Chapter 3. Classification of the Main Requirements to Inorganic Scintillators for Various Applications

Inorganic scintillators based on metal fluorides are widely used in detectors of various types of ionizing radiation. We shall consider here the application of scintillators based on metal fluorides for detection of single electrons (positrons) and γ-quanta. Interactions of these particles with matter are of the same electromagnetic origin. Detection of these particles is a common task in nuclear science and technology, in a wide range of energies and intensities. The development of a new generation of particle accelerators (LHC, SSC, UNK) stimulated most intensive studies and research works which have led to new results and materials. At the same time, employment of fluoride scintillators for detection of other types of particles - protons, neutrons, α-particles and multicharged ions is an interesting but narrow application in which an established set of materials and techniques is used.

Search for and preparation of new fluoride materials require an account of their future applications and operation conditions. Therefore, analysis of some common applications of scintillators in the detection systems of electrons and γ–quanta will be useful. Admittedly, there are no universal scintillators, and their employment depends on energies of the particles detected. Here we shall confine ourselves to considering the main requirements to materials that depend on the detected energy region. Each region is characterized by specific requirements to scintillators.

3.1. Application of Scintillators for Detection of Electrons and Gamma-Quanta in the 0.001 - 0.1 MeV Energy Region

In this region thin layers (or screens) of most inorganic scintillators effectively absorb electrons and γ–quanta, because the integral track lengths of the electrons are small and γ–quanta absorption is large due to a large absorption coefficient μ_1 of the photoelectric processes. For thin scintillators the efficiency of light collection in a photodetector $k_c \cong 1$ is easily ensured by using optical glues and various types of reflecting coatings of the scintillator surfaces [3.1]. The main requirement to scintillators for these energy regions is a high light output. Table III.1 shows a group of scintillators with the highest light outputs.

Table III.1.
CHARACTERISTICS OF SOME SCINTILLATORS WITH HIGH LIGHT OUTPUT
(20 °C, EXCITATION BY ELECTRONS AND γ-RAYS)

No, No	Crystal	I, % NaI:Tl	τ, ns	λ_{max}, nm	ΔI, %/°C	ρ, g/cm^3	Reference
1	NaI:Tl	100	230	415	0.4 - 0.9	3.67	3.2, 3
2	CsI:Tl	85	630	565	0.2 - 0.7	4.51	3.2, 3
3	CsI:Na	85	900	420	0.2 - 0.7	4.51	3.4
4	ZnS:Ag	180	40	460		4.10	3.5
5	CaI_2	200	550	410		3.69	3.6
6	CaI_2:Eu	200	790	470		3.69	3.6
7	CaI_2:Tl	220	1100	420		3.69	3.6

In this energy region NaI:Tl and CsI:Tl scintillators are commonly used. ZnS:Ag powder scintillator can be employed only in the form of screens of small thicknesses [3.1]. Despite their unique properties (scintillation efficiency is 0.25), the application of scintillators based on CaI_2 is far from being wide because they are highly hygroscopic and their crystals cleave perfectly. The characteristics of some scintillators based on the fluorides which are shown below in Table III.2, are poorer than those of the scintillators presented in Table III.1, as far as the light output is concerned. Therefore, most of them are inadequate for detection of electrons and γ-quanta with low energies. Among fluorides, only CaF_2:Eu is a promising material for this energy range. It is not hygroscopic, has smaller effective atomic number (Z_{eff} = 16.5 a.u.) and density (ρ = 3.18 g/cm^3) that ensure a smaller reflection of electrons from the scintillator surface (albedo). Note that the radiation resistance of CaF_2:Eu is more than 10^8 rad.

It is noteworthy that scintillators with a high light output usually have longer luminescence decay times τ = 230 - 1100 ns. Therefore, they cannot be applied for an effective detection of single particles in fluxes more than 10^5 particles/sec. The need to detect small amount of light from scintillations requires employment of photomultipliers (PMs) as photodetectors for this energy range.

In this energy region the luminosity (light output/absorbed energy) for most inorganic scintillators depends on the energy of the incoming particles. Because of that it should be taken into account for the accurate measurements of particle energies. This dependence is attributed to the type of the scintillator used, the technique of its preparation, the impurity level, etc. [3.1].

3.2. Application of Scintillators for Detection of Electrons and Gamma-Quanta in the 0.1 - 10 MeV Energy Region

Here the ability of materials to absorb γ-quanta is not so high, that is why the characteristic sizes of the used scintillators are as long as a few

centimeters. The efficiency coefficient of light collection from scintillators is $k_c < 1$, but it can be increased by using various techniques [3.1], mainly, highly effective reflecting surfaces. Table III.2 presents some characteristics of the known intrinsic and extrinsic scintillators based on metal fluorides [3.1 - 3.7], most of which are single-component in their main chemical composition (without account of activator). The up-dated list of scintillators with the core-valence luminescence mechanism is given in Chapter 1.

It follows from Table III.2 that scintillators based on fluorides can meet many needs in detection of electrons and γ -quanta in this energy region. Among these materials there is the lightest inorganic scintillator (based on LiF), as well as unique scintillators with luminescence spectra in the range of VUV ($KMgF_3$, $KCaF_3$). Among fluorides there are scintillators with nanosecond (CsF, RbF) and subnanosecond scintillation decay times ($LiBaF_3$). This ensures their application for detection of particles in high fluxes up to 10^7 particles/sec, as well as with a high time resolution. It was shown in [3.28] that, using the fast component BaF_2, the time resolution ~ 0.4 ns (FWHM) can be obtained in the detection of γ-quanta with the energies 1.17 MeV.

There are quite many scintillators whose temperature coefficient of light output is practically zero within a wide temperature range, namely, CaF_2:Eu, BaF_2:Ce, etc. Such scintillators are needed for prolonged and precision measurements of particle energies.

The refractive indices of most fluorides are close to that of the entrance windows of common PM's ($n \cong 1.5$), that enables removal of most of the light which is entrapped in fluoride crystals within the total inner reflection angles. Starting from energies around 1 MeV, silicon photodiodes can be used for readout from some scintillators. The main requirement to the application of these photodiodes is a large number of the detected photons N as compared to the total noise level (including the noise from the amplification channel) which is typically about 800 per cm^2 at 20°C [3.29]. The silicon photodiodes will be most effective for detection of scintillations in the range of wavelengths > 500 nm.

In this energy region inorganic scintillators are mainly used for detection of radiation of radioactive isotopes. Besides, they are employed as sensitive elements in various devices which use radioactive isotopes or hard X-ray radiation.

This energy region implies various scientific and applied problems in which scintillation technique is used for radiation detection. As a result, it is most difficult, if possible at all, to present general criteria for detectors in this region. Instead, we shall consider some specific applications and each one will have its own specific requirements to scintillators.

Table III.2.
CHARACTERISTICS OF SOME SCINTILLATORS BASED ON METAL FLUORIDES (20 °C, EXCITATION BY ELECTRONS AND γ-RAYS)

No	Crystal	I, % NaI:Tl	τ, ns	λ_{max}, nm	ρ, g/cm^3	Reference
1	LiF:U	3 - 6	10	520	2.30	3.8
2	LiF:Ti	2 - 4	10	460	2.30	3.8
3	NaF:U	2	10	550	2.56	3.8
4	NaF:Ti	3	10	470	2.56	3.8
5	NaF:Cu	5	10	500	2.56	3.9
6	CsF	5	3 - 4	390	3.58	3.10
7	RbF	3.5	1.2	230	2.88	3.10
8	CaF_2	50	940	290	3.18	3.11
9	CaF_2:Eu	60	800	430	3.18	3.11
10	SrF_2	18	190; 890	280 - 300	4.24	3.11, 12
11	SrF_2:Eu	10	100; 500	400	4.24	3.12
12	BaF_2	15	0.8; 620	225; 310	4.89	3.13, 14
13	BaF_2:Ce	20	100; 620	340	4.90	3.15
14	BaF_2:La	5	0.8	225	4.95	3.16
15	LaF_3:Nd	0.6	6.3	173; 215	5.95	3.17
16	CeF_3	4.5	30	340	6.13	3.18, 19
17	ThF_4		10; 30	315; 330; 450	7.56	3.20
18	$KMgF_3$	7	1.5	155; 171	3.16	3.21
19	$KCaF_3$	5	2	155; 171	3.56	3.21
20	$KLuF_4$	1	1.3	165; (200)	4.8	3.22, 27
21	$LiBaF_3$	5	2; (0.8)	435; (220)	5.2	3.20, 25
22	BaY_2F_8:Tm	7	1; 8; 100		5.08	3.23
23	KYF_4	5	1.9	165		3.22, 24, 27
24	KLu_2F_7	0.7	2	165		3.22
25	K_2YF_5	1.4	1.3	170	3.31	3.22, 24
26	$LiYF_4$:Rb	0.5	40	186		3.24
27	$RbCaF_3$	5	1			3.26

Scintillation gamma and X-ray chambers. Such chambers are used for measuring coordinates and energies of γ–quanta in the 0.1 - 0.3 MeV region. The most typical requirements to scintillators for this application are as follows:

- a high coefficient of absorption of γ-quanta, i.e., high values of the effective atomic number ($Z_{eff} > 51$) and density ($\rho > 3.61$ g/cm^3);
- a high light output (~ 30 - 100 % of NaI:Tl);
- small values of afterglow (ΔG = 0.005 - 0.5 %). Here the value ΔG characterizes the intensity of afterglow (in percentage to the total light output) within the delay time 3 μs after the excitation is stopped. There are no significant constraints to luminescence decay times of scintillators. That is why scintillators with luminescence decay times up to 5 μs can be used. Here heavy iodides (Table III.1) and some heavy oxides (Table III.3) are most widely used [3.30].

Table III.3.
CHARACTERISTICS OF SOME OXIDE SCINTILLATORS WITH HIGH DENSITIES (20 °C, EXCITATION BY ELECTRONS AND γ-RAYS)

No	Crystal	I, % NaI:Tl	τ, ns	λ_{max}, nm	ΔI, %/°C	ρ, g/cm^3	Ref.
1	CdWO4	38	5000	470 - 540	0	7.90	3.31
2	ZnWO4	28	5000	475	0.4 - 0.9	7.87	3.31
3	Bi4Ge3O12	10	300	480	1 - 2	7.13	3.32

Positron-emission tomography (PET). This type of equipment is widely used for the diagnosing of various diseases in medical radiology. These devices detect the coincidence of a pair of annihilation γ-quanta (with E = 511 MeV) which are emitted in opposite directions by short living ^{11}C, ^{13}N, ^{15}O, ^{18}F and other β^+-radioactive isotopes. Small amounts of such isotopes probe into the human organs to be investigated. Scintillators for PET should meet the following requirements:

- scintillator length in the direction of gamma quanta motion should ensure their high absorption (> 90 %), in order to minimize patient's irradiation dose;
- the scintillators should possess a high density and a high effective atomic number so that the length > 90 % of their absorption should be 30 mm which is necessary for a high spatial resolution (2 - 4 mm);

- scintillators should possess light output > 5 - 10 % of that of NaI:Tl (such light output is sufficient for an effective separation of the cases of total absorption of gamma quanta from the background of the scattered events);
- scintillators should ensure a high time resolution < 3 - 5 ns (FWHM) so as to separate effectively the true events from the background of random coincidences.

A $Bi_4Ge_3O_{12}$ crystal is the most suitable and it has been currently used in PET. Among fluorides, rather long CeF_3 and BaF_2 crystals are also good for such purposes. In order to provide a high spatial resolution, however, several layers (along the direction of gamma quanta) of BaF_2 scintillators are suggested for the application, the information is supposed to be read out by photodetectors. This, however, makes the arrangement of PET more complicated [3.33]. There is an arrangement of such PET [3.34] in which the fast BaF_2 component is detected (light output is about 5% of NaI:Tl). Proportional gas chambers filled by photosensitive additive TMAE (tetrakis (dimethylamino) ethylene) [3.35] are used as photodetectors.

Detection of double beta decay and solar neutrinos. At present, there are several fields, where experimental studies require application of inorganic scintillators. Such experimental studies are based on detection of rare events of double beta decay [3.35] and solar neutrinos [3.37]. The main requirements to scintillators for such measurements are as follows:
- presence of certain isotopes (^{48}Ca, ^{71}Ga, ^{115}In, ^{116}Cd, ^{150}Nd, ^{160}Gd etc.) in large amounts;
- a high light output, comparable to NaI:Tl. The high light output from scintillators is necessary for an effective separation from the background of natural radioactivity and cosmic rays. The authors of [3.38] showed a possibility of using CaF_2:Eu, enriched with ^{48}Ca for detection of double β-decay. Similar requirements are put forward in current discussions of possible usage of scintillators for the detection of the so-called "dark matter" in the Universe [3.39].

3.3. Application of Scintillators for Detection of Electrons and Gamma Quanta in the 10 - 1000 MeV Energy Region

This region is often called the intermediate. As for the character of interaction of these particles with the matter, cascade processes of electron-positron pair creation and bremsstrahlung begin to prevail, and at high energies they lead to the formation of the so-called electromagnetic showers. Longitudinal lengths of EM showers are described in terms of radiation lengths X_o (cm), the definition for that was given in Chapter 2. A simpler expression $X_o \cong 180A/(\rho Z^2)$ can be used for rough estimations of X_o, where

A and Z are the mean atomic weight and atomic number of the matter, respectively; ρ is the density.

The lateral sizes of a EM shower are characterized by the Moliere radius R_M (cm), which was defined in Chapter 2. A simpler expression:

$$R_M \cong 7A/(\rho Z)$$

can be used for rough estimations of R_M.

The longitudinal length of an element for a EM-calorimeter should be 15 – 20 X_o to provide a total absorption of an EM shower in this energy region. The typical lengths of the used scintillators are dozens of centimeters when the transverse sizes are several centimeters. A multi-element detector based on such scintillators is usually called a total absorption homogeneous EM-calorimeter, the features of the design of such devices are discussed below in Section 3.6. Such calorimeters are used for accurate determination of energies and coordinates of EM showers. For the best spatial resolution the typical transverse sizes of an element should be 20 % less than R_M. In this energy range EM-calorimeters are usually operated in fluxes up to 10^6 particles/sec. However, since the EM-calorimeter structure consists of many elements, the counting rate per one element is, as a rule, not high.

The main requirements to scintillators in this energy region are as follows:

- crystals of the needed sizes;
- moderate light output (5 - 10 % of that of NaI:Tl);
- cheap materials which can be manufactured in the single crystal form in amounts up to 1 - 3 tons;
- crystal densities 3.5 - 6.5 g/cm^3.

At present, moderate radiation hardnesses of about 10^4 – 10^5 rad/year and luminescence decay times shorter than 50 ns are sometimes required. In the near future, however, more severe requirements to such scintillators are expected. BaF_2 crystals are already being used in experimental studies [3.40].

3.4. Application of Scintillators for Detection of Electrons and Gamma Quanta in the Energy Region Exceeding 1 GeV

This energy region refers to high energy physics. Inorganic scintillators are used mainly in EM-calorimeters. Longitudinal sizes of elements of EM-calorimeters should reach 23 – 25 X_o. The requirements to materials for EM-calorimeters are accounted for by the operation conditions for particle detectors. The most severe requirements are imposed on the new generation of accelerators (LHC, SSC, UNK), namely:

- radiation resistance against electrons and γ -quanta of $10^6 - 10^8$ rad/year and against hadrons of $10^{12} - 10^{16}$ particle/cm^2/year [3.41];
- a possibility of preparing cheap crystals of the required sizes in the amount of up to 30 tons;
- the main scintillation decay times should be as short as 30 ns; however, 3 ns is preferable, because the periodicity of collisions of particles at LHC accelerator will be 15 ns.

Possibilities of application of new materials, which have weak scintillation components of long decay times, besides the main fast component, require a thorough analysis of particular experimental conditions. It should be noted that some promising materials possess certain intrinsic fluorescence (or induced fluorescence, as they are located in intensive ionizing radiation beams). The allowed levels of fluorescence in the materials which are promising for EM calorimeters should be studied more carefully as well.

There are no severe requirements for light output of scintillators, it can be equal to some percent of that of NaI:Tl and even less. The application of Cherenkov radiators at these energies will have certain advantages, namely:
- it is possible to obtain the fastest signals;
- the Moliere radius R_M for EM-showers in them is 20 % less than that found from the formula for scintillators [3.42].

Smaller values of R_M of EM-showers for the Cherenkov radiation are accounted for by the fact that this radiation takes place only in the case of fast charged particles with velocities exceeding the relation of light velocity in vacuum divided by the refractive index of the substance. This circumstance is an advantage of Cherenkov radiators for detection of some EM-showers in jet events with a high multiplicity. The light output of the Cherenkov radiation, however, is small (< 0.1 % of that of NaI:Tl). Its intensity is proportional to $1/\lambda^2$ and the total number of photons is $N_f \sim 1/\lambda_{min}$, where λ_{min} is the short-wave transmission cutoff of the optical material.

In order to obtain a high energy resolution the light output should be homogeneous from one element to another, as well as along the entire length of the element, at the level of not worse than several percent. It is rather difficult to fulfill this condition for extrinsic scintillators. As for intrinsic scintillators and Cherenkov radiators, shaped simply as rectangular parallelepipeds, this condition can be easily fulfilled, provided that the light attenuation length in the elements is > 1 m. When elements of other shapes are used, for instance, a long truncated-pyramid shape, the condition of equal light output along the length might require application of a combination of reflectors, and special coating of surfaces of elements.

The energy resolution of EM calorimeters, in which Cherenkov radiators are used, is typically given by the expression [3.43]:

$$\delta E/E \cong 4.5\ \%/\sqrt{E} \oplus a,$$

where $\oplus$ is the quadratic summation, a is a constant $\cong 0.5 - 1$ %, which is determined by a long time stability of calibration, optical properties of elements etc. The energy resolution of EM-calorimeters made of scintillators with the light output of about one percent of that of NaI:Tl is typically given by the expression [3.43]:

$$\delta E/E \cong 2.0\ \%/\sqrt{E} \oplus a.$$

At energies over 10 - 40 GeV the energy resolutions of these two types of calorimeters will be, in fact, the same, and they will be defined by a. The application of fluoride materials in this energy region is quite promising. The characteristics of some heavy fluorides which can be used in HEPh owing to their high absorption ability, are shown in Table III.4.

Table III.4.
CHARACTERISTICS OF SOME SCINTILLATORS BASED ON HEAVY METAL FLUORIDES

No,	Crystal	n_D	X_O, cm	R_M, cm	Luminescence	ρ, g/cm^3	Ref.
1	BaF_2	1.56	2.03	3.39	Scintillator	4.89	3.44
2	CeF_3	1.68(aver.)	1.66	2.63	Scintillator	6.13	3.45
3	CdF_2	1.55	1.73	2.71	Scint. + Cher.	6.38	3.46
4	PbF_2	1.82	0.95	2.21	Cher.	7.76	3.42

Although, unfortunately, such an important parameter as radiation hardness for the discussed applications is not universally defined, still, requirements of optical transparency of materials can be defined (see Chapter 2). The above data on radiation hardness of materials should be interpreted with certain allowances. If the measurements yield high values of this parameter, it means that one can speak about a possibility to obtain materials with such characteristics. If the material exhibits a low radiation hardness, however, it does not mean that it cannot be improved by using certain procedures (for instance, other preparation techniques, variations of chemical compositionn etc.). We shall give relevant examples below.

3.5. The Criteria for Preliminary Selection of Scintillators for High Energy Physics

It follows from the above chapters, that the energies higher than 1 GeV impose the most severe requirements to scintillating materials as far as radiation stability, absorption and luminescence decay times are concerned. Light output was the only parameter, for which the requirements were moderate, although this parameter is rather hard to control. Quite often it is most difficult to obtain scintillators even with one very good parameter. Obviously, one cannot expect to discover easily materials with several good characteristics.

In fact, none of the known materials satisfies all the requirements. This circumstance has stimulated intensive search for crystals which are promising for the above energy regions. First, the requirements to physical and chemical properties of materials are severe, second, there is a large amount of single crystals available. That is why the stage of choice of the main material for scintillators is vital.

Having in mind a wide scale search for new scintillators based on metal fluorides, we have chosen only materials for high energy physics. This has determined the strategy of the search and the main characteristics of the materials considered in this book.

In fact, the possibilities to obtain scintillating single crystalline materials based on simple (single component) metal fluorides have been practically exhausted.

The situation with selection of fluoride materials had become critical long before these materials were needed in HEPh. A possible way out is to employ materials with more complex chemical compositions. Their properties can be controlled now. Proceeding from this, basic directions of development of new materials for HEPh are discussed in the next Chapter.

As for energies of electrons and gamma quanta used in HEPh, the following simplified criteria of choice of materials and ranges of their measurements, which we consider as critical, can be suggested:

- *high densities of samples (over 5.5 - 6.5 g/cm^3);*
- *radiation resistances over 10^6 - 10^7 rad/year;*
- *short main luminescence decay times (3 - 30 ns).*

Selection of materials of complex chemical compositions (i.e., multicomponent) proceeding from this minimum set of parameters does not mean that all the samples which meet these requirements can be used as scintillators in HEPh. There are quite many factors which should be added to the general characteristics of scintillators considered in the next Chapter, when particular materials are selected. There are quite many examples in materials science when a seemingly insignificant feature becomes a grave obstacle for practical application upon a careful examination.

Therefore, we consider this investigation as the first stage of search for optical materials which are promising for HEPh. The results of this stage should lead to the second stage, which will require a more careful study of the most interesting materials and all their parameters, which are relevant to their applications.

Table III.5.
TYPICAL ELECTROMAGNETIC CALORIMETERS OF A LARGE SCALE FOR HIGH ENERGY PHYSICS EXPERIMENTS
(L 3P and CMS are at the stage of proposal)

Calorimeter:	Crystal Ball	CLEO II	L3-BGO	L 3P	CMS
Accelerator	SLAC	CESR	LEP	LHC	LHC
Scintillator	NaI:Tl	CsI:Tl	BGO	CeF_3	CeF_3
Total scint. volume, m^3	1	6	1.6	64	26
Number of modules	672	8000	11000	129.6 K	55 K
Module depth, (X_0)	16	16.2	21.4	23.2	25
Magnetic field	no	yes	yes	yes	yes
Readout	PMT	SiPD	SiPD	SiPD	SiPD
Readout noise / crystal (MeV)	< 1	< 1	< 1	~ 75	~ 50
Outer shape	sphere	barrel	barrel	barrel	barrel
References	3.50	3.53	3.54, 55	3.56	3.57

3.6. Some Construction Features of Detection Systems for HEPh

Precision measurement of γ-rays as well as electrons (or positrons) is an important stage in most high energy experiments. High quality electromagnetic calorimeters enable not only accurate measurements of single γ - rays, which is also very important, but also accurate detection and reconstruction of other elementary particles such as π^0, η, η', etc. which result from they decay into two γ-quanta. Moreover, measurement of the global flux of electromagnetic energies is also important at very high energies where the multiplicity of particles is too large to separate each particle precisely. NaI:Tl was first used for calorimeters of a large scale (see [3.47]), then followed CsI:Tl and rather recently BGO. The other scintillators such as pure CsI, BaF_2, etc. have also been used in smaller detectors in HEPh as well as in nuclear physics experiments. BGO [3.48] was an advance from NaI:Tl and CsI:Tl because of its shorter radiation length, 1.12 cm, and higher radiation resistance, 10^4 - 10^5 rad. Typical examples of the electromagnetic calorimeters include, as shown in Table III.5, Crystal Ball at SLAC (672 modules of

NaI:Tl, the total crystal volume $1m^3$ [3.49, 50]), CLEO II at Cornell (8000 modules of CsI:Tl [3.51 - 53]) and L3-BGO (11000 modules of BGO, 1.6 m^3 [3.54]). The first one is a spherical shell, while the second and the third ones are barrel-type shells equipped with both end plates. A sketch of L3-BGO calorimeters is given in Fig. 3.1.

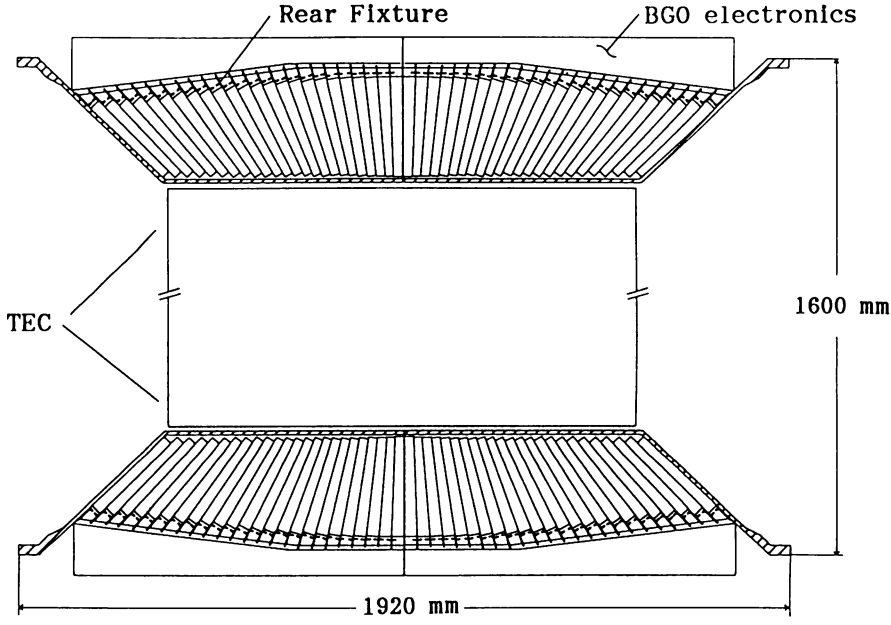

Fig. 3.1. Longitudinal cross-section of the L3-BGO calorimeters [3.55]. Both end caps made of similar BGO modules are not shown.

At the new accelerators such as SSC, LHC, UNK, etc., the accelerator energies and/or intensities are larger than the existing ones by more than an order of magnitude. For the calorimeters to be used with these new accelerators, BGO is inadequate in its radiation hardness by roughly two orders of magnitude. New radiation hard, dense and fast scintillators are required. Both L3P and CMS proposals at LHT have considered the use of CeF_3. The main parameters for their CeF_3 calorimeters are also shown in Table III.5. A typical geometry studied for a CeF_3 calorimeter for LHC is given in Fig. 3.2 with a 1m inner radius [3.56]. The CeF_3 calorimeter in the L3P proposal [3.57] is much bigger with an inner radius of 3 m and a length of 12 m. Recently, the use of $PBWO_4$ [3.58-59], instead of CeF_3, has also been considered by the CMS. These new accelerator projects have recently been

approved: B-factories at SLAC and KEK. CsI EM calorimeters of a similar scale as in CLEO II are discussed for the physics experiments at these facilities.

Some construction features, which are characteristic of electromagnetic calorimeters for high energy physics experiments, are as follows:

- **large scale.** The calorimeter usually subtends almost 4π around the collision point of the colliding beams or around the stationary target, as seen in Fig. 3.1 and 3.2;

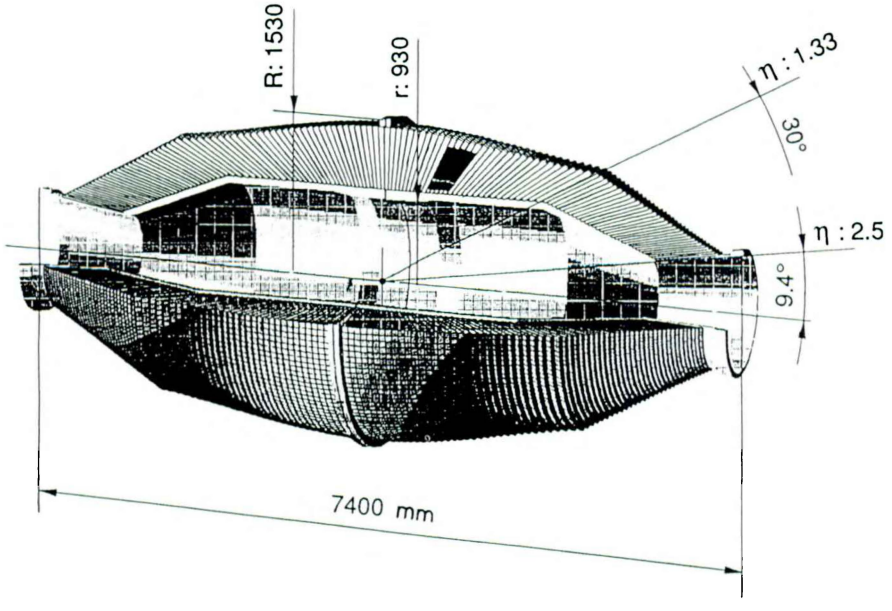

Fig. 3.2. Conceptual view of a CeF_3 crystal calorimeter for LHC, with 1 m inner size, from [3.56]. In the L3P proposal, a similar calorimeter of a larger scale with a 3 m inner radius and a length of 12 m is considered.

- **modular structure.** The size of each module is chosen roughly around 1 X_o or 1 Moliere radius, laterally, and as long as or longer than 20 X_o, longitudinally. The longitudinal length is based on the shower size which is approximately proportional to the logarithm of the incident γ-ray (or electron) energy. Each module is usually tapered in shape as shown in Fig. 3.1, In the CMS, the element is segmented intp two parts and the front part is further segmented laterally into four parts (see Fig. 3.3). Compared with the case of each module without further segmentation, the above design has advantages of a better position resolution for the shorter centre and easier production of crystals with shorter lengths;

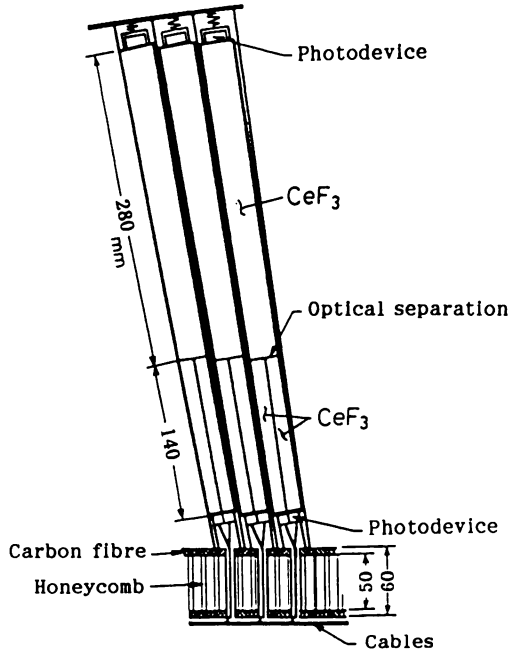

Fig. 3.3. CeF_3 modules designed for the CMS detector.

- **readout in magnetic field.** Magnetic field is usually incorporated in order to carry out precision tracking of charged particles. Electromagnetic calorimeters are located inside the magnetic coils (for superconducting solenoids) or the iron yokes (for ordinary magnets) in order to minimize the material in front of the scintillating crystals. As seen in Table III.5, silicon photodiodes (SiDPs) are used for readout, since at present they have the best combination of characteristics, such as quantum efficiency, gain stability, insusceptibility to magnetic field, price etc. Since the quantum efficiency of the photodiodes increases with the wavelength (about 20 % at 300 nm, 60 % at 500 nm), the emission at long wavelengths (in the visible region) is better in spectral matching;
- **refined mechanical support.** In order to obtain good energy resolution, the material in front of the crystal, as well as between the neighboring modules has to be minimized. This requires mechanical support for the total big mass in a thin walled structure. In the L3-BGO calorimeter, for example, air gaps were prepared between neighbouring crystals in order to avoid the overstressing of crystals during loading, assembling, transportation, installation, etc. For the above purpose, an alveolate structure made of

carbon-fiber reinforced resin with a wall thickness of 200 μm was used. Each module was mounted into an individual alveolus (cell). To make the mechanism assembling simple and reliable, the following qualities of crystals are desirable: absence of hygroscopicity, no or weak cleavage, large hardness, high Young modulus, small thermal expansion coefficient, etc.;

- **monitoring and calibration of gain.** Since the number of the modules is large, and the calorimeter is difficult to reach after it has been installed deep inside the whole detector complex, monitoring and calibration of gain of each module is very important in order to maintain the system operation for a long period. For example, in the L3-BGO calorimeter, gain monitoring is made frequently by using an optical fiber, which is mounted on the rear face of the crystal and connected to the master flash lamp. Absolute energy calibration [3.54, 60] was carried out from time to time by using such physical processes as $Z^{\circ} \rightarrow e^{+}e^{-}$, cosmic rays, a small RFQ accelerator which bombarded a Li target to produce 17 MeV photons, etc.

REFERENCES

3.1. Tsirlin Yu.A., Globus M.E., Sysoeva E.P., Optimization of Gamma Radiation Detection by Scintillator Crystals, Energoizdat, Moscow, 1991, 74 - 135 (in Russian).

3.2. Hofstadter R., Alkali halide scintillation counters, Phys. Rev., 1948, v. 74, 100 - 104.

3.3. Hearth R.L., Hofstadter, R., Huges, E.B., Inorganic scintillators, Nucl. Instr. and Meth., 1979, v. 162, 431 - 476.

3.4. Brinckman P., CsI (Na) scintillation of crystals, Phys. Lett., 1965, v.15, No 4, 3 - 7.

3.5. Medvedev M. E., Scintillation Detectors, Energoizdat, Moscow, 1977, 136 - 140 (in Russian).

3.6. Hofstadler R., CaI_2 and CaI_2(Eu) scintillation crystals, Rev. Scient. Instr, 1964, v. 35, No 2, 246 - 247.

3.7. Hand, book of the advanced material division of BDH limited (a member of the MERCK group), England, 1990, 24.

3.8. Victorov L.V., Skorikov V.M., Zhukov V.M. et al. Inorganic scintillation materials, Inorganic Materials, 1991, v. 27, No.10, 2005 - 2029 (in Russian).

3.9. Alybakov A.A., Kenzhabaev V.K., Kidibaev M.M. et al., Dosimetry and scintillation properties of NaF(Cu) crystals, Izv. Kirg. Acad. Sci., Ser. Fiz., 1990, v. 17, 23 - 26 (in Russian).

3.10. Van Sciver W., Hofstadter R., Gamma- and alpha-produced scintillation in cesium fluoride, Phys. Rev., 1952, v. 87, 522 - 523.

3.11. Moon R.J., The scintillation properties of CaF_2, Phys. Rev., 1948, v. 73, 1210 - 1213.
3.12. Fedorovskikh Yu.A, Shulgin Yu.V., Morozov E.G., Some optical and scintillation parameters of strontium fluoride, Proc. All-Union Conf. on Chemistry of Inorg. Fluorides, Moscow, 1970, 120 - 122.
3.13. Laval lM., Mozinski M., Allemand P. et al., Barium fluoride - inorganic scintillator for subnanosecond timing , Nucl. Instr. and Meth., 1983, v. 206, 169 - 176.
3.14. Beck F.A., Scintillation properties of BaF_2, Nucl. Scien. Research Conference Series, N. Y. Harwood Academic Publishers, 1985, v. 7, 3 - 47.
3.15. Visser R., Dorenbos P., van Eijk C.W.E., et al., Scintillation properties of Ce^{3+} doped BaF_2 crystals, IEEE Trans. NS 38 , 1991, No.2 178 - 182.
3.16. Schotanus P., Dorenbos P., van Eijk C.W.E. et al., Recent development in scintillator research, IEEE Trans., 1989, NS-31, No. 1, 132 - 136.
3.17. Schotanus P., van Eijk C.W.E., Hollander R.W., et al., Detection of LaF_3 - Nd^{3+} scintillation light in a photosensitive multiwire chamber, Nucl. Instr. and Meth., 1988, v. A272, 913 - 916.
3.18. Anderson D.F., Properties of the high density scintillator cerium fluoride, IEEE Trans., NS 36 , 1989, No. 1, 137 - 141.
3.19. Moses W.W., Derenzo S., CeF_3 - a new fast, heavy sclntillator, IEEE Trans., 1989, NS - 36N 1, 173 - 176.
3.20. Lecoq P., Homogeneous calorimeters at LHC/SSC, in: Proceed. of the Second Intern. Conference on Calorimetry in High Energy Physics, Capri 14 - 18 Oct. 1991, Italy, World Scientific, 1992, 283 - 285.
3.21. Valbis Ya.A., Rachko Z.A., Yansons Ya.L., Crossluminescence of KF and related compounds, Solid State Comm., 1988, v. 67, 183 - 185.
3.22. Buzulutskov A.F., Turchanovich L.K., Vasil'chenko V.G., Investigation of the crystal scintillation in the UVU region, Nucl. Instr. and Meth., 1990, v. A288, 659 - 661.
3.23. Aseev A.A., Devitsin E.G., Komar A.A. et al., New radiation hard heavy crystals for E.M. calorimrtry, in: Proceed. of the Second Intern. Conference on Calorimetry in High Energy Physics, Capri, 14 - 18 Oct. 1991 Italy, World Scientific, 1992, 313 - 319.
3.24. Dorenbos P., Visser R., van Eijk C.W.E., Valbis Ya.A., Khaidukov N.M., Photon yields and decay times of cross luminescence in ionic crystals, IEEE Trans., 1992, NS 39, N 4, 506 - 510.
3.25. Rodnyi P.A., Terekhin M.A., Mel'chakov E.N., Radiative core valence transitions in barium based fluorides, J. of Luminescence, 1991, 47, 281 - 288.
3.26. Mel'chakov E.N., Rodnyi P.A., Roentgenoluminescence properties of crystals with core valence transitions, Presented at the LUMDETR'91 Symposium, Oct. 9 - 12, 1991, Riga, Latvia.

3.27. Makhov V.N., Kaidukov N.M., Cross-luminescence peculiarities of complex KF-based fluorides, Nucl. Instr. Meth, 1991, v. A308, 205 - 207.
3.28. Wisshak K., Kappeler F., Large barium fluoride detectors, Nucl. Instr. and Meth., 1984, v. 227, 91 - 96.
3.29. Winter G.G., Ahme J., Marks J. et al., Performance of a lead scintillator sandwich hodoscope with photodiode readout, Nucl. Instr. and Meth., 1985, v. A238, 307 - 314.
3.30. Faruchi M.R., Recent developments in scintillation detecterors for X ray CT and positron CT application, IEEE Trans., 1982, NS 29, N 3, 1237 - 1249.
3.31.Kroger F.A., Some Aspects of the Luminescence of Solids, Elsevier, Amsterdam 1948, 107 - 127.
3.32. Weber M.J., Mounchamp R. R., J. Appl. Phys., 1973, v. 44, 5495.
3.33. Hollander R.W., Schotanus P., van Eijk C.W.E. et al., Recent development for a BaF_2 /TMAE PET camera, Nucl. Instr. and Meth., 1989, v. A283, 448 - 453.
3.34 Bateman J.E., Connoly J.F., Stephenson R., et al., Development studies for a high rate positron camera based on a BaF_2 /TMAE system, Nucl. Instr. and Meth., 1989, v. A283, 436 - 444.
3.35. Anderson D.F., Bouclier R., Charpak G., et al., Coupling of a BaF_2 scintillator to a TMAE photicathode and a low-pressure wire chamber, Nucl. Instr. and Meth., 1983, 217, 217 - 223.
3.36. Akimov Yu.K., Ignatyev O.V., Kalinin A.I., et al., Semiconducting Detectors in Experimental Physics, Energoizdat, Moscow, 1988, 83 - 105 (in Russian).
3.37 Haxton W.C., Solar neutrinos: prospects for detection and implications, in Proceed. of the X ,1 1TH Intern. Conf. on Neutrino Physics and Astrophysics at Nordkirchen near Dortmund, June 14 - 16, 1984, World Scientific, 1985, p. 214 - 228.
3.38. Alessandrello A., Brofferio C., Fiorini F., et al., Large mass bolometric detectors for double-beta decay experiments, IEEE Trans, 1992, NS - 39, N 4, p.610 - 614.
3.39. Gonzales Mestres L., Perret Gallix D., New results on detector developments for low energy neutrinos and dark matter, LAPP preprint LAPP - exp - 07 - 89, Annecy, 1989, 2 - 7.
3.40. Wissak K., Guber K., Kappeler F., et al., The Karlsruhe 4 π barium fluoride detector, Nucl. Instr. and Meth., 1990, v. 299, 60 - 64.
3.41. Stevenson G.R., New dose calculations for LHC detectors, in Proceed. of the Large hadron collider workshop, Aachen 4 - 9 Oct. 1990, CERN 90 - 10, ECFA 90 - 133, 1990, v. 3, 566 - 572.

3.42. Anderson D.F., Kobayashi M., Woody L.C., et al., Lead fluoride: an ultra compact cherenkov radiator for EM calorimetry, Nucl. Instr. and Meth., 1990, v. A290, 385 - 389.
3.43 Virdee T.S., Performance and limitations of electromagnetic calorimeters, in Proceed. of the Second Intern. Conference on Calorimetry in High Energy Physics, Capri 14 - 18 Oct. 1991, Italy, World Scientific, 1992, 3 - 23.
3.44. Newman H.B., A precision BaF_2 crystal calorimeter for the next generation of hadron colliders, CALT preprint CALT - 60 - 1690, Pasadena, 1990, 2 - 10.
3.45. Colas J., Klanner R., Repellin J. P., et al., Calorimetry at the LHC, in Proceed. of the Large hadron collider workshop, Aachen 4 - 9 Oct. 1990, CERN 90 - 10, ECFA 90 - 133, 1990, v. 1, 370 - 419.
3.46. Britvich G.I., Vasil'chenko V.G., Buchinskaya I.I., et al., Radiation resistant multicomponent inorganic materials for homogeneous e.m. calorimeters, Nucl. Instr. and Meth., 1992, v. A291, 64 - 68.
3.47. Ishii M., Kobayashi M., Prog. Crystal Growth and Charact., 1991, v. 23, 245.
3.48. Gevay G., Prog. Cryst. Growth and Charact., 1987, v.15, 145.
3.49. Chan Y., IEEE Trans. Nucl. Sci., 1978, v. NS-25, 333.
3.50. Kirkbride G.I. et al., IEEE Trans. Nucl. Sci., 1979, v. NS-26, 1535.
3.51. Blicher E. et al., IEEE Trans. Nucl. Sci., 1985, v. NS-32, 716.
3.52. Bebek C., Nucl. Instr. Method., 1988, v. A265, 258.
3.53. CLEO Collaboration, CLEOII - Updated Proposal, CLN85/634(1985).
3.54. Schneegans P., Nucl. Instrum. Meth., 1987, v. A257, 528.
3.55. Borgia B., Diemoz M., Morganti S., Nucl. Instrum. Meth., 1989, v. A278, 699.
3.56. Ferrere D., Lebeau M., Schneegans M., Vivargent M., Lecoq P., Nucl. Instrum. Meth., 1992, v. A315, 392.
3.57. L3P Collaboration, "L3P, Lepton and Photon Precision Physics", (letter of intent), CERN/LHCC 93-3, 1992.
3.58. Kobayashi M., Ishii M., Usuki Y., Yahagi H., Scintillation characteristics of $PbWO_4$ single crystals. Nucl. Instrum. Meth., 1993, A333, 429-433.
3.59. Kachanov V.A., Prokoshkin Yu.D., Singousky A.V., et al, Properties and beam tests of $PbWO_4$ crystals, presented at IEEE Nucl. Sci. Symposium, San Francisco, 1993.
3.60. Summer R., Nucl. Insrtum. Meth., 1988, v. A265, 252.