Electrical properties of various types of straw tubes considered for the LHCb Outer Tracker.

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Abstract.

Because of the substantial length (up to 3.6m), transmission line effects will have severe impact on operational properties of the straw detector. These effects were clearly observed in the 1.6m long straw chamber prototype. A few types of straw tubes have been examined from the point of view of electrical properties. Results of the measurements are presented. Particular attention has been paid to the study of signal transmission as well as cross-talk.

Introduction.

The straw proportional chambers will be employed in the LHCb Outer tracking detector. A basic cell of the detector consists of a straw tube and a 25µ anode wire located in the center of the tube. A minimum ionizing particle (m.i.p.) leaves a track of primary electron clusters when it traverses the straw volume. In an electrical field the electrons drift to the anode wire from every point of the track. When the electrons approach the close neighborhood of the anode wire, avalanche multiplication can occur, boosting the number of electrons by several orders of magnitude. With a fast speed, electrons move further towards the anode wire whereas ions move away producing an electrical signal induction in all the electrodes around. Among these electrodes are anode wire, straw tube cathode, ground plane and even the neighbouring straw. The last one is not welcome in this list. This parasitic straw-to-straw coupling, known as cross-talk, causes fake signals, which make a muddle of track finding. Straw tube shielding is the only viable way to minimize cross-talk. An aluminum foil layer around the straw tube can keep the induced electrical signal within the tube preventing the parasitic coupling.

The shape of the electrical signal is a very important issue, because the signal delay with respect to the time of beam passage contains information about the primary electron drift time and consequently about the track position in the straw. The electrical signal has two completely different parts (see Fig1.). The steep leading edge is the result of the fast charge motion in a strong electric field close to the anode wire. The slowly sloping trailing edge of the signal is determined by slow ion motion towards the cathode tube in the course of a few hundreds nanoseconds. It is common to characterize the signal position in time by the position of its leading edge. To get the best detector time resolution the signal should be delivered to the electronics without its risetime degraded or attenuated. It is not a problem in a short straw (less than 0.3m) wherein signal propagation time ($\approx$4ns/m) is smaller than the drift time uncertainty ($\sigma\approx$2ns) in the straw itself. For a longer straw, transmission line effects like reflections, signal shape deformation and attenuation influence the signal propagation to a degree. Since long straws (up to 3.6m) are going to be used in LHCb Outer tracking detector a dedicated study of such kind of effects should be conducted, with the purpose to find the most appropriate straw tube type and work out the best detector construction.
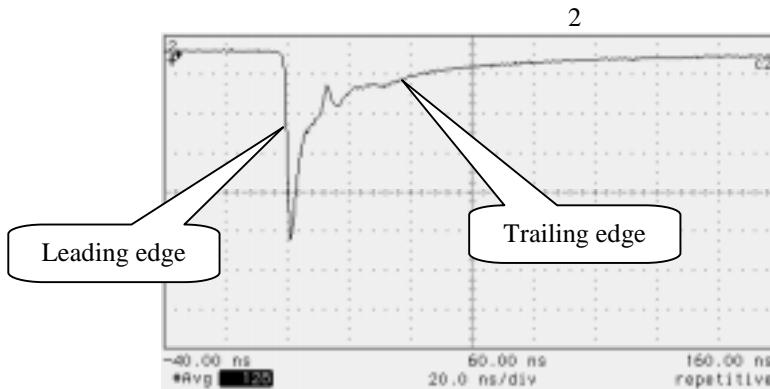
Fig.1 Current signal from a straw, filled with our Ar(65%) CO$_2$(5%) CF$_4$(30%) gas mixture.

The straw tube chamber.

The straw chamber consists of a 25µ anode wire and a straw tube of 5mm in diameter. The anode wire is made of gold-plated tungsten, with conductivity 110 Ω/m whereas the straw tube has a multi-layer structure.

Straw tubes are made by spiral winding of a film tape on a precisely tooled mandrel. To provide mechanical stiffness, two staggered spirals of tape are wound and glued on each other. Straw properties depend on the type of the tapes used. Kapton doped with carbon (Kapton XC) is the best candidate for the inner layer because of its high radiation hardness and robust behavior in an active gas environment. Double Kapton XC structure is formed by two Kapton XC layers bonded together (see Fig.2). To be able to take ion charge out of the tube the material must be slightly conductive. That is why carbon has been doped into nonconductive pure Kapton. Even if nonconductive adhesive is used for the tube bonding, an electrical contact occurs between inside and outside of the straw. It happens probably because of spikes on the surface coming through the thin adhesive layer. This feature simplifies detector construction because only contact with the outside of the straw is needed to take ion charge away. At the same time, double Kapton XC is rather expensive and has conductivity of order of 200Ω/square that yields 12kΩ/m. It is not enough for a good signal transmission and low cross-talk. In this respect the Kapton XC+Aluminum structure is much more promising because of high conductivity of the outer aluminum layer (see Fig.2). Moreover these straws are cheaper thanks to low cost of aluminum in comparison with expensive Kapton XC.
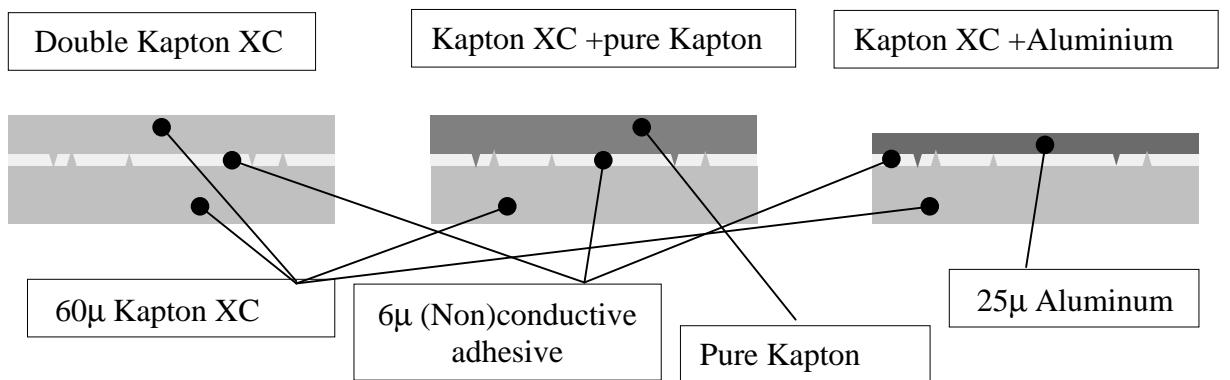

Fig.2 Examples of different types of straws. Straw wall cross-sections.

Preliminary study with test set-up.

Before a long straw chamber design had been started we examined possible chamber construction from the point of view of electrical properties. What is the characteristic impedance of the straw transmission line? What is the best possible termination? Is a ground plane needed close to the straw? What is the optimum straw-to-ground plane distance to provide good signal transmission and low cross-talk? Are there any unforeseen effects we have to eliminate? These questions were to be answered to provide inputs for the design.

The 1.6m long straw module construction.

A new straw module has been recently made in NIKHEF. It is equipped with long (1.6m) straws of different types. Every straw is glued on the aluminum foil of the honeycomb panel in order to provide electrical contact with the aluminum foil almost along its full length (see Fig.3).
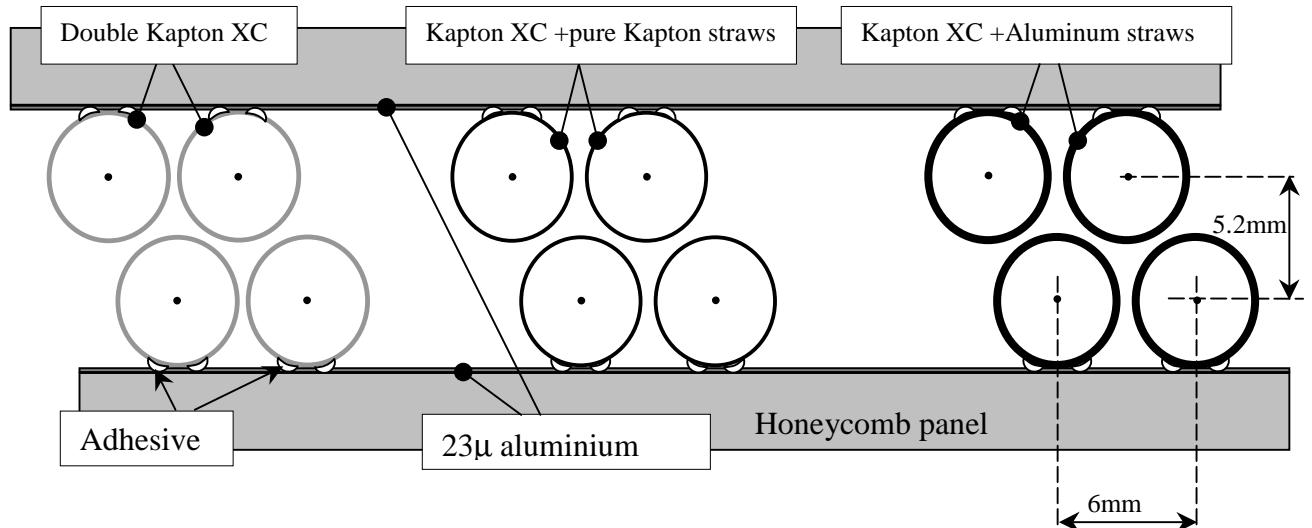

Fig.3 The straw-to-aluminum foil connection in the module.

The circuit, where a signal flows through, consists not only of the anode wire, but also of the front-end electronics ground plane and the aluminum foil, which is called signal ground of the detector (see Fig.4). If these ground planes are not firmly coupled, electronics is inclined to go into oscillations and it is more sensitive to external RF disturbances. Even the customary way of connection with a few wires is not satisfactory in this case. For these reasons, a special spring contact has been used to provide continuous connection between those ground planes over their whole length.
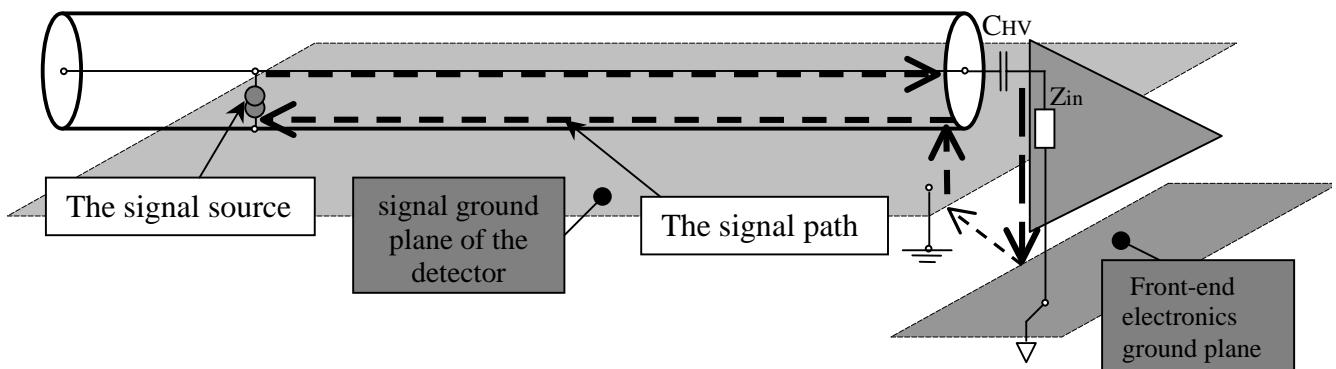

Fig.4 The signal path in the straw detector.

The long straw response to a [55]Fe source without an amplifier.

The test set-up used for studying the current signal coming out of the straw is illustrated in Fig.5. A straw is supplied with working gas mixture Ar65% $CF_4$30% $CO_2$5% and 1850 volts were put on anode wire. We consider [55]Fe as the most suitable radiation source for such kind of study. It produces a point-like cloud of about 200 primary electrons. Only one side of the straw is terminated with an adjustable resistor, coupled to the anode wire via a high voltage capacitor.
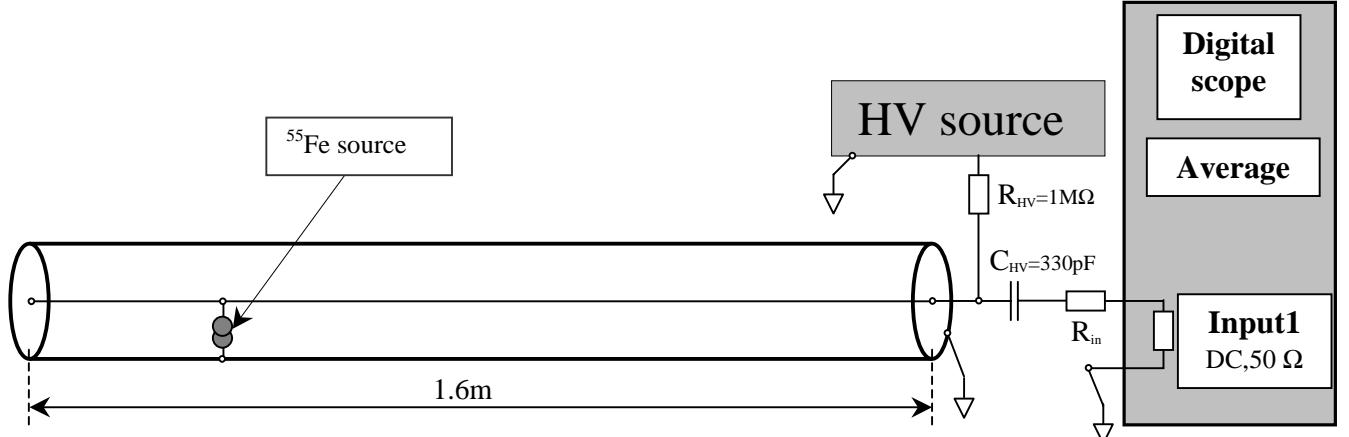

Fig.5 The test set-up for study of the current signal shape in a straw.

The signal shape depends on the position of the source along the straw. When it is close to the electronics side (near end), half of the signal directly goes to the load while the other half goes to the far end, reflects and then returns to the load after travelling a double straw length. So, the second half of the signal is delayed and attenuated with respect to the first one (see Fig.6). If the radiation source is in the center of the straw, both parts of the signal have to travel before they get to the load. However, the travel time difference is getting smaller in comparison to the previous case (see Fig.6). The difference disappears when the radiation source is shifted to the far end, therefore both parts of the signal simultaneously come to the load, forming the largest signal (see Fig.6).
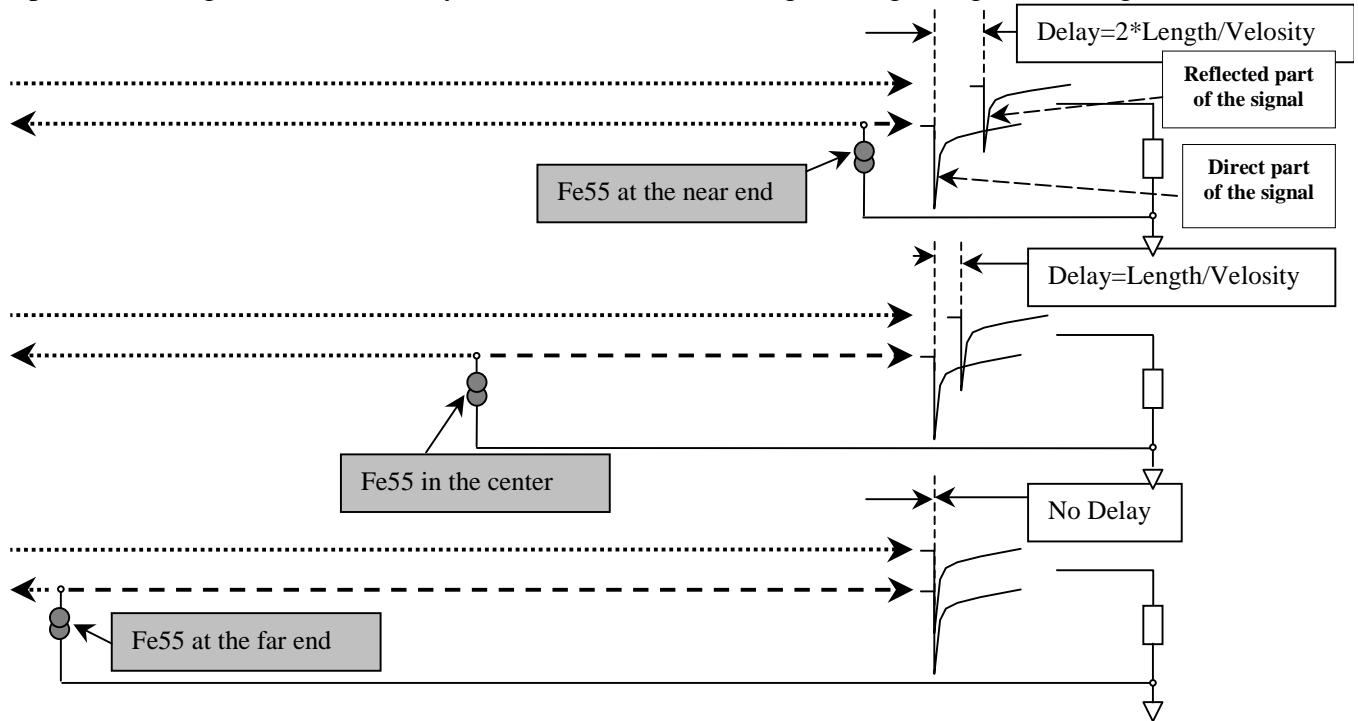

Fig.6 Examples of the signal formation depending on the radiation source position.

There is no difference in the signal shape between straws of different types (see. Fig.7). Propagation velocity can be found through the delay between the direct and reflected parts of the signal. With the straw length of 1.6m it yields 3.8ns/m.

Kapton XC +aluminum straw   **Double Kapton XC straw**

Near end

12ns/3.2m=3.8ns/m

Direct part of the signal

Reflected part of the signal

Center point

6ns

This is an indication that termination circuit does not completely match to characteristic impedance of the transmission line.
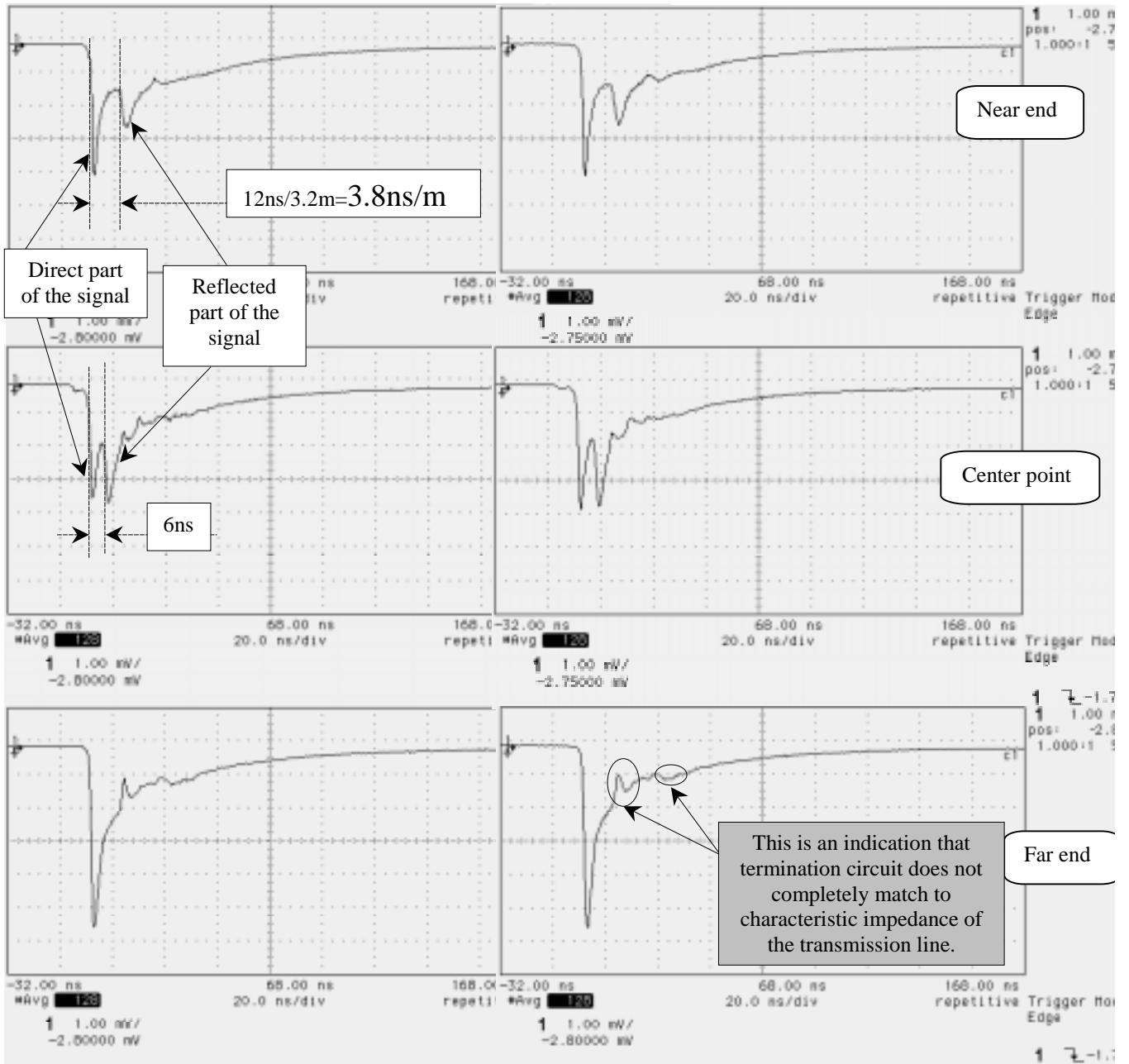
Far end

Fig.7 Signals from a straw depending on the [55]Fe source position. High voltage is 1850V. Termination circuit is C_{HV}=300pF+270 Ω.

The small spikes on the signal coming from the far end indicate that the termination circuit impedance does not completely match to the characteristic impedance of the straw. The circuit should be more carefully adjusted. The mismatch results in parasitic reflections that lead to afterpulsing at the front-end electronics output and thus to fake signals in the Read-out system of the detector.

Because of the anode wire serial resistivity, the characteristic impedance of the straw transmission line is frequency dependent which is not easy to match with ordinary RC-circuitry. By tuning of the input resistor we did not succeed to remove the spikes completely. Overall, a resistor of 300Ω gives the best result.

The long straw response to a ^{55}Fe source measured at ASDBLR output.

The ASDBLR chip (Amplifier-Shaper-Discriminator with Baseline Restoration) is the leading candidate to be employed as front-end chip of the LHCb Outer Tracker. Operational properties of the chip were studied before in combination with a short straw chamber [1]. Because of the different way of signal shape formation in a long straw, it seems to be reasonable to look at the ASDBLR outputs again. Figure 8 demonstrates the set-up used for this study. Both analog monitor and digital outputs have been observed.
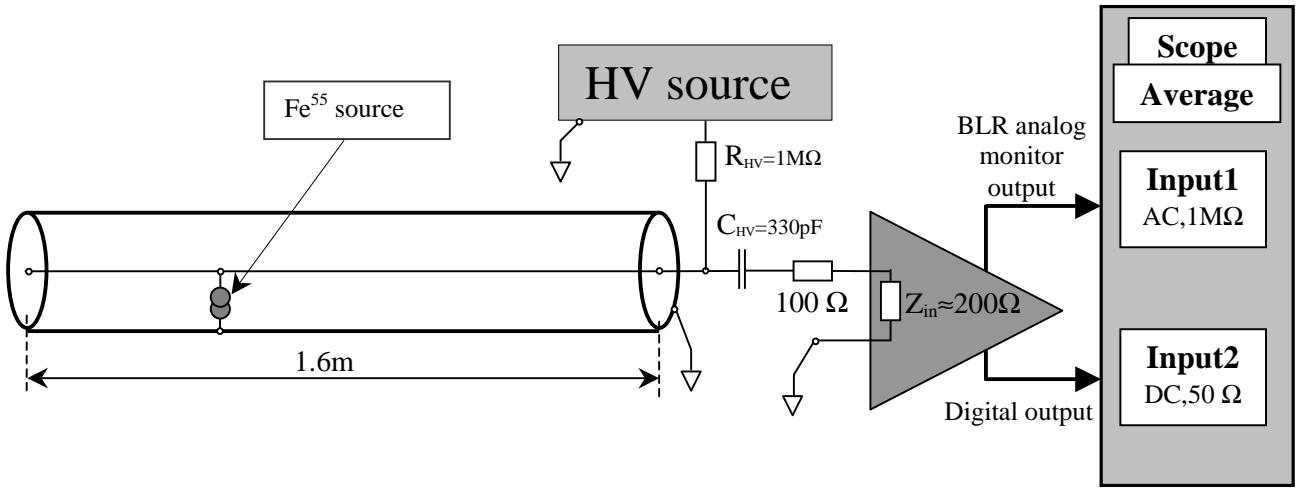
Fig.8. The test set-up for study of the signal shape at the ASDBLR output.

As we have found above that there is no difference between different types of straws from point of view of signal transmission, we expect no difference at the ASDBLR output. By doing the signal study this proved to be true. The only worry is about the mismatch between the straw characteristic impedance and the input impedance of the ASDBLR [2]. By tuning of the resistor in front of the ASDBLR we settled on a 100 Ω resistor, because it is enough to get the reflection down below the working threshold (2fC) (see Fig.9) even for very big signals (up to 500fC). Further increasing of the value of this resistor results on the one hand in better suppression of the reflection, but on the other hand the signal decreases in height.
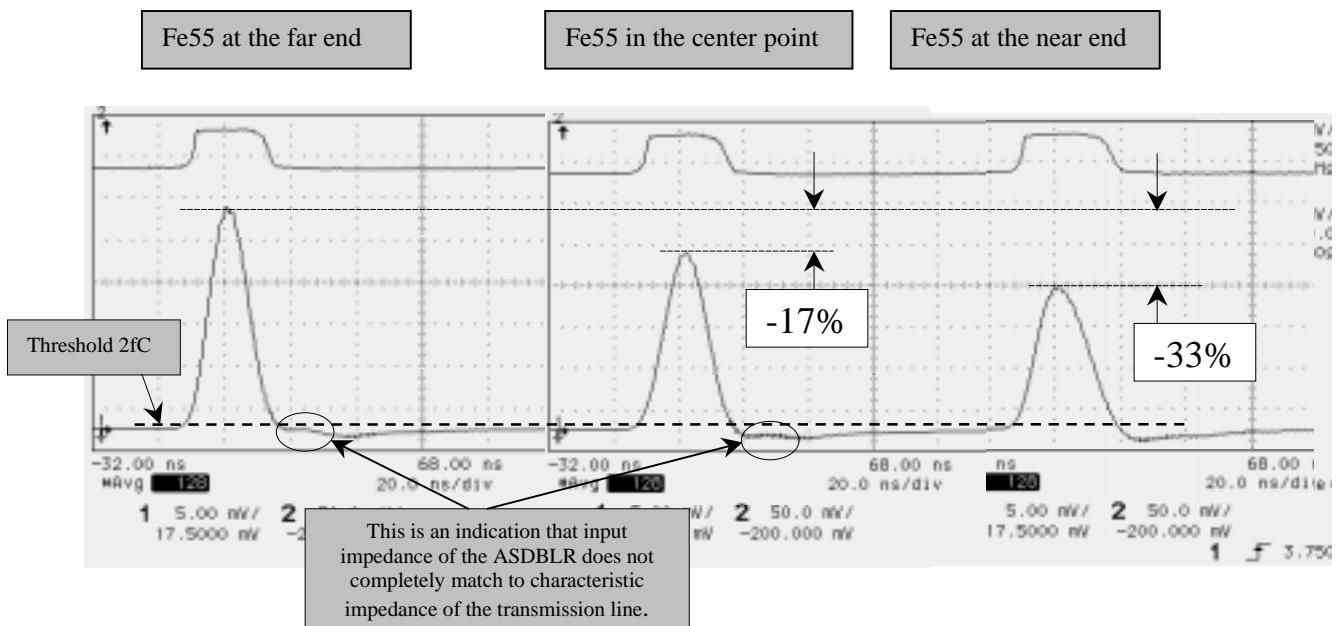
Fig.9 Signals at the ASDBLR output depending on ^{55}Fe source position. High voltage is 1550V, equivalent to 50fC m.i.p. signal. Resistor of 100Ω is placed in front of the ASDBLR chip.

The smallest signal occurs if the source is placed at the end near the electronics. Since the reflected part of the straw current signal is delayed with respect to the direct one by 12ns, which is quite compatible to the ASDBLR weighting function characteristic time ($\approx$ 14ns FWHM), the output signal loses amplitude. On the contrary, both parts of the straw current signal arrive at the electronics input at the same time, when the source is shifted to the far end. Thus the biggest signal comes from the far end, a signal from the center point is reduced by 17% and a signal from the near end is smaller by 33%.

The far end will receive the highest particle flux, since it is closest to the beam pipe. Although a signal from the far end is the biggest possible in a long straw, it still has to travel long distance (1.6m) to get to the electronics. There must be some effects in comparison with the signal in a short chamber, where the signal hardly travels (see Fig.10). We have done the comparison with the purpose to estimate to what degree degradation of time resolution and efficiency could be expected in a long chamber.

Average signal from Fe^{55} at 1550V in the short 30cm straw chamber

Average signal from Fe^{55} at 1550V in the 160cm Kapton XC +alu straw chamber

-23%

12ns

14ns

28ns

30ns
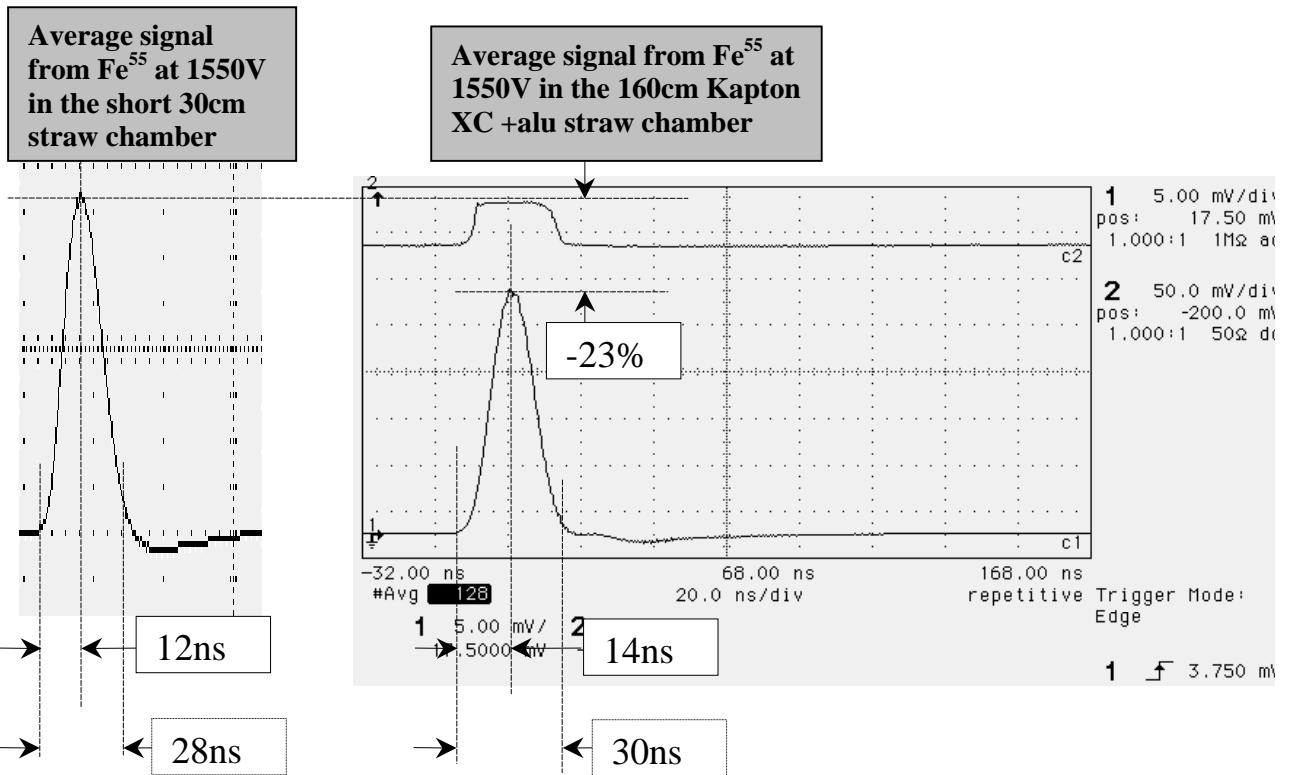
Fig.10. Signals at the ASDBLR output in straw chambers of different length. The ^{55}Fe source is placed at the far end. At 1550V the source is equivalent to 50 fC m.i.p signal.

The picture above indicates neither considerable rise time degradation nor pulse widening in the long 1.6m chamber in comparison with a short 30cm chamber. Rise time in the long chamber becomes 14ns instead of 12ns in the short chamber and pulse width on the base is 30ns instead of 28ns. At the same time a signal loses 23% of its height coming from the far end in the long chamber. It is equivalent to detector operation at lower gas gain, which leads to a slight degradation of efficiency and time resolution. Thus, in the best part of the long straw detector, which is the far end, we already get some degradation of the detector performance, compared to a short straw chamber.

Analog cross-talk measurements in the 1.6m long straw module.

Along with signal transmission properties, cross-talk is one of the most important issues to be taken into consideration on the way to choose the most suitable type of straw. If a big signal occurs in a straw (active straw) a part of the signal can reach the neighbour straw (channel of interest) due to parasitic coupling. By analog cross-talk we mean the degree of coupling between different straws in the module. It is common to quantify the coupling as a ratio of the amplitudes of the signals.

A source producing m.i.p. particles does not suit directly for such kind of measurements, since it leaves a track of primaries in as many straws as it has passed through. Both studied straws could be crossed by the m.i.p. particle, giving signals which have nothing to do with the cross-talk. On the other hand, a ^{55}Fe source produces γ-radiation, which is absorbed in only one point. In other words, when we see a ^{55}Fe signal in a straw, the neighbour surely must have nothing. If a signal is seen in the neighbour straw it is cross-talk. Although an electronic noise signal can accidentally be present, it is of no significance after averaging over a number of ^{55}Fe signals. This feature makes the ^{55}Fe radiation source ideal for cross-talk study.

The experimental set-up used for cross-talk measurements is given in figure 11. To measure the cross-talk in surroundings as close to the real one as possible, we used our normal ASDBLR board for processing of the signals. Apart from cross-talk in the detector itself, cross-talk on the electronics board is always present. Since the straw detector performances are under investigation, special care has been taken to get the cross-talk on the ASDBLR board down to the level of 0.2%. Digital output of the channel of interest is monitored on the scope in average mode. The analog monitor of the BLR output of the active channel triggers the scope and is coupled to input1. To be in the linear range of the ASDBLR a current divider is implemented in front of the active channel in such a way that just 20% of the straw current signal comes into the chip input. The input impedance of the electronics is equal to 300Ω for both channels.
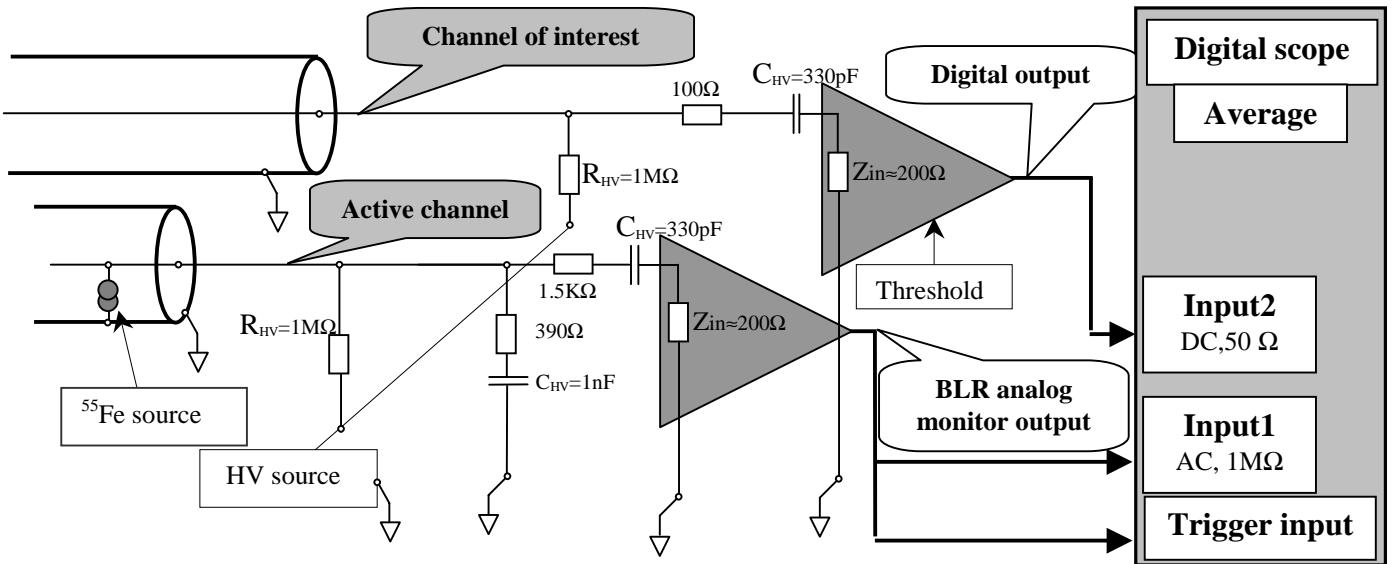
Fig.11. The experimental set-up for cross-talk measurements in the 1.6m long straw module. Cross-talk on the ASDBLR board itself is 0.2%.

The method used to determine the analog cross-talk coefficient is as follows. We increase the high voltage up to the level where the averaged digital signal in the channel of interest reaches half of its standard amplitude. This means that an analog cross-talk pulse there just touches the threshold and has 50% probability to cross it due to electronic noise (see Fig12). At this moment the amplitude of the signal in the active channel is to be measured. Through the calibration, that value is interpreted in terms of input charge (that is Qa) afterwards. Having the ASDBLR discriminator threshold set at the fixed level of 2fC, we are capable to define the analog cross-talk coefficient as follows: $K_{cross-talk}=2fC/Qa$
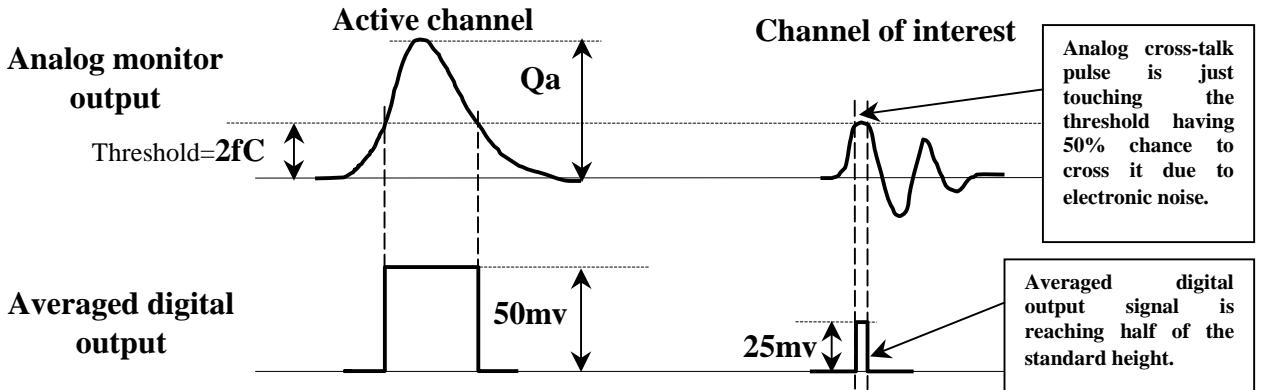
Fig.12. The method used for measuring the analog cross-talk coefficient. $K_{cross-talk}$=2fC/Qa.

The pictures below demonstrate the cross-talk level between neighboring straws.
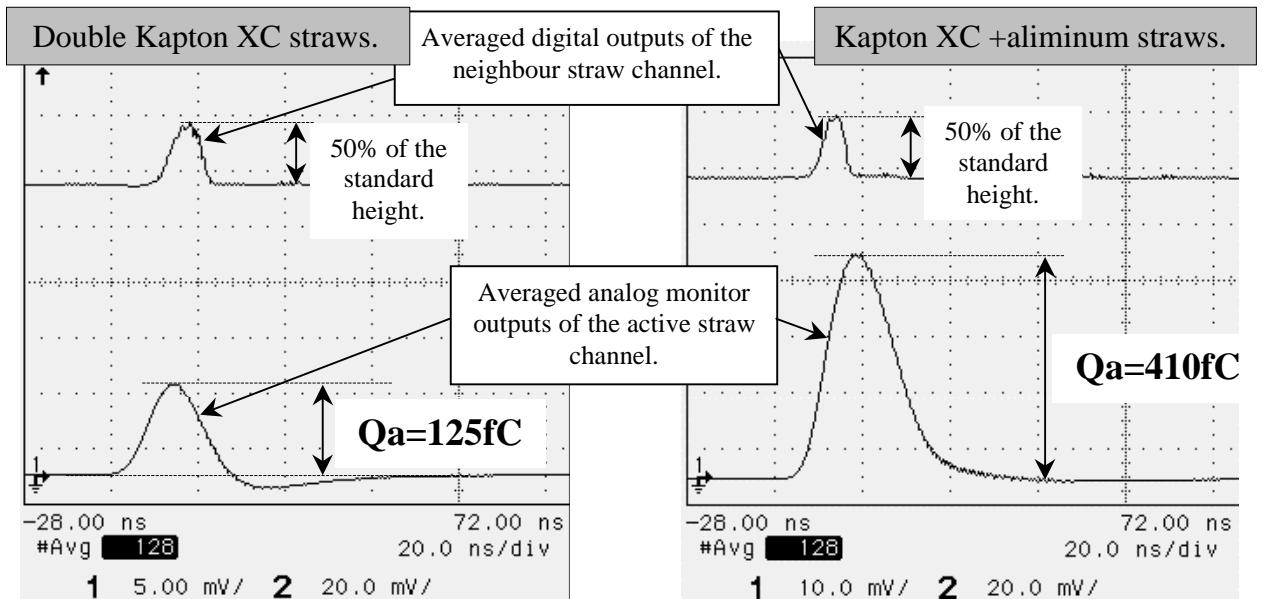
Fig.13. Cross-talk between two neighbouring straws made of double Kapton XC and between two neighbouring straws made of Kapton XC + aluminum. The ^{55}Fe source is placed at the far end, the threshold on the ASDBLR is 2fC.

Following the procedure described above we measured all kinds of cross-talks in the module, i.e. cross-talk between neighbouring straws, cross-talk to the straw next to the neighbour and cross-talk to the straw of the different layer. A summary of the measurements is presented in table 1 for different types of straws and different positions of the ^{55}Fe source on the chamber.

Table 1. Summary of the analog cross-talk measurements in the 1.6m long straw module.

Type of straw.	Fe ^{55} source position.	Cross-talk to the neighbour straw.		Cross-talk to the straw next to the neighbour.		Cross-talk to the straw of the different layer.	
		Qa, fC.	Analog cross-talk.	Qa, fC.	Analog cross-talk.	Qa, fC.	Analog Cross-talk.
Double Kapton XC straws	Near end	140fC	1.6%	560fC	0.4%	180fC	1.2%
	Center point	180fC	1.2%	560fC	0.4%		
	Far end	125fC	1.8%	460fC	0.5%	130fC	1.7%
Kapton XC + pure Kapton straws	Near end	150fC	1.5%	510fC	0.4%	150fC	1.5%
	Center point	165fC	1.3%	510fC	0.4%	180fC	1.2%
	Far end	130fC	1.7%	460fC	0.5%	130fC	1.7%
Kapton XC + aluminum straws	Near end	410fC	0.5%		Below 0.2%	560fC	0.4%
	Center point	500fC	0.4%				
	Far end	410fC	0.5%			540fC	0.4%

No noticeable difference is visible between double Kapton XC and Kapton XC +pure Kapton from the point of view of analog cross-talk level. Since the high-frequency electrical properties of Kapton XC are practically identical to those of pure Kapton it would indeed be hard to expect any difference in the cross-talk. Analog cross-talk depends on the source position, reaching 1.8% level between two neighbouring straws when the source is placed at the far end, which receives the highest flux in the real experiment.

The analog cross-talk level between straws made of Kapton XC+aluminum is much lower than in nonaluminized straws. When the source is placed at the far end, the analog cross-talk is just 0.5% between two neighbouring straws. The highly conductive aluminum layer acts as shielding for the electrical signals, providing good separation between different straws.

The analog cross-talk level between straws belonging to the different layers is almost the same, because the straw-to-straw distance is almost the same as the distance between the straws belonging to the same layer (see Fig.3).

Analog cross-talk to the straw next to the neighbour is much lower than to the neighbouring one for the obvious reason of the bigger distance. Whereas for double Kapton XC type it is 0.5%, in the case of Kapton XC +aluminum straws it goes below 0.2%.

Digital cross-talk in the 1.6m long straw module.

Having measured the analog cross-talk we are able to estimate what is the chance to get a fake digital pulse, called digital cross-talk. For this purpose we must know how often a signal bigger than Qa occurs in the straw.

During the last test beam run dedicated pulse height measurements have been performed. We used a slow charge sensitive preamplifier in combination with a gated ADC to be able to collect all the charge left by a m.i.p. particle. Due to the fast shaping of the ASDBLR it effectively integrates only 25% of the total charge, therefore the "visible" charge for the ASDBLR is the total charge times 0.25. The pulse height distributions in terms of equivalent input charge were measured at different high voltages on the straws (see Fig.14).
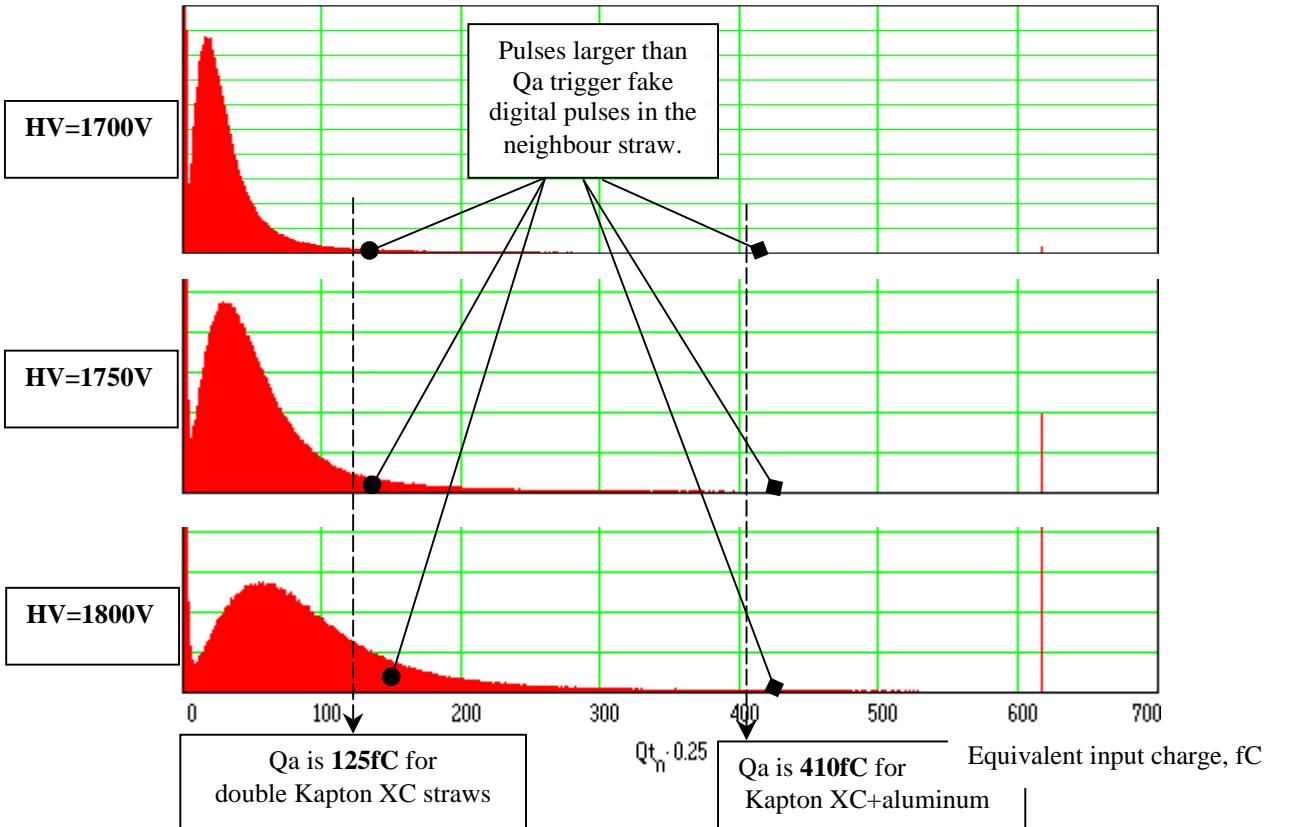

Fig.14. Pulse height distributions of the m.i.p. particles at different high voltages.

The pictures above give an idea how   different digital cross-talk is in the straws of different types. In the case of double Kapton XC every pulse larger then 125fC gives a digital cross-talk pulse in the neighbouring straw. In the case of Kapton XC + aluminum the chance to get a digital cross-talk pulse in a neighbouring straw is lower, because of the much lower percentage of pulses larger than 410fC.

The pulse height distribution gets wider when the high voltage goes up. At the same time the percentage of pulses larger than Qa increases, making it more probable that a fake digital pulse appears in the neighbour channel. In that way, the percentage of fake pulses in the Read-out system grows with high voltage rise.

To characterize the digital cross-talk numerically, normalized integrals of the pulse height distributions have been constructed (see Fig.15).
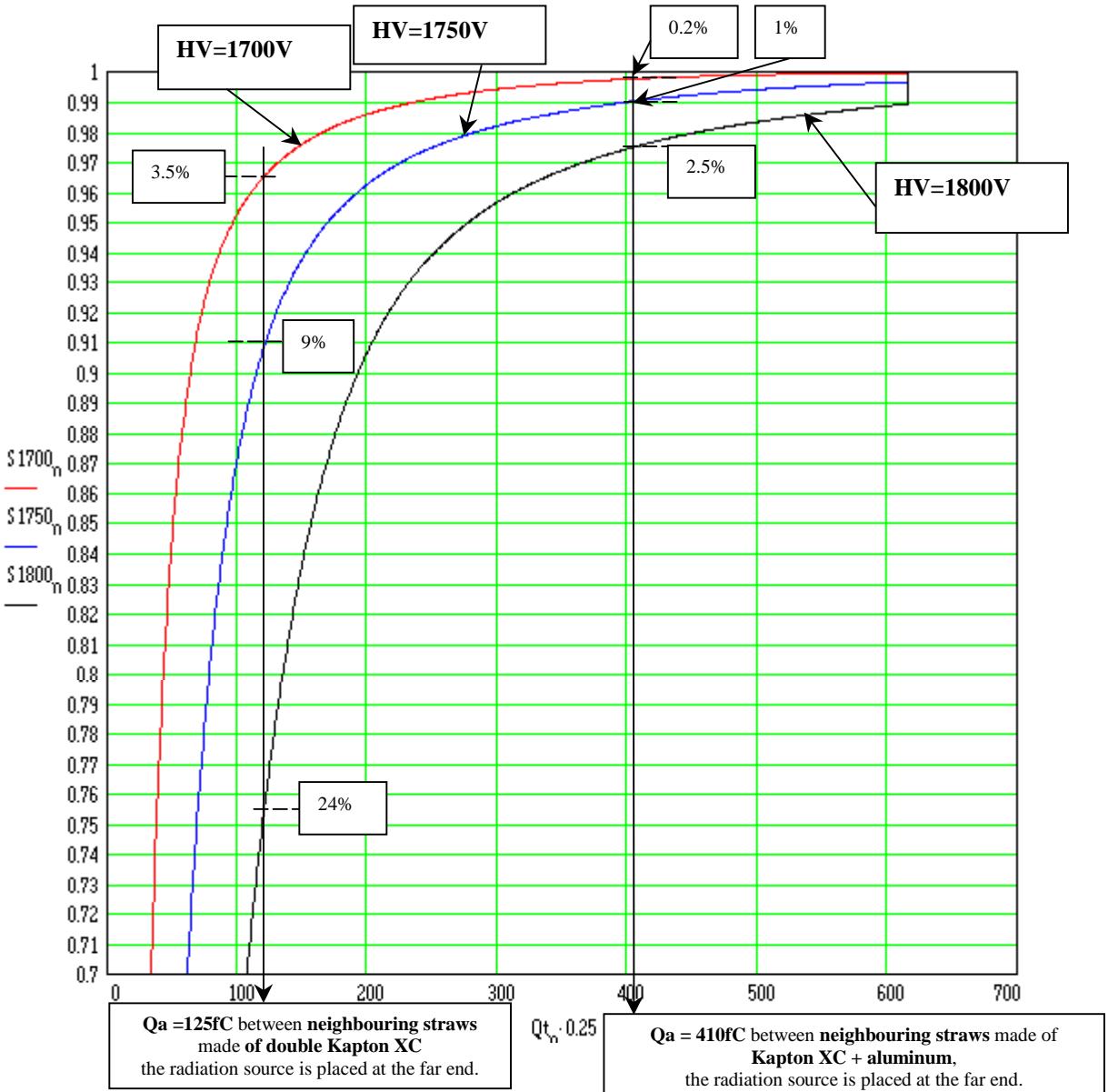

Fig.15. Normalized integrals of the pulse height distributions at different high voltages on the straws.

At the working point of the detector (HV=1750V) the digital cross-talk is 9% between two neighbouring straws of double Kapton XC type while it is just 1% between two neighbouring straws of Kapton XC + aluminum type. With high voltage rise up to 1800 Volts the digital cross-talk rapidly goes up to 24% for double Kapton XC type whereas between Kapton XC + aluminum straws it stays at the acceptable level of 2.5%.

Values of all kinds of estimated digital cross-   talk at HV=1750 Volts are presented in table 2 for different types of straws and different positions of the ^{55}Fe source on the chamber.

Table 2. Summary of the digital cross-talks in the 1.6m long straw module at HV=1750V.

Type of straw.	Fe ^{55} source position.	Digital cross-talk to the neighbour straw.	Digital cross-talk to the straw next to the neighbour.	Digital cross-talk to the straw of the different layer.
Double Kapton XC straws	Near end	7%	0.5%	5%
	Center point	5%	0.5%	
	Far end	9%	0.8%	9%
Kapton XC + pure Kapton straws	Near end	6%	0.6%	6%
	Center point	5%	0.6%	5%
	Far end	9%	0.7%	9%
Kapton XC + aluminum	Near end	1%	Below 0.2%	0.4%
	Center point	0.7%		
	Far end	1%		0.5%

Total cross-talk in the 1.6m long straw module.

It seems to be interesting to estimate what the overall percentage of the fake digital pulses in the Read-out system of the module could be. Such a percentage is called the total cross-talk in the module. By summing up contributions of every cross-talk source, the total cross-talk can be evaluated. (see Fig.16).
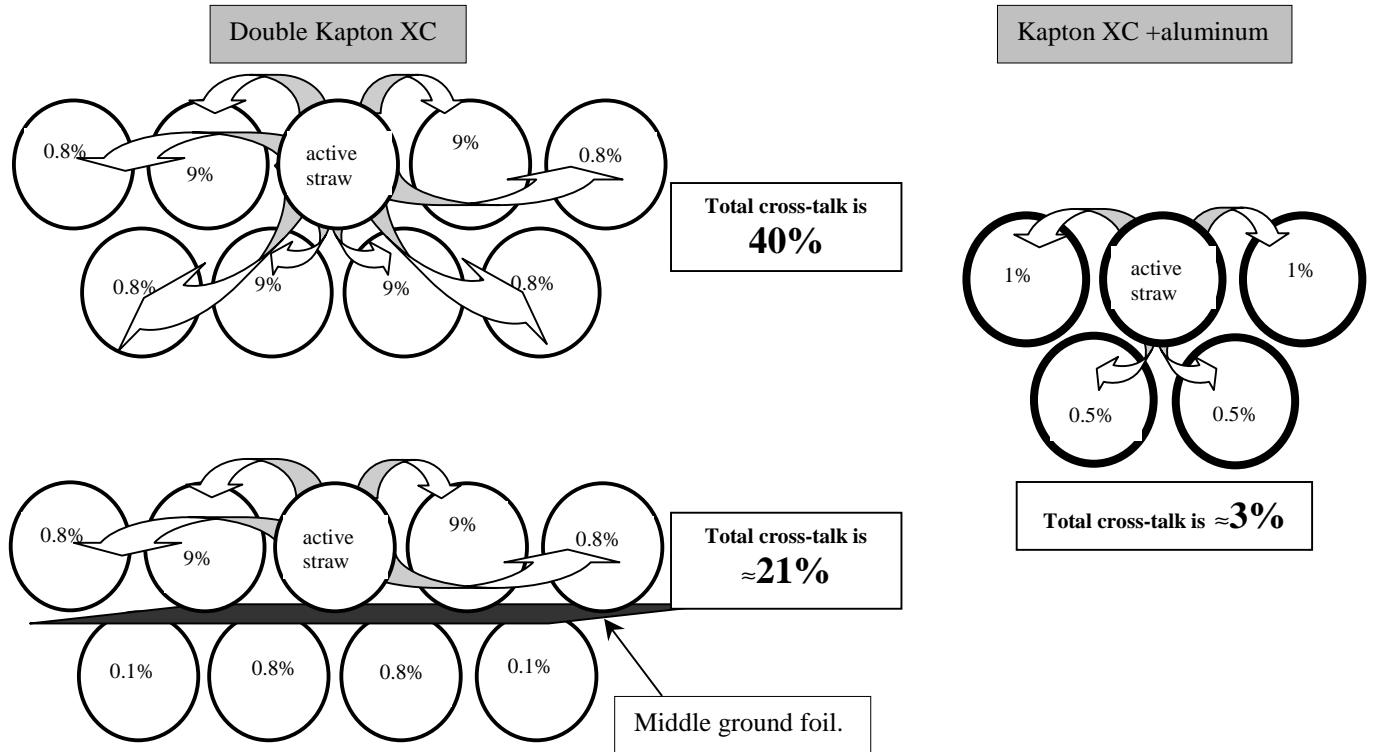

Fig.16. Total cross-talk in 1.6m long module made of straws of different types. HV=1750 Volts, all pulses come from far end of the straw.

Total cross-talk is 40% in the module consisting of double Kapton XC straws without middle ground foil. If a middle ground foil is placed between two layers of straws, cross-talk between straws belonging to different layers is very low. Total cross-talk in this case diminishes to the level of 21%.

Total cross-talk in the module consisting of Kapton XC+aluminum straws is just 3% thanks to much better straw-to-straw electrical separation. A ground middle foil hardly improves cross-talk, since the aluminum layer already provides electrical separation, like the ground foil is supposed to do.

Summary table of electrical properties of straws of different types.

Electrical properties of straws of different types have been gathered together in table 3 with the purpose to consider all advantages and disadvantages of each option.

Point of concern	Double Kapton XC or Kapton XC + pure Kapton straw.			Kapton XC + 25μ aluminum foil coated straw.	
Characteristic impedance	~300Ω			~300Ω	
Signal propagation velocity	~3.8ns/m			~3.8ns/m	
After pulsing behavior	No oscillation (if 100Ω resistor is placed in front of ASDBLR input)			No oscillation (if the straws are electrically connected to the ground foil along the whole length + 100Ω resistor is placed in front of ASDBLR input)	
Signal amplitude difference along the straw	~30% (in 1.6m long straw without termination at the far end)			~30% (in 1.6m long straw without termination at the far end)	
Signal amplitude attenuation (in comparison with a short straw chamber)	-20% in the best case			-23% in the best case	
Signal rise time degradation (in comparison with a short straw chamber)	14ns (instead of 12ns in a short straw chamber)			14ns (instead of 12ns in a short straw chamber).	
Signal widening at the base (in comparison with a short straw chamber)	30ns (instead of 28ns in a short straw chamber)			30ns (instead of 28ns in a short straw chamber)	
Cross-talk to the neighbour straw in the 1.6m long module without middle ground foil (digital cross-talk is estimated at HV=1750V)		Analog cross-talk	Digital cross-talk	Analog cross-talk	Digital cross-talk
	Near end	1.6%	7%	0.5%	1%
	Center point	1.2%	5%	0.4%	0.7%
	Far end	1.8%	9%	0.5%	1%
Cross-talk to the next straw to the neighbour in the 1.6m long module without middle ground foil. (digital cross-talk is estimated at HV=1750V)		Analog cross-talk	Digital cross-talk	Analog cross-talk	Digital cross-talk
	Near end	0.4%	0.5%	Below 0.2%	Below 0.2%
	Center point	0.4%	0.5%	Below 0.2%	Below 0.2%
	Far end	0.5%	0.8%	Below 0.2%	Below 0.2%
Cross-talk to the straw of the different layer in the 1.6m long module without middle ground foil. (digital cross-talk is estimated at HV=1750V)		Analog cross-talk	Digital cross-talk	Analog cross-talk	Digital cross-talk
	Near end	1.2%	7%	0.4%	0.4%
	Far end	1.7%	9%	0.4%	0.5%
Total cross-talk in the 1.6m long module without middle ground foil (HV=1750V).	Far end	40%		3%	
Total cross-talk in the 1.6m long module without middle ground foil (HV=1800V).	Far end	~100%		~8%	

Summary.

With the purpose to investigate transmission line effects and cross-talk, a 1.6m long straw module prototype has been constructed and tested. The prototype is approaching the final module design for the LHCb Outer Tracker. To be able to select the most appropriate type of straw tube the module is equipped with straws of different types, i.e. double Kapton XC, Kapton XC + pure Kapton and Kapton XC + aluminum. Electrical properties have been studied for straws of each type. By doing so we demonstrated the following.

First, there is no difference in signal transmission properties between straws of the different types.

Second, because of the anode wire series resistivity, characteristic impedance of the straw transmission line is frequency dependent which is not possible to match completely with an ordinary RC-circuitry. Since the input impedance of the ASDBLR chip (~200Ω at the frequencies of interest) does not directly match to characteristic impedance of the straw (which is about 300Ω) a resistor must be placed in front of the chip. By tuning of this resistor we have found that 100 Ω is the optimum value, in this case the parasitic reflections go down below the working threshold level (2fC).

Third, the propagation velocity of the signal in the straws has been found as 3.8ns/m for all types of straw.

Fourth, in the long straw with open far end the biggest signal come from the far end, a signal from the center point is by 17% smaller and a signal from the near end is smaller by 33%. No rise time increasing can be noticed for signals from the different positions.

Fifth, comparison between the 1.6m long prototype and the short 0.3m straw chamber shows that the signal risetime in the long chamber becomes 14ns instead of 12ns in the short chamber and pulse width on the base is 30ns instead of 28ns. At the same time a signal loses 23% of its height coming from the far end in the long chamber. It is equivalent to detector operation at a lower gas gain, which leads to some degradation of efficiency and time resolution.

Sixth, no noticeable difference is visible between double Kapton XC and Kapton XC + pure Kapton from point of view of analog cross-talk level. Analog cross-talk depends on the source position, reaching 1.8% level between two neighbouring straws when the source is placed at the far end.

Analog cross-talk level between straws made of Kapton XC+aluminum is much lower than in nonaluminized straws. When the source is placed at the far end, the analog cross-talk is just 0.5% between two neighbouring straws.

Analog cross-talk level between straws belonging to different layers is almost the same because the straw-to-straw distance is almost the same as the distance between the straws belonging to the same layer.

Analog cross-talk to the straw next to the neighbour is much lower than to the neighbouring one for the obvious reason of the bigger distance. Whereas for double Kapton XC type it is 0.5%, in the case of Kapton XC +aluminum straws it goes below 0.2%.

Seventh, at the working point of the detector (HV=1750V) the digital cross-talk is 9% between two neighbouring straws of double Kapton XC type while it is just 1% between two neighbouring straws of Kapton XC + aluminum type. When high voltage rises up to 1800 Volts, the digital cross-talk rapidly goes up to 24% for double Kapton XC type whereas between Kapton XC + aluminum straws it stays at the acceptable level of 2.5%.

Eighth, at the working point of the detector (HV=1750V) the total cross-talk is 40% in the module consisting of double Kapton XC straws without middle ground foil. If a middle ground foil is placed between two layers of straws, cross-talk between straws belonging to different layers is very low. Total cross-talk in this case diminishes to the level of 21%.

Total cross-talk in the module consisting of Kapton XC+aluminum straws is just 3% thanks to much better straw-to-straw electrical separation.

Ninth, when the high voltage rises to   1800V total cross-talk rapidly increases to the level of 100% for double Kapton straw modules without middle ground foil. For 1.6m long module with Kapton XC + aluminum straw, total cross-talk remains at the quite low level of 8%.

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