

Quartz Plate Calorimeter as SLHC Upgrade to CMS Hadronic EndCap Calorimeters

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Abstract. Due to an expected increase in radiation damage under super-LHC conditions, we propose to substitute the scintillator tiles in the original design of the hadronic endcap (HE) calorimeter with quartz plates. Quartz is proved to be radiation hard by the radiation damage tests with electron, proton, neutron and gamma beams. Using wavelength shifting fibers, it is possible to collect efficiently the Cherenkov light generated in quartz plates. This paper summarizes the results from various test beams, bench tests, and Geant4 simulations done on methods of collecting light from quartz plates, as well as radiation hardness tests on quartz material.

Keywords: Quartz, Cherenkov, calorimeter, radiation.

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INTRODUCTION

The Large Hadron Collider (LHC) is designed to provide 14 TeV center of mass energy with proton proton collisions every 25 ns. After a few years of running, the LHC will be upgraded to super-LHC (SLHC), that will operate at 10 times higher luminosity ($L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$), thereby allowing new physics discoveries. In the current design, the hadronic endcap (HE) calorimeter of the compact muon solenoid (CMS) detector uses Kuraray SCSN81 scintillator tiles, and Kuraray Y-11 double clad wavelength shifting (WLS) fibers. These materials have been shown to be moderately radiation hard up to 2.5 MRad. The scintillation photons are collected by wavelength shifting fibers lined close to the edge of the scintillators, which we defined as the HE-shape [1]. Under SLHC conditions the lifetime radiation dose in the HE calorimeter region will increase from 2.5 MRad to 25 MRad. The scintillator tiles used in the current design of the HE calorimeter will lose their efficiency due to radiation damage.

As a solution to the radiation damage problem in the SLHC era, we propose to substitute scintillators by quartz plates and carry out the light via UV absorbing, blue emitting WLS fibers. We performed radiation hardness tests on various types of quartz material in the form of fiber, under electron, proton, neutron, and gamma radiation. Results show that quartz will not be affected by the radiation dose at the SLHC. In the first part of this report we summarize these different radiation hardness studies performed by our group. Radiation damage to WLS materials will be studied at a later date.

However, when quartz plates are used, the detected photons come from Cherenkov radiation, which yields 100 times less light than the scintillation process. The focus of this study is to find an efficient way to collect light from quartz plates. At the University of Iowa and Fermi National Accelerator Laboratory, we tested and simulated different sizes of quartz plates with different fiber geometries embedded in them to obtain maximum light. To make up for the reduction in light production, use the far-UV region to collect Cherenkov photons since the number of generated Cherenkov photons increase as $1/\lambda^2$ [2]. The second part of this report presents the results from the studies performed on finding an efficient way to collect light from quartz plates.

RADIATION DAMAGE STUDIES ON QUARTZ FIBERS

Quartz is known to be radiation hard in general. However, not all the quartz types have the same amount of radiation hardness. Among the different types of quartz it is important to find the best option to replace the CMS HE calorimeter tiles. To investigate different fiber radiation damage properties under various radiation types the following tests have been performed;

Quartz Radiation Damage with Electrons

The quartz radiation damage test with an electron beam has been tested on nine different high OH⁻ quartz fibers, with hard plastic cladding (qp) and quartz cladding (qq) using 500 MeV electrons from the Linac Injector of LEP (LIL) at CERN. The transmission of Xe light was measured *in-situ* in the 350-800 nm range. The induced attenuation at 450 nm found to be 1.52 ± 0.15 dB/m for a 100 Mrad absorbed dose. We observed some darkening on the fibers, but the radiation did not change the tensile strength of the quartz fibers [3].

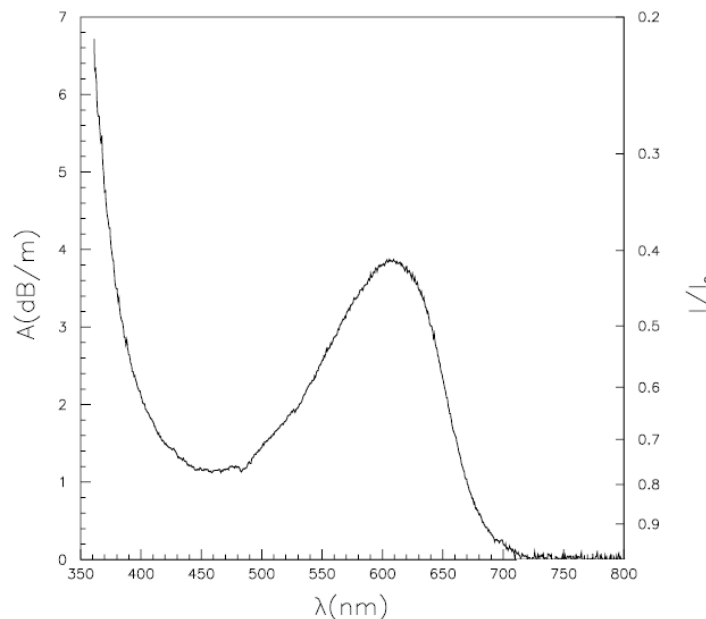


Figure 1: Typical behavior of induced attenuation versus wavelength for Polymicro qp fiber with 300 micron core, irradiated to 54 Mrad.

We achieved a set of mechanical and optical tests for the properties after irradiation, of nine types of fused-silica core fibers. We measured in situ the darkening and the recovery of two fibers at the same time. This arrangement allows us to make a direct comparison of the optical properties of two different fibers, independently of dose, injected light or electron beam fluctuations. The main results are: (1) there is no significant difference in optical properties between the polymer-clad (qp) fiber drawn by Polymicro Technology and the fluorine doped silica clad fibers drawn by Polymicro or Hesfibel from Heraeus performs under irradiation up to 100 Mrad. (2) Tensile strength measurements show that Polymicro fibers exhibit highest tensile strength with minimum RMS. There is no significant radiation effect on the tensile modulus, which remains at 4.6 ± 0.4 GPa. (3) The quality of the core material strongly affects the fiber performance. We measured a very different attenuation in the fibers drawn, by a single company (Polymicro), where the preforms came from two different suppliers located in Germany and in Russia. (4) The attenuation and recovery as a function of time are well represented by two-parameter fits. (5) The measurement of quartz fiber darkening by attenuation of light transmission 14.4 s after the beam stop is insensitive to short-lifetime luminescence induced by the Cherenkov UV emission or dose accumulation.

Three bands of luminescence have been observed in fused silica at 280, 470 and 650 nm with lifetimes around 4 ns; 2–10 ms; and 20 ms; respectively. The characteristics of the luminescence, mainly in the 470 nm band, in the fibers have to be further measured in order to fully evaluate the effects of this band on the performance of the quartz plate calorimeter.

Quartz Radiation Damage with Protons

To complete our knowledge of radiation damage in quartz fibers and to investigate their possible use at the Super LHC (SLHC) we initiated high level irradiation with 24 GeV protons at CERN. About 10^{16} protons/cm² were sent onto 1.20 m of quartz fibers, corresponding to a dose of 1.25 Grad [4]. The fiber radiation damage induced by protons exhibited the same well known behavior as with electrons: high light attenuation below 380 nm and in the band 550–680 nm, moderate attenuation in the band 400–520 nm and practically no attenuation above 700 nm. The damage varies exponentially with dose; fast in the first hours and slow after. Above 0.6 Grad we observe a new phenomenon: the radiation damage is not recoverable in the range 580–650 nm and below 380 nm. The two fibers tested, 0.6 mm quartz core diameter, one with hard plastic cladding (qp) and the other with quartz cladding (qq), were supplied by the US firm Polymicro Tech. Inc. (PT).

The fibers were installed, with their light support, on a remote controlled table at the CERN facility IRRAD. Three loops of qq and qp fibers (40 cm long) were wrapped together and placed with a slope of 2.5% relative to the beam. The total irradiated length (L) was about 1.2 m. No material was inserted in front of the fibers as in the case of electrons. The 24 GeV proton beam at IRRAD was delivered as 3–4 sub-cycles in a (19.6 ± 3.0) s long supercycle. This beam delivers 10^{11} protons/cm²/burst in a spot of 2×2 cm². The sub-cycle sharing changed during the irradiation. The number of protons delivered was recorded and the dose calibration was done using thin Al samples. We regularly checked the proton beam stability in position, width and time.

The attenuation measurements were performed *in-situ*. We tested quartz fibers with quartz cladding (qq) and with plastic cladding (qp). The light attenuation in the fiber is defined as

$$A(\lambda, D) = \alpha(\lambda) \left[\frac{D}{D_s} \right]^{\beta(\lambda)} \quad (1)$$

Where α and β are parameters for qq and qp fibers that are determined by fitting the ratios as a function of wavelength and dose.

$$\frac{I(\lambda, D)}{I(\lambda, 0)} = e^{\left[- \left(L / 4.343 \right) \alpha(\lambda) \left(\frac{D}{D_s} \right)^{\beta(\lambda)} \right]} \quad (2)$$

Choosing a scale factor $D_s = 100$ Mrad, α is the attenuation at 100 Mrad, in dB/m, L being expressed in m.

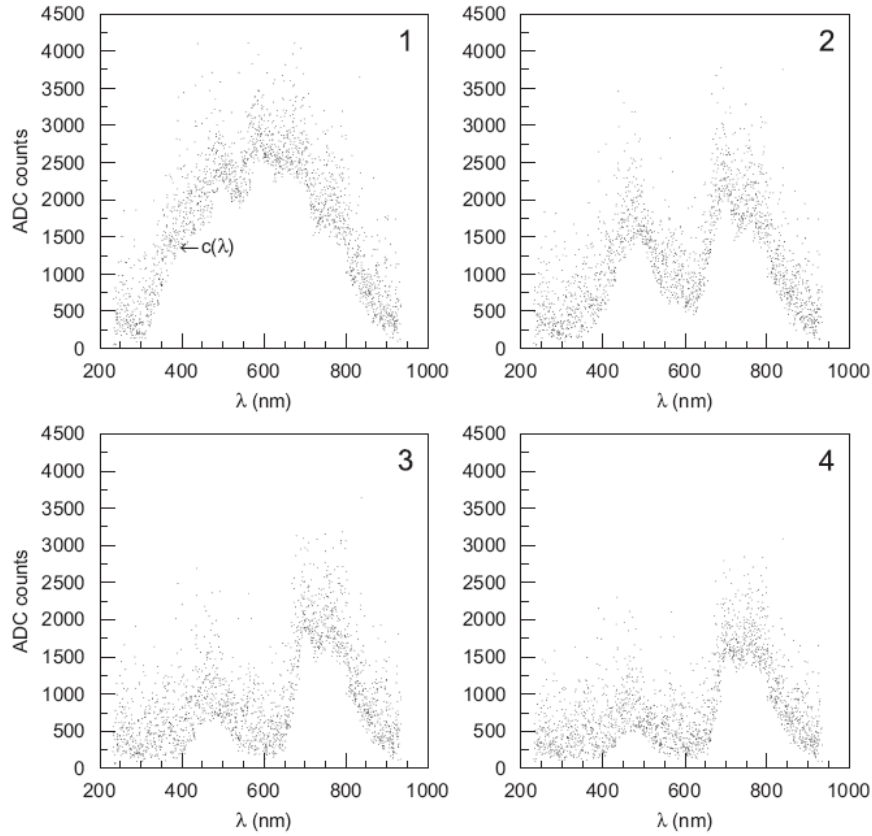


Figure 2: Evolution of the transmitted light spectra from a 1.25m of qq fiber as a function of dose 0 rad (1), 240 Mrad (2), 0.8 Grad (3) and 1.25 Grad (4).

Radiation damage due to protons and damage recovery are in agreement within errors with our previous results of electron irradiations with the same type of quartz used by Polymicro Technology Inc. The two types of irradiation were quite different: 24 GeV protons compared to 0.5 GeV electrons, in different geometries. 1.25 Grad with protons compared to 50Mrad with electrons.

As in electron irradiations we did not observe significant differences in proton irradiation between qq and qp fiber up to 1 Grad. Near 450 nm the observed difference appears in the fits at high dose and above 1 Grad there is a steep decrease of the transmitted signal in qp fiber.

For doses above 0.5 Grad there is no recovery of damage below 380 nm and in the range of 580–650 nm, the quartz becomes opaque. The PMTs detecting Cherenkov light are sensitive to the blue light (about 450 nm) emitted from the fibers where the effects are maximum.

For a 2 m qp fiber we observed a decrease of 30% in light transmission resulting from a dose accumulation of 20 Mrad, as well as an increase in light transmission by 22% 10 days after an irradiation of 100 Mrad in 200 days.

Quartz Radiation Damage with Neutron and Gamma

We also performed radiation damage tests to measure the degradation of quartz optical fibers under neutron and gamma radiation, which is expected to be present in the CMS hadronic calorimeters at the LHC and even more during SLHC.

For this purpose we selected seven different types of quartz material in the form of fiber from Polymicro Technologies. The selected quartz types were FVP 300-315-345, FSHA 300-330-350, FDP 300-315-345, FBP 600-660-710, FVP 600-660-710, FVP 600-660-710 UVM, and FSHA 600-630-800 [5]. The fibers were tested for light transmission degradation after a large radiation dose. They were bombarded with pulses of high-energy neutrons produced by the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory for 313 hours. Seven sets, of five fibers each, were placed in an irradiation tube about 25 cm away from the IPNS target. These fibers were irradiated for a two-week period during which the integrated current delivered to the IPNS target was 4456 $\mu\text{A-hrs}$. The fibers were exposed to a total of 17.6 MRad of neutron and 73.5 MRad of gamma radiation.

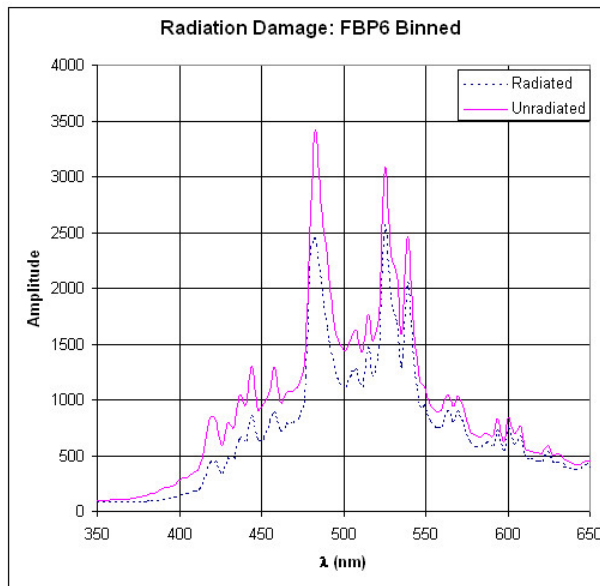


Figure 3: FBP 600-660-710 spectra before (red) and after (black) radiation.

The optical transmission of the fibers was then measured and compared to the baseline measurements. An Ocean Optics PX-1 Xenon flash lamp and an Ocean Optics SD2000 spectrometer were used for these measurements. The light was sent into a bifurcated optical fiber and was split into two channels. The tests show that a special radiation-hard solarization resistant quartz fiber (FBP 600-660-710) gives the best results. Solarization is defined as a phenomenon where a temporary change occurs to a material due to exposure to high energy electromagnetic radiation. The response of this fiber to the radiation can be seen in Figure 2, where the solid line is the response of the quartz fiber before being subject to the radiation and the dotted line is the response after irradiation.

CHERENKOV LIGHT AND A QUARTZ PLATE CALORIMETER

Cherenkov Light Collection from Quartz Plates

As stated before, our proposal is to collect the Cherenkov photons from the far-UV range to help make up for the deficiency against scintillators [6]. For this purpose we selected Saint Gobain BCF-12 WLS fibers, which can absorb photons down to 280 nm, and emit at 435 nm. In the current design of the HE plates, fibers collect the scintillation photons from the edges of the plates. This simple fiber geometry works well for the scintillators since the scintillation photons are generated in random directions. However, the Cherenkov photons are generated at a fixed angle with respect to the momentum of the charged particle. Since the photons are scarce we cannot afford to make them propagate to the edges of the plates. The fibers should be placed close to the photons for efficient light collection. We investigated the most uniform and efficient fiber embedding geometry to collect the Cherenkov photons. For this purpose, various fiber embedding geometries were considered. Here we report the results for the following geometries: Bar-shape, HE-shape, Y-shape, and S-shape (see Figure 4).

All of the plates were wrapped with Tyvek, which is a very strong, synthetic material. The University of Iowa bench tests showed that Tyvek is as good a reflective material as aluminum and Mylar in both the UV and visible wavelength region [7]. In all the tests reported below Hamamatsu R7525-HA photomultiplier tubes (PMTs) [8] were used to measure the light at the end of the fibers.

The calculations and simulated model for our system show that the amount of Cherenkov radiation in a quartz plate is around 1% of the scintillation photons from the same size scintillator tile. To collect the light in a more efficient way, we worked on different plates with different sizes and with different fiber geometries embedded in them. After many beam tests and bench tests we came to the conclusion that by using a quartz plate with the bar-shape fiber geometry, we can collect almost 70 percent of the light that the original HE tile would yield.

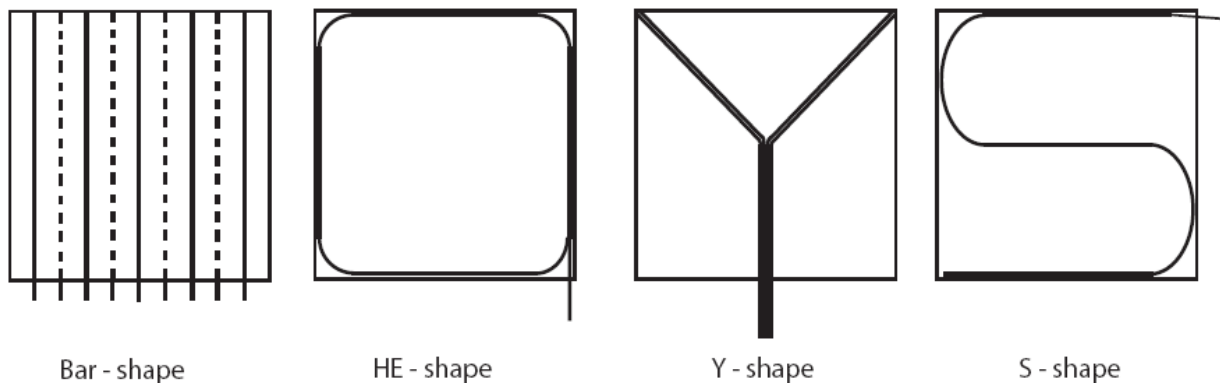


Figure 4: Fiber geometries embedded into quartz plates. The dotted lines of the bar-shape represent the fibers on the other side of the plate.

The plate with the barshape fiber geometry is shown to be very uniform since the fibers are distributed uniformly throughout the surface. To improve the light collection, a thick quartz plate with a small area, and many WLS fibers embedded in it should be used. It should be remembered that the space between the absorber layers of HE calorimeter (9 mm) limits the thickness of the quartz plates. Simulations show that the surface non-uniformity of light output is around 26% for

the bar-shape and the ratio of collected light with respect to HE scintillator is about 70%. The analyses of the mean arrival time showed that the light collection is extremely fast (< 5 ns) which makes quartz a good candidate for the SLHC era. Even if the 10 times higher luminosity is obtained by decreasing the bunch crossing to 12.5 ns, the photon arrival time for quartz plates will be well within the gate.

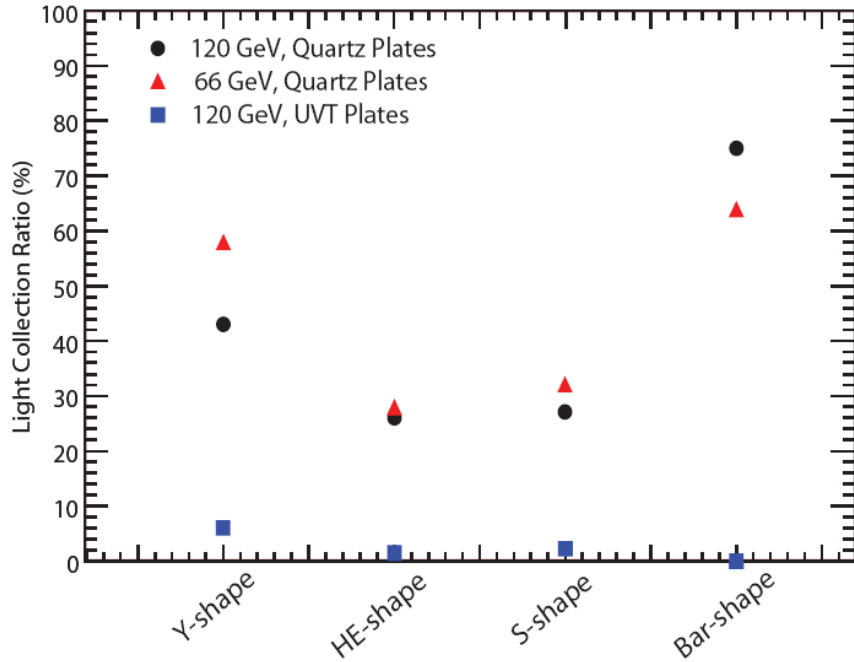


Figure 5: The light collection ratios of quartz plates with different fiber geometries to the original HE scintillator. The variations in the response for different beam energies are due to lack of statistics at 66 GeV beam energy. The test results of the UV Transmitting Acrylic (UVT) are also marked.

Quartz Plate Calorimeter Prototype – I (QPCAL-I)

Based on the R&D studies described above, we have built a quartz plate calorimeter prototype (QPCAL-I). The calorimeter consists of 20 layers of quartz plates with 20cm x 20cm x 5 mm dimensions. The Cherenkov light was collected by Saint Gobain BCF-12 WLS fibers, with “bar shape” geometry. Hamamatsu R7525-HA PMTs were used to collect the light from WLS fibers.

The prototype was tested at the CERN H2 test area with 2 different configurations; hadronic configuration with 7 cm iron absorbers between each layers, and electromagnetic (EM) configuration with 2 cm iron absorbers. The hadronic and EM configurations were tested with various energies of pion and electron beams, respectively.

QPCAL-I showed superior response linearity and uniformity (see Figure 6). QPCAL-I has a preliminary hadronic resolution of 18%. The preliminary hadronic and EM resolutions are shown in Figure 7.

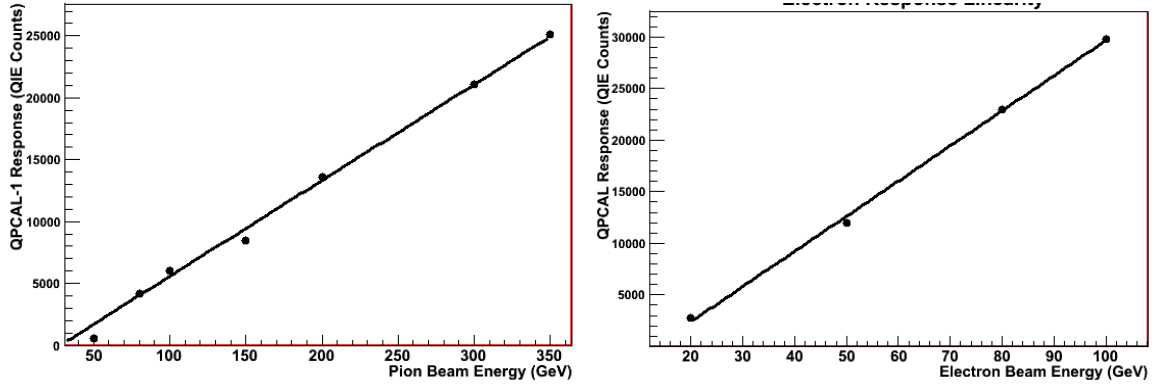


Figure 6: Hadronic (Left) and EM (Right) response linearity of QPCAL-1, versus beam energy.

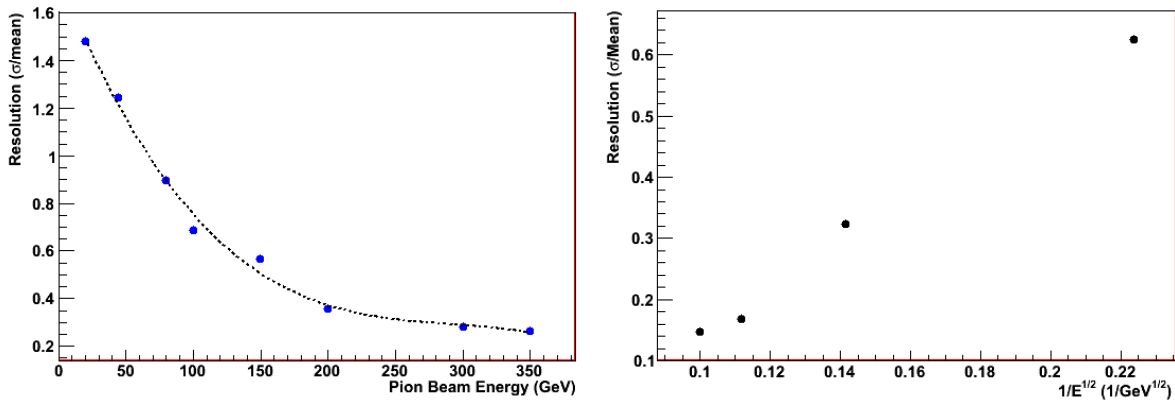


Figure 7: Preliminary Hadronic (Left) and EM (Right) energy resolution of QPCAL-1, versus beam energy.

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