TEC Calibration and Analysis

TWIST Technote 95

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> *A pure and simple truth is rarely pure and never simple*

1 Introduction

μ^+ beams are depolarized in the fringe field, and the magnitude of the depolarization depends on the beam position and emittance with regard to the fringe field. For a precise measurement of $P_\mu\xi$, beam profiles have to be accurately measured and then simulated by GEANT in order to match the data and MC in term of the beam polarization. The Time Expansion Chamber (TEC) is used in TWIST for the measurment of the beam, and it therefore plays a critical role in the $P_\mu\xi$ measurement.

The accuracy of the TEC measurements relies on how well it is calibrated and also on how well it is aligned to the yoke as well. A bunch of TEC calibrations were developed when the TEC performance was gradually understood (though still not completely yet). Table 1 gives a list of all TEC calibrations we have got so far.

Name	Description
tc_t0	TEC T0 file. It is to trim individual wire.
tc_twk	TEC time walk correction file.
tc_str	TEC STR file produced by the Garfield.
tc_cor	TEC STR correction file. It corrects drift times distorted by the field interference
tc_eff	TEC efficiency file. It measures the change of TEC efficiency with the drift distance.
$trig\_t0$	The 5^{th} entry is for TEC, which manages the global T0 variation when the trigger changes.

Table 1: TEC related calibration files.

This technical note will present

- the function of each calibration and the procedures to get the calibration done
- uncertainties in TEC measurements
- discussion about how to compensate the inefficiency effect due to the long drift distance and produce correct beam profile.

- some issues still unsolved in TEC analyses, such as the mismatch between the TEC and DC in beam position and angle measurements, etc.

2 TEC Calibrations

As described in Table 1, the calibrations (except *tc_str*) are applied mainly to correct wire inefficiency, field distortion and edge effects. Some special data were taken for this purpose (see Table 2). Most of the data listed there are collimated, taken under various circumstances. When the TEC was put in use at the very beginning, a 1-hole collimator, 1.0 cm in diameter, was used for TEC T0 calibrations. With more understanding of the TEC performance, we realized later that the 1-hole collimator was not sophisticated enough and a better tool was needed. A 4-hole collimator, shown in Fig. 1 schematically, was then deliberately designed. Almost at the very end of 2004 runs, some important runs were taken with the collimator, which makes *tc_cor* correction possible though this 4-hole collimator are still far from being ideal.

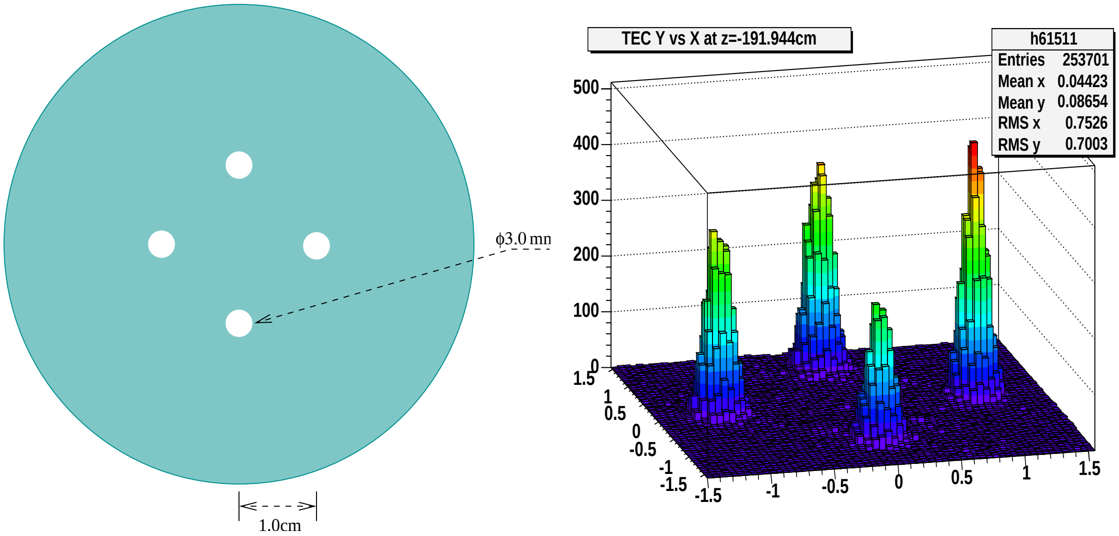

Figure 1: The collimator. Left: a schematic plot and right: four holes reconstructed from data (run 20718).

The basic idea of TEC calibrations is to get *tc_t*0 and *tc_cor* from the multiple hole collimator data, and then apply them to the other runs. A global shift in T0 might be added to make the TEC measurement consistent with those 1 centimeter collimator data.

2.1 T0 Calibrations

TEC T0 calibration includes two parts- *tc_t*0 and *trig_t*0. The former affects the measurements of beam positions and emittance, whereas the latter affects the position measurements

Run #	Description	Trigger	Comments
17310	X and Y modules HV ON	M	Bfield off; wire eff. high.
17616-9	X and Y modules HV ON	Mtec	Bfield off; wire eff. low.
17746	X and Y modules HV ON	Mtec	Bfield off; wire eff. low; widely spread beam data
17899-900	X and Y modules HV ON	Mtec	Bfield off; wire eff. low; check TEC with DC.
20566-73	X and Y modules HV ON	M	Bfield on; wire eff. low.
20638,20641	X and Y modules HV ON	M	Bfield on; wire eff. low.
20639,20642	X module HV ON	M	Bfield on; wire eff. low.
20640	Y module HV ON	M	Bfield on; wire eff. low.
20718-9,20724-5	X and Y modules HV ON	Mtec	Bfield off; wire eff. high.
20720-1	X module HV ON, Y module OFF	Mtec	Bfield off; wire eff. high.
20722-3,20726	X module HV OFF, Y module ON	Mtec	Bfield off; wire eff. high.

Table 2: Data used for TEC calibrations.

only. Another difference is- *trig_t0* is trigger dependent, *i.e.* it changes when the trigger changes from **Mtec** to **M**, but *tc_t0* is not.

2.1.1 *tc_t0*

It takes care of the time offsets due to differences in the cable length, preamplifier pulse shape of individual sense wire. Similar to the cable trimming, it makes all sense wires see a beam particle at a same time when the beam track is parallel to the sense plane (*i.e.* when the drift distance to each wire is the same).

To avoid the field interference between two TEC modules when both are turned on, runs 20720-1 and runs 20722-23,20726 were used to obtain the *tc_t0* parameters for X and Y modules, respectively. The procedure is

- histogram the drift times of all sense wires; the drift time distribution will show 3 peaks.
- get the peak positions ($t_{0x}(i)$, $t_{0y}(i)$, $i = 1, \cdots, 24$) for the central peak (corresponding to the two holes in the middle).

  Since the diameter of holes is small (3.0 mm in diameter), we used the peak positions instead of the mean values of the upper and lower edges because it is not easy to determine the hole brim on a drift time distribution.

  As the beam for the nominal M13 beamline setting is nearly centred when it enters the TEC, the cental peak is used in the *tc_t0* calibration.
- calculate the deviations,

$$\overline{t_{0x}} = \sum_{i=1}^{24} t_{0x}(i)$$

$$\Delta t_{0x}(i) = t_{0x}(i) - \overline{t_{0x}} \quad i = 1, \cdots, 24$$

where the $\Delta t_{0x}(i)$ will be recorded as the calibration parameters.

Fig. 2 shows one of TEC *tc_t*0 distributions. Enhancements are found when the wire number is less than 10 or greater than 40, the reason for which is not fully understood. A preliminary FEMLAB study (done by C. Lindsay, who will give a report on the FEMLAB simulation of the TEC field later.) indicates that it could be caused by the field distortion due to the sense wires and wall of the TEC gas chamber. Another possibility is, the two collimators are not aligned, there might be a twist between them.

It is not known why wires 12, 22 (X module) have Δt_{0x}'s quite different from the others.

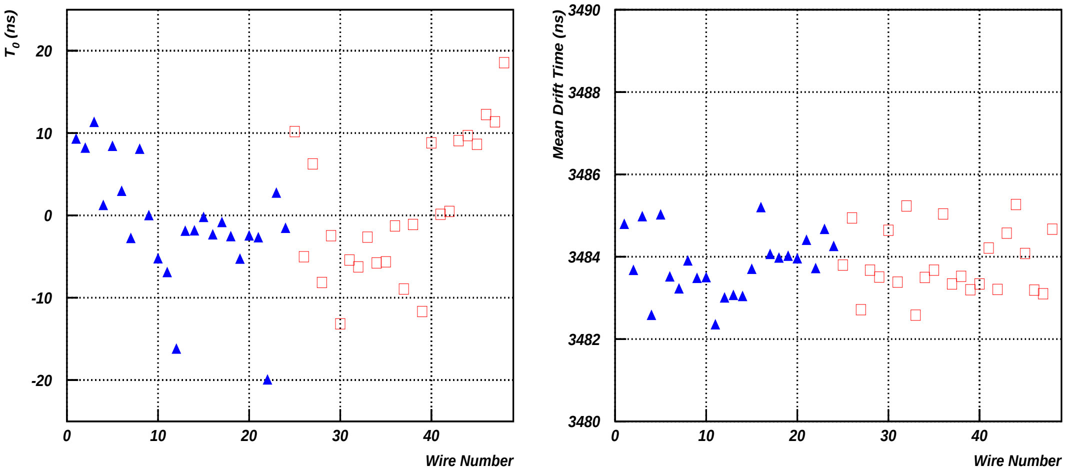

Figure 2: *tc_t*0 calibration. Left: distribution of calibration parameters; right: distribution of mean drift times for the middle holes (x or y = 0.0cm) after the *tc_t*0 calibration.

2.1.2 *trig_t*0

It takes care of the T0 variations when we change the triggers. Collimated data (runs 17310, 17616-9, 20720-1, 20722-3, 20726) and widely spread beam data (run 17746) were used for this calibration. The procedure is

- histogram beam positions (projected to the planes where the collimators are mounted) measured by the TEC
- check the brim of the collimator or the beam pipe
- alter the *trig_t*0 to make the collimator or the beam pipe centred.

*trig_t*0 parameters got from different triggers are listed in Table 3. There is a roughly 17.0 ns time offset between M and Mtec triggers (Time of flight included).

Run #	*trig_t*0 (TEC) in ns	trigger	Solenoid Field
17616-19	-312.0	Mtec	OFF
20566-73	-295.0	M	ON

Table 3: A comparison of TEC global t_0's.

2.2 Time Walk Correction

It takes care of the time jitter of small pulses. Usually, this calibration can be done by fitting and removing the correlation between the pulse height and the drift time. But, for the instance of the TEC, in addition to the time walk effect, the diffusion of electrons also contributes to this correlation. The long drift time clusters have more chances to break because of the diffusion and therefore produce smaller pulses on the sense wires (Fig. 3). To distinguish the time walk effect from the diffusion, a cut on the drift distance was applied (as suggested by D. Mischke). The procedure for this calibration is -

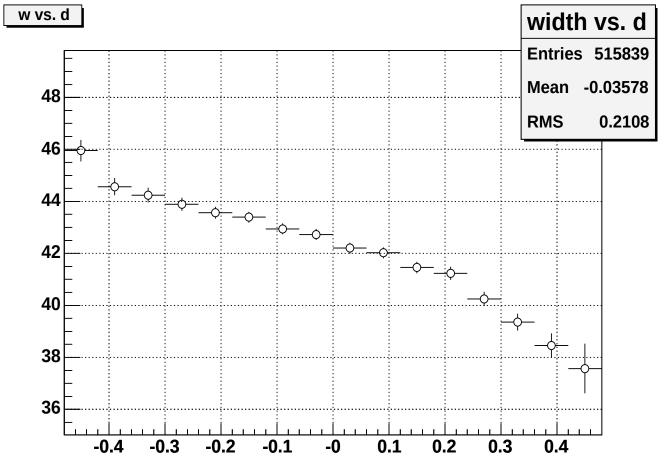

Figure 3: TDC width *vs.* drift distance

- histogram distributions of drift times versus pulse widths for all wires
- use a linear function $T_{raw} = T_{mean} + A_{corr} \times width$ to fit the profiled curves of the above histograms, as shown in Fig. 4 (left).

For a consistency check, a distribution of A_{corr} for 48 wires is presented in Fig. 4 (right). In the TEC analysis, the drift times are corrected as the following

$$T_{corrected} = \begin{cases} T_{raw} + A_{corr} \times 0.0 & \text{if } width > 120.0\text{ns} \\ T_{raw} + A_{corr} \times (120.0 - 20.0) & \text{if } width < 20.0\text{ns} \\ T_{raw} + A_{corr} \times (120.0 - width) & \text{otherwise} \end{cases}$$

*tc_t*0 and *trig_t*0 calibrations have to be done again after the time walk correction.

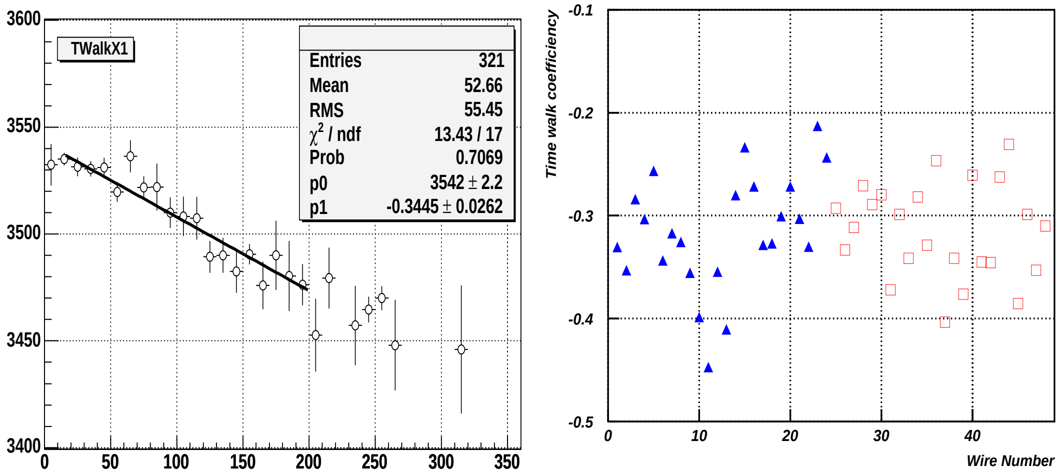

Figure 4: TEC time walk correction. Left: fit the A_{corr} for X module wire 1. x axis represents the TDC width and y is the drift time (ns in units); right: distribution of coefficients A_{corr} (runs 20718-9).

2.3 STR

tc_str, measured by Garfield, is actually not a calibration. Like a lookup table, it provides the drift time for a hit at any given drift distance in a TEC cell and *vice versa*. The following is a definition of the TEC cell in Garfield.

```
&cell
cell-id  "TEC"
*final variant for calculations @B=0.
DEFINE Vs=1500.0
DEFINE Vf=750.0
DEFINE Vg=0.0
DEFINE L=6.0
*options cell-print layout
plane x=-3.048, v=-1000.0
gravity 0 1 0
rows
s  28   0.0025  3.45  -2.7+0.2*i     Vs   30   L  19.3
f  27   0.0125  3.45  -2.6+0.2*i     Vf   80   L  19.3
f   1   0.0125  3.45  -2.9           Vf   80   L  19.3
f   1   0.0125  3.45  -2.8           Vf   80   L  19.3
f   1   0.0125  3.45  -2.7           Vf   80   L  19.3
f   1   0.0125  3.45   2.7           Vf   80   L  19.3
```

```
f   1   0.0125  3.45   2.8             Vf   80   L  19.3
f   1   0.0125  3.45   2.9             Vf   80   L  19.3
g 141   0.015   3.85  -3.5+0.05*i      Vf   120  L  19.3
n  58   0.005   3.05  -2.9+i*0.1+0.05 Vg   50   L  19.3
```

The resolution of a Garfield simulation depends on its mesh size. But, the smaller the mesh size, the more CPU time the simulation consumes. In our case, it took about one week to produce a gas file. Even though, a granularity problem is still spotted in STR files. Fig. 5 gives an example of the STR smoothing, where a small bump is seen on a Garfield-produced STR curve.

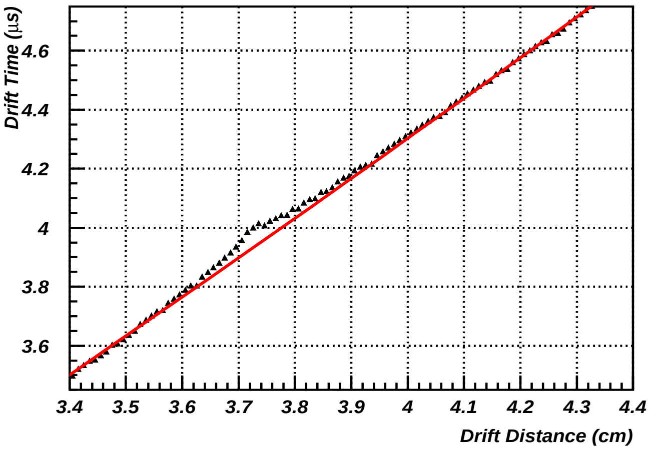

Figure 5: STR Smooth. The small bump is smoothed by a 2^{nd} order polynomial fit

A few things could affect an STR: the TEC geometry, drift field, sense wire high voltage, magnet field, gas composition, pressure and temperature. Therefore, a new STR is needed if any of the above setup variables are changed. During the 2004 nominal data taking, all setup remained unchanged except the magnet field (the temperature effect will be discussed later in this note). Two STR files, produced the magnet field $B_z = 0$ and 0.1 Tesla, are installed in CFM for the TEC analysis. Here are some general features of an STR file:

- drift volume is between $d = 0.45$ cm to 6.45 cm.
- drift velocity is almost constant, ~ 1.0 cm/μs.
- drift time spread for hits from a track at $d = 3.45$ cm could go up to 100 ns because of the TEC geometry.
- the drift time is longer when the solenoid field is on.

Fig. 6 gives a quantitative comparison of the two STRs.

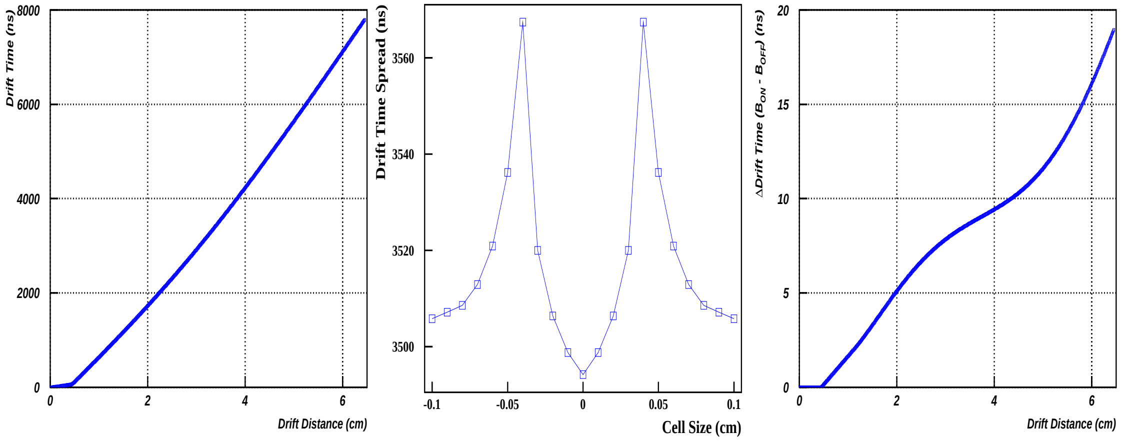

Figure 6: TEC STR. Left: t *vs.* d when $z = 0.0$cm and Bfield is off; middle: t *vs.* z when $d = 3.45$cm; right: drift time difference (Bfieldon-Bfieldoff) for $z = 0.0$cm. t, d, z stand for drift time, drift distance and local Z position in a TEC cell.

2.4 STR Correction

The STR given by Garfield assumes the all setup in the geometry and high voltage are perfect. It doesn't take into account any plane or wire misalignments, field distortions, and neither field penetration from the other module. Runs 20718-25 were analyzed in order to get a data derived STR.

First, let's take a look at how much the STR is distorted in the data. When the other module is off, for a certain hole, the drift time should be the same on every wire or have a symmetric distribution along z. Fig. 7 plots the mean drift times of all wires. A clear distortion is seen for wires at the edge. The middle hole is used for the *tc_t0* calibration, that is why the curves in the middle are flat. A further look at the plot you will see the drift times in every hole are different by $10 \sim 60$ ns between X and Y modules. This indicates that two modules are somehow different (or, there was an offset in X or Y direction when two collimators were mounted).

When both modules are turned on, the field penetration effect is easily seen by comparing Fig. 7 and Fig. 8 where a trend is found that the drift time becomes shorter for a wire closer to the other module (e.g. bigger wire numbers for X module and smaller wire numbers for Y module). The main purpose of the *tc_cor* calibration is to correct this skewed time distribution. The calibration is done by using collimated data taken when both modules were on (runs 20718-9, 20724-5), assuming the two collimators are aligned well with regard to the TEC. The procedure is

- histogram the drift time for all wires.
- get the mean drift times (t_i) for 4 holes ($d_i = 2.45$, 3.45 and 4.45 cm, i = $1, \cdots, 3$).

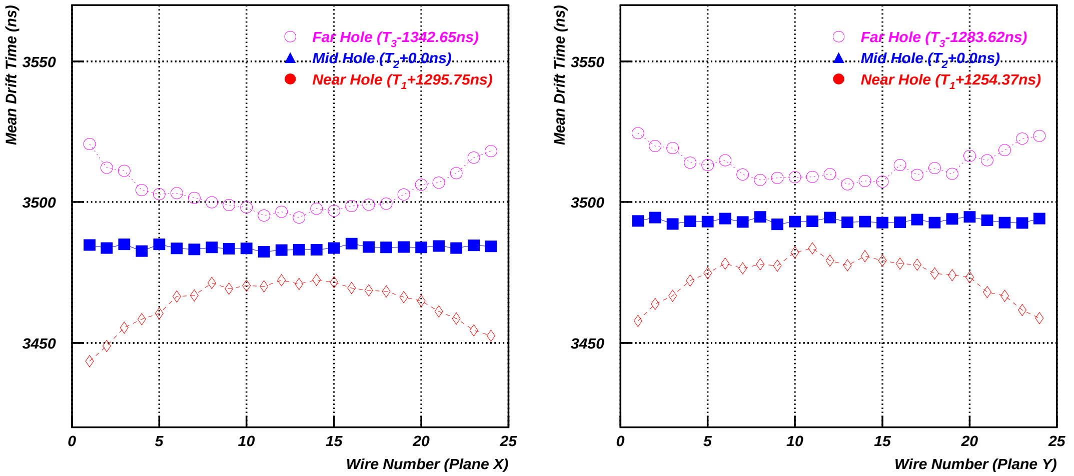

Figure 7: Mean drift times for 3 holes when only **ONE** module is on (left: X module; right: Y module). To make the plot easier to read, we shifted the curves for the far and near holes.

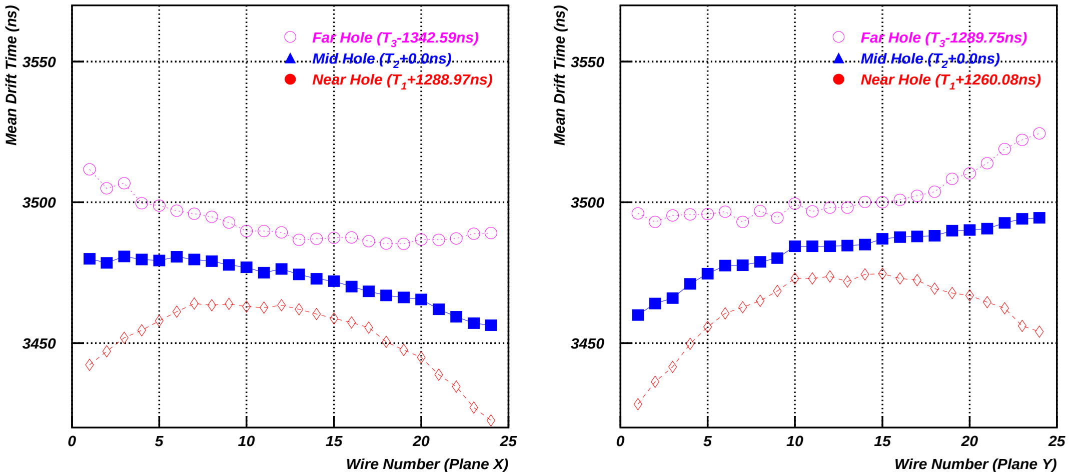

Figure 8: Mean drift times for 3 holes when **BOTH** modules are on (left: X module; right: Y module). The curves for the far and near holes are shifted.

- record the Garfield drift time at $d_4 = 0.45$ cm as t_4 (the location of grid plane) assuming that the field interference doesn't affect the amplification region.
- fit (d_i, t_i) using a 2^{nd} order polynomial function

$$t_i = t_4 + a_1 \cdot (d_i - d_4) + a_2 \cdot (d_i - d_4)^2 \qquad (i = 1, \cdots, 4)$$

From the Garfield simulation we know a 2^{nd} order polynomial fit is a good approximation. If, in the future, a collimator with more holes is available, we definitely can try with a higher order function.

Fig. 9 is an example of the fit on X module wire 1. A global fit, *i.e.* to fit the all wires at once, was also tried, but the results are worse than to fit wire by wire.

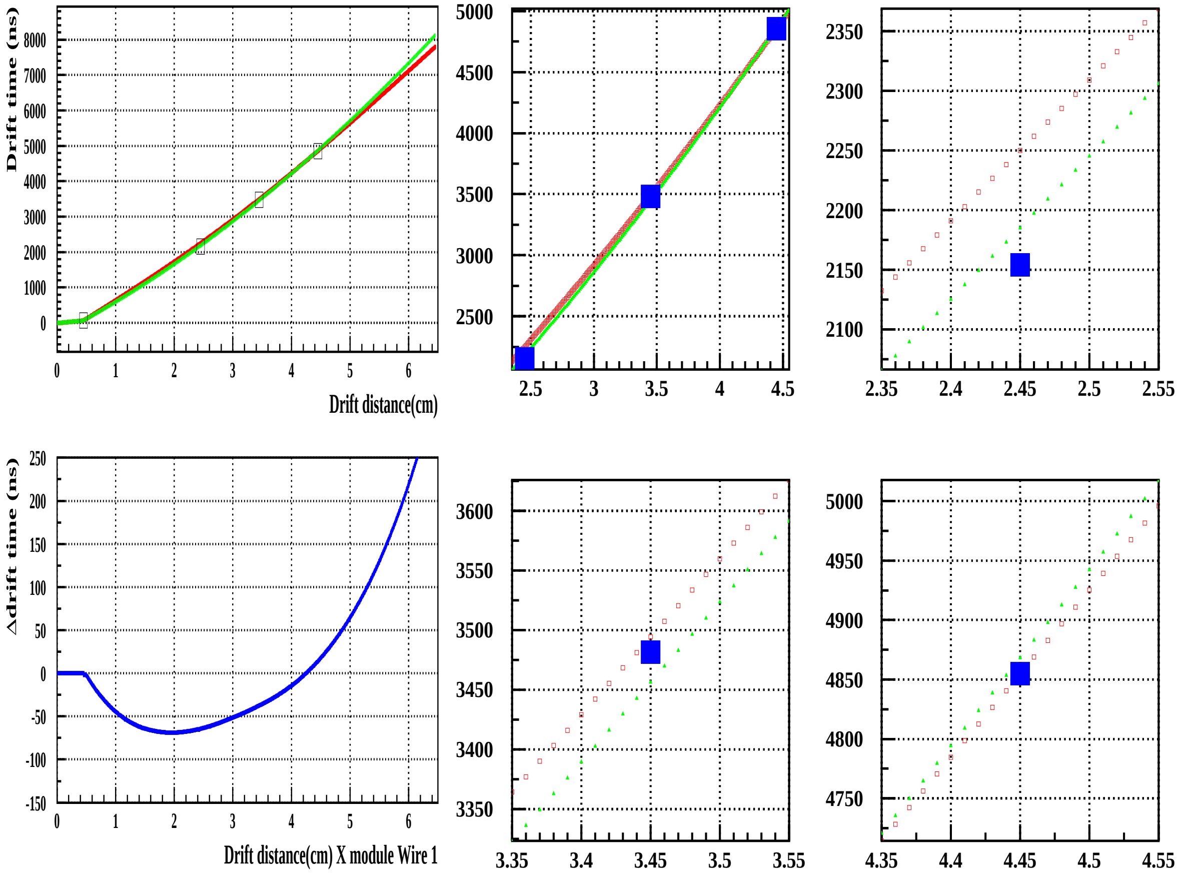

Figure 9: Derive STR from data. Top left: data derived STR (in green) *vs.* Garfield STR (in red). The open boxes represents 4 points; bottom left: difference in STRs (data derived STR - Garfield STR); right: check of the fit (x axis stands for drift distance (in cm) and y for drift time (in ns).

48 STRs are produced after this step is done. The next is to extract STRs for the TEC when the solenoid field is on. Since we don't have the multiple hole collimator data

when the B field is on, here we have to make an assumption- the field penetration from the other module affects the STR in a same scale whenever the solenoid is off or on.

$$\frac{T_{\mathrm{R,Boff}}}{T_{\mathrm{G,Boff}}} \approx \frac{T_{\mathrm{R,Bon}}}{T_{\mathrm{G,Bon}}}$$

where $T_{\mathrm{R,Boff}}$ stands for a drift time given by the data driven STR when the solenoid field is off, $T_{\mathrm{G,Boff}}$ is a drift time given by Garfield when the solenoid field is off.

- calculate the ratio

$$R(T_{\mathrm{R,Boff}}) = \frac{T_{\mathrm{G,Boff}}}{T_{\mathrm{R,Boff}}}$$

Hereafter T_{R} and T_{G} will be used, short for $T_{\mathrm{R,Boff}}$ and $T_{\mathrm{G,Boff}}$, respectively. A distribution of $R(T_{\mathrm{R}})$ is given in Fig. 10. An empirical function is employed to fit the $R(T_{\mathrm{R}})$ curves:

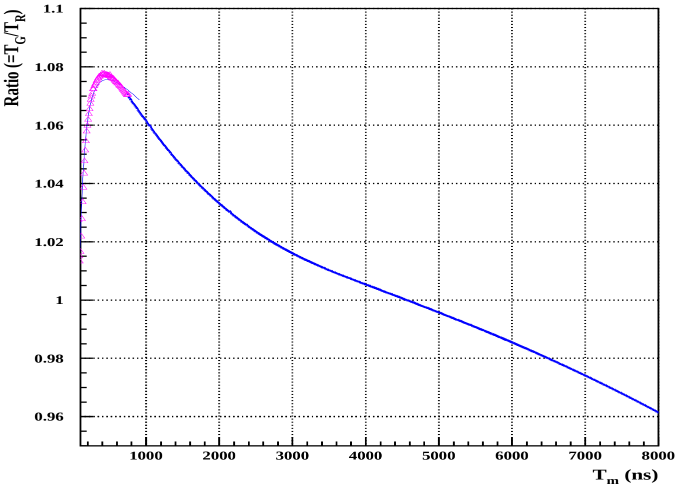

Figure 10: Distribution of ratio $R(T_{\mathrm{R}})$. The curve is split and fit with two functions

$$R(T_{\mathrm{R}}) = \begin{cases} \displaystyle\sum_{i=0}^{4} a_i (T_{\mathrm{R}})^i & (\ T_{\mathrm{R}} \geq 0.7\ \mu\mathrm{s}) \\ b_0 + b_1\sqrt{T_{\mathrm{R}}} + b_2/\sqrt{T_{\mathrm{R}}} + b_3/\sqrt{T_{\mathrm{R}}^3} & (0.1\ \mu\mathrm{s} \leq T_{\mathrm{R}} < 0.7\ \mu\mathrm{s}\ ) \end{cases}$$

The fitted a_i and b_i for 48 wires are plotted in Fig. 11. All distributions show a wire number dependent pattern. The curves for two modules are shifted and approximately mirrored. However, the curve of the X module is more smooth. As a quality check, Fig. 12 shows residuals of the fit. The difference is less than 2.0 ns ($\sim 20.0 \mu m$).

In MOFIA analysis, the drift time of each TEC hit is corrected according to its plane number and wire number, and then by the means of the Garfield STR, we obtain the drift distance which is correspondent to the corrected drift time. Fig. 13 shows mean *corrected* drift times

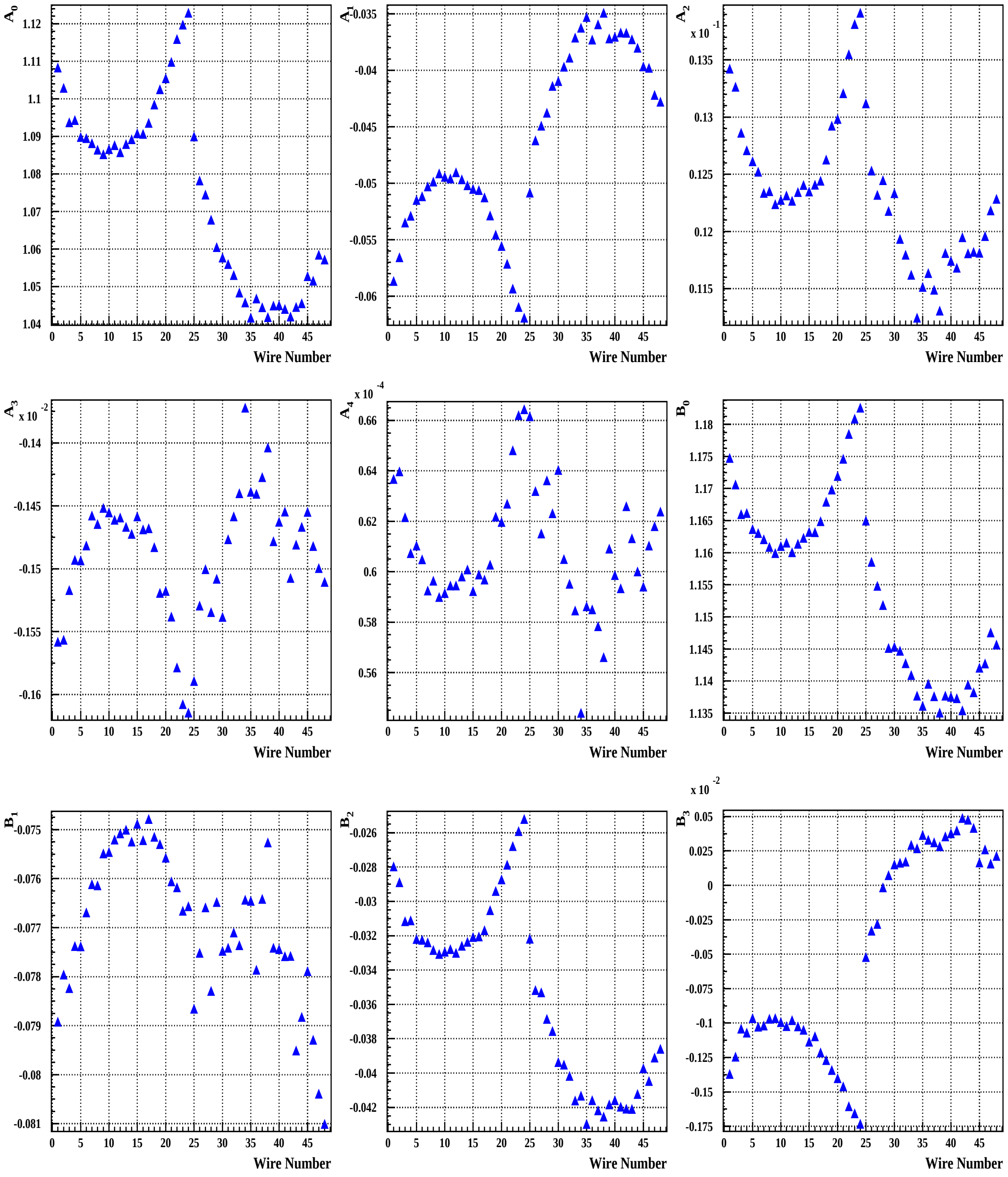

Figure 11: Parametrization of $R(T_{\mathrm{R}})$.

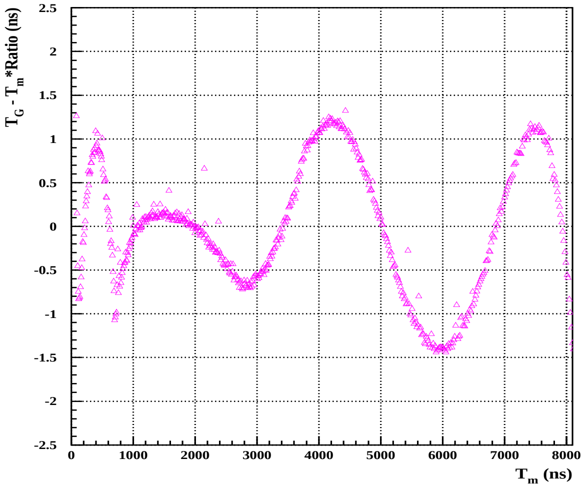

Figure 12: Distribution of residuals (T_{G} - $R(T_{\mathrm{R}}) \times T_{\mathrm{R}}$).

of all sense wires for the collimated data (runs 20718-9, 20724-5). For the near hole, the edge effect is still visible, but much reduced (roughly by a factor of 2). And for the middle holes, there is a hint of the field interference in X module (drift time difference between wire 1 and wire 24 is ~ 5.0 ns, which is ~ 25.0 ns before the correction). A measurement of beam x positions is shown in Fig. 14, where the near hole (the one closest to the sense plane) is moved back to $x = -1.0$ cm after the STR correction.

In the TEC Monte Carlo simulation, things will be done reversely.

- for a given hit the drift time, say T_{G}, can be calculated by using the Garfield STR since the hit position is exactly known.
- get the $R(T_{\mathrm{G}})$ from *tc_cor* calibration file
- measure the T_{R}, which is the drift time in the distorted drift field.

$$T_{\mathrm{R}} = \frac{T_{\mathrm{G}}}{R(T_{\mathrm{R}})} = \frac{T_{\mathrm{G}}}{R(T_{\mathrm{G}}) + R'(T_{\mathrm{G}})(T_{\mathrm{R}} - T_{\mathrm{G}})}$$

$$= \begin{cases} \dfrac{-[R(T_{\mathrm{G}}) - R'(T_{\mathrm{G}})T_{\mathrm{G}}] + \sqrt{[R(T_{\mathrm{G}}) - R'(T_{\mathrm{G}})]^2 + 4T_{\mathrm{G}}R'(T_{\mathrm{G}})}}{2R'(T_{\mathrm{G}})} & \text{if } R' \neq 0 \\ \dfrac{T_{\mathrm{G}}}{R(T_{\mathrm{G}})} & \text{otherwise} \end{cases}$$

Fig. 15 tells us the above approach is reasonable if we want to simulate the field distortion in MC.

Only one *tc_cor* calibration file has been produced and installed in the CFM for 2004 data.

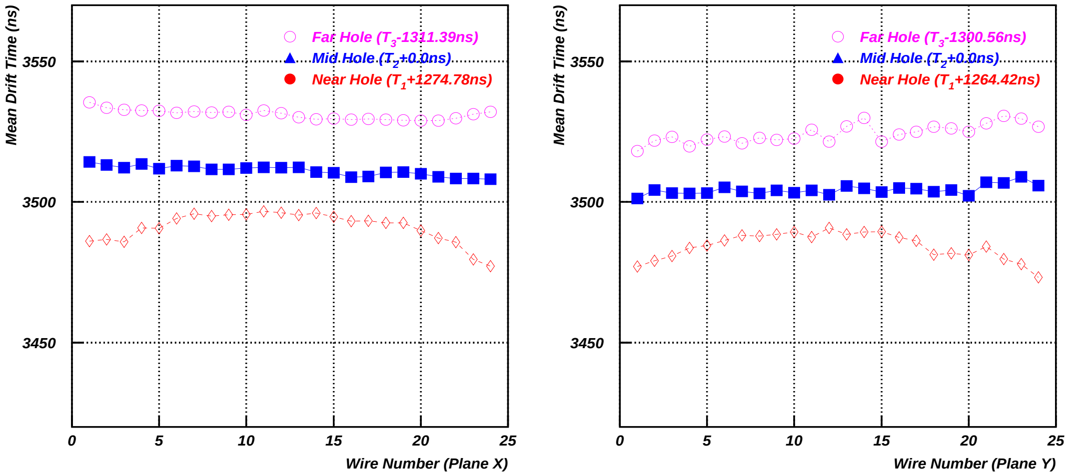

Figure 13: Mean drift times for 3 holes when **BOTH** modules are on and *tc_cor* correction is made (left: X module; right: Y module). The curves for the far and near holes are shifted.

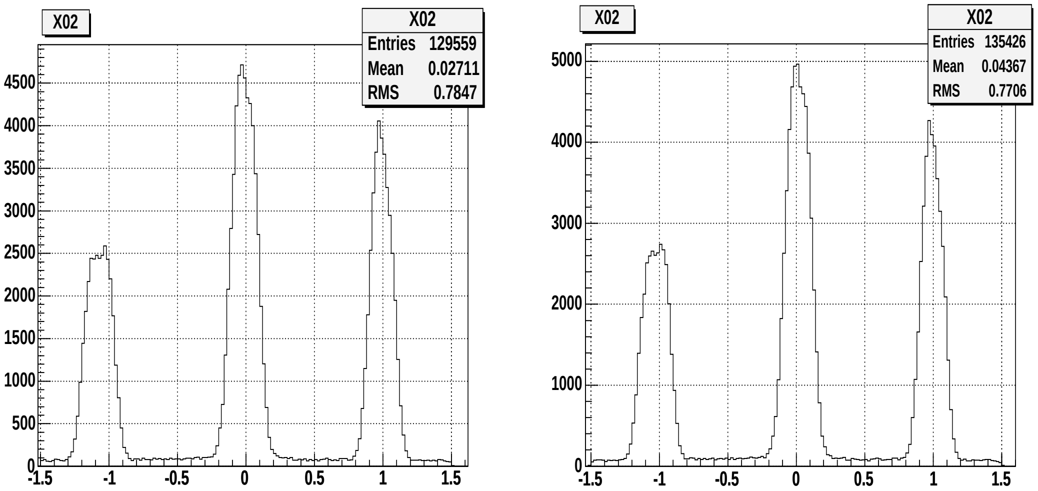

Figure 14: Measurement of the beam x positions before (left) and after (right) the correction).

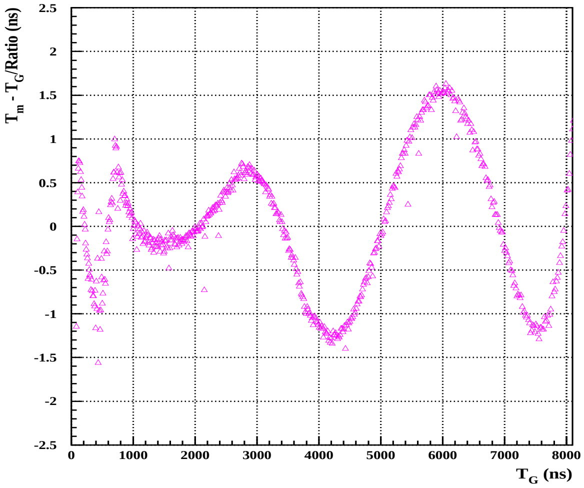

Figure 15: Distribution of residuals (T_{R} - $T_{\mathrm{G}}/R(T_{\mathrm{R}})$).

2.5 tc_eff

This calibration takes care of the inefficiency of long drift time hits. Due to the diffusion, a cluster could fail to get registered if it has a long drift distance. The 4-hole collimator data are used for the calibration, simply because they are high efficiency data and the distribution of the total number of hits on each track is clearly above 4, a cutoff for a quality fit.

The calibration procedure is

- histogram the number of hits on a beam track seen by TEC (beam particle type selection needs to be applied here).
- for each hole, get the mean value of the number of hits, N_{mean}
- fit the N_{mean} to the mean drift time (or distance) and get the ratio, A_{ineff}.

Fig. 16 shows the magnitude of the efficiency loss. Later I will discuss more about how to use this calibration to write out beam profiles.

2.6 Installation in CFM

Most of the TEC related calibrations (except tc_eff) have been installed in CFM. Here below is a part of the CFM record, which lists run ranges for various TEC calibration files.

```
HUJL      Thu Feb 24 13:35:35 2005modify 17294:17487 tc t0 3
HUJL      Thu Feb 24 13:35:35 2005modify 17488:18159 tc t0 4
HUJL      Thu Feb 24 13:35:35 2005modify 18160:20704 tc t0 5
HUJL      Thu Feb 24 13:35:35 2005modify 20705:25000 tc t0 6
HUJL      Thu Feb 24 13:35:40 2005modify 17294:17487 trig t0 12
HUJL      Thu Feb 24 13:35:40 2005modify 17488:18159 trig t0 13
```

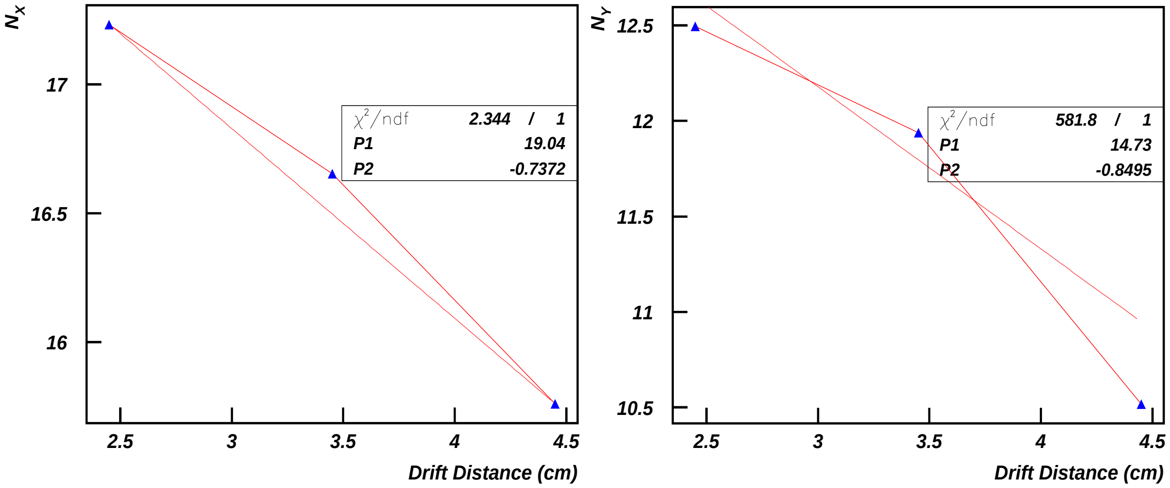

Figure 16: tc_eff calibration. N_X and N_Y stand for mean values of the number of hits used in the track fitting in X and Y modules.

```
HUJL      Thu Feb 24 13:35:40 2005modify 18160:20654 trig t0 12
HUJL      Thu Feb 24 13:35:40 2005modify 20655:25000 trig t0 13
HUJL      Thu Feb 24 13:35:45 2005modify 17294:18203 tc str 6
HUJL      Thu Feb 24 13:35:45 2005modify 18204:20602 tc str 7
HUJL      Thu Feb 24 13:35:45 2005modify 20603:25000 tc str 6
HUJL      Thu Feb 24 13:35:50 2005modify 17294:20638 tc cor 1
HUJL      Thu Feb 24 13:35:50 2005modify 20639:20640 tc cor 0
HUJL      Thu Feb 24 13:35:50 2005modify 20641:20641 tc cor 1
HUJL      Thu Feb 24 13:35:50 2005modify 20642:20643 tc cor 0
HUJL      Thu Feb 24 13:35:50 2005modify 20644:20719 tc cor 1
HUJL      Thu Feb 24 13:35:50 2005modify 20720:20723 tc cor 0
HUJL      Thu Feb 24 13:35:50 2005modify 20724:20725 tc cor 1
```

3 Uncertainties in TEC Measurement

The precision of TEC measurements depends on the TEC calibrations and the TEC alignments. Here, the TEC alignments include the alignment of the TEC chamber to the yoke and the alignment of the collimators to the beam line. The latter is TEC calibration related. In this section, we will give a list of possible systematic uncertainties (or offsets) and an estimate of their magnitudes.

- T_0 calibrations
  For the 0.3 cm hole collimator data, uncertainty is small, $\sim$ 2.0 ns. But, For the 1.0 cm hole collimator data, the uncertainty is big, $\sim$ 15 ns, which is correspondent to 150.0 μm.

The structure on the t_0 distribution in Fig. 2 is not understood. It will introduce a +2.0mrad and +4.0 mrad offsets in dx and dy measurements if the structure is due to the fact that the collimators are misaligned.

- STR

  In Section 2.4, when fitting the STR we borrowed (d_4, t_4) from the Garfield simulation since we don't have enough points for the STR extraction. It gives us an uncertainty of about 300.0 μm in the position measurement, and about 1.0 mrad in the angle measurement (see Figs. 9 and 14).

  A big uncertainty comes from the STR variation when the gas temperature changes. Fig. 17 shows the drift times at different temperatures for drift distance $d = 3.45$ cm. A change of $3 \sim 5\ ^0C$ in temperature could cause a shift of $500.0 \sim 1,000.0\mu$m! Fortunately, all TEC runs were taken within a short time, temperature variation should be small. An uncertainty due to this is $< 200.0\mu$m.

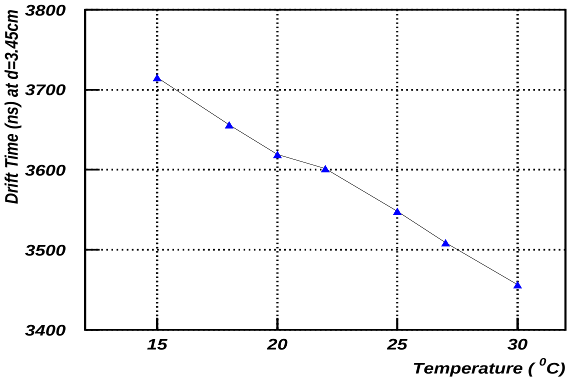

Figure 17: Drift time $vs.$ gas temperature.

- analysis algorithm

  TEC track fitting code could also produce a bias in the measurements because of the tracking algorithm employed. A Monte Carlo study (with the wire inefficiency simulated and the MULS off) shows the uncertainty due to this is $\sim 50\mu$m in position measurements and < 1.5mrad in angle measurements.

- multiple scattering

  A problem observed recently is that the resolution of the angle measurement is worsen by almost a factor of 2 due to the multiple scattering. Fig. 18 shows how the beam angle distributions vary with the z. The top row is the dx distributions at $z = -205.0$cm (a little bit upstream the TEC), -200.0cm (beginning of the TEC X module) and -183.0cm (end of the TEC Y module) when the MULS is OFF; the bottom is the same but the

MULS is ON. A beam particle is scattered by the TEC window and 2.45cm DME gas before it reaches the TEC X module, which makes its dx distribution smeared by a factor of 1.5. An MC test with a thinner TEC window (changed from 6.35μm to 3.25μm) gives a result in Fig. 19.

To understand the impact of the multiple scattering on the beam polarization, another MC study is done.

1. run A
   - 2003 beam tune ($CAL_DB/surface_tune_03.dat)
   - 10K triggers
   - TEC turned OFF
   - Spin in target: 0.99786 ± 0.00004 (got from plot 70 in .hbbook generated by Geant3)
2. run B
   - 2003 beam tune ($CAL_DB/surface_tune_03.dat)
   - 50K triggers
   - TEC turned ON
   - the generated data were analyzed by MOFIA. A beam rays file, surface_tune_03.tec, was produced (38,937 entries). the x and y are positions when the beam is projected to $z = -191.944$cm, the middle of the TEC chamber.
     Fig. 20 shows a comparison of the beam profile ($CAL_DB/surface_tune_03.dat) we use as an input in the MC and the beam profile we got from the TEC analysis from the run B data (surface_tune_03.tec). The top are from the surface_tune_03.tec at $z = -191.944$cm, while the bottom are from the surface_tune_03.dat at $z = -191.3$cm. There is a pretty good consistence between the input and the measured in term of the x, y measurements; but for the dx and dy, the discrepancy is clear. A further study is undergoing to understand why the measured dy has a funny shape.
3. run C
   - used beam rays file, surface_tune_03.tec.
   - 10K triggers
   - TEC turned OFF
   - Spin in target: 0.99460 ± 0.00004
4. run D
   - used the beam profile obtained from the surface_tune_03.tec.
   - 10K triggers
   - TEC turned OFF
   - Spin in target: 0.99549 ± 0.00004
     (all correlation between x and y, a part of correlation between x and dx, y and dy are discarded when converting a beam rays into a beam profile.)
5. run E

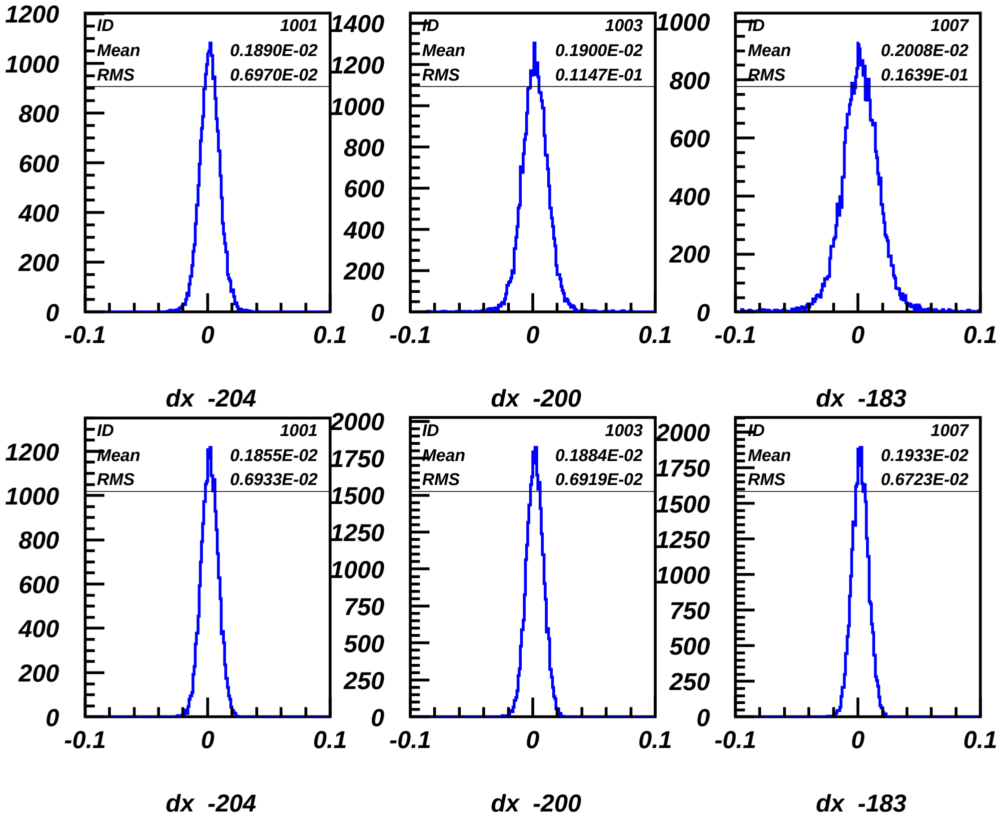

Figure 18: Effects of multiple scattering on TEC angle measurements (I).

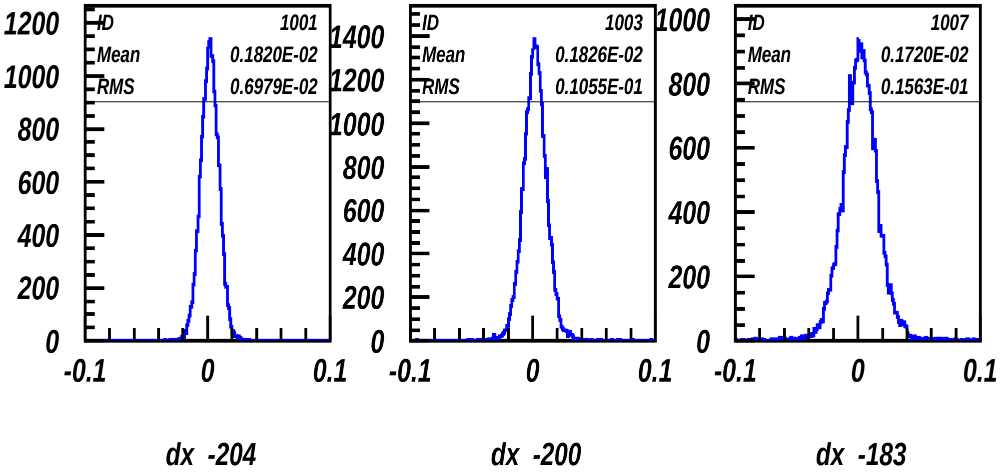

Figure 19: Effects of multiple scattering on TEC angle measurements (II): thickness of TEC gas window is narrowed and gas pressure reduced.

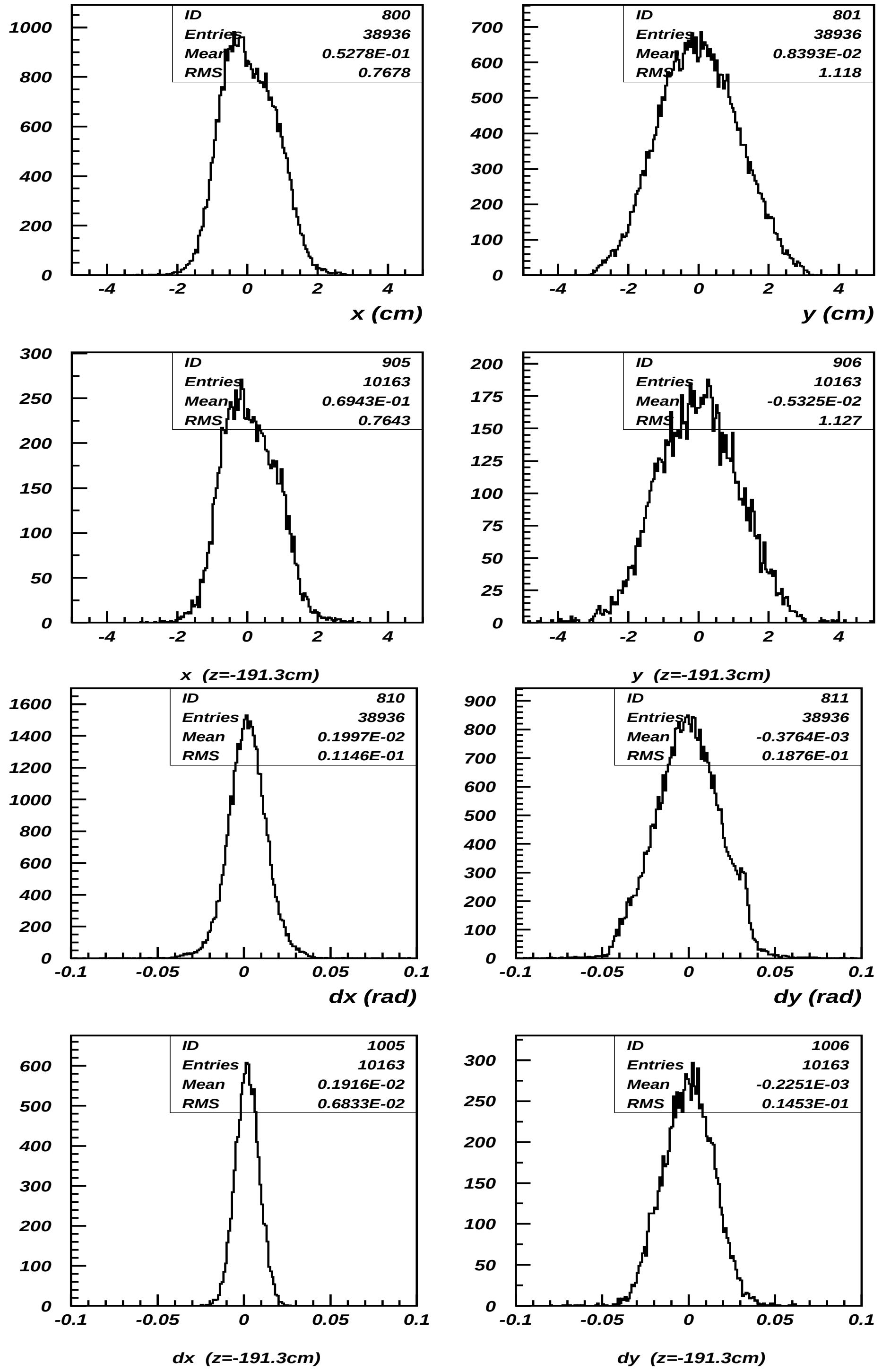

Figure 20: Beam profile: input *vs*. measured. See the text for explanation.

  - used the beam profile obtained from the surface_tune_03.tec, but the *dx* and *dy* distributions were narrowed down by a factor of 1.35 for X module and 1.85 for Y module, simply to deconvolute the multiple scattering effect.
  - 10K triggers
  - TEC turned OFF
  - Spin in target: 0.99713 ± 0.00004

The results indicate the deconvolution does help to some extent. Therefore, in the MC production runs, we might have to use beam profiles instead of the beam rays.

- alignment of collimators
  Two collimators, mounted on the entrance/exit windows of the TEC gas box, were used to align the TEC sense planes. Any noticeable shift or rotation between the collimators will deteriorate the *tc_t0* calibration and STR correction, and further introduce a bias in the TEC analysis. According to Grant, the uncertainty in the alignment of the collimators is around 500.0 μm. More accurate number will come when Grant finishes the remeasurement of the "total station".

  A study has been done to see if there is any dependency of the drift time on the hit position along the sense wire. In another word, we checked how the drift times for a fixed drift distance in the X module vary with the hit y positions. Fig. 21 shows the result from run 20718-9 (4-hole collimator data, both modules on), where, for the X module (wire number ≤ 24), T_{near} and T_{far} are the mean drift times in holes $y = +1.0$ cm and -1.0 cm, respectively; for the Y module, T_{near} and T_{far} are the mean drift times in holes $x = -1.0$ cm and $+1.0$ cm. It is not quite understood why the $(T_{near} - T_{far})$ is wire number dependent. It should not be related to T_0 or STR calibrations. A few possible causes are

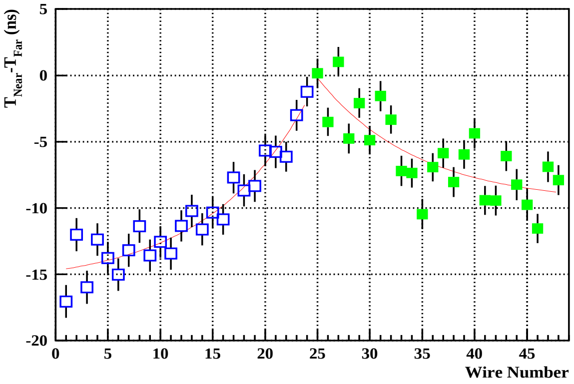

Figure 21: Hit position dependency. See the text for more explanation.

1. collimators are twisted.
   This can be fixed by redoing the calibrations with corrected hole positions.
2. TEC sense planes are tilted.
   This can be fixed by doing the y position correction to the x measurements and *vice versa*.
3. field interference from other module.
   The fix is as same as in 2.

- alignment of TEC chamber
  Grant is going to present some numbers here later.

To get a feel how much the above uncertainty affects the beam polarization, I present here a plot (Fig. 22) from a Monte Carlo study by D. Gill, which shows that the depolarization changes quadratically when the beam position is off axis or the beam incident angle is tilted. On this figure the x's are for a beam started on the z axis, at the angles shown to that axis. The +'s are for the same beam started at 5mm off the z axis and the filled squares are for 1cm off the z axis.

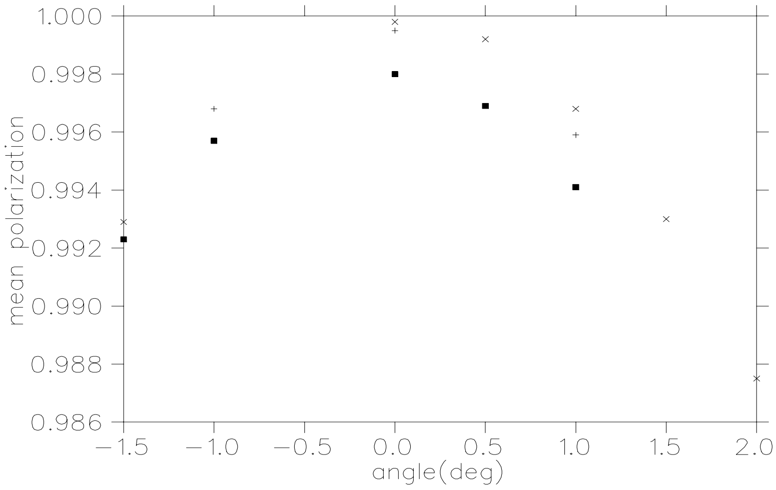

Figure 22: Sensitivity of the polarization to the alignment of the TEC.

Here is a hard copy of a part of his post:

```
A fit of the X's to  a*angle^2 + b*angle + c gives:
a = -0.00309862
b = 0.0000218182
c = 0.99989
so that a 2.5 mrad mistake in the TEC alignment to the z axis would mean
a ~6 x 10^-5 reduction in the polarization.

Note that distance off axis is a very important factor so that the size
of the beam must be as small as possible!
```

4 How to produce an Unbiased Beam Profiles

One goal of the TEC analysis is to produce a beam profile for the simulation of the beam in the Monte Carlo. Simply, it can be done by writing out x, y, dx and dy into a beam rays file event by event. But, for long drift time tracks, fewer TEC wires see them because of the low efficiency, *i.e.*, the number of hits on a track also becomes fewer. Since there is a cutoff ($N_{hit} \geq 4$) in the number of hits required by the straight line fitting in the TEC analysis, the acceptance for the long drift time tracks will be systematically lower, which will definitely distort the beam profile shape. Therefore, a correction should be taken to make the acceptance uniform over the whole drift region.

One approach I suggest to take is-

1. do tc_eff calibration on the TEC data from which we plan to write a beam profile.
2. then, we know the mean value of hits at a given drift distance, d,

$$N_{mean} = N_0 - A_{ineff} \cdot d$$

3. assuming the number of hits on a track follows a Poisson distribution (Fig. 23), we calculate the acceptance when there is a cutoff

$$\mathcal{A} = \sum_{r>N_{cutoff}}^{24} \frac{1}{r!} N_{mean}^{r} e^{-N_{mean}}$$

   A longest drift distance track corresponds to a maximum $1/\mathcal{A}$, say R_{max}.

4. for each event, we generate a random number, r, between 0 and R_{max}. And we accept the event only when $r < 1/\mathcal{A}$.

The downside of this approach is that it discards good events at shorter drift distances. So, the statistics is an issue.

Another method. We implement the long drift efficiency loss in the Monte Carlo and generate a broad and uniform beam over the beampipe. Therefore, an acceptance function can be obtained from the TEC analysis. We then do the same thing as the above step 4.

If we only need to get the beam shapes, things will be easier- we could simply correct the beam profiles got directly from the TEC analysis.

5 Issues Open to Question

In the TEC studies, there are still some puzzling things.

1. Wire dependency of the fit resolution
   In the TEC analysis, beam tracks are fit by straight lines. The residual of a hit is calculated by excluding the hit in the fit. For some runs, the RMS of the residual distributions increases with the wire number. It is found that this is TEC efficiency related. Fig. 24 presents a result from run 20718-19. After a cut on the number of

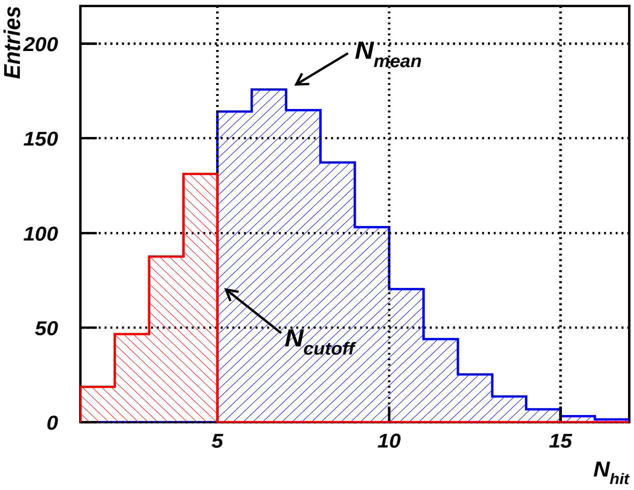

Figure 23: Correction of TEC inefficiency due to long drift time.

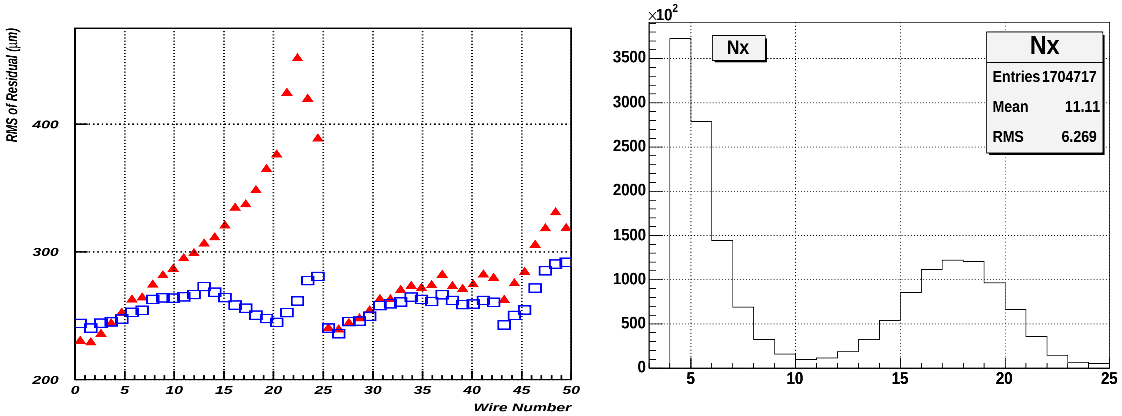

Figure 24: Resolution of the track fitting. Right: the number of hits on a track; left: fit resolutions for $N_X \leq 9$ (red triangles) and $N_X > 9$ (open boxes).

hits, the resolution distribution becomes normal- the small twiggle could be due to the feature of a straight line fitting to a multiple scattered track. But, why does the resolution distribution have that funny feature when the N_X is small?

2. Discrepancy between TEC and DC measurements
   Once a time, there was an attempt that we could align the DC by using the measurements from the TEC or *vice versa* when the B field is off. So, runs 17899-17900 were taken for this purpose. But the results are rather discouraging- there is a remarkable difference in the angle measurements. The reason is not known yet. (Fig. 25).

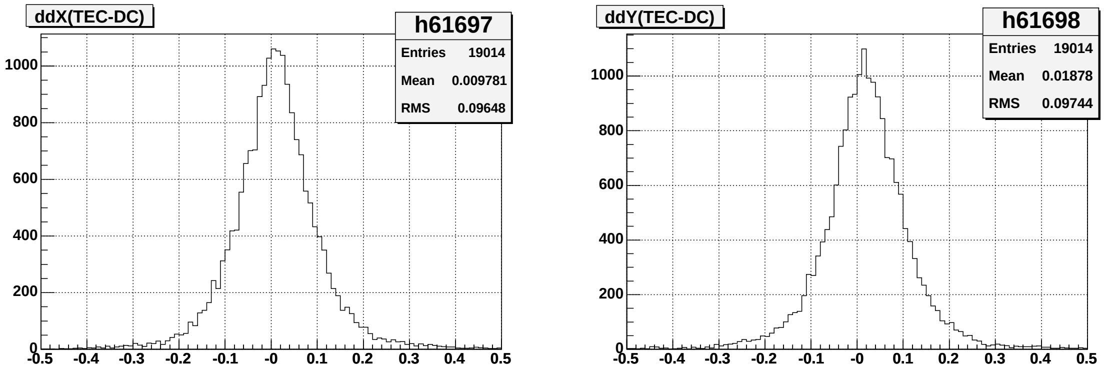

Figure 25: Comparison of TEC *vs.* DC measurements of beam angles.

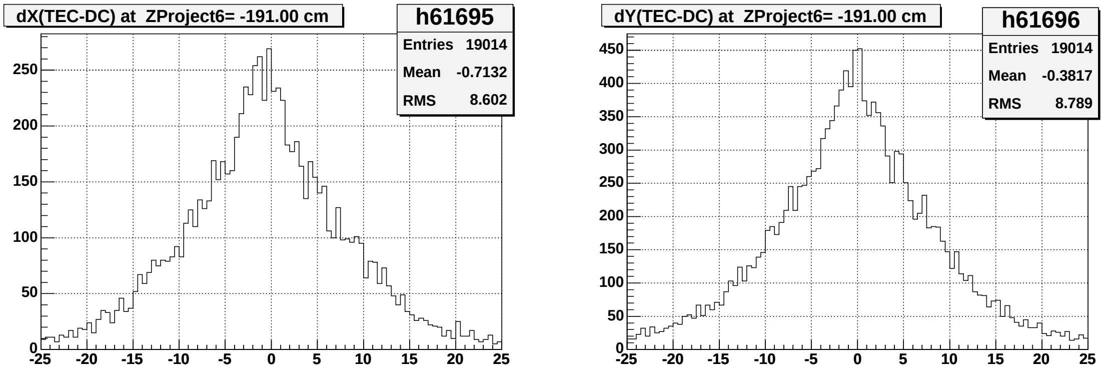

Figure 26: Comparison of TEC *vs.* DC measurements of beam positions.

3. TEC measurements during the B field ramping down
   At the end of 2004 runs, some TEC data were taken during the time when the solenoid field was ramped down. Those data were analyzed to undertand how the beam moves with the B field. It is found that the number of hits on a track, N_X, decreases when

the beam moves towards the sense plane of the X module (Fig. 27), which is totally opposite to our observation in other data- the shorter the drift distance, the bigger the N_X (this still holds for the Y module, see Fig. 28). A further study indicates that the problem with the N_X is caused by a drop in the TDC multiplicity, as shown in Fig. 29 where a correlation betwenn the TDC multiplicity and the B is seen. Compared to the Y module, the X mudule is farther away from the yoke, and supposed to be less affected. But, it is actually not. Why?

Fig. 30 directly indicates that the solenoid field affects the M13 beam optics.

6 Summary

TEC has been studied using collimated data and Monte Carlo simulations. Based on the understanding of the TEC, some approaches have been developed to calibrate it. Functions and procedures of all TEC related calibrations were described. Uncertainties in the TEC measurements were discussed.

In the future, for a precision measurement of TWIST beams, a few things should be paid with more attention

- alignment of the TEC to the solenoid field
- TEC performance: wire efficiency. A bench test needs to be done to understand the cause of the aging.
- DME gas: we have a good control of the gas pressure. We also need a good monitor of the gas temperature since the STR is very sensitve to it.
- calibration of the TEC: due to the existence of the field distortion, a better collimator is needed to get a data derived STR. A proposed collimator is shown schematically in Fig. 31, which provides us with more points for the STR correction fit. Moreover, it enables us to check the angle measurement by the TEC analysis.

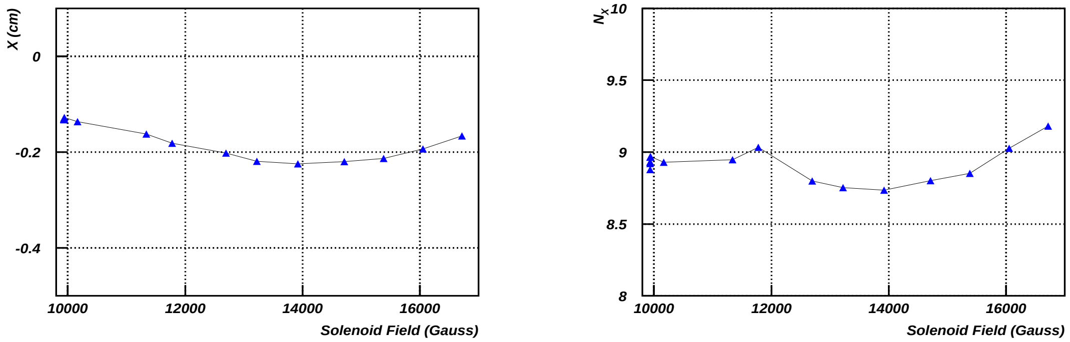

Figure 27: Effect of the B field on beam. Left: x $vs.$ B; right: N_X $vs.$ B

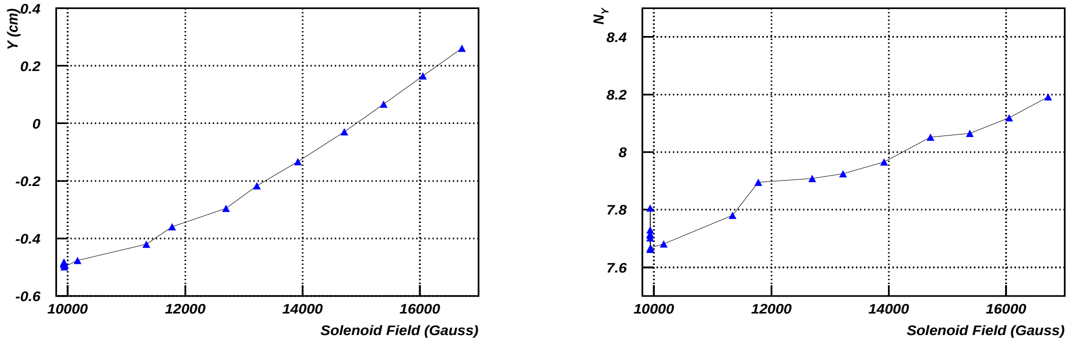

Figure 28: Effect of the B field on beam. Left: y $vs.$ B; right: N_Y $vs.$ B

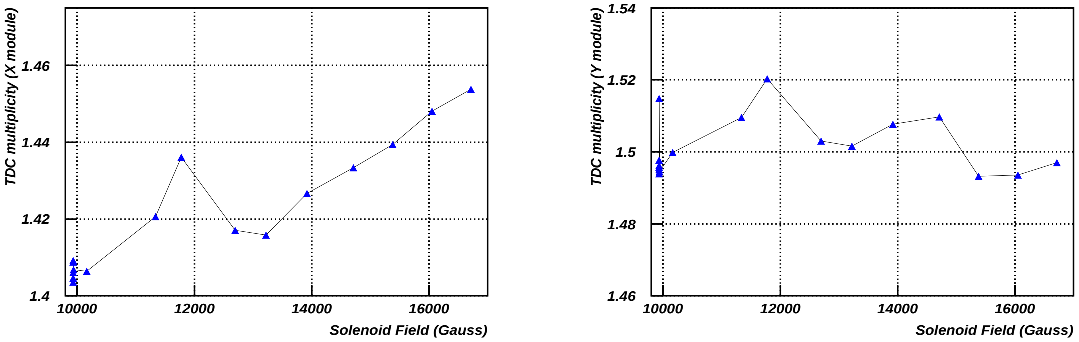

Figure 29: Effect of the B field on TDC multiplicity. Left: X module; right: Y module.

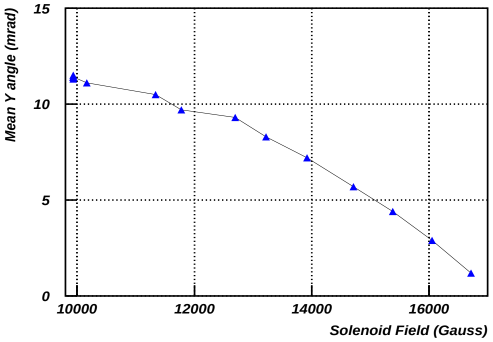

Figure 30: Effect of the B field on dy.

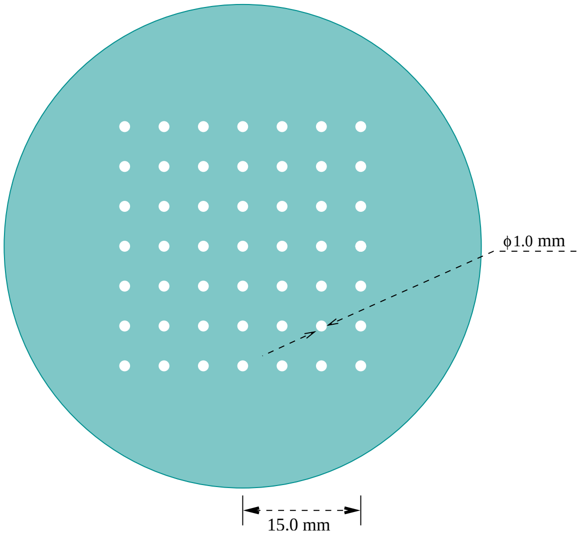

Figure 31: A proposed new collimator.