The SuperB Factory Electromagnetic Calorimeter

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Abstract. The SuperB project is an asymmetric $e^+e^-$ accelerator of $10^{36} \text{cm}^{-2} \text{s}^{-1}$ luminosity, capable of collecting a 50 - 75 $ab^{-1}$ data sample in five years of running. The SuperB electromagnetic calorimeter (EMC) provides energy and direction measurement of photons and electrons and identification versus other charged particles for electrons. A matrix of 25 LYSO crystals has been tested at the Beam Test Facility at Frascati in May 2011 at energies between 100 MeV and 500 MeV. Results from this test will be presented. Design and Monte Carlo studies for the general EMC system will also be presented.

1. Introduction

The SuperB project is an asymmetric $e^+e^-$ accelerator of $10^{36} \text{cm}^{-2} \text{s}^{-1}$ luminosity [1], capable of collecting a data sample of 50-75 $ab^{-1}$ in five years of running (two orders of magnitude higher than the previous B-factories). The SuperB detector [2] concept is based on the Babar detector [3], with modifications required to operate at a luminosity of $10^{36}$ or more, and with a reduced center-of-mass boost. Further improvements are needed to cope with higher beam-beam and other beam-related backgrounds, as well as to improve detector hermeticity and performance. A number of Babar components are reused: the flux-return steel, the superconducting coil, the barrel of the EMC and the Cherenkov detector fused silica bars while the other parts will be replaced with new detectors. The hermeticity of the SuperB detector, and, thus, its performance for certain physics channels will be improved by including a backward veto-quality EMC detector comprising a lead-scintillator stack and a forward particle identification detector consisting of a fast Cherenkov light based time-of-flight system.
Figure 1. Schema of the BaBar calorimeter with dimensions and crystal arrangement. The forward endcap covers the angular range $15.8^\circ < \theta < 26.8^\circ$ with respect to the beam axis.

Figure 1 shows a sketch of the BaBar calorimeter, made of CsI(Tl) crystals arranged in a central part (barrel) and a forward endcap. While the barrel, with the necessary upgrades to match the new requirements of an accelerator operating at higher luminosity, can also be used in the SuperB environment, a new forward electromagnetic calorimeter has to be conceived due to the high rate of luminosity related background, especially radiative Bhabhas, and the radiation damage of the BaBar CsI(Tl) crystals.

2. The Forward Electromagnetic Calorimeter

The forward electromagnetic calorimeter (FwdEMC) designed for SuperB is a new device replacing the BaBar CsI(Tl) forward calorimeter. Because of the increased background levels, a faster and more radiation hard material is required in the forward region. One proposed solution assumes the full or partial replacement of CsI(Tl) crystals with LYSO (Lutetium Yttrium Orthosilicate, with Cerium doping) crystals [4]. The advantages of LYSO include a much shorter scintillation time constant (LYSO: 40 ns, CsI(Tl): 680 ns and 3.34 $\mu$s), a smaller Molière radius (LYSO: 2.1 cm, CsI: 3.6 cm), and a better tolerance to radiation.

For the option of partial replacement for the endcap crystals, the BaBar mechanical structure is reused and each cell in the inner rings is filled with four LYSO crystals. A full LYSO endcap the FwdEMC will be composed by 20 rings of crystals, arranged in four groups of 5 layers each. The crystals maintain the almost projective geometry of the barrel. Each group of five layers is arranged in modules of 5 crystals each. Each crystal is up to $2.5 \times 2.5 \, \text{cm}^2$ at the back end, with a projective taper to the front. The maximum transverse dimensions are dictated by the Molière radius. The length of each crystal is approximately 20 cm, or 17.5 $X_0$. The readout sensors for the LYSO crystals are Avalanche Photodiodes (APD). A new Very Front End (VFE) board has been designed and it incorporates a dual-gain amplifier ($1 \times$, $16 \times$); the VFE output signals are shaped by a Gaussian shaper with a shaping time of 100 ns. Finally signals are digitalized by a twelve-bit Analog-to-Digital Converter (ADC).

LYSO crystals are widely used in medical applications like PET but they have never been used in large High Energy Physics experiments which require much larger crystal size. Several years of R&D have been performed [5] in order to obtain from manufacturers large size crystals with high light yield (LY); special care has been devoted to the study and improvement of the longitudinal LY uniformity, which is related to Ce doping concentration.
2.1. Beam Test
A test beam has been performed with a prototype LYSO matrix (see Figure 2) at the Beam Test Facility (BTF) [6] in Frascati in May 2011. The prototype matrix is composed by 25 LYSO crystals of pyramidal shape inserted in a support structure assembled by the RIBA company (Faenza, Italy). Each crystal is coupled to an APD and the same VFE boards and Gaussian shaper designed for the FwdEMC are used in the test. The processed signals are acquired by four 12bit sampling ADC (Caen V1720 250 MS/s 54 sampling ADC [6]). Beside the effect of the variation of Ce doping concentration, the crystals show an intrinsic longitudinal LY non-uniformity related to the focusing effect of the tapering. Due to this focusing effect and to the fact that all the crystals have been cut with the same orientation from the boule, all of them show an LY increasing from the direction of the large face with the photosensors to the small face. To obtain a crystal LY longitudinal uniformity within 5% a 15 mm band of black paint has been applied on the small side close to the face opposite to the photosensor as shown in Figure 3. This operation causes an average light yield loss of about 40%.

![Figure 2. Prototype mechanical structure.](image1)

![Figure 3. Crystal uniformisation technique.](image2)

![Figure 4. Test beam setup at BTF.](image3)
The setup for the beam test of the matrix at the BTF is shown in Figure 4, where the end of the electron beam line, two planes of silicon strip detector (one horizontal and one vertical position measurement) and the box containing the matrix with the crystals and the VFE boards are shown. The silicon strip detector is composed by two planes with orthogonal strip orientation with digital readout, each plane is composed by 384 silicon strip with a pitch of 228 µm. Data are taken at 5 different electron energies: 486, 398, 297, 198 and 99 MeV, with the beam pointing to the center of the matrix. The dimension and the energy spread of the beam depend on the electron momentum becoming larger at lower energies.

![2D Silicon Position](image)

**Figure 5.** Beam intensity profile at 486 MeV as measured by the silicon detectors and the corresponding X-Y(horiztonal-vertical) selection highlighted by the black box.

![e total energy](image)

**Figure 6.** Measured energy distribution, in ADC counts, for the 198 MeV beam where the peaks for 1, 2 and 3 $e^-$ have been fitted with Crystal Ball functions.

In order to select particles hitting the LYSO matrix face approximately at the same point, a selection on the electron position measured by the silicon detector is applied before the total energy deposit is evaluated. The selected area is about $6 \times 4$ mm$^2$. The plot in Figure 5 shows the beam profile at 486 MeV, the black box represents the selected area at this energy. Figure 6 shows the total energy distribution for the selected events at 198 MeV. Here the deposited energy of 1, 2 and 3 electrons are evident and each one is fitted with a Crystal Ball function. Since the beam energy spread is not known with precision, it is estimated directly from data. Events with more than one electron of the same energy are used in order to have more than one independent measurement at the same energy (i.e. 200 MeV could be measured with one $e^-$ of 200 MeV or two $e^-$ of 100 MeV). Starting from the assumption that the calorimeter prototype resolution for two particles of energy $E$ is the same of one particle with twice the energy (2E), we can estimate the beam energy spread at different beam line energy configurations, and then subtract these values from the total resolution in order to extract the intrinsic LYSO EMC prototype resolution. All the results are extracted with a minimization procedure where the matrix resolution is assumed to be: 

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E \text{[GeV]}}} + \frac{b}{E \text{[GeV]}} + c \%.$$ 

The beam energy spread at 486 MeV is assumed to be 1%, similar to the nominal LINAC spread at 510 MeV. The results are shown in Figure 7, the resolution as a function of energy obtained with this technique is:

$$\frac{\sigma(E)}{E} = \frac{1.1}{\sqrt{E \text{[GeV]}}} + \frac{0.4}{E \text{[GeV]}} + 1.2 \%.$$ 

A Geant4 Monte Carlo simulation has been developed encompassing all the dead materials on the beam hall and with a detailed representation of the crystals and the support structure.
Figure 7. Resolution as a function of energy. The symbols display the measurements ( * 99 MeV, ⊙ 198 MeV, ■ 297 MeV, * 397 MeV, □ 487 MeV), the solid line the fitted resolution and the shaded area the estimated beam energy spread.

geometries. The effects of electronic noise as measured on the beam, electronic cross-talk, LY non uniformity and crystals intercalibration uncertainties have been added to the simulation. The output of the simulation includes the sampling of the signal shape from the ADC emulating the real data output format so that after the first step, beam and Monte Carlo data are processed with the same analysis chain. Once the beam energy spread, as evaluated from the data, has been included in the simulation, the Monte Carlo results are well in agreement with the measured matrix resolution as shown in Figure 8.

Figure 8. Comparison between data and Monte Carlo energy resolution with the beam energy spread in the simulation as estimated from the data using the minimization technique. The shaded area displays the data and the dots the Monte Carlo.
3. Barrel optimization
In order to be confident that the barrel can cope with the higher radiation and background level expected at SuperB, several studies about the CsI(Tl) crystals are being carried out both on the background simulation and readout electronics sides. The aim of the combined effort is to find a compromise where the VFE electronics can extract short enough signals from the slow CsI(Tl) crystals to avoid signal pile-up and mitigate the background effect but is still retaining a good signal to noise ratio.

4. Conclusions
The SuperB electromagnetic calorimeter will reuse the BaBar barrel while the forward endcap need to be replaced, in part or in toto, with a detector more suitable to cope with the level of radiation expected at higher luminosity. We presented the results of a beam test, performed after years of studies and R&D on the crystals, showing that the LYSO is a very good solution for the SuperB forward endcap. The studies on the readout for the CsI(Tl) crystals from BaBar are still ongoing to find a good compromise between the mitigation of machine backgrounds effects and a safe electronic noise level.

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