Memorandum

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Results of the LEM μE4-momentum scan, measured 21/Nov/2006 (Runs 1707-1779)

The purpose of this measurement is the determination of the muon moderation efficiency $\varepsilon_\mu(p, \Delta p)$ as a function of beam momentum p and momentum width Δp at highest beam intensity. Knowing ε_μ the μE4 intensity on LEM moderator can be estimated as a consistency check for μE4 beam transport: from the beam scanner data in 2005 we expect 85 M/mAs μ^+ on moderator at $p = 28$ MeV/c, 4.2-cm target E, at a total μ^+ rate of about 210 M/mAs. For the determination of $\varepsilon_\mu(p, \Delta p)$ we measured the LEM e^+-rate as a function of beam momentum p for various settings of the $\mu E4$ slits FS62 (horizontal slit in ASR62, allowing for the reduction of $\Delta p/p$) and FS63 (horizontal and vertical). By fitting a simple model function to the data the momentum bite $\Delta p/p$ of the μE4 channel can be estimated. Within this model, the relative moderation efficiencies for different $\Delta p/p$ can then be calculated and compared with the known result from πE3, where $\varepsilon_\mu = 6.1 \cdot 10^{-5}$ has been found in 2001 for a N_2 moderator and $\Delta p/p = 4\%$ (FWHM), see Appendix. This determination of $\Delta p/p$ can be compared with independent $\Delta p/p$-measurements from p-tunes across the surface edge at 29.8 MeV/c.

Basics: The moderation efficiency ε_μ is defined by

$$\varepsilon_\mu = N_\mu^{slow}/N_\mu^{moderator}. \tag{1}$$

In Eq. 1 N_μ^{slow} is the number of epithermal μ^+ exiting the moderator, divided by the number $N_\mu^{moderator}$ hitting the moderator.

For a monoenergetic beam the efficiency $\varepsilon_\mu(p, \Delta p = 0)$ as a function of p can be approximated by a gaussian

$$\varepsilon_\mu(p) \propto e^{-\frac{(p-p_m)^2}{2\sigma_0^2}}, \tag{2}$$

with the optimum momentum p_m and the "intrinsinsic" width σ_0, which are defined by the stopping distribution of the surface muon beam in the moderator. For an incoming μ^+ beam with gaussian momentum distribution with width σ_B, we can derive a simple expression for the slow-μ^+ intensity $I_\mu^{slow}(p)$ as a function of p by folding of the beam distribution $I(p)$ with Eq. 2:

$$I_\mu^{slow}(p) \propto N_0 \cdot \frac{\sigma_0\sigma_B}{\sqrt{\sigma_0^2+\sigma_B^2}} \cdot e^{-\frac{(p-p_m)^2}{2(\sigma_0^2+\sigma_B^2)}}, \tag{3}$$

where $\sigma_B = \Delta p/2.36$ (Δp denoting the FWHM). The efficiency is obtained normalizing Eq. 3 to the incoming beam rate, which is proportional to $N_0 \cdot \sigma_B$. This then gives for $\varepsilon_\mu(p)$

$$\varepsilon_\mu(p) \propto \frac{\sigma_0}{\sqrt{\sigma_0^2 + \sigma_B^2}} \cdot e^{-\frac{(p-p_m)^2}{2(\sigma_0^2+\sigma_B^2)}}. \quad (4)$$

Procedure:

- Meausure for slit settings (surface edge results from LB "New uE4 beamline 2, p.88):
  - FS61-500/FS62-555/FS63-500: $\Delta p/p = 8.5\%$, maximum intensity.
  - FS61-500/FS62-350/FS63-350: $\Delta p/p = 7.0\%$.
  - FS61-500/FS62-250/FS63-350: $\Delta p/p = 6.5\%$.
  - FS61-500/FS62-150/FS63-350: $\Delta p/p = 5.6\%$.
- Measure `PosL` and `PosR` positron rates (normalized to proton current) as a function of p for B_parallel setup settings: *WSXon_13Oct2006_300kV_scale099.set*.
- Quote p in "units" of $p_0 = 28.0$ MeV/c.
- Measure e^+ rates for Mirror on/off; substract Mirror-off rate from Mirror-on rates to obtain background (bkg) corrected positron rates. This bkg-corrected e^+ are due to LE-μ^+ decaying in the LEM sample region.
- Fit Eq. 3 to the data to determine σ_B. Fix σ_0 to 1.7% of p_0, which is from a MCV3K [1] simulation of the μ^+ stopping distribution in the moderator, see Figs. 3,4.
- Use Eq. 4 to plot $\varepsilon_\mu(p)$ together with the function for $\Delta p/p = 4\%$ to determine $\varepsilon_\mu(p_m)$ in μE4 at highest intensities.
- With this $\varepsilon_\mu(p_m)$ estimate the rate of μ^+ impinging on the moderator and compare with the beam scanner data of 2005.

Results: The background corrected e^+ rates and fits of Eq. 3 are shown in Fig. 1. With the fitted beam widths σ_B in Fig. 1 the relative moderation efficiencies ε_μ are calculated according to Eq. 4 and are shown in Fig. 2. Comparing with the $\Delta p/p = 4\%$-data of 2001 we obtain

$$\begin{aligned} \varepsilon_\mu(\mathrm{FS62} = 555) &= \varepsilon_\mu(\Delta p/p = 4\%) \cdot \frac{0.396}{0.711} \\ &= 6.1 \cdot 10^{-5} \cdot 0.56 \\ &= 3.4 \cdot 10^{-5}. \end{aligned} \quad (5)$$

Determine now the μ^+ rate on moderator:

- Transport and detection efficiencies at 15 kV settings:
  transport moderator-sample $\varepsilon_{Mod-Sample} = 0.32$ (HG Memo).
  e^+ detection efficiency (PosL+PosR) $\varepsilon_{e^+} = 0.25$ (TP Memo Geant3, 21/04/99).
- run 1565: bkg rates `PosL, PosR` = 22/mAs and 50/mAs, respectively, at p_m.
  run 1707: bkg rates `PosL, PosR` = 28/mAs and 62/mAs, respectively.

- bkg corrected rates:
  run 1565: `PosL+PosR` = 232/mAs $\Longrightarrow$ 2900/mAs at moderator.
  run 1707: `PosL+PosR` = 230/mAs $\Longrightarrow$ 2900/mAs at moderator.
- μE4 rate I_μ^{Mod} on Moderator: $I_\mu^{Mod} = 2900/(3.4 \cdot 10^{-5})$/mAs = 85 M/mAs, in excellent agreement with beam scanner data.

Summary:

Table 1: Summary of πE3 and μE4 results for $\Delta p/p$, moderation efficiencies ε_μ for a s-N_2 moderator, and beam intensity I_μ^{Mod} on muon moderator (3×3 cm^2, "structured" Ag substrate), 4.2-cm target E. Rates linearly scale with target E thickness, which means that for the 6-cm target, the intensities are about 50% higher. $\Delta p/p^{edge}$ means a determination of the momentum width by tuning across the μ^+ surface edge.

beam	$\Delta p/p$ [FWHM]	$\Delta p/p^{edge}$ [FWHM]	$\varepsilon_\mu(N_2)$	I_μ^{Mod}
πE3, FS71O/U=200	4.0%	4.0%	$6.1 \cdot 10^{-5}$	
πE3, open slits	7.0%	7.0%	$4.3 \cdot 10^{-5}$	8.7 M/mAs (LB35/97) = $0.78 \cdot 11.1$ M/mAs ($\varepsilon_{BC-Mod} = 0.78$)
μE4, FS62=555	9.4%	8.5%	$3.4 \cdot 10^{-5}$	85 M/mAs
μE4, FS62=350	8.1%	7.0%	$3.8 \cdot 10^{-5}$	
μE4, FS62=250	6.9%	6.5%	$4.3 \cdot 10^{-5}$	
μE4, FS62=150	5.9%	5.6%	$4.9 \cdot 10^{-5}$	

Excellement agreement is found for I_μ^{Mod} between the beam scanner measurements in 2005 and LEM efficiency measurements. The momentum bite $\Delta p/p^{edge}$ determined by the p-tune across the surface edge is always smaller than the one determined by the efficiency measurements. The $\Delta p/p^{edge}$ data should be re-analyzed by fitting the edge – up to now $\Delta p/p^{edge}$ is derived from a "geometrical" analysis. Additionally, the determination of σ_0 – which determines the fit parameter σ_B and therefore $\Delta p/p$ – in the MCV3K simulations is a simple approximation. Therefore, a deviation between both methods can be expected.

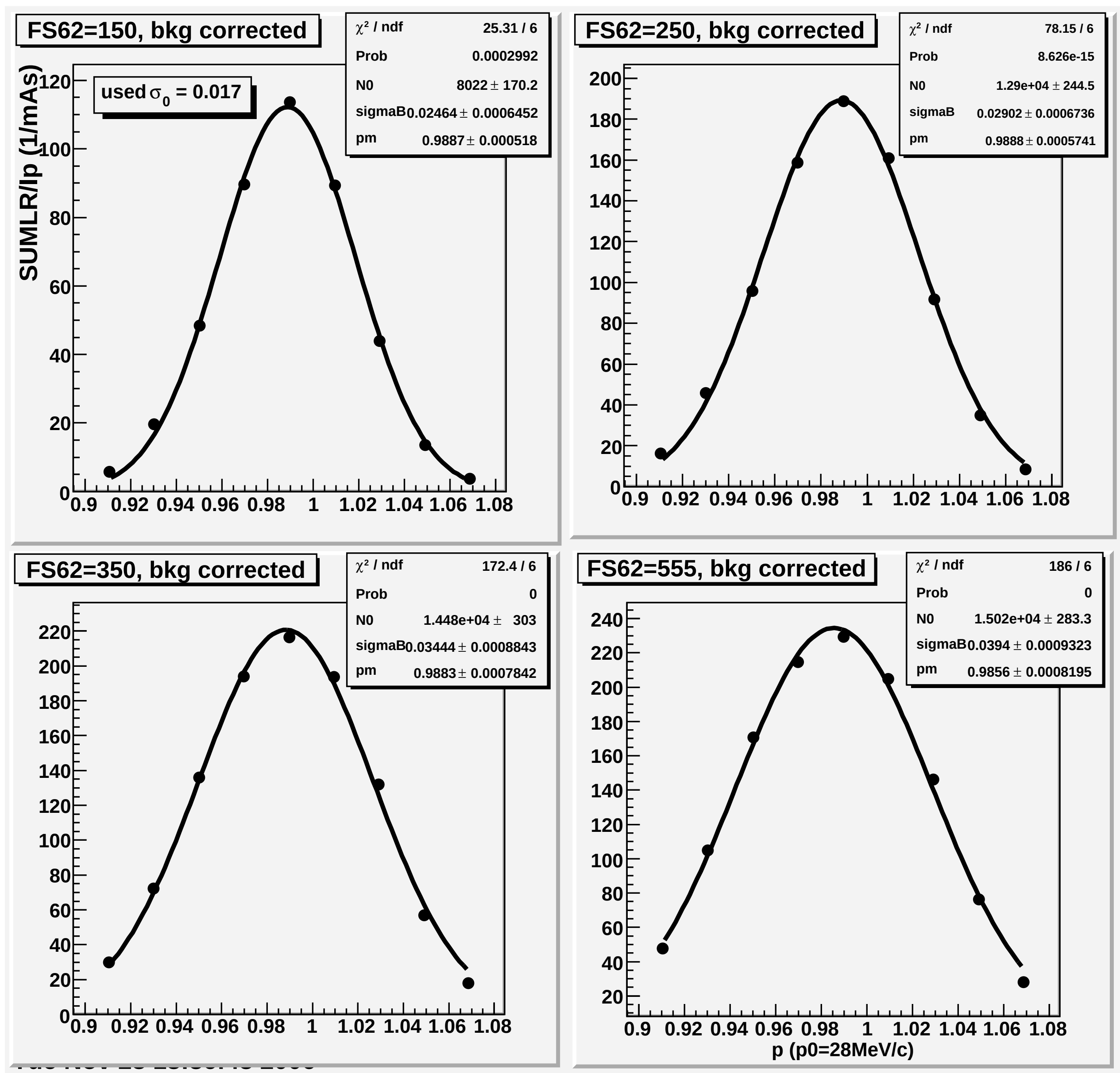

Figure 1: Background corrected positron rate (1/mAs) as a function of beam momentum. Fitted Eq. 3 to the data with a fixed intrinsic width $\sigma_0 = 0.017$.

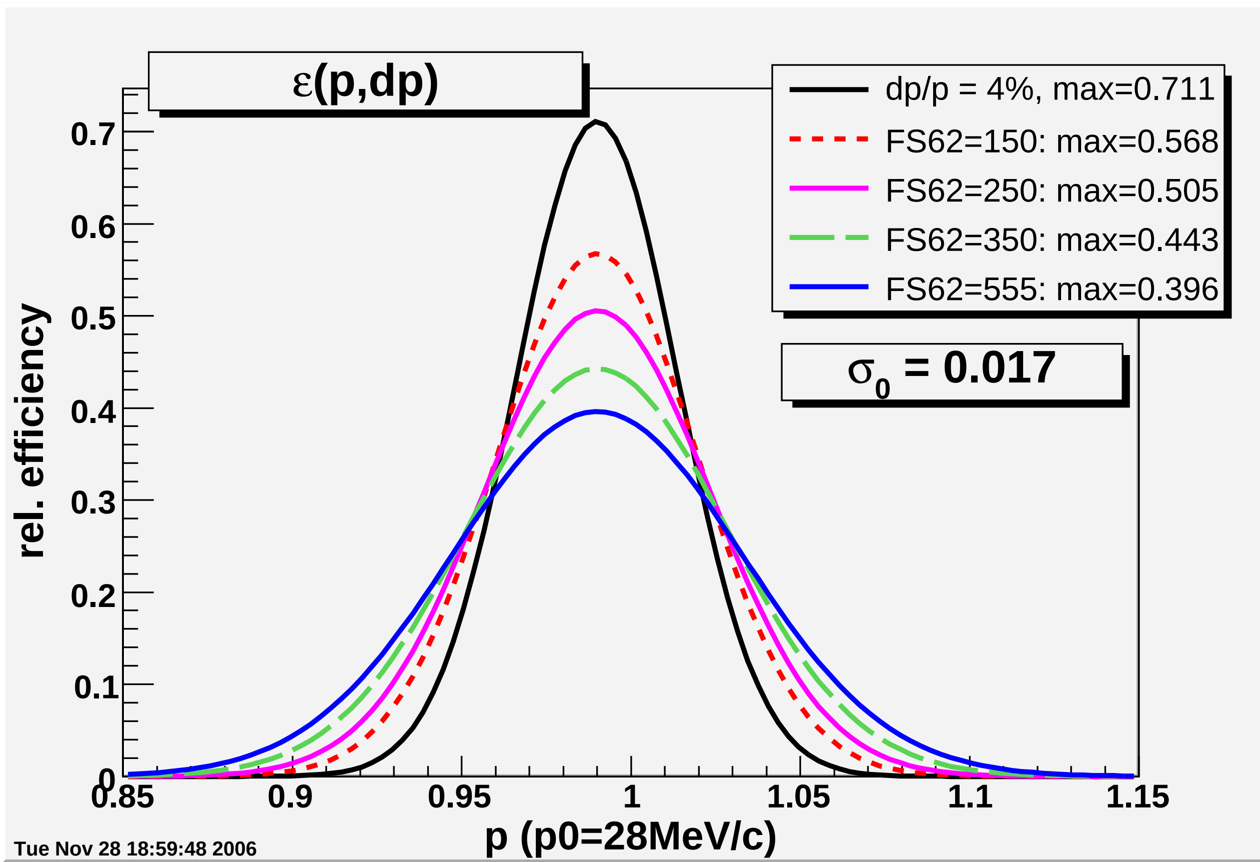

Figure 2: Moderation efficiency $\epsilon_\mu(p, dp)$ as a function of momentum p and momentum bite, calculated with Eq. 4.

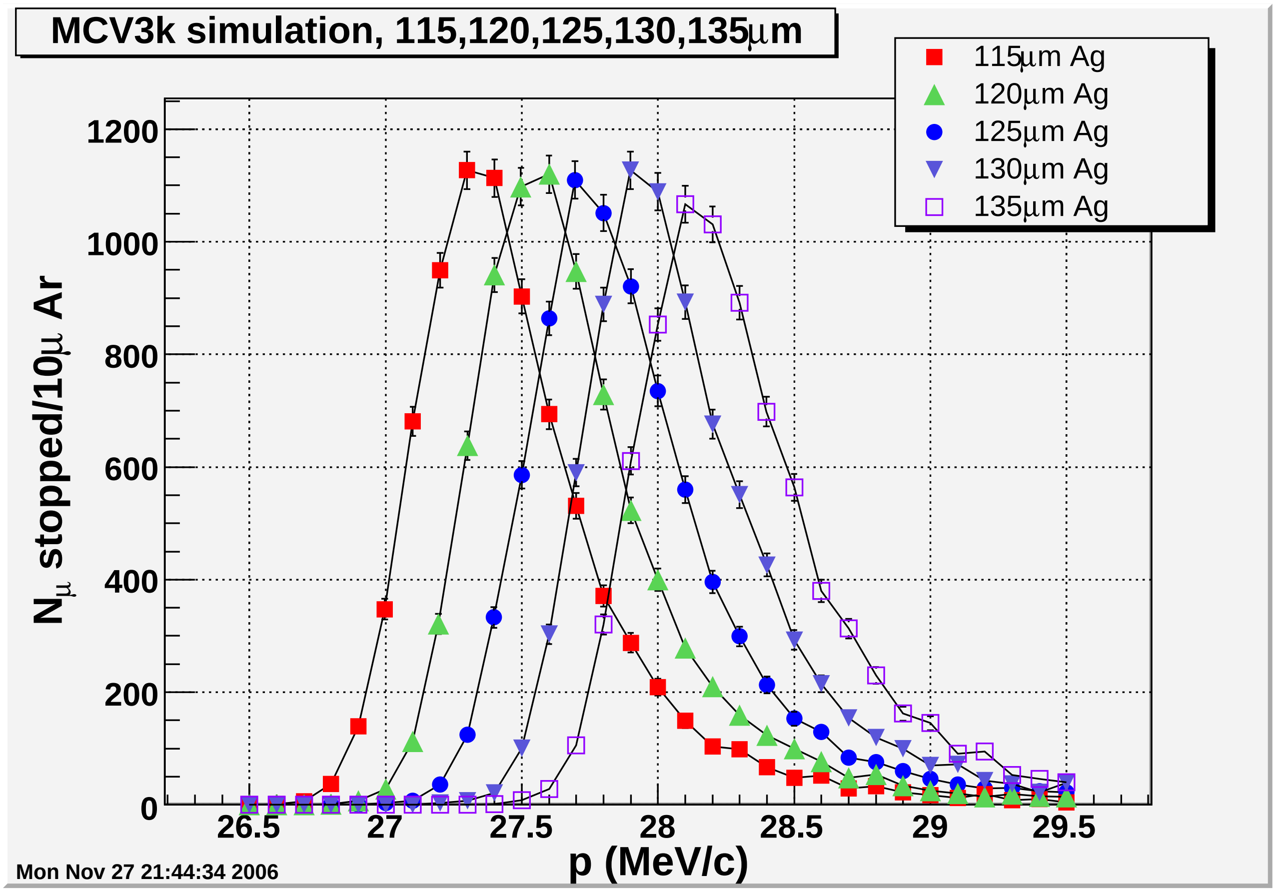

Figure 3: Simulated μ^+ stop density in a 10-μm-thick s-Ar layer on a Ag substrate with different thicknesses. The different thickness are due to the ”20-μm deep V-shaped” surface of the Ag substrate [2]: at the bottom of the groove the thickness of the substrate is 115 μm, at the top edge it is 135 μm and the mean thickness is 125 μm.

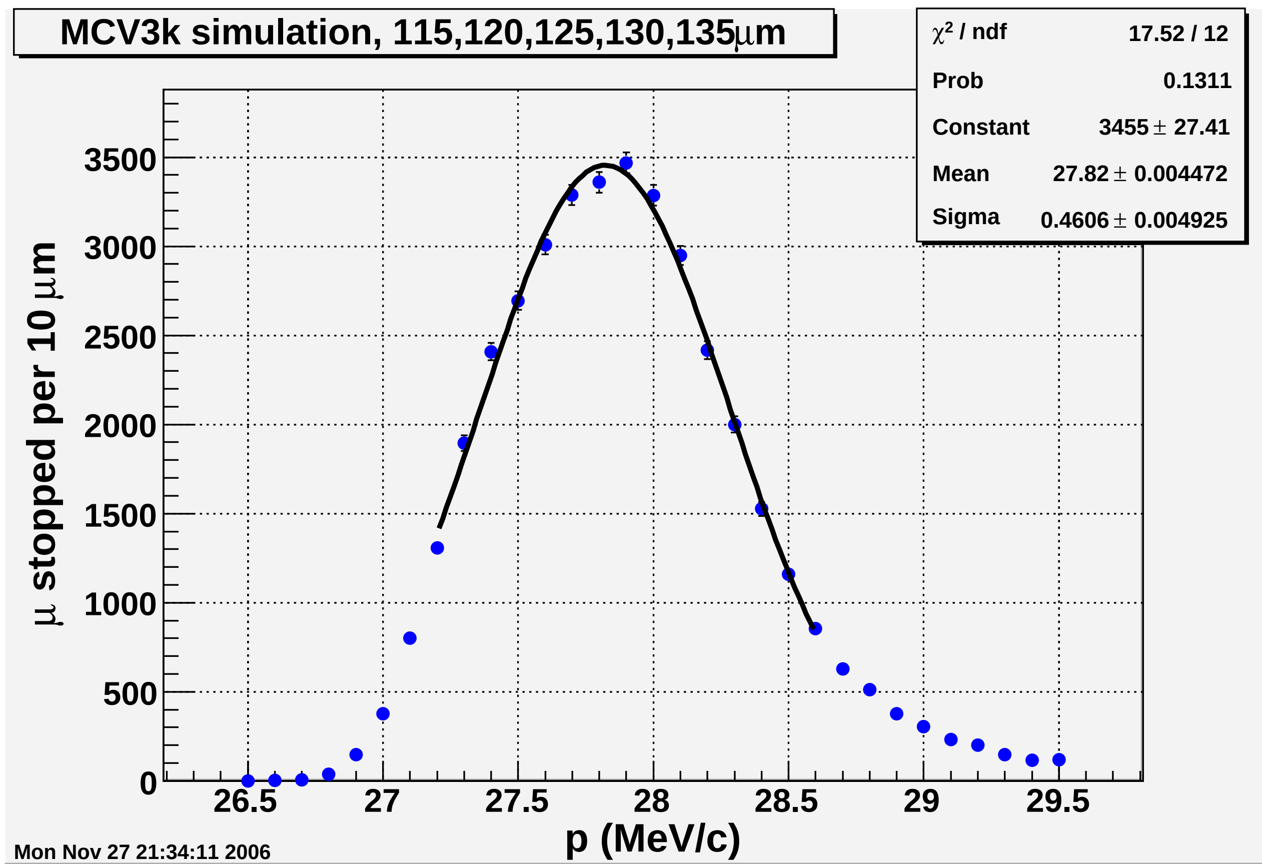

Figure 4: Sum of simulated μ^+ stop densities of Fig. 3 in a 10-μm-thick s-Ar layer on a Ag substrate with different thicknesses, fit by a gaussian. The relative width Sigma/Mean is 0.017.

Appendix:

- πE3 efficiency:
  - In 2001 $\Delta p/p = 4\%$ FWHM for FS71O/U = 200, NE13_1 settings ("mixed mode"); see LB36/141 and "Beamlines" folder.
  - In 2001, run 1125: N_2 efficiency (from TOF TD-BC$_{cl}$) $\varepsilon_\mu^{uncorr} = 2340/10^8$ BC$_{cl}$, uncorrected for efficiencies; LB36/160.
  - **Corrected efficiency** $\varepsilon_\mu(\mathrm{N}_2) = \varepsilon_\mu^{uncorr}/\varepsilon_{det} = 6.1 \cdot 10^{-5}$, $\Delta p/p = 4\%$ FWHM.
  - Efficiencies:
    total detection efficiency $\varepsilon_{det} = 0.384 = 0.78 \cdot 0.60 \cdot 0.82 = \varepsilon_{BC-Mod} \cdot \varepsilon_{Mod-TD} \cdot \varepsilon_{TD}$.
    - ε_{BC-Mod} : transport beamcounter-moderator: 0.78 (TP memo 05/05/1998).
    - geometric transmission from moderator to TD: $0.95 \cdot 0.95 \cdot 0.93 \cdot 0.93 \cdot 0.88 = 0.687$ (grid1 x grid2 x mirror x mirror x TD-grid, see HG memo on Simion/MuTrack simulations;
      grid1: 50 μm wires, 1.0 mm distance, the same for grid2 (since 2001)
      grid1: 25 μm wires, 0.5 mm distance; grid2: 25 μm, 1.0 mm distance (1999)).
    - transport Mod-TD (15kV): 0.975 (HG memo).
    - lifetime correction: 0.90 (TOF (15kV) = 230 ns).
    - $\varepsilon_{Mod-TD} = 0.60 = 0.687 \cdot 0.975 \cdot 0.90$.
    - ε_{TD} : TD efficiency (2001): 0.82, LB36/135.
- Used Root macros (available in LEM SVN repository in analysis/root/macros, except setup_treeviewer.C):
  - pscan.C: read LEM run summary files to extract relevant transport HV, beamline and scaler information; output is written to root file *p-scan_lem06_1707-1779.root*.
  - setup_treeviewer.C: a file generated on the fly from TTreeViewer to save cuts and variables to be plotted.
  - getGraph.C and getGraphDifferences.C: two macros to copy plots from tree->Draw() in to TGraph objects; needed to subtract from the measured e^+ rates the uncorrelated e^+ background rate.

References:

[1] MCV3K: a Monte-Carlo simulation for the passage of particles through matter, M.W. Gladisch, W. Jakobs, K. Träger, T. Prokscha et al., Univ. Heidelberg/PSI, 1981-2001.

[2] T. Prokscha, E. Morenzoni, C. David, A. Hofer, H. Glückler, L. Scandella, *Moderator gratings for the generation of epithermal positive muons*, Appl. Surf. Sc. **172**, 235 (2001).