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R & D Proposal to DRDC

Fast EM Calorimeter With Excellent Photon Angular Resolution and Energy Resolution Using Scintillating Noble Liquids

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1 Goal

Scintillating liquid krypton and xenon (LKr/Xe) calorimeter technologies have significantly progressed lately [1,2,3,4,5,6,7]. Our recent test beam data have shown the following:

- Fast speed and large signals: LKr, mixed with more than 1% LXe, is as fast as LXe with 20 ns decay time, and a large signal (4 x10^7 photon/GeV) [6]. We note that natural krypton contains about 8% xenon and the production process is cheaper if Xe and Kr are not separated,
- Excellent uniformity in LXe and LKr is achieved over a 37 cm long cell, [7] and we are confident that it can be achieved for any reasonable cell length,
- CsI cathode works well inside LKr/Xe with O(1%) resolution at 5 MeV [8]. With pad readout, it becomes possible to get O(1 mm) position resolution and thus be able to measure the directions of multi-photons hitting near-by cells.
- Precision calibration in-situ using α's has been demonstrated.
- Scintillating LKr/Xe detectors are sufficiently radiation hard for LHC environments.

These new developments significantly simplify the construction of LKr calorimeters (such as purification and making mirrors). We believe that the technology for building a large prototype EM LKr/Xe calorimeter is now ripe. We propose to build a prototype EM LKr/Xe calorimeter with 7x7 cells and two longitudinal segments for each cell, in our existing 50 liquid liter cryostats to demonstrate the following properties, which are vital for the detection of particles from π^o for K_L CP violation experiments to the intermediate mass Higgs at the LHC, i.e. π^o or H $-> \gamma + \gamma$:

- Superior e/γ energy resolution with small constant terms, i.e. $\delta E/E < 1\%/\sqrt{E} + 0.5\%$,
- The determination of photon direction using longitudinal and transverse segmentations. Because of the large signals in scintillating LKr, an angular resolution of 5 mr has been predicted for photons above 50 GeV,

A precise determination of the invariant mass of the $\gamma+\gamma$ states requires the precise measurement of the energies and the directions of the two photons.

2 Applications

Scintillating LKr calorimeters with 3-D shower measuring capability is useful for K_L CP violation experiments and for the detection of Higgs at the LHC in the $\gamma+\gamma$ mode. For example, L3P uses Liquid Krypton as the Option for Precision Barrel EM Calorimeter. The homogeneous scintillating liquid krypton EM calorimeter proposed by L3P covers the inner tracker over an η range of ± 1.4 at a radius of 2.45m. The depth of the calorimeter is 23 Xo (1.05m) resulting in an active volume of 140 m^3. Figure 1) shows the side view of the proposed LKr EM calorimeter.

The calorimeter is divided into small cells with a front area of 5 x 5 cm^2 and two longitudinal segments per cell. The scintillation light is recorded using photodiodes, mounted at the inner and the outer radius of the cells as shown in Figure 2. The diodes as well as the fast amplifiers are submersed in LKr/Xe with the mirrors serving as Faraday shields, providing a stable operating environment.

Thin walls separating detection cells occupy <0.2% of the active volume. They are coated with Al and either wavelength shifter or MgF_2 to serve as mirrors. Such mirrors have been shown to be radiation hard for UV light from LKr/Xe [1] and an average reflectivity of 88% for 170 nm light was achieved by the DELPHI Detector at LEP [9]. The LKr EM calorimeter. will be monitored by the scintillation light from one α source per photodedtector, thermal sensors, and pressure gauges [5,1].

Each cell has two longitudinal segments, pointing toward the intersection point. Monte Carlo simulations show that the transverse shower center of a high energy e/γ can be located with 1 mm precision using the center of gravity method. Using the centers of gravity determined at each of the two longitudinal segments separated by an effective distance of about 33 cm, the direction of an e/γ shower above 50 GeV can be determined to $<$ 5 mrad or the interaction point to $<$ 1 cm for photons above 50 GeV (Figure 3).

The expected intrinsic energy resolution for isolated e/γ, integrated over 4x4 LKr cells, is better than 0.4% above 40 GeV, as shown in Figure 4. The effect of rear leakage has been corrected for by using the longitudinal energy measurement [4]. The electronics noise is negligible due to the large signal size of LKr. The excellent energy and angular

resolution leads to a predicted (by Geant) mass resolution of H $->$ 2γ about 0.4%, including pile-up, photon vertex uncertainty, and electronics noise (Figure 5). The total energy together with the longitudinal and transverse shower profile measurements, is expected to yield an overall excellent π/e suppression (better than 10^{-4}).

3 Recent R&D Results

Liquid krypton (LKr) is radiation hard and its scintillation light is intense ($3 \times 10^7 photons/\mathrm{GeV}$, [5,1,3] comparable with that of NaI. Its radiation length is 4.6 cm and Moliere radius 4.8 cm.

Table 1 shows the scintillation yield (number of photons) per unit energy loss of noble liquids and solids [5,10,11], normalized to that of NaI(Tl).

Table 1: Relative light outputs

	Ar	Kr	Xe	NaI(Tl)
Liquid	0.35 ± 0.04	0.53 ± 0.05	0.9	
Solid	0.42 ± 0.04	1.3 ± 0.1	1.9	1.0

Using α, e/π beams and heavy ion beams, it has been shown that silicon photodiodes and amplifiers work well inside LKr, with an effective quantum efficiency > 50% and 10 ns peaking time. The detector can be calibrated using α's in situ to an accuracy <0.5% [5,1].

The pure LKr scintillation signals are characterized by a fast rise time (< 10 ns) and about 100 ns decay time. A timing resolution of $\sigma = 0.8$ ns has been achieved in a time-of-flight experiment [5]) using a conic shaped LKr scintillating detector of 75 liters of liquid. By experimenting with a method developed used for LAr [12], we discovered that the decay time of pure LKr can be also reduced by mixing with a few % of xenon. Figure 6 shows a typical spectrum [6] for LKr + 3.34% LXe: the fast component of the scintillation signal, excited by the electrons in LKr produced by the photons from a Co^{60} source, for LKr doped with xenon is much enhanced compared with that of pure LKr. The signal shape reaches plateau and remains the same when the amount of additive LXe is more than 1%. The measured wavelength conversion efficiency of LXe in LKr is about 120%, making the light yield of LKr+ a few % of LXe equal to that of pure LXe. The small remaining slow component in

Figure 6 can be eliminated by data handling (e.g. using the well known zero pole cancellation technique).

The attenuation length of scintillation light (150nm) has been recently measured [5] to be about 1m by varying the LKr thickness between an α source and a photo-detector as shown in Figure 6.

Two pieces of important test beam data obtained lately after the LOI are listed as follows:

- Excellent uniformity in LXe and in LKr is achieved [7] by scanning particles transversing through different part of a 37 cm long cell. The mirrors were made by coating WLS on 100 μ thick mylar foils. Figure 8 shows our recently measured uniformity in LXe and LKr in comparison with previous data [14]. To achieve uniformity is one of the hardest problem for any liquid scintillator due to the lack of total internal reflections. Here we have found a simple and elegant solution, which greatly simplifies the requirements on the quality of the mirrors and the purity of the liquids (LXe/Kr). In addition, Figure 8 shows LXe and LKr have essentially identical optical properties and uniformity. Thus to demonstrate the energy and angular resolution for photons for a LKr/Xe calorimeter, we can use pure LXe, instead of LKr, in order to reduce the size of the cryostats, required to contain the shower of a high energy e/γ.

  Using this measured uniformity, The Geant Monte carlo program predicts a resolution of $1\%/\sqrt{E}$ and a photon angular resolution of 5 mr for LKr calorimeters. The goal of this proposal is to prove them;

- CsI cathode with 1.6 mm thick parallel chamber amplification chamber works well inside LKr/Xe with O(1%) resolution at 5 MeV [8]. With cathode pad readout, it becomes possible to get O(mm) position resolution. By putting such a device inside LKr or Xe at a depth of about 4 radiation lengthes, to allow photons to convert efficiently but before the shower spread out more than 1 mm, makes the detection of the directions of multi-photons possible even if they hit near-by cells.

The production yield of krypton is twelve times larger and the price more than one order of magnitude lower than xenon [13]).

4 Detector to be tested

The proposed prototype homogeneous scintillating LXe/Kr EM calorimeter consists of the following essential components:

- (existing) gas supply system,
- (existing) cryostats and 150 channels of double feedthroughs (Figure 9).

  The pressure tank is sufficient to house 7x7 cells of scintillating LKr/Xe calorimeter divided into 2 segments, each viewed by a diode,
- Mirrors: the mirrors will be mylar based, coated with Al and and strips of wave length shifters (e.g. p-terphenyl, BC-482A), to shift the 170 nm UV light of LKr/Xe to visible region. WLS evaporation works as diffusing strips for visible light. Standard blue scintillator-green WLS system of BC-408 scint.-BC-482A WLS exhibits 1-2 Mrad rad-hardness [15] We expect p-terphenyle to be similar. Since the absorption of UV occurs at the surface, only one wavelength thickness of WLS needs be rad-hard.
- Photo-detectors: silicon photo diodes and fast amplifiers have been proven to give large and stable signals in LXe/Kr,
- Calibration system: two α sources will be used to monitor each cell to provide in-situ calibration.

Figure 10 shows the schematic drawing of diodes and pre-amplifiers inside an array of tapered mirrors. The mirrors made of flat mylar sheets coated with Al, WLS and MgF_2 are fixed between one small metal grate in the front and one big metal grate in the back of the mirrors. The mylar structure is connected together through several mylar strips fixed onto the grates. The grates are fixed together by wires outside of the volume of the cells. The structure is sturdy and self-supporting.

5 Calibration

We can calibrate the cell using 2 α's/cell, with one situated at the middle of the cell and one at the far end from the photon detector. WLS such as BC-482A is radiation hard to 2 MRad. Beyond 2 MRad, it starts to turn yellow and lose transparency. However the loss of transparency of

WLS due to radiation damage is never a issue here, since UV is absorbed at the surface (about 1 wavelength deep) of the WLS, and the visible light is scattered diffusely also at the surface.

Small loss of quantum efficiency of WLS does not change uniformity, since each UV photon interacts with WLS only once. The measured pulse height is linearly proportional to the Q.E. of the WLS. It affects only the absolute energy scale, which is calibrated in-situ by the α's in liquid.

Thus the excellent energy resolution can be maintained.

6 Milestones

We plan to start beam tests of the 7x7 detector within 6 months after the approval of this proposal.

Such short schedule becomes possible mainly due to the simplification in the construction of the detector described above. We have built one 50 liter LXe and two 75-liter LKr conic shaped cryostats. One of the 75 liter LKr detector was beam tested with LKr to obtain TOF, Pulse shape information, attenuation length and uniformity measurements etc., providing most of the test beam data presented above. We have purification system, storage system, 150 liters of LKr and 50 liters of LXe, 100 channels of fast pre-amplifiers and a dozen silicon diodes. We need 80 more silicon diodes, 7x7 cell mirror system and electronics. Assembling, shipping, testing and data taking are the main cost of this beam test.

7 Existing Equipment Contribution

Equipment	from	cost (SF)
Gas system		200 k
Photo-diodes/pre-amp.		30 k
Pressure cryostat		200 k
LXe	50 liters	150 k
LKr	150 liters	45 k
Total		625 k

8 New equipment requested

In the following we summarize costs for the Noble Liquid Scintillating calorimeter test in 1993. We discuss the test beam requirements, computing resources and engineering support.

Equipment	Engineering/responsibility	cost (SF)
Mirrors/supports	7x7 cells by ITEP	30 k
Shipping/ins.	MIT/ITEP	6 k
Si-diodes	MIT	25 k
Electronics	IHEP	20 k
DAQ	Johns Hopkins/MIT	20 k
Re-assembling cryostats	ITEP	30 k
Re-assembling gas system	MIT/ITEP	15 k
Cooling system	70 liters by MIT/ITEP	20 k
Assembling/testing	ITEP/MIT	50 k
Total		216 k

8.1 Beam requirements

To demonstrate an energy resolution of 0.5% for the proposed detector, we need a clean electron beam up to 100 GeV with an energy resolution of 0.25% and well defined direction (< 2 mr). This is a formable technical request and we are ready to collaborate in finding a solution.

8.2 Computer time

Our estimate is based on the computer usage for simulation during the LOI preparation in 1992, indicating that we will need 500 hours (IBM equivalent) to be shared as follows:
200 hours at CERN
300 hours at outside Institutes.

9 Collaborations

We are in contact with the RD14 Collaboration and discussing possible collaborative efforts. Their work has been mostly to measure the intrinsic resolution with noble liquids. They say " high energy resolution ($< 0.5\%$) and excellent directionality (about 2 mrad) are surely achievable using noble liquid detectors."

References

[1] M. Chen et al., ECFA Workshop, CERN 89-10, 1989; M. Chen et al., The Xenon/krypton Detectors, to be published in Nucl. Inst. & Meth. (92).

[2] M. Chen et al. p. 389 and T. Ypsilantis et al., p. 393, ECFA/LHC Workshop, CERN 90-10, ECFA 90-133 Vol. III, 1990.

[3] T. Ypsilantis, ECFA/LHC Meeting on Detector R&D, Aachen, 90; and LAA Progress Report, CERN 90/1; J. Seguinot et al., CERN LAA 92-004, Submitted to NIM.

[4] T. Doke, Portgal Phys. 12 (1981)9; K. Masuda et al., Nucl. Inst. & Meth. A309,(92)489; N. Ishida, T. Doke et al., submitted to Nucl. Inst. & Meth. (92); M. Miyajima, Japanese Physical Society Meeting at Osaka, March, 1990; S.Sugimoto, M.Miyajima, S.Sasaki, and H.Tawara, Osaka Univ. OULNS 90-8, June 30, 1990.

[5] D.Yu.Akimov, A.I.Bolozdynya et al., Condensed Krypton Scintillators, to be published in Nucl. Inst. & Meth., 92.

[6] A.I.Bolozdynya et al., submitted to Nucl. Inst. & Meth., 92.

[7] A.I.Bolozdynya et al., submitted to Nucl. Inst. & Meth., 93.

[8] E. Aprile et al., submitted to Nucl. Inst. & Meth., 92.

[9] Measured mean reflectivity of the 300 RICH counters used by DELPHI at LEP, P. Baillon et al., Nucl. Instr. & Meth. A276 (89) 492 and 277 (89) 338.

[10] J.A.Northrop, J.C.Gursky, and A.E.Johnsruf. IRE Trans. on Nucl. Sc. NS-5(1958)81.

[11] J.A.Northrop and R.A.Nobles. IRE Trans on Nucl.Sc. NS-3(1956)59.

[12] S. Nanba et al., J. Phys. Soc. Jpn. 37, 1031 (1974). T. Doke, et al., Proceedings of International Conference on Liquid Radiation Detector, Waseda University, April 1992, also PHENIX Workshop, BNL, Aug. 24, 1992.

[13] P.K. Lebedev et al, submitted to Nucl. Inst. & Meth, 92. This recent survey shows that the yearly output of liquid krypton from the Confederation of Independent States (the former USSR) companies will double, from 10 m^3 in 1992 to 20 m^3 in 1993. Two companies, Spectra Gases INC of USA, and L'Air Liquide of France, have independently quoted a price of 0.2$/c.c. for 100 m^3 of LKr to be delivered by 1999.

[14] T. S. Virdee, Nucl. Inst. & Meth, A323 (1992)22; A. Braem et al., Nucl. Inst. & Meth, A320(1992)228.

[15] C.R.Hurlbut and M.R.Kusner. Organic scintillators for modern calorimetry, Proc. of the Second Int. Conf. on Calorimetry in High Energy Phys., Capri, Italy, October 1991, Ed.A.Eridato INFN Napoli, p.182).

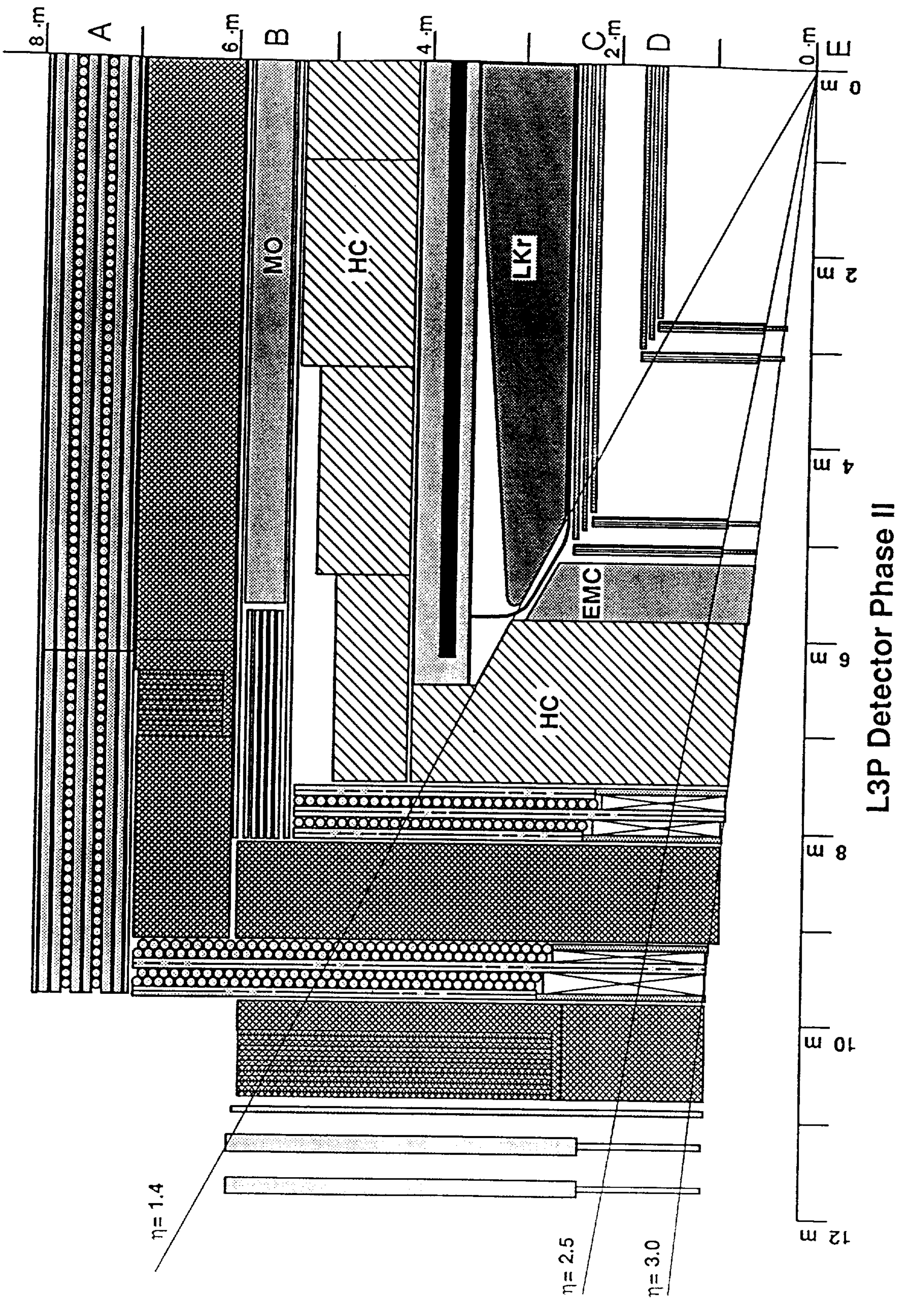

Figure 1: Side view of the LKr EM detector for L3P of LHC.

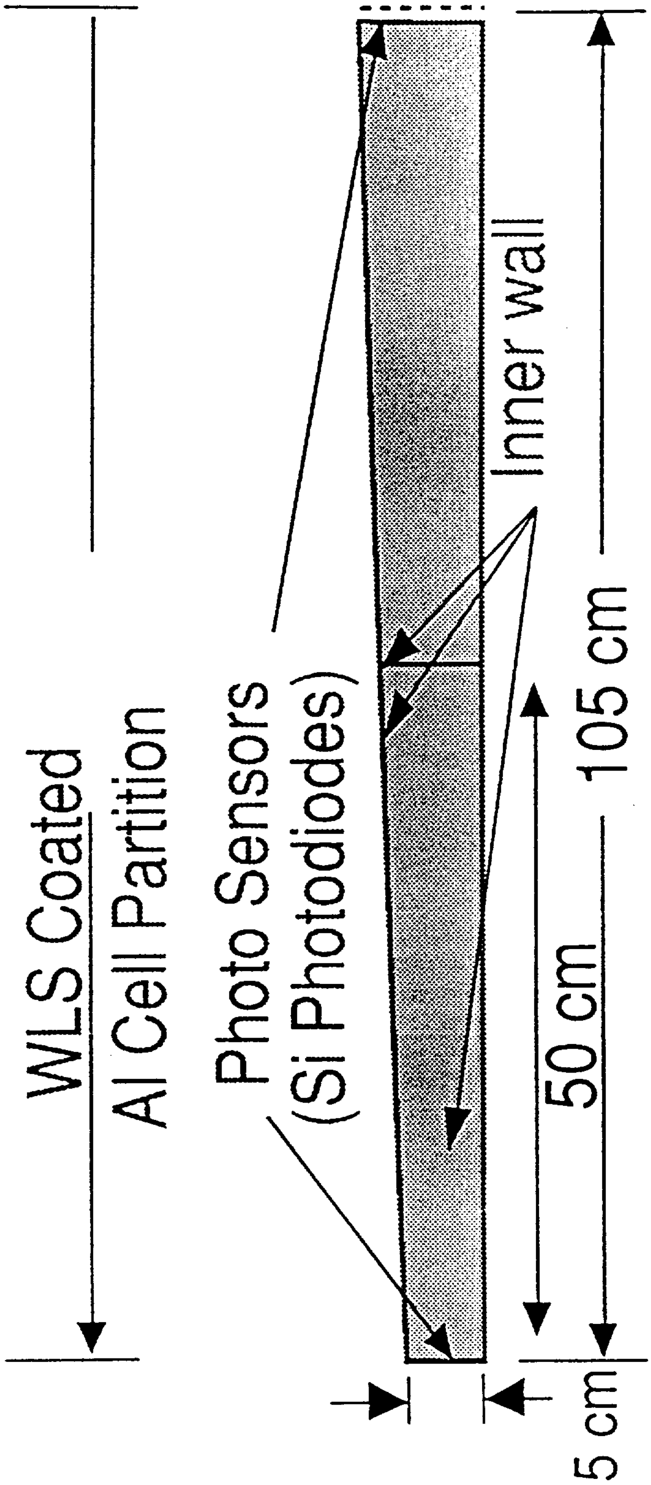

Figure 2: Schematic drawing of a single cell of a scintillating LKr calorimeter, showing two longitudinal segments with diodes/amplifiers at the two ends, surrounded by mirrors.

LKr EM calorimeter resolution (E in GeV):

(Intrinsic) pileup noise calibration

$$\frac{\Delta E}{E} = \left(\frac{1\%}{\sqrt{E}} \oplus 0.14\%\right) \oplus \frac{0.17}{E} \oplus \frac{0.007}{E} \oplus 0.4\%$$

Photon vertex determined to 1.2 cm

Photon direction determined to 5 mRad

Rear leakage corrected using segmentation

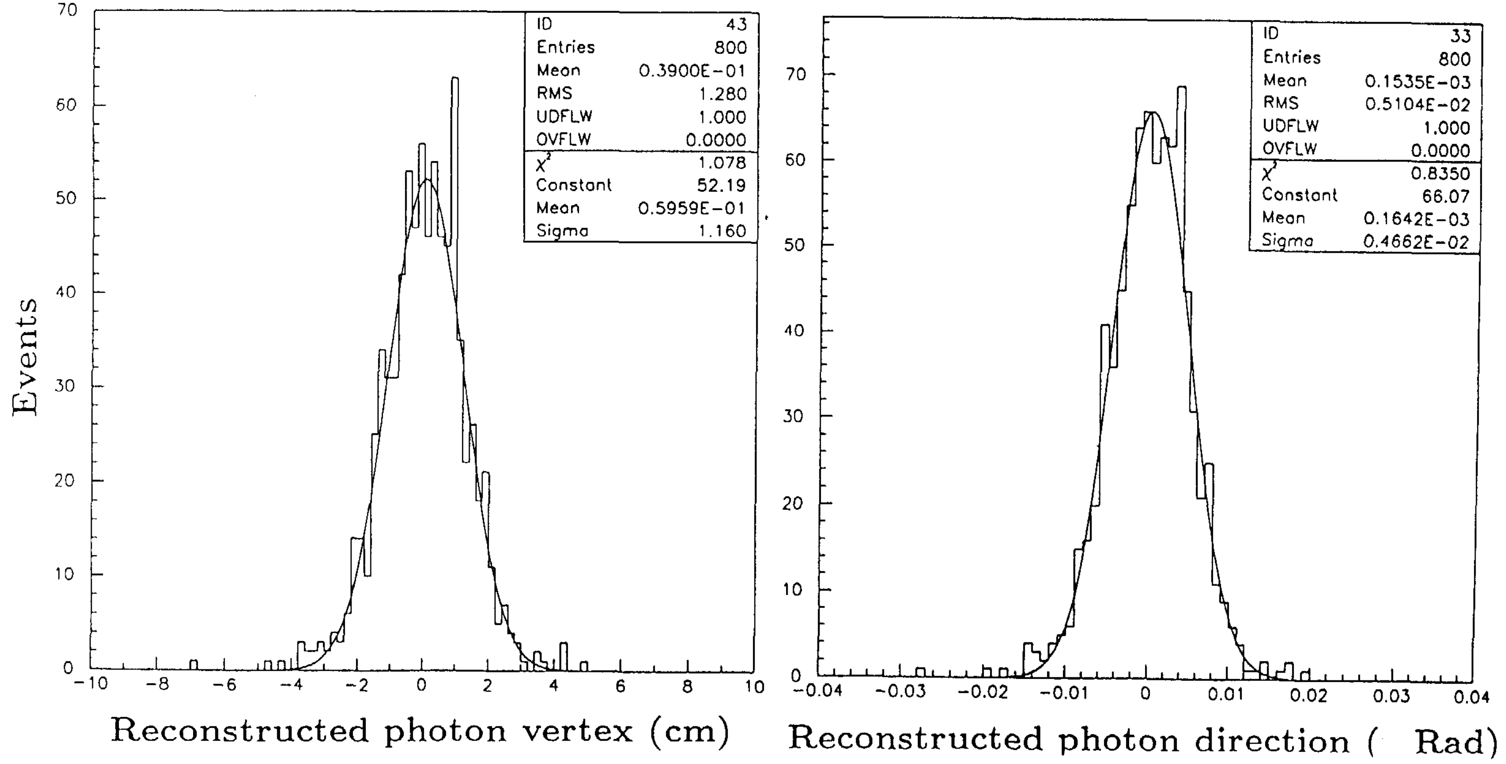

Figure 3: The a) angular resolution, b) vertex resolution, of 50 GeV photons predicted by the Geant Monte Carlo program, for a LKr calorimeter with two longitudinal sections.

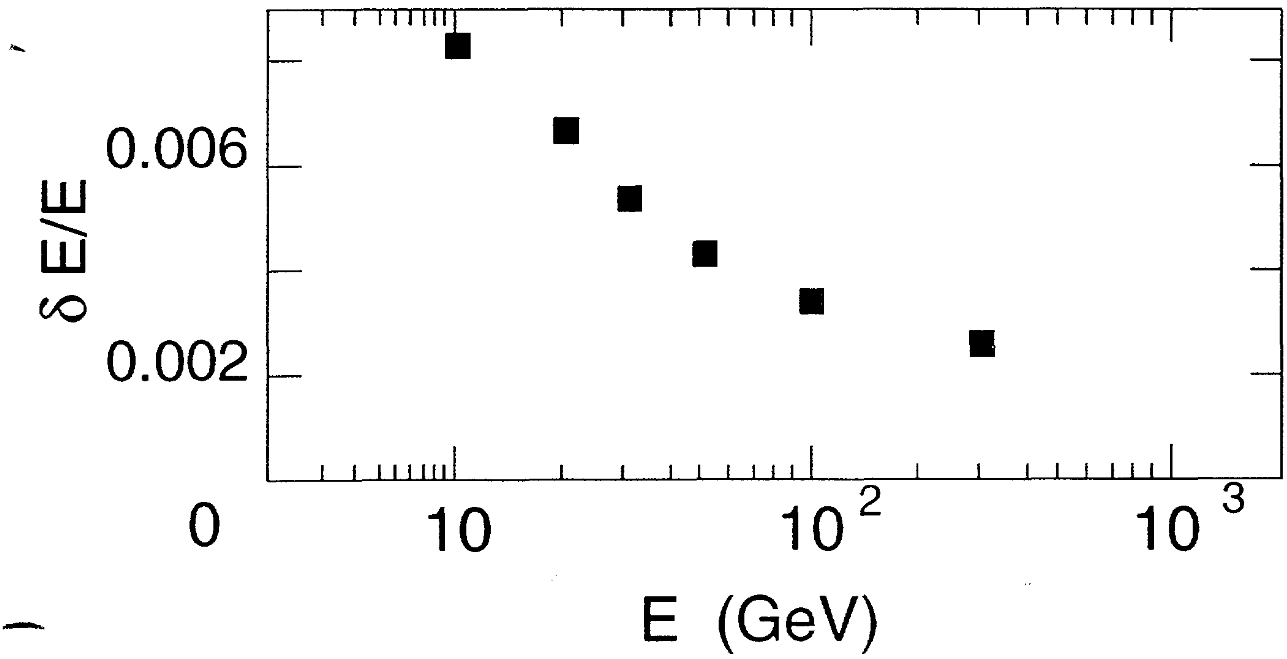

Figure 4: Energy resolution, predicted by the Geant Monte Carlo program, as a function of e/γ energy, for a LKr calorimeter with two longitudinal sections.

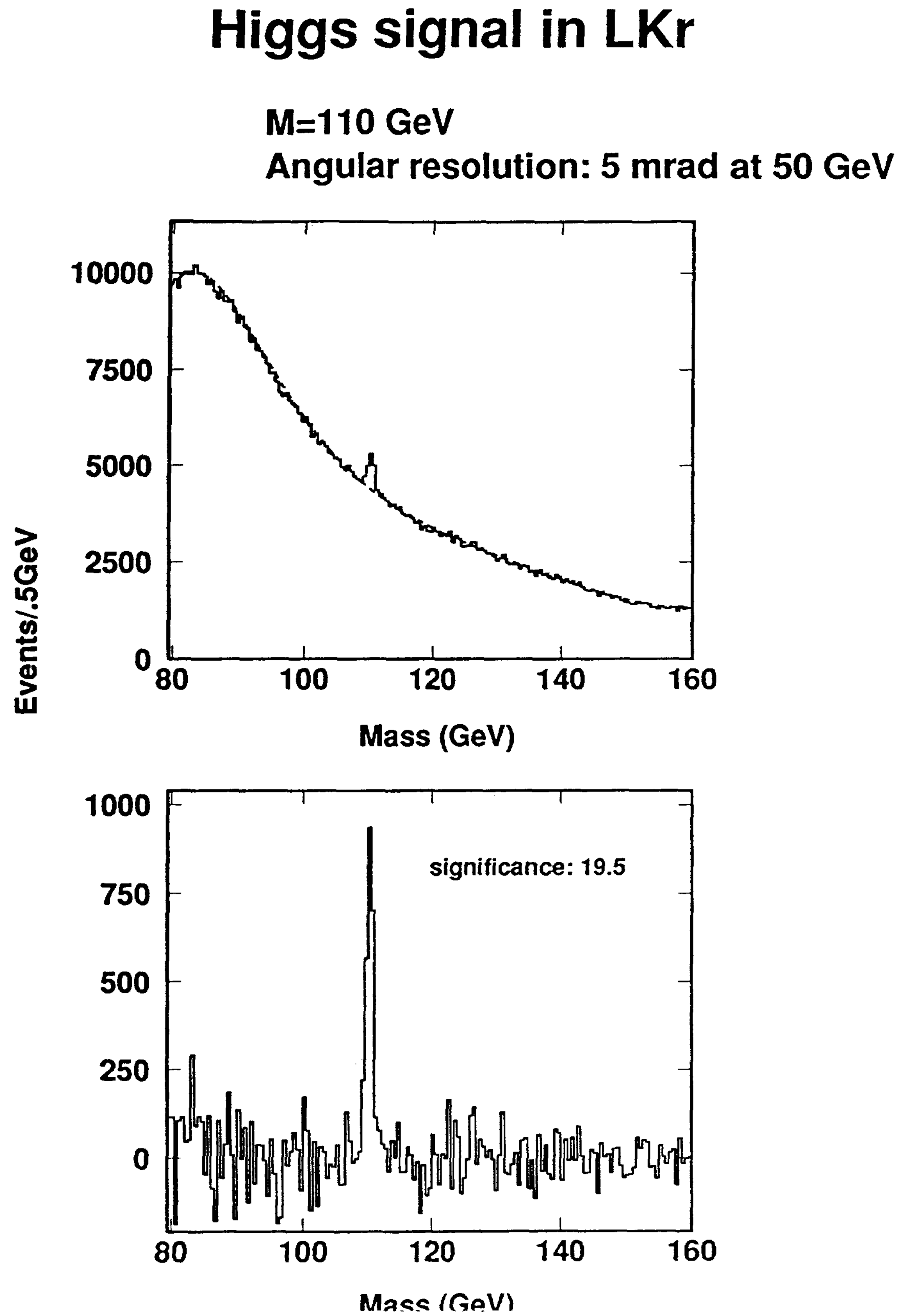

Figure 5: The 110 GeV Higgs mass resolution and signal in the two γ mode a) with QCD background, b) after background subtraction, predicted by Pythia with the Geant Monte Carlo program, for a LKr calorimeter with two longitudinal sections after one year of LHC running.

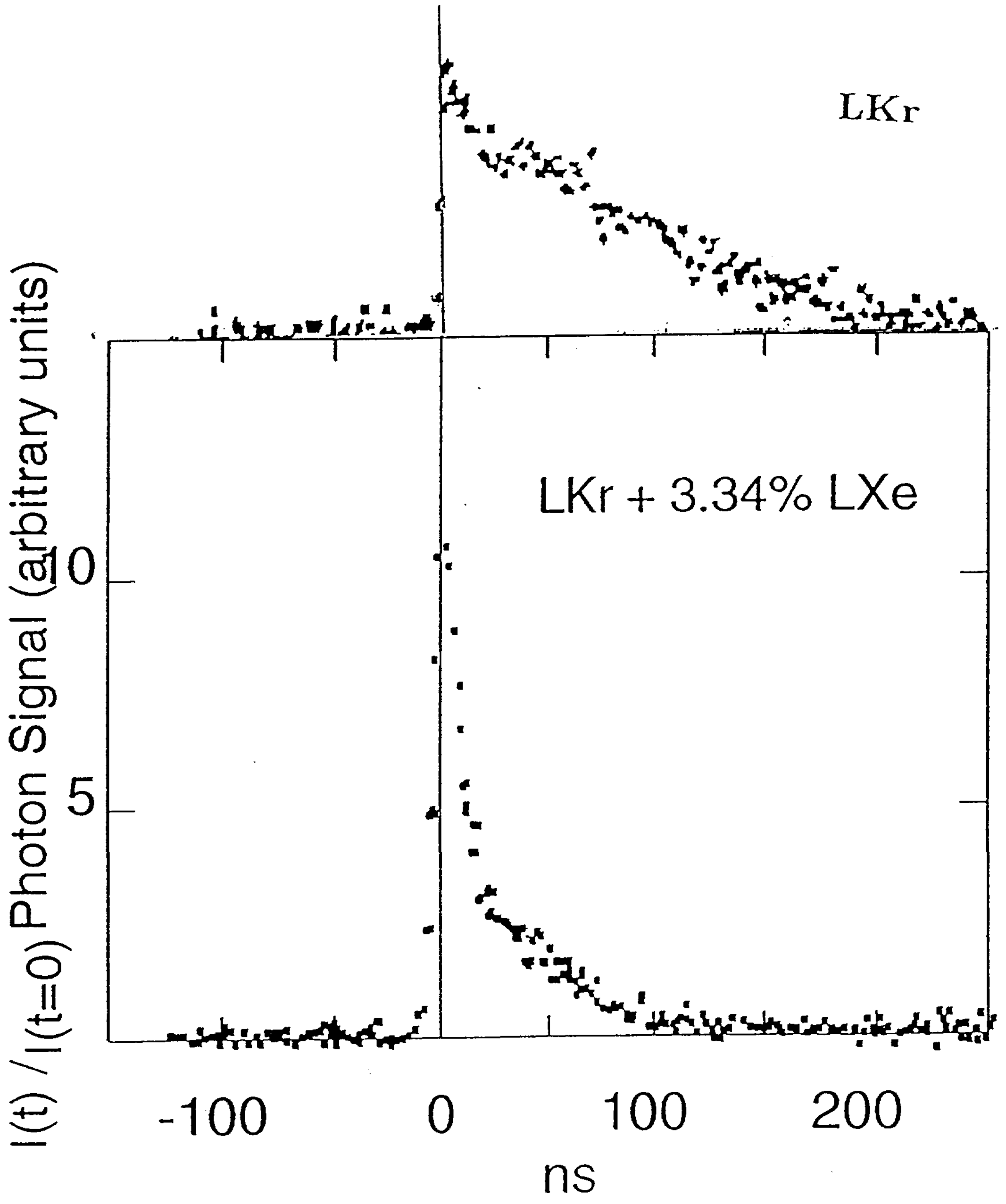

Figure 6: The time dependence of the scintillation light signals, excited by the photon-electrons from an Co^{60} source for a) pure LKr and b) LKr doped with 3.34% of LXe.

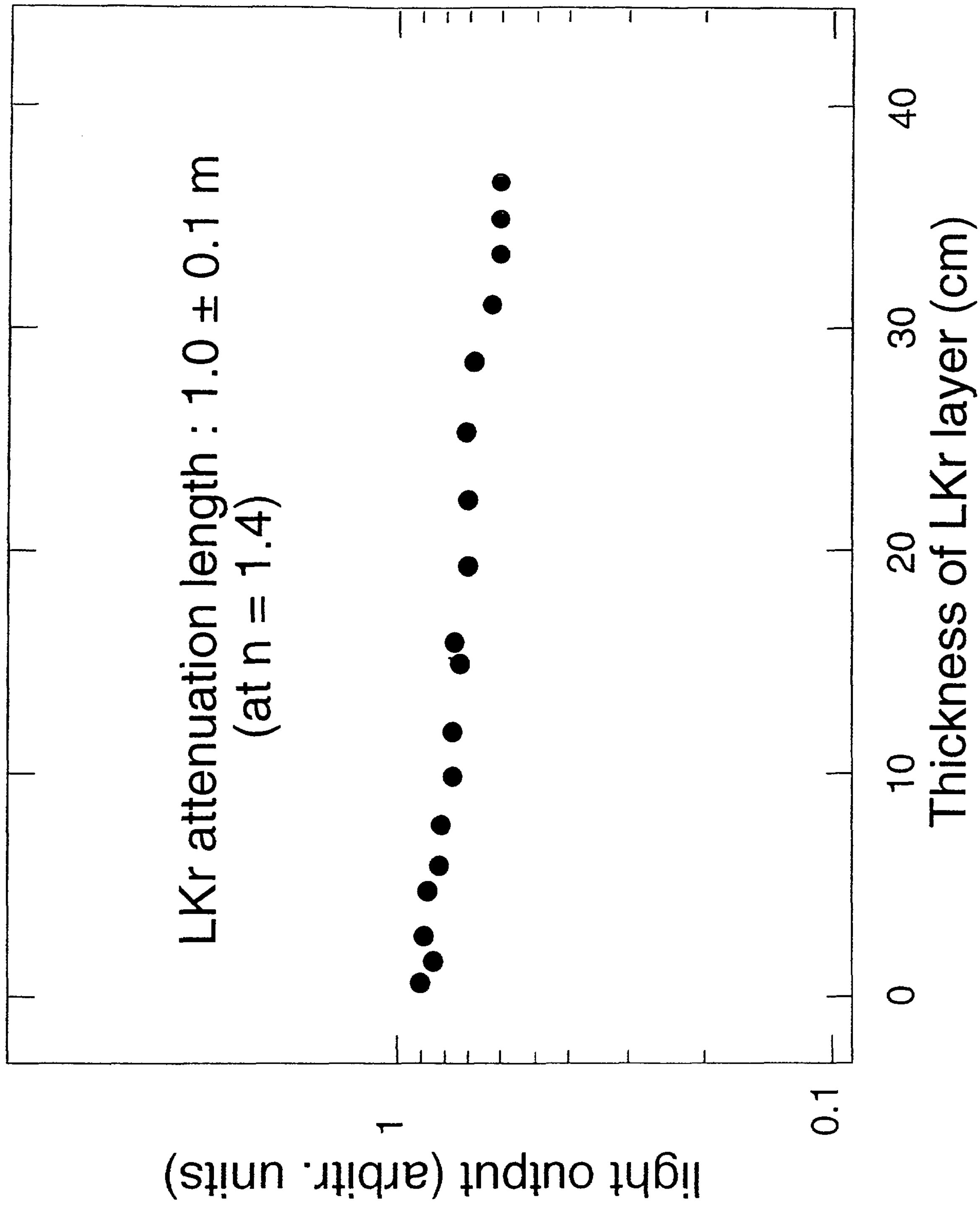

Figure 7: The dependence of the LKr scintillation light signal at 150 nm, after the correction due to refraction of UV rays, on the thickness of LKr layer for a LKr scintillation detector with non-reflecting walls.

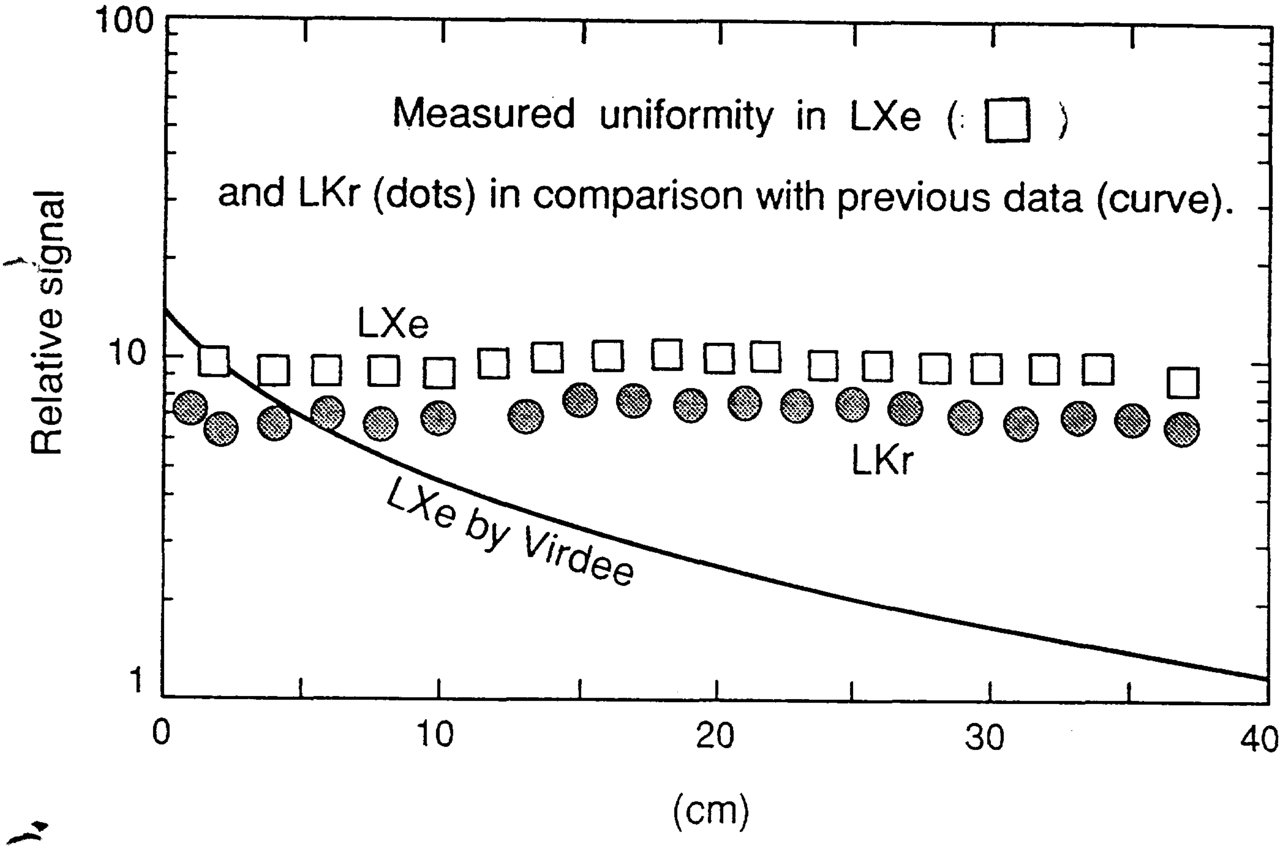

Figure 8: Measured uniformity using our WLS coated mirrors in LXe (squares) and LKr(dots) in comparison with previous data (curve).

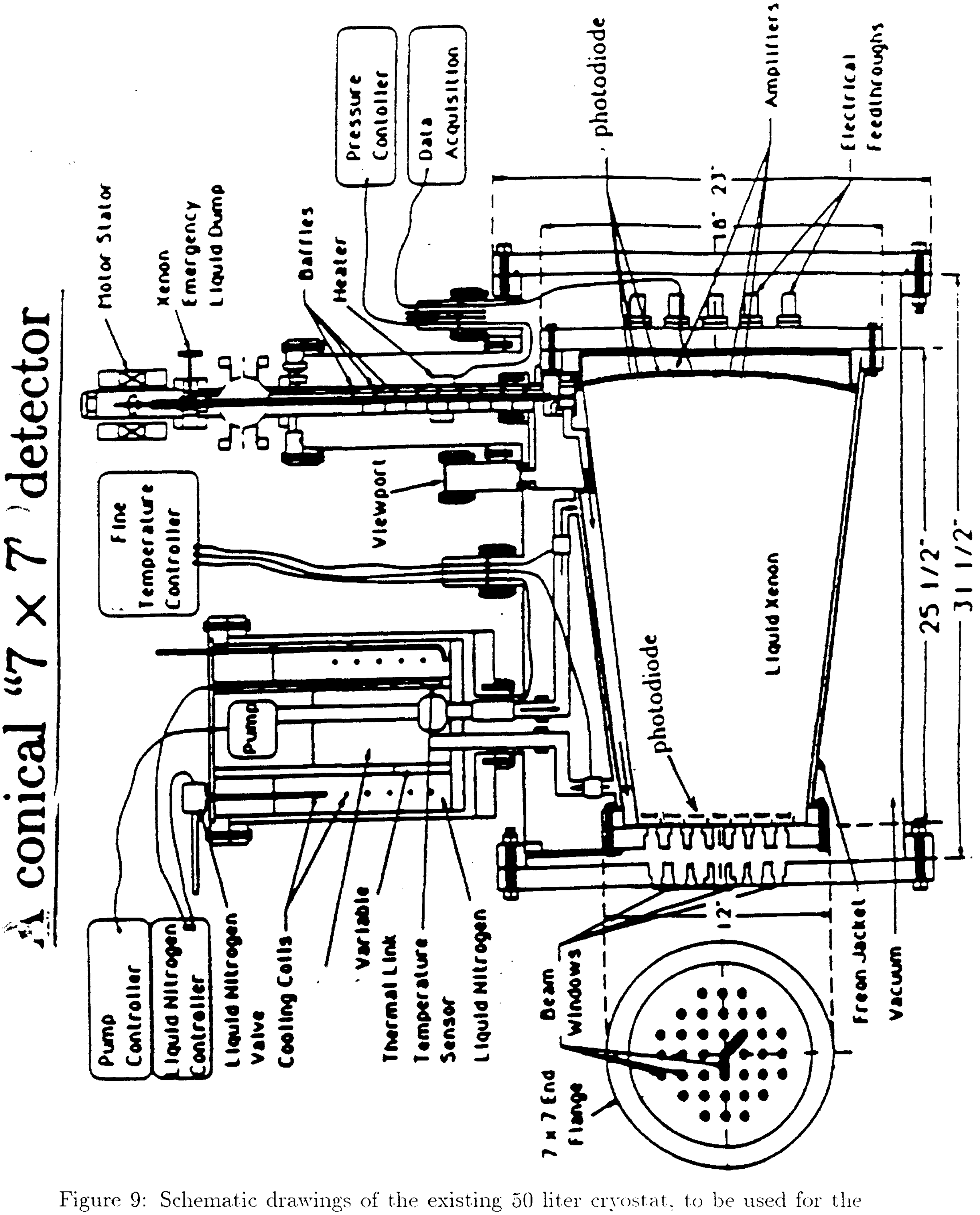

Figure 9: Schematic drawings of the existing 50 liter cryostat, to be used for the proposed 7x7 cell noble liquid scintillating detector.

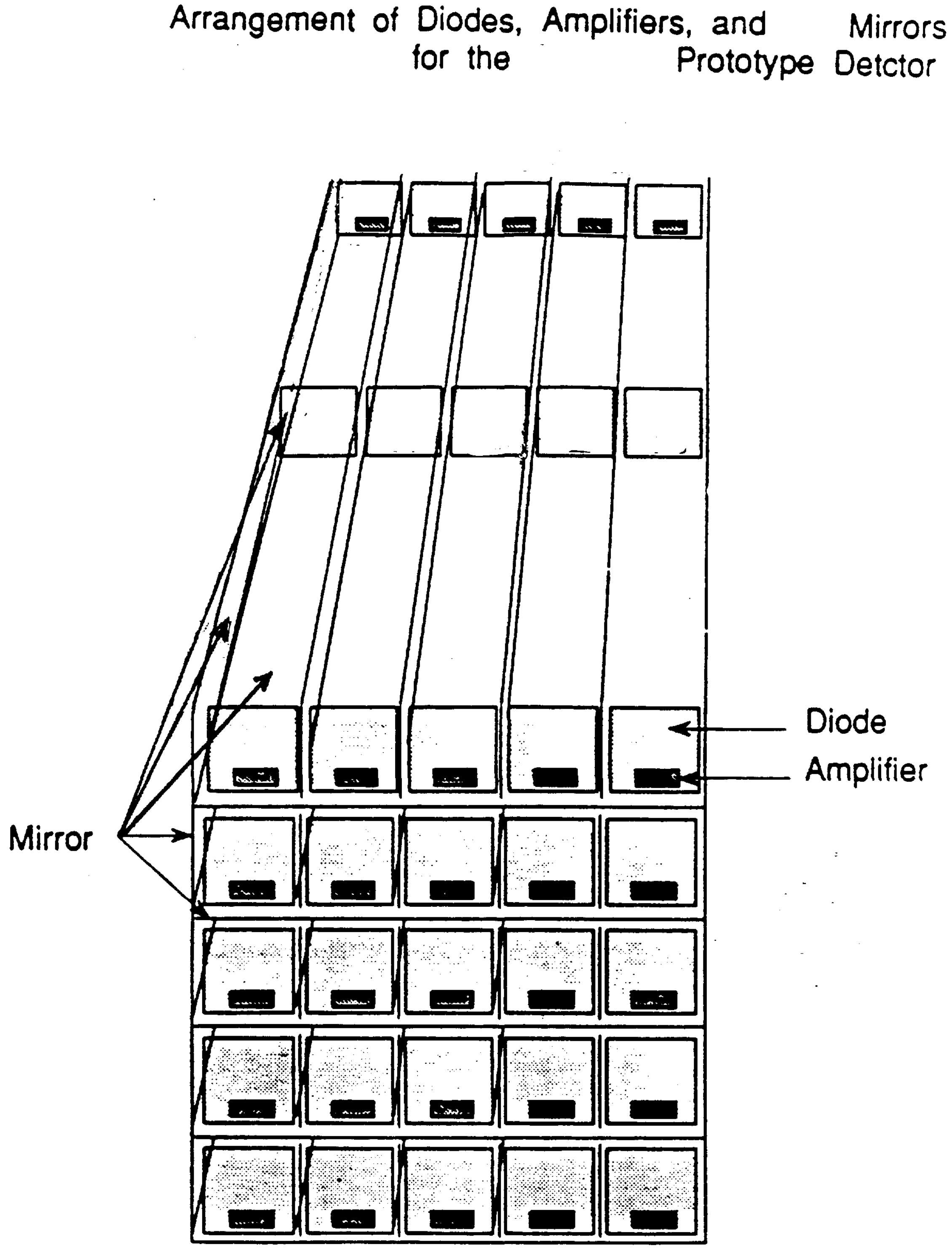

Figure 10: Schematic drawings of the diodes/pre-amplifiers and mirror system for the proposed noble liquid scintillating detector.