D0 Forward-Angle Muon Tracking Detector and Its Gas System

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***Abstract*—The design of the new D0 forward angle muon tracking detector and its gas system are described in this paper. The new D0 forward muon tracking detector is based on a minidrift tube technology. The minidrift tubes are operated in proportional mode using a fast nonflammable gas mixture. The basic operational characteristics of this gas mixture and the effects of impurities are presented. Special requirements of the gas system that lead to our design choices are discussed. The gas distribution, recirculation, control, and monitoring system are described.**

***Index Terms*—Gas detector, gas system, muon detector, wire chamber.**

I. D0 Forward Muon Tracking Detector

THE new D0 forward muon tracking detector is an important part of the D0 detector upgrade that is designed to exploit the physics potentials provided by the upgraded Tevatron p-pbar collider at Fermilab. It is expected that in several years, the instantaneous luminosity of the the Tevatron p-pbar collider will reach 5×10^{32} cm^{-2}s^{-1}, which will be approximately a 30-fold increase compared to the highest luminosity achieved previously. The goal of Fermilab is to deliver at least 15 fb^{-1} of integrated luminosity to the two collider experiments by 2007. The bunch spacing of the beam will be reduced to 132 ns from 3.5 μs, and the number of bunches will be greatly increased. The increased luminosity and reduced bunch spacing are the two main reasons for building a new forward muon tracking detector for the D0 experiment. The construction of the new D0 forward muon tracking detector started in 1998. The detector has been operating successfully since March 2001.

The new D0 forward muon tracking detector is based on a minidrift tube technology developed at JINR [1]. The basic mechanical structure of the minidrift tubes is similar to the structure of Iarocci tubes. A photograph of a minidrift tube with its cover partially removed is shown in Fig. 1. Each minidrift tube has eight 50-μm gold-plated tungsten anode wires suspended in a comb-shaped thin-wall aluminum profile. The wire spacing is 10 mm and the anode wire is supported at an interval of 1 m. The minidrift tubes are operated in proportional mode. Only the drift-time signals from the anode wires are recorded. A thin stainless-steel cover that is placed on top of the aluminum profile replaces the resistive cover of the original Iarocci tube. The stainless-steel cover and the aluminum profile form a cathode enclosure of eight 9.4×9.4 mm^2 drift cells. The metal structure that contains eight drift cells is enclosed in a 1-mm-thick plastic envelope made of polyvinyl chloride (PVC). The PVC envelope provides the gas seal and the electrical insulation for the metal cathode that is operated at negative high voltage. The anode wires in the minidrift tubes are held at near ground potential.

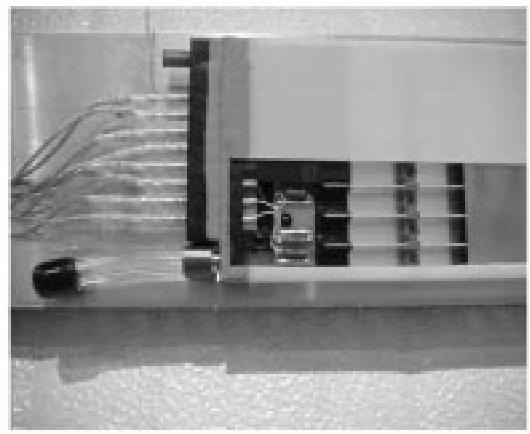

Fig. 1. A minidrift tube with cover partially removed.

The new D0 forward muon tracking system consists of 6080 minidrift tubes ranging in length from about 1 to 6.5 m. These minidrift tubes are constructed at the Joint Institute for Nuclear Research of Russia and sent to Fermilab, where they are assembled into 48 octants and installed into the D0 collision hall. These drift tubes are arranged in such a way that bend angles of muon trajectories after penetrating the iron toroids can be measured precisely. Crude determinations of the muon trajectories in the direction transverse to the magnetic bend directions are provided by pixel scintillating counters.

The D0 forward muon tracking detector covers the pseudorapidity range $1.0 < |\eta| < 2.0$. It is organized into three layers (A, B, and C), as shown in Fig. 2. Each layer has eight octants, with the A-layer octants being the closest to the interaction region. Each A-layer octant contains four planes of minidrift tubes, with each plane having 32 minidrift tubes. Each B-layer and C-layer octant has three planes, and each plane consists of up to 48

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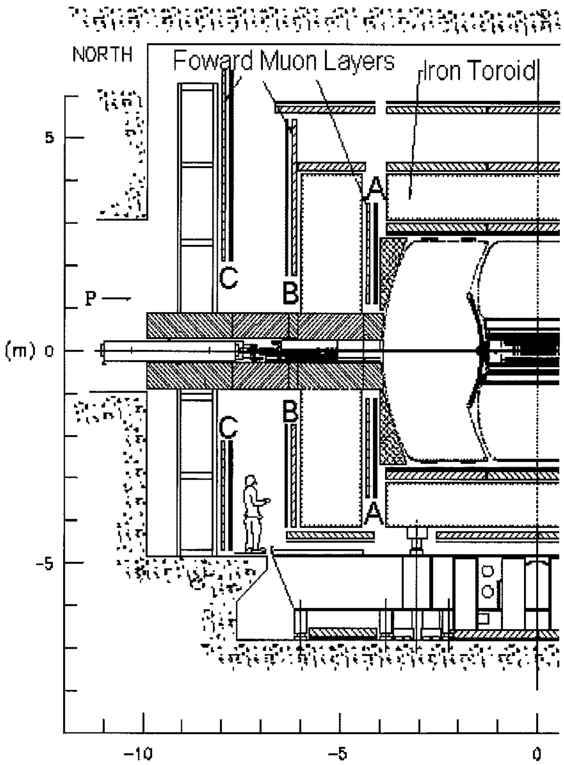

Fig. 2. Cross-sectional view of the D0 detector.

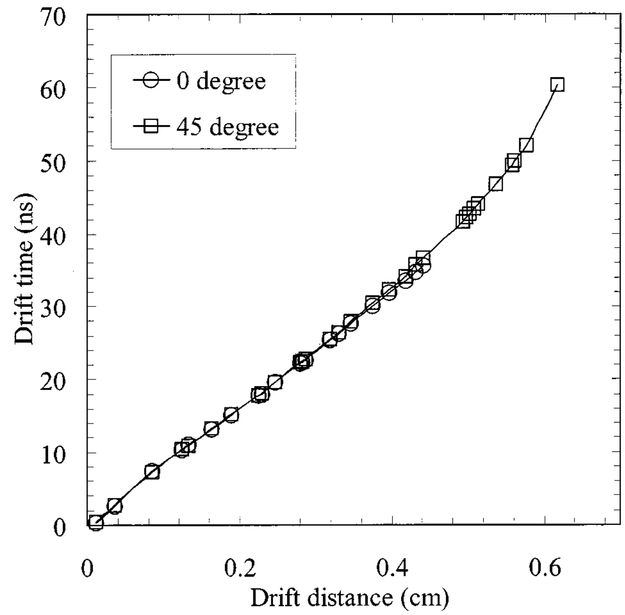

Fig. 3. R-t relation in a minidrift tube. The operating gas mixture is CF_4-CH_4 90:10.

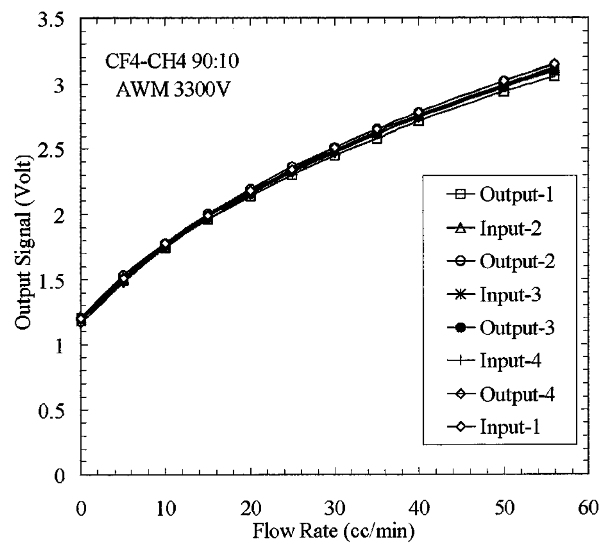

Fig. 4. Calibration curves of eight flow sensors.

minidrift tubes. A-layer octants are mounted on the inside face, and B-layer octants are mounted on the outside faces of the two iron toroids. The C-layer octants are mounted on two steel structures placed against the walls of the collision hall. The resolution of the drift cell is limited mainly by the 18.8-ns drift digitization that is equal to the 53-MHz beam bucket. This results a position resolution of 0.8 mm. Each layer of muon tracking detector is accompanied by a layer of plastic scintillating pixel counters. These scintillating counters provide muon trigger signals and determine azimuth positions of the muon trajectories. The shaded and solid vertical thin objects labeled as A, B, and C in Fig. 2 represent minidrift tube layers and pixel scintillating counter layers, respectively.

The gas mixture of the minidrift tube system consists of 90% CF_4 and 10% CH_4. The reasons for choosing this gas mixture will be discussed in the next section. The total gas volume of the system is fairly large (18 m^3). Recirculating the gas is necessary because of the high cost of the CF_4 gas. A purification system is installed in order to prevent the impurity accumulation that can potentially degrade the performance of the minidrift tubes. The gas circulation, purification, flow monitoring, and control systems are described in the following sections of this paper.

II. Gas Mixture Selection

The selection of the CF_4-CH_4 90:10 as the working gas mixture for the minidrift tubes is based mainly on the following considerations. The gas mixture must be nonflammable for safety reasons. The maximum drift time plus the propagation time of signals in a 6.5-m-long drift tube must be less than the 132-ns beam bunch spacing. Also, the gas mixture must not result in wire aging in a high-radiation environment. The gas mixture CF_4-CH_4 90:10 satisfies all these requirements. The operation of the system with this mixture is very stable, and minidrift tubes are fully efficient at the typical operating voltage of 3.25 kV. The length of high-voltage plateau is approximately 400 V (from 3.0 to 3.4 kV).

The r-t relation curves shown in Fig. 3 with the CF_4-CH_4 90:10 gas mixture are calculated by using the computer simulation program GARFIELD [3]. The r-t relations are calculated for two drift paths in a square drift cell. The curve labeled as 0° is for charged tracks that enter the drift cell perpendicular to the face of the drift cell. The curve labeled as 45° is for charged tracks that enter in the diagonal direction of the square cell. The maximum drift distance for 0° tracks is 4.7 mm, and the calculated maximum drift time is approximately 40 ns. In the 45° case, we consider only charged tracks that enter the drift cell within approximately 6 mm from the anode wire. Charged

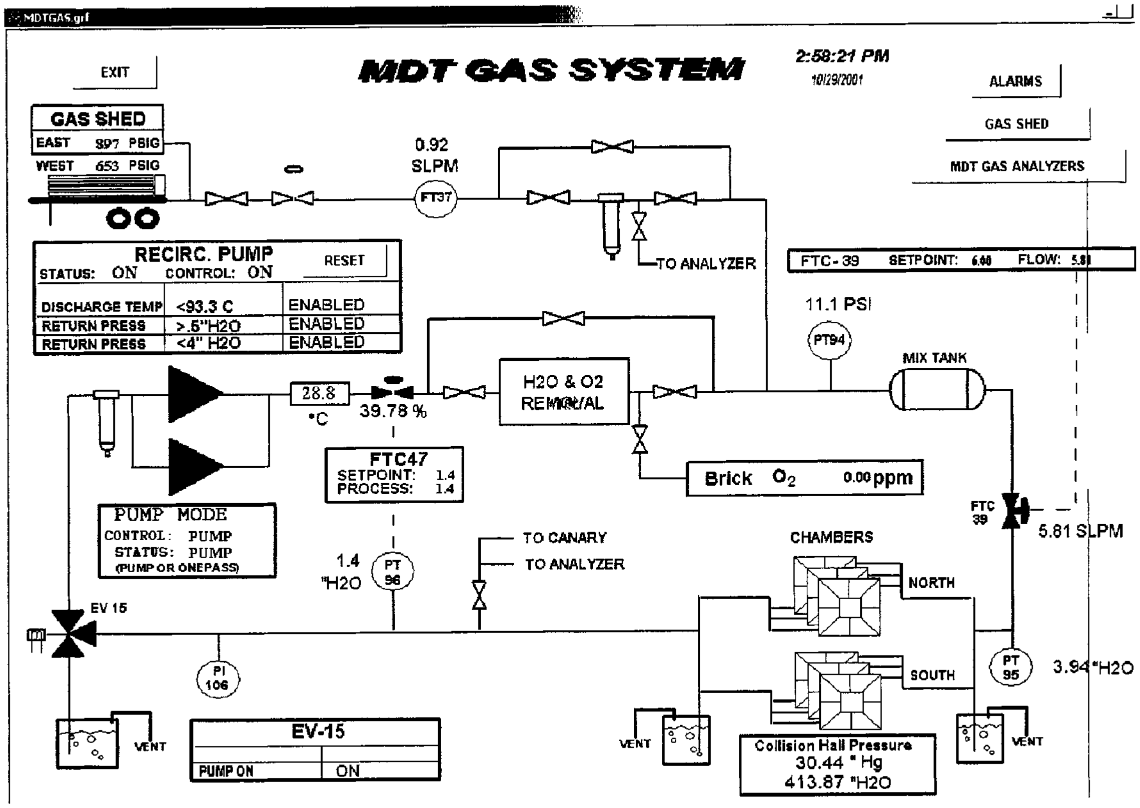

Fig. 5. Online display of the gas system control.

tracks beyond this limit cannot be detected efficiently. The maximum drift time for a 6-mm drift is about 60 ns. As shown in Fig. 3, the 0° and 45° r-t relation curves mostly coincide. This implies that the drift velocity is not significantly affected by different drift fields in these two directions. The linearity of the two r-t relation curves is reasonably good for most of the usable volume.

III. Gas Flow and Monitoring

The gas flow in the minidrift tube system is carefully optimized to minimize the pressure in the minidrift tubes and also to simplify gas connections. Because the 1-mm-thick PVC envelopes of minidrift tubes can expand under internal pressure, which can potentially affect the minidrift tube placement, the gas pressure inside the minidrift tube must be kept below 13 cm of water equivalent or 12.6 mbar. This requirement limits the maximum number of minidrift tubes that can be connected in series to about one plane or 48 minidrift tubes. Thus we distribute the gas in parallel to each of the 160 planes in the 48 octants and to connect the minidrift tubes in each plane in series. A control system consisting of flow meters and metering valves distributes the gas mixture to the 48 octants at desired flow rates.

The gas mixture is recirculated in order to minimize the operating cost. The flow rate of the recirculation system is chosen to be 6 l/min, which is equivalent to a gas exchange rate of approximately 0.5 volume per day. At this rate, the gas delivery pressure is 10 cm of water (9.7 mbar), while the return pressure is maintained at 4 cm of water (3.9 mbar). These values are relative to the atmosphere pressure and are measured in the gas control room approximately 15 m above the floor of the detector hall. The return pressure is kept slightly positive relative to the atmosphere pressure in order to prevent back diffusion of air into the minidrift tubes.

Gas-flow sensors are installed at the gas inlet and outlet of each minidrift tube plane. There are 160 planes of minidrift tubes, and 320 gas-flow sensors are deployed. These flow sensors are mounted on the octants. The average flow rate of each flow path is approximately 35 cm^3/min. The sensors are model AWM3300V mass flow sensors made by Honeywell Inc.[1] Calibration curves of eight sensors are shown in Fig. 4.

Fresh gas mixture from the gas supply stored in a tube trailer is added into the minidrift tube gas circulation at an average rate of 0.5 l/min. Fresh gas is needed to compensate the gas losses due to leaks in the system and also to refresh the gas. To operate the recirculation system successfully, the entire system must be gas tight. Vigorous leak check procedures were implemented at every level of the detector construction. The leak rate of the entire system is approximately 2% of detector volume per day. This rate of gas losses is quite small for such a large and complex detector, and the resulted operating cost is acceptable.

The block diagram of the gas system is shown in Fig. 5. Two gas pumps connected in parallel are used to circulate the gas. A pressurized gas buffering tank, a gas purifier, and oil bubblers for overpressure protection are included in the system. Mass flow controllers, pressure sensors, and automated valves are used for control and monitoring purposes. Instrumentation is included for monitoring the concentrations of CH_4, oxygen, water vapor, and carbon dioxide in the gas mixture.

[1]See http://www.honeywell.com/

Commercial hardware and software is used for the process control of all D0 detector subsystems, including the forward muon gas system [4]. It is based on a number of Siemens programmable logic controllers (PLCs) that connect to devices in the field. A graphical user interface communicates with the PLC and allows operators to see the real-time values of inputs, to set outputs, and to set desired control variables. The industrial control software is called FIX32 by Intellution.[2] Fig. 5 is the main control page of this graphical user interface. FIX32 provides computer alarms, operator security, and historical data collection. Automatic interlocks are incorporated so that safe control actions are taken independent of operators. Interlock programming and control valve loop control are accomplished by ladder logic programming that resides in the PLC. An additional alarm notification system is used that will contact appropriate experts by phone or pager when an abnormal condition is detected by the control system.

IV. Gas Contamination and Purification

As described above, the gas enclosure of the minidrift tube is made of extruded PVC. The thickness of the PVC envelope is 1 mm. The rigid PVC used in the minidrift tubes system has relatively low permeability coefficients for most gases. Nonetheless, due to the large surface area, effects of the gas diffusion through the PVC envelopes must be considered carefully. As mentioned earlier, the total volume of the D0 forward muon tracking detector is approximately 18 m^3. The total surface area of the 6080 PVC envelopes is approximately 4000 m^2. Impurities such as water vapor, oxygen, and nitrogen diffused into the minidrift tube gas can potentially change the electron drift velocity in the gas mixture and degrade the drift cell resolution. The contaminants can also affect the amplitude of the signals and change the efficiency. These problems can also occur if the mixing ratio of the gas mixture changes over time. Such changes can happen if the permeability coefficients of CF_4 and CH_4 through the PVC are different. The effects to the drift velocity due to the gas contamination and the changes of gas composition are studied using GARFIELD. Results of these studies are discussed below. The effects to the signal amplitude and detector efficiency are studied experimentally.

An important contaminant is water vapor. Water vapor in the air of the collision hall can diffuse into minidrift tube gas through the PVC envelopes and through the walls of the interconnecting soft PVC tubing that has relatively high water-vapor permeability. The water-vapor contamination level in the minidrift tube gas depends on the humidity of the air in the collision hall, the gas circulation rate, and the refresh rate of the recirculation system. The air in the D0 collision hall is dehumidified so that the relative humidity level is below 55%. The measured water-vapor contamination level in the minidrift tube system is 3000 to 4000 ppm under typical weather conditions at a gas flow rate of 0.5 volume change per day. We have not observed any significant changes of efficiency for detecting charged particles in the minidrift tubes due to water vapor contamination. The effect of water vapor on the drift velocity is shown in Fig. 6. Four r-t relation curves computed by using GARFIELD are shown.

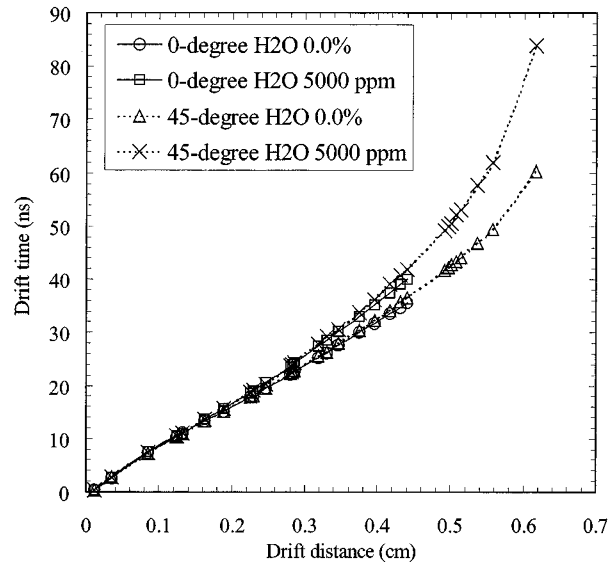

Fig. 6. Comparison of r-t relations in CF_4-CH_4 90:10 without water vapor and with 5000-ppm water vapor.

Two curves are for two drift directions (0° and 45°) without water vapor. Two other curves are with 5000-ppm water vapor in the minidrift tube gas. As mentioned earlier, the bin size of electronics used to digitize minidrift tube signals is 18.8 ns. Changes of drift velocity must be large enough to have significant effects on the resolution. By comparing these r-t relation curves, we conclude that the resolution degradation due to water-vapor contamination is not significant except for tracks initiated from the corners of the drift cell (drift distance greater than about 5 mm). The hits generated by charged tracks' hitting the corners of drift cells are less important, however. A hit that originates from the corners of a drift cell is often accompanied by a hit in the neighboring cell because of the detector geometry, as shown in Figs. 1 and 2. The accompanied hit in the neighboring cell is likely to be close to the anode wire.

The oxygen contamination level in the return gas is measured to be approximately 900 ppm when the gas flow rate is 0.5 volume changes per day. At this level, both the signal amplitude and the drift velocity are not affected. The oxygen diffused into the minidrift tube gas is removed by a gas purification device.

The purpose of the gas purifier installed in the gas circulation system is to prevent the accumulation of oxygen and water vapor that are diffused into the minidrift tube gas during the gas circulation. The gas purifier is custom designed and built by Resources System, Inc.[3] The purifier contains two parallel purification systems. Each system consists of a stainless cylinder filled with activated copper pellets and a molecular sieve cylinder. In the purification process, the oxygen in the return gas is absorbed by activated copper pellets and the water vapor is removed by the molecular sieve. While one system is in active use, the other system is being regenerated. The copper pellets are regenerated by heating and passing a gas with 5% hydrogen over the bed. The hydrogen and oxygen react, leaving the copper activated. The molecular sieve bed is regenerated by heating and vacuum pumping. This purifier is capable of

[2]See http://www.intellution.com/

[3]Model RS-3689, Hanover, NJ.

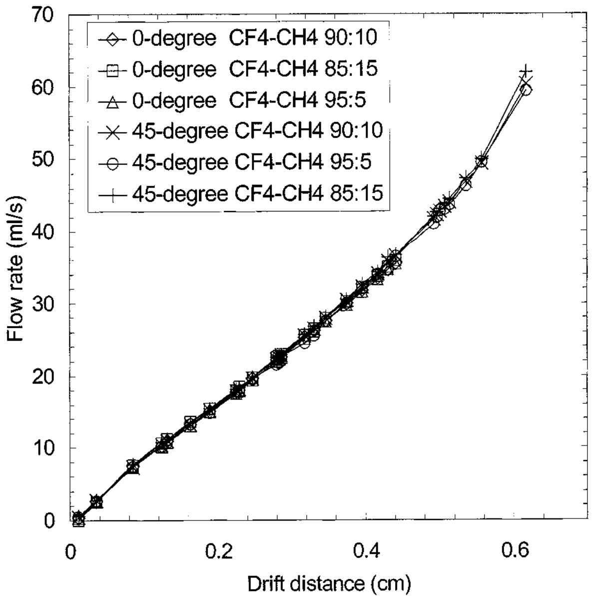

Fig. 7. Comparison of r-t relations in gas mixture CF_4-CH_4 85:15, 90:10, and 95:5.

reducing the oxygen and water vapor contents to about 100 ppm. The switching between the active operation mode and the regeneration mode is automatically made every 24 h.

As mentioned earlier, the gas refresh rate is 0.5 l/min or one volume every 25 days. Since we do not attempt to remove nitrogen from the minidrift tube gas, nitrogen can accumulate over time. The equilibrium level of nitrogen contamination is measured to be 0.8%. At this level, performances of the minidrift tubes are not adversely affected.

The percentage of CH_4 in the gas mixture is constantly monitored during gas circulation. The actual mixture supplied to the D0 experiment contains 9.9% CH_4. We have observed that the CH_4 content gradually drifts downward over time and eventually reaches a stable level of 9.6%. The reduction of CH_4 concentration can be attributed to the fact that permeability coefficients of CF_4 and CH_4 through the PVC envelopes of minidrift tubes are different. The mixing ratio, therefore, changes over time during the initial phase of the gas flow. As in the case of nitrogen accumulations discussed above, an equilibrium state is eventually reached and the gas mixing ratio stabilized. The amount of CH_4 concentration reduction is rather small. As shown in Fig. 7, the drift velocities in a minidrift tube cell are not significantly affected even with very large swings of CF_4-CH_4 mixing ratios.

V. Wire Aging

Tests using radioactive sources have shown there are no detectable aging effects up to 2.5 C/cm accumulated charges on the anode wires. These tests are conducted with short minidrift tubes. The gas mixture used is the recirculated gas returned from the detector. For minidrift tubes that are the closest to the interaction region, the total accumulated charges on the anode wires during their operational lifetime are expected to be much below 0.1 C/cm.

Acknowledgment

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