Leading Proton Detection in Diffractive Events for an LHC Low-β Insertion

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ABSTRACT

With the aim to identify diffractive events at the LHC collider we present a scheme which allows to measure the momentum loss of forward protons in the range $2 \times 10^{-3} < \Delta p / p < 0.1$. This momentum loss can be determined with a precision of about 10%. Using the optical functions of the machine for a standard insertion we have optimised the position of the detectors along the beam line.
1. Introduction

A large fraction (> 20%) of the total inelastic pp cross-section is due to diffractive processes where one of the two protons (single diffraction) or both protons (double diffraction) lose momenta but stay intact. It is currently believed that single diffraction is mediated by a Pomeron which interacts with the partons of the other proton giving rise to an excited mass $M$ recoiling against the intact proton. Recent studies indicate that the Pomeron is a quasi real particle with partonic structure $^{[1]}$. The study of inelastic diffractive processes is difficult since in most of the cases the particles leave in the very forward region. However, it is most interesting to study the interactions of such a Pomeron beam which may e.g. lead to an enhanced production of heavy flavours $^{[2]}$ or even to new particles. The possibly best way to identify diffractive events is the tagging of the intact forward proton and the measurement of its momentum loss which is equal to the momentum of the Pomeron. The mass $M$ of the system $X$ in which the other proton is excited is given by this relative momentum loss $\xi = \Delta p/p_0$.

$$1 - x = \xi = \frac{M^2}{s} \quad (1)$$

where $\sqrt{s}=2p_0$ is the centre of mass energy of the collision. At the LHC ($\sqrt{s}=14$ TeV) the physical meaningful range of $\xi$ is given by:

$$\frac{(m_\pi + m_x)^2}{s} < \xi < \frac{m_x}{m_p} \Leftrightarrow \quad 6 \times 10^{-9} < \xi < 0.15 \quad (2)$$

The largest momentum loss leading to an excited mass of around 4 TeV or a Pomeron momentum of above 1 TeV is limited by the coherence condition, whereas the lowest mass corresponds to the production of one additional pion. The momentum loss of the proton in diffractive events at the LHC is therefore in the range of $10^{-8}$ to $10^{-1}$. However, any measurement of the momentum loss is limited by the natural momentum spread of the beams to $\xi > 10^{-4}$.

2. Momentum Measurement Using the Machine Optics

Momentum measurement using the existing accelerator optics is based on the dispersion $D(s)$ of the machine, where $s$ is the distance to the interaction point along the beam. Consider a particle with a small momentum loss, which was produced at an interaction point by the collision of two protons in their nominal orbits. The particle's departure $x$ with respect to the nominal orbit at any point of the lattice is given by:

$$x = \xi D(s) \text{ with } \xi = \frac{\Delta p}{p_0} \quad (3)$$
$x$ is measured perpendicular to the beam and parallel to the bending plane. For all equations involving machine optical functions, see e.g. Ref. [3].

2.1 Acceptance

The momentum deviation $\xi$ can be obtained from a determination of the transverse displacement, $x$, of the particle using e.g. detectors in 'Roman Pots' [4]. The range which can be covered is, however, limited by the transverse dimension $\sigma_x$ of the beam at the point where the measurement is performed. In order not to disturb the beam, the detector has to be placed at least at a distance $K \cdot \sigma_x$ from the beam centre where a good choice of $K$ is about 10. The lower bound of $\xi$ is then given by:

$$\xi_{\text{min}}(s) = \frac{K \sigma_x(s)}{D(s)}.$$  \hspace{1cm} (4)

The size of the circulating beam has two components: one given by the beam emittance $\varepsilon$ and the $\beta$-value and the second given by the natural beam momentum spread $\xi_0 \sim 10^{-4}$ and the dispersion:

$$\sigma_x(s) = \sigma_\beta \oplus \sigma_\xi = \sqrt{\varepsilon \beta_x(s)} \oplus \xi D(s).$$  \hspace{1cm} (5)

In the LHC arcs, $D$ and $\sigma_x$ are typically 1 m and 0.2 mm, respectively, which results in a $\xi_{\text{min}}$ of $2 \times 10^{-3}$ for $K=10$.

The upper bound of the $\xi$ acceptance is given by the momentum at which the particle hits the beam pipe of radius $R$:

$$\xi_{\text{max}}(s) = \frac{R}{D_{\text{max}}(s)} \text{ for } \xi D \gg \sqrt{\varepsilon \beta}.$$  \hspace{1cm} (6)

$D_{\text{max}}$ denotes the maximal dispersion the particle has passed before reaching the point $s$.

2.2 Resolution

The precision with which the momentum deviation $\xi$ can be measured is principally limited by the natural momentum spread $\xi_0$ of the beam. However, this limit can only be reached if the position $x^*$ and the angle $\theta_x^*$ of the particle at the interaction point (both quantities measured in the bending plane) can be determined from a series of measurements at different positions. The momentum resolution of a single measurement is given by the width $\Delta x(s)$ of the beam formed by the scattered protons. Using the optical functions of the machine, $\Delta x$ can be related to the spatial and angular spreads ($\Delta x^*$ and $\Delta \theta_x^*$) at the interaction point.
The position $x(s)$ of a particle with nominal momentum depends on the initial conditions at the interaction point ($x^*, \theta^*_x$) and the optical transfer functions expressed by the magnification $v_x$ and the effective length $L^\text{eff}_x$:

\[
x(s) = v_x(s) \cdot x^* + L^\text{eff}_x \cdot \theta^*_x
\]

with \( v_x = \sqrt{\frac{\beta_x(s)}{\beta^*}} \cos \Delta \mu_x \)

\( L^\text{eff}_x = \sqrt{\beta_x(s) \beta^*} \sin \Delta \mu_x \)

\( \Delta \mu_x = \int_0^s ds' \frac{1}{\beta_x(s')} \), the betatron phase advance

Equivalently, the width $\Delta x$ of the scattered beam is:

\[
\Delta x(s) = v_x(s) \cdot \Delta x^* + L^\text{eff}_x(s) \cdot \left( \Delta \theta^*_x + \frac{1}{\sqrt{2}} \left( \theta^2_{\text{scat}} \right)^{\frac{1}{2}} \right)
\]

The \textit{angular} spread has two components: the \textit{rms} beam divergence $\Delta \theta^*_x$ at the interaction point and the \textit{rms} of the scattering angle $\theta_{\text{scat}}$. The factor $1/\sqrt{2}$ arises from the projection into the bending direction $x$. Since the scattering probability is proportional to the square of the particle density the spatial width $\Delta x^*$ of the scattered beam is a factor $1/\sqrt{2}$ smaller than the width of the circulating beam:

\[
\Delta x^* = \frac{1}{\sqrt{2}} \sigma_x^*.
\]

Fig. 1 shows a sketch illustrating the relations between the beam parameters and optical functions for the nominal and scattered proton beam.

Combining the natural momentum spread with the contributions from the angular and spatial beam spreads the resolution $\Delta \xi$ is given by:

\[
\Delta \xi = \xi_0 \oplus \frac{\Delta x}{D}
\]

\[
= \xi_0 \oplus \frac{1}{D} \left[ v_x \cdot \Delta x^* + L^\text{eff}_x \cdot \left( \Delta \theta^*_x + \frac{1}{\sqrt{2}} \left( \theta^2_{\text{scat}} \right)^{\frac{1}{2}} \right) \right]
\]

\[
= \xi_0 \oplus \frac{1}{\sqrt{2}D} \left[ \sigma_x \sqrt{1 + \sin^2 \Delta \mu} \oplus L^\text{eff}_x \left( \theta^2_{\text{scat}} \right)^{\frac{1}{2}} \right]
\]

At places with $\Delta \mu = k\pi/2$ (\(k=0,1,2,\ldots\)) $L^\text{eff}_x$ vanishes and the above expression reduces to:

\[
\Delta \xi = \xi_0 \oplus \frac{\sigma_x}{\sqrt{2D}}
\]
The resolution is then limited by the momentum spread and the beam size at the detector position.

Influence of the Chromaticity on the Resolution

The expression for the resolution involving the optical functions \( v \) and \( L_{\text{eff}} \) have been given in the limit of small momentum deviations \( \xi (\xi < 10^{-3}) \). For large \( \xi \)-values we have to consider that these optical functions are themselves functions of \( \xi \). In a low-\( \beta \) interaction region this chromaticity effect is caused mainly by the additional 'kick' given by the inner triplet quadrupoles (at the \( \beta \)-function maximum \( \hat{\beta} \)) to particles which are off-momentum and off-centre. In a low-\( \beta \) interaction region the chromaticity influences mainly the effective length. In the absence of sextupole correction magnets, the chromaticity effect can be described in first approximation by:

\[
L_{\text{eff}}^{s}(s, \xi) = L_{\text{eff}}^{s}(s, \xi = 0) + \xi v_{s}(s, \xi = 0)L_{c}
\]

\[v_{s}(s, \xi) = v_{s}(s, \xi = 0)\]

with \( L_{c} = \frac{1}{2} \beta \hat{\beta}(kl) \)

\( k \) is the strength and \( l \) the length of the quadrupole at the maximal \( \beta \). Using the LHC parameters \((kl) \sim 0.05 \text{ m}^{-1}, \hat{\beta} \sim 4000 \text{ m}, \beta^* = 0.5 \text{ m} L_{c} \) amounts to \( \sim 50 \text{ m} \). At places where the magnification \( v \) vanishes the chromaticity effect is small. It is largest where \( L_{\text{eff}} \) is 0 and \( v \) maximal. Since the effect is proportional to \( \xi \) it contributes with a constant term to the relative error \( \Delta \xi / \xi \). Using \( v = 15 \), \( D = 1 \text{ m} \) and a typical angular spread of 45 \( \mu \text{m} \) this contribution amounts to \( \sim 3 \% \) dominating the error for \( \xi \) above \( 10^{-2} \).

3. Results for the LHC Low-\( \beta \) Insertion

A detailed description of the LHC low-\( \beta \) insertion used for this study can be found in Ref. [5]. Fig. 2 shows the dispersion \( D \) and the beta function for an even insertion. The derived optical functions \( L_{\text{eff}, x} \) and \( v_{x} \) are given in Fig. 3 versus the distance \( s \) and the betatron phase advance \( \Delta \mu_{x} \). As a consequence of the alternate gradient focusing scheme, the optical functions modulated by the \( \beta \)-function oscillate with a relative phase shift of \( \pi/2 \). Within the low-\( \beta \) insertion the effective length \( L_{\text{eff}, x} \) reaches its maximum value of 45 m between Q2 and Q3 \((s=40 \text{ m})\) and crosses zero between the separation magnets and the outer triplet \((s=200 \text{ m})\).

The 10\( \sigma \) profile of the circulating beam is compared in Fig. 4 with the excursion of a particle having a momentum deviation of \( \xi = 5 \times 10^{-3} \). To reach the best acceptance for protons with small momentum losses the detectors have to be placed more than 300 m upstream in the large dispersion region. The smallest momentum change which can be detected with a counter placed 10\( \sigma \) away from the beam is shown in Fig. 5. At the end of the insertion region and in the arcs \( \xi_{\text{min}} \) varies only weakly around \( 2 \times 10^{-3} \). But due to the
large dispersion in this region particles with $\xi > 0.01$ are lost in the beam pipe. Therefore two "Roman pot" set-ups are needed to cover the whole region $0.002 < \xi < 0.1$.

There is a free space at $\Delta \mu = 495^\circ$ at an optimal place to detect small momentum losses. The beam is rather large there ($10\sigma$ corresponds to 3.6 mm) which is advantageous for the operation of the position detectors and also reduces edge effects. An ideal position to cover the high $\xi$ range (up to 10%) is found between the second separation magnet D2 and the first quadrupole of the outer triplet. In this region the dispersion amounts to 0.09 m. At $s=208$ m where the betatron phase shift $\Delta \mu \chi$ is 180$^\circ$ one obtains the largest acceptance.

The acceptance for these two detector positions is given in Fig. 6. There is enough overlap to ensure an almost full acceptance from $\xi = 0.002$ to 0.09. The upper bound is given by proton losses in the inner triplet and separation dipoles. For the large $\xi$ values considered here, acceptance and resolution are dominated by chromaticity effects.

We are now discussing the $\xi$ resolution. At the interaction point the spatial and angular spreads of the circulating beams amount to 16 $\mu$m and 32 $\mu$rad, respectively. The width of the beam formed by the scattered protons is 11 $\mu$m. In case of diffractive scattering the rms scattering angle projected into the bending plane is $\sim 30$ $\mu$rad which added in quadrature to the beam divergence results in a total angular spread of 45 $\mu$rad for the scattered protons. Using these values and placing the detector at $10\sigma$, Fig. 7 shows the resolution $\Delta \xi$ as a function of the detector position along the beam for $\xi = 0.001, 0.006$ and 0.01. From the resolution point of view the best detector positions are at $\Delta \mu \chi = (3+n)\pi$ ($n=0,1,2..$) where the effective length is zero and the resolution is not limited by the scattering angle. However, chromaticity effects are largest there. Shifting the position by $\pi/2$ ($v=0$) increases the resolution at low $\xi$–values slightly but reduces the chromaticity effects considerably. Our chosen detector position in the free space at $\Delta \mu = 495^\circ$ is optimal for the resolution which stays always below $2 \times 10^{-4}$ for the complete $\xi$-range.

Note that one can add the position measurement of one detector to that of a second placed at a relative distance of $\Delta \mu = 180^\circ$ ($\Delta s = 200$ m). Provided the detector resolution is small enough (order of 10 $\mu$m), the resolution is only limited by the natural momentum spread. The reason is that at these places magnification and effective length have the same absolute value but opposite sign.

The detector for large momentum losses has to be near 180$^\circ$ where the acceptance starts at 1%. Due to the requested small dispersion the error on $\xi$ is large, around 20% with a substantial chromaticity effect.

4. Background

The background in the forward telescopes is difficult to estimate since the gas pressure in the beam pipe and the proton losses due to machine imperfections are not well known. The rest gas in the vacuum chamber in the arcs, mainly CO$_2$ and CO, is liberated from the chamber walls by synchrotron radiation. Hence, beam-gas interactions scale with the square of the beam current, as beam-beam interactions do,
and the background-to-signal ratio is luminosity independent. In the straight section the background is smaller due to the reduced synchrotron radiation.

Assuming a diffractive cross-section of 1 mb, seen by the forward hodoscopes, and $2 \times 10^4$ beam-gas interactions per metre one obtains a signal-to-background ratio of a few percent if beam-gas interactions are integrated over the last 10 m before the hodoscope. By demanding a reconstructed single track pointing to the interaction region this background will be further reduced. Particles from beam gas interactions have momenta much smaller than the nominal beam momentum and those produced far away from the detector are bent into the beam pipe by the dipole magnets. Those produced close to the detector need large angles in order to reach it. Using a 'telescope' arrangement with a detector spacing of $\sim$1m and a spatial resolution of $\sim$20 μm the angular resolution is $\sim$ 20 μrad and it should be possible to reject a large fraction of the beam-gas background applying an angular cut on the measured tracks.

There is a substantial beam halo arising from protons elastically scattered or thrown out of the lattice by machine imperfections. At a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ it is assumed that protons drift with a rate of $2 \times 10^9$ s$^{-1}$ per beam onto the aperture limitations of the beam. With a uniform machine aperture this would correspond to a rate of $8 \times 10^4$ s$^{-1}$m$^{-1}$. The actual background is, however, reduced by at least two orders of magnitude since the beam is cleaned by a sophisticated collimating system placed much closer to the beams (6 σ) [7] than the hodoscope (10 σ). We therefore believe that the background in the forward hodoscopes is tolerable.
References


[5] The LHC Study Group, 'LHC: The Large Hadron Collider Accelerator Project', CERN AC/ 93-03 (LHC). Details of the LHC ring design parameters have been obtained from LHCRING@CERNVM serviced by T. Risselada.


Figure Captions:

Fig. 1
Sketch of the relations between beam parameters and optical functions for the proton beam and the beam formed by the diffractive protons.

Fig. 2
The betatron function $\beta(s)$ (solid line) and the dispersion function $D(s)$ (dashed line) for an even intersection region.

Fig. 3
The effective length $L_{x}^{\text{eff}}$ (solid line) and the magnification $\nu_{x}$ (dashed line) plotted as a function of the distance between detector and interaction point.

Fig. 4
The $10\sigma$ profile of the nominal proton beam as compared to the excursion of a particle with momentum deviation $\xi=\Delta p/p=5 \times 10^{-3}$.

Fig. 5
Minimal measurable momentum deviation $\xi_{\text{min}}$ as a function of the detector position $s$.

Fig. 6
Acceptance as a function of $\xi$ for two different detector positions: $\Delta \mu=495^\circ$ (solid line) and $\Delta \mu=180^\circ$ (dashed line).

Fig. 7
Momentum resolution limit $\Delta \xi$ as a function of the detector position $s$ for various values of $\xi$: Up to $s=880$ m: $\xi=2 \times 10^{-3}$ (solid line), $\xi=6 \times 10^{-3}$ (dashed line), $\xi=10^{-2}$; below $s=200$ m: $\xi=5 \times 10^{-2}$ (solid line), $\xi=10^{-1}$ (dashed line).
\[ \sigma^\text{Beam}_x(s) = \sqrt{\epsilon \beta_x(s)} \oplus \xi \mathcal{D}(s) \]

\[ \sigma^\text{diff}_x(s) = v_x(s) \bullet \Delta x^* \oplus L^\text{eff}_x(s) \bullet \left( \Delta \theta_x \oplus \frac{1}{\sqrt{2}} \left( \theta_{\text{scat}}^2 \right)^{1/2} \right) \oplus \xi \mathcal{D}(s) \]

\[ \Delta x^* = \frac{1}{\sqrt{2}} \sqrt{\beta^* \epsilon} \]

\[ v_x = \frac{\beta_x}{\sqrt{\beta}} \cos(\Delta \mu_x) \]

\[ \Delta \theta_x^* = \sqrt{\frac{\epsilon}{\beta^*}} \]

\[ L^\text{eff}_x = \sqrt{\beta_x \beta^*} \sin(\Delta \mu_x) \]