A Straw Drift Chamber for Operation in Vacuum

Cary Kendziora, John Krider, Hogan Nguyen†, Sali Sylejmani, Xiangrong Qi
Fermi National Accelerator Lab
(for the CKM Collaboration*)
Sept. 30th, 2002

We present the design, construction, and evaluation of a 20-channel thin-walled straw drift chamber built at Fermilab, as a prototype for the CKM experiment. The device is designed to operate inside a 10^{-6} Torr vacuum tank.

I. INTRODUCTION

A new initiative at Fermilab called "Charged Kaons at the Main Injector" (CKM) has been proposed to observe ≈100 events of the decay mode $K^+ \to \pi^+\nu\nu$ with about 10 background events[1]. Measuring this branching ratio would determine the Cabbibo-Kobayashi-Maskawa matrix element V_{td} to 10% statistical accuracy, with relatively small theoretical uncertainties. The Standard Model branching ratio for this mode is $O(10^{-10})$.

This is an ultra-rare decay mode, and so it is crucial to reject the more copious $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ background by using redundant and independent measurements of the K^+ and π^+ kinematics. A measurement of the π^+ kinematics will be made by a conventional magnetic tracking spectrometer based on an array of 5.1 mm diameter straw drift tubes. This detector will have a relatively modest hit rate of less than 120 kHz per straw. However, in order to reduce the background induced by multiple scattering and interactions, the straws are thin-walled and will operate inside a 10^{-6} Torr vacuum decay volume.

We present studies of the CKM straw's properties. We also present the design, construction, and evaluation of a 20-channel prototype system, with emphasis on the behavior of straws placed inside a vacuum.

II. PROPERTIES OF CKM STRAWS

While there have been many straw drift chambers constructed for use in high energy physics, ours are one of the few attempts to operate such a device in a vacuum. The target for the CKM vacuum decay tank is 1 μTorr, designed to minimize interactions of particles with the residual gas. CKM straws[2] are made from helically wound overlapping strips of 13 μm kapton[3] with 100 nm of copper on the inner surface. The winding is such that about 1.5% of the straw surface area is unmetallized. The straws have an inner diameter of 5.03 mm, a wall thickness of 30 μm including adhesives, and are about 1 m long.

The straws will contain gas at 1 atm.

The effect of temperature and humidity on kapton, and the kapton elasticity have been reported by many groups[4]. Table I shows the measurements based on our straws. They are consistent with the well-known bulk property of kapton. Under vacuum, the inner straw walls experience a 15 psi outward pressure. We observe that the straw dimensions increase both radially and longitudinally. The measurements of the straw linear expansion with respect to temperature, humidity, and differential pressure are done by *inference* and are described below.

The single most important effect is that the straws lengthen by 380 μm under vacuum. Therefore, it is important to compensate for this expansion during the straw chamber construction. Our solution is to assemble the straws into a rigid chamber frame with each straw having an initial tension T_i. In vacuum, the straw tension reduces by 75 grams, so that in order to keep the straw length fixed at 1 meter, T_i must exceed 75 grams. We choose T_i to be 300 grams in order to also absorb the expected temperature variation, the humidity change, and the tendency for the straw tension to relax over time. We also must leave adequate space (130 μm) between neighboring straws to allow for radial expansion.

Our measurement technique consists of stretching a 1 meter length straw by a known length, and then keep the resulting total length *fixed*. By monitoring the tension induced by the stretching, we get the elastic expansion coefficient. We also monitor the tension while varying the temperature, humidity, and differential pressure. Therefore, we can infer the linear thermal, humidity, differential expansion coeffients from the observed tension changes.

TABLE I: The linear elastic, thermal, and humidity expansion of a 1 meter length, 5.1 mm diameter CKM straw. The straw construction is described in the text. The last two rows are the resulting linear and radial expansion due to 15 psi differential pressure.

Linear Elastic Expansion	5.1 μm/gram
Linear Thermal Expansion	9.9 μm/°F
Linear Humidity Expansion	12.0 μm/%RH
Linear Expansion (15 psi)	380 μm
Radial Expansion (15 psi)	6.7 μm

Our setup consisted of a steel backbone on which a 1 meter long straw can be stretched. One end of the straw is connected to a load cell that is connected to the backbone. The other end of the straw is connected to an adjustable bracket in a way that allows the straw tension to be varied. The same straw end is connected to a gas port for pressurization. The entire assembly is inserted into a 5" diameter cylinder, which serves as an environmental chamber for temperature and humidity studies. The cylinder is wrapped with a temperature-controlled heat blanket and insulation. A source of dry N_2 can be flowed either directly through the cylinder, or first through a water-filled bubbler to add humidity.

Figure 1 shows the straw tension as a function of stretch. Figure 2 and 3 shows the diameter growth and tension as a function of differential pressure[7]. Figure 4 shows the tension, initially at 200 g and 0%RH, dependence on humidity. The straw required about 1 hour to stabilize after large changes in hu-

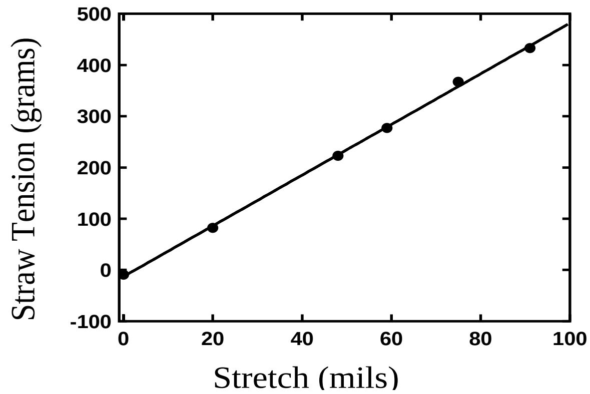

FIG. 1: The straw tension as a function of stretch.

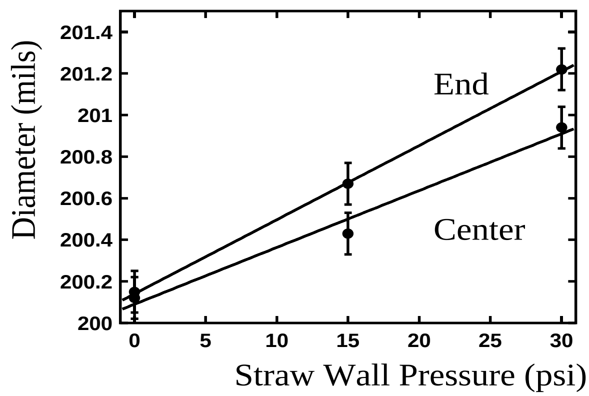

FIG. 2: The straw diameter as a function of differential pressure. Measurements were taken near the straw end and center.

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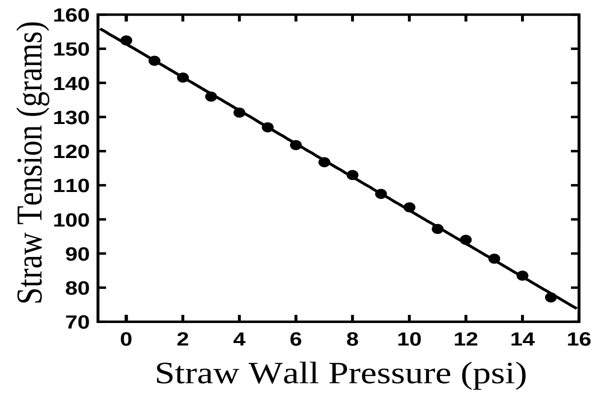

FIG. 3: The straw tension as a function of differential pressure. The 1 meter length straw was initially stretched to 153 grams.

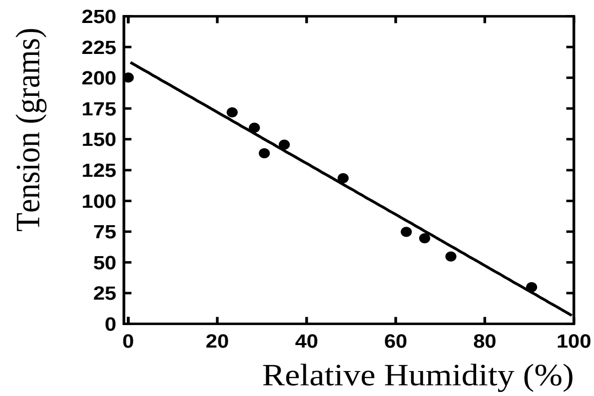

FIG. 4: The straw tension as a function of humidity. The 1 meter length straw is initially stretched to 200 g and 0%RH.

A. Straw Relaxation

Because the straws will be installed under tension, it is important to study the relaxation. We need the straws to maintain sufficient tension over the lifetime of the experiment. Figure 5 shows the relaxation of a new CKM straw over 70 days, where the straw is kept dry and the temperature is held roughly constant. The straw, initially stretched to about 300 g tension, loses about 30% of its tension within the first day. The straw relaxation then slows down significantly, and we fit the long-term behavior to the form Tension $= T_0 - A{\cdot}t^B$, where t is the time in days[5]. The fit (Fig. 5 inset) predicts the tension to be 54% of its initial value after 5 years, and 53% after 10 years. Varying the fit region makes a neglegible change to these predictions.

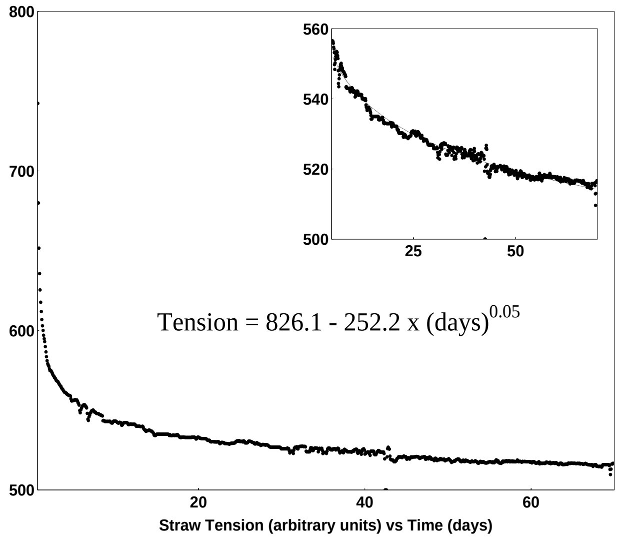

FIG. 5: The straw tension as a function of time for 70 days. The length straw has an initial tension of 844 (arbitrary units). The fit shown is based on an empirical form for plastics, and excludes the first 4 days. The inset shows the data points beyond 4 days and the fit. Although we correct for the temperature variation, there are residual variations due to the system's time lag.

B. Straw Effect on Vacuum

In this section, we describe measurements of gas permeating through the straw into the vacuum. This is important for understanding the load on the CKM vacuum pump due to straws. To the extent that true leaks such as small holes and cracks in the chamber manifold can be solved by careful engineering, an irreducible source of gas is permeation through the kapton straw wall. We measure this "leak" rate for several gases using two different techniques. The results are summarized in table II.

In the first technique, the apparatus consisted of a sealed straw residing in a vacuum tank. The gas pressure inside the straw, which is at roughly 1 atm, is monitored by a capacitance manometer that has a 1 mTorr accuracy. As the straw gas permeates into the vacuum, a pressure decrease is measured in the straw volume. From this, one can determine the straw permeation rate. The entire apparatus is thermally insulated and the straw is kept dry, in order to minimize the effect on the pressure measurement.

Figure 6 shows a typical result on a straw, when filled with nitrogen and helium. When filled with nitrogen, we observe a pressure difference of 1.3 Torr over 2 days. Given the straw volume of $2.5 \cdot 10^{-2}$ liters, we find a rate of $1.3 \cdot 10^{6} \cdot 2 \cdot 10^{-2}/(2 \cdot 24 \cdot 3600)$ $= 0.19$ μTorr-liters/sec. The time rate of pressure change is consistent with permeation through the unmetalized portion of the kapton straw. The rate is 9.8 μTorr-liters/sec when filled with helium.

We also performed measurements using a mass spectrometer leak detector. In this setup, a sealed straw filled with neon is inserted into a vacuum volume. The mass spectrometer is tuned to measure the leak rate of neon and is calibrated to a standardized leak source. This detection method is more robust against temperature variations and other impurities present in the kapton. We find a rate for neon of 0.4-0.9 μTorr-liters/sec, where the variation is given by what we found for a sample of 5 straws. All the measurements are consistent with the known relative permeation rates of helium, neon, and nitrogen through kapton.

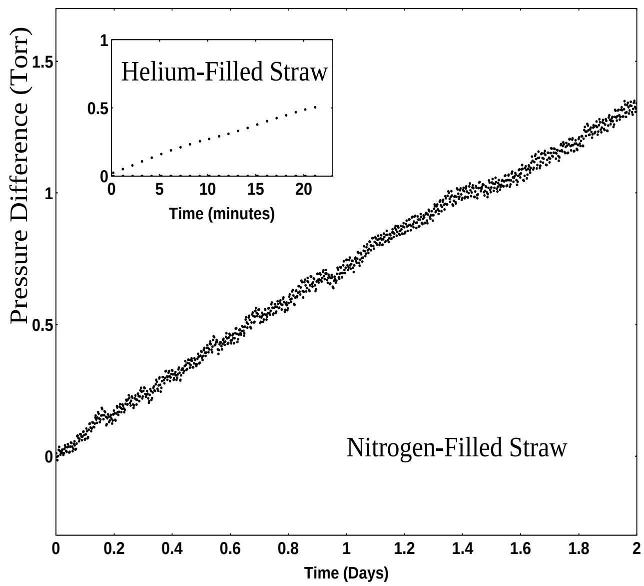

FIG. 6: The rate of gas pressure loss inside a straw, as it is inside a vacuum.

TABLE II: Summary of straw leak rates for several gases. The rates are consistent with gaseous permeation through the unmetalized portion of the straw.

Helium	9.8 μTorr-liters/sec
Neon	.4-.9 μTorr-liters/sec
Nitrogen	.19 μTorr-liters/sec

III. 20-STRAW PROTOTYPE DESIGN AND ASSEMBLY

The 20 straws, each approximately 1 meter long, are arranged as shown in figure 7. They are packed closely into a planar layer, with only a 35 μm gap between neighboring straws. Two layers, each 10 straws wide, are grouped together into a doublet, with a 1/2 straw relative transverse offset in order to resolve the left-right drift ambiguity.

The design of our 20-straw prototype, based on a similar design of experiment BNL-E871[6], is shown in figure 8. The chamber frame consists of two aluminum end plates supported by two rigid pillars. The straws are connected to precisely machined holes in the end plates (figure 9). Gas is routed into one of the pillars and returns through the straws in parallel. Two outer plates provide the chamber gas seal. The frame is designed so that it can be inserted into a small vacuum tank for testing. The distance between the end plates can be enlarged so as to stretch the straws.

An important consideration is how the straws and wires connect to the end plates (figure 9). We glue a brass insert into each end of a straw. The other end of the brass insert is glued into holes in the end plates. The adhesive is silver epoxy so that the chamber frame is electrically connected to the straw's copper coating via the brass insert. Since the straw diameter will expand under vacuum, the straw has a tendency to peel away from the brass insert. While silver epoxy is needed for electrical conductivity, it is weak and becomes brittle over time. Thus for both of these steps, nonconductive and low-viscosity structural epoxy was added for strength and to improve the vacuum seal.

Into the brass pieces, we insert the BNL-E871 "ultem", a molded insulator piece that centers the anode wire and routes chamber gas into the straw. The anode wires are 25 μm Au-plated tungsten and strung to 75 grams tension. The wire is secured into the ultem by a small brass pin and an insulating collar that squeezes the ultem. The brass pin connects the wire to HV and the electronic amplifier/discriminator. Outer plates cover the ultems to form the chamber gas seal (gas channel cover). One of the gas channel covers has holes to allow for the penetration of the brass pins for signal readout(figure 9).

For the prototype, we used an 80:20 mix of Ar-CO2[8] and the BNL-E871 straw chamber amplifier/discriminator cards.

A. Assembly

We developed a robust procedure that can be easily expanded to a large size chamber. The first step in the assembly is to glue the brass inserts into the straws. The adhesive was silver epoxy and cured overnight at room temperature. A fixture was used to ensure that the straws and brass inserts remained coaxial during the gluing process. After the adhesives cured, the individual straws were tested for leaks.

The next step is to insert the straw-brass assemblies into the frame, in an orientation where the straws are lying flat. Before insertion of the straw-brass assemblies into the frame, we align the frame precisely over a plate of machined straight grooves. The grooved plate serves to keep the straws straight, to support the straw weight, and to keep the straws aligned correctly with respect to the end plate holes during assembly.

The insertion process involves slightly bending the straw as the brass end pieces are inserted into the frame. The brass inserts were then glued to the frame with silver epoxy, followed by non-conductive epoxy. These adhesives make the necessary vacuum seals. After the full cure, the distance between the frame end pieces was increased such that each straw is stretched to 300 grams (see section II).

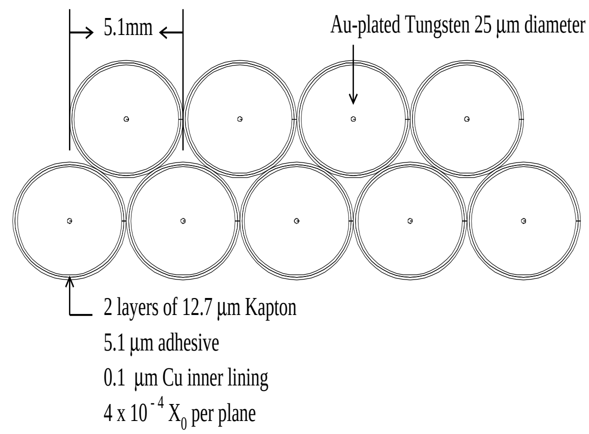

FIG. 7: The straw layout in a planar doublet.

To give the final straw assembly rigidity and to support the straw weight, the straws were glued to 2 "support" wires running transverse to them. A restraining device held the straws at the correct position during this gluing step. The last steps were to attach the outer cover plates, insert the ultems, and string the wires.

Throughout the assembly, an important consideration is to install the straws into the frame with the necessary straightness. An unconstrained straw is not always straight, and if the anode wire is too far displaced from the straw center, the straw will not have the correct gain. We used the combination of the grooved plate, the 300 grams tension, and ultimately the support wires to force the straw straightness to better than 100 μm. In the section IV, we discuss a technique of measuring the straw straightness.

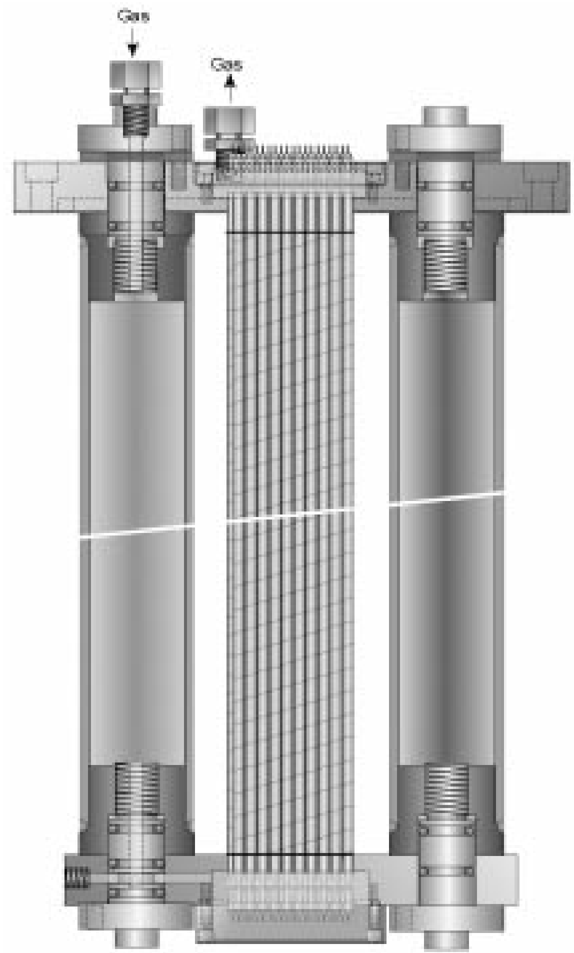

FIG. 8: Design of the 20-straw prototype.

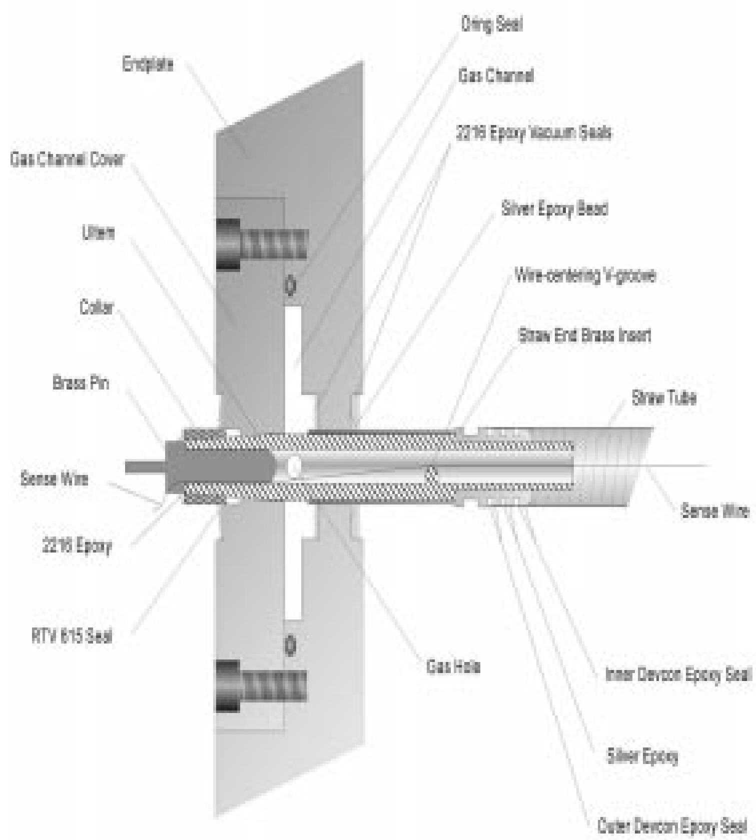

FIG. 9: Detail of straw and wire attachment to the end plate. The gas channel cover allows for penetration of the brass pins for signal readout.

IV. EVALUATION

We installed the 20-straw prototype into a vacuum chamber and measure an average leak rate of less than 0.38 (0.52) μTorr-liters/sec/straw for straws filled with nitrogen (argon). Figure 10 shows the count rate efficiency variation versus high voltage for straws filled with 80:20 Ar-CO2 exposed to an Fe55 X-ray source. The gain of the chamber doubles roughly every 55 Volts increase.

A. Determination of Straw and Wire Positions

In this section, we present a novel technique using an Fe55 X-ray source to measure the positions of the straws and wires. This verifies our construction technique, and the data is useful for understanding the position resolution and gain uniformity. While the position of the frontlayer straws could be determined visually, this is not practical for backlayer straws and wires.

We mounted an Fe55 X-ray source, whose beamwidth is collimated to 250 μm, on a motorized stage that can move in 10 μm increments. The

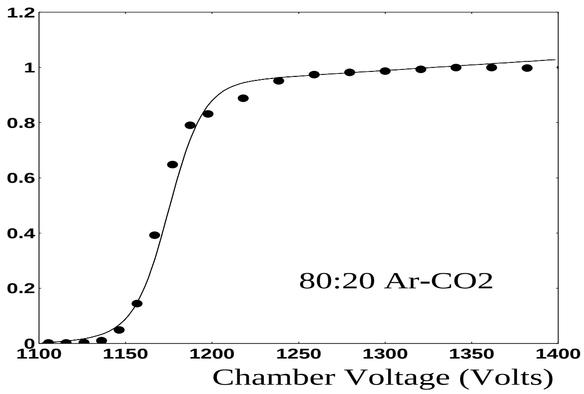

FIG. 10: Straw count rate (arbitrary unit) versus chamber voltage (Volts) in 80-20 ArCO2.

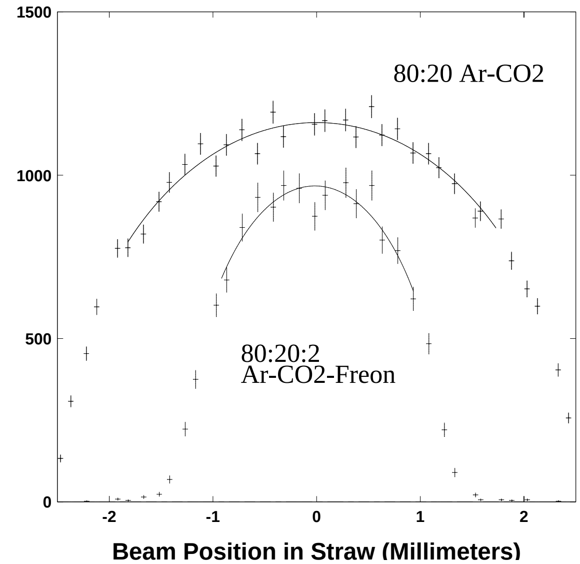

FIG. 11: The straw count in a 5 second interval versus x-ray beam position in the straw. The upper and lower curves are fits to straws filled with 80:20 Ar-CO2 and 80:20:2 Ar-CO2-Freon respectively. The fit function is $A\sqrt{R^2 - {R_0}^2}$ where R =active radius, R_0=centroid, and A =normalization.

absolute source position is given by a calibrated measuring tape. Figure 11 shows the count in a 5 second interval versus position across the straw. Since only a small percentage of the X-rays are absorbed by the gas, and the straw is fully efficient, the number of counts is proportional to the beam path length through the gas. The peak in the figure 11 gives the geometrical center of the straw.

We determine the wire positions in a similar fashion. By introducing 2% Freon 13bl into the Ar-CO2 mixture to increase the probability of electron capture, the sensitive volume is reduced to a smaller radius centered on the anode wire (see figure 11). The response to the collimated Fe55 X-ray beam, scanned across the straws, therefore has the centroid of the wire. Fits to both straw and wire responses have position resolutions of about 25 μm.

Figure 12 shows the deviation of straws and wires from the nominal position. Wires are within 50 μm of the design, consistent with the machining accuracy. Straws are within 100 μm of the design, but vary due to small bowing and radial eccentricities along the straw length.

V. CONCLUSIONS

The CKM straw drift tubes will be used track charged particles inside a 1 μTorr vacuum tank. We studied the CKM straws mechanical changes with respect to temperature, humidity, and straw wall pressure. The chamber design, construction, and assembly must account for these significant effects. We've measured the rate of gas permeation through the straw wall, which is an irreducible source of gas contamination to the CKM vacuum. The rate we measure is consistent with permeation through the unmetalized portion of the kapton straw. We've constructed a 20-straw drift chamber prototype, and de-

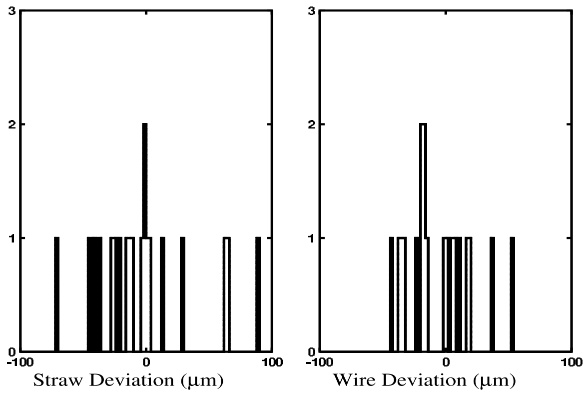

FIG. 12: Deviation of straws and wires from the nominal position.

veloped a robust assembly procedure that is applicable to a full scale prototype. We've developed a technique using an Fe-55 X-ray source to determine the locations of wires and straws to 25 μm accuracy.

The prototype is now in vacuum, and being studied for the response to cosmic rays. It will be exposed to test beam at the Fermilab MTest beamline.

VI. ACKNOWLEDGEMENTS

This work is supported by the U.S. Department of Energy through the Fermilab Particle Physics Division (PPD). We are grateful to Karol Lang of the University of Texas, Austin for his help and expertise with the BNL-E871 straw system. We thank Steve Kettell of Brookhaven National Lab for his help with the BNL-E871 straw chamber electronics. We also thank Robin Denham-Taylor and Dennis Graham of the Fermilab PPD for their help in the construction and assembly.

† To whom correspondence should be addressed: hogann@fnal.gov.

* The CKM Collaboration: BNL, Fermilab, IHEP Serpukhov, INR Troisk, U. of San Luis Potosi, U. of Colorado, U. of Michigan, U. of South Alabama, U. of Texas at Austin, U. of Virginia.

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[7] For these measurements, the effect of gas pressure pushing on the loadcell was eliminated.

[8] For production, we will use a fast gas based on CF_4 in order to shorten the drift time.