Report (2) 06th Sep 2012	**Experimental test of "Libera Single Pass H" for beam phase and "Time of Flight" measurements.**	P. Forck M. Almalki
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Web-Link:	http://www-bd.gsi.de/dokuwiki/doku.php?id=projects:bpm-linac	

Introduction

For the P-linac at GSI, the "Libera Single Pass H" has been empirically tested for signal phase measurement and bunch dependence using a four plate BPM. After pre-amplification, the signals are processed by "Libera Single Pass H" and compared inphase in order to detect the plate signals of the BPM in respect to RF signal. Using digital down conversion technique, "Libera Single Pass H" achieves this task where the signals go throught a sophisticated signal processing algorithm. The processor in "Libera Single Pass H", consists of an analog front-end and digital signal processing modules for IQ demodulation and phase determination.

The "Libera Single Pass H" unit used during the measurement has been optimized for p-LINAC signal processing at frequencies 325 MHz and 650 MHz. However for the measurements a UNILAC (108 MHz bunch repetition rate) setup has been used and the third harmonic of the 108 MHz beam signal is processed by the "Libera Single Pass H" system. Since the purpose of the measurement is to characterize the beam arrival time bunch shape dependence through beam phase measurement at 325 MHz it has to be stressed out that there are limitations to the adopted measurement setup validity in relation to the 325 MHz strength versus the applied bunch shape. For bunch shapes that present too small third harmonic component there is no enough signal to perform the measurement. In this case the specific UNILAC optimized unit has to be used in order to perform the beam arrival time measurement correctly at 108 MHz and 216 MHz components.

The aim of this study is to calculate the beam phase for the "time of flight" measurements. For this test a single BPM acts as a "Bunch arrival monitor". i.e the BPM signal is compared to the reference signal as the time reference. This experiment has been performed to test Libera capability to measure the phase with varying the signal amplitude and bunch shape. This report presents the results of this experiment.

Beam Parameters and Macroplulse Structure

The " Libera Single Pass H" provides the measured phase which is calculated in respect to a master oscillator – RF accelerating frequency. The amplitude from Libera is given in steps of 1 μs (correspond to 108 bunches) for a train of 129 μs. Every data set corresponds to one macropulse. A second system was used where the signal of the pick-up was taken at a 5 GSa/s scope together with the master oscillator signal.

Bunch rep. rate	Macropulse length	Macropulse rep.rate	Beam Current	Beam Energy
108.408 MHz	200 µs	1 Hz	60 ~ 90 µA	Ne^{4+} @ 1.4MeV / u

Table 1. The Macropulse structure for the test measurement at 28th March 2012.

➢ Data and Methods

This report is dedicated for studying the bunch shape sweep test. Using a buncher unit, several bunch shapes with different amplitudes have been generated during the experiment. These shapes have been reproduced and studied.

➢ Measured phase using Libera Single Pass H and an oscilloscope

▪ Libera Single Pass H

The produced signal from the PU is processed by "Libera Single Pass H" to calculate its amplitude, its phase and its position. Therefore, for the data stored on the "Libera Single Pass H" that give the measured phase, the standard deviation of the distribution (σ_{dist}) and the standard deviation of the mean σ_{mean} are calculated and listed in table 3, where:

$$\sigma_{mean} = \frac{\sigma_{dist}}{\sqrt{N}} \qquad (1)$$

N= 129 of the measured data with a macropulse.

▪ Oscilloscope

In the second system where the signal of the pick-up was taken at a 5 GSa/s scope, three steps have been done to treat the displyed shape:

1. The first step is that it is required to interpolate the sampled points for more precise analysis since the resolution of the sampled points is 200 ps. The signal shape displayed by the oscilloscope contains 102 samples (46 points for 1 cycle) at 5 GSa/s sampling frequency. The granularity can be short by the spline interpolation of the original curve. The signal is interpolated to contain 2^15 points which gives a resolution of 0.622 ps.

   In order to know how precise the recorded values by the dedicated scope for the input signal, the error bar of trigger jitter is measured in the lab and calculated using 500 readings. The standard deviation of these measurments (σ) is 54.53 ps for the recorded time and the standard deviation for the recorded amplitude is 0.0131 V as it explained in the appendix 1. The typical trigger and the interpolator jitter for the osilloscope is ≤ 3 ps (LeCory Waverunner 6200A).

Using the corresponding interpolated curve, the points of interest are determined and compared. The aim is to investigate how bunch width effects the phase measurements. These points are Zero-starting (Zs), Maximum (Max), Minimum (Min) and Zero-ending (Ze) with Zero-crossing (Zc) as the major point as it is shown in figure 1.

The method used for determining these points is that one cycle, with two arbitrary points represent the begining and the end of the bunch, is extracted. From the interpolated curve of the signal, the Max and the Min points are easily determined as it shown in figure 2 (upper trace). The integral of this curve is used to determine the Zs and Ze points from its minimum points whereas Zc point represents the maximum point as it shown in figures 2 (down trace). The values of these points are listed in table 2. After determining these points the relationship between the phase measured by Libera H and the bunch shape is studied. Bunch shape is studied by considering the bunch width parameters. These parameters are Zs – Zc, Zc – Max, Zc – Zs, Max – Zs, Min – Zc, Min – Max, Min – Zs, Ze – Min, Ze – Zc, Ze – Max, listed in table 3.

2. The bunch trace is triggered on the master oscillator – the RF accelerating frequency -. The purpose is to study the correlation between the phase measured by Libera in frequency domain and the phase detected using the scope in time domain. This is done by determining Zc points for all different shapes as the phase difference in respect to a reference shape. Shape (03) has an amplitude of 1.449 V and it is chosen as a reference shape. The phase differences in respect to shape (03), Zc – Zc (03), listed in table 3.

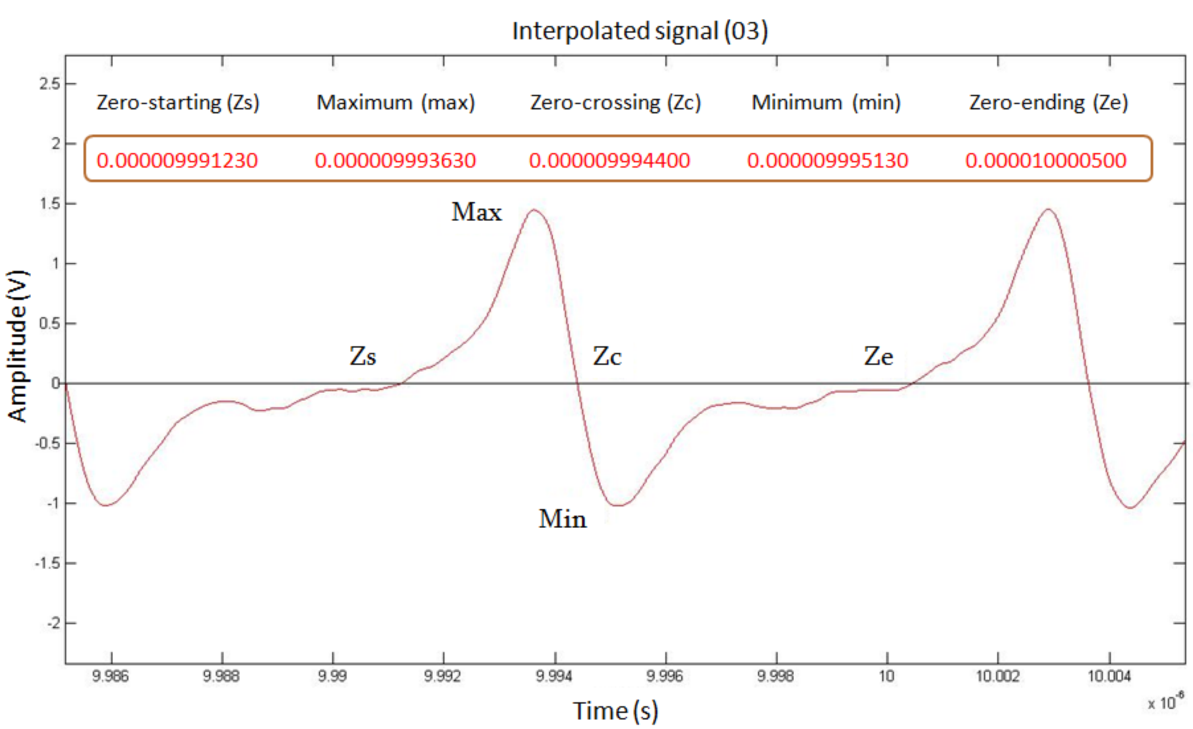


Fig.1, the reference bunch shape (data set (03) , table 3) with characteristic time & amplitude on the oscilloscope.

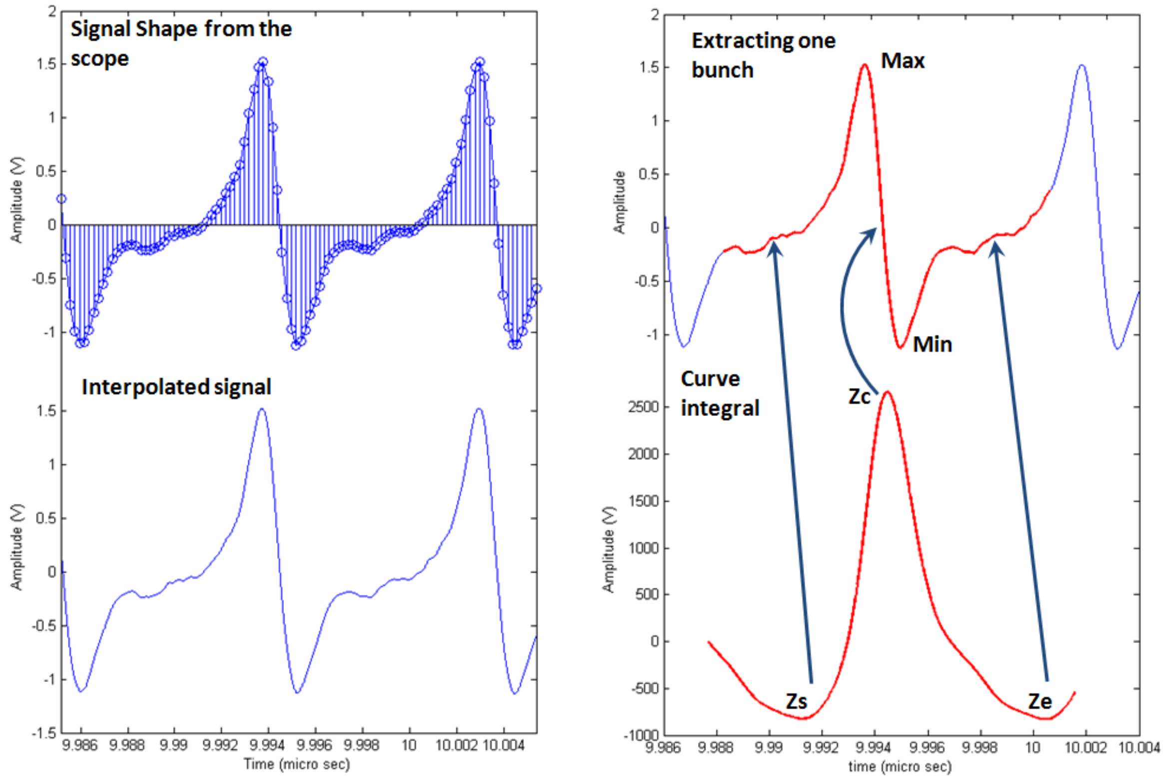


Fig. 2, left: the signal from the scope and its interpolated curve. Right: one cycle and its integral.

Shape No.	Signal amp	Zero starting (Zs) μs	Maximum (Max) μs	Zero crossing (Zc) μs	Minimum (Min) μs	Zero ending (Ze) μs
1	1.544	9.991219	9.99372	9.994506	9.995265	10.00045
2	1.529	9.99123	9.993702	9.994468	9.995207	10.000455
3	1.448	9.991236	9.993625	9.994404	9.995133	10.000455
4	1.340	9.99118	9.99367	9.99451	9.995295	10.000351
5	1.330	9.991197	9.993543	9.994542	9.995543	10.000383
6	1.234	9.991179	9.99336	9.994527	9.995705	10.000326
7	1.168	9.990983	9.993549	9.994325	9.995063	10.000292
8	1.109	9.991031	9.993566	9.994495	9.995356	10.000322
9	0.912	9.990899	9.993445	9.994499	9.995708	10.000076
10	0.754	9.990663	9.99319	9.994477	9.995783	9.9999258
11	0.556	9.99055	9.993301	9.994417	9.995604	9.9997501
12	0.433	9.990504	9.991882	9.994505	9.997541	9.9996743
13	0.423	9.990214	9.992753	9.99461	9.99635	9.9993968
14	0.417	9.990235	9.99296	9.994601	9.9969	9.9994098
15	0.413	9.990523	9.991784	9.994422	9.997722	9.999636
16	0.404	9.990714	9.992	9.99457	9.99739	10.0001
17	0.399	9.990116	9.992651	9.994521	9.996197	9.9992927
18	0.397	9.990878	9.991926	9.994519	9.997471	10.000076
19	0.388	9.990956	9.992149	9.994677	9.997573	10.00018
20	0.381	9.990216	9.992212	9.994461	9.996757	9.999366
21	0.376	9.990427	9.991761	9.994769	9.997158	9.9996484
22	0.338	9.990116	9.992492	9.994466	9.996112	9.9993475

Table 2

➢ Bunch position calculations

The bunch position is calculated for all shapes under the study. The coming signals from the PUs determine the beam position as the amplitude of the signal depends on the distance between the beam center and the electrode, see figure 3. The horizontal displacement x is given by:

$$H = \frac{\Delta_x}{\Sigma_x} = \frac{V_a - V_c}{V_a + V_c} \qquad (2)$$

$$\Longrightarrow \quad x = \frac{1}{S_x} \cdot H \qquad \text{Horizontal axis} \qquad (3)$$

Similarly, the vertical displacement y is given by:

$$V = \frac{\Delta_y}{\Sigma_y} = \frac{V_b - V_d}{V_b + V_d} \qquad (4)$$

$$\Longrightarrow \quad y = \frac{1}{S_y} \cdot V \qquad \text{Vertical axis} \qquad (5)$$

Where S_x and S_y are the position sensitivity is 10 / mm.

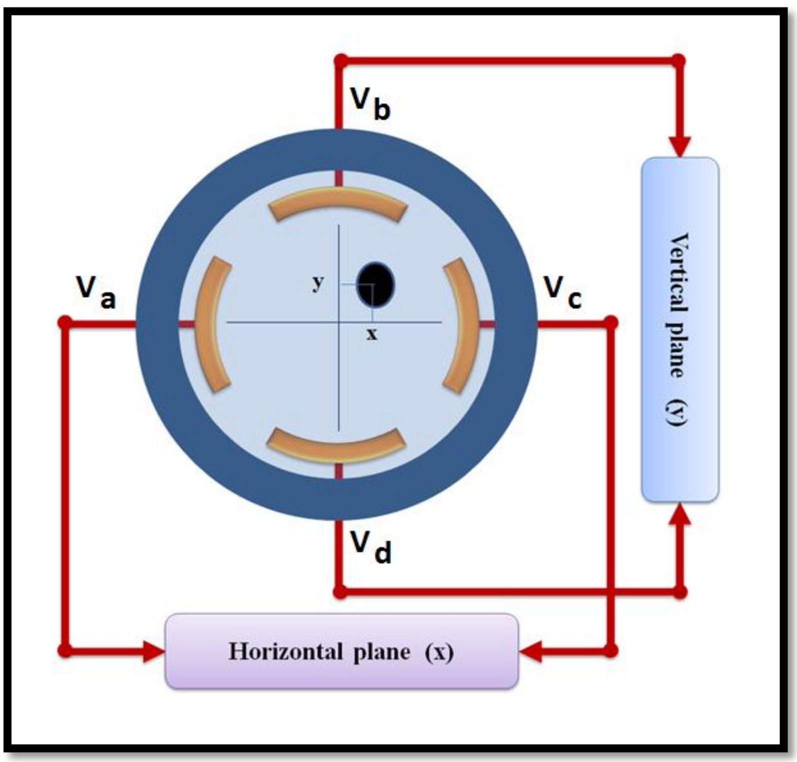


Fig. 3, BPM schematic showing the signals outputs and the bunch position.

The standard deviation for sums or differences is calculated from the following formulas:

$$\sigma_{\Delta(H,V)} = \sqrt{\left(\sigma^2_{(a,c)} + \sigma^2_{(b,d)}\right)} \qquad \& \qquad \sigma_{\Sigma(H,V)} = \sqrt{\left(\sigma^2_{(a,c)} + \sigma^2_{(b,d)}\right)} \qquad (6)$$

By using fractional errors for ratio between difference over sum :

$$\sigma_H = H \times \sqrt{\left(\frac{\sigma_{\Delta_H}}{\Delta_x}\right)^2 + \left(\frac{\sigma_{\Sigma_H}}{\Sigma_x}\right)^2} \qquad \& \qquad \sigma_V = V \times \sqrt{\left(\frac{\sigma_{\Delta_V}}{\Delta_y}\right)^2 + \left(\frac{\sigma_{\Sigma_V}}{\Sigma_y}\right)^2} \tag{7}$$

- Magnitude and Phase calculations

One bunch is captured at 9.22 ns @ 108.408 MHz. Using the signal's interpolated curve that contains 2^13 points, fourier transformation is calculated for the amplitude and the phase spectrum. For better treatment, zero padding technique is applied on all curves where 2^15 zeros are added to the interpolating points as it shown in plot 10.

- Plots discription

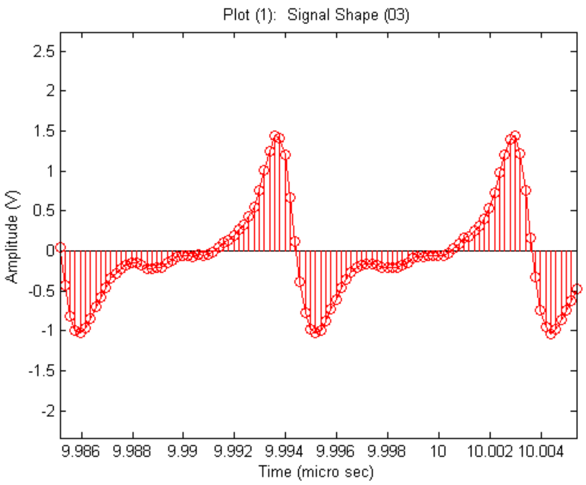
Only six bunch shapes with different amplitudes are shown in this report, a similar analysis is applied for all bunch shapes. The characteristics of each bunch shape and its measured phase by Libera and by the scope, amplitude and phase spectrum and bunch position are shown in the following plots :

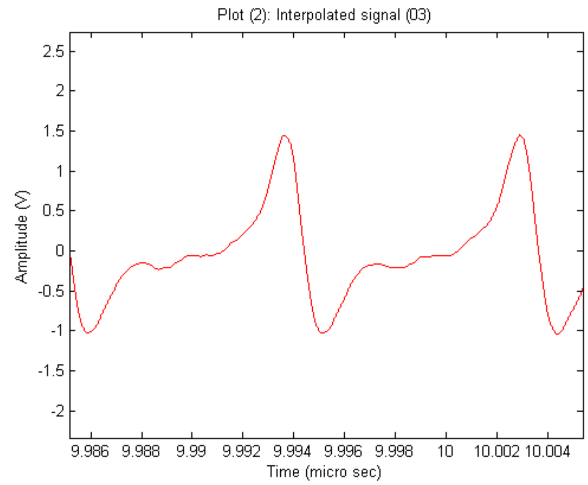
1. Plot 1 shows the displayed signal on the oscilloscope with 102 samples whereas the interpolated signal is shown in plot 2.
2. Plot 3 shows only one bunch and its integration.
3. Plot 4 shows the resulted curve for the extracted bunch.
4. Plot 5 illustrates in the upper part the measured phase by Libera H in steps of 1 µs for a train of 129 µs which represents a data set corresponds to one macropulse and the lower part shows its histogram distribution.
5. Plot 6 illustrates the phase difference in respect to the reference shape (03).
6. Plot 7 shows four curves represents the data collected by Libera H where each curve illustrates the amplitude of one pick-up for one macropulse.
7. Plot 8 illustrates the percentage of the difference over sum of two opposite pick-ups for one macropulse.
8. Plot 9 illustrates the bunch position.
9. Plot 10 the signal is interpolated shifted to zero point and zero padding technique is applied.
10. Plot 11 shows the amplitude and phase spectrum for the interpolated signal.

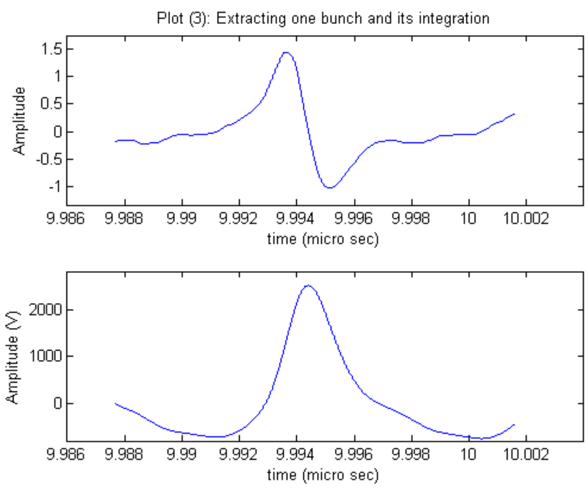
shape No.	Buncher phase	Buncher amp	Signal amp (V)	Libera read out (mean) degree	Std_dist (σ) (degree)	σ_mean (degree)	Zc - Max (ns)	Zc - Zs (ns)	Max - Zs (ns)	Min - Zc (ns)	Min-Max (ns)	Min - Zs (ns)	Ze - Min (ns)	Ze - Zc (ns)	Ze - Max (ns)	Zc - Zc(3) (degree)
1	140	7	1.545	6.34	1.274	0.112	0.787	3.288	2.501	0.759	1.546	4.047	5.185	5.944	6.731	12
2	140	5	1.529	3.533	1.153	0.102	0.765	3.237	2.472	0.739	1.504	3.976	5.248	5.987	6.752	7.446
3	140	6	1.449	-2.181	1.165	0.103	0.779	3.168	2.389	0.729	1.507	3.897	5.322	6.051	6.829	0
4	140	4	1.34	0.435	1.017	0.09	0.84	3.33	2.491	0.785	1.625	4.116	5.055	5.84	6.68	12.434
5	140	8	1.33	8.427	1.501	0.132	0.999	3.346	2.346	1.001	2	4.346	4.84	5.84	6.84	16.193
6	140	8.6	1.235	8.127	1.396	0.123	1.168	3.349	2.181	1.177	2.345	4.526	4.621	5.799	6.966	14.458
7	140	3.5	1.169	-15.397	2.029	0.179	0.776	3.342	2.566	0.739	1.514	4.08	5.229	5.967	6.743	-9.325
8	140	3	1.109	4.82	2.155	0.19	0.928	3.463	2.535	0.861	1.79	4.325	4.966	5.827	6.755	10.627
9	140	2	0.912	9.045	3.319	0.292	1.054	3.6	2.546	1.21	2.264	4.81	4.367	5.577	6.631	11.133
10	140	1	0.755	18.306	5.34	0.47	1.287	3.815	2.528	1.306	2.593	5.12	4.143	5.448	6.736	8.603
11	0	0	0.557	21.894	12.161	1.071	1.116	3.867	2.751	1.187	2.303	5.053	4.146	5.333	6.449	1.518
12	320	5	0.433	37.414	14.629	1.288	2.622	4	1.378	3.037	5.659	7.037	2.133	5.17	7.792	11.783
13	320	1.6	0.423	98.947	17.246	1.518	1.857	4.396	2.539	1.74	3.597	6.136	3.047	4.787	6.644	24.145
14	320	2	0.417	-148.101	16.508	1.453	1.642	4.366	2.725	2.298	3.94	6.665	2.51	4.808	6.45	23.133
15	320	6	0.413	52.003	14.156	1.246	2.638	3.899	1.261	3.3	5.938	7.199	1.914	5.214	7.852	2.096
16	320	7	0.404	52.349	15.199	1.338	2.57	3.856	1.286	2.82	5.39	6.676	2.71	5.53	8.1	19.446
17	320	1.5	0.399	42.802	25.544	2.249	1.87	4.405	2.535	1.677	3.547	6.082	3.095	4.772	6.642	13.663
18	320	8	0.397	66.543	12.933	1.139	2.594	3.641	1.047	2.952	5.545	6.593	2.605	5.556	8.15	13.518
19	320	8.6	0.388	65.901	11.518	1.014	2.528	3.721	1.193	2.896	5.424	6.617	2.606	5.503	8.031	32.025
20	320	3	0.382	-147.379	16.866	1.485	2.249	4.245	1.996	2.296	4.545	6.541	2.609	4.905	7.154	6.723
21	320	4	0.376	-127.469	17.413	1.533	3.008	4.342	1.333	2.389	5.397	6.731	2.491	4.879	7.888	42.796
22	320	3	0.338	17.246	31.354	2.761	1.974	4.35	2.376	1.645	3.619	5.995	3.236	4.881	6.855	7.301

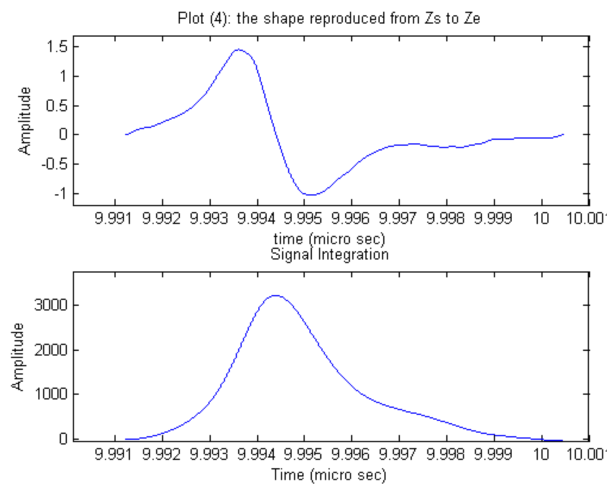
Table 3 At 325 MHz → 360° : 3.07 ns

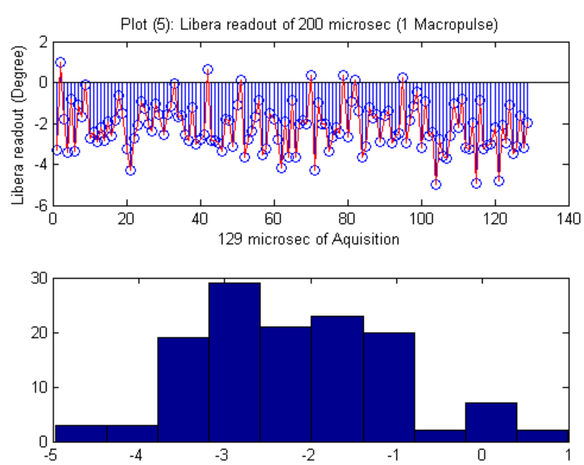
- Signal (03)

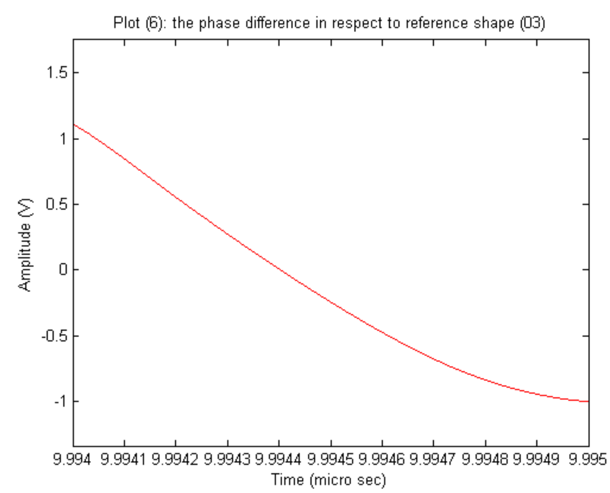

Plot (1): Signal Shape (03)
Amplitude (V)
Time (micro sec)

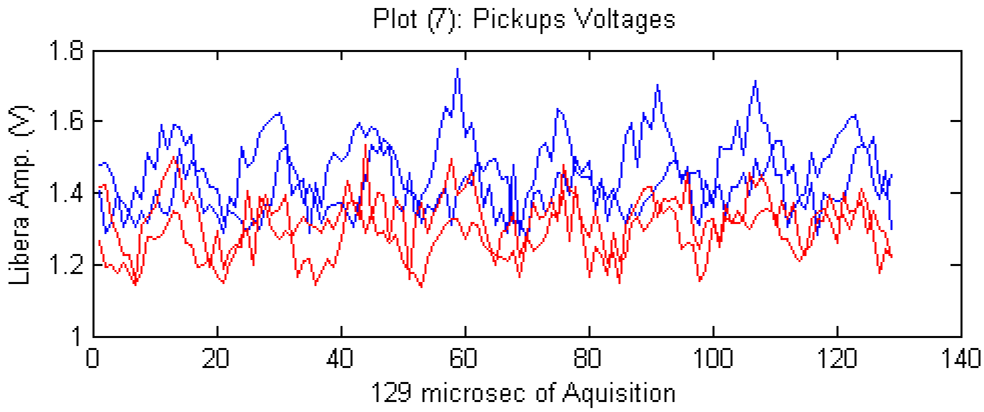

Plot (2): Interpolated signal (03)
Amplitude (V)
Time (micro sec)

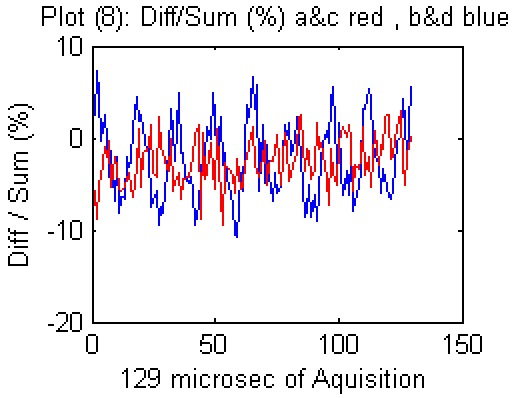

Plot (3): Extracting one bunch and its integration
Amplitude
time (micro sec)
Amplitude (V)
time (micro sec)

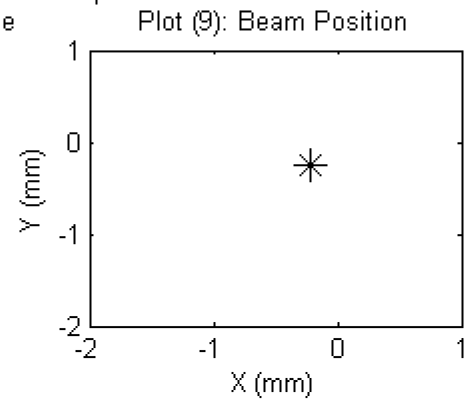

Plot (4): the shape reproduced from Zs to Ze
Amplitude
time (micro sec)
Signal Integration
Amplitude
Time (micro sec)

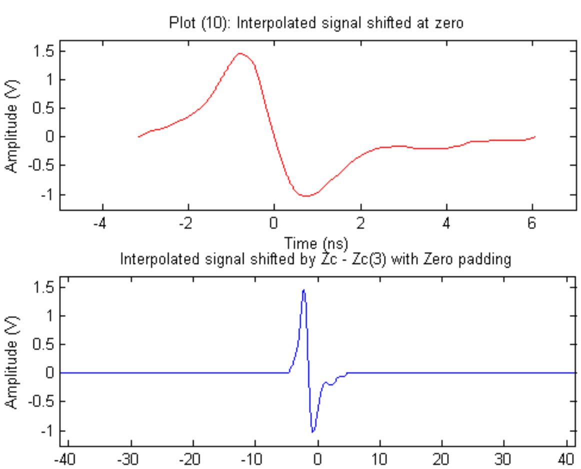

Plot (5): Libera readout of 200 microsec (1 Macropulse)
Libera readout (Degree)
129 microsec of Aquisition

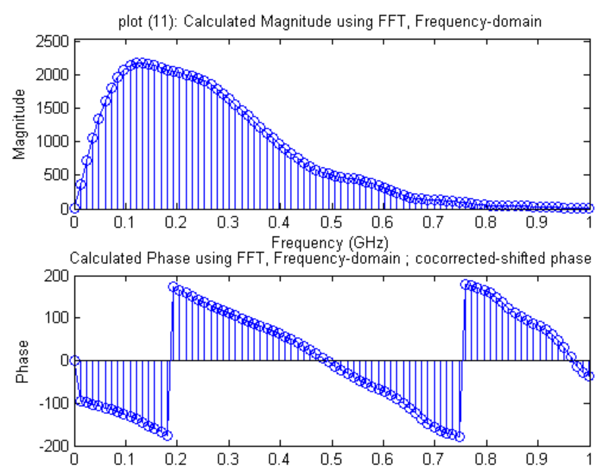

Plot (6): the phase difference in respect to reference shape (03)
Amplitude (V)
Time (micro sec)


Plot (7): Pickups Voltages
Libera Amp. (V)
129 microsec of Aquisition

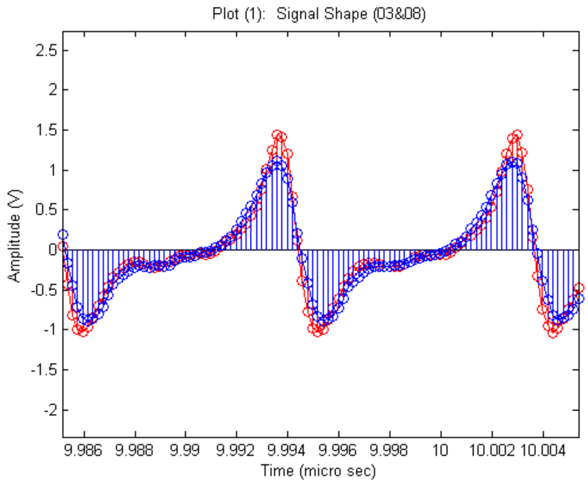

Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
129 microsec of Aquisition

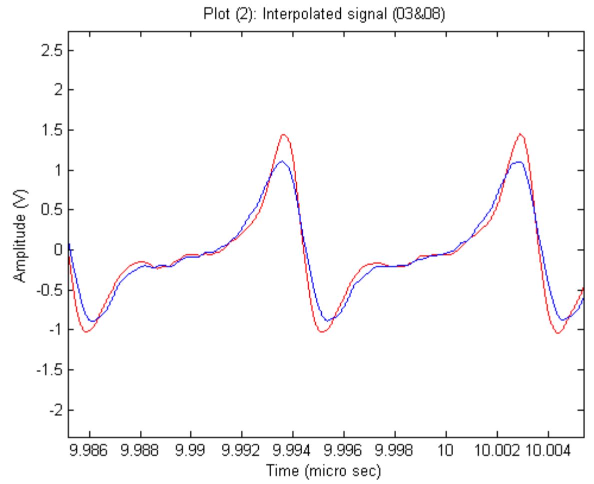

Plot (9): Beam Position
Y (mm)
X (mm)

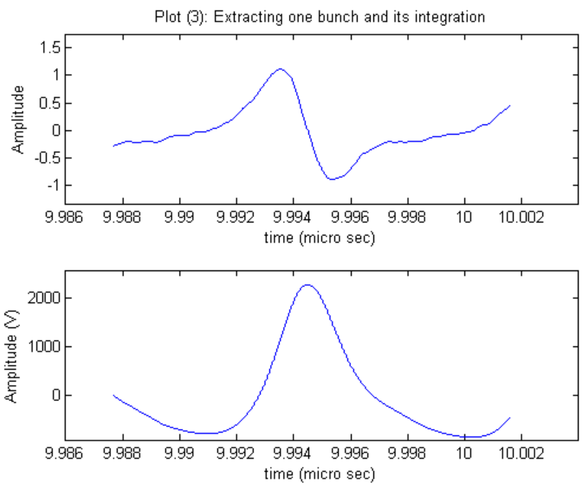

Plot (10): Interpolated signal shifted at zero
Amplitude (V)
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
Time (ns)

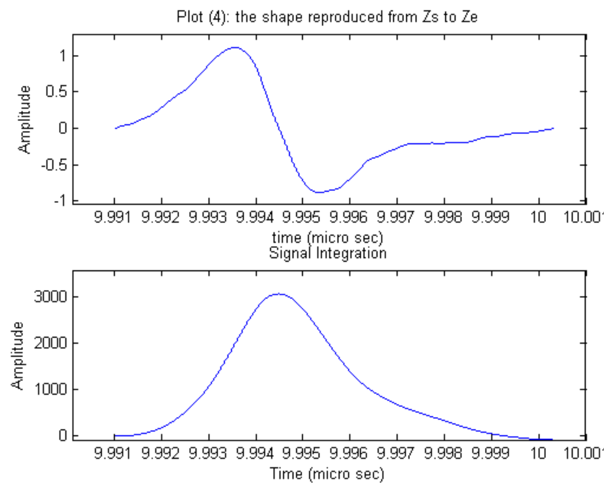

plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
Frequency (GHz)

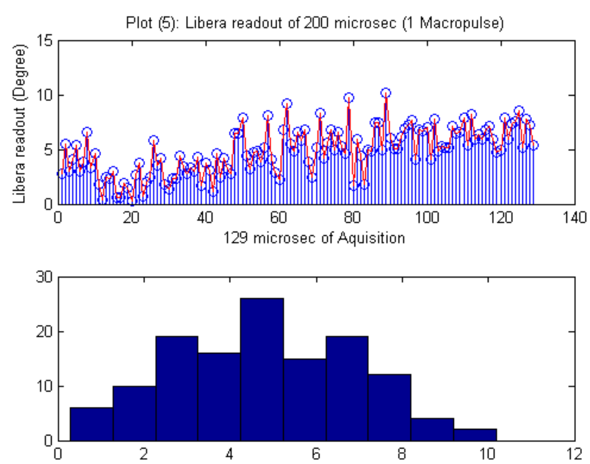
- Signal (03&08)

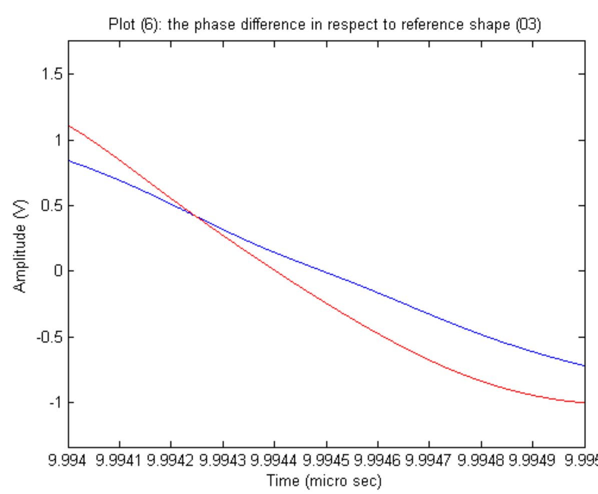

Plot (1): Signal Shape (03&08)
Amplitude (V)
Time (micro sec)

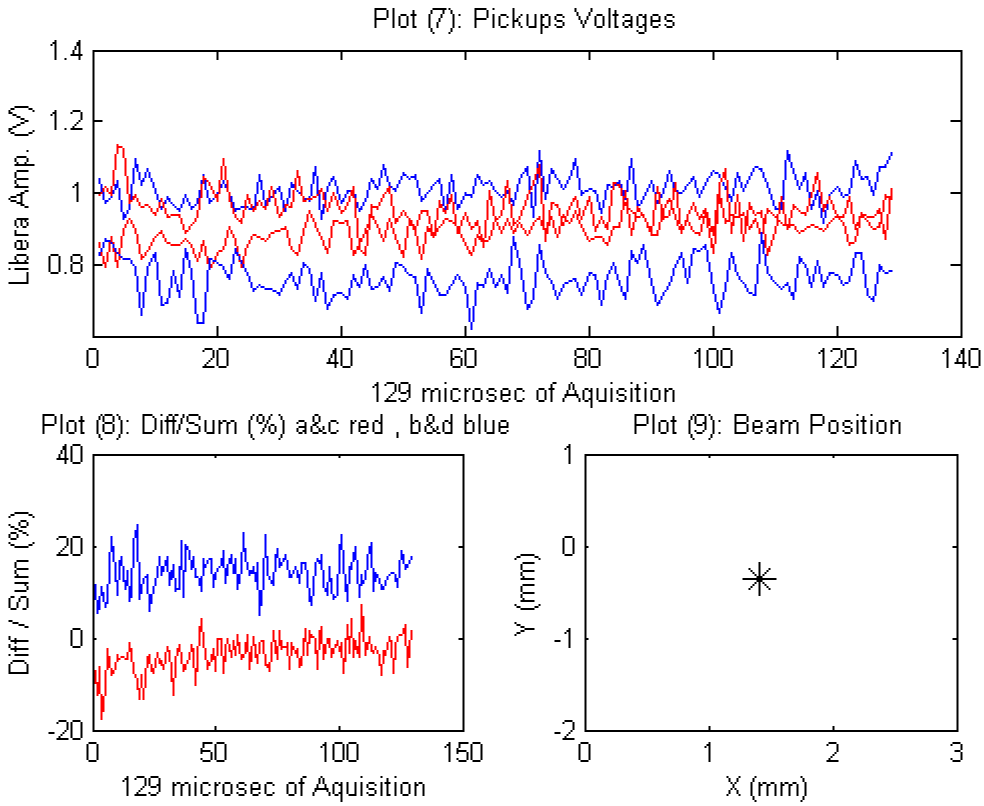

Plot (2): Interpolated signal (03&08)
Amplitude (V)
Time (micro sec)

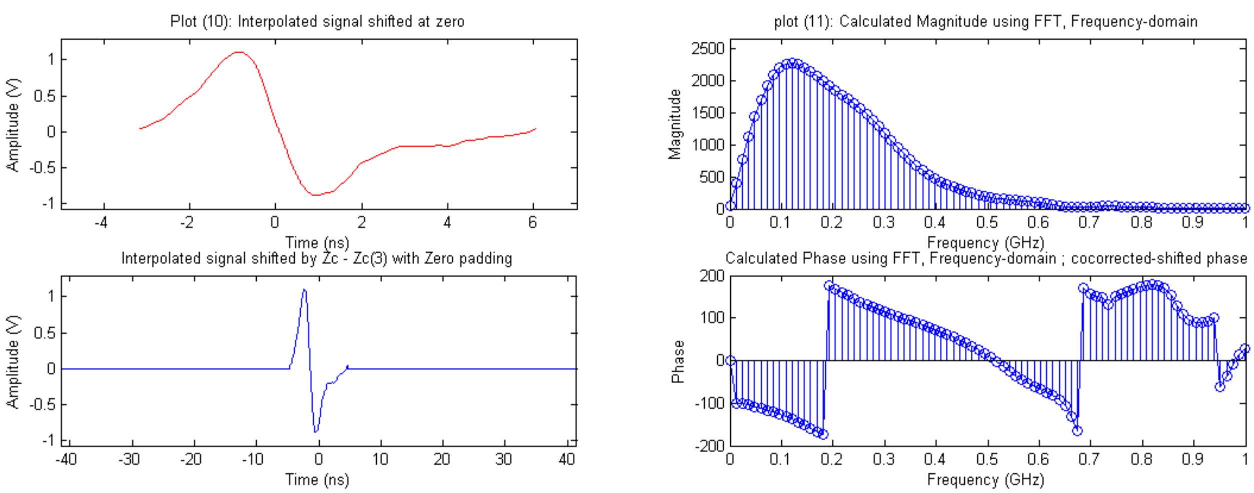

Plot (3): Extracting one bunch and its integration
Amplitude
time (micro sec)
Amplitude (V)
time (micro sec)


Plot (4): the shape reproduced from Zs to Ze
Amplitude
time (micro sec)
Signal Integration
Amplitude
Time (micro sec)

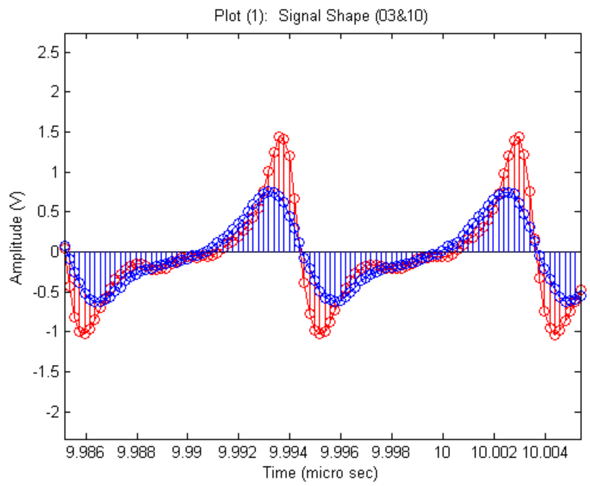

Plot (5): Libera readout of 200 microsec (1 Macropulse)
Libera readout (Degree)
129 microsec of Aquisition

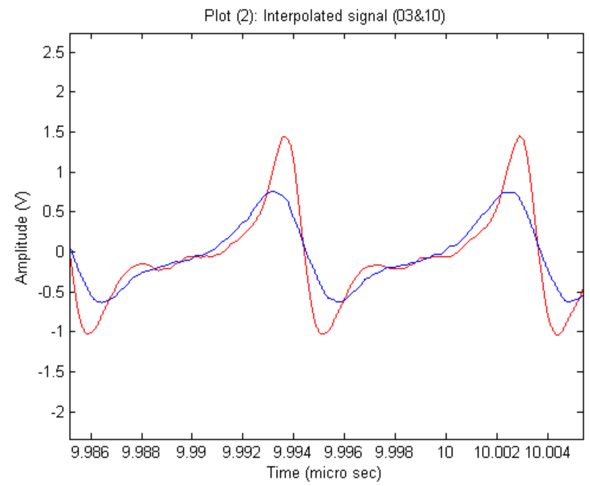

Plot (6): the phase difference in respect to reference shape (03)
Amplitude (V)
Time (micro sec)

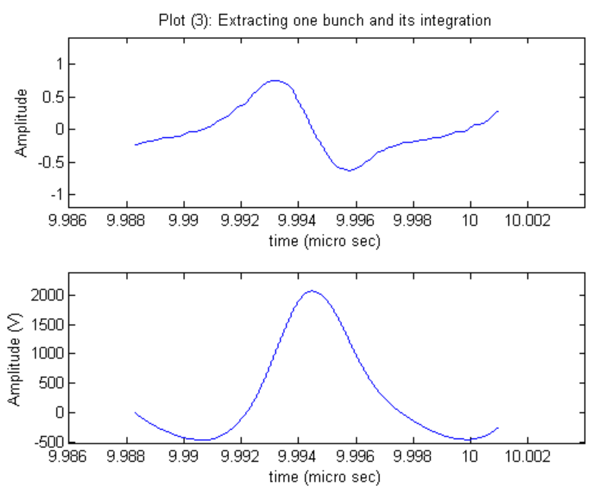

Plot (7): Pickups Voltages
Libera Amp. (V)
129 microsec of Aquisition
Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
129 microsec of Aquisition
Plot (9): Beam Position
Y (mm)
X (mm)

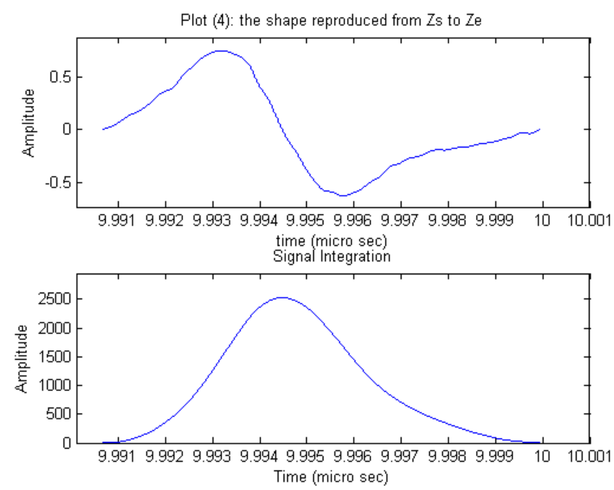

Plot (10): Interpolated signal shifted at zero
Amplitude (V)
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
Time (ns)
plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
Frequency (GHz)

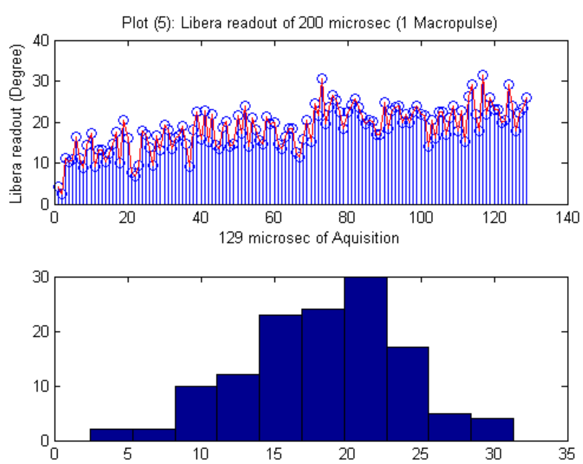
- Signals (03&10)

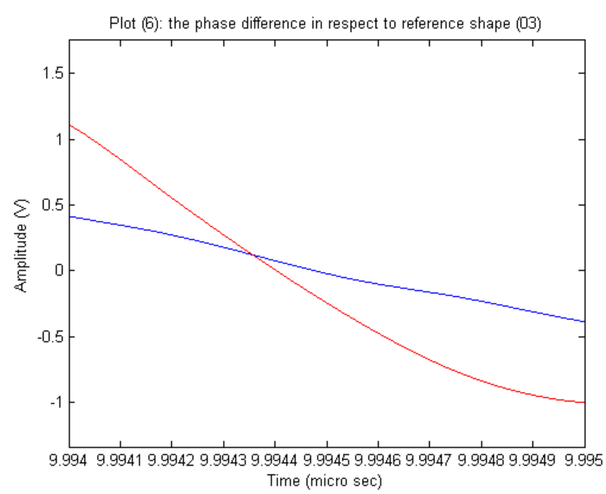


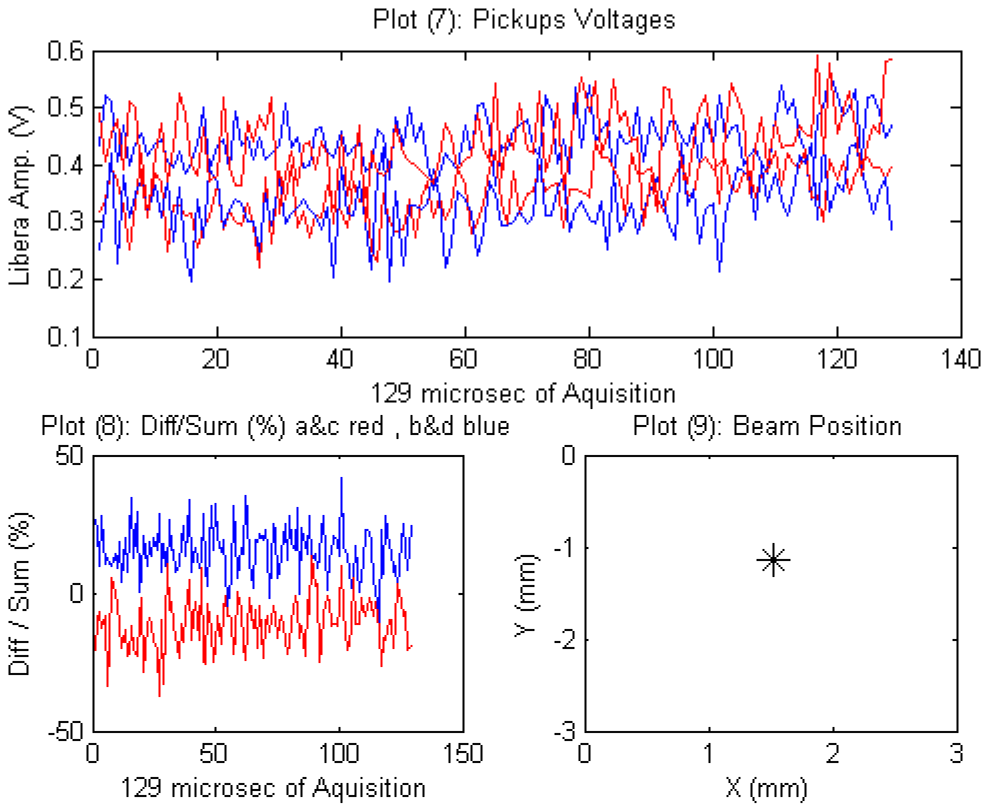


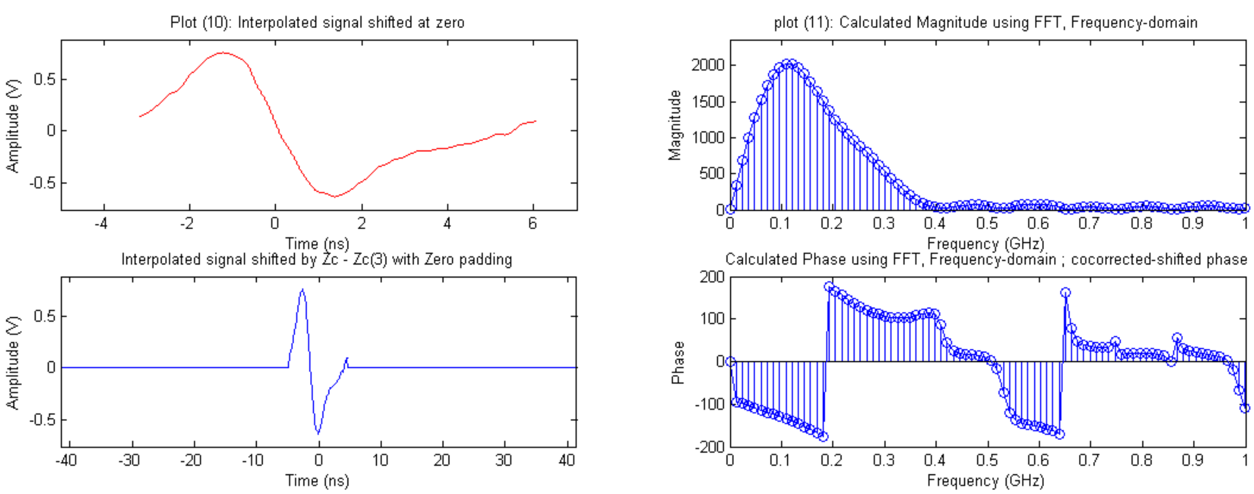




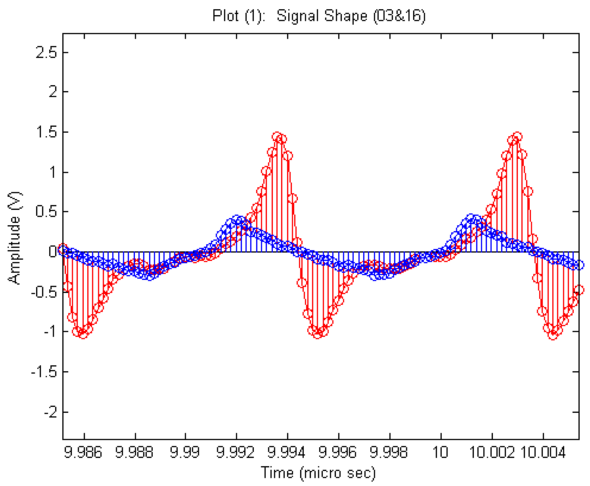


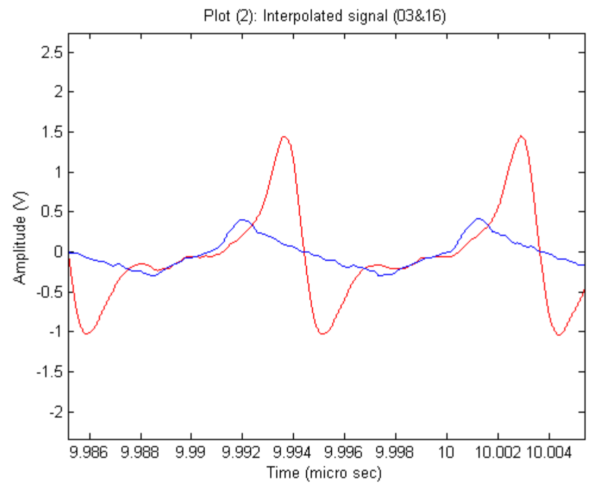


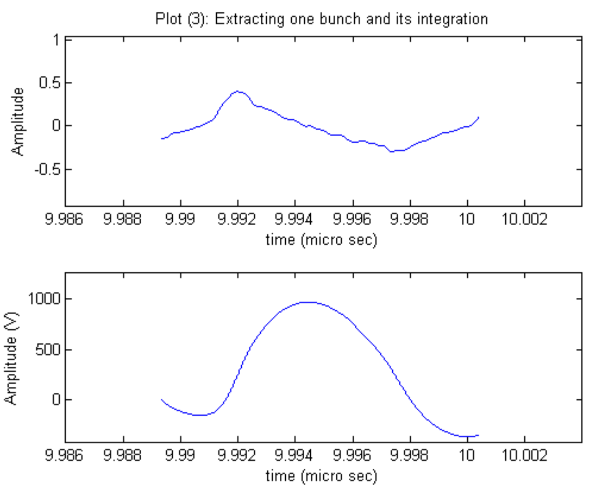

Plot (7): Pickups Voltages
Libera Amp. (V)
129 microsec of Aquisition
Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
129 microsec of Aquisition
Plot (9): Beam Position
Y (mm)
X (mm)

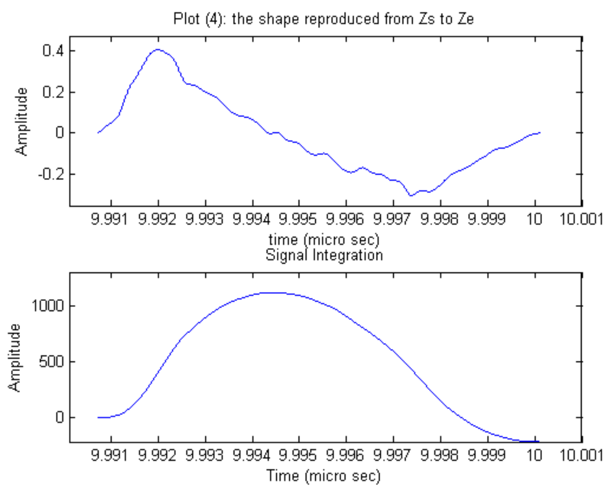

Plot (10): Interpolated signal shifted at zero
Amplitude (V)
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
Time (ns)
plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
Frequency (GHz)

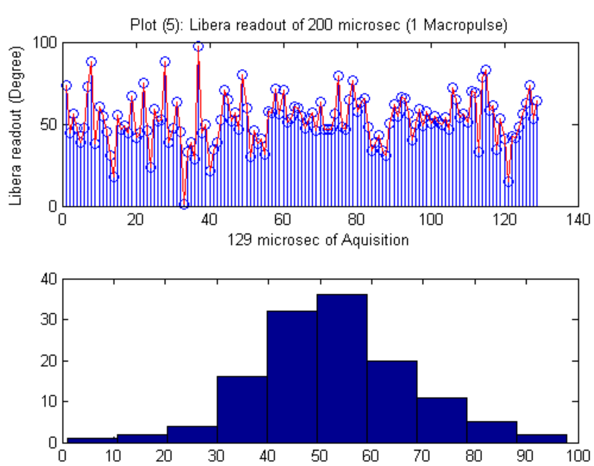
- Signals (03&16)

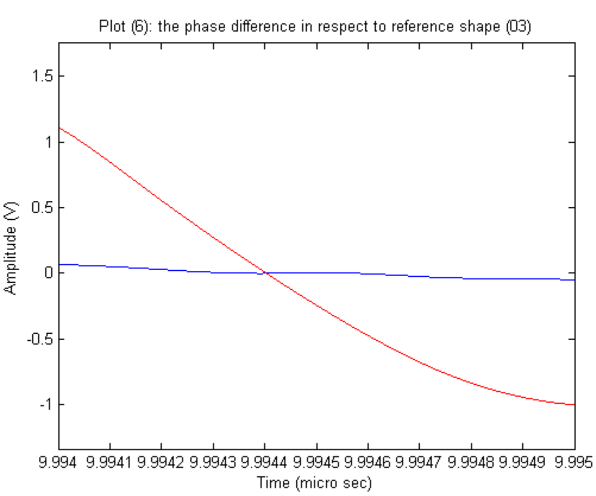


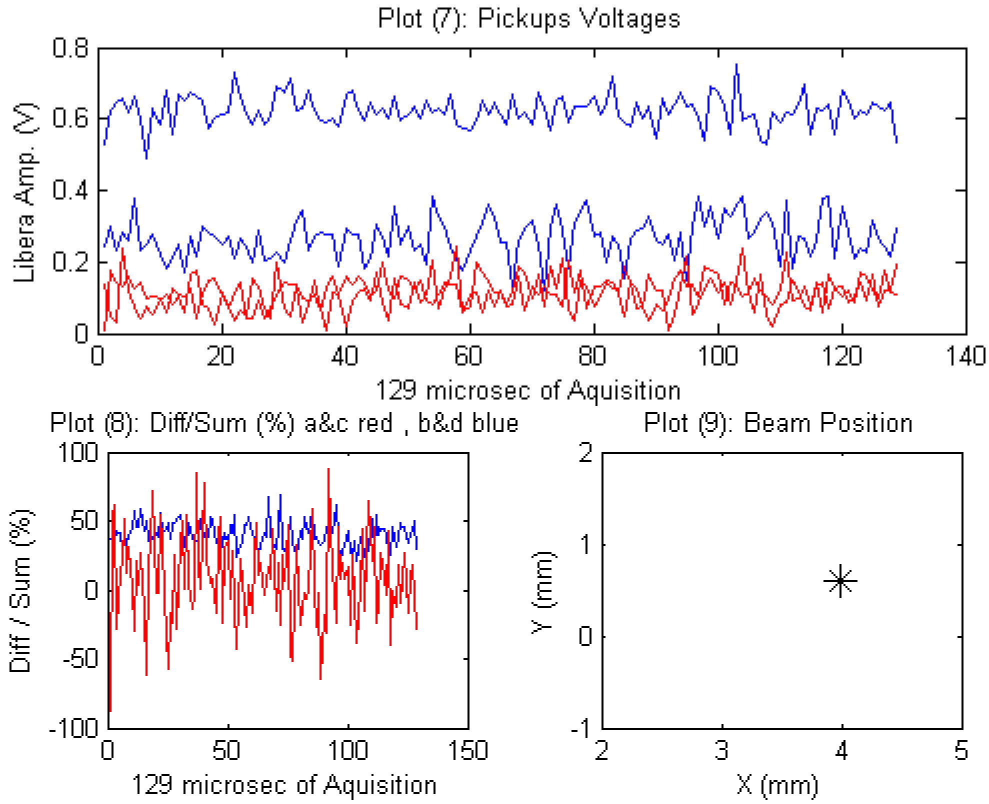


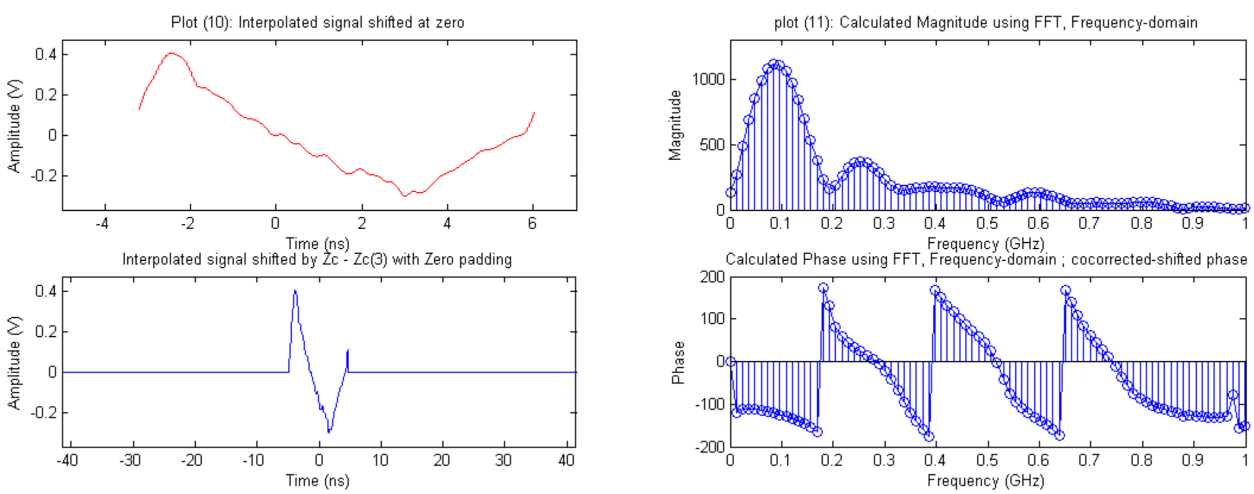




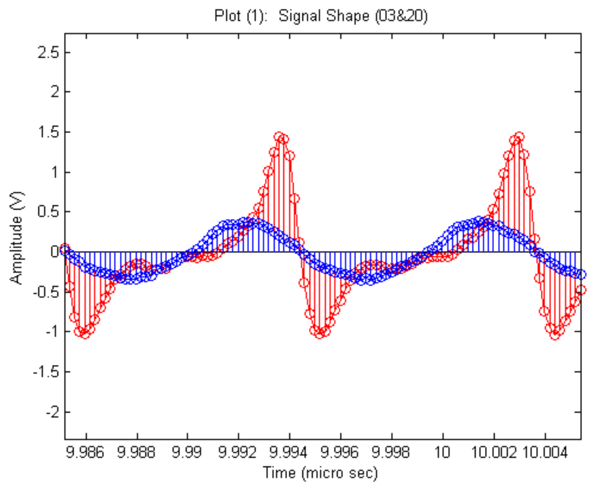


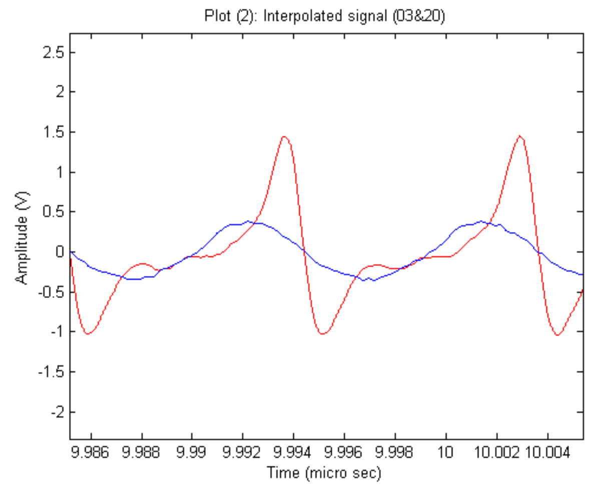


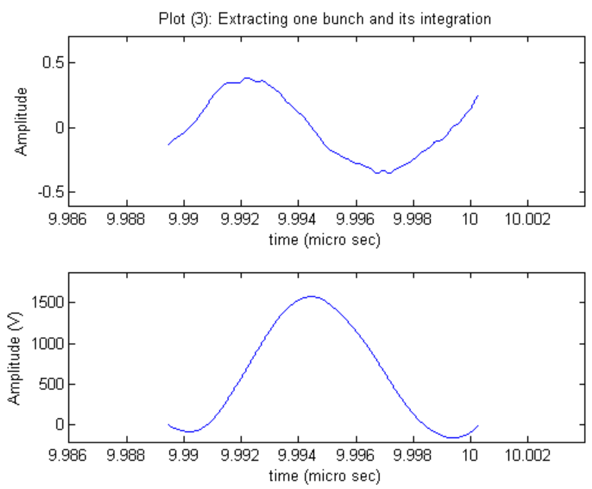

Plot (7): Pickups Voltages
Libera Amp. (V)
129 microsec of Aquisition
Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
129 microsec of Aquisition
Plot (9): Beam Position
Y (mm)
X (mm)

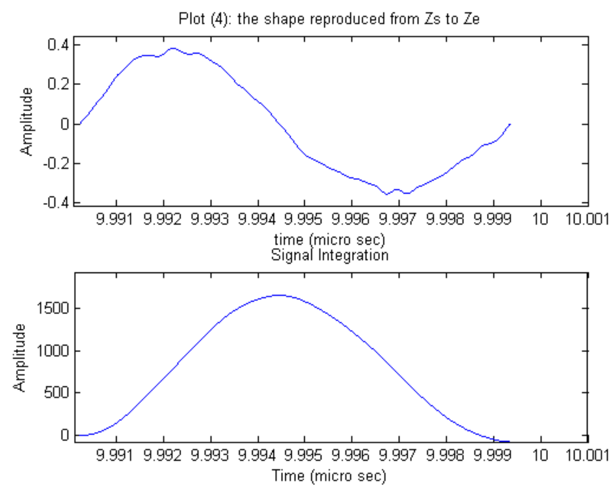

Plot (10): Interpolated signal shifted at zero
Amplitude (V)
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
Time (ns)
plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
Frequency (GHz)

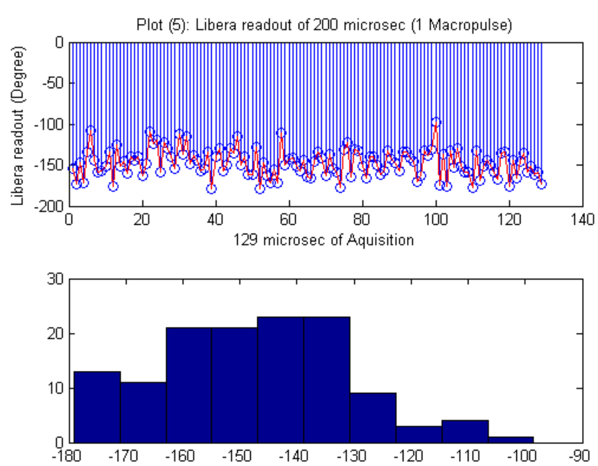
- Signal (03&20)

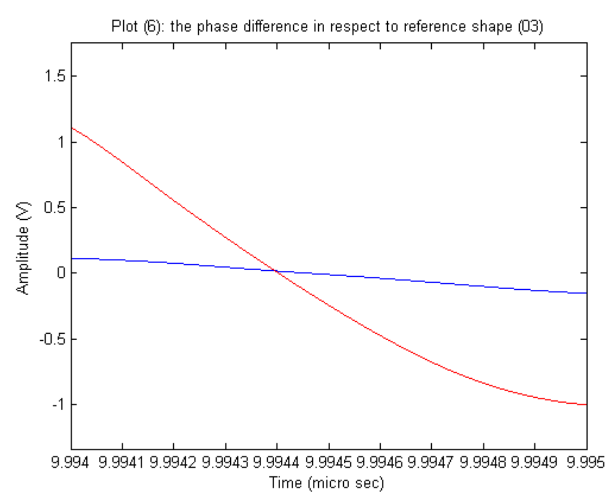

Plot (1): Signal Shape (03&20)
Amplitude (V)
Time (micro sec)

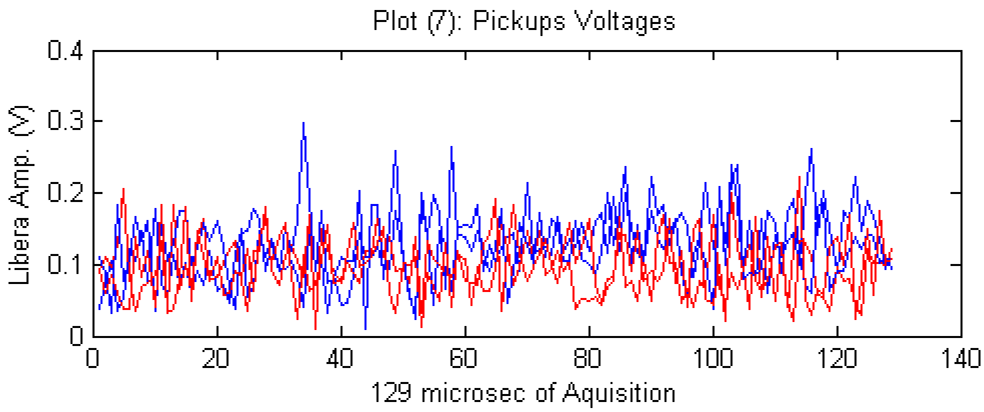

Plot (2): Interpolated signal (03&20)
Amplitude (V)
Time (micro sec)

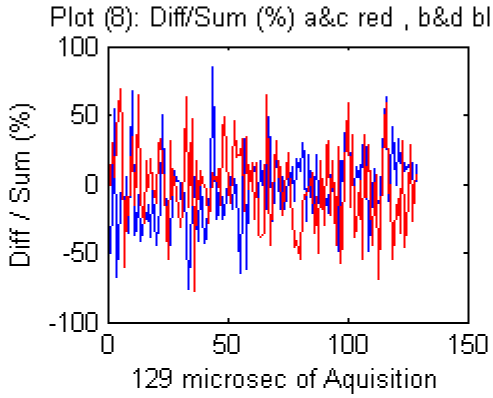

Plot (3): Extracting one bunch and its integration
Amplitude
time (micro sec)
Amplitude (V)
time (micro sec)

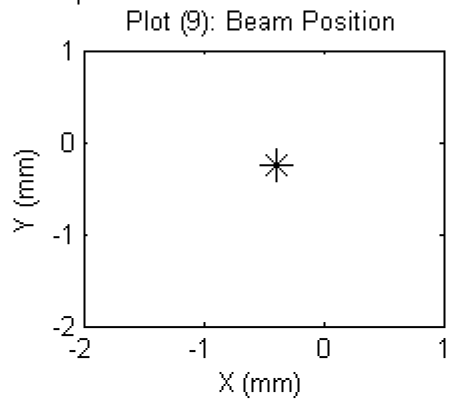

Plot (4): the shape reproduced from Zs to Ze
Amplitude
time (micro sec)
Signal Integration
Amplitude
Time (micro sec)

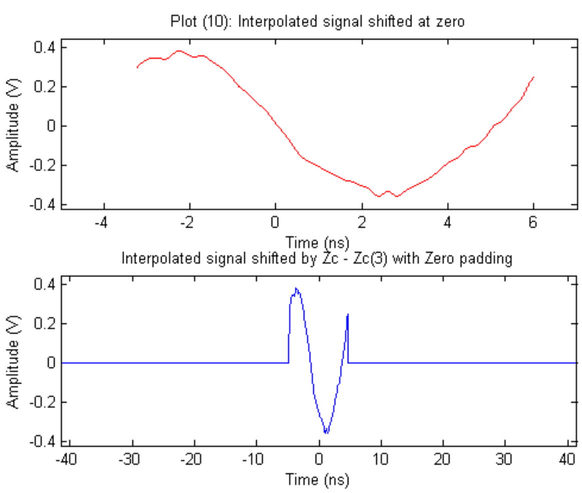

Plot (5): Libera readout of 200 microsec (1 Macropulse)
Libera readout (Degree)
129 microsec of Aquisition

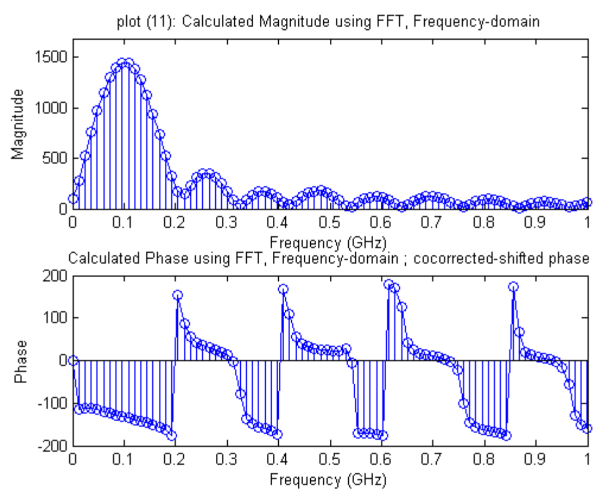

Plot (6): the phase difference in respect to reference shape (03)
Amplitude (V)
Time (micro sec)


Plot (7): Pickups Voltages
Libera Amp. (V)
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
129 microsec of Aquisition

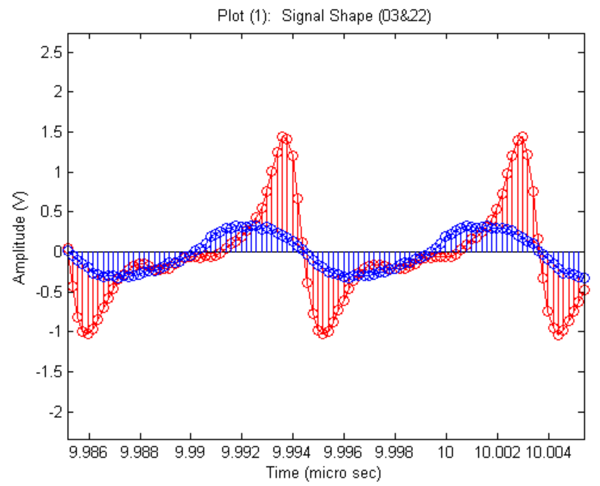

Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
100
50
0
-50
-100
0
50
100
150
129 microsec of Aquisition

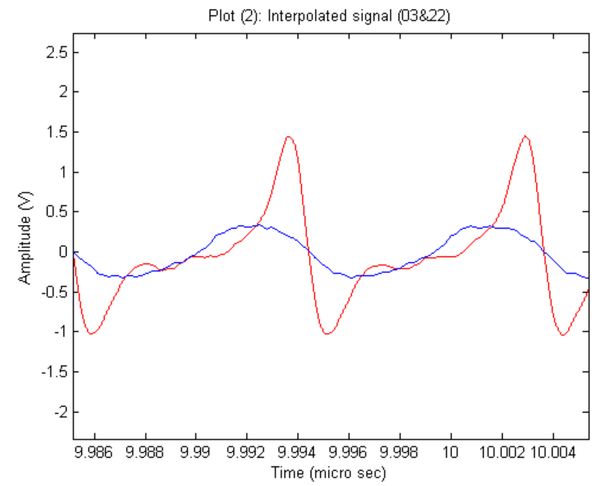

Plot (9): Beam Position
Y (mm)
1
0
-1
-2
-2
-1
0
1
X (mm)

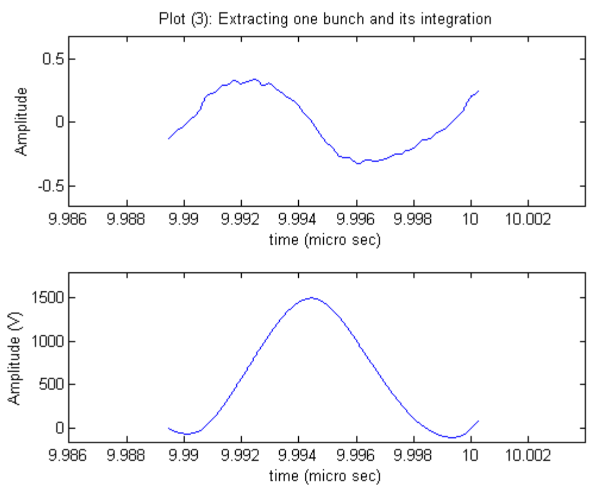

Plot (10): Interpolated signal shifted at zero
Amplitude (V)
0.4
0.2
0
-0.2
-0.4
-4
-2
0
2
4
6
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
0.4
0.2
0
-0.2
-0.4
-40
-30
-20
-10
0
10
20
30
40
Time (ns)

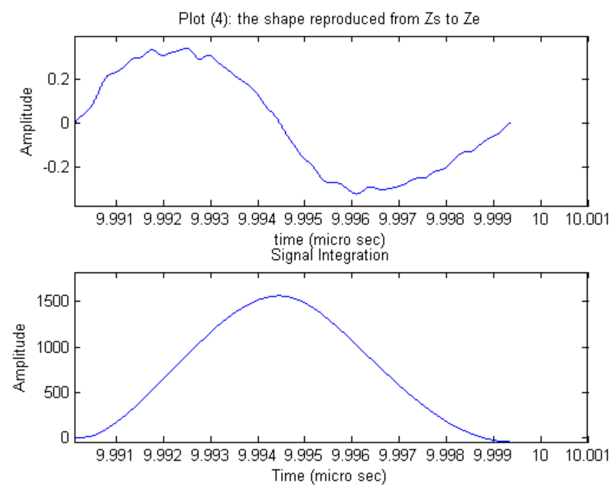

plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
200
100
0
-100
-200
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Frequency (GHz)

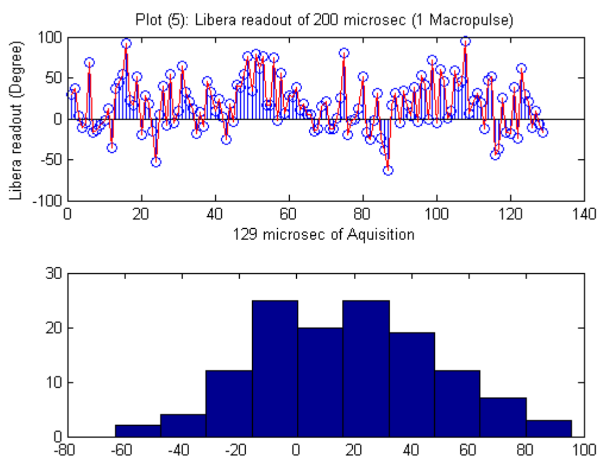
- Signal (03&22)

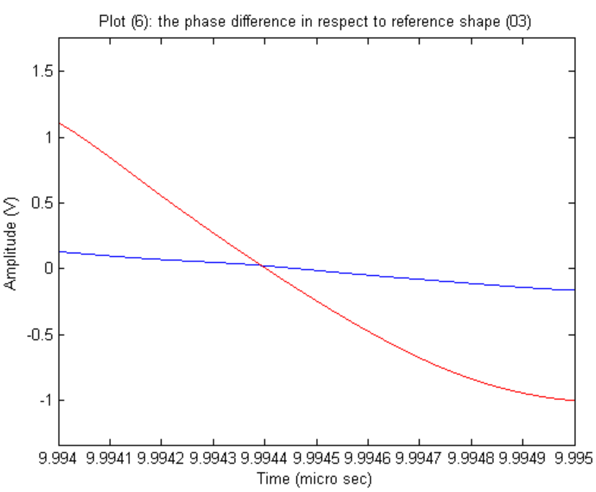

Plot (1): Signal Shape (03&22)
Amplitude (V)
Time (micro sec)

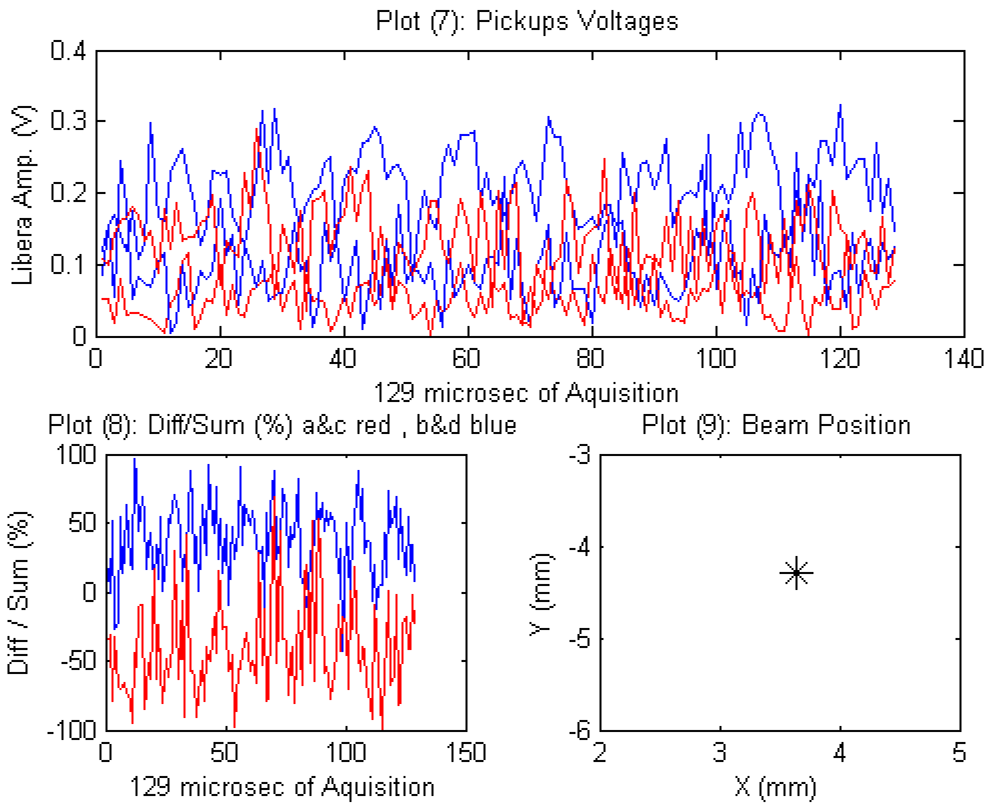

Plot (2): Interpolated signal (03&22)
Amplitude (V)
Time (micro sec)

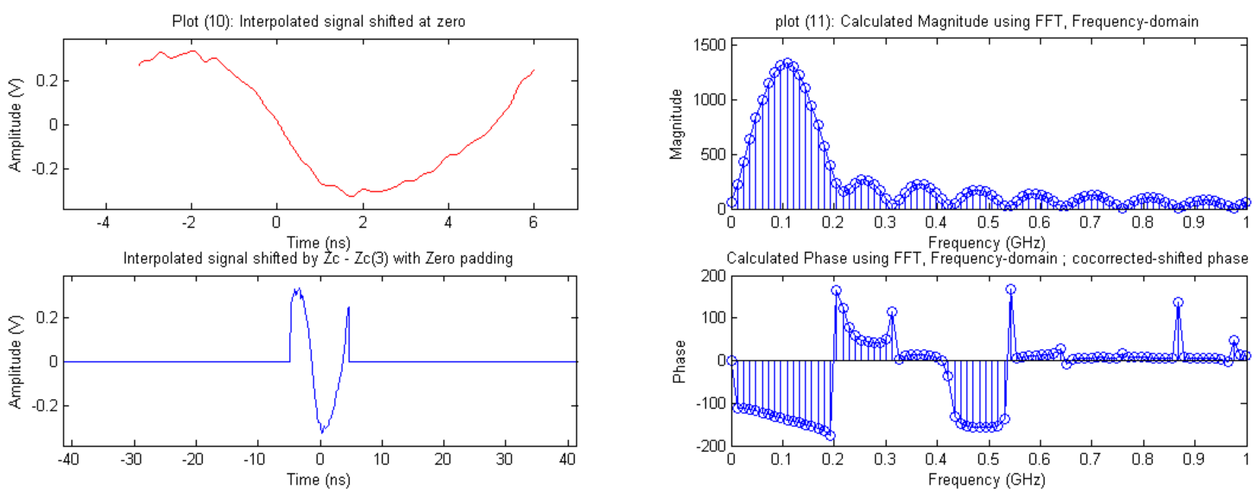

Plot (3): Extracting one bunch and its integration
Amplitude
time (micro sec)
Amplitude (V)
time (micro sec)


Plot (4): the shape reproduced from Zs to Ze
Amplitude
time (micro sec)
Signal Integration
Amplitude
Time (micro sec)


Plot (5): Libera readout of 200 microsec (1 Macropulse)
Libera readout (Degree)
129 microsec of Aquisition


Plot (6): the phase difference in respect to reference shape (03)
Amplitude (V)
Time (micro sec)


Plot (7): Pickups Voltages
Libera Amp. (V)
129 microsec of Aquisition
Plot (8): Diff/Sum (%) a&c red , b&d blue
Diff / Sum (%)
129 microsec of Aquisition
Plot (9): Beam Position
Y (mm)
X (mm)


Plot (10): Interpolated signal shifted at zero
Amplitude (V)
Time (ns)
Interpolated signal shifted by Zc - Zc(3) with Zero padding
Amplitude (V)
Time (ns)
plot (11): Calculated Magnitude using FFT, Frequency-domain
Magnitude
Frequency (GHz)
Calculated Phase using FFT, Frequency-domain ; cocorrected-shifted phase
Phase
Frequency (GHz)

➢ The Results

➢ Phase and bunch amplitude

Figure 4 illustrates the measured phase using Libera Single Pass H versus the bunch amplitude. It shows that for an input signal with an amplitude higher than 0.9 V, the standard deviation gives a range of $1^{o} - 3.3^{o}$ and increases dramatically as the input level is below 0.7 V. The points of the range higher than 0.9 V are highlighted and shown in figure 5. The phase value per the macropulse is represented by the center of the distribution where the shown error bars are the width of the distribution. The resolution can be characterised by the displayed width of the distribution divided by the number of samples, as it shown in eq (1).

The standard deviation of the distribution for Libera phase readout versus the input signal is depicted in figure 6. Figure 7 shows the phase resolution with an amplitude of the values higher than 0.9 V.

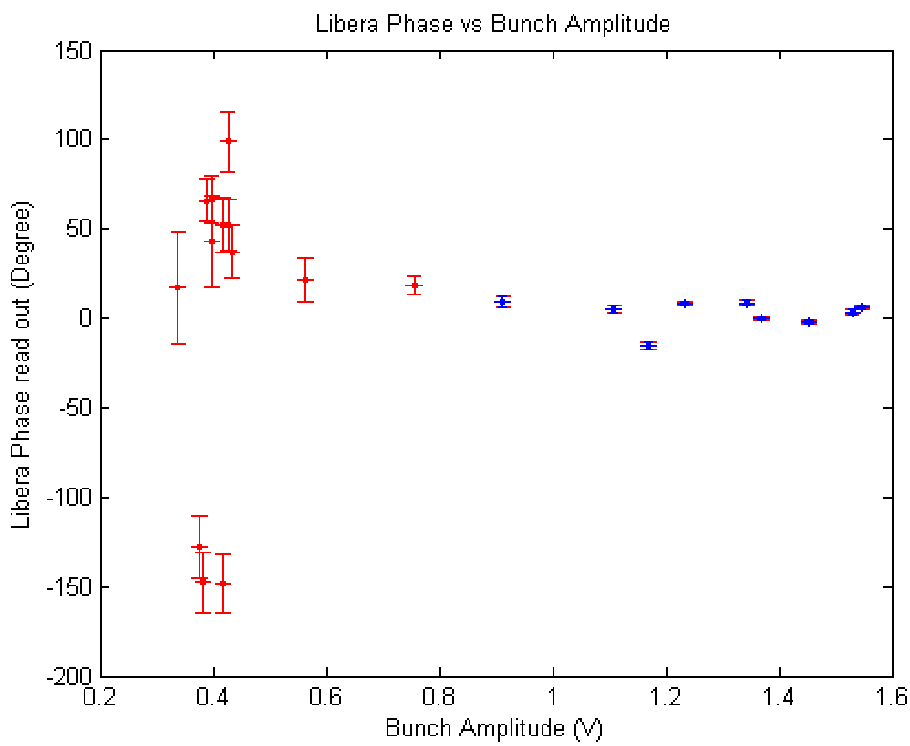


Fig. 4, Libera phase readout versus bunch amplitude.

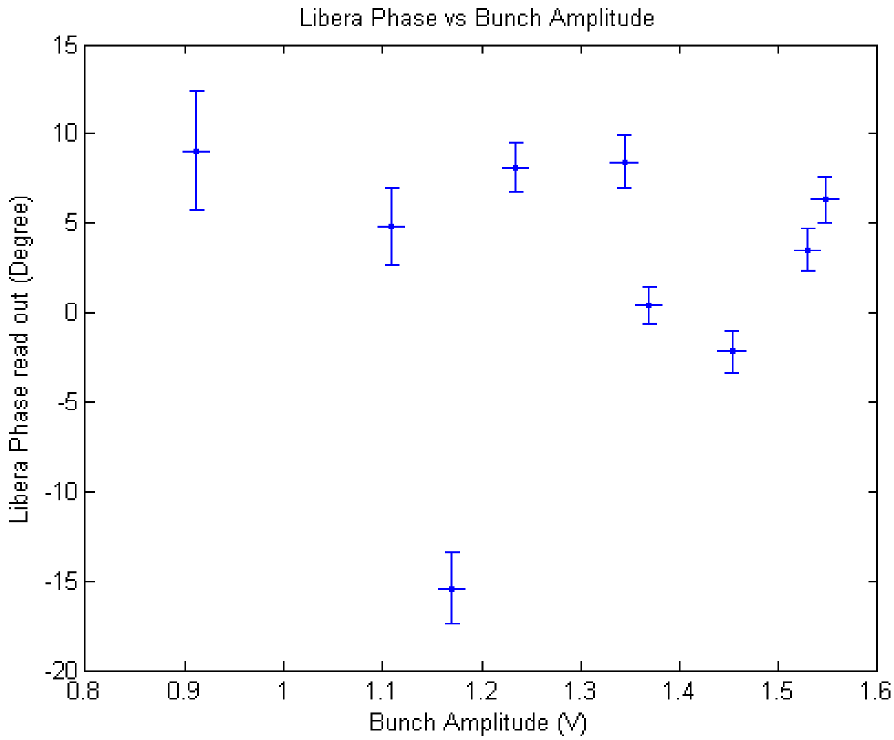


Fig. 5, Libera phase readout versus the bunch amplitude of higher than 0.9 V

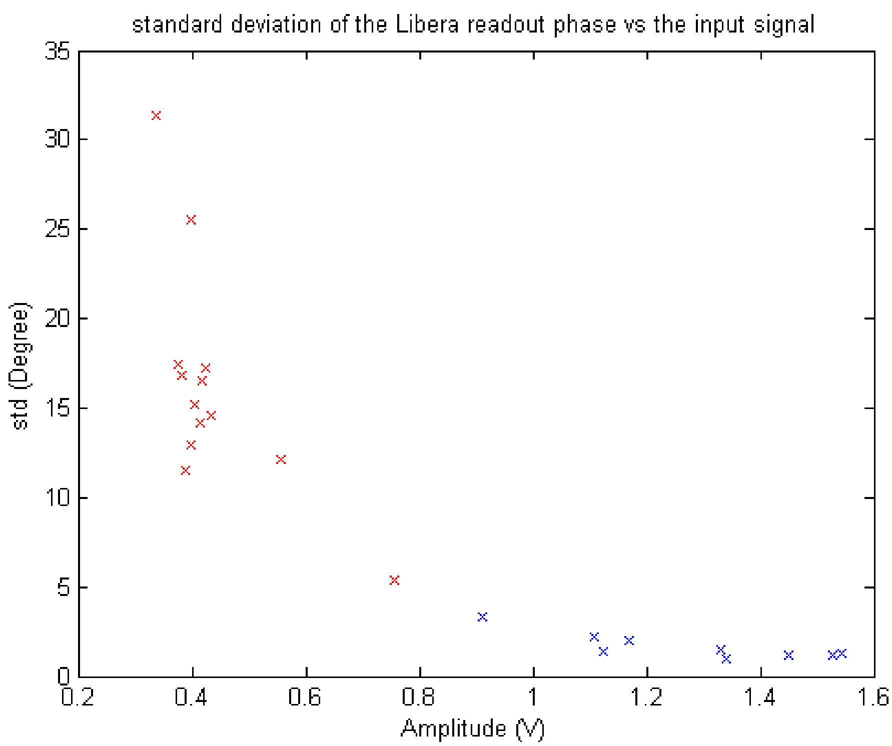


Fig 6, Phase resolution.

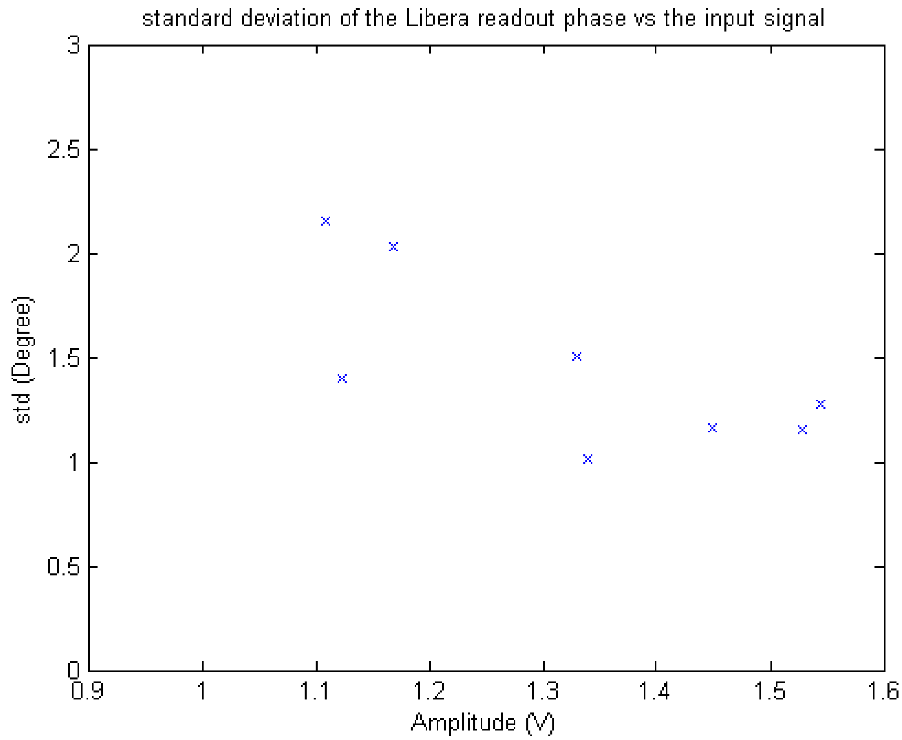


Fig. 7, Phase resolution with an amplitude of higher than 0.9 V.

- Phase and phase difference.

The measured phase by Libera Single Pass H has been compared to the phase of the interpolated curves shown on the oscilloscope with 5 GSa/s sampling frequency. Figure 8 shows the phase difference in respect to shape (03). figure 9 illustrates Libera readout phase versus phase difference for the bunch amplitude higher than 0.9 V.

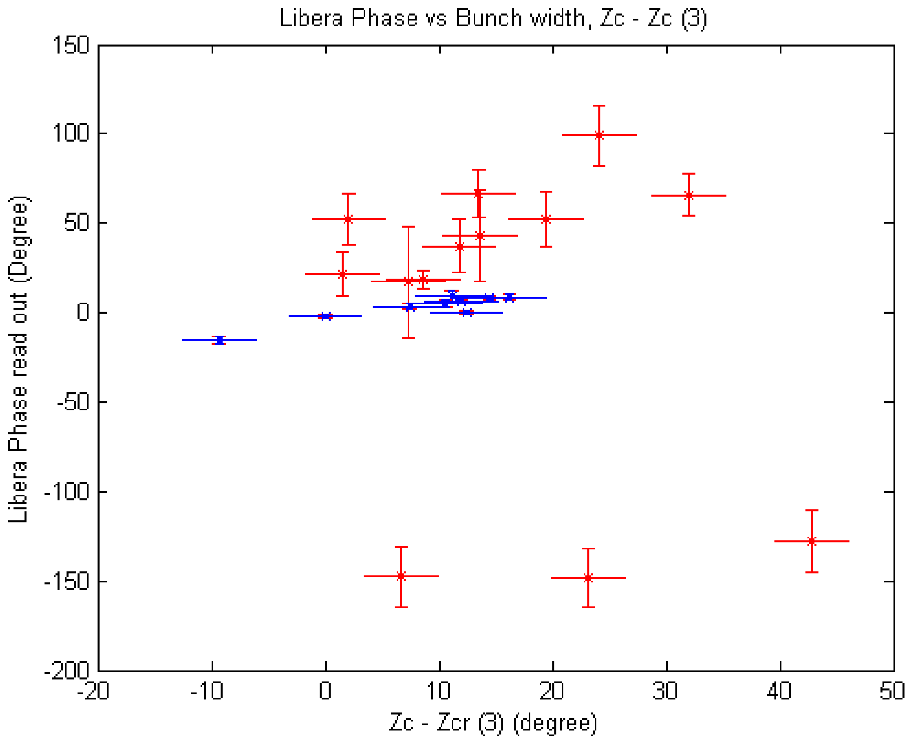


Fig. 8, Libera readout phase versus phase difference in respect to the reference shape.

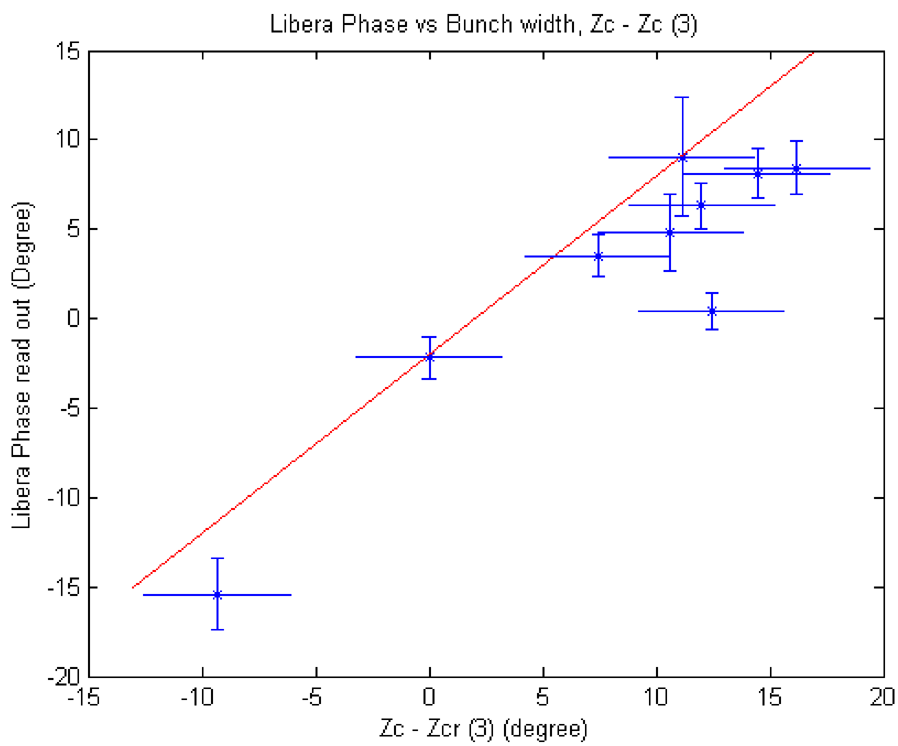


Fig. 9, Libera readout phase versus phase difference of the bunch amplitude of higher than 0.9 V.

➢ Phase and bunch width

By comparing Libera response with the signal width, the limitation of Libera performance in respect to the bunch shape -stretched bunch- is investigated. The characteristics of signal width are Zs–Zc, Zc–Max, Zc – Zs, Max – Zs, Min – Zc, Min – Max, Min – Zs, Ze – Min, Ze – Zc & Ze – Max, see figure1.

1. For the distance between the zero starting and the zero crossing points (Zc – Zs), figures 10 & 11 shows that for length of more than ~ 3.6 ns, Libera readout gives large fluctuation. On the other hand, figures 12 & 13 shows the phase fluctuation for distance between the zero ending and the zero crossing points (Ze – Zc).

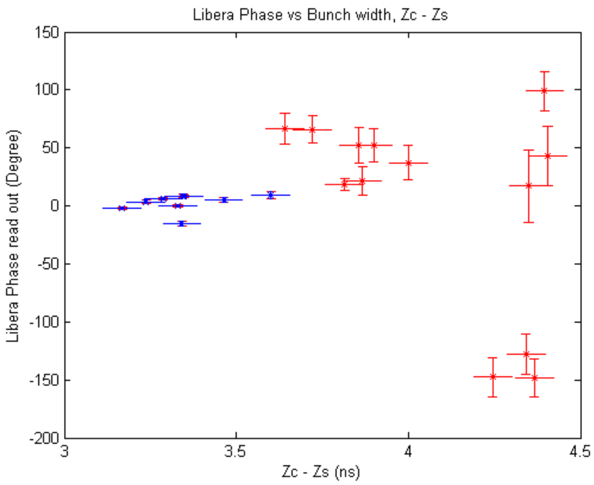


Fig. 10, Phase vs bunch width (Zc – Zs).

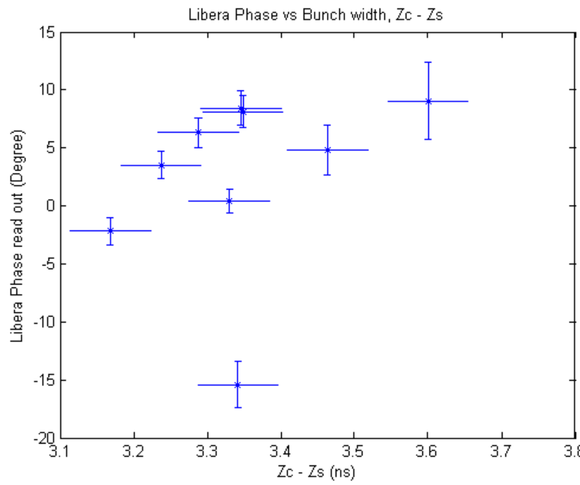


Fig. 11, Zc – Zs with amplitude of higher than 0.9 V.

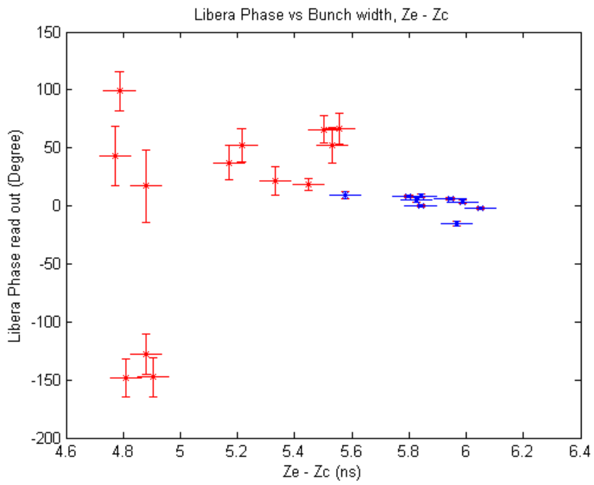


Fig. 12, Phase vs bunch width (Ze – Zc).

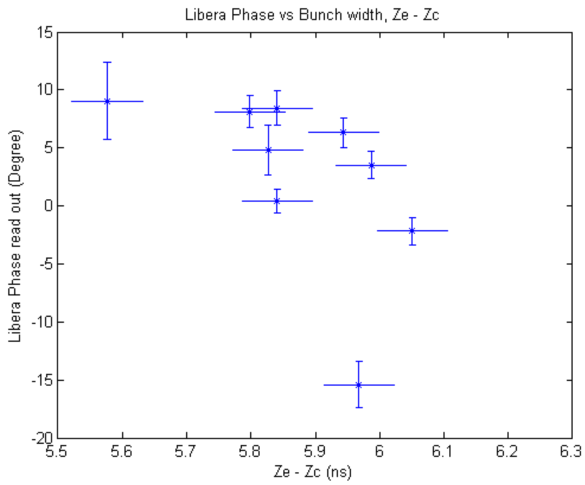


Fig. 13, Ze – Zc with amplitude of higher than 0.9 V.

1. For the distance between the zero crossing and the maximum points (Zc – Max), the distance between the minimum and the zero crossing points (Min – Zc) and the distance between the minimum and the maximum points (Min – Max) as it is dipicted in figures 14, 15, 16, 17 and 18,19, they show almost a similar behaviour where the large fluctuation occurs as the width of more than 1.3 ns, 1.3 and 2.4 ns respectivily and some correlation can be observed before these points.

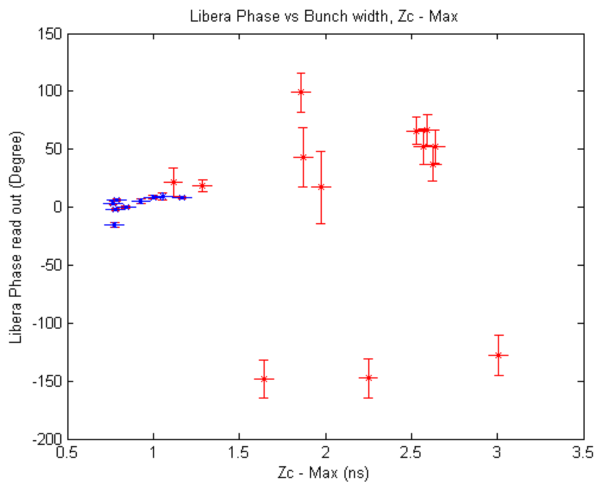


Fig. 14, Phase vs bunch width (Zc – Max).

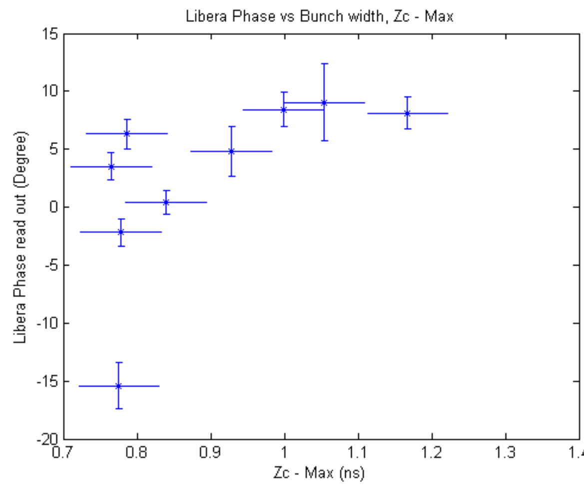


Fig. 15, Zc – Max with amplitude of higher than 0.9 V.

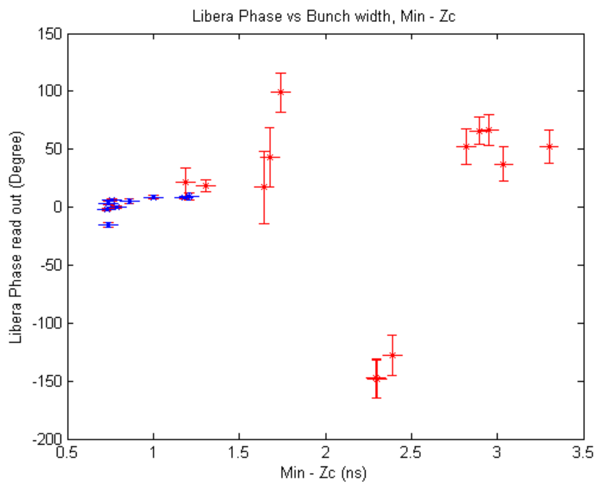


Fig. 16, Phase vs bunch width (Min – Zc).

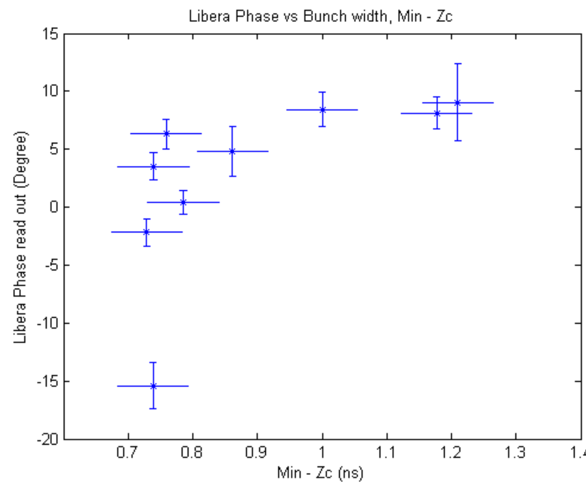


Fig. 17, Min – Zc with amplitude of higher than 0.9 V.

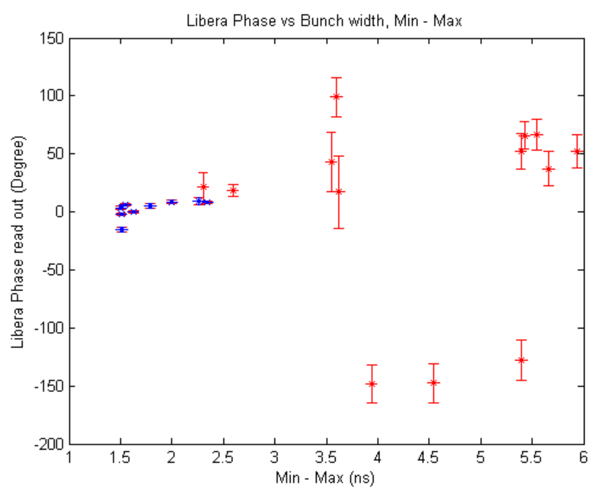


Fig. 18, Phase vs bunch width (Min – Max).

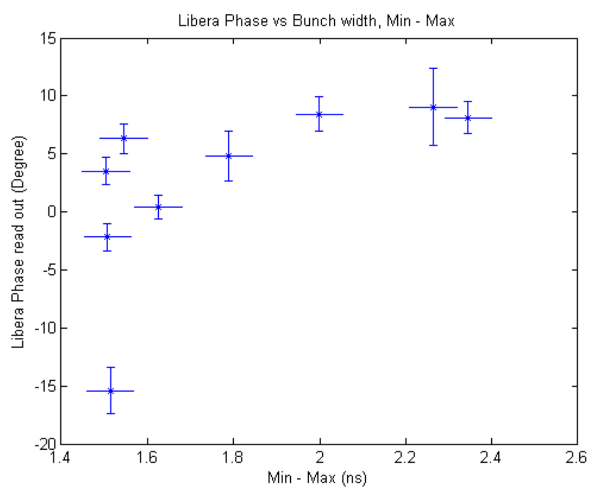


Fig. 19, Min – Max with amplitude of higher than 0.9 V.

2. For the distance between the minimum and the zero starting points (Min – Zs), the large fluctuation occurs as the width gets higher than 4.8 ns as it shown in figures 20 and 21. In figures 22 and 23, the mirror plot can be observed for the distance between the zero ending and the minimum points (Ze – Min).

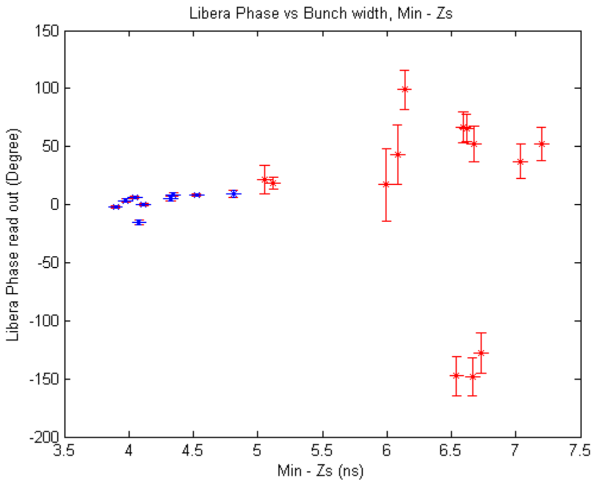


Fig. 20, Phase vs bunch width (Min – Zs).

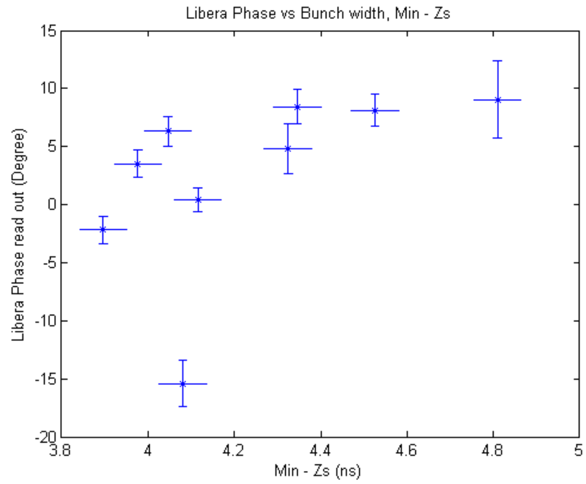


Fig. 21, Min – Zs with amplitude of higher than 0.9 V.

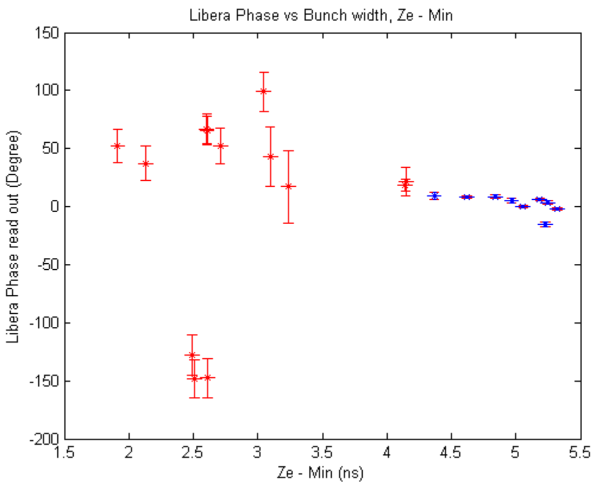


Fig. 22, Phase vs bunch width (Ze – Min).

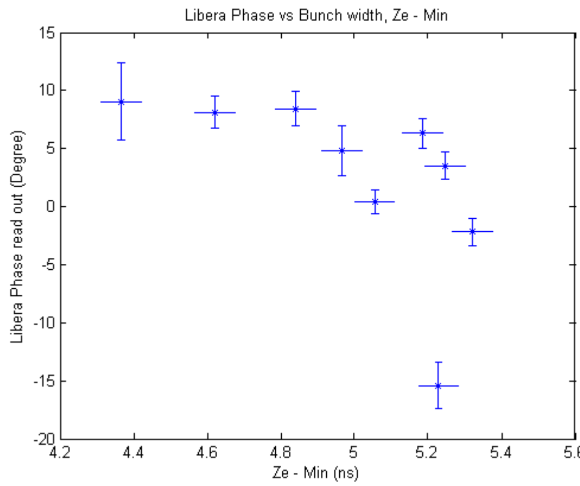


Fig. 23, Ze – Min with amplitude of higher than 0.9 V.

3. For the distance between the zero ending and the zero crossing points (Ze – Zc) and for the distance between the maximum and the zero starting points (Max– Zs), there is no corrolation.

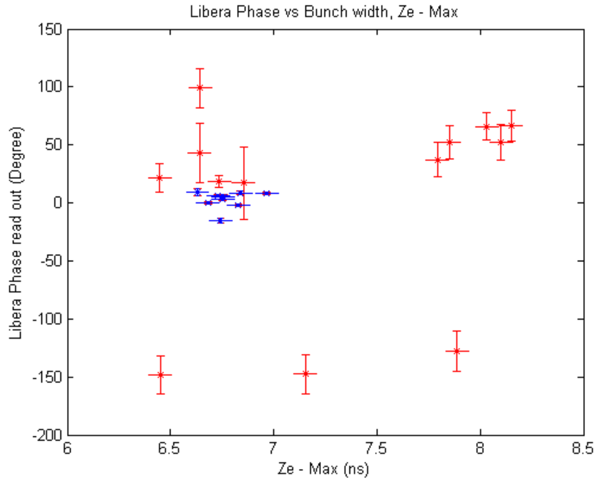


Fig. 24, Phase vs bunch width (Ze – Max).

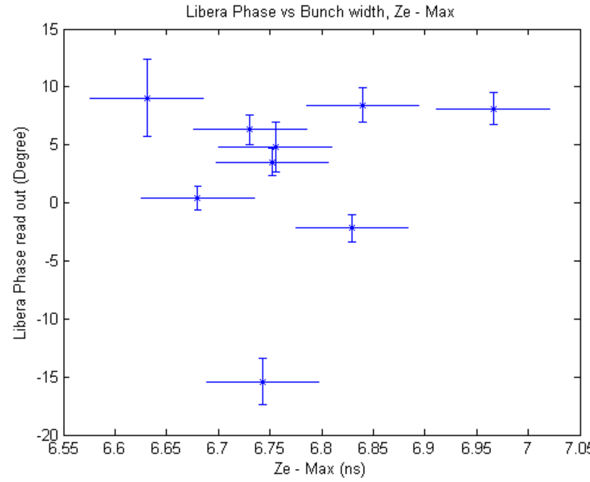


Fig. 25, Ze – Max with amplitude of higher than 0.9 V.

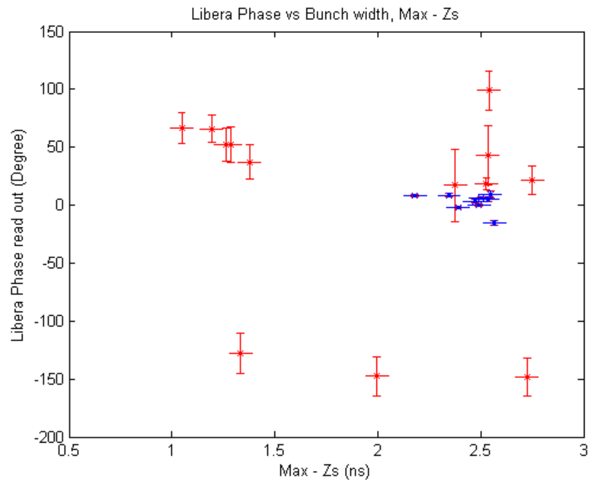


Fig. 26, Phase vs bunch width (Max– Zs).

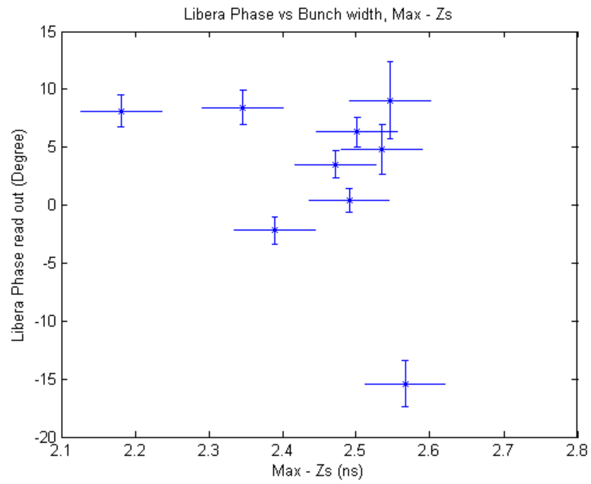


Fig. 27, Max– Zs with amplitude of higher than 0.9 V.

- Amplitude and Phase calculations

The amplitude and the phase spectrum are calculated using fourier transformation. Figure 28 shows linear relationship between the calculated amplitude and signal's amplitude recorded from the scope. Figures 29 and 30 show the calculated phase and signal's phase measured by Libera. The only correlation can be observed occurs for the first few shapes where the amplitudes are higher than 1.2 V. Figures 31 and 32 show similar relationship between the calculated phase and Zc – Zc (03) which represents the phase difference recorded by the scope. The amplitudes for 9 harmonics and the phase for all shapes are listed in table 4 and 5 respectivily. The third harmonic is highlighted.

From figures 33 and 34 and recalling figure 4, one can compare the calculated phase and the phase measured by Libera H in respect to the bunch amplitude.

shape No.	signal amp	1st (108) Harmonic	2nd (216) Harmonic	3rd (325) Harmonic	4th (433) Harmonic	5th (542) Harmonic	6th (650) Harmonic	7th (758) Harmonic	8th (867) Harmonic	9th (975) Harmonic
1	1.545	2359.89	2140.35	1507.72	756.26	379.45	125.10	61.55	25.43	15.78
2	1.529	2364.68	2163.56	1550.78	777.74	434.73	166.52	85.70	20.18	7.27
3	1.449	2152.80	2014.74	1477.46	759.45	447.69	176.93	92.24	37.50	15.75
4	1.340	2390.27	2014.62	1285.83	586.86	284.73	88.28	31.68	21.15	6.90
5	1.330	2291.23	1958.34	1176.23	365.47	114.89	120.37	99.15	50.45	20.27
6	1.235	2173.13	1761.25	869.11	208.39	277.79	203.76	83.21	11.51	13.39
7	1.169	1953.12	1725.72	1156.18	553.20	276.16	105.43	45.45	17.95	7.82
8	1.109	2245.51	1778.64	980.76	350.83	143.44	41.85	38.27	7.93	9.33
9	0.912	2166.14	1455.68	615.80	160.76	67.20	22.03	12.05	11.20	10.06
10	0.755	2015.77	1146.17	361.03	42.14	35.05	16.28	15.72	11.66	15.40
11	0.557	1699.41	775.25	202.12	31.74	32.73	11.90	14.20	14.33	3.28
12	0.433	1246.38	249.70	120.27	156.74	49.24	44.70	36.29	16.37	15.70
13	0.423	1549.02	278.06	21.98	54.36	37.09	11.90	29.92	14.81	12.30
14	0.417	1530.60	193.24	22.71	35.44	28.80	12.46	9.61	18.43	3.23
15	0.413	1144.68	277.83	153.75	167.22	67.88	19.45	21.63	13.11	4.47
16	0.404	1058.37	229.84	169.92	161.42	55.46	74.85	35.60	29.02	6.82
17	0.399	1423.55	385.11	72.53	16.40	12.06	15.12	3.83	7.36	17.11
18	0.397	967.62	273.93	173.10	183.05	56.55	34.07	40.11	23.00	10.81
19	0.388	915.48	246.38	157.06	173.21	66.43	50.93	30.72	12.71	10.69
20	0.382	1454.08	123.63	12.95	62.63	33.74	25.55	4.81	4.66	15.03
21	0.376	1296.58	131.95	114.72	96.13	28.84	28.59	6.55	6.54	8.24
22	0.338	1336.54	141.59	87.33	41.51	30.16	19.67	4.64	7.62	2.97

shape No.	Libera phase	1st (108) Harmonic	2nd (216) Harmonic	3rd (325) Harmonic	4th (433) Harmonic	5th (542) Harmonic	6th (650) Harmonic	7th (758) Harmonic	8th (867) Harmonic	9th (975) Harmonic
1	6.34	-127.92	165.11	109.73	53.83	-26.58	-103.23	174.17	90.13	79.46
2	3.53	-129.67	162.64	106.15	52.73	-27.05	-92.94	-167.94	158.93	23.40
3	-2.18	-131.73	158.05	99.13	42.62	-39.37	-111.65	178.53	102.45	-12.65
4	0.44	-129.65	163.56	108.71	56.91	-19.39	-88.49	-160.39	130.04	124.55
5	8.43	-127.46	164.52	108.49	48.03	-89.65	155.48	77.96	31.09	-52.06
6	8.13	-127.62	164.36	104.16	1.91	-145.32	148.76	74.90	162.91	78.61
7	-15.40	-43.84	29.67	91.42	150.41	-128.40	-46.81	32.41	90.48	-136.68
8	4.82	-131.62	160.43	104.40	54.58	-25.03	-106.99	155.68	129.63	-7.24
9	9.05	-132.46	158.19	103.16	53.11	-50.04	-126.23	-94.57	138.80	7.33
10	18.31	-134.69	156.10	102.99	26.55	-121.36	161.70	15.80	55.01	-18.45
11	21.89	-139.02	148.44	97.41	66.25	-21.40	100.87	9.43	143.67	8.08
12	37.41	-133.43	51.39	-89.22	92.39	-102.40	119.74	-62.28	121.29	-61.97
13	98.95	-133.15	169.00	173.41	154.52	-120.00	-170.78	111.89	110.38	-136.92
14	-148.10	-134.62	161.38	144.91	24.50	81.97	-28.47	72.10	-46.85	-144.98
15	52.00	-131.03	49.68	-86.74	109.83	-65.37	139.19	-34.66	113.83	-60.19
16	52.35	-128.84	57.69	-66.35	116.35	-74.32	166.55	-35.69	-120.78	-78.68
17	42.80	-137.96	159.75	125.42	41.56	132.66	175.99	10.32	68.80	-99.92
18	66.54	-130.08	52.60	-62.76	122.94	-61.14	154.93	-28.08	-152.67	11.07
19	65.90	-127.56	58.03	-52.59	134.57	-37.44	-164.59	4.07	-51.08	-113.75
20	-147.38	-134.93	87.97	-78.62	55.07	-6.69	42.51	-100.44	68.06	-129.88
21	-127.47	-129.74	32.16	-112.10	88.90	-122.16	56.14	57.02	82.37	-70.84
22	17.25	-139.28	122.75	1.84	-130.48	168.45	-8.67	17.44	138.10	47.11

Table 4, Up: calculated amplitudes to 9the harmonic. Table 5, Down: calculated phases to 9the harmonic.

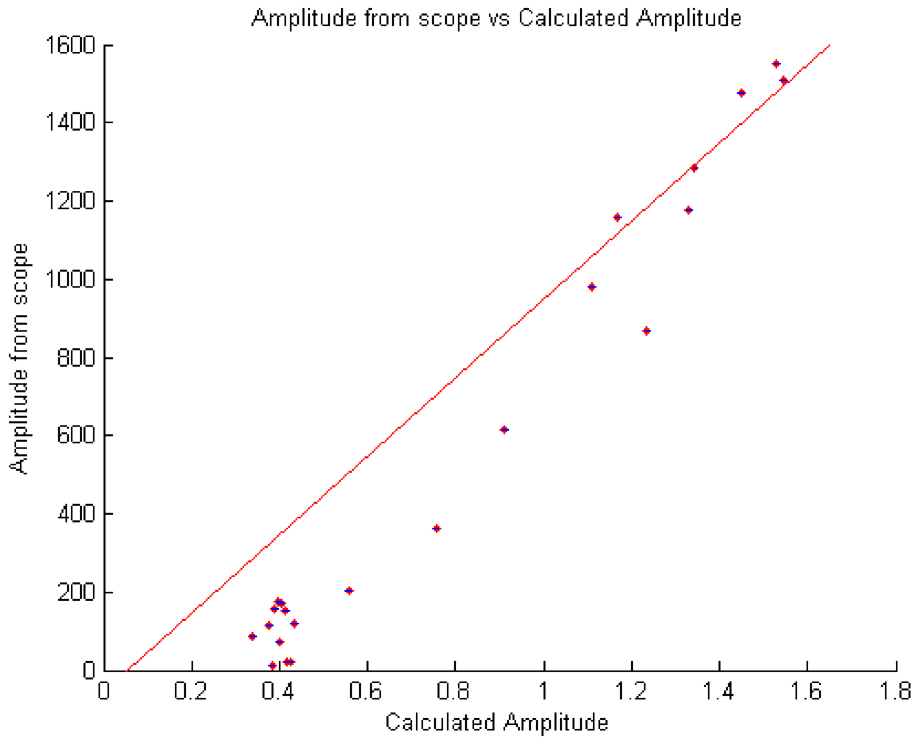


Fig. 28, Calculated amplitude vs recorded amplitude from the scope.

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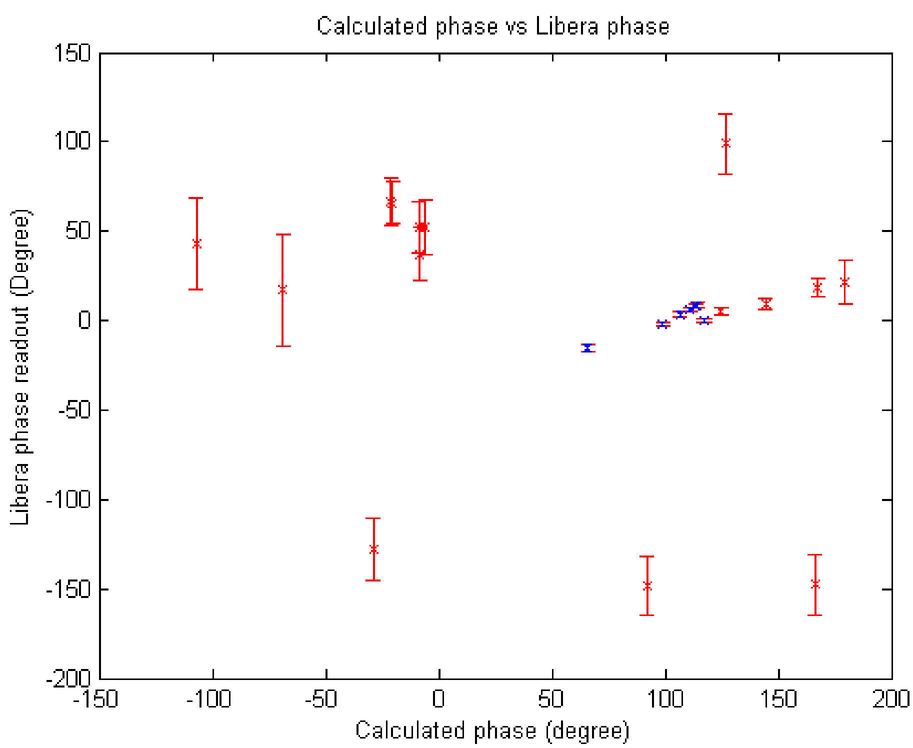


Fig. 29, Calculated phase and signal's phase measured by Libera H.

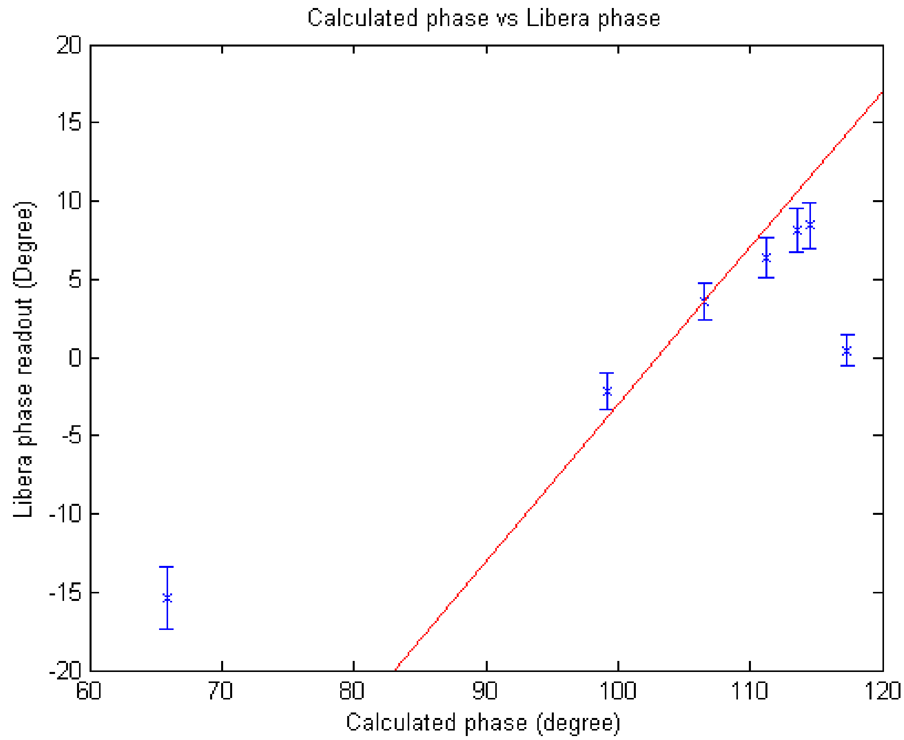


Fig. 30, Calculated phase and signal's phase measured by Libera with an amplitude of higher than 1.15 V.

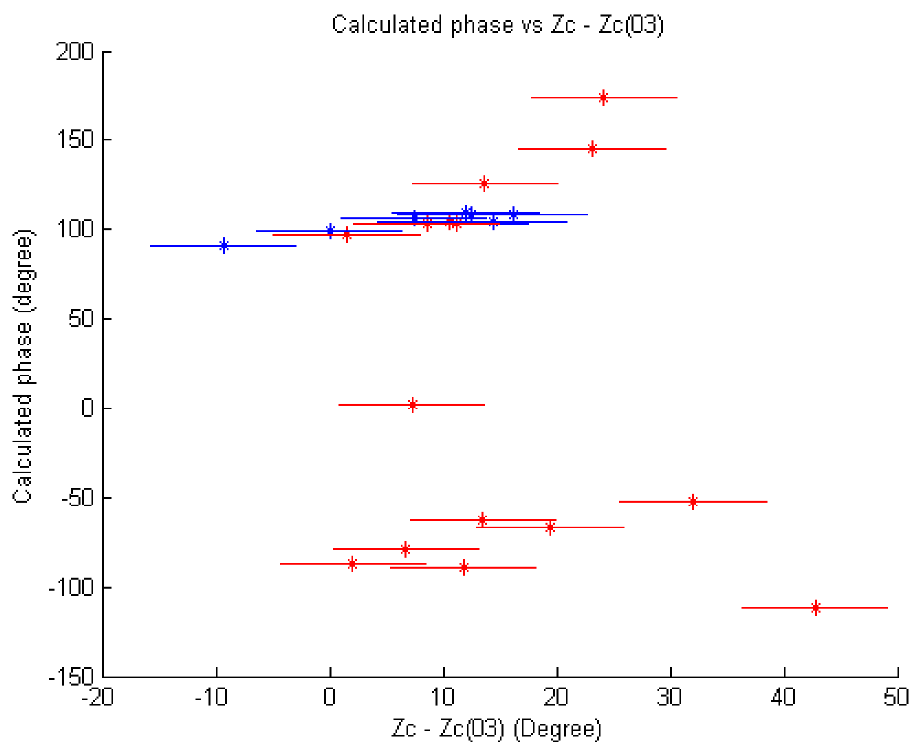


Fig. 31, Calculated phase versus the phase difference Zc – Zc (03).

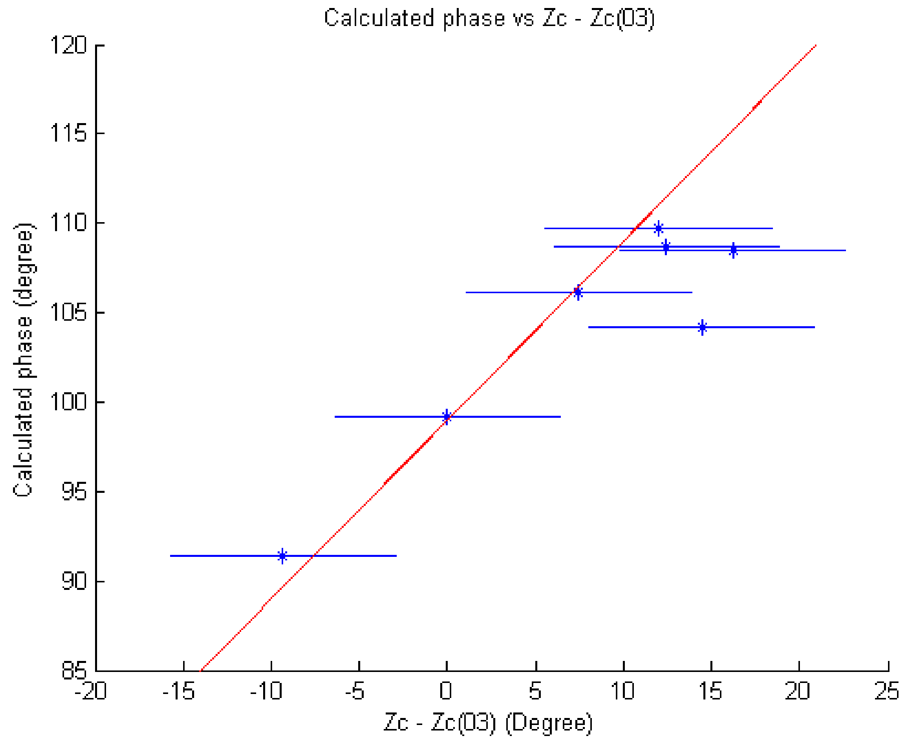


Fig. 32, Calculated phase versus Zc – Zc (03) with an amplitude of higher than 1.2 V.

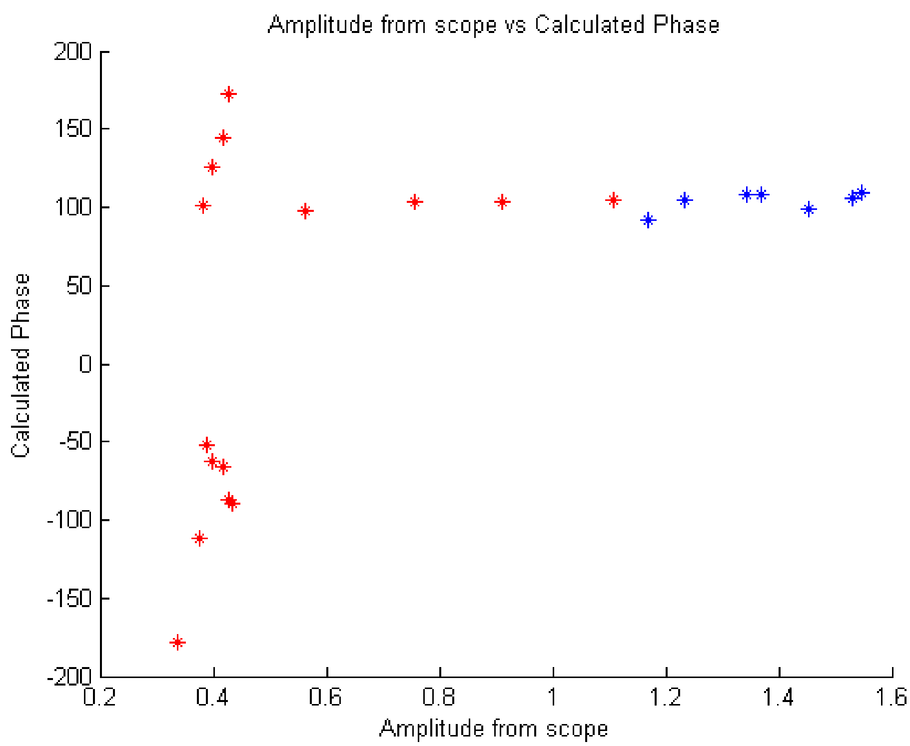


Fig. 33, Calculated phase vs amplitude from scope.

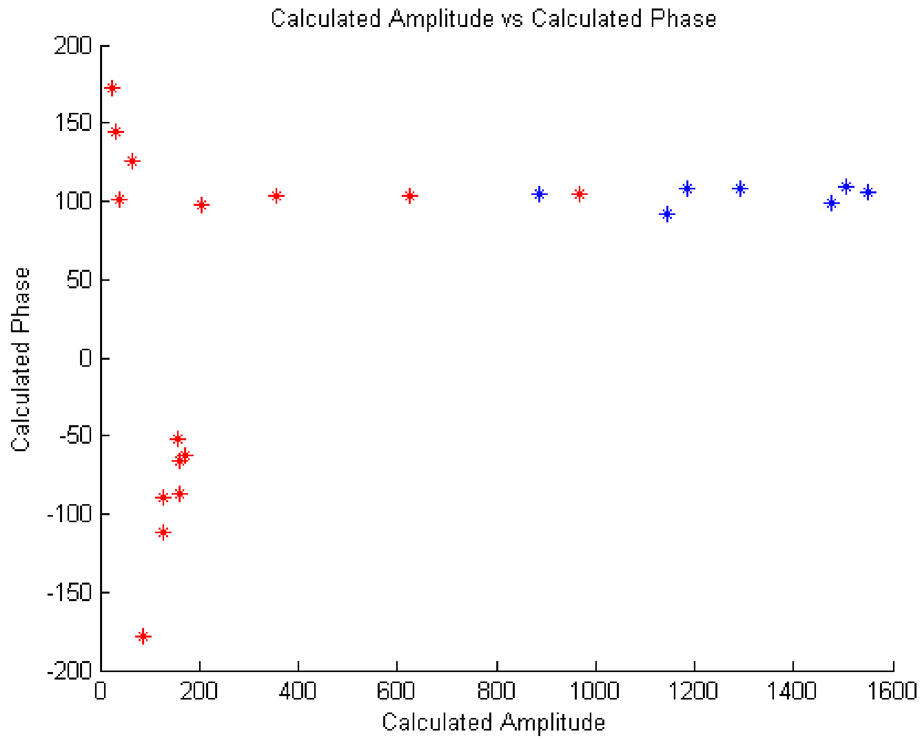


Fig. 34, Calculated phase vs calculated amplitude.

➢ Bunch position calculations

Table 6 contains the measured amplitudes by Libera Single Pass H from four electrodes a, b, c and d and their standard deviations. H and V (eqs. 2 and 4) and the bunch position (eqs. 3 and 5) are calculated and listed in table 7. Eqs 6 and 7 are used to calculate the standard deviation for H and V. Figure. 35 and 36 show H and bunch position in horizontal axis versus bunch amplitude. Figure. 37 and 38 show V and bunch position in vertical axis versus bunch amplitude. The standard deviation increases as the bunch amplitudes become smaller as it shown in figures 39 and 40.

Shape No.	Signal amp	PU (a)	std (a)	PU (b)	std (b)	PU (c)	std (c)	PU (d)	std (d)
1	1.545	172530.4	4368.1	121832.6	4062.2	169161.1	6020.0	106710.7	11105.1
2	1.529	173782.1	4601.6	139588.4	4252.0	169025.5	5189.5	134808.6	11017.7
3	1.449	141346.0	6802.2	127012.9	6761.2	147712.8	10559.9	133584.2	23249.8
4	1.340	154919.6	4564.5	137376.4	4202.0	133852.6	5734.8	140255.1	9985.6
5	1.330	170784.0	4522.8	108433.7	4781.5	166869.0	6599.6	88304.4	11584.6
6	1.235	168881.9	4613.3	106811.6	4064.7	165203.7	5799.2	86591.5	10991.2
7	1.169	75137.3	4531.5	105490.5	5687.1	146623.3	7430.8	105269.4	17717.8
8	1.109	101165.1	4367.7	89382.6	4321.4	76155.3	5357.1	95830.0	10312.6
9	0.912	69740.0	4098.4	58295.9	4397.1	50041.9	4864.5	67359.7	9968.1
10	0.755	44720.1	4408.2	34948.0	4741.0	32859.2	5361.7	43964.3	12370.1
11	0.557	24780.1	5169.3	20003.9	4407.9	24800.6	5415.0	31881.4	13267.7
12	0.433	44334.8	4284.0	10669.4	3573.9	16886.7	5238.1	9830.2	9184.8
13	0.423	12799.3	4953.5	8053.2	3487.5	15158.9	4772.6	12163.1	9520.6
14	0.417	12333.0	4654.4	9029.5	3706.8	12074.8	4913.9	9450.5	8740.2
15	0.413	62565.3	4348.2	12301.6	3992.3	26833.0	5982.6	10450.4	9578.4
16	0.404	62331.2	4315.3	12003.7	3962.9	26779.4	5741.6	10639.0	10278.3
17	0.399	19152.9	5095.3	9016.9	4794.5	14773.7	6221.0	21957.1	14650.8
18	0.397	72242.9	4706.1	13601.5	3693.4	41188.8	4926.4	9701.2	8670.5
19	0.388	72234.2	4554.4	13766.4	4135.6	40790.8	5602.5	10146.0	8506.4
20	0.382	12135.9	4757.3	9425.9	3908.8	13127.4	5075.3	9921.1	8541.6
21	0.376	14399.7	4734.4	9426.0	3728.4	12191.9	4909.9	10587.7	8782.9
22	0.338	21072.8	5282.7	5407.6	3101.4	9827.8	5197.8	13535.5	8924.0

Table 6&7

Shape No.	Signal amp (V)	H	std (H)	V	std (V)	X (mm)	Y(mm)
1	1.545	0.0099	0.0218	0.0662	0.0519	0.0986	0.6617
2	1.529	0.0139	0.0202	0.0174	0.0430	0.1388	0.1742
3	1.449	-0.0220	-0.0435	-0.0252	-0.0929	-0.2203	-0.2522
4	1.340	0.0730	0.0254	-0.0104	-0.0390	0.7295	-0.1037
5	1.330	0.0116	0.0237	0.1023	0.0640	0.1159	1.0232
6	1.235	0.0110	0.0222	0.1045	0.0609	0.1101	1.0455
7	1.169	-0.3224	-0.0412	0.0010	0.0883	-3.2236	0.0105
8	1.109	0.1410	0.0394	-0.0348	-0.0604	1.4104	-0.3481
9	0.912	0.1645	0.0538	-0.0721	-0.0869	1.6445	-0.7213
10	0.755	0.1529	0.0905	-0.1143	-0.1690	1.5289	-1.1426
11	0.557	-0.0004	-0.1510	-0.2289	-0.2764	-0.0041	-2.2892
12	0.433	0.4483	0.1211	0.0409	0.4812	4.4834	0.4093
13	0.423	-0.0844	-0.2469	-0.2033	-0.5118	-0.8440	-2.0330
14	0.417	0.0106	0.2773	-0.0228	-0.5139	0.1058	-0.2278
15	0.413	0.3997	0.0891	0.0814	0.4576	3.9970	0.8136
16	0.404	0.3990	0.0868	0.0603	0.4874	3.9896	0.6027
17	0.399	0.1291	0.2390	-0.4178	-0.5394	1.2908	-4.1778
18	0.397	0.2738	0.0623	0.1674	0.4101	2.7377	1.6737
19	0.388	0.2782	0.0663	0.1514	0.4001	2.7820	1.5140
20	0.382	-0.0392	-0.2756	-0.0256	-0.4857	-0.3925	-0.2560
21	0.376	0.0830	0.2574	-0.0580	-0.4776	0.8303	-0.5804
22	0.338	0.3639	0.2552	-0.4291	-0.5427	3.6391	-4.2907

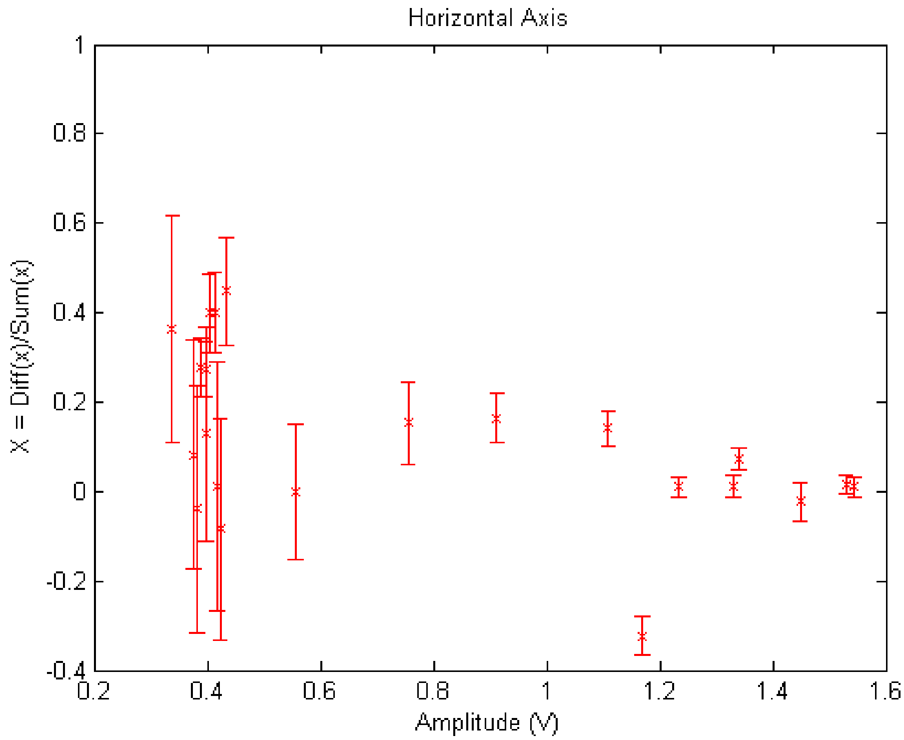


Fig. 35, H versus bunch amplitude.

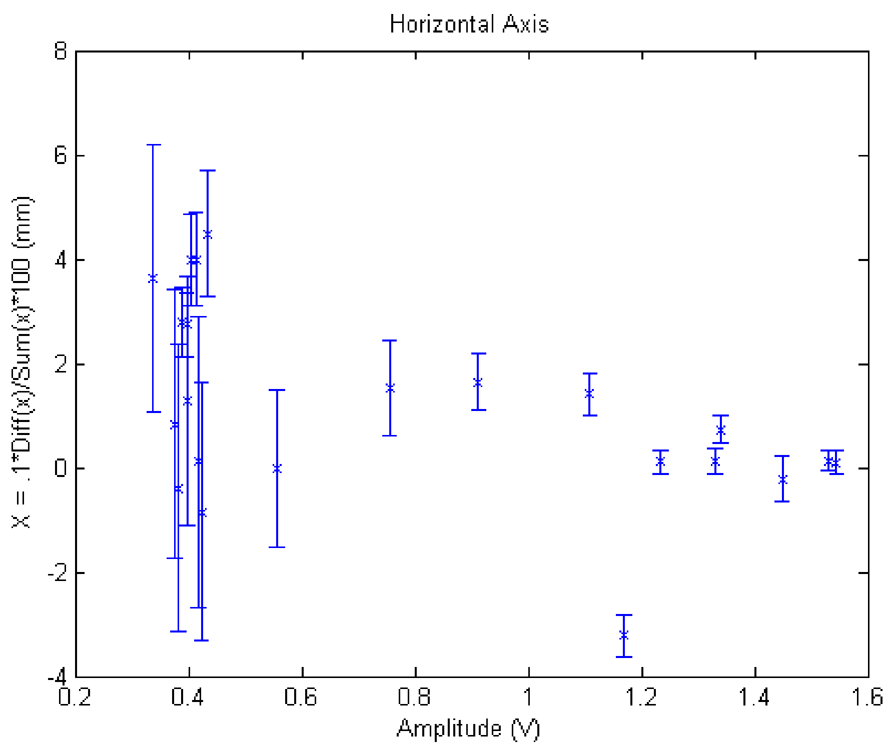


Fig. 36, Bunch position in horizental axis versus bunch amplitude.

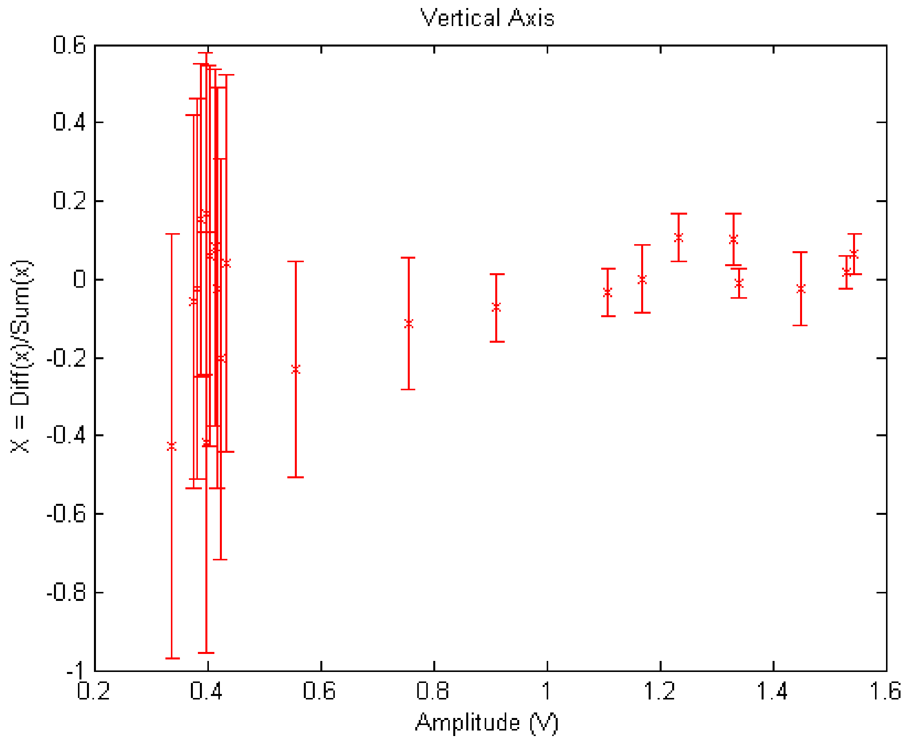


Fig. 37, V versus bunch amplitude.

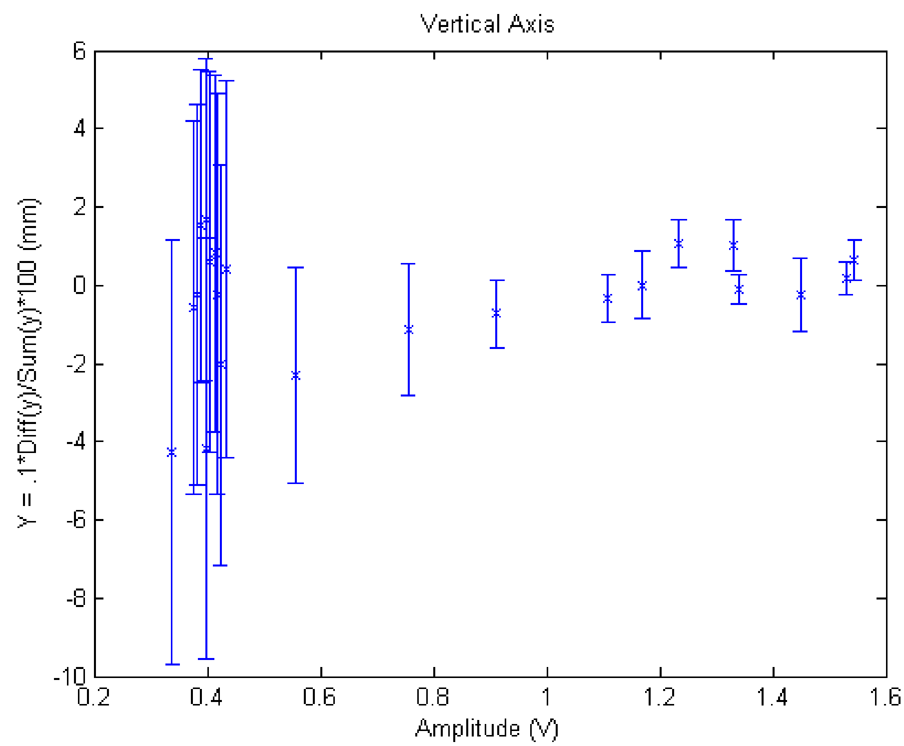


Fig. 38, Bunch position in vertical axis versus bunch amplitude.

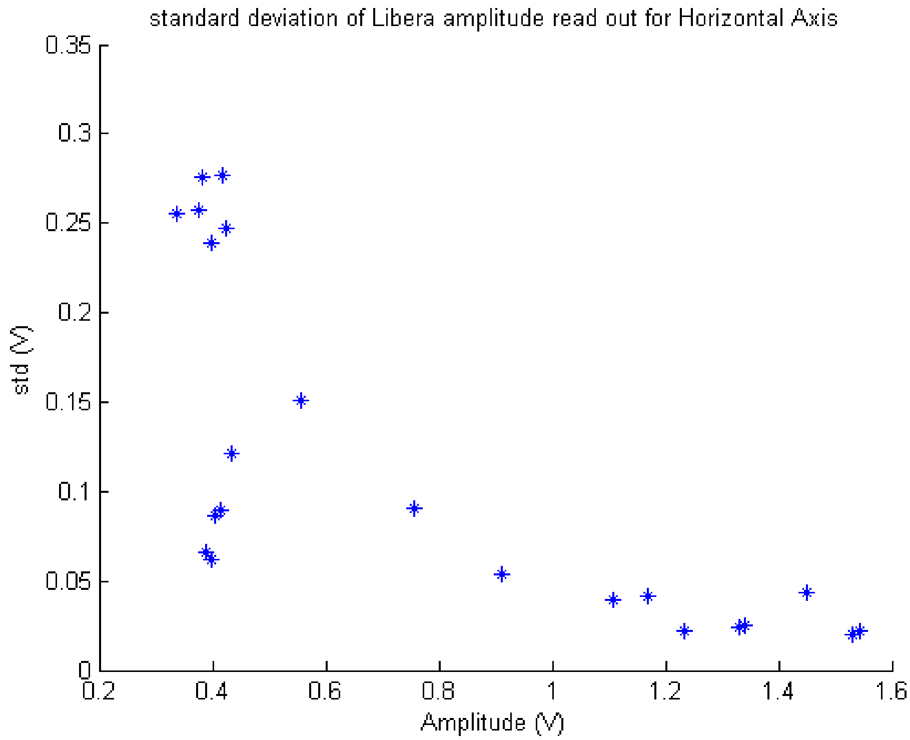


Fig. 39, The standard deviation in horizental axis versus bunch amplitude.

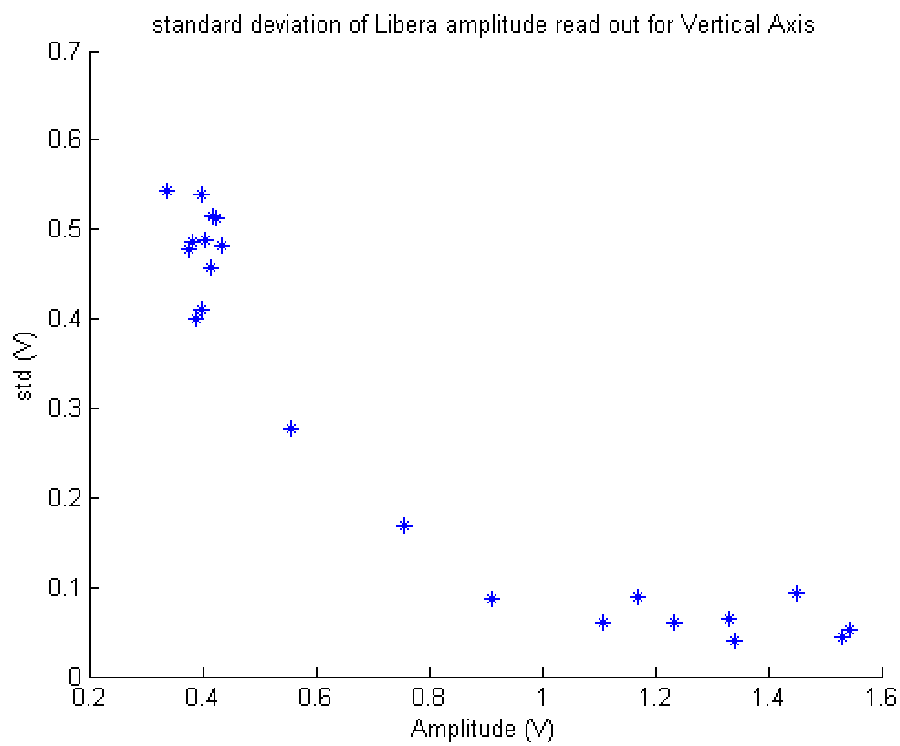


Fig. 40, The standard deviation in vertical axis versus bunch amplitude.

➢ Conclusion

For the given beam parameters and a varying bunch shape, the results of the first measurements show typically phase response achieved over the input amplitude of range 0.9 to 1.5 V with standard deviation of $1^{o} – 3.3^{o}$. In this range a correlation of the Libera phase reading and the time domain measurements by the oscilloscope is visible, but a linear function can not be fitted to data with the anticipated accuracy.

The fluctuation of the phase readout increases drastically with varying bunch width. Even though there is some correlation between the width read by the oscilloscope and Libera Single Pass H readout, a linear dependence can not be observed. Therefore, it can be concluded that " Libera Single Pass H" serves for phase measurement of bunchs with an amplitude over than 0.9 V. The time domain processing leads to a different arrival time compared to the phase evaluation for various bunch shapes.

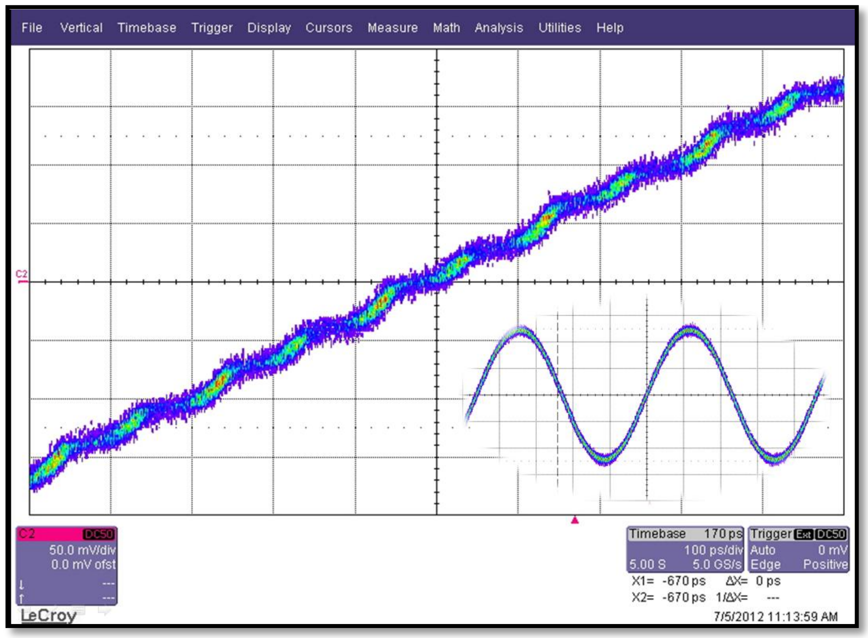
The third harmonic calculations for amplitude spectrum show linear dependency between the calculated amplitude and signal’s amplitude recorded from the scope as long as the signal amplitude not too low – below 0.5 V. On the other hand, a linear function can only be fitted for the third harmonic calculation for phase spectrum to the signal’s phase measured by Libera when the amplitude is high enough - more than 1.15 V.

Beam position calculations show an offset from the center in some shapes. The standard deviation increases steadily to hit a factor of 12 between the higher and the lower amplitudes measured during the experiment (0.33 → 1.54 V).

The applied bunch shape changes reduce not only input signal peak voltage, but also the frequency content drastically changes. In the first plot of "Signal (03&22)" the blue trace shows almost a sine signal at 108 MHz with negligible harmonics. Such a signal has to be processed with a "Libera Single Pass H" unit configured for signal processing of 108 MHz component. The limit of validity of the 325 MHz processing is defined not by the signal amplitude, but the signal frequency content.

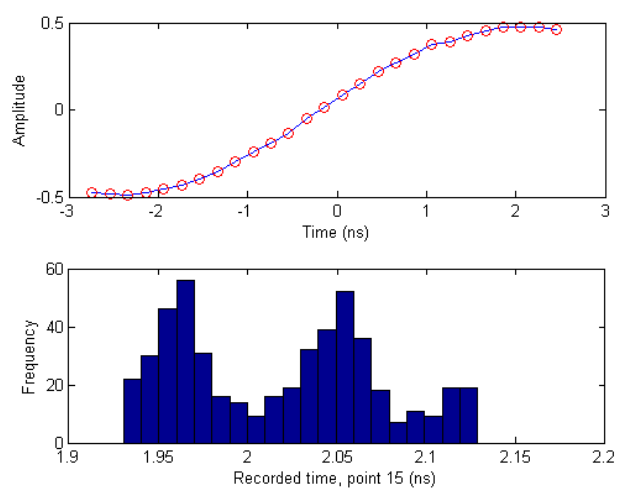
➢ Appendix

1 – In order to know how precise the recorded values by the dedicated scope for the input signal, the error bar of trigger jitter, shown in picture 1, is measured.



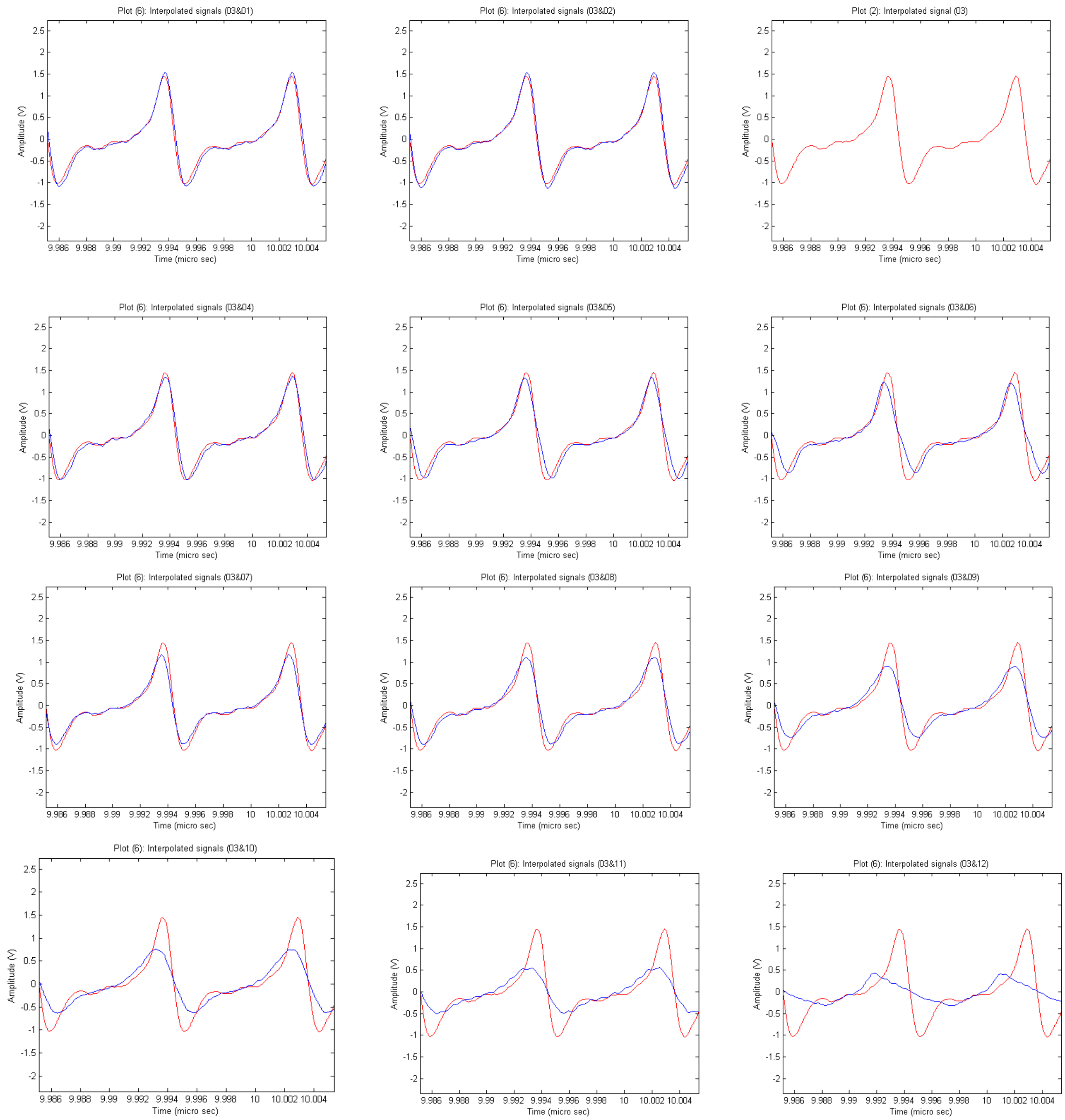
Picture, 1. Screenshot of the trigger jitter for 108.408 MHz signal displyed on a 5 GS/s ossilloscope (LeCory Waverunner 6200A)

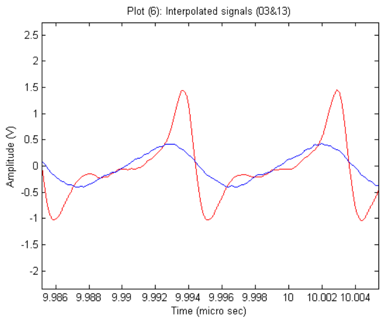
Using 500 readings, each contains time and amplitude values for a signal as shown in the upper plot in picture 2. The standard deviation is calculated for each sample individually. The histogram of only one point is shown in the lower part in picture 2. The standard deviation of the recorded sampling time (σ) is 54.53 ps. Similarly, the standard deviation for the recorded amplitude gives 0.0131 V.

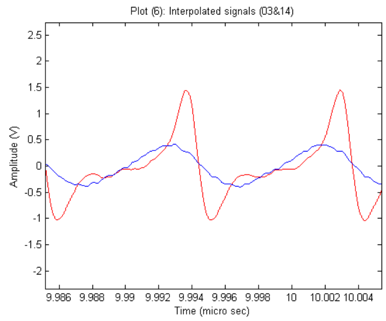


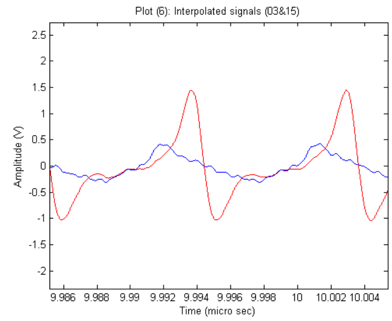
Picture, 2. (Up) plot of 27 samping points for signal @ 108.408 MHz. (Down). Histogram of reading values for one sample.

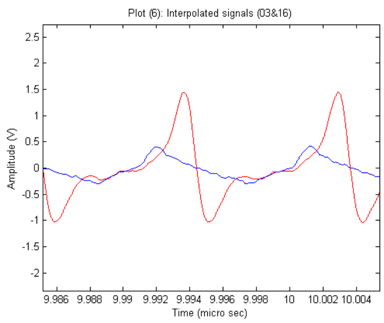
2 – the 22 different shape generated and studied.

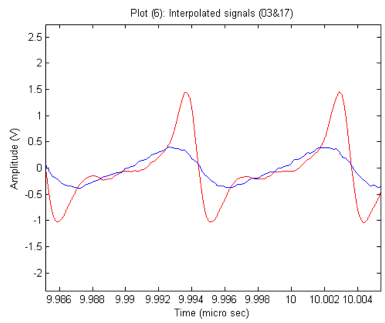


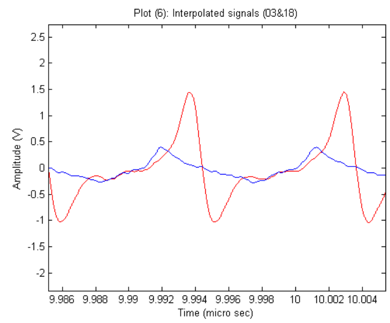

Plot (6): Interpolated signals (03&13)
Amplitude (V)
Time (micro sec)

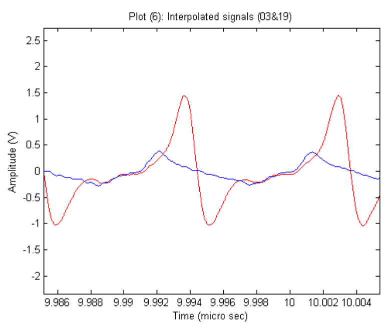

Plot (6): Interpolated signals (03&14)
Amplitude (V)
Time (micro sec)

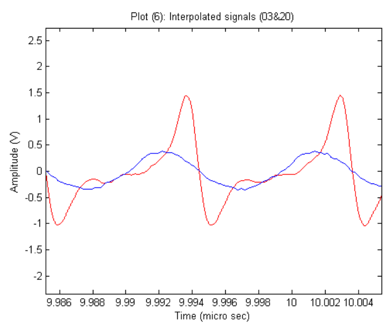

Plot (6): Interpolated signals (03&15)
Amplitude (V)
Time (micro sec)

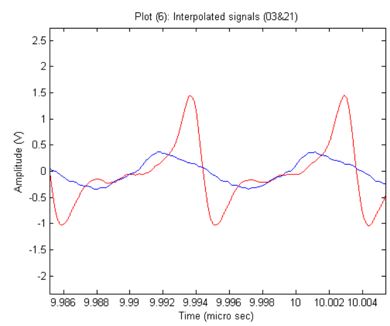

Plot (6): Interpolated signals (03&16)
Amplitude (V)
Time (micro sec)

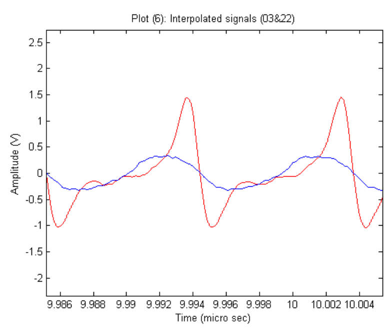

Plot (6): Interpolated signals (03&17)
Amplitude (V)
Time (micro sec)


Plot (6): Interpolated signals (03&18)
Amplitude (V)
Time (micro sec)


Plot (6): Interpolated signals (03&19)
Amplitude (V)
Time (micro sec)


Plot (6): Interpolated signals (03&20)
Amplitude (V)
Time (micro sec)


Plot (6): Interpolated signals (03&21)
Amplitude (V)
Time (micro sec)


Plot (6): Interpolated signals (03&22)
Amplitude (V)
Time (micro sec)