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USE OF SCINTILLATING FIBRES AND STANDARD TV EQUIPMENT FOR MONITORING OF EXTERNAL PROTON BEAMS AT THE C.P.S.

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I. INTRODUCTION

Scintillating screens, such as ZnS screens, have been widely used for the setting up of external proton beams [1]. Since this detector provides only limited information on the beam profile (particle density distribution), a filament device has been studied, having a comparable sensitivity combined with higher spatial resolution. The light output of this scintillator is observed by means of a closed-circuit TV system.

II. PRINCIPLE OF THE DETECTOR

A sketch of the device used is shown in Fig. 1. A number of fibres (say 100) are placed parallel to each other with a small spacing between them in a plane perpendicular to the beam axis. On one side, the extremities of the fibres are viewed by a TV camera, having its optical axis parallel to the axes of the fibres. The image of the line, formed by the ends of the fibres falls on the sensitive layer of the vidicon*) with such an orientation that the vidicon beam scans the line at right angle. Thus, the video signal is directly related to the density distribution along the axis of the beam normal to the axis of the fibres. Hence, by displaying the video signal on a scope, the profile of a single given beam burst can be observed immediately.

*) Use of an orthicon was not considered in detail because a vidicon was available and of sufficient sensitivity.

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In order to obtain information about the beam cross-section in the two axes, a second filament arrangement similar to the one described could be inserted into the beam in the same plane as the other, but perpendicular to it. It would be possible to view them both with one camera by means of a mirror system. It also could be interesting to use a fibre bundle which traverses the beam following the longitudinal axis. The outer fibres of such a bundle might be longer to obtain a larger signal from the periphery of the beam, which is in a given ratio to that obtained from the beam centre for a fixed application.

III. SCINTILLATING DETECTOR

1. Previous work

In various applications, it is very attractive to replace the homogeneous luminescent chamber by a bundle of fibres, thus obtaining well defined spatial resolution[2]. There have been numerous ideas for the use of fibres as beam monitors. Recently, Kalmus developed a beam profile camera[3] *) using a fibre bundle as energy transformer, together with Polaroid film, thus being capable of detecting $10^3 - 10^6$ particles/cm^2. Neet[5] suggested the use of a luminescent fibre as profile monitor and three fibres arranged in a triangle as a boundary monitor.

2. Material used

We have been using type NE 102A scintillating fibres of 0.5 mm diameter. According to Iredale[6] this scintillator has an efficiency of 10^4 photons/MeV for minimum ionizing particles. We are unable to answer completely the question concerning radiation damage effects and lifetime of the fibres. At the CERN synchro-cyclotron, after exposure to a dose of approximately $1.2 \cdot 10^7$ rad (corresponding to a particle flux of $4 \cdot 10^{14}$ p/cm^2) similar material shows a little browning. This will increase light absorption, but not necessarily limit the use of the detector, which was found to be usable up to an exposure of 10^{14} protons/cm^2.[7] The heating of the fibres due to the energy deposit is estimated in Appendix C.

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*) See also reference 4).

3. The optical coupling of the scintillator to the vidicon

Potter and Hopkins[8] have studied the light efficiency of three coupling methods :

a) Extension of the scintillating fibres to the aspheric surface of the objective, which transmits the light to the vidicon.

b) Direct coupling with a glass fibre bundle. This requires a vidicon with a very thin window or a fibre-face plate, such as provided by EMI (EMI type 9685).

c) Scintillator extension by a short curved glass fibre bundle to the surface of an objective.

Methods b)and c) have shown to give adequate performance with a relative efficiency of 10% , whereas method a) has an efficiency of 4% .

To make life easier, we simply viewed the filament device by means of a lens system having an aperture stop f $^1/$ 2.8 . Potter[9], computed the angular distribution of light emitted from a fibre, being a function of the fibre length. This justifies an isotropic first order approximation for the small axial angles and short fibres considered here. In other words, an optical system with an aperture stop f/1.0 would improve the sensitivity eight times.

Bovet emphasized the possibility of obtaining high light collection from the fibres by means of a mirror[10] .

4. Treatment of fibres

Potter[8] states the effects of various treatments on the face of the fibres, and shows that well polished faces give the greatest light output. Great care should be taken not to damage the surfaces of the fibres, which would result in a drastical loss in light transmission.

IV. VIDICON

1. Vidicon operated as integrator.

The pulse length of the slow ejected beam of the C.P.S. varies from 500 μs to 200 ms. Thus, in order to obtain information on the total amount of light emitted by the scintillator, we can conveniently make use of the storage properties of the vidicon. As long as the scanning of the photoconductive layer is suppressed, a charge pattern will be built up, corresponding to the amount of light, incident on every particular point of the layer. In our case, the suppression is achieved by applying a positive voltage pulse to the cathode of the image tube during a period which extends somewhat beyond the beam burst duration. Thus, the total light corresponding to the total beam pulse is converted into a charge image. This information is almost completely transmitted by the video signal resulting from the first scanning after the suppression.

2. Main characteristics of the vidicon.

i) Sensitivity.
Calculations show (App. A and B) that a standard vidicon can be operated at a flux of $\sim 7.1 \cdot 10^{11}$ photons / cm^2 sec at a wavelength of 5500 A.U. [Iredale states $5.3 \cdot 10^{11}$ photons / cm^2 sec.[16]]. The highest practicable sensitivity is limited to applying 50 - 70 V to the target electrode, because of the increase of the dark current.

ii) Dark current.
The dark current fluctuates up to 20% . This holds for good vidicons and scanning over the whole area of the layer[11].

iii) High light illumination.
For constant illumination of the vidicon face-plate, the signal current may fluctuate within 10% when scanning over the whole area. This figure is considerably reduced when observing only the central part of the image[11].

iv) Modulation depth.
The separate mesh EMI vidicon 9677 has as a characteristic value a modulation depth of 85% for 300 lines, which ensures very good performance in our application.

v) Radiation Resistivity.

There are now specially designed vidicons with high radiation resistance available: e.g. the GEC 1328 (7325) type vidicon can withstand a dose of 10^{12} erg/g without noticeable change in performance[12]. However, this should not be a great problem, since it has been shown that vidicons used for beam observations have no significantly shorter lifetimes than those tubes employed in non-radiation areas[11].

V. DISCUSSION

1. Sensitivity.

In order to obtain comparable results, we introduce a linear proton density δ (beam cross-section projected onto plane normal to the fibres axis).

$$\delta = \text{protons / pulse cm.}$$

With the figures calculated in Appendix B, we obtain for a EMI-standard 9677 type vidicon $\phi_{min} = 1.2 \cdot 10^{12}$ photons / sec cm^2

ϕ_{min} = ... min.flux on vidicon face-plate.

Using an objective with $f/D = 2.8$ $f = 75$ mm, and having a linear magnification $m = 1/10$, we estimate from the figure of Potter[8], assuming a light transmission factor of $T = 0.5$

$$\phi_{out} / \phi_{in} = 10^{-3}$$

ϕ_{out} ... flux from fibre surfaces

ϕ_{in} ... flux on vidicon face-plate.

Taking into account the fact that we only observe one TV image, corresponding to a time of 20 ms, having an efficiency $n = 4 \cdot 10^3$ photons/MeV and an average absorption of $7.2 \cdot 10^{-2}$ MeV/proton, we find the minimum observable density

$$\delta = 4.2 \cdot 10^9 \text{ protons / pulse cm.}$$

2. Accuracy

The accuracy of the profile detection is restricted by the noise of the video signal and changing characteristics of the individual fibres. Let us consider a 5% random fluctuation of the video signal for constant illumination; it should be possible to keep this figure smaller by selecting a homogeneous picture element from the layer. No figures are available for the effect of surface damage on the transmission properties of the fibres. For good performance the light transmission of the fibres should be tested by a method similar to the one described by Potter[8]. Errors are caused also by browning of the fibres, which reduces the transmission in the central fibres more rapidly.

VI. EXPERIMENTAL RESULTS

1. Scintillators tested

We placed three scintillators in the slowly ejected proton beam; the filament device, and two homogeneous plates, 1 mm thick, one viewed from behind, the other from the side. Photograph 1 show the video signal obtained by scanning the image of the scintillator viewing the front. Photographs 2,3,4 reproduce the video signal from the side-viewed counter and show the beam profile obtained with the filament device. A beam profile can clearly be seen in all three cases. The most remarkable difference is the apparent enlargement of the beam cross-section when observing it with a homogeneous scintillator. These light-piping properties of the fibres were confirmed in the following test. With the TV camera observing from the front side (at 45° to the plane of the fibre device), no TV signal could be obtained.

2. Comparison with calculation.

From pictures which have been taken at an intensity of $\delta = 2 \cdot 10^{11}$ protons / pulse cm, we estimate a minimum observable density $\delta = 7 \cdot 10^{10}$ p / pulse cm. If we take into account the delay of response of the vidicon, we obtain for an average value of 40 ms for the time interval between the proton pulse and the first scan, a loss of sensitivity by a factor ~ 2.5. The TV equipment ACEC, with which we have carried out our experiments, is approximately three times less sensitive than the EMI vidicon, for which the calculation has been carried out. Our theoretical figure $4.5 \cdot 10^9$ p/pulse cm should therefore be increased to $3.2 \cdot 10^{10}$ p/pulse cm. Calculation and measurement then agree within a factor 2.

However, with an EMI vidicon and a lens system of f/1.0, a density $\delta = 5 \cdot 10^9$ p/sec cm should be observable, if the suppression can be extended for about 100 ms after the end of the burst (thus avoiding loss due to delayed response).

VII. FUTURE WORK

1. Choice of materials

It would be interesting to find a material with comparable scintillating efficiency, but with somewhat higher radiation resistance. De Raad describes scintillation from a quartz plate[13]. He also refers to quartz which will withstand a dose of 10^{11} erg/g without alteration in optical properties, but it is not certain that both materials are identical.[12] There are also some glass specimens available having high light output under radiation[13]. One way to overcome radiation damage problems is seen from a suggestion by de Raad[12]: quartz tubing of high resistance quality filled with a liquid scintillator could be used instead of homogeneous scintillating fibres. Another possibility might be to fill these tubes with a noble gas, such as xenon, which would reduce the light output to 0.1% compared with a plastic scintillator of corresponding diameter. Using a xenon-nitrogen mixture and operating the chamber in an electric field, we would gain a factor 100 in intensity[14]. By introducing certain black fibres, it is possible to obtain a reference system for fixing the position of the beam. It is also possible to divide the ends of the fibres opposite the TV camera into two groups - each group being taken to a separate photomultiplier. If the current difference of these two PM becomes zero, the position would be well defined. The possibility of using a different thickness of scintillator in different parts of the beam has already been mentioned (p. 2).

ACKNOWLEDGEMENTS

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APPENDIX A

Absorption in the fibres

The calculation is based on a beam cross-section recorded by means of nuclear emulsions (Fig. 17a, b of reference 1). We define as beam radius the radius of the cross-section corresponding to a proton density of 10% of the maximum value, thus obtaining a radius $r = 2$ mm, total intensity: $5 \cdot 10^{11}$ protons/pulse. Approximately $1.2 \cdot 10^{11}$ protons will pass the central fibre.

Fibres: 0.5 mm diameter, $\rho = 1.032$ g/cm^3, giving an average area density

$$\rho_a = 0.0405 \text{ g/cm}^2.$$

With the data of Sternheimer[16], we find for 27.5 GeV protons $-(1/\rho)(dE/dx) = 1.835$ MeV/g cm^{-2} for beryllium.

Since no extrapolation of this value was possible, we take this figure for our calculation.

We find the average energy absorption

$$\Delta E = 1.8 \cdot 0.04 \text{ MeV/proton.}$$

Per pulse is deposited in the central fibre:

$$E_{abs} = 0.0720 \cdot 1.2 \cdot 10^{11} = 0.086 \cdot 10^{11} \text{ MeV}$$

$$E_{abs} = 8.6 \cdot 10^{9} \text{ MeV/pulse} \mathrel{\hat{=}} 3.25 \cdot 10^{-4} \text{ cal/pulse}$$

APPENDIX B

Light emission from the fibres

Sensitivities of photo-electric devices are normally stated for illumination with a tungsten lamp, T = 2870° K. From the known spectral energy distribution of the tungsten lamp and the radiant sensitivity of the human eye, the minimum light flux for different vidicons can be calculated[16].

Definition:

1 Watt light (λ = 5550 AU)

$\hat{=}$ 680 lumen (lm)

To simplify calculation, we assume linear response of the signal current to the illumination (more exactly:

$$S = k \cdot I^{\gamma}$$

S ... Signal current

I ... Illumination

k ... Constant

γ ... Constant $0.7 \leq \gamma \leq 1$) .

1. Vidicon Thomson-Houston (See Fig. 3).

   I_{min} = 0.39 μW (Tungsten lamp)

   $\hat{=}$ 7.1 · 10^{11} photons /sec [λ = 5500 AU]

2. Min. Flux from the scintillator. Since data on the spectrum of the NE 102A scintillator have not been available, we take a scintillator spectrum with max. emission at the same wave length (λ_{max} = 4150 AU).[17]

   a) Vidicon Thomson - Houston

   I_{min} = 0.70 μW

   $\hat{=}$ 1.5 · 10^{12} photons / sec (λ = 4150 AU)

   b) Vidicon EMI 9677 Standard

   I_{min} = 0.59 μW

   $\hat{=}$ 1.2 · 10^{12} photons/sec (λ = 4150 AU).

APPENDIX C

Estimate of the heating-up of the fibres

Assumptions:

$d = 1$ cm diameter of the beam

$N = 1.2 \cdot 10^{11}$ protons/pulse ....

..... number of particles transversing the central fibre (see Appendix A)

$E = 8.6 \cdot 10^{9}$ MeV/pulse $\hat{=}$ $3.25 \cdot 10^{-4}$ cal/pulse

$\hat{=}$ $1.60 \cdot 10^{-4}$ cal/sec absorbed.

$c_p = 0.174$ cal/g grad

(for quartz, we take this value for our estimation, in general solid organic substance have greater values).

For the calculation of the upper limit of the surface temperature, we assume : no heat conduction in the fibre, all heat only removed by radiation, radiation from inside the fibre is absorbed in the fibre.

The energy balance leads to

$$Q_{abs} = Q_{rad}$$

$$Q = \sigma \cdot A \cdot \epsilon \; (T_s^4 - T_a^4)$$

Q_{abs} ... energy absorbed / sec

Q_{rad} ... energy radiated / sec

σ ... Stephan-Boltzmann constant

ϵ ... emissivity $\epsilon = 0.5$

T_s ... surface temperature

T_a ... ambient temperature $T_a = 293^\circ$ K

and we find for the surface temperature

$$T_s = 308\,^\circ\mathrm{K} = 35\,^\circ\mathrm{C}.$$

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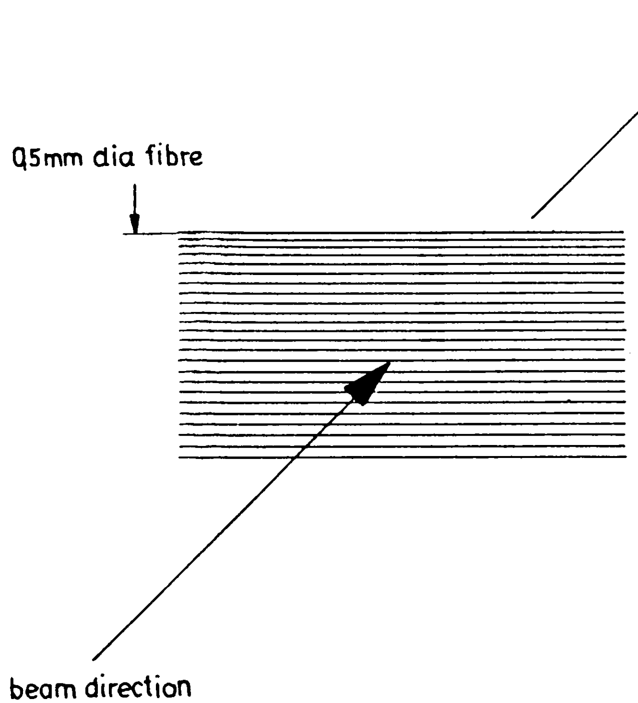
Detector arrangment



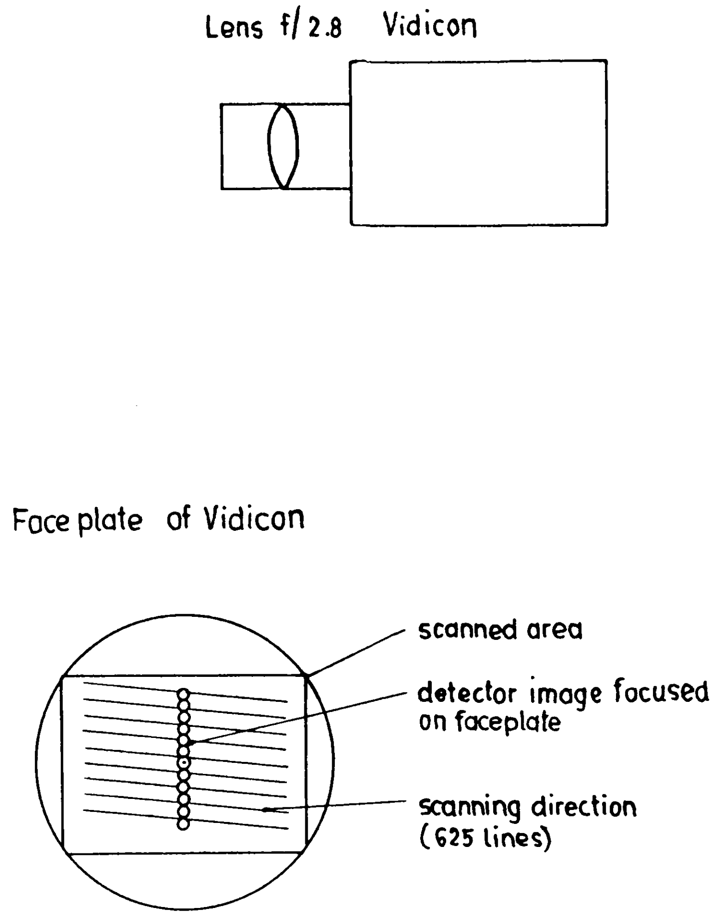


Fig. 1a , 1b

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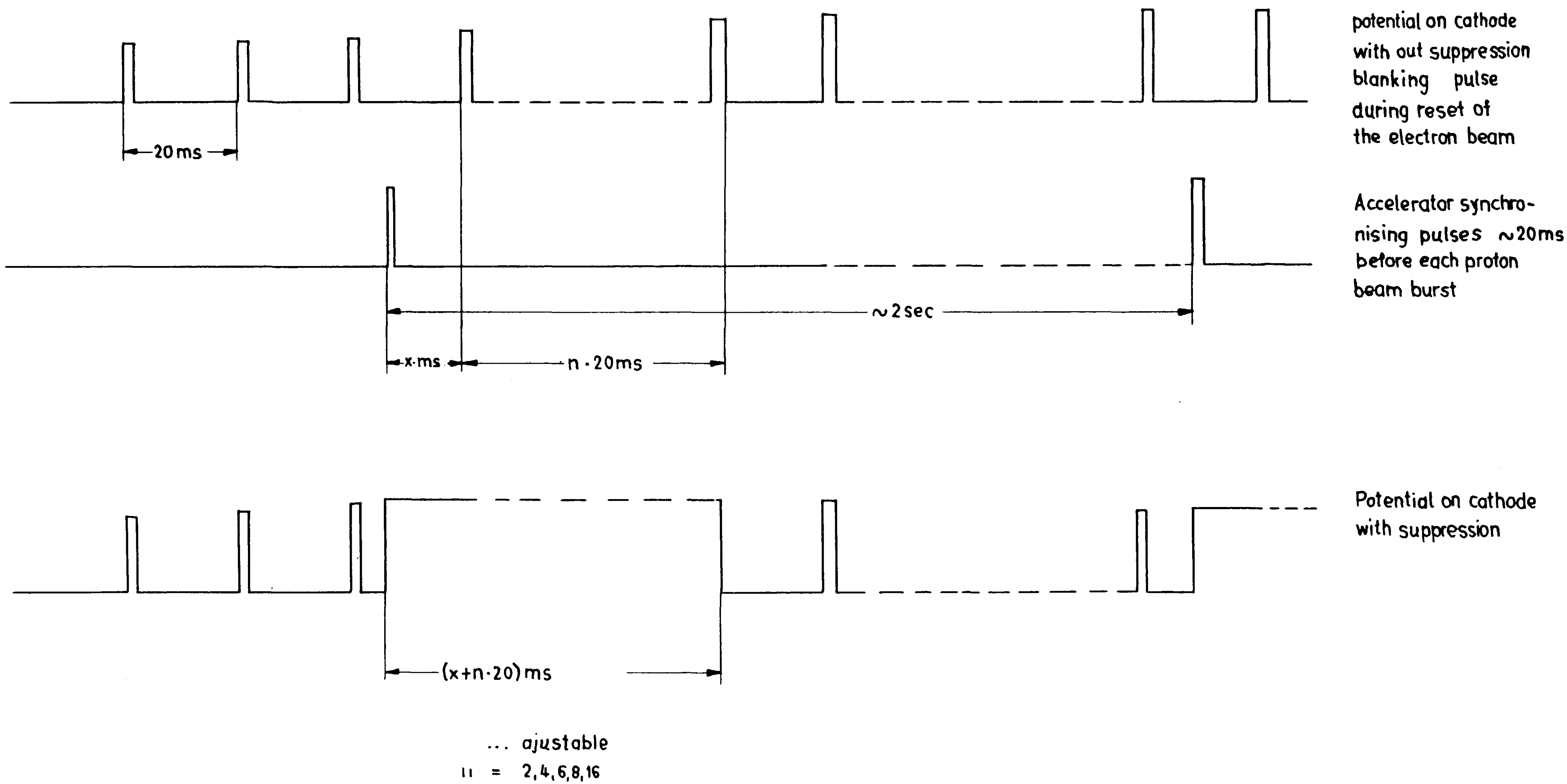
Fig. 2 Time diagramme of suppression pulses



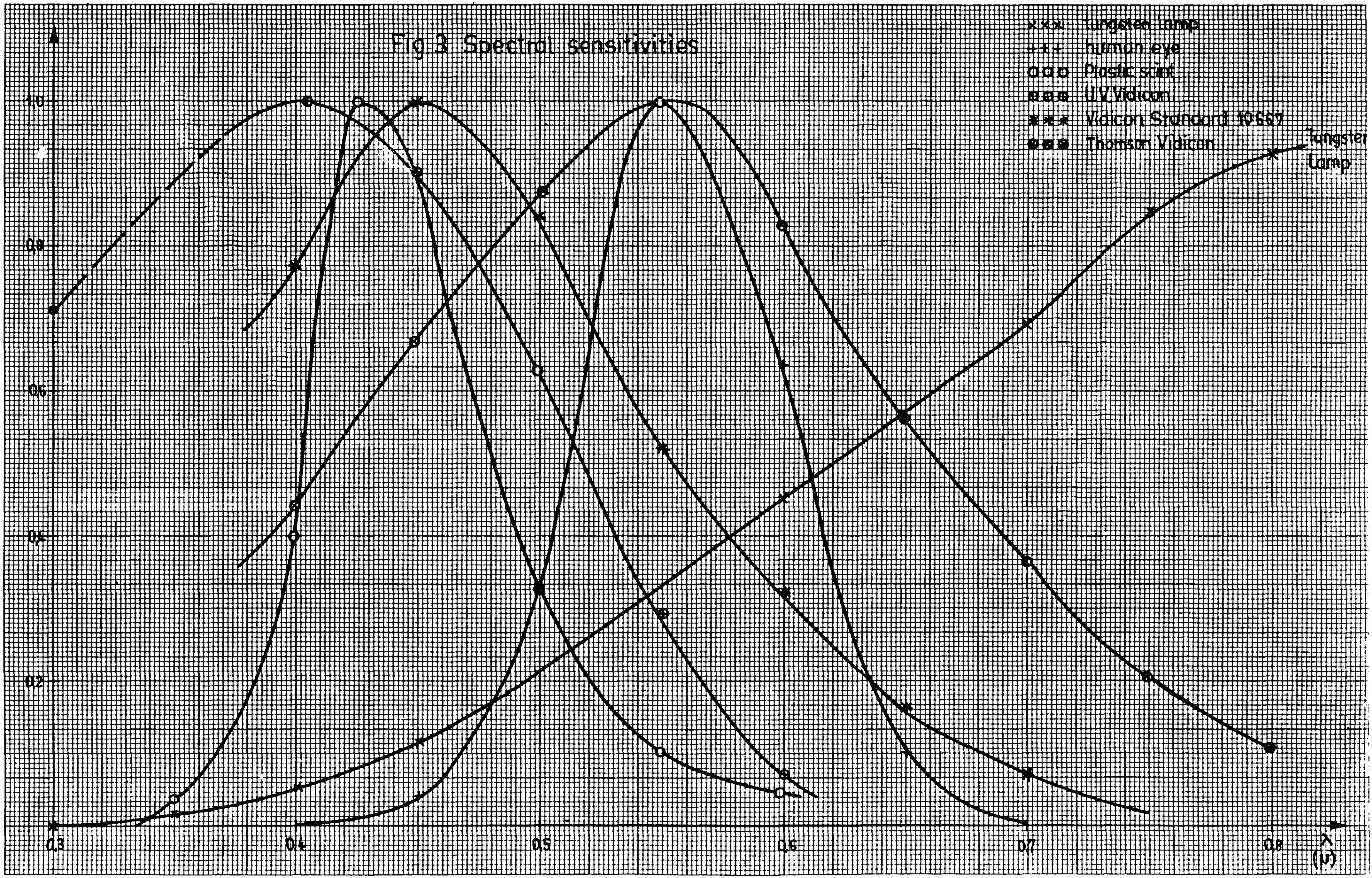


Fig 3 Spectral sensitivities
arbitrary units
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
λ (μ)
××× tungsten Lamp
+++ human eye
ooo Plastic scint
UV Vidicon
Vidicon Standard 10667
Thomson Vidicon
Tungsten Lamp

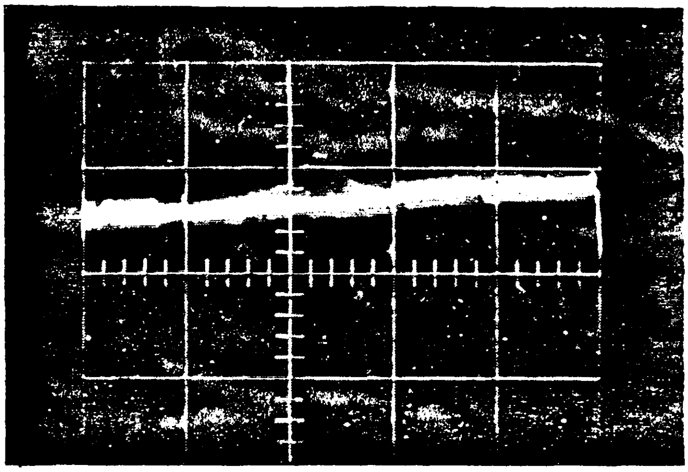


Photo 1
Plastic scintillator disc, viewed from behind
Intensity: $1\cdot10^{10}$ p/pulse
Scope: 2 msec/cm

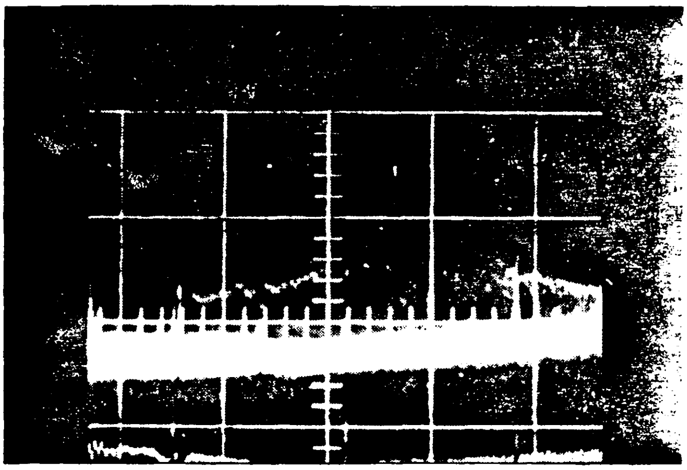


Photo 2
Plastic scintillator disc, viewed sideways
Intensity: $5\cdot10^{10}$ p/pulse
Scope: 2 msec/cm

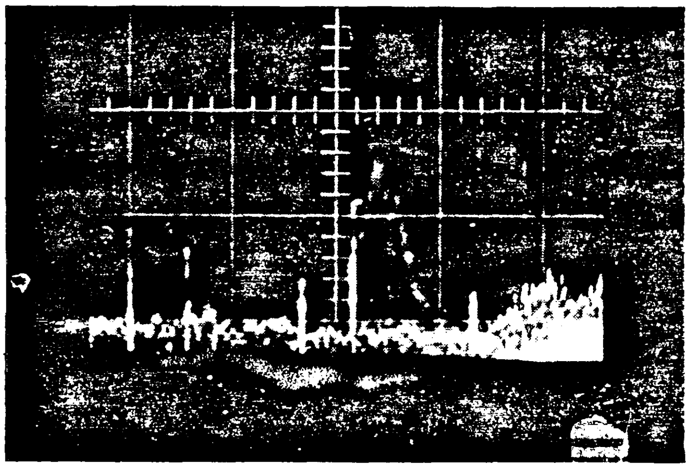


Photo 3
Filament device
Intensity: $4\cdot10^{11}$ p/pulse
Scope: 2 msec/cm

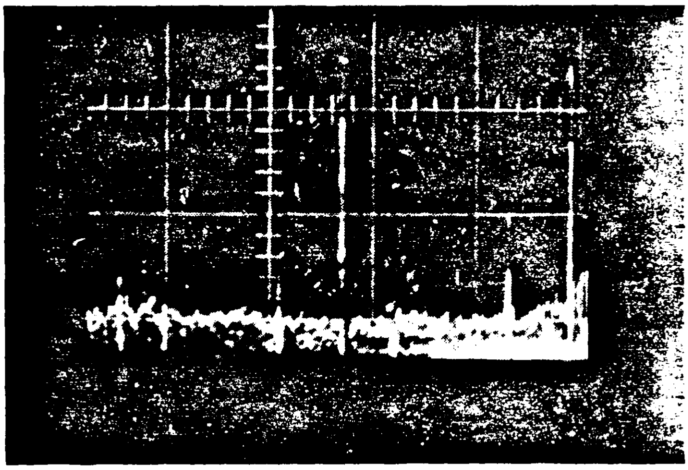


Photo 4
Filament device
Intensity: $2\cdot10^{11}$ p/pulse
Scope: 2 msec/cm