Remote-Imaging Spectrometer For Low Multiplicity B-Decays

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ABSTRACT

A double-arm focussing spectrometer for 2-body B-decays is examined. The nearest tracking elements are $\gtrsim$ 30m from the target, and the apparatus is intended to run at instantaneous interactions rates of tens of GHz. Yields of several thousand detected decays per mode per experiment at a branching fraction of 10^{-4} might be attained.

I. INTRODUCTION

Every minute the Tevatron operates in fixed-target mode, several million b-quark pairs are produced. While these are regrettably buried in the beam dumps, this simple fact is enough to inspire the most desperate efforts to try to observe them. In this contribution, we explore the outer limits of feasibility of the high-rate frontier. We are thinking of instantaneous interaction rates large compared to 1 GHz, perhaps 10-50 GHz. We here uncritically assume that under these circumstances

1) At best only the simplest decay modes of B, Λ_b, etc will be accessible. The best candidates include all-charged, low multiplicity modes.

2) The decay vertex must still be isolated; hence tracking must be done with "silicon accuracy".

3) For reason of radiation damage and pattern recognition problems (confusion from many events overlapping in time), no detectors placed near the interaction vertex will survive.

Does simply moving the silicon detectors back compromise resolution? In the absence of multiple scattering, detector stations at e.g. distances z and 2z have good enough lever-arm to extrapolate accurately a charged particle trajectory to the production region. However multiple scattering in the first (upstream) detector plane creates an unavoidable "cone of confusion" whose radius, in the absence of

any magnetic elements, grows linearly with distance. Therefore if the silicon planes are too far back from the target, the resultant circle of confusion in the production region will be unacceptably large (Fig 1a).

But it is possible, after all, to see small details with only instruments located at large distances away from the object of interest. (The CIA does it all the time.) The key lies in focussing. In particular, if there are magnetic focussing lenses between the target region and the detectors (with magnification of order unity) then the cone of confusion can be focussed as well (Fig 1b). It follows that

a) if relative to a given reference ray, there is betatron motion in both transverse planes for nearby trajectories (of the same energy), and

b) if the betatron phase advance from the source to the tracking system is approximately a multiple of π (i.e. there is approximate point-to-point focussing)

then the resolution of the tracking system is, in principle, as good as if it were adjacent to the source. The conditions (a) and (b) also appear to be necessary as well as sufficient. It must be emphasized that the optical system as a whole need not possess absolute linearity; what is needed is validity of a linear approximation for betatron motion within the cone of confusion (the size of which is defined by multiple scattering; it is typically of millimeter diameter or less) associated with an arbitrary reference ray within the detector acceptance.

A difficulty in satisfying the above criterion in a practical device has to do with acceptance, especially momentum acceptance. The dependence of focal length on momentum for typical alternating-gradient optical systems is roughly linear. To accept a large momentum bite therefore requires a series of mutually compatible detector planes configured along the locus of foci. Angular acceptance is also a problem, simply because the large-aperture magnets required must also be very strong, with field integrals at the coil measured in tens of tesla-meters.

Despite such daunting practical problems, it still seems to us worthwhile to examine the matters of principle. In what follows we consider a "minimal" experiment based on a classic double-arm focussing spectrometer geometry which would observe two-body hadronic decays,[1] namely $B_{d,s} \to \pi^+\pi^-$, $K^\pm\pi^+$, K^+K^-, $p\bar{p}$, and $\Lambda_b \to p\pi^-$, pK^-.

Supposing that there exists for $x_F \gtrsim 0.2$-0.3 a production asymmetry $\sigma(B_d)/\sigma(\bar{B}_d) \gtrsim 1.1 - 1.2$, it follows that B_d mixing and even CP violation studies in $B_d \to \pi^+\pi^-$ and $p\bar{p}$ can be done if large event samples can be acquired. Furthermore, the modes $B_d \to K\pi$ and $\Lambda_b \to pK^-$ are also promising channels for CP violation studies via Penguin-induced branching-ratio asymmetries; note that the $\Lambda_b/\bar{\Lambda}_b$ production asymmetry is determined by the $p\pi^-/\bar{p}\pi^+$ modes acquired concurrently. In addition, accurate $B_d/B_s/\Lambda_b$ lifetime comparisons would be an interesting byproduct of this program. Thus the physics of such a limited set of decays is not at all uninteresting.

II. SPECTROMETER LAYOUT AND BASIC OPTICS

We choose, with minimal attention to optimization, the spectrometer configuration shown in Fig. 2. Each arm consists of a FODO channel of 6 quadrupole magnets; the parameters are listed in Table I. 6 cm x 6 cm silicon microstrip tracking stations, spaced 3 m apart, are located in an array starting 35 m from the target and ending 60 m away. The target is a string of small tungsten wires 50-100μ in diameter, 3 mm in length, spaced 5 cm apart. A low β final focus for the incident beam is a reasonable match to this target geometry. We assume the region between target and tracking elements is evacuated. Downstream from the silicon stations may be placed conventional spectrometer elements to provide momentum verification and/or particle identification.

The axes of the spectrometer arms are 26 mrad from the beam, with central momentum of 100 GeV, implying an acceptance centered at $x_F \sim 0.25$. The angular acceptance of each arm is assumed to be a 28 mrad x 32 mrad rectangle. With this geometry, it is straightforward to estimate the idealized yield; we find it to be, assuming 3×10^{-7} $b\bar{b}$ produced per interacting primary, and neglecting inevitable losses due to tracking efficiencies, vertex cuts, etc.

$$\frac{\bar{B} \to h^+h^- \text{ into acceptance}}{\text{primary interaction}} = (6\times10^{-9}) \times \frac{\bar{B}_i}{b} \cdot \frac{\Delta p}{p}^2 \cdot B(B_i \to h^+h^-) \tag{2.1}$$

where $(\bar{B}_i/b) \sim 0.3$ is the fraction of b's which hadronize to the species in question. An experiment running at 50 GHz for 2×10^6 live seconds yields 10^{17} primary interactions. At a branching ratio of 10^{-4} this implies about ten thousand B-decay pairs per experiment per decay mode accepted into the apparatus.

The basic idea for extracting a signal from the enormous background is an impact parameter trigger:

i) Assuming for the moment a point target, the trajectory of a secondary particle emergent from the target is characterized by 3 parameters (two production angles and the momentum). The silicon tracking system measures four parameters x,y, x' = dx/ds, y' = dy/ds. Hence there is one constraint which we write

$$F(x,y,x',y') = 0 \tag{2.2}$$

ii) Each track which is detected in the downstream silicon system is processed on-line. The map function F is computed (on line) for each such track; indeed the parameters determining F are determined and updated in real-time from the target-associated background.

iii) Tracks from the B-decays of interest will be characterized by non-zero values of the map function F. Only tracks having the appropriate range

of F values are retained; of order 1% of input track candidates (per arm) may be kept.

iv) The candidates from one spectrometer arm are put in coincidence with candidates from the other arm.

v) The information from surviving candidates is further processed (a la ACP?) to check for opposite charge, appropriate mass, a common decay vertex in the fiducial region and acceptable decay kinematics, etc.

vi) The accepted candidates are written onto tape.

The singles rate in each arm can be estimated from existing data[2] to be 6 x 10^{-3} • ($\Delta p/p$) tracks per interacting proton. Even at 50 GHz primary interaction rate, this implies a 10-100 MHz target-associated singles rate per arm. After the impact-parameter cut (iii) and the coincidence requirement (iv), the accidental pair rate is $\lesssim$ 10 kHz, suggesting that indeed these pair data can be processed via ACP or other means and reduced to an output rate that can be written onto tape. The crux problem is no doubt the first step of extracting the track coordinates and computing the map function. This is discussed in a separate contribution by one of us.[3]

In these estimates, we have assumed that singles-rates are dominated by the charged particles produced in the target. Backgrounds from energetic neutral hadrons, photon conversions, etc have been estimated and appear small ($\lesssim$ 1 MHz). More difficult are contributions of slow-neutron and soft-photon albedo from showers in adjacent magnet yokes, etc. Scaling from reported E288 experience[2] gives grounds for cautious optimism, although a beam test is probably required to be fully convincing.

III. REMOTE-IMAGING OPTICS

We first consider tracks starting in the target with coordinates $x_0=0, x_0', y_0=0, y_0'$, $\Delta p/p$ which traverse a spectrometer arm and register in two measuring stations with coordinates x_1, y_1; x_2, y_2. As discussed in the previous section, there is one constraint on these coordinates; i.e. there exists a function $F(x_1, y_1, x_2, y_2)$ ("map" function) that is equal to zero. In principle this function can be computed from field maps; in practice the final determination will be empirical. In order to assess the feasibility of such a procedure, candidate tracks were propagated through the spectrometer using the tracking program TURTLE.[4] These data were then used to estimate the map function F, using a polynomial function with coefficients to be fitted from the data. In what follows are presented histograms of these approximations for the tracks coming from a finite, but small target and again for the case of the B meson produced in a finite, but small target and decaying downstream into two pions. Various levels of 12 pole content in the quadrupole field were included in order to simulate the most important non-

linearities that might be expected in quadrupoles with the strength that is necessary for this application.

A layout of the two spectrometer arms is shown in Figure 2. Both arms are identical in their optics. Each includes a number of coordinate measuring devices--presumed to be silicon strip detectors. Each detector location shown in the figure is taken to measure x and y in an unambiguous fashion.[5] The quadrupoles have been taken to be 1 meter in length, for convenience in making calculations, and the spectrometer parameters are listed in Table 1.

After invoking the symmetry of quadrupoles,[6] the most general polynomial term in the map function is:

$$(x_1)^{p_1} * (y_1)^{p_2} * (x_2)^{p_3} * (y_4)^{p_4}$$

where $p_1 + p_2$ must be odd and $p_3 + p_4$ must be odd. The value $n=p_1 + p_2 + p_3 + p_4$ is the order of the term. Table 2 exhibits the 60 terms up to order 6. Of these, four are of order 2 and eight are of order 4. Were the optics perfectly linear, only terms of order 2 would be present.

Two distributions of the map function that result from the calculations are shown in Figure 3. The inset shows the distribution that results from using tracks that originate in the target--taken to be a single target 3mm long, 50 microns in diameter. The quadrupoles have an assumed 10% duodecapole content. The distribution below the insert is that for B → 2 pions (details are given below). It can be seen that the map function distribution is very much broadened by the decay process.

The calculation that produced the distributions shown in Figure 3 was done using the innards of the program TURTLE to trace rays, but with modifications made so that B decay could be incorporated and so that the CERN histogramming package HBOOK could be used. Intermediate files were used, as necessary, to save results for a later program. For Figure 3, terms up to order 6 were included in the polynomial approximation to the map function. The coefficient of the term $x_2 * y_1$ was fixed to be 1; the other 59 were determined by a least squares fit to the hypothesis that the sum of the 60 polynomial terms be zero. The data set used for this fit consisted of 1554 rays traced from the 3 mm, 50 micron target to assumed detector stations at z=42 (x_1,y_1) and z=45 meters (x_2,y_2). For these 1554 rays, the values for the maxima of the absolute values of x', y' and $\Delta p/p$ were chosen to be 16 mr, 14 mr, and ± 30% respectively. The input distribution was an ellipsoid in phase space, of the modified type discussed in the TURTLE description.

The B meson decay was simulated by fixing the B momentum to be 200 Gev/c, but choosing its transverse momentum according to the distribution function

$$dN/dp_t^2 = a^{-1} \exp(-p_t^2/a)$$

with a being $(2.3\ \mathrm{Gev/c})^2$. The distribution was cut off at $p_t = 3.5$ Gev/c. The azimuthal angle of the transverse momentum vector was chosen at random. The B decay point was chosen with an exponential distribution, with $c\tau = .033$ cm. The decay was taken as isotropic in the reference frame where the B was at rest. The particular decay channel simulated was $B \rightarrow \pi^+\pi^-$. The $\cos\theta$ distribution (θ is the polar angle) was limited to ± .3 in order to limit the range of $\Delta p/p$ to ± .3, since that has been estimated as the range of acceptance of the spectrometer. The azimuthal angle was limited to -1.2 to 1.2 radians, since the spectrometer acceptance was close to zero at those extremes. The two decay particles were treated slightly differently, since they go through separate arms of the two-armed spectrometer (see Fig. 2). The spectrometer arms view the target at an angle of 26 milliradians. The tracking through each spectrometer arm was done relative to its optic axis--in a local coordinate system. Each particle was first tracked from the decay point backwards to z=0 in the local system in order to begin the spectrometer ray tracing from a common point at the longitudinal center of the target. The target diameter was taken to be 50 microns. The effect of transverse target size was included in calculating the effective displacement of the ray at z=0.

Figures 4a-d show the x-y distributions of the impact parameters of the tracks of the pions resulting from the B decay, after extrapolating them back to the longitudinal center of the target. The distributions are kept separate for each of the spectrometer arms. Figures 4c &d show the result of imposing the condition that the B decay occur at least 8 mm from the center of the target.

The effect of increasing the duodecapole content in the quadrupoles from 10 to 20% is shown in Figure 5c. It is not a significant effect, compared to the width of the distribution of the map function for B decay--seen with the same scale, in Figure 5d.[7] The zone of confusion where the map function cannot distinguish random tracks coming directly from the target and those tracks due to B decay, includes about 5% of the B decay events (neglecting other effects due to multiple scattering, single scattering, pion and kaon decay, and hard-to-anticipate tails on distributions that could further enlarge the confusion zone). The distribution of Figure 5a changes to that of Figure 5b when the order 6 terms are left out; this indicates the need for the order 6 terms.

The importance of each of the 60 terms in the order 6 approximation to the map function was studied, in order to judge whether it was easily concluded that some terms could be dropped out. For each ray tracked through the system, the contribution of each of the 60 terms in the "map" function was ranked on a scale of 1 to 60. A scatter plot was made of the ranking each term had for each event. This scatter plot showed a large spread in ranking for each term; the conclusion was that it wouldn't be easy to pick terms to drop.

The distributions that have been discussed in this section do not include the effects of multiple scattering in any material, pion and kaon decay, or single scattering. It is possible to study such effects, but the emphasis here was to study the behaviour of approximations to the map function without including other effects.

The ray tracing that was done did take into account quadrupole apertures, but ignored detector apertures. The effect of detector apertures was studied; from that study it was concluded that the discussion of the behaviour of the map function was best done without including their effects. It is clear that there needs to be optimization with respect to acceptance of the spectrometer parameters used in this study.

IV. OFF-LINE PROBLEMS IN EXTRACTING A SIGNAL

Even presuming success of the online data acquisition system in achieving rejection factors sufficient to write out events into permanent storage, there remains a formidable problem in extracting the signal from background in the off-line analysis.

At the very least, a careful Monte-Carlo study of all imaginable background sources is required in order to get some feeling for the true nature of the difficulties; even that arguably falls short of the real situation that would ensue. Evidently such an analysis has not been carried out. Here we sketch some rough estimates of what may perhaps be the most serious intrinsic problem. Unstable particle decays will provide candidate B-decay tracks; random coincidence in time and chance intersections in the B-decay fiducial volume of such tracks produce an irreducible background.

We guess that hadrons from K and Λ decays are the most serious background sources. Charm decays seem, at back-of-the-envelope level, more benign; the typical impact parameters are considerably smaller than for 2-body B-decays, and the high p_T of candidate tracks demands a high p_T for the parent charmed hadron, hence some extra suppression.

Specializing mainly to strange particle decays, we proceed as follows:

i) The probability P that an observed hadron originating from a strange-particle decay has projected impact parameter (at the target plane) less than r is linear in r: $P(<r)=r/R$.

We estimate from straightforward geometry that

$$R = \begin{array}{ll} 1.6\ \text{cm} & K_s \to \pi + \ldots \\ 0.6\ \text{cm} & \Lambda \to p + \ldots \\ 0.3\ \text{cm} & \Sigma^+ \to p + \ldots \\ (60\mu & D \to K^+ + \ldots) \end{array}$$

We expect these sources to be the leading contributors.

ii) The probability that an observed high-p_T hadron originated from a weak decay, irrespective of impact parameter value, is estimated to be

π^+ from K's/hadron ~ 0.9%
p from Λ's/hadron ~ 1.2%
(K^+ from D's/hadron ~ 2×10^{-4})

iii) As seen by the spectrometer, the fiducial region for B-decays (0.7 to 2.5 mean lives) projected onto the target plane is roughly circular, with radius ~ 1mm. This allows, together with estimates (i) and (ii), an estimate of the fraction of track pairs which penetrate the fiducial region and which possess a candidate vertex from which a reconstructed parent B momentum points back to the target.

Tracks with minimum possible impact parameter greater than 2.5 mm are completely rejected. After this cut, we estimate ~ 30% of the double-decay background events will have acceptable candidate vertices within the fiducial B-decay volume. For such events one can reconstruct the locus of possible source-points in the target plane of the candidate parent which are consistent with the momentum constraints on the secondary tracks. This locus is a line-segment in the target plane, with a roughly linear distribution of impact-parameters b out to a maximum of 1-2 mm. We cut at $b < 70\mu$, giving a rejection of $\lesssim (70\mu/1\ \mathrm{mm})^2 \sim 5 \times 10^{-3}$.

When all this is put together, we find that the fraction f of accidental pair triggers containing an acceptable secondary vertex candidate due to strange-particle decay is roughly 10^{-9} a(i)a(j), where the species-dependent parameters a(i) are estimated to be 1.4 for π^+, 8 for p, and 4 for $\bar{p}$.

A mass cut might bring the fraction f down a factor ~ 300, yielding typical backgrounds per random pair ~ 3×10^{-12}a(i)a(j). At a 50 MHz singles rate at 2×10^6 sec/expt there are of order 10^{14} dihadrons per experiment accepted into the spectrometer. This gives ~ 300 a(i)a(j) background events under a signal, an amount comparable to the signal (assuming a 10^{-4} branching fraction). Since the above estimate is clearly order of magnitude at best, the conclusion is neither good nor bad news. A serious simulation will be essential.

V. CONCLUDING REMARKS

The results of this study indicate that the remote-imaging idea may in principle work. However the spectrometer and experiment we have explored appears to do only about as well (on paper) as the letter of intent[8] for proposal P789 of Kaplan et. al. does (on paper). This latter initiative represents a relatively modest upgrade of an existing facility, while a remote-imaging spectrometer would be a very costly device, built from scratch, using an unproven technique.

To do better with remote-imaging at Fermilab energies most likely involves an architecture with an acceptance in solid angle and/or momentum bite competitive with that of P789. And it may be that it is better to consider the idea only in

the context of multi-TeV beams such as will eventually be available at UNK. As the energy scale increases, the required magnet apertures decrease and signal-to-noise increases; hence the overall problems rapidly become more manageable.

In either case, crucial issues for further work include more study of the remote-imaging optics, realistic Monte Carlo simulations of signal and especially backgrounds, detailed study of the front-end electronics and data acquisition system, and finally a design study of the large-aperture, very high-field magnets required.

REFERENCES

1. A discussion of the physics can be found in I. Bigi and B. Stech, SLAC-PUB-4495 (1987), and these proceedings.

2. H. Jostlein, et. al., Phys. Rev. D20, 53(1979).

3. D. Jensen, these proceedings.

4. D.C. Carey, TURTLE (Trace Unlimited Rays Through Lumped Elements), A Computer Program For Simulating Charged Particle Beam Transport Systems, Fermilab Report No. 64 (1978).

5. See the paper in these Proceedings by D. Jensen for further discussion of the method of measurement.

6. The 12 pole contribution is the next lowest order pole term that maintains the quadrupole symmetry.

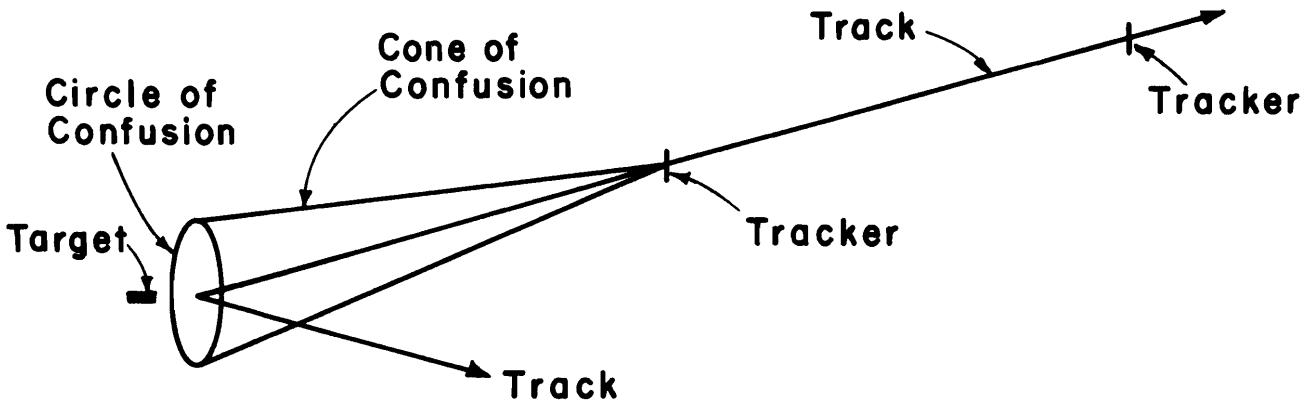
7. Figure 5d and the bottom part of Figure 3 differ only in the histogram bin size and the limits of the histogram.

8. P789 letter of intent, D. Kaplan spokesman, 9 Nov 1987; see also the proposal P789, D. Kaplan and J. Perry, spokesmen, March 1988.

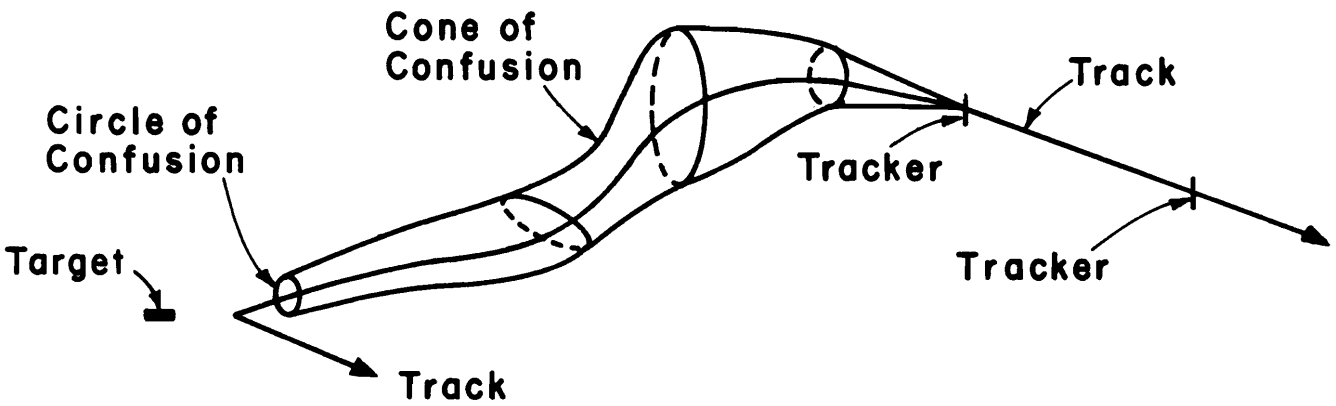
TABLE 1

Spectrometer Parameters

	Length meters	Radius of Aperture (cm)	Field at Aperture (tesla)
Drift	10	--	--
Q1	1	7.5	3.8
Drift	2	--	--
Q2	1	15	-7.5
Drift	3	--	--
Q3	1	15	7.5
Drift	5	--	--
Q4	1	30	-15
Drift	6	--	--
Q5	1	30	15
Drift	7	--	--
Q6	1	30	-15
Drift	8.5	--	--
Station 1	0	sample measuring pair	
Drift	3		
Station 2	0		



(a)



(b)

FIGURE 1

(a) Cone of confusion resulting from multiple scattering in the upstream detector plane;

(b) the same in the presence of a magnetic focussing system.

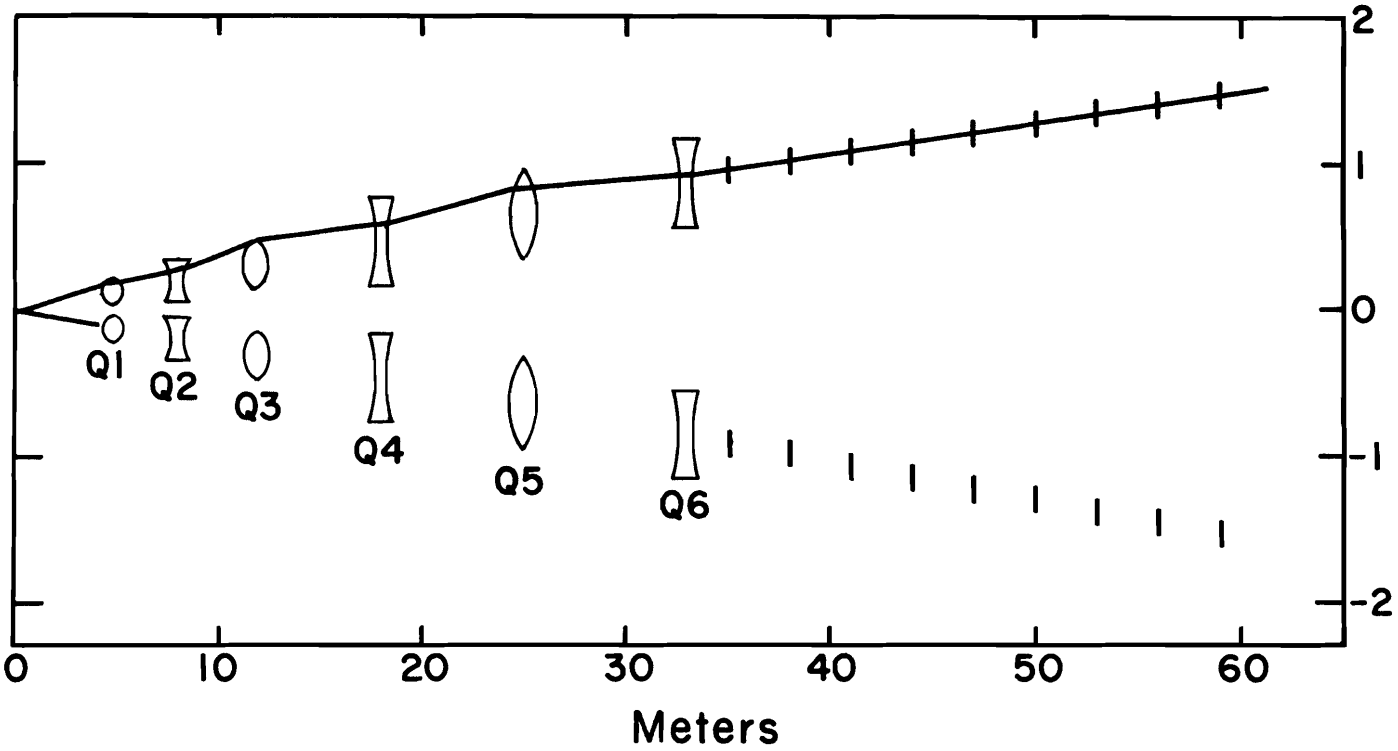


FIGURE 2

Layout of the double-arm spectrometer.

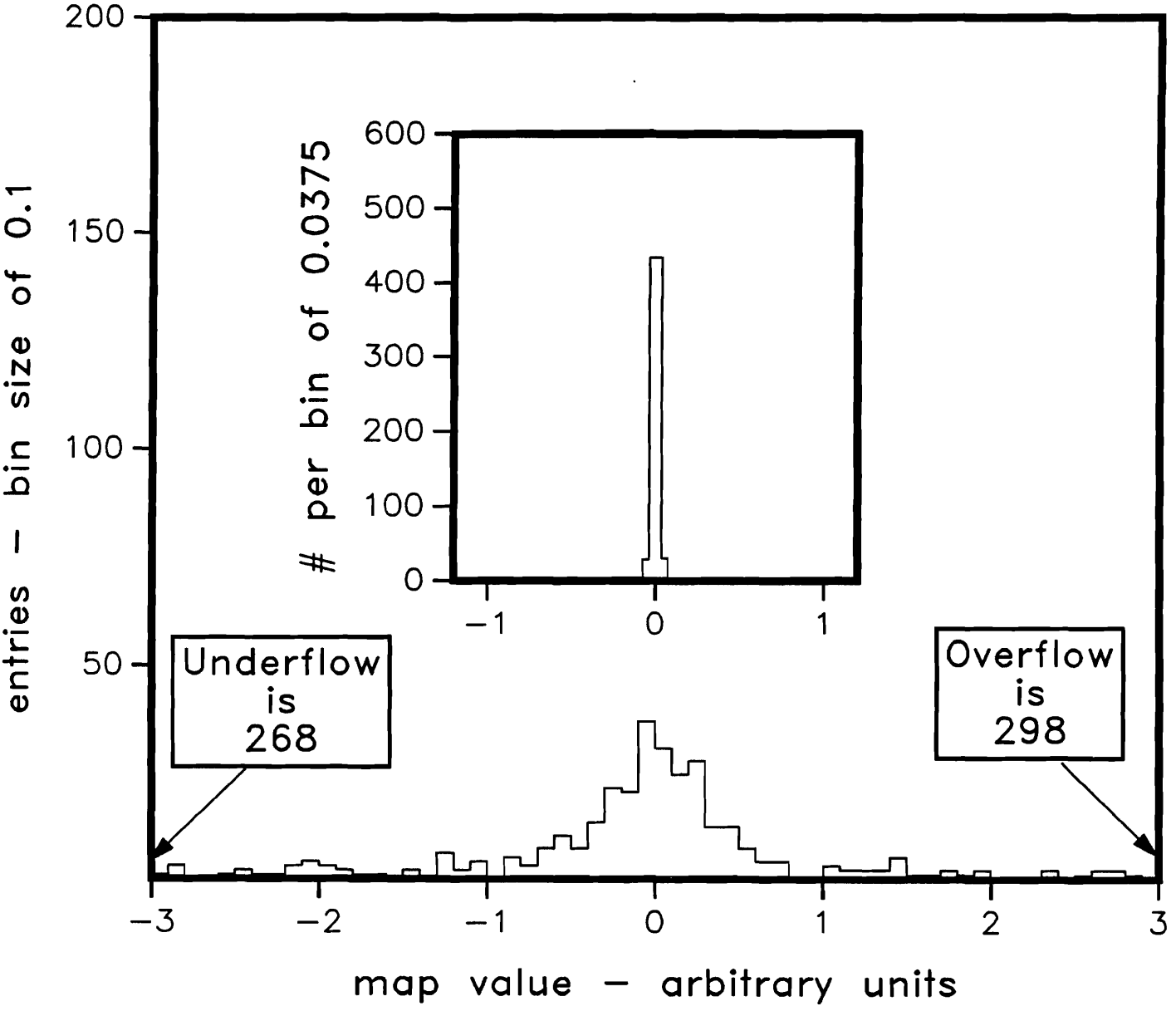


FIGURE 3

Direct comparison of Map Function Distributions in a single spectrometer arm for $B \to \pi^+\pi^-$ particles and for single decay tracks originating in the target (inset).

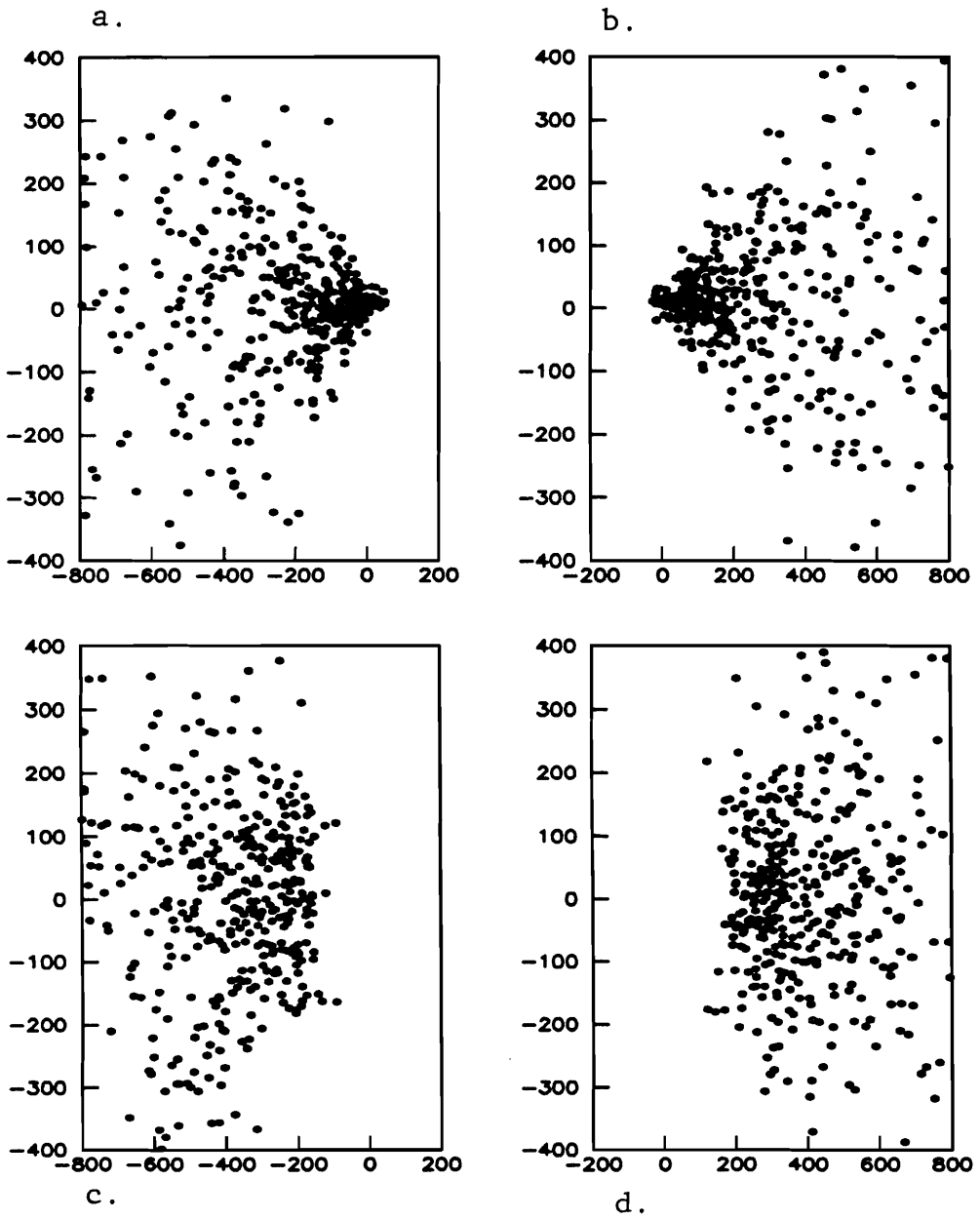


FIGURE 4

x-y scatter plot for $B \to \pi^+\pi^-$ decay particles projected back to the transverse plane at the center of the target (units are centimeters)

a) and b): no minimum decay distance is imposed

c) and d): B decay forced to occur $\geq$ 8 mm from the center of the target

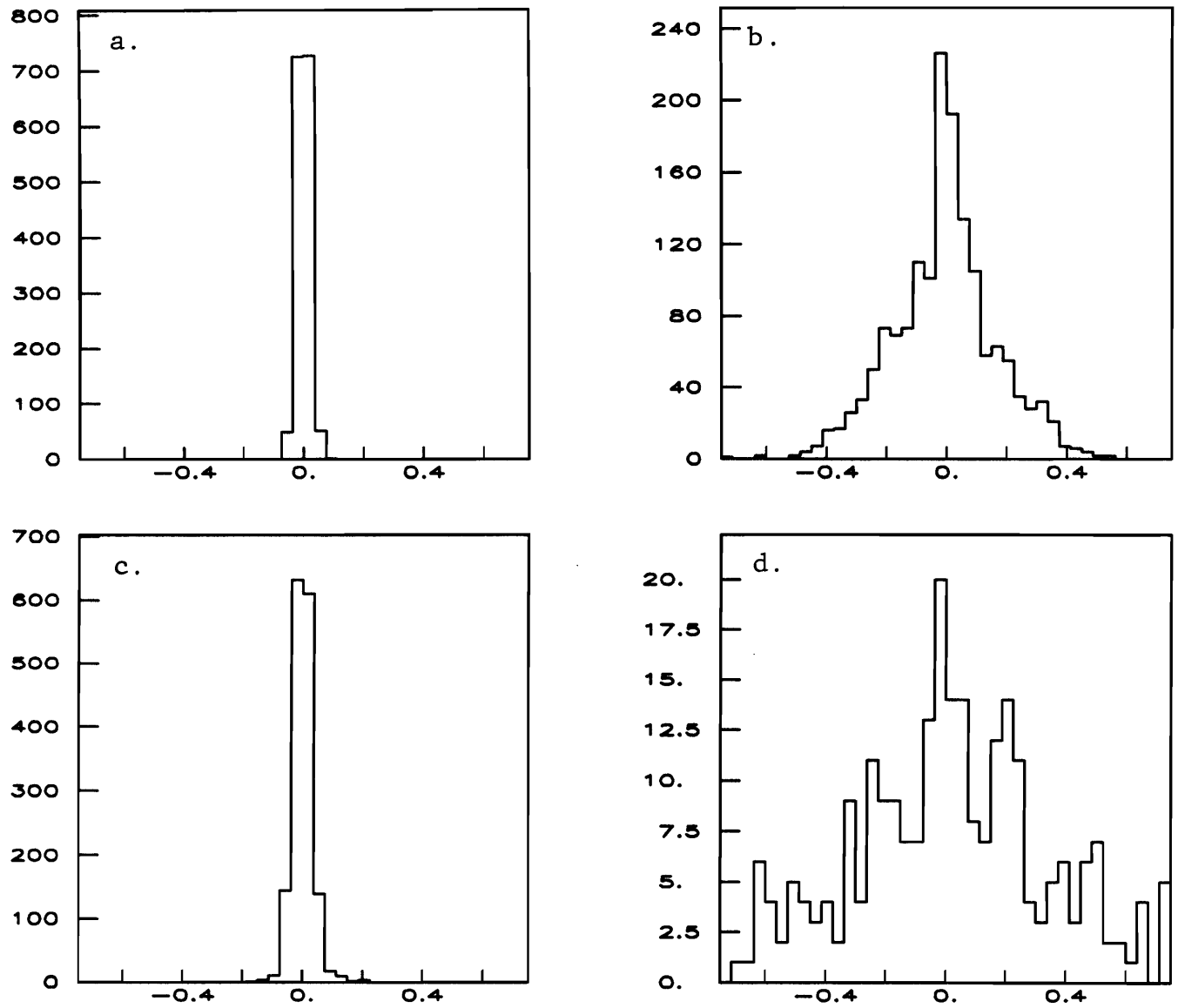


FIGURE 5

Distributions of the Map Function * 10^5

a), b), c): rays originate in 50μ diameter, 3 mm long target

a) spectrometer quadrupoles have 10% 12 pole contribution; 60 terms in map approximation;

b) quads have 10% 12 pole, 20 terms in map approximation;

c) quads have 20% 12 pole, 60 terms in map approximation;

d) rays are decay particles, $B \to \pi^+\pi^-$; no minimum decay distance imposed