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Bunch length measurements with the SPS AEW.31731 wall current monitor

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Abstract

The wall current monitor AEW.31731 is the workhorse for bunch profile measurements in the SPS. The way the pick-up is used, its transfer function and the transfer function of the whole bunch profile acquisition system is described. This information is used to deconvolve measured bunch profiles. A functional relation between the bunch length obtained from raw data and the bunch length obtained from deconvolved data is established. This relation can then be used to estimate the true bunch length without actually doing the deconvolution. Simulated bunch profile data confirm the functional relation found from experimental data.

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1 Introduction

The wall current monitor AEW.31731, also known as WC-2, is the workhorse for bunch profile measurements in the SPS. It is frequently used for the setting-up of beams and for machine developments by the RF Group or by other Groups of the AB Department. This Note describes the pick-up, its installation and the pick-up signal treatment applied to deconvolve the measurement set-up response. Based on measured data functional relations between bunch lengths obtained from a Gaussian fit of raw data and of deconvolved data are established. Simulations confirm these relations within the measurement errors. In the past bunch lengths were determined from raw data as acquired on an oscilloscope and without any signal treatment and also from data which was only corrected for the pick-up transfer function. However, the best estimate of the bunch length is solely obtained from pick-up and cable transfer function corrected data. The relations presented here serve to obtain the correct bunch lengths from incompletely deconvolved data without the need of the original bunch profile data.

2 System description

2.1 Installation

AEW.31731 is a wall current monitor of the coaxial type [1]. It is located in LSS3 of the SPS, see Fig. 1. The eight outputs of the monitor are summed with an ANZAC DS-8 power combiner, the signal passes then through an attenuator, a CG50 (7/8", air dielectric, phase stabilised) coaxial cable, a resistive splitter (MICROLAB DA C05), another CG50 cable (in total 38 m), 130 m of CH50 (1 5/8", air dielectric) coaxial cable, 20 m of 7/8" foam dielectric coaxial cable, an H-9 hybrid and a few meters of RG214 type cable. The monitor signal is then observed with a Tektronix TDS 7254B oscilloscope (with a Tektronix TDS 784A oscilloscope up to 2004).

2.2 Transfer functions

The pick-up transfer function can be obtained by considering its step response [2]. In the ideal case it goes from zero to a positive constant value at $t = 0$ and stays at this value for twice the propagation time of the coaxial line , τ_1, until it decays exponentially due to the low-frequency cut-off of the pick-up at $1/(2\pi\tau_2)$. The transfer function is therefore

$$1 - \frac{e^{-j\omega\tau_1}}{1 + j\omega\tau_2} \ , \tag{1}$$

with $\tau_1 = 4.5$ ns, $\tau_2 = 40$ ns, $j = \sqrt{-1}$, and $\omega = 2\pi f$ the angular frequency.

The attenuation of the signal from the power combiner to the end of the RG214 type cable has been determined at eight frequencies in the range of 20 MHz to 4500 MHz. It is described using a cable transfer function. This transfer function [3] is obtained by a least square fit of the attenuation

$$20 \log_{10} e^{a_0 + a_1\sqrt{2f} + a_2 f} \ ,$$

which provides the parameters $a_0 = 1.82763, a_1 = 0.0132379$, $a_2 = 0.000551724$, for f in MHz. The complete cable transfer function is then

$$e^{-a_0 - a_1\sqrt{2jf} - a_2 f} \ . \tag{2}$$

3 Bunch length measurements

The influence of the pick-up and cable transfer functions on the measured bunch length is studied using bunch profiles acquired with proton LHC beam. The bunch length τ is obtained by a Gaussian fit of a longitudinal bunch profile ($\tau = 4\sigma$). Bunch profiles acquired throughout the years 2002 to 2006 and combined into one data set of nearly 4000 bunch lengths are analysed ($1.4\ \mathrm{ns} \leq \tau \leq 5\ \mathrm{ns}$, for the distribution of the bunch lengths see Fig. 2). For each measured bunch profile a Gaussian fit was applied to the raw data to obtain τ_r^i, to the raw data deconvolved using once the pick-up transfer function (Eq. 1) to obtain τ_p^i, and finally to the raw data deconvolved using both the pick-up transfer function (Eq. 1) and the cable transfer function (Eq. 2 with an additional high frequency cut-off at 2 GHz) to obtain τ_{pc}^i, for $i = 1, 2, 3, ..., N$ with N the number of bunch profiles.

To better understand the effect of the pick-up and of the cable transfer functions their influence on the bunch length obtained from a Gaussian fit is analysed in three steps by comparing pairs of bunch lengths $\{\tau_1^i, \tau_2^i\}$, with $i = 1, 2, 3, ..., N$, where either $\tau_1 = \tau_r$ and $\tau_2 = \tau_p$ (analysis of type I), or $\tau_1 = \tau_p$ and $\tau_2 = \tau_{pc}$ (analysis of type II), or $\tau_1 = \tau_r$ and $\tau_2 = \tau_{pc}$ (analysis of type III), see also Table 1.

Analysis	τ_1	τ_2
type I	τ_r	τ_p
type II	τ_p	τ_{pc}
type III	τ_r	τ_{pc}

Table 1: Explanation of the three bunch length analysis types mentioned in the text.

For the correct interpretation of bunch lengths obtained from raw data the results of the type III analysis are important. For the interpretation of bunch lengths obtained from data already corrected for the pick-up transfer function the results of the type II analysis are of interest.

3.1 Analysis

For all types of analysis one observes that the relation between the bunch lengths τ_1 and τ_2 follows approximately a linear relation (Figs. 3-5, top left). It is described with

$$\tau_2 = a_0 + \tau_1 + m(\tau_1 - \tau_0)\ . \tag{3}$$

Least square fits are used to determine the parameters a_0, m, and τ_0 from the bunch length data, $\{\tau_1^i, \tau_2^i\}$, with $i = 1, 2, 3, ..., N$. Eq. 3 allows to separate out a first order approximation for τ_2

$$\tau_2 = a_0 + \tau_1\ , \tag{4}$$

and a second order contribution

$$m(\tau_1 - \tau_0)\ . \tag{5}$$

Fitting the τ_2 versus τ_1 data according to Eq. 4 (and calling this type of fit for short "a_0-fit") shows that for the type I analysis the residuals lie on a straight line with nonzero slope (Fig. 3, centre left and bottom left). For the type II analysis the residual for the combined data sets are lying on a straight line of zero slope, (Fig. 4, centre left and bottom left). In case of the type III analysis the residuals show again a straight line of nonzero slope (Fig. 5, centre left and bottom left).

The offset a_0 (estimated error $\pm 5\%$) for the three types of analysis is:

$a_{0,\mathrm{I}}$[ns]	$a_{0,\mathrm{II}}$[ns]	$a_{0,\mathrm{III}}$[ns]
- 0.073	-0.381	- 0.460

As the residuals lay on a straight line for all types of analysis, the residuals were fitted with a straight line to obtain the second order correction parameters m and τ_0 (Eq.3). The application of this correction results in fits (for short "m-τ_0-fits") which are shown in Figs. 3-5 (centre right, m-τ_0-fit), and the residuals in Figs. 3-5 (bottom right). The values obtained for m and τ_0 are within $\pm 5\%$:

m_{I}	$\tau_{0,\mathrm{I}}$[ns]	m_{II}	$\tau_{0,\mathrm{II}}$[ns]	m_{III}	$\tau_{0,\mathrm{III}}$[ns]
-0.046	2.683	-0.002	2.610	-0.057	2.750

These values show that for the type I analysis $m = -46$ ps/ns and $\tau_0 = 2.683$ ns, for the type II analysis m is practically zero and for the type III analysis it is again different from zero. This means that in the case of the type II analysis the second order approximation does not really improve the fit with respect to the first order. This is also reflected in the change of the standard deviation, σ_1, of the residuals obtained with Eq. 4, first order approximation, and the one for the residuals obtained with Eq. 3, σ_2. The corresponding values are within $\pm 5\%$:

$\sigma_{1,\mathrm{I}}$[ns]	$\sigma_{2,\mathrm{I}}$[ns]	$\sigma_{1,\mathrm{II}}$[ns]	$\sigma_{2,\mathrm{II}}$[ns]	$\sigma_{1,\mathrm{III}}$[ns]	$\sigma_{2,\mathrm{III}}$[ns]
0.030	0.009	0.041	0.041	0.061	0.046

Applying the second order correction, going from Eq. 3 to Eq. 4, improves the standard deviation significantly for the type I analysis (compare $\sigma_{1,\mathrm{I}}$ with $\sigma_{2,\mathrm{I}}$), where in the case of the type II analysis practically nothing is gained (compare $\sigma_{1,\mathrm{II}}$ with $\sigma_{2,\mathrm{II}}$). In case of the type III analysis the improvement of the standard deviation is small (compare $\sigma_{1,\mathrm{III}}$ with $\sigma_{2,\mathrm{III}}$).

3.2 Summary

The type I analysis shows that the application of the pick-up correction function on the uncorrected pick-up data changes the bunch length obtained through a Gaussian fit as follows (using $a_{0,\mathrm{I}}$, m_{I}, and $\tau_{0,\mathrm{I}}$)

$$\tau_2 = -0.073 \text{ ns} + \tau_1 - 0.046\,(\tau_1 - 2.68 \text{ ns}) \tag{6}$$

or

$$\tau_2 = 0.050 \text{ ns} + 0.954\,\tau_1\ . \tag{7}$$

The standard deviation of the residual errors using these equations is $\sigma_{2,\mathrm{I}} = 9$ ps.

The type II analysis shows that for bunch lengths obtained from pick-up transfer function corrected data the following equations can be used to estimate the bunch length for pick-up and cable transfer function corrected data (using $a_{0,\mathrm{II}}$, m_{II}, and $\tau_{0,\mathrm{II}}$)

$$\tau_2 = -0.381 \text{ ns} + \tau_1 - 0.002\,(\tau_1 - 2.61 \text{ ns}) \tag{8}$$

or

$$\tau_2 = -0.376 \text{ ns} + 0.998\,\tau_1\ . \tag{9}$$

The standard deviation of the residual errors using these equations is $\sigma_{2,\text{II}} = 41$ ps.

The type III analysis shows that the combined effect of pick-up and cable transfer function correction can be described as follows (using $a_{0,\text{III}}$, m_{III}, and $\tau_{0,\text{III}}$)

$$\tau_2 = -0.460 \text{ ns} + \tau_1 - 0.057\,(\tau_1 - 2.75 \text{ ns}) \tag{10}$$

or

$$\tau_2 = -0.325 \text{ ns} + 0.952\,\tau_1\ . \tag{11}$$

For the interpretation of bunch lengths obtained from uncorrected data, τ_1, Eq. 10 or Eq. 11 should be used to estimate the true bunch length, τ_2. The standard deviation of the residual errors using these equations is $\sigma_{2,\text{III}} = 46$ ps.

4 Expected influence of the transfer functions on bunch length

Using Gaussian pulses of various lengths the effect of the pick-up transfer function was simulated and the results were analysed the same way as the measured data (Sect. 3). The bunch length τ_1 was chosen to fall in the same range as for the measured data, 1.4 ns $\leq \tau_1 \leq$ 5.0 ns.

Fig. 6 shows the outcome of the type I analysis and Table 2 summarises the results. It shows both the parameters obtained from measured data (top) and from simulated data (bottom). The difference between τ_0 from observations and from simulation might be related to the different bunch length distributions, non-uniform for the observations (see Fig. 2) and uniform for the simulated data.

$a_{0,\text{I}}$ [ns]	m_{I}	$\tau_{0,\text{I}}$ [ns]	$\sigma_{1,\text{I}}$ [ns]	$\sigma_{2,\text{I}}$ [ns]	Remarks
-0.073	-0.046	2.683	0.030	0.009	measurement
-0.090	-0.052	3.190	0.059	0.008	simulation

Table 2: The type I analysis parameters for the measured data (top), and the simulated data (bottom). The estimated error of these values is about $\pm 5\%$.

Fig. 7 (top) shows the difference, $\Delta\tau = \tau_2^s - \tau_2^m$, between the expected bunch lengths, once using Eq. 3 with parameters obtained from measured data, τ_2^m, and once from simulated data, τ_2^s. The maximum difference between the two is 17 ps or 1.2% in the worst case. The results from simulated data are in good agreement with the results obtained from real data.

Fig. 8 shows the outcome of the type II analysis and Table 3 summarises the results. It shows both the parameters obtained from measured data (top) and from simulated data (bottom).

$a_{0,\text{II}}$ [ns]	m_{II}	$\tau_{0,\text{II}}$ [ns]	$\sigma_{1,\text{II}}$ [ns]	$\sigma_{2,\text{II}}$ [ns]	Remarks
-0.381	-0.002	2.610	0.041	0.041	measurement
-0.400	-0.000	3.024	0.000	0.000	simulation

Table 3: The type II analysis parameters for the measured data (top), and the simulated data (bottom). The estimated error of these values is about $\pm 5\%$.

Fig. 7 (centre) shows $\Delta\tau = \tau_2^s - \tau_2^m$, once using Eq. 3 with parameters obtained from measured data, τ_2^m, and once from simulated data, τ_2^s. The maximum difference between the two is now 23 ps or 1.6% in the worst case. The results from simulated data are again in good agreement with the results obtained from real data.

Fig. 9 shows the outcome of the type III analysis and Table 4 summarises the main parameters. It shows both the parameters obtained from measured data (top) and from simulated data (bottom).

$a_{0,\text{III}}$ [ns]	m_{III}	$\tau_{0,\text{III}}$ [ns]	$\sigma_{1,\text{III}}$ [ns]	$\sigma_{2,\text{III}}$ [ns]	Remarks
-0.460	-0.057	2.750	0.061	0.046	measurement
-0.460	-0.059	3.160	0.067	0.007	simulation

Table 4: The type III analysis parameters for the measured data (top), and the simulated data (bottom). The estimated error of these values is about $\pm 5\%$.

Fig. 7 (bottom) shows $\Delta\tau$, once using Eq. 3 with parameters obtained from measured data, τ_2^m, and once from simulated data, τ_2^s. The maximum difference between the two is 27 ps or 1.9%. The results from simulated data are also in this case in good agreement with the results obtained from real data. Fig. 10 shows the measured data together with τ_2^m (solid line) and τ_2^s (dashed line). In both cases the standard deviation of the residuals is 46.4 ps. This confirms the consistency between measurement and simulation.

5 Conclusions

With the knowledge of the AEW pick-up and the cable transfer functions it is possible to deconvolve longitudinal bunch profile data. Based on a data set of nearly 4000 bunch profiles functional relations were established between bunch lengths obtained from raw data, raw data deconvolved with the pick-up transfer function, and raw data deconvolved with both the pick-up and the cable transfer function (Eq. 6 to Eq. 11). The bunch lengths are in the range of 1.4 ns to 5.0 ns and in the worst case the standard deviation of the residual errors using these equations is 46 ps. Simulated data confirm these functional relations. Knowing these relations allows bunch length data obtained by a Gaussian fit to be interpreted without actually doing convolutions and in the absence of bunch profile data to which a convolution could be applied.

6 Acknowledgements

I would like to thank T. Linnecar for explanations about the coaxial wall current monitor and stimulating discussions, E. Shaposhnikova for a critical revision of the manuscript and U. Wehrle for the help with measuring the pick-up cable attenuation.

References

[1] T. Linnecar. *The high frequency longitudinal and transverse pick-ups used in the SPS*, CERN SPS ARF 78-17, August 1978.

[2] T. Linnecar. *Private communication*, August 1996.

[3] G. Brianti. *Distortion of fast pulses in coaxial cables.* CERN 65-10, MSC Division, Geneva, May 1965.

A Figures

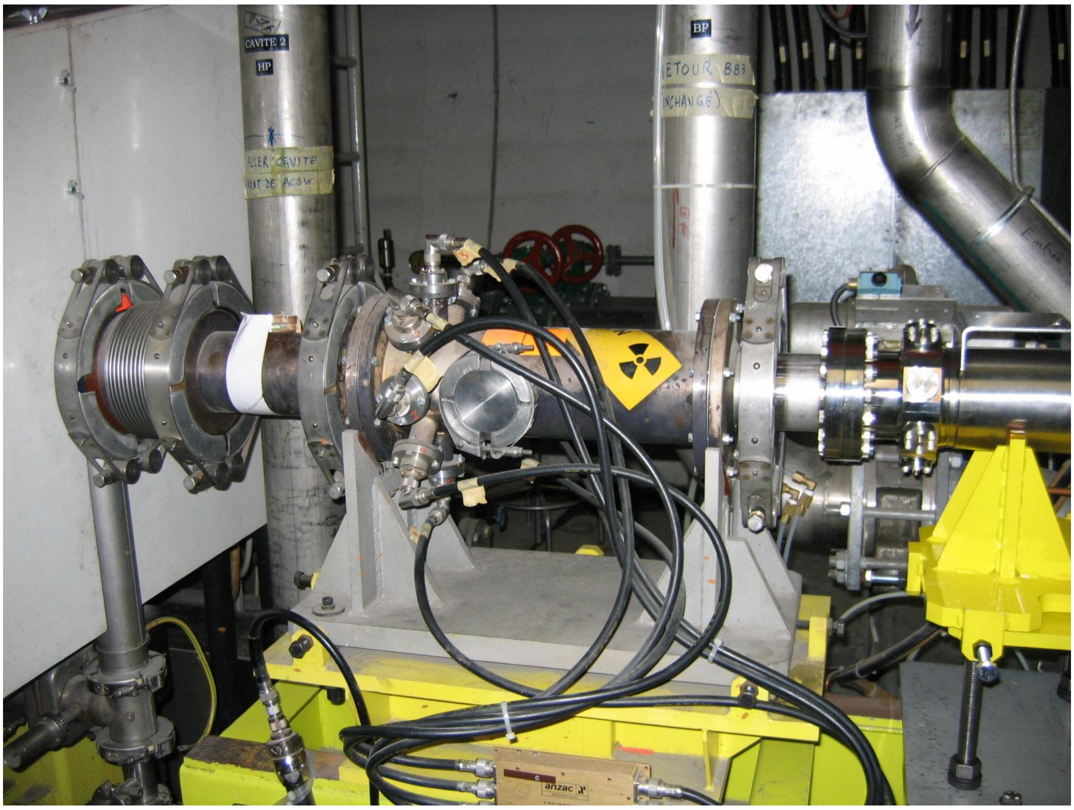

Figure 1: AEW31731 in LSS3 of the SPS, March 2006.

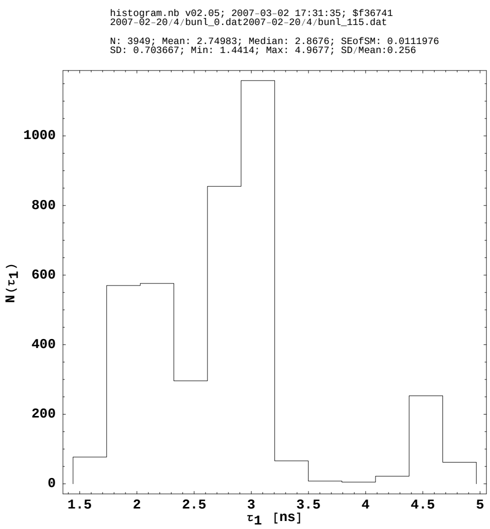

Figure 2: Bunch length distribution of the combined data set.

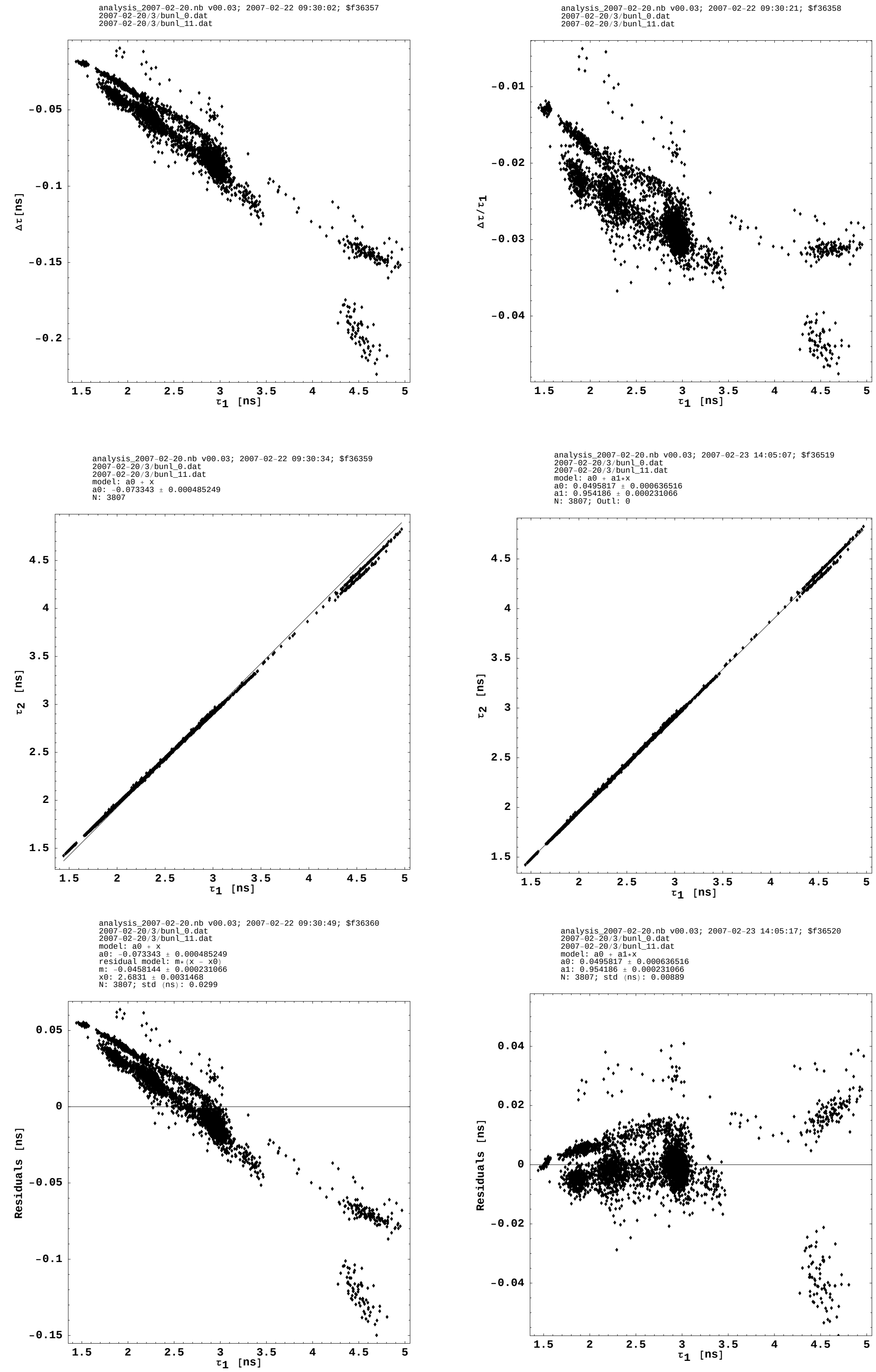

Figure 3: Comparison of bunch lengths obtained from uncorrected and from pick-up transfer function corrected data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

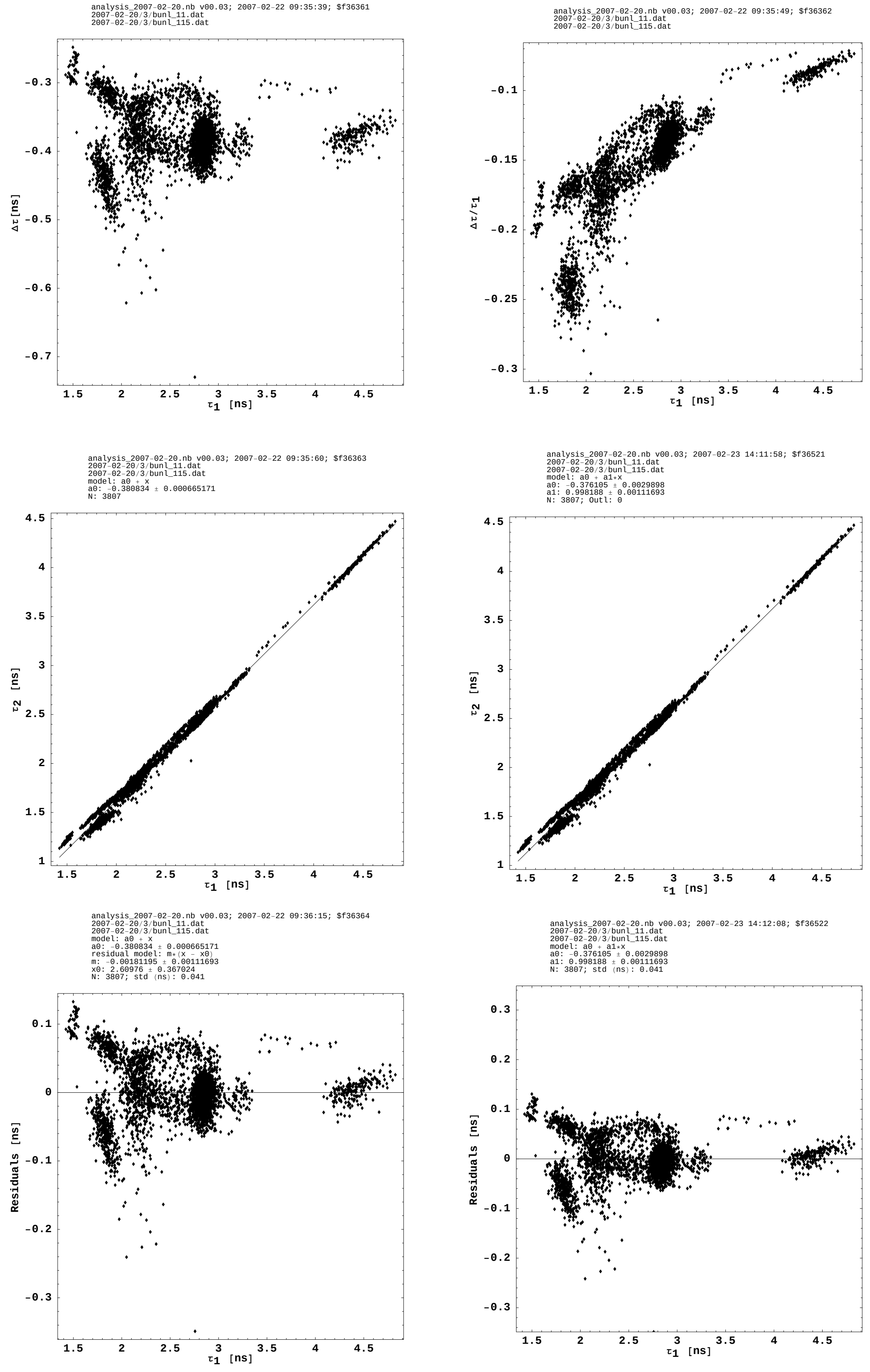

Figure 4: Comparison of bunch lengths obtained from pick-up transfer function corrected and from pick-up and cable transfer function corrected data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

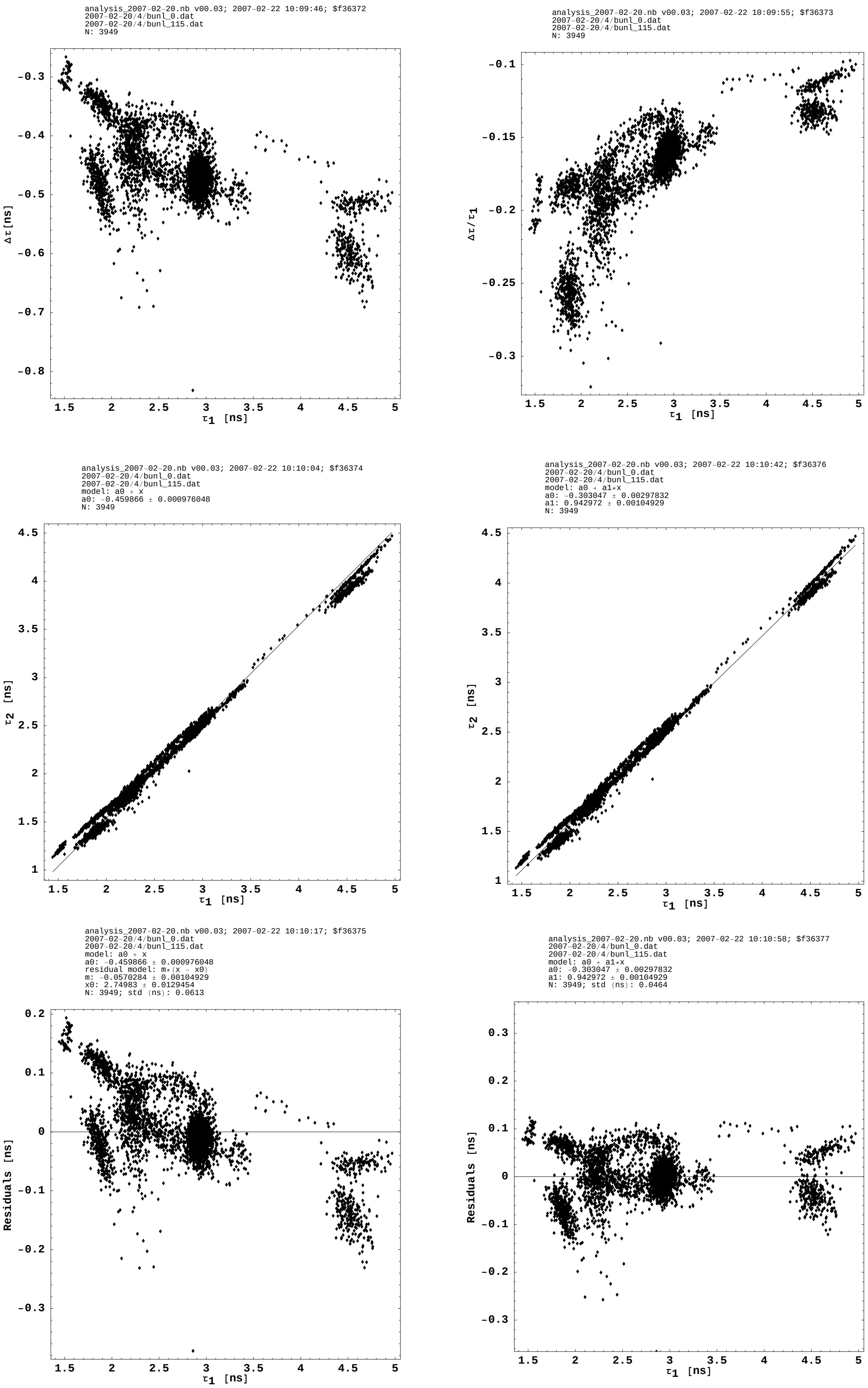

Figure 5: Comparison of bunch lengths obtained from uncorrected and from pick-up and cable transfer function corrected data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

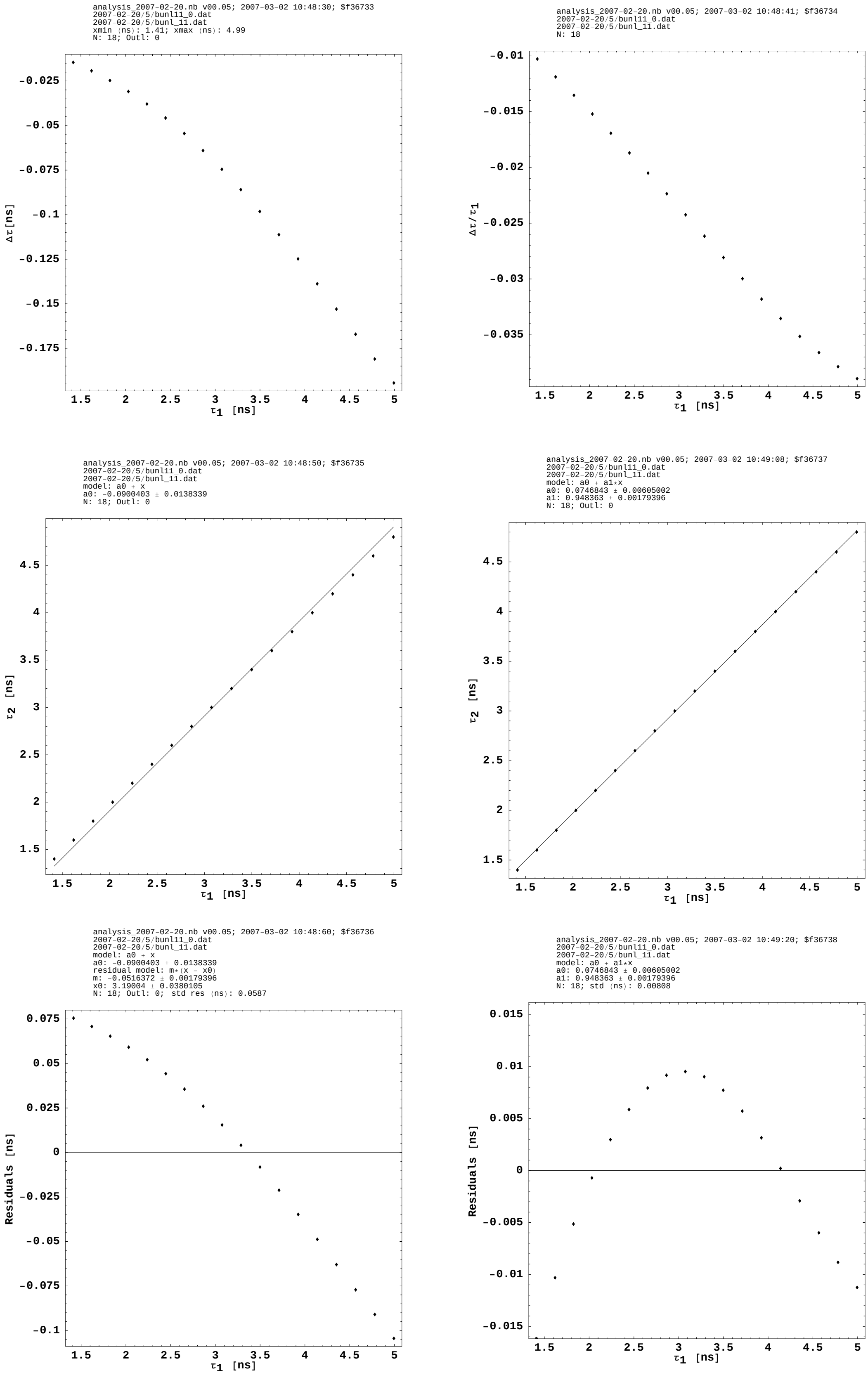

Figure 6: Comparison of bunch lengths obtained from uncorrected and from pick-up transfer function corrected simulated data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

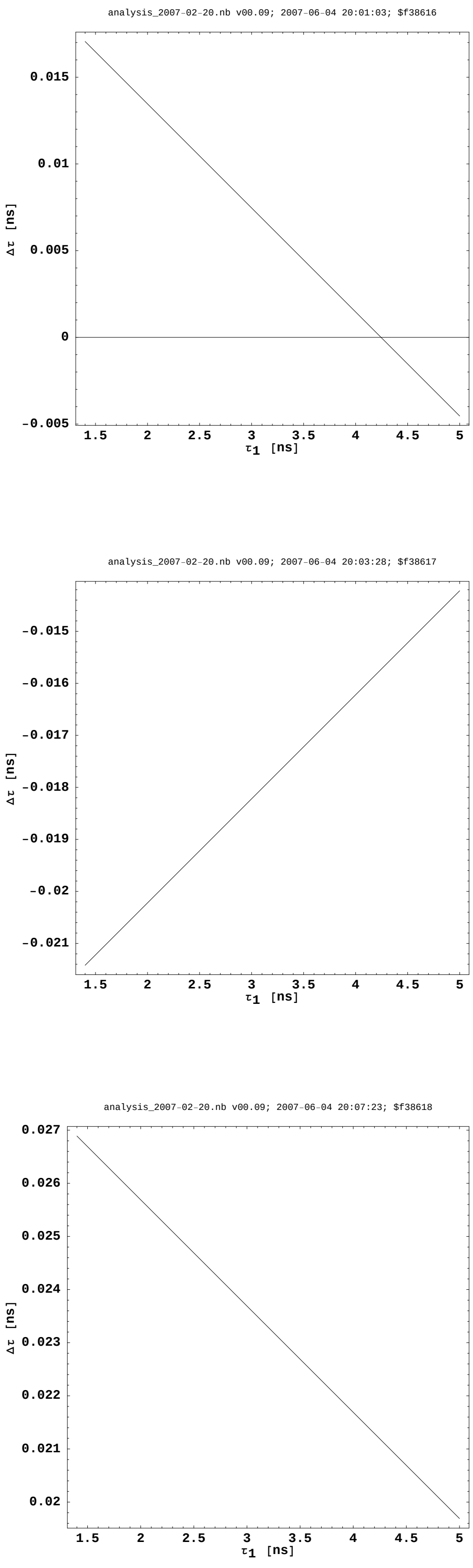

Figure 7: $\Delta\tau = \tau_2^s - \tau_2^m$ versus τ_1. For the type I analysis (top), for the type II analysis (centre), for the type III analysis (bottom).

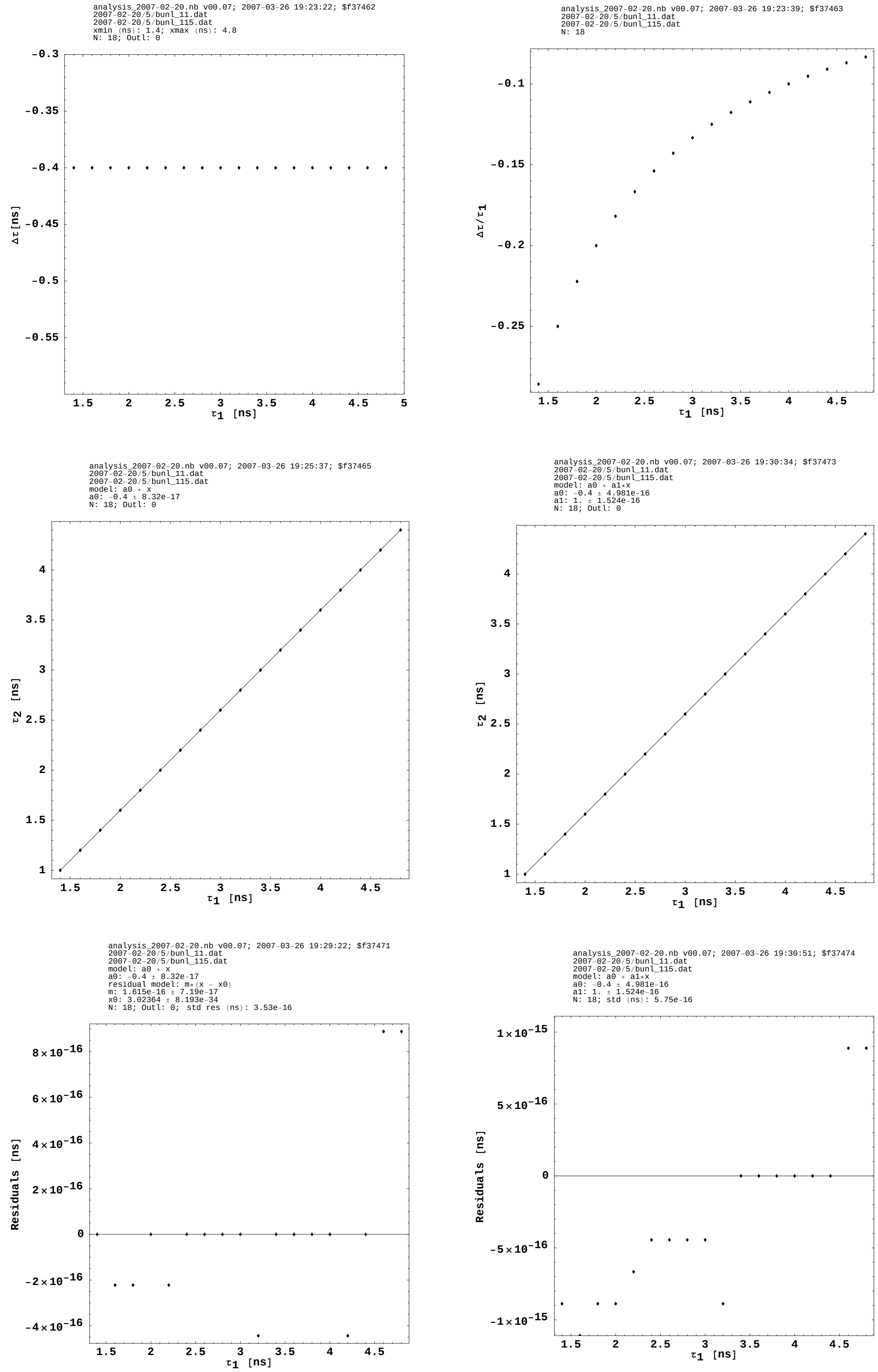

Figure 8: Comparison of bunch lengths obtained from pick-up transfer function corrected and from pick-up and cable transfer function corrected simulated data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

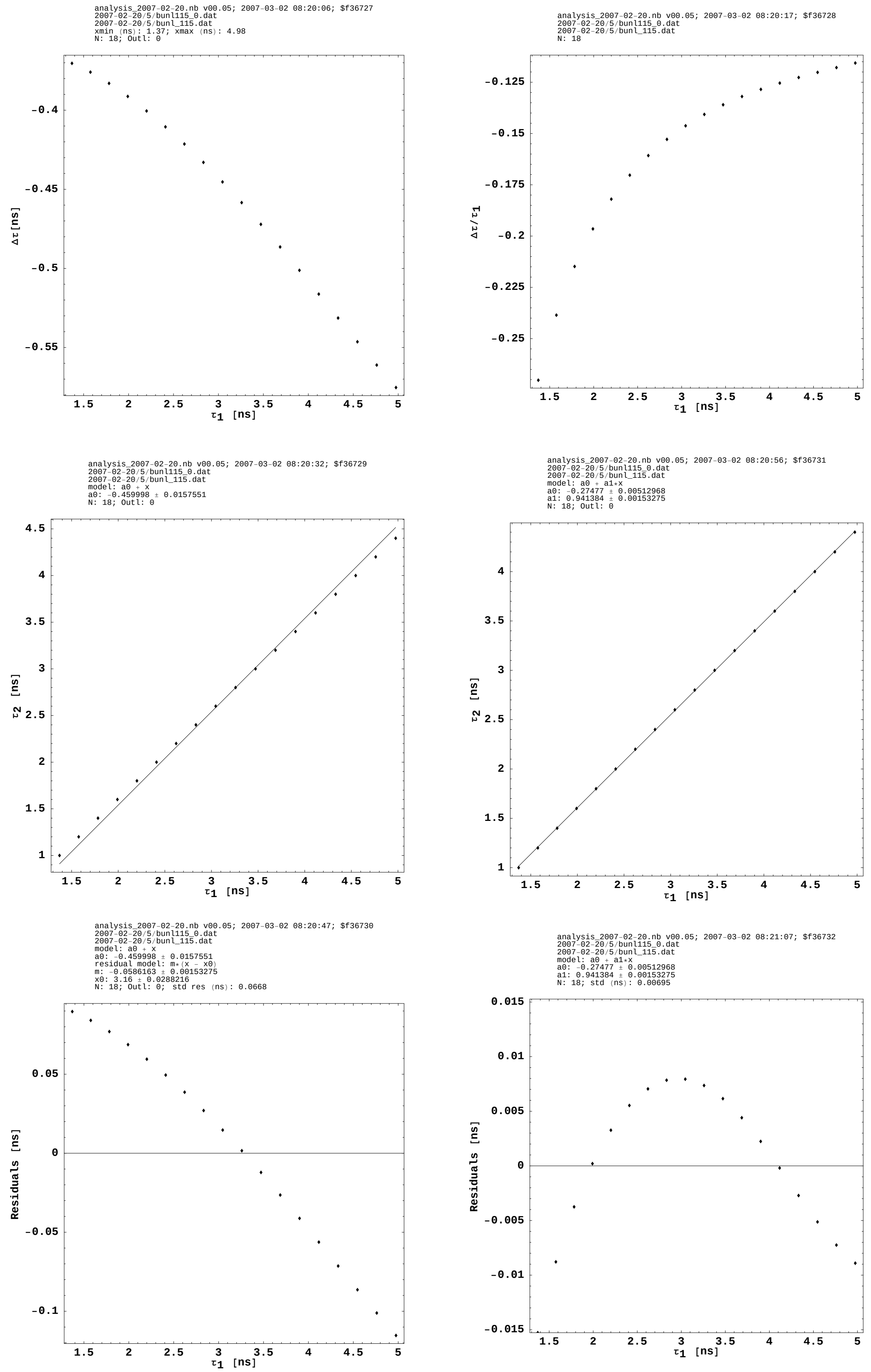

Figure 9: Comparison of bunch lengths obtained from uncorrected and from pick-up and cable transfer function corrected simulated data. $\Delta\tau$ versus τ_1 (top left), $\Delta\tau/\tau_1$ versus τ_1 (top right), a_0-fit (centre left) and its residuals (bottom left), and m-τ_0-fit (centre right) and its residuals (bottom right).

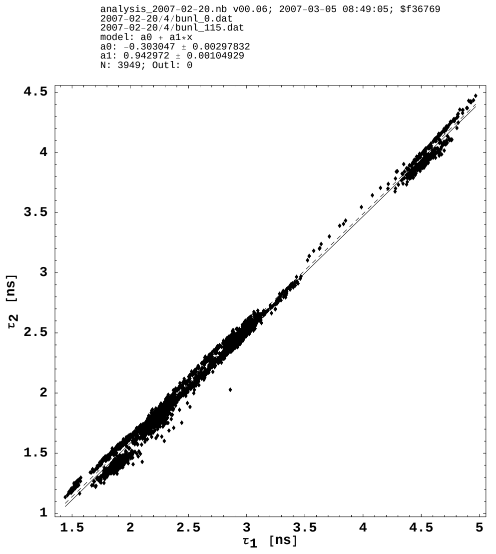

Figure 10: Comparison of bunch lengths obtained from uncorrected and from pick-up and cable transfer function corrected data using the combined data set of 2002-02-20, 2006-10-27, 2004-07-01 (I), and 2003-10-29 with m-τ_0-fit (τ_2^m, solid line) and m-τ_0-fit from simulated data (τ_2^s, dashed line).