Fundamentals of Cherenkov Fiber Calorimetry

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ABSTRACT

The basics of operation of a new calorimetry technique based on detection of Cherenkov light in optical fibers are presented and discussed. The use of this effect instead of conventional techniques where detection is based on ionization of the detection medium causes certain peculiarities that are discussed in the text. Some uncommon consequences of this choice of detection medium observed in experimental and Monte Carlo studies are discussed.

The new generation of experiments in high energy physics is facing a challenge of extremely high interaction rates and radiation doses. Fixed-target experiments using CERN lead beam, as well as RHIC and LHC colliders are examples of such a demand. The most forbidding environment for both is in high pseudorapidity regions: "very forward" detectors for colliders and "zero-degree" detectors in fixed-target experiments. In such conditions the speed and radiation hardness are detector characteristics that take precedence to properties such as position or energy resolution. This is even more so in hadron calorimetry where some of the basic processes accompanying the shower development have an intrinsic time scale much longer than the limit imposed by the rate of collisions. The most "dangerous" ones are numerous, slowly propagating neutrons and delayed gamma emission from absorber nuclei excited by thermal neutron capture, that can in certain types of calorimeters extend the pulse duration out to one microsecond [1] and lead to energy mis-measurements.

Cherenkov fiber calorimetry is a sampling calorimetry technique designed to measure particle energy exactly in those environments where extreme speed and radiation hardness are paramount. Like other sampling calorimeters, it consists of a heavy metal absorber with detection medium interspersed in the volume. In our case, the detection medium is clear optical fibers, preferably made of synthetic fused silica ("quartz"). The high radiation hardness of these fibers enables their use in even the most demanding regions ([2, 3]). In this way we achieve a compact and stable device without any exchangeable material that may present potential radiological or chemical hazard.

The high radiation hardness of quartz, and silica as its amorphous derivative, is a consequence of a particularly strong Si-O bond. We should note that the rad hardness of quartz fibers has several components: rad hardness of the core and cladding in visible and UV parts of the spectrum. The defects induced by high doses in the visible part of the spectrum come basically from chemical impurities and can be minimized by the use of chemically very pure material. The damage in the UV part is induced by structural defects whose number can be decreased by relatively simple improvements in fiber production process. Commercially available quartz fibers have core made of high purity quartz, making it possible to achieve very good rad hardness in visible spectrum with no additional effort. However, for good behavior in the UV region some simple adjustments of the preform preparation and fiber drawing processes might be needed. The rad hardness of fiber cladding is a completely different story: it is made either of fluorinated quartz or plastics. Neither of these materials exhibit particularly good resistance to transparency losses due to radiation damage. Even though the cladding will be damaged by irradiations, the fiber as a whole will be hardly affected simply because the quantity of light that passes through cladding is negligible. The loss of transparency of cladding is therefore not dangerous as long as there is no significant change in the internal structure of the material which could change its electromagnetic properties, i.e. the conditions for the internal reflection of light inside the fiber. For plastic clad fibers, such a heavy damage happens at the level of a few hundred Mrads, while for quartz clad fibers its limit has still to be measured. It should be emphasized that all these considerations are valid only

\footnote{To the authors knowledge, there are no available experimental data for the rad hardness of fluorinated silica. However, this assumption is plausible when the very fast degradation of the transparency of silica with higher percentage of impurities is taken into account.}
with a dose distribution that follows the pattern of irradiations in a real calorimeter: a sharp peak and slow decrease of the dose along the fiber. Uniform irradiations with very high doses along long distances would give worse results.

The high purity needed for rad hardness in the visible spectrum has as the disadvantage that it excludes use of dopants that can produce scintillation. The only light produced by the passage of shower particles comes from Cherenkov effect. As this effect has some peculiarities that strongly influence the behavior of the calorimeters we will discuss them in the following paragraphs.

The Cherenkov effect takes place only when a charged particle passes through a transparent medium with a speed higher than the speed of light in that medium. This energy threshold for light production is fairly high in quartz ($\beta = 0.67$) efficiently cutting off response to recoil protons from neutron scattering, as well as the majority of beta electrons produced by decays of the excited absorber nuclei. Also, the low energy part of the shower, which is responsible for the bulk of the response in dE/dx based calorimeters is practically invisible for Cherenkov effect based calorimeters. This feature is of an extreme importance when considering high radioactivation of the absorber induced by hadron showers. The photon yield of the Cherenkov effect is directly proportional to trajectory length in quartz. The electrons entering quartz with slightly more energy than the threshold will be quickly stopped, producing few, if any, photons. On the other hand, high energy particles will cross much longer trajectories, producing more photons as the light yield increases sharply with $\beta = v/c$.

Cherenkov effect based calorimeters usually give far fewer photons per GeV than scintillation based ones, predominantly in the UV region as Cherenkov light yield follows $1/\lambda^2$ law. However, the energies that these devices are supposed to measure are so high that an adequate energy resolution can be obtained. The results of Cherenkov light yield measurements for some commercially available fibers are published in [4]. One of the interesting features is that plastic clad fibers give approximately the same number of photons as quartz clad fibers when both are read out by UV sensitive devices. This higher yield is a consequence of higher numerical aperture for these fibers (N.A. =0.37-0.40) when compared to the N.A. of quartz clad fibers (N.A. =0.22). So, even though in plastic clad fibers we collect only visible part of the spectrum, permitting the use of cheaper photodetectors sensitive only in this region, the collection is much better due to the better angular acceptance. Unfortunately, as an increase of the numerical aperture of quartz clad fibers is difficult to achieve, this cannot be used as a method of improvement of the photostatistics. On the other hand, in cases where quartz clad fibers are used due to the radiation hardness requirements, use of photodetectors sensitive only in the visible spectrum would lead to unreasonable loss of light and deterioration of the overall energy resolution.

With respect to timing requirements Cherenkov calorimetry has obvious advantage when compared with other techniques: the basic effect is for all practical purposes instantaneous. There is no decay time such as with scintillators or transport of electric charge, as in liquid argon or high pressure gas. The limited angular acceptancy of the fibers has as a consequence that only photons with velocities within a narrow angular interval around the fiber axis can actually remain in the fiber. This gives a narrow distribution of photon velocities along the fiber, and extremely fast signal. As the relatively high threshold for the onset of the effect makes the calorimeter insensitive to the late (and low energy) component of the shower, it means that the speed of the response of such a calorimeter depends strongly on the readout and the accompanying electronics.

Figure 1: Angular distribution of response to 8 GeV electrons of a single fiber with numerical aperture N.A.=0.51.

An important characteristic is anisotropy of the Cherenkov effect: the light is emitted along a cone with angular opening defined by $\cos \theta = 1/\beta n$, where n is index of refraction. When combined with quite limited angular acceptance of fibers, this feature leads to a much higher probability of photon survival if the particle crosses the fiber at 45° with respect to the fiber axis. This is illustrated in Fig. 1 where data points represent measured distribution of light output from a single fiber as a function of the angle between the trajectory of the incident particle and the fiber axis. We can see that for, a single particle, the response is much higher at 45° than for any other angle.

Therefore, by putting fibers at 45° with respect
to the direction of the particles entering calorimeter we can improve the light collection in the fibers and, consequently, get a better photostatistics. Even though the scattering of shower particles in the absorber quickly removes electrons and positrons from the shower axis, the overall angular distribution remains strongly forward pitched even for electromagnetic showers. This is reflected in the distribution shown in Fig. 2 where results of an angular scan by 8 GeV electrons of a specially constructed prototype are shown. The prototype was made of lead sheets where clear plastic fibers were embedded in grooves. The prototype was 8cm tall, 20cm wide and 25cm long, ensuring a good shower containment for all entry angles. The ratio of volumes of fibers to lead was 1:4, as in ordinary "spaghetti" calorimeters with scintillating fibers. The fibers had 1mm diameter and numerical aperture of 0.51. Even with fibers with so high numerical aperture and, consequently, angular acceptance, there is a clear increase in response in the case when incoming particles arrive at 45° with respect to the fiber axis.

The fact that only fast particles from the shower core can be detected with this technique leads to a very useful property - the visible shower size is several times smaller than for ionization based calorimeters. Apart from better position information, this characteristic enables the use of these devices in environments where small available space demands as small fiducial volume as possible. This feature is illustrated in Figs. 3 and 4 where the same GEANT simulation of the shower created by 30 GeV pions in copper is shown. The difference between two figures is in the energy threshold: while in the first one trajectories of all charged particles

Figure 2: Angular distribution of response to 8 GeV electrons of an electromagnetic calorimeter described in text.

Figure 3: GEANT simulation showing charged shower particles in copper created by 30 GeV pions.

Figure 4: The same event as in previous figure, but showing particles that can give Cherenkov light in quartz optical fibers.
are recorded, the second figure contains only trajectories of particles that can produce Cherenkov effect in quartz.

The diagram in Fig. 2 is obtained with electrons as projectiles and might be misleading if applied to hadron calorimetry. Electromagnetic showers are less forward pitched than hadronic ones due to the lower lepton mass. In hadron calorimeters, the relatively long interaction length for pions induces much stronger forward pitch for the hadronic component. Consisting predominantly of pions and kaons, this part of the shower is far less influenced by scattering. So, the positioning of the fibers at 45° with respect to the direction of incoming particles will enable detection of this shower component. If, however, we position the fibers at 0° or some similarly small angle in order to avoid channeling, the hadron component of the shower will become invisible, apart from a weak contribution from delta rays. In this configuration, the π+ induced electromagnetic showers are the predominant source of the calorimeter response. The multiple scattering of electrons and positrons will induce a certain percentage of the shower particles to cross the fibers with an angle that permits detection of Cherenkov light. However, the π0 yield is not linear with energy, causing an inherent nonlinearity of such a device. On the other hand, if the overall energy resolution of the calorimeter is not very good, this non-linearity can be efficiently masked by response fluctuations.

It should be noted that even though the 0° configuration is potentially non-linear and offers worse energy resolution for the same fiber to absorber volume ratio than 45° configuration, it has to its advantage the direct information on the impact position of the initial particle and possibility to have projective geometry. The 45° configuration can offer this information only if used with a stereo geometry similar to wire-chambers, i.e. with successive layers of fibers with different orientation. For very high occupancies, this method can prove to be difficult to apply for particle-particle separation. Two hadron prototypes, one with fibers at 45° and another with fibers at 0° have been constructed as a part of CERN RD40 project which deals with studies of fundamental properties of this calorimetry technique. The very precise studies performed during the summer of 1995 should set the limitations of both approaches. The results should be available shortly.

Within this project a number of both hadron and electromagnetic prototypes has been constructed and tested. More comprehensive review of this calorimetry technique, as well as results of numerous experimental tests are reported in [2] and [5]. Detailed results of the studies of electromagnetic calorimeters are reported in [6].

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References