CERN Report

AFP and ALFA detectors as a momentum spectrometer system feasibility study

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Abstract

We consider a possibility to measure a leading proton momentum using simultaneously the AFP and ALFA detectors. The idea is based on the simple fact that the proton trajectory through the magnetic field between the AFP and ALFA$_1$ detectors, depends on the proton's momentum loss ξ. The feasibility of the proton momentum measurement is directly related to the availability of the magnetic fields and their configuration, the overlap between ALFA and AFP detectors and their resolutions as well as energy losses and the multiple scattering effect that could wash away little actions from the magnets on the proton.

Contents

1 Determination of proton momentum loss

Between AFP(tracker 1) and ALFA(tracker 2) (see Figure 1) there is a vertical kicker and a quadrupole. Their fields affect the traversing proton and the effect depends on the proton's energy or by different terms, on it's energy loss.
To derive the proton momentum loss ξ[1], we have to extrapolate the coordinates $(z,\, z')$ of the proton measured by the AFP system into ALFA location assuming that it has $\xi = 0$. Then we measure the final coordinates $(\tilde{z},\, \tilde{z}')$ by ALFA system. Afterwards, we calculate the difference between $\tilde{Z}(\xi)$ and $Z_{\text{extrapolated}}(\xi = 0)$ which is basically the action of the magnet system on the coordinates of the proton. Finally, we end up with the dependency on ξ and thereby we determine the momentum.

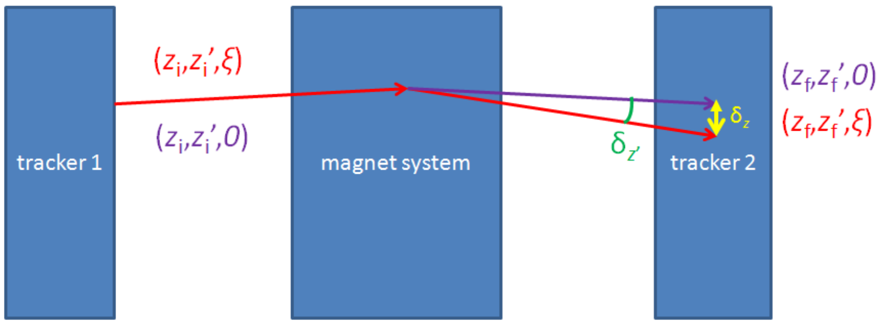


Figure 1: The track parameters, measured by tracker 2(ALFA), of 2 protons with the same position and angle at location of tracker 1 (system AFP) allows to determine ξ.

2 Summary of the project steps and results

2.1 Accelerator optics

The transport matrix between AFP [1] and ALFA [2] stations was derived keeping magnets parameters as free. Then we implemented one of the current settings of the magnets using Twiss files from MADx [5] for which we used the collision optics $\beta* = 0.55$ m and 8 TeV. The steps were as follows:

- First and second order approximation of the quadrupole [3, 4] were considered.
- Construct an analytical total transfer matrix T[2] between AFP and ALFA.
- Numerical results were compared with the EasyTracker [6] software.

2.2 Energy losses and multiple scattering effect

The derivation of a proton momentum from coordinates measured by the AFP and ALFA detectors has to cover all effects which can potentially affect it: energy losses, multiple scattering and detectors resolutions. We made estimations both using existing theoretical models, and by running simulations on a simple model of AFP and ALFA detectors that we have created in Geant4.

2.2.1 Calculations based on theories

The energy loss of the diffractive proton caused by the multiple scattering while traversing the Roman pots (different material for each), using the *Landau-Vavilov* formula [7] is:

$$\Delta_p \longrightarrow \xi(\ln \frac{2mc^2\xi}{(\hbar\omega_p)^2} + j)\,\text{when} : \beta\gamma > 100 \tag{1}$$

[1]The momentum loss : $\xi = \frac{P - P_0}{P_0}$

[2]The matrix T represents the total transformation of the elements between the AFP and ALFA detectors: Drift_{AFP} - Drift_1 - Vertical kicker - Drift_2 - Quadrupole - Drift_3.

The energy losses are of the order of MeV and can be safely neglected as we are interested in measuring $\xi \in [0.001; 0.2]$ which corresponds to a range of energy of [1 GeV;0.2 TeV].

The spatial/angular deviation caused by the multiple scattering (see Figure 2)is well described by:

Lynch and Dahl's formula [7]:

$$\theta_0 = (\frac{\chi_c^2}{1+F^2}(\frac{1+\upsilon}{\upsilon}ln(1+\upsilon)-1))^{1/2} \tag{2}$$

Or Highland's formula [7]:

$$\theta_0 = \frac{13.6MeV}{\beta cp}z(\frac{x}{\chi_0})^{1/2}(1+0.038ln(\frac{x}{\chi_0})) \tag{3}$$

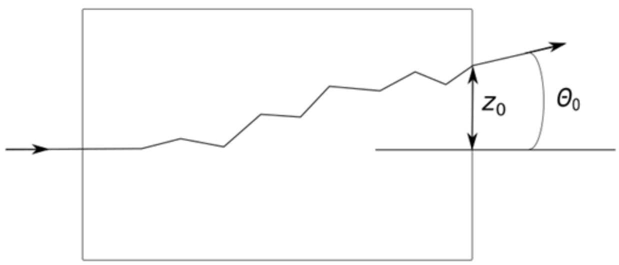


Figure 2: Multiple scattering effect

We estimated:
The deviation angle for AFP $\sim$ 4.4 $\mu rads$ for 1 TeV, which by momentum scalling gives 0.6 $\mu rads$ for 7 TeV
Similarly, the deviation angle for ALFA $\sim$ 5.1 $\mu rads$ for 1 TeV, and 0.72 $\mu rads$ for 7 TeV

2.2.2 Simulations using Geant4

We designed a simple model detector of the AFP and ALFA detectors (see Figure 3) and ran simulations with 100k events. We got confirmed that the multiple scattering effect on energy can be neglected. As for the spatial/angular distribution:
In AFP, the deviation angle $\approx$ 3.9 $\mu rads$ for 1 TeV which by momentum scalling gives 0.55 $\mu rads$ for 7 TeV.
Similarly, in ALFA, the deviation angle $\approx$ 3.9 $\mu rads$ for 1 TeV and 0.55 $\mu rads$ for 7 TeV.

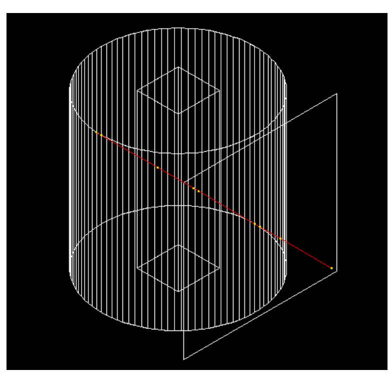
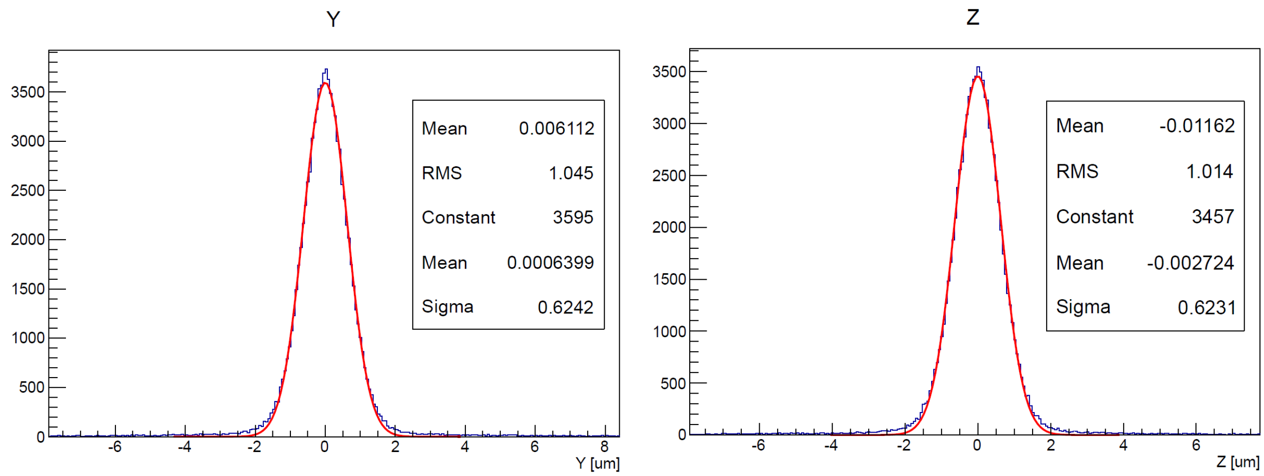


Figure 3: OGL visualization of the model Detector (Geant4)

2.2.3 Plotting the results using ROOT

The data output of the 100k protons generated with 1 TeV and traversing perpendicularly the detector's surface, was plotted using ROOT (see Fig 4). The deviation angle was derived from the standard deviation of the Gaussian fit. The following plots are for the AFP - Silicon detector. The results for the ALFA - Fiber detector was obtained in a similar way.



(a) AFP in Y direction

(b) AFP in Z direction

Figure 4: Multiple scattering effect for AFP - angular distribution

2.3 Calculation of ξ

As explained in Section 1, the determination of ξ is derived from the difference of coordinates measured and extrapolated. For collision optics $\beta* = 0.55$m (8 TeV):

$$\Delta(Z) = f(\xi) - f(0) = \tilde{Z} - Z_{\text{extrapolated}} = \begin{pmatrix} \delta_z \\ \delta'_z \\ \xi \\ 0 \end{pmatrix} = \begin{pmatrix} 0.652\,\mathrm{z}' + 0.0314\,z + 6.341 \times 10^{-4} \\ 0.0615\,\mathrm{z}' + 0.00296\,z + 3.9495 \times 10^{-5} \\ 1 \\ 0 \end{pmatrix} \xi \tag{4}$$

Since the term 0.652 z' is of the order of 10^{-7} m $\lesssim 6.341 \times 10^{-4}$ and the term 0.0314 z is of the order of 10^{-5} m $\lesssim 6.341 \times 10^{-4}$, we assume that $z = 0$ and $z' = 0$ in the following to analyze the range of ξ.
We can write:

$$\Delta(Z) \approx \begin{pmatrix} \delta_z \\ \delta'_z \\ \xi \\ 0 \end{pmatrix} \approx \begin{pmatrix} 6.341 \times 10^{-4} \\ 3.9495 \times 10^{-5} \\ 1 \\ 0 \end{pmatrix} \xi \approx \begin{pmatrix} 6.341\,[\mu m] \\ 0.39\,[\mu rads] \\ 0.01 \\ 0 \end{pmatrix} \xi[\%] \tag{5}$$

However the AFP detector has limited resolution and in addition, we have to include the multiple scattering effect and the propagation of the full error due to the measuring in AFP of (z, z').

2.4 Deterioration effects: multiple scattering and detectors resolution

The error on measurement of AFP transported[3] to ALFA location[4] is shown in the variance matrix where: T[5] is the transport matrix, Σ is the variance-covariance matrix. The effect of ξ is omitted or it can be totally neglected:

$$
\begin{aligned}
V_{\text{error}} &= T\,\Sigma\,T^t \\
&= \begin{pmatrix} 0.968 & 24 & 0 & -0.000636 \\ -0.00296 & 0.973 & 0 & -0.0000396 \\ 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 1.0 \end{pmatrix} \begin{pmatrix} \sigma^2_{\text{zAFP}} & 0 \\ 0 & \sigma^2_{\text{z}'\text{AFP}} \end{pmatrix} \begin{pmatrix} 0.968 & -0.00296 & 0 & 0 \\ 24 & 0.973 & 0 & 0 \\ 0 & 0 & 1.0 & 0 \\ -0.000636 & -0.0000396 & 0 & 1.0 \end{pmatrix} \\
&= \begin{pmatrix} 26.8^2\,[\mu m]^2 & 4.77^2\,[\mu m\,.\mu rads] \\ 4.77^2\,[\mu m\,.\mu rads] & 0.855^2\,[\mu rads]^2 \end{pmatrix}
\end{aligned}
\tag{6}
$$

The effect of multiple scattering, caused by the passage of the proton through AFP, transported to ALFA location is:

$$
\begin{aligned}
V_{\text{MS}} &= T\,\Sigma_{\text{MS}}\,T^t \\
&= \begin{pmatrix} 0.969 & 29.8 & 0 & -0.000635 \\ -0.00296 & 0.956 & 0 & -0.0000396 \\ 0 & 0 & 1.0 & 0 \\ 0 & 0 & 0 & 1.0 \end{pmatrix} \begin{pmatrix} \sigma^2_{\text{zMS}} & 0 \\ 0 & \sigma^2_{\text{z}'\text{MS}} \end{pmatrix} \begin{pmatrix} 0.969 & -0.00296 & 0 & 0 \\ 29.8 & 0.956 & 0 & 0 \\ 0 & 0 & 1.0 & 0 \\ -0.000635 & -0.0000396 & 0 & 1.0 \end{pmatrix} \\
&= \begin{pmatrix} 22.4^2\,[\mu m]^2 & 4.45^2\,[\mu m\,.\mu rads] \\ 4.45^2\,[\mu m\,.\mu rads] & 0.897^2\,[\mu rads]^2 \end{pmatrix}
\end{aligned}
\tag{7}
$$

and finally we have also an error of measurement at ALFA location, which corresponds to the resolution of the ALFA system (2 stations): $\sigma_{\text{zALFA}} = 21.2\,[\mu m]$ and $\sigma_{\text{z}'\text{ALFA}} = 3.75\,[\mu rads]$

Thereby the final error on $\Delta(Z)$ is:

$$\sigma_{\text{total}}(z) = (\sigma^2_{\text{zMS}} + \sigma^2_{\text{zAFP}} + \sigma^2_{\text{zALFA}})^{1/2} = 40.8\,[\mu m] \tag{8}$$

$$\sigma_{\text{total}}(z') = (\sigma^2_{\text{z}'\text{MS}} + \sigma^2_{\text{z}'\text{AFP}} + \sigma^2_{\text{z}'\text{ALFA}})^{1/2} = 4\,[\mu rads] \tag{9}$$

2.5 Project conclusion

From the last section (2.4) we conclude that by deriving ξ using the difference in z, the precision on ξ would be 6.3% and as the limit of ξ is 20%[6] we can only make 3 bins in the ξ range of [0;20 %] and therefore we have a poor precision on ξ.

As for deriving ξ using the difference in z', the precision on ξ would be 10.1% which is even larger.
However, a deeper study must be done on the current overlap of AFP and ALFA detectors.
The optimization of the possibility to determine the momentum could be achieved by:

[3]Transported from the middle of the AFP detector system.
[4]Transported to the middle of the ALFA detector system.
[5]The matrix is defined in footnote of Page 2.
[6]This value is the maximum energy loss ξ determined from the histogram of the detector ALFA's acceptance

- Improving the resolution and the overlap of the detectors
- Changing the configuration of the magnets between AFP and ALFA in a way to maximize their effect.

3 Learned and developped skills

3.1 Physics

- Accelerator optics
- Passage of particle through matter
- Basics of statistics

3.2 Software (basics of)

- **Geant4** Designing a basic Detector - Creating a source of particles - Running simulations - Extracting Data - Visualization.
- **Root**
  Stocking Data - Plotting - Fitting
- **Linux, Git, Python, Web technologies**
  Automating tasks with the Unix shell - Version control with Git - Building programs with Python - Visualization and Interaction using Web Technologies.

3.3 Communication skills

- Took part in ALFA and AFP meetings
- 2 talks presented about the project

3.4 Workshops

- Root workshop (15/07/2015)
- Cloud chamber workshop (01/07/2015)
- CERN Webfest Software Carpentry workshop (27/07/2015 untill 30/07/2015)
- MadGraph workshop (20/08/2015)

References

[1] ATLAS collaboration, "Technical Design Report for the ATLAS Forward Proton Detector", Report number: CERN-LHCC-2015-009 ; ATLAS-TDR-024

[2] ATLAS collaboration, "ATLAS Forward Detectors for Measurement of Elastic Scattering and Luminosity", Report number: CERN-LHCC-2008-004 ; ATLAS-TDR-18

[3] Klaus Wille, "The Physics of Particle Accelerators"

[4] J.Rossbach and P.Schmuser, "Basic course on accelerator optics"

[5] https://twiki.cern.ch/twiki/bin/viewauth/Atlas/AlfaOptics

[6] KOMAREK, T.: "Visualization of particle tracks in an accelerator magnetic field" - Univerzita Palackého v Olomouci

[7] Particle Data Group, "Review on particle physics - 2014", Section 32. "Passage of particles through matter"