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Performance of a tungsten–cerium fluoride sampling calorimeter in high-energy electron beam tests

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ABSTRACT

A prototype for a sampling calorimeter made out of cerium fluoride crystals interleaved with tungsten plates, and read out by wavelength-shifting fibres, has been exposed to beams of electrons with energies between 20 and 150 GeV, produced by the CERN Super Proton Synchrotron accelerator complex. The performance of the prototype is presented and compared to that of a GEANT4 simulation of the apparatus. Particular emphasis is given to the response uniformity across the channel front face, and to the prototype's energy resolution.

1. Introduction

Future hadron colliders are expected to have high instantaneous luminosity ($>10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) and will operate for long data-taking periods, delivering to experiments large quantities of data ($>1\mathrm{ab}^{-1}$). This high-radiation environment sets stringent requirements on the radiation hardness of all detector parts, and on the components placed in the forward region in particular.

A sampling calorimeter made of cerium fluoride (CeF_3) scintillating crystals, interleaved with tungsten plates, constitutes a viable option for forward electromagnetic calorimetry. Cerium fluoride spontaneously recovers, at room temperature, from hadronic damage [1], and its stoichiometry can be tuned in order to make it extremely resistant to ionizing radiation [2]. These features, together with the fact that its scintillation light has a spectrum which is suitable for wavelength shifting (the scintillation peak is around 340 nm) and is fast enough for the high-repetition frequencies of modern colliders (it has a decay time of 30 ns), make cerium fluoride a very attractive active material.

Stemming from the design of a previously tested prototype [3], a new channel has been built, consisting of a single tower of 15 layers of alternating CeF_3 crystals and tungsten absorber plates. This paper describes the results of irradiating this prototype with electrons of energies between 20 and 150 GeV, produced by the CERN Super Proton Synchrotron (SPS) accelerator complex. Particular attention is given to the response uniformity and energy resolution.

2. The W-CeF_3 prototype

A picture of the prototype during assembly can be seen in Fig. 1. It is made of 15 layers of 10 mm-thick CeF_3 crystals, interleaved with 3.1 mm-thick tungsten absorber plates, for a total length of

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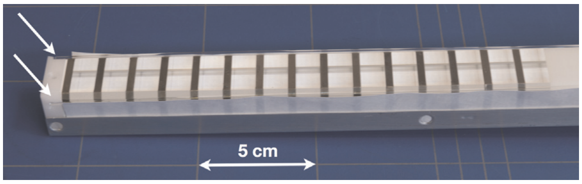

Fig. 1. The sampling calorimeter tower during assembly. The arrows indicate the position of the chamfered edges, along which the WLS fibres are placed.

25 X_0. High-purity metallic, rolled tungsten plates were used, as also employed for the PEBS calorimeter prototypes [4]. The CeF_3 crystals have a Barium doping of 0.5% and have been produced by Tokuyama [5], and their faces have been polished for total internal reflection. The tower transverse dimension of 24×24 mm^2 matches the effective Molière radius of the sampling compound, which is found to be 23.1 mm from a Geant4 [6] simulation. A smaller effective Molière radius, which might be desirable in high-occupancy environments such as high-luminosity hadron colliders, can be achieved by increasing the absorber fraction, at the cost of a lower sampling fraction. As a comparison, a homogeneous CeF_3 calorimeter would require a factor 2 deeper calorimeter to achieve the same longitudinal shower containment.

Four 3 mm-wide chamfers are cut on the short edges of the crystals and tungsten plates, allowing wavelength-shifting (WLS) fibres to run alongside the tower, transmitting the scintillation light to the back of the detector. The crystal chamfers have been lapped to a roughness of $R_a = 0.4 \pm 0.1$ μm, so as to allow the light to escape the crystals and be collected by the WLS fibres. A 0.2 mm layer of highly-diffusive DuPont™ Tyvek® [7] foil is inserted between each crystal and its neighboring absorber plates, in order to maximise the light collection of the fibres.

In this beam test four 3HF fibres produced by Kuraray [8] have been employed, one per chamfer. The fibres have a peak excitation of 340 nm, compatible with the emission spectrum of the CeF_3, and an emission peak at 540 nm. The fibres have a single 0.02 mm layer of cladding made of Polymethyl Methacrylate (PMMA) surrounding the core of Polystyrene. One end is coupled with optical couplant to a Hamamatsu [9] R1450 photomultiplier tube (PMT) at the rear end; the other end is aluminized. The quantum efficiency of the PMTs for the light emitted by the fibres has been measured to be about 7%. More details on the effective light yield of this optical chain are given in [3]. The radiation hardness of the adopted fibres is not sufficient for future high-luminosity hadron collider applications, therefore R&D targeted at developing radiation-hard fibres is currently ongoing.

In order to test the prototype in an environment close to that of an extended electromagnetic calorimeter, the W-CeF_3 prototype has been surrounded by 24 BGO crystals, to complete a 5×5 matrix. The BGO crystals have been taken from the disassembly of the electromagnetic calorimeter of the L3 experiment [10] operating at LEP, are 24 cm long and have a front face of 22×22 mm^2 and a rear face of 30×30 mm^2. The light from each BGO crystal is read out with a Hamamatsu R1450 PMT. The matrix was placed in a light-tight box, and kept at a temperature of 18.0 ± 0.1 °C. The box was placed on a moving table, which allowed to center the beam anywhere on the matrix, with a precision of 0.1 mm.

The fibre signals were then read out by a CAEN V1742 digitizer [11], while the BGOs were read out by a CAEN V792 ADC. The digitizer gives access to the full pulse-shape of the signal, which is stored in 1024 samples, at a frequency of 5 GHz. The width of the readout window (200 ns) allowed a baseline subtraction on a per-event basis. A low-pass filter, which was found to reduce high-frequency noise present in the signal and to improve the stability of the measurement, was applied to the output of the digitizer. A typical average pulse-shape after the application of the low-pass filter can be seen in Fig. 2. The tower response is defined as the full charge-integrated signal, after the baseline subtraction.

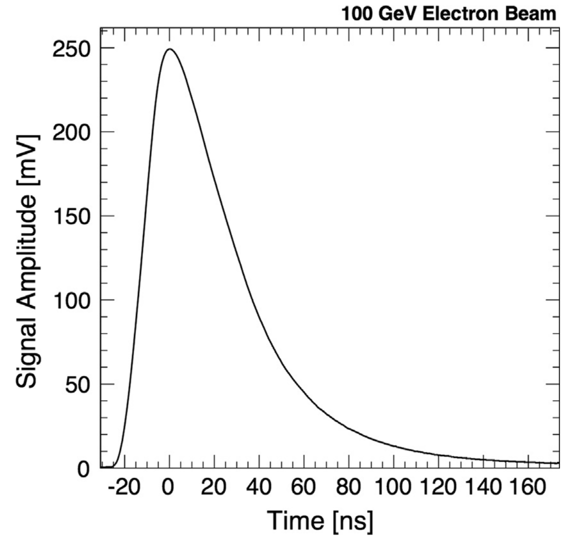

Fig. 2. Typical average pulse-shape of the scintillation signal from the W-CeF_3 prototype.

3. Experimental setup and electron selection

The prototype was exposed to the electron beam of the CERN SPS North Area, which delivers electrons of energies between 20 and 150 GeV, with a pion contamination smaller than 0.1% [12]. The electrons are tracked before hitting the front face of the W-CeF_3 prototype with a wire-chamber (placed 12 m upstream of the front face of the tower) and two scintillating-fibre hodoscopes (at 6 and 3 m, respectively).

The wire chamber is made of two planes of 55 cathode wires and 28 anode wires, organized in a grid with an active area of 80×80 mm^2. Each plane provides, respectively, a measurement of the electron position in the x and y directions with a nominal resolution better than 200 μm [13].

Each of the two scintillating-fibre hodoscopes is composed of two layers of 64 plastic fibres of 0.5 mm diameter, oriented in the x and y directions, respectively. The signals from the fibres are clustered by grouping together adjacent fibres, up to a maximum of 4 fibres per cluster. The cluster position is defined as the average position of its fibres and it is used to estimate the trajectory of the particle before impacting the calorimeter.

Finally, a small 2×2 mm^2 hodoscope is placed in front of the calorimeter front face, and aligned with the center of the W-CeF_3 tower. This hodoscope is made of two pairs of 1-mm fibres, again oriented in the x–y directions. Being fixed to the calorimeter box, this small hodoscope is used to align the center of the tower front face with respect to the tracking detectors: events are selected in which the particle produces a signal in one of the two fibres of each coordinate pair of the small hodoscope, and the average recorded position is measured in each of the other three tracking devices. The average position measured by each tracking device is then used as an alignment offset, and is subtracted from subsequent measurements. This is done separately for each beam energy. After the alignment procedure the hodoscopes and the wire chamber are aligned within 0.5 mm.

Four plastic scintillators of varying size, the smallest of which has a transverse dimension of 1×1 cm^2, are placed on the