Noise reduction technique in APD time resolution measurement

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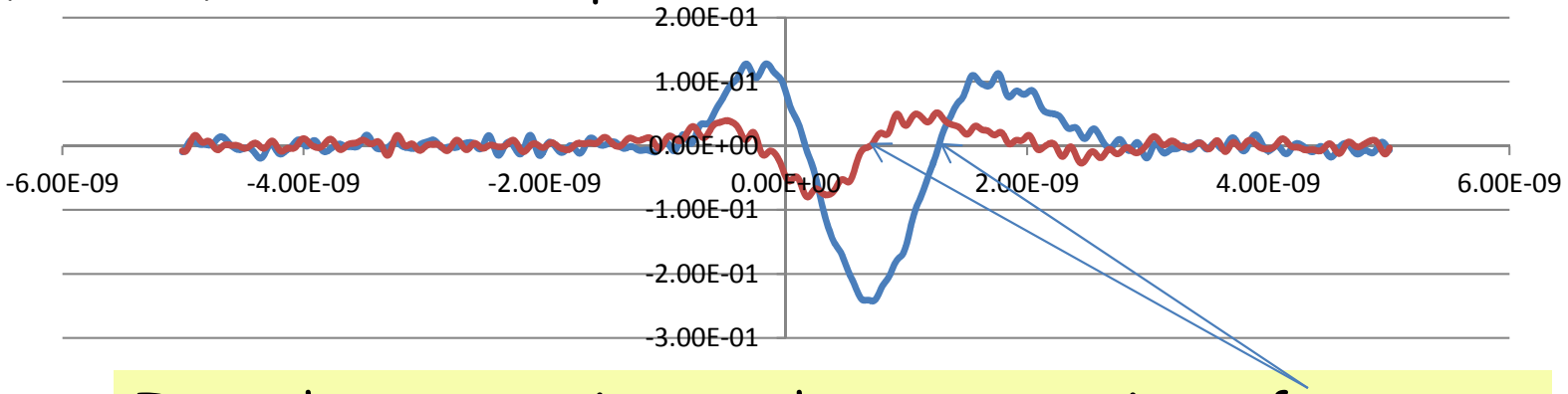
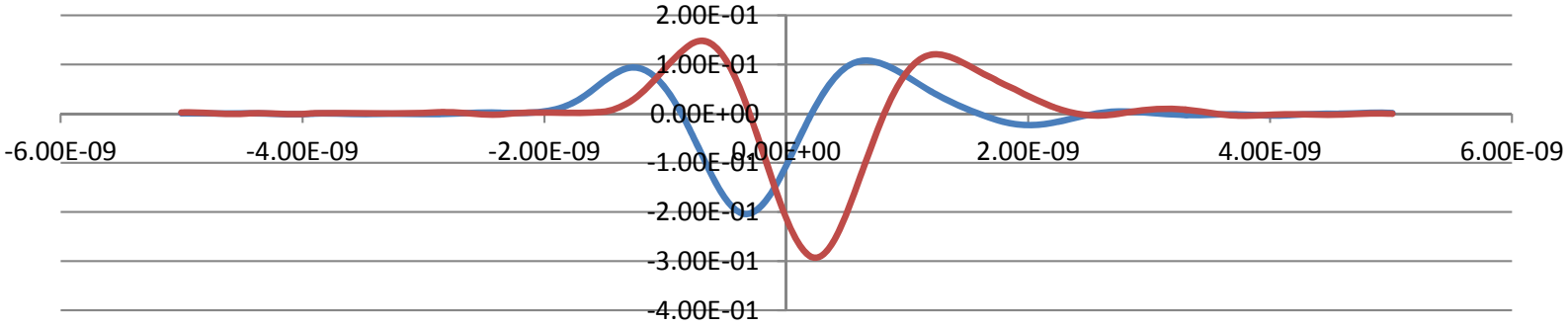
Digital scope in high resolution mode

Agilent digital scope has a "High Resolution Mode", which performs box-car averaging, averaging adjacent samples within a single capture of a waveform. This averaging provides lower noise and higher (vertical) resolution samples for the waveform.



Normal resolution mode, full BW @ 4GHz, sampling rate 20 GSa/sec.

I use these two points as the zero crossing references.



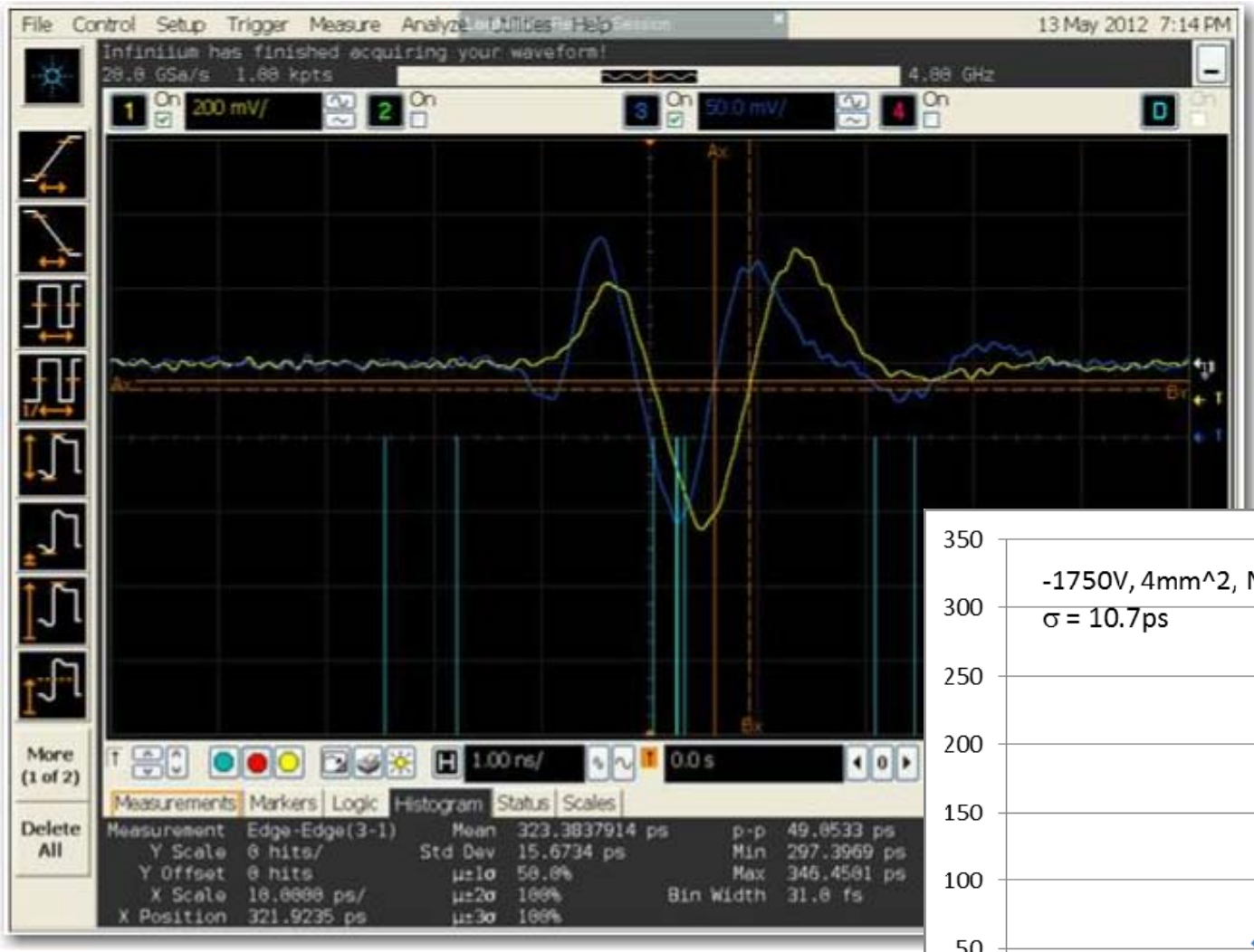
High resolution mode, BW reduced to 1.1 GHz, sampling rate reduced to 5 GSa/sec.

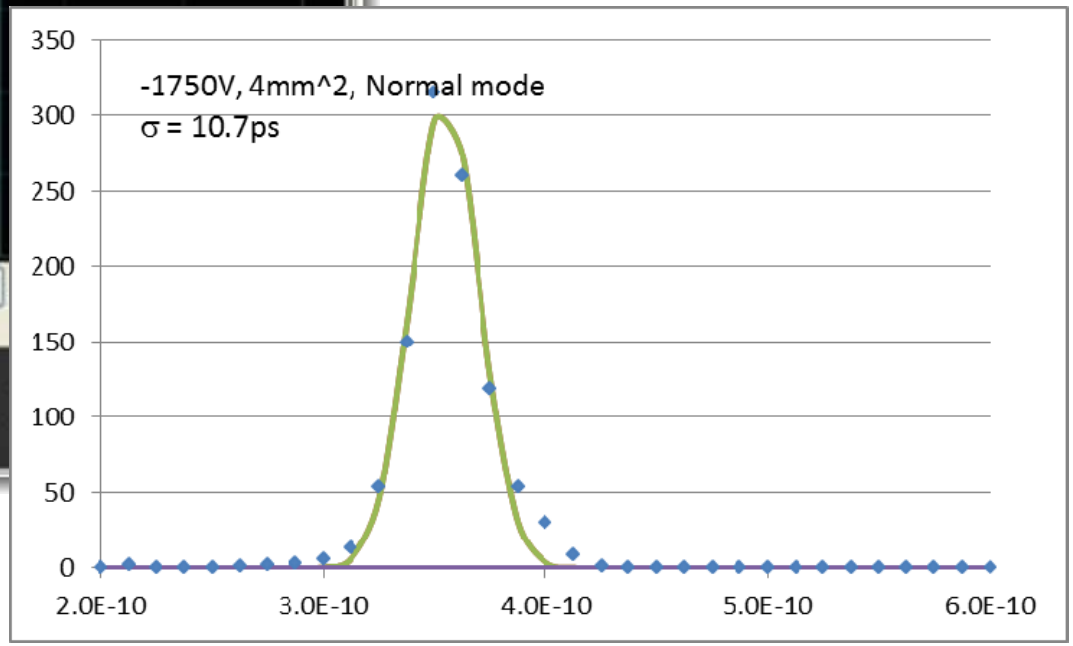
Time resolution with high resolution mode

Waveform data files are available here:
http://physics.princeton.edu/babar/fasttiming/05122012/4mm/1750V/
There are three subdirectories: ../No smooth; ../9bits and ../10bits, they are for three resolution modes. The data analysis results are as follows:

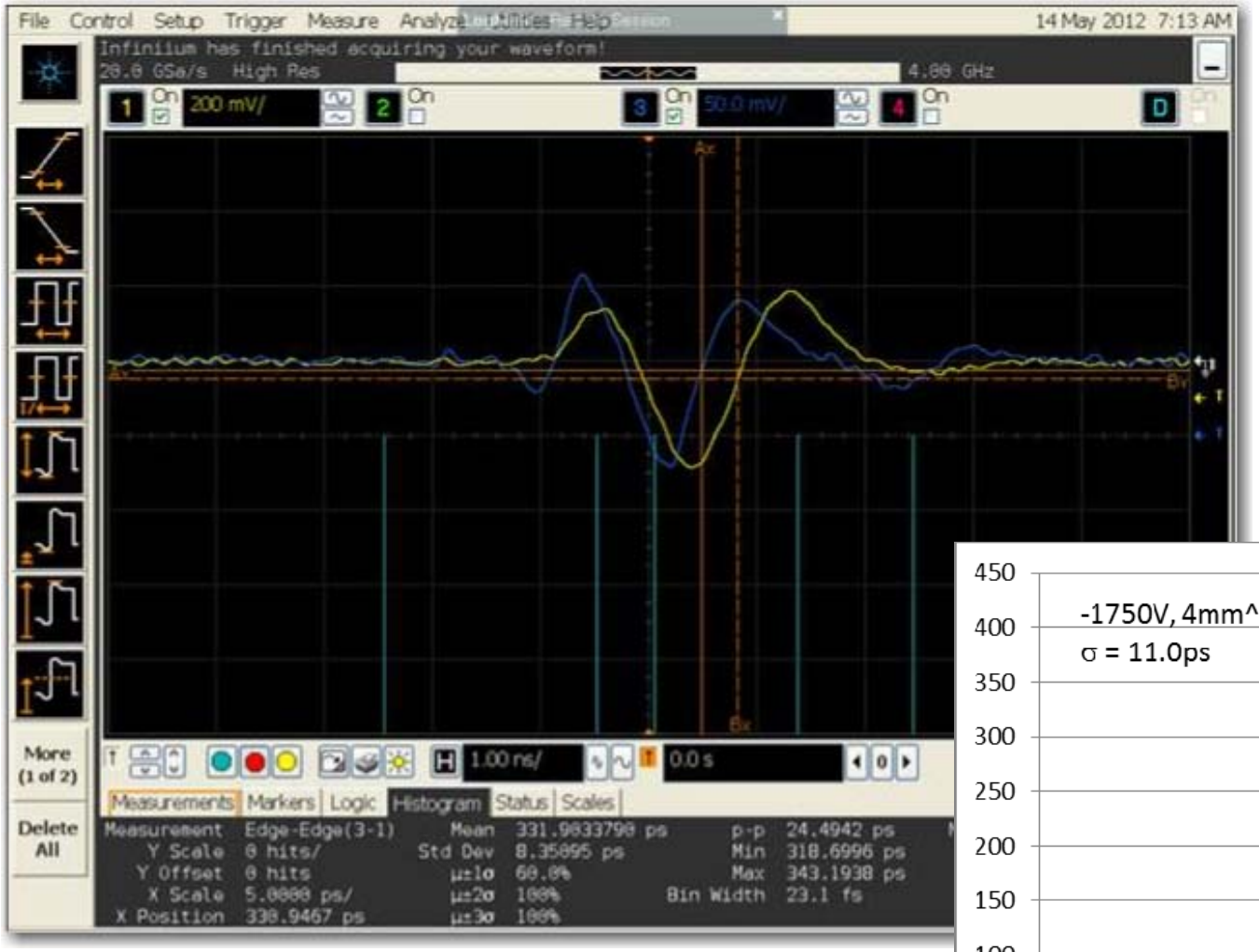
Scope Mode	Band width	Sampling rate	Single APD time resolution (ps)
Normal	4GHz	20Gsa/sec	10.7
9 bit	4GHz	20GSa/sec	9.9
10 bit	1.12GHz	5GSa/sec	8.3

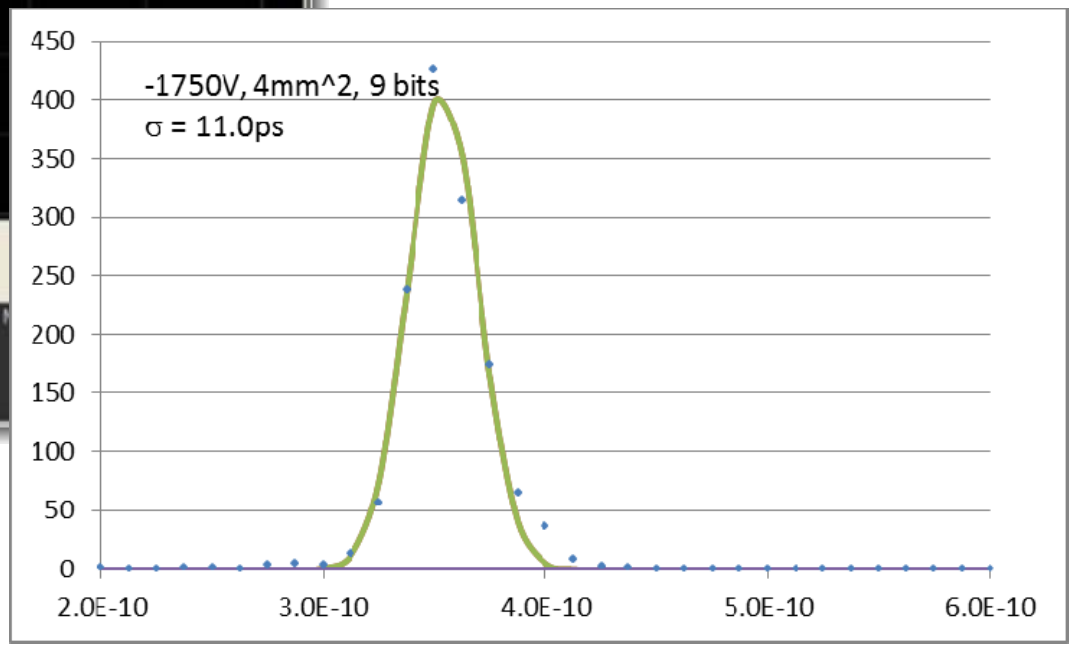
Normal mode


File Control Setup Trigger Measure Analyze Utilities Help
13 May 2012 7:14 PM
Infiniium has finished acquiring your waveform!
20.0 GSa/s 1.00 kpts
4.00 GHz
200 mV/
50.0 mV/
More (1 of 2)
Delete All
1.00 ns/
0.0 s
Measurements Markers Logic Histogram Status Scales
Measurement Edge-Edge(3-1)
Y Scale 0 hits/
Y Offset 0 hits
X Scale 10.0000 ps/
X Position 321.9235 ps
Mean 323.3837914 ps
Std Dev 15.6734 ps
µ±1σ 50.0%
µ±2σ 100%
µ±3σ 100%
p-p 49.0533 ps
Min 297.3969 ps
Max 346.4501 ps
Bin Width 31.0 fs

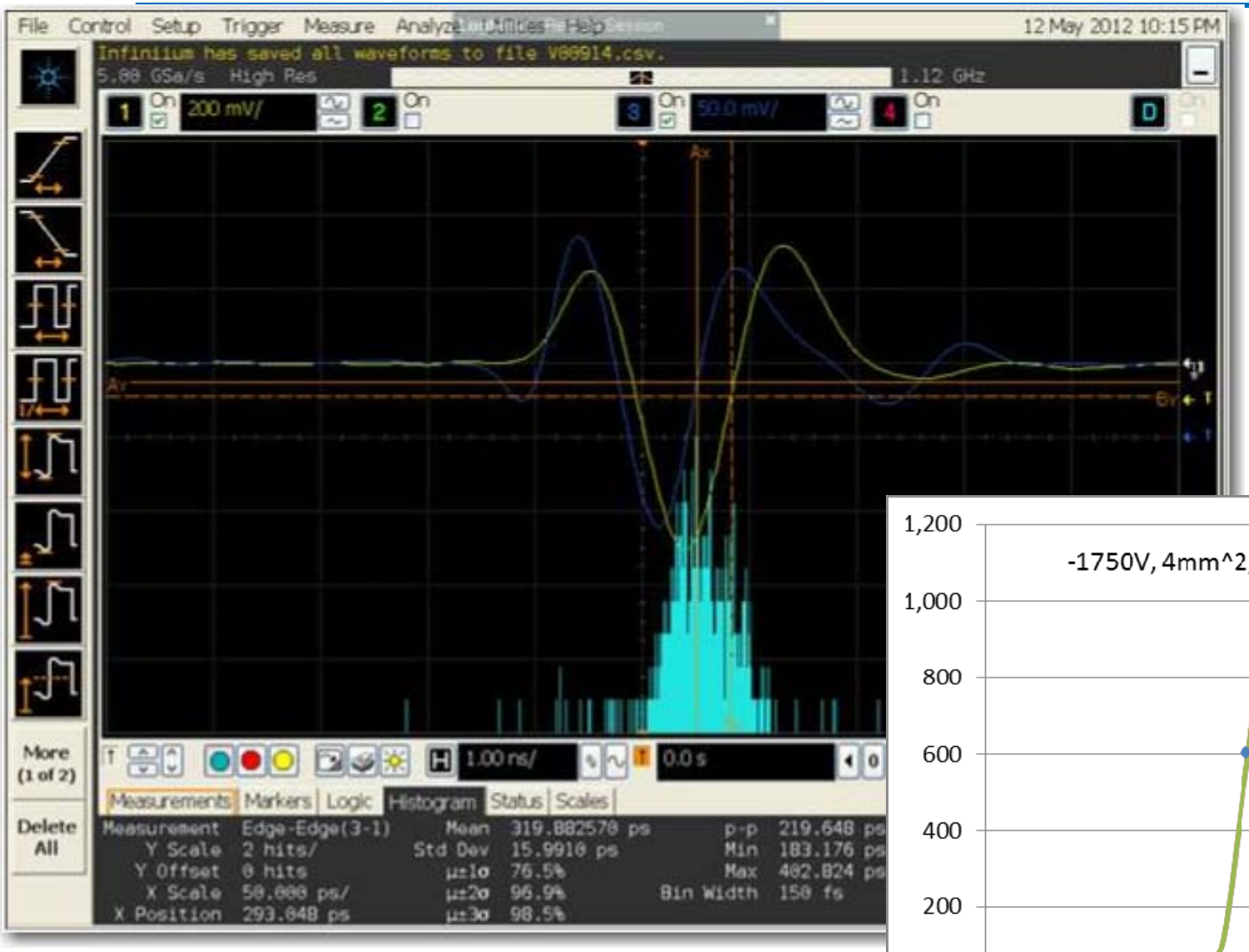

-1750V, 4mm^2, Normal mode
σ = 10.7ps
350
300
250
200
150
100
50
0
2.0E-10
3.0E-10
4.0E-10
5.0E-10
6.0E-10

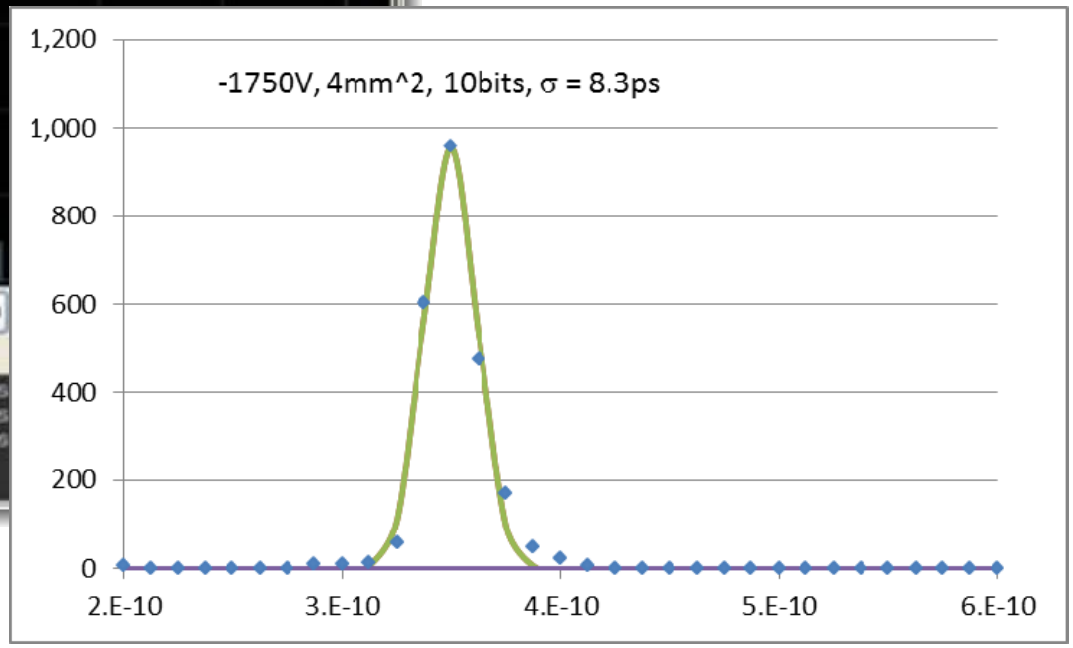
9 bit mode


File Control Setup Trigger Measure Analyze Utilities Help
14 May 2012 7:13 AM
Infiniium has finished acquiring your waveform!
20.0 GSa/s High Res
4.00 GHz
1 On 200 mV/ 2 On 3 On 50.0 mV/ 4 On D
More (1 of 2)
Delete All
1.00 ns/
0.0 s
Measurements Markers Logic Histogram Status Scales
Measurement Edge-Edge(3-1)
Y Scale 0 hits/
Y Offset 0 hits
X Scale 5.0000 ps/
X Position 330.9467 ps
Mean 331.9833790 ps
Std Dev 8.35095 ps
μ±1σ 68.0%
μ±2σ 100%
μ±3σ 100%
p-p 24.4942 ps
Min 318.6996 ps
Max 343.1938 ps
Bin Width 23.1 fs

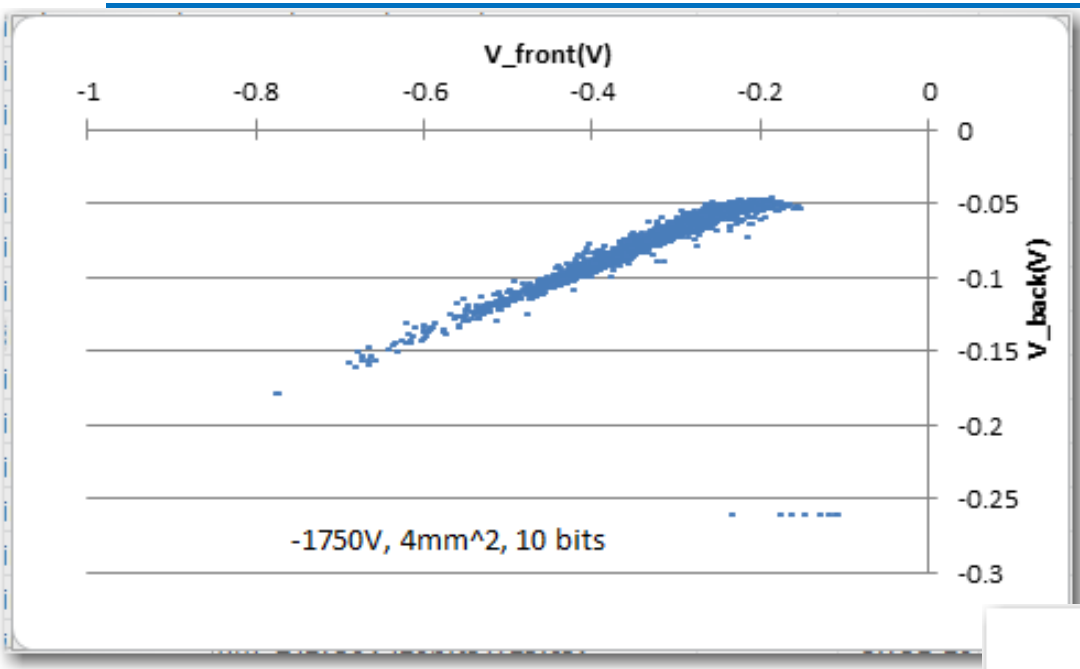

-1750V, 4mm^2, 9 bits
σ = 11.0ps
450
400
350
300
250
200
150
100
50
0
2.0E-10
3.0E-10
4.0E-10
5.0E-10
6.0E-10

10 bit mode

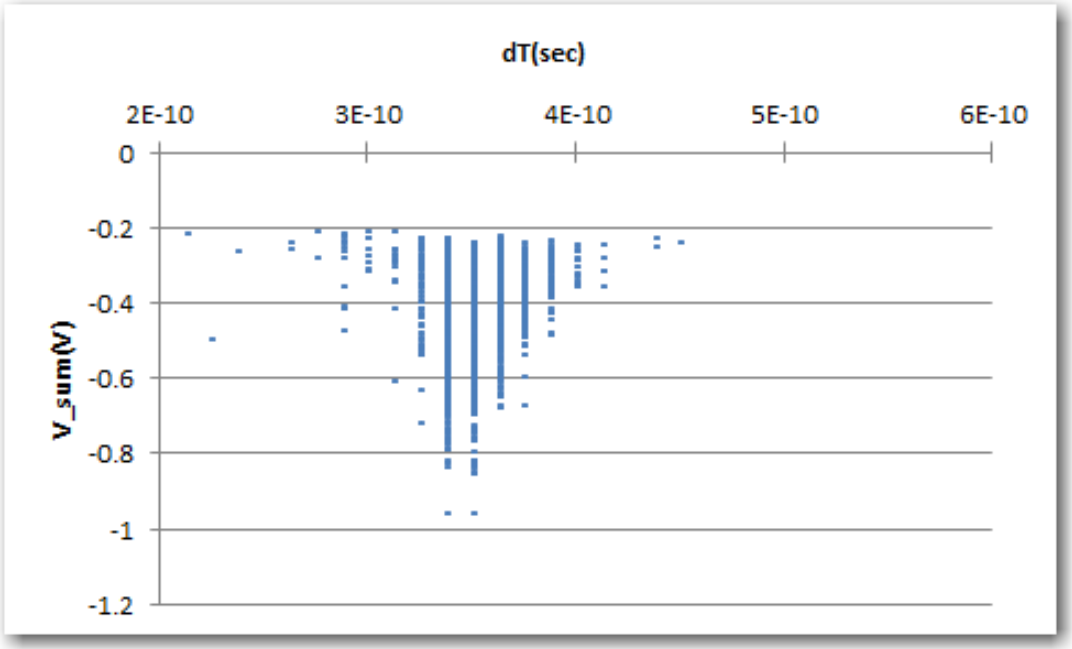

File Control Setup Trigger Measure Analyze Utilities Help Session
12 May 2012 10:15 PM
Infiniium has saved all waveforms to file V00914.csv.
5.00 GSa/s High Res
1.12 GHz
1 On 200 mV/
2 On
3 On 50.0 mV/
4 On
D
More (1 of 2)
Delete All
1.00 ns/
0.0 s
Measurements Markers Logic Histogram Status Scales
Measurement Edge-Edge(3-1)
Y Scale 2 hits/
Y Offset 0 hits
X Scale 50.000 ps/
X Position 293.048 ps
Mean 319.882570 ps
Std Dev 15.9910 ps
µ±1σ 76.5%
µ±2σ 96.9%
µ±3σ 98.5%
p-p 219.648 ps
Min 183.176 ps
Max 402.824 ps
Bin Width 150 fs


-1750V, 4mm^2, 10bits, σ = 8.3ps
1,200
1,000
800
600
400
200
0
2.E-10
3.E-10
4.E-10
5.E-10
6.E-10

10 bit mode



Scatter plot of two APD's signal amplitudes



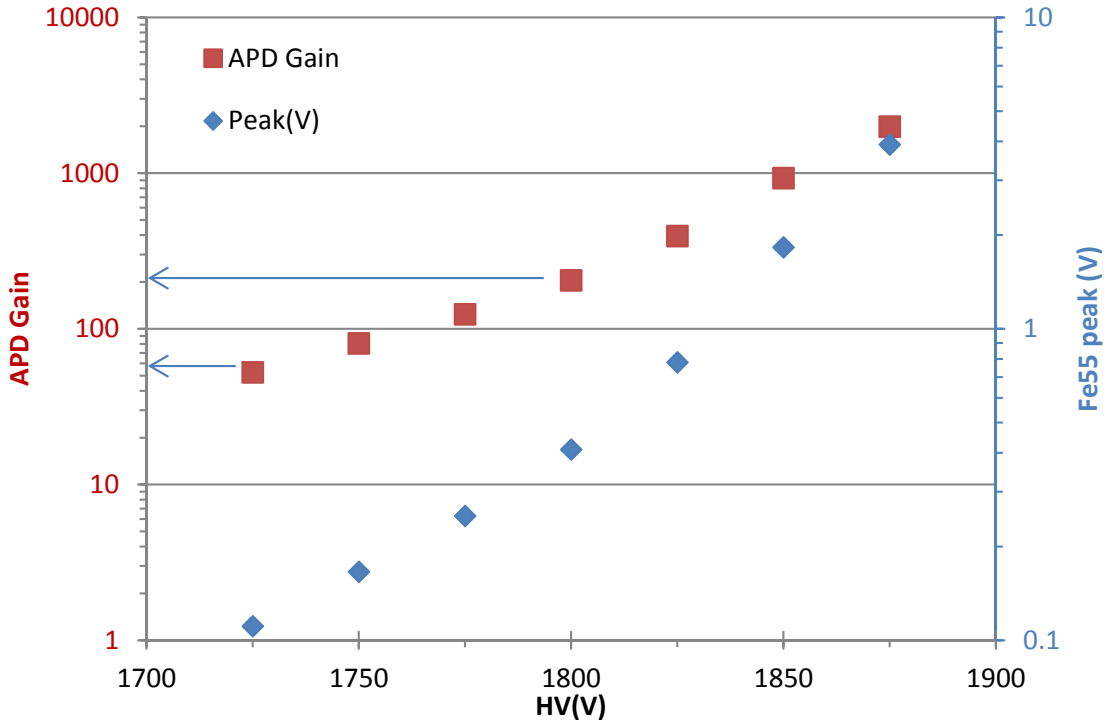
Scatter plot of dT vs. sum of two APDs signals.

Summary

H.V. (V)	Resolution mode	Time resolution (ps)
-1800V	Normal	15.3
	9 bit	13.7
	10 bit	12.9
-1775V	Normal	12.9
	9 bit	10.8
	10 bit	9.7
-1750V	Normal	10.7
	9 bit	9.9
	10 bit	8.3
-1725V	Normal	10.96
	9 bit	9.4
	10 bit	7.1

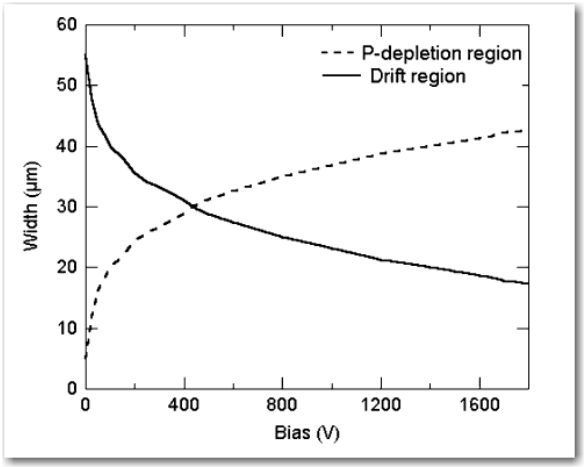
Discussion

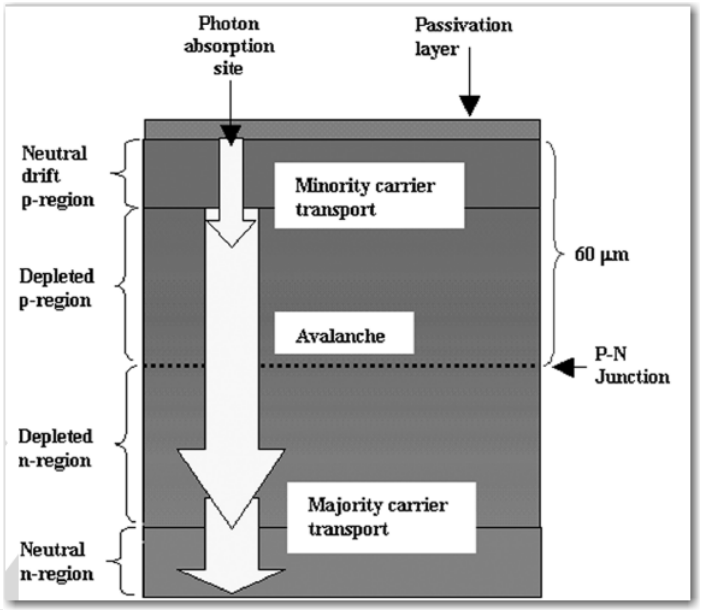
We have calibrated the APD gain with Fe-55 source. At 1725 V and 1800 V the APD gains are ~ 50 and ~ 200, respectively.

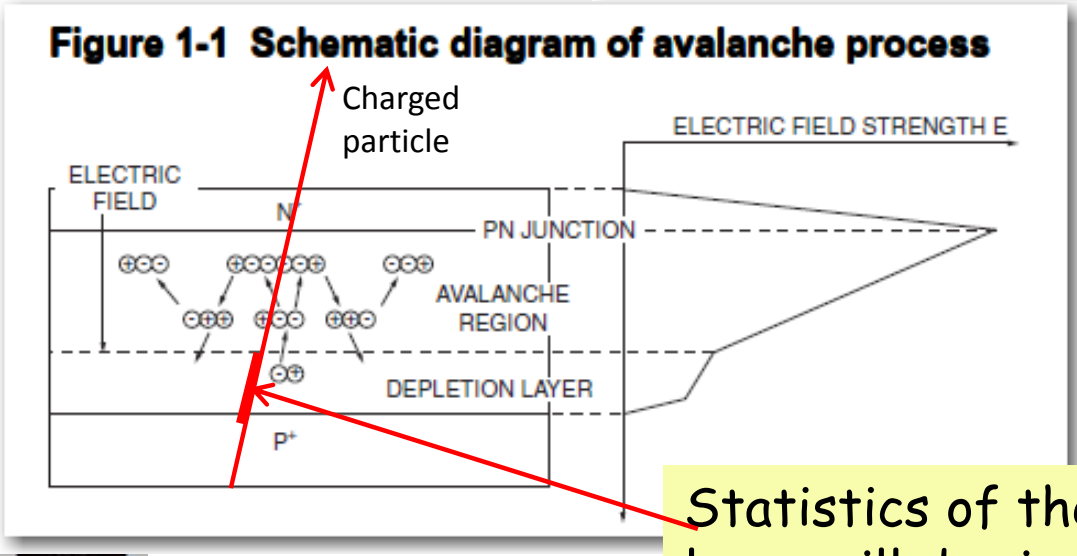


We saw the trend of lower HV corresponding to better time resolution. As the trigger condition are fixed for all these tests, at lower high voltage the events passing the trigger need to have larger primary e/hole pairs, that might reduce the primary statistical error.

Discussion (cont'd)







Typical electron mobility in silicon at room temperature is 1400 cm^2 /(V*s).
At ~ 1800 V, the P-depletion region is ~ 30 μm.
The APD avalanche multiplication starts at electric field strength ~ $2x10^5$ V/cm, if we assume the E-field in the depletion region is 1/3 of this number, it would be ~$7x10^4$ V/cm.
The total drift time range across the P-depletion region would be $30x10^{-4}$ cm/ ($1400x7x10^4$cm/s) = ~ 30 ps.
This will contribute to the intrinsic time resolution of the APD.

Statistics of the primary ionization in this layer will dominate the time resolution.