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C. Dardini, G. Iaci, M. Lo Savio and R. Visentin: A TRANSISTORIZED TIME-TO-AMPLITUDE CONVERTER.

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A TRANSISTORIZED TIME-TO-AMPLITUDE CONVERTER

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A fully transistorized time-to-amplitude converter, based on the start-stop principle, will be described. The converter exhibits a 10 ps intrinsic resolution and a 0.5 ns physical resolution (fwhm) using as detectors photomultipliers 56 AVP.

The whole apparatus does not need selected components and presents good stability against the varying external temperatures. The measuring range is easily changeable by simply substituting a timing capacitor.

1. Introduction

The possibility of measuring short time intervals in the nanosecond range is assuming a more and more important role in analyzing either lifetimes of positrons in various materials or of excited states, in time-of-flight techniques, in the mass-spectrometry with charged particles, etc.

In similar problems there always exists a time interval Δt which separates, e.g., the two instants at which a particle is colliding with a pair of suitable detectors, placed at a distance "1" from each other; or which elapses between the creation and the decay of a certain unstable state.

Time-to-amplitude converters, commonly used to measure such intervals, have now substituted the devices based on the delayed-coincidence principle.

The time-to-amplitude converter generates an output-signal voltage which depends linearly on each time interval to be measured.

There exist several converter types, realized with electronic tubes as well as with semiconductors. They are distinguished according to the conversion principle. For a detailed discussion about this subject one can refer to the survey given by Bonitz¹), where the matter is widely examined and a suitable reference list is reported.

Among the first fully-transistorized circuits we wish to mention the Culligan and Lipman circuit²). Successively Wieber³), Ophir⁴) and recently Weisberg⁵) have proposed more sensitive designs by introducing tunnel diodes. Weisberg has shown that, with a proper and careful assembly, together with a suitable selection of the components, a 2.25 ns resolving time in the prompt peak of ⁶⁰Co can be obtained (resolution width).

Eventually it is worth mentioning Present et al.⁶), who using commercial but first-class apparatuses and new-type photomultipliers, achieved the same resolution.

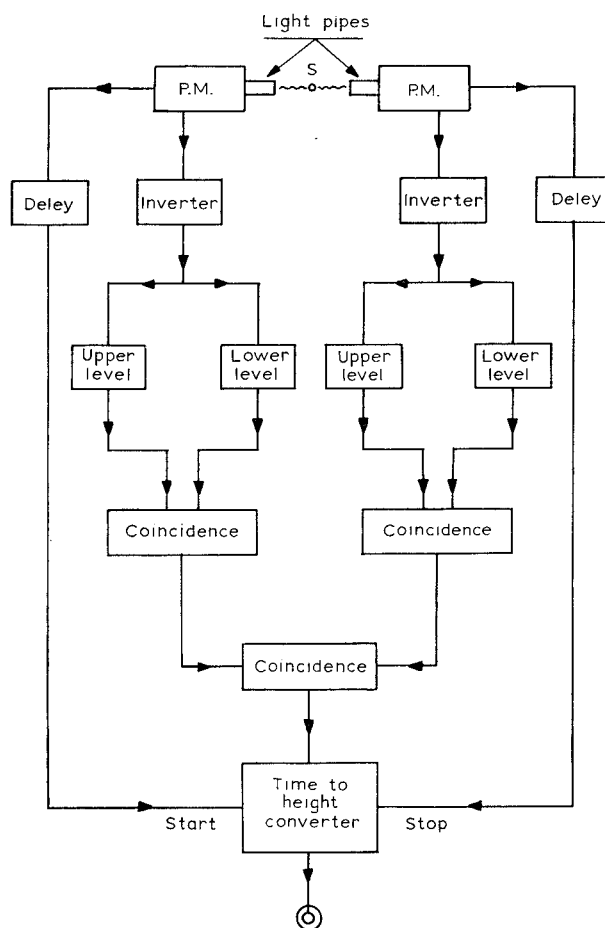


Fig. 1. Block diagram of the apparatus.

Among the recent electronic-tube circuits the Bell et al. converter⁷) realizes a 0.7 ns resolving time.

The converter described in this paper is based on the start-stop principle. It is simple in design and exhibits good reliability as well as a short resolving time.

2. Apparatus

When, as in positron lifetime measurements, there does not exist a geometrical correlation between the time-zero photon, individuating the emission instant of the positron and the photon individuating the annihilation instant, two side channels have to be added to the converter, in order to select the first type photons from the second type.

The coincidence between the side-channel output signals enables the converter to measure the corresponding time interval. The two-side-channel coincidence ensures, in fact, that the two signals, related

in time, have amplitude requirements that ensure their identity.

The block diagram of the whole system is shown in fig. 1. All circuits are fully transistorized except the output stage of the time-to-amplitude converter, realized with a nuvistor.

The input- and output-impedances are unified to 125 ohm value and the connections are made by means of 125 ohm coaxial cables equipped with BNC connectors.

3. Detectors

Photomultipliers Philips 56AVP, coupled with plastic scintillators Naton 136, have been used as detectors.

They are supplied with a voltage of about 2500 V applied through the voltage divider shown in fig. 2.

The scintillator dimensions were restricted to 1" x 1" for limiting the interested cathode area, and then limiting the time-spread, without reducing too much the counting rate.

For our purposes (positron-lifetime measurements in a magnetic field) we need to couple the scintillators to the photomultipliers by means of light pipes 20 cm in length. As a result the prompt coincidence curve becomes about 60% wider (from 0.5 to 0.8 ns) in consequence of the time spread introduced by reflections in the guides.

The anode-output pulses drive the start- and stop-circuit of the converter, while the last-dynode-output pulses are fed into the side channels for the selection.

4. Side channels

As already stated, each channel must select the photomultiplier pulses according to their amplitude.

For this purpose the channels have been made up with two amplitude discriminators followed by an (anti-)coincidence (fig. 3 and 4). For a detailed circuitry description we refer to the respective reports^{8,9}.

Since the discriminators as well as the coincidences have been designed for 100 Mc/s counting rate, it has been necessary to increase the anticoincidence-output-pulse width by means of open-circuit coaxial cables. In this manner the resolving time of the coincidence between the side-channel pulses increases to about 18 ns which for our purposes is the range of interest.

The schematic diagram of this coincidence is still the one shown in fig. 4; the only modification concerns the output which has been modified in order to provide the proper positive pulse for gating the converter.

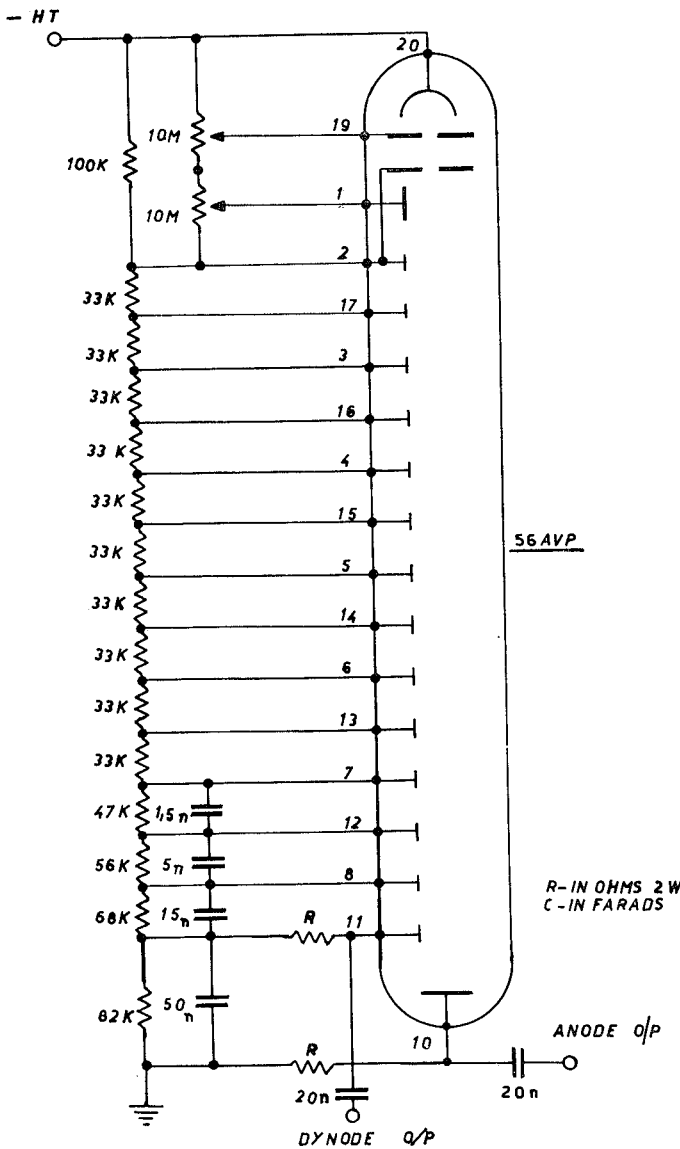


Fig. 2. Voltage divider for Philips 56AVP photomultiplier.

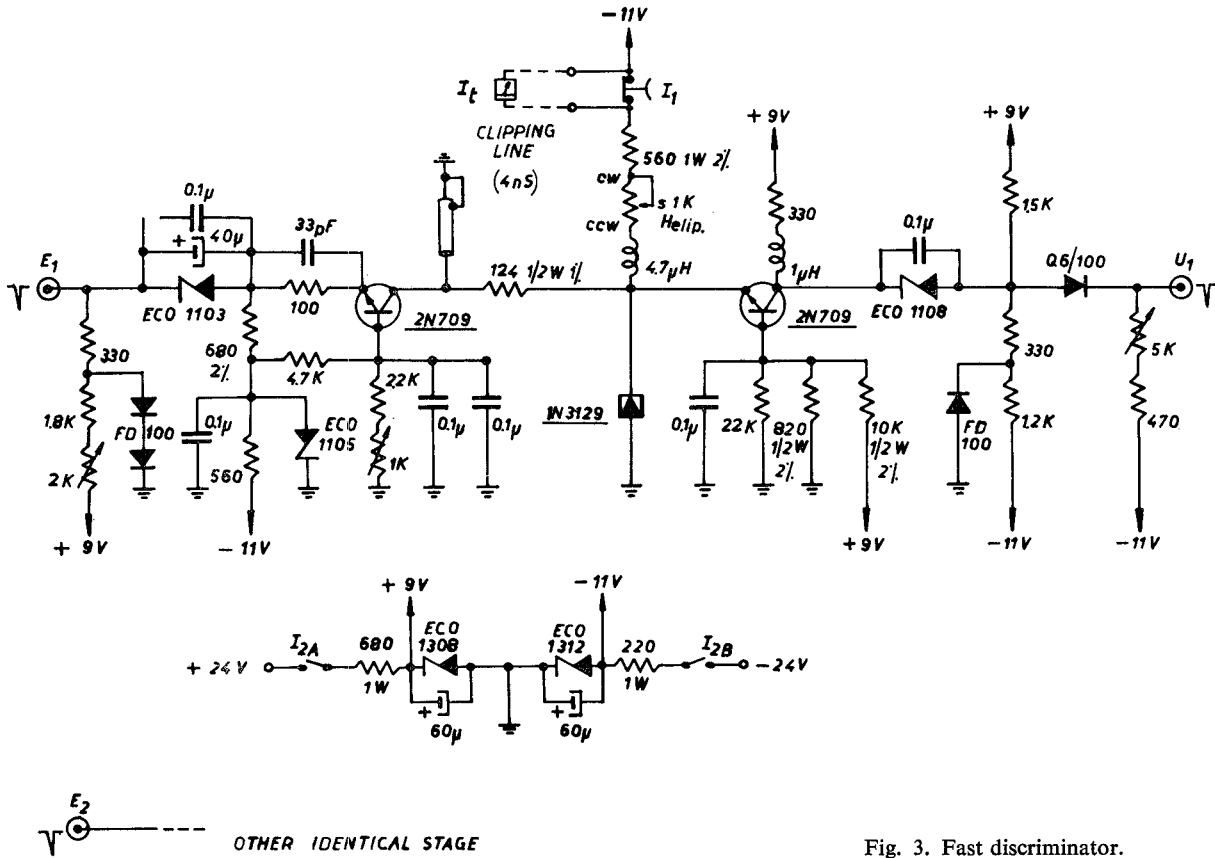


Fig. 3. Fast discriminator.

TABLE 1

<i>Start- and stop- signal input</i>	
Impedance	125 ohm
Coupling	dc BNC connector
Sensitivity	250 mV
Pulse polarity	negative
Pulse width	≥ 5 ns
Pulse amplitude	3 V max.
Overload	Diode limiters protect input circuit from pulses larger than 1 V.
<i>Gate input</i>	
Impedance	125 ohm
Coupling	dc BNC connector
Sensitivity	200 mV
Pulse polarity	positive
Pulse width	≥ 6 ns
Pulse amplitude	3 V max.
<i>Output</i>	
Impedance	70 ohm
Coupling	ac BNC connector
Pulse polarity	positive
Pulse width	150 \div 500 ns adjustable
Pulse amplitude	10 V max. 1 V min. (zero level)

5. Time-to-amplitude converter

5.1. GENERAL INFORMATION

As said, it has been used the "Start-stop" principle. The circuit specifications are reported in table 1.

5.2. CIRCUIT DESCRIPTION

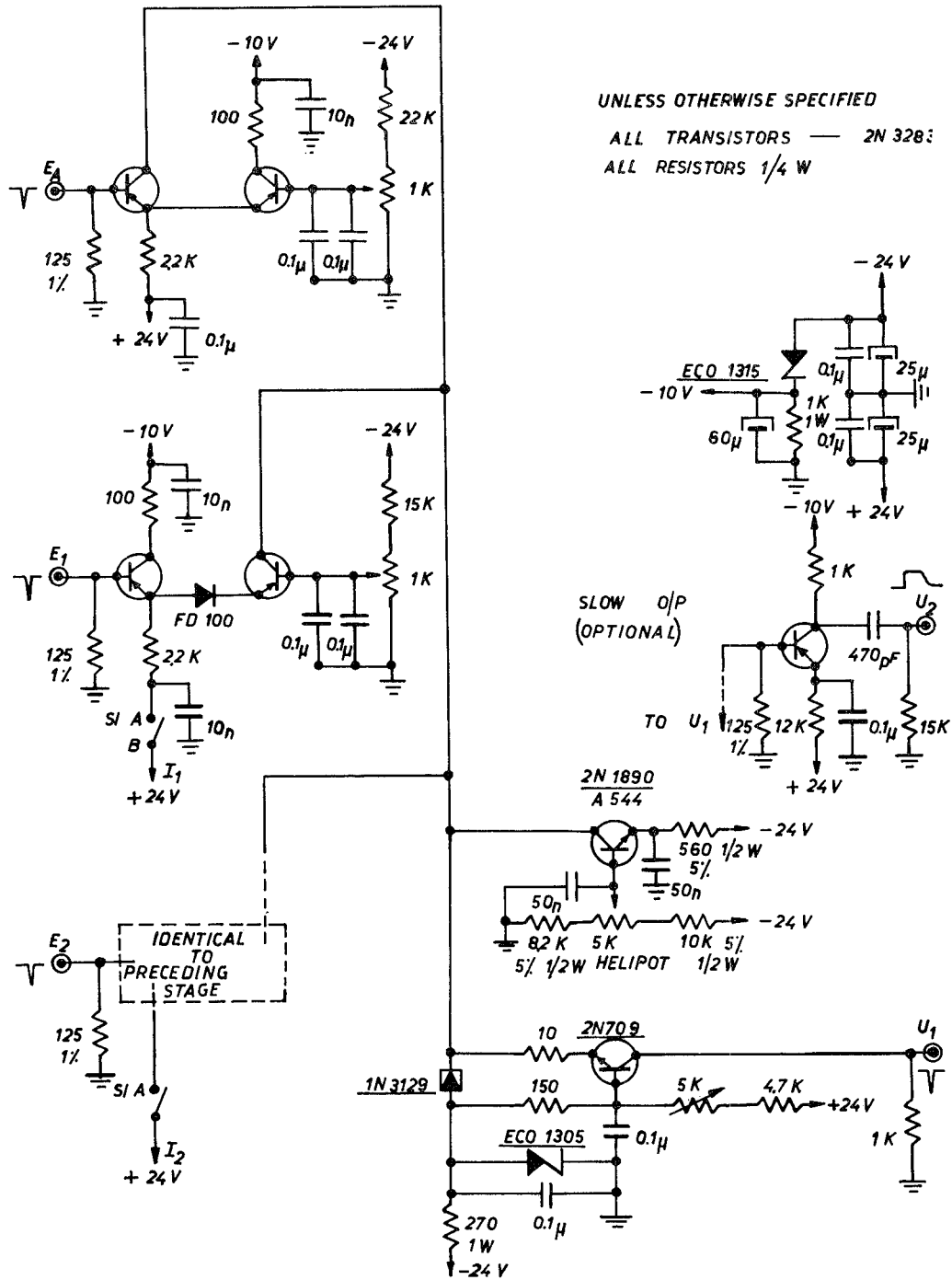
The logical scheme is shown in fig. 5, while the waveforms at the numbered points are shown in fig. 6.

A positive-going pulse at G-input triggers the gate-monostable circuit which switches on, and applies a signal Δt_G in duration to the two bistable circuits in the start- and stop-channels. This signal allows the start-bistable circuit to trigger if an external negative-going pulse, whose amplitude exceeds the threshold value, is fed into the 1-input.

The start-circuit switching starts the constant-current charging of the condenser C, thus realizing the time-to-amplitude conversion.

A similar negative-going stop-pulse at 2-input stops the charging current flowing in C.

The voltage-signal amplitude V_C across the capacitor



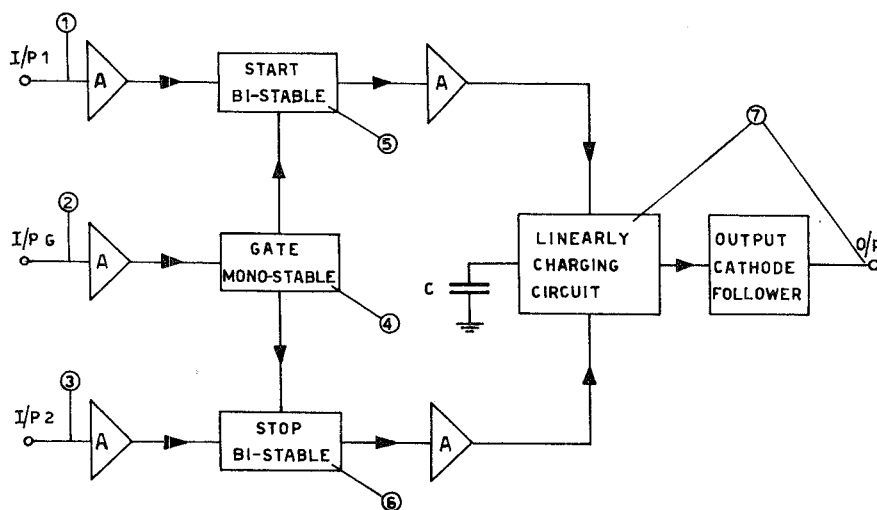


Fig. 5. Block diagram of the converter.

C is then proportional to the time interval τ , separating the two I_1 and I_2 pulses.

When the gate signal Δt_G ends, the two bistables are disabled and resetting causes the output signal to cease abruptly.

This scheme presents the following operative properties:

- a. The circuit can be used for measuring very short time intervals (of the order of 1 ns or less) as well as long time intervals (of the order of μ s).
- b. The gate signal presets the input channels to sense the timing pulses arriving at 1 and 2 inputs.
- c. The input channels are triggered by the first pair

of pulses arriving after the gating pulse; they store the information as long as the gate pulse is present, being at the same time unaffected by other pairs of pulses.

d. Single pulses at the stop input give substantially no output; single pulses at the start input give rise to saturated output pulses of $V_{max} \approx 10$ V in amplitude.

e. In the absence of the gating pulse, the input channels are insensitive to the driving pulses, irrespective of their amplitude.

f. The gate-signal width is adjustable and practically the same as the output-signal width. Thus it is possible to use directly multichannel analyzers eliminating the usage of stretching circuits.

g. The dead time τ_d of the whole circuit is essentially determined by the gate-circuit dead time. In the present apparatus a blocking oscillator has been employed as gate circuit. It was not absolutely necessary to use this particular monostable circuit.

Its output signal has an adjustable width ranging from 150 to 500 ns. With a 300 ns duration it is possible a repetition frequency of about 1.2 Mc/s. The frequency limit depends upon the amplitude analyzer.

The converter-circuit diagram is shown in fig. 7. The start- and stop-channels are identical.

The input grounded diodes avoid damaging the input transistors caused by signals with amplitude greater than the breakdown voltage of the base-to-emitter junction. The grounded-anode one limits the input-pulse amplitude at a level of about 1 V without affecting the leading-edge slope and then unaffected the time-spread. The other one serves to cancel the back-reflected pulses occurring if, e.g., the PM output is not correctly terminated.

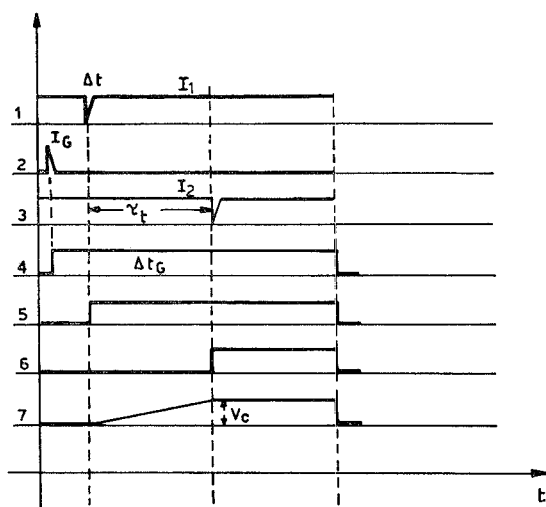


Fig. 6. Waveforms at corresponding points of fig. 5.

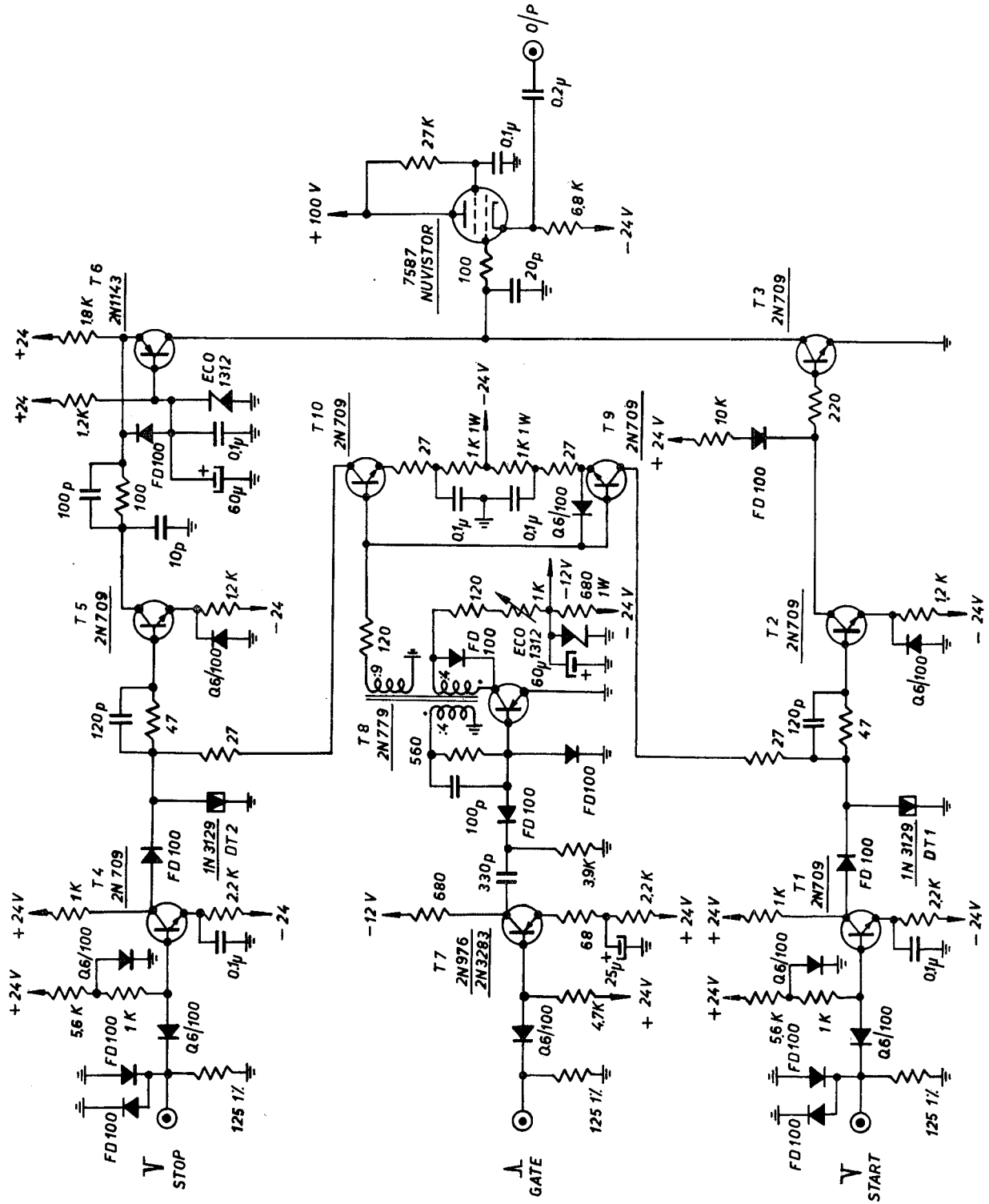


Fig. 7. Time-to-height converter. R in ohm; C in farad; all resistors are 1/4 W, unless otherwise specified.

The transistor T_1 normally is conducting the current $I_2 = 10$ mA. The resistor at the collector carries a current $I_1 = 24$ mA. Thus a current $I = 14$ mA is flowing through the FD100 diode towards the TD_1 tunnel diode, which is the bistable element. In the quiescent operation TD_1 is reverse biased by a -10 mA current (point A in fig. 8) since the transistor T_9 is conducting a 24 mA current.

The gate signal cuts off T_9 and TD_1 is now forward biased at a level of $+14$ mA (point B in fig. 8) and preset to switching.

A negative-going signal applied to START input cuts off T_1 , whose current is thus diverted in TD_1 causing it to switch on (point C in fig. 8). As the drive signal has ended, T_1 conducts again, and TD_1 operates at point V_2 (fig. 8) thus storing the information until the gate signal has ceased.

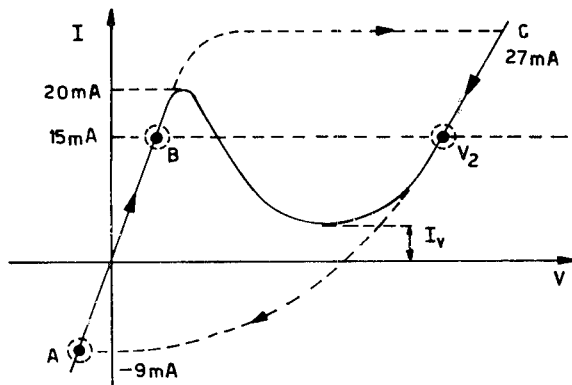


Fig. 8. Tunnel-diode working paths.

Two circuits like this one are used to start and stop the constant-current charging of the timing condenser C.

This charging circuit is formed by the transistors T_3 (nnp) and T_6 (pnp), the former operating as a grounded emitter transistor, the latter as a grounded base transistor. The amplified TD_1 pulse cuts off T_3 and therefore T_6 acts as a current generator charging linearly the capacitor C. The amplified TD_2 pulse, applied to the T_6 emitter, stops its charging action.

Since the T_3 and T_6 transistors remain cut off as long as the gate signal is present, the waveform across C is trapezoidal, owing to the large value of resistance in parallel with the capacitance.

The choice of this arrangement has been suggested by the following reasons:

- a. the good linearity of the waveform;
- b. the possibility of getting the output signal in the

shape of a trapezium, which is useful for amplitude analysis;

c. the possibility of varying the slope of the linear ramp, and consequently the measuring range, by changing simply C;

d. the very short recovery time;

e. the considerable reliability of the scheme, whose performance is independent of the complementary-transistor pair which is used.

A similar scheme has been usefully employed by Gatti and Zaglio¹⁰, who used a White-follower circuit for cutting off, with a large voltage pulse, the transistor T_6 . In our case we have preferred to drive T_6 with a current pulse (the collector current of T_5) fed into the T_6 emitter, since the current carried by it is not too high (~ 7 mA).

The output signal is supplied through a nuvistor cathode-follower that exhibits a high input impedance and ensures the signal flatness.

5.3. LINEAR WAVEFORM ANALYSIS

We can assume the transistor T_6 as a current generator because of the constant voltage drop (12 V) across the emitter resistor (1.8 k Ω) which is very large in comparison with the input resistance of the tran-

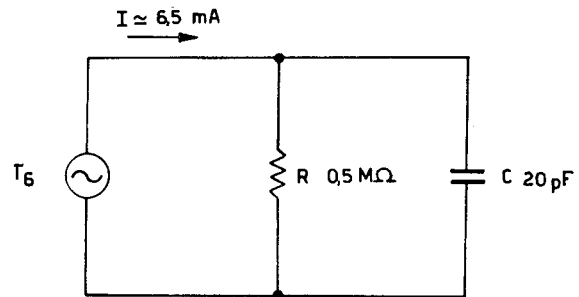


Fig. 9. Equivalent charging circuit.

sistor. With a collector dynamic resistance of about 0.5 M Ω , the equivalent circuit is shown in fig. 9 and yields the following formula for the timing capacitor voltage

$$V_C = IR(1 - e^{-t/\tau}),$$

where $\tau = RC \approx 10$ μ s is the time constant of the charging path.

Since the time intervals to be measured are of the order of 10 ns, only a very small portion of the charging curve is actually used and the ramp voltage produced is extremely linear.

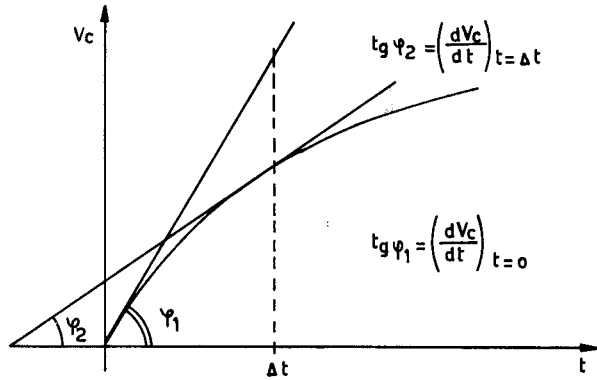


Fig. 10. Drawing for calculating the slope error.

In these conditions we can consider

$$V_c = (I/C)t,$$

with a resolution $\Delta V_c/\Delta t \approx 0.3 \text{ V/ns}$ and a slope error defined by (fig. 10)

$$\Delta P/P = \{(dV_c/dt)_{t=\Delta t} - (dV_c/dt)_{t=0}\} / (dV_c/dt)_{t=0}$$

and equal, for $t = 20 \text{ ns}$, to $3^0/_{00}$.

6. Performance

The following tests have been carried out on the converter:

6.1. ELECTRONIC PROMPT RESOLUTION

According to the arrangement of fig. 11 a pulse generator was feeding the same pulse into the start- and stop-channel inputs and moreover into the gate input. Each pulse was suitably delayed by cables in order to assure the proper succession, and the gate pulse was inverted for correct driving. The output signal was applied to a RCL 256 Channel Analyzer and fed into the multichannel amplifier through a 125 ohm cable correctly terminated.

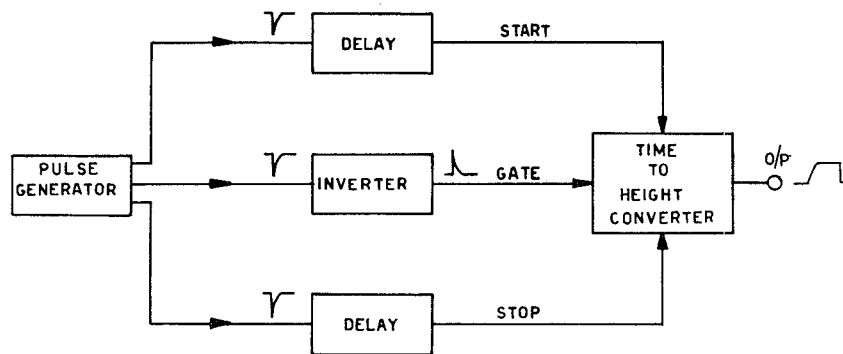


Fig. 11. Test setup for electronic prompt resolution.

With a minimum gain of about 320 and a conversion of about 0.08 V/ch , there has been obtained a 4-channel-split line.

The time distance between two adjacent channels has been measured by inserting in the stop channel a 1 ns-delay cable. A 170 channel shift occurred in the peak position (fig. 12).

Therefore, there results an intrinsic electronic resolution of the order of 10 ps.

Substituting the pulse generator with a photomultiplier – in our case a 56AVP equipped with a plastic scintillator and detecting a ^{60}Co - γ -ray source – we get a response about the device resolution in working conditions. The difference between a standard- and a PM-pulsar lies on the driving-pulse amplitudes, spread in the second case on the whole range of the spectrum.

Operating in order to reject the too small pulses, for avoiding a noticeable time-spread, a 0.1 ns resolution width has been obtained in the corresponding prompt peak.

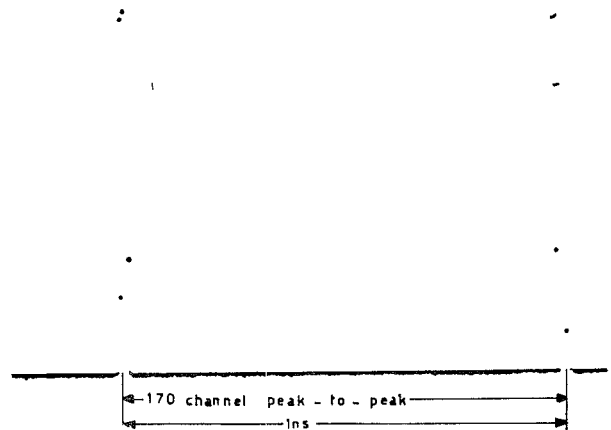


Fig. 12. Multichannel CRT display of the electronic-prompt resolution response.

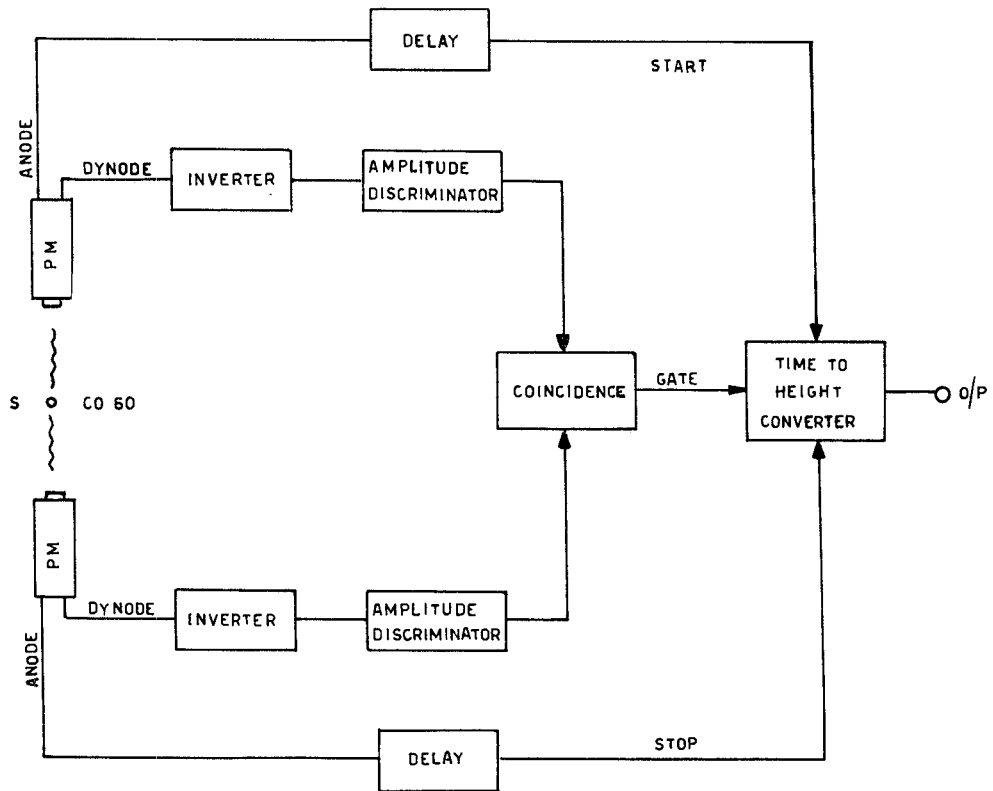


Fig. 13. Setup for physical prompt resolution.



Fig. 14. Display of the physical-prompt-resolution response.

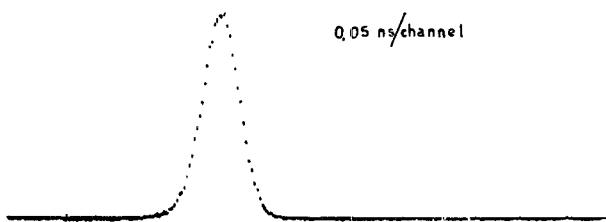


Fig. 15. Physical prompt resolution in working conditions.

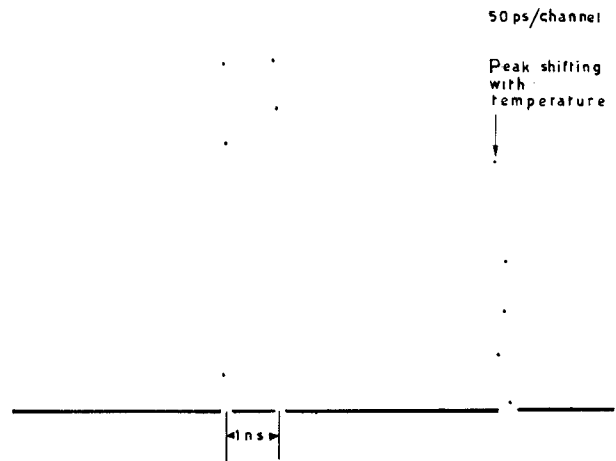


Fig. 16. Display showing the temperature effect.

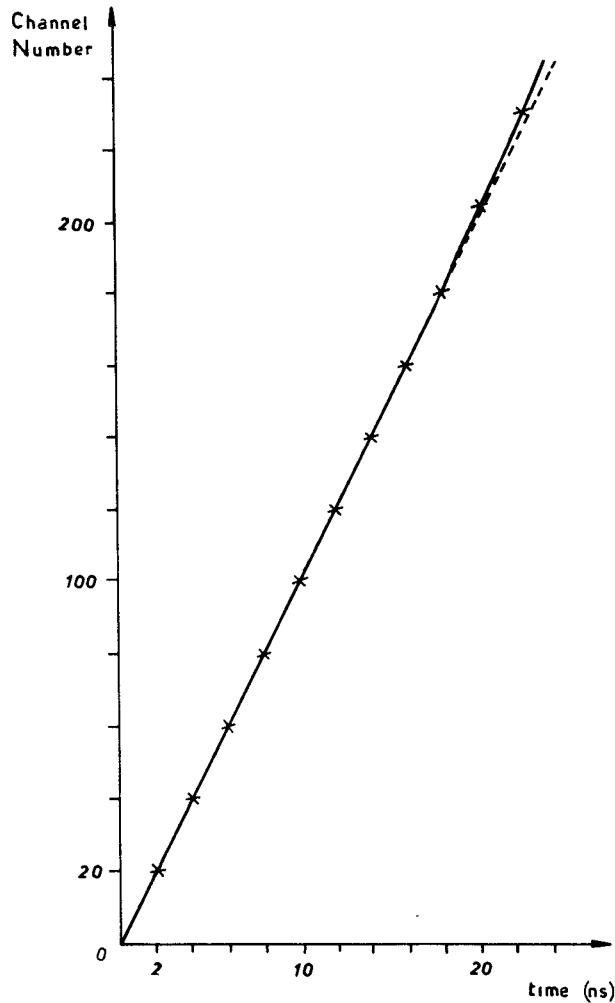


Fig. 17. Linearity curve.

6.2. PHYSICAL PROMPT RESOLUTION

Here we are really in working conditions, i.e. two detectors and the time meter. A ^{60}Co source, emitting a pair of simultaneous γ -rays, allows us to check the practical resolution of the whole apparatus.

The arrangement is shown in fig. 13. Centering the single-channel windows at the end of the Compton spectrum given by the photomultipliers, a 0.5 ns resolution width (fwhm) in the prompt peak has been obtained (fig. 14).

Obviously, with light pipes the resolution reduces to 0.8 ns (fig. 15).

6.3. STABILITY VS TEMPERATURE

The arrangement is the same of fig. 11, but the conversion was reduced to a 50 ps/ch value by adding in series with the output cable a 9.1 k Ω resistor and increasing the amplifier gain to about 640.

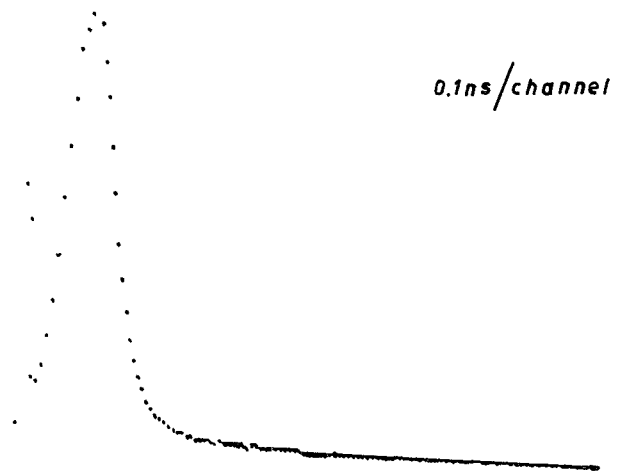


Fig. 18. Typical display of a lifetime curve.

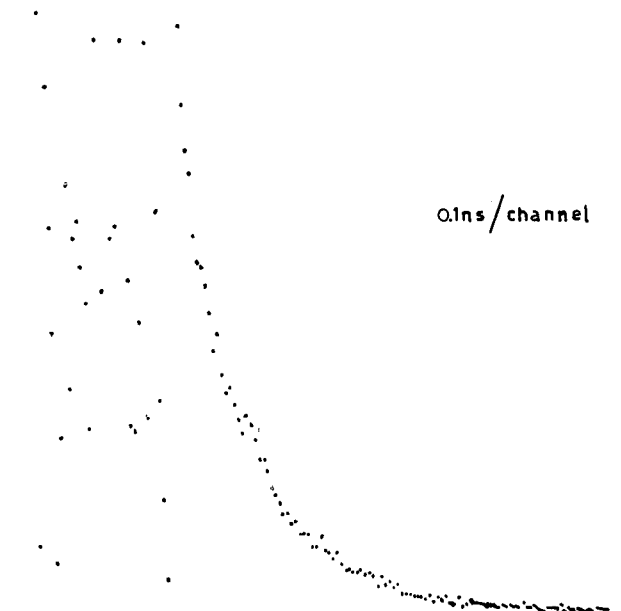


Fig. 19. Detail of lifetime curve.

In these conditions, heating the converter from 25°C to 50°C, a 10 ps/°C conversion drift has been noted (fig. 16).

6.4. LINEARITY

Reducing now the amplifier gain to the previous value of 320 we get the normal working conditions with a 0.1 ns/ch conversion rate.

Linearity in working conditions has been checked by adding successively 2 ns-delay-cable pieces to the stop channel and plotting the peak channel address versus delay time (fig. 17). The linearity is fairly satisfactory in the whole interval of interest.

7. Applications

At Catania University the circuit is currently employed according to the scheme of fig. 1 for both positron lifetime and magnetic quenching measurements¹¹).

A many months continuous work has proved the apparatus-performance stability which allows the measurements to be reliable and repetitive.

In fig. 18 is shown a typical lifetime curve; a detail of the exponential part is shown in fig. 19.

8. Conclusions

Reducing the gating-pulse duration to a 50 ns value, it is possible to perform measurements at frequencies up to 10 Mc/s.

Of course, in these conditions it is impossible to operate with conventional multichannel amplitude analyzers.

Coupled with a single-channel analyzer the converter realizes a differential discriminator for time intervals.

The same circuit can be used as a coincidence with high resolution time, if the window width is reduced.

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