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D.A.G. Neet
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BEAM ENERGY SPECTRUM ANALYZING INSTRUMENTATION

Observation of the energy spectrum of the beams in the switchyard is of fundamental importance for proper adjustment of the accelerator.

For this reason I would like to review present ideas on this instrumentation and would be glad to receive comments.

We propose 2 types of spectrum monitors in the beam switchyard: A rough monitor in front of the first quadrupole of beam A and a precise analyzer in front of the slit in each beam.

In this note we discuss different display techniques, and make a recommendation on the most suitable technique for each monitor.

We consider the following subjects:

1. Monitors
   - 1.1 Precise spectrum analyzer
   - 1.2 Rough spectrum monitor
   - 1.3 Energy spectrum in the straight ahead beam
   - 1.4 Feedback to the accelerator
2. Display and Electronics
   - 2.1 Summary of display methods and techniques
   - 2.2 Display for the rough monitor
   - 2.3 Display for the precise analyzer
     - 2.3.1 A fast electronic scanner
     - 2.3.2 Display of dynamic pulses on an oscilloscope
     - 2.3.3 Conclusions
3. Combination of Display Techniques for Beams A and B

1. Monitors

1.1 The Precise Spectrum Analyzer

For a general description of the analyzer we refer to TN-63-21.[1] In this note we will only discuss some parameters of importance as design criteria for the spectrum analyzer.

The analyzer will be placed in front of the slit. We expect that the secondary emission due to back scattered neutrons and electrons from the front surface of the slit will be negligible. (Some tests will be arranged to check this.)

The horizontal dimension of the vacuum chamber in the field lens (just preceding the analyzer) is 11 inches. This dimension limits the energy acceptance of beam A to ±2.3% ΔE/E and of beam B to ±4.6% ΔE/E.

We propose to use 12 sec ndary emission foils for each spectrum analyzer with dimensions shown in Fig. 1. The width of the foils in the center is 6 mm; this width increases to 48 mm at the edges. The foil width for beam A and B will be the same. The two half foil assemblies may be retracted sideways over a 9 cm long stroke. This will enable us to observe the energy tails intercepted by the slit during nuclear physics experiments for which scattering by the foils is prohibited.

With the quoted dimensions the analyzer in beam A will cover ±1.8% ΔE/E, the resolution in the center is ±0.1% ΔE/E and at the edges 0.8% ΔE/E. The gap between the foils in the retracted position corresponds to ±1.5% ΔE/E. For beam B these figures are ±3.6%, 0.2%, 1.6%, and ±3.0% ΔE/E.

There are two reasons for choosing larger foil sizes further outside the beam center: (1) It reduces the number of coaxial cables, amplifying channels, etc.; (2) It improves the signal to noise ratio on the larger foils.

The signal amplification in each channel will be made inversely proportional to the width of the foils in order to obtain a uniform vertical scale for the display pattern. The horizontal energy scale will not be linear. Some simple indications in the display, however, will clearly show the energy range covered by each foil.

The large foils with the reduced energy resolution are certainly acceptable in the low energy tail of the spectrum.

With the large foils in the high energy tail of the spectrum we will observe

[1]TN-63-21, "A beam energy spectrum analyzer for the two-mile accelerator," D.A.G. Neet, April 1963.

Fig 1 Dimensions of foils

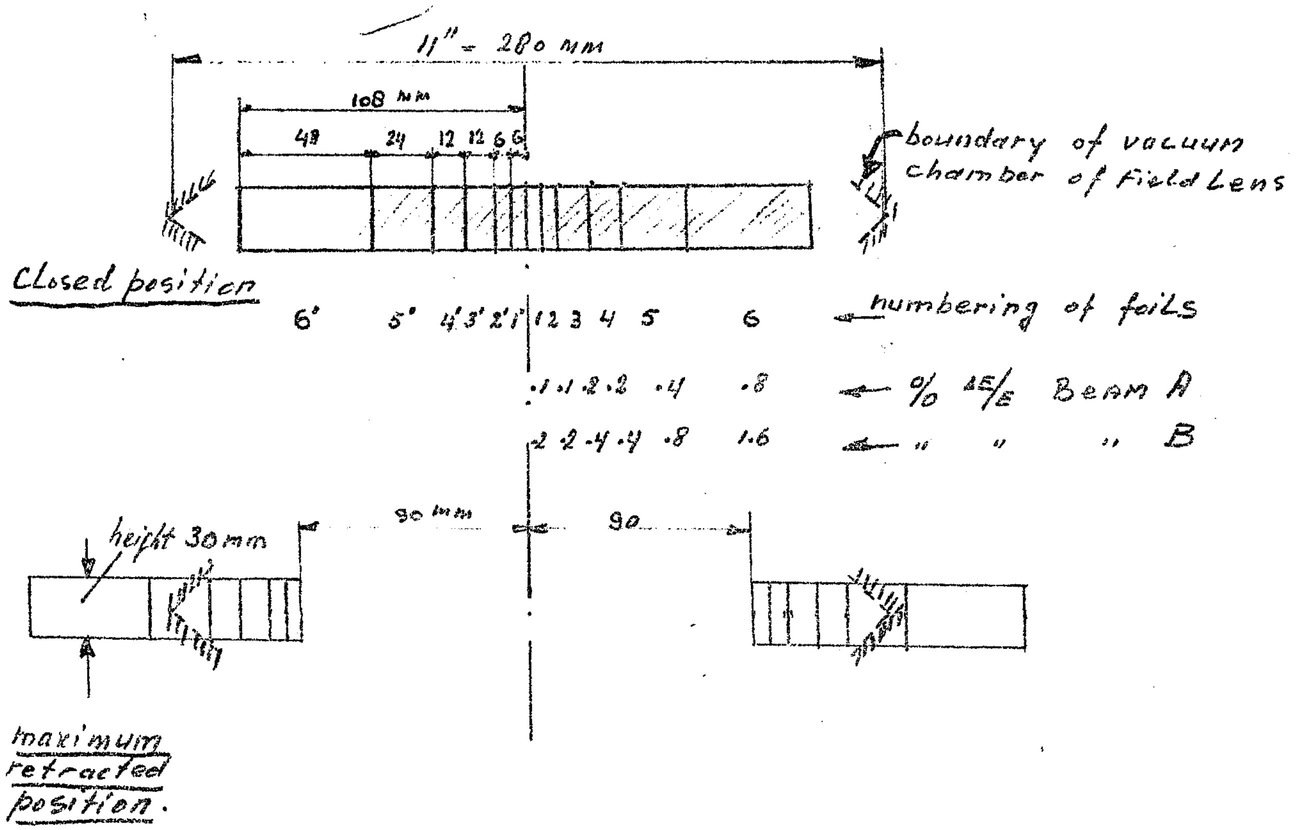


TABLE I	Beam A	Beam B
Design value for $\Delta E/E$	± 1%	± 3%
Accepted by 11" vacuum chamber	± 2.3%	± 4.6%
coverage by closed foils	± 1.8%	± 3.6%
maximum resolution in the center (6mm foils)	± .1%	± .2%
Passage in max. retracted position	± 1.5%	± 3%

the (non) loading energy peak at the beginning of a beam pulse. This peak is normally 10% $\Delta E/E$ and will be reduced to about 1% $\Delta E/E$ by delaying the rf in some of the 30 sections.

These loading adjustments could be done as follows: We observe the energy spectrum over the first part of the beam pulse (say over the first 200ns). If the loading effect is 10% $\Delta E/E$, we may not yet be able to see very much signal since the foils cover only ±1.8% $\Delta E/E$ (beam A). The rf timing should now be delayed until we observe reasonable signals on the larger foils at the high energy side of the spectrum. Subsequently, the rf time adjustments should be refined, moving the spectrum peak slowly to the center of the analyzer.

A good energy resolution is not needed for this process, but rather a good signal to noise ratio. The larger foils therefore are also acceptable in the high energy tail of the spectrum.

We have made a prototype monitor, consisting of one half-section with a somewhat different foil arrangement. This section has been tested at Mark IV. The results of these tests are satisfactory, and also suggested a number of useful improvements in the construction.

The final construction of the vacuum chamber around the monitor will probably look quite different from the sketch in Fig. 1 of TN-63-21. The reason for this is the need for a quick way to take the monitor out of the vacuum chamber when the area is radioactive and for a simple drive mechanism to displace the two half-sections sideways.

1.2 The Rough Spectrum Monitor

A rough spectrum monitor is placed in front of the first quadrupoles of beam A. It will be used to establish roughly (within ±1.5%) the mean energy and the energy spectrum of the beam before it is being deflected into the high resolution dc magnet system.

The justification for this monitor is the following: At the Mark III the beam is set up by deflecting it with the analyzing magnet over a large angle until a beam current signal is observed at the slit. The beam is then adjusted for proper energy (by adjusting the magnetic field for the desired value) and optimized for a narrow spectrum.

This simple technique is not acceptable in the switchyard, since we would sweep the beam outside the vacuum chamber and build up in a very short time a high level of radiation throughout the switchyard and probably also damage equipment.

We therefore suggest to proceed in two steps as follows: The dc magnet system is adjusted in advance for the desired electron energy value $\bar{E}$. The pulsed magnet is adjusted to 2/3 of the field value which actually is required for an energy $\bar{E}$. Under this condition the initial beam is deflected over about 0.33° instead of 0.5°, and absorbed in a dump of about 60 kW (see Fig. 2).

This dump is at the same time a protection collimator for the coils of the first quadrupoles (Fig. 3).

To reduce heat dissipation in the dump the average beam power should be kept low. Since part of the beam monitors work on peak currents rather than on average currents, and in order to maintain the effect of beam loading we should use low repetition rates, e.g., 5 or 10 pps, in order to reduce beam power.

The rough spectrum monitor is placed in front of this dump. It is made of 24 fixed foils covering a large energy range (see Fig. 2). The foils in the center of the dump (the two-thirds deflection point) have a resolution of 1.5% $\Delta E/E$ and will be used to adjust the beam energy $\bar{E}$ and the energy spread within the limits of this resolution. The larger foils further outside the two-thirds point will be used for analytical purposes in case of abnormal behavior of the accelerator (great instability in energy, etc.). The last feature may be particularly useful in the early days of operation.

Once the beam energy and the beam energy spectrum are under control we change the magnetic field in the pulsed magnet to the proper value (increase by 1/3) and deflect the beam into the precise spectrum analyzer for further adjustments.

The construction of the rough monitor is simple. There are no moving parts. We need some expensive bellows to allow proper alignment of the 2.8 inch protection collimator hole (see Fig. 2).

The common part of the vacuum chamber after the pulsed magnet has to be extended close to the quadrupoles in order to obtain a resolution at this point of about 1.5% $\Delta E/E$.

We consider it adequate to have one rough spectrum monitor and one 60 kW dump only, say in beam A. Beam B could use the same facility without disturbing beam A. The polarity at the pulsed magnet has to be reversed when setting up beam B. This can be done with a polarity switch.

The layout is sketched in Fig. 3.

Fig. 2 Rough Spectrum monitor

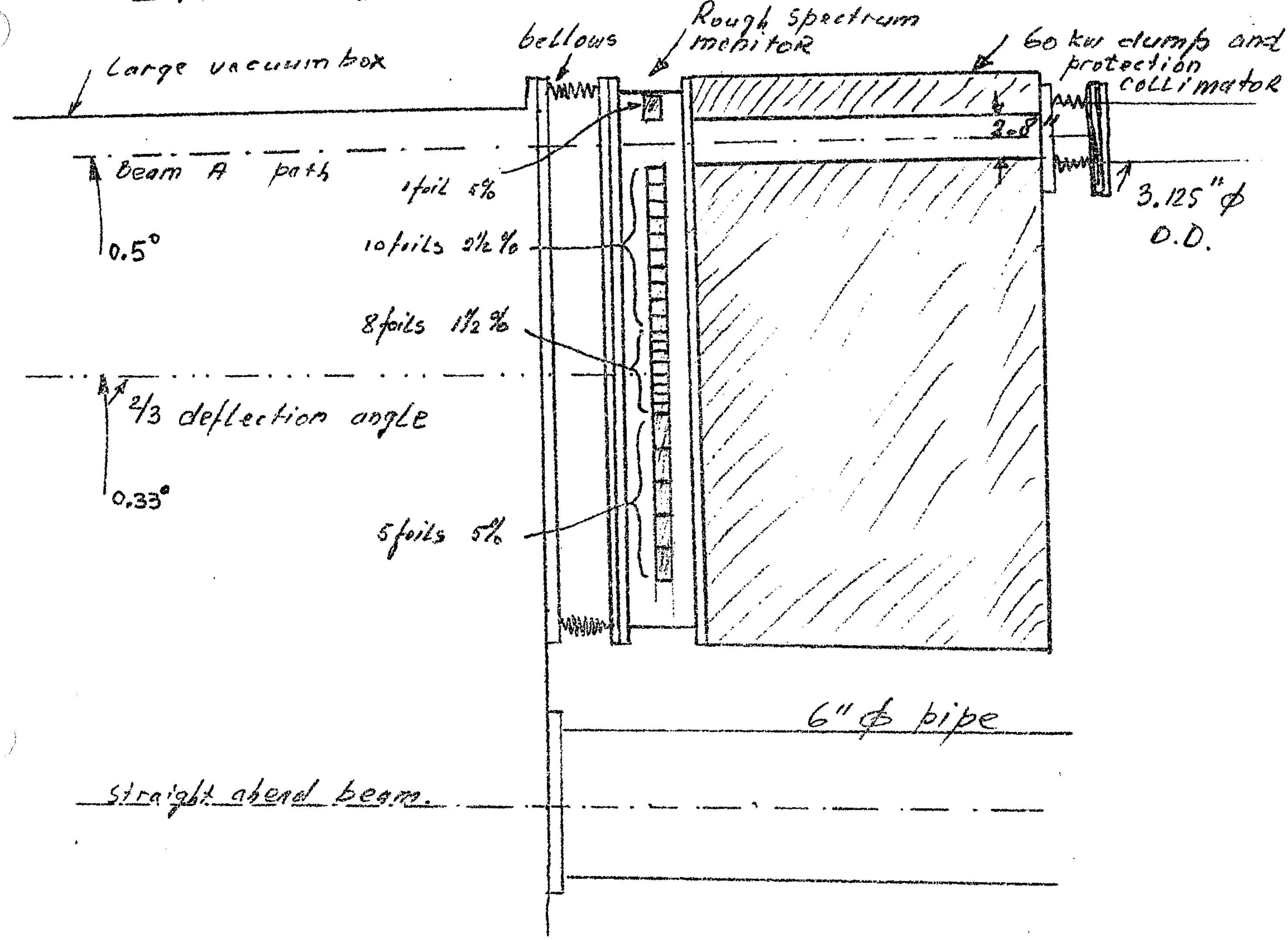
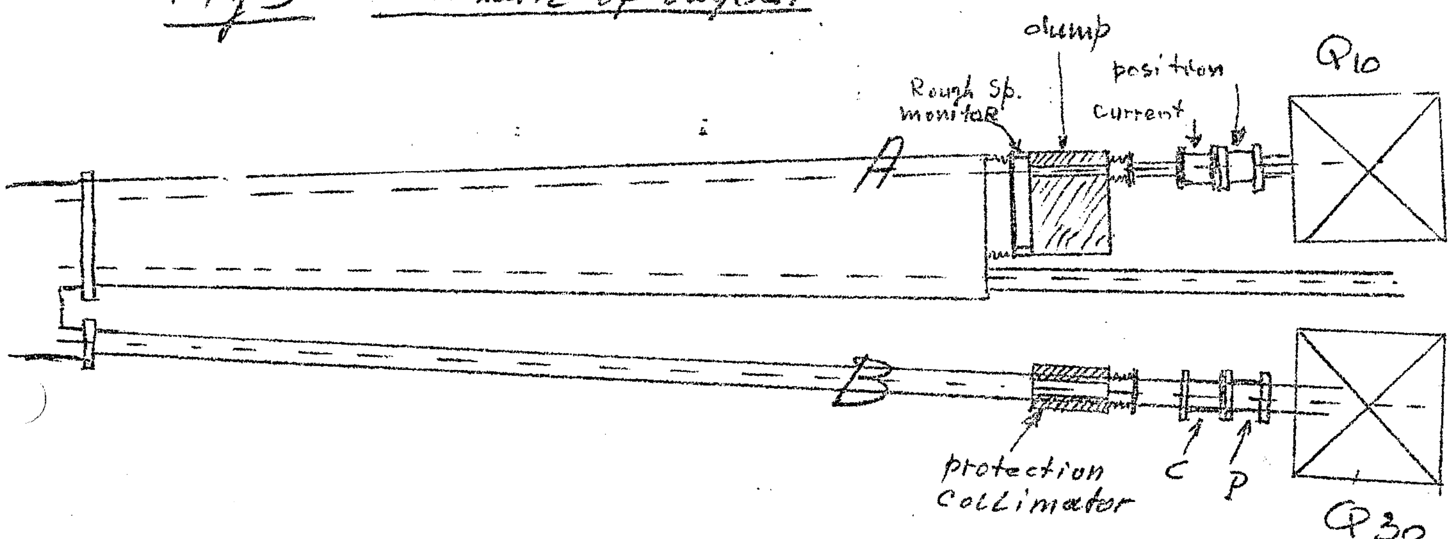


Fig 3 Schematic of layout



1.3 Energy Spectrum in the Straight-Ahead Beam

The straight-ahead beam will be laid out initially as a neutrino facility. There seems no need to know the energy of the electrons in this beam to a better precision than a few percent.

To measure the energy in the straight-ahead beam we have the following alternatives:

(a) We can use the rough monitor described above with 1.5% energy resolution. For this purpose beam A or B has to be interrupted, since the pulsed magnet is needed.

(b) If the energy has to be known with a greater precision, we will have to use the precise analyzer in beam A or B. When doing this we have to adjust the setting in the whole dc magnet system to this energy value. This would be an undesirable procedure, particularly if beams A and B are running.

(c) We may be able to place a simple spectrum monitor after the one-third degree vertical correction magnet in the straight-ahead beam. Whether this will be feasible depends on the available drift distance after this magnet. In the planned neutrino beam there will probably not be enough drift space between the one-third degree magnet and the target.

1.4 Feedback to Accelerator

At this time we do not intend to provide any automatic feedback from the energy spectrum. However, we think that the following schemes should be considered for later addition:

Signals from the rough spectrum monitor may be used to bring the beam energy quickly within 1.5% of the desired energy by "adding" the proper number of stand-by klystrons when the energy is too low, or by "eliminating" the proper number if the energy is too high.

Jim Ball has considered a possible feedback circuit for this purpose in TN-63-90.[2] Signals from the foils are fed into amplitude discriminator circuits. Feedback signals are produced by the discriminators when off-center foils intercept a too large fraction of the beam.

Feedback signals from the precise analyzer will be much more important, in particular, when a good beam quality has to be maintained during long runs.

These feedback signals should compensate during operation automatically for small variations in energy or in energy spread.

The scheme could be used to replace single klystrons in case of failure if

[2]TN-63-90, "Display and correction circuits for rough beam spectrum monitor," J. Ball, November 1963.

standby klystrons are made available. Small energy changes might be compensated by action on a de-phased sector pair or by changing slightly the klystron high-voltage pulse. A broad energy spectrum may be compensated using the signals from two foils. The two foils define the half-width of the spectrum. The signal should be fed back to the injector phasing.

2. Display and Electronics

2.1 Summary of Display Methods and Techniques

We may distinguish the following display methods for an energy spectrum:

I. The average spectrum over one beam pulse.

II. The average spectrum over n beam pulses.

III. The spectrum over any (200ns long) gated part of one beam pulse.

IV. Display of all dynamic secondary emission signals of one beam pulse.

As display techniques* we are considering the following:

(a) Rotating switch: The secondary emission current of each foil is collected on a capacitor. The charge on each capacitor is scanned periodically by a rotating switch and displayed on an oscilloscope. Immediately after a capacitor has been scanned by the rotating switch it is discharged by a second rotating switch. The charge on each capacitor is collected during a period of about one revolution of the rotating switch ($\approx$ 90 msec). This technique is suitable only for Method II.

(b) Fast electronic scanner: (see 2.3.1) This technique is suitable for Methods I and III.

(c) Pulse height analyzer: This instrument could be applied to Methods I and II, but would require much extra electronics to adapt it to Method III and even more so to adapt it to Method IV. It will be difficult to use it for remote display in the central control room. We have not yet studied this possibility in detail, but at first sight it seems a rather complicated and expensive solution.

(d) Oscilloscope display: (see 2.3.2) This is the proper technique for Method IV.

2.2 Display for the Rough Monitor

For this monitor we are satisfied with an average spectrum over n pulses. The monitor will be working only during beam setup periods.

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*Since the display is primarily needed in the central control room, we should consider particularly the adaptability of the technique to remote display.

The rotating switch technique with a scanning speed of 10 rps appears to be a satisfactory solution.

We shall place this mechanical switch as close as possible to the foils so as to reduce cable cost and cable capacity. The pulse train from the switch representing the spectrum will be displayed on a properly triggered oscilloscope in the switchyard control room and relayed to the central control room by a coaxial line for similar display. Remote controls will be provided in both control rooms.

The rotating switch-type scanner is currently used at Mark III. It has a good signal to noise ratio and the system may work nicely for beam currents as low as 5m μA.

2.3 Display for the Precise Spectrum Analyzer

It would be good to have all display Methods I to IV available for the precise analyzer.

Before coming to proposals we will first discuss some aspects of a fast electronic scanner we have developed and of the display of dynamic signals on an oscilloscope.

2.3.1 A Fast Electronic Scanner

The principle of this scanner was described in TN-63-21 (see Ref. 1). The scanner operates on a pulse-to-pulse basis. C. MacDonald has developed a prototype system with 6 amplifying channels. The signal of each foil is brought up by a coaxial cable and is connected to a signal channel. Each signal channel consists of an attenuator, a pulse amplifier and a sample-hold circuit. The sample-hold circuit is able to take a pulse height sample from any 200ns long part of the amplified secondary emission signal.

An electronic multiplexer with 12 channels and some switching logic scans the signal levels of the sample-hold circuits within 12 × 50 μs. The output signal from the multiplexer is displayed on an oscilloscope.

The system has been tested at Mark IV and works satisfactorily.

There is some dc offset in the output of the sample-hold circuits, but this can be improved.

The noise at Mark IV was such that we were limited to intercepted peak beam currents $\geq$ 600 μA per foil. (This corresponds to secondary emission currents of 25 μA.) We expect at least a 10 times higher sensitivity in the switchyard. We expect this improvement to come from a better noise situation in the switchyard, and from the use of amplifiers with symmetrical input.

The system described so far provides us only with the gated spectrum (Method III) which may be taken at any part of the pulse by changing the timing of the trigger pulse for the sample-hold circuit.

In order to obtain the average spectrum over one beam pulse we shall provide a simple integration network ($\tau \approx 10$ μsec) at the input of the amplifier.

When the energy spectrum of the beam is unstable from pulse to pulse, it may be desirable to display the average spectrum over n pulses. A way to do this with the electronic scanner would be to insert pulse-current integration circuits after each amplifier, but this looks rather complicated.

We believe that the rotating switch scanner has a much better performance to provide this average spectrum and, therefore, we intend to incorporate this display system into the precise spectrum analyzer (see Section 3).

The spectrum from the fast electronic scanner can be displayed in the central control room by providing a good coaxial cable.

2.3.2 Display of Dynamic Signals on an Oscilloscope

The idea of showing the 12 secondary emission signals on the screen of a cathode ray tube has been suggested repeatedly and is attractive since it shows the complete spectrum information of a single beam pulse over its full duration.

Although this idea seems simple in principle it involves some difficulties in practice. These difficulties come primarily from the fact that long delay lines are needed with a good rise time and a low attenuation. We shall discuss some aspects of this technique.

(a) Use of special large size cathode ray tubes: The most attractive way would be to display the 12 pulses on a screen with large vertical dimension, one below the other. In this way it would be easy to observe the energy spectrum at any given time during the pulse by drawing vertical lines across the screen.

The ideal CRT to do this would be a tube with 12 guns, a fast writing speed, and a vertical screen size of 24 cm. Such a tube is not available, however, and the development of a special scope with such a special tube is certainly beyond our budget.

It is also possible to use a single gun CRT with a raster-type time base and a 24 cm vertical screen size. The last pulse must then be delayed by 11×4 μs (2 μs for flyback!) = 44 μs. The only usable delay line for this purpose would be a special delay cable like, e.g., HH 1500 A (80 ns/ft; 1500 Ω; 0.2 db/μs). The last pulse, therefore, would be attenuated by 8.8 db and the rise time would be deteriorated to > 0.3 μsec. This solution, therefore, appears not practical.

(b) Use of Standard Oscilloscopes: First of all, we can display the 12 pulses in the normal way - side by side on one horizontal trace; however, this would still require a 22 μs delay for the last pulse resulting in an attenuation of 4.4 db and risetime > 0.24 μs.

The attenuation could be compensated, but this gives an additional complication. Reading the spectrum as a function of time from this display could be facilitated using masks properly centered in front of the screen (see Fig. 4).

The three methods discussed above under (a) and (b) show the difficulties with scope display technique.

A compromise solution between all adverse factors may be the use of two double gun Tektronix-type 551 oscilloscopes. The idea is sketched in Fig. 5. The maximum delay required is 8 μs. The risetime will be < 100ns, and the attenuation < 1.6 db.

The signals from the high resolution foils (center part) are displayed on the upper CRT, the energy tails on the lower one. The lefthand signals represent the low energy tail of the spectrum and the righthand signals the high energy tail.

When we make use of two simultaneously actuated polaroid cameras we could photograph the complete spectrum of 1 beam pulse and study the results in peace.

Visual analyses could be improved using masks with narrow vertical slits in the same way as shown in Fig. 4.

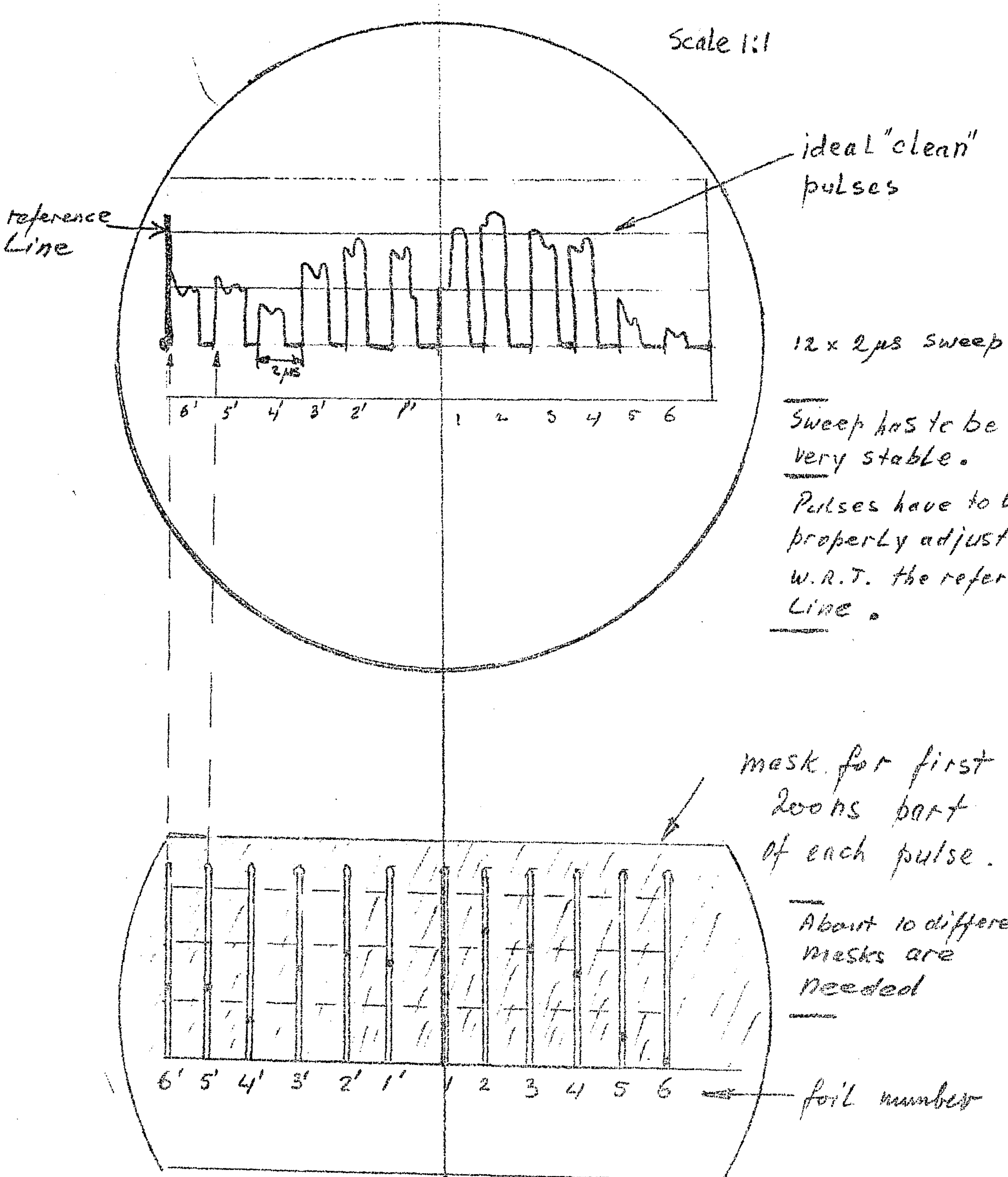
A disadvantage of this scope display is that it cannot easily be transmitted without distortion to the central control room unless we provide 4 expensive low-loss "heliax" coaxial cables. Alternatives for this problem are to bring polaroid pictures over or to use a good closed circuit TV system. A further disadvantage of the scope display is that it cannot show the average spectrum.

There are some electronic problems in the scheme of Fig. 5 requiring more study; like impedance matching in the 1500 Ω delay lines, the dc level shift required on the second CRT, etc. It seems, however, that these problems can be solved.

2.3.3 Conclusions

From the above discussions it is concluded that the electronic scanner is the most versatile solution for the precise spectrum analyser. It is the primarily recommended display technique. The electronic scanner may be backed up, however, with the scope display and the rotating switch scanner.

Fig 4 Simple display of dynamic pulses



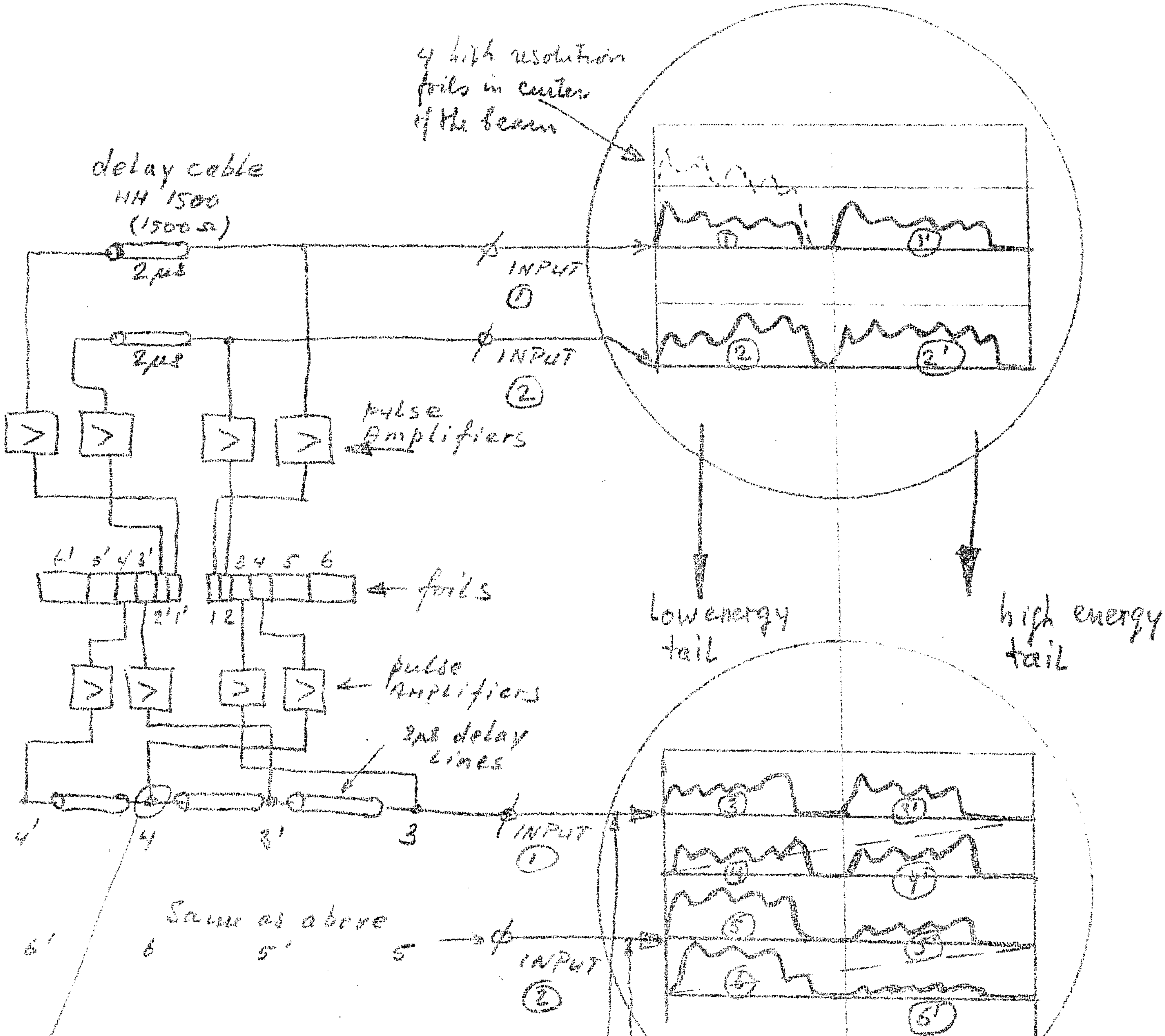
Sweep has to be very stable.

Pulses have to be properly adjusted W.R.T. the reference Line.

About 10 different masks are needed

Spectrum during first 200ns of beam pulse.

Fig 5 Dynamic pulse display with 2 double gun CRT's (Tektronix Type 551)



matching!

Remark: In order to avoid the matching problem one might use separate delay lines for each signal.

A possible solution for the display of the spectra in both beams A and B is proposed in the next section. It makes use of a combination of the three techniques and may be a flexible and economic solution providing the distinct advantage of each technique for both beams.

3. Combination of Display Techniques for the Precise Spectrum Analyzers in Beams A and B

It is not sure that the four display methods we have summarized in Section 2.1 are all needed in both beams A and B.

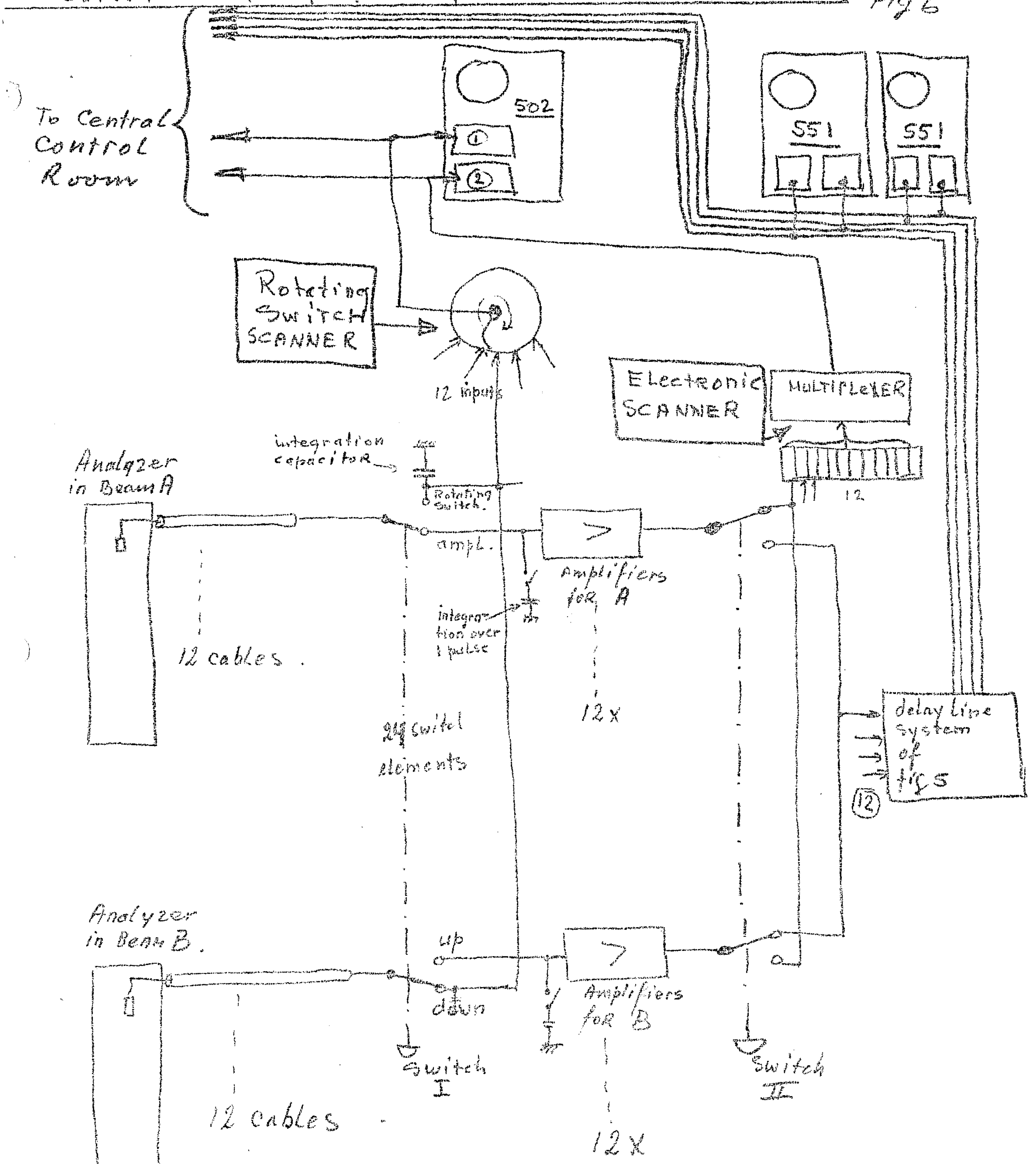
However, with a combination of an electronic scanner, a rotating switch scanner and 2 type 551 display oscilloscopes we can have these features for both beams for a price comparable to 2 electronic scanners.

The idea is shown and clarified in Fig. 6. Details of this combination scheme have not yet been studied to a greater extent. However, there does not seem to be any major difficulty and therefore it is believed to be a proper proposal for the switchyard.

ACKNOWLEDGMENT

I would like to thank R. Taylor and B. de Raad for helpful discussions; Charles MacDonald for developing the electronics for the prototype analyzer; P. Thingstad and F. Dunn for their contribution on mechanical design, and J. Carey and A. Chapin for assistance with assembly and testwork.

Combination of display techniques for Beams A and B



Switch I → up — { beam A on Rotating switch; " B on amplifiers → Switch II { up → B on dynamic display; down → B on electronic scanner }

down — { beam B on Rotating switch; " A on amplifiers → Switch II { up → A on ~; down → B on dyn. display }