PROTON ARM SPECTROMETER FOR THE R^3B SET-UP AT FAIR

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1. Introduction

The R^3B (reaction studies with relativistic radioactive beams) experimental facility for the study of reactions with relativistic radioactive beams is part of the FAIR project. The goal of the R^3B Collaboration is to develop and create a universal reaction set-up with high efficiency, acceptance and resolution for kinematically complete measurements of reactions with high-energy radioactive beams. The installation will be located in the focal plane of the high-energy branch of the super fragment separator (Super-FRS). The installation is adapted to the highest beam energies up to 1 GeV/nucleon provided by the Super-FRS, which ensures the maximum possible transmission of secondary beams. The R^3B facility will cover experimental studies of reactions with exotic nuclei that are far from stability, which will allow implementing a broad physical program with beams of rare isotopes with an emphasis on the structure and dynamics of nuclei. The work is carried out within the R^3B Collaboration, which includes more than 50 different institutes from around the world. To cover such a large physical program, several different tracking detection subsystems are provided (Fig. 1*a*). One of these systems will be a spectrometer for determining the momentum of emitted protons with energies up to E_p = 500–900 MeV. Unstable nuclear beams formed by the Super-FRS hit a secondary target, the reaction products being magnetically analysed with the superconducting magnet GSI large acceptance dipole (GLAD). Protons emitted in flight from excited fragments are bent in the GLAD and tracked using the dedicated proton arm spectrometer (PAS), which creation is the subject of responsibility of PNPI.

In 2016, the FAIR scientific council approved the PAS detector design and concept proposed by the Tracking Detector Department (TDD) of the HEPD [1]. The TDD proposal calls for the PAS facility to be based on thin-walled drift tubes (DT), which have a small material budget (X/X0 ≈ 0.05% per tube) and operate in vacuum. PAS will consist of four straw tube walls (STW), two walls for horizontal (X1&X2) and two walls for vertical (Y1&Y2) particle coordinate detection. A schematic arrangement of the PAS STWs, which are placed on a moving platform inside a vacuum chamber, is shown in Fig. 1*b*.

Each STW of the PAS will consist of three layers of straw tubes filled with a gas mixture at an overpressure of about 1 bar. The tubes are glued together, each layer being shifted by one tube radius with respect to the previous layer. In this way, for an orthogonal proton track, a lower detection efficiency close to the tube wall is always combined with a high efficiency in the centre of the straw in the following (staggered) layer. Also, the track's left/right ambiguity from the wire can be disentangled in the next layer.

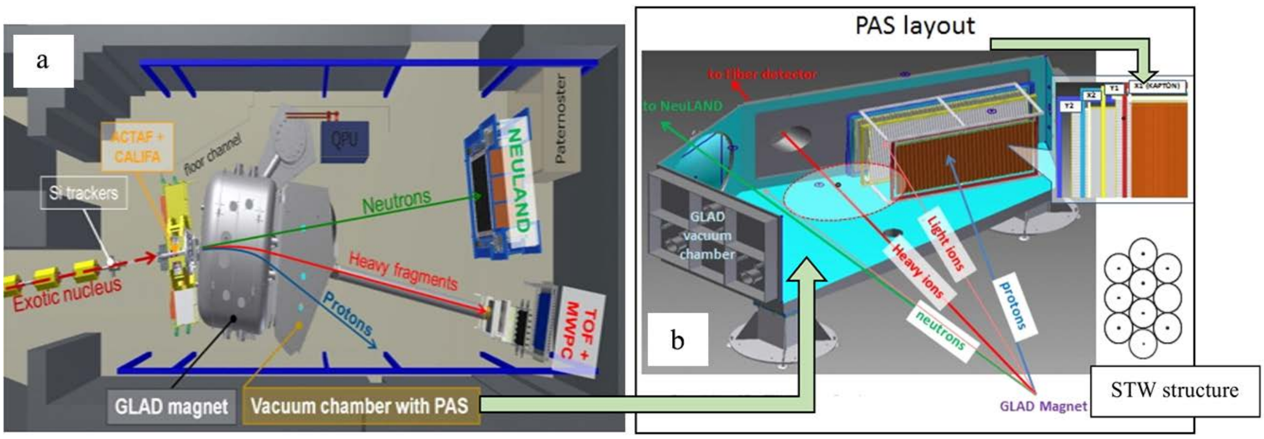

Fig. 1. R^3B set-up (*a*); proton arm spectrometer lay-out (*b*)

As follows from the technical requirements, the PAS installation must have a minimum amount of substance to ensure small angular straggling of the passing particles. First of all, this requirement applies to the first STW-X1. Therefore, it was decided to make this plane from Mylar tubes with a wall thickness of 60 µm, and the other three planes from ultrathin aluminum tubes with a wall thickness not exceeding 300 µm. Although the angular straggling caused by these tubes is larger compared to the thin Mylar tubes, their influence on the angular resolution is small since they are located near the end of the track.

The front-end electronics is placed in vacuum close to the straw-tube detectors for optimum performance in terms of noise. The PAS infrastructure, such as the gas supply, high-voltage (HV) and low-voltage (LV) power supply will be located outside the vacuum chamber. The technical requirements for the PAS spectrometer were discussed in more detail in the previous edition of HEPD Main Scientific Activities.

2. Drift tubes technology at Tracking Detector Department

A thorough search showed that there is no production of aluminum tubes with such parameters in Russia. A similar production was found in Switzerland and Germany, however, the minimum wall thickness of European pipes is 400 µm. As a result, the company MedSpetsTrub LLC was found, which agreed to develop and debug the necessary tube technology on the basis of its production. Within three years, with the direct participation of experts from the TDD, a technology was developed for the production of tubes from aluminum alloys AMg-5 and AMg-6 with a wall thickness of 220–240 µm [2].

Below are the main technical parameters of the tubes manufactured by this technology [3]:

- Inner diameter – 9.50–9.70 mm;
- Wall thickness – 0.22–0.24 mm;
- Uniformity of the inner surface $R_a \approx 0.32$ µm;
- Straightness of tubes is not worse than 150 µm per one metre of length;
- Tube material corresponds to aluminum alloy Amg-5;
- The tube leak is on the level of no worse than $5 \cdot 10^{-6}$ mbar · l/s.

On the basis of that technology, about 2 800 aluminum tubes (with a length of 2 750 mm) for the PAS spectrometer were manufactured. These tubes have passed through the output quality control (OQC) at the company (MedSpecTrub LLC) and the input quality control (IQC) at the TDD PNPI [2]. The mandatory incoming inspection of each tube included: visual inspection (the tube was rejected if any defects were found); mechanical machining of the tube ends; pressure steam washing; checking geometric parameters; checking the tube vacuum strength at overpressure of 4 bar.

After successfully passing through the IQC, the tube was cut out to the required length. Then this tube was used to manufacture the drift tube, which has its own procedure of certification including: gluing and checking of end pieces, leak test on a straw leak test station (SLTS) and HV tests with radioactive sources (^{55}Fe and ^{90}Sr) [3].

At the moment, about 1 400 drift tubes have passed through certification. Three prototypes and two working planes (STW-X2 and STW-Y2) for PAS were assembled from them. The gas leaks of these tubes did not exceed $2 \cdot 10^{-6}$ mbar · l/s, which is an order of magnitude better than required.

3. The choice of the gas mixture for proton arm spectrometer

This activity was based on GARFIELD simulations of the drift tubes. The operating characteristics of a gaseous detector are highly dependent on the gas mixture. One can select it for one or more of the following criteria: stability; low tendency to spurious discharges; good detection efficiency; high amplification; the drift velocity can be either slow (for good position measurement) or fast, for small dead time; non-flammability for safety; low diffusion for better time and space resolution; minimum aging effects for longer operational life of the detector.

As a result of Monte Carlo modeling of PAS drift tubes functioning in the GARFIELD program package, 70% Ar + 30% C_2H_6 was selected as a working gas mixture. It was used in tests of both prototypes and directly in the PAS STWs.

4. Proton arm spectrometer prototyping

These works were performed to test the PAS technology, to determine the diameter and length of the anode wire, to investigate the drift tube behaviour under different pressures (1–3 bar). Three prototypes were assembled and tested: prototype 1 (X2, length – 1 000 mm), prototype 2 (Y2, length – 2 500 mm) and prototype 3 (length – 300 mm).

Prototype 1. We have fabricated and tested the detector module, structurally corresponding to the STW-X2. This detector performance was studied at PNPI with a β-source ^{90}Sr and a photon source ^{55}Fe, as well as a high-energy (600 MeV/u) beam of carbon ions at GSI. The gas mixture Ar + 30% C_2H_6 was used. A general view of the prototype 1 and its location on a carbon beam at GSI is shown in Fig. 2*a*. The space structure of the beam and its halo were measured, the time spectra of the drift tubes were obtained, and algorithms for event selection were worked out [4, 5].

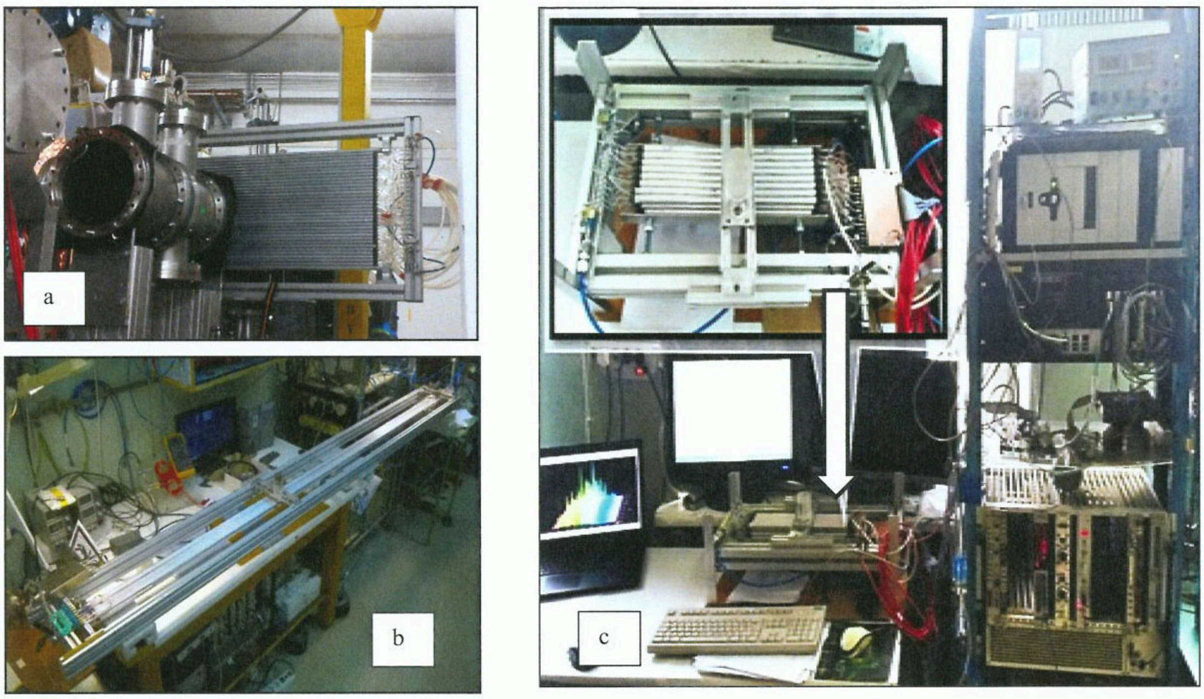

Fig. 2. Prototype 1 testing on a carbon beam at GSI (a); prototype 2 testing at PNPI (b); prototype 3 as a part of the proton arm spectrometer test station (*c*)

Prototype 2. We have fabricated and tested the detector module with the length L = 2 500 mm, which is larger than the tubes in the longest plane STW-Y2 (L = 2 180 mm). In addition, some of the drift tubes had anodes with different diameters – 30 and 35 µm with and without a special support. The operation of the detector with electronics was tested at a working gas pressure of 1–3 bar and different deformation of the drift tube [5].

Prototype 3. It was used to test the front-end electronics modules DT_ASD16 (amplifier / shaper / discriminator) and to study their interaction with the R^{3}B data acquisition system using a special test station (Fig. 2*c*). The test station includes: a time-code converter (CLK-TDC-128) with a control personal computer (PC) and an auxiliary module EXPLODER, four DT_ASD16 modules with a drift-tube unit, a server PC for remote operation with the test station, LV and HV power supplies (LVPS, HVPS).

Based on the results of our research, the following conclusions were made: the diameter of all PAS anodes will be the same and equal to 35 µm; the anodes of the drift tubes work confidently without special supports at pressures of 1–3 bar; the allowable deformation of the tubes is 300 µm [5].

5. Construction and testing of X2 and Y2 planes

A general view of the X2 and Y2 planes is shown in Fig. 3. (Note that in this paper we use symbols ST wall and ST plane, which are identical to each other.) In the upper right corner of the plane X2 one can see preamplifiers (two preamplifiers on each side) which are mounted on both sides of the frame.

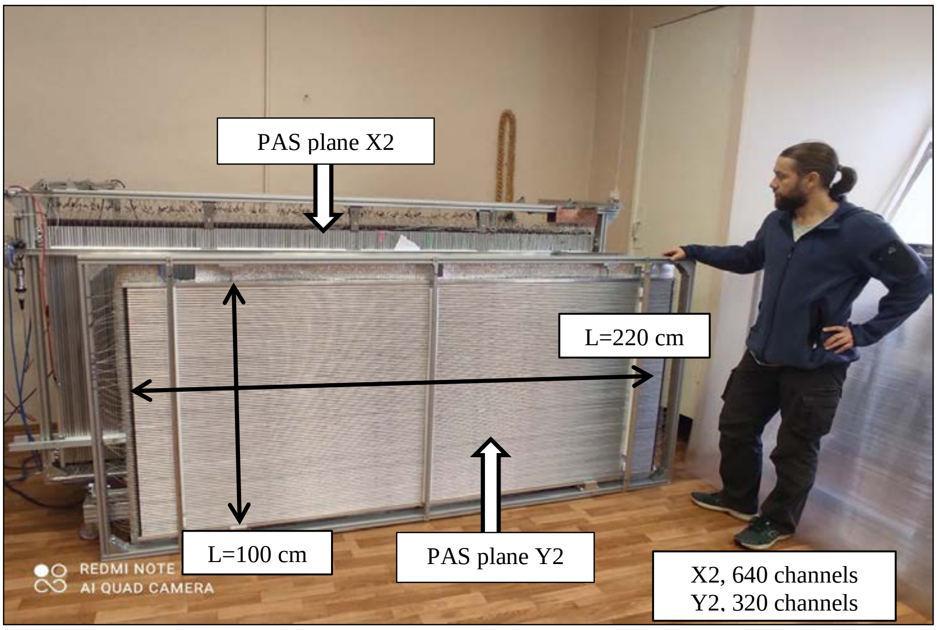

Fig. 3. General view of two proton arm spectrometer planes (X2 and Y2)

All drift tubes were tested for the vacuum leak (Fig. 4*a*) and after that their current and counting characteristics were measured. The tubes selected in this way were glued together in three layers by a specially developed technology and placed in a frame for the PAS spectrometer. The distance between the drift tubes for each of the planes was measured and shown in Fig. 4*b*. It is seen that the absolute position of these tubes in space has no deviation, and the accuracy of their positioning will be 10 250 ± 30 μm, which is 2 times better than the technical requirements.

The vacuum leak was measured independently for each drift tube and plane. Since we do not have a vacuum chamber of sufficiently large dimensions, the gas leak rates were tested at a pressure much higher than the atmospheric pressure (not less than 2 bar). As a result, the gas leakage rates were tested at the following gas pressures:

- Hydrotesting of drift tubes $P = 4$ bar;
- Gas tests of drift tubes $P = 3$ bar;
- Gas tests of the plane from drift tubes $P = 2$ bar.

The pressure and temperature in the planes were recorded during seven days. The data obtained for the X2 and Y2 planes are shown in Fig. 4*c*. The temperature was practically constant in the range 22–25°, and so the density of the gas inside the tubes depended only on the behaviour of the pressure. As one can see, the pressure dropped down from 2 to 1.1 bar in X2 during (74 – 16) / 24 h = 2.4 days and in Y2 during (135 – 28) / 24 h = 4.5 days. These are upper estimates! The obtained data on the leak level in the planes differed by a factor of about two, which corresponded to the number of drift tubes in the X2 and Y2 planes. This allows us to state that the gas leaks in the planes are mainly associated with the gas connections between the tubes, and they are rather small.

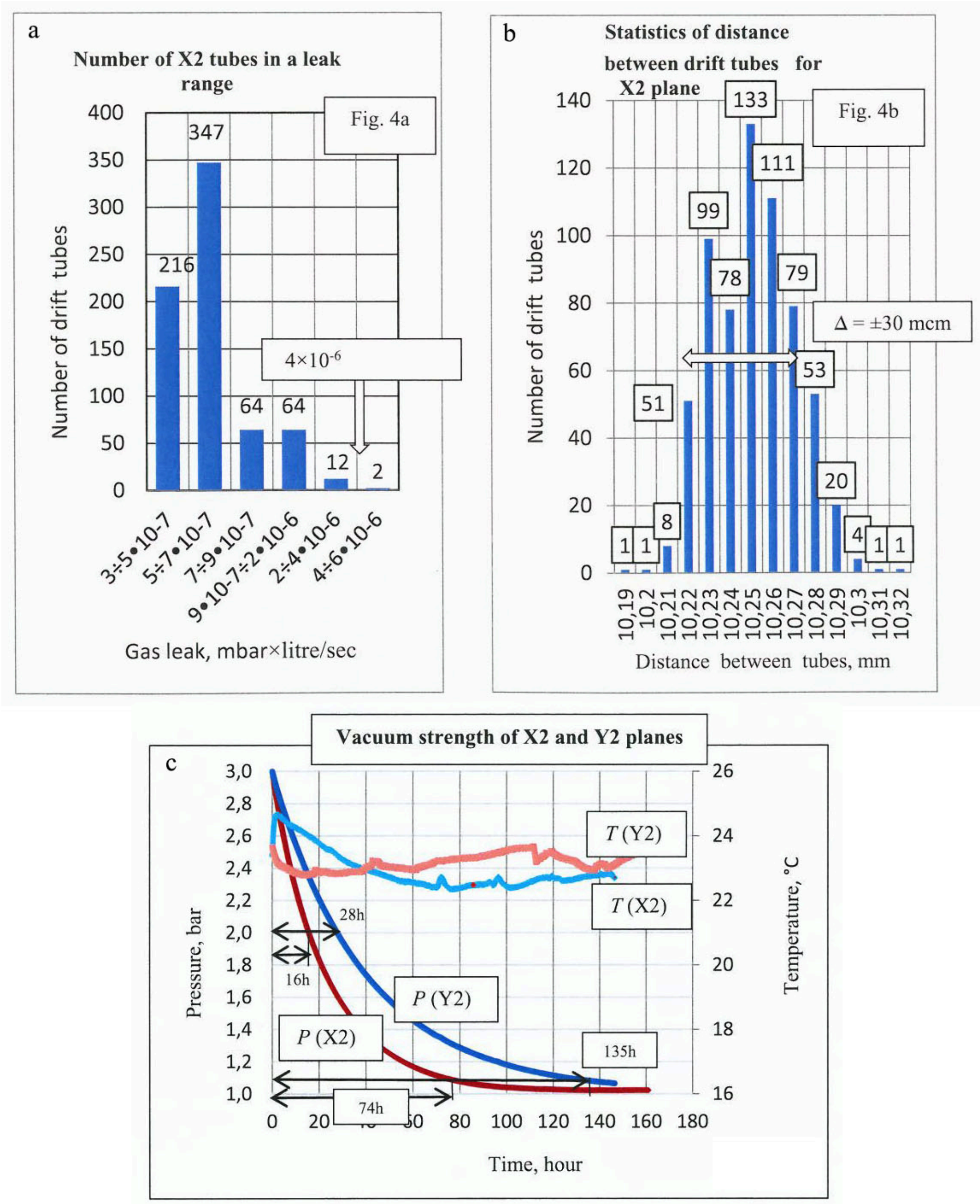

Fig. 4. Number of X2 tubes in a leak range (*a*); statistics of distance between drift tubes in STW-X2 (*b*); plane's pressure and temperature time behaviours (*c*)

6. The straw leak

To investigate the straw leakage, two methods were used by us. The first method was implemented on the basis of the straw leak test station (SLTS, Fig. 5) and answered the question of the gas leakage rate into vacuum. It had high sensitivity and allowed us to select drift tubes with small leakage. The second method was based on the behaviour of the tube in water. It had a slightly lower sensitivity, but it allowed to accurately spot the place where the leak occurred. By combining both methods, it was possible to efficiently select drift tubes with no leakage to vacuum under an absolute pressure of 4.0 bar. We worked with tubes leaking up to $4 \cdot 10^{-6}$ mbar · l/s.

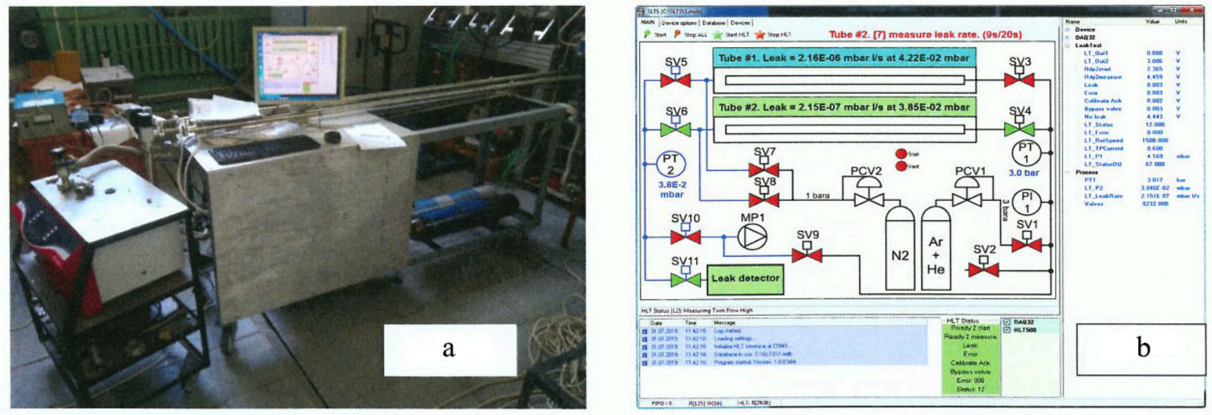

Fig. 5. Straw leak test station (*a*); straw leak test station software main window (*b*)

The main task of the SLTS was to measure the leak rates from the straw drift tubes into vacuum. The parameters of the system are listed below: the leak rate sensitivity – $\sim 1 \cdot 10^{-8}$ mbar · l/s; the straw working gas mixture – Ar + 8% He; the absolute pressure range was 0.5–5.0 bar; the maximum straw length was 3 m. The system was mounted in a special bench with two vacuum cartridges and a control console on top of the bench. All valves, a vacuum pump and gas cylinders were located inside the bench.

7. Proton arm spectrometer gas supply system

The main task of the gas system (Fig. 6*a*) is to provide a pure (70% Ar + 30% C_2H_6) mixture to the PAS detector at the chosen operating pressure. The gas supply system works in flushing mode, with the total flow rate of up to 4 litres per minute. The absolute pressure in the straw tube walls is stabilized in the range 1–3 bar with ~ 1% accuracy. The oxygen and moisture concentration in the mixture is kept at the 5 ppm level.

The wiring of the control and gas panels was finished. All sensors and control devices were checked. The control software of the gas system is shown in Fig. 6*b*. The software package consists of the main control program, the CHARTS program for online parameters visualization, the DBVIEWER program for handling the databases with the gas system parameters. The pressure stabilization in X1 plane (PT4) and in X2, Y1, Y2 planes (PT5) is shown in Fig. 6*c*.

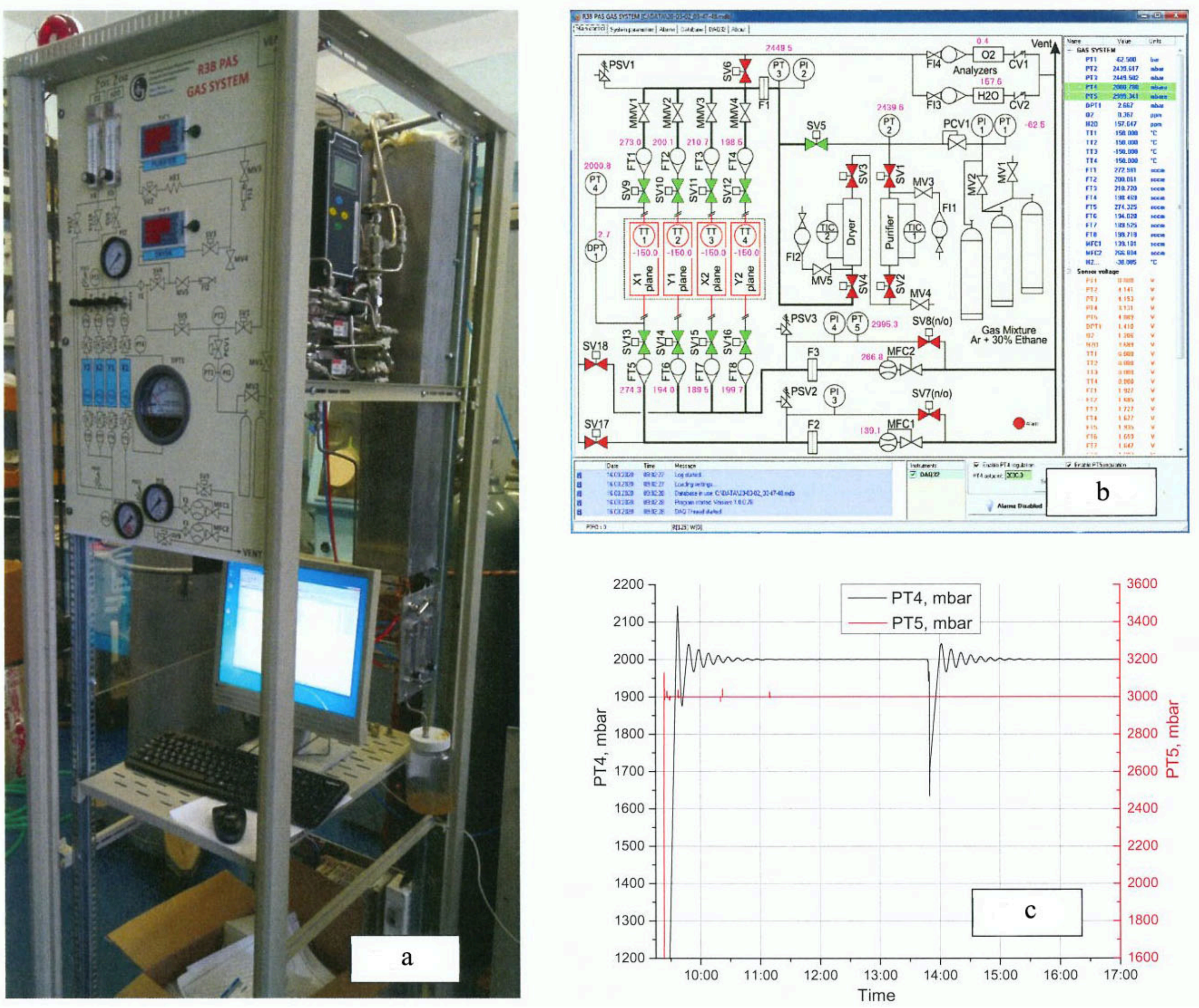

Fig. 6. Proton arm spectrometer gas supply system appearance (*a*) and system software main window (*b*); pressure stabilization in X1 plane (PT4) and in X2, Y1, Y2 planes (PT5) (*c*)

The pressure histogram for the X1 plane was measured during the stable operation of the system. The standard deviation of the pressure was only 0.22 mbar at the total pressure of 1999.99 mbar, so the stability is about 0.01%. This is very good, but should be checked again with the real detector planes. The gas system is ready to operate with the detector planes.

8. Front-end electronics

The Radio Electronics Department (RED) of the HEPD has developed a version of the front-end electronics that combines an amplifier, a shaper and a discriminator on one 16-channel DT_ASD16 card (amplifier, shaper, discriminator), see Fig. 7*a*–*c*. Its specification is in the Table. These cards are located directly on the STW frame in vacuum. The DT_ASD16 card is optimized to work with straw tubes manufactured by PNPI and has an output connector compatible with the CLK-TDC-128 digitizing module of the data acquisition system. These modules are produced at GSI.

The LVPS has a LV switchboard (not shown in Fig. 7*a*) located on the STW frame to supply power to each DT_ASD16 *via* a separate 3.8–4.5 V wire. (This is LV IN, see Fig. 7*a*.) Low dropout voltage regulators (LDOs) provide a nominal 3.3 V (LV OUT) voltage to power on-board circuits. LV switchboard combines up to 20 DT_ASD16 cards per one LVPS.

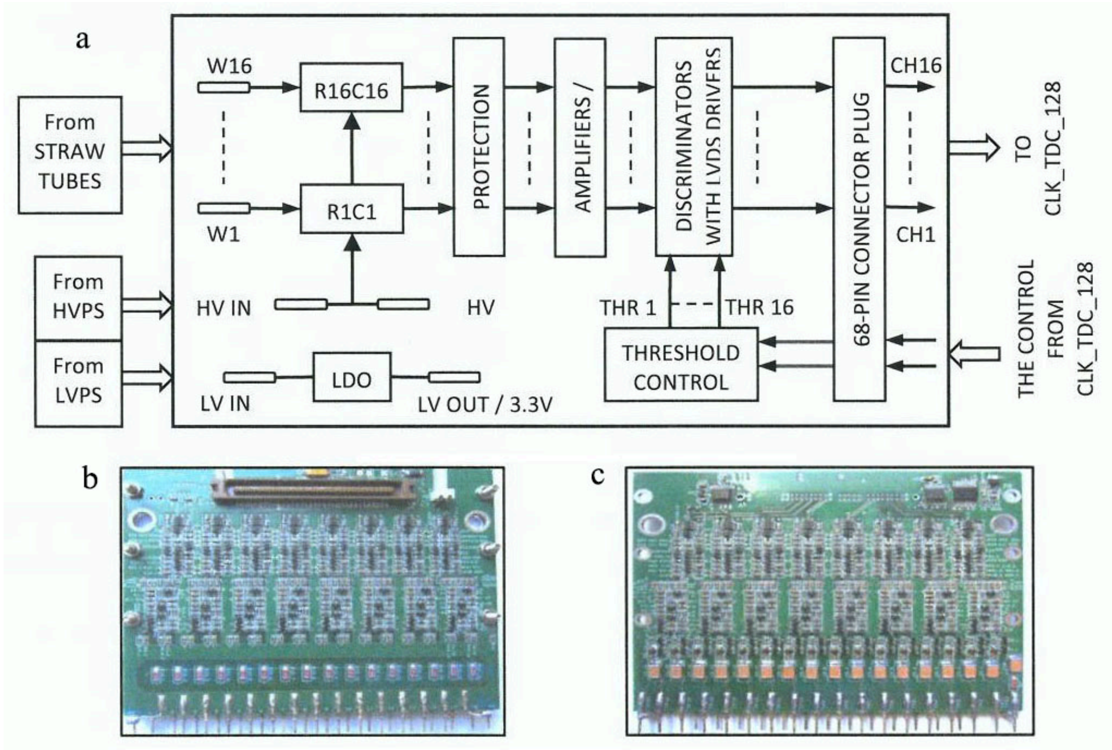

Fig. 7. DT_ASD16: *a* – block diagram; *b* – top view; *c* – bottom view

Table

DT_ASD16 specification

Parameter	Value
Board size	105 × 84 mm^2
Input	Charge sensitive
Input impedance	260 Ohm
Gain	5.4 mV/fC
Shaping	8.5 ns
Threshold control	Per channel
Supply Voltage	3.8–4.5 V
Output standard	Low voltage distribution system
Internal noise	2 fC
Double pulse resolution	100 ns
Output connector	68-pin 1.27 mm pitch low profile plug (by KEL Corporation)
Current consumption per card	240 mA

The HVPS comes from a HV switchboard (not shown in Fig. 7*a*), also located on the STW frame. The DT_ASD16 distributes the high voltage from the HV IN pin to each straw wire (W1… W16). The HV OUT pin allows multiple DT_ASD16 boards to be connected in series, allowing more straws to be powered per HV channel.

Placing the DT_ASD16 cards on both sides of the frame made it possible to achieve two important things: firstly, to minimize the couplings between the amplifier inputs and drift tubes, and secondly, to ensure efficient removal of the generated heat from the electronics, which should operate in vacuum. The measured temperature of the hottest elements on the DT_ASD16 card does not exceed 45°C, which should ensure long-term stable operation in vacuum without active cooling.

Up to eight DT_ASD16 cards are connected to one CLK-TDC-128 module, also located in vacuum on the inner wall of the vacuum chamber, which allows minimizing the length of the connecting flat cables to 6 m. Individual thresholds in each DT_ASD16 channel allow to compensate gain fluctuations in tubes and are set *via* the CLK-TDC-128 module.

All DT_ASD16 cards were tuned and quality controlled on the set-up shown in Fig. 8*a*. The LVPS of the preamplifiers was carried out from standard power supplies. The HVPS of the drift tubes was carried out through the preamplifier board by power sources developed in the RED. The modules of this power supply (HVCD MASTER and DB50) are shown in Fig. 8*b*.

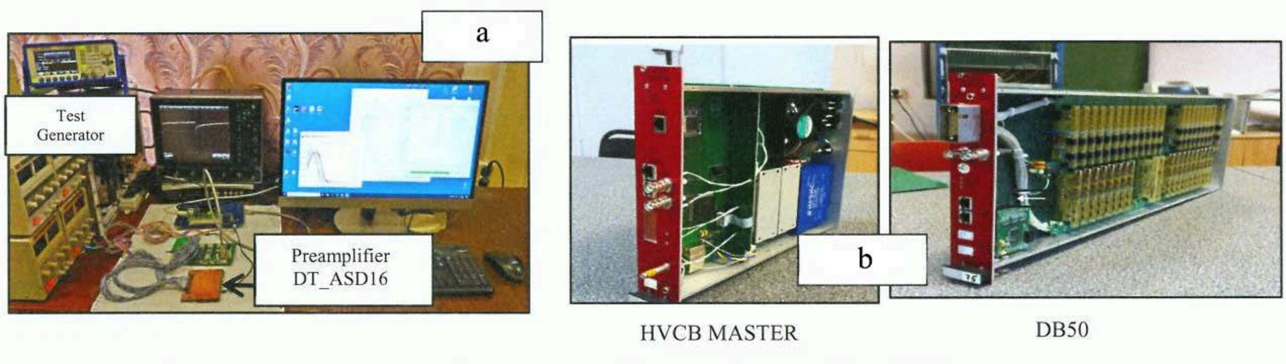

Fig. 8. The set-up for DT_ASD16 tests of quality (*a*); the modules of HVDS1600 (*b*)

The development of the HVPS HVDS1600 (high voltage distribution system) was performed in the RED in accordance with the parameters of the required technical specifications [6].

Tests of four DT_ASD16 modules at a test bench and a test station with the CLK-TDC_128 module showed that their characteristics comply with the technical specifications (Fig. 9). As a result, this version represents the final technical solution DT_ASD16 for PAS, which will be put into serial production.

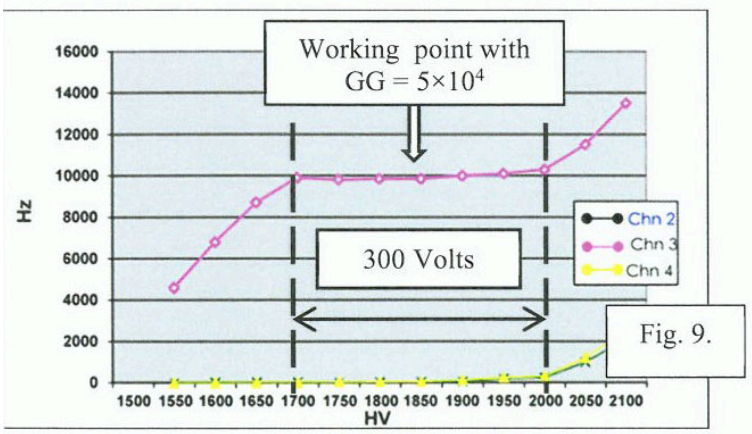

Fig. 9. The counting rate versus high voltage from ^{90}Sr source for different channels of DT_ASD16

The results of testing of four DT_ASD16 modules are presented below. The following parameters are ensured, which cover the entire range of lengths of the drift tubes (0.3–2.2 m) for PAS:

- The counting rate plateau is in the range of 1 700–2 000 V;
- The operating point is at 1 850 V, which corresponds to the gas gain (GG) factor of GG = $5 \cdot 10^4$;
- The measured cross couplings within the plateau do not exceed 2.0%.

Currently, four DT_ASD16 modules are installed on the system test station and demonstrate stable operation with the CLK-TDC-128 module. These modules are reference ones and will be used for product tests during serial production. The threshold control is also provided by the CLK-TDC-128 module; thus no special threshold control unit is required.

9. Conclusion

1. The manufacturing technology of the PAS spectrometer based on long drift tubes with ultrathin walls for vacuum operation has been developed at PNPI.

2. The PAS spectrometer is in a high state of readiness:
   - The plane X2 is ready for work;
   - The plane Y2 is already done and ready to be equipped with electronics;
   - The plane Y1 is in the process of being assembled;
   - The plane X1 will be made from Mylar drift tubes. This technology has been developed at PNPI. The tubes for this plane were ordered in England, delivered to GSI and are ready to be sent to PNPI.

References

1. Technical Report for the Design, Construction, and Commissioning of Tracking Detectors for R^3B, 101–117 (2014).
2. V.A. Andreev, M.I. Gasanov *et al*., Preprint NRC “Kurchatov Institute” – PNPI 3052 (2021).
3. V.A. Andreev, V.Yu. Ivanov *et al*., Preprint NRC “Kurchatov Institute” – PNPI 3059 (2021).
4. A.G. Krivshich *et al*., Preliminary Results of the PAS Prototype Test with a ^{12}C Beam: GSI Scientific Report 2016, 217 (2017). DOI:10.15120/GR-2017-1.
5. A.G. Krivshich, V.A. Andreev *et al*., Preprint NRC “Kurchatov Institute” – PNPI 3062 (2022).
6. A.A. Fetisov, A.G. Krivshich, D.A. Maisuzenko, in *Contract Between FAIR and PNPI: Technical Specifications*, 1–7 (2018).