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The Instrumentation Channel for the MUCOOL Experiment*

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Abstract

The MUCOOL facility is proposed to examine cooling techniques that could be used in a muon collider. The solenoidal beam channel before and after the cooling test section are instrumented to measure the beam emittance. This instrumentation channel includes a bent solenoid to provide dispersion and time projection chambers to measure the beam variables before and after the bend. The momentum of the muons is obtained from a measurement of the drift of the muon trajectory in the bent solenoid. The timing measurement is made by determining the phase from the momentum of the muon before and after it traverses RF cavities or by the use of a fast Cherenkov chamber. A computer simulation of the muon solenoidal channel is performed using GEANT. This study evaluates the resolution of the beam emittance measurement for MUCOOL.

1 INTRODUCTION

The MUCOOL facility has been proposed as an experimental program for testing techniques that can be used for muon cooling in a muon collider[1]. The facility would include a target area in the FNAL meson area, followed by a quadrupole focussed decay channel, a bending magnet for muon momentum selection, an instrumented muon solenoid channel before and after the experimental region to measure the beam emittance[2]. This paper will discuss the measurement of the emittance in the instrumentation channels. Fig. 1 illustrates the instrumentation channel. It is a bent solenoidal channel. The solenoidal bend causes a drift vertical to the plane that is proportional to the particle momentum. This drift will be used to measure the muon momentum. Time projection chambers (TPC) are positioned before and after the solenoidal bend. These TPCs are filled with a low pressure methane gas that has a long mean free path. The TPCs can measure the transverse beam variables : x, y, x' and y'. By comparing TPC beam measurements before and after the bend one can measure the beam momentum. Fig. 1 shows two bent solenoid regions with RF cavities in between. This arrangement is chosen to be able to measure the muon momentum before and after the RF cavities. The comparison of the momenta can be used to extract the time information from the RF phase. Using RF for the time information is one of two approaches under consideration. The other is to use a fast Cherenkov device for the time information. The scope of this paper is to examine how well one can measure the beam momentum using the bent solenoid. Table 1 lists the important parameters describing the instrumentation channel.

The experiment has set as a goal the ability to measure the emittance with a relative error of 3%[3]. To achieve this goal the desired relative uncertainty in the measurement of each of the six phase space variables should be $\approx 1\%$. Table 2 shows the required detector resolution to achieve 1 % accuracy in the measurement of the phase space parameter.

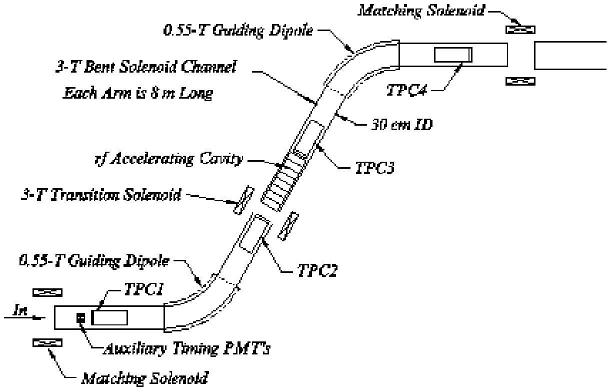

Figure 1: Schematic of the measurement channel

Table 1: Parameters used for the MUCOOL Instrumentation Channel.

Parameter	Value
RF frequency	805 MHz
Momentum	171 MeV/c
$B_{solenoid}$	3 tesla
$B_{guiding}$	0.56 tesla
θ_{bend}	1 radian
R_{bend}	100 cm
$R_{aperture}$	15 cm
β^*	36.7 cm
TPC length	45 cm
$\sigma_x = \sigma_y$	12 mm
$\sigma_{x'} = \sigma_{y'}$	60 mrad
Total length	9.2 m

2 SIMULATION

The MUCOOL instrumentation channel was modelled in GEANT[4]. The channel is designed to transport muons with a mean momentum of 171 MeV/c. The solenoidal magnet field of the instrumentation channel is described with current rings. The field for a single ring can be expressed by an analytic expression[5]. The field at any point in the solenoidal channel is obtained by summing the con-

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Table 2: Required detector resolution to achieve 1 % accuracy of the phase space parameter.

Parameter	**Resolution**
$\delta\sigma_x = \delta\sigma_y$	200 μm
$\delta\sigma_{x'} = \delta\sigma_{y'}$	5 mrad
$\frac{\delta P}{P}$	0.14%
$\delta\sigma_z$	2 mm
$\delta\sigma_t$	8 ps

tributions of the single rings. This procedure accurately describes the field in the transition region between the straight and curved solenoids. A dipole magnet field is superimposed on the bent region of the solenoid. This dipole field is set to cancel the drift of a muon with the mean momentum. Fig 2 shows the local magnetic field components along the center of the channel. The axial field is 3 tesla at the center and varies radially from the center of curvature in the bent region. The vertical field in the bent region has a central value of 0.56 tesla and has a *hyperbolic tangent* form as an approximation for the ends. The dipole field falls off with an attenuation length equal to the solenoid aperture radius. The shape of the local B_x (in-plane transverse field) component depends on how abrupt the transition is between the straight and curved regions of the channel.

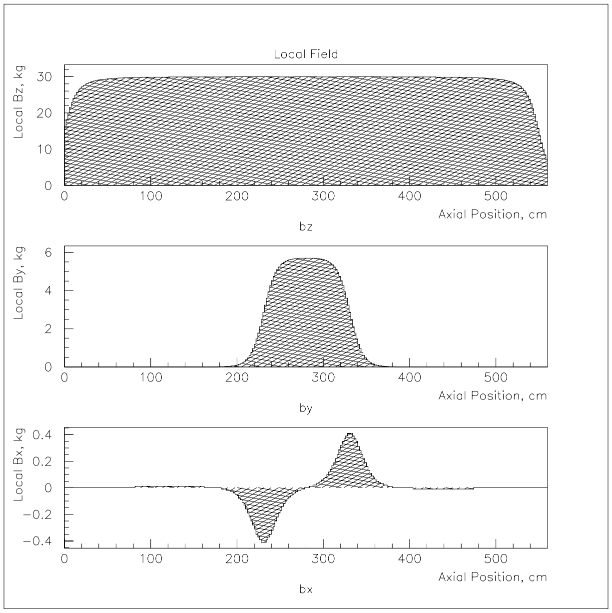

Figure 2: Components of the field as seen in the local coordinate system along the center of the solenoid channel. The field is in *kilogauss.*

The GEANT simulation will produce hit digitization in the TPCs. These hits include uncertainties for the measurement and for drift in the TPC low pressure methane gas. The measurement uncertainties for the hit position are 200 μm in transverse directions and 2 mm in the axial direction. The uncertainties from diffusion in the TPC gas is $0.0025\,\sqrt{z}\,cm$ in the transverse direction and $0.135\,\sqrt{z}\,cm$ in the longitudinal direction. The longitudinal drift error can be 1 cm for a point that is on the opposite side of the chamber from the readout.

3 ANALYSIS

Events are generated in GEANT corresponding to a normalized transverse emittance of 1300 $\pi\ mm\ mrad$ in each direction. 184 MeV/c muons initially have a spread of $\frac{\Delta P}{P} = 3\%$ and loose energy traversing the auxiliary timing scintillator. The TPCs before and after the bent solenoid will typically produce about 12 hits on a track. The TPC hits are fitted to a helix in a reconstruction program[6]. The beam variables can be determined from the fitted helix parameters and compared to the beam variables known in GEANT. Fig 3 shows the deviation of the reconstructed beam variables x, x', y, y' from the known variables. Table 3 gives the RMS errors for the beam variables determined from Fig 3.

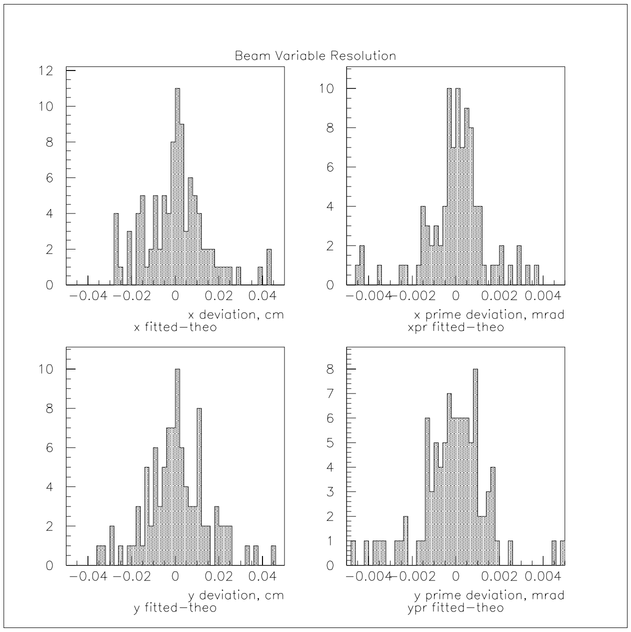

Figure 3: Deviation of reconstructed beam variables, x, x', y, y', from known values in GEANT. x and y are in cm and x' and y' are in radians.

The muon will traverse the solenoidal channel with a helical path. One wishes to measure the drift of the centroid of the helix, not the position of the muon at some specific phase. The center of the helix is known from the path reconstruction. The errors in the measurement of the helix center (x_{ctr}, y_{ctr}) at the TPC is given in Table 3. The error in determining the helix center will contribute to the ultimate error in the determination of the momentum.

Fig 4.a shows a scatter plot of P_μ known from GEANT verses the vertical drift traversing the bent solenoid. There is a strong correlation between P_μ and Δy as expected.

Table 3: Resolution of the beam variables achieved in the simulation.

Parameter	Resolution
$\delta x = \delta y$	127 μm
$\delta x' = \delta y'$	1.0 mrad
$\delta x_{ctr} = \delta y_{ctr}$	150 μm
$\frac{\delta P}{P}$ from ΔY	1.3%
$\frac{\delta P}{P}$ from Pitch	1.8%

Fig 4.b shows the deviation in momentum of the points from the best fit straight line through the data. This figure establishes the error in momentum from the vertical drift to be 2.3 MeV/c or $\frac{\delta P}{P} = 1.3\%$. Fig 4.c shows the deviation in momentum obtained from measuring the helix pitch in the TPC alone. This independent measurement sets the momentum error at 3.0 MeV/c or $\frac{\delta P}{P} = 1.8\%$. These determinations of momentum are not adequate for the emittance measurement, particularly if time is measured from the RF phase since a difference in momentum before and after the RF cavities would be necessary for that.

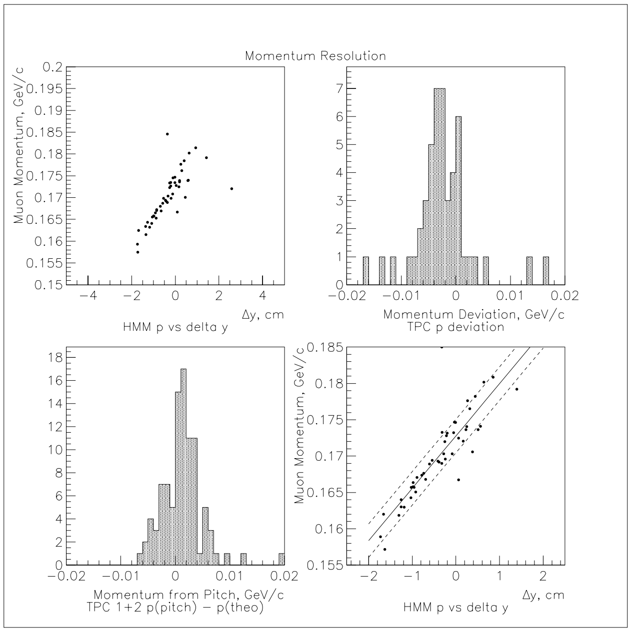

Figure 4: *a*: Scatter plot of P_μ vs Δy; *b*: Deviation of P_μ from best line fit to data. *c*: Deviation of momentum determined from pitch measurement in the TPCs.

4 DISCUSSION

The ΔP_μ spread in P_μ determined from the vertical drift shown in Fig 4 is likely to come from different paths that the different muons take through different parts of the field. Fig 5 shows a histogram of the path lengths that the individual muons traverse from the center of TPC1 to the center of TPC2. An individual muon will sample a different B_x as it enters the bent part of the solenoid than when it leaves the bent solenoid. The non cancelation of the B_x component can affect the vertical displacement of a particle. Fig 5 shows the path length and integrated fields seen by each muon in its local frame. The variation in $\int B_x\, ds$ could account for the ΔP_μ.

A possible procedure to improve the precision of the muon momentum measurement is the following: Using the vertical drift as a first estimate of the muon momentum, track a particle from TPC1 through the solenoid channel magnetic field to TPC2 using several values of the momentum in the vicinity of the first estimate. A χ^2 comparing x, x', y, y' can be assigned to each momentum *guess*. One can use an iterative process find the best momentum. An evaluation of this procedure has not been completed at this moment.

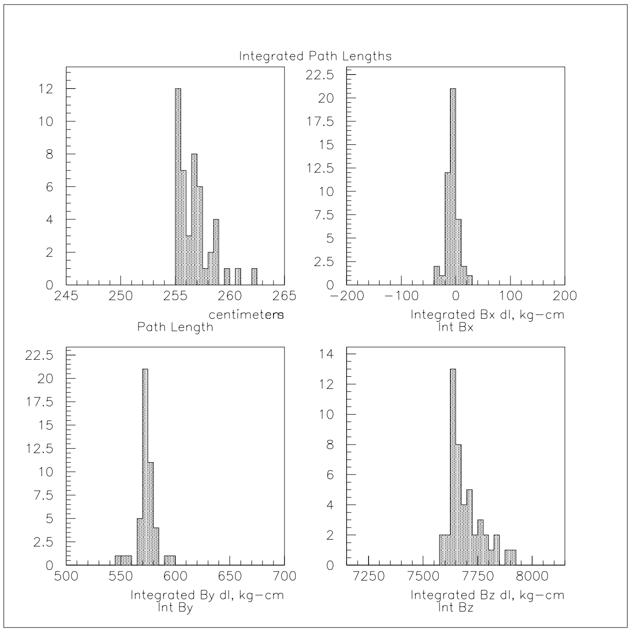

Figure 5: *a*: Total path length from TPC1 to TPC2; *b*: $\int B_x\, dx$ *c*: $\int B_y\, dy$, *d*: $\int B_y\, dz$

5 REFERENCES

[1] MUCOOL Proposal: Ionization Cooling R & D Program for a High Luminosity Muon Collider, Fermilab proposal 904

[2] A Detector Scenario for the Muon Cooling Experiment, C. Lu, K.T. McDonald and E.J. Prebys, Princeton/$\mu\mu$/97-8.

[3] Accuracy of Measurements in the Muon-Collider Cooling Experiment, K.T. McDonald and E.J. Prebys, Princeton/$\mu\mu$/97-4.

[4] GEANT Detector Description and Simulation Tool, CERN Program Writeup W5013.

[5] W.R. Smythe, Static and Dynamic Electricity, 2nd. Edition (1950), p271.

[6] The program uses TpcTrack fitting algorithms written by Xihong Yang for use in the BNL E910 experiment