A LYSO Calorimeter for the SuperB Factory

Claudia Cecchi1, Valerio Bocci3, Stefano Germani1, Pasquale Lubrano2, Elisa Manoni1, Alessandro Rossi1, Michel Lebeau2, Marco Bizzarri1, Giacomo Chiodi3, Andrea Papi2, Luigi Recchia3.

1 Università di Perugia e INFN Sezione di Perugia
Via A. Pascoli, 06123 Perugia, Italia
2 Istituto Nazionale di Fisica Nucleare, INFN Sezione di Perugia,
Via A. Pascoli, 06123 Perugia, Italia
3 Università di Roma “La Sapienza” e INFN Sezione di Roma1
P.zzle Aldo Moro 2, 00185 Roma, Italia

E-mail: claudia.cecchi@pg.infn.it

Abstract. The SuperB project is an asymmetric e+e- accelerator of $10^{36}$cm$^{-2}$s$^{-1}$ luminosity, capable of collecting a data sample of 50-75 ab$^{-1}$ in five years of running. The SuperB electromagnetic calorimeter (EMC), that will be described in this paper, provides energy and direction measurement of photons and electrons, and is used for identification of electrons versus other charged particles. In particular we will present its design, geometry study and related simulations, as well as R&D on LYSO crystals, a project for the mechanical structure and development on readout and electronics. A matrix of 6 crystals has been tested this year June 2010 at the Beam Test Facility of Frascati (BTF) at energies between 200 MeV and 500 MeV, and a beam test with the complete prototype of 25 crystals is foreseen at CERN in October 2010 to cover the energy range between 500 MeV and 7 GeV.

1. Introduction

SuperB is a proposed next generation asymmetric e+e- flavour factory, designed to run at a baseline luminosity of $10^{36}$cm$^{-2}$s$^{-1}$, between 50 and 80 times the peak luminosity reached by earlier B factories, KEKB and PEPII. The BaBar [1] detector has been a very effective instrument to perform precision measurements in the field of flavour physics. Therefore its main design remains a very good baseline option for an experiment at the SuperB factory [2]. The detector is composed by an Inner Vertex Detector, a Tracking System, an Electromagnetic Calorimeter, a Solenoidal Magnet and a Muon/Hadron System. A picture of the detector with the baseline (high) and the improved option (low) is shown in figure 1. The electromagnetic calorimeter is made of three parts: a central part (barrel) calorimeter, which will be reused from BaBar, a forward endcap calorimeter, which will replace the BaBar one, and the backward endcap calorimeter, not present in BaBar, a new device to improve the backward solid angle coverage. A new forward electromagnetic calorimeter has to be conceived, due to the high rate small angle Bhabhas and the radiation damage of the BaBar CsI(Tl) crystals, while the barrel of the CsI(Tl) calorimeter will be reused, with the necessary upgrades, in order to match the new requirements of an accelerator operating at the above mentioned luminosity.
In this paper only the new forward calorimeter will be addressed. Figure 2 shows a view of the BaBar calorimeter barrel plus endcap.

The goal of the study described in this paper is to have a calorimeter with fast response, small Molière radius and high radiation hardness. A very good candidate for this purpose is the LYSO (Lutetium Yttrium Orthosilicate, with Cerium doping) crystal, which has a decay time of about 40 ns, a Molière radius of 2.07 cm, a high light yield and high density.

2. Forward Endcap Calorimeter
The forward endcap calorimeter for SuperB is a new device replacing the BaBar CsI(Tl) forward calorimeter with coverage starting at the end of the barrel and extending down to 270 mrad with respect to the beam line. It will be made of 4500 LYSO crystals arranged as described in section 2.1.2. The readout and electronics will be presented in section 2.1.3.

2.1 R&D for the LYSO crystal calorimeter
A deep R&D phase has started in 2008 for the new LYSO crystal calorimeter. In these two years many progress have been done in studying optical properties of the LYSO (under study since years in Caltech to prove the effective use in the high energy physics field, but already largely used in medical applications), a possible readout system and Very Front End (VFE) electronics to collect the signal, and a design of the mechanical structure to support the detector. In the meantime simulation packages have been developed both for the optimization of the detector in terms of geometry and performance, to study physics impact of different options, and to study the effect of the machine background in the detector. All these points will be addressed and described in the following sections.
2.1.1 LYSO crystals

R&D on LYSO crystals is ongoing mainly in Caltech and since about one year also in Italy (Perugia University and INFN). The characterization of the LYSO is being studied since years in order to have, from manufacturer, crystals with high light yield, and especially uniformity of the light along the longitudinal dimension; in particular the quality of the product in terms of Ce doping has been largely studied. A consistent uniformity has been found between PMT and APD readout, while there is a difference once reading the signal at the two ends of the crystal. This problem has been understood and solved; an extra green component was present in the radio luminescence spectrum at the tail end for some studied samples.

Figure 3 shows the light yield as a function of the distance from the end of the crystal coupled to PMT after different level of irradiation. No degradation of the performance is observed.

![Figure 3](image1.png)

**Figure 3.** Light yield uniformity for a LYSO crystal after different level of irradiation. The crystal was coupled to a PMT. Consistent results have been obtained with the APD readout.

Different producers are being investigated, able to grow crystals of the requested dimensions (25mm x 25mm x 20cm) (see figure 4). The maximum transverse dimensions are dictated by the Molière radius and by the desire of obtaining two crystals from one boule. The length of 20cm corresponds to 17.5 $X_0$. A first production of new SIPAT (China) crystals has given very good results in terms of light yield, of the order of 86% of the best production (on this subject see dedicated talk at this conference by L. Zhang).

![Figure 4](image2.png)

**Figure 4.** LYSO ingot growth at SIPAT. Dimensions are indicated below.
Tests on LYSO crystals have been performed also in Italy (Perugia) with a sample of 12 crystals produced by Saint Gobain in order to measure optical properties of the crystals, like transmittance, scintillation and emission spectra, light yield and uniformity. A measurement of the light yield has been done using a Cobalt source and reading the signal with a PMT. In figure 5 (left) the spectrum of the light is shown, while the right plot shows the uniformity of the light along the crystal. The measured light yield is about 900 ph/MeV for the bare crystals, which is in agreement with the expected value; further measurements will be performed with the crystal wrapped in a tyvek foil and also putting a crystal in a cell made of the material that will be used for the mechanical structure. As can be seen the uniformity is very good, better than 1%, to be compared with our actual request of having a uniformity better than 5%.

An alternative choice to the LYSO would be the pure CsI even if the light output is much smaller in this case. Therefore tests on this crystal will be done in the next months.

2.1.2 Mechanics
Crystals are arranged in the calorimeter in 20 rings divided in 4 groups of 5 layers each. Each group of 5 layers is arranged in modules of 5 crystals wide, for a total of 4500 crystals. The crystals maintain the almost projective geometry of the barrel. Figure 6 shows the geometry of the calorimeter. The preferred structure for the forward LYSO calorimeter would be a continuous ring, however there is a possibility of building a structure divided in two halves if requested by installation constraints. The support structure is an alveolar, with each cell containing one crystal and a shell connecting the alveolar together, made either of carbon fibre or glass fibre. The outer diameter is 2m, the inner one is 1m. This structure is bounded by two cones at the radial extremes. The outer cone is a carbon fibre structure, 6-10 mm thick, in order to reduce the material between the barrel and the forward. The inner cone is 20-30 mm thick as there is no material issue in this part. A prototype of the mechanical structure has been built in Italy by RIBA company, to contain 25 crystals, of global overall dimensions of 130x130x250 mm3 (figure 7).
Cell walls are made by wrapping several layers of pre-impregnated glass fibre epoxy composite plus a single inner layer of aluminium reflective foil. This prototype will be used in October 2010 for a beam test at CERN. It has already been put under beam at the Beam Test facility of Frascati in June filled with only a subsample of the crystals, to test the electronics readout boards.

2.1.3 Electronics

Two possible readouts are under study for this calorimeter, PiN diodes as used in the barrel and APD’s (Avalanche Photodiodes). Two photodetectors per crystal are foreseen for redundancy. APD’s have a low-noise gain factor of 50 and allow to calibrate crystals using sub MeV radioactive sources. The disadvantage of APD’s is the strong dependence of the gain on the temperature. For more details on this see talk of R.Y. Zhu at this conference. As far as the electronics is concerned, two options are considered: one possibility is to send all data from the calorimeter over synchronous 1Gbit/s links to
the level1 buffer in the trigger system; alternatively a “triggered” pull architecture will be used, where the trigger system receive only sums of crystals, and only triggered events are sent to the ROMs. The second option (figure 8) requires a much small number of links and is at the moment the baseline one. The signal from the APD’s or PiN’s, glued on the 4500 crystals of the forward LYSO calorimeter are sent to a charge preamplifier which translates the charge into voltage and then to a shaper with 100ns shaping time which provide a pulse of FWHM of 240ns. The shaped signal is amplified with two gains (x1 and x64) and at the end of the analog chain the chosen gain is digitized by a 12 bits ADC running at 14 MHz. With this scheme the full range from 10 MeV up to 10 GeV is covered with a resolution better than 1%. As stated above, the number of links can be reduced summing channels together at detector level and sending only the sums to the trigger. The natural granularity of the LYSO calorimeter is a module of 25 crystals. The data from the 25 crystals are summed together forming a word of 16 bits. Then 4 modules are grouped again. In this case the number of links would be only 90

![Figure 8. EMC electronics scheme.](image)

(with respect to about 1000 in the case of non triggering architecture), but limiting the trigger granularity.

3. Simulations
Simulation studies are under way in order to optimize the detector configuration. First studies have been devoted to the geometry configuration taking into account constraints coming from the space available in the detector and from the maximum possible size of the crystals. The result of this simulation is the geometry described in paragraph 2.1.2 and shown in figure 6. In addition simulations have been developed to study the response of the calorimeter as function of the amount of dead material between crystals. Figure 9 (left) shows the resolution, for the prototype 5x5 crystal matrix, as a function of the energy for different configuration of the mechanical structure (thickness of the dead material between crystals).
Figure 9. Left: Energy resolution as function of the energy per different types of the mechanical structure. Right: Scaled resolution (90% containment of the energy distribution) as function of the PID quartz thickness for different energies.

The simulation has gone further approaching more detailed aspects, for example the material in front of the calorimeter due to the possibility of installing a Particle Identification Detector (PID) in the forward region. A study has been performed to study the effect of the PID as a function of the thickness of the quartz bar and also as a function of the position of the PID in front of the calorimeter. Figure 9 (right) shows the resolution as a function of the thickness, showing a non negligible impact of the material on the resolution. The effect is more relevant in the case of low energy particles and slightly increase with the thickness. The evaluation of the benefits, in terms of signal over noise, in some physics channels particularly affected by the PID detector, with respect to the worsening of the resolution, is under study. Another important effect arise from the transition region between the barrel and the forward which should be ideally smooth in order to contain the electromagnetic showers and to keep pattern recognition simple. However the possible presence of the forward PID detector requires the forward calorimeter to be moved back. The effect of this on photon energy resolution has been studied and the resolution degrades in the barrel-endcap transition region as expected. In figure 10 shows the effect on the resolution due to the position of the calorimeter far from the transition region (left) and in the transition region (right).

Figure 10. Effect on resolution of z-position forward calorimeter. Left: resolution as function of the calorimeter position for showers away from the transition region. Right: resolution as function of the calorimeter position for showers in the transition region.

Furthermore the impact of a realistic clustering algorithm has been studied as in the actual event environment multiple particles are present in an event and pattern recognition is then required.
Figure 11 (left) shows how the measured energy distribution changes for different reconstruction algorithms. Finally we started to study the effect of the background coming from the machine on the calorimeter performance. In particular radiative Bhabha events have been simulated and added to the signal Monte Carlo events. This study can give valuable input on electronics requirements like the shaping time and the integration time, in order to be able to handle pile up events between signal and background. Most of the background events are coming from neutrons, while electrons and photons are very few. The physic channel used for this study is the $B^+ \rightarrow K^+ \nu \nu$. The recoil analysis approach is used where one of the two $B$’s is fully reconstructed in the events in the semileptonic or hadronic modes (this is called the $B_{tag}$) and used to constraint the kinematics, while the other emisphere is used to search for the signal ($B_{signature}$). This method is used when there are undetectable particles in the signal in order to have a clean sample.

This method has been applied in the same analysis in the BaBar experiment where it was possible to distinguish very effectively between signal and background using the $E_{\text{extra}}$ distribution shown in figure 10 (right). A clear peak in the first bin at zero (blue crosses) is present for the simulation done in the case of a BaBar-like geometry. The other configurations, which correspond to two different possible geometry configurations for the SuperB experiment, do not show anymore this peak. This means that in the geometry configuration of SuperB, when adding background to the signal, is it not possible to distinguish it from the signal. This is due to the fact that the machine background events are superimposed to the signal ones. It has to be stressed that, a very high level of background has been taken into account for this analysis, much worse than the expected one, making this result very conservative. The electronics of the detector has to be studied in detail in order to avoid this kind of behaviour. Moreover, it has been seen that this happens only in the barrel where the electronics integration time is much larger than in the endcap and is then related to the fact that the CsI crystals have a decay time much longer than the LYSO ones. In the LYSO forward calorimeter is then possible to use a time window of only 100 ns (300 ns in the barrel) and the peak of the $E_{\text{extra}}$ is clearly visible in this part of the detector. This study, strictly correlated with the development of the electronics of the detector, is still ongoing.

4. Beam Test
A beam test has been performed for one week in June 2009 at the Beam Test Facility (BTF) of LNF (Laboratori Nazionali di Frascati, INFN). One LYSO crystal has been equipped with one photodiode
PIN [Hamamatsu S2744-08 (1x2cm²)] and with two APD’s [Hamamatsu S8664-55 (0.5x0.5 cm² each)] as showing in figure 12.

Figure 12. Picture of the LYSO crystal with a PiN diode and two APD’s glued at the end.

The crystal has been studied with a beam of electrons of energies in the range between 100 MeV and 500 MeV. The BTF allows to adjust the number of electrons arriving at the detector by setting up dedicated collimators. We worked with the collimators adjusted to have 1 electron, a small contamination was present of events with 2 electrons as shown in the following. Figure 13 (left) shows the signal response in the APD and in the PiN diode and a strong correlation is observed. In figure 13 (right) the signal in ADC count for the data collected at 500 MeV is shown.

Figure 13. Left: correlation between the signal response in the PiN diode and in the APD. Right: Signal in the crystal with the readout made with the PiN diode. Dots are data, red is Monte Carlo simulation and blue is the fit to the distribution with a Crystal Ball function.

The peaks for one and two electrons are well separated and there is a good agreement between data and simulations, taking into account the poor shower containment in only one crystal. In June 2010 the matrix with 6 crystals has been put under test at the BTF to test the electronics boards. 3 crystals where equipped with PiN diodes and 3 with APD’s. It was possible with 6 crystals to test the linearity
and also to have an estimation of the resolution as function of the energy. Results are shown in figure 14.

![Figure 14](image1.png)

**Figure 14.** Left: Signal in ADC counts as a function of the energy, a good linearity is observed. Right: resolution as a function of the energy.

In October and November 2010 a matrix with 25 LYSO crystals will be put under test at CERN (1GeV-7 GeV) and then at BTF again. The LYSO will be surrounded by a ring of CsI crystals. Figure 15 shows the mechanical structure with the first column filled with crystals (left). In the right panel a CAD design of the LYSO matrix at the centre with the surrounding CsI crystals in blue and one of the five electronics board is shown.

![Figure 15](image2.png)

**Figure 15.** Left: mechanical structure of the beam test with one column filled with LYSO crystals. Right: CAD design of the test beam matrix at the centre surrounded with CsI crystals. One of the 5 electronics boards is also shown in green.

Five electronics boards have been developed and are ready to be installed. The readout will be done with PiN diodes in one row (5 crystals) and the rest of the matrix with APD’s. the DAQ system is developed with sampling ADC’s to read the LYSO matrix, and peak sensing ADC’s for the Cherenkov counters which will be used at CERN to separate electrons from pions, a silicon telescope which will be put in front of the matrix to have information on the beam position and to study the
beam profile and finally to read a quartz bar to be put before the calorimeter to study the effect of the particle identification system.

5. Conclusions
R&D for the use of the LYSO crystals in high energy physics applications has started and is developing in order to cover many different aspects. Characterization of the LYSO is under development mainly to understand Ce doping and Light Yield uniformity response. As of today more than one manufacturer is available for the growing and production of the LYSO and quality is improving fast. The simulation for a possible LYSO calorimeter for the Superb factory has also been developed starting from the basic points of the expected resolution and going into details of needed application. A test beam has been performed with only one crystal allowing the understanding of the beam facility at LNF and showing that there is a high symmetry between the two possible readouts which are at the moment under study, PiN diodes and APD’s. Two tests beam will be done in October and November one at CERN and one at the BTF.

6. Acknowledgment
This work has been supported by “Fondazione Cassa di Risparmio di Perugia”. We would like to thank Prof. Ren Yuan Zhu for useful discussions and help about R&D for crystals.

References

[1] B. Aubert et al. 2002 The BaBar Detector Nucl. Instrum. Meth. Phys. Res. Sect A 479 1
[2] SuperB Conceptual Design Report 2007 A High Luminosity Asymmetric e+e- Super Flavour Factory INFN/ AE-07
[5] Ren Yuan Zhu private communications