BEAM POSITION STUDIES for E93050

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by

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Abstract

Knowledge of the true event-by-event beam position on the target is a major issue for the analysis of E93050, the goal being to reach a 0.5mm accuracy. In this document we will discuss what kind of hardware is available for the beam position determination, the different methods we have to calculate this beam position, the rephasing procedure between the beam position monitor and the raster measurements, the part of Espace that computes the beam position, and the effect of these corrections on variables of interest.

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1 Introduction

VCS-E93050 experiment $ep \rightarrow ep\gamma$ has been performed in TJNAF Hall A in March & April 1998. It uses a 15cm cryogenic hydrogen target, a rastered beam and two high-resolution spectrometers in coincidence.

Knowledge of the vertical and transverse beam positions beamX and beamY on the target event by event is essential for VCS analysis.

1.1 Vertical Position

The vertical position of the beam (see section 2.1for definition of coordinates) couples to the momentum resolution via the determination of x_{tg} which is the vertical extension of the track at target in the [z=0] plane [1].

There are two contributions to x_{tg}: one is due to the extended target (vertex points distributed along 15cm in z), and the other is due to beamY, the vertical position of the beam.

The expression of the focal plane dispersive coordinate to first order is given by:

$$x_{fp} = <x|x> x_{tg} + <x|\delta> \delta + ...$$

where:

$\delta = \frac{p-p_0}{p}$

p_0= central momentum

p = particle momentum

$<x|x> = -2.5$

$<x|\delta> = 11.8$ cm/%

Knowledge of x_{tg} as well as measurement of x_{fp} is required to reconstruct $\delta = \frac{\delta p}{p}$:

$$\delta = \frac{[x_{fp} - <x|x> x_{tg}]}{<x|\delta>}$$

[1]Beware: for an extended target, x_{tg} is generally NOT equal to y_{vertex}, the vertical coordinate of the vertex point.

A resolution of $\sigma(\delta) = 10^{-4}$ requires:

$$\sigma(x_{tg}) = 10^{-4}\frac{< x|\delta >}{< x|x >} \approx 0.5mm$$

So $\sigma(beamY)$ must be $\leq 0.5mm$.

First order Transport shows that the resolution on the vertical angle θ_{tg} of the track also depends on the knowledge of x_{tg} for an extended target and hence on the knowledge of beamY.

1.2 Horizontal Position

The horizontal position beamX of the beam is required in order to reconstruct the vertex point coordinate in the horizontal plane (x_{vertex} & z_{vertex} coordinates).

More precisely, for single arm events beamX is a necessary input for the vertex point (x_{vertex} & z_{vertex}) calculation, as one single track does not give enough information. For coincidence events, the crossing of the Electron and Hadron arms tracks gives a vertex point (x_{vertex} & z_{vertex}), and then the knowledge of beamX can be used as a cross-check of x_{vertex}. Indeed for E93050 this is one of the most powerful geometrical cuts to eliminate background events.

Again, a resolution $\sigma(beamX)$ of $\sim 0.5mm$ is most desirable in order to have efficient cuts in the analysis.

2 Instrumentation for beam position measurement

2.1 Introduction

The beam position on the target is determined by the orbit of the beam in the accelerator and by the fast raster in Hall A. The horizontal and vertical deflection coils of the Hall A raster operate at 18.30kHz and 24.62kHz respectively. The accelerator noise is primarily 60Hz (and harmonics). Besides the spectrometers vertex reconstruction, the beam position on the Hall A target is monitored by three separate systems:

- The current to the raster coils is monitored by a passive toroidal pickup coil (Pearson Probe).
- The beam position is measured by two sets of beam position monitors (BPM), located 7.524m (IPM1H03A) and 1.286m (IPM1H03B) upstream of the target (Hall A origin). Each BPM consists of a 4-wire antena array. This monitor is non-destructive.
- A pair of wire-scanners located just downstream of the BPMs can be used to profile the beam. These monitors are destructive. Harp #5 is located 7.353m and Harp #6 1.122m upstream of the target.

2.2 Coordinate systems

Let's first give a description of the different coordinate systems:

- Accelerator beam coordinate system: this is the system where all the EPICS informations are given.
- Hall A coordinate system: this is the general coordinate system where for example all the survey informations are given (like the instruments positions along the beam axis)
- Transport coordinate system: in these systems (one for each spectrometer) are given all the spectrometer's variables (like x_{tg} or y_{tg}).

Figure 1 shows that the accelerator-EPICS coordinate system is left-handed.

2.3 Raster readout

The current in the raster coils is readout by a Pearson Probe [2]. This is a passive transformer (see Figure 2). The current driving the raster coil is the single turn primary, whereas the secondary has N =turns. If the self-inductance of a single turn is L_0, then the output signal V_{out} is given as follows:

$$V_{out} = R_{tot}.I$$

[2] $N = 500$ windings and internal shunt resistance $R = 50\Omega$. At high frequency, the output voltage is 0.1V/A of raster current, when terminated into a high impedance.

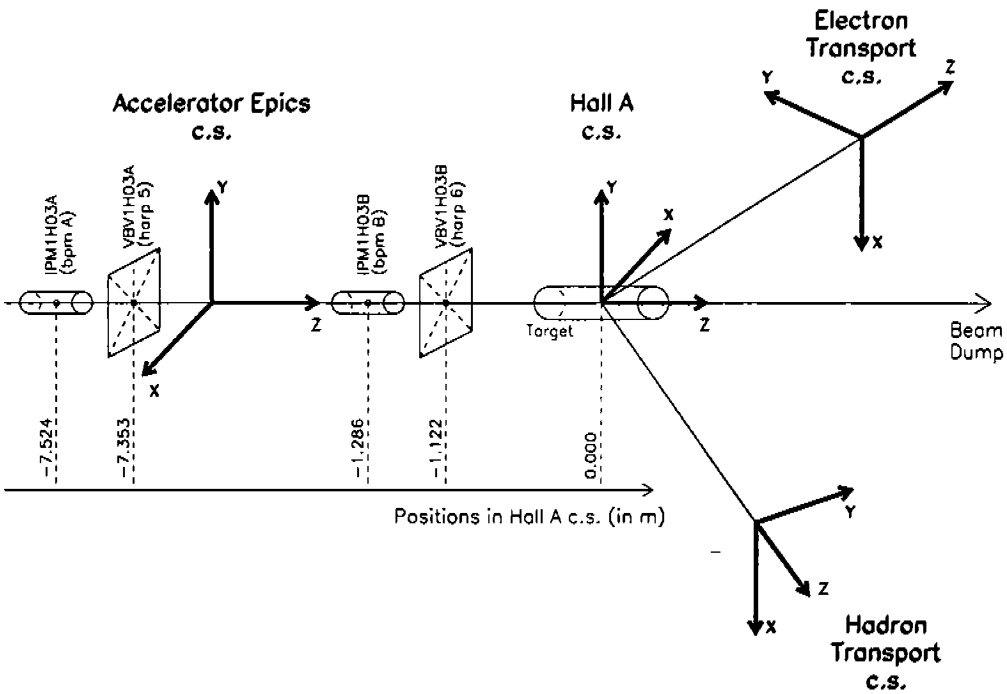

Figure 1: *Coordinate systems.*

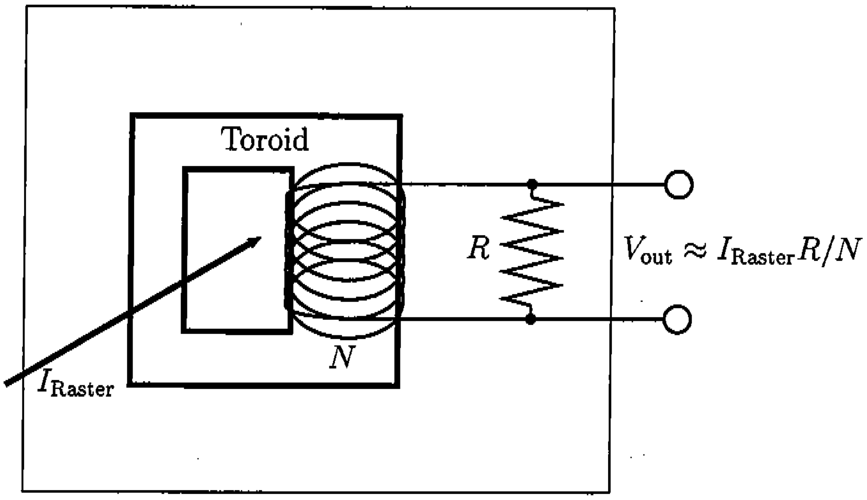

Figure 2: *Pearson probe on fast raster current.*

$$N^2.L_0\frac{dI}{dt} + N.L_0\frac{dI_{raster}}{dt} + RI = 0$$

$$I(t) = -\frac{1}{N}\int_{-\infty}^{t}\frac{dI_0(t')}{dt'}e^{-\frac{t}{\tau}}$$

$$\tau = N^2\frac{L_0}{R_{tot}}$$

where R_{tot} is the parallel resistance combination of the internal resistance R and the external load resistance. For E93050, I_{raster} was a sinusoidal current:

$$I_{raster}(t) = I_{X,Y}.cos(\omega_{X,Y}.t)$$

$$\omega_X = 2\pi.18.2kHz \quad \omega_Y = 2\pi.14.63kHz$$

$$V_{out} = R_{tot}I(t) = -\frac{I_{X,Y}.R_{tot}}{N}\frac{1}{\sqrt{1+tan^2\delta}}cos(\omega_{X,Y}t + \delta)$$

Coord	Size (mm)	Set Current (A)	Readback Current (A)	Scope (V)	Run E93027	ADC 3123 (chan)
		(amplitudes)				(peak-to-peak)
X	0.25	6.02	13.07	1.30	2368	9800
Y	0.25	2.42	5.94	0.60		6950
X	0.50	8.74	18.61	1.90	2370	14400
Y	0.50	5.2	12.67	1.35		15100
X	1.00	17.47	37.62	3.68	2371	28100
Y	1.00	10.48	24.95	2.52		29700
X	2.00	34.72	73.66	6.88	2372	55100
Y	2.00	21.02	50.29	5.04		59200

Table 1: *06-Aug-98 Calibration of Raster Current Readout.*

$$tan\delta = \frac{1}{\omega_{X,Y} \cdot \tau}$$

At high frequency, the Pearson Probe output is perfectly in phase with the raster current, and the output amplitude is 1V /10A if the probe is terminated with a high impedance. However, the sign of the output voltage is ambiguous, depending upon the orientation of the raster cable through the probe. We will come back to this ambiguity in section 4.3.2.

The electronics for this probe are located in rack 1H75B02. The Pearson signal is sent to the EPICS system, and to rack 1H75B10 for CODA. In the rack 1H75B10, the Pearson signal is split and one branch feeds a VMIVME 3123 Bipolar Sampling ADC. The other branch has a negative DC bias applied and feeds a LeCroy 1182 CAMAC integrating ADC, with an approximatively 60ns gate.

The raster ADCs were calibrated on 06-Aug-1998. In a series of runs, e93027_2368->2372, the raster coils were energized to currents corresponding to required raster amplitudes of 0.25, 0.5, 1.0 and 2.0mm in both X and Y, for a nominal beam of 4.520GeV (beam was off). The set points and readback points of the raster currents agreed with the values obtained from an oscilloscope display (we still don't know whether the oscilloscope was terminated in 50Ω or greater than $1M\Omega$). The 1182 ADC readings saturated at the high current, so we have only analyzed the 3123 ADC. Table 1 lists the 06-Aug-1998 calibration data. Note factor 2 disagreement between set point and readback current.

The extracted conversion from ADC counts peak-to-peak to raster current peak-to-peak is:

$$I_X^{pp} = 2I_X = (2.67mA/chan)\Delta ADC_X^{pp}$$

$$I_Y^{pp} = 2I_Y = (1.69mA/chan)\Delta ADC_Y^{pp}$$

2.4 Harp Scans

The wire scanners are located directly downstream of the BPM antenna arrays. Several Harp scans were done during E93050. Unfortunatly, during most Harp scans, the data acquisition system was off, so we do not have simultaneous BPM and Harp informations. However, we do have BPM data taken just before or just after the Harp scans, at the same raster settings.

During E93050, the Harp data acquisition system was not fully operational. The only records we have of the Harp scans are the online plots, there are no data files. Table 2 summarizes the information about raster profile gleaned from the Harp scans.

h1 is the peak-to-peak dimension obtained from the first wire (vertical wire measuring the raster horizontal size); h2 and h3 are the total peak-to-peak dimensions measured with the two wires at 45 degrees. The vertical size of the raster is $hv = \frac{h2+h3}{2} - h1$. Error bars are approximately 0.5mm. All measurements were done with Harp #6 located near IPM1H03B, 1.12m upstream of the target. The measured raster size is systematically larger than the requested size, as can be seen by comparing Xpp with h1 and Ypp with hv.

The following items summarize the calibration results for run e93050_2076 (in horizontal only):

- bpmB peak-to-peak = 7mm
- bpmA peak-to-peak = 5mm
- Harp6 peak-to-peak = 9mm
- requested raster peak-to-peak = 3.6mm
- calculated raster current from the hafrangx code = 40.4A
- amplitude of raster current logged by the accelerator software = 24.55A

Run #	Date (1998)	Time	requested raster (mm) (peak-to-peak) X^{pp}	Y^{pp}	h1 (mm)	h2 (mm)	h3 (mm)	hv = $\frac{h2+h3}{2} - h1$ (mm)
2018	28-03	06:44:26	3.0	3.0	7.1	13.5	12.6	6.0
2076	30-03	03:38:09	3.6	3.6	8.9	16.1	16.1	7.2
2092	30-03	10:34:32	2.0	2.0	4.8	8.9	8.9	4.1
2110	30-03	18:57:15	2.0	2.0	4.3	8.6	8.6	4.3
2128	31-03	04:26:16	3.0	3.0	7.5	14.5	13.0	6.3
2176	01-04	08:59:53	3.0	3.0	7.0	12.0	11.6	4.8
2177	01-04	09:06:44	0.4	3.0	1.6	7.3	6.9	5.5
2178	01-04	09:09:20	3.0	0.4	6.6	7.0	6.9	0.4
2179	01-04	09:11:13	0.0	0.0	0.8	0.6	0.6	0.2
2198	01-04	22:42:00	2.0	2.0	5.7	9.8	9.8	4.1

Table 2: *Harp scans results from E93050.*

- 06-Aug-1998 calibration of CODA raster ADC VMIVME 3123 = 2.44mA/ADC count
- CODA ADC readout of raster = 36040 ADC counts
- CODA readout of raster current = 88A
- calculated raster size from CODA and hafrangx (peak-to-peak) = 7.8mm

2.5 Beam Position Monitors

The Beam Position Monitor cavity (BPM) is a 4 wire antenna array. The readout electronics is shown schematically in Figure 3.

The BPMs have to be calibrated before we can use their information. Three different kinds of parameters are involved in the calibration:

- the offsets of the four channels X_p^{off}, X_m^{off}, Y_p^{off} and Y_m^{off}
- their relative gains α_X and α_Y
- the absolute conversion factors κ_X and κ_Y.

The detection method is based on comparing the signals induced by the beam passing in two opposite antennas (p and m). From the recorded signals X_p, Hall A BPM Readout

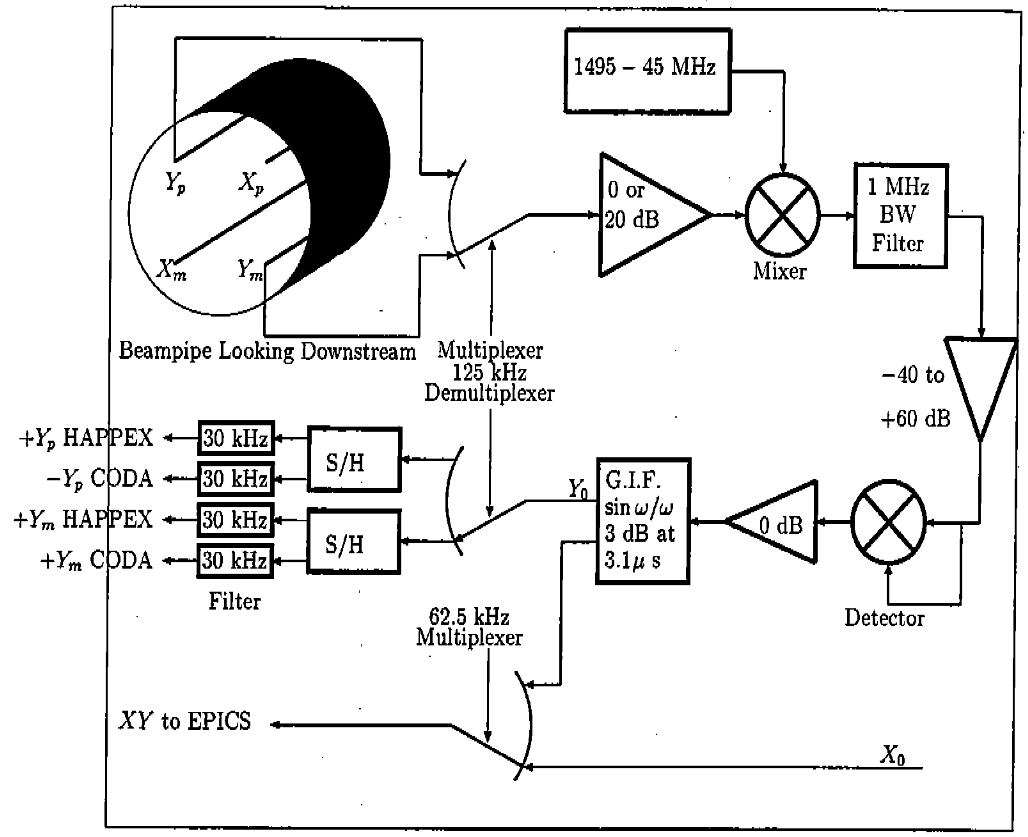

Figure 3: *Hall A Beam Position Monitor read-out electronics for E93050, March-April 1998.*

X_m, Y_p and Y_m, the beam coordinates X_{bpm} and Y_{bpm} are reconstructed as follows:

$$\begin{aligned} X_{bpm} &= \kappa_X * (18.87mm) * \frac{\left(X_p - X_p^{off}\right) - \alpha_X * \left(X_m - X_m^{off}\right)}{\left(X_p - X_p^{off}\right) + \alpha_X * \left(X_m - X_m^{off}\right)} \\ Y_{bpm} &= \kappa_Y * (18.87mm) * \frac{\left(Y_p - Y_p^{off}\right) - \alpha_Y * \left(Y_m - Y_m^{off}\right)}{\left(Y_p - Y_p^{off}\right) + \alpha_Y * \left(Y_m - Y_m^{off}\right)} \end{aligned}$$

The BPM measures the beam position with respect to a coordinate system rotated 45° counterclockwise with respect to the EPICS Hall-A coordinate system, and 135° clockwise with respect to the Hall-A Transport coordinate system.

There are two BPM devices on the beam line before the target: IPM1H03A is located 7.524m and IPM1H03B 1.286m upstream from the target (nominal point 0,0,0).

The BPM information was recorded in 3 different ways: by the EPICS control system, during the B-Scope procedures, and in the CODA acquisition system.

2.5.1 Epics Log

The averaged position over 0.3s was logged into the EPICS database (1Hz updating frequency) and injected in the data stream every 3-4s, unsynchronized but with an orientative timestamp. From these values, we can consider that we know the average position of the beam, calculated in the EPICS coordinate system which is left oriented.

In the EPICS readout, there is a common electronics chain from the multiplexor to the readout. Consequently the electronics offsets are the same for the p and m signals: $X_p^{off} = X_m^{off}$ and $Y_p^{off} = Y_m^{off}$. The asymmetry parameters $\alpha_{X,Y}$ remove the differential response of the two antenna leads and the inputs to the multiplexer.

There is an automatic procedure used by the MCC to calibrate the offset and the relative gains corrections. A 1.497GHz signal is introduced on one of the Y wires and the gain is varied in the X chain (this calibrates the X chain; a similar procedure is applied for the Y chain). This procedure was performed on March 09, 1998. The results are archived in /cs/ops/iocs/iocse10/dumbcal.dat. Channels 4 and 5 of IOC-10 correspond

BPM	α_X	X^{off}	α_Y	Y^{off}
IPM1H03A	0.977	0.9	1.109	-36.3
IPM1H03B	0.986	-30.4	1.120	-2.7

Table 3: *Calibration of EPICS readout of the BPMs. Offsets are in channels of the EPICS ADCs*

to BPMs IPM1H03A and IPM1H03B, respectively. The calibration results are shown in Table 3. These calibration constants were incorporated into the EPICS (and B-Scope, see below) readout of the BPM during E93050, with $\kappa_{X,Y} = 1$.

2.5.2 B-Scope

Approximately once a shift was done a B-Scope procedure which gives us the peak-to-peak deviation of the beam. Unfortunately, simultaneous B-scope and CODA event-by-event recording was not available during e93050.

As the B-Scope electronics chain is the same as EPICS, the calibration constants determined on March 09, 1998 were also used to calibrate this system (see Table 3).

2.5.3 CODA Logging

< MAYBE REORGANIZE ALL THIS PART >

Event by event in the data stream were recorded the raw signals from the 8 BPM antennas (2x4) measured by a VME 3123 ADC. However, these raw values belong to another electronics chain (different from EPICS), whose calibration constants we had to retrieve.

As we started to work on understanding the BPM information, the offsets were considered 0, the relative gains α were taken 1, and the conversion factor κ was equal to its nominal value of 18.87mm in the Hall A analyzer Espace.

To learn what the offset corrections were for each of the 8 signals, a special procedure had to be applied (see Log Book 22 page 295). The correct values according to the measurement on April 03 1998 are summarized in Table 4.

The relative gain of the two signals was not known or calibrated at the time of the experiment. The EPICS electronics was calibrated, but the raw information to CODA (data acquisition) wasn't totally identical. We expected

BPM	α_X	X_p^{off}	X_m^{off}	α_Y	Y_p^{off}	Y_m^{off}
IPM1H03A	0.975	-695	-656	1.109	-206	-190
IPM1H03B	0.983	-519	-464	1.119	-440	-415

Table 4: *Calibration of CODA readout of the BPMs. Offsets are in channels of the VMIVME 3123 ADC (bipolar).*

BPM	Coord.	Theoretical values obtained from electronics schematic	Experimental values obtained from CODA vs B-Scope Fit
IPM1H03A	X	1.1714	1.2171
	Y	1.2938	1.2521
IPM1H03B	X	1.1714	1.2577
	Y	1.2938	1.3194

Table 5: *Theoretical and experimental values of the κ coefficents.*

to have similar values with the ones we had for EPICS but not necessarily identical.

To calibrate this relative gain we used the fact that it influences the central position of the beam. It means that if we take a big number of events and average the calculated beam position (thus cancelling out the raster effect), we should obtain the same values as the EPICS position. In the rotated (45 deg) BPM coordinate system the difference between the average calculated beam position and the EPICS corresponding information is minimized if the correct value of α is considered. Taking sample data from a collection of runs we noticed a strong linear effect of this difference. The right values for α are summarized in Table 4.

Apparently the simplest but most delicate problem was to figure out the correct value of the conversion coefficient κ and the way to apply it. We started from the well-known and calibrated constant 18.87mm. First, we learned that on the CODA electronics chain, there were some low-pass filters with cutting frequency of 30kHz. Since the raster frequencies were 18.3kHz in X and 24.63kHz in Y, it is obvious that the amplification has to be corrected with a theoretical factor of 1.1714 on X and 1.2938 on Y (see Figure 4).

Another way to determine these κ coefficients is to calibrate the amplitudes given by the BPMs versus those given by the B-Scope/Harps. The result of such a fit is summarized in Table 5.

However, what we actually recorded are not the signals in X and Y directions, but a linear combination resulting from the rotated directions of the

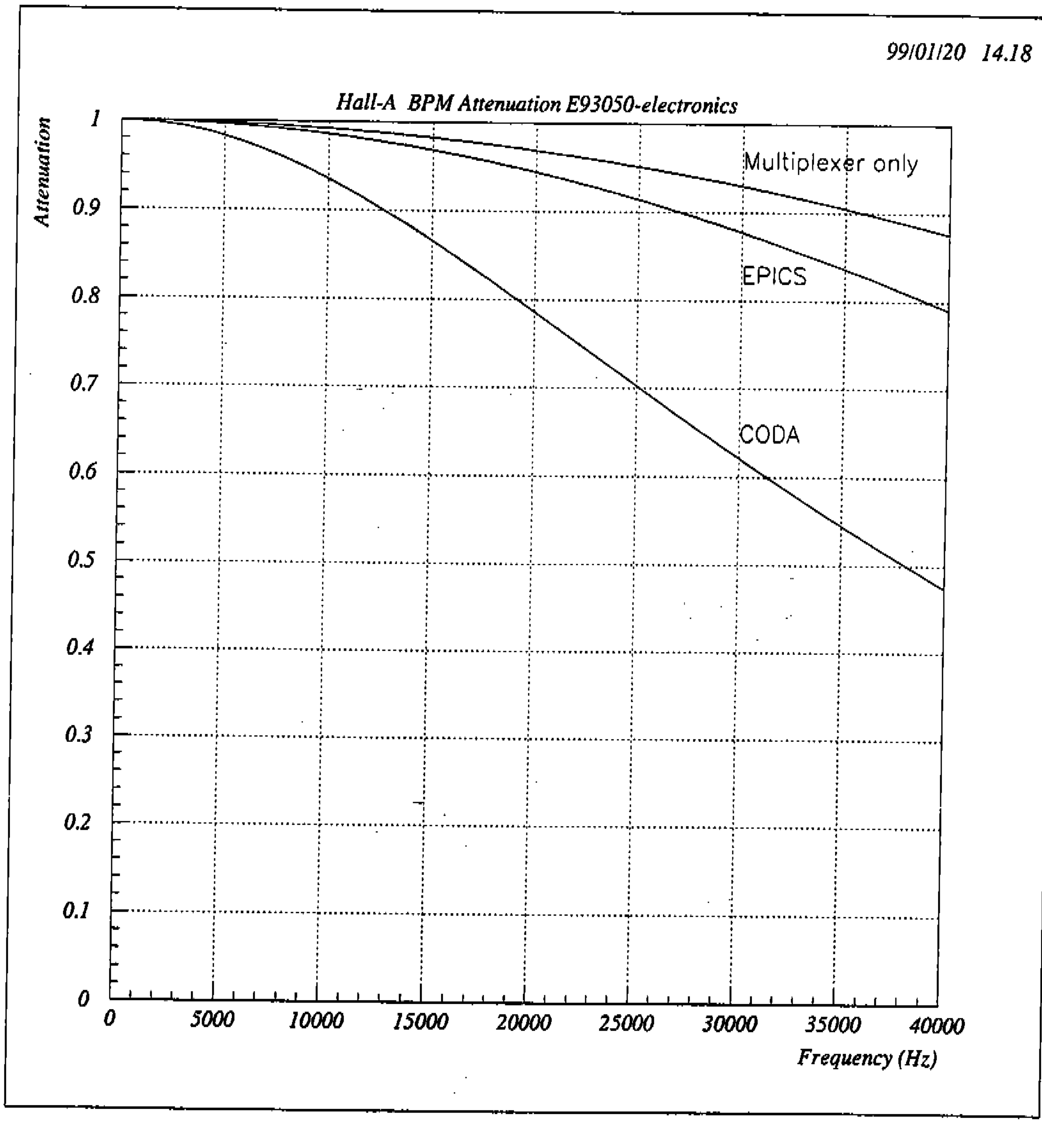

Figure 4: *Comparison between CODA and B-Scope (EPICS) electronics.*

BPMs. The procedure we applied is to calculate the positions in the BPM rotated system using the nominal values, and then applying the coefficients to calculate the positions in the beam coordinate system.

3 Beam position event-by-event: choice of strategy

We have two ways of reconstructing the beam position event-by-event:

1. Using the raster information and some beam optics code. On one hand this information is very convenient because it is in phase with the events, but on the other hand, we may have some trouble to convert the ADC values in mm at the target (i. e. how reliable is the beam optics code?).

2. Using the BPMs information. It is very easy to have a position in mm at the target because we have two informations, one from each BPM, both already calibrated. However these informations are not in phase with the events.

The following chapter is devoted to the second method, i. e. how to rephase the BPMs information in order to reconstruct the beam position at the target.

At the moment, the first method has not yet been fully investigated.

4 Beam position determination from the BPMs

4.1 Introduction

Let's first give a preliminary description of the quantities:

bpmbxraw = incident beam RAW (no rephasing) horizontal position given by the last Beam Position Monitor on the beam line (IPM1H03B)

bpmbxraw = incident beam RAW (no rephasing) horizontal position given by the last Beam Position Monitor on the beam line (IPM1H03B)

beamX = incident beam horizontal position at the target, obtained by extrapolati on of the line given by the two Beam Position Monitors (IPM1H03A and IPM1H03B) up to the center of the Hall A coordinate system.

rastX = adc value of the current in the horizontal raster coil (RAW data).

2armX = vertex horizontal position obtained by the crossing of the trajectories in the two spectrometers (= x_{vertex} quantity of section 1.1).

The pictures in Figure 7 have been made with the official version 2.6.1 of Espace. Basically they show that:

- The rephasing process has modified the width of the beam position spectrum (top left plot), wheras it should remain the same.
- After rephasing, we observe a negative slope between beamX and rastX (top right plot), wheras it should be positive.
- For some reason, beamX agrees perfectly with 2armX (bottom left plot); this is important because it validates other studies that have been done with Espace 2. 6. 1 using beam position information.
- We also observe a negative slope between 2armX and rastX (bottom right plot), whereas it should be positive.
- The need for the κ calibration coefficients described in section 2.5.3 is not explained.

We have to conclude that this version of Espace does not rephase the beam position properly.

Thus we decided to look at the Espace subroutine *interpret_ bpm_ rast.f* more carefully. As it is very easy to make mistakes in these phases studies, we first write down the complete detailed procedure.

4.2 Detailed Calculation

4.2.1 Basic Equations

The basic equation describing the time evolution of the raster is arbitrary (i. e. we can add an arbitrary phase in equation (1)) as long as we assume a

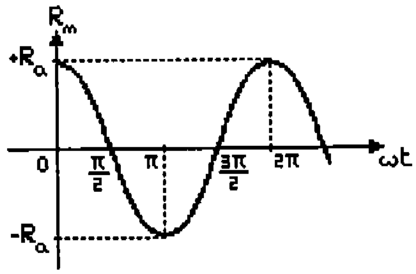

Figure 5: *Raster definition.*

sinusoidal function (see Figure 5). Nevertheless, all the following calculation depends on it. Also, whatever equation we take, the final position of the beam in mm must stay independent of our calculation.

$$R_{i_m} = R_a.cos(\omega t_i) \quad (1)$$

where:

R_{i_m}= measured value of the raster in event buffer #i, associated to time t_i.

R_a = raster amplitude .

The expression of the beam position comes from (1) by adding an unknown phase ϕ, which we have to determine from the two equations (1) and (2):

$$B_{i_m} = B_a.cos(\omega t_i + \phi) \quad (2)$$

where:

B_{i_m}= measured value of the beam position monitor in event buffer #i, associated to time t_i.

B_a= beam amplitude

4.2.2 Phase Calculation

We have a set of measurements indexed i and we can build the quantities:

$$\frac{R_{i_m}}{R_a} = cos(\omega t_i) = cos(\omega t_i + \frac{\phi}{2} - \frac{\phi}{2}) = cos(\omega t_i + \frac{\phi}{2})cos\frac{\phi}{2} + sin(\omega t_i + \frac{\phi}{2})sin\frac{\phi}{2}$$

$$\frac{B_{i_m}}{B_a} = cos(\omega t_i+\phi) = cos(\omega t_i+\frac{\phi}{2}+\frac{\phi}{2}) = cos(\omega t_i+\frac{\phi}{2})cos\frac{\phi}{2}-sin(\omega t_i+\frac{\phi}{2})sin\frac{\phi}{2}$$

and then we get:

$$\sum_{i=1}^{N}\left[\frac{R_{i_m}}{R_a}+\frac{B_{i_m}}{B_a}\right]^2 = 4.\sum_{i=1}^{N}\left[cos^2(\omega t_i+\frac{\phi}{2})\right].cos^2\frac{\phi}{2} = 4\frac{N}{2}cos^2\frac{\phi}{2}$$

$$\sum_{i=1}^{N}\left[\frac{R_{i_m}}{R_a}-\frac{B_{i_m}}{B_a}\right]^2 = 4.\sum_{i=1}^{N}\left[sin^2(\omega t_i+\frac{\phi}{2})\right].sin^2\frac{\phi}{2} = 4\frac{N}{2}sin^2\frac{\phi}{2}$$

From there you can easily extract:

$$abs(\phi) = 2.arctan\sqrt{\frac{\sum_{i=1}^{N}\left[\frac{R_{i_m}}{R_a}-\frac{B_{i_m}}{B_a}\right]^2}{\sum_{i=1}^{N}\left[\frac{R_{i_m}}{R_a}+\frac{B_{i_m}}{B_a}\right]^2}} \quad (3)$$

We still have to get rid of the ambiguity on the sign of ϕ . To do that, we can build the following χ^2 for each sign of the phase. The right phase corresponds to the smallest χ^2:

$$\begin{aligned}\chi^2_\pm &= \frac{1}{N}\sum_{i=1}^{N}[B_{i_m} - B_a.cos(\omega t_i \pm \phi)]^2 \\ &= \frac{1}{N}\sum_{i=1}^{N}\{B_{i_m} - [B_a.cos(\omega t_i).cos(\pm\phi) - B_a.sin(\omega t_i).sin(\pm\phi)]\}^2\end{aligned}$$

Figure 5 easily shows that:

$$sin(\omega t_i) = -S_{i_m}.\sqrt{1-\left[\frac{R_{i_m}}{R_a}\right]^2} \quad (4)$$

where:

S_{i_m} =measured value i of the sign of the time derivative of the raster.

And so we obtain:

$$\chi^2_\pm = \frac{1}{N}\sum_{i=1}^{N}\left[B_{i_m} - B_a.\left(\frac{R_{i_m}}{R_a}cos(\pm\phi) + S_{i_m}.\sqrt{1-\left[\frac{R_{i_m}}{R_a}\right]^2}.sin(\pm\phi)\right)\right]^2 \quad (5)$$

4.2.3 Beam Position Determination

The true event by event position of the beam is given by:

$$B_{i_{true}} = B_a.cos(\omega t_i) = B_a.\frac{R_{i_m}}{R_a} \tag{6}$$

So we calculate (2) − (1) × $\frac{B_a}{R_a}$ and we obtain:

$$B_{i_{true}} = B_{i_m} + B_a.[cos(\omega t_i) - cos(\omega t_i + \phi)] \tag{7}$$

This formula has to be associated with (1) by the calculation of ωt_i:

$$\omega t_i = -S_{i_m}.acos\left(\frac{R_{i_m}}{R_a}\right) \tag{8}$$

BEWARE!!!

The two equations (6) and (7) both depend on the form chosen for equation (1) and *are not* independent one from the other. In Espace version 2.6.1 (and earlier versions), the corresponding set of equations is not consistent. Indeed it reads:

$$B_{i_{true}} = B_{i_m} + B_a.[cos(\omega t_i - \phi) - cos(\omega t_i)] \tag{9}$$

$$\omega t_i = S_{i_m}.acos\left(\frac{R_{i_m}}{R_a}\right) \tag{10}$$

However, the two equations (3) and (4) used to determine the phase ϕ *are* independent of the choice of equation (1).

4.3 Results

4.3.1 BPM and Raster Agreement

Figure 8 was obtained by adding the above corrections in the subroutine *interpret_bpm_rast.f* of Espace version 2.6.1 (i.e. implementation of equations (6) and (7) instead of (8) and (9)). It shows a good agreement between the raw BPM amplitude and the rephased beam position amplitude (top left plot). Moreover, the rephased beam position and the raster measurement agree in sign (top right plot). These features are the ones expected by a correct rephasing between BPM and raster.

However, the rephased beam position given by the BPM disagrees with the position obtained by the crossing of the two spectrometers (2armX), both in sign and in amplitude (bottom left plot).

If we plot the raster measurement versus the position given by 2armX, we observe that the sign problem remains (bottom right plot); it doesn't come from the BPM, but either from the raster data or the spectrometers data. It is very unlikely that the horizontal vertex position given by the spectromet ers could have the wrong sign; therefore we simply assume that the raster measurements have the opposite sign (which is possible considering our lack of hardware information: raster coils cabling, adc cabling, etc...).

4.3.2 Raster Sign

Figure 9 was obtained from Fig.8 by changing the sign of the raster raw data in the subroutine *interpret_ bpm_ rast.f* of Espace. We can see a good sign agreement between the BPM measurements, the raster measurements and the spectrometers measurements.

Of course, the rastconsts.dat file has been modified; the final changes are:

- the signs of the raster average values have changed
- both horizontal and vertical phases have changed by π (roughly $1.7 \rightarrow -1.4$ in X, and $1.4 \rightarrow -1.7$ in Y for the analyzed runs)

From now on *opposite raster* will represent the raster data with an opposite sign.

4.3.3 Calibration Corrections

The amplitudes given by the rephased BPM and the spectrometers crossing still disagree by a 25% (roughly) factor (see Fig.9 bottom left plot). Figure 10 shows the effect of the BPM vs Harp/Bscope calibration κ coefficients. Here, d=2armX-beamX is represented in ordinate versus beamX in abscissa.

The top left plot has been obtained with the corrected version of espace 2.6.1 that includes the Opposite raster sign. It is just another way to display the 25% discrepancy between beamX and 2armX that was in Fig.9. In the top right plot the BPM vs Bscope/Harp κ corrections factors obtained from fit have been added. In the last plot, the equivalent coefficients calculated from the theory have been added.

As far as the horizontal position is concerned, in both cases the residual correlation is suppressed, which shows the two amplitudes (BPM and 2armX) are in agreement. The correlation coefficient shows that the coefficients obtained from the fit give a better result (because d and beamX should NOT be correlated at all).

4.3.4 Summary of the implementations

We can now compare several versions of Espace:

- the official version 2.6.1 (*original*). This version already contains the corrections described in section 2.5 (offsets and α).
- the version that contains the corrected subroutine interpret_bpm_rast.f (*corrected*). corrections have been described in section 4.2.
- the same version as before with an opposite raster sign (*corrected + opposite raster*) (see section 4.3.2).
- same as before but with the BPM vs B-Scope/Harp κ calibration coefficients (*final*) added (described in section 2.5.3).

The last version will be the one used in the analysis.

4.3.5 Effect in Vertical Beam Position

Basically, the vertical position of the beam is the only way to determine the vertical position of the vertex, which enters the corrections to momentum reconstruction. Therefore, the best variables we can look at are the electron momentum (Pkin) for elastic ($ep \to ep$) scattering, and the missing mass square (MX2) for VCS ($ep \to ep\gamma$) events. We compare the spectra obtained with the four different versions of Espace mentioned above.

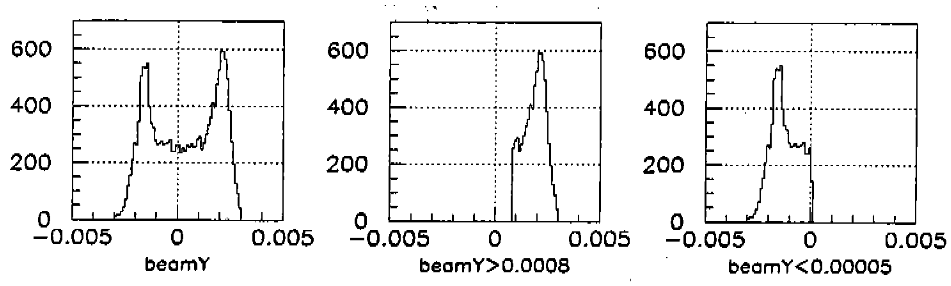

Figure 6: *beamY cuts.*

4.3.5.1 Missing Mass in VCS: Figure 11 shows the Missing Mass spectra for each version of Espace earlier mentioned.

The final MX2 doesn't change much from the original one, but we previously noticed that there was a very good agreement between the BPM and the spectromet ers in Espace 2.6.1 non corrected, so we don't expect a big improvement.

4.3.5.2 Electron Momentum in Elastic Scattering: Figure 12 shows that the Pkin spectrum itself (see the 4 biggest histograms) is not very sensitive to the vertical position of the beam. In fact, only a small correction is applied on the momentum in Espace due to beamY$\neq$0 (roughly $\Delta\left(\frac{\delta p}{p}\right) = 2.10^{-4}$ for 1mm of vertical displacement). Therefore it is interesting to compare also the Pkin spectra obtained by adding two cuts: one on the lower edge of the BPM spectrum, and then one on the upper edge (we take the two edges of the beam in order to maximize the effect on the momentum; see Figure 6). These two plots are represented for each of the four versions of Espace on Fig.12.

If the rephasing is done properly, then the two spectra should be identical, provided we normalize to the same number of events (the cuts define different numbers of events!). If we observe a shift between the two spectra, it means the rephasing is wrong. One can actually quantify this effect by calculating a χ^2:

$$\chi^2 = \frac{1}{N} \cdot \sum_{i=1}^{N} \left[\frac{\left(b_{1_i} - b_{2_i}\frac{S_1}{S_2}\right)^2}{b_{1_i} + b_{2_i}\frac{S_1}{S_2}} \right] \quad (11)$$

where:

N= total number of bins of the Pkin spectra

b_{1_i}= number of events in bin i of the Pkin spectrum obtained with cut #1 (lower edge of the beamY spectrum)

b_{2_i}= number of events in bin i of the Pkin spectrum obtained with cut #2 (upper edge of the beamY spectrum)

$S_1 = \sum_{i=1}^{N} b_{1_i}$ and $S_2 = \sum_{i=1}^{N} b_{2_i}$ are used to renormalize the two spectra to the same number of events.

The best χ^2 is obtained for the last plot of Fig.12, that is with Espace 2.6.1 with the corrected subroutine, the opposite raster signs, and the BPM vs Harp/Bscope calibration correction factors. It shows that the raster sign has to be inverted (w. r. t. the raw data) both in horizontal and in vertical.

4.3.6 Comparison of the two calibration sets

Figure 13 shows for information the effect of the two different sets of κ coefficients on the Pkin and MX2 variables (see Table 5).

It seems hard to conclude anything by looking at these plots, both sets give equivalent results. We decided to believe in experimental data and thus to keep the BPM vs Bscope/Harp calibration coefficents set obtained from the fit.

4.4 Conclusions about the BPM method

The BPM study developed in section 4 has been conducted on several E93050 runs (1500, 1780, 2124) and the results look very consistent for each of them. With the final version we get the following results:

Horizontal position of the beam:

- beamX is rephased properly w.r.t rastX
- beamX is calibrated properly in absolute (mm)
- the sign of rastX has to be changed from the raw data
- the agreement between beamX/rastX and 2armX is a good crosscheck.

Vertical position of the beam:

- beamY is rephased properly w.r.t rastY
- beamY is calibrated properly in absolute (mm)
- the sign of rastY has to be changed from the raw data
- the coherent behaviour for the physics variables such as Pkin or the missing mass is a good crosscheck.

5 Conclusion

Using the BPMs measurements together with the method described in section 4, we think we have a sufficient knowledge of the beam transverse position on the target in order to analyse the E93050 experiment: typically

$$\sigma(beamX) = \sigma(beamY) \leq 0.5mm$$

event by event.

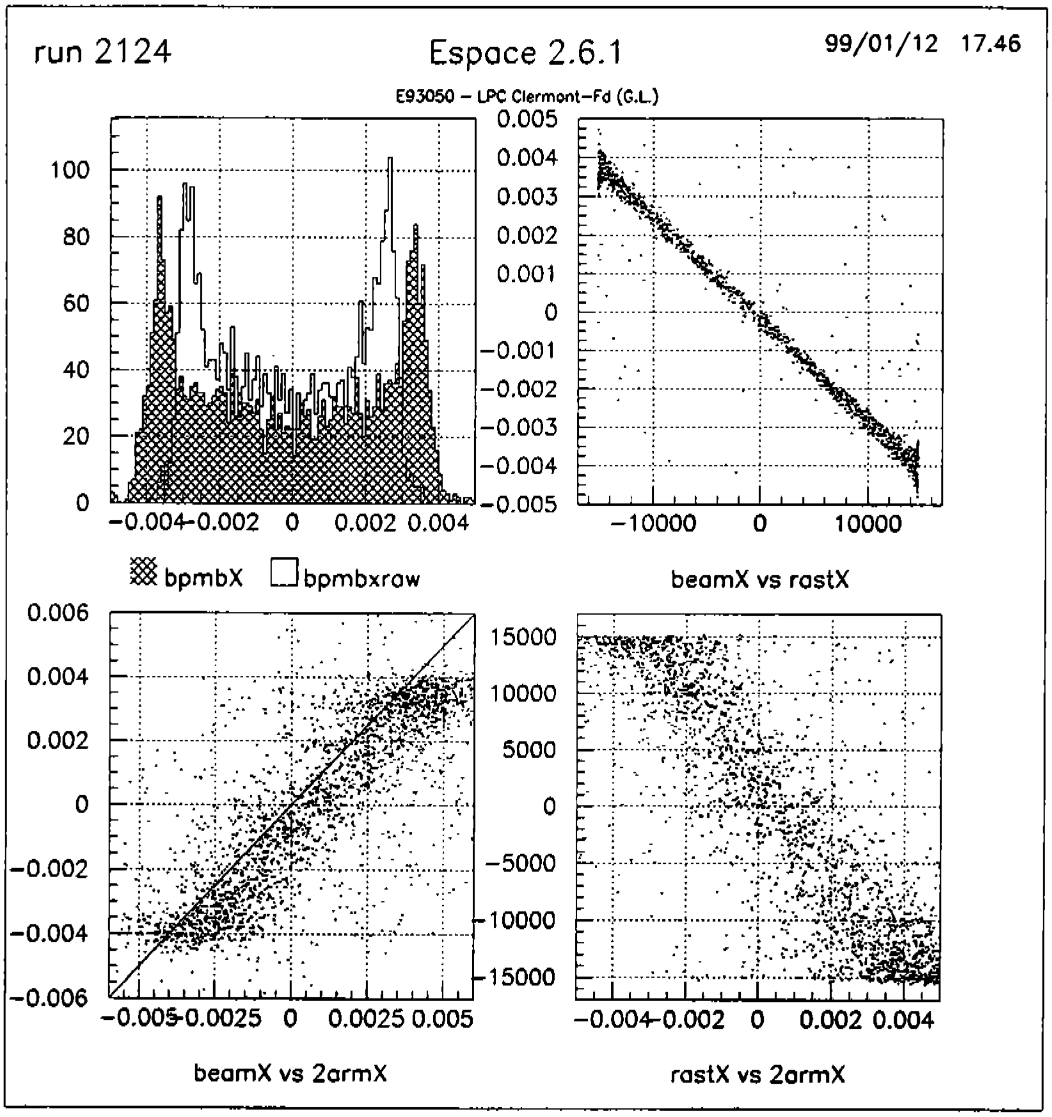

Figure 7: *Espace 2.6.1.*

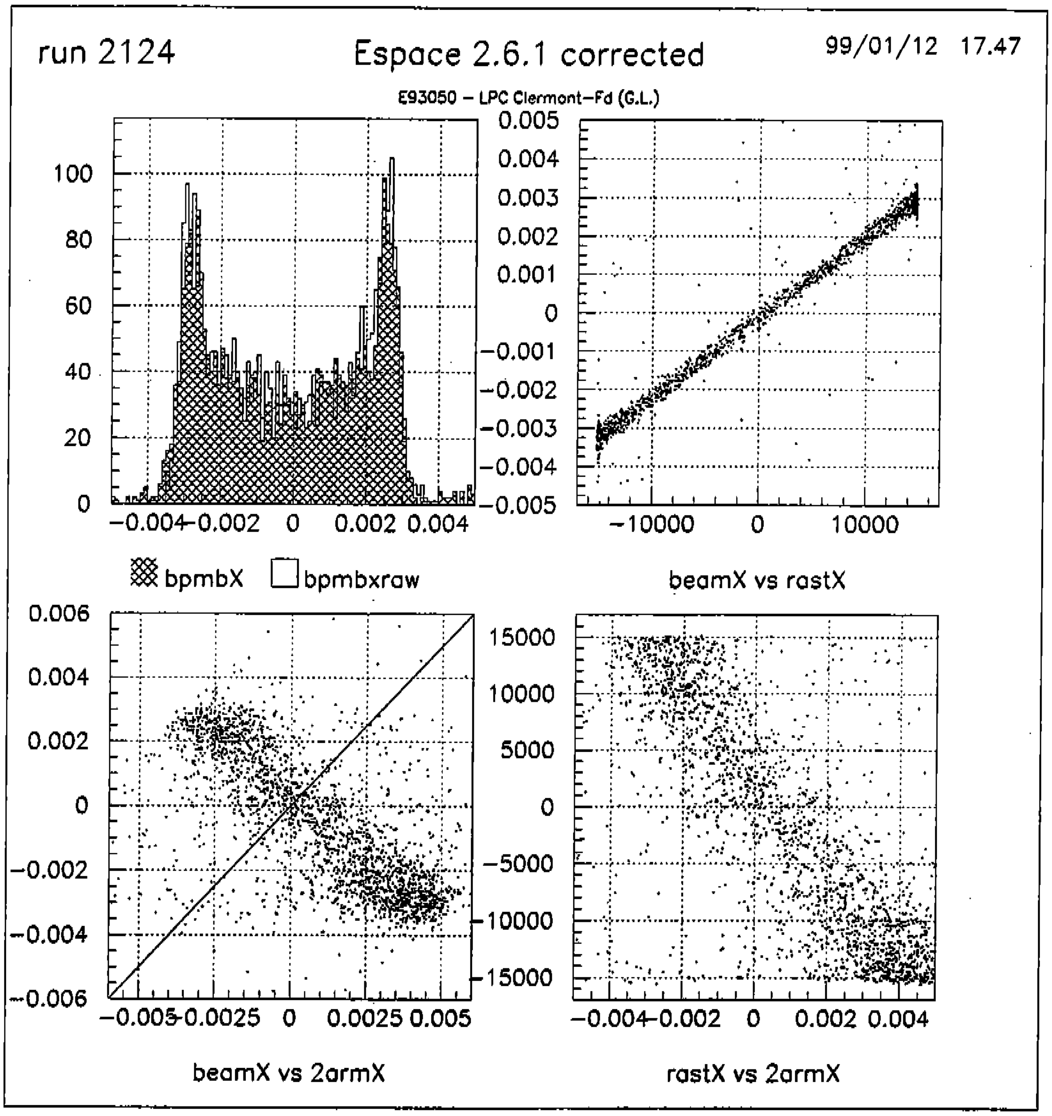

Figure 8: *Espace 2.6.1 corrected*

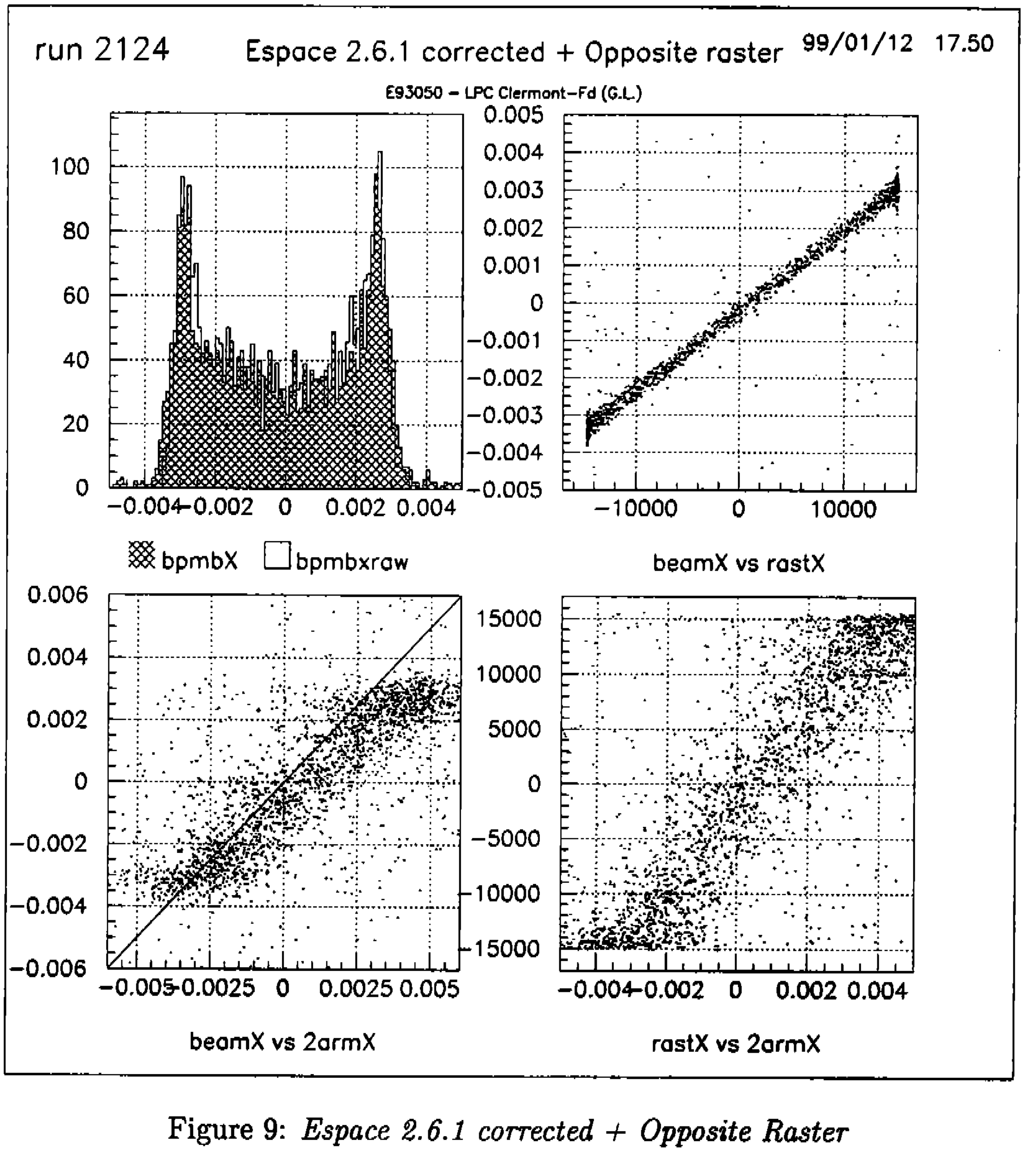

Figure 9: *Espace 2.6.1 corrected + Opposite Raster*

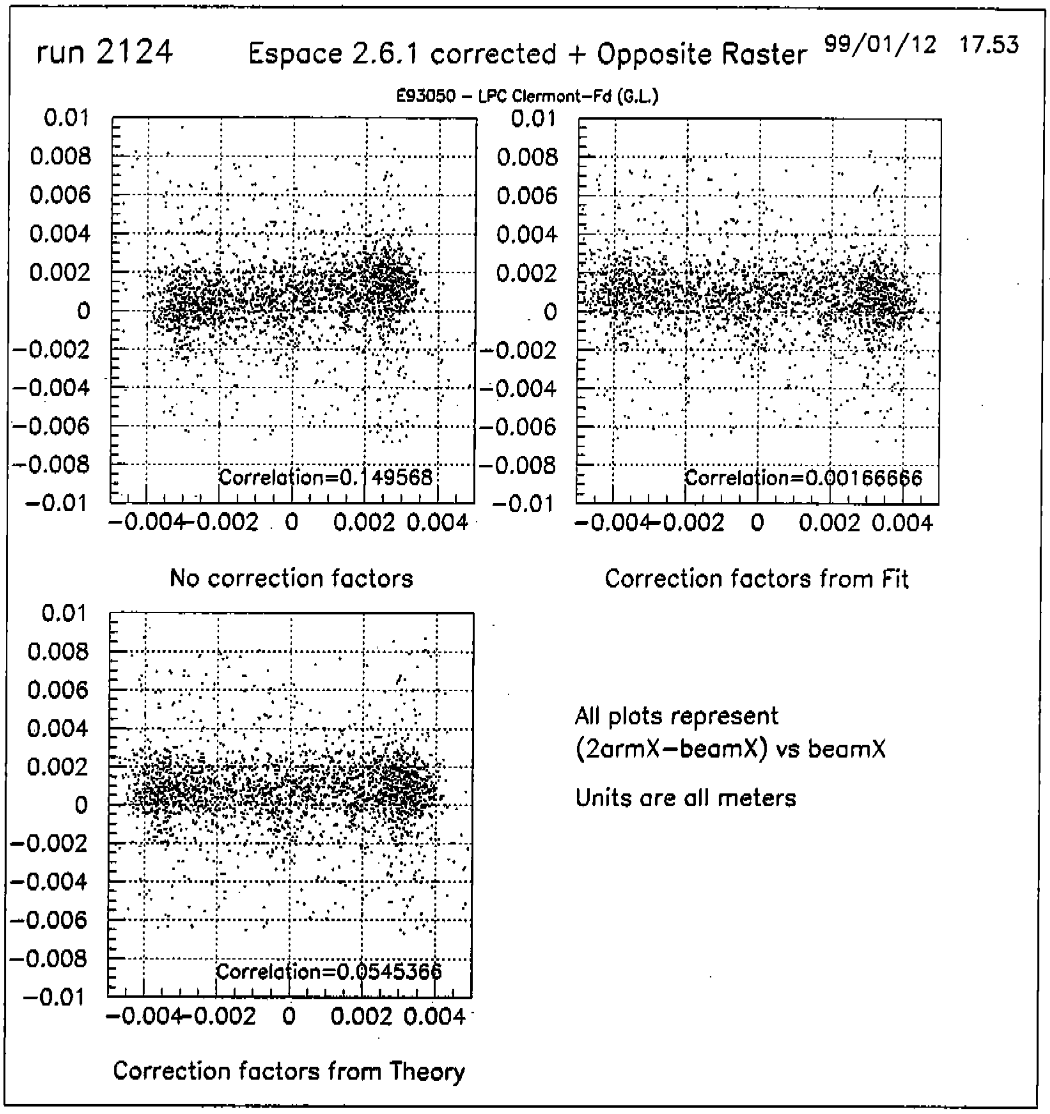

Figure 10: *Effect of BPM vs Bscope/Harp Calibration Corrections*

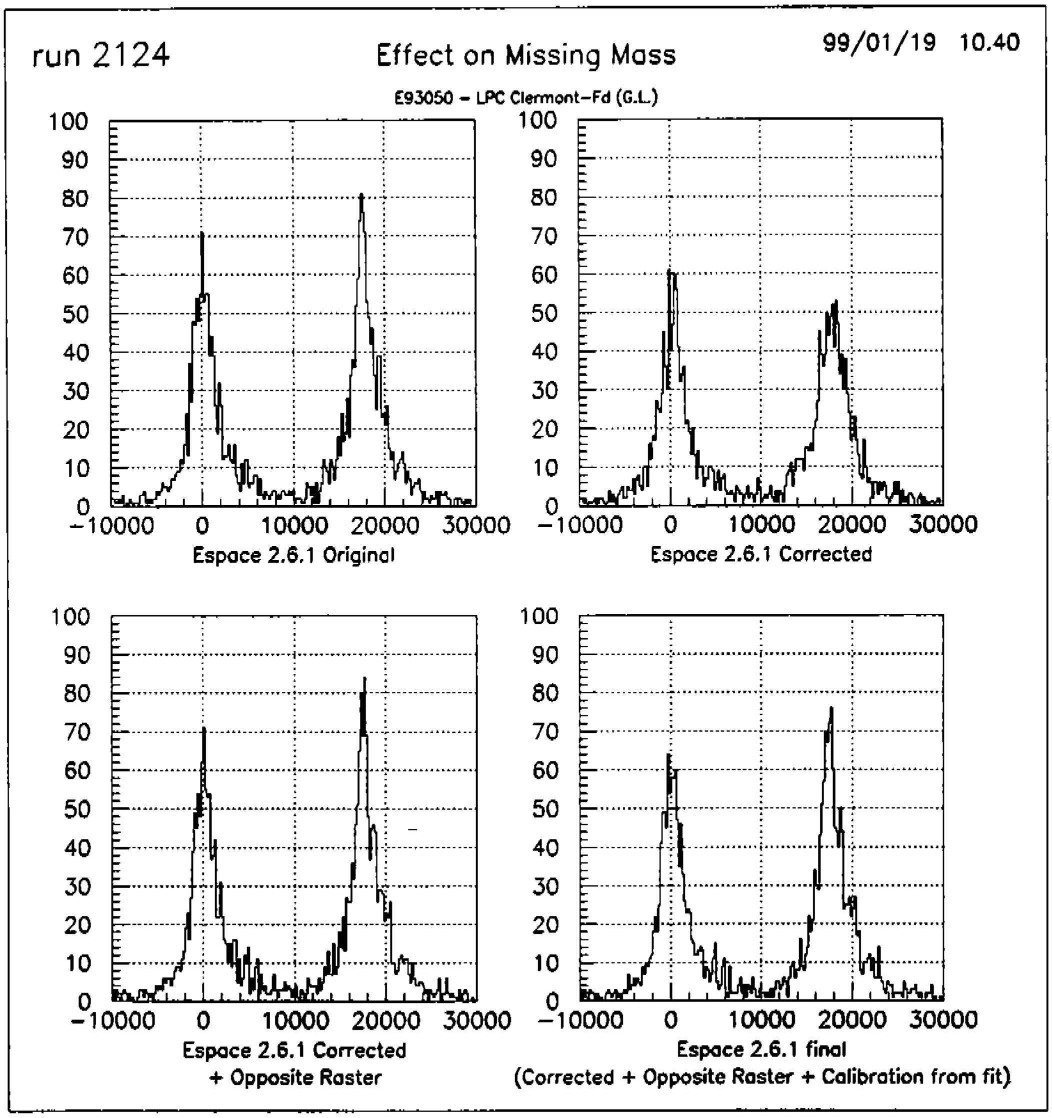

Figure 11: *Missing Mass spectra; the 2 peaks correspond to the photon mass squared ($ep \to ep\gamma$) and the π^0 mass squared ($ep \to ep\pi^0$).*

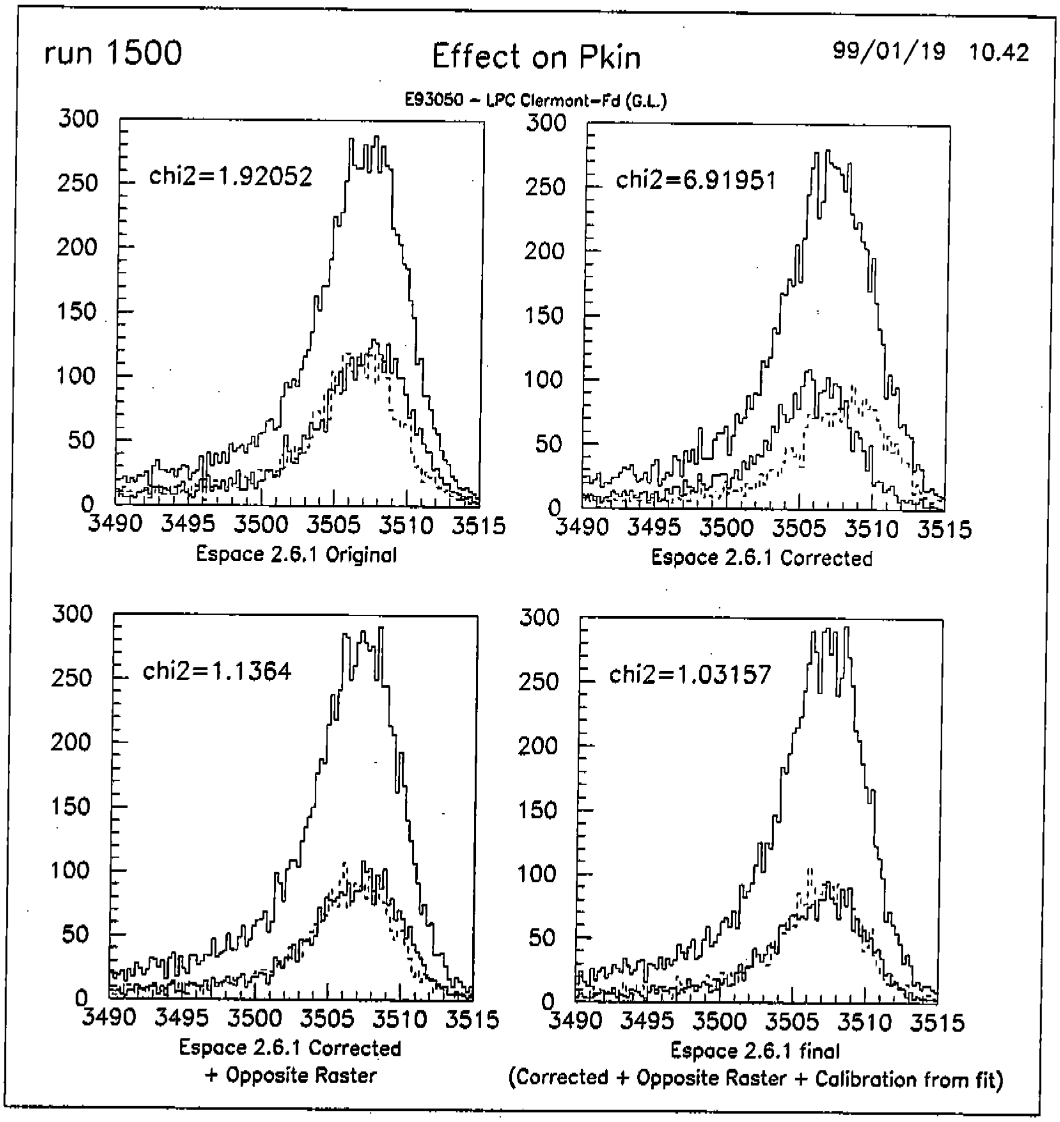

Figure 12: *Pkin spectra*

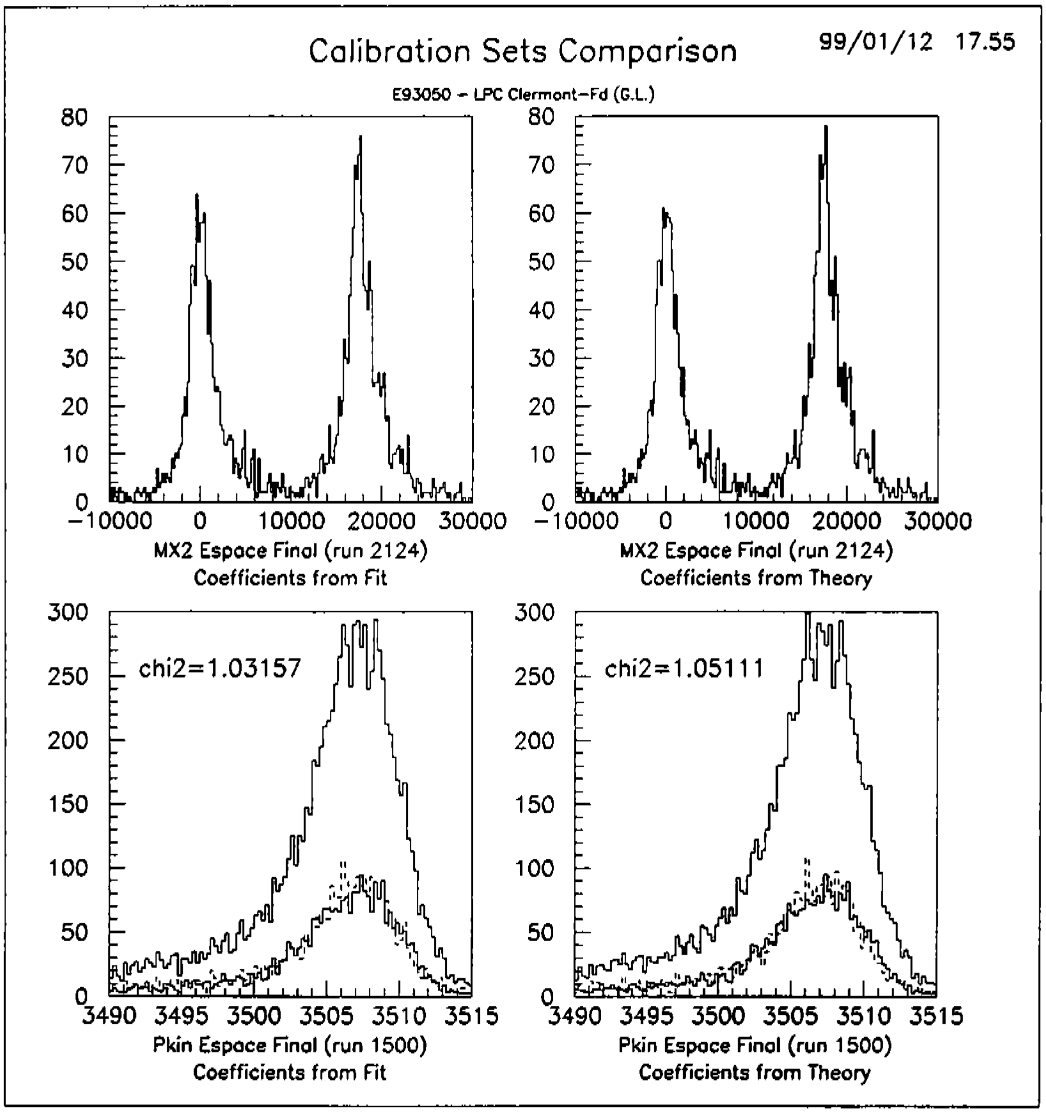

Figure 13: *Calibration Sets Comparison*