CMS Upgrade MB Response to SLHC Document:

09.08: LSO/LYSO Crystal Development for the CMS Endcap Calorimeter Upgrade at the SLHC

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We do not foresee large-scale application of LSO/LYSO crystals as part of the CMS upgrade. While we have not identified a wide-spread use for LSO/LYSO crystals in CMS, there may be some possibilities for more limited applications. In addition, this R&D is appropriate as a generic R&D project. There are a number of significant questions raised by this proposal that need to be addressed. The two most important questions are:

1. How well is it known that the present EE PWO crystals will not survive at the SLHC as presently conceived (post-Chamonix) and will need replacement? How well do we understand the degradation in energy resolution?

2. Is the estimated cost of a LSO/LYSO crystal calorimeter consistent with the financial structure laid out in the CMS upgrade planning?

There are additional questions that also need to be addressed:

3. How is the 27% increase in material needed for LSO/LYSO crystals over that of the present PWO crystals and specifically, the 28 cm length of the LSO/LYSO crystals to be accommodated in the design of the upgraded CMS endcap? Is removal of the preshower all that is required to provide sufficient space? What are the impacts on the HE and endcap muon systems? What is the plan to coordinate the LSO/LYSO crystal calorimeter design with the HCAL and Muon subsystems?

4. What are the prospects to make the needed number of 28 cm long LSO/LYSO crystals reliably and economically manufacturable with satisfactory light output uniformity on timescales consistent with building a new EE? What is the plan to address these issues?

5. What is the plan to ensure there are at least two vendors capable of providing the crystal production?

6. What R&D on LSO/LYSO crystals usable for CMS is possible given the intellectual property rights and patents for LSO/LYSO belonging to the medical imaging companies that have been developing and using this technology? What agreements on R&D results are possible that permit transfer to other vendors?

7. What is the impact on using LSO/LYSO of its self-radioactivity, mechanism of damage to scintillation by radiation (decrease in scintillating ions) and delayed luminescence (degradation in energy resolution)? What is the plan to address these issues?

8. What is known about the performance of LSO/LYSO in the multi-GeV energy range? What is the plan to make measurements in the energy regime relevant for the LHC?

9. What is known about the hadron damage effects in LSO/LYSO and the comparison with those in PWO considering that unlike PWO, there is no thermal recovery in LSO/LYSO?

We request answers to these questions as well as the preparation of a plan for the R&D activities with a schedule showing milestones and checkpoints for continuation including validation of:

- adequate performance with respect to optical self-absorption
- light output uniformity along the crystal length
- radiation hardness performance
- affordable large scale production costs.

In addition, we request you to address the detailed comments on the proposal from the referees below.

Referee #1:

The authors present a comprehensive report on a possible upgrade of the CMS endcap calorimeter using LSO/LYSO crystals. The upgrade of CMS calorimeter will be necessary due to the particularly harsh radiation conditions foreseen at the SLHC but also due to the expected damage of the detector during the use at LHC. The upgrade proposal is supported by the remarkable scintillation and radiation hardness properties of LSO/LYSO crystals and by the recent progress made in the ability to produce these crystals at industrial scale. The two laboratories involved in the R&D activities proposed in this report have a proven expertise in the study of scintillating crystals for HEP and medical application. This expertise is further consolidated by the reliability of the crystal growth industry and institutes foreseen as partners. Last but not least, an indirect support may come from other research programs dedicated to the use of LSO/LYSO crystals in other experiments. The main comments on the drafting of this report, which is of a very good quality, are the following:

-The full names of all institutes and industries mentioned should be given at their first appearance in the text. Their acronyms may be used afterwards. -Parameters like photoluminescent emission-weighted longitudinal transmittance (EWLT) or Average Light output should be explicitly defined. -Fig. 4 left: it is not clear if there are transmittance or EWLT spectra. -Fig.4 right: the normalization seems to be made at 10 rad. Why? If there is no damage after the first (10 rad) radiation exposure, it should be mentioned.

-The text at page 5 is incomprehensible and should be corrected. The phrase “Methods of studying hadron damage … collisions from FLUKA simulations [12]” is much too long, possibly as the result of a typing (copy/paste) error.

-The potential use of LSO/LYSO crystals for a sampling calorimeter (suggested at pag. 7 and 10) should be better explained. Is it referred to an electromagnetic, hadronic or combined electromagnetic/hadronic calorimeter?

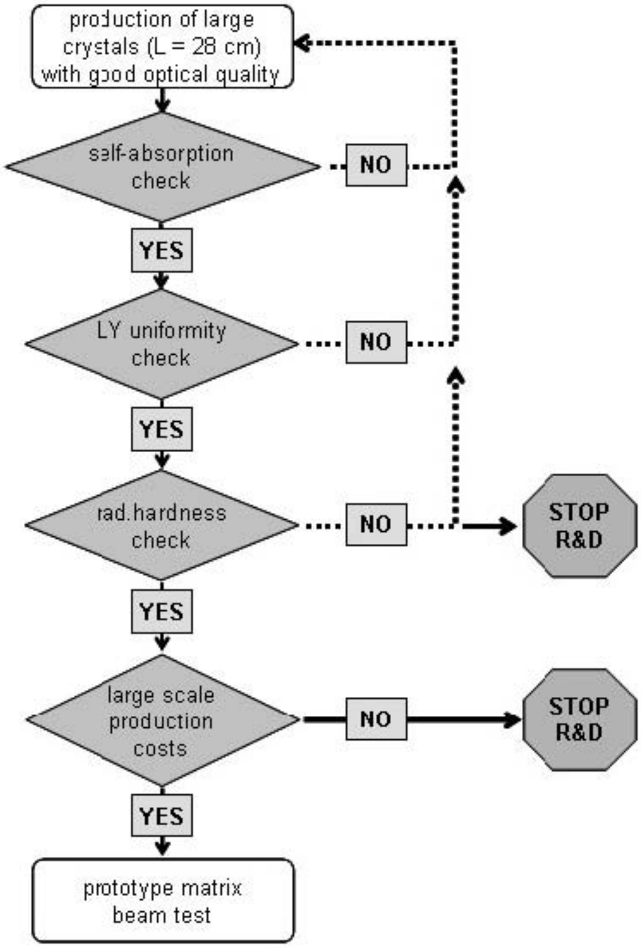
The comments concerning the feasibility of the R&D program proposed in this report and its resulting benefits for CMS, are the following: 1) Finding an upgrade solution for the Endcap Calorimeter is an indispensable action for the future use of CMS in the harsh SLHC conditions.

2) The development of LSO/LYSO crystals having suitable dimensions, light output uniformity and

radiation hardness characteristics is a very promising solution for the upgrade of CMS Endcap Calorimeter.

3) CMS resources will not be strongly affected in terms of labor and funding. The number of persons directly involved in this activity will be quite low and the necessary funds for R&D are relatively small. The R&D program exploits the progress made in producing LSO/LYSO crystals in the frame of other activities supported by medical industries and other funding agencies or research groups.
4) Nevertheless there are still several problems to be solved in view of a possible use of LSO/LYSO crystals for the CMS Endcap Calorimeter upgrade at the SLHC, some of which are also mentioned by the authors: availability of large crystals (28 cm long), difficulty in ensuring the light output uniformity along the whole crystal length and the prohibitive price of LYSO crystals. The seriousness of the price problem is further amplified by the amount of needed material for a total absorption calorimeter which should be in terms of volume, approximately 27% larger inthe case of LYSO crystals than in the case of currently used PWO crystals. Last but not least, the enlarged dimension of the Electromagnetic Calorimeter Endcap, needs a detailed study of the consequences that this modification will have on the other components of the CMS (hadron calorimeter, muon detectors, magnet, etc).
5) The R&D activities aimed at improving scintillating crystals performance should be regarded with the utmost interest and supported by the whole HEP community. However, for CMS benefit, the schedule of the R&D program should contain milestones and check-points very strictly defined, where the progress made should be analyzed and the plans for continuation should be reviewed. The project should be accompanied by a work breakdown structure (WBS) specifying the production of long (L = 28 cm) crystals of good optical quality (optically clear, colorless, bubbles and veils free, having no core and growth striation macroscopic defects) and:

a. the validation of the optical properties of the crystal from self-absorption point of view (possibly define a limit value for optical absorption in the region of the emission peak);
b. the validation of light output uniformity along the crystal length;
c. the validation of radiation hardness performance of the crystal;
d. the possible variation limits for large scale production costs.



The hierarchical tree of a possible WBS is suggested in the figure. The schedule defined at point 5 of the project should be reviewed accordingly, and the time scale should be defined following the availability of crystal producers and research groups involved in crystals testing activities (measurement and data analysis).

Referee #2:

1- **Context :**

Two groups of the CMS/ECAL community, CALTECH and ETHZ, are proposing a 3 years R&D program for the development of LSO or LYSO crystals as possible candidates for a major upgrade of the CMS endcap electromagnetic calorimeter.

These two groups are experienced in the domain of electromagnetic calorimetry and have been involved in the construction and exploitation of several crystal based calorimeters.

They propose to conduct this R&D with 5 crystal growth companies, 2 in USA, 1 in France and 2 in China.

2- **Remarks on LSO/LYSO :**

a- Discovered in 1991 LSO has been extensively developped for medical imaging applications and is now mass-produced (Figure) at the level of several m^3/year (33 tons in 2003).

Although the pixels used in PET scanners are small (typically $3x3x20mm^3$), they are cut from large ingots, about 5cm in diameter and 20 to 25 cm in length, grown by Czokralski technology.

LSO has been protected by a patent Pat. No. 4958080 owned by CTI (Knoxville) until 2008.

To escape the monopoly of CTI on LSO, a similar crystal has been developped, where some quantity of Lutetium is replaced by Yttrium. This is called LYSO and is also patented by the University of Florida (US **Patent** No. 6323489). As of today, only CPI and Saint Gobain have an exploitation licence on LYSO.

The situation of the patents and exploitation rights (particularly in China) must be carefully studied before considering any crystal as a possible alternative to PWO in the ECAL. There is no mention of this problem in the proposal.

b- Contrary to PWO, LSO/LYSO are not intrinsic scintillators. They are activated by Ce^{3+} ions, which have unfortunately a very different ionic radius than Lu or Y they substitute to. This results in a very strong segregation coefficient of Ce^{3+} ions, introducing therefore a non-uniformity of crystal optical properties, such as optical transmission and scintillation yield. This may also affect the radiation hardness, although LSO and LYSO are quite radiation hard. This is a physical limitation and it seems very unlikely that a practical and reasonably cheap solution can be developed to overcome this difficulty.

Non-uniformity is an intrinsic limitation in activated long scintillator crystals.

c- A large effort has already been made over the past 15 years to understand and to cut-down the cost drivers in the production of LSO/LYSO, leaving not much room for further improvement on the price. The present production cost (without margin) of single crystal boules is at the level of $20/cc, but the yield of large flawless crystals from such boules carries a huge uncertainty. For this reason the cost of medical imaging pixels is between 40 and 50$/cc, with much less constraints on crystal uniformity and radiation hardness than for HEP applications.

Considering that the lower density of LSO/LYSO as compared to PWO requires a volume increase of about 20% for the same stopping power it is very unlikely that we can replace the ECAL endcaps for less than 100M$ for the crystals alone. Replacing a fraction only of the endcap crystals could be a solution but the activation of PWO will prevent long working periods on the present detector and make the implementation of this solution impractical. Moreover this approach will pose severe engineering problems.

Even with a large development effort LSO/LYSO will never provide a reasonably cheap solution for the ECAL endcaps.

d- LSO/LYSO are naturally radioactive crystals through the presence of 2.5% of ^{176}Lu isotopes, which decays with the emission of several γ-rays between 100KeV and 700KeV. This problem is not addressed in the proposal and deserves a particular consideration. Indeed the total volume of 2 LSO-based endcaps with 25 radiation lengths would be 3.2m^3, representing a radioactive source of 4MBq, producing a dark counting rate of 2.5KHz per crystal. This is probably acceptable but needs to be assessed. Similarly the induced radioactivity and production rate of evaporation neutrons needs to be studied and compared with the PWO situation.

Natural and induced radioactivity study of LSO/LYSO needs to be included in the R&D program.

3- General remarks for an ECAL endcaps strategy at SHLC :

a- It seems unreasonable to embark on resource consuming R&D efforts on a possible replacement of the ECAL endcaps without answering at least two questions:

- Is it really established that PWO will not survive the SLHC conditions ?
- If we have to replace the endcaps, what are the new design requirements?

To the first question different interpretations exist, but it should be the first priority and mandate given to the ECAL to bring an unambiguous response. The simple facts that severely damaged crystals do not seem to alter dramatically the energy resolution of the system (H4 testbeam results of 2009 Summer) and that hadron induced damage recovers with moderate additional energy (300°C or optical bleaching) seem to contradict a too dramatic interpretation of the PWO radiation damage consequences. In particular the recovery of crystals irradiated with hadrons at dose rates nearly 10^4

times higher than at SLHC could exclude an unrecoverable and cumulative damage of the crystals.

Finally the recent Chamonix workshop concluded to a revision of the integrated luminosity at SLHC. The 6000fb-1 are now clearly excluded and the expected exposure of the crystal has to be reduced by a factor 2 to 3.

To the second question we have to take into consideration that a replacement of the present endcaps is a major investment, which cannot be seen only through the problem of radiation resistance of the crystals. Would this replacement be unavoidable, a complete revision of our objectives should be made in view of the physics channels to be studied at SLHC. This could affect the detector granularity and a more integrated vision of the ECAL/HCAL calorimetric chain. It is not clear at this stage that a LSO/LYSO solution as described in this proposal would be the best solution.

The ECAL community should not disperse its efforts and concentrate first most of its resources to reach a clear assessment on the behaviour of the PWO endcaps at SLHC and to develop solutions (optical bleaching) for curing the crystals in-situ.

b- The study of new crystals, particularly in the development phase requires an expertise in different domains that the two groups involved in this proposal do not necessarily have. If they can without any doubt characterize very seriously the different crystal samples produced in the frame of this project from the end-user's viewpoint, the feedback they can provide to the crystal growth companies will be limited by their lack of characterization equipment (ESR, EPR, ENDOR, etc…) and knowledge on the details of crystal growth technology, as well as on the thermodynamics of optical and structural defects in solids.

Would this program be pursued it would make sense to involve the expertise presently missing in the CMS-ECAL community, as was done successfully in the early development phases of PWO.

The development of new materials for a different crystal-based calorimeter at SLHC requires a mutualisation of efforts beyond the restricted CMS/ECAL group.

4- Conclusions :

Generic R&D on LSO/LYSO as well as on other scintillating materials (LuAG:Ce, LuAG:Pr, LuAP:Ce, crystalline fibers, etc…) for their possible use at SLHC or other accelerators is certainly interesting and should be encouraged at the level of laboratories having interest and expertise in this domain.

On the other hand it is, in my view, not a priority for CMS as a whole in the present situation.

Referee #3:

In spite that I know submitters as a high professional experts in calorimetry, to my regret, I have arguments to recommend to refuse Proposal. There are several limitations which make doubtful a possibility to reach an optimal combination of factors which allows to use this material in CMS ECAL Endcaps at SLHC.

1. **Intellectual Property Rights Limitations.** The situation with Intellectual Property rights (IP) is very different, I mast to say opposite, in a case of $PbWO_4$ (PWO) and Lu_2SiO_5:Ce (LSO), $(Lu_x\text{-}Y_{1-x})_2SiO_5$:Ce(LYSO) scintillation crystals. PWO was proposed and developed by scientific community. LSO and LYSO are under development and mass production for medical imaging for two decades and are well patented scintillation materials. Not only materials themselves but also each improvements are carefully patented. For instance, **Siemens** *US # 4958080 and 5025151 Patents* for LSO are expired in October, 2008 but they already have new patent application which protects LSO properties improvement by divalent cations crystal codoping. Also appropriate data are published (*Kan Yang, Charles L. Melcher, Philip D. Rack, Lars A. Eriksson, Effects of Calcium Codoping on Charge Traps in LSO:Ce Crystals IEEE TRANS. NUC. SCI., V. 56, N. 5(2009)2960-2965*). **Saint Gobain Crystals** has nonexclusive license from **Florida University** (*US Patent # 6624420*) for the production of LYSO but they already developed significant improvement of the LYSO properties by codoping and patented it (patent # WO 2006/018586 A1). On a first glance Chinise producers have an opportunity to come in the market due to LSO expired patents or have a plan to get nonexclusive license to produce LYSO. However, both species in a "virgin" form as they were patented need a lot of improvements. These improvements are already done by commercial producers and patented. There is not too much spare to make further improvement. So, new developing and installing of LSO or LYSO crystal production technology by Czochralski method put Chinise producers and their customers inevitably to a dispute with commercial producers.
2. **Limitations by properties.** LSO and LYSO scintillation materials very well meet requirements of medical imaging applications where pixels with typical dimensions 0.4x0.4x2 cm^3 or even less are used. So, some drawbacks of the material do not create significant problems for medical imaging but may be crucially important for HEP applications.

First drawback is **selfradioactivity** of the material. Lu contains 2.7% of natural β-active isotope with activity of about 200Bq/cm^3. Relatively large surface square of 2.5x2.5x28 cm^3 crystal will emit β-particles and soft γ-rays. A possibility to work with such crystals in regular research facilities at CERN has to be carefully investigated by appropriate CERN service. Second drawback is a **damage of the scintillation mechanism**. This phenomenon is well studied in Ce^{+3} doped crystals (*S.Boccaro at al., NIM A 537 (2005)431-434 or P.Lecoq, A.Annenkov, A.Gektin, M.Korzhik, C.Pedrini, Inorganic Scintillators for Detector Systems, Spinger, 2006, P.251(chapter4.4.3.2)*). Part of Ce^{3+} ions in crystals is recharged under ionizing radiation even at low doses. It means that concentration of the scintillating ions is permanently decreased in the crystal with irradiation. Effect is clearly detected in thin (less than 1mm) crystals but masked in a long crystal due to high intensity of Ce^{3+} f-d transition.

Third drawback is **strong delayed luminescence** (**afterglow for a simplicity**) of both LSO and LYSO species. Afterglow may be of critical importance under intense radiation environment. In (*Rogers, J.G.; Batty, C.J. Afterglow in LSO and its possible effect on energy resolution. IEEE Transactions on Nuclear Science, Volume 47, Issue 2, Apr 2000 Page(s):438 – 445.*) it was found that LSO "exhibits afterglow following activation by gamma rays in normal scintillation counting. This scintillation afterglow is characterized by an exponential decay time constant of $T_{afterglow}$=50 min and an absolute light yield, relative to the fast scintillation component, of 1.7. Unless special attention is paid to the afterglow signal in designing the data acquisition electronics used with LSO, the gamma ray energy resolution of the spectroscopy system can he ruined by baseline shifts occurring during the acquisition of an energy spectrum". Thus, light yield of LSO slow component is about two times higher than that of fast one!

To our estimation, LSO and LYSO afterglow may cause noticeable energy resolution degradation in intense radiation environment, in particular in CMS ECAL. Let us make a simple estimation for γ-radition dose rate of 500 rad/h, or 5Gy/h which is even less than expected at CMS ECAL Endcaps at SLHC. For the LYSO crystal with size 2.5×2.5×28 cm (~1.2 kg) the value of deposited energy will be ~6 J per hour per crystal (1 Gy = 1J/kg), or ~$3.8*10^{19}$ eV per hour per crystal. Taking into account LYSO light yield (~$3*10^{4}$ photons/MeV) the total number of scintillation photons emitted in fast 40 ns fraction will be: $N_{fast} = (3.8*10^{19}/10^{6}) \times 3*10^{4} = 1.1*10^{18}$ ph/h. For slow $T_{afterglow} = 50$ min fraction the number will be: $N_{afterglow} = 1.7 \times N_{fast} = 1.9*10^{18}$ ph/h.

The average number of scintillation photons in 100 ns gate will be respectively: $N_{fast\ 100} = (1.1*10^{18}/3600) \times 10^{-7} = 3*10^{7}$ ph; $N_{afterglow\ 100} = 1.7*N_{fast\ 100} = 5*10^{7}$ ph, and the energy equivalent of the afterglow photon number in 100 ns gate will be equal to $E_{afterglow} = N_{afterglow\ 100}$/LYSO LY = $5*10^{7}$ ph /$3*10^{4}$ ph/MeV = 1.7 GeV! This value can be considered as an energy background caused by LSO/LYSO afterglow. Its statistical dispersion sqrt($5*10^{7}$ ph) = $7*10^{3}$ ph, that corresponds to 0.23 MeV. However, background is dose rate and time dependant, therefore not only its dispersion but also fluctuations of its absolute value can make worse the ECAL energy resolution. For instance, 10% fluctuation will give 170 MeV shift of energy scale. After start-up of the beam each time this shift will raise exponentially with time from 0 to 1.7 GeV during a period of several T_{slow}. At SLHC this situation will become even worse.

Crystal codoping with Ca (see patents and publications mentioned above) significantly suppress afterglow in both crystals but make them **useless for discrimination of Cherenkov and scintillation**. It is well known that band gap of LSO is 6.2eV, so fundamental absorption of the matrix starts at 200 nm. There are two windows in a spectral range 200-250 and 300-350nm in an absorption spectrum of Ce^{3+} f-d transitions. They are suitable to detect Cherenov light. However, suppression of afterglow in LSO or LYSO by divalent doping modifies absorption spectrum in UV region. Fig.4 in (*Kan Yang, Charles L. Melcher, Philip D. Rack, Lars A. Eriksson, Effects of Calcium Codoping on Charge Traps in LSO:Ce Crystals IEEE TRANS. NUC. SCI., V. 56, N. 5(2009)2960-2965)* shows that crystal becomes not transparent for UV. Thus, crystals with suppressed afterglow become useless to discriminate Cherenkov light and scintillation and lose an advantage to be used in a combination with HCAL.

3. Limitations by technology. LSO and LYSO are slowly pulling crystals. Production cycle, following to submitters takes one months. Right now there is no problems to grow long LSO, LYSO crystals. However, to minimize risks to lose ingots commercial producers have optimized technology to grow relatively large diameter (till 4 inches) and relatively short crystals with cylindrical part ~ 200 mm. Another reason to grow relatively short crystals is nonuniform distribution of Ce along crystal growth axis. As longer crystal is as risk to lose it is increased. Just for a comparison, yield of lead tungstate ingots pulled with rate 10mm/h at 1123C was stable at the level of 0.93 at the production for CMS. One oven produced 12 ingots per month. Even, if hypothetically, yield of LSO/LYSO crystals which are pulled at 2000C will achieve this level, one oven can produce only 12 ingots per year. It total, with current capacity they can produce less that 600 ingots (not certified crystals!) per year. An adaptation of the 2 in 1 technology to LSO also seems useless. In case of PWO, increasing of the crystal ingot diameter from 36 to 68 mm and doubling of its mass correspondingly led to fall of the ingot yield less than 0.7 after crystallization. Moreover, yield of scintillation elements after all treatment operations with large diameter ingots became near 0.5. In case of crystals to be grown at 2000C situation will be even worse.

Partial substitution of Lu by Y improves situation with non-uniform Ce distribution in the crystal . While Y content in the crystal in more than a few percents crystal becomes a solid solution. LYSO is solid solution of Lu_2SiO_5 (density 7.4g/cm^3) and Y_2SiO_5 (4.45g/cm^3). As larger fraction of yttrium silicate is in the crystal as resulted density is smaller and X_O larger correspondingly. For instance, while Y fraction becomes 15% the absorption length is 1.2cm. So, the 25X_O length of the scintillation element becomes already 30cm. While length of the required ingot is longer the risk to lose it becomes larger.

4. Limitations by cost. As it was mentioned, commercial product from LSO and LYSO is pixel with the most frequently asked dimensions of 0.4x0.4x2cm^3. Yield of such elements from large ingot even with cracks, twins and other macro-defects is already high because producer is flexible to use even small volume of the material. Conversion coefficient of the crystalline mass in pixels is not less than 90%.

Conversion coefficient of crystalline mass of ingot with diameter 36mm (minimal diameter needed to produce proposed scintillation element) in scintillation element with cross section 25x25 mm^2 is not more than 60%. This factor is not so important in case of relatively cheap crystalline material like PWO, but becomes a cost driver at the production of the 25x25x280 mm^3 scintillation elements from LSO or LYSO. Current price of LSO, LYSO at the level 40-50usd per cc is the price of the material production which is optimized during long time to manufacture pixels. Production of the long crystals to make required scintillation elements have high risks, so final economically justified price may be only high.

Conclusions.

Both LSO and LYSO scintillation materials are under mass production for a long time. They are commercially available at the market. So, Topic 1 of the Proposal is the matter of producer and can not be the subject of research.

Advantages and drawbacks of both species are observed in literature in details. Detailed routine measurements to see a quality evolution of the crystal production technology is a matter of Producers themselves. However, measurements of thin (see reasons in item 2) samples to see change of the crystal properties under γ -irradiation, neutrons and hadrons with high cumulative fluence are important, particularly as a systematic measurements. So Topic 2 is partly appropriate to needs of SLHC.

Both LSO and LYSO scintillation materials are very well studied materials. Admittable concentrations of the different impurity ions in the material are the matter of the specification for the raw material. It is well known. Optimization of Ce concentration in the crystals also is already done and implemented in commercial goods. An appearance of the Topic 3 in the list of Topics and Goals of the Proposal indicates that quality of the crystals of selected Producers is far from quality of the crystals available in the market and they need some resources to reach quality. However, limitations listed in items 1-3 will have strong negative impact on this process.

Topic 4 in the Proposal looks not realistic due to reasons mentioned in items 3,4 above.

Thus, proposed scintillation materials are not appropriate for the needs of CMS at SLHC as well as generally for high energy physics applications, in spite of good properties for low-energy gamma-radiation detection. Proposed research program is excessively duplicated. Materials have been available in the market for a long time and still remain the most expensive among mass produced scintillators.

Referee #4:

1. Introduction.

According to the current understanding of the radiation effects in CMS crystal calorimeter, at the end of "LHC experiment lifetime", equivalent to the accumulated luminosity of $500 fb^{-1}$,
EndCap part of the ECAL will be significantly damaged, up to 80% loss of the effective light yield. The damage will be caused essentially by the loss of crystal transparency and loss of VPT light collection efficiency. Although the recent test beam results (reported to the CMS ECAL collaboration in 2009: http://indico.cern.ch/conferenceDisplay.py?confId=70213, http://indico.cern.ch/conferenceDisplay.py?confId=76233) indicate quiet high performance estimates for the EE crystals, irradiated to 10^{13} n/cm^2 (="500 fb^{-1} at eta=2.7). In particular, almost no effect on the energy resolution at high (≥ 100GeV) energies ➔ constant term in the standard energy resolution equation remains unchanged.
But as not all effects have been taken into account so far, in particular VPT damage, the performance estimate looks more like the upper limit, the consideration of the possible partial or even complete replacement of the EE elements looks relevant.

2. EE performance improvement with LYSO.

The subject of Proposal – development of the LYSO production technology. And the fact, that replacement of the currently used PWO crystals by LYSO will improve EE performance is not much justified. Two advantages of LYSO are mentioned: higher light yield and better radiation hardness.
Light yield. Practically all published tests of LYSO were done with the low energy photons (KeV to several MeV), suitable for the tomography. The LHC application require a good performance in multi-GeV energy range, where the photo statistics, defined mostly by the light yield, is not very important and the crystal uniformity and calorimeter hermeticity , which define the constant term "c" in the standard parameterization of the energy resolution
$(\sigma_E/E)^2 = (a/\sqrt{E})^2 + (\sigma_n/E)^2 + c^2$ becomes important. The only experimental value for the constant team at relatively "high" energy, 490MeV (highest quoted energy, I could find) is 5.5% {ref: R.Novotny et. al. High energy photon detection with LYSO crystals. 2006 IEEE NSS Conference record, N30-2} (should be compared to 0.55% for the actual ECAL). The reason of such a high integral non-uniformity could be variation of the Ce concentration and Lu/Y ratio, which both change the effective light yield (ref. 4 of Proposal). The constant term of 0.5%, declared in the Proposal, page 6, is not justified.
So, in summary, although the light yield of LYSO is much higher than one of PWO, is it not at all clear, that the performance of the LYSO calorimeter will be better than the PWO one for the LHC energy range. The currently available data indicates the opposite.
Radiation hardness. According to Proposal, LYSO radiation hardness has advantage with respect to the PWO in two points: small gamma-induces effects, much lower and simpler hadron-induced damage.
As to the gamma-induced damage, all measurements were done with very limited set of the selected samples and the damage values are not significantly lower that ones of the best PWO samples. The fare comparison should be done on the large set of the production samples, not available now. But it should be mentioned, that LYSO has no thermal recovery, hence the damage is cumulative and the overall effect after several years of operation can be rather large, even if the effect for the given doze (typically 1MRad in most tests) is small. Here the advantage vs. PWO, if any, can disappear after several years of operation.

The hadron-induced damage effects in PWO are not sufficiently studied by now to be used as an argument. First, the damage mechanism is not clear and the recent observation of the thermal recovery indicates that some slow spontaneous recovery can exist. Plus it was shown, that PWO stimulated recovery works for the hadron-induced damage as well as for the gamma-induced one. The certain disadvantage of LYSO is the fact that the crystal transmission is cutting the emission spectrum at the maximum. Hence, the visible light yield at the and of the long 20cm crystal will be very sensitive to the damage effects, most strong near the emission threshold. Which is not the case for PWO, where the emission spectrum is shifter to the higher wavelength and is not intersecting with the transmission threshold.

In summary, although LYSO samples show rather good radiation hardness both for gamma and hadron irradiations, the very limited statistics (one sample for the hadron irradiation so far) does not allow to state, that in case of the mass production, it will be more rad. hard than PWO.

3. Conclusion

I consider the proposal on “LSO/LYSO Crystal Development for the CMS Endcap Calorimeter Upgrade at the SLHC” irrelevant on the current stage, first of all because the advantage of using LYSO as the material for the ECAL Endcap is not sufficiently justified.

Referee #5:

If we could afford this kind of calorimeter, it would be great. But I feel CMS collaboration as a whole (if not the ECAL group) has to come to agreement about how much we can possibly spend in ECAL upgrade. What is the upper limit? If $20/cc is realized, would the total price (I have not calculated this, but presumably, RenYuan knows what this number is) be under this limit?

It is crucial that if this kind of project goes forward that there are at least two vendors which are capable of providing crystals. For this to happen, we need to cultivate more than 2 vendors at the beginning. So, if we do this, it is very important that proponents or someone else in CMS help more than 2 vendors collaborate with us. Crystal Ball had a hard time keeping the schedule with one vendor, and CMS had hard time with basically one vendor. CLEO, Belle and Babar had much easier time because their crystals were supplied by at least two vendors, and for this to happen, they had to work with more than 2 initially.

In the proposed case, even if there are two vendors, if both are Chinese, I am a bit worried because I cannot judge how independent they are as business.

Finally, if we spend significant amount of money to develop crystal production suitable for mass production, we should be able to have the access to the know-how, meaning that some of them, if not all, can be transferable to other vendors. I would like to see an open discussion about under what terms this research is done in collaboration with the proposed vendor(s), and they proceed only when CMS management agrees to the terms.