ToF/SPD   
Dubna, December 2021, Rev. 0.0

Dubna, January 2022, Rev. 1.0

**Technical Design Report**   
**of the**   
**Time of Flight system (ToF) SPD NICA**

Dubna 2021-22

**Content**

TECHNICAL DESIGN REPORT OF THE TIME OF FLIGHT SYSTEM (TOF) SPD NICA 1

1. TIME OF FLIGHT SYSTEM CONCEPT 3

2. TOF SYSTEM DESIGN 4

2.1. BARREL 5

2.2. END CAP 5

3. DESIGN OF THE TOF MODULE. 7

4. R&D PROGRAM AND PROTOTYPE TEST RESULTS 9

4.1 SMALL MRPCS RESEARCH FOR THE OPERATION AT LARGE COUNTING RATE 10

4.2 EXPERIENCE OF MRPC USE FOR THE BM@N EXPERIMENT 12

4.3 REDESIGN OF THE MRPC TO IMPROVE THE OPERATION PERFORMANCE 14

4.4 TEST OF THE CONSTANT FRACTION METHOD 17

4.5 SPD PROTOTYPE TEST RESULTS. 21

5. MRPCS PRODUCTION 23

5.1 THE PRODUCTION TECHNOLOGY 24

5.2 THE POST-PRODUCTION TEST FACILITY 25

5.3 TIME ESTIMATION FOR THE TOF DETECTOR MANUFACTURING. 26

6. FRONT END ELECTRONICS 26

6.1 SPECIAL ANALOGUE ASIC FOR MRPC READOUT 27

6.2 TIME OVER THRESHOLD METHOD 28

6.3 CONSTANT FRACTION METHOD 31

7. MRPC READOUT AND SLOW CONTROL 32

7.1 HIGH VOLTAGE AND GAS CONTROL SYSTEMS 32

7.2 MRPC DATA QUALITY MONITORING SYSTEM 34

8. COST ESTIMATION AND THE TIME SCALE 35

9. REFERENCES 36

# Time of Flight system concept

The newest SPD detector required to have a good Time of Flight (ToF) system. The purpose of the TOF system is to do π/K and K/p separation in the momentum range up to a few GeV/c. The external radius of the TOF barrel is 115 cm. This size dictates the requirement for the time resolution of the TOF to be better than 60 ps. Such time resolution allows to separate π/K and K/p up to about 1.2 GeV/*c* and 2.2 GeV/*c* respectively.

Glass made MRPC have been chosen to construct TOF system in such experiments as ALICE [1], HARP [2], STAR [3] and PHENIX [4]. In our early tests [5, 6] with six and ten gap MRPCs equipped with the 25 mm wide strips the time resolution of ~50 ps was reached that is typical for MRPCs with the pad pick-up electrodes. High resolution was achieved at the efficiency above 98% and at cross-talk signal in the adjacent strips about few percent. The advantages of MRPC are low cost, high efficiency of registration of charged particles and ability to work in a high magnetic field.

Monte Carlo (MC) simulation show that in the barrel part of the ToF the charged particle flux is about 100 Hz/cm2. The particle flux in the end-cap part rapidly increases up to 1 kHz/cm2 when approaching to the ion pipe. It must be considered that the actual radiation flux is always higher. Such conditions make it possible to build a ToF system based on the traditional MRPC with floating electrodes. For example, in [1] a 12 gaps MRPC made of 0.55 mm glass allows to obtain a time resolution of 60 ps and an efficiency above 98% at a background particle flux of 500 Hz/cm2. However due to a spread in the performance of individual MRPCs and front-end electronics the resolution of the ToF system is always worse than that of a separate chamber. Therefore, for SPD it is proposed to use an MRPC with independently distributed potential over gas gaps (it is similar to a multi-gap ceramic PPC). As will be shown in the sub-section 4, a high time resolution of about 30 ps can be achieved for these detectors. To ensure the best rate capability MRPCs should be made from a thinner glass.

# ToF system design

The ToF system consists of two separate parts that are barrel and end-caps. The barrel part is located inside of the solenoid magnet between the tracking system and the electromagnetic calorimeter. This part occupies a cylindrical space with inner radius of 950 mm and outer radius of 1150 mm. The length of this cylinder is 3432 mm. Each end-cap is a washer with a hole for the ion pipe. The end-cap width can be up to 300 mm.

The cylindrical shape allows filling the barrel with chambers of the unified size. But for the ends-cap it is better to use a set of chambers of several sizes. This allows to reduce the overlap of the individual chambers and thereby reduce the amount of parasitic detector material.

* 1. **Barrel**

Possible arrangement of MRPCs for the TOF detector shown in Figure 2.1. The barrel consists of 16 overlapping sectors. Each sector contains 9 MRPCs. The whole barrel ToF is composed of 144 chambers. It is supported by a spatial frame structure that also supports the straw tracker. Each of the MRPC sector is mounted to an aluminum profile beam fixed to the support structure. MRPC strips are located tangentially in the barrel annular geometry. In sector adjacent modules are positioned in a way to create an overlap of 0.5 strip width at the edge of the MRPC active area. In places of conjugation, two sectors overlap by 1 cm of strip length. All material has been concentrated at the sector boundaries. MRPC can only be accessed by pulling out the support structure from the solenoid magnet. The weight of the barrel chambers together with the support beams should not exceed 1.5 tons

|  |
| --- |
|  |
| Figure 2.1: ToF layout for the barrel part |

Overall dimensions of one MRPC are 500×406×18 mm. The MRPC thickness is about 0.09 of radiation length (X0) excluding chamber frame. The complete set of geometrical parameters of barrel MRPCs shown in the table below. Each MRPC equipped with 16 readout strips. Strips are 20 mm wide and 450 mm long. The strip pitch is 21 mm. Considering expected event rate is about 3 MHz and the barrel charge particle rate is ~100 Hz/cm2, for a single event, the strip double hit probability can be 0.003. This value is sufficiently low for the event reconstruction procedure.

|  |  |
| --- | --- |
| External dimensions | 500 х 406 x 18 mm |
| Sensitive area | 440 х 340 mm |
| Strip size | 450 х 20 mm |
| Number of strips | 16 |
| Number of gas gaps | 10 |
| Gas gap thickness | 0.25 mm |
| Glass thickness | 0.33 mm |

## End Cap

An arrangement of ToF modules in the end-cap is shown in Figure 2.2. The hole in center of the end-cap is for the beam pipe. The external radius of the end-cap is 1150 mm. The internal radius is 200 mm. The end-cap has a support frame that is not mechanically connected to the barrel. All electrical communications are also separated from the barrel part. This separation allows for easier access to independent parts of the ToF system.

|  |
| --- |
|  |
| Figure 2.2: end-cap ToF layout |

The one end-cap consist of 16 overlapping modules. Overall dimensions of one module in plane is 140×420×850 mm. The thickness of module is 30 mm. Each module consists of 3 MRPC’s. Each of them has the trapezoid shape of an individual size in the plane. The main geometrical parameters of these MRPCs are shown in the table below. Each MRPC in the module overlaps the next one by 0.5 of strip width. The whole end-cap consist of 3x16x2 = 96 MRPCs. The MRPC thickness is about 0.1 of radiation length (X0) excluding chamber frame.

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | MRPC1 | MRPC2 | MRPC3 |
| External width1, mm | 140 | 233 | 326 |
| External width 2, mm | 234 | 327 | 420 |
| External length, mm | 300 | 300 | 300 |
| Number of strips | 16 | 16 | 16 |
| Strip pitch, mm | 17 | 17 | 17 |

Each MRPC equipped with 16 readout strips. Strips are 15 mm wide and variable length depending on the position in the chamber. The structure parameters of these MRPCs are shown in the table below.

|  |  |  |
| --- | --- | --- |
| Name of component | Dimensions, mm | quantity |
| Honeycomb | 216 x (336 – 136) x 6 | 2 |
| PCB | 246 x (340 - 140) x 0.8 | 5 |
| Maylar | 216 x (336 – 136) x 0.25 | 8 |
| Float glass | 216 x (336 – 136) x 0.3 | 28 |
| Gas gap | 0.128 | 24 |
| Readout strip | (340 - 140) x (15+2) | 16 |

# Design of the ToF module.

Design of the ToF system based on our experimental results obtained during multiple tests of various modifications of glass MRPC exposed in charge particles beam and cosmic rays. For module development we were guided by a few simple statements:

* Better to use high-voltage sources up to 3 kV. To realize this, we refuse design of the MRPС with floating electrodes.
* To reduce the radiation length of the detector better to use glass with a minimum possible thickness. For practical reasons the thickness of 0.33 mm was chosen.
* In the barrel the radiation rate should be around 100 Hz/cm2. Due to this, we chose the dimensions of the strip is 2x45 cm. This reduces the number of electronic channels. The main geometrical parameters of produced MRPC’s are shown in the table below.

|  |  |
| --- | --- |
| External dimensions | 500 х 406 x 18 mm |
| Sensitive area | 440 х 340 mm |
| Strip size | 450 х 20 mm |
| Number of strips | 16 |
| Number of gas gaps | 10 |
| Gas gap thickness | 0.25 mm |
| Glass thickness | 0.33 mm |

To maximize the high-rate performance of MRPC it is decided to use a glass plate with 0.33 mm thick. This could be important for the successful application of the ToF system. The schematic cross section of a MRPC is shown in the Figure 3.1. It consists of two identical gas gaps stacks with anode strip readout plate in between. In this design all electrodes are at a fixed potential from an external HV source.

Each gaps stack is formed by 10 glass plates with the 3x1012 Ω×cm bulk resistivity. The gas gap in between glasses is 0.25 mm. The gap is fixed by spacers which is a usual fishing-line. Fishing-lines ran directly through the MRPC working area. Graphite conductive coating with surface resistivity of ~1 MOhm×cm is painted to outer surfaces of glass plates to distribute the high voltage.

The anode readout strips plate is a one-sided printed PCB with the thickness of 0.1 mm. The thickness of the PCB copper is 35 microns. Signals are taken from both ends of anode strips. The entire MRPC assembly is put into a gas-tight box. The bottom of the box is made of a double side PCB (motherboard) with a thickness of 2.5 mm. The side frame of the box is made of an aluminum profile. The top of the box is closed by a 1.5 mm aluminum lid.

|  |
| --- |
|  |
| Figure 3.1: the schematic cross-section of the MRPC. It consists of two identical five gaps stacks with anode strip readout plate in between. |

Figure 3.2 represent the placement of the electronics on the MRPC module. Number 1 denotes the MRPC itself. The front-end electronics card is designated by number 2. Each chamber is equipped with mounted on the motherboard four front-end cards. Front-end cards are connected by short cables with one Time to Digital Converter (TDC). TDC mounted on the module. The desired TDC time quanta should be at least 10 ps.

|  |
| --- |
|  |
| Figure 3.2: the schematic layout of MRPC equipped with FEE. Number 1 is the MRPC, 2 is the dual threshold CF discriminator and 3 is the TDC. |

# R&D program and prototype test results

The evolution of the current program went through three successive stages. Initially [7] these were studies of how to increase the rate capability of the float glass MRPC up to 2-3 kHz/cm2. These studies smoothly turned into the development of a ToF-700 system for the BM@N experiment [8]. The evolution of a MRPC for the BM@N experiment led to the creation of an MRPC prototype for the ToF SPD.

Most of the research has been done on floating electrodes MRPC. Versions of MRPC from sections 4.2 and 4.3 differ in glass thickness, the size of the gas gap and the number of gas gaps. However, their structure is the same as is shown in the Figure 4.1. In the section 4.3 we will move on to another design which is shown in the Figure 3.1.

The general description of used float-electrode MRPC as follow. The MRPC consist of two stacks of gas gaps. The anode readout strips are placed in between of gaps stacks. Signals are taken from both ends of anode strips. The gap between the glasses is fixed by spacers. Spacers are usual fishing-lines, which ran directly through the RPC working area. A conductive coating is painted to outer surfaces of external glass plates of each stack to distribute the high voltage and thus to form the uniform electrical field in the stack sensitive area. The entire MRPC assembly is put into a gas-tight box.

|  |
| --- |
|  |
| Figure. 4.1. Schematic cross-section of the ten gap MRPC |

## 4.1 Small MRPCs research for the operation at large counting rate

A glass MRPC suffers from serious shortcoming. It is had rather low-rate capability. Because of high bulk resistivity, 1012 - 1013 Ω×cm, a MRPC made of ordinary window glass works well up to several hundred Hz/cm2 only. To increase the MRPC rate capabilityis necessary to decrease a resistivity of glass electrodes. Can be seen two ways to decrease a resistivity of window glass. First is to decrease the glass thickness. And second one is to warm-up a glass electrode. The results obtained using both these methods are described in [7].

Two glass chambers were investigated on the test beam line of the U-70 accelerator at the Institute for High Energy Physics. The required radiation flux density at the detector was produced by means of radioactive sources. A photograph of one of the chambers is shown in the Figure 4.1.1. It is a single stack small cell. The thickness of the gas gaps in both chambers was 230 μm. The dimensions of the glass plates were also 2.5 × 2.5 cm. The active area in both MRPCs was 1.9 × 1.9 cm. The difference between the chambers was only in the thickness of the glasses from which they were made. In this section the MRPK made of 0.55mm glass will be designated as “thick cell”. At the same time, an MRPK made of 0.16 mm glass will be denoted as a “thin cell”.

|  |  |
| --- | --- |
|  |  |
| Figure 4.1.1 The photograph of the tested singe cell. | Figure 4.1.2 The volume resistivity of two type of used glass. |

Figure 4.1.2 shows the volume resistance of used glass as a function of temperature. A temperature rises from 25 ° C to 45 ° C leads to a 10-fold decrease in the volume resistance of the glass. Therefore, the heating has a significant effect on the rate capability. At any temperature the efficiency of MRPCs is higher than 97%. See Figure 4.1.3. A change in the volume resistance of glass can lead to a shift in the dependence of the time resolution on voltage. This effect for a thick cell is shown in the Figure 4.1.4.

|  |  |
| --- | --- |
|  |  |
| Figure 4.1.3 The MRPC efficiency. | Figure 4.1.4 The time resolution at different temperatures versus operating voltage. Thick single cell. |

The dependence of the efficiency on the detector counting rate for two MRPC samples is shown in Figure 4.1.5. It follows that as the operating temperature rises, the efficiency of the MRC is weaker depending on the counting rate. The "thin cell" is less sensitive to the large rate than "thick cell". Finally, the time resolution as a function of the MIP flux is presented in the Figure 4.1.6. These graphs confirm that an increase in operating temperature or a decrease in glass thickness leads to an improvement in rate capacity. With a particle flux of few kHz/cm2 for a float-glass MRPC, it is possible to obtain a time resolution of about 40 ps. This circumstance is important for the end-cap of the SPD. Studies of the rate capability of the TOF-700 MRPC were carried out of different beam intensities [9]. Despite the complexity the results obtained at the pulse load these studies confirmed the general conclusions set out in [7].

|  |  |
| --- | --- |
|  |  |
| Figure 4.1.5 Cell efficiency as a function of the counting rate. | Figure 4.1.6 The time resolution as a function of MIP flux. |

## 4.2 Experience of MRPC use for the BM@N experiment

The development of the TOF-700 detector for the BMN experiment served as an important stage in the development of the MRPC testing technology. During this period, there was a transition from testing a small to full-sized MRPCs. Scintillation counters with high time resolution are commonly used for testing small MRPC cells. These counters are needed for the accurate start time definition. This technology is not suitable for the study of large-area MRPCs. Therefore, a new method was used in which the time resolution of MRPC pairs was restored from their mutual data.

The BM@N TOF-700 wall is divided into two zones. Zone with high radiation load is located around the ion pipe. The area of this zone is about 2 m2. This part is filled with so called warm MRPC. This part is filled with so called warm MRPCs. The operating temperature of these chambers is maintained at 40 degrees. The rest part of the TOF-700 wall does not experience significant radiation loads and is therefore filled with cold MRPCs. The temperature of these MRPCs is the same as the ambient temperature.

A warm MRPC has 12 gas gaps of 0.22 mm width. A cold MRPC has 10 gas gaps of 0.3 mm width. The thickness of used glass is 0.55 mm. During 2015-2017, there were few tests of ToF-700 detectors and electronics. During 2015-2016 runs first tests were done on the muon test area at the IHEP U-70 PS. Typical obtained efficiency and time resolution of cold and warm MRPCs are given in Figure 4.2.1 and 4.2.2 respectively.

|  |  |
| --- | --- |
|  |  |
| Figure 4.2.1 Efficiency and time resolution of a cold MRPC. | Figure 4.2.2 Efficiency and time resolution of a warm MRPC |

A final test was done on Nuclotron beam in 2015-2017. These results were obtained during BM@N test runs. Analysis of deuteron beam runs data allow us to estimate the TOF-700 MRPC time resolution. The distribution of time difference between the T0 counter and TOF-700 chambers are given in the Figure 4.2.3. For various runs and different chambers, we obtain this time difference is in the range from 84 to 98 ps. A distribution of time of flight between ToF-400 and ToF-700 chambers is shown in the Figure 4.2.4. For a gaussian sigma of this distribution we got the value of 85 ps.

|  |  |
| --- | --- |
|  |  |
| Figure 4.2.3. Distribution of the time of flight between ToF-700 and T0. Time is in ns | Figure 4.2.4. Distribution of the time of flight between ToF-400 and ToF-700. Time is in ns |

To estimate the intrinsic MRPC time resolution we produced the time difference in between two ToF-700 chambers. See Figure 4.2.5. For different run conditions and chamber pairs this difference vary from 75 to 85 ps. These values let possibility to estimate the intrinsic resolution of one chamber as 52 - 59 ps. To confirm the good performance of the TOF-700 system, we used the reconstructed momentum values for those particles that reached the ToF-700. The plot of time of flight as a function of particle momentum is shown in the Figure 4.2.6. This experimental data agrees with the theoretical function for protons shown by the red line.

|  |  |
| --- | --- |
|  |  |
| Figure 4.2.5. Distribution of the time of flight between two TOF-700 MRPCs. Time is in ns. | Figure 4.2.6. Dependence of the time of flight (X-axis, time is ns) on track momentum (Y-axis, momentum is in GeV/c) |

## 4.3 Redesign of the MRPC to improve the operation performance

Our experience with the TOF-700 system showed some inconveniences of operation with voltages over the 10 kV. First, there are certain difficulties with the acquisition of commercial multi-channel high-voltage systems for such voltage range. Secondly, an inexpensive high-voltage sources can interfere with the FE electronics, reducing the time resolution of the ToF system. The transition from MRPC construction with floating electrodes to a "parallel plate chamber" type detector where an external voltage is directly applied to the electrodes of each gas gap was an obvious solution to this problem. That is, transition from the structure in Figure 4 to the structure in Figure 3.1.

It is possible that the new approach can improve the rate capability of the MRPC. This can be represented as follows. In the floating electrodes MRPC, the potential difference between adjacent gas gaps is established due to presence of "dark" gas discharges. However, at high radiation load, these "dark" discharges will no longer be able to compensate for the discharge of the inner surfaces of the electrodes. On the other hand, if a fixed potential is applied to the outer surfaces of the electrodes, then the dependence on the dark discharges rate disappears. The correctness of these speculations should be influenced by the ratio of the thickness of the electrodes and the gas gap itself. But there is no confirmation of this yet because comparative studies of the rate capability of chambers of this types have not been carried out.

The 10-gap chamber with distributed potentials was assembled. The gap size is 0.25 mm. All geometric parameters for this chamber are identical to BM@N warm MRPC: the active is 16x35.1 cm, number of strips is 32, strip size is 1x16 cm. The chamber was made of glass with a thickness of 0.55 mm. The main goal was to compare the efficiency and time resolution with the same for BM@N chamber. For holding research, a cosmic setup was assembled. A description of setup is given in the section 4.5. The measurements were performed using FE electronics and a readout system from the BM@N experiment.

The efficiency and time resolution are shown in the Figure 4.3.1 and 4.3.2 respectively. The graphs are plotted depending on the voltage applied to one gas gap. The measurements were made with a gas mixture composed of TFE/SF6/Isobutane = 85/5/10. The graphs show a slight shift in operating voltage. Highly likely, it is consequence of the fact that about 2 times more glasses were used in the construction of the new chamber. The full operating voltage for the new chamber is ~5 times less for the BM@N MRPC. Both MRPCs have demonstrated the efficiency more than 97% and the time resolution is not worse than 50 ps. The new chamber even claimed a time resolution of close to 40 ps. An unexpected advantage of the new over the old MRPC scheme is the much weaker dependence of the time resolution on the applied voltage.

|  |  |
| --- | --- |
|  |  |
| Figure 4.3.1 The efficiency for the BM@N and distributed potentials chambers. | Figure 4.3.2 The time resolution for the BM@N and distributed potentials chambers. |

In simple understanding, if the overall working gas thickness is maintained, the reduction in the size of the gas gap leads to an improvement in the MRPC time resolution. However, a strong decrease in the size of the gas gap leads to a decrease in the overall signal amplitude. This forces to use of more sensitive FE electronics. since we have only certain amplifiers at our disposal, it was necessary to determine which value of the gas gap is more suitable for us. Were additionally investigated two chambers with a distributed potentials consisting of 12 gaps of 0.18 mm and 10 gaps of 0.3 mm. In the Figure 4.3.3 MRPC time resolution as function of gas gap size is presented. The efficiency of all chambers was more than 97%. It follows from the graph that a gas gap with a size of 0.25 ±0.1mm is better suited for practical use.

|  |
| --- |
|  |
| Figure 4.3.3. The MRPC time resolution as function of gas gap size. Cosmic test. |

To obtain reliable data on the newly developed MRPC studies were carried out on the muon beam of the U-70 accelerator. Four MRPCs were tested at the same time. It was three MRPCs with distributed potentials and one BM@N chamber as a reference one. The new chambers consisted of 10 gaps of 0.25 mm, 12 gaps of 0.25 mm and 10 gaps of 0.30 mm. All chambers were equipped with strips with a width of 10 mm and a pitch of 11 mm. Each chamber was involved 16 strips.

The efficiency and time resolution of new MRPCs are shown in the Figure 4.3.4 and 4.3.5. All MRPCs are more than 99% efficient. The time resolution of a 0.3 mm gap chamber is about 54 ps, which is noticeably worse than for MRPCs with 0.25 mm gaps. The time resolution of the 12 gaps chamber is 45 ps. It is slightly better than for the 10th gaps MRPC. However, the production of 10 gap chambers is less expensive than 12 gap chambers. For this reason, the 10th gap chamber was chosen as the main option for the future.

|  |  |
| --- | --- |
|  |  |
| Figure 4.3.4. MRPCs efficiency at the beam test. | Figure 4.3.5. MRPCs time resolution at the beam test. |

All presented here results were reported at SPD meetings on June 7, 2019 and January 28, 2021.

## 4.4 Test of the constant fraction method

At present, to improve the time resolution of the MRPC, it is proposed [10] to increase the number of gas gaps while decreasing their width. However, this extensive path leads to an increase in the radiation thickness of the chamber and an increase in its production costs. Instead of this a different method of restoring the MRPC response time can be probed.

For recovering the MRPC response time the time-over-threshold (TOT) method are widely applied. The essence of this method is to use the signal width to correct the threshold crossing time. The schematic representation of the TOT method is shown in the Figure 4.4.1. The method uses the correlation between the signal amplitude and signal width. Gas fluctuations somehow smear this correlation probably limiting the accuracy of the method. The idea is to use two time-stumps on the signal front. In order not to consider the initial slow ramp of the amplified signal, the signal constant fraction transformation can be done. A graphical explanation is shown in the Figure 4.4.2. The challenge is to find the zero-crossing point in a simple way.

|  |  |
| --- | --- |
|  |  |
| Figure 4.4.1 Schematic explanation of the TOT method | Figure 4.4.2 Schematic explanation of the CF method |

At the first stage, we made a four-channel front end electronics consisting of a GSI amplifier and a constant fraction transformer. The handmade transformer was made of 5 GHz transistors. As the digitizer a fast of 1GHz analog bandwidth oscilloscope (Tektronix DPO4104b) was used. The setup scheme for the cosmic test is shown in the Figure 4.4.3. A narrow trigger was used due to the small number of readout channels. The trigger consists of three scintillation counters and two MRPCs. For simplicity, scintillation counters are not shown here. In each of the trigger MRPCs only one strip was involved. Two test MRPCs were placed between these chambers. In each of the test MRPCs, one strip was used for time measurements, and two adjacent ones were used for cross-talk measuring. Here we mean that for our setup, the track from a cosmic particle may not hit exactly the “time” strip. Same approach was used when testing the CF method on the muon beam of the U-70 accelerator. Also, this approach was used when testing SPD prototypes on cosmic rays. This will be discussed in section 4.5.

|  |
| --- |
|  |
| Figure 4.4.3 The scheme of CF measurements with using the oscilloscope. |

The data obtained on the U-70 beam will be shown below. Photos and the installation setup are shown in the Figure 4.4.4 and Figure 4.4.5. Three chambers were involved in the measurements. Two of them are already described in section 4.3. These are 12 and 10 gaps chamber with the 0.25 mm gas gap width. In this section they are referred to as rpc0 and rpc1 respectively. The chamber with a gas gap of 0.3 mm was not used. The third chamber is designated as rpc2. This is large chamber being about to SPD purpose. The rpc2 consist of 10 gas gaps of 0.25 mm each. It is equipped with 16 strips. Strip dimensions are 2.5 x 31 cm. During the measurements, a high voltage of 2.5 kV was applied to all chambers.

|  |  |
| --- | --- |
|  |  |
| Figure 4.4.4 The photo of the beam setup | |
| Figure 4.4.5. The beam setup layout. | |

Figures 4.4.6 and 4.4.7 show examples of waveforms. Each waveform is the result of MRPC signal transformation for delay of 200 or 250 ps respectively. The red line in each Figure represents the linear segment that is used to find the zero-crossing time. The corresponding difference between the response times of rpc0 and rpc1 is shown in the Figures 4.4.8 and 4.4.9. The RMS deviation of this difference is sensitive to the value of delay. The best result of 45 ps was obtained with a delay of 250 ps. Therefore, the results for this delay will be shown below.

In Figures 4.4.10, 4.4.11 and 4.4.12 zero crossing time differences for rpc0 - rpc1, rpc0 -rpc1 and rpc2 - rpc0 pairs are presented. Using these differences, the time resolution for the three MRPCs can be found. This time resolution depending on the cross-talk cut is presented in Figures 4.4.13, 4.4.14 and 4.4.15. The cross-talk cut is related to cross-talk signal amplitude. A lower cutoff value means a lower allowable amplitude on the adjacent strip.

|  |  |
| --- | --- |
|  |  |
| Figure 4.4.6 The waveform for the constant fraction delay of 200 ps. | Figure 4.4.7 The waveform for the constant fraction delay of 250 ps. |

|  |  |
| --- | --- |
|  |  |
| Figure 4.4.8 The MRPCs time difference for the 200 ps delay. | Figure 4.4.9 The MRPCs time difference for the 250 ps delay. |

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure 4.4.10 The rpc0 and rpc1 time difference. | Figure 4.4.11. The rpc2 and rpc1 time difference. | Figure 4.4.12. The rpc2 and rpc0 time difference. |

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure 4.4.13. The rpc0 time resolution. | Figure 4.4.14. The rpc1 time resolution. | Figure 4.4.15. The rpc2 time resolution. |

Compare to the value of 45 ps for the TOT method the time resolution for the CF method has improved to 30 ps. There is no dependence of the time resolution on either the cutoff value or the strip size. Perhaps this is an indication that the time resolution of any of the MRPCs is better than 30 ps. And the measured resolution is completely limited by the front-end electronics and the used oscilloscope. These results were reported at SPD meetings on January 28, 2021.

## 4.5 SPD prototype test results.

To carry out further R&D, four prototypes of the MRPK for the barrel ToF were made. These prototypes were manufactured and tested during the fall of 2021. A series of measurements were carried out with cosmic ray setup at the IHEP. The prototypes were made of glass with a thickness of 0.33 mm. The description of prototypes is almost completely the same as in Chapter 3. The exception only in length of the build modules and, accordingly, strips. The prototype chamber length is 46 cm. The strip length is 41 cm. The layout of the cosmic setup is shown in the Figure 4.5.1. And the photograph of the cosmic setup is shown in the Figure 4.5.2.

|  |  |
| --- | --- |
|  |  |
| Figure 4.5.1. The scheme of the setup for testing MRPCs on cosmic rays. | Figure 4.5.2 The photograph of the cosmic ray setup. |

The cosmic setup consisted of four MRPCs, three scintillation counters, and a muon filter. Scintillation counters were used to generate the trigger. The counters cover an area of 19x19 cm2. Three counters are needed to suppress the fake coincidence, which can arise from external electromagnetic interference. The detected muons are predominantly produced in extensive air showers (EASs). Therefore, to filter muons with energies <200 MeV, a lead filter 9 cm thick was used.

The manufacturing accuracy of the detectors makes it possible to align the horizontal displacement of the MRPC strips in the setup with an accuracy of at least 0.3 mm. The height distance between adjacent chambers was 48 mm. Information about triggered strips was used to reconstruct the muon track. Hence, MRPCs were also used as a coordinate detector. If the deviation of the reconstructed track from the axis of any triggered strip exceeded the half of the strip width (10 mm), then it was assumed that the muon experienced too much scattering in the matter and such an event was discarded. The efficiency and time resolution were determined in relation to reconstructed tracks.

The test results with the front-end electronics of the ToF-700 detector from the BM@N experiment are presented in the Figure 4.5.3. In the working voltage range (~ 2.7 - 2.8 kV), we reach the time resolution of 45 ps, a particle detection efficiency at level of ~ 99%, and an average multiplicity of strips of 1.25. These results are consistent with the data presented at the SPD workshop on June 8, 2021 for a similar type of MRPC, but with 10 mm wide strips.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure 4.5.3. Efficiency, time resolution and strip multiplicity for three samples of the MRPC prototype. | | |

Also, to confirm the high time resolution for prototypes, we made additional measurements using handmade realization of the CF method. Measurements were carried out with the cosmic setup in the same way as described in subsection 4.4. In this case two prototypes were placed between trigger MRPCs. Figure 4.5.5 shows the averaged time resolution for a pair of two samples versus of the applied voltage. From this Figure follows that the prototypes have a high internal time resolution that is no worse than 30 ps. To probe the effectiveness of the applied method, the proportion of signals that can be used to measure the time resolution "in practice" was determined. If the minimum signal extracted from the noise of the used electronics should be 4 mV, the probability to measure signals with large amplitudes was measured. This probability is shown in the Figure 4.5.4. In the operating voltage range, this probability is at the level of 99%, which indicates that the data in the Figure 4.5.5 correspond to the reality.

|  |  |
| --- | --- |
|  |  |
| Figure 4.5.4 Probability of oscilloscope measurement of signal amplitude which is more than 4 mV. | Figure 4.5.5 The time resolution obtained by the CF method. |

As a summary, the table below summarizes all the main parameters of the tested samples.

|  |  |
| --- | --- |
| working gas composition | TFE/SF6/Isobutane = 90/5/5 |
| Chamber efficiency | 99% |
| Working voltage | 2.75 kV |
| Maximum applied voltage | 2.9 kV |
| Dark current at the temperature of 23 ºС  at the working voltage of 2.75 kV  at voltage of 2.90 kV | < 5 mA  < 10 mA |
| Time resolution | <50 ps |

# MRPCs production

MRPCs can be manufactured using the production facilities of the IHEP and FIAN. At the IHEP the special workspace was prepared for the MRPC production. The workspace is divided into two zones. The first zone includes the space for glass washing and the place for applying a conductive coating to the glass. The second zone is a clean room for MRPC assembling. The clean room has a storage space for cleaned glass. Some aspects of MRPCs production are shown in Figures 5.1, 5.2.

|  |  |
| --- | --- |
|  |  |
| Figure 5.1. washing glass in an ultrasonic bath | Figure 5.2. Applying a conductive coating with a blowgun in a fume hood |

A photo in the Figure 5.3 shows some stages of the assembling. The left photo shows the box with one bottom glass and fishing lines. In the middle photo there is one stack of gaps covered by the strip PCB. In the right photo there is the chamber without an aluminum cover. There is a copper pad on the top. It is used as a signal ground. It is separated from the box cap by a sheet of mylar. This photo also shows a way to fix fishing lines in the box.

|  |  |  |
| --- | --- | --- |
|  |  |  |
| Figure 5.3: an assembling of the MRPC module. | | |

## 5.1 The production technology

The process of assembling of a MRPC includes two stages: applying a highly resistive coating to glass and assembling the chambers.

The procedure for manufacturing glasses for cameras is carried out in the following sequence:

* Washing and drying the required number of glasses.
* Fixation on one side of the glass of a contact pad made of 35 μm annealed copper foil.
* Formation on one side of the plate of a protective 5 mm wide zone, free from a conductive coating.
* Application of a highly resistive coating to the prepared side of a glass plate by spraying a previously prepared conductive composition.
* Drying of plates.
* Control of the obtained surface resistance. The value of the resistance should be within the range of 1 to 3 MOhm×cm.
* Removal of elements that formed a protective zone on the plate.

The MRPC is assembled in the following sequence:

* On the prepared PCB motherboard, a frame borders are installed. All parts are fixed to the board with screws with the additional use of neutral silicone sealant.
* In the proper places of the border frame by using a neutral silicone sealant, the gas mixture supply connection and the high-voltage cable are fixed.
* The first layer on the motherboard is laid with an insulating mylar film.
* Next, the first glass is laid, with a conductive layer downward.
* A layer of 17 parallel stretched spacers is laid on top of the glass.
* The next layer is the glass, with the conductive side up. A sheet of the insulating mylar film is laid on top of this glass.
* Then the procedure is repeated 4 more times so that five gas gaps are obtained.
* Through a sheet of mylar film a signal strip board is laid on the upper glass of the fifth gas gap.
* Above the strip board a five more gas gaps are placed symmetrically with the lower ones.
* Signal, high-voltage and grounding conductors are soldered.
* All layers are glued with a sealant at the corners of the assembly.
* A signal ground pad is placed on top of the assembly. It connects to the motherboard signal ground.
* A mylar sheet is placed on top of the pad. This sheet is covered with a mesh of silicone sealant. After the drying, the mesh will serve as a compensation layer.
* The box is closed with an aluminum cover using screws and sealant.
* The chamber is left for two days until the sealant dries.

In the process of the chamber assembling, the quality control of soldered junctions is performed by checking the ohmic contact between the installed elements of the chamber. All work on the MRPCs assembly must be carried out in a room with a cleanliness class not worse than ISO6. The temperature and humidity uniformity must be sustained throughout the whole period of the chambers production.

## 5.2 The post-production test facility

Each produced MRPC must be tested for its functionality. It is enough to check the efficiency and time resolution only at one reference high voltage point. A cosmic setup is well suited for such kind of work. The cosmic test set-up should consist of muon filter trigger scintillation counters and investigated MRPCs. Its structure is similar to that described in chapter 4, except for the size of the counters have to be large. However, a newly made MRPC cannot be tested immediately. The new MRPC must be trained under high voltage for at least 3 days prior to this testing. Therefore, the post-production processing is reduced to four steps.

1. Install of the new MRPC on the cosmic test setup. Flush the chamber with a working gas mixture for 8 hours.
2. Apply the operating voltage of 2.8 kV. Check that after three days operation the dark current is less than 5 μA.
3. Collect the data on cosmic muons for 2 days. During this time, can be collected more than 2 thousand events per one MRPC strip.
4. At the last stage, the data analysis is carried out, the efficiency and time resolution are calculated. Based on this information, a decision is made about the quality of the manufactured MRPC.

Simultaneously a 4 to 6 new MRPCs can be tested at the cosmic set-up. The whole procedure takes no more than 6 days. This testing can occur concurrently with the other chambers production. Therefore, it should not slow down the assembly of the entire ToF detector.

## 5.3 Time estimation for the ToF detector manufacturing.

A total of 144 chambers for the barrel and 96 for end-caps are required. A time estimate can be made for the barrel section as the largest ToF part. For start the MRPK production some preparation has to be done. It is necessary to order 144 PCBs and 2880 glasses of the required sizes. Based on the available experience, this will take at least 3 months. Also, it takes about 3 months to produce the box parts. This includes the cost of one month for the purchase of materials and two months for milling frames and drilling holes in frames and covers. Considering possible bureaucratic delays and busy of manufacturing facility, this preparatory work can take up to a half year.

The longest operation in the MRPC production is the painting of a conductive coating to the glass. Because of this, one man can assemble about four chambers per month. This translates into manpower of about 36 people per month. It does not consider such operations as warehousing and transportation of materials and end-products. For two to three people, it will take about 3 months to install chambers on the SPD detector and lay cables. Summarizing the above, 3-4 people will be able to make a barrel ToF in 3-4 years.

# Front End electronics

Analog signals from any detector have a spread in their own amplitude and width. Therefore, to determine the time of occurrence of the signal very accurately, it is necessary to consider some "shape parameter" of that signal. Traditionally correction is carried out using three possible solutions:

* hardware CFD.
* multichannel ADC.
* TOT method.

The first is a hardware solution implemented in various applications of the CFD method. In the past, the common CFD method is currently not used for the following reasons:

* Cost - cheap and fast ADCs have appeared for some time,
* the complex structure and specific components of the CFD dramatically increase its cost.
* The CFD-based systems known in past experiments turned out to be ineffective and required constant complex configuration.

The second method is ADC conversation. The method is characterized by high power consumption and price. The price also includes the cost of communication cables, which also reduce the reliability of the system.

The TOT method charge to width transformation has lowered price for different application. We are considering two versions of this method. The first simplest is implemented in the NINO chip. The second one is implemented in the electronics of the TOPH detector of the BMN experiment. The second one meets our requirements to a greater extent but has higher costs.

Two methods of constructing readout electronics with MRPC are being considered today. The first is the long-standing time-over-threshold method. The second one is constant fraction method. Both methods have their own advantages and disadvantages. The FE electronics for the TOT method are quite simple to manufacture and use. The TOT method shows the time resolution of about 45 ps instead of the desired 30ps. The CF method require a more complex FE electronics. However, according to our measurements this method allows to receive a better time resolution. To implement the capabilities of the SF method a TDC with a time resolution of at least 10 ps is required. An attempt is now being made to combine both methods to achieve the utmost time resolution. It should be noted that such amplifiers (TOT and CF) integrated into the microcircuit are not available now. Therefore, it was decided, at the first stage, to use commercial microcircuits of amplifiers and comparators. The developed amplifiers with the CF method have already shown encouraging results. A time resolution of about 40 ps was obtained.

The main priority of the readout system is its cost. The main contribution to the cost is made by multi-channel readout systems, including analog ASIC and TDC digitization channels. The main problem is there no available commercially. Unlike the DAQ system, which is completely based on commercial elements.

## 6.1 Special analogue ASIC for MRPC readout

Systems with a large number of readout channels require the use of special integrated circuits, such as NINO and PADI. We do not yet can get the right number of chips, but in any case, we could fix the parameters of these chips as absolutely required and completely sufficient. The table below summarizes the main parameters of NINO and PADI ASICs.

|  |  |  |
| --- | --- | --- |
| Main parameters comparison | NINO ASIC (ALICE) | PADI ASIC (GSI) |
| Channels per chip | 8 | 8 |
| Conversion Gain, (mV/fC) | 1080 | 1900 |
| PA Bandwidth (MHz) | 500 | 410 |
| PA Voltage Gain, (V/V) | 30 | 250 |
| TOT function available | Yes | No |
| Stretch timer | Yes | No |
| Baseline DC offset, (mV) | 2 | 1 |
| Equivalent Noise Charge (e RMS) | 1750 | 1150 |
| Input Impedance Range (Ω) | 35 - 75 | 30 - 160 |
| Power consumption (mW/channel) | 27 | 17 |
| Threshold type | External | SPI protocol |
| Timing jitter (ps) | <5 | <5 |

Both chips are specially designed for time-of-flight applications, but they have significant differences. The main difference of PADI is the absence of the TOT function of measuring amplitudes. The absence of the TOT function will require the use of an additional ADC channel to measure the charge. The second problem of PADI is a large Preamplifier Voltage Gain 250, against Gain 30 of NINO chip. For this reason, PADI is unstable, especially when building large systems.

PADI applications are limited due to the absence of a pulse stretcher in its structure (pulse duration range is 1-6 ns), because TDC have restrictions on the minimum duration of the input pulse usually 5-10 ns. This is an important parameter that must be considered when choosing both an amplifier-discriminator and an TDC types.

Summing up, we can say that the PADI chip, although it was developed considering the experience of creating a NINO chip and produced using faster technology, did not exceed the parameters of the NINO chip due to errors in the task formulation, and in some applications it lost. For these reasons, when determining the required parameters of the analog part of the electronics in the project, we will use as a prototype the basic parameters of the NINO chip indicated in the table.

## 6.2 Time over threshold method

For research tests, an 8-channel map has been developed on which it is possible to conduct research on various options for implementing this method and obtain the parameters necessary for design. 8-channel discriminator amplifier card with low threshold and the TOT function (AMPS-M) is designed to conduct research prior to the development of analog reading electronics of the MRPC TOF for experiments involving the use of modern solutions for measuring charges by converting to a time interval (TOT method). The AMPS-M card is designed to work with low-amplitude signals (various avalanche photodiodes), the minimum threshold is 1-2 mV under control and as part of the TRB3 module.

The development of this map is based on the experience of using the TRB ToF AddOn module for the HADES experiment. A feature of the AMPS-M card is the expansion of the functionality of this method compared to the prototype by separating the output pulses of fast and slow channels and digitizing them in independent TDC channels. This configuration allows you get a set of possibilities for the formation of a TOT function due to the combination of a different fronts of two pulses compared to the only functional Q-T dependence of the prototype. This approach, together with the recalculated parameters of the SLOW channels, guarantees a change in the pulse duration of no more than 100ns in the maximally extended dynamic range of signals. The AMPS-M card contains 8 channels, including each:

* two channels FAST and SLOW, working respectively on different NINO chips from a single input signal,
* the FAST discriminator, whose output pulse is formed by the NINO discriminator#1 of the chip and contains the front intersection of LE\_ S,
* SL The SLOW discriminator, whose output pulse is formed by the NINO discriminator #2 of the chip and contains the front intersection of LE\_S and the rear intersection of TE\_S with the threshold THR\_S,
* a circuit for generating an ORx8 trigger signal in NIM levels,
* a circuit for generating the voltages of 8 DACs (LTC2620CGN chip) recorded using the digital SPI protocol from the TRB3(or 2) module

The threshold control circuit of NINO chips (thresholds of the ORx8 Threshold, Threshold circuits) provides a direct dependence (modulo) of the threshold difference on the control voltage with a factor:

of 1/2, for example, 100 MV control / 50 MV difference. Then the typical pairs are 0/0, 10mV/-5mV, 100mV/-50mV, 1V/-500mV, 2.5V/-1.25V (end of the control range).

|  |
| --- |
|  |
| Figure 6.2.1. The circuit of the shaper of THAT function, channels 1 and 3. |

|  |
| --- |
|  |
| Figure 6.2.2. |

Table 1. Main parameters of the AMPS-M electronic card.

|  |  |
| --- | --- |
| Main parameter | Value |
| Number of channels | 8 |
| Input impedance | 50 |
| Output signals standard | LVDS / NIM |
| Rise time (fast channel) | < 1 ns |
| Input voltage dynamic range | (1 – 4000) mV |
| Cross talking factor | < 1/200 |
| Leading edge timing jitter | < 10 ps rms |
| Charge to width (TOT) accuracy | < 0.3% |
| Output signal width deviation  (2-200 thresholds range) | 5 - 100 ns |
| Threshold settings range | (1 – 10) mV |
| Stretch timer settings range | range >1ns |
| Hysteresis settings range | 0 – 13% |
| Power consumption by channel | < 70 mW |

|  |
| --- |
|  |
| Figure 6.2.3. Dependence of the threshold of NINO chips on the control voltage. |

## 6.3 Constant fraction method

To implement the constant-fraction method, several cards of front-end electronics were developed and produced. Each FEE card has 8 analog inputs and 16 LVDS outputs. One readout channel consists of a fast amplifier (~ 1GHz bound width), CF transformer and two threshold discriminators. See Figure 6.1. The photograph of the CF card is shown in the Figure 6.2. The second threshold is needed to calculate the sluing correction for the response time of the first threshold.

|  |  |
| --- | --- |
|  |  |
| Figure 6.1 The CF amplifier schematic. | Figure 6.2 Photo of an 8-channel front-end card that implements the CF method. |

To obtain the best time resolution, it is proposed to use the specially adapted for MRPC signals the CF method. To simplify the implementation of the CF method, it is assumed to use a two-threshold discriminator. Triggering this discriminator creates two-time marks (t1 and t2) for the low and high thresholds. An offline processing of this marks allows to calculate the MRPC response time (t0 that is ‘zero crossing’) by the formula:

,

where ‘k’ is the ratio of high and low values of the threshold and the ‘const’ is an arbitrary time shift. The parameter ‘k’ must be set with the high accuracy by the circuitry solution.

# MRPC readout and slow control

## 7.1 High voltage and gas control systems

The main tasks of slow-control system are enabled or disable HV supply, MRPC current monitoring and gas flow management. The low voltage control and threshold management on FEE can be added as an option.

A relatively low operating voltage (2.8 kV) is used for the detectors. On average, the current consumption does not exceed 5 μA per one chamber. This allows the use of readily available multichannel high-voltage power supplies. One high-voltage channel can power one or a group of several MRPCs. This commercially available sources allow to monitor the current consumption through standard communication lines such as Ethernet, USB, RS-485. The cable length can be up to 100 meters. Therefore, this source can be installed far from SPD radiation area.

It is supposed to use a simple monitoring program that periodically poll the sources data and signal if the current threshold is exceeded. The current excess can be caused by an unsuitable composition of the gas mixture or the destruction of glass electrodes during the operation.

|  |
| --- |
|  |
| Figure 7.1.1 The dark current versus applied voltage for a 3 MRPC samples (SPD prototypes). |

The ToF detector uses non–flammable gas mixtures. The absence of toxic, corrosive or flammable components makes the ToF an safe detector. The required gas flow through the chamber does not exceed 20 cm3/min. This allows the use of an “open” gas system. That is, release gas into the atmosphere after passing through the detector once. To manage a gas mixture, it is proposed to use a gas mixer based on mass flow controllers of the RRG12 type [11]. The flows of component gases will be measured by RRG12, which have an absolute precision of 0.1%. Flows will be monitored by a process control computer, which continuously calculates and adjusts the mixture percentages supplied to the system.

|  |
| --- |
|  |
| Figure 7.1.2 The gas supply system schematic |

## 7.2 MRPC data quality monitoring system

It is assumed that a distributed data system will be used for the ToF. Each MRPC module have to be equipped with a TDC. The data stream from TDCs have to be transmitted first to the communication nodes and then to an event builder. In such a system, it is important to control the data flow densities and the error flow from each MRPC module, communication node an event builder. The data quality monitor should measure these flows and monitor an averaged over about several hours their values. For example, an alert can be triggered by sharp change in these values over time or a mismatch between the flows and the cylindrical symmetry of the detector.

# Cost estimation and the time scale

The manpower needed for construction of the TOF detector is estimated to be 30-man years and will be provided by the participating institutions. Some specific items will be performed by industrial firms. The cost of the TOF system split into mechanics, detectors, electronics, modules, read-out, slow control and other services is shown in the table below.

|  |  |  |
| --- | --- | --- |
| Item | amount | Material and production cost (k$) |
| Glass sheets for 144 barrel and 96 end-cap modules | 20x144 + 26x96 = 5568 | 94 |
| Module PCB | 480 | 48 |
| Other module materials |  | 29 |
| MRPC module assembling | 144 + 96 = 240 | 116 |
| Gas for the module testing | For the 33-month operation | 14 |
| Module testing and transportation operations | For the 33-month operation | 190 |
| FE ASIC development | Stage 1 and 2 | 250 |
| Front-end electronics boards | 4x240 = 960 | 215 |
| TDC design and on-board readout modules | 240 | 461 |
| Gas system | 1 | 200 |
| High Voltage source | 240 | 210 |
| Low Voltage source | 240 | 150 |
| Cables and connectors |  | 10 |
| Tools for R&D (fast generator, scope, crates, etc.) |  | 120 |
| Slow control, Data transfer | 1 | 230 |
| Mechanics |  | 350 |
| TOTAL |  | 2687 |

The ToF time scale starting from 2022 to 2031 to be commissioned and ready for installation in SPD hall for data taking with beam.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Items** | **2022** | **2023** | **2024** | **2025** | **2026** | **2027** | **2028** | **2029** | **2030** |
| **Infrastructure** |  |  |  |  |  |  |  |  |  |
| **Support frame design** |  |  |  |  |  |  |  |  |  |
| **Support production** |  |  |  |  |  |  |  |  |  |
| **Slow control** |  |  |  |  |  |  |  |  |  |
| **FE R&D** |  |  |  |  |  |  |  |  |  |
| **FEE production** |  |  |  |  |  |  |  |  |  |
| **Modules R&D** |  |  |  |  |  |  |  |  |  |
| **Mod. assembling** |  |  |  |  |  |  |  |  |  |
| **Module testing** |  |  |  |  |  |  |  |  |  |
| **ToF installation** |  |  |  |  |  |  |  |  |  |

# References

1. A.V. Akindinov et al., Nucl. Instr. and Meth. A 533 (2004) 74.
2. V. Ammosov et al., Nucl. Instr. and Meth. A 578 (2007) 119.
3. The STAR TOF Collaboration, Proposal for a Large Area Time of Flight System for STAR, May 24, 2004
4. J. Velkovska et al., Time-of-Flight of the PHENIX high-Pt Detector, Conceptual Design Report, June 2005
5. Ammosov V.V. et al. Properties of a Six-Gap Timing Resistive Plat Chamber with Strip Readout. JINR Commun. E13-2009-86. Dubna, 2009. 10 p.
6. Gapienko V.A. et al. Test of Strip Readout MRPC with Amplifier Discriminator Based on the NINO Chip. JINR Preprint. E13-2012-69. Dubna, 2012. 12 p.
7. V.A. Gapienko et al. Studying the Counting Rate Capability of a Glass Multigap Resistive Plate Chamber at an Increased Operating Temperature, Instruments and Experimental Techniques, Vol. 56, No. 3, 2013
8. A. Golovin et al, Technical Design Report of the Time of Flight System (TOF-700) BM&N, JINR, Dubna, June 2017
9. N.A. Kuzmin et al., Nuclear Inst. and Methods in Physics Research, A 916 (2019) 190–194.
10. An S., Jo Y.K., Kim J.S. et al. Nuclear Inst. and Methods in Physics Research, A 594 (2008). p. 39.
11. https://eltochpribor.ru/en/