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Memorandum

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LEM LF setup considerations, Geant3 simulation

For a future LEM setup with LF capabilities up to 3 kG, i.e. muon spin parallel/anti-parallel to its momentum, we need to split the LEM positron counters into a "forward" (in beam direction) and "backward" section. Due to space restrictions this splitting is impossible with the current detector technology, which uses bulky light guides and bulky XP2020 photo-multiplier (PM) tubes. Instead of light guides and large PM's the recently developed detector technology based on avalanche microchannel photodiodes (AMPD) [1] allows to build a very compact setup which will replace the present LEM positron counters.

For "forward-backward" detectors, other complications arise for the LEM setup:

1. at the moment it appears to be nearly impossible to have forward and backward detectors under angles (with respect to the beam axis z) of $\Theta = 0 - 35°$ and $\Theta = 145 - 180°$ due to RA and the sample cryostat, see Fig 1 for a sketch of the present setup. This is a significant disadvantage because we are forced to use the existing positron detectors which have $\Theta > 35°$. This reduces immediately the observable decay asymmetry of ~ 0.30 (ideal case for 100% polarization, integrating over all positron energies, integrating from $\Theta = 0°$ to $\Theta = 35°$) to less than 0.16.
2. absorption and scattering of decay positrons in the sample holders heavily affects the positron count rate in the "forward" section. Additionally, the positron counters are centred to the centre of the sample chamber, whereas the sample is about 14 mm downstream. Therefore, it is not clear if a symmetric splitting of the detectors yields the highest decay asymmetry.

These two items have been studied in more detail by a Geant3 simulation of the LEM setup in order to determine the maximum obtainable asymmetry with the existing positron detectors which are splitted at some position z_{cut} with respect to $z = 0$ (centre of sample chamber, positive z pointing in beam direction).

Summary of results:

- use an overall scintillator length of 26 cm, as before.
- keep the detectors centred with respect to the sample tube, and not to the sample which is at $z \sim 1.4$ cm, as before.

- cut the detectors at $z_{cut} = -1$ cm for maximum asymmetry; i.e. the "backward" detectors (upstream side, towards RA) have a length of 12 cm, and the "forward" detectors (downstream side, towards cryostat) have a lenght of 14 cm.
- the maximum asymmetry A_{LF}^{max} is ≤ 0.12 for either positive, P^+, or negative polarization, P^-, where P^+ means muon spin parallel to z (beam direction). Since the beam polarization is about 90% the asymmetries decrease correspondingly.
- with "small" (4.2 cm) sample plates asymmetry does not change, but event rate increases between 12% and 15%.
- we can "increase the asymmetry by a factor of two" by determining the difference A_{LF}^{+-} of asymmetries A_{LF}^+ and A_{LF}^- for both P^+ and P^-: $A_{LF}^{+-} = A_{LF}^+ - A_{LF}^-$. Note, that A_{LF}^+ and A_{LF}^- contain an "offset" asymmetry for zero polarization due to the geometry of the detectors and positron absorbtion in the sample plates. This offset cancels in A_{LF}^{+-}.
- a spin-rotator for LEM for $\pm 90^\circ$ spin rotations seems to be feasible up to 20 keV muon energy: a 300 mm long device with max. fields of ± 360 G and ± 210 kV/m would meet the demands. At 15 keV the fields are lower by $\sqrt{15/20}$. Such a device can't be placed in the moderator chamber, but it could be installed in the trigger chamber: it must be positioned in front of TD (TD blows up phase space too much) and it requires a redesign of the TD chamber, with the trigger moved closer to the sample, thus improving the time resolution. The spin-rotator also acts as a very efficient proton/ion separator to get rid off ions from the moderator before hitting TD.

Details:

Input parameter for Geant3 simulation:

- z points along beam axis/direction.
- $z = 0$ is the centre of the sample tube; sample is at $z \sim 1.4$ cm.
- start 10^5 decay positrons at sample position, homogeneous beam spot with 2 cm diameter.
- annular positron detectors.
- secondary particle generation (γ, electrons) enabled, minimum energy 10 keV.
- for a valid hit: require energy deposition > 0.2 MeV in inner and outer scintillator.

Figure 2 shows the distribution of positron detector hits along the beam axis (z) for unpolarized muons for a) only the sample tube and RA are present, and b) the sample cryostat with Al plates is in place.

Figure 3 shows the forward/backward asymmetry for longitudinal polarizations of -100,0,+100% as a function of cut position z_{cut} where the detectors are splitted into the forward section and backward section. $z = 0$ is the centre of the sample chamber, and the positron counters are centred at this position.

The observable asymmetry as a function of z_{cut} for the case that one measures either with positive or negative polarization is obtained by subtracting the asymmetry A^0_{LF} for zero polarization from the respective asymmetries A^+_{LF} and A^-_{LF}. The result is shown in Fig. 4. The maximum asymmetry is obtained at $z_{cut} = -1$ cm.

If measurements with both polarities are possible, the difference $A^+_{LF} - A^-_{LF}$ allows to get rid off the A^0_{LF} "offset", and to "double" the observable asymmetry. This is shown in Fig. 5. The same is shown in Fig. 6 for positron counters centred at the sample position ($z = 1.4$ cm). In this case, the observable asymmetry is about 7% reduced. The results of the simulation are summarized in more detail in the following. The "N0's" are the number of detected hits in the detectors for a minimum energy deposition of 0.2 MeV. The initial number of muons was 10^5.

```
 z_sample l_det z_det    N0-Pol0 N0-negPol N0-posPol  z_cut   Pol0-Asym  negPol-Asym  posPol-Asym
 1.4        26    0.0      49929     53421     46508   -5.0       0.547        0.479        0.633
 1.4        26    0.0      49929     53421     46508   -4.0       0.434        0.349        0.533
 1.4        26    0.0      49929     53421     46508   -3.0       0.297        0.197        0.403
 1.4        26    0.0      49929     53421     46508   -2.0       0.137        0.026        0.253
 1.4        26    0.0      49929     53421     46508   -1.0      -0.053       -0.167        0.071
 1.4        26    0.0      49929     53421     46508    0.0      -0.268       -0.379       -0.154
 1.4        26    0.0      49929     53421     46508    1.0      -0.503       -0.600       -0.400
 1.4        26    0.0      49929     53421     46508    2.0      -0.649       -0.735       -0.567
#
# shift detectors to sample position
#
 1.4        26      1.4    48759     51891     45791   -5.0       0.587        0.534        0.666
 1.4        26      1.4    48759     51891     45791   -4.0       0.474        0.402        0.563
 1.4        26      1.4    48759     51891     45791   -3.0       0.333        0.244        0.434
 1.4        26      1.4    48759     51891     45791   -2.0       0.168        0.068        0.283
 1.4        26      1.4    48759     51891     45791   -1.0      -0.020       -0.131        0.093
 1.4        26      1.4    48759     51891     45791    0.0      -0.240       -0.350       -0.134
 1.4        26      1.4    48759     51891     45791    1.0      -0.481       -0.578       -0.385
 1.4        26      1.4    48759     51891     45791    2.0      -0.635       -0.718       -0.552
#
# shift detectors to sample position, 28.8cm length instead of 26cm
#
 1.4      28.8      1.4    50151     53690     46556   -5.0       0.548        0.484        0.633
 1.4      28.8      1.4    50151     53690     46556   -4.0       0.436        0.350        0.532
 1.4      28.8      1.4    50151     53690     46556   -3.0       0.299        0.198        0.409
 1.4      28.8      1.4    50151     53690     46556   -2.0       0.141        0.032        0.257
 1.4      28.8      1.4    50151     53690     46556   -1.0      -0.044       -0.157        0.071
 1.4      28.8      1.4    50151     53690     46556    0.0      -0.257       -0.371       -0.147
 1.4      28.8      1.4    50151     53690     46556    1.0      -0.491       -0.598       -0.396
 1.4      28.8      1.4    50151     53690     46556    2.0      -0.644       -0.728       -0.559
#---------------------------------------
# small sample plates
#---------------------------------------
 1.4        26      0.0    56795     59853     53863   -5.0       0.602        0.536        0.684
 1.4        26      0.0    56795     59853     53863   -4.0       0.505        0.423        0.596
 1.4        26      0.0    56795     59853     53863   -3.0       0.386        0.288        0.490
 1.4        26      0.0    56795     59853     53863   -2.0       0.248        0.136        0.359
 1.4        26      0.0    56795     59853     53863   -1.0       0.086       -0.030        0.205
 1.4        26      0.0    56795     59853     53863    0.0      -0.097       -0.219        0.014
 1.4        26      0.0    56795     59853     53863    1.0      -0.308       -0.424       -0.201
 1.4        26      0.0    56795     59853     53863    2.0      -0.459       -0.561       -0.361
#
# shift detectors to sample position
#
 1.4        26      1.4    55837     58052     53144   -5.0       0.643        0.580        0.716
 1.4        26      1.4    55837     58052     53144   -4.0       0.536        0.464        0.628
 1.4        26      1.4    55837     58052     53144   -3.0       0.413        0.323        0.521
 1.4        26      1.4    55837     58052     53144   -2.0       0.267        0.167        0.390
 1.4        26      1.4    55837     58052     53144   -1.0       0.101       -0.006        0.234
 1.4        26      1.4    55837     58052     53144    0.0      -0.089       -0.201        0.045
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 1.4       26      1.4   55837    58052    53144   1.0     -0.305     -0.410     -0.176
 1.4       26      1.4   55837    58052    53144   2.0     -0.457     -0.551     -0.342
#
# shift detectors to sample position, 28.8cm length instead of 26cm
#
 1.4     28.8      1.4   57079    59880    54019  -5.0      0.605      0.541      0.687
 1.4     28.8      1.4   57079    59880    54019  -4.0      0.508      0.425      0.600
 1.4     28.8      1.4   57079    59880    54019  -3.0      0.391      0.293      0.494
 1.4     28.8      1.4   57079    59880    54019  -2.0      0.250      0.141      0.367
 1.4     28.8      1.4   57079    59880    54019  -1.0      0.090     -0.028      0.211
 1.4     28.8      1.4   57079    59880    54019   0.0     -0.094     -0.218      0.025
 1.4     28.8      1.4   57079    59880    54019   1.0     -0.302     -0.418     -0.191
 1.4     28.8      1.4   57079    59880    54019   2.0     -0.456     -0.557     -0.348
```

Spin rotator considerations:

If we want to rotate the spin on an effective length $l_{eff} = 300$ mm by 90° we have to do the following estimates:

- velocity of a 20 keV μ^+: $v = \sqrt{2E/m} = 5.83$ mm/ns. The drift time for 300 mm is then 51.5 ns.
- spin precession by 90° in 51.5 ns means 360° in 206 ns which corresponds to $\nu_\mu = 4.85$ MHz. This requires a field of about 360 G.
- Which E-field is needed? In order to keep the μ^+ on a straight path we must have $v = E/B$ from which we get $E = v \cdot B \sim 210$ kV/m.
- for 15 cm gap electrodes this means 31.5 kV potential difference to be applied. For 10 cm gap, this reduces to 21 kV.
- For 15 keV transport energy, the values above scale down by $\sqrt{15/20} = 0.866$.

Check the deflection angles (see [2]): the deflection angles ϕ_E and ϕ_B of the E- and B-field are given by:

$$\phi_E \simeq \frac{e \cdot l_{eff} \cdot E}{p \cdot v} = \eta_E \cdot \frac{E}{\beta \cdot p} \quad (1)$$

$$\phi_B \simeq \frac{e \cdot l_{eff} \cdot B}{p} = \eta_B \cdot \frac{B}{p}, \quad (2)$$

where e is the charge, v the velocity, p the momentum, and $\beta = v/c$. For $l_{eff} = 300$ mm we get

$$\eta_E = 0.3\,\text{mrad}\frac{\text{MeV/c}}{\text{kV/m}} \quad (3)$$

$$\eta_B = 9.0\,\text{mrad}\frac{\text{MeV/c}}{\text{G}}. \quad (4)$$

Now, consider the deflection angles for 20 keV μ^+ ($\beta = 0.01946$, $p = 2.056$ MeV/c) and 20-keV protons ($\beta = 0.00653$, $p = 6.126$ MeV/c). For the muon we obtain $\phi_E = \phi_B \simeq 1575$ mrad which is about 90° as it should. For the protons we get

$$\phi_E(\text{proton}) = 1574.6\ \text{mrad} \quad (5)$$

$$\phi_B(\text{proton}) = 528.9\ \text{mrad}, \quad (6)$$

yielding a net deflection of $\phi_E - \phi_B \simeq 1050$ mrad ($\simeq 60°$). This should allow to efficiently get rid of protons before hitting TD.

References:

[1] R. Scheuermann, A. Stoykov, D. Renker, Z. Sadygov, R. Mehtieva, A. Dovlatov, V. Zhuk, *Development of scintillation detectors based on avalanche microchannel photodiodes*, Nucl. Instr. Meth. **A571**, 317 (2007).

[2] T. Prokscha, *The new μE4 separator*, PSI internal memorandum, 2007, http://lmu.web.psi.ch/lem/newmue4/mue4_separator/.

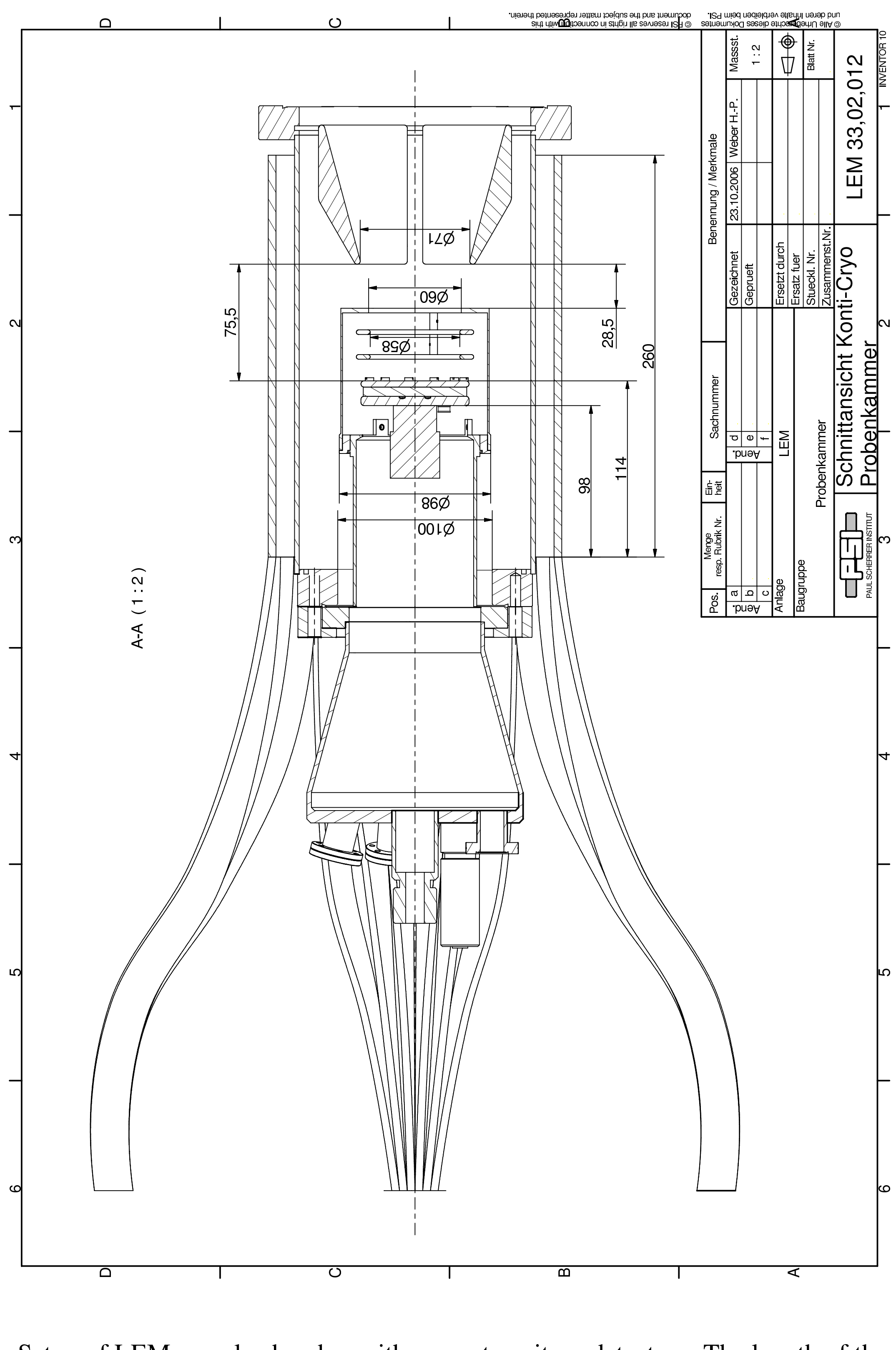


Figure 1: Setup of LEM sample chamber with present positron detectors. The length of the sample tube is 324 ± 0.1 mm.

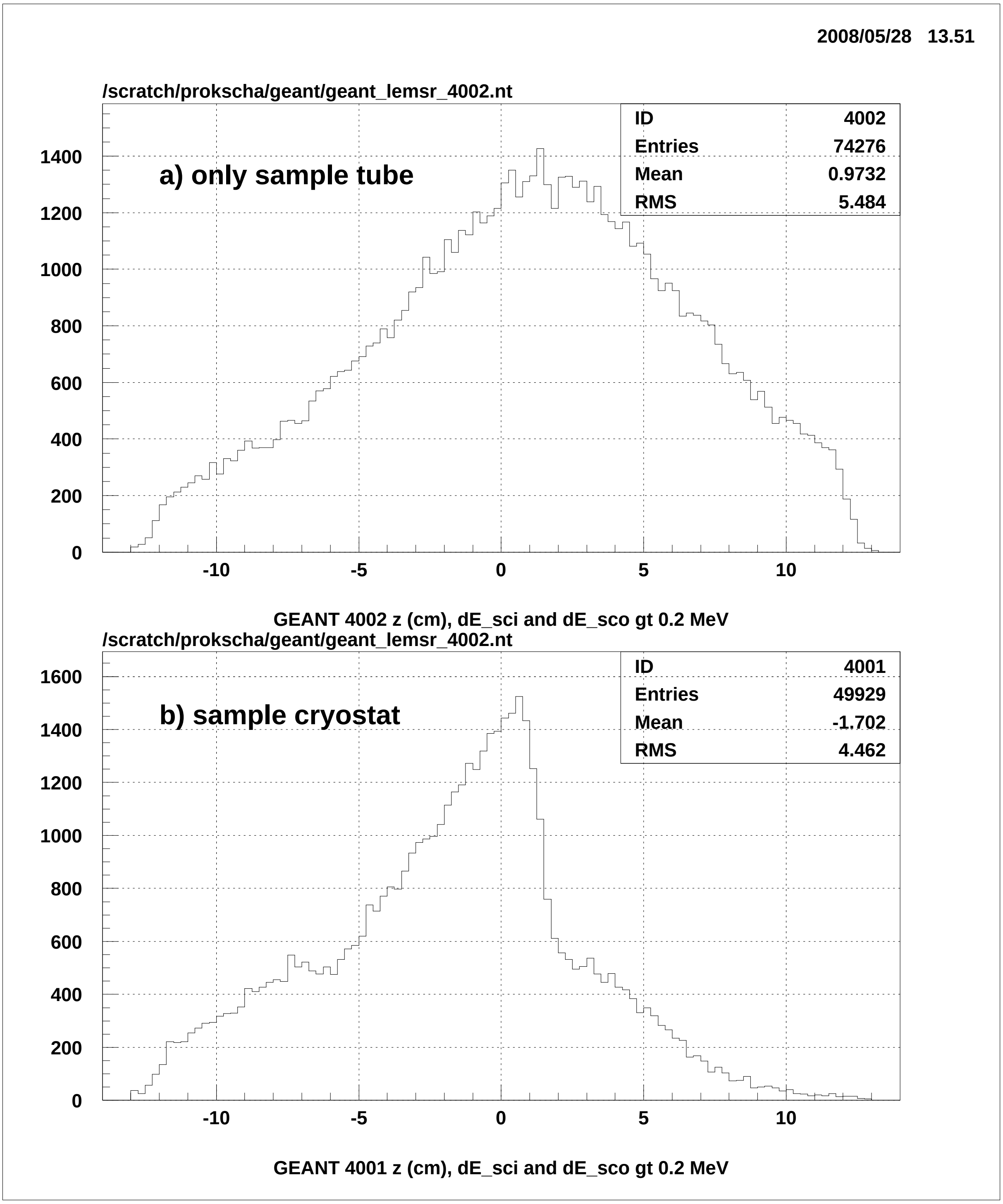


Figure 2: Geant3 simulation: z position of positron detector hits for unpolarized muons decaying at rest at $z = 1.4$ cm. a) only sample tube and RA mounted, b) sample cryostat with Al plates installed. The "bump" at about $z = -7$ cm is due to particles scattering in the RA.

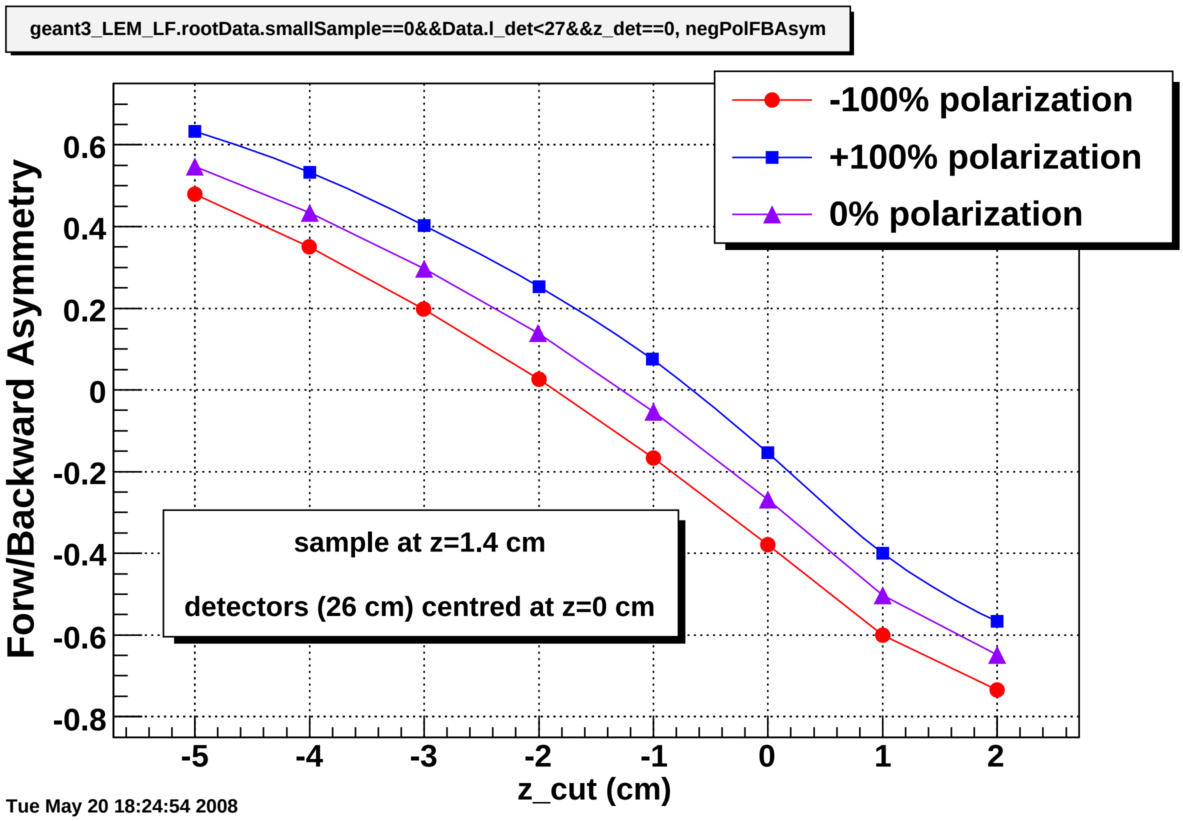
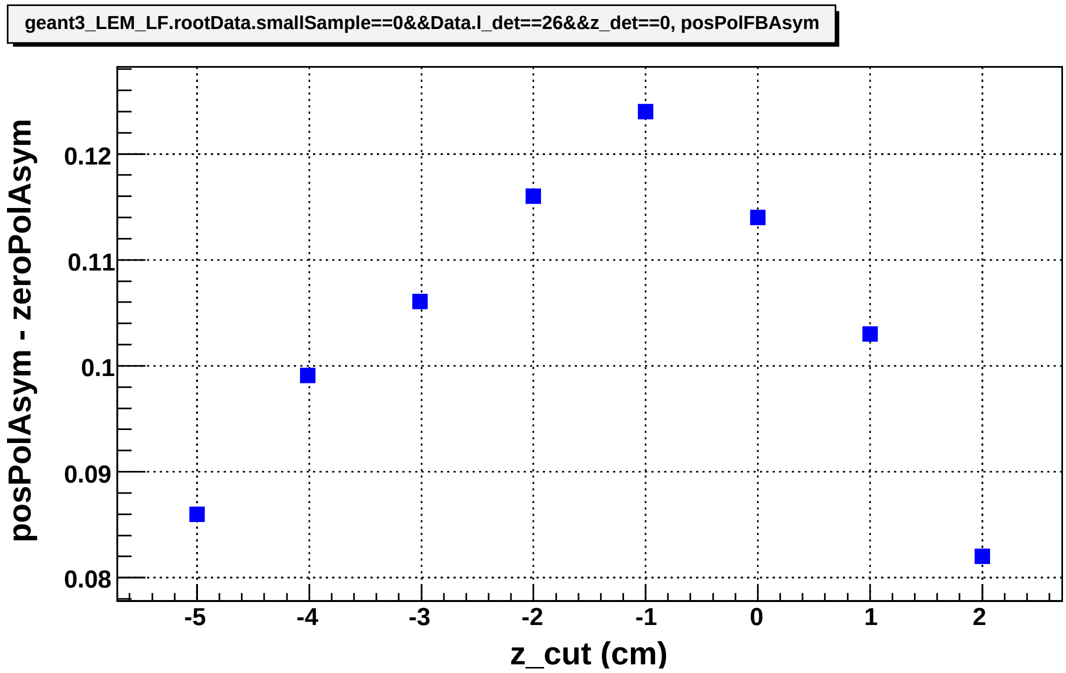


Figure 3: Geant3 simulation: forward/backward asymmetry as a function of z_{cut} where the detectors a separated into a forward and backward section. Detectors of 26 cm length, centred at $z = 0$, sample position is $z = 1.4$ cm.



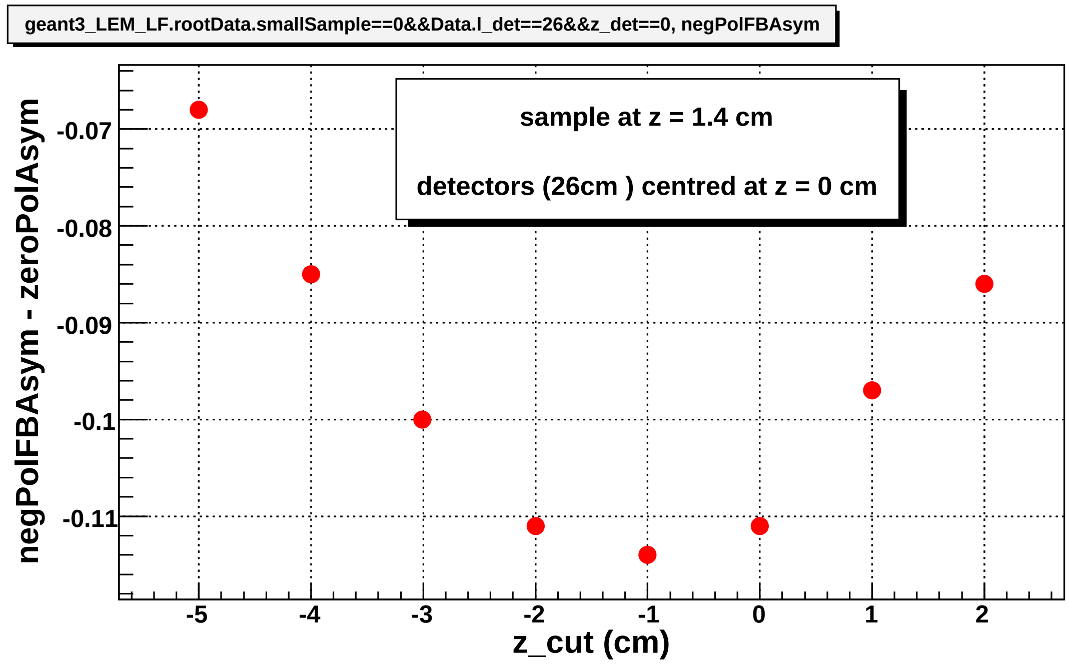


Figure 4: Geant3 simulation: observable decay asymmetries $A^+_{LF} - A^0_{LF}$, top, and $A^-_{LF} - A^0_{LF}$, bottom, as a function of z_{cut}.

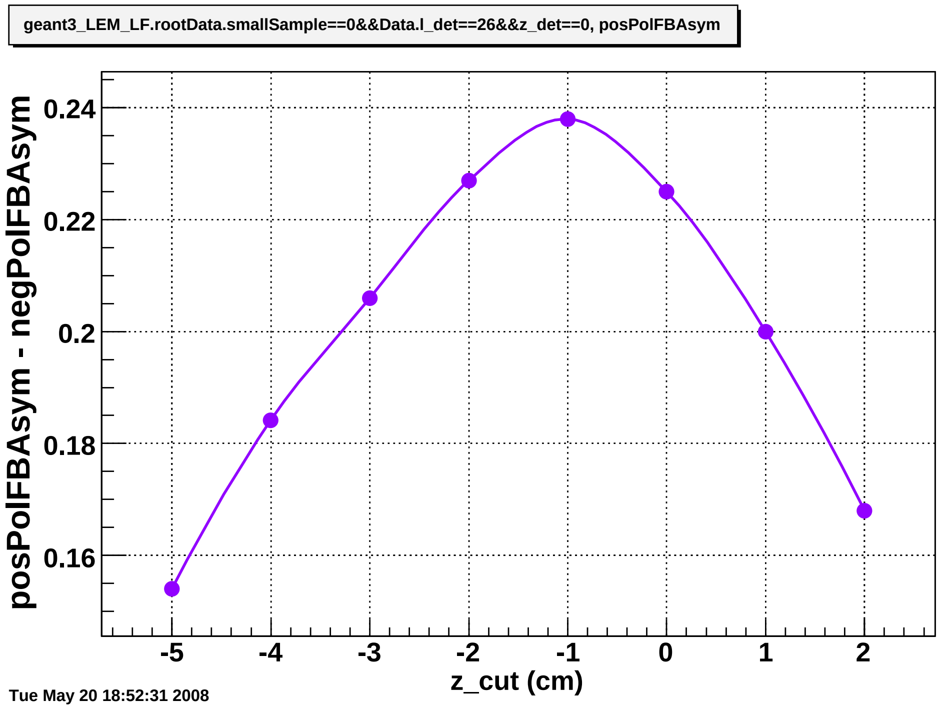


Figure 5: Geant3 simulation: observable decay asymmetries $A_{LF}^{+} - A_{LF}^{-}$ as a function of z_{cut}.

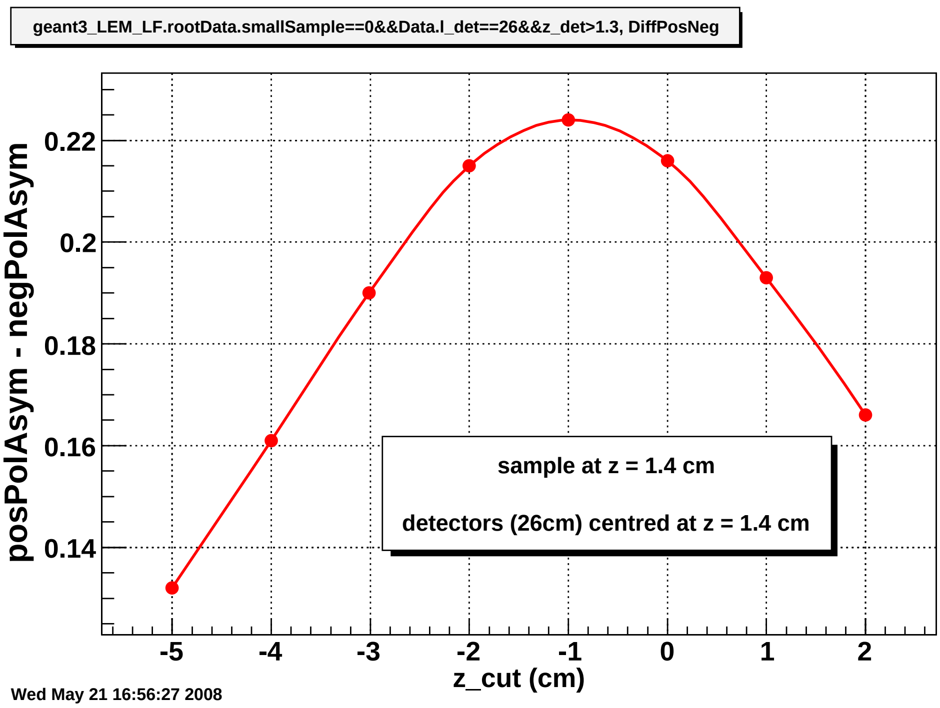


Figure 6: Geant3 simulation: observable decay asymmetries $A_{LF}^{+} - A_{LF}^{-}$ as a function of z_{cut}. Detectors are centred at the sample position at $z = 1.4$ cm. For 28.8-cm long detectors, centred at 1.4 cm, the asymmetry is ~ 0.228, about 0.01 less than in Fig. 5.