Technology Choices for the Super$B$ Forward Calorimeter Endcap

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In the wake of the presentation and discussion at the February 2, 2012 Proto-Technical Board meeting on the EMC, we thought that it might be useful to summarize the options before us, gathering into one place all the considerations relevant to a choice of forward endcap technology: cost, energy and position resolution, radiation hardness, time resolution, ability to withstand backgrounds,calibration, operational concerns and upgrade possibilities. This note is written from our perspective; the conclusions do not necessarily represent those of the EMC group.

There is a lot of background to this discussion; we will not attempt to start at the beginning, but rather we assume that we are all current on the various options, performance studies, *etc.*. At a later stage it could prove useful to generate an expanded version of these remarks, perhaps for inclusion in the TDR.

We have used dollars for these comparisons, we trust in a consistent manner; conversion to euros should be straightforward. As of this writing, the exchange rate is 1.31 \$/€. In the case of the mounting structure, we have monetized labor costs using €9K/man-month for engineers and €6K/man-month for technician labor.

The Barrel

The *BABAR* barrel EMC, utilizing CsI(Tl) crystals and photodiode readout, is clearly not optimal for the Super$B$ environment. It is, however, so expensive that it cannot be replaced. The practical solution is replacement of the preamplifiers with a version having a shorter shaping time. This replacement provides, at the nominal (radiative Bhabha) background rate, somewhat deteriorated energy resolution over that obtained at PEP-II. At the safety margin 5$\times$ background rate, the barrel performance is seriously degraded. This is not comfortable situation; more study is needed, particularly to achieve a better understanding of the effect of Touschek and (non-radiative Bhabha) neutron-induced backgrounds at nominal and 5$\times$ background rates. Our options for remediation are quite limited; the only obvious knob is the preamplifier shaping and integration time. Optimization of these parameters is likely to produce only small improvements. Improvements in the shielding could perhaps produce significant gains, but this is in the realm of speculation at this point.

The Forward Endcap

Since the performance of the barrel will manifestly be somewhat degraded from that of *BABAR* at PEP-II, the question naturally arises as to why we are even considering proposing a forward endcap with better resolution than that of the barrel, especially in view of the associated costs? This question has been posed by Gruppo Uno, and naively is a good one. Deeper examination of the problem indicates, however, at least in my opinion, that this not the right perspective on the problem. Our goal is not to improve the energy resolution of the endcap, but to produce an endcap that can function in the Super$B$ environment,

If we could find a technically viable solution that has comparable performance to that of the barrel, that is, one that can provide this performance in the more hostile (that is, higher background, higher radiation dose) environment of the endcap, we would certainly propose it. It turns out, however, that the viable technical solutions for the forward endcap have one thing in common: they all (with the exception of undoped CsI), provide better resolution than that of the barrel. Achieving this improved resolution is therefore **not the objective**, but is, rather, **a consequence** of satisfying the other technical criteria (radiation hardness, scintillation light decay time, small Molière radius) that must be met if the forward endcap is to work in the Super$B$ environment.

We will briefly go through the relevant properties of the various options we have discussed to try to illuminate this point. We have spent a great deal of time on sophisticated fast and full simulations of the calorimeter, so we believe that the performance of most of the options is reasonably well-understood (with the *caveat* that Touschek and neutron-induced backgrounds remain to be addressed. These backgrounds will not materially alter the discussion below. It is also important to emphasize that the various options present different technical challenges; they are not at the same stage of technical readiness for inclusion in the TDR. Certain options are technically mature, while others are R&D projects. Proposing a baseline technical solution that requires major R&D does not strike me as a wise course of action, although it may be OK as a backup alternative, should the R&D be successfully concluded in a timely manner.

The LYSO CDR design

The forward endcap design proposed in the CDR consists of 4500 LYSO crystals, mounted in a new aveolar structure and read out by APDs. The fast decay time, excellent radiation hardness and small Molière radius of LYSO are a full match to the technical and performance requirements of Super$B$. This design is, of course, the most expensive, requiring .4 m^3 of crystals, a new mounting structure, and two APDs per crystal. This cost motivates us to search for alternative, less expensive solutions.

The LYSO calorimeter has been the subject of an extensive R&D effort over the last five years. This entails detailed interactions with several vendors to bring the crystal quality to acceptable levels of light output, uniformity of response, radiation hardness and production efficiency. There have also been beam tests that have advanced our understanding of the subtleties of crystal preparation, APD readout, calibration, DAQ issues and other system-level aspects of building a successful calorimeter.

Were it not for the cost, the choice of LYSO for the forward endcap would be the consensus choice. If the cost of the LYSO system is judged to exceed available resources, we must perforce consider alternatives. This must be done with an eye to total system cost, technical readiness, operational considerations and practicality.

Methodology of evaluating alternative designs

The baseline design, employing 4500 LYSO crystals, contemplates complete replacement of the existing mechanical structure. A new carbon fiber aveolar and associated structure to mount the crystals on the doors of the magnet is estimated in the Super$B$ TDR to cost $2.27M

For comparison with the BGO and $PbWO_4$ options, we have assumed the same aveolar structure as for the original LYSO design, so the number of crystals remains 4500. The crystal volume thus scales roughly as the radiation length of each crystal type, and the number of readout sensors (assumed to be two APDs/crystal) remains 9000. Were either of these options to be chosen, we would certainly reoptimize the crystal matrix configuration; this will make little difference to the cost comparison.

For the pure CsI configuration, we have assumed reuse of the *BABAR* mounting structure, designed for 900 CsI(Tl) crystals. Complete replacement of the CsI(Tl) with undoped CsI thus obviously requires 900 crystals in nine rings (providing that the inner ring, currently unpopulated, were to be filled).

We also consider three hybrid options, in which a number of the outer CsI(Tl) rings of the endcap are retained (since they are approximately at the same distance from the interaction region as are the forward barrel crystals) and the inner rings are replaced by LYSO crystals. The retention of the existing *BABAR* mechanics is intrinsic to this option; a hybrid design with a new mounting structure is not considered.

In all options involving reuse of the *BABAR* mechanics, we have estimated a cost of $0.25M, largely monetized labor, for dismounting modules, inserting crystals and remounting.

We have not included certain common items, such as crystal development costs (certainly larger for the non-LYSO options, at this point), measurement and setup equipment, cables, cooling (largest for a -25∘C $PbWO_4$ system), the source calibration system, project management costs, power supplies, or the DAQ system, so "Total Cost" does not mean this is an all-encompassing estimate.

The $PbWO_4$ option

$PbWO_4$ has been used in the CMS EM calorimeter and has been thoroughly investigated for the PANDA detector. Light output is very low (<4% of LYSO), placing severe constraints on control of electronic noise. A new type of $PbWO_4$ has been developed which has improved light output, but must be operated at low temperature.

The cost of $PbWO_4$ crystals is relatively low. However, the supplier of these crystals to CMS is bankrupt; there is no current supplier of the improved type of crystal. The cost of $PbWO_4$ is thus currently uncertain. Were a new supplier to be found, it is not unlikely that the crystal price could be significantly higher than the estimate furnished by the bankrupt supplier. It would also be necessary to undertake a crystal development program with the new supplier that is of the same scale as the one we have been pursuing with LYSO for the past four or five years.

The light output of $PbWO_4$ is not only low, it is rate-dependent. CMS has developed an elaborate laser system to track the variation of the response; the cost of such a system must be included in evaluating the cost of this option. Even with such a system, tracking this variability is a substantial ongoing task, requiring dedicated manpower over the operational life of the detector.

The (very uncertain) radiation rates for the forward endcap of Super$B$ are estimated as 3 krad/year averaged over the endcap, corresponding to 0.6 rad/hour, or 3 rad/hour at our 5× mandated safety factor. Two PANDA $PbWO_4$ crystals have been shown to show an average of 10% of their light output at a dose rate of 10 rad/hour, approximately linear with dose rate. This means that crystals in the endcap would show instantaneous changes in light output varying with beam intensity and position in the array at a level comparable to the energy resolution. This is inconvenient at best, and requires a multi-wavelength laser or LED monitor system to track the variation. The 6 MeV source system, typically used on a weekly basis, is not suitable for tracking these rate-dependent variations in light output.

The cost of such a calibration system can be estimated by scaling from CMS, using information supplied by Ren-yuan Zhu. The lasers and high level distribution system cost $2M (M&S + labor) in ten year old dollars. This part of the system does not scale with the number of crystals. The $4M low level fiber distribution system does scale (approximately): $0.4M is a reasonable estimate. Using our NASA inflation index algorithm, this should be increased by about 25%, so the total laser monitoring system cost is $3M. M&O costs to maintain the system have averaged $0.2M/year; these are not included.

If the system is run at -25○C, the rate-dependence of the light output is somewhat reduced. It *might* then be possible to use a multi-wavelength LED monitoring system. In this instance, the cost of the expensive lasers is replaced by a less expensive light source, but the cost of the devices for light mixing and distribution on fibers remains, and the added cost of an insulated, carefully temperature-controlled mounting structure must be included. We have included a crude estimate of these costs of $1.2M in Table 1.

The BGO option

BGO has been carefully considered for the forward endcap crystals, because it has a relatively fast decay time, and were the L3 crystals to be used, it would be inexpensive. Unfortunately, the variation of light output with radiation dose rate is severe. The light yield monitoring issues cited above would have to be dealt with, and since the changes with dose are very large, it seems inescapable that the monitor system is much more likely to resemble the complex laser system of CMS than a simpler LED-based system. Thus, BGO is not in reality an inexpensive option, nor is it, in my opinion, a good choice to be proposed as a baseline.

The undoped CsI option

Undoped CsI has a short scintillation decay time, but no other characteristic that would make it a suitable choice for the forward endcap. The large Molière radius is particularly unsuitable for the environment of the forward region, and radiation hardness remains a serious question, especially since there are still uncertainties in the background rates in the endcap region. Photopentodes are required for readout. These are expensive, have gain stability and reliability issues and allow the use of only a single device per crystal, thereby further decreasing system reliability. It would be difficult to achieve factory-quality reliability and operation with this choice. On the plus side, the existing mechanics could be re-used, at a considerable savings.

The hybrid option

As the Moliére radius of LYSO is one half that of CsI(Tl), four LYSO crystals can be placed into one compartment of the existing structure built for CsI(Tl). If the outer three CsI(Tl) rings are retained, the required volume of LYSO is reduced by 40%. Including the savings in mechanics, this represents a nearly factor of two reduction in the cost of the endcap. The volumes of LYSO needed for replacement of four and five of the nine rings are also included in the table for comparison.

Given the strength of LYSO crystals, it is possible to place four crystals in a single existing compartment with only optical isolation and no additional carbon fiber support structure. This reduces the amount of dead material in the endcap, thereby improving energy resolution.

This approach has several advantages:

1. It saves a considerable sum of money on crystals and mechanics.

2. The fast, small Molière radius crystals are placed where they are most needed to cope with the Super$B$ environment.

3. Even with reuse of the exising mounting structure, the mechanical strength of LYSO allows for a reduction of dead material in the structure.

4. No further R&D is required: the CsI(Tl) and LYSO technologies are well-proven. Now that we have a method in hand to linearize the LYSO crystal response, a beam test at Mainz would be a good idea.

5. There is a clear upgrade path for the future. Implementation requires no additional R&D.

All three hybrid options have now been evaluated in fast simulation. The performance of the three ring CsI(Tl)/six ring LYSO version, in particular, is very good. We do not yet have a full simulation result, but it is clear that we understand the expected performance, at nominal and 5× background, quite well.

Table 1 is a comparison of the volume and total cost of the scintillating crystals required for the forward endcap in several different configurations. The baseline design, employing 4500 LYSO crystals, contemplates complete replacement of the existing mechanical structure. A new carbon fiber aveolar and associated structure to mount the crystals on the doors of the magnet is estimated in the Super$B$ TDR to cost \$2.7M, which includes monetization of the engineering and technical manpower required. This is an approximation, as some engineering and assembly will take place using laboratory labor, but the bulk of the labor will be passively included in the tender for an outside fabrication. Thus one obvious alternative is a full LYSO configuration in the existing carbon fiber structure.

The total cost of the endcap is the sum of the crystal production and preparation costs, the photosensor readout and associated electronics, the mechanical structure, associated cooling and electronic services and the laser and/or LED calibration system plus the source calibration system. (The latter is a constant, independent of the crystal configuration, so will not be further considered herein.) Thus the crystal cost is only one component, *albeit* typically the largest, of the total cost of a complete system. The purpose of this note is not to arrive at the absolute lowest apparent cost of the forward endcap. It is rather to emphasize that there are several technical options of comparable cost. It is important to choose a forward endcap solution that will function in the Super$B$ environment without undue operational difficulties, as well as one that has a plausible upgrade path. It would be, in our opinion, a less than optimal strategy to propose a baseline for Super$B$ that depended on technology that required substantial future R&D, especially when we have an affordable solution based in proven technology that will function adequately and has an upgrade path: a hybrid CsI(Tl)/LYSO endcap with the existing mechanical structure.

Table 1: Comparison of crystal volume and crystal costs for several forward endcap configuration options.

Option	Number of new crystals	New crystal volume (cc)	Crystal cost/cc (\$)	Crystal cost (M\$)	Photo-detectors (M\$)	Laser/LED system (M\$)	Mounting structure (M\$)	Total cost (M\$)
LYSO full (baseline)	4500	401622	25.00	10.04	0.57	-	2.27	12.88
LYSO old structure	3600	401622	25.00	10.04	0.57	-	0.25	10.86
Hybrid (CsI(Tl)+LYSO)								
3 CsI(Tl) + 6 LYSO	2160	244734	25.00	6.19	0.49	-	0.25	6.93
4 CsI(Tl) + 5 LYSO	1760	197911	25.00	4.95	0.40	-	0.25	5.60
5 CsI(Tl) + 4 LYSO	1360	153783	25.00	3.84	0.31	-	0.25	4.40
Pure CsI	900	692220	5.09	3.52	0.56	-	0.25	4.33
BGO	4500	392181	9.00	3.53	0.57	1.2-3.0	2.27	7.57-9.37
$PbWO_4$	4500	305714	5.00	1.53	0.57	1.2-3.0	2.27	5.57-7.37