PEPR FOR BEBC?

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1. INTRODUCTION

In determining whether PEPR can scan BEBC film, one must consider the ways in which BEBC film differs from conventional film. There are four principal differences between the two types of film (see Table 1).

Table 1

Ways in which BEBC Film Differs from Conventional Film

(1) Lower contrast
(2) Greater range of track widths
(3) Greater range of background transmission
(4) Greater distortions

The greater range of track widths requires a more complex track signal processor: this will be described later. The greater range in background transmission is dealt with by a background sampling scan, which gives the new signal processor more information about the background pedestal. The greater distortions should not appreciably effect PEPR's ability to follow tracks. However, the lower contrast of tracks in BEBC film must be carefully studied when considering whether PEPR can scan the film, as CRT devices in general have always had signal to noise (S/N) problems. To see how PEPR's S/N ratio becomes critical it is necessary to consider the flux losses in the system in detail.

2. FLUX LOSSES IN THE PRESENT PEPR I SYSTEM

Fig. 1 shows the flux losses in the present Oxford PEPR I system. From this figure it can be seen that the light output of the scan line on the CRT is about 12.5 microwatts. This is the maximum light output that we can get from a high resolution, high speed, P16 type phosphor. Increasing the phosphor loading further tends to age the phosphor intolerably. We also use the ultimate in objective lenses, as we have to combine high resolution with a large aperture. The track and background film transmissions are also optimised for maximum S/N ratio; as will be described later. The transmission of the light collection system in PEPR I is poor; and we hope to increase this by about 30% with blooming in our improved PEPR II system. Also the photomultiplier with the highest possible quantum efficiency in the convolved phosphor-photocathode spectrum is chosen. The filter bandwidth is matched to PEPR's sweep speed of 33 µm/µsec. With these flux losses we observe a S/N ratio of $\underline{9}$ for central, 50% ionised tracks, on reverse developed film from the Saclay chamber.

To determine how PEPR II will perform on conventional and low contrast BEBC film, it is necessary to consider the PEPR S/N ratio in terms of CRT and track parameters, and also film contrast parameters.

3. THE TRACK DETECTABILITY

Consider first of all the PEPR S/N ratio in terms of CRT and track parameters.

Table 2

PEPR S/N in terms of CRT and track parameters, assuming Gaussian distributions for track and scan-line.

Standard deviation of track:	s
Standard deviation of PEPR scan line on film:	σ
Light output of CRT scan line:	A

(cont.)

Scan line crossing parallel track gives PM anode pulse of standard deviation: $\sqrt{(\sigma^2 + s^2)}$

PM anode pulse amplitude is proportional to: $\dfrac{A \cdot s}{\sqrt{(\sigma^2 + s^2)}}$

PM shot noise is proportional to: $\sqrt{A}$

Therefore S/N is proportional to: $\sqrt{\dfrac{A}{1 + \delta^2}}$

where $\delta = \sigma/s$

This is modified by filtering to: $\dfrac{\sqrt{A}}{(1 + \delta^2)^{1/4}}$

which we define as track detectability.

By calculating the track detectability we were able to predict, accurately, the improvement in S/N ratio given by inserting a 5 inch, 75 gun Ferranti CRT in PEPR I, to replace the original 5 inch Dumont CRT. Track detectability figures have also enabled us to determine the best operational grid drive for the Ferranti CRT.

4. THE FILM SIGNAL TO NOISE RATIO

It is also possible to obtain better PEPR S/N ratios by optimising the track and background film transmissions. For scanning systems limited by photomultiplier shot noise, it is fairly easy to show that light tracks on a dark background are more easy to detect than dark tracks on a light background. We therefore used Saclay chamber film, which had been reversed developed by the Rutherford Laboratory, for our first experiment.

Let us consider the PEPR S/N ratio for light tracks on a dark background in terms of photographic parameters, (see Fig. 2). For light tracks on a dark background, let B be the ratio the (track transmission / the background transmission) which is the photographic S/N ratio; let 'b' be the track ionisation; and let 'i' be the absolute transmission of the background. Now the optimum PEPR S/N ratio is not given by the maximum value of B, as would perhaps be thought at first sight. To see this, consider again the photomultiplier anode pulse. The amplitude of this pulse will be proportional to Bbi; and the shot noise will be proportional to $\sqrt{i}$. Therefore the PEPR S/N ratio will be proportional to $Bb\sqrt{i}$, which we call the film S/N ratio. In optimising the reversal process for PEPR, we maximise this film S/N ratio, $Bb\sqrt{i}$, rather than B. By measuring B and i with a microphotometer it is therefore possible to measure the variation in PEPR S/N ratio, due to variations in contrast, over a single frame and also from film to film. In particular, we find that the value of $Bb\sqrt{i}$ for the brightest track on BEBC-model film is about 1/6th that of the brightest track on reverse developed Saclay film. The film S/N ratio varies by a factor of 3 over one frame of the Saclay film; a comparable measurement on BEBC-model film would not be meaningful, as the film sample available is not as uniform as the eventual BEBC film is expected to be. We should perhaps worry if the range in film S/N ratio is greater than 5 in BEBC film. However, apart from this factor, the values of $Bb\sqrt{i}$ for BEBC-model film and conventional bubble chamber film can be used to predict the performance of PEPR II on BEBC film.

5. THE CHARACTERISTICS OF PEPR II

In the Oxford PEPR II system, a 9 inch, 75 gun Ferranti CRT is demagnified about 1.5:1, so as to cover two views of film from the CERN 2 metre chamber. A moveable platen enables access to be obtained to a third view also. Dynamic astigmatism correction, which varies as the square of the deflection, is applied to the 9 inch CRT, so as to prevent the scan line from growing by more than 5 microns. This is the same scan line growth as occurs at present on the 5 inch PEPR I CRT. The image plane scan line growth will, in fact, be less on PEPR II, because of the higher demagnification, and also because a higher quality objective is being used. This results in a smaller variation in the detectability of 22 micron tracks over the PEPR II image plane. We will now use the central detectability of PEPR I, which gave an absolute S/N ratio of 9 on Saclay film, and the edge detectability of PEPR II, (see Table 3) to predict the performance of PEPR II on conventional and BEBC film.

Table 3

Performance of the Oxford PEPR's I and II

	PEPR I, 5" CRT 1:1 optics		PEPR II, 9" CRT 1.5:1 optics	
	CENTRE	EDGE	CENTRE	EDGE
CRT scan line width	14.6μm	19μm	15μm	20μm
Image plane scan line width	15.6μm	22μm	13.4μm	17.4μm
Detectability on 22μm tracks, arbitrary units	9.34	8.71	9.57	9.20

6. THE PERFORMANCE OF PEPR II ON CONVENTIONAL FILM

Consider first the performance on conventional film. The slightly lower edge detectability of PEPR II reduces the worst PEPR II signal to noise ratio, r_w, to 8.9. Now the larger faceplate area of the 9 inch PEPR II CRT can only be covered by an objective of sufficient resolution by reducing the aperture to f/2.8; at 1.5:1 this reduces the fraction of the total forward light collected to 1/174th, which reduces r_w to 7.6. However, as already mentioned, the transmission of the PEPR I light collection system is rather poor, and in PEPR II it could be improved by at least 30%; it is also hoped to use a photomultiplier with a gallium phosphide coated first dynode in PEPR II, which will give nearly 10% increase in S/N ratio. Thus the worst PEPR II S/N ratio for conventional film will be 20% better than the central S/N ratio in the present PEPR I system.

7. THE PERFORMANCE OF PEPR II ON BEBC FILM

It is considered by CERN that the smallest tracks will have a width at half height of about 12μm*, although the smallest track width observed on a

*) This number is currently quoted as 10μm (note added by editors).

sample of BEBC model film at Oxford is about 20µm. Taking the worst case, if the contrast of BEBC film were equal to the contrast of conventional film, we would have an edge detectability of 7.8, giving a value for r_w of 9.2. However, the film S/N ratio for the brightest track on BEBC film is 1/6th that of the brightest track on conventional film, which reduces r_w to 1.5. The only way we could make PEPR II detect tracks on BEBC film would be to demagnify the 9 inch CRT further. It is reasonable to assume that an objective could be made to demagnify the CRT 3.1:1, at f/2.8, and give a worst image plane, scan line width of about 8µm. The decreased scan line width would then increase the edge detectability from 7.8 to 9.5, which would increase r_w to 1.8. Thus the decrease in line width, by itself, would not increase the S/N ratio very much. However, because the objective would now be closer to the CRT, we would collect a larger fraction of the total forward light output, which will increase r_w to 2.3. We could then return to a S/N ratio of 9 by slowing the sweep speed down by a factor of 15.

8. THE SIGNAL PROCESSOR

8.1 Signal to Noise Performance

As stated above, a reduction in the PEPR sweep speed of 15:1 would be required to obtain a S/N ratio (on BEBC film) comparable with our current system. However, the PEPR II signal processor will maintain the current sweep time, of approximately 50 µsec per angle, and give the enhanced S/N ratio by operating in two modes with limited sweep ranges (see Table 4).

Table 4

PEPR II Signal Processor

a) Maximum S/N

Scanning Mode	Sweep Time * (μsec)	Sweep Distance (in microns)	Resolution (in microns)	Mode of Operation		
				Normal Mode S/N	Averaging Mode	
					Range	Maximum S/N
FIND	50	2000	20	N	1-64	$\sqrt{64N}$
TRACK	50	400	4	$\sqrt{5N}$	1-10	$\sqrt{50N}$
SUPER TRACK	50	100	1	$\sqrt{20N}$	1-10	$\sqrt{200N}$

b) Hardware Timings (as % of total event time)**

	Normal Mode	Averaging 10 Times
FIND	5%	20%
TRACKING	2.5%	13%

Reduction in measuring rate (throughput) with (10 times) averaging 26%.

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* Sweep time to be multiplied by number of sweeps averaged in "Averaging Mode".

** Assuming current software

The FIND mode, which is used to locate starting points for Track Follower must sacrifice time to improve the S/N ratio. To insure maximum flexibility, an analogue hit detector is followed by digital averaging which takes the form of a 6 bit 100 word Summing Store (see Fig. 3) allowing an averaging range of 1 to 64 times. Track and Super Track which provide adequate sweep distances while track following, give an improved S/N ratio without a time penalty.

However, they can be used in an averaging mode, limited to the range of 1:10. In this case the pedestal-free signal is digitized with a resolution of 1/100 of the sweep distance and the numbers resulting from successive sweeps are summed by the Summing Store.

To indicate the effect averaging has upon total system timing, table 4 shows the results of averaging 10 times in both FIND and TRACKING modes. The reduction in measuring rate of 26% assumes NO overlapping of software processing and consequently the final reduction will be somewhat smaller.

8.2 Background Transmission

To overcome the problem of rapid variations in the background, a detailed record of the local area is obtained during a dummy sweep using a defocussed spot. The enlarged spot acts as a low-pass spatial frequency filter, recording background changes which have wave lengths substantially longer than that of the widest tracks. The resulting signal is digitized with a resolution 1/100 of the total sweep distance and placed in a 6 bit 100 word recirculating Background Store.

Subsequent data sweeps in the same local area use a reconstituted background to provide a pedestal signal, which can be subtracted from the analogue input, resulting in a pedestal-free track signal.

8.3 Complex Processing

The large range of track widths and contrast predicted for BEBC film has made simple analogue detection of the track centre doubtful. Therefore threshold and width discrimination are under programme control; and the data buffers contain track position and width information.

As the ultimate weapon, the total contents of the Summing Data Store can by-pass the threshold and width discriminator and be transferred via the data buffers to memory for subsequent analysis. This approach would be painfully slow (600µsec per sweep) and therefore used only in extreme conditions; but as a diagnostic tool, it may be invaluable when developing new algorithms for determining the threshold and width discriminator parameters.

9. BEBC-Model Film

Returning to BEBC-model film, fig. 4 shows a TV* scan of a frame selected from the November, 1969 run of the 1m model; and indicates that PEPR I can at least detect the higher quality tracks. Fig. 5 shows signals associated with these tracks after filtering and the removal of the pedestal. (Note the significant background change within a 2mm sweep). Using our current production system we were able to track-follow all the prominent tracks in this frame.

In conclusion, although the above calculations may be considered as optimistic, we feel that there is a considerable safety factor with regard to the minimum S/N ratio acceptable to our current software strategy.

To strengthen this argument, tests at various light levels were carried out using our current production system (see Table 5).

Table 5

Oxford PEPR I Signal/Noise Performance

(Totals from a complete roll of Saclay π^- p 740 MeV/c)

EVENT PERFORMANCE

Run No.	Light Intensity	Good Events	Suspect Events	Rate (Events/hr)
1	100%	163	16	384
2	50%	162	17	388
3	25%	163	16	395
4	12.5%	164	15	390
5	6.25%	148	31	368

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[*] Scanning and Signal processing done with PEPR I hardware

Table 5 (contd)

TRACK PERFORMANCE

Run No.	Light Intensity	average vertex Error (in microns)	average Track Length (in mm)	calls to Track Follower	Track Follower Time
1	100%	6.97	15.46	3398	24.8%
2	55%	6.7	15.23	3272	23.5%
3	25%	3.86	15.29	3417	23.2%
4	12.5%	3.79	15.14	3849	23.2%
5	6.25%	4.20	14.42	4631	21.5%

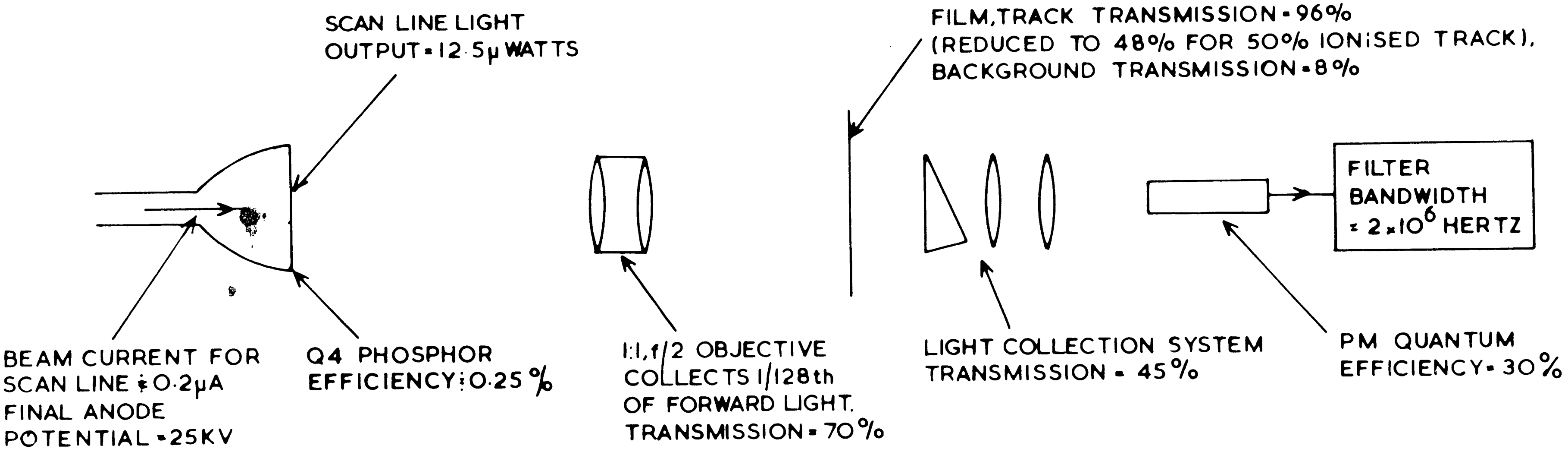
This table indicates the EVENT and TRACK performance for a sample of 179 events (measured automatically) at five different light output levels.

The results show no significant change in performance down to a light level of 12.5% demonstrating that our software strategy would still be applicable with a S/N ratio reduced by a factor of $\sqrt{8}$.

Acknowledgement

The authors would like to acknowledge the encouragement and many useful suggestions received from Mr. P.G. Davey (Project Engineer Oxford PEPR).

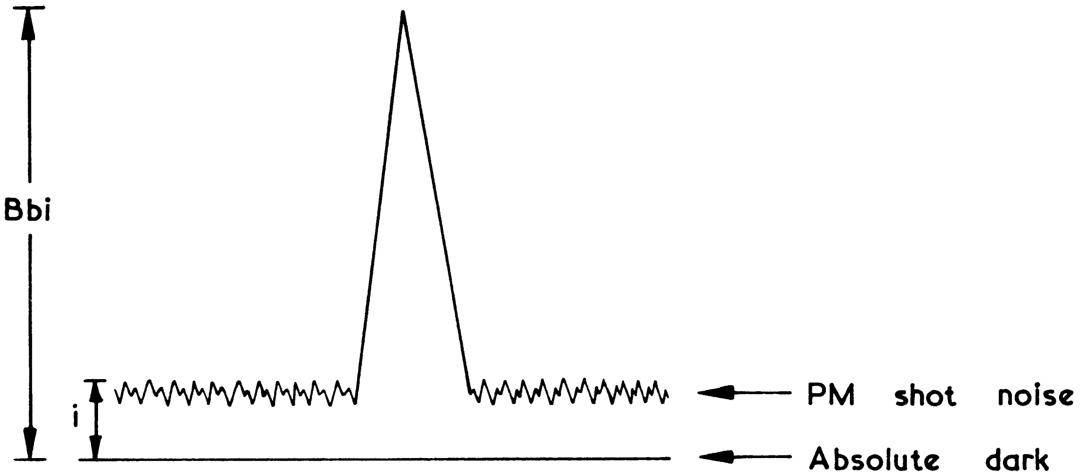
LIGHT LOSSES IN THE OXFORD PEPR I SYSTEM



OBSERVED S/N RATIO FOR A CENTRAL TRACK ON REVERSE DEVELOPED SACLAY FILM = 9

FIG. 1

PEPR SCAN LINE CROSSING A LIGHT TRACK
ON A DARK BACKGROUND



$$B = \frac{\text{transmission of light track}}{\text{transmission of dark background}} = \text{Photographic S/N}$$

b = track ionisation

i = absolute transmission of the dark background

PM anode pulse amplitude $\propto Bbi$

PM shot noise $\propto \sqrt{i}$

Therefore film S/N $\propto Bb\sqrt{i}$

$Bb\sqrt{i}$ for the brightest track on BEBC film is $\frac{1}{6}$th that of the brightest track on reverse developed Saclay film.

FIG. 2

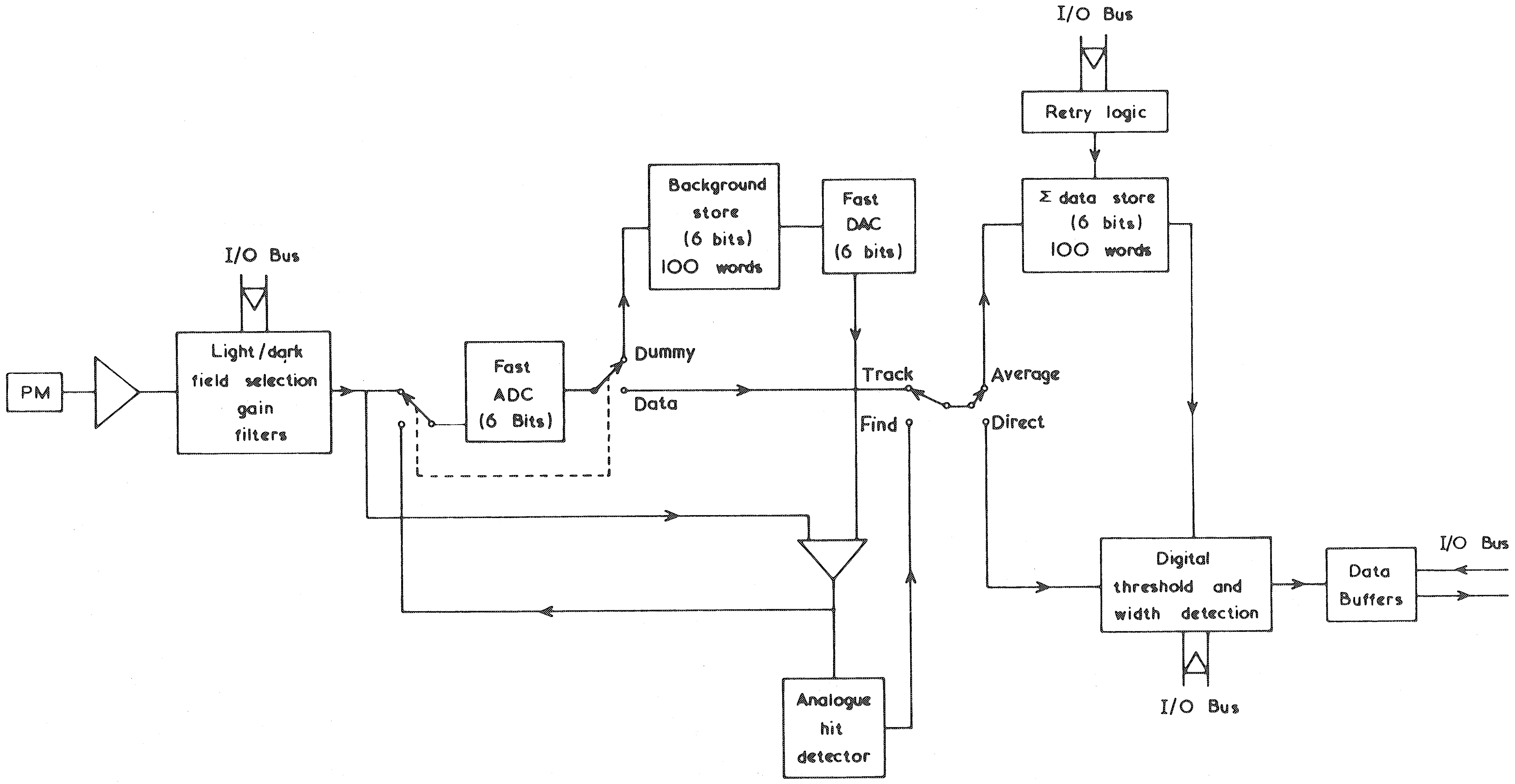


FIG. 3 PEPR II SIGNAL PROCESSOR

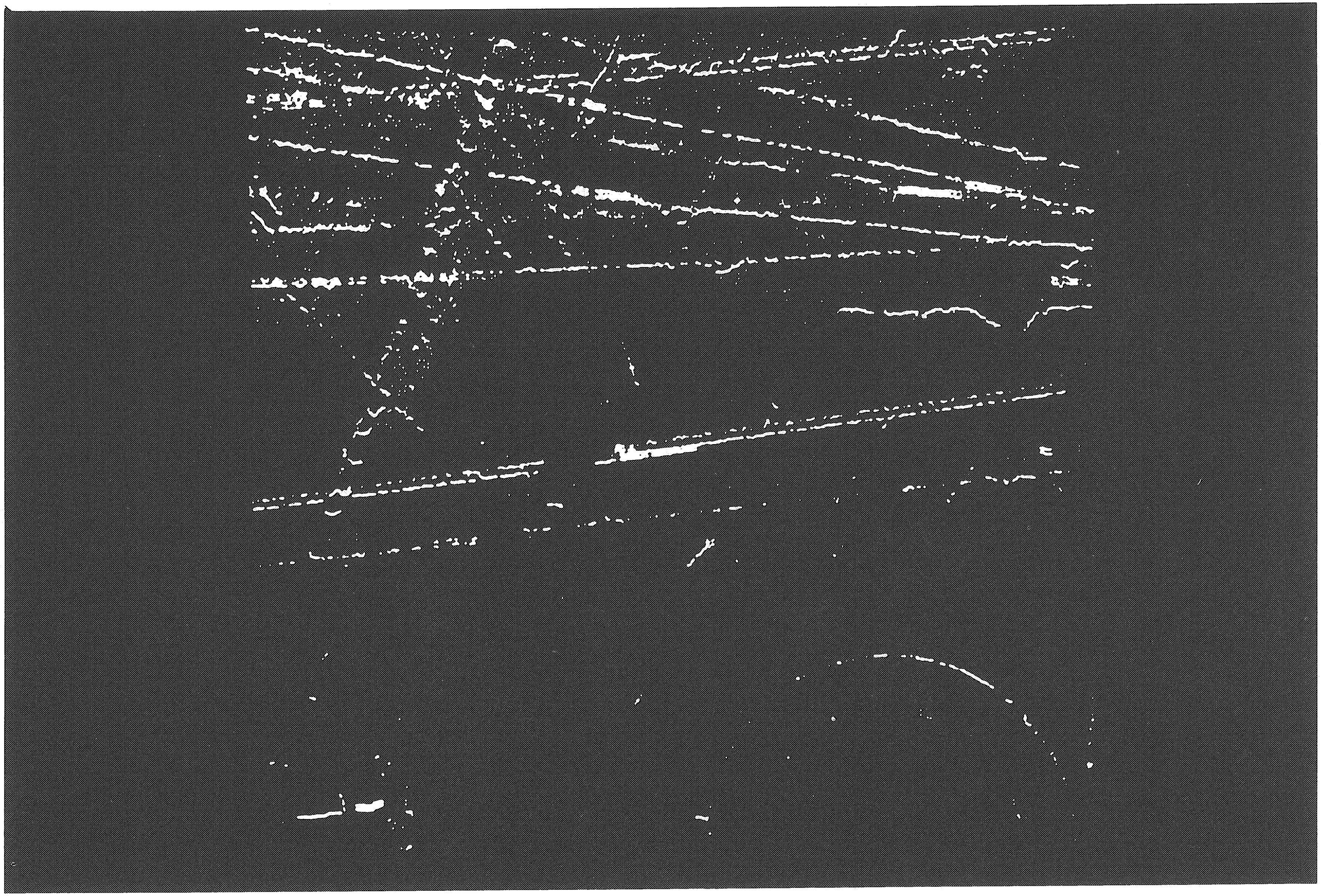


FIG. 4 TV SCAN

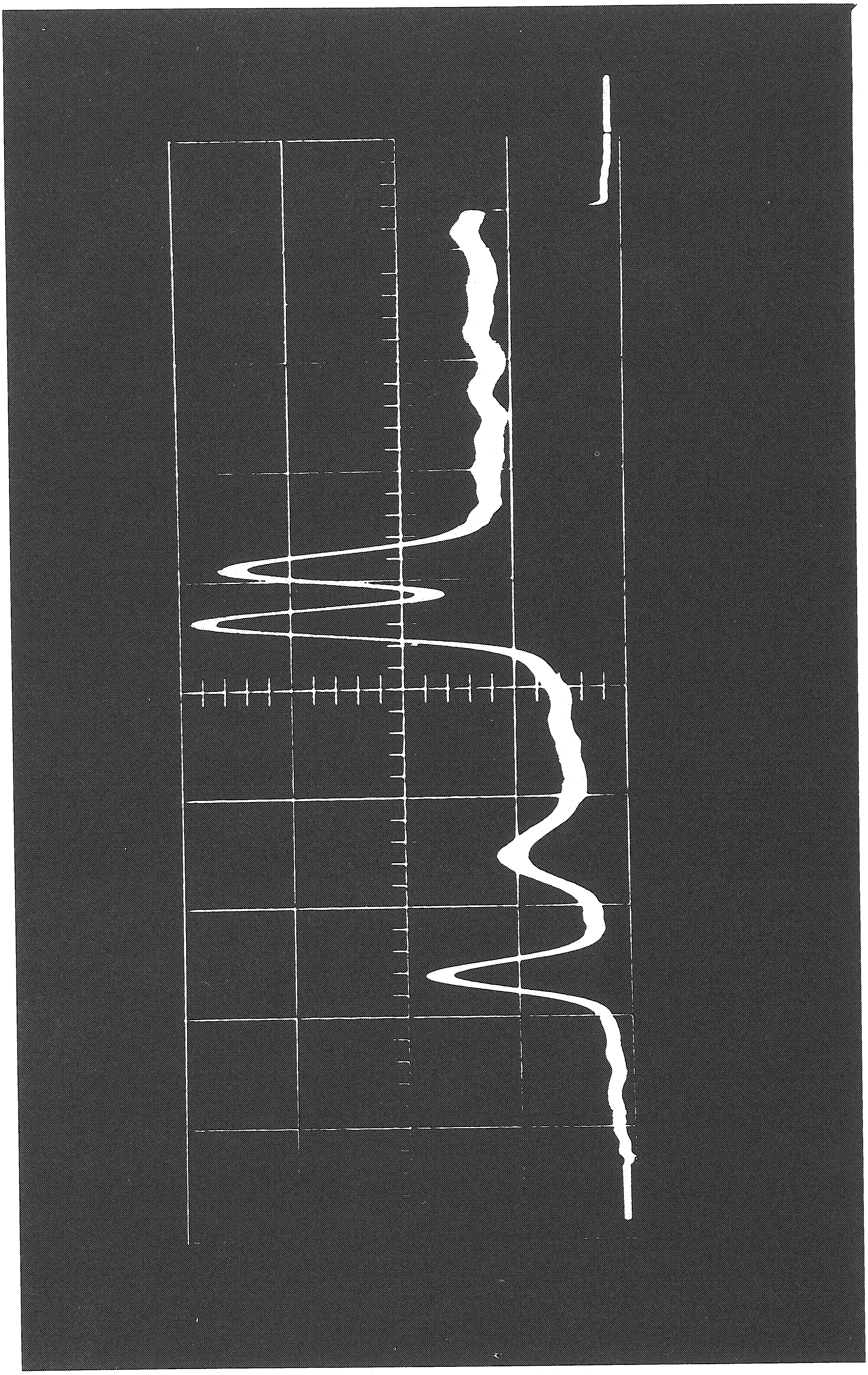


FIG. 5 TRACK SIGNALS

DISCUSSION

T.L. WATTS *(MIT):* Is there any other phosphor giving more light at the same wavelength since you sweep slowly and do not need the fast phosphor.

C.B. BROOKS: Our problem is that lenses are expensive, and having bought a lens one does not want to change phosphors -- the lens is so optimized to the particular wavelength of the light emitted by the phosphor. It is not clear that there are phosphors which are better. We find that Q4 or B16 is adequate.

H. ANDERS *(CERN):* Could you please give an exact definition of "signal-to-noise ratio".

C.B. BROOKS: We define this as the ratio of the peak amplitude of the track signal and the r.m.s. value of the shot noise, after filtering. The figure of 9 was taken for central tracks of about 50% ionization.

H. ANDERS *(CERN):* I just want to add that I will come to the question of other phosphors in my paper tomorrow.

W. SLATER *(UCLA):* What size area can be measured by this 9-inch tube using 1.5× demagnification?

C.B. BROOKS: At 1.5:1 you can cover a diameter of 135 mm. You can just fit two views of the CERN 2 m chamber into this. In PEPR-2 we have access to a third view by a movable platen.