean detection of gamma-conversions in front of the EMC in particular within the region of DIRC. In addition, it is best suited for discrimination between charged and neutral particles. The conceptual design[5] of the SciTil is shown in the Figs.1 and 2.

Figure 1. A conceptual design of half shell of the SciTil is shown along with the EMC crystal.

Figure 2. (left) Design view of a single scintillator tile with SiPM attached. (Right) a quad SciTil module with planned PCB readout.
2.1. R&D studies with Silicon Photomultiplier

Silicon photomultiplier (SiPMs) are very new type of photon counting devices that show great promise to be used as detection device in combination with scintillators/Cherenkov radiators. SiPM is essentially an avalanche photo-diode operated in limited Geiger mode. The SiPM module is a photon counting device capable of low light level detection. It is essentially an opto-semiconductor device with excellent photon counting capability and possesses great advantages over the conventional PMTs because of low voltage operation and insensitivity to magnetic fields. In many of the high energy physics experiments, the photon sensors are required to operate in high magnetic fields precluding the use of conventional PMTs. This problem can be overcome with the use of SiPMs. SiPM operating in Geiger mode, a very large gain ($\sim 10^6$), magnitude of which is determined by the internal diode capacitance and applied over-bias voltage, comparable to that of PMTs can be achieved. A SiPM consists of matrix of micro cells (known as pixels), typically between 100 and 10000 per mm$^2$. Each micro cell acts as digital device where the output signal is independent of the number of photons absorbed. When all the cells are connected in parallel, the SiPM becomes an analog device thereby allowing the number of incident photons to be counted. Detailed R&D studies with SiPM are needed for the use of this device in PANDA experiments. SiPM test facility has been developed both at GSI, Darmstat and at the Nuclear Physics Division, BARC, Mumbai. Several commercially available SiPMs (Hamamatsu make MPPC with active area 1 x 1 mm$^2$ and different pixel density, Zecotek make MAPD3N with dimension 3 x 3 mm$^2$ and pixel density as large as 15000) have been tested for their performance[6, 7, 8, 9] and comparison with other photon counting devices. Studies are also being done with an array (2 x 2) of silicon photomultiplier, Hamamatsu make, having a total active area 6 x 6 mm$^2$.

During the measurement, all devices were mounted in a light tight box and were illuminated by a pico-second pulsed diode laser (make Pico-Quant) of 660 nm wavelength as well as LED with $\lambda = 460$ nm. In order to be able to distinguish between single and multi-photon peaks, the laser intensity was controlled. The voltage and current on the SiPM were measured by high precision multimeter and I-V characteristics of the photo-diode was studied. The preamplifier used was ”Photonique SA” make of two varieties: one with high gain(20x….60x) but relatively slow rise time(5ns) and the other one with lower gain(10x….20x) but having faster rise time ($\sim 700$ps). We have also measured the particle detection efficiency (PDE) of SiPM as a function of wavelength of the incident photons. For this, a monochromator that spans wavelength from 200 to 800 nm was used. Different intensity filters were used for light intensity attenuation. The photo-sensitivity of different SiPMs was normalized with a PIN diode which itself was calibrated by the producer. The dark count of the MPPCs (Multi Pixel Photon Counter) were measured at 0.5thr and 1.5thr and found to be in agreement with the specifications provided by the supplier.

In fig.3, we plot the photon detection efficiency (PDE) distribution as a function of the wavelength $\lambda$ for Zecotek make MAPD3N and Hamamatsu make MPPC. For MAPD3N, the distribution has been normalized with PDE=24.5% at $\lambda = 450$ nm[10] and for MPPC, PDE=32.4% at $\lambda = 450$ nm[11]. It is to be noted that the present data for MPPC shows much broader distribution extended over larger wavelength range as compared to the report of Hamamatsu.

For the SciTil hodoscope, in order to optimize the geometry of SiPM and light collection efficiency, simulations are being performed with a Monte Carlo simulation program SLitrani. SLitrani stands for light transmission in anisotropic media, with ‘S’ having the meaning of super. It is a general purpose Monte Carlo program that simulates light propagation in isotropic media (it can also be used for anisotropic media) and is built upon ROOT. The main emphasis of this hodoscope detector is to provide very fast timing ($\sim 100 - 200$ ps). A detailed simulation studies
Figure 3. left part) Photon detection efficiency distribution of MAPD3N as a function of wave length normalized with data from ref.[10] at $\lambda = 450$ nm. (Right part) Photon detection efficiency distribution of MPPC normalized with data from ref.[11] at $\lambda = 450$ nm.

and prototype development work are in progress[12] to achieve this sub-nanosecond timing.

3. Luminosity Monitor

The basic concept of the luminosity monitor is to reconstruct the angle (and thus the momentum transfer 't') of the scattered anti protons in the polar angle range of 3-8 mrad with respect to the beam axis. Due to the large transverse dimensions of the interaction region when using the pellet target, there is only a weak correlation of the position of the anti proton at e.g. $z = +10.0$ m to the recoil angle. Therefore, it is necessary to reconstruct the angle of the anti proton at the luminosity monitor.

As a result the luminosity monitor will consist of a sequence of four planes of double sided silicon strip detectors located as far downstream and as close to the beam axis as possible. The planes are separated by 10 cm along the beam direction. Each plane consists of 4 sensors arranged radially to the beam axis. Four planes are required for sufficient suppression of redundancy and background. The use of 4 sensors (up, down, right, left) in each plane allows systematic errors to be strongly suppressed.

The Sensors are Trapezoidal in shape with dimensions $3.35 \text{ cm} \times 7.8 \text{ cm} \times 7 \text{ cm}$. The thickness of each sensor is $150 \mu\text{m}$ and pitch of $50 \mu\text{m}$. Strips are oriented parallel to side walls of trapezoids and the overlapping of front side strips with strips on back side form a diamond shape structure. Figure 4 and 5 show conceptual design of luminosity sensor and graphical 3D-view, respectively, of the LMD detector.

The silicon wafers will be placed inside the vacuum chamber to minimize scattering of the anti protons. The acceptance for the anti proton beam in the HESR is about 3 mrad, corresponding to the 89 mm inner diameter of the beam pipe at the quadrupole position which is located at about 15 meter downstream of the interaction point. The luminosity monitor can be located between $z = +10 \text{ m}$ and $z = +12 \text{ m}$ downstream of the target. At this distance from the target point, the luminosity monitor needs to measure particles at a radial distance of between 3 and 8 cm from the beam axis. As simulations show, at a beam momentum of 6.2 GeV/c the proposed detector measures anti protons elastically scattered in the range $0.0006 \text{ GeV}^2 < -t < 0.0035 \text{ GeV}^2$, which spans the Coulomb-nuclear interference region. Based upon the granularity of the readout the resolution of $t$ could reach $\sigma_t \approx 0.0001 \text{ GeV}^2$. In reality this value is expected to degrade to $\sigma_t \approx 0.0005 \text{ GeV}^2$ when taking small-angle scattering into account. At the nominal
PANDA interaction rate of $2 \times 10^7 / s$ there will be an average of 10 kHz/cm$^2$ in the sensors. In comparison with other experiments an absolute precision of about 3% is considered feasible for this detector concept at PANDA, which will be verified.

3.1. Radiation Induced Defects

Damage caused by radiation can be divided into two groups, surface damage and bulk damage. Due to the interest of electronic industry, the surface damage is better understood and can be controlled to certain extent by proper design and manufacturing process. Surface damage mainly manifests as charge accumulation in the oxide and subsequent breakdown. Charge accumulation at the silicon-oxide interface significantly decreases the inter-strip resistance of micro strip detectors. Therefore the signal has to be collected very quickly to minimize the loss due to leakage to neighboring strips.
Charge trapping at defect centers and Enhancement in generation or recombination currents causes reduction in charge collection efficiency (CCE). Electrostatic potential within the device changes due to modification in space-charge profile. Also the depletion bias voltage is a strong function of radiation fluences.

To overcome all these defect the simulation of GaN and Diamond sensors is done to build the radiation hard detector. Gallium Nitride (GaN) is Binary III/V direct band gap semiconductor detector with energy gap of 3.4 eV (average e-h creation energy 8-10 eV ) and energy gap of a Diamond is 5.5 with average e-h creation energy 13 eV. It can be used at high temperature making it promising material for application in detection of ionizing radiation. In table 1, the properties of some wide band gap materials like GaN and Diamond are listed.

| Property          | Diamond | Si   | GaN  |
|-------------------|---------|------|------|
| $E_g$ (eV)        | 5.5     | 1.12 | 3.39 |
| $\mu_e$ (cm$^2$ V s$^{-1}$) | 1800    | 1500 | 1000 |
| $\mu_h$ (cm$^2$ V s$^{-1}$) | 1200    | 450  | 30   |
| e-h energy (eV)   | 13      | 3.6  | ~8-10|
| Density (g cm$^{-3}$) | 3.52    | 2.33 | 6.15 |
| Radiation length, $\chi_0$ (cm) | 12.2    | 9.4  | 2.7  |
| e-h pairs/$\chi_0$ (106 cm$^{-1}$) | 4.4     | 10.1 | ~2-3 |

**Table 1.** Properties of wide band gap materials and Silicon

**Figure 6.** The resolution of the reconstructed hit position after clustering with respect to the simulated value along x and y direction.

### 3.2. Technology

To form Double Sided Strips from GaN or Diamond material the growth technology is needed. GaN layer deposition on both sides polished sapphire substrate needs Atomic Layer Deposition (ALD) growth setup. Lithography technique can be implemented to form the strips of GaN on Sapphire.
3.3. Simulation and Analysis
The simulation is done using Pandaroot environment and particle tracking through the complete PANDA detector is done by using the GEANT4 transport code. The Monte Carlo simulation is done for forward going anti-proton with energy 8.9 GeV and single particle event generator is used to create events. Digitization which models the signals of the individual detectors and their processing in the front-end-electronics (APV25) provides detector response of interaction with incident particle.

The LMD provides very precise space point measurements as a basis for the track and vertex reconstruction. The hit resolution of individual LMD measurements is shown in Fig. 6 along x and y direction. The distribution in Fig. 6 shows the difference between the reconstructed position on the sensor and the generated Monte Carlo value. The contribution from hits where two strips are fired (i.e. multiplicity = 2) are more preferable as it gives precise measurement of hit position. Dividing total energy deposited by energy required to create one e-h pair gives total charge create by hit. Fig 7 shows effect of solenoid field on particle propagation, for

![Figure 7](image1.png)

**Figure 7.** Simulation results showing the effect of solenoid magnet field. Left panel shows the result when the magnetic field is off and the right panel with field on

![Figure 8](image2.png)

**Figure 8.** Simulation result for GaN detector, (left panel) Charge deposition and (right panel) Position Resolution

anti-proton of momentum 3.5 GeV/c, at fixed theta 5.2 mrad. Solenoid field gives rise to shift
in $\theta$ towards beam axis for anti-proton. Further study of the effect due to solenoid magnetic field is being carried out. We have also performed simulation for radiation hard sensor Gallium Nitride GaN. Initial simulation results for energy distribution and position resolution are shown in Fig. 8. We have also plans to carry out further simulation with Diamond material.

4. Physics Analysis Tools

The PANDA detector is a complex detector consisting of various sub detectors for tracking and particle identification with almost complete solid angle coverage. The detector consists of a central spectrometer with a solenoid field and a forward spectrometer with dipole field. The tracking in the central part of PANDA is performed by innermost sub detector, which is a micro-vertex detector of Si pixels and strips followed by a central tracker which will be tracker of straw tubes (STT). The simulation and the physics analysis for the PANDA experiment are performed using the Pandaroot software framework [13]. The implementation of the Pandaroot software framework is based on ROOT [14]. The efficient reconstruction of the primary and secondary vertex is crucial for many topics of simulation and data analysis in the PANDA physics program. The vertex position of a set of tracks can be determined by varying the track parameters such that the error is minimized under the condition that the tracks pass through a common vertex point. In addition, the kinematic information of various particles in a particular decay chain can be used as the constraints, for the better determination of track parameters. This leads to an improvement in the momentum and the mass resolution of the measured particles and a larger signal to background ratio in the analysis of the various physics channels. The tools of the vertex and kinematic fitting have been implemented in the Pandaroot software package.

4.1. Algorithm

The algorithms for the vertex and kinematic fitting is based on the minimization of suitably defined $\chi^2$ function using the constraints [15]. The constraints are incorporated by the Lagrange multipliers method. An iterative $\chi^2$ minimization procedure is employed for the vertex fitting. The calculation uses a track representation in a Cartesian frame for the particle tracks with parameters. The trajectory parametrization consists of a three-dimensional position along the trajectory, the particle momentum at this position and the particle energy. The initial track parameters and the covariance matrix are obtained through the conformal mapping based track finder and subsequent track fitting using a Kalman filter procedure in the Pandaroot software. The Cartesian track parameters are obtained by converting the helix representation track parameters and assigning a mass to the final-state particle.

The constraints used for the vertex fitting are expressed in terms of a vector of equations $H(\alpha, x) = 0$, where $\alpha$ is a vector of track parameters for all tracks included in the fit and $x$ is the vertex position. The constraint equations are linearized by using the first order Taylor expansion around a convenient point $(\alpha_A; x_A)$ leading to equation

$$D(\alpha - \alpha_A) + E(x - x_A) + d = 0$$

(1)

where $d$ is the vector of values of the constraint equations at a suitable expansion point, $D$ is the matrix of partial derivatives of the constraint equations at the expansion point with respect to the track parameters and $E$ is the matrix of the partial derivatives of the constraint equations at the expansion point with respect to the vertex coordinates. The constraint equation is included by Lagrange multiplier variable $\lambda$ in the $\chi^2$ function which is written as:

$$\chi^2 = (\alpha - \alpha_0)^T V_{\alpha 0}^{-1} (\alpha - \alpha_0) + 2 \lambda^T (D\delta\alpha + E\delta x + d)$$

(2)

where the terms include the contributions from errors in track parameters with respect to initial values $\alpha_0$ with covariance matrices $V_{\alpha 0}$ and the constraints, respectively. The values of improved
track parameters $\alpha$ and the vertex position $x$ that satisfy the given set of constraints can then be found by minimizing the $\chi^2$ equation with respect to $\alpha$, $x$ and $\lambda$.

4.2. Test simulations
The performance of the vertex fitter has been tested by reconstructing the short lived decay particles $D_s^{\pm}$ mesons using the simulated events from the reaction $p\bar{p} \rightarrow D_s^{\pm}D_s^*(2317)^{\mp}$. The decay particle $D_s^{\pm}$ has been reconstructed in the $D_s^{\pm} \rightarrow \phi\pi^{\pm}$, $\phi \rightarrow K^+K^-$ decay modes. The proper lifetime distribution for the reconstructed $D_s^{\pm}$ particles obtained using the 4-momentum obtained from vertex fitting at the vertex point. A fit to the proper time distribution is performed using the function which is the convolution of an exponential and a Gaussian (with the width derived from the fit to the residual of the position distribution) as shown in the Fig. 9. The slope gives a decay length value of $c\tau = 150 \pm 4 \mu m$ which is in good agreement with the PDG value of $c\tau = 147 \mu m$. The fitting procedure provides the quality of the vertex fit in terms of a normalized $\chi^2$ probability distribution.

In addition to the vertex fit, the possibility to include other kinematic constraints such as mass constraint, total momentum constraint, total energy constraint, four momentum constraints etc. have been developed and tested. Depending on the physics case, one or many constraints can be used for the analysis. For testing the kinematic fit, the simulations have been performed with events generated in the $p\bar{p}$ collisions at the centre of mass energy corresponding to $\psi(2S)$ resonance. After reconstruction of $J/\psi$ resonance through the $J/\psi \rightarrow e^+e^-$ decay channel, a 4-momentum kinematic fit using the energy momentum of the initial $p\bar{p}$ system has been performed. The kinematic fitting leads to improved track parameters for the daughter particles and a better resolution of the mass for the $J/\psi$ resonance as shown in Fig. 10.

Figure 9. Proper time distribution in terms of decay length for the reconstructed $D^{\pm}$ candidates with the reconstructed mass ($M$) and 4-momentum ($P$).
Figure 10. Reconstructed mass of the $J/\psi$ resonance state without (dashed line) and with (solid line) the 4-momentum fit.

5. Summary
The facility for anti proton and ion research (FAIR) will be a unique facility for the investigation of hadron structure and QCD in the charm sector. The Indian hadron physics community has taken a strong initiative to be a part of this exciting physics programme and to contribute to the detector construction, simulation & software development and physics case studies. In collaboration with the research centre GSI, Darmstadt and FZ-Juelich, the Indian group has taken up R&D activities. The initial studies with SiPM show a great promise of this device to be used as photon counter for nuclear physics experiments. For the determination of beam luminosity, double sided silicon micro strip detector as well as radiation hard GaN and Diamond sensors are being considered. The analysis tools of vertex and kinematic fitting have been developed and tested for the studies of PANDA physics programme.

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References
[1] PANDA collaboration- physics performance report, arXiv:0903.3905 and PANDA technical progress report, Gold version, 2005
[2] Geissel H et al, Phys. Rev. Lett. 88, 122301(2002), Phys. Lett. B., 549 (2002) 64 and references therein.
[3] Nekipelov M. et al, Phys. Lett. B, 540 (2002) 207, Rudy Z. et al, Euro. Phys. J A15 (2002) 303
[4] QCD studies with anti-protons at FAIR: Indian participation in PANDA, S.Kailas, B.J.Roy, D.Dutta, V.Jha, R.Varma, Current Science, Vol. 100, No.5 (2011) and references therein.
[5] Proposal for a Scintillation Tile Hodoscope for PANDA, K.Goetzen, H.Orth, G.Schepers, C.Schwarz, A.Wilms (private communication).

[6] SiPM as photon counter for Cherenkov detectors, B.J.Roy, H.Orth, C.Schwarz, A.Wilms, K.Peters, DAE Symp. Nucl. Phys. Vol. 54, 666 (2009).

[7] Study of the spectral sensitivity of G-APDs in the wavelength range from 250 to 800 nm, B.J.Roy et al., 12th Vienna Conf. on Instrumentation, Feb. 2010, Vienna.

[8] In-beam test of a DIRC Cherenkov radiator with SiPM, B.Kroeck, A.Hayrapetyan, K.Foehl, O.Merle, M.Duren, B.J.Roy, K.Peters, DAE Symp. Nucl. Phys. Vol. 54, 668 (2009).

[9] Development of SiPM based scintillation detector for fast timing application in the PANDA experiment, H.Kumawat, B.J.Roy, V.Jha, U.K.Pal, A.Chatterjee and S.Kailas, DAE symp. Nucl. Phys. Vol.56, 1074 (2011).

[10] D. Renker, PSI (private communication).

[11] N.Anfimov, Dubna (private communication).

[12] Simulations of SiPM based scintillation detector for PANDA, U.K.Pal, B.J.Roy, V.Jha, H.Kumawat, A.Chatterjee and S.Kailas, DAE symp. Nucl. Phys. Vol.56, 1072(2011).

[13] Journal of Physics: Conference Series 119 (2008) 032035.

[14] http://root.cern.ch

[15] P. Avery, Fitting theory write-ups, http://www.phys.ufl.edu/avery/fitting.html(1998).