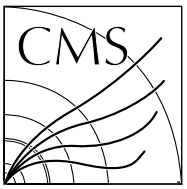
Available on CMS information server

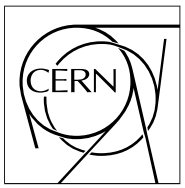
**CMS NOTE 1997/107**



**The Compact Muon Solenoid Experiment**

# CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland



**17 December 1997**

# Gamma Induced Transparency Loss of Thick Quartz Fibres

A.D. Avezov, E.M. Gasanov, E.M. Ibragimova, B.S. Yuldashev
*Institute of Nuclear Physics, P.Ulughbek, 702132 Tashkent, Uzbekistan*

M.Kh. Ashurov, I.R. Rustamov
*Scientific Association "Phonon", S.Yusupov st.50, 700054 Tashkent, Uzbekistan*

A.G. Volod'ko
*Joint Institute for Nuclear Research, Dubna, Russian Federation*

**Abstract**

Radiation response of thick multi-mode *Ge, P, F* -doped quartz fibre has been examined after exposure to $^{60}$Co gamma-source within a dose interval of $10 \div 10^7$ Gy at a dose power of 2.3 and 24 Gy/s at 300 K. The induced transparency losses A at the wave length of 1.06 mkm do not exceed 0.2 after a dose of $10^6$ Gy and reach a saturation, while the fibres are closed for visible light after a smaller dose. Varying focus and an angle of leading a probe light beam in fibre, the core modes were found to close at a dose of $10^4$ Gy due to radiation induced colour centres of *Ge* and non-bridging oxygen *O*, and the clad modes were suppressed at 500 Gy by the expense of Al impurity colour centres.

# 1 Introduction

## 1.1 Requirements to fibres as a part of calorimeters in high energy experiments

A study of radiation response of optical fibres to a mixed flux of high energy particles is necessary for designing and optimal choice of fibre material for calorimetry in experiments at colliders. This problem became especially important for collider experiments with very high energies and luminosities when secondary particles cascading in the detector material produce high fluxes of neutrons and gammas which could damage the fibres used to collect a light from scintillation crystals. For example, in CMS detector which will be used in experiments at Large Hadron Collider at CERN the maximal dose per year for the luminosity of $10^{34} n/cm^2 s$ is expected to be $3 \div 4 * 10^5$ Gy ($30 \div 40$ MRad) and in some experiments - above 1 GRad, and the maximal annual fluence of neutron is near $10^{15} n/cm^2$ [1, 2]. Use of the scintillation doped fibres in this case is limited by a level of radiation damage at doses of $\sim 0.1$ GRad. Besides, the response rate is limited by scintillation decay. Cherenkov radiation is 10 times weaker and faster than the scintillation, so several high pure and transparent dielectrics like quartz are radiation hard even at doses about 1 GRad [3, 4]. The threshold of electron energy for excitation of the Cherenkov radiation in quartz is 180 keV and the flux ratio of electrons to hadrons in the shower is $2.2 < e/h < 2.7$ [4].

Normally, in high energy detectors, the quartz fibres are put inside of an absorber at a low angle to an incident beam. Also the construction of $0^o$ calorimeter assumes use of thick fibre of a large diameter with a crude arrangement in absorber. The radiation is maximal if shower particles fall at an angle of $\sim 45^o$ to the fibre's axis. Qualitative hadron calorimetry is secured by equalising hadronical and electromagnetic responses of the detecting system. The preliminary experiments have shown, that at angles $\sim 6^o$ it is not necessary to equalise the fibre of the hadron calorimeter along the Cherenkov angle as it appears along the meridian beam of thick fibre of 0.5 mm in diameter [4]. So, exploring thick quartz fibres might be preferential if they appear to be radiation hard as well. Preliminary results were published by us in [14].

## 1.2 Radiation characteristics of quartz fibres

Influence of $^{60}$Co gamma-rays and neutrons on optical properties of thin quartz fibres were studied intensively [5]-[10]. Eight types of radiation colour centres have been found in the induced absorption spectra within $0.3 \div 1.9$mkm of quartz fibres of $SiO_2 - SiO_2 : B_2O_3$ after $^{60}$Co $\gamma$ - irradiation doses of $3 \div 100$ Gy at temperatures of 77 and 300 K [5, 6]. These centres anneal at different temperatures and are bleached by laser illumination. The "effect of transfer" of UV-band at 0.34mkm into IR-band was discovered under pumping with the 3-rd harmonics of $YAG : Nd$ laser followed by recovering at 300 K. The induced band at 0.67mkm was found to be discoloured by He-Ne laser irradiation. Also relaxation (anneal) of the colour centres is accompanied sometimes by luminescence, which should be taken into account in the scintillator's response. The induced losses at 1.3mkm were examined with a high accuracy and were proved to be proportional to a gamma dose rate and unstable [7]. Moreover, the losses in IR-region turned to be equal for 14 MeV neutrons and $^{60}$Co gammas, provided with the same ionisation dose [8]. Therefore the authors concluded that the radiation response of the fibre is due presumably to ionisation effects and is determined by an accumulated dose and not by structure changes from neutron induced atom displacements. This conclusion was confirmed by calculation of elastic and inelastic losses in quartz fibre after reactor exposure [10]. Radiation testing the fibre with pure quartz core and doped quartz clad, explored as an element of photometer in the region of $400 \div 900$ nm [9], after gamma-irradiation to the dose of $8 * 10^5$ Gy (80 MRad) showed the maximal induced loss $\sim 2 \div 3$ dB/m at 600 nm, the band being caused by the colour centre of non-bridging oxygen $O^-$.

As far as the radiation induced loss in quartz fibres depends strongly on their composition and processing technology, it was necessary to carry out a comparative analysis of absorption spectra within $200 \div 700$ nm of the fibres having different content of OH-groups at $\gamma$- irradiation to a dose of $10^7$ Gy at a dose rate of 6.4 Gy/s. It has been accomplished lately by [11] for the Cherenkov radiation calorimeter based on quartz fibre. A strong absorption at 350 and 630 nm and luminescence at 670 nm appear at a dose of $10^5$ Gy, depending on $OH^-$ group concentration. The higher content of $OH$, the more intensive absorption at 630 nm, but the weaker absorption at 400 nm. Thick fibre might possess a bigger radiation induced loss than thin one.

Thus, it is important to investigate both the radiation induced absorption (optical loss) and luminescence, including time parameters (dose rate dependence and relaxation), in order to determine a contribution from atomic and ionisation energy losses into defect production and to predict the radiation hardness of fibres under the mentioned conditions.

The aim of this work was to study radiation hardness and radiation induced loss at a wave length of 0.35, 0.53, 0.63 and 1.06 mkm of the gradient quartz fibres of a large diameter under effect of $^{60}$Co $\gamma$ - radiation at the temperature of 300 K in a wide range of integral absorbed doses $10 \div 10^7$ Gy at a dose power of 1.3 and 24 Gy/s. Using both pulse lamp and laser as a probing light enables to separate the optical loss of core and clad modes.

# 2 Experiment

## 2.1 Characteristics of fibres

Objects were quartz gradient multi-mode fibres, the core of which is of 530mkm in a diameter and made of pure $SiO_2$ with uncontrolled impurities of $10^{-6} \div 10^{-7}$ wt. percent. The gradient of refraction index is conditioned by adding of $GeO_2$ component from 0 to 10 wt. percent to the core, the clad with a diameter of 1050mkm is made of two -component silica glass $SiO_2 : F(0.02)P_2O_5(0.001 \div 0.002)$ and the total diameter including a polymer cover is 1480mkm. The numerical aperture is 0.22 and the initial optical loss *k* for the wave length of 0.85mkm is 2.8 dB/km, 1.3mkm - 0.5 dB/km and 1.55mkm - 0.25 dB/km, the temperature of drawing is $2100^o$ C. As far as the drawing condition is the chemical precipitation from a gas phase, a concentration of *OH*-groups is supposed to be high and therefore absorption in the region of 350 and 630 nm can be correspondingly high. So a length of the fibre samples was chosen to be 10 cm for a visible spectrum and 50 cm for IR-region where the optical loss are much less.

## 2.2 Conditions of irradiation

Design of $^{60}$Co $\gamma$- radiation source, developed at the Institute of Nuclear Physics, Uzbekistan Academy of Sciences, allows to carry out irradiation of different size objects with different fluxes of the gammas in ambient (air) and inert environment. Specimens of 10 or 50 cm long fibres were inserted into a glass tube and placed inside a stainless steel hermetic cylindrical chamber with an inner diameter from 7 to 60 cm and a height from 20 to 70 cm. The chamber is installed into a water filled basin of 5 m depth, with the isotope capsules surrounding the chamber and providing with a homogeneous irradiation and several kinds of in-situ measurements. Three samples with the ends broken off normally to fibre axis were exposed sequentially to doses from 10 to $10^5$ Gy at a dose rate of 2.3 Gy/s and from $10^3$ to $10^7$ Gy at 24 Gy/s with an accuracy of 15 percent at $300 \div 350$ K depending on a dose rate. Therefore there was an opportunity to examine the dose rate dependence of the gamma-induced loss within the interval of $10^3 \div 10^5$ Gy/s, if any, and to compare with the results of experiments done at 6.4 Gy/s by [5, 6, 10, 11]. The optical loss was measured 10 minutes later the irradiation, so this could include a sufficient part of the radiation induced centres unstable at 300 K.

## 2.3 Optical loss measurements

The experimental set-up is shown in Fig. 1. It includes the table (8) with the freedom degrees for fitting and tuning a fibre sample (7), short-focal lenses (6) for entering and leading the probe light out off the fibre, neutral filters (3) for attenuation of the reference beam, optical detectors based on photodiode PD-10g (9) and calorimeter IMO-2 with digital registration of a signal amplitude (10), sources of a probing light (1) based on the $He-Ne$ laser with the wavelength of $\lambda$ = 0.63 mkm, the power of $\sim$ 30 mW and $YAG : Nd$ laser with the 1-st harmonics at the $\lambda_1$ = 1.06 mkm and the 2-nd one at the $\lambda_2$ = 0.53 mkm , operating in the regime of free generation and modulation by $LiF : F_2^-$ providing with a pulse of 20 ns. The optical loss at the wave lengths of 0.35 and 0.53mkm were also taken by means of the pulse lamp INP-3/45 with a condenser (2) and the proper colour filters as an incoherent light source (labelled as Lamp). So far as the thick gradient multi-mode fibre has a different composition of it's core and clad, it should expect a different response to irradiation depending on an entrance angle of probing light. The entry angle varied by different lenses, and axial and cladding modes were distinguished at an image of the fibre's end. If the probing light passes throughout the fibre's core, the output signal is maximal. If the light's path includes the fibre's clad, the image is like a ring. Laser beams passed preferentially through the core and incoherent light of the lamp can pass both the core and the clad of fibres. The quasi two beam scheme was used for determining the initial intensity of the passed light $I_1$, which was detected and memorised by the oscilloscope after being weakened by the proper neutral filters till the level of the signal $I_2$ attenuated by the radiation induced absorption of the fibre

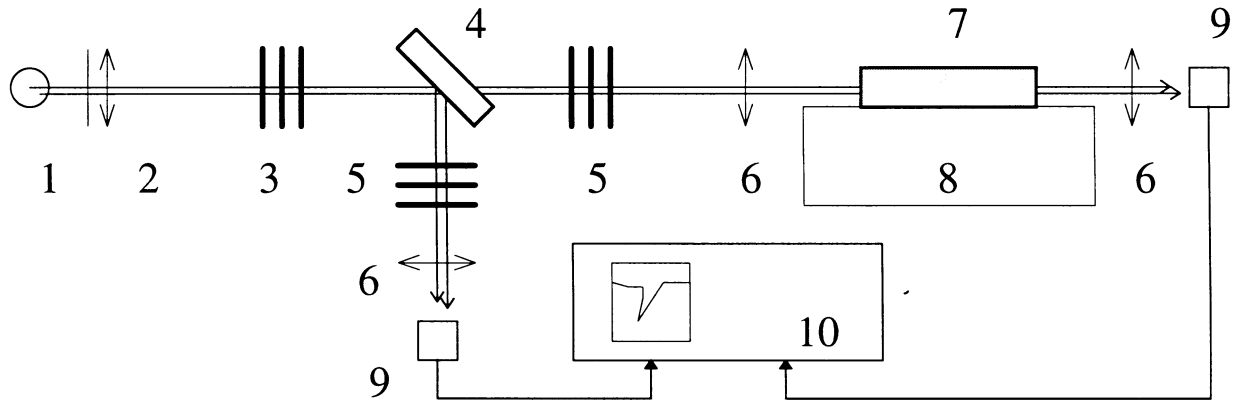



Figure 1: Experimental set-up for measuring $\gamma$-induced losses.

examined. The optical loss as a function of a probing wave length $A(\lambda)$, in the units of $dB/m$ for a fibre of $L$ meters long was calculated as follows:

$$A(\lambda) = \frac{10}{L} Log(\frac{I_2(\lambda)}{I_1(\lambda)})$$

The initial apparatus value of the light beam attenuation was measured in arbitrary units of $k = I/I_o$ by the ratio of an incident and outlet beam, which varied within $0.01 \div 1.0$ range. The attenuation of neutral light filters for conforming amplitudes of the reference and the sample signals was defined with the same accuracy. The measured $\gamma$ -dose dependencies of the light attenuation coefficient and the calculated optical loss for different wave lengths and the conditions for leading the light beam into the fibre are shown in Fig. 2- 4.

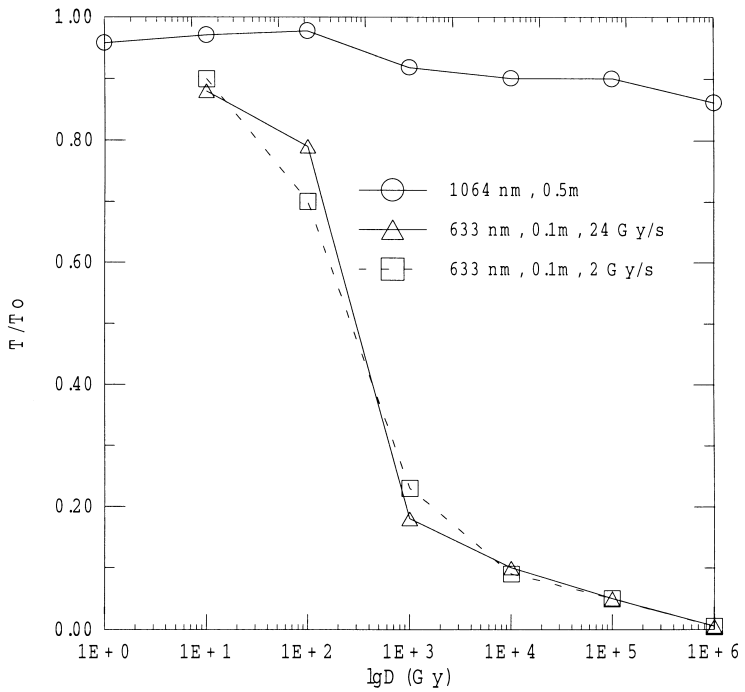



Figure 2: Gamma-dose dependence of optical transmittance at different dose rates and wavelengths indicated.

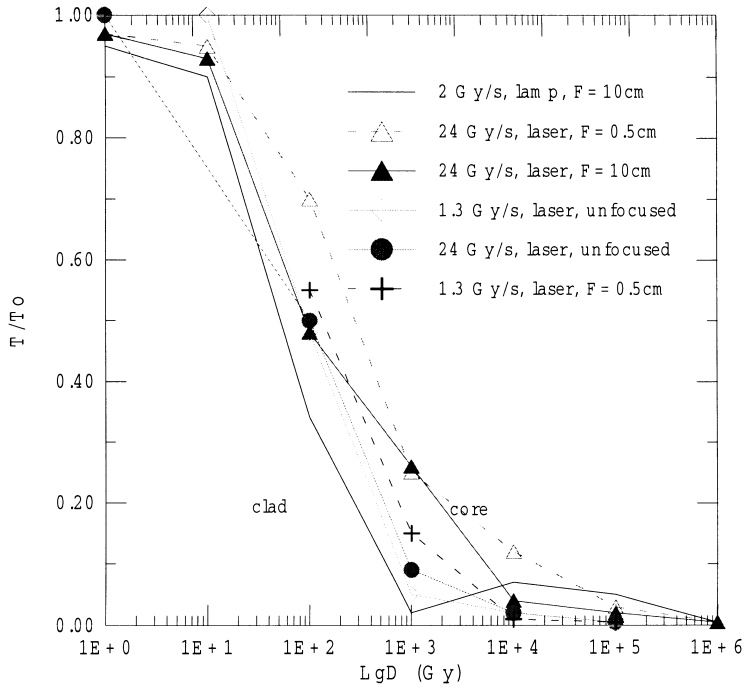



Figure 3: Gamma-dose dependence of optical transmittance at different dose rates and beam focusing at a wavelengths of 532 nm.

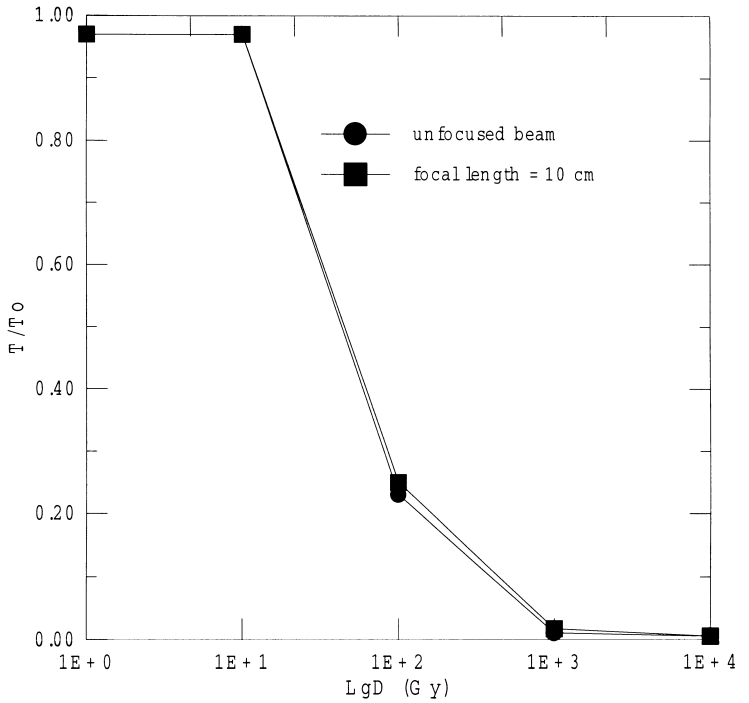



Figure 4: Gamma-dose dependence of optical transmittance at the lamp wavelengths of 330 nm at low dose rates of 1.3 Gy/s and 2 Gy/s and under different focusing.

# 3 Results and discussion

The *Ge* doped quartz fibre has rather high loss in visible range due to the radiation induced absorption bands at 290 and 540 nm. Besides, *OH*-groups give rise to absorption at 630 nm, so the experiments were started on fibres of 0.1 and 0.5 m length respectively at the laser wave length of 0.63 and 1.06mkm. Gamma dose rates of 2.3 and 24 Gy/s were chosen for determining a starting dose of detectable radiation coloration, i.e. the radiation hardness of the fibres at the above mentioned wavelengths. Figure 2 shows dependencies of the optical loss A at a wavelength of 0.63 and 1.06mkm on the logarithm of integral gamma - dose (scale $lg(D_\gamma)$ in the range of $1 \div 1.5 * 10^6$ Gy: doses $1 \div 10^3$ Gy were accumulated at the dose rate of 2.3 Gy/s and $10^3 \div 10^6$ Gy were at 24 Gy/s. Solid and dashed curves indicate A values taken at the two different dose rates and demonstrate a weak dose rate dependence of the loss at 633 nm for this fibre. At a dose as small as $5 * 10^2$ Gy the 0.63mkm laser gets 3 times weaker and at a dose of $10^6$ Gy a value of $k$= 0.005 or 240 dB/m. The radiation induced absorption at 0.63mkm is due to the well-known centre of non-bridging oxygen [6, 11] and a tail of the band at 540 nm of $Ge$-center. As it should be expected, the induced losses in the near IR-region are getting noticeable at the dose of $10^4$ Gy and don't exceed $15 \div 20$ dB/m at $10^6$ Gy - the saturation level keeping till 1.5 MGy. This fact implies suppression of the metal containing hole $O_2^{3-}M^+$ centres causing a wide stable absorption band about 1mkm attributed to absorption of self-trapped holes in quartz [12]. Then the observed luminescence at 670 nm of the non-bridging oxygen centres makes unstable the self-trapped hole centres and diminishes the radiation induced losses in IR -region [13].

Figure 3 demonstrates the loss at the wavelength of 0.53mkm (the 2-nd harmonics of laser radiation in the regime of 20 ns pulses at 25 Hz) within an expand dose range from 5 Gy to 1 MGy. As soon as different kind of colour and glow centres can contribute to this spectral region, it was of particular importance to separate the light beams passed through the core and the clad of the fibres. This was achieved with several means of focusing beam also unfocused one. There were observed visually uncoloured core of $\sim 100$ mkm in diameter and rings at boundaries of layers with different composition. As it was supposed, the central part of the core containing the minimal trace of impurities appeared to be the most radiation hard till doses as high as 10 MGy, therefore at a rigid (F=0.5 cm) focusing beam into the fibre's core the registered losses are minimal (dashed curves). While the gradient layers drawn from $SiO_2 : GeO_2$ glass have the $\gamma$ - induced hole absorption both at 0.44 and 0.63mkm due to the non-bridging oxygen and at 0.53mkm due to $Ge$ -centres. The clad has a coloration quite different from that of the gradient $Ge$ part. The absorption is supposed to be due to fluorine centres substituting the non-bridging oxygen and aluminium centres substituting in $SiO_2$ tetrahedrons and $P_2O_5$ octahedrons. Therefore without focusing (circles) when the laser beam passes mainly through the clad, the induced losses are maximal (solid curves). One should expect the dose rate dependence of radiation induced losses within the dose interval of $100 \div 10^5$ Gy. At the rigid focusing into the core some dose power dependence was found at 1.3 and 24 Gy. While at the soft focusing involving the core and the clad the dependence is not obvious within the measured interval of $5 * 10^2 \div 5 * 10^4$ Gy. For a better comparison with the data available [5, 11] the losses were measured with the lamp illuminator glow filtered in $0.50 \div 0.55$ mkm, as shown in Figure 3 as well (solid curves). As the incoherent lamp light (530 nm) can't be focused rigidly into the fibre's core, the dose dependent losses were even higher than those at the soft focusing of laser beam (532 nm). Figure 4 displays the losses in the near UV-region obtained by filtration of the pulse lamp illuminator light within $0.33 \div 0.37$ mkm and 0.53 mkm at $10 \div 100$ Gy. As usual, unfocused beam passes the fibres with a larger losses. The losses at 530 and $330 \div 370$ nm seem to come from the $Ge$ - doping colour centre. More moderate dose dependence at 630 nm relates to the hole centre of non-bridging oxygen, and the weakest dose dependence does to the unstable hole centres in the near IR-region $\sim 1$ mkm.

Uncoloured area at the different composition layer's boundaries of the fibre imply the possibility of effective recombination of carriers and one should expect an intensive luminescence induced by ionising radiation. As far as the fibres are destined for leading a luminescent signal from the scintillation detector, it is necessary to study optical spectra and an intensity of the fibre's glow under the irradiation. An important question is whether the induced glow of linking fibre interferes with the scintillator's signal.

# 4 Conclusions

The experimental techniques used here allowed to measure separately the radiation induced losses in the core and the clad of the fibre, as they have different colour centres. At the dose region of $5 * 10^2 \div 10^5$ Gy the dose rate dependence of radiation induced losses can be studied, when the same doses are accumulating at dose rates differ by one order. There was not any noticeable dose rate dependence of the losses at the wavelengths of 0.63 and 1.06mkm, although it was at 0.53mkm due to different contributions from the core and the clad. Presence of

Ge dopant and non-bridging oxygen in the core and $F, Al$ impurity in the clad cause the observed high level of the $\gamma$ -induced losses $\sim 100$ dB/m at 0.53 and 0.63mkm after a dose of $10^4$ Gy in the core and as small as 500 Gy in the clad. The tested fibre has the satisfying radiation hardness only at the wavelength of 1.06mkm, with the saturated losses being less than 10 dB/m after a dose of $10^6$ Gy.

# References


[1] **NIM A294 (1990) 193; NIM A305 (1991) 55.**, D. Acosta et al.

[2] **Proc.LHC Workshop, Aachen, 4-9 Oct. 1990, CERN 90-10, Vol.III, p.566.**, G. Stevenson, *"New dose calculations for LHC detectors"*.

[3] **Radiat.Phys.and Chem. 4 (1992) 253.**, Gorodetzky, B. Grosdidier and D. Lazic.

[4] **CMS TN/94 - 327, CERN, 1994.**, Arrington, D. Kefford, P.Podrasky, C.Sanzeni et al.,*"Test Beam Results of a $0^o$ Fibre Cherenkov Fibre Sampling Hadron Test Calorimeter: A Preliminary Study for CMS Very Forward Calorimetry"*.

[5] **Sov. Quantum Electronics, 10 No 3 (1983) 473.**, E.Dianov, L. Kornienko, E. Nikitin, A Rybaltovsky et al.

[6] **Sov. Quant. Electronics 11 (1984) 2480.**, E.Dianov, V.N. Karpechev, L.S. Kornienko, A.O.Rybaltovsky and P.V. Chernov.

[7] **IEEE Trans.on Nucl. Sci. 35 (1988) 894.**, Y. Chigusa et al.

[8] **ibid, p.898.,** T. Iida et al.

[9] **IEEE Trans. on Nucl.Sci. 40 (1993) 307.**, J.B. Chesser.

[10] **J.of Nucl.Mater. 203 (1993) 136.**, D.E. Holcomb and D.W. Miller.

[11] **CMS TN-94-324, CERN 1994., V. Gavrilov, S. Kuleshov, Yu.Chumarovskii, I. Azhgirey et al, *"Study of Quartz Fibre Radiation Hardness"*.**

[12] **Nuclear Instrum. and Methods B1 (1984) 187.**, K. Tanimura, T. Tanaka and N. Itoh.

[13] **Phys.stat.sol.(a) 115 (1989) K255.**, E.M. Ibragimova and V.N. Stepanov.

[14] **Abstracts of MRS-95 Spring Meeting, April 1995, San Francisco.**, Yuldashev B.S., Gasanov E.M., Ibragimova E.M, Ashurov M.Kh. and Rustamov I.R.