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DETERMINATION OF THE ANODE WIRE POSITION IN A NEW TYPE OF THIN-WALL DRIFT TUBES (STRAWS) FOR THE NA62 DRIFT CHAMBERS USING VISIBLE LIGHT

I. Measurements in Transmitted Light

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1. INTRODUCTION

Spatial resolution of charged particle tracks in experiments with drift chambers depends on a lot of factors. First, it is mechanical precision to which the chamber, tubes, tips, and their supports are manufactured. The other important factors are the gas mixture composition and pressure, physical processes in the drift tubes, readout electronics, etc. Of no less importance are the positioning precision of anode wires in the chamber and the maintenance of the distance between them (their parallelism) over the entire length of the tubes.

Coordinates of the track of any charged particle that passed through the drift chamber plane are strictly referenced to the anode wires nearest to this track. That is why it is so important to check their real position in the chamber.

When the anode wire cannot be visually observed, a radioactive electron source or X rays are used. Devices employing these methods are rather complicated. To scan the wires, the source and the wire-scattered radiation detector must move synchronously on the opposite sides of the chamber (passive, or shadow, method). Alternatively, the drift tubes themselves can be used as a detector (active method, entirely unsuitable for manufacture of chambers). In both cases the positions of the anode wires are determined from the centers of the distribution of the radiation scattered by them. It is a rather long and laborious procedure (see, for example, [1–3]).

The drift tubes of the new type designed for operation in vacuum and used in the drift chambers of the NA62 experiment (a total of 7200 tubes 9.80 mm in diameter and 2300 mm long) [4, 5] turned out to be semitransparent with a transparency factor of $\sim 2\%$. When they are illuminated by a directional beam of visible light, anode wires are well seen under the microscope. Consequently, their position can be accurately measured while the chamber or the microscope moves. This finding allowed us to develop a simple method for measuring coordinates of anode wires in drift chambers with these tubes [6, 7]. As the experience showed in work [6], positions of 30-μm-diameter wires could be directly determined under the microscope with an accuracy of about ± 5 μm. The wires were observed both

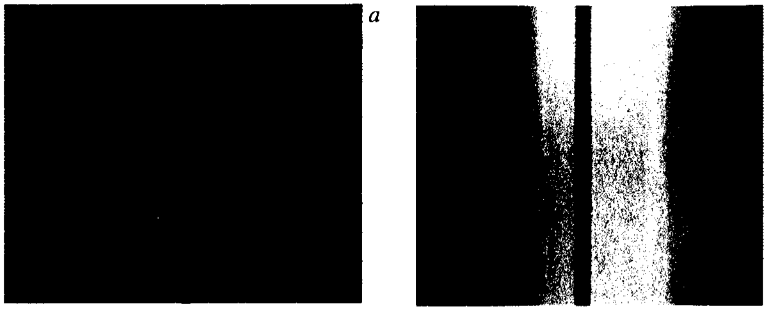

Fig. 1. Photo of the anode wire 30 μm in diameter in the semitransparent tube 9.80 mm in diameter under transmitted light (*a*) and reflected light (*b*)

in transmitted light and in light reflected from them. As an example, Fig. 1 shows the image of the anode wire inside the drift tube obtained in transmitted light (*a*) and reflected light (*b*).

In this work, methods for determining coordinates of anode wires in tubes using visible light are described, and new results of calibration measurements performed with an accuracy of about $\pm 1-2$ μm using the UIM-23 microscope are presented. It is also shown that the measurements can in principle be automated. The first semiautomatic measurements accurate to about ± 0.003 μm are reported, which were made using an MBS-type microscope with a digital eyepiece.

We carried out two series of independent measurements to estimate and eliminate systematic errors. One was with the UIM-23 microscope, in which calibration data were obtained, and the other was with the MBS-type microscope with a digital eyepiece, which allowed the measurement process to be automated for using it in real chambers.

2. CHAMBER MODEL

Thin-wall drift tubes (straws) of the new type used for measurements were made from a 36-μm Mylar film by ultrasonic welding with the seam along the generatrix. They were 9.80 mm in diameter and coated with 0.05 μm of copper and 0.02 μm of gold on the inside [8].

A model with the drift tubes was made with high mechanical precision. A two-row arrangement of the tubes and spacing between them followed their geometry in the drift chambers for the NA62 experiment (see Fig. 2). The distances between the axes of the tube sockets, coaxiality of the tubes at their ends, and diameters of the holes were accurate to about 10 μm. The model comprised ten tubes with the active length of 150 mm. Gold-plated 30-μm-diameter tung-

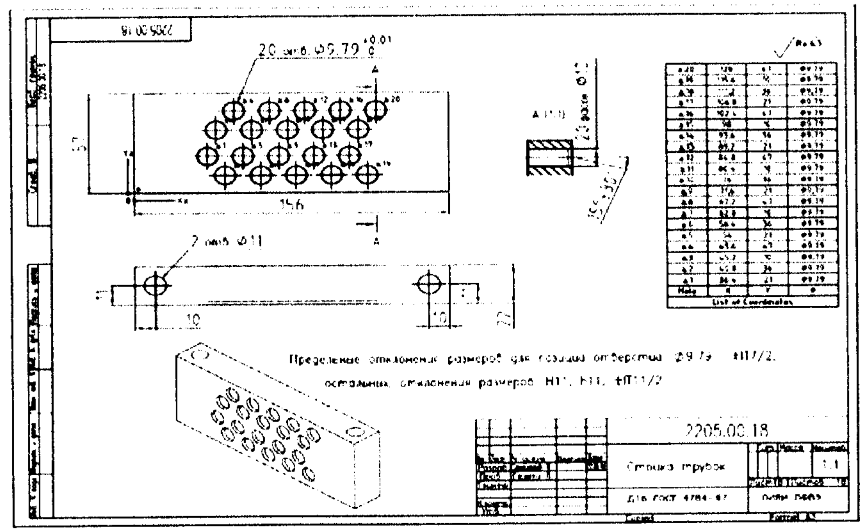

Fig. 2. Drawing of the model (in the real model two rows were used)

sten wires were also used as anodes. Note that unlike the case in a real chamber, where tubes normally have a spread in diameter, the tubes for our model were selected to be strictly identical in diameter (spread below 0.01 mm). The tips were also thoroughly selected for the mounting diameter of the tubes. They were set into tips without free play. Consequently, it is highly probable that the wire position spread in the model mainly depends on the diameter spread of the pins used to fix the wires and of the holes for them in the tips.

Note that during the assembly of real chambers there can also be other causes of wire displacement from the calculated position, which are due to the assembly procedure and other factors, and the wire position spread will be appreciably greater in them.

3. CALIBRATION MEASUREMENTS IN TRANSMITTED LIGHT UNDER THE UIM-23 MICROSCOPE

A stationary UIM-23 microscope allows the object to be moved and measured with an accuracy of about $\leqslant 1$ μm, but in our case the real accuracy substantially depended on the operator's skill to bring the microscope crosshairs into coincidence with the center or edges of the wire. The measurements were performed by three operators to study the arising systematic errors. In each measurement the microscope crosshairs were successively brought to two edges of the wire image and both coordinates were read. Their difference yielded the known wire diameter (30 μm). The distributions obtained from the diameter measurements

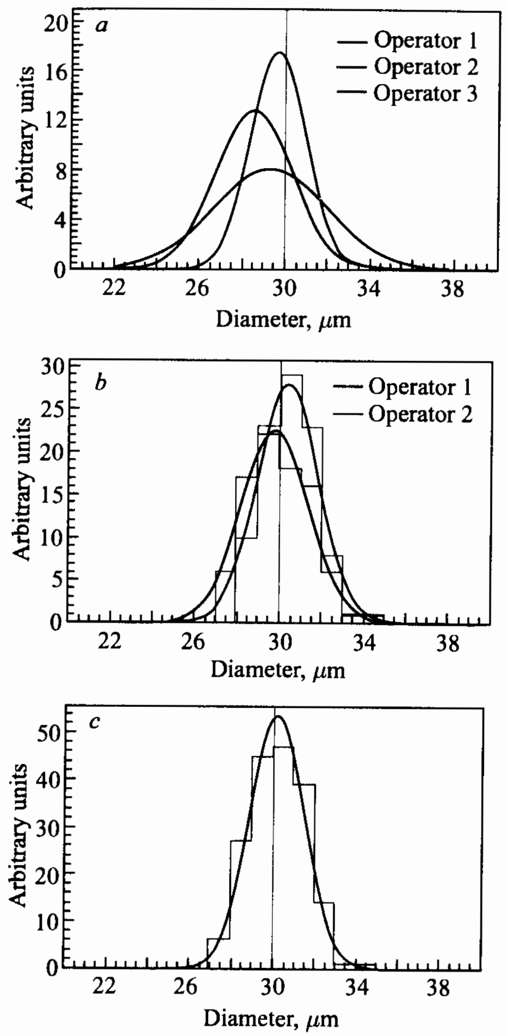

Fig. 3. Wire diameter measurements: (*a*) first measurements, (*b*) measurements after the training, (*c*) average data from two operators

are shown in Fig. 3, *a*. As is seen, the spread was first rather large for different operators. It was found by trials that the operators' training significantly improves the quality of measurements (see Fig. 3, *b*).

The average wire diameter was found to be (29.8 ± 1.0) μm (see Fig. 3, *c*), which, to our mind, is quite acceptable. Note that averaging of the edge coordinates in the wire image allows the wire center to be determined more accurately.

Table 1. **Measurements of two wire layers at a step of 17.60 mm by UIM-23 microscope. (Here and below up and down measurements were performed at a distance of 135 mm along the tubes)**

W. nn	Operator 1 (mm)		Operator 2 (mm)		σ	Average
	10.07.2015	28.07.2015	09.07.2015	10.07.2015		
1–3 top	17.627	17.630	17.630	17.632	0.002	17.630
1–3 bot.	17.550	17.551	17.552	17.550	0.001	17.551
3–5 top	17.664	17.667	17.668	17.668	0.002	17.667
3–5 bot.	17.632	17.632	17.631	17.630	0.001	17.631
5–7 top	17.591	17.588	17.588	17.587	0.002	17.589
5–7 bot.	17.594	17.600	17.600	17.602	0.003	17.599
7–9 top	17.605	17.609	17.607	17.606	0.001	17.607
7–9 bot.	17.630	17.632	17.631	17.633	0.001	17.632
2–4 top	17.704	17.710	17.712	17.708	0.003	17.709
2–4 bot.	17.584	17.586	17.586	17.585	0.001	17.585
4–6 top	17.569	17.571	17.572	17.572	0.001	17.571
4–6 bot.	17.591	17.594	17.591	17.592	0.001	17.592
6–8 top	17.592	17.596	17.592	17.597	0.002	17.594
6–8 bot.	17.630	17.629	17.633	17.629	0.002	17.630
8–10 top	17.579	17.580	17.579	17.577	0.001	17.579
8–10 bot.	17.560	17.561	17.561	17.562	0.001	17.561

Since the tubes in the model are arranged in two rows (see Fig. 2), the measurements are performed in two stages. First, the microscope is focused on the wires in the first row and then in the second row. Coordinates of individual wires should be measured in at least two separated planes along the tubes. The thus obtained coordinates will allow determining not only the position of the wire at the measurement point but also the direction of each wire. The average accuracy of the wire position measurement using the UIM-23 microscope is $\pm 1-2$ μm. Tables 1 and 2 summarize the results of measuring distances between the wires at steps of 17.60 and 8.80 mm. These accuracies are somewhat a limit for the proposed method. They can hardly be reached with real chambers, but the average accuracy on the order of ± 0.003 to ± 0.004 μm is quite attainable. This accuracy usually suffices for practical purposes.

Figure 4 shows positions of nine wires in the model measured with respect to the first one. Deviations of the wire ends from the calculated position are shown on an enlarged scale for ease of visualization.

Table 2. **Measurements at a step of 8.80 mm by UIM-23 microscope**

W. nn	Operator 1 (mm)		Operator 2 (mm)		σ	Average
	07.10.2015	28.07.2015	09.09.2015	23.09.2015		
1–2 top	8.910	8.914	8.912	8.911	0.002	8.912
1–2 bot.	8.862	8.862	8.864	8.862	0.001	8.863
2–3 top	8.719	8.715	8.720	8.718	0.002	8.718
2–3 bot.	8.686	8.690	8.689	8.690	0.002	8.689
3–4 top	8.988	8.992	8.992	8.993	0.002	8.991
3–4 bot.	8.895	8.891	8.893	8.896	0.002	8.894
4–5 top	8.676	8.677	8.671	8.675	0.003	8.675
4–5 bot.	8.736	8.740	8.738	8.736	0.002	8.738
5–6 top	8.897	8.896	8.898	8.894	0.002	8.896
5–6 bot.	8.858	8.856	8.857	8.852	0.003	8.856
6–7 top	8.691	8.692	8.694	8.694	0.002	8.693
6–7 bot.	8.743	8.745	8.742	8.745	0.002	8.744
7–8 top	8.900	8.901	8.899	8.900	0.001	8.900
7–8 bot.	8.886	8.882	8.882	8.883	0.002	8.883
8–9 top	8.706	8.705	8.706	8.707	0.001	8.706
8–9 bot.	8.742	8.748	8.743	8.743	0.003	8.744
9–10 top	8.871	8.876	8.871	8.872	0.002	8.873
9–10 bot.	8.818	8.814	8.819	8.821	0.003	8.818

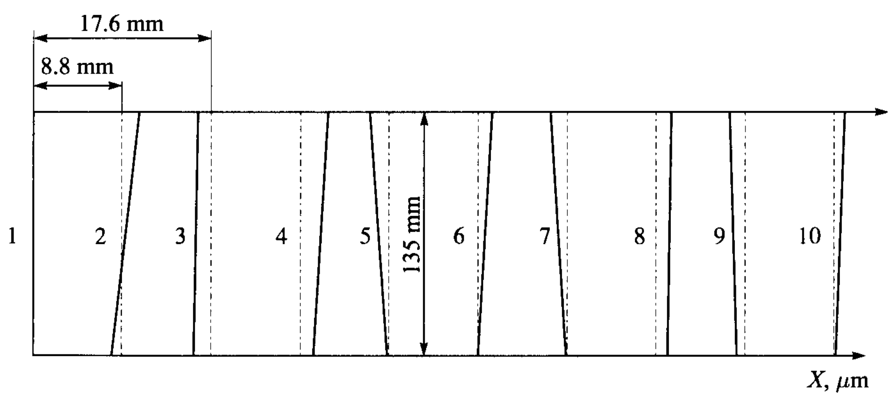

Fig. 4. Wire spread in the model

4. MEASUREMENTS IN TRANSMITTED LIGHT WITH AUTOMATIC WIRE RECOGNITION

The next stage was measurements under realistic chamber conditions. Figure 5 depicts an approximate scheme of determining wire positions in tubes in transmitted light [6]. It involves a microscope, a source of light, an optical bench, and a chamber model with tube. In our case the model moved with respect to the microscope. To this end, the model was mounted on the computer-controlled Huber optical bench with a positional accuracy of $\sim 0.6\ \mu$m [9]. Wire coordinates were registered by the MBS-type stereo microscope. A Levenhuk digital eyepiece with a resolution of 5.1 MP was used for scanning images and automatically storing information in a PC. To avoid the effect of parallax typical of stereo microscopes, the anode wire was located in the plane passing through the axes of the microscope stereo tubes.

To illuminate tubes with transmitted light, we used a fixed extended source in the form of a LED matrix attached to the model behind the tubes instead of a light source moving synchronously with the microscope along the row of tubes (an analogue of the passive method [3]). The diodes were arranged in the matrix with a step equal to the step of displacement of the tubes in the first and second rows (8.80 mm), as is shown in Fig. 5. Each LED illuminated "its own" wire through the tube wall. The luminous area of a LED was 1.5 mm in diameter; therefore, their precise arrangement with respect to the wire was not necessary. This generally simplified the measurements.

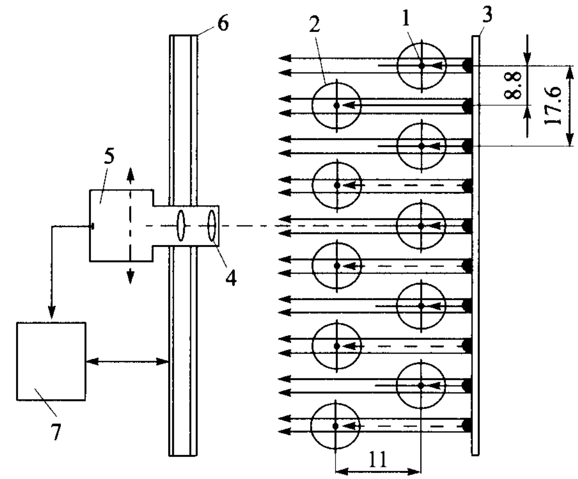

Fig. 5. Schematic of a setup for measuring wire positions in semitransparent tubes in transmitted light. (1) Anode wire, (2) semitransparent drift tubes, (3) extended light source (LED matrix), (4) microscope, (5) digital eyepiece, (6) optical bench, (7) control computer

Requirements on microscope optics are quite simple. It must have a magnifying power of about 50–80^{x}, a relatively large working distance ($\sim$ 40–80 mm), and a high depth of focus, if possible. The microscope moves along and perpendicular to the row of tubes in one plane with the LED matrix in the directions shown in the figure by arrows.

In the semiautomatic mode the image of the wire is recorded to the PC, which processes it and outputs a table of coordinates. In the manual mode the operator directly (or using the digital eyepiece) reads successive coordinates of the wire image as its edges are brought into coincidence with the microscope crosshairs.

As was pointed out above, measurement of coordinates should be repeated to reconstruct the direction of the wires in the chamber. When tubes are arranged vertically, these data are enough. But when tubes are arranged horizontally or slanted or when there are wires in the support tubes, additional measurements along the tubes should be performed in several places, depending on their free length, to take into account sagging of the tubes due to gravitation.

To automate the measuring procedure, a "Straw Recognition" application was developed for recognizing images of anode wires and calculating their displacement from the calculated position. In addition, this program must exclude systematic errors typical of manual measurements.

In the Straw Recognition the image was directly obtained from the digital eyepiece without using the standard Levenhuk software. This speeds up the recognition and also makes it possible to develop a completely automated measurement system in the future.

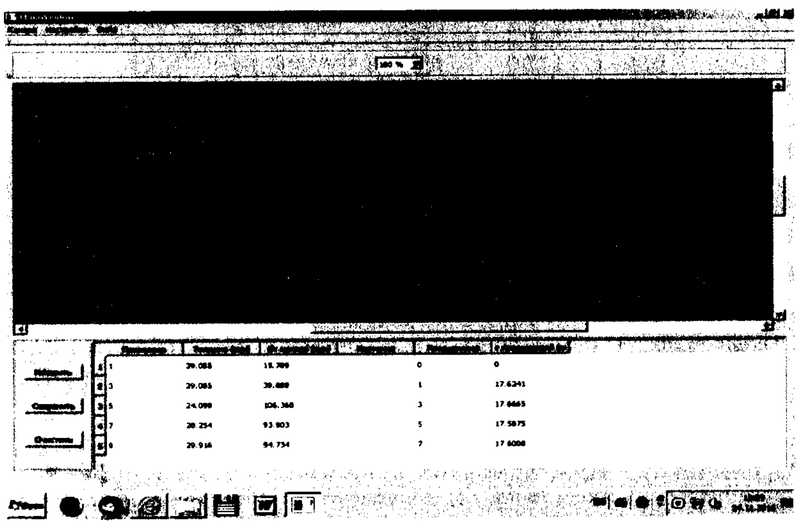

Fig. 6. Main Straw Recognition screen

The graphic interface was created using the Qt library [10], and the image processing is performed using the OpenCV library [11]. The main screen of the application is shown in Fig. 6.

The following image recognition algorithm is used:

1. Imaging of the anode wire using the microscope with the digital eyepiece.
2. Preparation of the image (adaptive background processing, application of filters to reduce noise).
3. Creation of the brightness gradient using the Sobel operator [12].
4. Recognition of the anode wire image.
5. Calculation of the wire diameter in micrometers.
6. Calculation of the wire displacement from the frame center.
7. Calculation of the distance from the neighboring wire.
8. Storage of the measurement results in the form of Excel files and dimensioned images.

The number of pixels was conversed to micrometers using two kinds of calibration:

1. By measuring the scale graduated in 100 μm.

Table 3. **Measurements under the MBS microscope with the digital eyepiece**

W. nn	Operator 1 (mm)		Operator 2 (mm)		σ	Average
	19.10.2016	19.10.2016	29.10.2016	29.10.2016		
1–3 top	17.632	17.637	17.632	17.632	0.003	17.633
1–3 bot.	17.669	17.670	17.667	17.667	0.002	17.668
3–5 top	17.590	17.590	17.587	17.587	0.002	17.589
3–5 bot.	17.606	17.604	17.608	17.608	0.002	17.607
5–7 top	17.712	17.711	17.712	17.708	0.002	17.711
5–7 bot.	17.572	17.573	17.571	17.572	0.001	17.572
7–9 top	17.593	17.596	17.589	17.591	0.003	17.592
7–9 bot.	17.578	17.579	17.576	17.578	0.001	17.578
2–4 top	17.554	17.550	17.554	17.553	0.002	17.553
2–4 bot.	17.633	17.634	17.628	17.629	0.003	17.631
4–6 top	17.600	17.601	17.599	17.599	0.001	17.600
4–6 bot.	17.631	17.629	17.627	17.627	0.002	17.629
6–8 top	17.584	17.588	17.585	17.585	0.002	17.586
6–8 bot.	17.594	17.593	17.591	17.592	0.001	17.593
8–10 top	17.628	17.631	17.627	17.628	0.002	17.629
8–10 bot.	17.560	17.563	17.559	17.556	0.003	17.560

2. By measuring the optical bench travel over the known distance (measurement of the wire images before and after the travel within one field of view).

Calibration by the travel distance is more reliable because, in addition to the optical properties of the microscope and the eyepiece, it is based on the high positional accuracy of the optical bench.

Moving the model at a step of 17.6 mm, we measured the deviation of each anode wire from the frame center in each row of the tubes. These data were used to calculate distances between neighboring wires. The results are summarized in Table 3. A comparison of the data in Tables 1 and 3 shows good agreement within the errors of two independent measurements. At this stage the accuracy of the manual measurements with the UIM-23 microscope was slightly higher.

Further automation of measurements requires fulfillment of four important tasks.

1. Improvement of the recognition algorithm for increasing the accuracy of measurements under nonideal conditions (faint illumination or defocusing).

2. Improvement of the Straw Recognition interface for easier use.

3. Control of the optical bench travel directly from the Straw Recognition routine without using separate software.

4. Focusing automation.

5. CONCLUSIONS

Positions of anode wires in thin-wall tubes of the new type for the NA62 experiment, which turned out to be transparent for visible light, can be measured with an optical microscope in both transmitted and reflected light. These tubes are now supposed to be used in other experiments as well.

Calibration measurements in transmitted light using the UIM-23 microscope showed that an accuracy of about $1-2$ μm was attainable. Realistic measurements with an ordinary microscope of the MBS type and a model placed on the Huber optical bench were performed using semiautomatic electron scanning. This allows eliminating systematic errors that arise from bringing the microscope crosshairs into coincidence with the wire edge. Automated measurements yield results that statistically agree with the UIM-23 calibration data.

In the future the measurement process can be almost completely automated, except for referencing the coordinates to the chamber body.

In the future it seems important to obtain similar results with reflected light because measurements in reflected light have a prominent advantage of having the microscope and the illuminator on the same side of the tube plane. It is convenient when there is no access to the tubes from the other side for illumination of wires. Apart from that, they are identical to measurements in transmitted light, but now they require laborious illumination adjustment. It would be probably helpful to develop a special source of light that allows a simple way of obtaining a high-quality wire image in reflected light.

The method proposed in this work is convenient as it allows measurements to be performed both before and after the assembly of the chamber. In addition, it can be used for investigating the anode displacement in the tube under the effect of gravity or the electric field after high voltage is applied to the tube. In principle, it is also possible to measure simultaneously coordinates of not only wires but also tubes themselves.

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