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The Super C-τ Factory particle identification system options

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Abstract. The Super C-τ (SCT) Factory at Novosibirsk is a project of new colliding beam experiment proposed in Budker Institute of Nuclear Physics. Electron-positron collider based on Crab-Waist technique for operation energy range 2–5 GeV in center of mass is suggested. The luminosity up to $10^{35}\text{cm}^{-1}\text{s}^{-1}$ (in 100 times higher than in operated today experiments in this energy region) is expected. To perform broad experimental program of the project successfully the excellent particle identification (PID) system is needed. A number of options are under consideration. Three of them are described in the paper: Focusing Aerogel RICH (FARICH) detector, threshold Cherenkov counters based on ASHIPH (Aerogel SHifter PHotomultiplier) technique with 6000 litres of aerogel of two refractive indexes and time-of-flight counters with TOP (Time of Propagation) approach with time resolution better than 30 ps. Comparison of PID capabilities with help of parametric simulation is given.

1 Introduction

The main purposes of the Super C-τ experiment are search for effects of CP-violation in the decays of charmed particles, tests of the Standard Model in the decay of the τ-lepton, the search and study of an entirely new form of matter in the energy region from 2 to 5 GeV in center of mass. The data, which are planned to record, by 3–4 orders exceed everything that has been recorded so far in any other experiment. The proposed program requires construction of a universal magnetic detector with a field of about 1–1.5 T [1].

The excellent PID system is needed for successful execution of the broad experimental program especially for search of “new physics” and study of rare processes.

In the paper three options of PID system proposed in Budker Institute of Nuclear Physics (BINP) are considered:

– Ring Imaging Cherenkov detector FARICH (Focusing Aerogel RICH) (see sec. 3);
– Threshold aerogel Cherenkov counters ASHIPH (Aerogel SHifter PHotomultiplier) used a silicon photomultipliers (SiPM) as photon detectors (see sec. 4);

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– Time of Flight with Time of Propagation technique (ToF + TOP) based on very fast photon detectors like photomultiplier with microchannel plates (MCP-PMT) (see sec. 5).

The main operation conditions which have to be taken into account during the development of the PID system:

- event rate is varying from 50 to 300 kHz (the largest rate is expected in J/ψ peak [1]);
- neutron dose per year $\geqslant 2{\cdot}10^9 \mathrm{n}_{eq}/\mathrm{cm}^2$ for barrel part and $\geqslant 10^{10} \mathrm{n}_{eq}/\mathrm{cm}^2$ for endcap part [2];
- space for PID system is limited by gap between electromagnetic calorimeter and drift chamber and it is about 25 cm [1].

2 Aerogel

Two PID options for the Super C-τ Project proposed in BINP are based on aerogel. The most unique parameters of aerogel is its refractive index (from 1.006 to 1.20) and its small dispersion in comparison with fused silica. In Novosibirsk the production of aerogel based on SiO_2 has been started in 1986. The refractive index of aerogel produced in Novosibirsk can vary within wide range from n=1.006 to n=1.13. A very good optical parameters of aerogel were achieved [3]. It has been used used in various threshold and ring imaging Cherenkov (RICH) detectors for the following experiments: KEDR [4] and SND [5] (BINP, Novosibirsk, Russia), LHCb [6] (CERN, Switzerland), AMS-02 [7] (International Space Station), CLAS12 [8] (J-Lab,Newport, USA).

3 Focusing Aerogel RICH

The general idea of FARICH is to arrange several aerogel layers with the different refractive indices so that Cherenkov rings from different layers overlap at the photon detector plane (Fig. 1). In this way it is possible to increase the number of photoelectrons by increasing the radiator thickness without degradation of the Cherenkov angle resolution for single photons. It is possible to provide focusing effect by using a stack of several aerogel blocks as in the Belle II ARICH system [9] or produce a monolithic multiple layer block. The second approach was considered for the FARICH endcap system of the Super B factory (LNF, Italy) [10] and the SCT project [11]. To improve the single photon resolution even more it is also possible to use monolithic aerogel with a continuous density gradient [16]. The first monolithic 4-layer aerogel block for FARICH was produced in 2004. Since then several tens of focusing aerogel samples have been produce but the mass production of focusing aerogels is still very challenging issue. Main challenges are is to achieve a designed density profile of aerogel.

The FARICH technique is able to provide excellent particle separation that was demonstrated with simulations and the prototype beam test at CERN in 2012 [13, 14]. Its main parameters are following:

- hermetic system covering 98% of the full solid angle with two endcap and one barrel parts;
- 4-layer aerogel Cherenkov radiator with $n_{\max} = 1.07$ and thickness of 35 mm covering 17 m^2 area;
- distance between input face of the radiator and that of photon detector is 20 cm;
- position sensitive photon detector with 3×3 mm^2 pixel size covering 21 m^2 area;
- about 1.8 millions of electronics channels;
- material budget is 15–30% of X_0 depending on the type of photon detectors for the normal incidence.

FARICH system for SCT detector

The sketch of the proposed system is presented in Fig. 2.

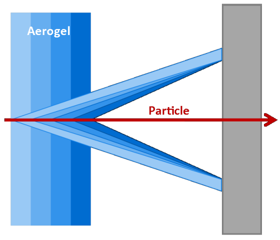

Figure 1. The Focusing Aerogel RICH concept.

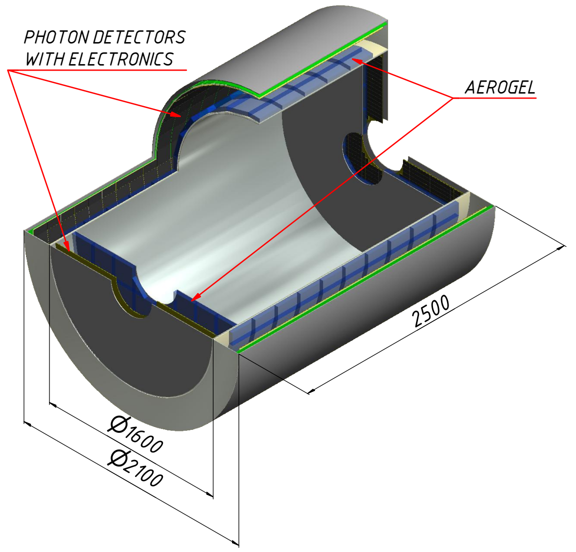

Figure 2. The scheme of the SCT detector FARICH system.

The photon detector is an important part of the FARICH system. There are two possible candidates for operation in the magnetic field of about 1 T inside the SCT detector: microchannel plate (MCP) PMTs and silicon photomultipliers (SiPM). SiPM is able to work in strong magnetic fields of arbitrary direction while MCP-PMT could work only in a strong axial magnetic field. Photon detection efficiency (PDE) is usually higher for SiPMs than for MCP-PMTs. PDE of MCP-PMTs is also limited due to photoelectron collection efficiency that typically amounts to $0.6 \div 0.7$. One of the main drawbacks of SiPMs is a high level of the dark count rate (DCR). Dark counts are impossible to discriminate by amplitude from the Cherenkov single photon hits in RICH counters that results in high data throughput for triggerless systems and increased power consumption. Another disadvantage of SiPMs is the succeptibility to non-ionizing radiation leading to significant increase of DCR at the 1 MeV equivalent neutron fluence of $\sim 10^9$. A feasible solution seems to be usage of SiPMs cooled down to temperatures with a tolerable level of dark count rates. Hamamatsu [17] and ON Semiconductor (former SensL) [18] SiPM arrays both offer high PDE, excellent active area ratio, one of the lowest DCR in the market, capability for operation at the temperature of -40°C and thus represent attractive options for application in the FARICH system. Multianode MCP-PMTs are considered for the use in the endcap part of the system.

The front-end electronics (FEE) for the FARICH system should be sensitive to single photoelecton signals of ~ 100 pC, have a time-to-digital converter (TDC) with 1 ns or better timing resolution, have matching footprint to photon detector and be compact – the available space for FEE and cooling system is just a few cm behind the photon detector. That imposes very challenging limitations requiring a highly integrated solution. One of the promising solutions is the CLARO ASIC chip with 8-channels discriminator developed for the LHCb RICH upgrade [19]. Its declared power consumption is about 1 mW/channel, the maximum couting rate is 10^7 hits/channel. An external TDC based on ASIC or FPGA technologies should be used to digitize CLARO signal timings. In order to minimize the FEE power consumption an ASIC chip with integrated analogue and digital parts should used. Such an approach was realized in the SAMPIC chip developed by CAE (Saclay, France) and LAL (Orsay, France) [20]. Power consumption of this chip is about 12 mW per channel. For the SAMPIC option the total dissipated power by the FARICH FEE would be about 20 kW. A rather attractive option is represented by the TOFPET-II ASIC produced by PETsys Electronics (Lisbon, Portugal) [21] though its timing resolution is an overkill for the FARICH application.

FARICH R&D progress

The beam tests were performed with the electron test beam facility of the VEPP-4 accelerator complex at BINP [22]. Electron beam energy is tunable up to 3.5 GeV. At first specialized drift chambers were used to track electrons and measure their positions in the FARICH prototype. In 2012 they were replaced by gaseous multistrip tracker with gas electron multipliers (GEM). The first FARICH prototype to demonstrate the FARICH method was built and tested in 2011. The Cherenkov light was detected by 32 MRS APDs by CPTA (Moscow) with 2.1×2.1 mm^2 pixel size arranged in 4 custom-made arrays. SiPMs were read out by custom discriminator boards with built-in preamplifiers and 64-channel multi-hit TDC V1190B (CAEN) with 100 ps timing resolution. Single photon resolution for 4-layer aerogel sample was measured and focusing effect was compared to a single-layer aerogel sample [14].

The second prototype featured Digital Photon Counters by PDPC (Germany) [12] as photon detector and demonstrated good particle separation performance when tested at the hadron beam line T10 at CERN in 2012 [13].

The following prototype coined as FARICH-3 is based on multianode PMTs which are readout by PADIWA (amplifier-discriminator) and TRB3 (TDC DAQ platform) electronics developed for PANDA, CBM and HADES experiments at GSI [15].

The next FARICH prototype is envisaged that will be based on the new generation of SiPM arrays.

In 2018 a series of beam tests with the FARICH-3 prototype with MaPMT readout were carried out at BINP. In Fig. 3 one can see a photograph of the photon detector plane with 4 PMTs: two H12700 MaPMTs produced by Hamamatsu and two XP85012 (Planacon) MCP PMTs produced by Photonis. Aerogel samples were installed in front of the photon detectors on a moving stage. PADIWA3 boards were used for fast amplification and discrimination. Two TRB3 boards were employed for readout. A TRB3 board has 4 peripherial FPGA which are configured as 48+1-channel TDCs with 7 ps instrinsic timing resolution and one central FPGA which serves as a readout controller and provides a Gigabit ethernet link. Particle tracking was performed by two GEM detectors with intrinsic resolutions $\sigma_x \approx 100\mu$m, $\sigma_y \approx 200\mu$m installed upstream of the prototype with about 1 m distance between each other. Measurements by the third GEM detector installed downstream of the prototype used for additional rejection of particles scattered in the prototype's material.

A number of aerogel samples were tested with "full size" pixels (6×6 mm^2) and "reduced" pixels (ø1 mm). Reduced pixels were obtained by covering each PMT with a plastic mask that has 64 ø1 mm diameter holes aligned with anode centers. With 1-mm pixels a contribution of photon detector position resolution to the Cherenkov angle resolution should be negligible. In Fig. 4 a distribution of registered Cherenkov photons at the photon detectors plane is presented for "full size" pixels.

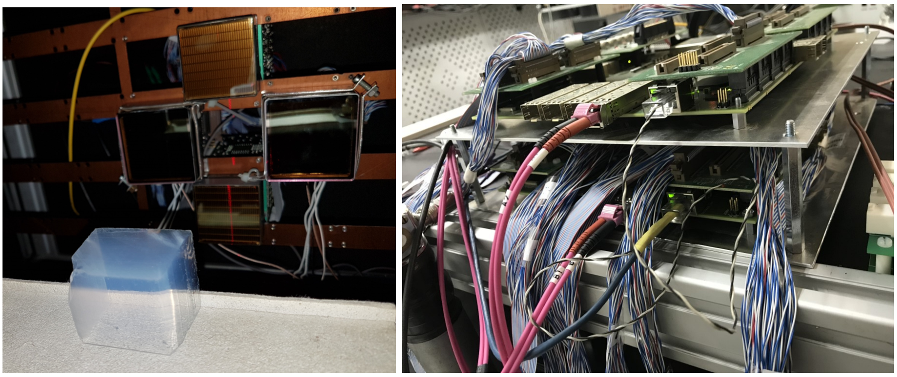

Figure 3. Photograph of the FARICH-3 prototype's MaPMTs and MCP PMTs (left) and TRB3 boards (right).

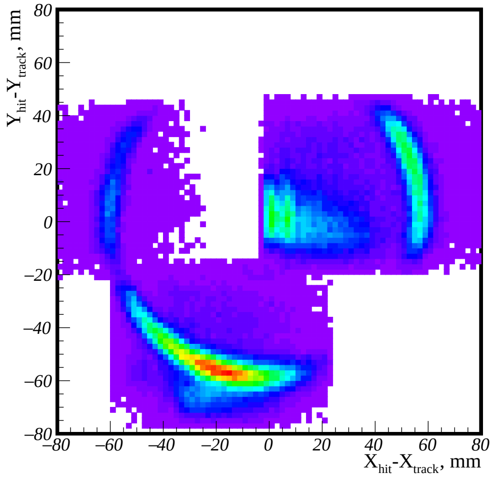

Figure 4. An example of the hit map for 4-layer aerogel (430f61) in the FARICH-3 prototype.

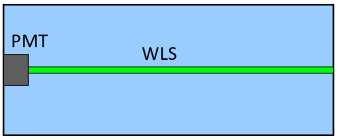

Figure 5. Scheme of the ASHIPH method.

The detailed results of the FARICH-3 beam test in 2018 has been reported in [23]. Comparison of the FARICH particle separation capability with other considered PID options is presented in sec. 6.

4 Threshold aerogel counters ASHIPH

The first project of the ASHIPH (Aerogel, SHIfter, and PHotomultiplier) counters was proposed for the KEDR detector in 1991 [4]. Light collection in such counters is performed using wavelength shifters, which were designed in the form of light guides. The Cherenkov light from aerogel is reemitted and partially appears in conditions of total internal reflection. This part of the reemitted light is transported to the photomultiplier and then recorded.

Schematically the ASHIPH method is shown in Fig. 5. The PID systems based on ASHIPH counters are used in the KEDR detector [24] for experiments at VEPP-4M e^+e^--collider and in the SND detector [25, 26] at VEPP-2000 e^+e^--collider.

The ASHIPH system for SCT detector

For SCT project the ASHIPH system consists of two layer with aerogel of two different refractive indexes (1.03 and 1.015), with wavelength shifters based on PMMA (poly-methyl-methacrylate) with dope of BBQ (benzo(de)benzo(4,5)imidazo(2,1-a)isoquinolin-7-one) and SiPM as photon detector was proposed. Aerogel with refractive index $n = 1.030$ could be used for π/K separation from 0.6 up to 2 GeV/c and μ/π separation from 0.4 up to 0.6 GeV/c. To extend the momentum range for the μ/π separation two possible implementations are considered:

- additional layer of ASHIPH counters with refractive index of aerogel $n = 1.015$ could extend the upper momentum limit to 0.9 GeV/c;
- in the region just above $P_{\rm thr}(\pi)$ we could use signal amplitude difference to discriminate between muons and pions.

SiPMs might be employed for the light detection as they quite compact, immune to the magnetic field and have high PDE.

The main parameters of the proposed ASHIPH system (see Fig. 6):

- 3 layer system design: one layer with $n_1 = 1.03$ (2000 litres) and two other layers with $n_2 = 1.015$ (4000 litres);
- the counter dimensions are $18 \times 30 \times 8$ cm^3;
- WLS dimensions are $0.3 \times 28 \times 6$ cm^3;
- a counter is readout by one SiPM array of 20 pixels each with 3×3 mm^2 size or 60×3 mm^2 SiPM area in total;
- material budget for the normal incidence is $14\% X_0$;
- number of counters in the system is 1'400, number of SiPMs in the system is 28'000;
- SiPMs are cooled to $-40°$C to minimize DCR and radiation damage effects.

According to our estimations based on the previous experience and operation of ASHIPH counters of the KEDR and SND detectors, about 20 Cherenkov photons could be detected in the proposed system for relativistic particles with $\beta \approx 1$ in each subsystem: one with $n_1 = 1.030$ (8 cm thick) and the other with $n_2 = 1.015$ (16 cm thick). The main contributions to subthreshold detection efficiency were estimated as following:

- δ-electrons production $\sim 5\%$ ($n_1 = 1.030$, 8 cm thick) and $\sim 3.3\%$ ($n_2 = 1.015$, 16 cm thick)
- accidental coincidence with SiPM dark counts is $\sim 0.7\%$ ($n_1 = 1.030$, DCR=70 kHz), $\sim 1.4\%$ ($n_2 = 1.015$, DCR=140 kHz) in the time window of 100 ns width.

In Fig. 7 the dependences of the number of detected photons in the ASHIPH system on momentum for different particles are presented: for the system with $n = 1.030$ (top) and for the system with $n = 1.015$ (bottom). The dependences are obtained with help of parametric simulation for tracks with polar angle $-75° \leqslant \Theta \leqslant 75°$. According to calculation and parametric simulation (see sec. 6) such PID system is able to provide good μ/π-separation from 0.5 to 0.9 MeV/c and good π/K-separation from 0.5 to 2.5 GeV/c.

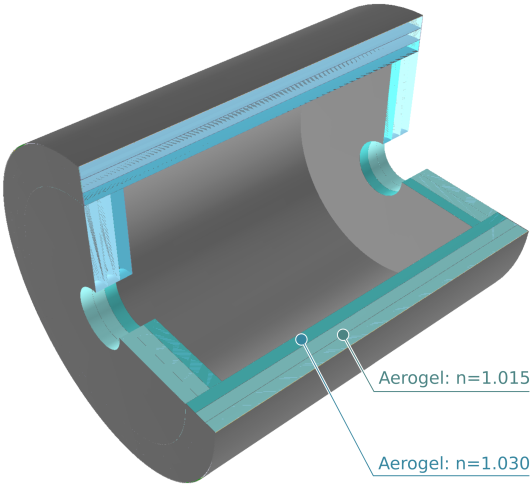

Figure 6. Scheme of the ASHIPH system for SCT detector.

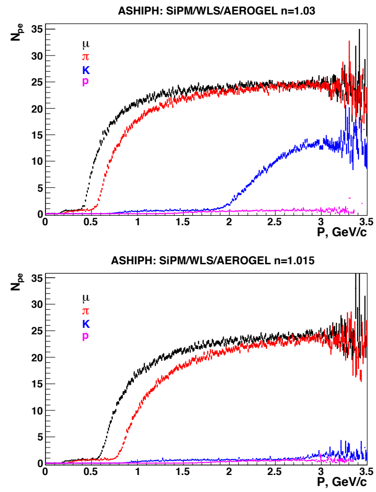

Figure 7. Dependences of the detected photons number in the ASHIPH system on momentum for different particles: muons (black), pions (red), kaons (blue), protons (magenta). The signals for the ASHIPH system based on aerogel with n=1.030 are presented on top plot and for ASHIPH system based on aerogel with n=1.015 — on bottom plot.

5 "ToF + TOP" approach

The proposed aerogel Cherenkov counters are not able to provide μ/π-separation in momentum range below 0.3 GeV/c (FARICH) and 0.5 GeV/c (ASHIPH). μ/π-separation in this region could be especially useful for study of semi-leptonic decays of D-mesons. At the Super C-τ Factory operation energies approximately half of muons in such processes have the momenta below 0.4 GeV/c. The "ToF+TOP" (Time of Flight and Time of Propagation) technique is considered as extension of the μ/π-separation capability for one of the proposed system based on aerogel. The best time resolution achieved in currently operating colliding beam experiments is about 100 ps at ToF system of the BES-III experiment [27]. For the future colliding beam experiments the time resolution is about 30 ps is considered for instance in Minimal-ionising particle Time Detection system for the CMS detector upgrade [28]. It was demonstrated in paper [29] that the 5 ps time resolution is achievable in counters based on Cherenkov radiator and photomultiplier tube with micro-channel plates (MCP PMT). These circumstances allow us to consider the option of ToF system for particle identification with time resolution better than 30 ps. Other limitations of the time resolution come from accelerator uncertainties in time of the beam interaction (bunch length) and electronics synchronization jitter.

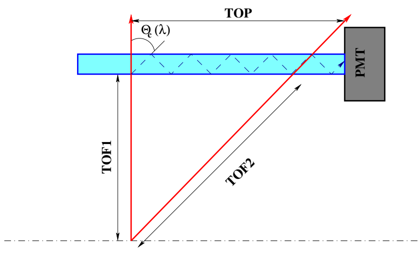

Figure 8. The "ToF+TOP" approach scheme.

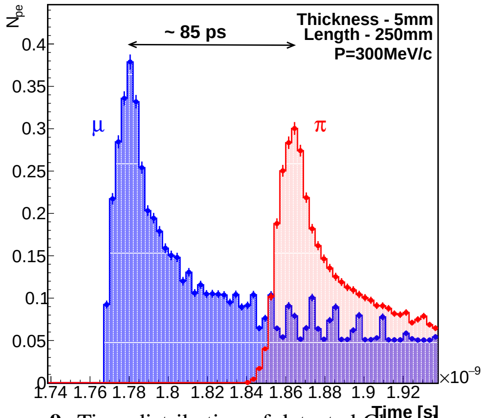

Figure 9. Time distribution of detected Cherenkov photons generated by muon (blue) and pion (red) in quarts bar (5×5 mm^2 cross-section) at the distance 250 mm from PMT.

Using of the quartz bars as Cherenkov radiators could increase the difference in time detection of particles with different masses due to delay of Cherenkov light propagation into bars. The illustration of this idea is presented in Fig. 8. There are two components of measured time in such approach: Time of Flight (ToF) and Time of propagation (TOP). The time distributions of detected Cherenkov photons produced in quartz bar (5×5 mm^2 cross-section) by pion and muon with momentum 0.3 GeV/c at the distance 250 mm from PMT with Super Bialkali photocathode are presented in Fig. 9. These distributions are obtained with help of Monte-Carlo simulation in GENT4 framework. It is shown that ToF + TOP approach is possible to increase the time difference between muons and pions with the same momenta and consequently extend the momentum range for reliable μ/π and π/K-separation. The similar approach was considered in DIRC-like TOF (or FTOF) PID system proposal for forward region of the Super B Factory detector [30].

The first conceptual design of the ToF system for Super C-τ Factory is shown in Fig. 10 The main construction parameters of the system:

- 10000 quartz bars with sizes 5×5×250 mm;
- 1648 MCP PMTs rectangular shape 40×20 mm with 12 anodes;
- material budget is ~ 7%X_0 (for perpendicular crossing particles).

In Fig. 11 the comparison of time difference between muons and pions with the same momentum obtained with help of parametric simulation for the proposed system. It is shown that time difference between muons and pions is more than 100 ps up to 0.55 GeV/c for "ToF+TOP" approach while for ToF approach the same time difference lasts only up to 0.35 GeV/c.

6 Parametric simulation of the particle separation

The parametric simulation of the Super C-τ Factory detector was used to compare different PID options. Muons, pions and kaons were generated with momenta from 0 to 3.5 GeV/c in full solid angle acceptance. The system geometry was the same for all options: barrel radius is 80 cm and length along beam pipe is ±100 cm. Other key detector parameters:

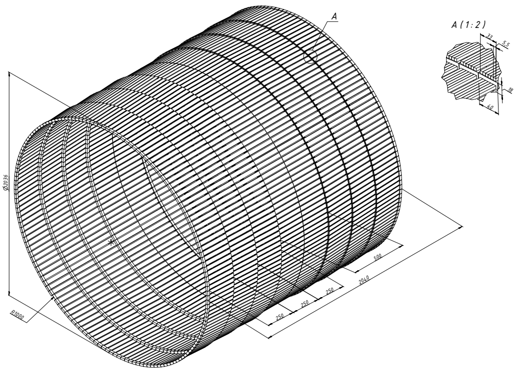

Figure 10. The sketch of the barrel part for Time of Flight system for SCT detector.

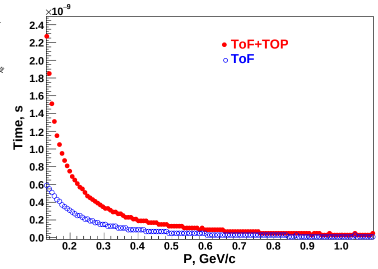

Figure 11. The dependence of time difference between muons and pions on momemtum: ToF approach (open circles), ToF+TOP approach (solid circles).

- Momentum resolution

$$\frac{\sigma_{p_T}}{p_T} = (0.13 \pm 0.01)\% \cdot p_T + (0.45 \pm 0.03)\%$$

  was taken from conceptual design report [1];

- Axial magnetic field in detector is 1 T;

For FARICH option the particle velocity resolution was taken from stand-alone GEANT4 simulation [1];

The estimated parameters of ASHIPH systems: numbers of detected photons ($N^{\perp}_{ph}$) and subthreshold efficiencies ($Eff^{\perp}_{s.thr.}$) for perpendicular crossing particles were recalculated for different track lengths inside the system in dependence on track polar angle, momentum and detector magnetic field value (see Fig. 7).

For ToF option the time resolution σ_t=35 ps was taken as a quadratic sum of the counters time resolution (30 ps) and time uncertainty of bunch interaction (20 ps). The electronics synchronization jitter is not considered here.

To evaluate the particle separation capability the cut on polar angle was implemented: $-75° \leqslant \Theta \leqslant 75°$. In Fig. 12 and Fig. 13 the π/K and μ/π-separation dependences on momentum are shown correspondingly for different options in terms of standard deviation parameter (σ): FARICH (●), ASHIPH with n_1=1.030 (▲), ASHIPH with n_2=1.015 (▼) and ToF (■). It is shown that ASHIPH system based on aerogel with two refractive indexes (1.030 and 1.015) is able to provide π/K-separation at the level of three σ in momentum range from 0.5 to 2.5 GeV/c as well as the FARICH method, while the ToF technique provides the separation pions and kaons at the same level up to 1.5 GeV/c. The μ/π-separation at the level of three σ is possible in momentum range from 0.5 to 0.9 GeV/c with ASHIPH approach and from 0.45 to 1.3 GeV/c with FARICH. For μ/π-separation in momentum range below 0.5 GeV/c it is possible to use ToF+TOP technique.

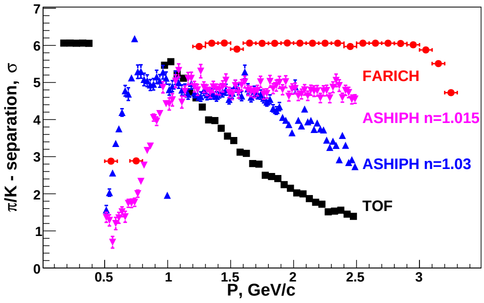

Figure 12. π/K-separation in terms of standard deviation (σ) for several PID options obtained with help of parametric simulation: FARICH (●), ASHIPH with n_1=1.030 (▲), ASHIPH with n_2=1.015 (▼) and ToF (■).

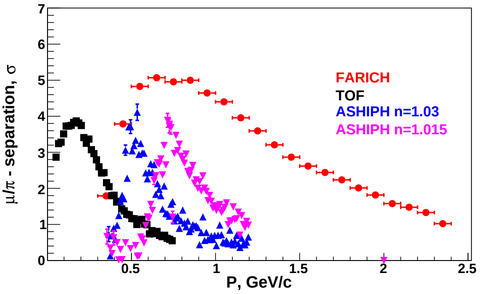

Figure 13. μ/π-separation in terms of standard deviation (σ) for several PID options obtained with help of parametric simulation: FARICH (●), ASHIPH with n_1=1.030 (▲), ASHIPH with n_2=1.015 (▼) and ToF (■).

7 Summary

Special PID system is necessary to separate π/K mesons above 0.6 GeV/c and μ/π mesons from 0.2 to 1.2 GeV/c. Kaons with momentum below 0.6 GeV/c as well as pions below 0.2 GeV/c could be identified by energy loss deposition into drift chamber of the SCT detector. And muons with momentum above 1 GeV/c will be properly detected in muon counters placed in the yoke of the detector magnet. With help of parametric simulation it was shown that good π/K-separation for momentum range from 0.6 GeV/c to 2 GeV/c is expected for all considered PID methods. For μ/π-separation in momentum range from 0.2 to 1.2 GeV/c it is possible to use combination of the methods.

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