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Scintillating fibres

Heinrich Leutz

CERN, Geneva, Switzerland

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Abstract

This review first describes the basic working principles of scintillating fibres together with their most common readout techniques. It concentrates on plastic fibres, since they are better suited for application in High Energy Physics. The following section reviews fibre trackers and lead/scintillating calorimeters. Both detector devices are compared with competing techniques based on other media. The review continues with dose rates at the LHC collider and discusses the radiation damage on scintillating fibres. The conclusion covers the progress achieved with the fibre technique and presents an outlook on future developments.

1. Introduction

Particle detection with scintillating organic or inorganic solids and liquids has been refined during the last decade by the fibre technique, where scintillating cores with diameters ranging from several micrometres up to a few millimetres are surrounded by a cladding layer ($\leq 5 \mu\text{m}$) of lower refractive index. This structure is called "step-index" fibre in contrast to the "gradient-index fibre", (not used for scintillating fibres), where the refractive index decreases smoothly from the fibre axis to its surface. The step-index fibre traps by total reflections on its core-cladding interface a small fraction of the scintillation light, induced by ionization losses, and guides it via total reflections to the fibre end. There, it is detected by the photocathode of a photomultiplier or of an image intensifier. Scintillating fibres should not be confused with clear optical fibres, which are not doped with scintillators and are principally used to transport optical communications over long distances.

The detection of ionizing radiation with scintillating material has been quite generally practiced in the past, first in nuclear physics and subsequently in particle physics. Early attempts for improved granularity were reported during the late fifties, in which unclad plastic filaments were used [1-4]. These first fibre approaches became obsolete, since bubble- and spark chambers were the most frequently applied techniques for particle tracking at that time. In particular bubble chamber techniques offered bet-

ter track quality and spatial resolution. Chambers filled with liquid hydrogen provided ideal proton targets with long radiation- and interaction lengths. Scintillating fibre techniques became interesting again in the early eighties, with the advent of particle colliders and the necessity to detect rare particles in the presence of high background rates. Short light decay times of scintillators allowed high data acquisition rates and the mechanical properties of fibres permitted them to follow the required geometries of 4π detectors. In addition, considerable advances in the technologies associated with the fibre technique have been achieved since the late fifties, e.g., multi-anode photomultipliers, image intensifiers, and CCD cameras of high performance.

Since the early eighties, two main kinds of scintillating fibres have been used in parallel: glass fibres and plastic ones. In 1981, Borenstein et al. [5] reported on the properties of plastic fibres, with light decay times of a few nanoseconds, followed by Allemant et al. [6] and Blumenfeld et al. [7] in 1984. Potter [8] initiated in 1981 the application of glass fibres. In 1983, terbiumoxide doped glass fibres with $25 \mu\text{m}$ diameter were assembled by Ruchti et al. [9] to a 4 mm thick target plate, which was viewed by a three-stage image intensifier. Three years later, Bross [10] applied multi-glass fibres doped with ceriumoxide. They were of square cross sections ($25 \mu\text{m}$ edges) and formed a square bundle of 0.5 mm edges. Their light decay time was about 120 ns, a definite advantage compared to the 10 ns of the terbium doped ones.

Scintillating fibres are produced nowadays either from glasses, or from plastic polymers, e.g. polystyrene (PS) for the core (Table 1) and polymethylmethacrylate (PMMA) for the cladding. Instead of solid fibres, also glass capillar-

Tel +41 22 767 2709, fax +41 22 785 02 07

Table 1
Properties of polystyrene

General properties	
Average atomic number	3.5
Density [g cm^{-3}]	1.03
Proton/neutron ratio	1.17
Melting point [$^{\circ}\text{C}$]	240
Thermal conductivity [$\text{W cm}^{-1} \text{K}^{-1}$]	0.105
Linear thermal expansion coeff. [K^{-1}]	7×10^{-5}
Tensile modulus (E) [MPa]	3200
Dielectric constant	2.5
Optical properties	
Refractive index	1.59 (590 nm) 1.58 (480 nm)
Optical dispersion [ns m^{-1}]	0.04 (400 to 500 nm)
Light decay ($1/e$) [ns]	2 to 3 (depending on dopant)
Light velocity in PS [m ns^{-1}]	0.21
Numerical aperture	0.53 ($n_{\text{cladding}} = 1.49$) 0.69 ($n_{\text{cladding}} = 1.42$)
Photon yield (with dopant) [(keV) $^{-1}$]	~ 10 (depending on dopant)
Absorption peak [nm]	265
Emission peak [nm]	330
Fluorescence yield (pure)	0.03
Radiation properties	
Radiation length [cm]	42.4
Gamma conversion length [cm]	54.5
Nuclear interaction length [cm]	79.6
Multiple scattering angle [mrad]	0.73 (1 GeV/c; 1 mm PS)
(dE/dx) min [MeV/cm]	2.0

ies, which serve as cladding, can be filled with scintillating liquids of higher refractive index [11-13]. As compared with glass fibres [14] (Table 2), plastic ones and scintillating liquids in capillaries, which have similar properties, have better photon yield, longer light attenuation [15], shorter scintillation decay times [16,17] and longer nuclear interaction and radiation lengths, all of which make them more suitable for detector applications.

Therefore, this article is mainly concerned with plastic fibres and it starts with basic principles, including working conditions of scintillating fibres, the scintillation process and photoelectron counting. Then, it continues with a section on the detection of fibre scintillations, which treats photocathodes, position-sensitive photomultipliers, visible light photon counters, phosphor screens, spatial resolution of optoelectronic chains, proximity focussed image intensifiers, microchannel plates, charged coupled devices and imaging with silicon pixel arrays (ISPA).

The main applications of scintillating fibres in High Energy Physics are in particle tracking with fibre diameters well below 1 mm, and in calorimetry with diameters of 1 mm and above. Therefore, the last chapter on scintillating fibres in High Energy Physics is structured in the

Table 2
Properties of Ce-doped GSI^a scintillating glass [14]

General properties	
Density [g cm^{-3}]	2.64
Transition temperature [$^{\circ}\text{C}$]	620
Linear thermal expansion coeff. [K^{-1}]	7.5×10^{-6}
Optical properties	
Refractive index	1.59
Maximum emission [nm]	395
Photon yield [(keV) $^{-1}$]	~ 5
Decay time ($1/e$) [ns]	70 (fast component 30% intensity)
Numerical aperture	0.5 ($n_{\text{cladding}} = 1.51$)
Radiation properties	
Radiation length [cm]	9.8
Gamma conversion length [cm]	12.6
Nuclear interaction length [cm]	37.4
Multiple scattering angle [mrad]	1.52
(1 GeV/c; 1 mm GSI)	
(dE/dx) min. ionizing [MeV/cm]	4.6

^a Levy Hill Laboratories, Cheshunt, Waltham, England.

following way: particle tracking (the UA2 fibre tracker, the Cnorus fibre tracker, the proposed fine grain central tracker) and calorimetry with scintillating fibres.

The chapter on High Energy Physics applications ends with a paragraph on dose rates and radiation damage for fibre detectors at LHC. It quotes dose rates for fibre trackers with different distances of fibre shells from the collider axis and discusses the main parameters, which could influence the radiation damage of plastic fibres. Finally, the conclusions review the progress achieved with the scintillating fibre technique within the last few years and present an outlook on future developments.

2. Basic principles

2.1. Working conditions of scintillating fibres

The PS core is clad with PMMA of lower refractive index ($n_{\text{clad}} < n_{\text{ps}}$) and the fibre traps a fraction t of the scintillating light contained within its total reflection cones (Fig. 1). The cladding also protects the fibre core against deterioration of its surface, which otherwise would result

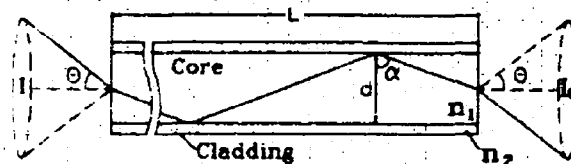


Fig. 1. Light cone injected with a numerical aperture NA and passing through a step-index fibre under the total reflection angle α .

Table 3.
Properties of fibre dopants dissolved in polystyrene, toluene and cyclohexane

Compound	Maxima		Molar mass [g mole ⁻¹]	Decay time [ns]	Fluor. yield	Stokes shift [eV]	Supplied by
	Abs. [nm]	Emiss. [nm]					
Two component scintillator:							
p-terphenyl ^b	275	340	230	0.95	0.93	0.86	NE-110 ^c , NE 102A ^c , BC400 ^d , BC412 ^d , SCSN81T ^e
PBD ^b	300	360	354	1.0	0.83	0.69	Saclay, Gif sur Yvette, France, SCSN38 ^e
wavelength shifter:							
POPOP	360	420	364	1.5	0.93	0.49	NE 102 A ^c , BC 400 ^d
BBOT ^b	370	425	430	1.1	0.74	0.43	SCSN81T ^e
TPBD ^b	345	450	358	1.8	0.6	0.84	NE-110 ^c , BC412 ^d
BDB	350	415	414			0.55	SCSN38 ^e
One component							
3HF	340	530	238	8.0	0.4	1.27	Kuraray ^c , Bicon ^d
PMP 420	300	415	264	3.0	0.88	1.11	Kuraray ^c
PMP450	305	435	294	3.6	0.74	1.24	Kuraray ^c
PBBO	330	395	347	2.1	0.79	0.62	Saclay, Gif sur Yvette, France
R39 ^a	~ 330	480	346	~ 7.0		~ 1.17	Geosphera, Moscow, Russia
R45 ^a	~ 330	490	364	~ 7.0		~ 1.22	Geosphera, Moscow, Russia

^a Toluene.

^b Cyclohexane.

^c Nuclear Enterprises, Edinburgh, Scotland.

^d Bicon Corp., Newbury, Ohio, USA.

^e Kuraray, Tokyo, Japan.

in bad total reflection conditions. For meridional light rays¹ the trapping fraction amounts to

$$t = 1 - (n_2/n_1)^2 \quad (1)$$

where n_1 refers to the PS core and n_2 to the acrylic cladding.

The untrapped light fraction n_2/n_1 is absorbed by an extra mural absorber (EMA) if the fibre is coated with a black layer. Even if the EMA is not present, the untrapped light fraction escapes at an angle, which prevents it from being retrapped in a neighbouring fibre and disappears after some 50 mm of fibre length without causing noticeable cross-talk.

The trapped light fraction is guided via N subsequent total reflections (critical angle α , $\sin \alpha = n_2/n_1$) to the fibre end:

$$N = \cot \alpha L/d, \quad (2)$$

with L the fibre length and d its diameter. The numerical

aperture NA of the fibre is again defined by the respective refractive indices (see Fig. 1):

$$NA = (n_1^2 - n_2^2)^{1/2} = \sin \theta. \quad (3)$$

The fibre diameter defines the spatial resolution and, for tracking detectors, we are interested in keeping it small. A decrease in fibre diameter is counterbalanced by the increasing number N of reflections (Eq. (2)). Since imperfections at the fibres' core-cladding interfaces, cause small reductions from unity for the total reflection coefficient q , the increased number of reflections induces light losses ($I/I_0 = q^N$) and we obtain as an approximation [15] the reflection length A_R (m), which indicates the distance l , where the injected light intensity $I/I_0 = e^{-l/A_R}$ is reduced to $1/e$ due to these reflection losses

$$A_R = \frac{1.5}{1-q} \frac{n_1}{NA} d. \quad (4)$$

Therefore, with small fibre diameters d [m], the reflection losses, which have been measured for Kuraray fibres [15], contribute noticeably together with the absorption length A_A ($I_A/I = 1/e$) and the scattering length A_{sc} ($I_{sc}/I = 1/e$) to the total fibre attenuation length A :

$$A^{-1} = A_A^{-1} + A_R^{-1} + A_{sc}^{-1}. \quad (5)$$

The absorption length A_A [m] is mainly caused by the decadic molar extinction coefficient ϵ_A [1/m mol⁻¹] of the

¹ Skew light rays arise mostly at the rim of the fibre core and spiral along the core-cladding interface. Adding them to meridional rays would change Eq. (1) to $t = 1 - (n_2/n_1)^2$. They suffer much more total reflections than meridional ones and are diffused out of the core after short travelling paths compared to meridional rays.

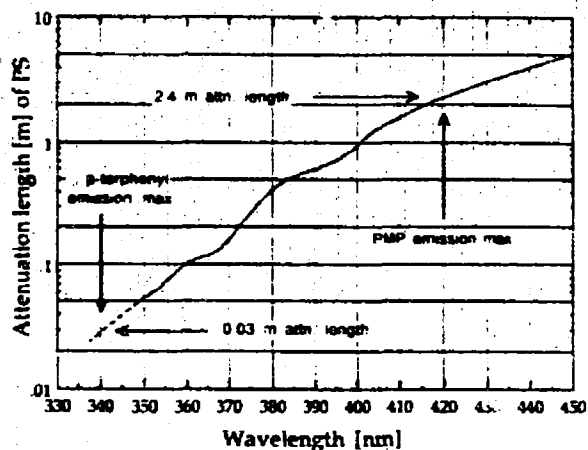


Fig. 2. Light attenuation measured at CERN by the RD-7 collaboration.

fibre dopant within the dopant's emission band (Fig. 3), and is defined as the value of the light pathlength D [m] at which the light yield $Y(D)$ drops to $1/e$ of its initial value at zero D :

$$Y(D) = \int_{cm} I_{\lambda}^{em} 10^{-\epsilon_{\lambda} CD} d\lambda \quad (6)$$

with I_{λ}^{em} the emission intensity normalized to unity and C the scintillator concentration [mole/l]. It is therefore important to use scintillators where the absorption and emission maxima are well separated, i.e. with large Stokes' shifts.

The scattering length λ_c [m] quantifies Rayleigh scattering on small density fluctuations in the PS core. Fig. 2 shows the attenuation lengths mainly caused by light scattering for light injected parallel to the axis of an undoped PS fibre. They contribute noticeably to the total light attenuation below 400 nm and drop to 0.03 m at 340 nm, the p-terphenyl emission maximum (Table 3). This behaviour explains the opacity of polystyrene although its absorption band peaks at 265 nm (Table 1), far from the p-terphenyl emission.

2.2. The scintillation process

The energy lost by an ionizing particle first excites the electronic (rotational and vibrational) levels of PS (Fig. 3a). Since the PS fluorescence yield is rather poor (Table 1), it must be enhanced by adding an aromatic scintillator. The intermolecular energy transfer between the respec-

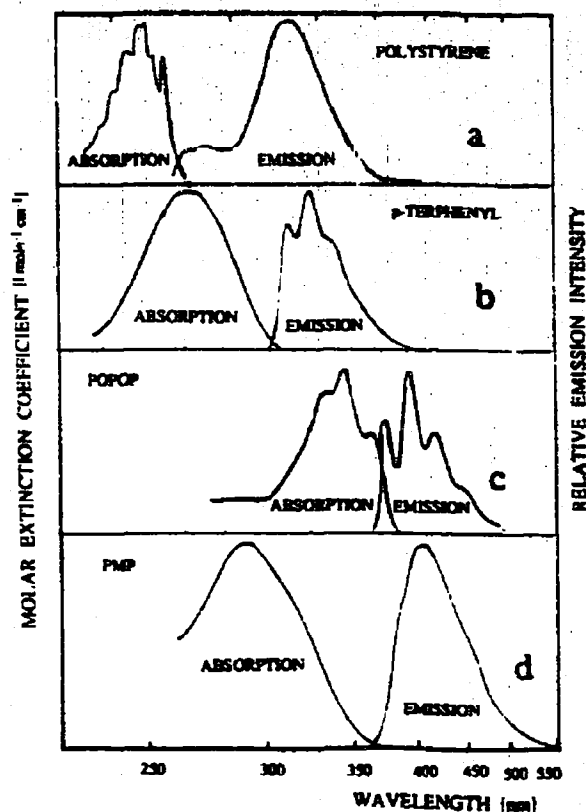


Fig. 3. Absorption and emission bands of the PS fibre core (a), the p-terphenyl scintillator (b). The wavelength shifter POPOP (c) matches with its absorption band the p-terphenyl emission. The PMP 420 scintillator (d) spans due to its large Stokes' shift directly the wavelengths between the PS emission and the transparent PS region without needing a wavelength shift.

tive quantum levels requires that the PS emission band overlaps the scintillator absorption band. If the added scintillator emits in the opaque region of PS (see Fig. 2), e.g. p-terphenyl (Fig. 3b), a wavelength shifter (Fig. 3c) is needed to shift its light emission into the transparent region of PS (two-component system), where Rayleigh scattering becomes unimportant and the PS attenuation length reaches about 2.4 m (Fig. 2).

A sufficiently high scintillator concentration (above 0.015 molar fraction) provides mainly nonradiative and therefore local energy transfer (Förster transitions) [18] between the PS and the scintillator. This comparatively high concentration can be added with PMP (1-phenyl-3-mesityl-2-pyrazoline) [19], since due to its large Stokes' shift (Table 3) it emits in the transparent PS region (one-component system) and the long wavelength tail of its absorption band (Fig. 3d) causes only small self-absorption within its emission band. This is not the case with a two-component system, since absorption and emission of POPOP and other wavelength shifters (Table 3) overlap within a large wavelength region (Fig. 3c). This overlap must be compensated by a much lower POPOP concentra-

¹ A historical development of theories on the excitation of electronic states and the intermolecular energy transfer can be found in the books of I.B. Berlman: Handbook of Fluorescence spectra of aromatic molecules (Academic Press, New York, London, 1971) and Energy Transfer Parameters of Aromatic Compounds, same publisher (1973).

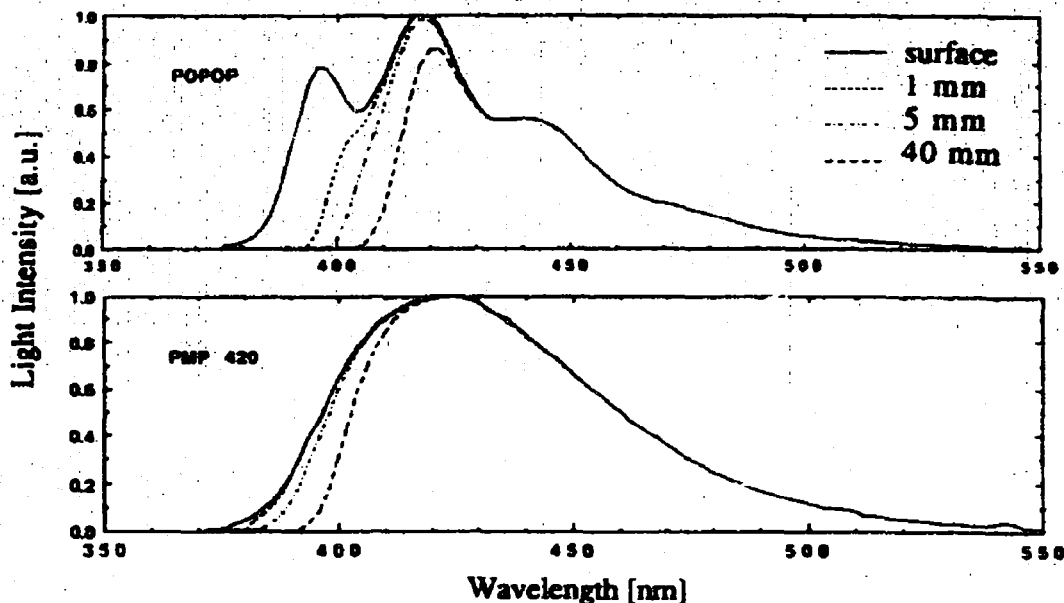


Fig. 4. Distortions of the short-wavelength flank of a 0.025M PMP-420 solution in toluene caused by different absorption paths of the same solution compared with a 0.0025M POPOP solution. The POPOP concentration had to be ten times lower, because of its strong self-absorption in the overlap region.

tion and its molecules are therefore too distant to enable nonradiative Förster transitions. This is obvious in Fig. 4 which shows the self-absorption of POPOP and PMP-420 solutions in toluene caused by different absorption lengths. The respective absorption bands were excited with light from a double-monochromator and the emission was analysed by a single-monochromator [20]. In spite of a POPOP concentration (0.0025 molar fraction) ten times smaller than that for PMP-420 (0.025 molar fraction), the POPOP self-absorption is still much more pronounced due to its large overlap.

Therefore, with a two-component system, normal radiative exchange of light emission and reabsorption takes place between the two dopants which requires optical absorption lengths longer than 150 μm . Consequently the light emitted from the first dopant can escape from fibres of small diameters, excite the wavelength shifter in neighbour fibres and cause unwanted cross-talk. This is particularly true for bundles of PS fibres, since it is not possible to produce them with extra mural absorbers. Cross-talk can be avoided by doping the PS matrix with only one scintillator (one-component system) having a large Stokes shift and therefore small overlap between its absorption and emission bands, e.g. PMP or 3HF (3-hydroxyflavone) [21]. At appropriate concentrations, they produce local Förster transitions between the relevant PS and their proper energy levels. 3HF has practically zero overlap but yields only about 40% emission as compared with PMP (Table 3).

This is demonstrated in Fig. 5. Two fibre bundles of 1 mm diameter containing 30 μm diameter individual fibres have been excited with a Nd-YAG laser at 265 nm wave-

length. The emitted light, guided through 150 mm bundle length, was photographed with a CCD camera [22]. The left-hand photograph shows the result obtained from the fibres doped with p-terphenyl and the POPOP wavelength shifter. It indicates cross-talk over six fibre layers. In contrast, the right-hand photograph displays the picture taken with the PMP doped fibre bundle, where light is emitted and guided only from the first fibre layer exposed to the laser beam. Since no light is lost via cross-talk, the light yield from this layer is much higher than on the left-hand photograph.

2.3. Photoelectron counting with scintillating fibres

Photoelectron counting characterizes quality and performance of scintillating fibres in an objective way in contrast to the often quoted attenuation lengths. Attenuation lengths are composed of different attenuation terms (Eq. (5)) and their attenuation plots deviate therefore from straight lines in logarithmic representations. Therefore, they depend on the fibre lengths between which they are quoted. Until recently, most photoelectron counting procedures were based on photomultipliers, where the Quantacon³ resolved up to three photoelectron peaks [23]. Since 1992 an electrostatically focused hybrid photomultiplier tube (HPMT)⁴

³ NSSL, Burle Electron Tubes, Lancaster, PA, USA.

⁴ BV Delft Elektronische Producten (DEP) NL-9310 AB Roden, The Netherlands.

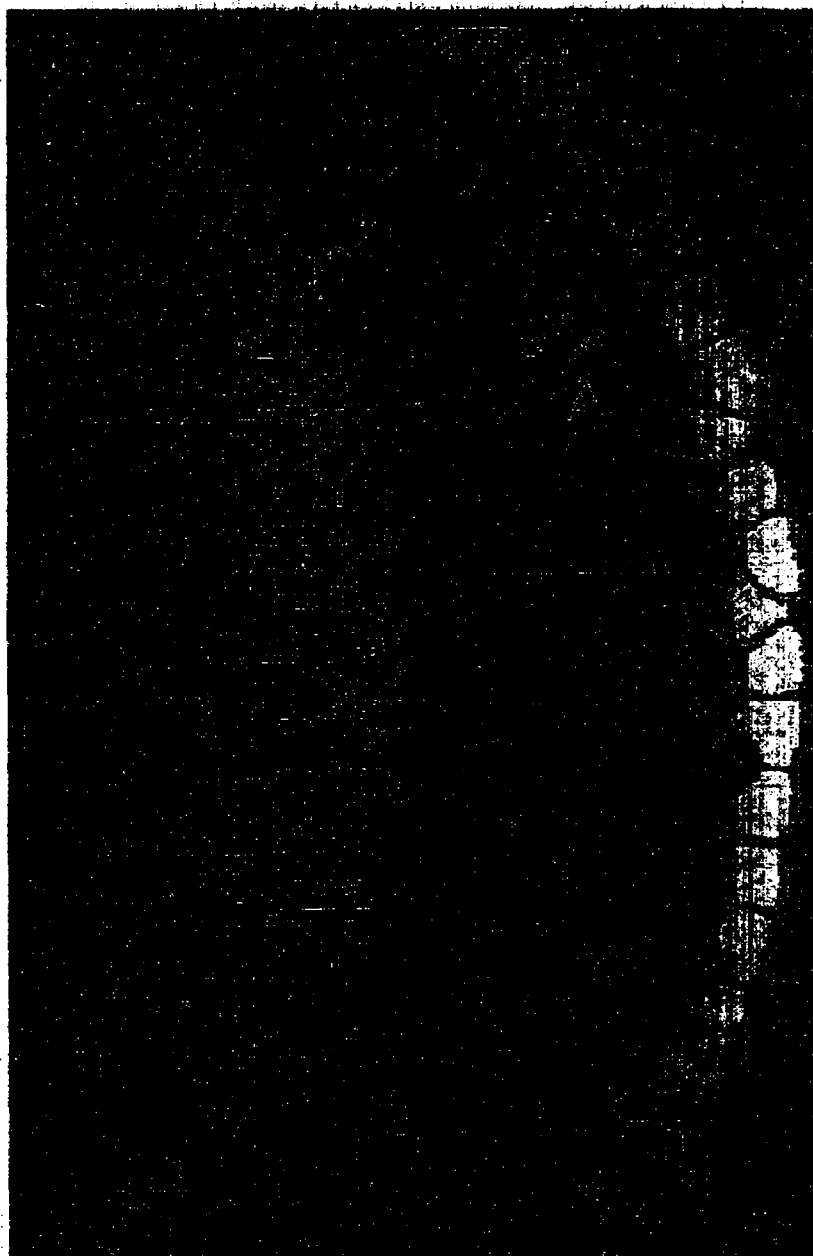


Fig. 5. Cross-talk of scintillating fibres (left hand) in a fibre bundle doped with *p*-terphenyl and POPOP (2-components). No cross-talk (right hand) in a fibre bundle with PMP doping (1-component), otherwise same excitation and light detection as for the left hand picture. The higher light output of the right hand monolayer also indicates that no scintillating light crosses to the neighbouring fibre layer.

has been commercially available, which contains a silicon diode bombarded with electrons from a light detecting photocathode (Fig. 6). With 13 kV potential difference, it results in an average of 3575 electron-hole pairs per photoelectron and exceeds by more than two orders of magnitude the electron multiplication at the first dynode of a photomultiplier. This is reflected in the statistical fluctuations and increases the number of resolved photoelectron peaks to about 15 [24].

Photoelectron yields were measured [25] on fused fibre

bundles [26] containing 1600 fibres of 60 μm diameter within squared cross sections of 2.5 mm edges⁵ (Fig. 7). Each individual fibre (Fig. 8) shares its double cladding [23,25], which consists of standard polymethyl-methacrylate of 1.49 refractive index and fluorinated polymethacrylate of 1.42 refractive index, with its next neighbours.

⁵ Kuraray Co. Ltd. Tokyo, Japan.

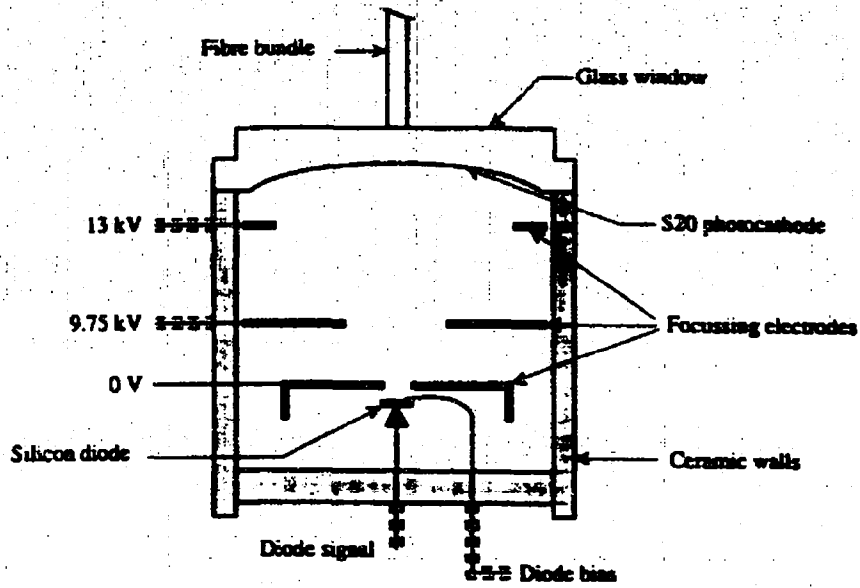


Fig. 6. The hybrid photomultiplier tube (HPMT).

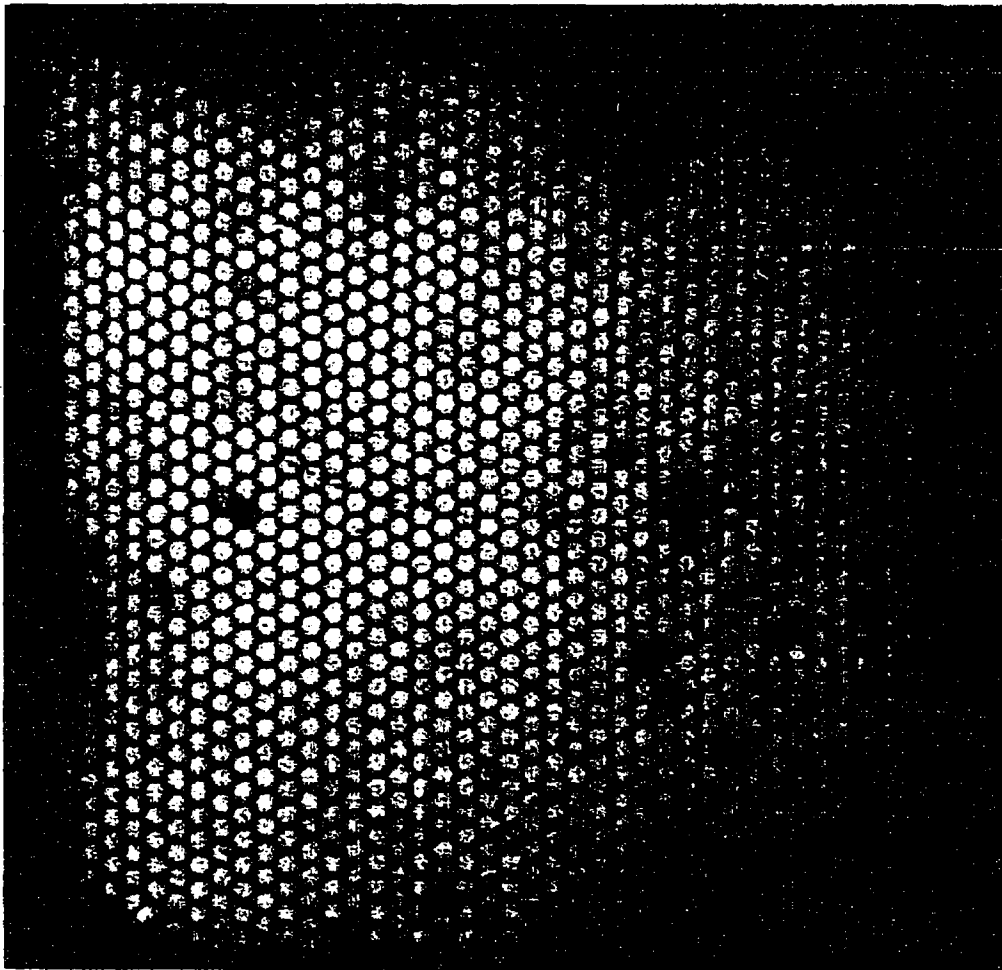


Fig. 7. Square bundle with 2.5 mm edge length. It contains about 1600 individual fibres of 60 μm diameter. The photograph is taken with a CCD camera through 2 m bundle length.

Typical measured photoelectron spectra are displayed in Fig. 9 for different source positions. They show discrete Gaussian peaks on top of a continuum, caused by backscattering of photoelectrons from the HPMT diode. The number b of backscattered electrons follows a Poisson distribution

$$P(b) = \frac{(\langle n \rangle \alpha)^b}{b!} e^{-\langle n \rangle \alpha}, \quad (7)$$

with $P(b)$ being the probability of having b backscattered photoelectrons. The measured backscattered fraction α agrees with Ref. [27] and completely explains [24] the spectral shapes in Fig. 9.

Hit densities measured with a Quantacon for 1 mm monofibres from different suppliers are listed in Table 4. The Bicon fibre (99-02) showed the outstandingly small light attenuation with distance of only 3.3 times between zero position and 2 m.

Four fibre bundles were more recently measured with the HPMT [25] and these results are listed in Table 5. The improvement in hit densities is mainly due to the fluorinated polymethacrylate cladding, which increases, with its 1.42 refractive index, the trapping fraction by 1.75 times. Additional improvement is due to the better photoelectron collection efficiency of the HPMT as compared to that of the first Quantacon dynode.

3. Detection of fibre scintillations

3.1. Photocathodes

Photocathodes can be manufactured from a variety of compounds and each type has its characteristic spectral response: S11 (Sb-Cs), bialkali (Sb-K-Cs or Sb-Rb-Cs), S20 (Na-K-Sb-Cs) trialkali, S1 (Ag-O-Cs) and others.



Fig. 8. An individual fibre within a bundle (Fig. 7) surrounded by its six adjacent neighbours. It was illuminated at one end through a microscope objective and photographed at the other end after remagnification with a CCD camera.

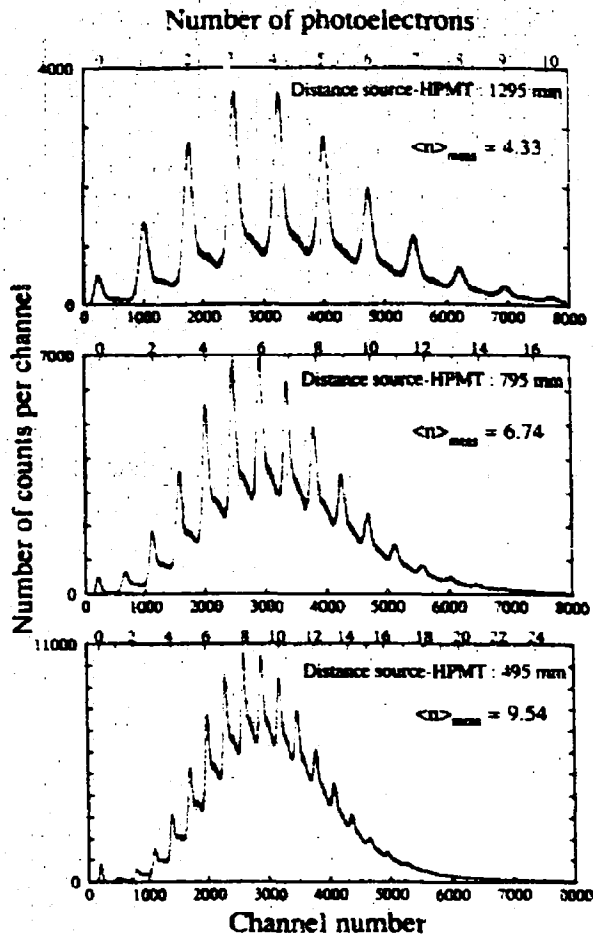


Fig. 9. Photoelectron distributions at different β -source distances measured with HPMT, and 60 μm diam fibres.

Table 4

Comparison of hit densities per mm for different monofibres measured with our equipment. M, Optoelectron aluminised monofibre, $\varnothing=1$ mm; N, Bicon 99-102, $\varnothing=1$ mm; O, Bicon BCF10, 2×2 mm²; P, Kuraray SCSF81, $\varnothing=1$ mm

Pos. [mm]	M	N	O	P
0	6.88	4.78	3.27	3.55
50	6.07	4.51	3.05	3.18
100	5.24	4.16	2.78	2.69
200	3.97	3.82	2.31	2.34
300	3.44	3.58	2.02	2.09
400	3.03	3.31	1.78	1.88
500	2.86	3.07	1.63	1.70
800	2.25	2.59	1.29	1.41
1000	1.88	2.34	1.07	1.23
1200	1.70	2.10	0.94	1.12
1400	1.43	1.94	0.77	0.98
1600	1.27	1.77	0.67	0.86
1800	1.15	1.60	0.58	0.78
2000	1.00	1.45	0.54	0.69

Table 5

Hit densities [photoelectrons mm⁻¹] for four bundles of same dimensions: square cross section with 2.5 mm edges containing 1600 individual fibres of 60 μm diameter

Position [mm]	Bundle No. 1	Bundle No. 2	Bundle No. 3	Bundle No. 4	Average
0	10.94	10.38	10.67	10.38	10.59
50	8.41	8.34	8.27	8.40	8.36
100	7.03	7.15	7.06	7.18	7.11
200	5.56	5.72	5.65	6.05	5.75
300	4.71	4.8	4.71	5.09	4.83
400	4.11	4.12	4.11	4.32	4.17
600	3.20	3.27	3.24	3.34	3.26
800	2.58	2.69	2.68	2.72	2.67
1000	2.14	2.18	2.19	2.24	2.19
1200	1.77	1.77	1.81	1.88	1.81
1400	1.47	1.48	1.53	1.57	1.51
1600	1.25	1.24	1.28	1.32	1.27
1800	1.08	1.09	1.10	1.15	1.11
2000	1.01	0.97	0.94	1.04	0.99

Their spectral response is measured as radiant sensitivity $R(\lambda)$ (photocathode current emitted per watt of incident radiation at wavelength λ) or as quantum efficiency $QE(\lambda)$

$$QE(\lambda) = R(\lambda)1.24/\lambda, \quad (8)$$

where $R(\lambda)$ is in mA W⁻¹, the wavelength λ in nm, and 1.24 is the conversion factor from wavelength to photon energy. For example, a quantum efficiency of 0.25 at 400 nm wavelength is equivalent to a radiant sensitivity of 80.6 mA/W.

Photocathodes are evaporated as thin films on the inside of the tube's light input window. To preserve the spatial resolution of the attached scintillating fibres, this window is made from a stack of fused clad glass fibres (\varnothing 5 to 20 μm). The light transmission of optical fibre windows depends on their numerical aperture ($NA_{\text{fibre}} \leq NA_{\text{window}}$), packing fraction (related to the fibre diameter) and the absorption characteristics of the fibre cores.

3.2. Position sensitive photomultipliers (PSPM)

The photon image of scintillating fibres hitting the photocathode is conserved through the electron multiplication at the dynode stages and is reproduced in the multianode plane. Losses in spatial resolution are mainly due to the spread of secondary electrons at the dynodes. This drawback is counterbalanced by high gain and by fast response (a few ns). The anode plane consists either of crossed wires (up to 16×16) or arrays of up to 256 anodes with about 3 mm pitch. Aligned with a solenoidal field, cross-talk between anode wires or pixels is reduced and the spatial resolution improved but the gain of one

Table 6

Properties of phosphor screens mounted in image intensifiers. The numerical order follows the nomenclature of the EIA Tube Engineering Advisory Council (TEPAC). Decay time: 10% of initial intensity.

No.	Phosphor composition	Max emiss. [nm]	Decay time [ns]	Matched to
P16	Ca-Mg-silicate (Ce)	380	120	Bialkali, S20
P37	ZnS, Ag, Ni	460	150	multialkali, S20
P46	Y-aluminate (Ce)	530	160	CCD, GaAs, photodiodes
P47	Y-silicate (Ce)	400	85	Bialkali, S20
P48	blend of P46 and P47	400/530	125	multialkali

million at zero magnetic flux density drops to some ten thousands at 1 T. Several types of PSPMs are offered by principally two manufacturers^o.

3.3. Visible light photon counters (VLPC)

VLPCs are silicon solid-state photomultipliers [28] with optimized response in the visible light region. A visible photon is either absorbed in the undoped blocking layer or in the doped gain region. From the blocking layer the electron is collected at the top contact and the hole drifts into the gain region, where it produces free electrons by impact ionization with neutral donor (As) impurities. The impurity concentration is high enough to form an energy band separated from the silicon conduction band by 0.05 eV ionization energy. The photon absorbed in the gain region produces almost the same electron avalanche as the hole from the blocking layer if the electric field is approximately 1 kV cm^{-1} . The avalanche is limited to some 10^4 electrons because of electron-hole recombinations.

With antireflective coating the VLPC quantum efficiency reaches about 85% at 550 nm. In order to reduce intolerably high thermal noise, the VLPCs need to be cryogenically cooled to an optimum operating temperature T of 6.5 K. Below this temperature ($\Delta T = -0.1 \text{ K}$) the avalanche gain is reduced and above ($\Delta T = +0.1 \text{ K}$) the signal-to-noise ratio worsens rapidly. Fig. 10 shows three photoelectron spectra taken of a Sr-90 β -source positioned at different distances. They should be compared with those shown in Fig. 9, which were taken with an HPMT tube and clearly show better signal-to-noise ratios. VLPCs can be attached to individual fibres only, which limits the tracker's granularity. In contrast, detectors converting scintillations into electrons via photocathodes are not limited in fibre sizes since the photolayers with less than $3 \mu\text{m}$ granularity match fibres down to $10 \mu\text{m}$ diameter.

^o Hamamatsu Photonics K.K., Toyooka-village, Japan and Philips Photonics, with offices in USA, UK, France, Germany, Japan.

3.4. Phosphor screens

Phosphors are highly purified inorganic crystalline materials to which small amounts of dopants have been added. They convert electron energy into radiant energy. Their crystals are sized between 0.2 and $20 \mu\text{m}$ and are

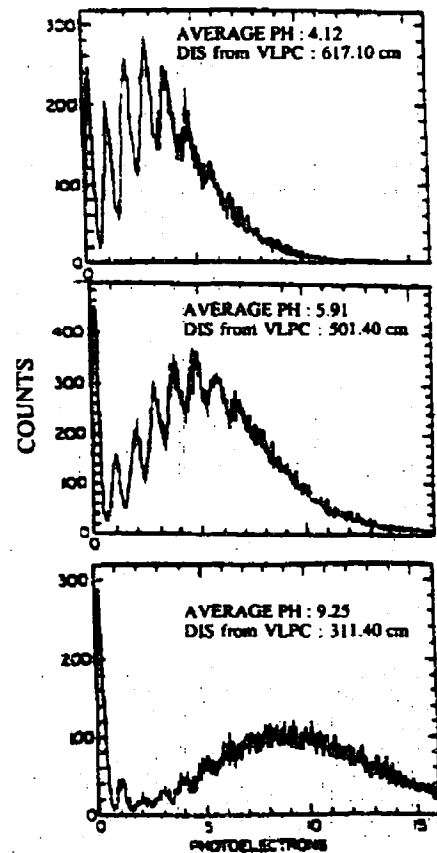


Fig. 10. Pulse height spectra [29] obtained at the indicated β -source positions. They include 3 m of clear fibres that guided the light from the $830 \mu\text{m}$ diam scintillating fibre to the He-Dewar that housed the VLPC at 6.5 K.

photo- or vapour deposited on glass substrates at the output optical fibre windows of image intensifiers. For conversions of fibre images in an optoelectronic chain, they must be fast, of high spatial resolution and their light emission must be matched with the subsequent photocathode or CCD sensitivity. Some typical phosphors used for image intensifiers are listed in Table 6.

3.5. The spatial resolution of optoelectronic chains

In this context, we should clearly distinguish between spatial precision, which means the accuracy to locate a hit within the detector's frame, and spatial resolution. This latter term is defined as the classical resolving power in optics: two neighbored objects are resolved if the principal maxima of their diffraction patterns (Airy discs) are just separated. This is mathematically defined with the modulation transfer function (MTF), which for circular apertures and far field has the form:

$$\text{MTF} = 2/\pi \left[\arccos(\omega/2) - \omega(1 - \omega^2/4)^{1/2} \right], \quad (9)$$

with $\omega = (f\lambda l)/(\pi\rho)$, where f [line pairs/mm] means the spatial frequency, ρ [mm] the diameter of the aperture, λ [mm] the wavelength and l [mm] the distance between aperture and image plane. The MTF varies between unity (complete separation of the Airy discs) and zero (complete overlap): $0 \leq \omega \leq 2$.

For a scintillating fibre bundle directly attached to a detecting photocathode, the MTF becomes

$$\text{MTF} = (2J_1(df)/\pi df)^2, \quad (10)$$

with J_1 being the Bessel function of the first kind and d [mm] the fibre diameter.

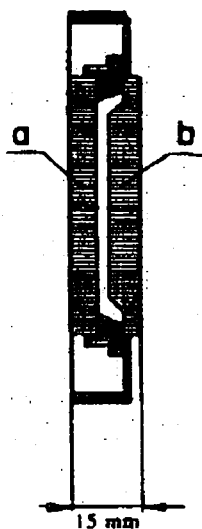


Fig. 11. Proximity focussed image intensifier: (a) optics fibre window with photocathode; (b) phosphor screen with optics fibre window.

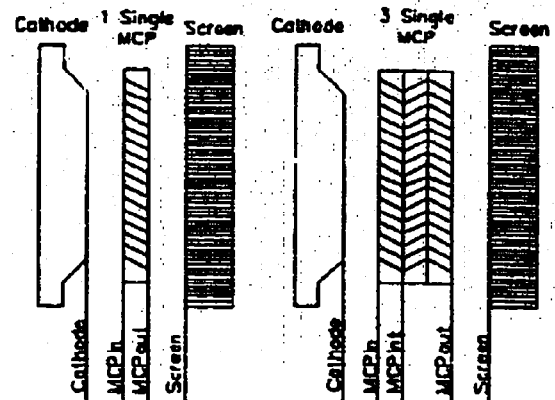


Fig. 12. Image intensifier multichannel plate (MCP) configurations.

In an optoelectronic chain, consisting of scintillating fibres, fibre optics windows, image intensifiers, scintillation screens, etc., the total MTF_{tot} is given by the product of the individual components MTF_i :

$$\text{MTF}_{\text{tot}} = \prod \text{MTF}_i. \quad (11)$$

Accordingly, the number f_{tot} of line pairs per mm of an optoelectronic chain is composed of the individual spatial frequencies f_i , and their reciprocal values add quadratically

$$f_{\text{tot}}^2 = \sum f_i^2. \quad (12)$$

In most cases, the spatial frequencies of image intensifiers, fibre optics windows, and other optical components are quoted as the limiting resolution for $\text{MTF} = 0.03$.

3.6. Proximity-focussed image intensifiers

These devices achieve distortion-free image conversions between photocathode and phosphor screen which are in close proximity (between 3 and 5 mm) to each other (Fig. 11). Their gain of about 50 W/W is due to their high potential difference of 25 kV.

Their limiting resolution is about 40 line pairs/mm. Proximity focussed intensifiers immediately follow the fibre end faces. Depending on the desired amplification one might use a chain of up to three intensifiers followed in many arrangements by MCPs and CCDs.

3.7. Microchannel plate image intensifiers (MCP)

These tubes yield large photoelectron multiplications, which are achieved with microchannel plates, located inside the tube between photocathode and phosphor screen (Fig. 12). A microchannel plate is a 0.5 to 1 mm thick disc, which contains closely packed 6 to 15 μm thin hollow tubes, across which a potential difference of several

hundred V is applied. The electrons, emitted from the opposite cathode, are accelerated by a 200 V potential difference and enter the MCP, where electron multiplication is produced via successive interactions with the walls of the hollow tubes. Electrons leaving the MCP are finally accelerated to the phosphor screen by a potential difference of approximately 10 kV.

A drawback of MCPs is the packing fraction of the hollow tubes, which worsens the spatial resolution and reduces the original hit density of scintillating fibres. In addition, moderate magnetic flux densities (≥ 0.5 T), prevent the electrons from hitting the tube walls and therefore stop electron multiplication.

3.8. Charged coupled devices (CCD)

CCDs convert optical images (in most cases from phosphor screens of image intensifiers), into electronic signals. This is achieved by an array of photoelements (silicon pixels) of some tens of μm edge dimensions arranged in a two-dimensional matrix of about 1 cm^2 area (image zone). Each pixel stores the photocharges in a MOS capacitor (space charge zone) and transfers them sequentially as an analog shift register to a memory zone, which is masked from incident light. The charges are finally accumulated in the readout register, and a diode converts the electric charges into voltage signals. These operations are driven by a clock in the MHz frequency range and the entire readout process for a CCD array takes a few ms. In most cases, each pixel is protected against over-illumination (antiblooming), by a diode, which is separated from the photoelement by a potential barrier. The excess charges are drained off as a weak current.

A thinned CCD matrix yields electronic signals if bombarded with electrons at its rear face (EB-CCD). The electrons hit the pixels on their rear side, which is thinned to allow their penetration into the space charge zone. In this way, photoelectrons emitted from photocathodes can

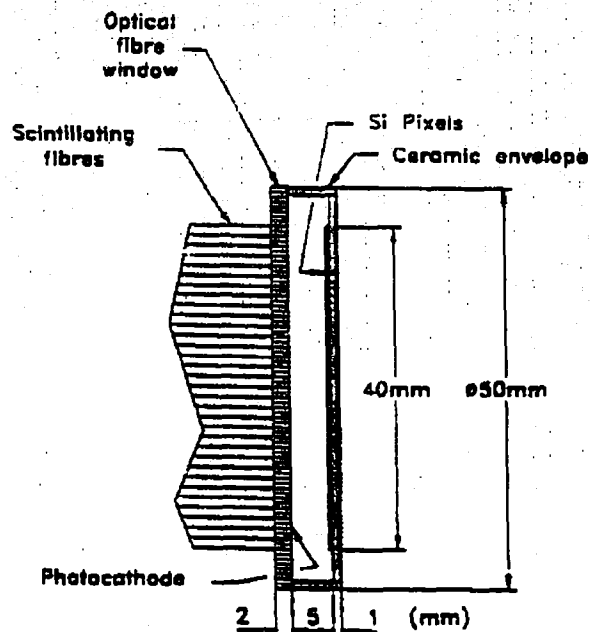


Fig. 13. Image intensifier with silicon pixel arrays (proximity focussed ISPA tube).

be directly detected by the CCD matrix without the intermediate stage of a phosphor screen. Drawbacks are their readout times of several ms and their noise sources, which necessitate additional light amplification with an image intensifier to achieve satisfactory signal/noise ratios.

3.9. Imaging with silicon pixel arrays (ISPA)

A new development for photon counting and imaging of low intensity light patterns, in particular from scintillating fibres, is the use of hybrid photomultiplier tubes (HPMT) or imaging silicon pixel arrays (ISPA) directly bombarded with electrons emitted from light detecting

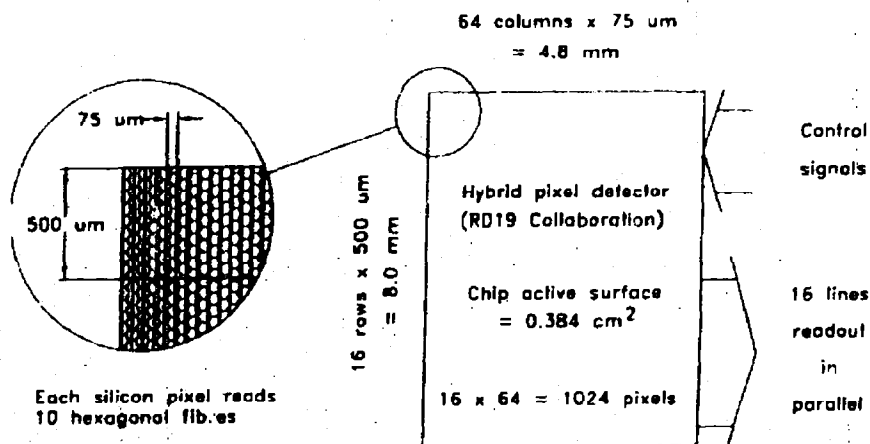


Fig. 14. Silicon pixel readout organisation in a line-parallel mode for an ISPA tube.

photocathodes. The principle of HPMTs has been known since the sixties [30–37] and has been further developed in recent years [24,38]. Photon counting with HPMTs has already been realized [25] and is described earlier in this article.

Replacing the silicon diode by an avalanche photodiode (APD) results in a hybrid avalanche photodiode (HAPD) with intrinsic APD gain. Unfortunately, as reported by several authors [39–41], APDs fail abruptly when operated in the presence of particles, even well below their maximum gain.

Ongoing developments [42–44] are currently emphasizing the replacement of phosphor screens of customary image intensifiers by silicon pixel anodes, mounted inside a phototube (Fig. 13) and digitally read out in a line-parallel mode (Fig. 14). This solution improves the electron multiplication, shortens the readout time, and allows one ISPA stage to achieve better spatial resolution (see Eq. (12)) than with the normally adopted bulky optoelectronic chain of several image intensifiers. Spatial resolution of photoelectrons is conserved by either proximity arrangement of photocathode and pixel matrix (replacing the phosphor screen in Fig. 11), or by electrostatic or magnetic focussing. In the latter case, the tube axis is aligned parallel to a solenoidal magnetic field of flux density B (T), and the electrons, emitted from the photocathode with transverse momentum mv (eV/c, Lambertian angular distribution), follow a helix of diameter ϕ [μm] = $2mv/B = 17.5 \mu\text{m}$ for 1 T and 2.6 eV kinetic energy. This version is particularly suitable for so-called delay tubes [42], where electrons that travel slowly to-and-fro ($\sim 1 \text{ m}/\mu\text{s}$) achieve delays of about 1 μs before a selected image can be gated by the first-level trigger of a detector for further data processing via the silicon pixel anode.

First experiments with an ISPA tube have been performed recently by tracking cosmic muons [45] and 120 GeV/c negative pions [46] through 60 μm diameter scintillating fibres. The applied ISPA tube encloses with its vacuum sealed cylinder of 45 mm length and 35 mm diameter, a photocathode viewed at 30 mm distance by a 8 mm \times 4.8 mm silicon chip containing 1024 pixels of 75 μm \times 500 μm edges. Each silicon pixel is bonded with Pb–Sn solder bumps to its proper electronic front-end channel. The electronics consist of preamplifier, comparator with adjustable threshold, delay line, coincidence logic and memory element [47,48]⁸. The pixel response is binary and the 64 columns of 16 pixels are read out at 5 to 10 MHz frequency resulting in 6 to 12 μs readout time. The bump-bonding of the individual pixel electronics mini-

mizes the noise and their line-parallel readout reduces the wire connections through the tube's envelope to 34 instead of more than thousand. The tracking results are reported in Section 4.1.5.

4. Scintillating fibres in high energy physics

4.1. Particle tracking

4.1.1. Basic considerations

Particle tracking, in particular at high luminosity colliders, requires fast response, good spatial precision, high two-track resolution and fine granularity for good momentum resolution and small occupancy (the fraction of tracker cells occupied by particle hits). This fraction O is proportional to the collider luminosity L , the cross section σ of colliding particles, the number n per interaction of minimum bias particles per unit of rapidity η and the time t_b between two bunch crossings.

Apart from these collider parameters, we have also to take into account those of the tracker elements: their radial distance r from the collider axis, the rapidity range η_{max} covered, and their transverse cell dimensions s (e.g. fibre diameter):

$$O = (L\sigma n t_b) \frac{s \eta_{\text{max}}}{2r\pi} \quad (13)$$

In spite of lively development activities, direct applications of scintillating fibres as tracking devices in high energy physics experiments are still rare.

Apart from reducing the occupancy, fine granularity provides via high spatial resolution also excellent momentum resolution of the traced particles. The spatial resolution is composed of the spot size of individual hits and of the root-mean-square track residuals (spatial precision). The spot size is defined either by the pixel size of an ISPA tube (binary readout) or by the barycentres of several pixels (analog CCD readout), or by drift clusters (gas filled detectors). The track residuals measure the displacements of spots (hits) from a fitted track.

The combined effect of spot size and track residuals defines the spatial resolution for a statistically meaningful sample in a Gaussian distribution, if the errors are calculated in a correct way. Its full width at half maximum

⁸ Assembled and manufactured by BV Delft Electronische Producten (DEP), NL-9300 AB Roden, The Netherlands. The chip was wire bonded at U.C.I. Microélectronique, F-91946 Les Ulis, France.

⁹ The CERN-ECP Microelectronics group designed the chip and supervised its manufacturing at different places: Canberra Semiconductor NV, B-2430 Olen, Belgium (silicon pixel array); GEC-Marconi Materials Technology Ltd, Caswell Towchester NN 128 EQ, United Kingdom (bump bonding); Smart Silicon System SA, CH-1012 Lausanne, Switzerland (electronics).

(FWHM) indicates the two-track resolution. For the momentum resolution we finally obtain [49]:

$$\left(\frac{\Delta p}{p}\right)^2 = \left\{ \left(\frac{G_c}{N}\right)^{1/2} \frac{\sigma}{L^2} \frac{p \sin \theta}{0.3B} \right\}_{\text{curvature}}^2 + \left\{ t^{1/2} \left(\frac{0.016 \sin \theta}{0.3BL}\right) \right\}_{\text{coul. scattering}}^2 \quad (14)$$

with σ [m] meaning the spatial precision, B [T] the magnetic flux density, L [m] the track length, N the number of hits along the track, G a number which varies between 256 for optimum hit spacing (e.g. fibre shells) and 720 for continuous hit distribution (e.g. gas filled chambers) along L [50], θ the polar angle of the track and t the material layer in units of radiation lengths.

4.1.2. Sources of noise in particle tracking

Noise, disturbing the clear appearance of particle tracks in readout patterns, can originate from different parts of the fibre setup and its optoelectronic readout:

- from the fibres themselves, which can produce cross-talk and δ -rays generated by the traced particle;
- from photoelectron backscattering at the anodes of image intensifiers;
- from the electronic noise in the analog CCD readout, which is not present in the binary readout of ISPA tubes.

Cross-talk between fibres is caused by two different processes, one already described, is the transmission of scintillator light (e.g. p-terphenyl, Table 3) across a small

diameter fibre (radiative transitions) and its absorption in a neighbouring one by the wavelength shifter (e.g. POPOP, Table 3). This can be avoided by doping the fibre with a one-component scintillator (e.g. 3HF, PMP; Table 3), which emits its light locally (~ 3 nm; Förster transitions).

The second source of cross-talk originates from the big fraction of untrapped scintillation light (approximately 90%). Although this fraction does not match the total reflection angle in order to be retrapped, it can reach the photocathode via scattering or diffusion if produced close to it. With fibre trackers (Fig. 25) this noise can be neglected (fibre length ≥ 2 m), but it disturbs track reconstructions in short fibre targets [51]. This cross-talk can be strongly reduced with extra mural absorbers (EMA) surrounding each fibre with a light absorbing or reflecting layer. For plastic fibre bundles such an EMA protection for each individual fibre is not feasible. It can be partly replaced by an EMA at the bundle edges.

Photoelectrons are partly isotropically backscattered from the anodes of image intensifiers into the hemisphere towards the photocathode. Intensity coefficients for backscattering can be found for selected materials in Ref. [27]. In many cases, the backscattered photoelectron carries away a considerable fraction of its initial energy, and its primary impact is therefore lost as a track signal. Since the accelerating electric field of the image intensifier turns the backscattered electron back towards the anode, it reappears as a noise hit. Without magnetic focussing the maximum displacement of this noise hit from its initial track position is twice the distance between cathode and anode. Therefore, most of the image frame is affected by

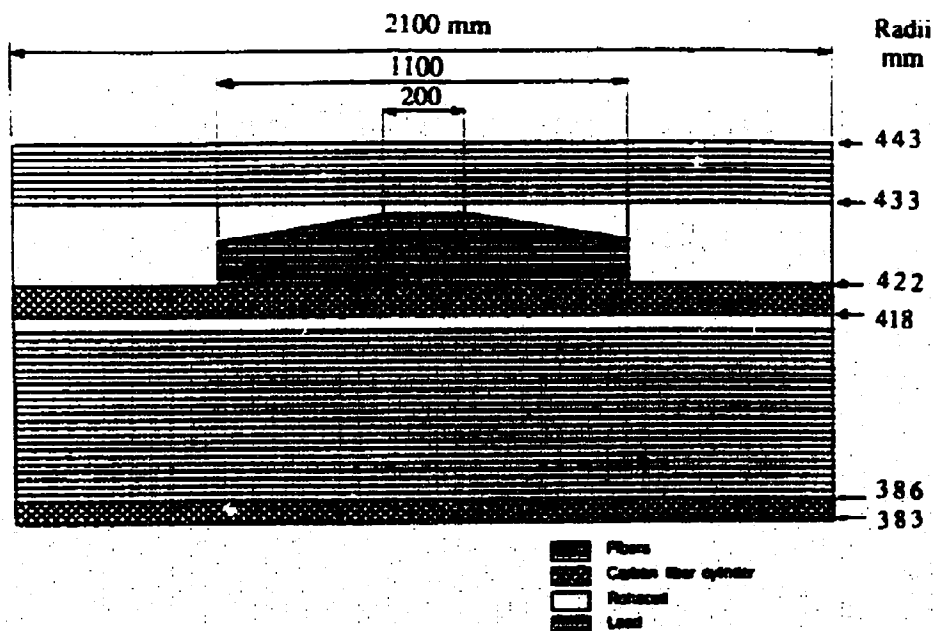


Fig. 15. Vertical cut of the UA2 scintillating fibre detector.

this noise. This effect applies mainly to phosphor screen anodes. With digital readout from silicon pixels (ISPA tubes [45,46]) this noise is suppressed by appropriate threshold settings.

Typical CCD noise sources are: a) photonic noise, which equals \sqrt{N} (N being the number of electrons in a pixel), b) reset noise, which appears during charging the readout diode to its reference potential; c) dark signals, which are generated by thermal excitation of electrons into the silicon conduction band. They double for every 10° of temperature rise.

4.1.3. The UA2 fibre tracker

The first large size fibre tracking detector was studied, developed and built for the upgrade of the UA2 detector [52,53] in collaboration between CERN and Saclay. The cylindrical fibre arrangement contained 60000 plastic fibres (polystyrene clad with polyvinyl acetate and doped with two components, PBD and POPOP, Table 3). To avoid cross-talk, a thin aluminium layer was sputtered around each fibre. For stereo views, the fibres were grouped into triplets, with one layer each running parallel to the detector axis and two layers placed at angles of $\pm 16^\circ$ with respect to this axis. Details of the fibre tracker are shown in Fig. 15. The eighteen actual tracking layers were followed by a tapered lead converter (1.5 rad. lengths) and six preshower fibre layers. In front of the tracking layers a Jet Vertex Detector, Silicon Hadroscope and Transition Radiation Detectors were placed. These devices introduced additional material in front of the fibre tracker and increased the probability of particle interactions and gamma conversions.

The fibre ends were bunched and coupled to 16 optoelectronic readout chains (Fig. 16) placed at each detector

end. Each chain consisted of two electrostatically focused image intensifiers and a proximity focussed one containing a microchannel plate (MCP). The images were transported subsequently via fibre optics windows, photocathodes and phosphor screens of the chain to CCDs, which provided finally the electronic signals for further data processing.

Alignment and intrinsic accuracy of the 1 mm fibres provided 0.4 mm track residuals. The two track resolution was about three fibre diameters. According to the material layers from other detectors in front of the fibres, there were roughly as many secondaries and conversions as primary tracks. Together with combinatoric overlaps this led to a serious ghost track problem.

4.1.4. The Chorus fibre tracker

A more recent application of fibre tracking is found in the Chorus experiment [54] which is designed to search for $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations in the CERN neutrino beam. The τ -decays will be detected in a 230 litre emulsion stack. To locate neutrino interactions in the emulsion targets, they are followed by flat rectangular fibre sheets, from which the tracks of secondaries are backpointed to find the neutrino interaction coordinates in the emulsions.

There are more than 1 million fibres of 0.5 mm diameter installed having a total length of 2500 km. One of the optoelectronic readout chains is shown in Fig. 17. It consists of four image intensifiers including an image demagnification of 100:11, an MCP and a CCD of 550×228 pixels.

4.1.5. The proposed fine grain central tracker

A different geometry [49,55,56] for particle tracking with scintillating fibres is found in the Fine Grain Central Tracker that uses three cylindrical fibre shells (Fig. 18) of

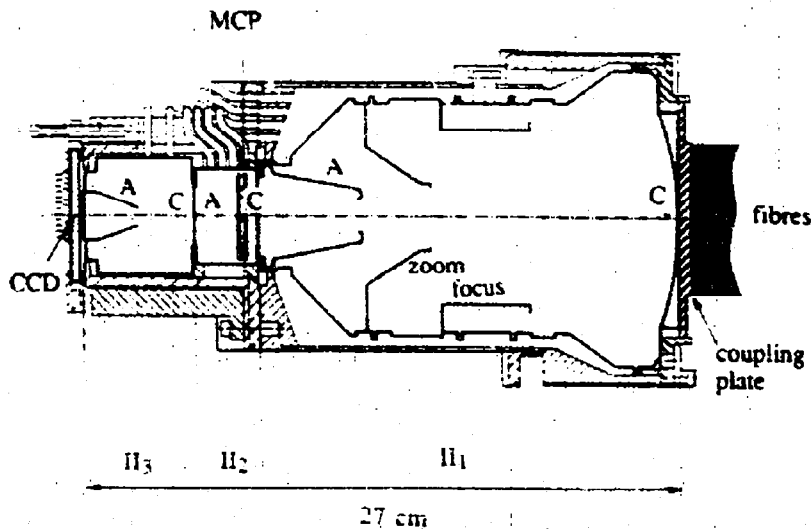


Fig. 16. An optoelectronic readout chain of the UA2 fibre tracker. A, photocathodes; C, phosphor anodes; II, image intensifiers.

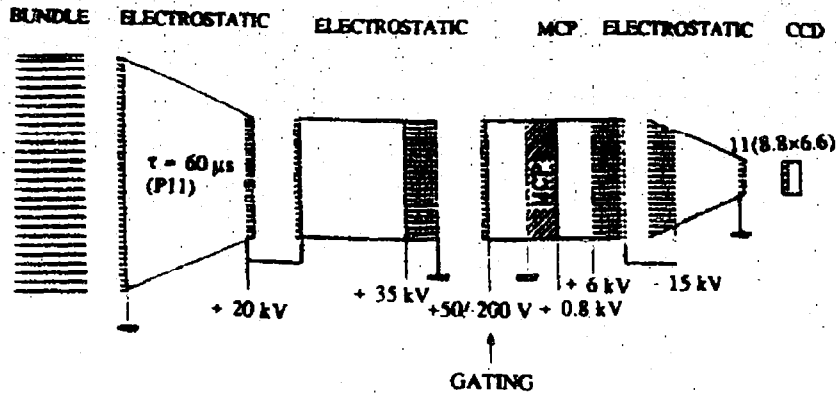


Fig. 17. A chain of four image intensifiers ending with a CCD electronic readout for the Chorus scintillating fibre tracker.

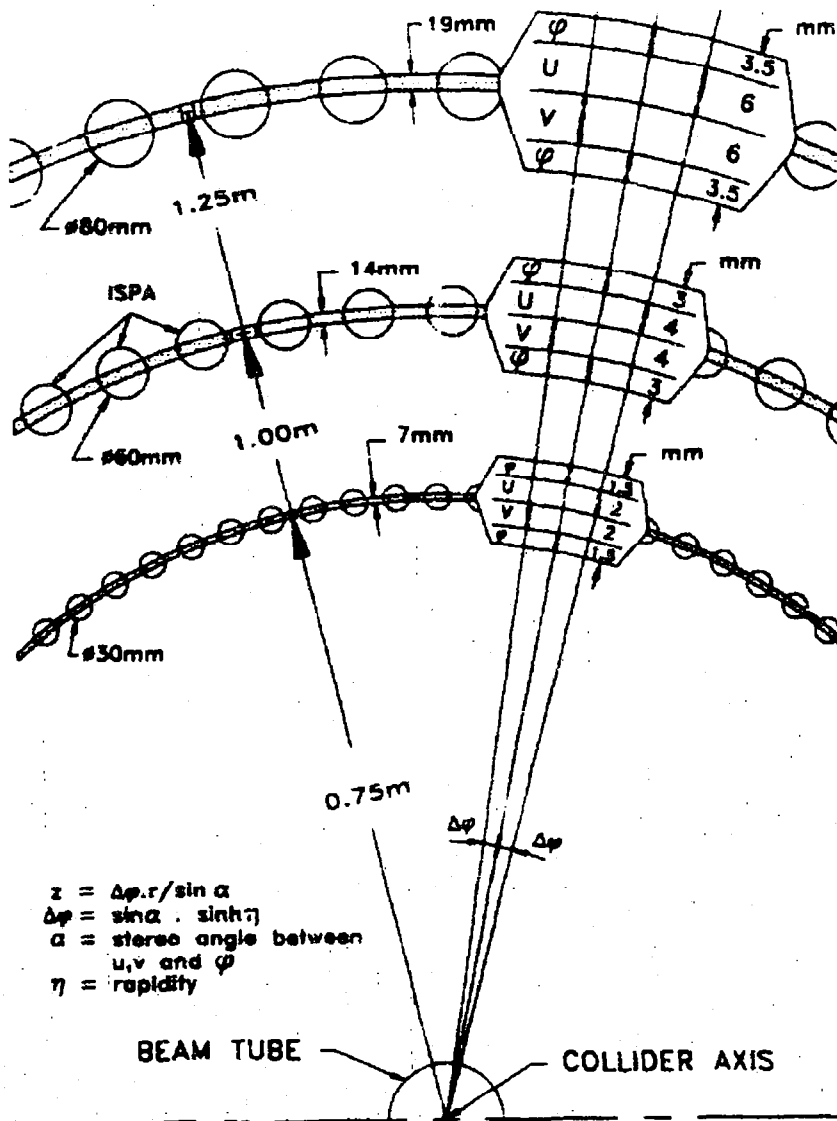


Fig. 18. Arrangement of scintillating fibre shells for tracking within the free barrel region of the calorimeter. $r-\phi$ plane seen at $z=0$. The magnified parts show the subdivision into the straight ϕ and the oblique u and v layers. The symmetric angles $\Delta\phi$ indicate the z coordinate via the indicated relation.

different radii with a common axis coinciding with that of the collider. There, the fibres will be arranged in four layers for each shell. Two layers (Fig. 18) with fibres parallel to the shell (collider)-axis indicate the (r, φ) -coordinates. The two other layers u and v , sandwiched between the two φ -layers, with oblique fibre directions, running at an angle of a few degrees with respect to the parallel ones, provide via their corresponding stereo view the z -coordinate of a particle track.

For all tracking arrangements, small diameter fibres are indispensable. Since fibres with diameters below $200 \mu\text{m}$ become difficult for individual handling and precise alignment, fused fibre bundles (Fig. 7) were developed, which are strands of square cross section with edge dimensions between 1 mm and a few mm and contain many hundreds of individual fibres with hexagonal shape and transverse dimensions corresponding to the requirements of the tracker design.

A major advantage of this fine grain tracking arrangement is that it produces several hits per fibre layer, according to the Poissonian probability of n hits within the path length l

$$P_n = \frac{(hl)^n}{n!} e^{-hl}, \quad (15)$$

where h is the number of photons produced per mm fibre thickness in r - φ projection.

Typical ISPA tracks are displayed in Fig. 19a. They were obtained with a 120 GeV/c negative pion beam [46], which traversed four fibre bundles (10 mm) glued together into a ribbon. Each bundle is of square cross section with 2.5 mm edges (Fig. 7) and contains 1600 coherently aligned hexagonal shaped scintillating fibres of $60 \mu\text{m}$

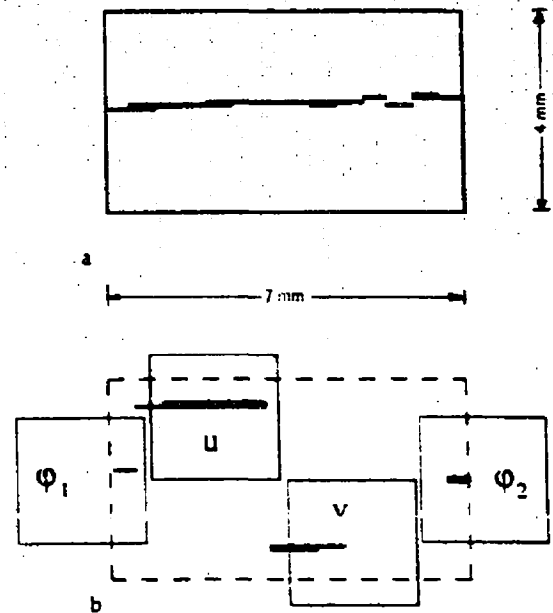


Fig. 19. (a) Typical track pattern from a 120 GeV/c negative pion beam traversing a 10 mm ribbon, with $60 \mu\text{m}$ diameter of scintillating fibres. The active frame size of the silicon chip is $4 \text{ mm} \times 7 \text{ mm}$ (along the beam). The pixel size is $75 \mu\text{m} \times 500 \mu\text{m}$ along the beam. (b) Track pattern obtained with a stereoscopic bundle arrangement. The bundles u and v run with an angle $\pm \alpha = 7 \text{ mrad}$ oblique to the bundles φ_1 and φ_2 . The beam passes straight through all four bundles and the ribbon end-face confronts the photocathode. There, its microvectors indicate the track distance from the photocathode: $d = (u + v) / 2 \text{tg} \alpha$. Note that the bundles φ_1 lengths ($500 \mu\text{m}$) do not exactly coincide with the bundle edges. The stereo angle is about ten times smaller than in Refs. [49,57] in order to match the bundles u and v with the active chip frame.

Table 7

Comparison of relevant parameters between different tracking detectors. X_0 means radiation length and H the material layer required to achieve one hit or cluster

Parameters	Si strips	MSGCs	Fibres
Number of hits $[(0.1 X_0)^{-1}]$	15-30 ^a	~ 10-15 ^b	70-200 ^c
Cell busy time [ns]	< 15	~ 50	< 15
Intrinsic spatial precision (σ) [μm]	5-14 ^d	40 ^e	20-40 ^f
Two track resolution [μm]	100	300 ^e	50-100 ^f
Occupancy ($10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity) [%]	< 1	2-3	< 1
Number of readout channels [$\text{m}^{-2} \text{ H}^{-1}$]	2×10^5 ^g	5×10^4 ^h	3.2×10^3 ⁱ
Heat production [$\text{W m}^{-2} \text{ H}^{-1}$]	200 ^j	50 ^k	3.2 ^l

^a (0.3 mm detector + 0.3 mm electronic layer) per hit; higher number without electronics

^b F. Angelini et al., CERN-PPE 91-122.

^c 1.7 (5) hits) per mm at 2 m (0.3 m); bundles with mirrored end face.

^d Silicon strips with 20 or 50 μm pitch, divided by $\sqrt{12}$.

^e MSGC with 200 μm pitch, taking the centroid: F. Angelini et al., Nucl. Phys. B (proc. Suppl.) A23 (1991) 254.

^f Measurements [26,43] with 60 μm diameter fibres.

^g Silicon strip of 50 μm pitch and 10 cm length

^h Microstrip gas counter of 200 μm pitch and 10 cm length.

ⁱ Each pixel channel of an ISPA tube covers 0.0375 mm^2 (Fig. 14) fibre endsection. This corresponds to a subtended detector surface of: $0.0375 \text{ mm}^2 \times 2.5 \text{ m}$ (fibre length): 0.3 mm (1 hit layer) = $3.1 \times 10^3 \text{ cm}^2$.

^j Assuming 1 mW per channel.

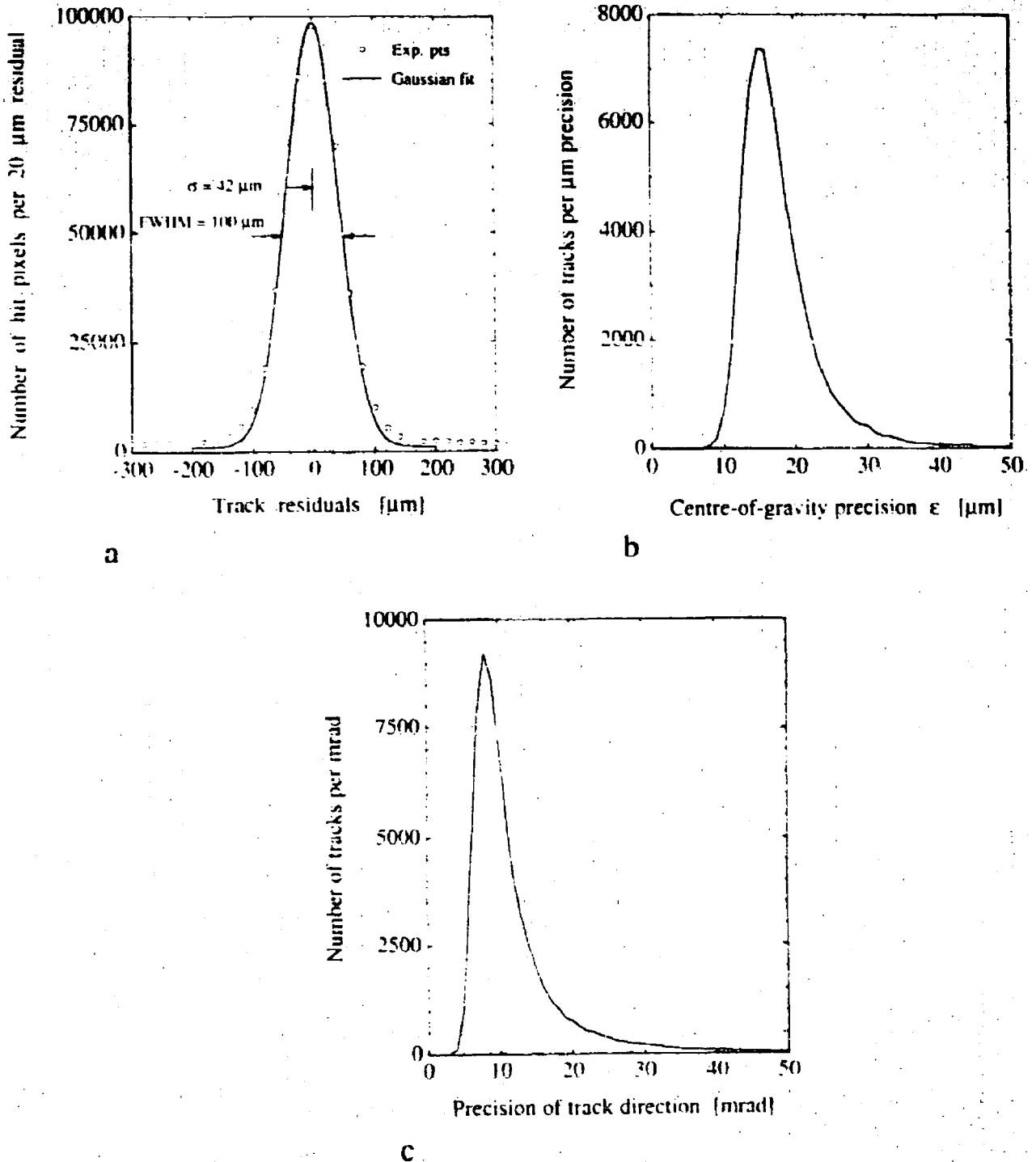


Fig. 20. (a) Residuals from 10^5 beam tracks (circles) and their Gaussian fit. The values for the standard deviations σ and full widths at half maximum (FWHM) are due to the binary readout, which does not indicate the number of hits within one pixel. An analog readout would reduce the dominant contribution of the $75 \mu\text{m}$ pixel width and improve σ and FWHM. (b) Measured centre-of-gravity precision ϵ . It is related to the residuals σ of (a) via the number of hit pixels N : $\epsilon = \sigma/\sqrt{N}$. The asymmetric shape is mainly due to the diminishing number of hit pixels at the right-hand part. (c) Measured direction precisions of 10^5 accumulated tracks. They indicate the accuracy with which the microvectors of a tracker plane or shell [57] can be projected to the next plane or shell.

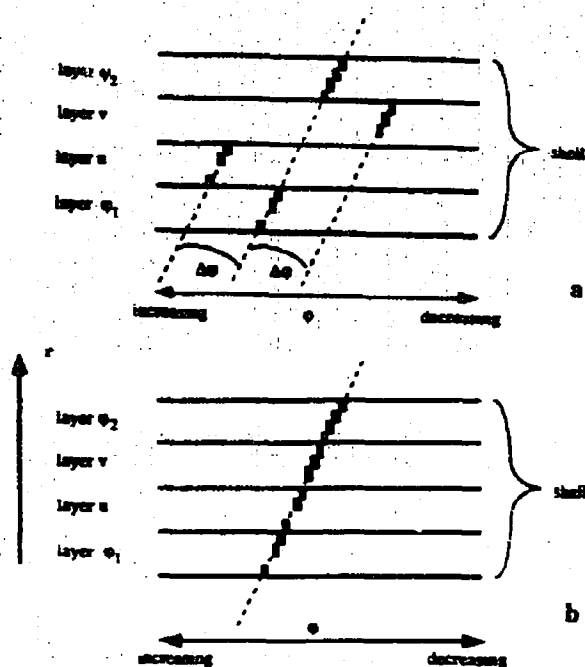


Fig. 21. (a) A typical microtrack triplet from a particle passing through a tracker shell. The track segments in the u and v layers are shifted by $\Delta\varphi$ in increasing and decreasing azimuth angle φ . The shift $\Delta\varphi$ corresponds to the z -coordinate of the track (Fig. 18). (b) The resulting track segment after shifting the u and v microtracks by $\pm\Delta\varphi$.

transverse dimensions (Fig. 8), fused together by repeated drawing procedures. The magnetic focussed⁹ ISPA tube was operated at 20 kV acceleration voltage across the 30 mm photocathode–anode gap. With 0.05 T magnetic flux density parallel to the electric field, the photoelectrons made one full helical turn until they hit after 30 mm distance the anode chip exactly opposite to their emission point. The oblong pixel dimensions (500 μm) were approximately aligned with the pion beam, whereas the 75 μm edges allow for spatial resolution perpendicular to the tracks.

Fig. 19b shows tracks from another fibre ribbon, where the two bundles u and v (with fibres oriented oblique to the pion beam by the angle α) are sandwiched between the bundles φ_1 and φ_2 running parallel to the beam. The symmetric stereo displacements u and v with respect to φ_1 and φ_2 provide the stereo view of the track and indicate the track distance d from the ISPA tube: $d = (u + v)/2 \tan \alpha$. All tracks show the expected microvectors

⁹ ISPA tube prototypes with electrostatic or proximity focussing are also envisaged, depending on the applications considered.

¹⁰ The centre of gravity precision is related to the residual σ in Fig. 20a via the number of hit pixels N : $\varepsilon = \sigma/\sqrt{N}$.

already assumed in Ref. [49], rather than single hits (silicon microstrips, Table 7) or clusters (microstrip gas chambers, Table 7).

The transverse hit distribution of 10^5 tracks is plotted in Fig. 20a. The Gaussian with a background level of $\sim 1\%$ shows a residual standard deviation σ of 42 μm , which corresponds to a two-track resolution (FWHM) of $2.4 \times \sigma = 100 \mu\text{m}$. These values are mostly due to the binary readout of the 75 μm wide pixels, which does not indicate the number of hits within one pixel. An analog readout would reduce the dominant contribution of the pixel width and result in smaller residuals. This can be improved by producing anode chips with smaller pixel widths. The measured values for the centre-of-gravity precisions ε (Fig. 20b) and for the track directions (Fig. 20c) (which correspond to the precisions of the generated microvectors) are 15 μm and 8 μrad respectively¹⁰.

The symmetric microtracks of u and v layers can be paired (Fig. 21) with respect to the φ -microtracks to form triplets, which finally indicate a real track. This advantage can be used for a new track recognition algorithm [57], which traces a particle from the outer layer to the inner one, following the φ and the u , v sublayers. Comparison of Monte Carlo generated collider events with reconstructed ones [57] shows for only two fibre shells a reconstruction efficiency close to 100% with less than 1% ghost contribution. The average error on the reconstructed total momentum per event amounts to 6%.

4.1.6. Comparison of fibres with other tracking media

In the domain of particle tracking, scintillating fibres compete with other tracking media, mainly gas counters (in particular: microstrip gas chambers, MSGC [58–60]) and semiconductors (in particular: silicon strips and pixels [55–56]). Some parameters of the three detector media, with respect to their application as tracking elements in the central detector region, are listed in Table 7. These values are best estimates of the present state of detector performance. For valuable comparisons, the numbers given are normalized in the following way:

The number of hits is shown in units of 0.1 radiation length X_0 . Heat production and the number of readout channels are indicated in units of subtended surface area [m^2] and hit thickness H , which means the layer of detector material required to achieve one readout signal (hit) from the energy loss of a minimum ionizing particle. (Si-detectors: 0.3 mm, MSGC: 2 mm, scint. fibres: 0.3 mm).

Spatial precision means the accuracy in locating a hit within the detector frame. The number listed for scintillating fibres represents the standard deviation (σ) of a Gaussian-shaped hit distribution [26,43]. For silicon, most experimenters take either the sigma of the centroid (analog readout) or divide the shortest dimension of a detector element by $\sqrt{12}$ (binary readout). For gas filled chambers,

the spatial precision results from the accuracy with which the centroids of drift clusters can be located. In addition, for MSGCs there is a correlation between precision and detection efficiency. The single strip efficiency of 96% for perpendicular tracks decreases to between 35 and 15% for 30° angular deviation depending on the threshold [61]. This worsens precision and two-track resolution accordingly.

For scintillating fibres, the two-track resolution is defined like the classical resolving power in optics, for separating two neighbouring objects (particle tracks), and the listed number refers therefore to the full width at half maximum (FWHM = 2.36σ) of the Gaussian mentioned above [26,43]. The two-track resolutions reported in most cases for silicon ($\approx 100 \mu\text{m}$) and for perpendicular tracks in microstrip gas chambers ($\sim 300 \mu\text{m}$) do not relate in the same way to their claimed precisions.

An important difference between fibres and the other media is in the readout. Every element (strip) of MSGCs and of silicon detectors (pixel or strip) needs a complete electronic readout chain. Fibres are read out at the end sections of their shell arrangements in parallel by optoelectronic tubes (ISPAs). Consequently, their number of channels is considerably reduced. This reflects also on the heat production, which represents a particular problem for semiconductors. It is caused by the leakage current of each detector element and by its electronics. A cautious estimate for semiconductors leads to about 1 mW per element.

4.2. Calorimetry with scintillating fibres

4.2.1. Basic considerations

A calorimeter measures the energy of incident electromagnetically or strongly interacting particles. Its energy resolution amounts to

$$\frac{dE}{E} = \left(\frac{a^2}{E} + b^2 \right)^{1/2} \quad (16)$$

where a is the energy dependent term. The constant term b describes the response of the calorimeter to electromagnetic (e) and to hadronic (h) interactions. Equal response ($e/h = 1$) means a completely compensating calorimeter.

Normally, hadronic interactions terminate in nuclear breakups, where the nuclear binding energies ($\sim 20\%$ of incident energy) will not contribute to the visible and measured energy. This can be compensated by employing uranium as radiator material where the fission processes increase the neutron component and make up for these losses [62]. In another approach plastic scintillators are employed as active sampling material, because their hydrogen atoms respond better to the low energy neutron component of the hadronic cascade [63], and therefore enhance the hadronic response.

At the same time the calorimeter response to electromagnetic showers (mainly gammas from neutral pions which make about 30% of the incident energy) can be

reduced by an appropriate fraction of high Z material (e.g. lead) which absorbs low energy photons before they reach the plastic sampling scintillator [64]. These requirements for a compensating calorimeter point to lead as energy absorber and to plastic scintillators as sampling material.

4.2.2. The lead/scintillating fiber calorimeter

These considerations and the requirement of fine grain energy sampling lead naturally to the lead/scintillating fibre (spaghetti) calorimeter. It is composed of 1 mm diameter scintillating fibres pointing at the colliders interaction region, which are interspersed in a lead matrix at 1:4 (plastic to lead) volume ratio. This geometry provides hermeticity and the different timing response for electromagnetic and hadronic interactions allows the electromagnetic and the hadronic calorimeters to combine into one detector of about 2 m absorption thickness. This development has been initiated by Barmeister et al. [65] with a lead-scintillating fibre sandwich geometry and was pursued by the LAA project [66].

The electromagnetic energy resolution measured with a prototype of 41 modules [67] amounts to:

$$\frac{dE}{E} = \frac{14.4\%}{\sqrt{E(\text{GeV})}} + 0.17\% \quad (17a)$$

and the hadronic energy resolution, measured with a 155 module prototype of longitudinally unsegmented nonprojective towers [68], is given by:

$$\frac{dE}{E} = \frac{28\%}{\sqrt{E(\text{GeV})}} + 2.5\% \quad (17b)$$

These modules are now used as a calorimeter in the WA-89 experiment behind the Omega-fixed target spectrometer at CERN.

The position resolution for incident electrons is [69]:

$$\sigma_x = \frac{5.0 \text{ mm}}{\sqrt{E(\text{GeV})}} + 0.2 \text{ mm} \quad (18a)$$

For single hadrons this resolution amounts to [70]:

$$\sigma = 31.4 \text{ mm} / \sqrt{E(\text{GeV})} \quad (18b)$$

Several fibre calorimeters are already in use or are planned at different particle physics experiments. One of the earliest applications was with the electromagnetic calorimeter of the JETSET experiment [71] at the CERN Low Energy Antiproton Ring (LEAR). It is assembled of individual towers which point to the interaction region and form a hermetically sealed structure [72]. The design depth is 12.5 radiation lengths (0.2 m). A matrix of 1 mm polystyrene scintillating fibres is embedded in a lead-antimony alloy via an epoxy, which envelops the cladding of each fibre. The resulting volume ratio fibre:lead:epoxy amounts to 50:35:15. This layout is not intended to yield

e/h compensation but is optimized for electromagnetic energy resolution: $dE/E = 0.06/\sqrt{E}$.

The Chorus experiment [54] uses a longitudinally segmented fibre calorimeter with scintillating fibres running transverse to the neutrino beam. This allows for the insertion of limited streamer tubes to track penetrating muons. It consists of three sections: the first one of high granularity measures the electromagnetic component, and the two others with lower granularity the hadronic one. The volume ratio is four parts of lead to one part of plastic fibres.

A "spaghetti" type calorimeter is being built for the KLOE experiment [73] at the ϕ -factory DAPHNE in Frascati, Italy. In the 3.75 m long barrel region of 4 m outer diameter, the scintillating fibres run parallel to the collider beam. At the two endcaps, the fibre directions are orthogonal to the beam. The construction uses a gluing technique and the resulting fibre:lead:epoxy volume ratio is 48:42:10.

At the DESY electron-proton collider HERA the H1 experiment plans to build a fibre calorimeter to extend their large liquid argon calorimeter in the backward p-scattering region [74]. The electromagnetic section would contain 0.5 mm diameter scintillating fibres embedded in lead at a volume ratio of 2 (Pb):1. The hadronic part is planned for 1 mm diameter fibres with 4(Pb):1 volume ratio and will be one interaction length deep.

4.2.3. Comparison with other calorimeter techniques

There are several competing methods for calorimetric energy measurements. Closely related to scintillating fibres are scintillating plates, interleaved with heavy material absorbers. A new development [75] is the calorimeter with scintillating tiles oriented radially to the collider axis. Each tile is coupled to a clear or wavelength-shifting read-out fibre. Simplicity of mechanical construction is purchased at the expense of coarse granularity and difficult tuning of complete compensation.

A completely different class of detectors is defined by liquid argon calorimeters containing absorber plates and electrodes for charge collection. The electron drift velocities of ~ 5 mm/ μ s produce long occupation times of 300 to 500 ns within the argon gaps between the plates. This drawback must be compensated by bipolar pulse-shaping, which decreases the signal/noise ratio. An interesting arrangement is the accordion geometry [76], which provides very short cable connections from the charge collecting electrodes to the preamplifiers. They yield rise times of ~ 30 ns. The electromagnetic energy resolution achieved with an accordion calorimeter is similar to that of the spaghetti calorimeter with a tiny advantage of the accordion.

4.3. Dose rates and radiation damage for fibre detectors at LHC

Minimum biased events, produced as background from pp collisions scale with luminosity, multiplicity and parti-

cle cross section. They are by far the main source for the radiation dose around the crossing points of a hadron collider. The dose rate in Gy ($\text{Gy} = 1 \text{ J Kg}^{-1}$) per year (yr^{-1}) can be expressed in the following way:

$$D_0(r) [\text{Gy yr}^{-1}] = \text{const} \frac{dE}{dx} \frac{1}{\sin \theta} L \sigma_{\text{inel}} H (\pi r^2)^{-1} \sin \theta, \quad (19)$$

with $(dE/dx) (\sin \theta)^{-1}$ meaning the stopping power (LHC: $2 \text{ GeV cm}^2 \text{ kg}^{-1}$) for minimum ionizing particles emitted at the polar angle θ ($\cos \theta = \tanh \eta$, where η is the rapidity), L the luminosity [$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$] of the collider, σ_{inel} [cm^2] the inelastic cross section for pp collisions (LHC: 85 mb), H the number of particles per collision and per unit of rapidity (LHC: 6), r [cm] the distance from the collider axis and $H \sin \theta / \pi r^2$ is the number of particles per unit surface of a cylindrical detector. The term const [$1.6 \times 10^{-3} \text{ J GeV}^{-1} \text{ yr}^{-1}$] contains the conversion from GeV into J (1.6×10^{-10}) and from seconds to year (10^7) if we assume a yearly operation of 10^7 s, which corresponds to about 115 days.

This relation changes if a solenoidal field with flux density B is applied in the tracking region [44]:

$$D_B(r) = D_0(r) \left\{ 2 \langle n_c \rangle \int_{-x}^x f(x') dx' + \int_{-x}^x f(x') dx' \right\}, \quad (20)$$

where $\langle n_c \rangle = \sinh \eta_{\text{max}} / \pi \sinh \eta$ [49] is the average number of particle curls in the rapidity range $0 < \eta < \eta_{\text{max}}$, $f(x) = x e^{-x}$ is the transverse momentum distribution of minimum bias particles taken from Monte Carlo data, and $x = 2 p_t / \langle p_t \rangle = 0.3 B r / \langle p_t \rangle$. The average transverse momentum p_t of minimum bias particles depends on the

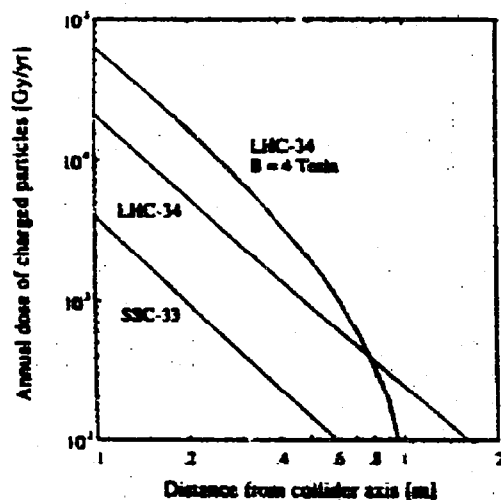


Fig. 22. Annual dose at the inner detector cavity, within ± 3 rapidity for the indicated decadic luminosities. At 4 T, the particles curl with ~ 1 m max. radius. The unit gray (Gy) equals 1 J/kg or 100 rad .

collider's centre-of-mass energy E_{cm} and can be approximated by: $\langle p_t \rangle \sim 0.44 + 0.071 \log E_{cm}$.

Particles with curling diameters between zero and distance $r = p_t/0.15B$ from the collider axis do not contribute to the radiation dose, therefore the first integral of Eq. (20) spans between x_c and x_c' , where c means the outer radius of the free barrel, with a calorimeter or a solenoid as boundary. The second integral covers the contribution due to those particles which are stopped curling by this boundary.

The annual dose rates for LHC are shown versus the distance from the collider axis in Fig. 22. A solenoidal field of 4 T changes the dose rates for LHC as indicated in Fig. 22 [44]. For the tracker scenario shown in Fig. 18, this means maximum annual dose rates at 0.75 m distance of 0.45 kGy (45 krad), which is certainly tolerable for the scintillating fibres during several years of operation.

In general, radiation damage from ionizing radiation and from neutrons results in complex deteriorations of scintillating fibres: it causes optical colouration (colour centres) of the basic matrix (core), which decreases its light transmission; it also can yield chemical degradation of the added scintillators, which reduces their light emission; it can worsen the quality of cladding layers, which increases the reflection losses at their core-cladding interface; together with the infiltration of gases, it may produce radicals, which change the chemical structure and affect the fibre performance.

The extent of damage in scintillating fibres is influenced by many parameters: dose rate [77], recovery [78,79], ambient temperature [80], colouration of basic matrix [81,82], chemical structure and molar fractions of added dopants [83,84,44], nature of surrounding gases [85,86], etc. Therefore, it is difficult, to disentangle the different contributions to radiation damage of scintillating fibres. An

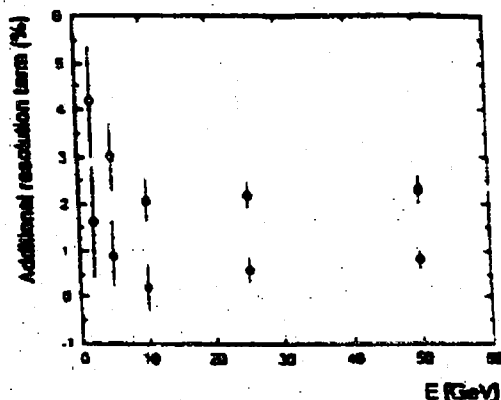


Fig. 23. Monte Carlo results on the additional constant term in the electromagnetic energy resolution for the measured radiation hardness of 3HF (500 ppm) fibres with radiation hard cladding (black dots) and for SCSF81 Y9 fibres with standard cladding (white dots), as a function of the incident electron energy (Spaghetti calorimeter [88]).

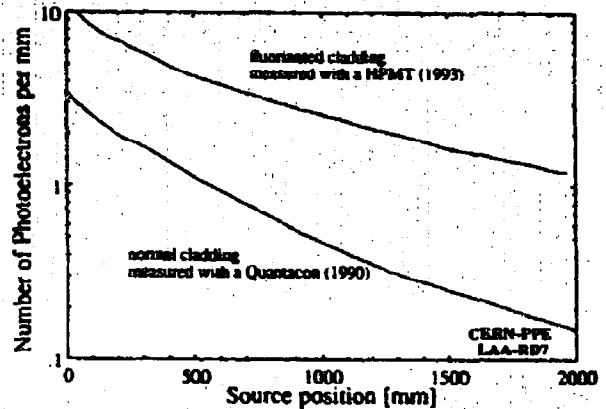


Fig. 24. Improvements on hit densities (photoelectrons/mm) for fibre bundles, containing 60 μm fibres, during the last years. The main progress is due to higher trapping fractions from fluorinated cladding, better collection efficiencies of photoelectrons from the HPMT photocathodes and improved manufacturing procedures.

exhaustive treatise of these effects would require a separate review.

It is already certain that high dose rates to which scintillators are exposed for tests, cause more damage than low ones. The dose rate of LHC at $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ luminosity would average only 3.9 Gy/day (Fig. 22) at 0.75 m distance of the inner fibre shell (Fig. 18). Even for long term irradiation tests, the applied rate is about 100 times higher, in order to achieve doses of several tens of kGy within a reasonable time (months).

As far as dopants are concerned, it has been clearly demonstrated [83,84] that 3-hydroxyflavone (3HF) [21] doped fibres show smaller permanent radiation damage than those doped with other aromatic compounds. Fortunately, this dopant shows a large Stokes' shift and can be applied as a one-component system (Table 3) which emits around 530 nm. On the other hand, its fluorescence yield is only 0.4 (Table 3), which makes it less suitable for particle tracking but is still more than adequate for calorimetric applications.

With LHC, neutron fluxes in calorimeters reach levels well above 10^{15} neutrons per cm^2 and year [87] at an integrated luminosity of 10^{41} cm^{-2} and 60 mb inelastic p-p cross sections. Although the lead/fibre calorimeter yields the lowest neutron production (Table 5 in Ref. [87]), the radiation load on the fibres is important. Also the radiation level caused by gammas from neutral pion decay is considerable. Damage to the calorimeter's scintillating fibres from these processes would change the e/h ratio and therefore worsen its energy resolution via the constant term b (Eq. (16)). Also, all changes in uniformity of the fibres' light transmission, which could occur because of local radiation damage, would necessitate frequent recalibrations of the calorimeter. Therefore, the RD-25 collaboration studied carefully the resistance of different fibre

types with full length modules at a high intensity 0.5 GeV electron beam (CERN-LIL) [88]. Fig. 23 shows the added constant term (Eq. (16)) as a function of incident electron energy after an exposure at LIL which would correspond to 4 y LHC operation at 2.5 rapidity. The figure shows clearly the advantage of 3HF doped fibres clad with fluorinated polymethacrylate.

5. Conclusions

During the past few years the performance of scintillating fibres has improved considerably. Developments were mainly based on polystyrene cores and include the introduction of one component dopants (Table 3: PMP [19,20], 3HF [21], etc.) which prevent cross-talk for small diameter fibres [22]. For fibres with diameters below 100 μm fused bundles were developed [15], with high packing fractions [26] and excellent coherency for precise alignment in tracking arrangements. The fraction of trapped light has been improved by a factor of 1.75 [23] with fluorinated polymethacrylate cladding. In addition, general improvements on fibre production, which mainly reduced the light attenuation in the polystyrene cores and the reflection losses at the core-cladding interfaces, enhanced finally the number of photoelectrons/mm (hit densities). These improvements on fibre performance are illustrated in Fig. 24 which shows the considerable differences in hit densities of 60 μm fibres contained in fused bundles between 1990 and 1993.

Recently, new readout techniques have been developed in two different ways, which both avoid the bulky optoelectronic chains of classical image intensifiers, where the scintillating light is transported via phosphor screens to CCD readout. One, is the new development of visible light photon counters (VLPC), which are silicon solid state photomultipliers [28]. They need to be cryogenically cooled to 6.5 K and are coupled to the scintillating fibres via clear ones. They reach 0.85 quantum efficiency at 550 nm [29].

The second technique follows the development of hybrid photomultiplier tubes (HPMT, Fig. 6) [30–37,24,25], which employ photocathodes to allow light detection from scintillating fibres for photoncounting. The high potential difference (> 10 keV) between photocathode and silicon anode enhances considerably the collection efficiency of electrons emitted from the photocathode, as compared to the Quantacon with 300 to 500 V at the first dynode. Newest developments [45,46] place a silicon pixel readout opposite and in proximity to the photocathode (ISPA tube, Fig. 13) to maintain the fibre granularity also for the electronic readout. ISPA tubes replace in a cheaper and space saving way the classical optoelectronic chains with better spatial resolution and higher signal/noise ratios.

Until now, particle tracking with scintillating fibres has been mainly hampered by coarse fibre granularities and by

the bulky optoelectronic readout chains. Fibre occupancy, resolution of particle momenta, and reconstruction efficiency of collider events [57] can be improved with thin shell arrangements of fine grain bundles aligned for stereoscopic views (Fig. 18). These shells are distributed over the free barrel diameter bordered by the inner surface of the calorimeter or the solenoid of the detector. This arrangement results in large track lengths L (in Fig. 18: $L = 1.25$ m), which improve considerably the measurement of track curvature (L^2 dependence in Eq. (14)), and increase the backpointing accuracies to the collision vertices of hadron colliders. Each fibre bundle produces several hits (Eq. (15)) and therefore micro tracks of a few mm (Fig. 19), rather than single hits or clusters as with silicon layers or MSGC modules. Since all bundles are read out at the cylindric end-sections rather than at the shell surfaces, the number of readout channels is much lower than with competing silicon strips or pixels and MSGCs (Table 7). Therefore, extra cooling loops, representing additional passive material to remove electronic heat are not needed for the fibre tracker.

In calorimetry, the volume fraction of scintillating fibres, distributed as sampling material in a lead absorber, can be precisely tuned to achieve full electron-hadron compensation. This improves the energy resolution of the calorimeter since the constant term in Eq. (16) becomes small. Another advantage is the fast signal response (~ 15 ns) due to the short decay time of the emitted fibre light (Table 3). These response times are achieved without signal shaping, which would further shorten them by a significant factor. Electron/pion discrimination can be achieved with longitudinal shower sampling, effective shower time and/or lateral shower sampling. In combination, these selection criteria yield rejection of 10^3 within about 100 ns.

Acknowledgements

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Glossary

Absorption band: Wavelength region, where incident light is absorbed due to excitations of the electronic and the vibrational energy levels of chemical compounds.

Cladding: Thin (2 to 5 μm) material layer (mostly PMMA) surrounding the fibre core. Its refractive index is smaller than that of the fibre core, to enable total light reflections at the core-cladding interface.

Cross-talk: Light produced via particle ionisation in one fibre is transmitted into neighbouring fibres due to

radiative exchange between scintillator and wavelength shifter (two component systems, Table 3). The absorption length of the emitted scintillation light exceeds the fibre diameter and excites the wavelength shifter in a neighbouring fibre. This phenomenon can be avoided either by a one component dopant (e.g. PMP, 3HF, Table 3) or by surrounding each fibre with an EMA coating.

Extra mural absorber (EMA): Light absorbing or reflecting coatings which surround each fibre to suppress cross-talk between neighbouring fibres. For fused plastic fibre bundles it is not possible to coat each individual fibre with EMA (as it is with glass fibre bundles). Therefore, it is imperative to dope them with one component scintillators (Table 3) at concentrations, which allow for local Förster transitions to avoid cross-talk.

Extinction coefficient (decadic molar) $\epsilon(\lambda)$: Transformation of recorded light intensities (I) after transmission of incident light (I_0) through absorbing media:

$$\epsilon(\lambda) = -0.4343 \ln(I/I_0)/Cd \quad [1 \text{ mole}^{-1} \text{ cm}^{-1}],$$

with C the molar concentration of the absorber and d the absorption thickness.

Fibre bundle: Small diameter fibres fused coherently together during the drawing process. The bundles are of square or hexagonal outer cross sections with edge lengths greater than 1 mm. They contain several hundreds of individual fibres. Their cross sections are hexagonal due to the energy minimum required for this configuration. They are separated from each other by thin cladding layers.

Fibre optics window: Clad glass fibres of 5 to 20 μm diameter are fused together to serve as vacuum tight windows (thickness $> 5 \text{ mm}$) for photocathodes and phosphor screens. They are indispensable, if spatial resolution of fibres must be conserved. To avoid light losses, their numerical aperture (NA) must be greater than that of scintillating fibres.

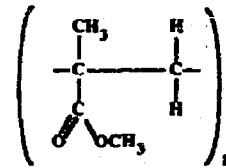
Förster transitions: Radiationless energy transitions between donor molecules (e.g. polystyrene) and acceptor (scintillator) molecules (in contrast to radiative energy transfer). They require small distances (0.5 to 3 nm) between donors and acceptors, which requires molar scintillator concentrations (above 0.02 molar fraction), at which, on the average, one scintillator molecule is inside a sphere with a radius corresponding to these distances. Förster transitions provide local light emission (in contrast to radiative ones) and therefore avoid cross-talk between fibres of small diameters (Fig. 5). Since they require high scintillator concentrations they can be achieved only with one-component dopants, which have no (e.g. 3HF) or only small (e.g. PMP) overlaps between their absorption and emission bands (large Stokes' shift). Förster [18] calculated critical distances between donor and acceptor molecules, if there is sufficient overlap between the emission band of the donor and the absorption band of the acceptor. An extensive list of computed critical distances and molar concentrations can be found in Ref. [89].

Hybrid photomultiplier tube (HPMT): Electrons, emitted from a light detecting photocathode, are accelerated by a potential difference ($\geq 10 \text{ kV}$) towards a silicon diode. With low capacitances of the diode, the preamplifier input, and the connecting cables, it is possible to resolve energy peaks corresponding up to 15 photoelectrons.

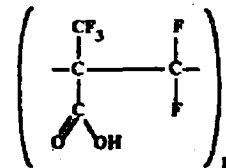
Magnetic flux density B : is measured in T (1 T = 1 V s m^{-2}). The old unit is Gauss [G]: 1 G = 10^{-4} T. It is connected to the magnetic field strength H [A m^{-1}] via $B = \mu \mu_0 H$, with μ_0 [$\text{V s A}^{-1} \text{m}^{-1}$] the permeability of free space and μ [dimensionless] the permeability of the material present in the magnetic field. The Lorentz force F between a particle of charge q and velocity v in a magnetic field amounts to: $F = q(v \times B)$. From this, the curling radius r of a charged particle with mass m in a solenoidal field is deduced: $r = mv/(qB)$ with $v \perp B$.

Microstrip gas chambers (MSGC): Anode strips of 5 to 10 μm width and 50 μm wide parallel field strips are deposited via UV lithography or plasma etching on substrates of high ohmic resistance. They form detector elements of about 200 μm pitch and 2 mm gas depth (cathode distance) for the development of electron avalanches.

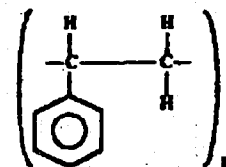
Polymethylmethacrylate (PMMA):



Cladding material of plastic step-fibres with 1.49 (590 nm) refractive index. The refractive index is reduced to 1.42, if fluorinated polymethacrylate is used as cladding material. This increases the trapping fraction by a factor 1.75.



Polystyrene (PS):



forms the basic structure of a fibre core. Its low fluorescence yield (0.03) must be enhanced by a scintillator.

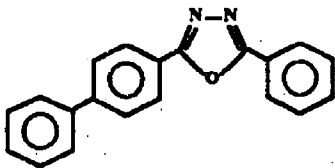
Radiation dose: Absorbed ionization energy [J] per mass unit [kg] quoted in Gy; $1 \text{ Gy} = 1 \text{ J kg}^{-1}$. This unit is equivalent to the old unit rad; $1 \text{ rad} = 10^{-2} \text{ Gy}$.

Scintillators: Aromatic compounds added to the styrene monomer (~ 0.02 molar fraction) of the fibre core for combined polymerisation. Scintillators enhance the poor fluorescence yield (0.03) of PS and provide Förster transitions. The following two scintillators emit in the opaque wavelength region of polystyrene. Therefore, a wavelength shifter is needed (two component system, Table 3) to obtain an emission band in the transparent region of polystyrene ($> 400 \text{ nm}$).

p-terphenyl:

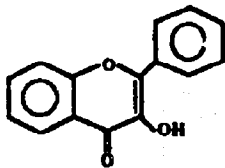


PBD: 2-phenyl-5-(4-biphenyl)-1,3,4-oxadiazole

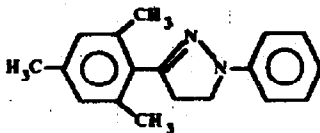


The following six scintillators emit in the transparent wavelength region of PS (one component system, Table 3), and do not need a wavelength shifter:

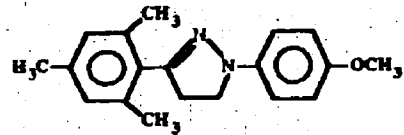
3HF: 3 hydroxyflavone



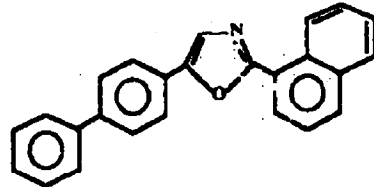
PMP 420: 1-phenyl-3-mesityl-2-pyrazoline



PMP 450: 1-p-anisyl-3-mesityl-2-pyrazoline



PBBO: 5-(1-naphthyl)-2-biphenyl-oxazole



R39, R45: Composition and structure unknown.

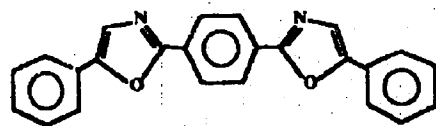
Silicon strips and pixels: are operated as diodes with reverse bias voltage. Electrons and holes, induced by ionizing particles, drift in a bias field of $\sim 300 \text{ V mm}^{-1}$ across a depletion layer of typically 0.3 mm thickness. Detector elements are geometrically arranged as single or double sided strips with 25 to $100 \mu\text{m}$ pitch. Their lengths of several cm are limited by increasing capacitance. For two-dimensional readout, they are arranged as square or rectangular pixels with edges longer than $50 \mu\text{m}$. All strips or pixels are wire- or bump-bonded, if not monolithically integrated to their individual front-end electronics.

Spatial frequency: means the number of line pairs per mm. The spatial frequency at which the MTF equals 0.03 represents the limiting resolution of an optoelectronic element. This number is often quoted by manufacturers of image intensifiers, fibre optics windows, etc.

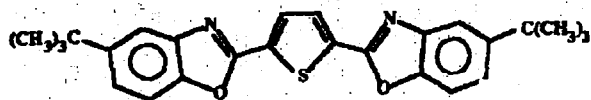
Stokes' shift: Difference between the wavelengths of the absorption (λ_A) and emission (λ_E) maxima: $\lambda_A^{-1} - \lambda_E^{-1} [\text{cm}^{-1}]$ or $hc (\lambda_A^{-1} - \lambda_E^{-1}) [\text{eV}]$.

Wavelength shifters: They form together with a scintillator (mostly p-terphenyl, which emits in the opaque wavelength region of polystyrene), a two-component system (Table 3). Their absorption bands overlap the scintillator's emission and their emission bands are in the transparent polystyrene region above 400 nm . Since their emission overlaps significantly their absorption band (small Stokes' shift, Fig. 3c), they can be added to the styrene-monomer only in small molar fractions (< 0.002). This results in radiative (nonlocal) energy transfer between scintillator and wavelength shifter and therefore produces cross-talk between fibres of small diameter (Fig. 5).

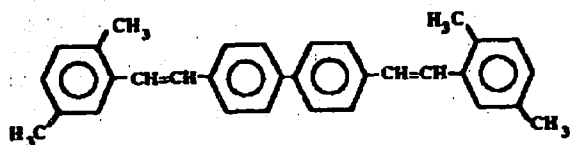
POPOP: p-bis [2-(5-phenyl oxazolyl)] benzene



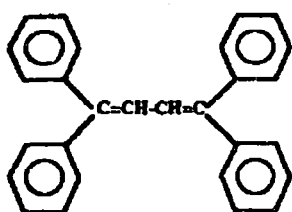
BBOT: 2,5-bis [5-tert-butylbenzoxazolyl (2)] thiophene



BDB:



TPBD: 1,1,4,4-Tetraphenylbutadiene



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