LHCb 2002-008

TRACK

17 February 2002

The Forward Tracking, An Optical Model Method

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ABSTRACT

This Note describes the so-called Forward Tracking, and the underlying optical model, developed in the context of LHCb-Light studies. Starting from Velo tracks, cheated or found by real pattern recognition, the tracks are found in the ST1-3 chambers after the magnet. The main ingredient to the method is a parameterisation of the track in the ST1-3 region, based on the Velo track parameters and an X seed in one ST station. Performance with the LHCb-Minus and LHCb-Light setups is given.

1 Introduction: Towards LHCb Light

In the setup still recently foreseen for the LHCb detector, so-called LHCb-Classic, the tracking stations providing space point measurements along particle trajectories were roughly equally spread out from the end of the Vertex Locator to the entry window of RICH-2. In its latest version[1], there were nine such Tracking Stations: two stations upstream from the magnet (T1, T2), three stations inside the magnet (T3, T4, T5) and finally four stations just downstream of this (T6 to T9).

Under such conditions, the track finding and reconstruction method has been based on the Kalman filter techniques (for its application to High Energy Physics, see for instance Refs. [2]), which performs simultaneously pattern recognition and track fit. Indeed, as the measurement planes are spread out regularly along the detector, a stepwise method is sharply motivated and of optimum quality. The corresponding algorithms dedicated to the tracking strategy in LHCb are described in Refs. [3].

With such a setup for the LHCb detector, the standard tracking strategy is first to reconstruct track segments in stations T6 to T9 (the so-called seeding region) which carry also some momentum information (10% - 20% accuracy for $\delta p/p$); this is the track seeding step [4]. One then follows these seeds upstream [5] from Station T5 to Station T1 by swimming into the field, opening search windows determined by the uncertainties, first on the seed itself, then on its forthcoming continuations in following Stations. The performance of the combined algorithms is described in [6].

This track solution, constructed from only the Tracking Stations, is then connected with tracks segments identified/reconstructed (independently) in the Vertex Locator (VELO). A global refitting procedure can then be performed [7] in order to combine both kinds of track information in an optimum way. In this approach, the VELO and the T1-T9 Tracker are actually, considered as separate and independent devices and their information is combined only at the very end of the reconstruction procedure.

However, the various parts of the LHCb detector have now been thoroughly considered and most subdetectors have published their Technical Design Report, especially the VELO [8], the RICH [9], and the Outer Tracker [1]. Thus, it becomes possible to give a motivated and realistic estimate of the total thickness (radiation and interaction lengths) of the whole detector, and compare this to what was foreseen at the time of the Technical Proposal [10]. It happens that the detector thickness has increased by a factor of about 2, the total radiation length for VELO + Tracking increased from 0.24 X_0 to 0.46 X_0. This clearly affects the physics performance of the detector.

In order to cure this problem, reduction of the material budget of the LHCb detector has been strongly considered since summer 2001. The main purpose is to lessen the probability of track interaction inside the detector and to allow electrons and photons to reach the electromagnetic calorimeter with reasonable probabilities. This modified setup has been named LHCb-Light and aims at recovering a material budget for the LHCb detector close to the one foreseen at start[10].

Several variants of the LHCb-Light setup have been considered, and the final choice is still pending. They all implement different thinner solutions for the VELO and/or RICH-1 subdetectors, the material of which affecting the tracking downstream; the question of removing the shielding plates which protect RICH-1 from the magnetic field is still pending, but is considered in order to improve the Trigger efficiency and quality. The beam pipe (see [1]) is now implemented with large sections made of an Al-Be alloy, instead of stainless steel.

The baseline is to reduce the material budget for the VELO detector/tank by about 8% radiation length and RICH-1 by a similar amount; however, such improvements are still subject to serious hardware constraints and the actual level of material budget reduction is still awaiting the end of feasibility studies (especially for the RICH-1 mirrors and their support).

In all variants considered to date, however, the Tracking System is strongly reduced: in the present working assumptions, there remains only one station (TT1) upstream from the magnet, located at the exit of RICH-1, and three stations in the region located after the magnet (ST1, ST2, ST3), the former Seeding Region, hereafter called "ST region". From the tracking point of view, the only pending question is whether the region between the VELO and TT1 (essentially the RICH-1 volume) will be finally field free or affected by a significant magnetic field.

As each Tracking Station contributes by about 3% radiation length to the total material budget, going from 9 to 4 Tracking Stations represents a saving of ≅15% radiation length, i.e. about half of the total planned saving. This material reduction relies on the existence of a tracking algorithm which allows good pattern recognition and reconstruction performance with such a drastic reduction of the Tracker part of the LHCb detector.

With such a reduced Tracking System, one can no longer treat separately VELO and Tracker information; stated otherwise, these two kinds of information should be tightly associated from the start at the pattern recognition level, and therefore the tracking strategy should be deeply reconsidered.

Two approaches have been developed so far. The one named "Track Matching" [11] relies on the strategy of reconstructing separately track segments in the ST region and in the VELO. The combination of both sets is done by extrapolating both sets of tracks as straight lines to the magnet centre where one looks for their matching; in this approach, TT1 and the momentum information from the track seed can help in order to reduce fake associations.

The second approach has been named "Forward Tracking" and turns out, basically, to associate the VELO track information with only one plane located in the ST region measuring a track coordinate in the bending plane; of course one has *a priori* to loop over all hits in this plane. Adding such information from the ST region is equivalent to providing momentum information to the VELO track seed. The VELO track information and this additional coordinate x_S are sufficient to define a candidate trajectory anywhere and has to be confirmed by finding enough additional hits in the other layers of all stations in the seeding region and at TT1.

Basically, these two strategies rely on the same physics background, which is to consider tracks as light rays and the magnet as a thin prism. They have different advantages/drawbacks and are complementary to a large extend. Among other properties, let us mention:

- The Forward Tracking should intrinsically be faster as each VELO track, when associated with a x measurement in some layer from the ST region, already defines search windows anywhere in between and these windows can be made narrower using the information provided by each newly found hit. The method can also apply to a given subset of VELO tracks (for instance, those coming from a secondary vertex) without proceeding to a full reconstruction in the ST region. Moreover, tracks that leave relatively poor information in the ST region can be accessed with a reasonable efficiency.

- The Track Matching can allow more easily than the Forward Tracking a relative alignment of the VELO and the ST stations. The standalone reconstruction in the ST region is the only way to reconstruct K^0_S that leave little (or no) information in the VELO.

In the rest of the paper, we first describe the tracking concept that underlies the Forward Tracking pattern recognition method; this is basically a common work of both authors. We then present in details the pattern recognition algorithm, which is mostly the work of O.C.

The paper is organized as follows: In Section 2 we first review the basics of the Transfer Formalism which defines an Optical Model to perform tracking and pattern recognition; then we discuss how fringe field effects modify the usual picture. Finally, we present a track parameterization well adapted to the structure of the LHCb tracker stations. With respect to the standard Transfer Formalism, this turns out to give up parameterizing particle hits on planes located at given locations in favour of parameterizing the track trajectory itself. In this way, the Forward Tracking pattern recognition algorithm is able to deal with a very few parameters, which can be determined using events generated with the standard LHCb Monte-Carlo program. Section 3 develops the iterative method used in order to get the "Forward Tracking" parameters. Section 4 describes the pattern recognition algorithm: Seed finding, track extrapolation from station to station, ghost and clone cleaning up. The performance is given in Section 5 for the LHCb-Light setup, and for what is known as "LHCb-Minus" which is the classic LHCb setup, with nominal RICH and VELO detectors, but with the tracking system of the LHCb-Light setup. The conclusions are gathered in Section 6 .

2 The Transfer Formalism Framework

The trajectory[1] of a particle travelling in any electromagnetic field can be entirely defined anywhere knowing 5 parameters (and the field). When the field is generated by a magnetic dipole, it is appropriate to parameterize the track trajectory in terms of one space coordinate (for instance along the beam direction) z and write it: $\{x=P_x(z), y=P_y(z)\}$. In this case, an appropriate choice for the track parameters are the track coordinates (x,y) at some given z, the components of the tangent to the trajectory there (S = dx/dz, $T = dy/dz$) and the associated momentum (p), which is conserved all along the trajectory, if energy losses can be neglected. One can replace the momentum by the x coordinate at another z, provided there is field between the two points.

These track parameters are appropriate phase space variables: knowing one point in the phase space and the field map, it is indeed possible to derive track information and predictions anywhere, using only the equations of motion.

2.1 The Transfer Model Trivialized

For illustrative purposes, let us consider an idealized experimental setup consisting of two measurement planes before an ideal dipole magnet, with no fringe field, and two more measurement planes after it, as depicted in Figure 1; let us also specialize into the bending plane. These 4 planes give information that, for each pair, are equivalent to a coordinate and a slope.

[1] We discard problems related with energy losses, which require a special treatment.

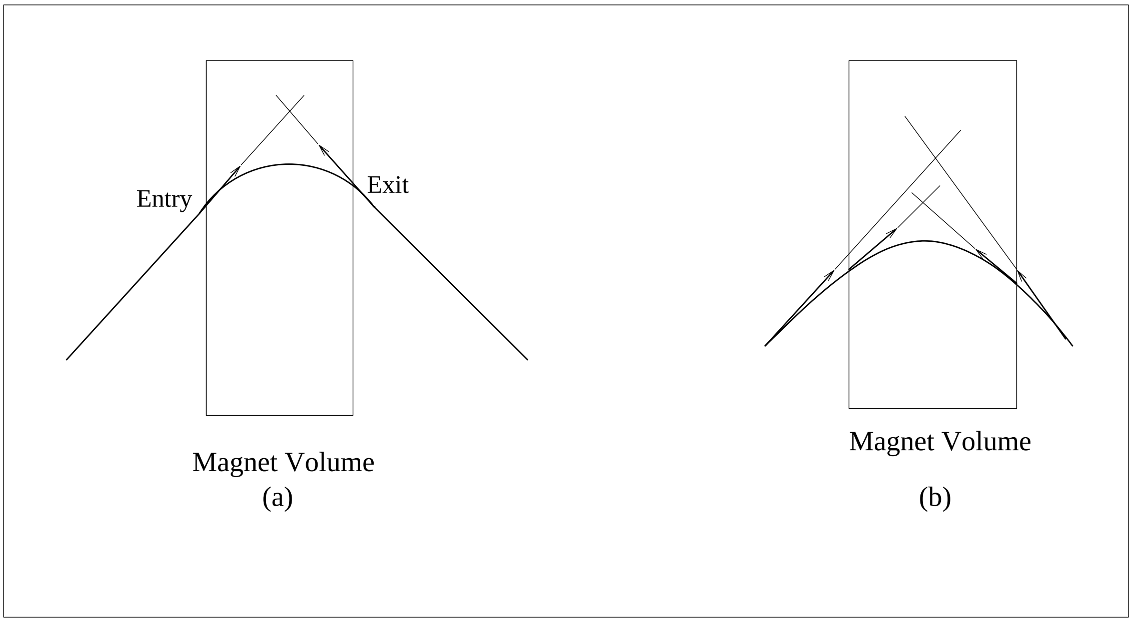

Figure 1 Principle of the Transfer Model. a) No fringe field. b) With fringe field

Any track trajectory before and after the magnet is a straight line and both pieces intersect at a point named the magnet centre. The angle between the upstream and downstream track segments is related with the momentum by:

$$\theta = \frac{\int \vec{B}.\vec{d}l}{p} \tag{1}$$

and depends also on the field integral along the path actually followed by the track inside the field. The magnet centre *z* coordinate is not a fixed value; it depends on the track slopes before and after the magnet, or on one of these slopes and the momentum, as its location finally is related with $\int \vec{B}.\vec{d}l$ along the path really followed by the track inside the magnetic field.

This can be expressed in another way by the transfer formalism[2] [12]. Let us define a vector state *v(z)* by $v^T[z]=(x, y, S, T, 1/p)$ associated with a track trajectory at some *z*, then we can write:

$$v[z^{final}] = F(v[z^{init}]) \tag{2}$$

The function *F* here depends *only on the field and on the z location of the coordinates occurring in the vector states*. This equation gives rise to several others, depending on what is considered known and what should be determined. For instance, in the ideal case we discuss, if we know $(x, y, S, T)^{init}$ and x^{final} at some *given* z^{init} and z^{final}, one has (*I* stands for *init* and *F* for *final*):

[2] The interested reader is referred to [12] which gives a comprehensive account of this method. Let us mention that the transfer method is basically the way beam lines are designed.

$$p = G(x^I, y^I, S^I, T^I, x^F) \quad (3)$$

where the function G depends only on the field (supposed to be known) *and* on z^I and z^F. Similarly, one has equations of the form

$$\begin{cases} S^F = G_1(x^I, y^I, S^I, T^I, x^F) \\ T^F = G_2(x^I, y^I, S^I, T^I, x^F) \\ \cdots = \cdots \end{cases} \quad (4)$$

The functions given in Equations (2) to (4) are generally complicated functions of their arguments; however, in most cases [12], they are well approximated by relatively low degree polynomials of their arguments, provided one chooses appropriately the quantities to fit and the variables one uses; for instance, $1/p$ is more easy to fit by a polynomial than p (see Equation (3)) as soon as the range of p is large; depending on the symmetries of the field, $[S^I]^2$, $[T^I]^2$ can be better fitting variables than S^I, T^I.

The question arises of how to determine these functions. The simplest reliable way is to generate a large sample of tracks (a few thousands is certainly enough) in the whole phase space to cover, store the relevant information, perform some polynomial fits and store the relevant fit parameters. If the sample is large enough and generated in the appropriate phase space, the fit parameters apply to any subsequent track sample. In practice, there are however, a few subtleties which are setup dependent; we will describe some of them below, specific to the LHCb setup.

2.2 Fringe Field Effects

Even if trivial, the case sketched above is not far from real life for a setup like LHCb, where the central part is the dipole magnet. Complications actually arise due essentially to the fringe field, which extends significantly at the location of the tracking stations.

As first consequence of this fringe field, we have no longer a fixed z coordinate (z_{magnet}) for the magnet centre and, actually, z_{magnet} depends on the phase space variables of the track considered and on the z location of the Tracking Stations, which are no longer outside the field.

Moreover, the definition of z_{magnet} itself becomes a little bit non-trivial: we have no straight lines before and after the field, as we are always inside the field! However, the actual definition of the magnet centre, even if phase space dependent, is an important ingredient of the Optical Model, which underlies the Forward Tracking method and should be addressed.

Using Figure 1-a, it is obvious to find its general definition. Indeed, the straight-line trajectories outside the magnet are also the tangents to the curved trajectory inside the field at $z = z_{entry}$ and at $z = z_{exit}$.

This provides the general definition of the magnet centre: the magnet centre associated with two measurement planes located resp. at z_I and z_F, along the beam is the intersection of the tangents to the trajectory at z_I and z_F. This is sketched in Figure 1. So, the magnet centre depends on the field map, on the phase space variables (see above), but also on z_I and z_F. For reasonable fringe field values (compared to the highest field of the magnet internal region), it does not vary by more than a few centimetres over the whole phase space.

In order to fix one's ideas (see Figure 2), one measurement plane being located at the VELO origin ($z = 0$), which is practically field free in our case, and the other being located at ST3 ($z \approx 9$ meters), one sees that the standard deviation of the spread in z of the magnet centre location (which is a pure effect of the available phase space) around the mean value (5.28 m) is less than 4 cm. In order to illustrate the dependence of z_{magnet} upon z_I and z_F, let us mention that choosing $z_I \approx 2.30$ m and $z_F \approx 7.70$ m, the mean value of z_{magnet} becomes 5.17 m and its spread 2.3 cm (standard deviation). The total spread of the z_{magnet}, for the largest phase space of the LHCb acceptance does not exceed 10 to 20 centimetres.

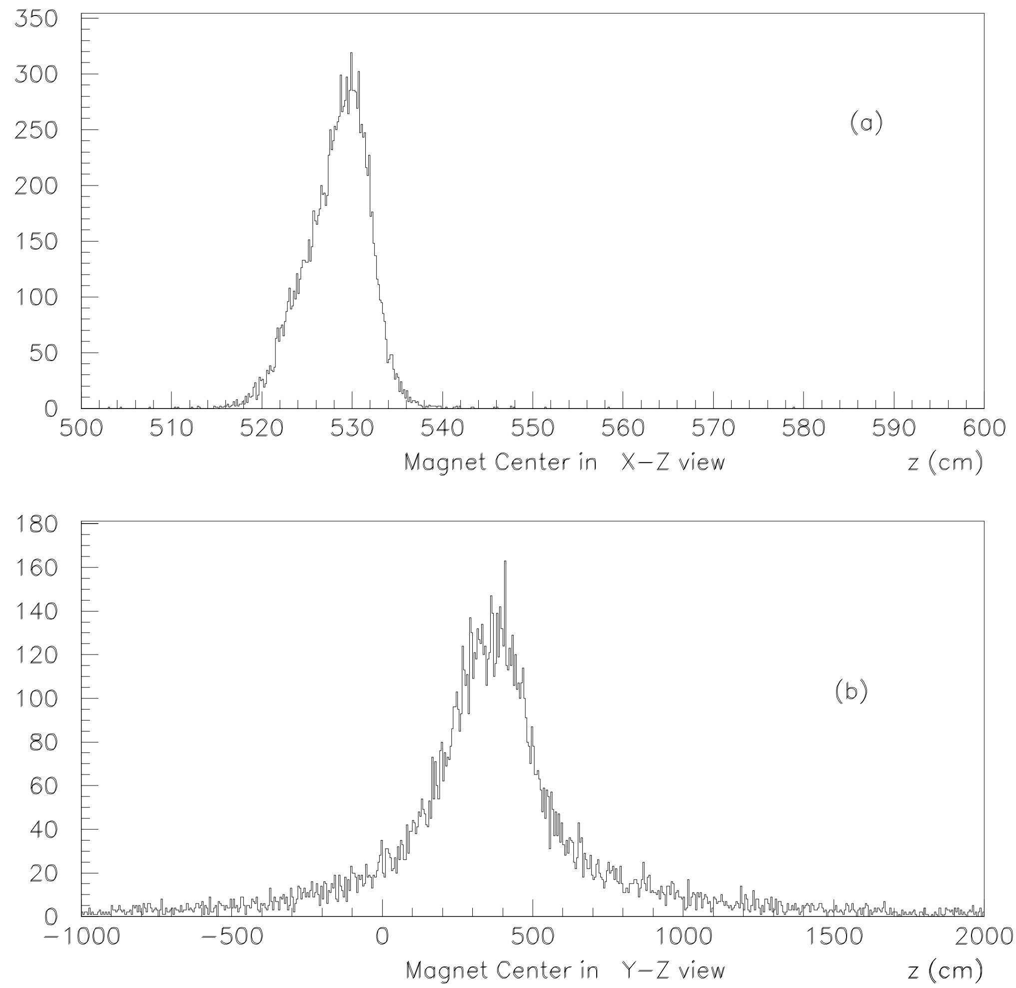

Figure 2 Position of the magnet centre. a) X-Z view b) Y-Z view

Figure 2-a shows the spectrum of the magnet centre z coordinate in the x-z view (bending plane); in Figure 2-b we show the same information in the y-z view. The magnet centre is now strongly displaced and reflects also the inhomogeneity of the field; the large tails are a clear effect of multiple scattering all along the detector, which makes the tangent intersection able to move in a completely erratic manner from its expected position. This high sensitivity to multiple scattering effects, due to the smallness of the field components in the non-bending plane, makes the magnet centre location in the y-z view much less useful than in the x-z view.

2.3 Consequences of the LHCb Tracking Station Geometry

In a detector where a direction (named *z* above) is privileged, as it is in the LHCb detector, one could, in principle, apply straightforwardly the method above. Let us sketch what this would be.

We have, on the one hand, the VELO track information which can be summarized, by means of a trivial linear fit, by the track coordinates at $z = 0$ and the *x* and *y* slopes. On the other hand, we scan the information carried by an x-plane at a given z_{ref} in order to get each x_{ref} candidate. Then, we can derive the predicted coordinates at any layer position (each at a given *z*) using some reference data sample. The windows around these predictions could be derived theoretically, knowing the accuracy on the input phase space parameters, but for pattern recognition purposes, this is an unessential complication and numerical guesses, motivated by the observed residuals, are appropriate enough.

For each layer position, we then would get a function of the phase space parameters $(x_0\ y_0\ S_0\ T_0\ x_{ref})$. When using the polynomial approximation this represents for each layer position some set of numbers.

In the case of the LHCb detector, the *z* structure of each station is somewhat complicated. We have, first, the Outer Tracker (OT) layers (4 per station) each consisting of 2 sub layers; this represents 8 *z* positions (or only 4 if one neglects the 5 mm gap between the two straw tube sub layers of each layer). Then, each Inner Tracker (IT) layer is split between up-down and right-left (cross geometry), which means in total 8 *z* positions (here the gaps are large enough to prevent taking some *z* mean values). So, for each station, we have to store information at, at least, 12 *z* positions. As we have 3 stations, storing the function information begins to look like a database.

It happens that such a tool is not really needed and, therefore, should be avoided. Basically, the idea is to sample for each trajectory the (*x, y, z*) coordinates of the hits and fit this set of points, all along the ST region, by polynomials in *z*. Taking into account the finite resolution of the OT and IT layers, we can write, choosing a reference value for *z*:

$$\begin{cases} x = x_{ref} + B_x(z - z_{ref}) + C_x(z - z_{ref})^2 + D_x(z - z_{ref})^3 \\ y = A_y + B_y(z - z_{ref}) + C_y(z - z_{ref})^2 \end{cases} \quad (5)$$

the reference values for *z* need not be the same for the *x* and *y* projections of the track trajectory and can be chosen in order to lessen the range of variation of some of the track parameters (see Section 3).

Let us first consider the equation for the *x-z* projection of the track trajectory. As clearly stated by Equation (5) we require the point (x_{ref}, z_{ref}) to be on the track trajectory. Reminding the LHCb station structure sketched above, no definite layer can clearly be requested to play the reference role. Additionally, taking into account that some *x* measurement planes can be inefficient, there is even no reason to require a given station to play definitely a reference role. There is, therefore, some arbitrariness in choosing a given value for z_{ref}. In the Forward Tracking algorithm, the choice is a point slightly downstream from ST3 (z = 9300 mm).

Now, the problem is no longer to parameterize the coordinate predictions at 36 (or 48) layer locations, but to parameterize only the 6 coefficients in Equation (5) in terms of $(x_0, y_0, S_0, T_0, x_{ref})$, given z_{ref}. This does not spoil the precision for the predictions as the degrees of the polynomials have been chosen in such a way that the polynomial track fit is accurate enough in the region of interest (ST).

However, in the approach defined by parameterizing the coefficients in Equation (5) in terms of phase space variables, x_{ref} is no longer a measurement. The question is now how to get it from a given measurement, a seed (x_S, z_S). This relies on an iterative procedure using the magnet centre. At start, we take the central value of its spectrum and approximate x_{ref} by projecting linearly x_S onto the plane at z_{ref}. Then one iterates using the prediction at z_S until the change in x_{ref} is smaller than some bound, see Section 3.1 ; here also several methods are possible.

As soon as (x_{ref}, z_{ref}) is derived, the magnet centre coordinate z_{magnet} is fixed. Then we can derive the coefficient B_X in Equation (5), as the magnet centre is the point where the two tangents to the trajectory should intersect; therefore the derivative $B_X = dx/dz\big|_{z=z_{ref}}$ is determined.

Indeed, denoting x_0 the coordinate of the VELO track at some z_0 (which can be taken as 0) and S_0 its slope, denoting also (x_{magnet}, z_{magnet}) the coordinates of the magnet centre for the phase space point considered (x_{magnet} is actually unknown), we have:

$$S_0 = \frac{x_{magnet} - x_0}{z_{magnet} - z_0}, B_x = \frac{x_{magnet} - x_{ref}}{z_{magnet} - z_{ref}} \quad (6)$$

which gives:

$$B_x = \frac{x_0 - x_{ref} + S_0\,(z_{magnet} - z_0)}{z_{magnet} - z_{ref}} \quad (7)$$

Therefore, B_X is determined using the VELO track information, and the z magnet centre coordinate corresponding the VELO centre and to (x_{ref}, z_{ref}) or (x_S, z_S).

The fit of the y projection in term of the phase space variables does not require special subtleties. The form in Equation (5) simply accounts for field inhomogeneity that the trajectory projection onto the "non-bending" plane can feel (minor field components along x and z directions, the main field component being oriented along y). Additionally, the slope dy/dz should be corrected for the change of slope in x-z, as what is constant is dy/ds (s is the abscissa along the track trajectory); the way this is done is emphasized in some detail in Section 3.2 .

3 Finding the parameterisation

The parameterisation given in Equation (5) uses the position x_{ref} in a reference plane. As already stated, this is not a measured quantity, and there is some iterative process to find this value: It is defined as the value at $z = z_{ref}$ of the parameterisation which passes through the seed point x_S at $z = z_S$. There are then 6 quantities to parameterise: B_x, C_x, D_x, A_y, B_y and C_y. One can see from Equation (7) that B_X can be easily deduced from z_{magnet}. Each of these quantities will be a function of the known parameters, X_V, Y_V, S_V, T_V, x_S and z_S. S_V and T_V are the slopes in x and y of the VELO track, x_S and z_S are the coordinates of the seed. In order to find the parameterisation, one uses the truth information (GEANT hit) in the ST stations, fits them according to Equation (5) and finds the dependence of these fitted values from the known parameters. This is studied first using Ntuples and PAW to see the main correlations. Then the correlation matrix is filled by the program and inverted to obtain the numerical value of the coefficients

3.1 X coordinate

Finding the proper parameterisation requires some idea of the physics behind. In first approximation, the VELO track and the ST1-3 tracks are straight lines, crossing in the centre of the field region. The Z position of this plane, z_{magnet} , is an important parameter; the second a-priori important parameter is the deflection by the field *dSlope* (θ in Equation (1)), inversely proportional to the momentum. These two quantities are shown on Figure 3. We expect most coefficients to depend linearly (at first order) on this deflection, as an infinite momentum track will just be a linear extrapolation of the VELO track! The real computation is a bit more complex, as there is some field in the ST region. The straight line we measure there is in fact given by the first two terms of the X parameterisation in Equation (5). The procedure is iterative: z_{magnet} depends on *dSlope*, which is computed using z_{magnet}, and the parameterisation of the C_X and D_X coefficients. The convergence is very fast, as the field is quite low in the ST region.

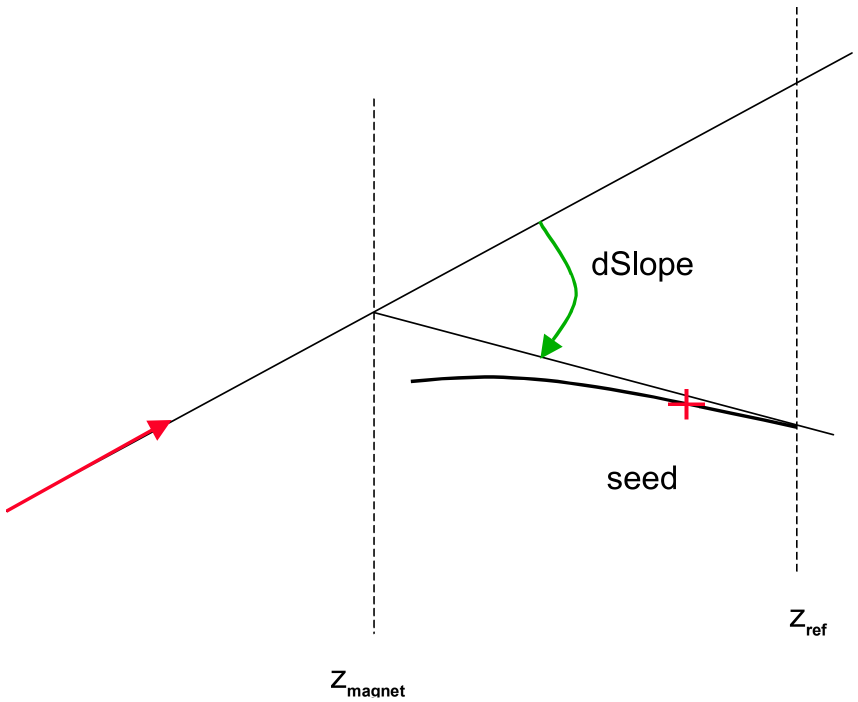

Figure 3 Definition of the main parameters

The result of the parameterisation with the standard LHCb field map is the following, with all numbers in mm and denoting x_{magnet} the extrapolation of the VELO track at z_{magnet}

$$z_{ref} = 9300.$$

$$\begin{cases} z_{magnet} = 5475/5 - 828.6 \cdot S_V^2 - 1676.4 \cdot T_V^2 + 186.4 \cdot B_X^2 + 253.6 \cdot dSlope^2 \\ B_X = (x_S - D_X \cdot (z_S - z_{ref})^3 - C_X \cdot (z_S - z_{ref})^2 - x_{magnet})/(z_S - z_{magnet}) \\ dSlope = \arctan(B_X) - \arctan(S_X) \\ D_X = dSlope \cdot (-6.44 + 97.66 \cdot T_V^2 - 7.68 \cdot B_X^2) \cdot 10^{-9} \\ C_X = dSlope \cdot (8.21 - 232.7 \cdot T_V^2 + 65.79 \cdot S_V^2) \cdot 10^{-6} \end{cases}$$

We iterate on the previous five relations until *dSlope* is stable, which takes rarely more than 2 iterations. Then we get the last parameter by forcing the seed to be on the track trajectory.

$$x_{ref} = x_S - B_X \cdot (z_S - z_{ref}) - C_X \cdot (z_S - z_{ref})^2 - D_X \cdot (z_S - z_{ref})^3$$

3.2 Y coordinate

For the Y coordinate, the naïve approximation is that the track has the same parameterisation as the VELO one. But one should first correct the slope dy/dz by the change of X slope: What is constant is the change of Y per unit length of track, not per unit of Z. This is a pure geometrical effect, and the new slope is called T_V^{After}. The second correction is due to the apparent longitudinal field (along the trajectory) for track at angle, which induces a vertical bending when the field deflects the track horizontally. This is quadratic in *dSlope*, and proportional to T_V. y_{magnet} is the extrapolation of the VELO track at z_{magnet}

$$z_{refY} = 6050.$$

$$T_V^{After} = T_Y \cdot \sqrt{\frac{B_X^2 + T_V^2 + 1.}{S_V^2 + T_V^2 + 1.}}$$

$$C_Y = -75.1 \cdot 10^{-6} \cdot T_V \cdot dSlope^2$$

$$B_Y = T_V^{After} - 0.841 \cdot T_V \cdot dSlope^2$$

$$A_Y = y_{magnet} + T_V^{After} \cdot (z_{refY} - z_{magnet}) + 8.9 \cdot T_V \cdot dSlope^2$$

3.3 Accuracy

Clearly, these parameters depend on the field map. However, they don't depend on the ST1-3 position, so they can be used with any z_S position, which is the desired behaviour. As it can be seen, there are only 15 parameters. One can try to improve the quality of the description, but in fact this doesn't seem to be needed: as the track suffers some multiple scattering, there is no gain by having a perfect parameterisation: a given VELO track passing by the seed may have scattered before the field, in the VELO exit window, in the RICH or in TT1, and have then a different trajectory with a slightly different momentum. This will be taken into account when performing the pattern recognition.

4 Pattern recognition

We have now defined the parameters of the parameterisation of the track in the ST region. The real job starts now. For each event, for each VELO track, loop on the possible seeds. In order to have good rejection, one asks that at least one station is fully efficient, i.e. all 4 planes fired. The loop on seed is then a loop on the 3 stations, and a loop on every hit in the X2 plane of each station. As explained earlier, each station is in fact 5 objects, 4 IT boxes and the OT. But the OT is also split top-bottom. We then loop on the 6 regions, and ask for the 4 planes in the same region, to avoid stupid combination, like using U or V coordinates from a different hardware box.

4.1 Seed finding in a station

For each seed, one computes the candidate's parameterisation with the formulae given in section 3 and one looks at hits in all other planes. First in the X1 plane, which is about 20 cm from the seeding plane X2, allowing for a slightly incorrect direction due to multiple scattering: the track may have scattered before the field, and then may come from a slightly different X_{magnet}, thus with a different slope. As we have already a good approximation of the momentum, we can define a momentum dependent window.

With the two X measurements, one can refine the seed so that the residual in X1 and X2 are equal and opposites. We now try to find U and V. For that we need to know Y, and here the information is very inaccurate: Y and the Y slope are measured in the VELO, the tracks crosses material where multiple scattering takes place, and the trajectory is extrapolated over 8 or 9 meters. The window in Y is then quite large, typically 40 cm/P (P in GeV). U and V being tilted by only 5 degrees, the zone to search in the U and V planes is smaller, typically 35 mm/P. Note that one adds about 3 sigma of the chamber resolution to the momentum dependence, here and for all other windows. The probability to have several candidates is then far from zero, and one must choose. The argument here is to select the best pair, compatible with a common Y. The distance to the expected point in X and Y is also taken into account in this selection. Once the point is found, the measured Y coordinate is used to update the parameterisation, assuming that the displaced Y is due to multiple scattering before the magnet: The VELO parameterisation is changed to predict the measured Y value. This allows using smaller windows in Y when extrapolating the track to the next stations.

4.2 Extrapolating to the other stations

Once all reliable seeds (4 planes) have been found in one station, one extrapolates them to the next station. Here, one has to take into account the multiple scattering in X, and thus to open relatively wide windows. The extrapolation is only from one station to the nearby one, less than a meter. We allow some inefficiency on the non-seeding stations, asking for at least 3 planes. We look in the X planes with a window of 40 mm/P, and find all hits. If only one plane has hits, we select the hit closest to the extrapolation. If the two planes have hits, we select the best pair in a way similar to what was done for the UV matching in the seeding station. This gives a refined X parameterisation; here again, we attribute this change in X slope to multiple scattering after the VELO, and update the parameterisation of the track before the field to reproduce the slope after the field. One computes the change in x_{magnet} from the measured X slope after the magnet, and then the change in S to produce this x_{magnet}.

This adjustment of the *x* parameterisation is done only for the 'next' station. Once done, a normal point search is performed in this station, with smaller tolerance, typically 8 mm/P. If at least 3 planes are fired, the station information is good and one stores all hits compatible with a 3-sigma resolution. This is mainly because the OT can give up to 4 hits per plane, and having all the hits improves the track resolution. If not, the update in X is undone, and one continues to search in order find the point in other IT boxes or OT half.

When the track has been found in the 3 stations, it is stored as a good candidate. There can be many candidates, as there can be many good seeds. Furthermore, one loops on the stations to use as seed, and we should find again three times the same track if the stations are fully efficient. An efficient cleaning is needed!

4.3 Cleaning

As indicated earlier, the method produces many clones. Cleaning is then very important to reduce as much as possible the number of clones, and to select the best track candidate when several are very close.

4.3.1 Local cleaning

This cleaning is performed between candidates found for the same Velo track. Candidates for the same track should be different enough. A first clean up is performed by comparing the number of shared hits between tracks. If a track has more than 80% of its hits in common with another track, it is removed. If two tracks share at least a hit, the one with a worst χ^2 is removed, if this χ^2 is different by more than 0.5

A second criterion is used to reduce the number of candidates for the same Velo track. It is based on the quality of the matching before the magnet. As explained earlier, multiple scattering in the Velo + RICH-1 is used to explain the difference between the measured points and the nominal track, this is done by changing the slope before the magnet to fit better through the measured points. Now we compare the measured slope in the Velo and the adjusted slope, taking into account the measurement error. As this change in slope should be due to multiple scattering, we multiply it by the momentum. This is called "**errSlope**". Tracks with 'errSlope' higher than the lowest value from the other candidates plus a tolerance of 15 mrad.GeV are discarded, as being a wrong match between the Velo track and a track after the magnet. Note that information in TT1 could also be used in the setup LHCb-Light where there is field between the Velo and TT1.

4.3.2 Global cleaning

Similar arguments can be used to compare tracks that are the same after the magnet, i.e. which share more than 80% of their hits. A track with more than 80% of its hits common with another track is discarded if it has a worst "errSlope", or a χ^2 higher than the one of the other track plus the usual tolerance of 0.5.

A last cleaning is based on the comparison of the momentum. If a Velo track has still several candidates, the candidates with a momentum lower than half the momentum of the highest candidate for this Velo track, are removed.

5 Performance

When measuring tracking efficiencies, the first question is to define properly the set of tracks on which efficiency should be measured. Here we use the official definition of the LHCb-Light working group: A track with at least 3 GEANT hits in the Velo and 3 GEANT hits in the ST1-3 stations is a track to be measured. This is the set of tracks used as denominator. We also quote the efficiency when this algorithm, which implies that the track has at least 3 hits in each of the 3 stations, can measure the track. A track is "good" if at least 70% of the hits are from the same Monte-Carlo particle as the Velo track. If there is more than one good track, these are counted as "clone". "Ghosts" are tracks which are not good, either because they have hits from the good track, but not enough, or because they are from a different VELO track. The results are listed in Table 1 and displayed on Figure 4 and Figure 5 for tracks seen in the 3 stations ST1, ST2 and ST3, for the two detector configurations. One can clearly see that the low momentum tracks have a lower efficiency.

	LHCb Minus at 5.10^{32}			**LHCb Light at 2.10^{32}**		
In %	Efficiency	Clone	Ghost	Efficiency	Clone	Ghost
All tracks	90.25	.03	7.57	91.55	.01	3.98
Tracks over 5 GeV	91.85	.05	6.56	93.23	0	3.44
Tracks in all ST stations	92.28	.03	6.70	93.36	.01	3.42
B decay products	92.95	0	3.59	93.54	0	1.57
B decay in all stations	94.24	0	2.86	94.71	0	1.25
Average time per track	42.5 ms			26.6 ms		
Average time per event	1590 ms			764 ms		

Table 1 Forward Tracking performance

6 Conclusion

The code for the Forward tracking is now available in CVS and in Brunel. The performance is largely adequate, but there is clearly room for improvement. In particular, TT1 could be used in the LHCb-Light setup to reject some ghosts, allowing to open a bit the tolerance and gain some efficiency. The parameterisation could also be improved; there may be corners of the phase space where a global polynomial description is not good enough. But the feasibility of a tracking without magnet stations has been clearly demonstrated.

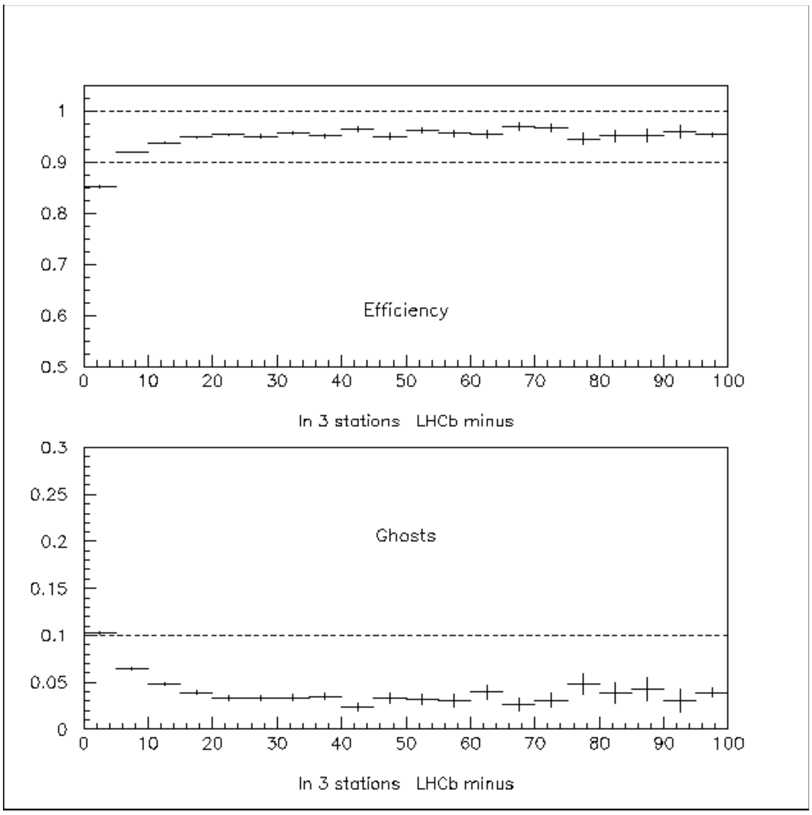

Figure 4 Efficiency and ghost rate with a track seen in all 3 stations in the LHCb minus setup

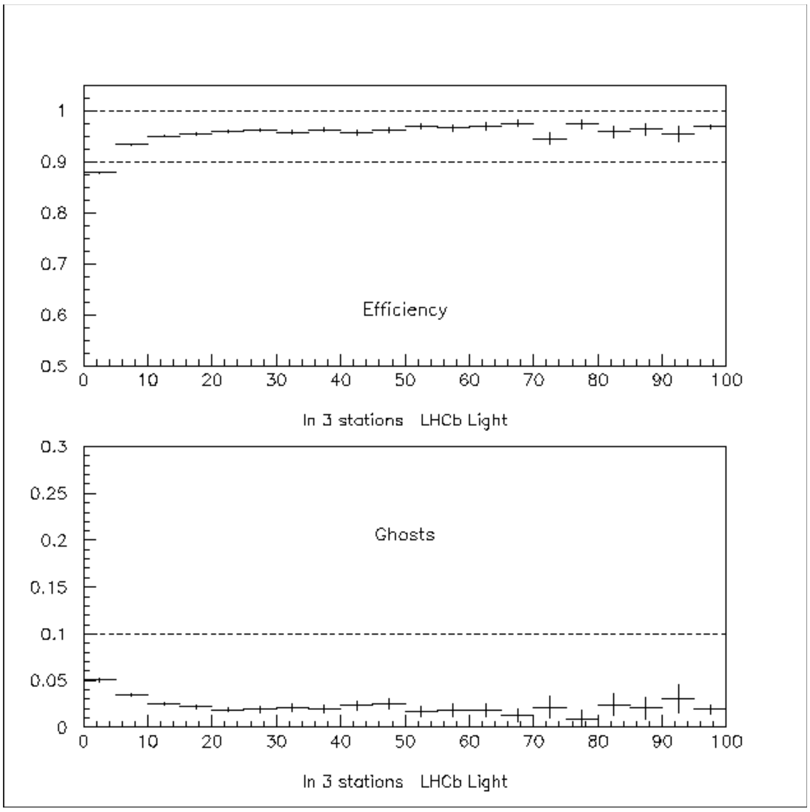

Figure 5 Efficiency and ghost rate in the LHCb-Light setup

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