TRIUMF Experiment E614
Technical Note #39

Alignment of "muon beam – magnetic field" and "muon spin – magnetic field" systems

(Estimations)

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Possibilities of the magnetic field alignment with respect to the muon beam or the muon spin are discussed. Two PC2(X+Y) placed in center of the magnet provide to measure the misalignment between the beam and the field with precision about 1mr. Two scintillator counters placed in the center of magnetic field can measure the misalignment between the muon polarization and the field with precision about 1mr also.

1 Suppositions

Several suppositions have been used to simplify the estimations. Additional computer calculations are needed to make more precise estimations.

- Focus of muon beam crosses Z axis (X=Y=0) of magnetic field in point Z= – 140cm. The line X=Y=0 corresponds to the axis of cylindrical symmetry of the fringe field.
- Magnetic field B=0 at Z< – 140cm, and B=2.2T at Z≥ – 140cm.
- Beam spot size at B=0 was calculated as $\sigma_{X,Y}(Z)= \sqrt{(\sigma_R)^2 + (\sigma_\theta \cdot Z)^2}$ where σ_R and σ_θ are the beam emittance parameters, Z is distance from the beam focus to a measured plane, $\sigma_{X,Y}(Z)$ is the beam size in XZ or YZ plane.
- The B=2.2T case:

It has been suggested the $\sigma_\theta(B)= \sqrt{(\sigma_\theta)^2 + (20\text{mr})^2}$. The beam spot size is $\sigma_{X,Y}(B)= \sqrt{(\sigma_R)^2 + (\Delta R)^2}$ where $\Delta R= p_\mu \cdot \sin(\sigma_\theta(B))/3 \cdot B$ is average radius of the muon cyclotron spiral, p_μ is the muon momentum.

- Estimations have been done for two muon beam momentum p_μ = 29.8MeV/c (surface beam) and p_μ = 29.5MeV/c (–1%).

2 Alignment "muon beam – magnetic field"

Muon beam profiles at the center of the magnet (Z=0) are shown on Figs.1–2 for tunes #1 and #3 [1]. A muon beam crossing Z axis at point Z= –140cm with angle θ_{XZ} = 10mr in XZ plane at B=0 will be shifted at Z=0 on Δ_{XZ} = 14mm, as it is shown on Figs.1–2. The same beam will move along a spiral at B=2.2T and it will be rotated on angle $\Delta\varphi \cong 5 \cdot 2\pi - 26°$ around Z axis at Z=0. Its center of gravity will be shifted on radius $\underline{r} \cong$ 0.45mm ($\underline{r}$ is radius of cyclotron spiral of muon at p_μ= 29.8MeV/c, θ = 10mr, B=2.2T) from central axis of the magnet (X=Y=0), and on additional angle $\Delta\varphi$. The above picture is correct for a possible misalignment θ_{YZ} in YZ plane also.

Therefore one can suggest below procedure of the alignment. Two PC2 chambers (X+Y) are placed in plane Z=0. The muon beam profiles are measured at B=0 and B=2.2T. Shifts between the beam center of gravity Δ_{XZ} and Δ_{YZ} are defined. Angle misalignment is therefore $\theta_{XZ}= \Delta_{XZ}/140$cm and $\theta_{YZ}= \Delta_{YZ}/140$cm correspondingly. Next procedure is an alignment of muon beam or magnet on the above angles. Maximum systematic error is obviously $2\underline{r}$ = 0.9mm. It corresponds to θ= 0.9mm/140cm $\cong$ 0.64mr. The same second step of the alignment may be done after the above first step. The systematic error of $2\underline{r}$ will be much less after the first step. Obviously the suggested procedure of the step by step alignment works from any value of the initial misalignment. Statistic error will be defined by total statistics of muon stops. I believe 1 hour at muon intensity 10^3 s^{-1} (total statistics is about $4\cdot10^6$) will be enough for providing of statistic precision < 0.2mm. Difference of phases $\Delta\varphi$ between muons with momentum 29.8MeV/c and 29.5MeV/c (−1%) is about 18° at Z=0. This difference will cause a small contribution to the systematic error.

Target module [PC(−2), PC(−1), target, PC(+1), PC(+2)] could be used as the device for the alignment.

Angle misalignment only has been discussed above, but the muon beam can have some deflection with respect to the axis of symmetry of a fringe field (X=Y=0). The deflection will cause some additional broadening of the muon beam at Z=0 as it is shown on Figs.1−2. One can see the broadening is not so much. It means the suggested procedure is not so sensitive to the deflections. On the other hand the deflection causes an additional angle shift $\Delta\varphi$ at Z=0. Fig.3 demonstrates beam profiles with the shift 10mr at two magnetic field values of B=2T and B=2.2T. The shift of 0.9mm is easy to be measured. Sensitivity of the procedure comes better with decreasing of magnetic field. For example the shift will be 0.9mm · 2.2T/0.5T= 3.95mm at magnetic field around B=0.5T, but one needs to calculate total magnetic field distribution at B=0.5T in order to approve the estimations.

The above measurement of the deflection can be done after the end of the angle alignment.

Third question is the search of an optimal length of beam focus in area of the fringe field. Width of muon beam profile at Z=0 can be used as criterion of the minimum of fringe field depolarization.

3 Alignment "muon spin – magnetic field"

The above procedure provides the alignment of muon beam momentum $\mathbf{p}_\mu$ with respect to magnetic field $\mathbf{B}$. However one needs to measure components of muon polarization $\mathbf{P}_\mu$ in stopping target with respect to magnetic field $\mathbf{B}$. The components are define by the polar angle θ between vectors $\mathbf{P}_\mu$ and $\mathbf{B}$: $(P_\mu)_\| = |\mathbf{P}_\mu| \cdot \cos\theta$ and $(P_\mu)_\perp = |\mathbf{P}_\mu| \cdot \sin\theta$. $(P_\mu)_\|$ is longitudinal polarization of muon along $\mathbf{B}$, $(P_\mu)_\perp$ is transversal polarization.

The layout of experiment for transverse polarization measurement is shown on Fig.4. The muon counter scintillator is placed in a center of the magnet around point X=Y=Z=0. Incoming muon stops in the 2mm thick scintillator. Value of $(P_\mu)_{||}$ in a scintillator is ≅0.3 at B≅0 [2] and it grows to ≅ 1 at B>1T [3]. Positron counter with cubic 2″ scintillator registers decaying positrons. Both counters have light guides with length ≅ 2.5m to remove photomultipliers out of the big magnetic field (out of iron shield). Muon and positron signals from Constant-Fraction Discriminator (CFD) serve as <u>start</u> and <u>stop</u> of TDC. A typical μSR picture should be observed. Amplitude of the precession equals to $A_\perp \cong 1/3\cdot|\mathbf{P}_\mu|\cdot\sin\theta$. Period of the precession equals to T_μ= 3.5ns at B=2.2T. Time resolution of the counters can decrease the amplitude. This decreasing is $\exp[-2(\pi\sigma_t/T_\mu)^2]$, where σ_t is total time resolution. For example the decreasing is ≅0.2 at σ_t=1ns, and ≅0.87 at σ_t=0.3ns.

One can estimate number of photoelectrons (p.e.) from the counters. There are ≅110p.e. and ≅140p.e. for muon and positron counter correspondingly (1γ per 100eV of energy losses, 0.1 is collection efficiency for a small plastic scintillator, 0.1 is an attenuation of the light guides, 0.25 is quantum efficiency of the photomutiplier cathode). The number of p.e. will provide the time resolution σ_t < 0.3ns.

Positron flying forward (from beam or from μ decay) will produce about 54cm^{-1} of Cerenkov photons in the light guide of "muon counter" and < 30p.e. from cathode of the photomultiplier (30p.e. correspond to 50MeV of energy losses). Some part of the events is reject by a threshold of the CFD. Rest part of them can be rejected by prohibition of registration of "two muons" during a time interval of the muon decay observation ΔT. It will decrease an useful rate. The decreasing will be < 5% at $I_\mu = 10^3$ s^{-1}, $I_e = 3\cdot10^3$ s^{-1}, ΔT=10μs.

The mentioned above difference of phases Δφ =18° of muons with momentum 29.8MeV/c and 29.5MeV/c (–1%) at Z=0 (B=2.2T) will cause a small decreasing of $(P_\mu)_\perp$. A small deflection ϕ of the center of the positron scintillator from the perpendicular with respect to the center of the muon scintillator will cause decreasing cosϕ of the $(P_\mu)_\perp$.

Measurement of the amplitude of muon precession $A_\perp \cong 1/3\cdot|\mathbf{P}_\mu|\cdot\sin\theta$ will define the misalignment angle θ. The knowledge of the θ with error of 10mr allows to say that the difference $[|\mathbf{P}_\mu|-(P_\mu)_{||}]$ is not more than $1-\cos(10\text{mr}) \cong 5\cdot10^{-5}$. Generally speaking the precision of the θ has a big systematic error because the multiplier 1/3 in the formula $A_\perp \cong 1/3\cdot|\mathbf{P}_\mu|\cdot\sin\theta$ is defined by the solid angle of the positron counter and the lower energy threshold of positron registration. The multiplier equals to 1/3 at the solid angle 2π and at the energy threshold E_e=0. More precise measurement of the multiplier can be done by comparison of the angles θ measured simultaneously by the PC2 and the scintillator counters at a remarkable initial misalignment θ=30mr, for example. The angles must be equals each other. We can estimate the real value of the multiplier from here. More easy way is to align $\mathbf{p}_\mu$ with respect to **B** by the PC2 assembly up to the θ=1mr. It removes any questions about the real value of the multiplier. After that we must measure the angle θ by the scintillator counters and confirm the previous value of θ≅1mr in order to exclude its influence on the Michel parameter ξ with precision <10^{-4}. Statistic error of the θ in the μSR experiment equals to ≅1mr at total statistics 10^8 of muon decays. It corresponds to ≅10^{5}s of total time at $I_\mu = 10^3 s^{-1}$, and at solid angle $0.1\cdot 4\pi$ of the positron counter. A differential non-linearity of TDC can distort essentially the μSR precession curve because the amplitude $A_\perp \cong 3\cdot 10^{-4}$ is too small.

The misalignment can distort the muon damped exponential by the precession with the amplitude $A_\perp$. Value $A_\perp = 3\cdot 10^{-4}$ (it corresponds to the $\theta \cong$ 1mr) can cause an increasing of χ^2 criterion value at any attempt to fit the curve by an exponential one only. Fortunately the time resolution of the PC2 chambers is about 2.5ns [4]. It will decrease the $A_\perp$ value on additional multiplier factor $\cong 4\cdot 10^{-5}$.

4 Procedure

Both tools the PC2(X+Y) and the scintillator counters are placed into the magnet. The alignment procedure is realized as it has been described above.

5 Remark about M13 beam study

The suggested equipment is useful for study of a time distribution muons, pions and positrons between the cyclotron bunches. The PC2(X+Y) with an amplitude analysis of signals from 48 wires in the central area will provide separation muon from positron. One scintillator with thickness 5mm and diameter 2″ glued just on photomultiplier's cathode allows to measure the particle time distribution with respect to the RF–pulse with a high precision. Combined amplitude analysis of the PM's and the PC2 signals will provide the reliable identification of pions, muons, and positrons. The suggestion requests an additional Monte Carlo simulation. The time distribution of the beam particles is important, for example, for a reliable estimation of the long tail of the cloud muons.

6 References

[1] B. Ramadanovich, D.W. Wright, E614 Technical Note 31, 1999
[2] R. Swanson, Phys. Rev. 112 (1958) 580
[3] Muon polarization in a scintillator at longitudinal magnetic fields has been measured in an article of "Nuovo Cimento" journal. I do not remember the year (1958 or 1968) and the title. I remember only that A. Zichichi is author of the article. I had not to find out the article.
[4] Y.Y. Lachin, L.V. Miassoedov, I.V. Morozov, V.I. Selivanov, I.V. Sinitzin, V.D. Torokhov, Nucl. Instr. and Meth. A361(1995)77.

7 Figure captions

Figure 1. Muon beam profiles at Z=0 for the tune #1. Misalignment between $\mathbf{p}_\mu$ and **B** is 10mr.
Figure 2. Muon beam profiles at Z=0 for the tune #3. Misalignment between $\mathbf{p}_\mu$ and **B** is 10mr.
Figure 3. Muon beam profiles at Z=0 for B=2.2T and B=2.0T.
Figure 4. The layout of experiment for measurement of transversal polarization $\mathbf{P}_\mu$. Center of the 2mm thick scintillator coincidences with the point X=Y=Z=0. Center of the positron scintillator is on plane Z=0.