APPENDIX D

Phi Factory Detector Requirements[1]

Detector and Simulation Working Group

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[1] presented at the April, 1990 UCLA Workshop on Testing CPT and Studying CP Violation at a ϕ Factory by J. A. Thompson

1 INTRODUCTION

A Φ-factory project with luminosity $1-3 \times 10^{33}/cm^2/sec$ will improve by 2-3 orders of magnitude the measurement of rare decay modes of ϕ and K mesons, and allow concurrent experiments to study the violation of CP symmetry in decays of neutral kaons. Luminosities of 10^{33} will yield 10^{10} K_S K_L events per year and $10-30\%$ of the K_L decays can be detected in a detector with a fiducial volume of reasonable size. Figure 1 shows K_L detection efficiency as a function of fiducial volume radius and aspect ratio. For a modest detector of about 50 cm in fiducial radius one has approximately 10% K_L detection efficiency. Including a 0.002 branching ratio for the K_L two pion CP-violating decay modes, and a 50% assumed reconstruction efficiency, one expects to collect approximately a million events of the "CP-violating topology" $K_S K_L \rightarrow \pi^+\pi^-\pi^0\pi^0$. The attainable uncertainty on ϵ'/ϵ is taken as a figure of merit of such machine-detector combinations; a million events allows a measurement to the statistical uncertainty of 0.001-0.002 using the double ratio method typically employed in fixed target machines and a statistical uncertainty of 0.002-0.003 using the asymmetry method, which compares the distances of the charged and neutral modes from the interaction point [11].

The planning for the detector must be done in close conjunction with the machine itself. We have taken as a prototype experiment the measurement of ϵ'/ϵ. A benchmark hoped for by all groups is to measure this ratio to a statistical precision of 0.001-0.003, with correspondingly good control of systematic errors. Therefore a lower luminosity machine needs a larger volume detector for K_L decay collection; machines with lower luminosity and lower focusing fields have a milder trigger problem and more favorable conditions for a possible TPC operation; and detectors operating with low magnetic fields are less troubled by intricate trajectories close to the interaction point and therefore less likely to need a vertex detector - to name only a few of the many interrelated conditions.

Figures 2 and 3 show two detailed designs which were presented at the beginning of the conference. Both have a central drift chamber and about 15 X_0 of calorimetry. Figure 2 shows the planned detector for the Novosibirsk phi factory– with higher design luminosity, higher focusing fields, and a rather compact size. The Italian design (Figure 3) includes a ring-imaging Cerenkov counter for particle identification. The Italian design is larger, to recover somewhat from the planned lower luminosity (10^{32}) of the Frascati machine, compared to the design luminosity of 10^{33} of the Novosibirsk factory.

Our plan for this contribution was to identify the experimental problems and the conditions required for successful phi-factory operation, and show the range of detector parameters which, in conjunction with different machine designs, may meet these conditions.

We started by considering, comparing and criticizing the Italian and Novosibirsk designs. With this discussion as a background, we defined the apparent experimental problems and detector constraints. In this article we summarize our understanding.

2 Backgrounds in the ϵ'/ϵ Measurement: Detector constraints

The expected ϵ'/ϵ effect is a tenth of a percent effect in a decay which occurs only approximately once in every thousand K_L decays. Hence, backgrounds must be controlled (with respect to the usual decay modes) to one part in a million, the level of the expected effect with respect to normal K-decays.

A physical background - a soft photon in the final state. One important background, thought by some before this conference to be important, is the final state $\phi \rightarrow K\,K\,gamma$. The importance of such a decay is that it allows the two kaons to be produced in a CP-even state, leading, e.g., to two K_S decays, and contaminating the sample of $\pi^+\pi^-\pi^0\pi^0$ final state events. While such events can be removed by cuts on events in which both decay paths are short (e.g., [46]) and would display only detector-induced asymmetries, they increase the denominator and artificially reduce the observed asymmetry from that due to the direct CP-violating decay amplitude.

One estimate of this final state was rather large (of order 10^{-4}) [42], but discussions at this Workshop seem to indicate that a smaller value of order 10^{-8} (which would obviate any concern about this process) is more likely. [2]

Backgrounds from K_L three body decays. Large rejection factors for these backgrounds come from kinematic cuts, aided, for the $K_L \rightarrow \pi^0\,\pi^0\,\pi^0$ and $K_L \rightarrow \pi^+\,\pi^-\,\pi^0$ decay by highly efficient calorimetry, with nearly complete geometrical solid angle coverage and a low limit for the energy which can be detected by the calorimeter. Barbiellini and Santoni [11] have discussed these backgrounds and conclude that to reduce the leptonic decay backgrounds sufficiently one must suppress electrons, and muons, with respect to pions, by about a factor of 100.

Results presented at this conference indicate that a factor of 10 can be obtained by simple cuts on ionization deposit [41] and a factor of 100-300 can be obtained for momenta at 200 MeV/c by a combination of range and ionization deposit (Figure 4) [45]; however the ionization patterns overlap more for the upper range of the momentum required (up to 260 MeV/c), and even at 200 MeV/c, the ionization must be measured to $2-3\%$ for successful particle identification (see Figure 5) [41].

While the ring-imaging Cerenkov counter included in the Italian design gives easily the particle identification required, there was concern about the material and space required before the calorimeter, as well as its effective functioning in the substantial non-homogeneous fields which seem likely to be required at high luminosity. However, the Frascati machine has lower luminosity and a correspondingly larger detector design and smaller focusing fields. For such a factory the disadvantages of a ring imaging counter are not as strong, but even for this case it may not be required.

Design of detectors must include particle identification at these levels. The consensus in this group was that probably careful use of the magnitude and pattern of the ionization would be sufficient, but that further detailed study should be done to substantiate this conclusion.

3 Detector requirements

From a discussion of the detectors shown in Figures 2 and 3 and other studies, we made a list of some requirements of detector parameters.

Some requirements arise from the need to reject backgrounds. The major backgrounds are from the K_L three-body decay modes ([11], [41]). The $K_L \rightarrow \pi^+\pi^-\pi^0$ mode is rather easily removed with good calorimetry and good tracking. The requirements for the apparatus are set by the three π^0 mode and the leptonic decay modes. These requirements are summarized below. [11],[41],[45],[54]

3.1 $K_L \rightarrow \pi^0\pi^0\pi^0$ background

The detector must be highly hermetic (of order 98% solid angle coverage) for good rejection of the $K_L \rightarrow \pi^0\pi^0\pi^0$ mode. Besides hermeticity, good efficiency for low energy photons (down to about 15 MeV) is required. The efficiency tends to fall off (see Figure 8) [41] for very low energy photons, and this must be taken into account in calculating rejection factors against this background.

Fractional energy resolution should be $< 0.05/\sqrt{E}\,GeV$ to allow proper pairing of photons for a good kinematic fit to the $K \rightarrow \pi^0\pi^0$ decay mode. But it may be that a fractional energy resolution of $(0.01 - 0.03)/\sqrt{E}\,GeV$ is required to reject the $K_L \rightarrow 3\pi^0$ background decay mode from the sum of neutral energy deposited in the calorimeter. While some rejection can also be done with more complicated fitting, it seems preferable to make a clean removal of background wherever possible rather than to depend on kinematic fitting, and to leave the overall kinematic fitting as a valuable cross-check or as a guard against pattern mis-reconstruction backgrounds or other problems which have not yet been carefully studied.

As an existence proof of a successful rejection of the three π^0 background, a realistic description of the calorimeter planned for the Novosibirsk detector gives an overall factor of about 30 against this mode, [41] which is sufficient.

3.2 K_L semileptonic decays

The K_L semileptonic decays are an important background kinematically, since the neutrino is a missing zero mass particle, and the phase space includes a part with very small neutrino momentum. To remove this background, both particle identification (rejection of electrons and muons by a factor of 100-300 and muons, while keeping pions) and good charged track reconstruction (fractional momentum resolution of order $1 - 2\% \times p(MeV/c)$) are required.

3.3 Systematic Checks

Other requirements arise from requirements for checks against systematic errors:

1. Good spatial resolution in the calorimeter is required to give a good fit to the vertex position of the neutral two pion decay. Resolution of the shower apex position to about 3 mm gives the longitudinal vertex position to again a few mm, (a fraction of the K_S lifetime), required for the asymmetry method measurement, and useful in either the branching ratio or assymmetry method to control systematic checks.

2. Regeneration should be minimized and must understood; the low momentum decay products must survive to the calorimeter without substantial energy loss; to achieve precise momentum resolution of charged particles, multiple scattering should be small. All these conditions indicate a low mass detector. Our rough requirement on the detector was $< 3\%$ r.l. before the calorimeter.

3. The vacuum pipe should allow a large interference region with no regeneration, but should be small enough that it could be structurally sound though still very thin, to avoid regeneration and multiple scattering. A radius of 5-8 cm. (10-16 K_S lifetimes) seemed appropriate. We estimated that it could be built from 0.5-1 mm Be/Al alloy.

4. A vertex detector may be required, depending on the inhomogeneity of the magnetic field. Good angular resolution (of order 2 mrad) seems required for the calculation of the vector momentum sum used in the rejection of the semileptonic decay backgrounds. A vertex detector at the beginning of the drift chamber facilitates such a good measurement. It is important to have a precise measurement of the charged particle position before the multiple scattering in the drift chamber material, which can limit the resolution on the initial decay angle for particles from early decays. The Novosibirsk phi factory seems to require such a device, while it is less necessary in the low field Frascati factory design. One idea for such a detector was 2 sets of 6 crossed layers of scintillator fibers. The material estimated for such a detector is about 0.7% r.l.

5. The magnetic field should be as uniform as possible, and particles of greater than 150 MeV/c (the lower end of the spectrum of the kaon two pion decay mode) should always reach the calorimeter; for some physics and background rejection strategies, particles down to as low as 60 MeV/c should reach the calorimeter. The 150 MeV/c limit implies a 5 kGauss field for a 1 meter tracking volume.

6. The high precision tracking of $2 - 3\%$ P implies tracking position precision of 100-200 microns, and angular resolution of a few mrad. A jet or single cell drift chamber seemed appropriate for this. For ϕ factories with high focusing fields the magnetic fields would be too inhomogeneous for effective functioning of a TPC; the TPC is also too slow to be used in the fast trigger. The required precision is achieved; for example, in the design of the drift chamber for the CMD2 experiment soon to begin its commissioning and data taking. (Figure 6)

7. Extra dE/dx information from the tracking device would be useful, but not at the expense of loss of precision in the tracking. Estimates of the gains involved were that 10^5 (avalanche mode with large charge collection) would be required for high precision, but less than 10^4 (operation in the proportional range) would be required for good dE/dx measurements.

3.4 Calorimetry Considerations

The $0.03 - 0.05/\sqrt{E}$ energy resolution and few mm shower apex resolution required seemed to indicate a liquid such as Ar, Kr, or Xe. Ar would make too large a calorimeter (about 1.6 m travel in the calorimeter), while Xe is would require only about 40 cm. On cost, however, Xe is not preferred, since its cost is about 1 million dollars per cubic meter. Krypton thus seemed the best choice for an entirely liquid calorimeter. The Novosibirsk group plans to try a hybrid Xe-CsI calorimeter, allowing a rather modest 2 cubic meters of Xe (of which they have presently stockpiled 1 cubic meter) to suffice. The Novosibirsk design would have 15 gaps, 2 by 7 mm, a drift time of 3.5 microseconds, ganged strip x,y readouts (Figure 7a) in each gap (4000 channels), and about 1000 channels of towers with waveform digitizing and a fast trigger. Calculations by Piccolo [45] for a liquid Argon calorimeter are shown in Figure 5, and a possible design for a radial gap calorimeter suggested by Atac ([10]) is shown in Figure 5b. Details of the efficiency and energy resolution are shown in Figure 8.

Our conclusion from this preliminary work was that a satisfactory calorimeter solution could be found.

3.5 Trigger and Data Processing Rates

At luminosities of order 10^{33}, the trigger rates of interesting events will be very high, and of non-interesting events even higher: about 120 kHz of Bhabba scatter events down the beam pipe, about 60 kHz Bhabba scattering in the detector, and about 30 kHz from storage ring losses; 12 kHz of phi decays, with about 1 kHz of K_S, K_L decays detected in the fiducial volume of the detector.

Ideas from the Novosibirsk group on the trigger suggested a first level trigger based on scintillators and the CsI calorimeter (available in 1-2 nsec), the drift chambers (200 nsec) and the tower structure of the LXe calorimeter (100 nsec), with about a 250 ns decision time and about 5% deadtime, could pick out phi decays to either neutral or charged kaons, rejecting Bhabbas and soft junk from lost beam particles.

A second level trigger reconstructing a vertex in the drift chambers and possibly doing an invariant mass calculation, as well as pattern recognition in the calorimeter was proposed for the second level. One must be careful at this level since the events in which both K decays occur in the detector yields about a 300 Hz rate and all the (2000 Hz) K_S decays must be treated for tests of systematic errors arising from acceptance non-uniformity. Some calculations will probably need to be done online, and the information stored, rather than storing complete events. Better studies of data acquisition and processing requirements must be made, but it seems likely that a high degree of parallelism in the data treatment will be required.

4 Summary of Possible Detector Parameters

1. Vacuum pipe. 5-8 cm radius; < 1 mm Be alloy ($< .3\%$ r.l.)

2. Vertex Detector. Needed for some designs. Scintillator fiber design would give angular resolution of order a mrad, with about 10 milliradian multiple scattering for about 0.7% r.l.

3. Tracking Detector. 50 cm-2.0 m radius; jet or single cell drift chamber was favored. 100-200 micron setting error and $\sigma(p)/p = 1 - 2\%$ at 200 MeV/c ($< 3\%$ r.l.) are required.

4. Calorimeter. 40 cm (LXe) - 80 cm (LKr) thick (about 14 X_0); $(3-5)\%/\sqrt{E}$ fractional energy resolution and 3 mm photon shower apex measurement required.

5. Magnet. 1-3 m inner radius. 1-10 kGauss field, to allow 60-150 MeV/c particles to reach the calorimeter. (5 kGauss for 150 MeV/c, and a 1 m detector radius)

6. Particle Identification. Necessary to accept pions with high efficiency while rejecting electrons at (100-300):1. Ionization deposit may be sufficient, but few per cent measurements are required. Time of flight and drift chamber dE/dx, if available, may also be useful.

7. Scintillator or straw tubes for fast charged particle triggering.

8. Parallel capability computing system or special processor to process of order 1 kHz interesting events at luminosities of 10^{33} $cm^{-}2$ $sec^{-}1$.

A sketch of a detector satisfying these criteria (Figure 10), appropriate for the proposed UCLA phi factory, was provided by M. Atac. We were all inspired to go home and start building (either this one or the one already in progress at our home institution).

List of Figures

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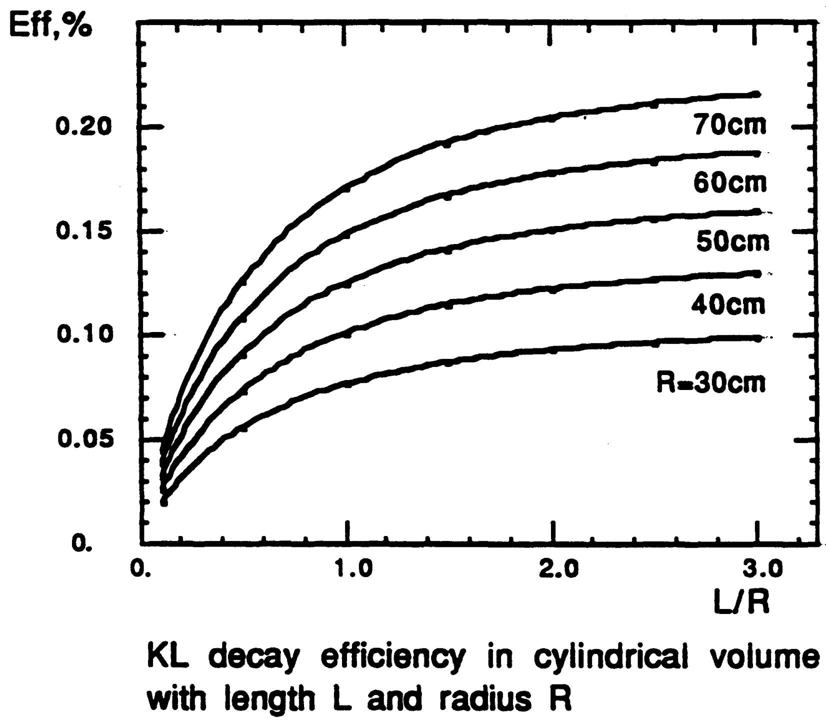


Figure 1: K_L decay probability in fiducial volume.

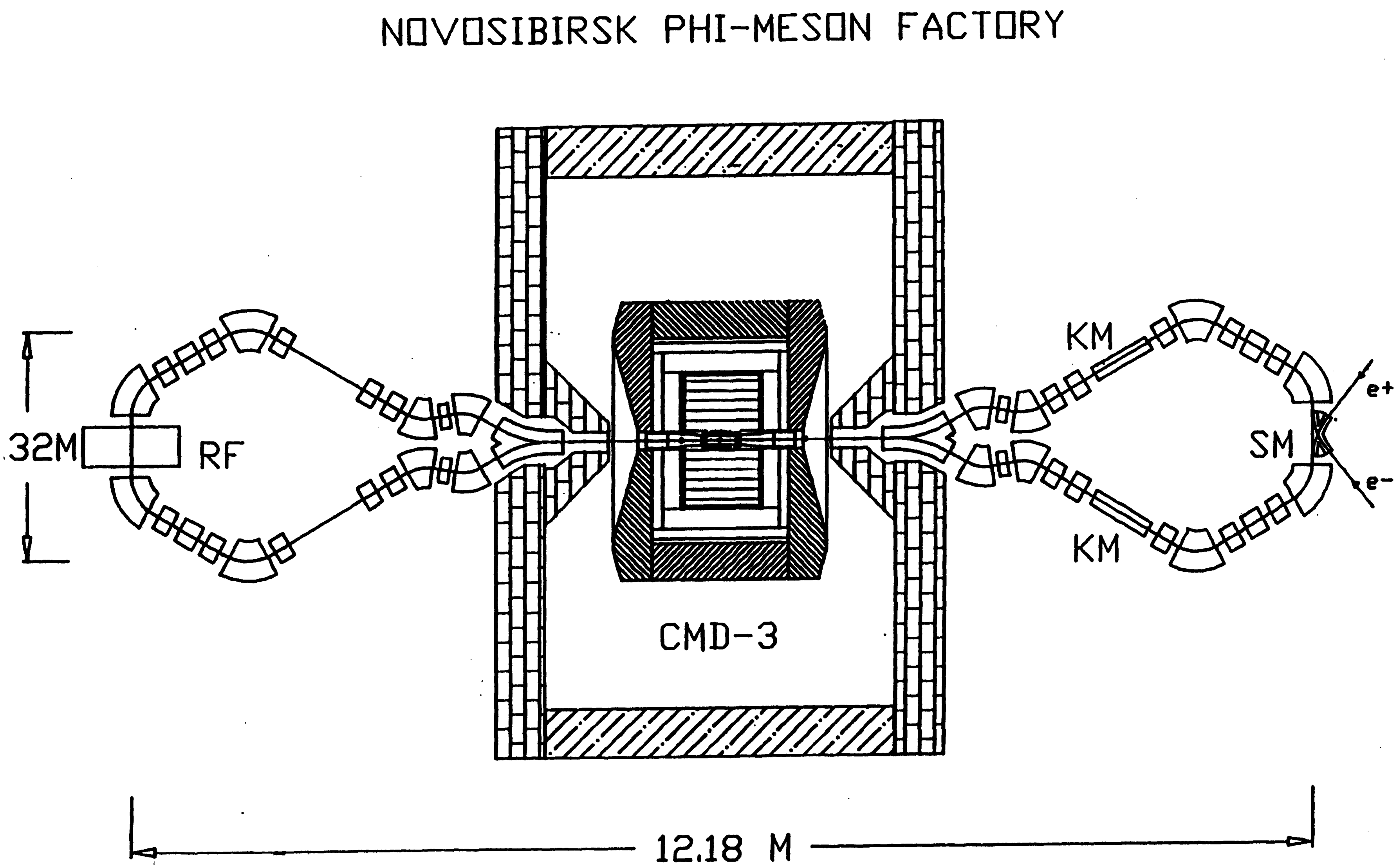


Figure 2: Layout of ϕ-Factory and Detector.

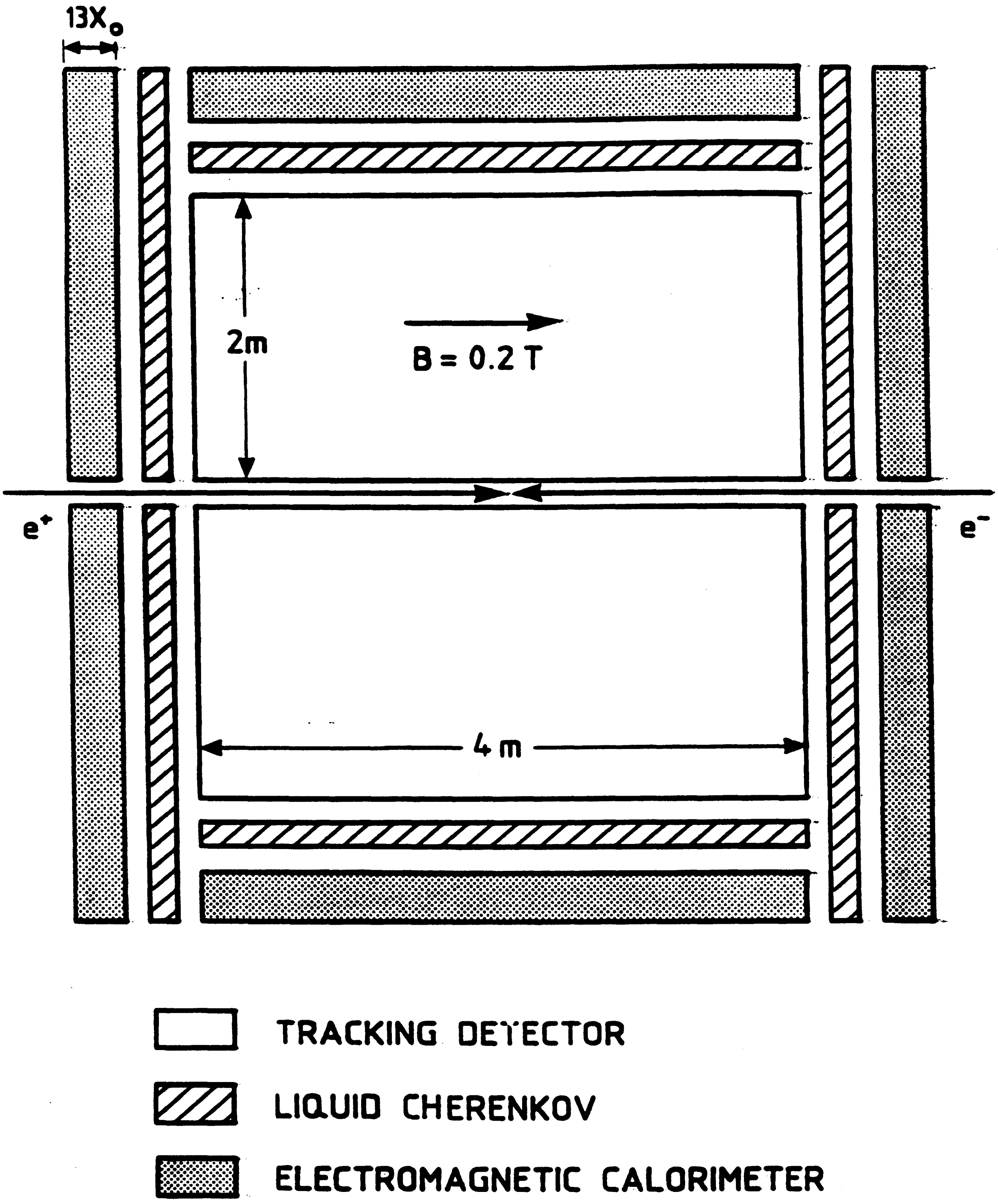


Figure 3: Possible Detector for the Frascati Phi Factory

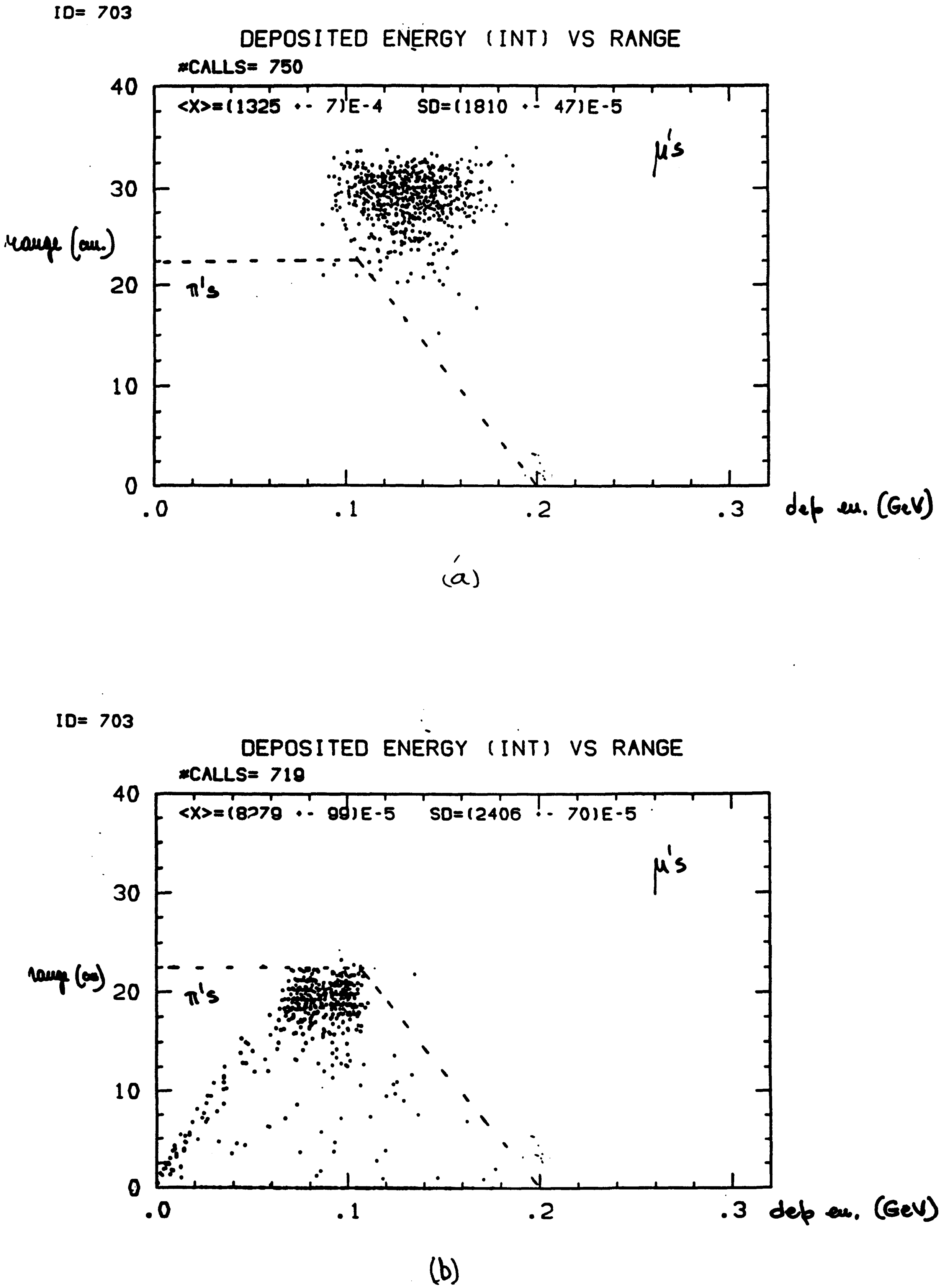
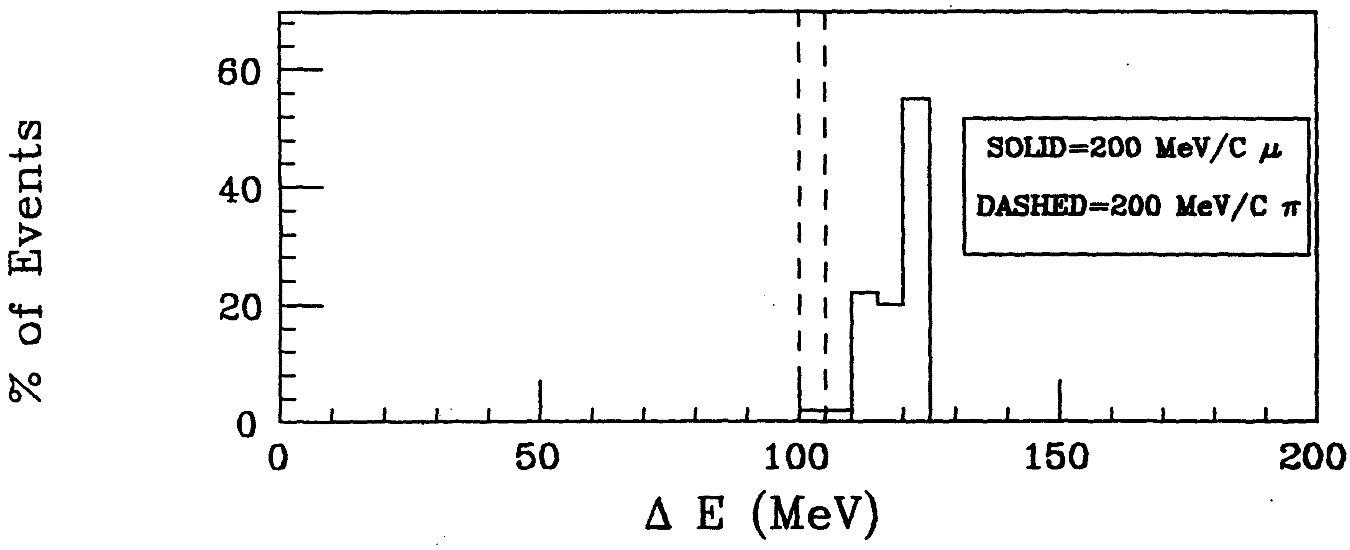


Figure 4: Energy deposit vs range for a 200 MeV/c particle in liquid Argon. a) Muons; b) Pions.



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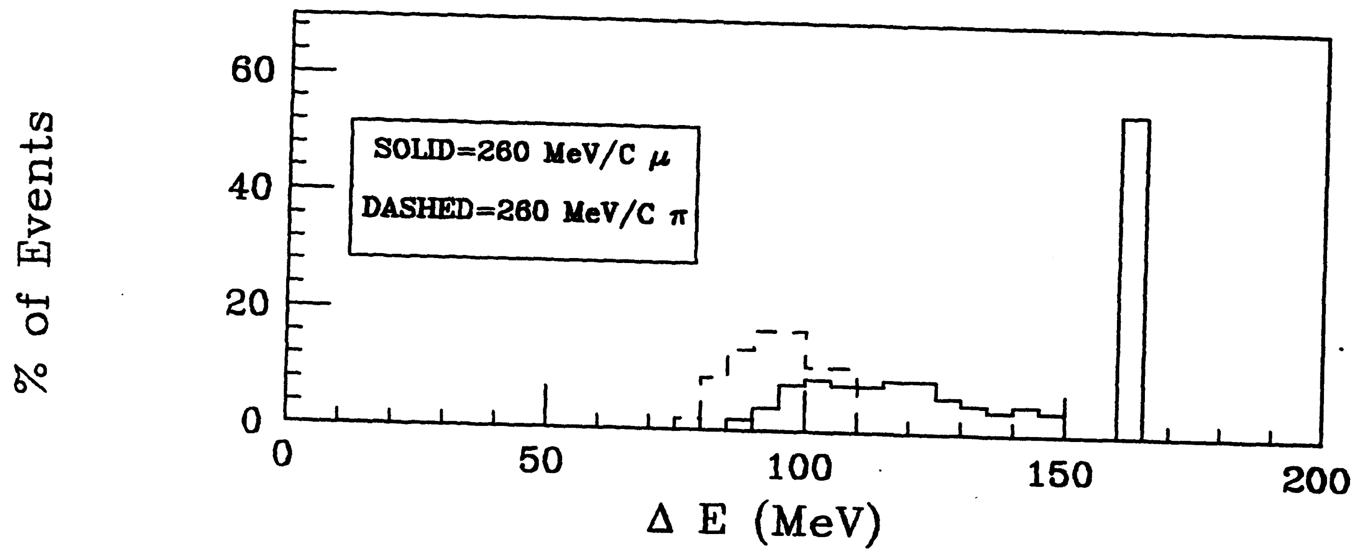


(b)

Figure 5: Ionization deposit in liquid Xenon. a) 200 MeV/c muons and pions. b) 260 MeV/c muons and pions.

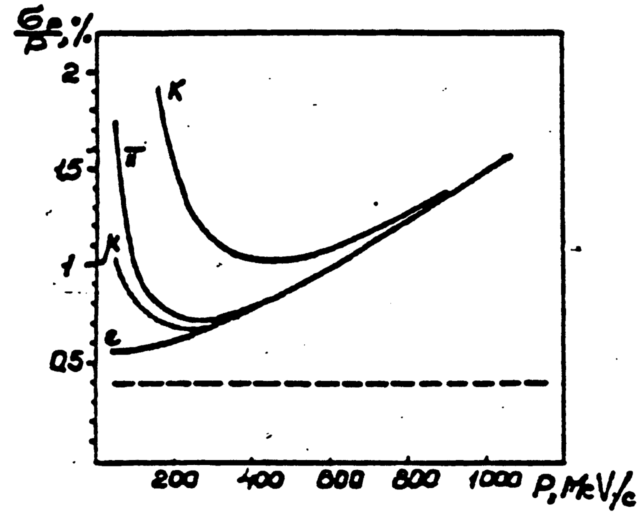
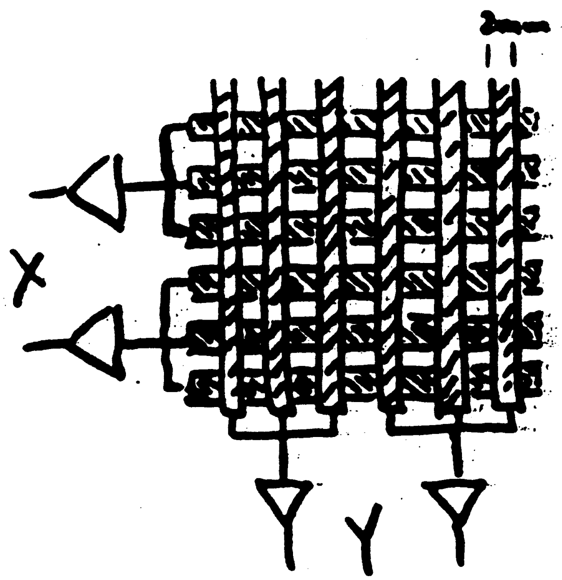


Figure 6: Momentum resolution for the proposed Novosibirsk drift chamber.



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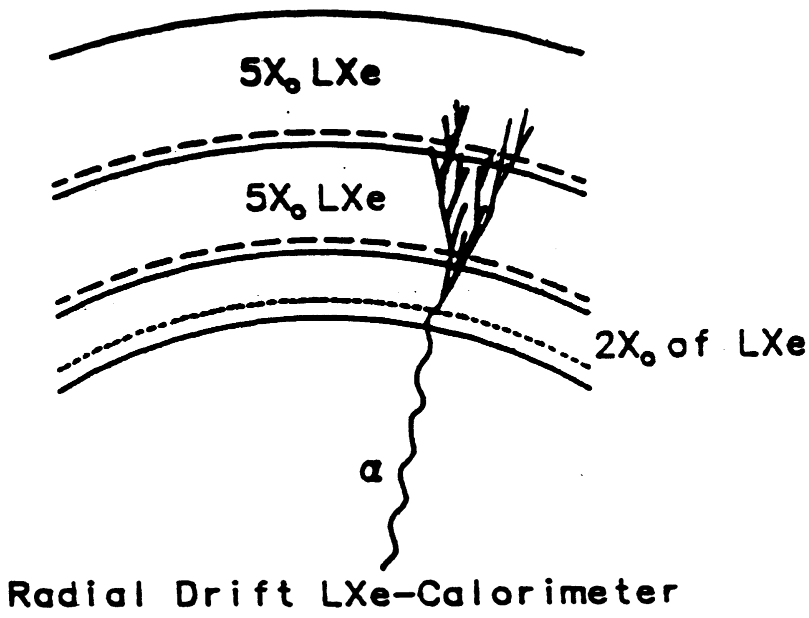


(b)

Figure 7: Possible physical layouts of a liquid Xenon calorimeter. a) Ganged x,y channels: Novosibirsk design; b) Radial drift: Atac design

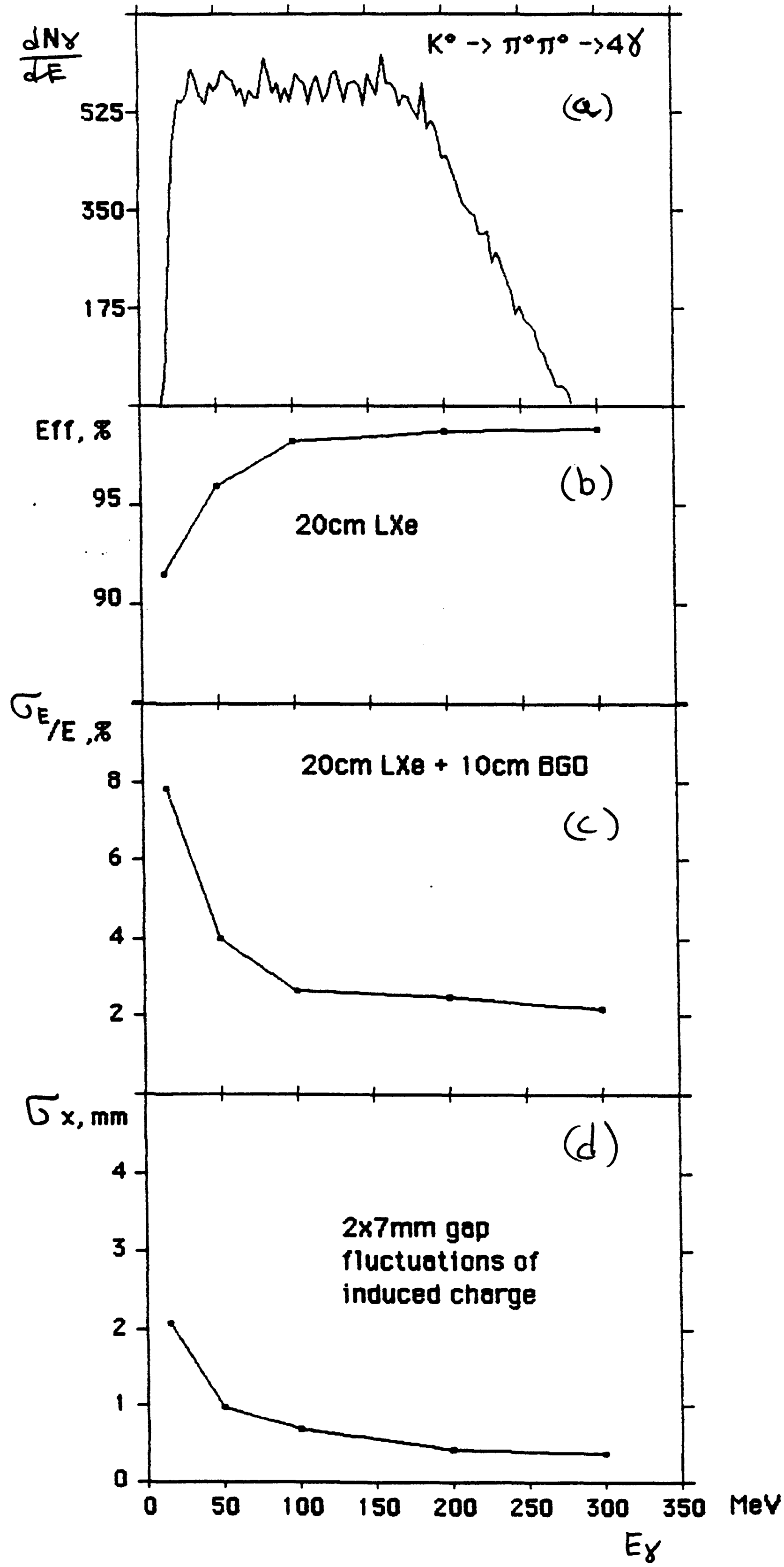
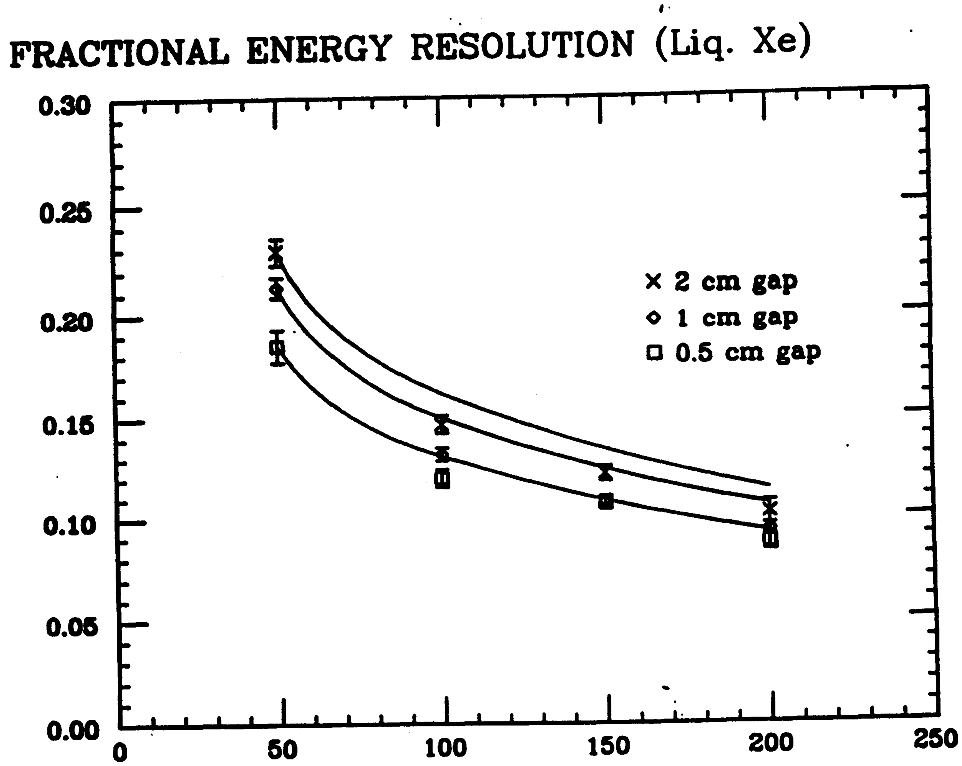


Figure 8: Distributions for gammas from the decay $K_S \rightarrow \pi^0\pi^0$, for the calorimeter system: 20 cm LXe, 10 mm Al, 15 cm CsI.

a) Complete energy distribution of gammas from the decay; b) Detection efficiency for gammas with good LXe spatial resolution; c) Energy resolution for the LXe-CsI system (10mm Al is assumed between the LXe and CsI); d) Spatial resolution for LXe, for perpendicularly incident gammas.



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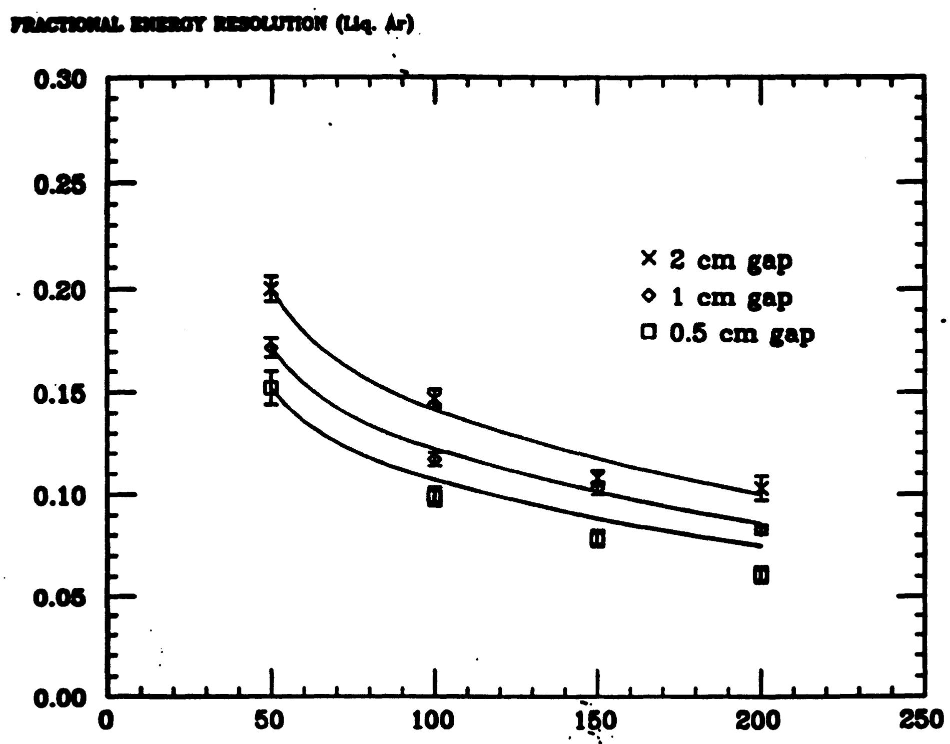

(b)

Figure 9: Energy resolution for different size gaps in a nobel liquid calorimeter. a) Xenon; b) Argon

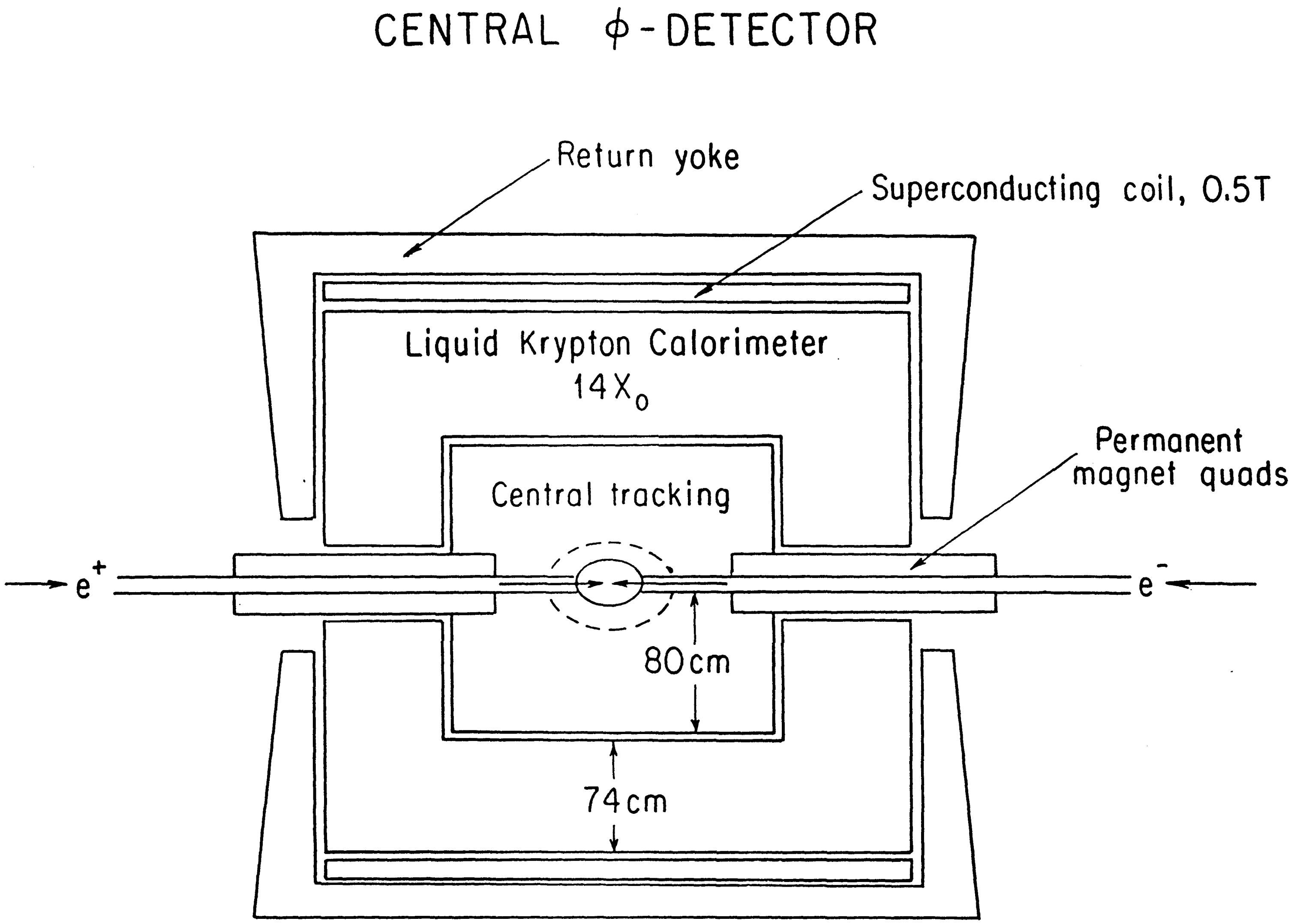

Figure 10: Possible Detector for the UCLA Phi Factory