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ELECTROMAGNETIC DELAY LINES IN SPARK, PROPORTIONAL AND DRIFT CHAMBERS APPLICATIONS

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Summary

The delay line readout technique of spark, proportional, and drift chambers is widely described in the literature, but the specific constraints on design parameters of the lines set by these applications are not always well understood. We describe here various techniques, old ones as well as more recent ones, of building and optimizing delay lines, reviewing the advantages and inconveniences of each approach in conjunction with the usual applications in high energy physics and nuclear medicine.

Introduction

The electromagnetic delay line readout technique applied to proportional chambers presents some interesting advantages, but has also drawbacks and difficulties of application.

One immediate apparent advantage is a lower cost than the use of one amplifier per wire, despite somewhat more elaborate electronics.

A second point of interest is the possibility of reading cathode planes and interpolating between wires, leading to better spatial resolution than obtained from the anode plane; by using three delay lines to read one anode and two cathode planes, a very simple, self triggering chamber, having extremely good spatial resolution (typically five times better than the anode wires spacing) and capability of solving multitracks ambiguities can be built. A fast triggering signal can also be obtained from the ground plane of one delay line. As in the magnetostrictive technique, the times can be read either by one end or by both, the latter way allowing improved spatial resolution when the line would be the limiting factor and potentially better two pulse resolution, without requiring fiducial marks. A fast start signal for the timing electronics can be obtained either from the anode plane or from the ground plane of the delay line. In general delays between 5 and 100 ns/cm are used, depending on the available electronics, the spatial resolution required, and the tolerable dead time. For large chambers, in some applications, the dead time can become prohibitive, but in most cases an acceptable compromise between dead time and spatial resolution can be found. A more serious objection, when multitracks events are expected, is a degradation by the line of the intrinsic two pulse resolution of the chamber. Delay lines having a large delay to rise time ratio are therefore highly desirable to preserve both the spatial accuracy and two pulse resolution of proportional chambers. We obtain presently a two pulse resolution of 15 to 20 mm with a line 50 cm in length read by one extremity, with a spatial resolution $\sigma \simeq 100$ μm.

The design of lines with large delay to rise time ratio, acceptable delay per unit length, tolerable attenuation, and high impedance is far from being straighforward. (A high impedance is desirable because it improves the coupling efficiency between chamber and line, but also because it minimizes the effect of the resistance of the line, as we will see later). Some practical designs also suffer from nonlinearity of the electrical parameters along the line, with resulting reflections and variations of delay per unit length. The reflections are usually tolerable or smothered out by attenuation, but variations of delay are more annoying. Admittedly, this may be corrected by calibration of the system, but it is in general an undesirable complication.

The dynamic range over which signals can be detected is limited by reflections along the line and by its degree of correction. We achieved a dynamic range of one hundred to one without major difficulties.

Signals from the chamber can be transmitted either directly or by capacitive coupling. Due to its simplicity, we generally favor the second approach; the resulting loss of amplitude is tolerable even when detecting low energy x rays if we use high impedance (1000 to 1500 Ω) delay lines with good low noise amplifiers.[1] When "magic gas" is used, lower impedance lines can be employed, because of the higher signal amplitude.

Another interesting feature of delay lines is that they can serve directly to read the coordinate along the wire of a proportional or drift chamber, by using them as cathode planes. In drift chambers, this allows us to read the second coordinate and when applied to long drift spaces, gives a very simple two-dimensional detector requiring only one anode wire, one cathode plane (the line itself), and a drift space. The detector needs an external trigger to time the signal properly. The dead time is in general defined by the drift time, not by the line, and the resolution is limited by the diffusion of the electron cloud (a magnetic field along the drift direction may reduce the diffusion, improving spatial resolution). Performances without field are: 200 ns/cm drift speed, resolution after 50 cm around 1.2 mm FWHM.[2] With a magnetic field of 5 kG, the resolution can typically be improved by a factor of five.

This type of simplified two-dimensional detector (without magnetic field) is also interesting when large numbers of chambers are required, as for example in shower detectors using alternate layers of converters and detectors, where a very good spatial resolution is not necessary. These chambers seem also ideally suited for use in magnetic fields, especially with 4π detectors using a solenoid to create the field along the drift direction.

Low mass delay lines were also developed for drift chambers, to minimize multiple scattering when the line has to be in the particle path.[3,4] Finally, other applications of delay lines presently investigated include the readout of microchannel plates as imaging detectors for various types of particles and radiations, as well as the readout of photoionization chambers for Cerenkov detectors.

Delay Lines Theory

The delay lines we consider here, solenoid wound ones, printed circuit ones, as well as most of the other types, present analogies with both uniform and lumped circuit lines. The lumped circuit description would be adequate, providing that we use a complex model containing bridging capacitors and mutual inductance between cells, as well as introducing the frequency dependence of the various parameters. Models of this type exist in the literature, and we will use some of their results in the optimization process of our delay lines. Since we do not deal here with lumped circuits elements, we usually cannot optimize separately each capacity, resistance or inductance, so the usefulness of these models is strongly restricted. On the other hand, as we consider here lines equivalent to a large number of elementary cells, useful information may be obtained from the theory of uniform lines, which we will briefly summarize (detailed demonstrations may be found in Ref. 5). We assume lines with a serial impedance

$$R + j\omega L$$

and parallel impedance

$$\frac{1}{G + j\omega C}$$

per unit length. For uniform lines, the resulting impedance is known to be:

$$Z = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad .$$

The attenuation and phase shift at a distance x from the origin are given by:

$$V_x = V_o e^{-\gamma x}$$

with

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta \quad .$$

Two conditions are known to give lines without phase distortion, assuming that L, C, R, and G are independent of ω.

(a) R = G = 0, giving

$$Z_o = \sqrt{\frac{L}{C}} \; ; \; \alpha = 0 \; ; \; \beta = \omega\sqrt{LC}$$

(b) LG = RC, giving

$$Z_o = \sqrt{\frac{L}{C}} \; ; \; \alpha = GZ \cong \frac{R}{Z_o} \; ; \; \beta = \omega\sqrt{LC} \quad .$$

Unfortunately, these conditions are usually not fulfilled in our applications, even approximately, the first one being incompatible with physical limitations of the size of the line and therefore of wire diameter and length; the second condition introduces large attenuation and requires a lossy dielectric with values of G difficult to obtain, especially if the variation of G with frequency has to compensate to some extent the variations of L, R and C.

A further constraint on our design is that we often wish to operate our lines in magnetic fields, so we will not consider the use of high permeability cores. In practice, when using a good dielectric, G can be neglected, so we have:

$$Z \simeq \sqrt{\frac{R + j\omega L}{j\omega C}} \simeq \sqrt{\frac{L}{C}}\left(1 - \frac{jR}{2\omega L} + \ldots\right) \text{ if } \frac{R}{2\omega L} < 1$$

we obtain to first order:

$$Z = Z_o\left(1 - \frac{jR}{2\omega L}\right) \; ; \; \alpha = \frac{R}{2Z_o} \; ; \; \beta = \omega\sqrt{LC}$$

so there is no dispersion (β is the same as in the ideal case, R = G = 0), but attenuation appears. The impedance of the line has now a capacitive component which will modify the step response, but as we are interested in transmitting only relatively narrow pulses, we will not consider this point further.

By taking into account the second order terms, we see that the attenuation remains the same, but dispersion appears:[5]

$$\alpha = \frac{R}{2Z_o} \quad , \quad \beta = j\omega\sqrt{LC}\left(1 + \frac{R}{8\omega^2 L^2}\right) .$$

Again, as we consider only narrow pulses, a first order approximation is satisfactory enough.

Now, it is necessary to note that R, L, C depend on the frequency and will limit the rise time of the line accordingly; their variation laws are well known for uniform lines, but in solenoidal lines the situation becomes complex, because the mutual inductance and self inductance behave differently and because the effect of the turn to turn capacity changes with the relative phase between turns, which is also frequency dependent. A discussion of these effects can be found in Refs. 6-8.

From lumped circuit delay line theory, especially when the model includes mutual inductance and capacitance between tie points, we can deduce some guidelines; first, the number of cells must be large to obtain a good delay to rise time ratio, as this ratio is given by:[9]

$$\frac{t_d}{t_r} = Kn^{2/3} \quad .$$

(If possible, the rise time should be limited by the variations of R, L, and C and not by the number of cells.) Secondly, the change of mutual inductance with frequency can be compensated to some extent by adding bridging capacitors between cells.

Similarly, solenoidal delay lines have phase distortion due to the decrease of mutual inductance when frequency is increased (currents in neighboring turns do not remain in phase when the frequency increases). Capacitive coupling between turns compensates this effect to some extent, and the delay line is usually improved by adding floating capacitive patches from turn to turn, but the inductance decreases faster than the capacitive compensation effect increases.

So, in practice, the variations of mutual inductance with frequency is the factor limiting the rise time of most of the lines we consider, provided that the effective number of elementary cells is large enough; alternately, the cell size is defined by the distance at which mutual inductance between turns can be neglected.

Two approaches appear possible to produce lines with improved delay to rise time ratio within the frame of the physical size limitations set by the chambers and their applications (the arguments which follow are based on similar core sizes and lengths).

(a) Suppress mutual inductance and rely only on self inductance; at the same time, turn to turn capacity should be minimized. This approach is described for example in Ref. 10. The suppression of mutual inductance can be obtained either by using a conductive core or by making extremely thin, flat delay lines with spaced turns. Lines obtained in this way have a low inductance, usually high capacity to maintain a reasonable delay $t = \sqrt{LC}$ and, therefore, their impedance $Z_o = \sqrt{L/C}$ is low; when trying to obtain long delays per unit length, limitations due to the resistance appear rapidly, because more conductor wire is needed to obtain a given inductance--large resistance with low impedance is unacceptable because of the resulting attenuation given in first approximation by

$$|V| = |V_o|\, e^{-R/2Z_o} \quad .$$

(b) Try to confine the mutual inductance, or in other words increase the number of cells, but keeping into one cell a large amount of inductance between wires. With solenoidal lines, a simple way to achieve this is to build flat thin lines, thin enough to reduce mutual inductance between distant wires, but thick enough so that mutual inductance is not totally suppressed. A description of lines of this type will be given later. Further applications of this technique could include lines with transversally slotted aluminum cores and etched delay lines with unequal spacing between strips to minimize inductance in some regions, maximize it in others. An interesting variation of this technique uses cross coupled coils, either etched or continuously wound.[11,12]

Description of Various Lines

(a) Lumped circuit delay lines. Arrays of solid state counters[13] as well as spark chambers[14] can be read by these lines. Their performance can be tailored to most applications, with delays ranging from some nanoseconds to milliseconds, but the large number of cells required to obtain good delay to rise time ratios makes these lines difficult and expensive to build with discrete components, especially when complex cells using bridging capacitors or controlled mutual inductance are needed. Renewed interest in these lines is generated by the availability of lumped elements in dual in-line packages.

(b) Coaxial and helix cable lines. These lines serve to read cathode planes with high resolution. With coaxial cables, the impedance is low (50Ω usually), therefore, long delays are not practical, except with quite cumbersome, low resistivity cables, but good linearity and excellent delay to rise time ratio can be achieved,[15] provided that connections along the line are made with care and in limited number.

Delay cables made of a copper helix wound on ferrite or ceramic core were also used to read proportional chambers.[16,17] Coupling of the signal to the line with external coils was investigated, as well as capacitive coupling with conductive strips. The second solution was found to be preferable not only because of its simplicity, but also due to the lower amount of distortion introduced. Impedance and delay per unit length are an order of magnitude larger than with coaxial cables, but delay to rise time ratio is generally mediocre (less than 20).

(c) Flat solenoidal lines. Initially, we tested lines wound on circular cores, then decided to use flat rectangular cores to obtain a better coupling efficiency to the chambers;[18] as a by-product, we also obtained a better delay to rise time ratio, despite a somewhat lower delay per unit length; at the same time, we opted for a phase compensation technique and for reasons of simplicity we selected floating patches[19] instead of introducing skewed turns.[20] Further improvements were mainly obtained by decreasing the line thickness, affecting losses and impedance as well as two pulse resolution.[4,21] Our results are summarized in Table 1.

We also built various other lines of similar design, with delays per centimeter varying from 10 to 72 ns and delay to rise time from 10 to 50 for short pulses, finding that careful optimization and compensation were almost always necessary. Results obtained with the last of these lines appear on Fig. 1; details of their construction are shown on Fig. 2. Chamber pulses are simulated and injected capacitively, using a coupling board similar to the one of the chambers. The line is optimized by adjusting the width of the compensating strip, as indicated in Fig. 3. To summarize briefly our results, these lines have medium to high impedance (200 to 1500 Ω approximately), good delay to rise time (best performance is 50 to 1, 25 to 1 being usually simple to achieve), reasonable attenuation (R/2Z can be kept around 0.2 for a 50 cm line 2.5 to 3.5 cm wide) with a feasible range of delays per unit length well matched to standard electronics; but these lines also present some drawbacks, mainly due to their manufacturing process: exact reproducibility is difficult to achieve; for

Table 1. Characteristics of flat solenoidal delay lines.

Line	A	B	C
Length (cm)	57	51	55
Width (cm)	2.6	3.3	3.3
Thickness (cm)	0.9	0.33	0.15
Turns/cm	34	78	60
Resistance (Ω)	300	590	300
Impedance (Ω)	750	1500	800
Delay/cm (ns)	39	72	38
Two-pulse resolution[a] (cm)	≃5.0	≃2.5	≃1.5

[a] For equal amplitude pulses fed capacitively in the middle of the line (see also Fig. 1b), the line being read by one extremity.

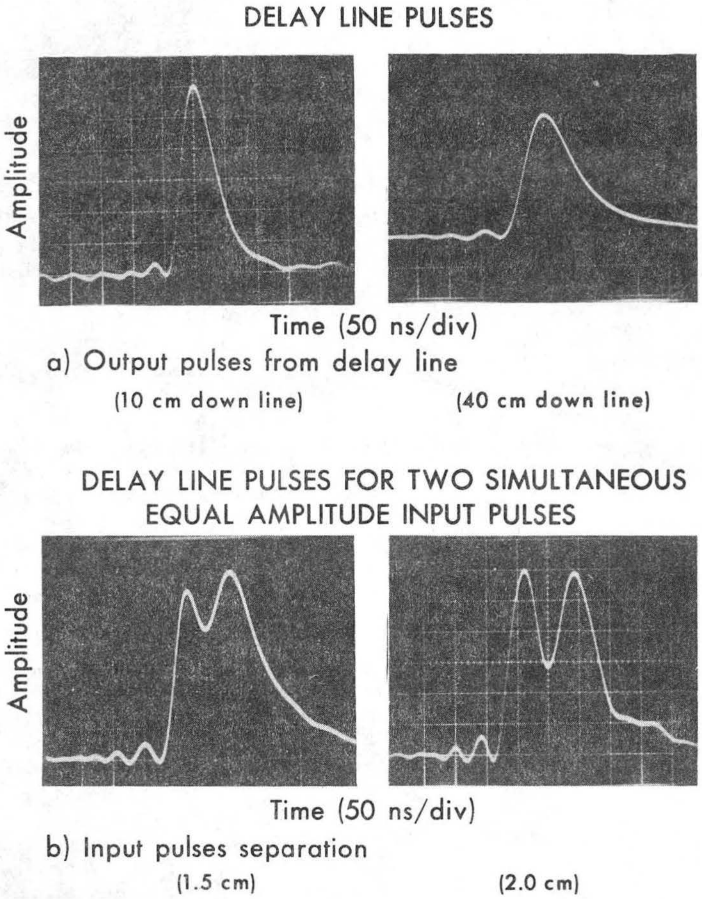
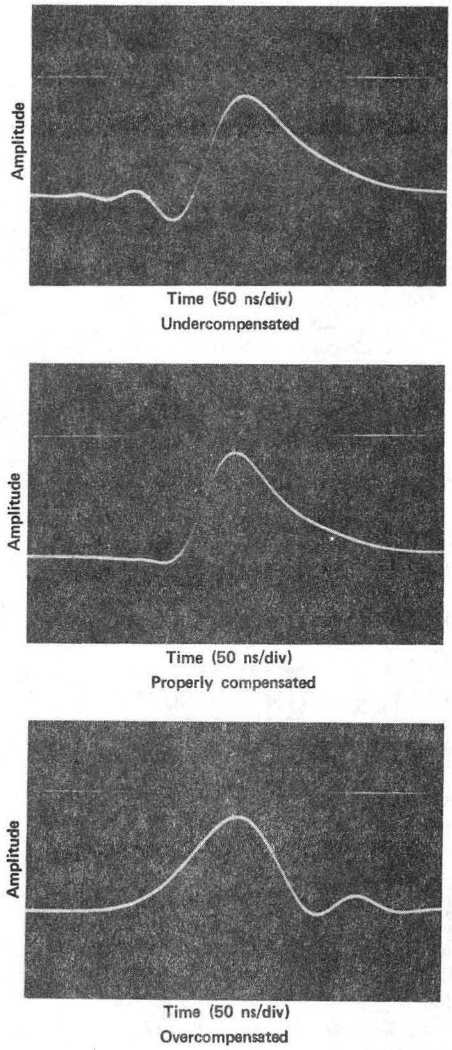


Fig. 1. Response of delay line C to simulated chamber pulses fed in capacitively.



Undercompensated

Properly compensated

Overcompensated

Fig. 3. Adjustment of the compensating strips. The line is pressed against a board simulating the chamber. Pulses are fed in at one extremity of the line and observed at the other, with various amounts of compensation.

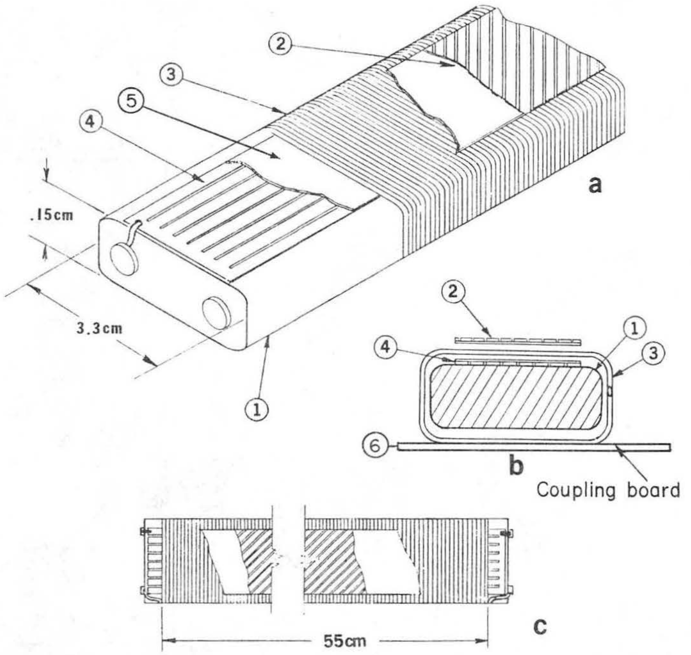


Fig. 2. Structure of delay line C.

1) Core (G10).
2) Floating aluminum strips on mylar base: strips 1.8-mm wide at 45°; gaps = 0.3-mm wide; mylar = 25μ thick. Adjust width for optimum compensation.
3) Winding (Formvar wire).
4) Copper strips on mylar base: 1.8-mm wide; gaps = 0.3 mm; mylar = 25μ. Strips are connected together at one end.
5) Insulation: mylar base from 4) is often used. Sometimes, depending on the parameters required, we add a layer of mylar or polyethylene.
6) Coupling board.

best results, each line must be compensated individually on the chamber or on a board simulating the chamber; electrical characteristics vary with the pressure applied and inhomogeneities may be introduced in this way. Immobilizing the winding in epoxy with low dielectric losses could probably solve this problem, but at the expense of increased complexity in the manufacturing process.

In our research for high performances delay lines with good mechanical and electrical stability as well as ease of manufacture, we investigated several other techniques which we will describe now.

(d) Aluminum core delay line. The use of this type of lines with proportional chambers was developed by D. M. Lee and others[10] to read anode signals. Copper wire is wound on aluminum tubing, with insertion of a polyethylene sheet and the anode wires are individually soldered along the line; the spacing between helix and cylinder is kept smaller than all the other dimensions. The inductance of the line is then essentially the self inductance of the wire itself and the shape of the core should not affect delay to rise time ratio as it does for insulated core lines, so this ratio is not limited by the decrease of mutual inductance with increasing frequency, but by the effective number of cells, the losses in core, in the dielectric or by skin effect.

Usually, impedance is low (50 to 200 Ω), as is delay per unit length. We built several such lines, either with circular or rectangular cross sections and their performances, normalized to a standard 55 cm line, are summarized in Table 2. The best performance was obtained with circular cross section 2 in. in diameter, apparently because this geometry allowed us to maximize the self inductance per unit length of the line.

Table 2. Characteristics of some aluminum core delay lines.

Core Size	1 1/4 in. x 1/8 in. x 22 in.			2 in.ϕ x 22 in.	
Resistance (Ω)	30	30	60	60	160
Impedance (Ω)	100	420	900	680	900
Delay/cm (ns)	11	12	15	24	32
Turns/cm	31	31	40	31	40
Delay/rise time[a]	10	12	21	22	28
Dielectric[b] (cm)	0.005	0.05	0.1	0.1	0.1

[a] Measured with simulated chamber pulses.

[b] Polyethylene between Formvar winding and aluminum core.

Due to the lack of mutual inductance, these lines present a low delay per unit length of wire, which can only be compensated by increased capacity, with resulting attenuation problems; but they appear to be a reasonably satisfactory solution where simplicity of construction is important, if low delay and modest delay to rise time ratio are acceptable.

(e) Coupled delay lines. They are described in Ref. 12 and consist basically in two flat solenoidal delay lines with same helicity, separated by a gap small compared to the thickness of the lines. The magnetic coupling reduces the effect of mutual inductance, or, in other words is equivalent to an increased number of sections. The compensation is adjusted by varying the gap between lines.

Presently available data suggest that lines with delay to rise time above 30 are feasible. Coupling to a chamber can be done by inserting a capacitive coupling board in the gap between both coils.

(f) Printed circuits delay lines. Several different approaches are possible and exhibit good reproducibility, dimensional stability, and insensitivity to pressure.

Let us first discuss the simplest solution: a zig-zag pattern against a ground plane;[22] this solution leads to low impedance, low delay per unit length, high resistance and resulting high attenuation for long delays. These lines can be etched easily, even on flexible material, and packed into a small volume. So they prove very convenient for low delays and where attenuation and two pulse resolution are of secondary importance. In Table 3 we list typical characteristics of two lines of this type which we tested.

Table 3. Properties of printed circuit delay lines (zig-zag pattern against a ground plane; the line is etched on an approximately square substrate). Note the high resistance to impedance ratio.

Strips/cm	8	5
Conductor length (cm)	16,400	24,400
Substrate thickness (cm)	0.04 Teflon	0.1 G10
Resistance (Ω)	115	200
Impedance (Ω)	50	70
Total delay (ns)	700	1100

A better way of making printed circuits delay lines is described in Refs. 3 and 11, and is similar in its principle to the coupled lines we discussed above: two etched zig-zag patterns are cross-coupled, resulting in a considerable increase of delay per unit length, as well as in a somewhat higher impedance. Furthermore, these lines can be etched on thin supports and can serve as cathode planes in proportional or drift chambers without introducing excessive multiple scattering. Delay to rise time ratio in excess of 60 is reported in Ref. 11.

We built several of these lines and experienced at first difficulties in coupling them to the amplifiers, but balanced to unbalanced transformers (Baluns) solved this problem.[3] The lines require a substrate with well controlled thickness; care is also needed when aligning both patterns during the etching process. Asymmetric patterns as used in Ref. 3 can improve coupling efficiency to the chamber.

Impedance has to be kept below 200 Ω typically, in order to obtain satisfactory delay per unit length while maintaining good coupling between both zig-zag patterns.

A third approach uses etched coils: we print copper strips on both sides of a NEMA G-10 blank, usually 1/32 in. thick, and connect them with metallized holes to form a continuous flat solenoid. Against this blank, we glue a polyethylene sheet, then another blank with a ground pattern (Fig. 4).

The manufacturing process also requires care, but the lines are uniform and reproducible. The characteristics of two of our prototypes are summarized in Table 4; both use strips 15 mils wide separated by 15 mils gaps; ground planes are made of 22 (or 33 for the thin line) copper strips 1.8 mm wide, separated by gaps of 0.3 mm, the dielectric being a mylar sheet 25 μm thick. This approach seems promising, despite the fact that metallized holes are needed; the present technology allows the manufacture of these lines with very good mechanical and electrical tolerances, with satisfactory delay per unit length and with an excellent delay to rise time ratio obtained without lengthy adjustments.

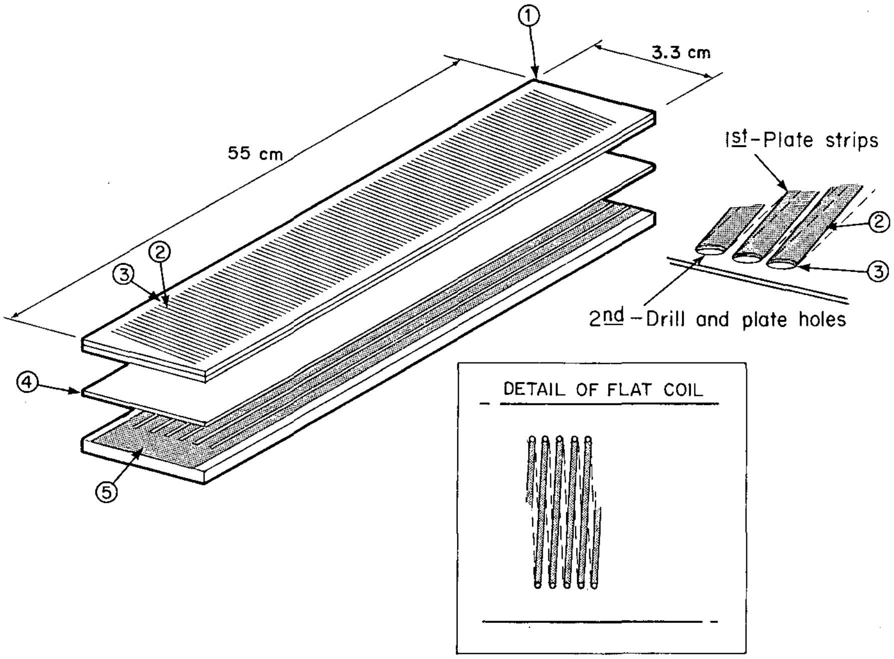


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Fig. 4. Structure of an etched coil delay line.
1) G10 substrate 0.8-mm thick.
2) Copper strips 0.38-mm wide, separated by 0.38-mm gaps.
3) Metallized holes connecting top and bottom strips to form a coil.
4) Mylar insulation (25μ).
5) Ground plane: copper strips 1.8-mm wide with 0.3-mm gaps.

Table 4. Properties of etched coil delay lines. The same pattern is used for both lines. Substrates are NEMA G 10, respectively 1/16 in. and 1/32 in. thick.

Width (cm)	3.3	3.3
Length (cm)	55	55
Thickness (cm)	0.08	0.16
Impedance (Ω)	190	170
Resistance (Ω)	70	68
Delay/cm (ns)	6.7	7.2
Delay/rise time (Simulated chamber pulses)	50/1	42/1

(g) Spiral wound cathode. The cathode of a proportional chamber can be constructed as a delay line with axis parallel to the anode wire.[23,24] A single helix or a bifilar one can be used. In the second case, one winding is grounded at every turn. Bifilar cathodes described in Ref. 23 have a delay of 20 ns/cm, 300 Ω impedance and 1/e attenuation after 6 cm for a pulse rise time of 10 ns. The advantage claimed is the good coupling efficiency (direct coupling to the electron cloud). Taps are necessary because of the short attenuation length. The authors also tested monofilar lines[24] and obtained delays of 40 ns/cm with 1/e attenuation after 2 μS for a pulse rise time of 40 ns. Evidently, these lines can be built as integral part of the chamber, with low mass and acceptable electrical characteristics.

(h) Bucket brigade delay line. The advent of charge coupled tapped analog shift registers should open up a new approach to delay line readout of proportional and drift chambers. Presently, only relatively long delays are feasible (clock frequency of some Megaherty at most) and processing of very low level signals may be hampered by the intrinsic noise of the device, but this approach promises high delay to rise time ratios as well as simple digitization and interfacing with processing electronics.

Associated Electronics

The electronic circuitry associated with delay lines has to fulfill several stringent conditions; the amplifiers must have input impedances which match the characteristic impedance of the lines (which may be complex). The gain and signal-to-noise ratio should be favorable enough to allow detection and timing of the lowest signals without introducing spurious time jitter or excessive noise. The amplifiers must also preserve the rise time and two-pulse capability of the line. Their optimum design is well discussed in Ref. 1, and most of the amplifiers we presently use are similar to the ones described in this reference.

Discriminators have also to satisfy severe constraints, especially when short delay per unit length of the line with good one and two pulse resolution are required over a wide range of amplitudes, in presence of rise time variations (these variations are only partly due to the line; the dominant contribution, when magic gas is not used, is produced by collection time spread from non-perpendicular tracks). Very good discriminators satisfying some of these conditions exist, but a compromise is usually required. Here, once more, magic gas is helpful, by reducing the dynamic range, increasing the average input amplitude and producing pulses with approximately constant rise time. The type of discriminator selected depends also to some extent of the readout mode chosen; when the delay line is read at both ends, it may be preferable to time only on the front of the first incoming signal to resolve two merging pulses better. Finally, the long tail produced by lines having a high resistance and high capacity may also affect adversely the timing capability of some discriminators.

Data produced by the chambers may be processed in many ways, but here again delay lines allow the implementation of some elegant solutions. For example, a simple system can use a memory scope, two time-to-amplitude converters and some simple logic to generate directly a picture on the screen. It is also quite possible to use equipment similar to the one developed for magnetostrictive chambers, if the utmost resolution is not required,[25] and this is often an important advantage to reduce the overall cost of a system. Optimum performances, on the other hand, can only be expected with digitizing systems tailored to the delay lines. At present several commercial CAMAC modules performing these functions are available, and systems performing fast digitization are in operation.[8]

Conclusions

Electromagnetic delay lines offer elegant solutions to one- and two-dimensional readout problems, even in presence of high multiplicities. Most of their early drawbacks disappear with new designs and improved manufacturing techniques.

Acknowledgements

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