IP BPM resolution study results

N. Blaskovic

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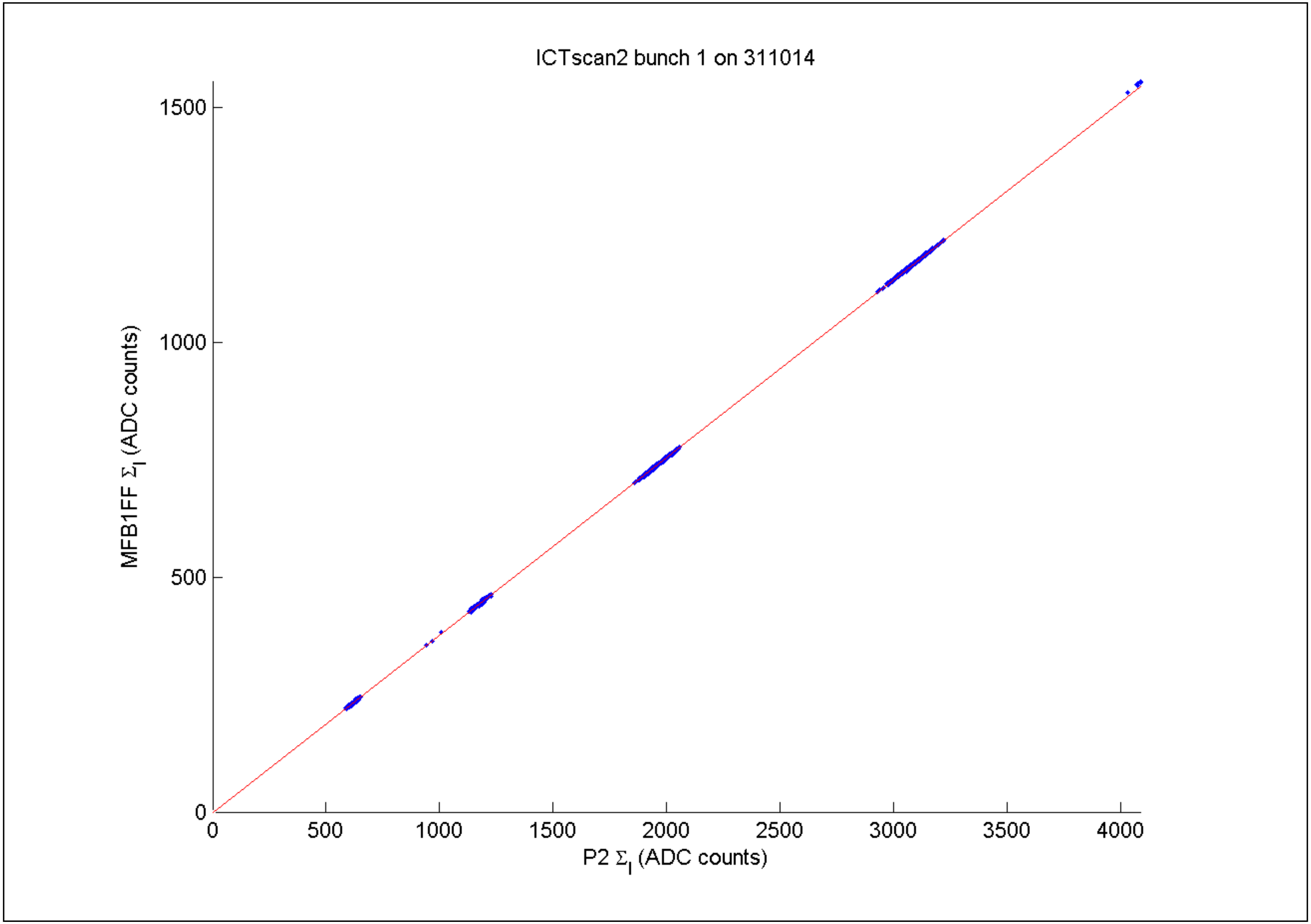
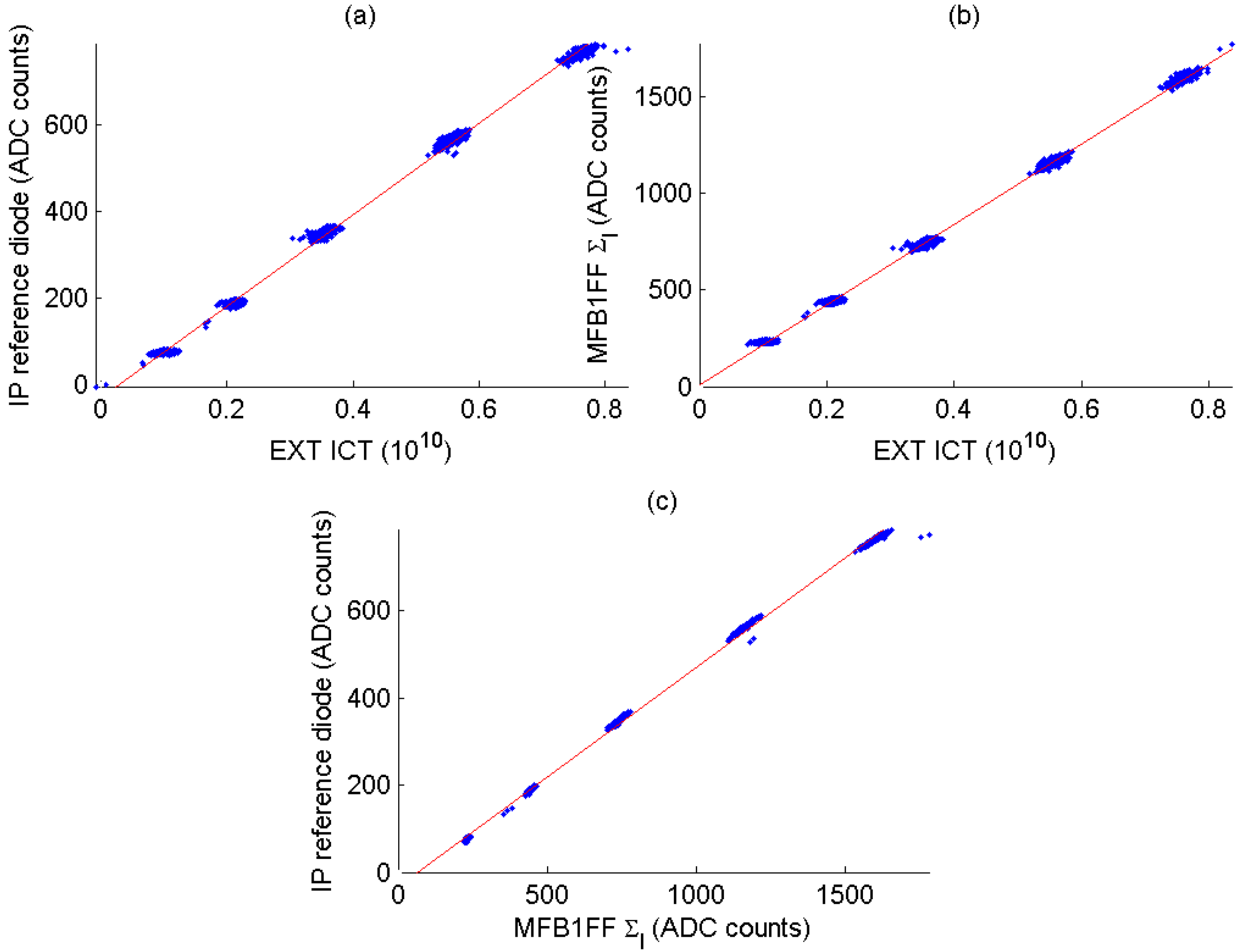
Charge information

- Correlation between:
  - P2 Σ_I (with no stripline attenuation)
  - MFB1FF Σ_I (with 6 dB stripline attenuation)
- Correlation between:
  - MFB1FF Σ_I (with 6 dB stripline attenuation)
  - IP reference diode
  - EXT ICT (0.047×10^{10} pedestal removed)


ICTscan2 bunch 1 on 311014
MFB1FF Σ_I (ADC counts)
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500
4000
P2 Σ_I (ADC counts)

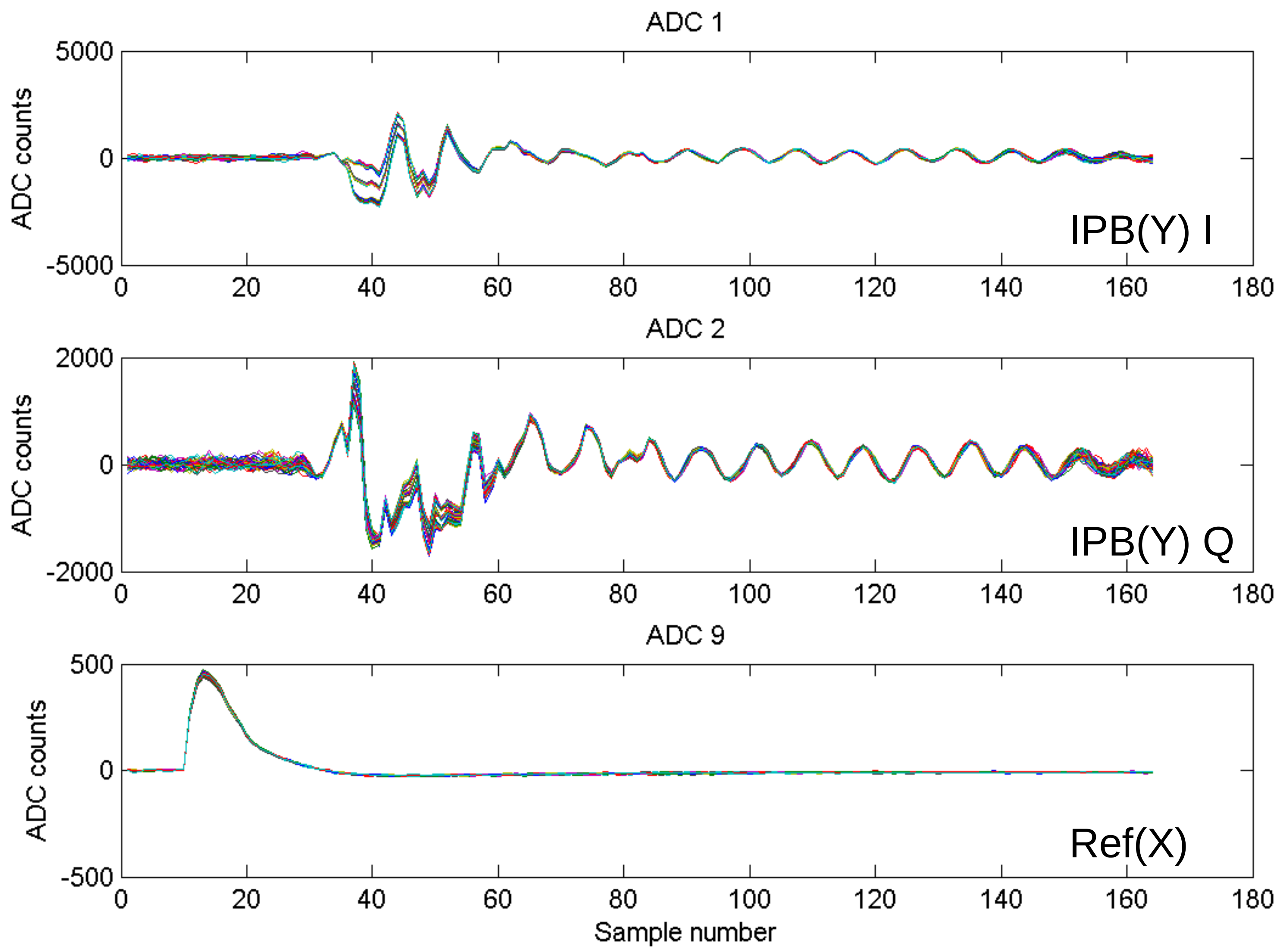
Pedestal subtracted MFB1FF Sigma_I vs. IP reference diode vs. EXT ICT
using triggers 1 to 2500 for fit for ICTscan2 bunch 1 on 311014



Waveforms over calibrations

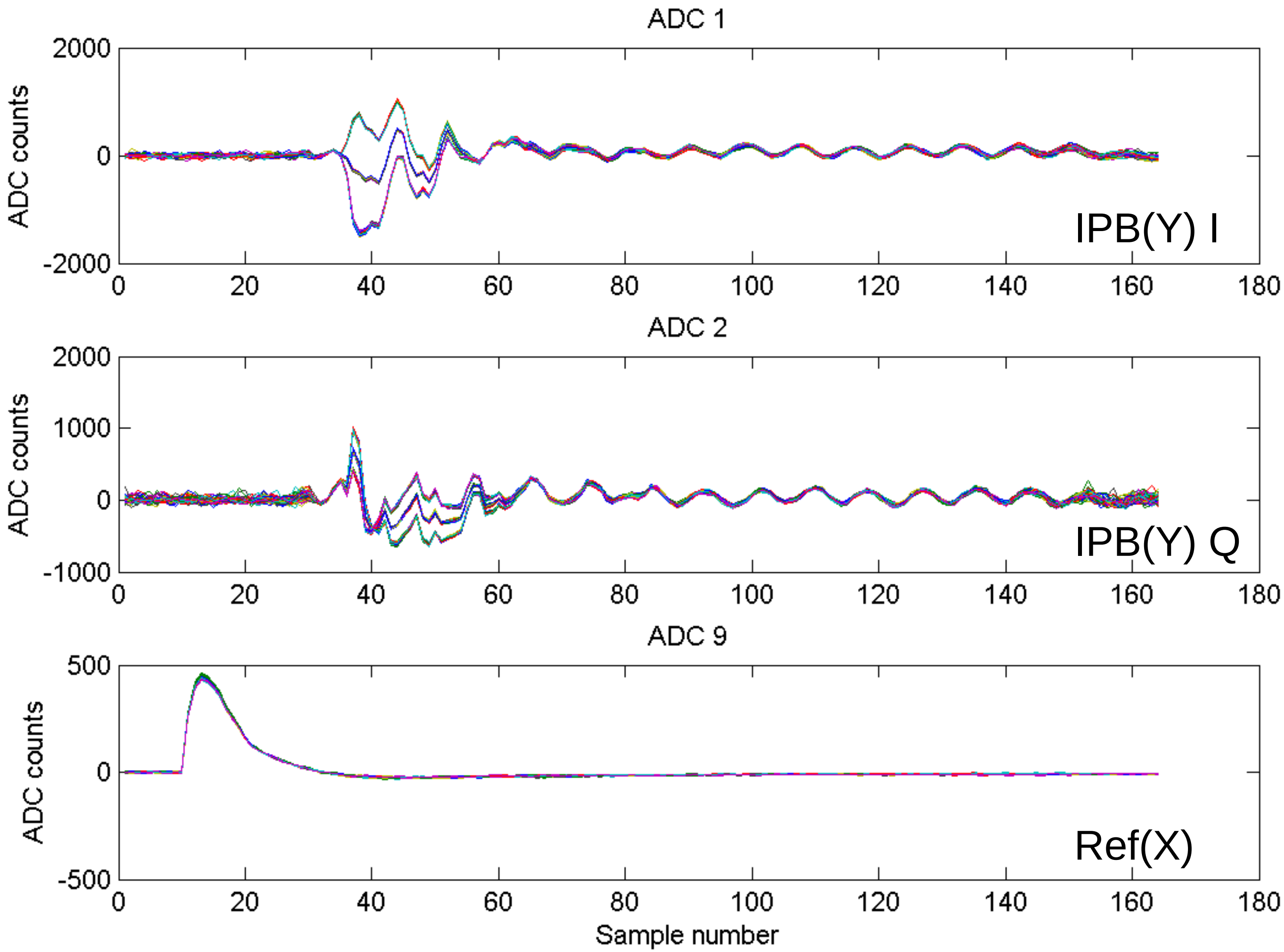
- Data presented from 31st October, for each attenuation from of 0 to 50 dB
- Conditions:
  - Charge of ~0.5×10^{10}
  - No splitters
- Waveforms at centre & extreme positions of IPB(Y) calibration with waist at IPB:
  - I & Q
  - Ref (X) diode

0 dB Positions plotted: 0, ±1.8 um

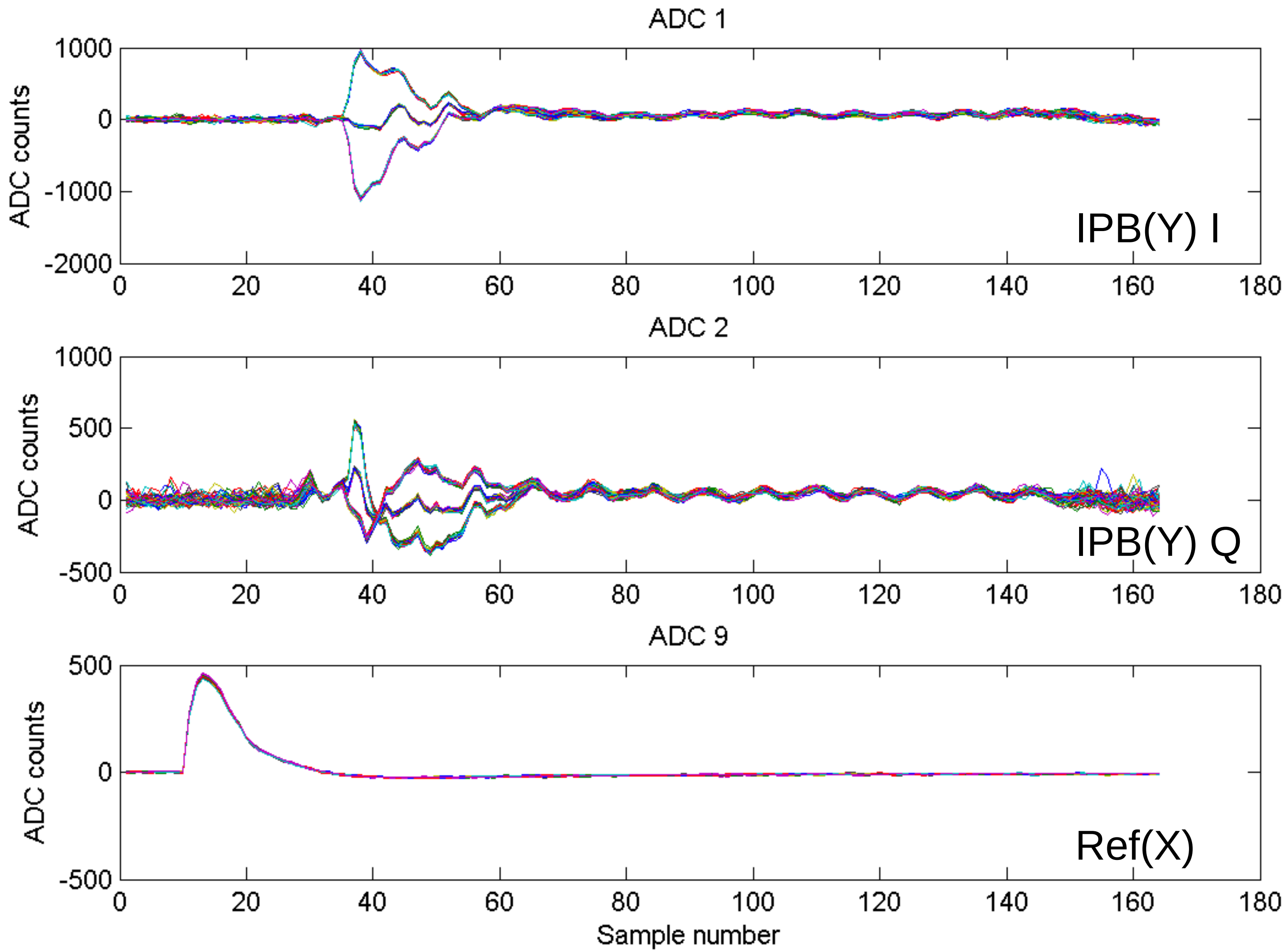


10 dB

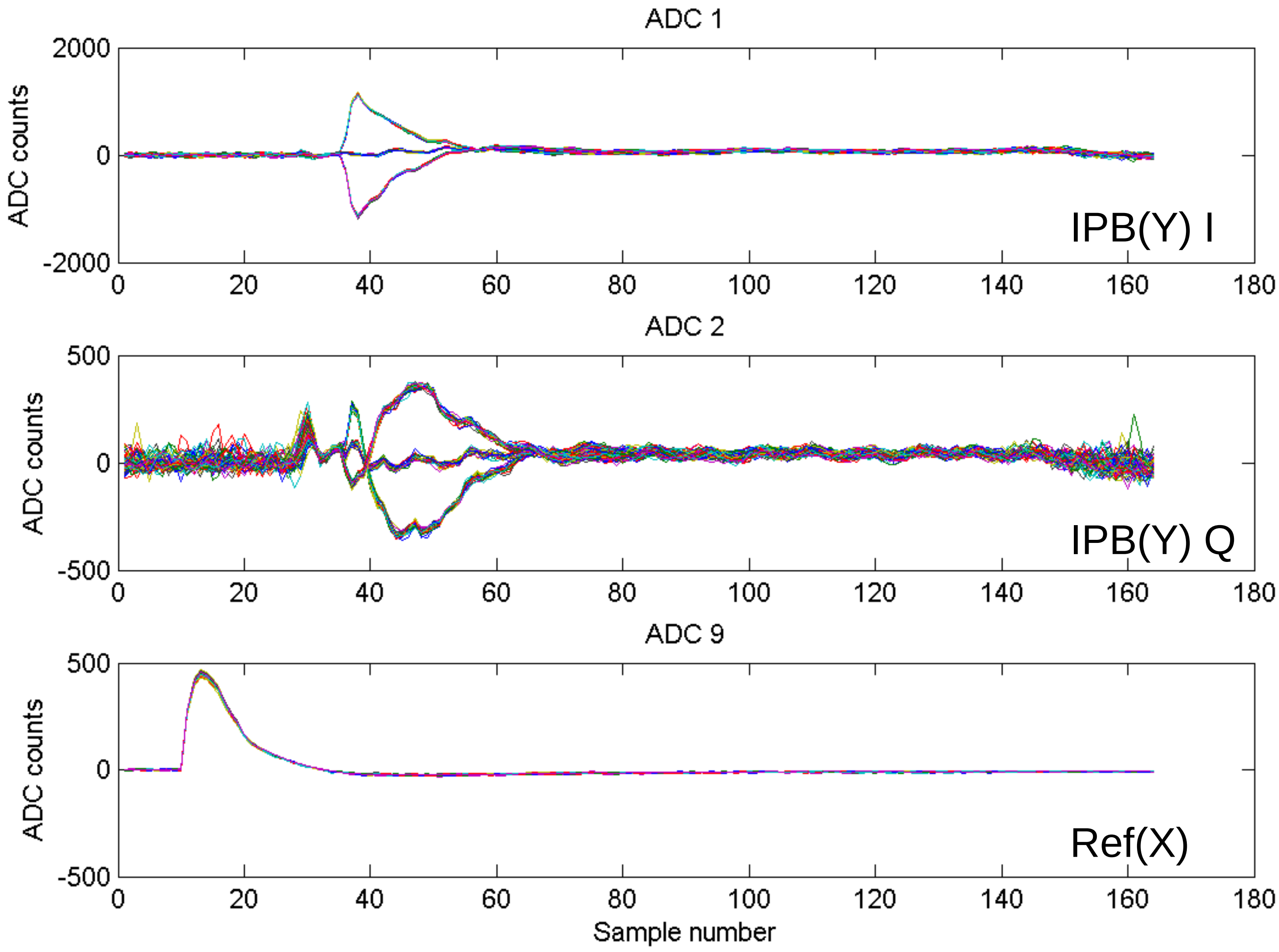
Positions plotted: 0, ±6 um



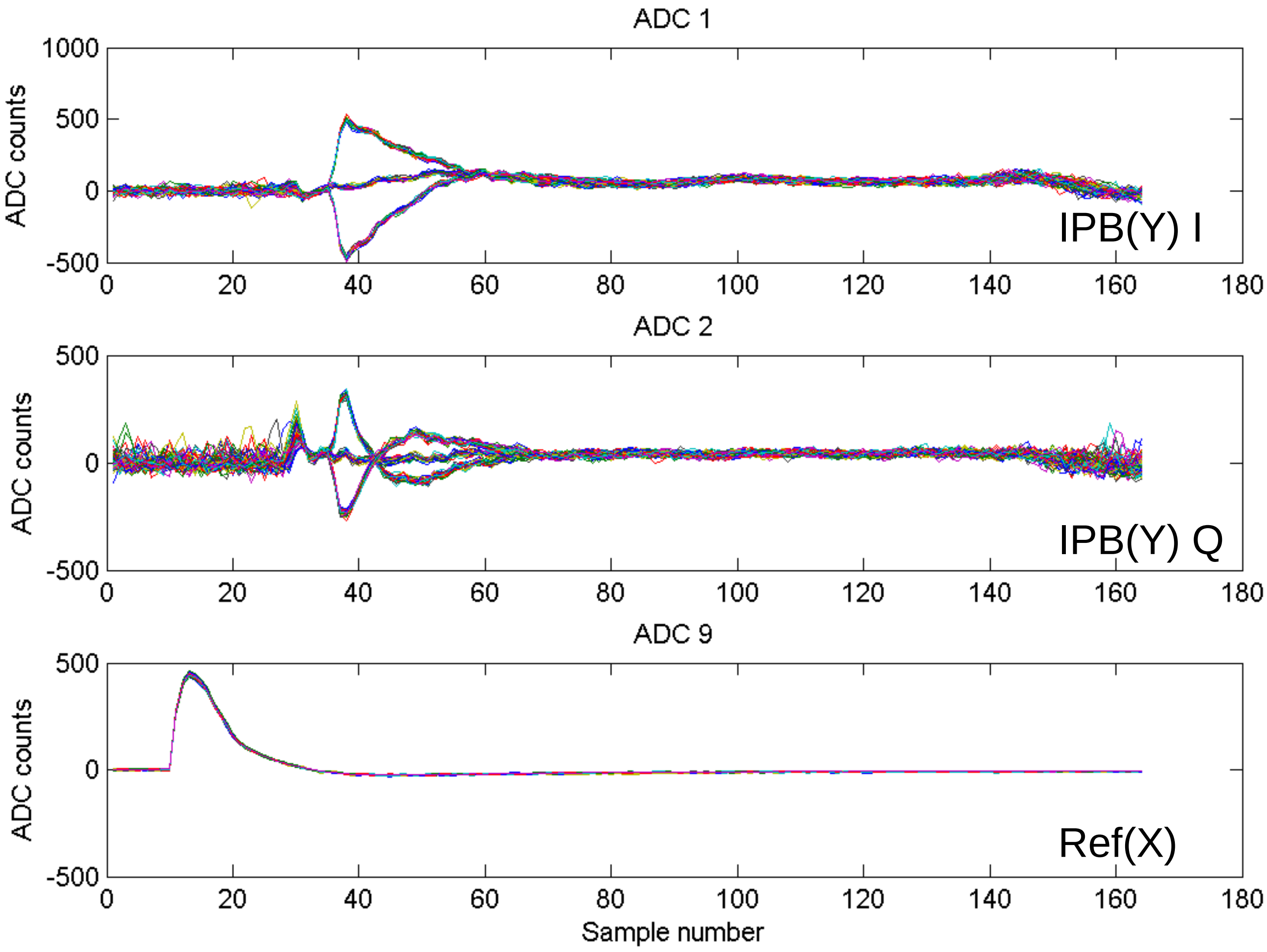
20 dB Positions plotted: 0, ±18 um



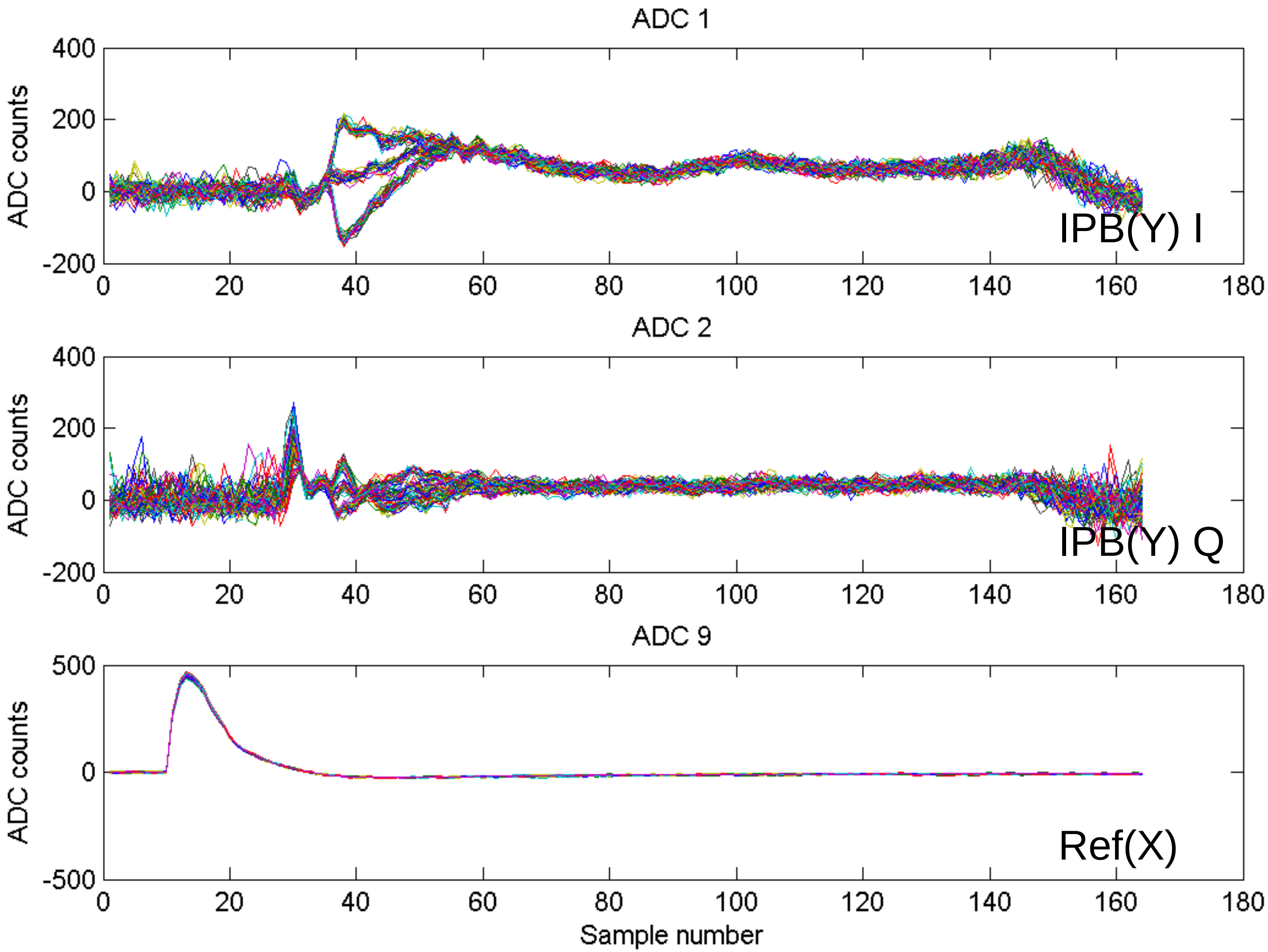
30 dB — Positions plotted: 0, ±60 um



40 dB Positions plotted: 0, ±90 um



50 dB | Positions plotted: 0, ±90 um



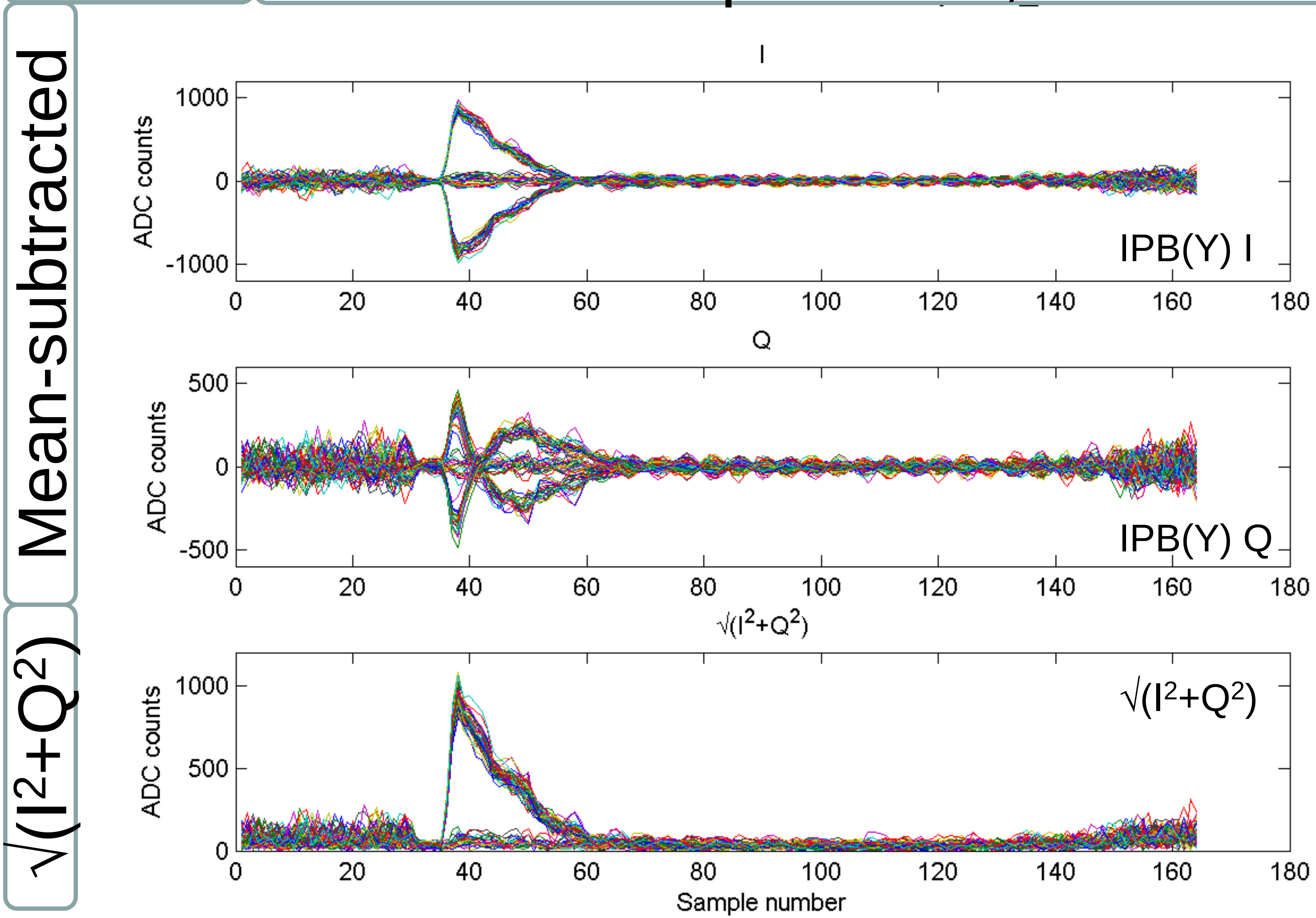
Mean-subtracted waveforms

- For the same IPB(Y) calibrations, waveforms at centre & extreme positions:
  - Mean-subtracted I & Q
  - Sum in quadrature of mean-subtracted I & Q

Vertical scale of plots

- The vertical scale of all waveforms is set equal for attenuations 0 to 30 dB as calibration range scales with attenuation
- For 40 and 50 dB, the calibration range was limited by the mover range; hence, the vertical scale of the waveforms is scaled accordingly

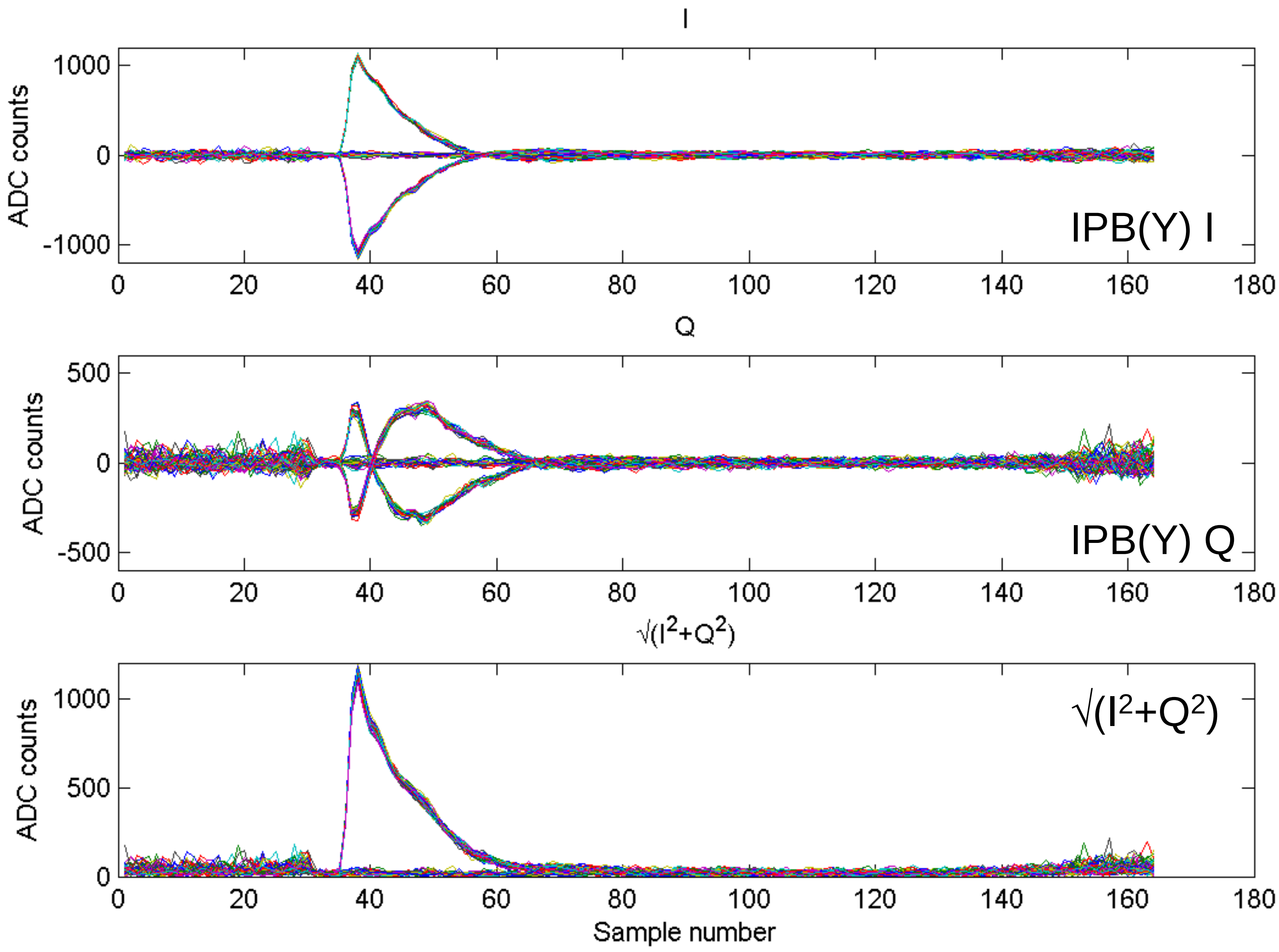
0 dB | Positions plotted: 0, ±1.8 um



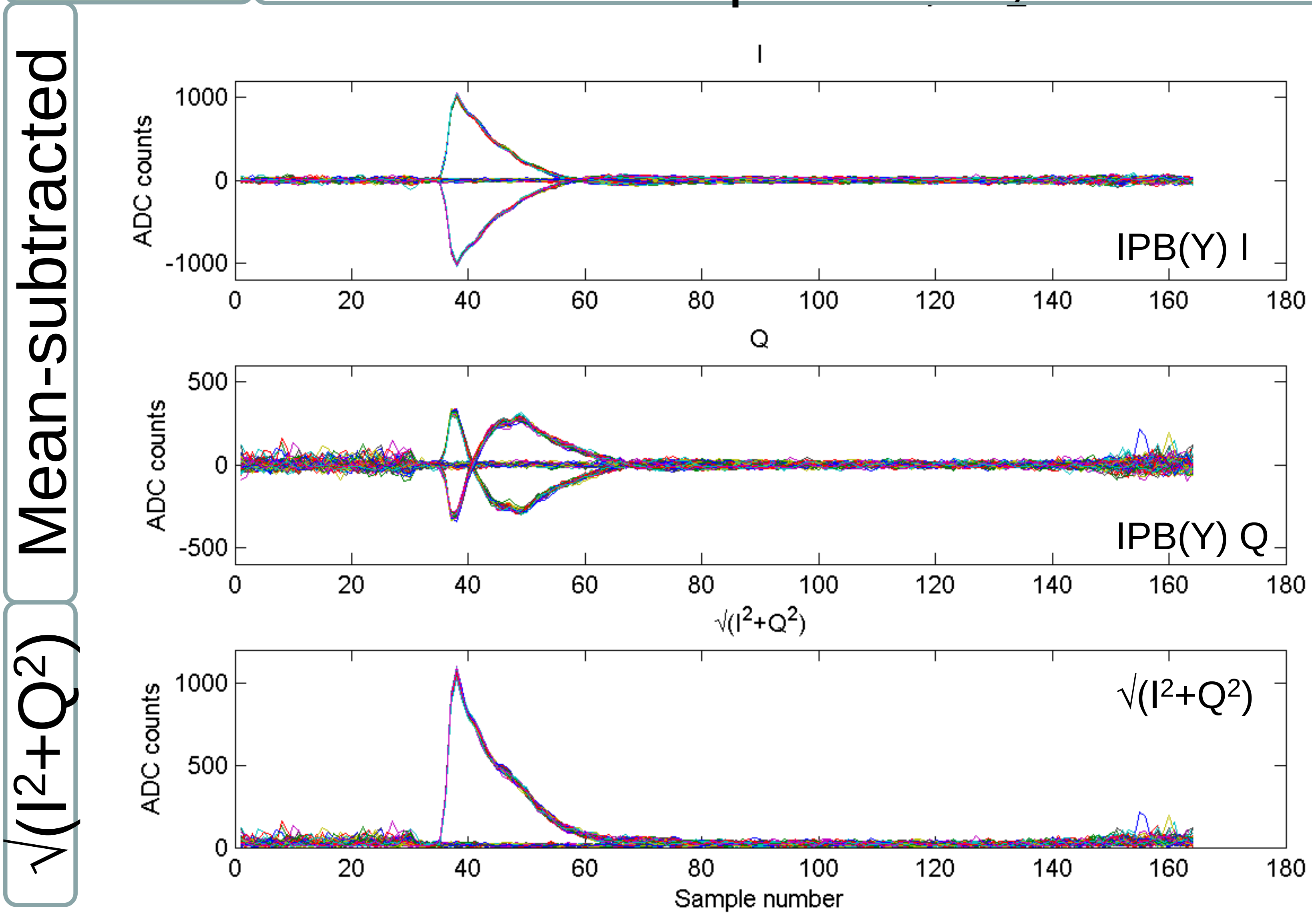
10 dB Positions plotted: 0, ±6 um

Mean-subtracted

$\sqrt{(I^2+Q^2)}$



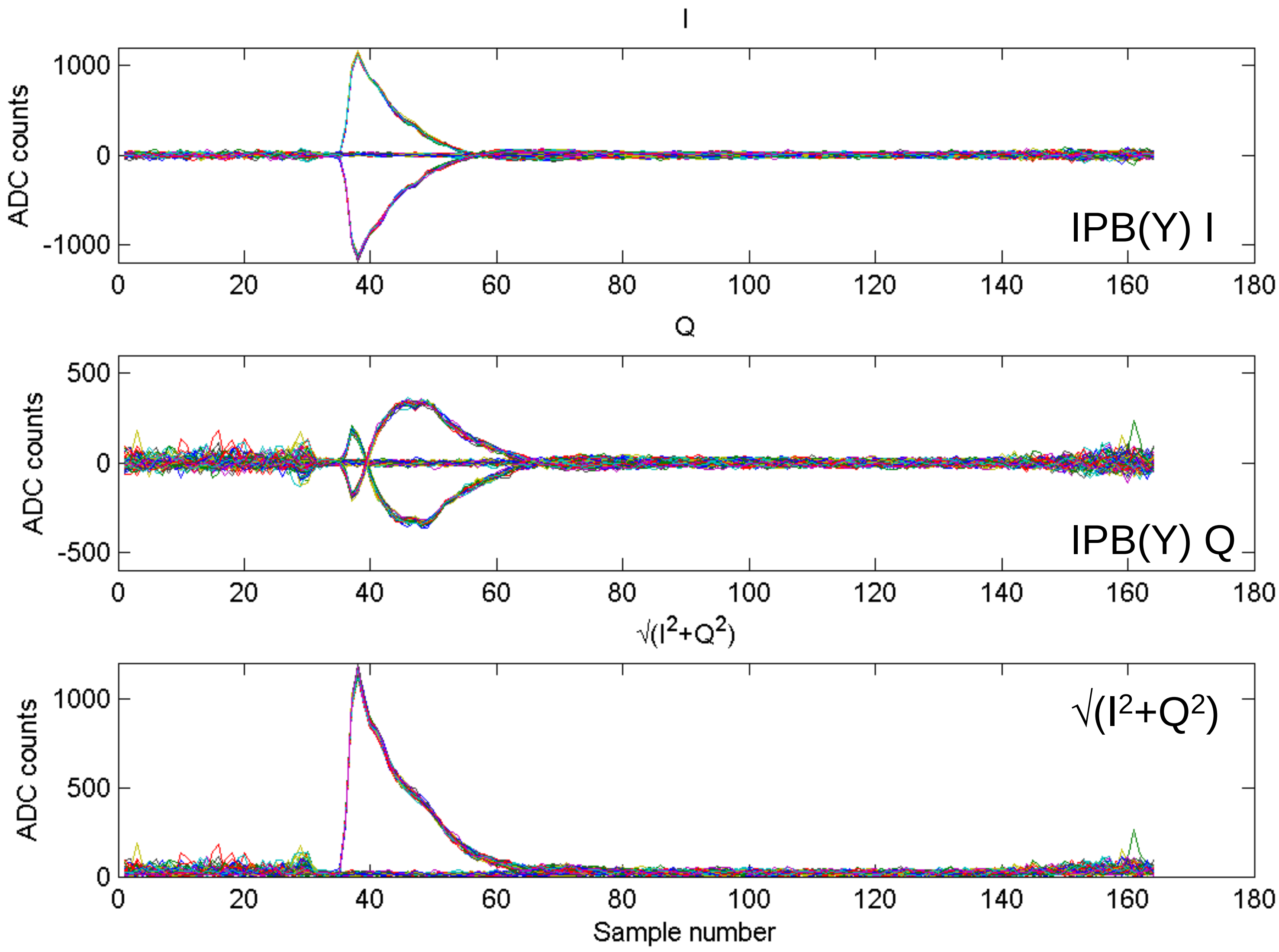
20 dB | Positions plotted: 0, ±18 um



30 dB | Positions plotted: 0, ±60 um

Mean-subtracted

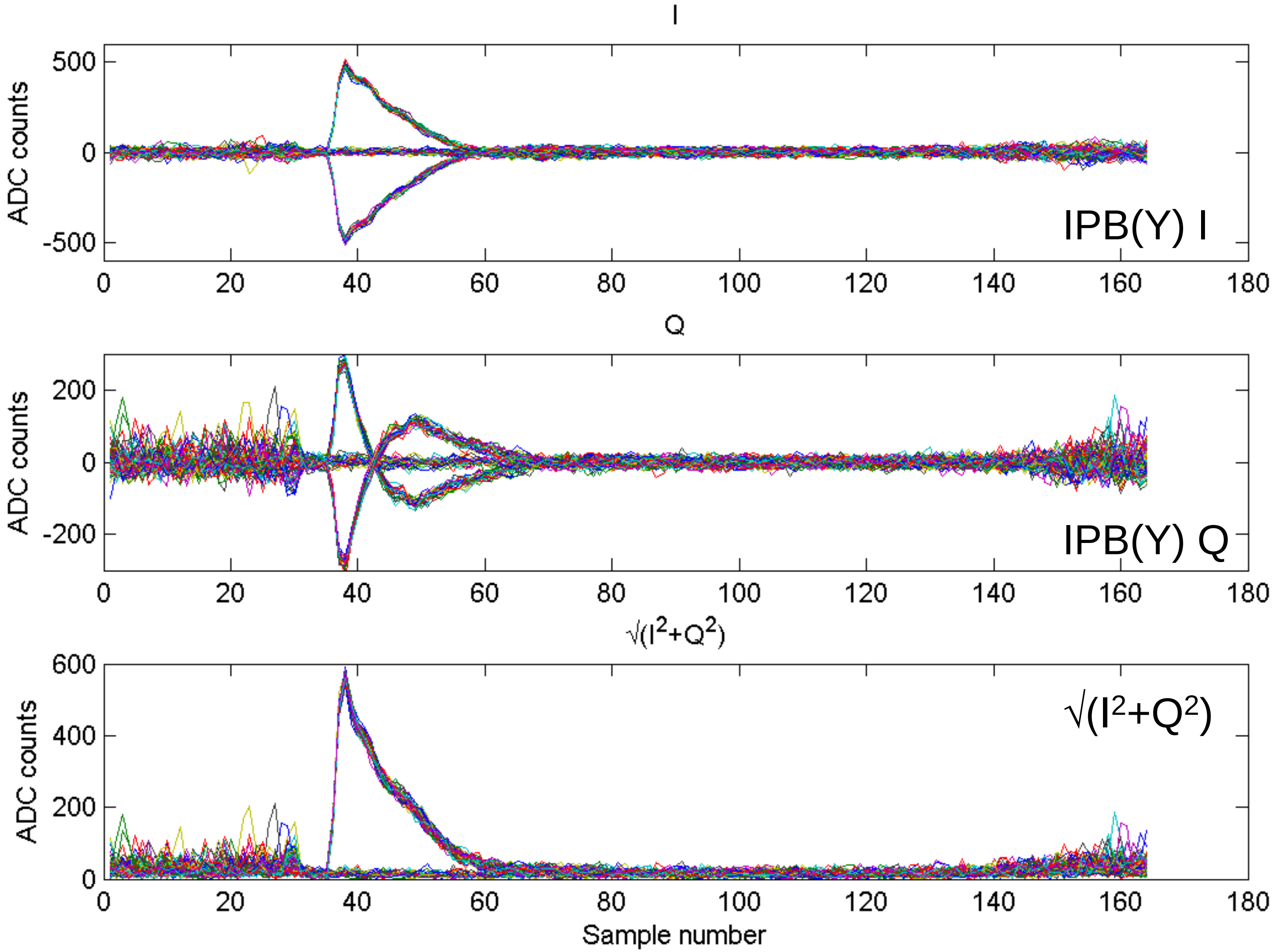
$\sqrt{(I^2+Q^2)}$



40 dB — Positions plotted: 0, ±90 um

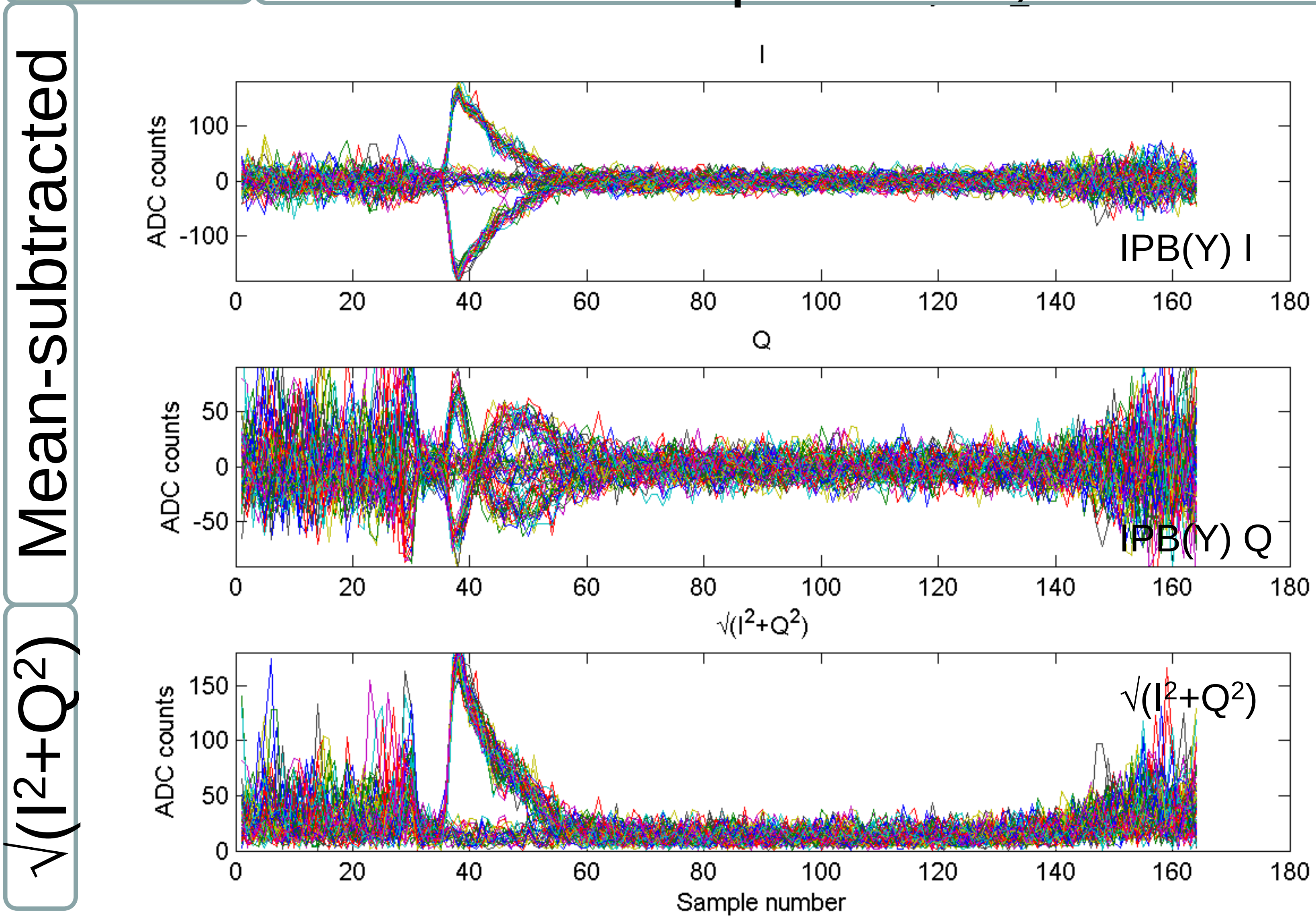
Mean-subtracted

$\sqrt{(I^2+Q^2)}$



50 dB

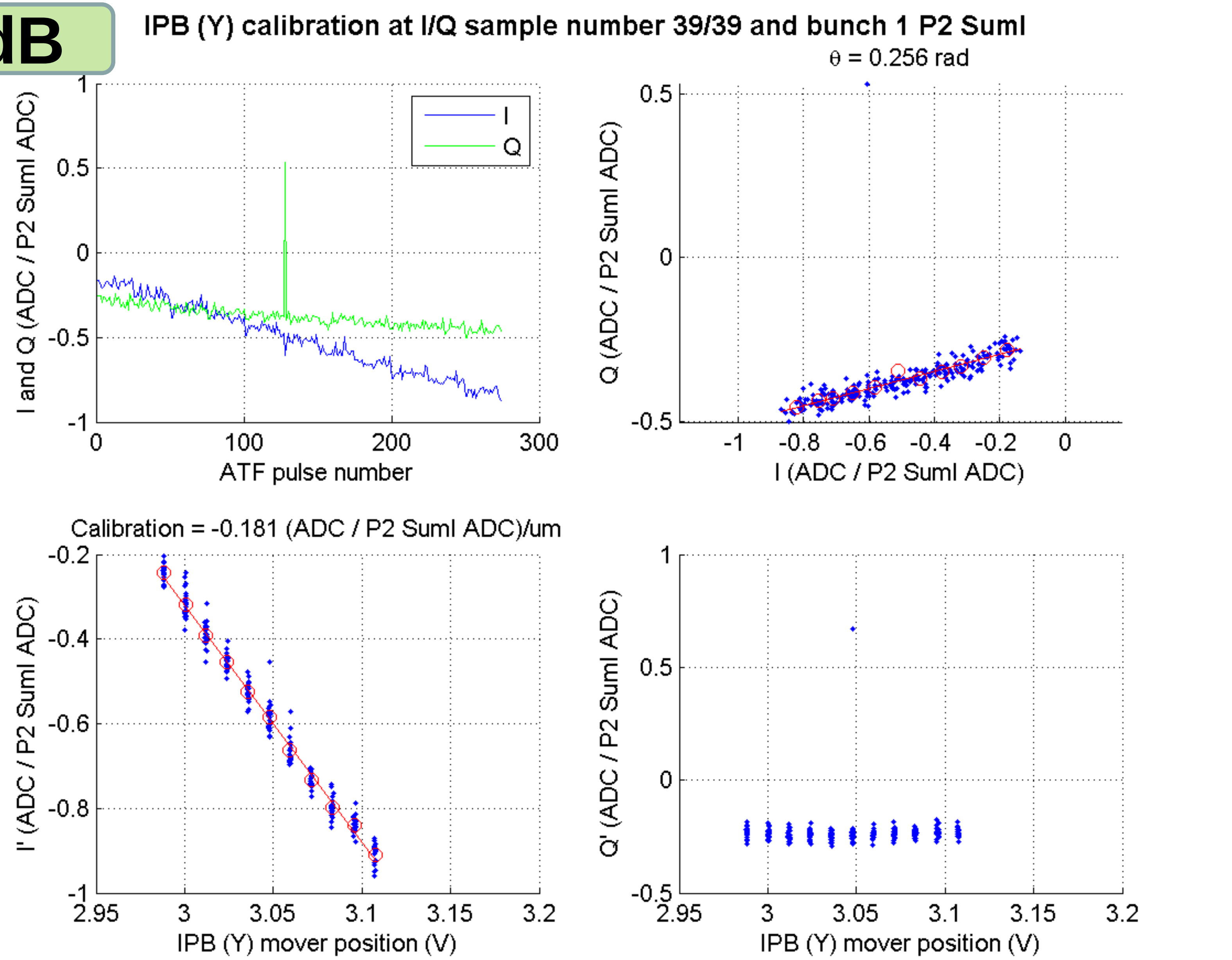
Positions plotted: 0, ±90 um



Calibration vs. attenuation

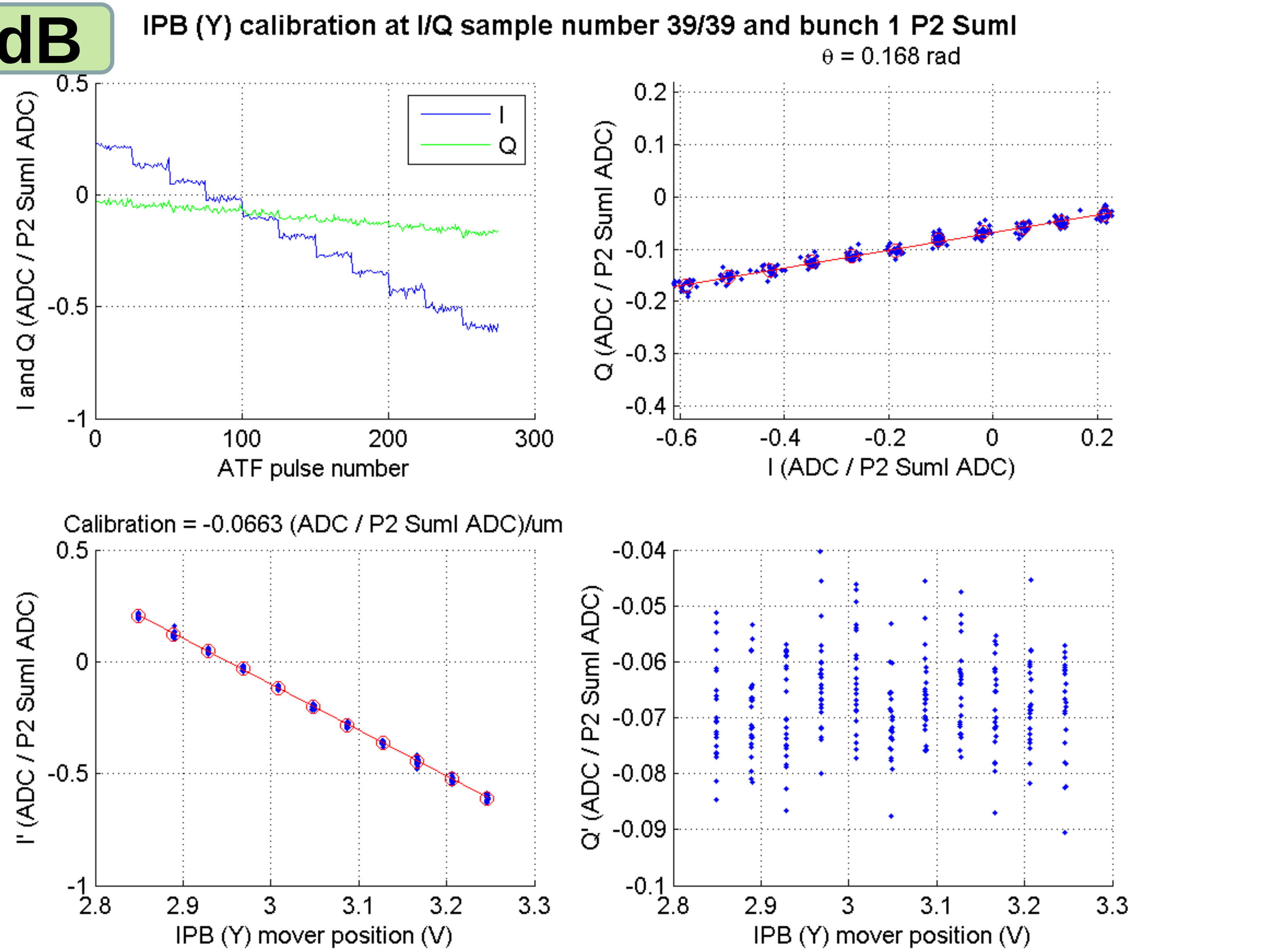
- For the same IPB(Y) calibrations, calibration plots for each attenuation

0 dB



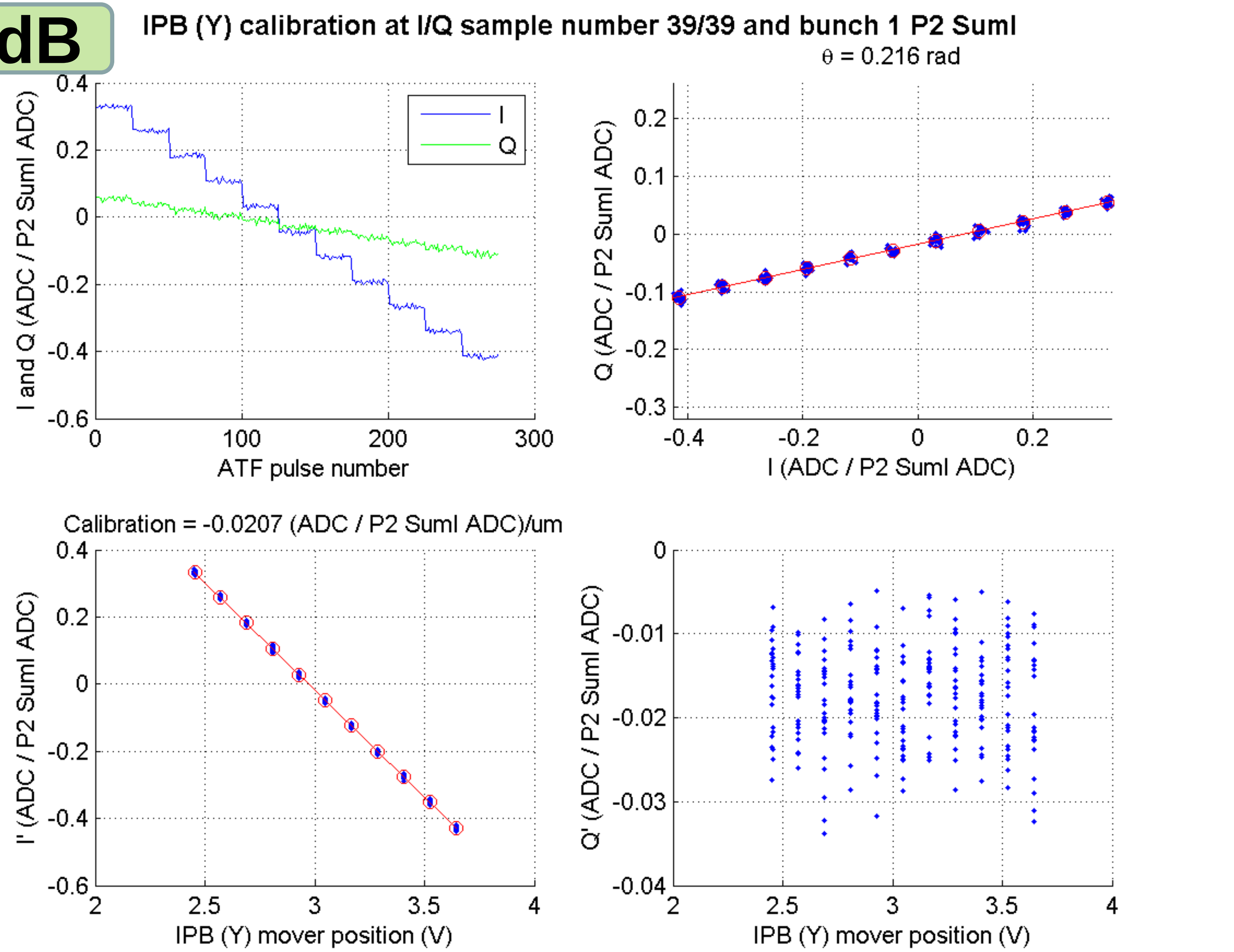
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.256 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.181 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)

10 dB

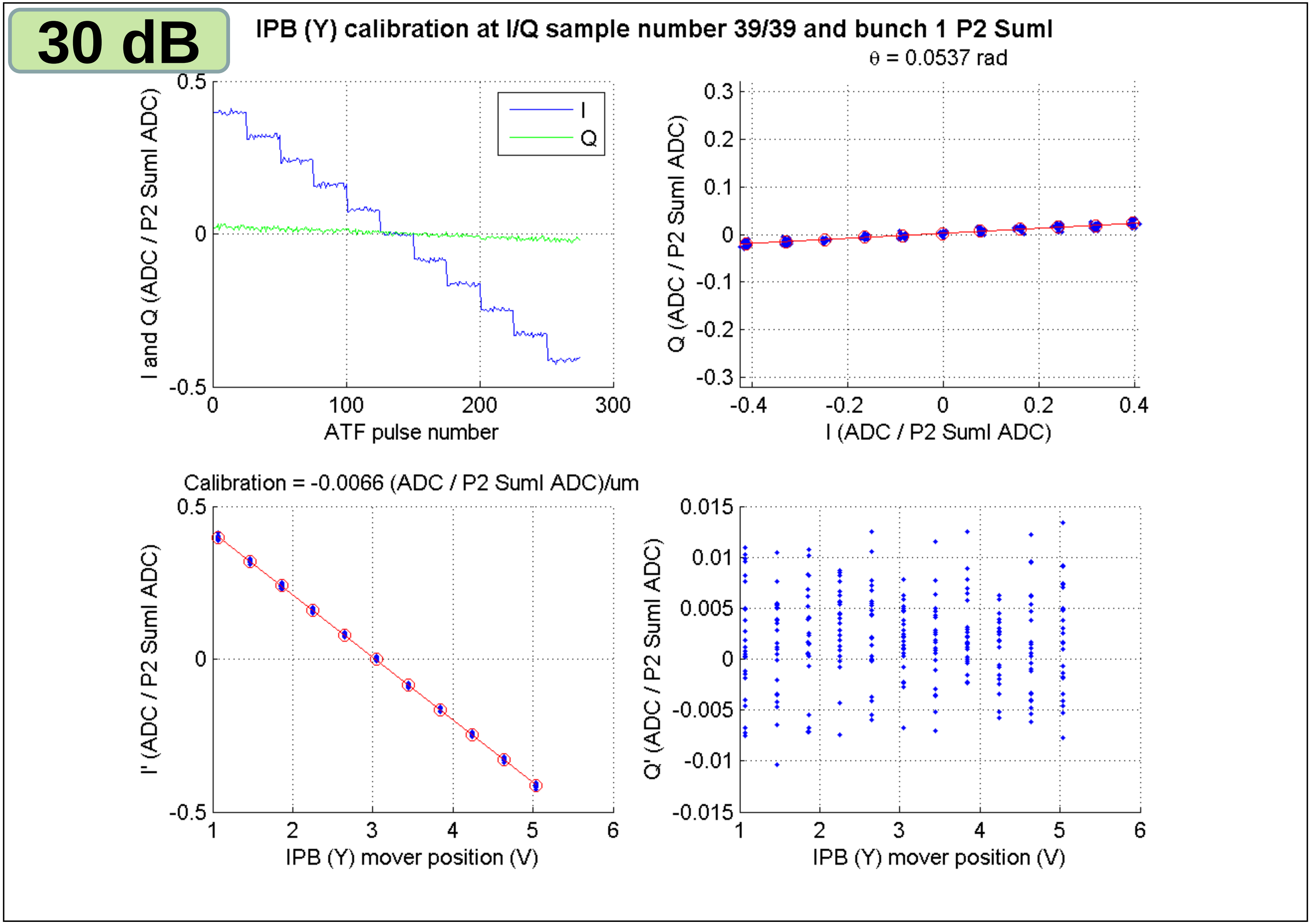


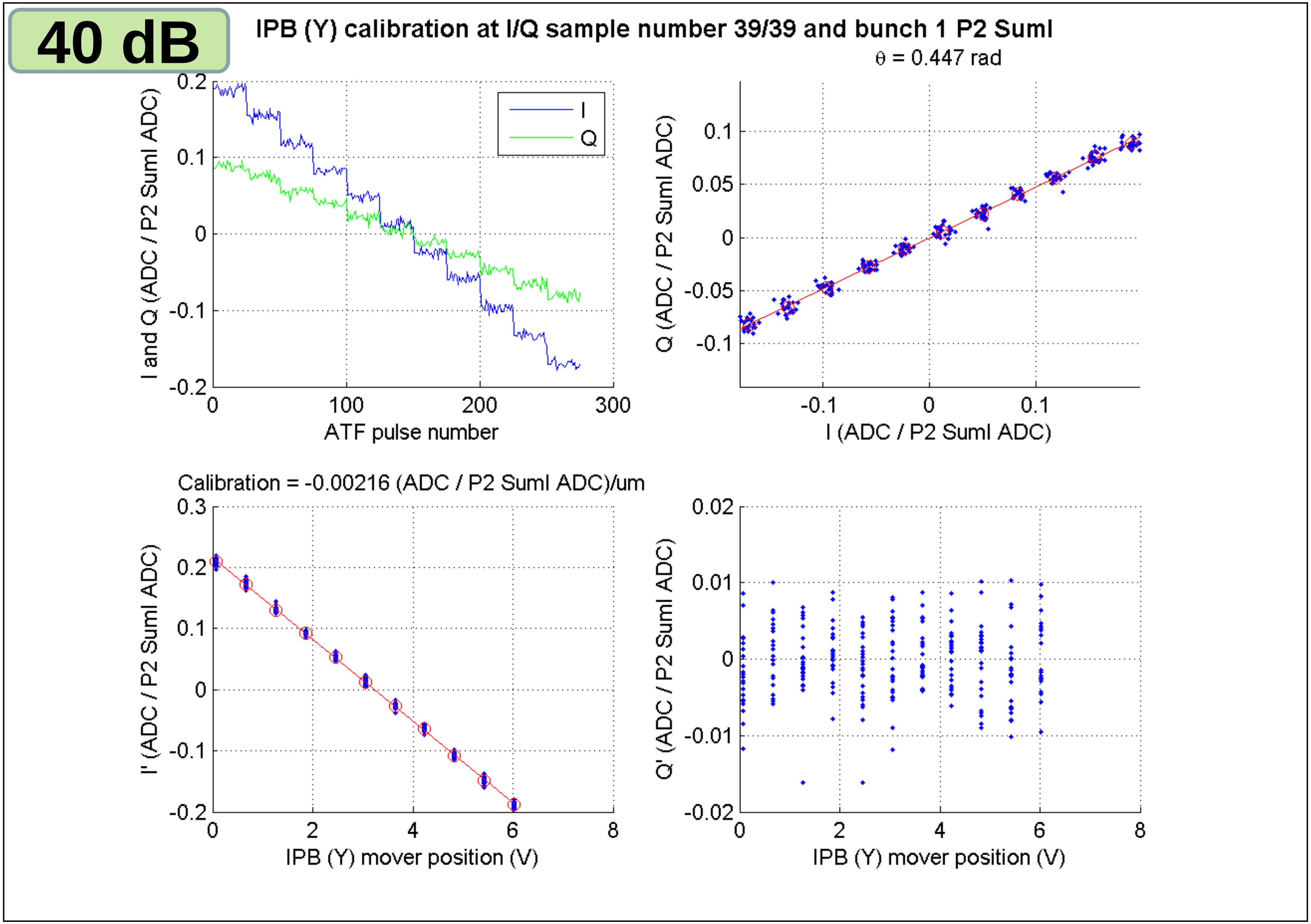
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.168 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.0663 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)

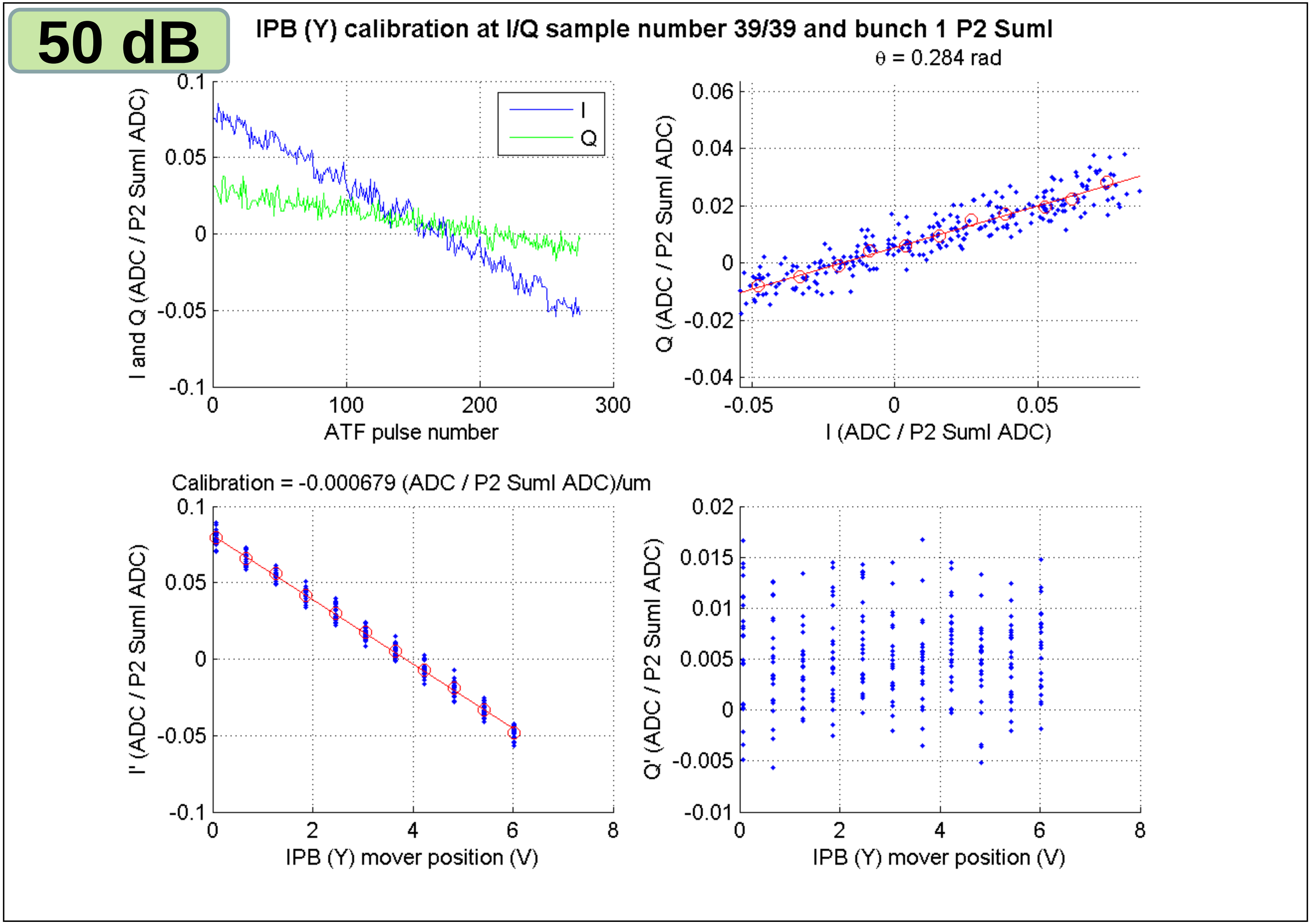
20 dB



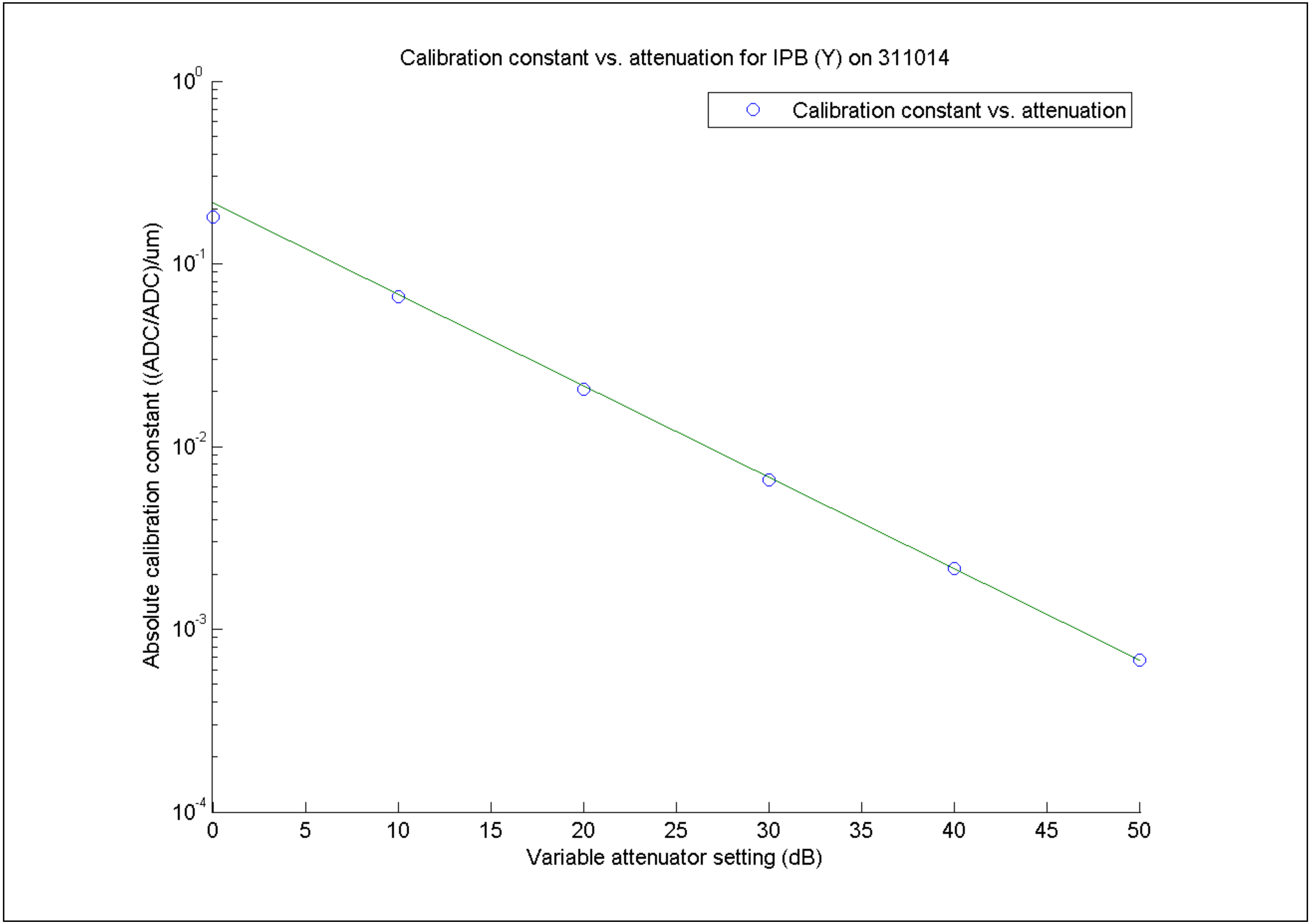
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.216 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.0207 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)


30 dB
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.0537 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.0066 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)


40 dB
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.447 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.00216 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)



50 dB
IPB (Y) calibration at I/Q sample number 39/39 and bunch 1 P2 SumI
θ = 0.284 rad
I and Q (ADC / P2 SumI ADC)
ATF pulse number
I
Q
Q (ADC / P2 SumI ADC)
I (ADC / P2 SumI ADC)
Calibration = -0.000679 (ADC / P2 SumI ADC)/um
I' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / P2 SumI ADC)
IPB (Y) mover position (V)


Calibration constant vs. attenuation for IPB (Y) on 311014
Calibration constant vs. attenuation
Absolute calibration constant ((ADC/ADC)/um)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
40
45
50
Variable attenuator setting (dB)

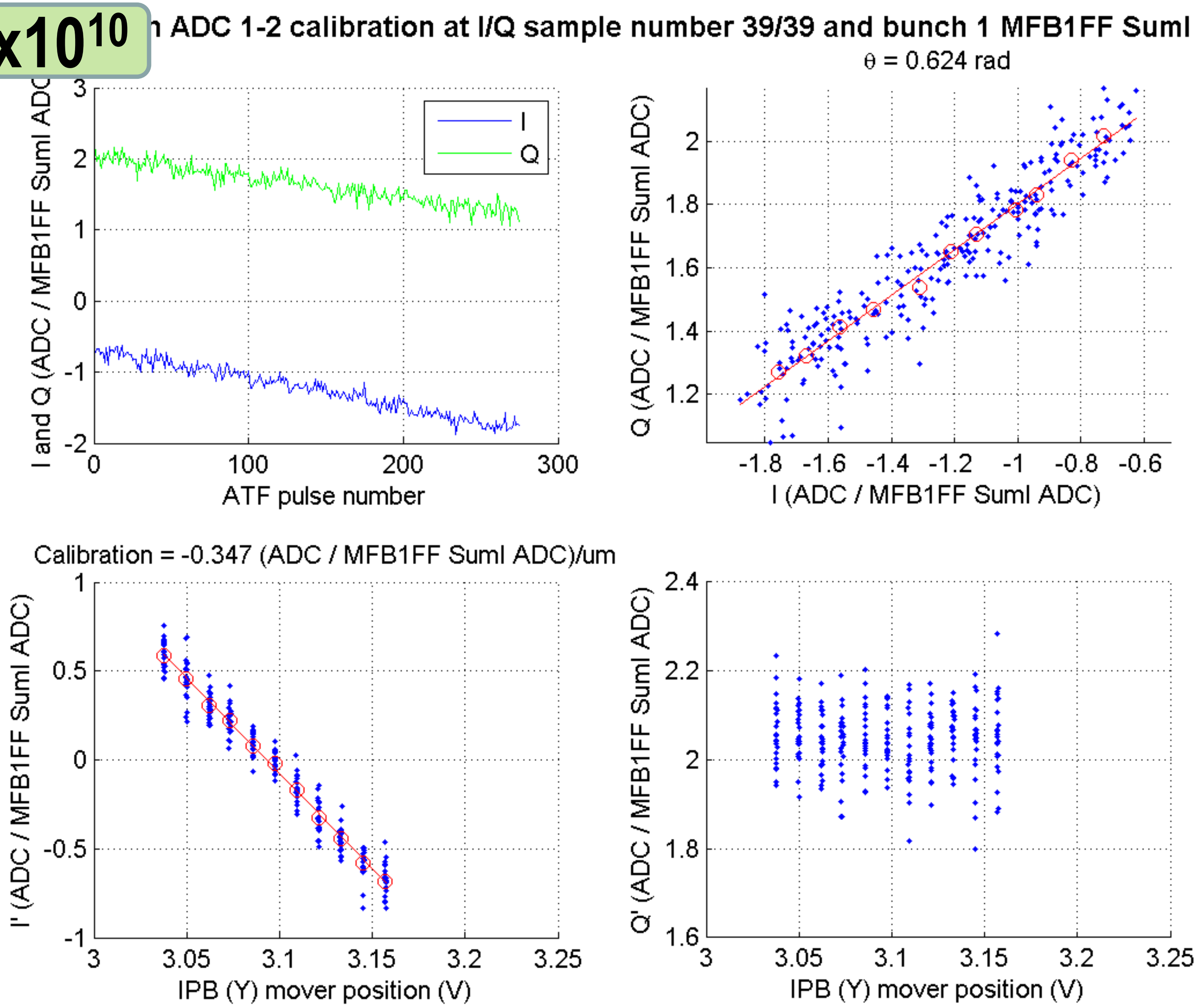
Calibration vs. charge

- Calibrations performed at different charges
- Charge-normalised calibration

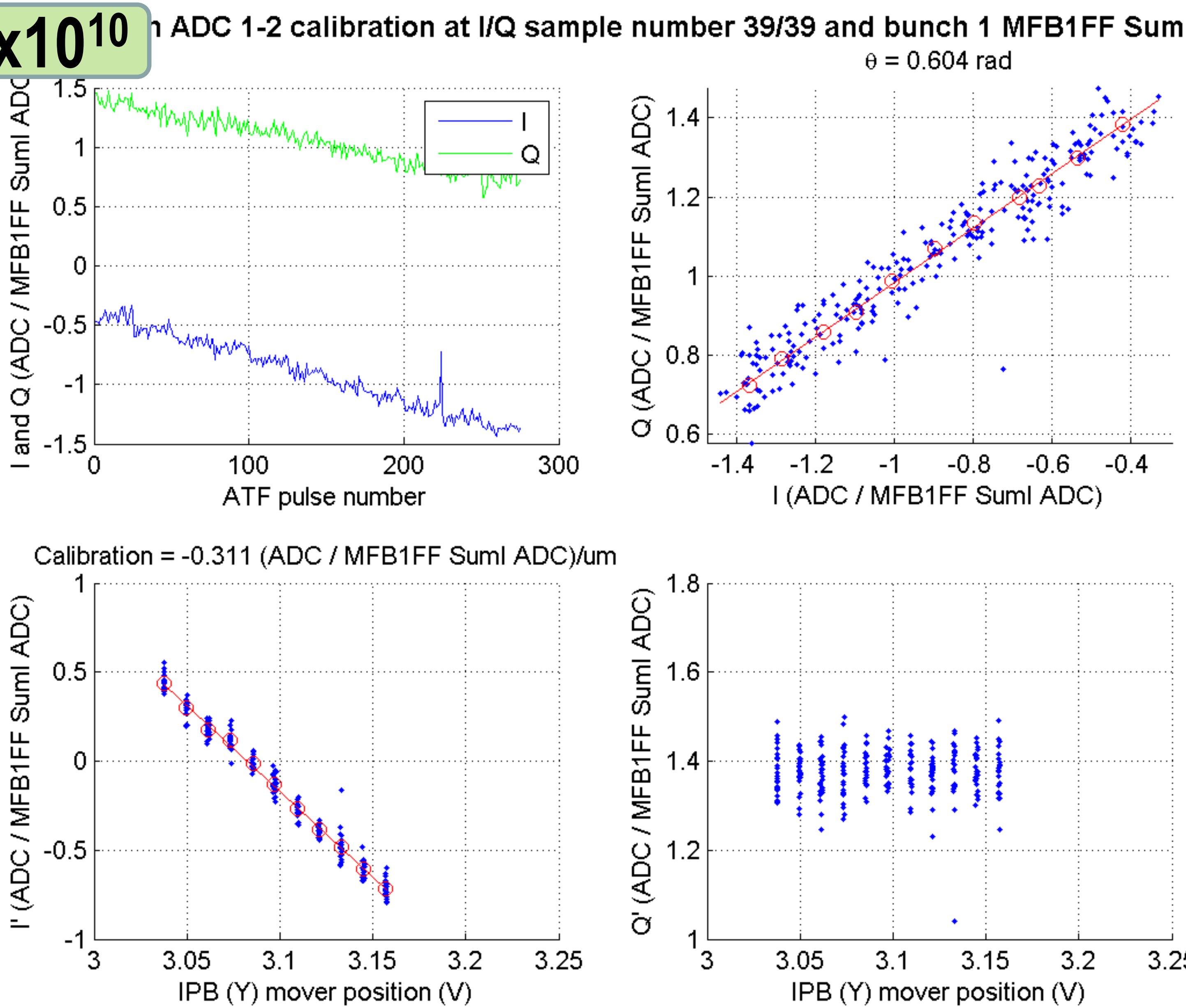
$$\frac{\left(\frac{I\cos\theta_{IQ} + Q\sin\theta_{IQ}}{\text{charge}}\right)}{\text{position}}$$

  should be charge-independent
- However, considerable dependence found both when using stripline MFB1FF and reference cavity signal for normalisation

0.13×10^{10}

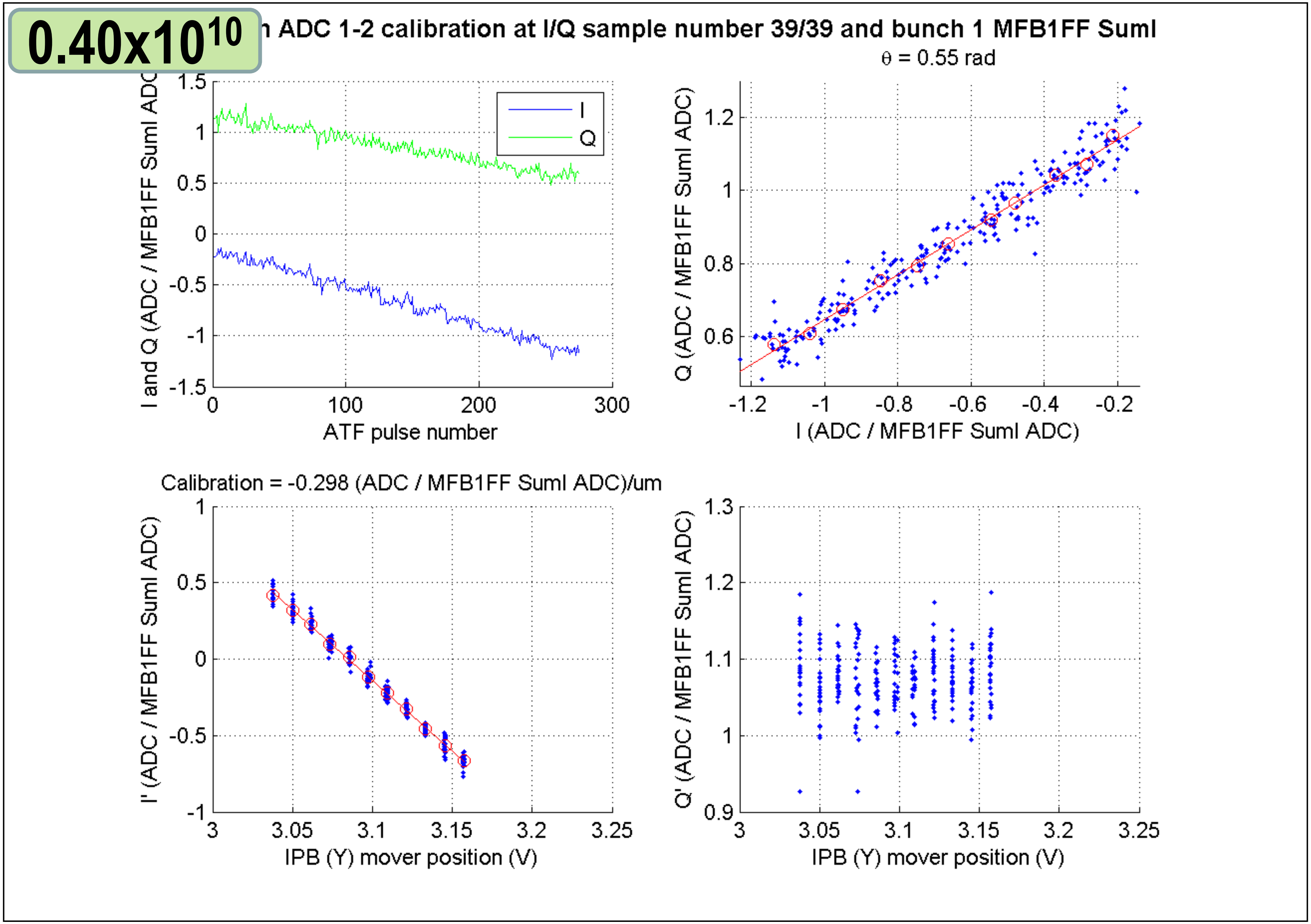


0.24x10^10



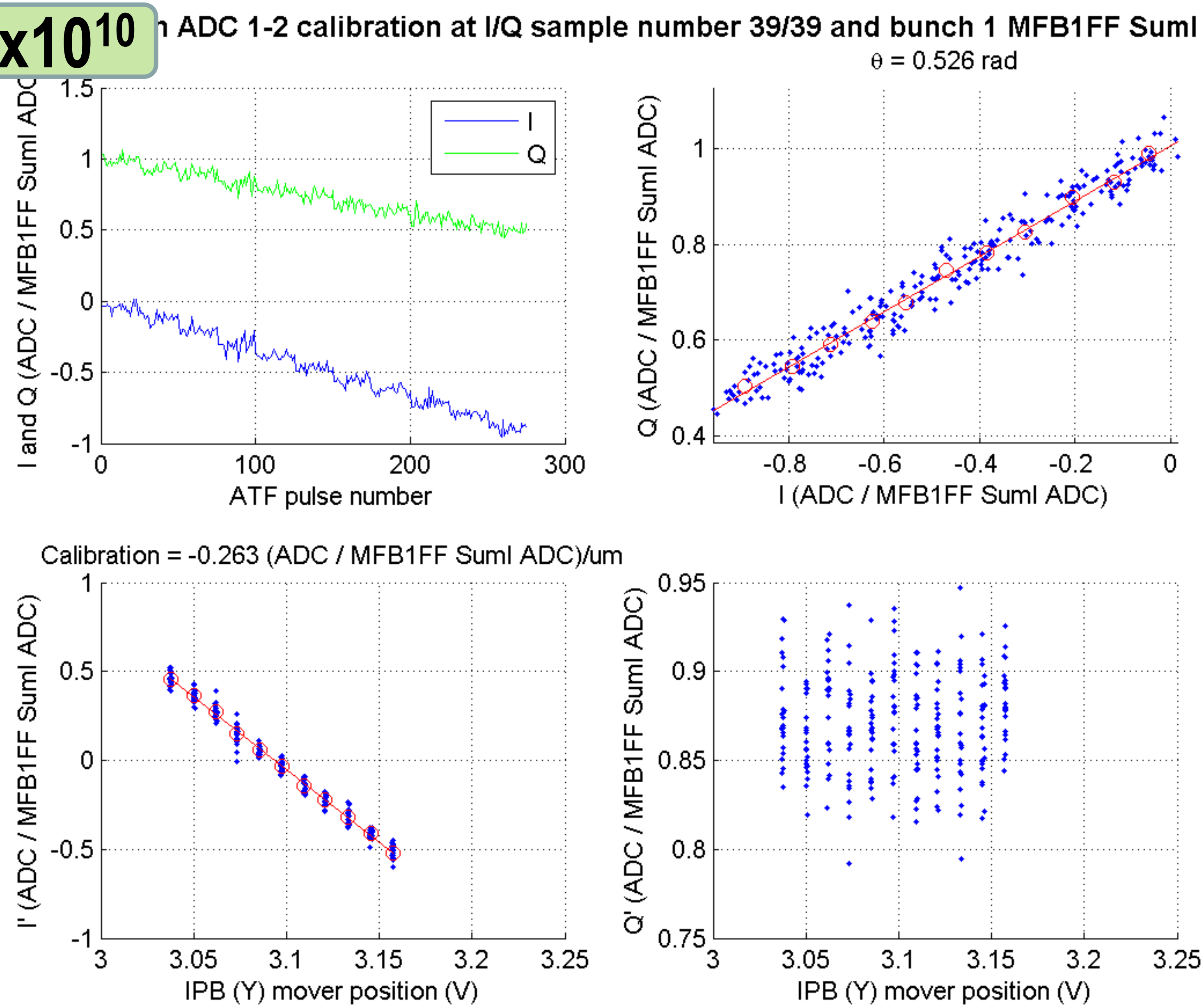
h ADC 1-2 calibration at I/Q sample number 39/39 and bunch 1 MFB1FF SumI
θ = 0.604 rad
I and Q (ADC / MFB1FF SumI ADC)
ATF pulse number
I
Q
Q (ADC / MFB1FF SumI ADC)
I (ADC / MFB1FF SumI ADC)
Calibration = -0.311 (ADC / MFB1FF SumI ADC)/um
I' (ADC / MFB1FF SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / MFB1FF SumI ADC)
IPB (Y) mover position (V)

0.40x10[10]

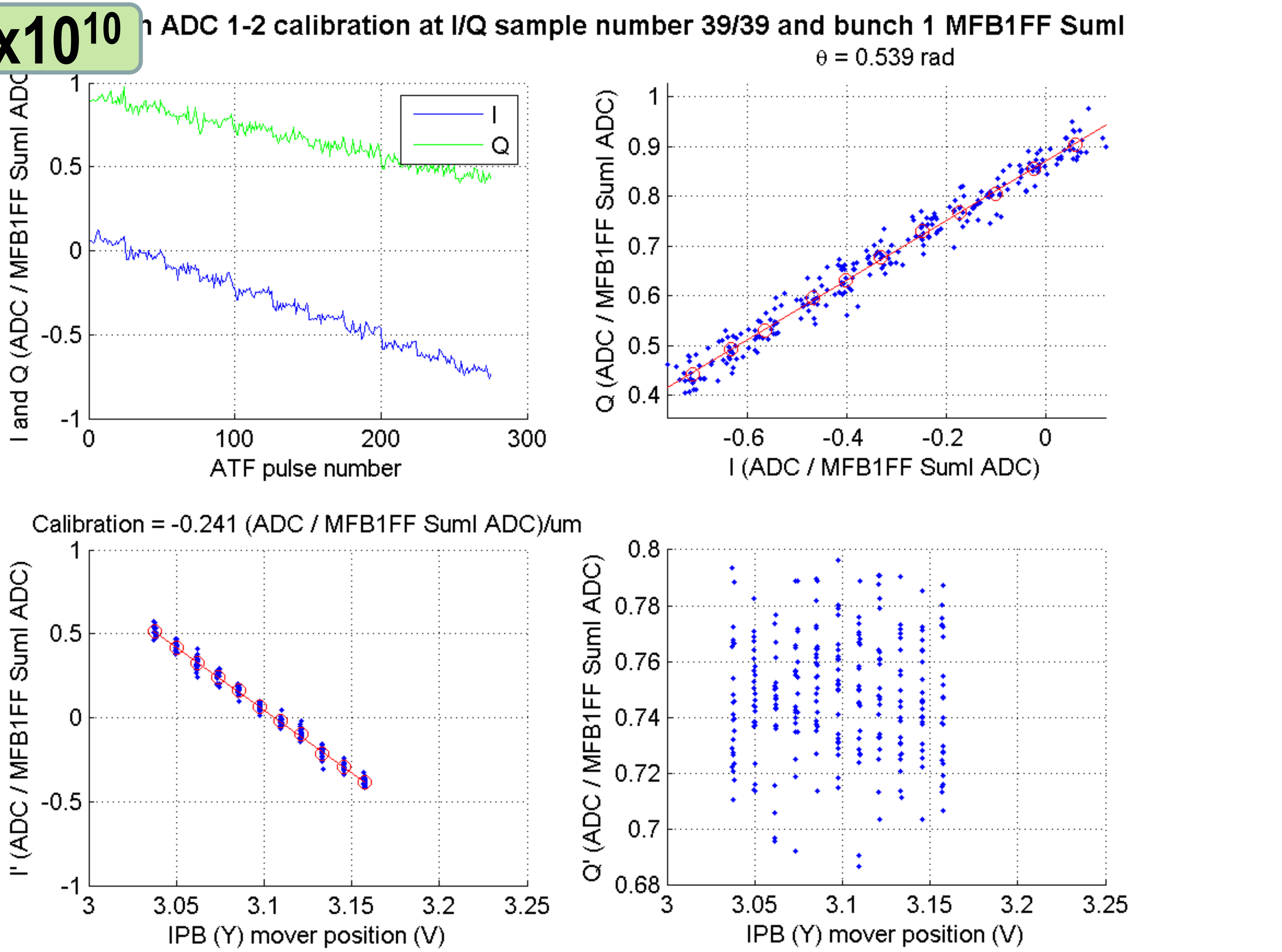


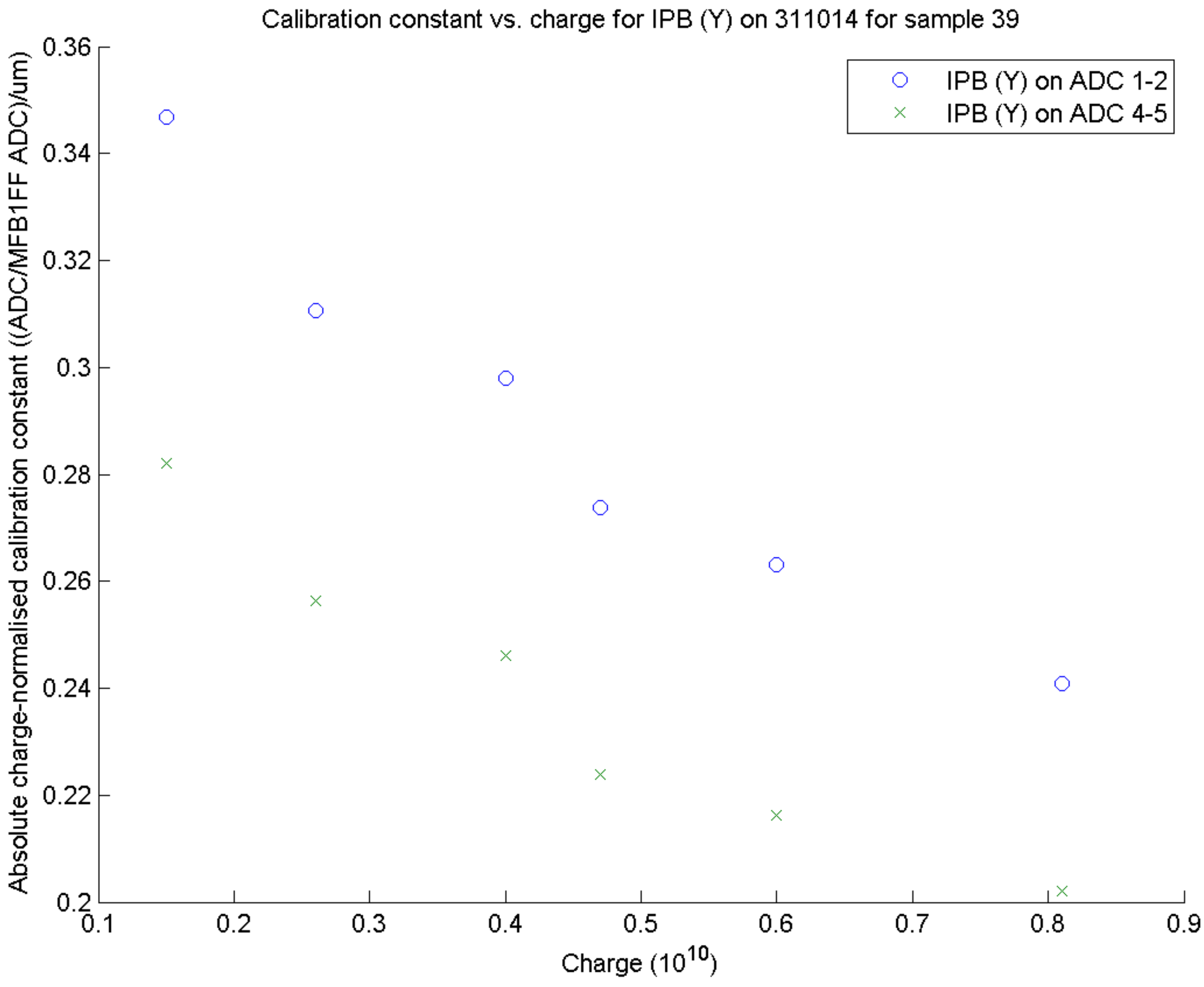
...n ADC 1-2 calibration at I/Q sample number 39/39 and bunch 1 MFB1FF SumI
θ = 0.55 rad
I and Q (ADC / MFB1FF SumI ADC)
ATF pulse number
I
Q
Q (ADC / MFB1FF SumI ADC)
I (ADC / MFB1FF SumI ADC)
Calibration = -0.298 (ADC / MFB1FF SumI ADC)/um
I' (ADC / MFB1FF SumI ADC)
IPB (Y) mover position (V)
Q' (ADC / MFB1FF SumI ADC)
IPB (Y) mover position (V)

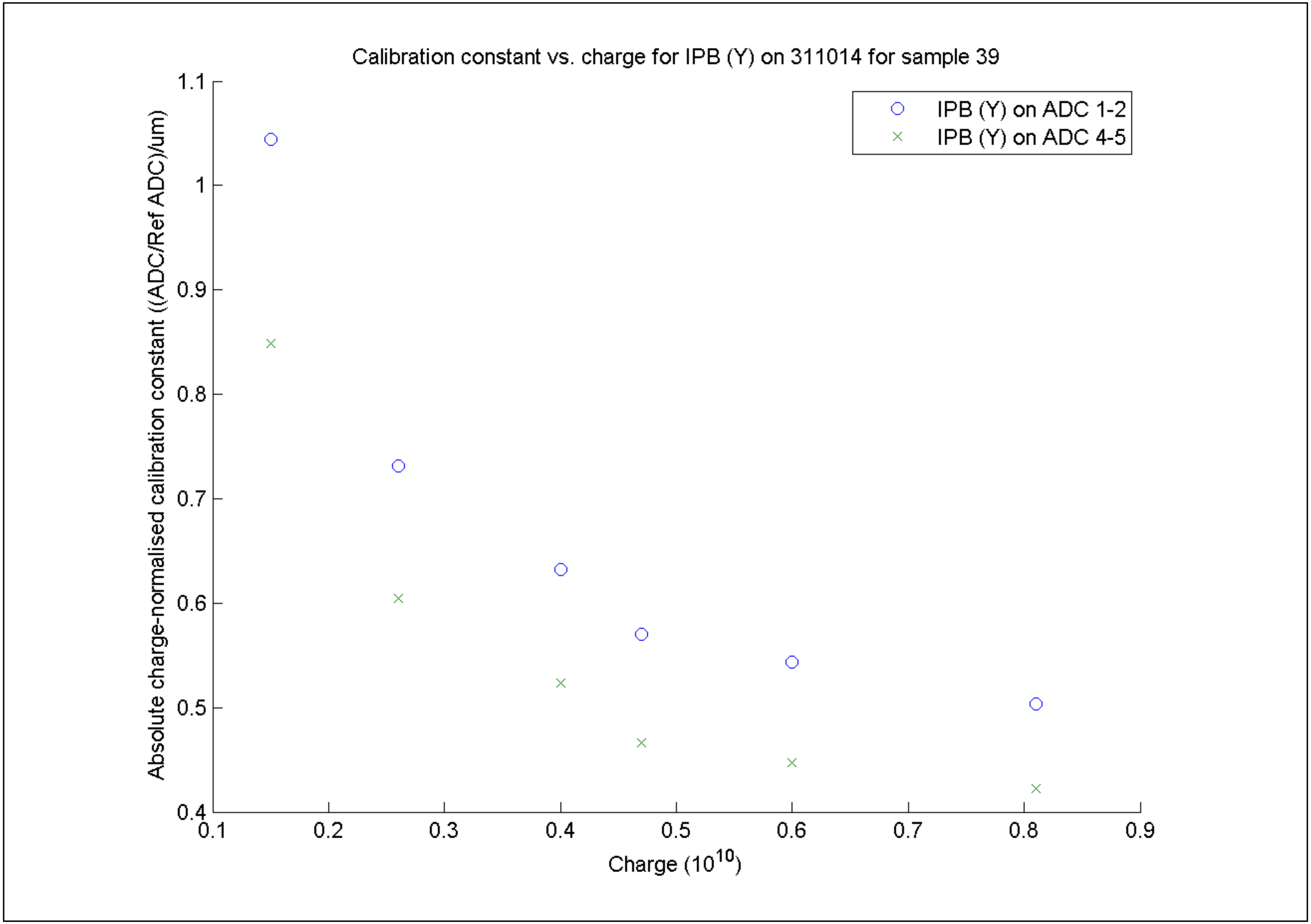
0.61×10^{10}



0.84×10^{10}



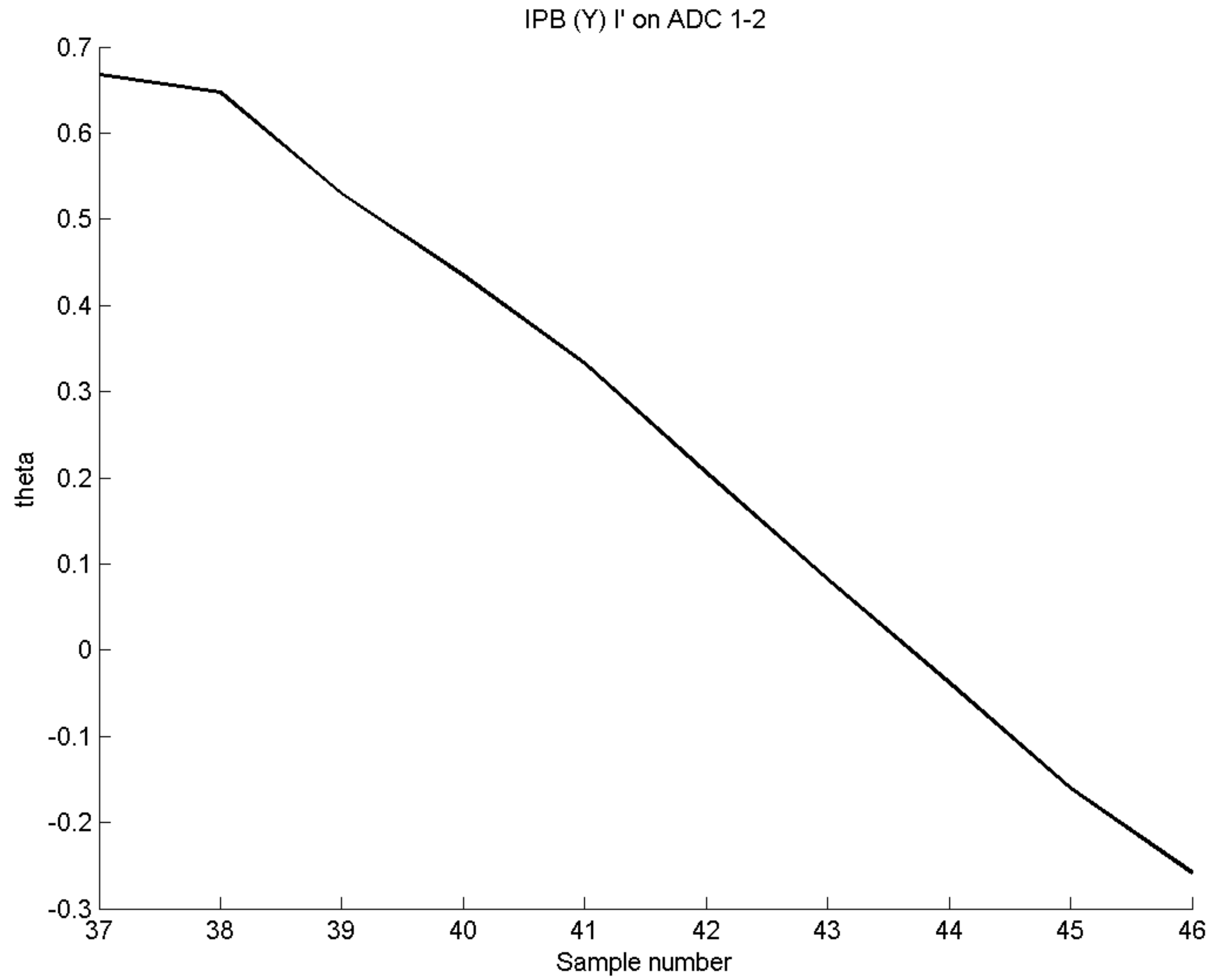

Calibration constant vs. charge for IPB (Y) on 311014 for sample 39
IPB (Y) on ADC 1-2
IPB (Y) on ADC 4-5
Absolute charge-normalised calibration constant ((ADC/MFB1FF ADC)/um)
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Charge (10^{10})

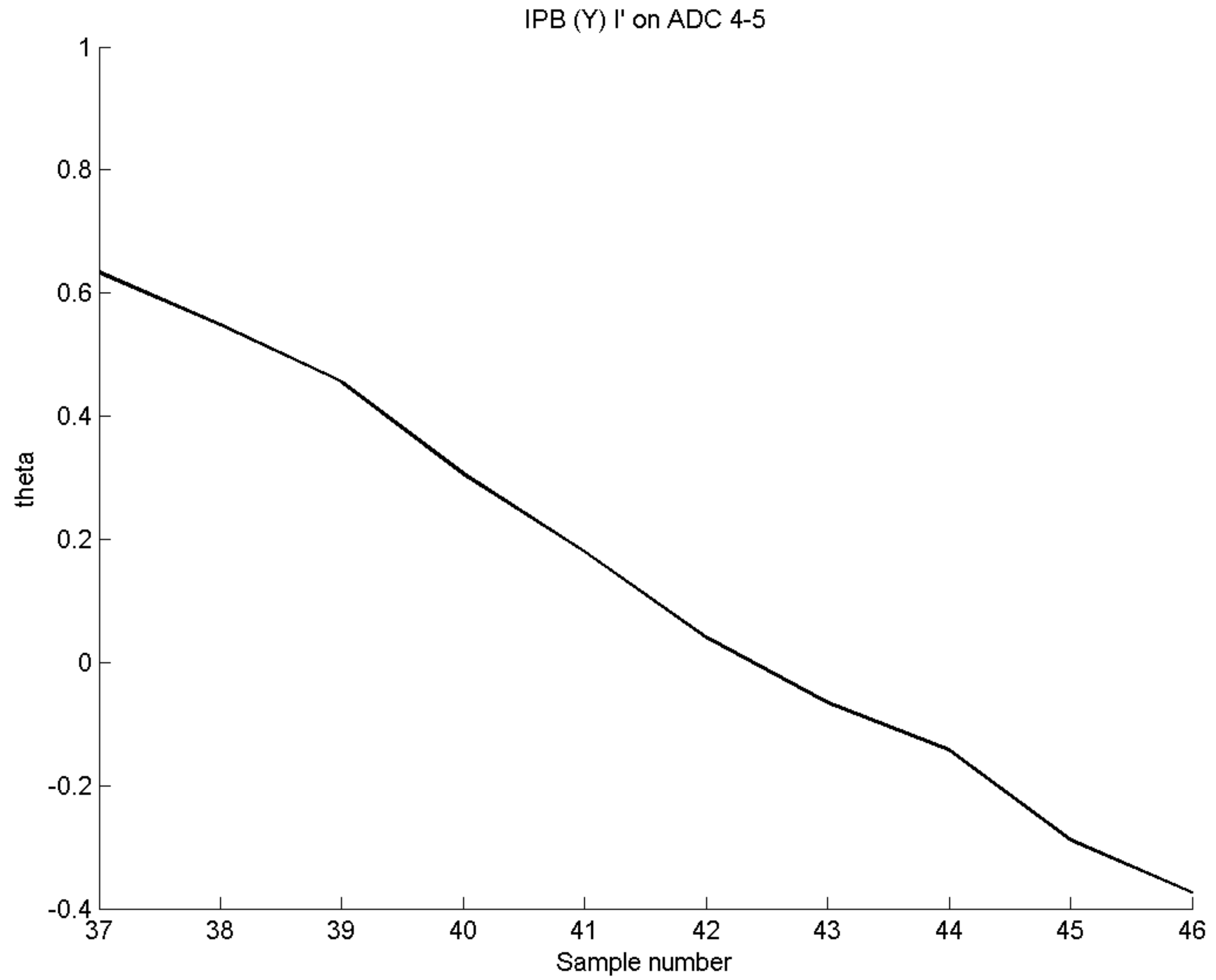


Calibration constant vs. charge for IPB (Y) on 311014 for sample 39
IPB (Y) on ADC 1-2
IPB (Y) on ADC 4-5
Absolute charge-normalised calibration constant ((ADC/Ref ADC)/um)
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Charge (10^10)

θ_{IQ} vs. sample number

- The frequency with which θ_{IQ} goes through 2π is both:
  - The frequency of the ‘baseband’ I & Q signals
  - The dipole-to-reference cavity frequency mismatch
- θ_{IQ} presented here obtained for IPB(Y) for a calibration in the 2-on-1 resolution study


IPB (Y) I' on ADC 1-2
theta
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
37
38
39
40
41
42
43
44
45
46
Sample number


IPB (Y) I' on ADC 4-5
theta
Sample number
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
37
38
39
40
41
42
43
44
45
46

θ_{IQ} vs. sample number

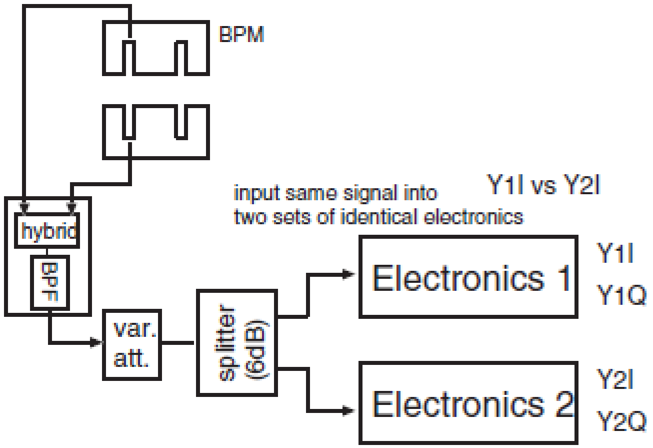
- θ_{IQ} changes by 1 radian over 10 samples (28 ns) or 2π over 180 ns
- The I and Q frequency is:

$$\text{frequency} = \frac{1}{180\ \text{ns}} = 6\ \text{MHz}$$

- This matches the dipole-to-reference cavity frequency mismatch reported at the ATF IP BPM meeting

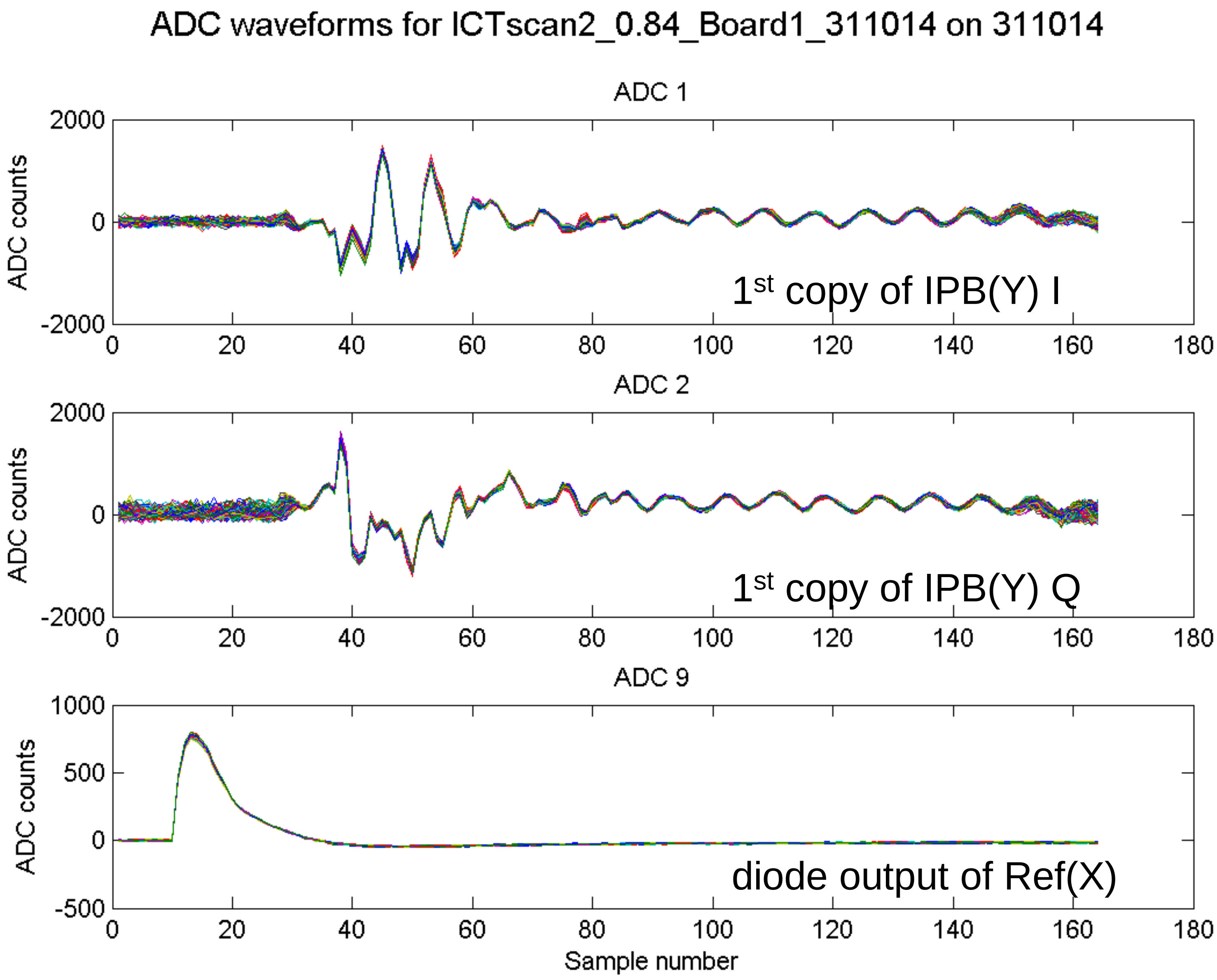
2-on-1 resolution study

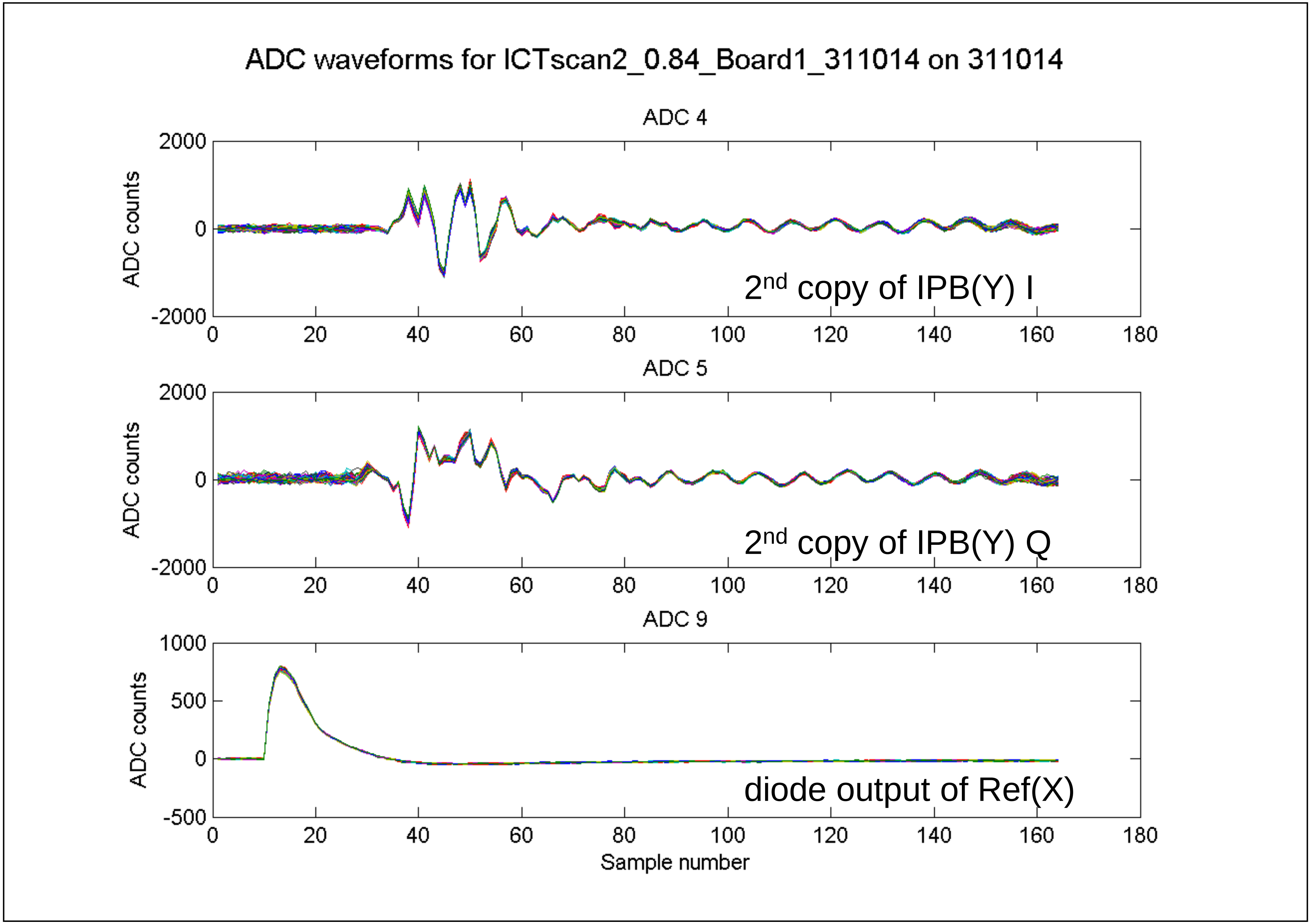
- 2 processors on one BPM to estimate resolution limit due to electronics noise (Inoue et al., 2008):



Waveforms

- Outputs from the two sets of electronics digitised by the FONT5 board at 357 MHz:
  - Electronics Y1 & 07-2: I on ADC1, Q on ADC2
  - Electronics Y2 & 07-3: I on ADC4, Q on ADC5
  - Ref(X) diode output on ADC9
- Data not charge normalised given charge stability (standard deviation of 0.01 x 10^{10}), i.e. $\text{position} = I\cos\theta_{IQ} + Q\sin\theta_{IQ}$


ADC waveforms for ICTscan2_0.84_Board1_311014 on 311014
ADC 1
ADC counts
1st copy of IPB(Y) I
ADC 2
ADC counts
1st copy of IPB(Y) Q
ADC 9
ADC counts
diode output of Ref(X)
Sample number

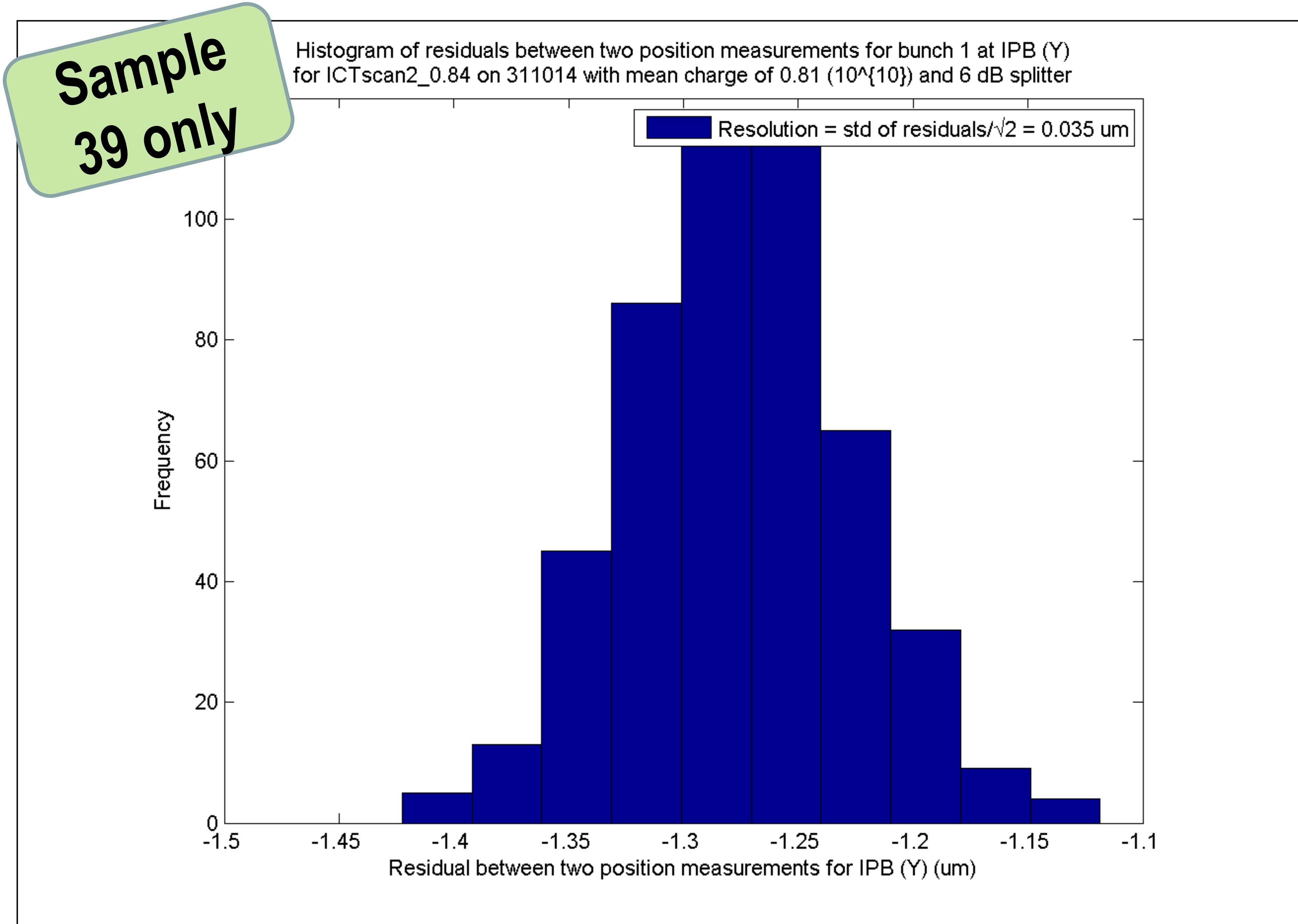

ADC waveforms for ICTscan2_0.84_Board1_311014 on 311014
ADC 4
ADC counts
2nd copy of IPB(Y) I
ADC 5
ADC counts
2nd copy of IPB(Y) Q
ADC 9
ADC counts
diode output of Ref(X)
Sample number
2000
0
-2000
1000
500
-500
0
20
40
60
80
100
120
140
160
180

Resolution

- One method to calculate the resolution is to obtain a set of position measurements from each set of electronics
- The resolution then is

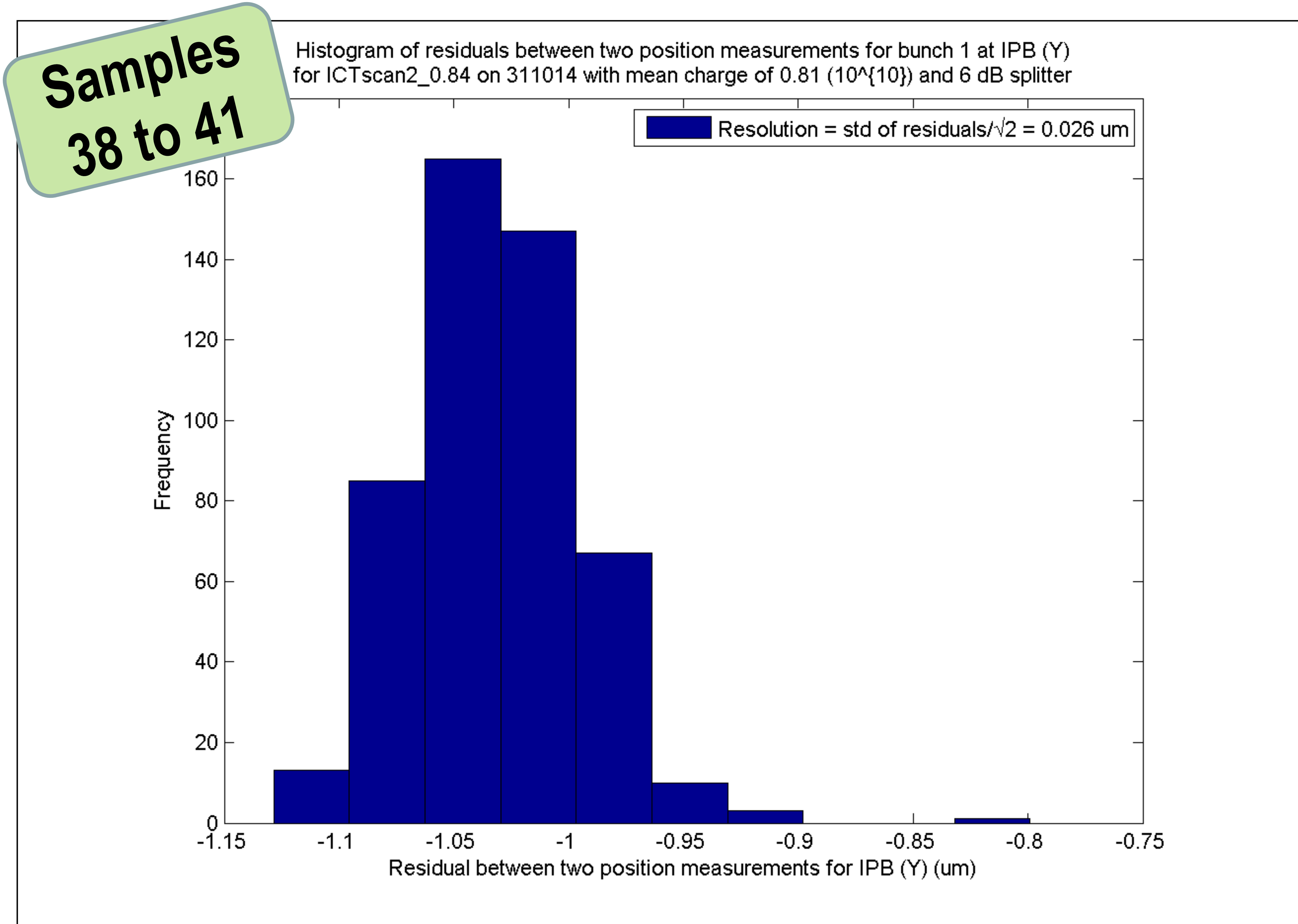
$$\text{Resolution} = \frac{\text{std}(\text{Residual})}{\sqrt{2}}$$

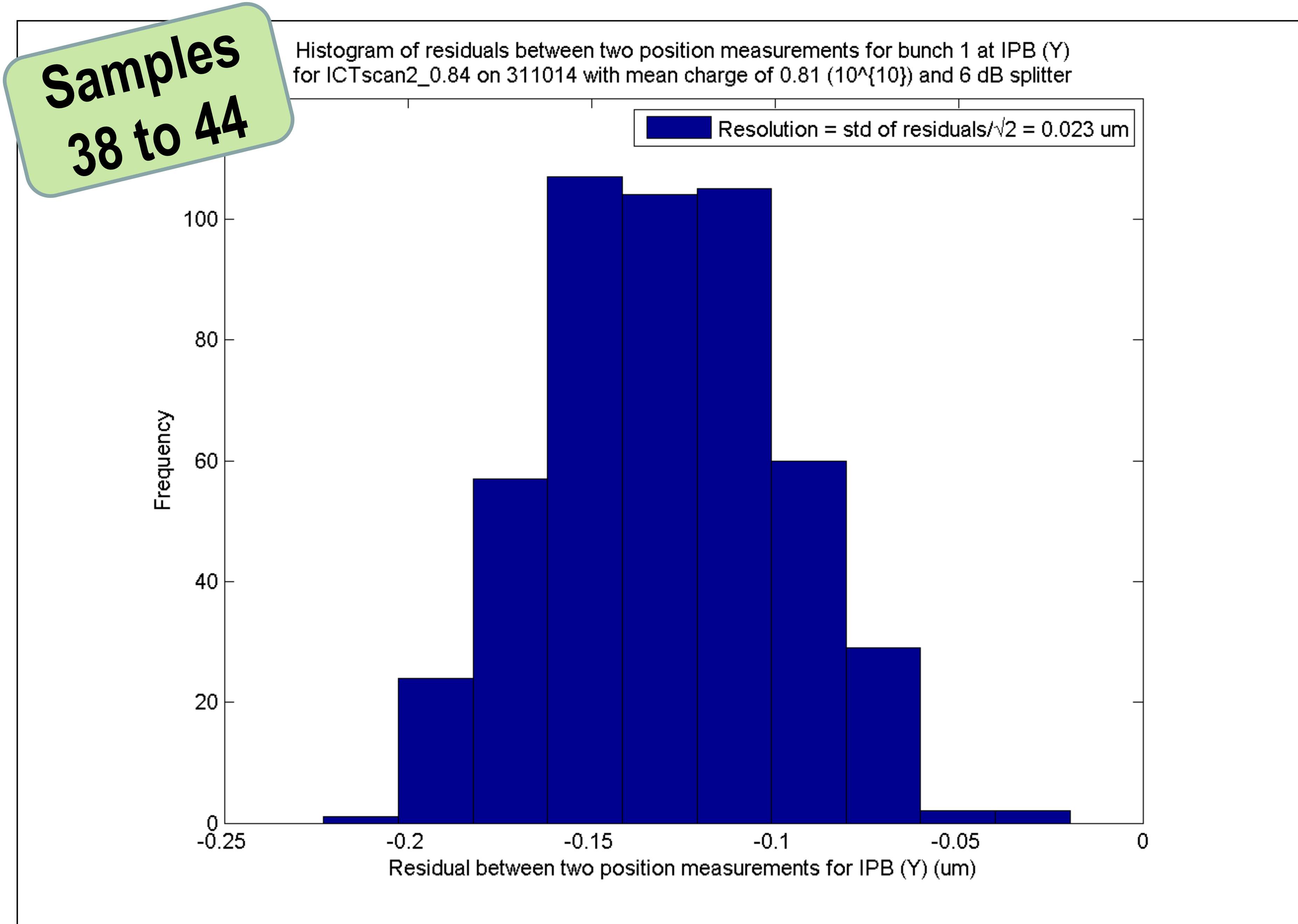
where the residual is the set of differences between the two sets of measurements


Sample
39 only
Histogram of residuals between two position measurements for bunch 1 at IPB (Y)
for ICTscan2_0.84 on 311014 with mean charge of 0.81 (10^{10}) and 6 dB splitter
Resolution = std of residuals/√2 = 0.035 um
Frequency
100
80
60
40
20
0
-1.5
-1.45
-1.4
-1.35
-1.3
-1.25
-1.2
-1.15
-1.1
Residual between two position measurements for IPB (Y) (um)

Averaging

- When averaging, a position is obtained for each sample number; then, the position measurements from each sample are averaged with equal weighting
- The alternative (not done here) is to integrate the data across a window first and then obtain a position measurement


Samples
38 to 41
Histogram of residuals between two position measurements for bunch 1 at IPB (Y)
for ICTscan2_0.84 on 311014 with mean charge of 0.81 (10^{10}) and 6 dB splitter
Resolution = std of residuals/√2 = 0.026 um
Frequency
0
20
40
60
80
100
120
140
160
-1.15
-1.1
-1.05
-1
-0.95
-0.9
-0.85
-0.8
-0.75
Residual between two position measurements for IPB (Y) (um)


Samples
38 to 44
Histogram of residuals between two position measurements for bunch 1 at IPB (Y)
for ICTscan2_0.84 on 311014 with mean charge of 0.81 (10^{10}) and 6 dB splitter
Resolution = std of residuals/√2 = 0.023 um
Frequency
Residual between two position measurements for IPB (Y) (um)
100
80
60
40
20
0
-0.25
-0.2
-0.15
-0.1
-0.05
0

Resolution

- Another method to calculate the resolution is to fit:

$$y_1 = \alpha y_2 + \beta q + \gamma$$

where y_1, y_2 are positions from the two sets of electronics, q is the charge (from MFB1FF) and α, β, γ are fit constants

- For ICTscan_0.84 using samples 38 to 44, $\alpha = 0.98, \beta = 0.00042, \gamma = -0.44$

Resolution

- The resolution is

$$\text{Resolution} = \frac{\text{std}\left(\text{y}_1 - \text{y}_1^{\text{pred}}\right)}{\sqrt{2}} = 23\ \text{nm}$$

for charge of 0.81 x 10^{10} with 6 dB splitter

- Equivalent to 19 nm resolution at 0.5 x 10^{10} with no splitter

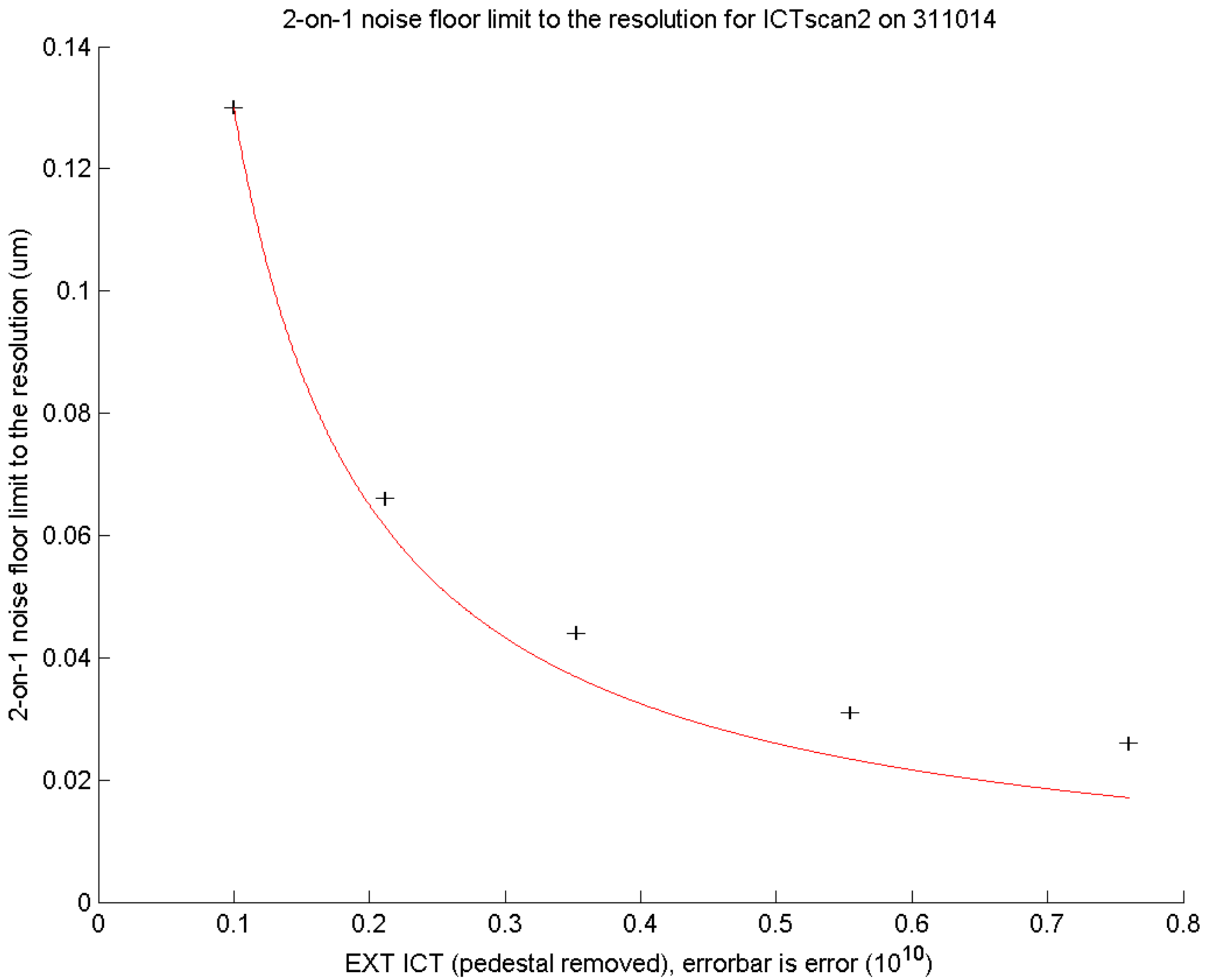
Resolution

- Including Q' to fit:

Method	Resolution (nm)
$\mathrm{std}(y_1 - y_2)/\sqrt{2}$	22.9
Fitting charge, constant	22.6
Fitting charge, Q' of 2nd set, constant	22.3
Fitting charge, Q' of both sets, constant	22.2

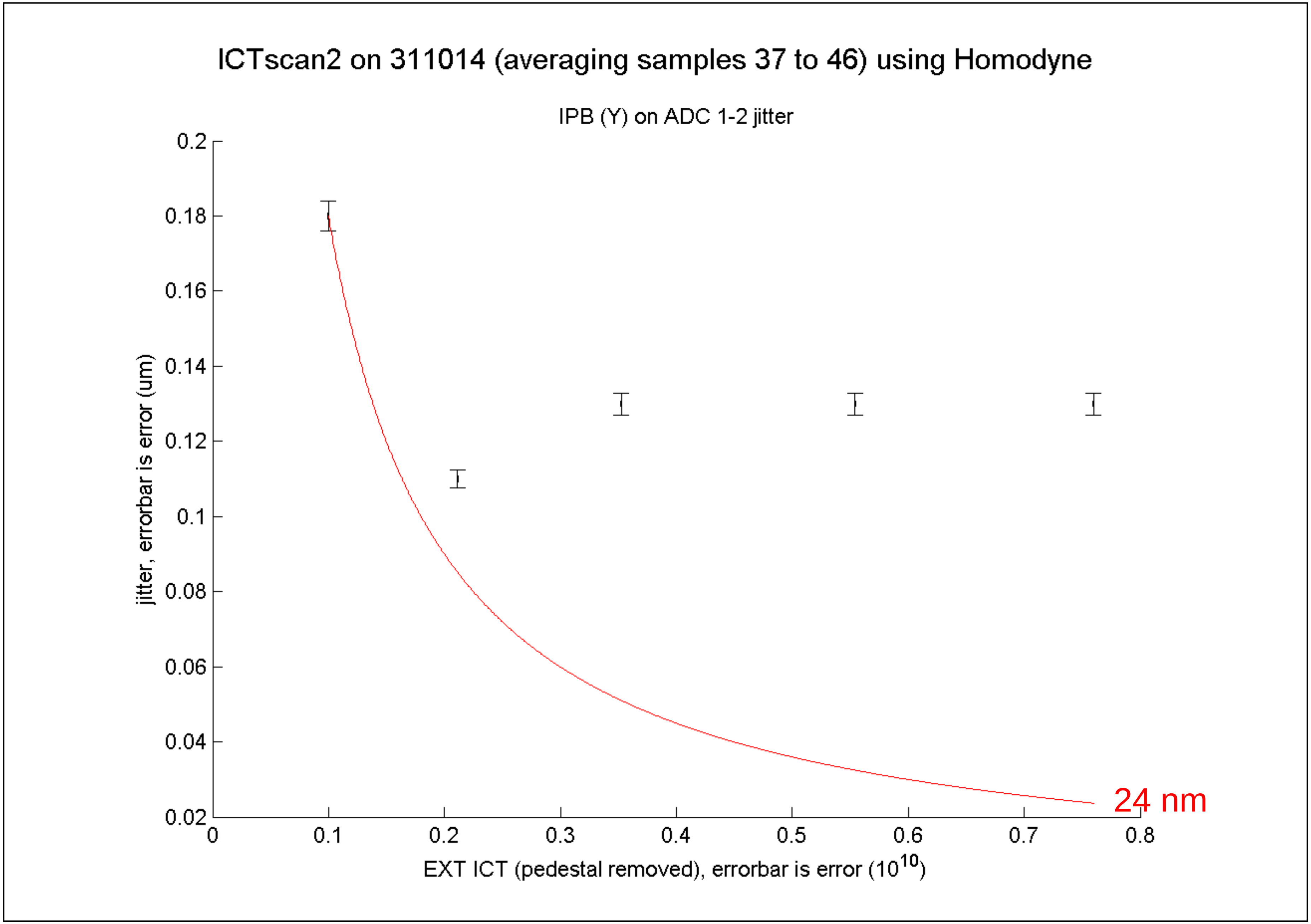
Resolution vs. charge

- Calibrating at each charge using MFB1FF for charge normalisation produces plot of 2-on-1 resolution vs. charge
- 0.047 x 10^{10} EXT ICT pedestal removed
- Curve shown takes $\mathrm{resolution} = 1/\mathrm{charge}$ dependence taking lowest-charge point as starting point


2-on-1 noise floor limit to the resolution for ICTscan2 on 311014
2-on-1 noise floor limit to the resolution (um)
EXT ICT (pedestal removed), errorbar is error (10^10)
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

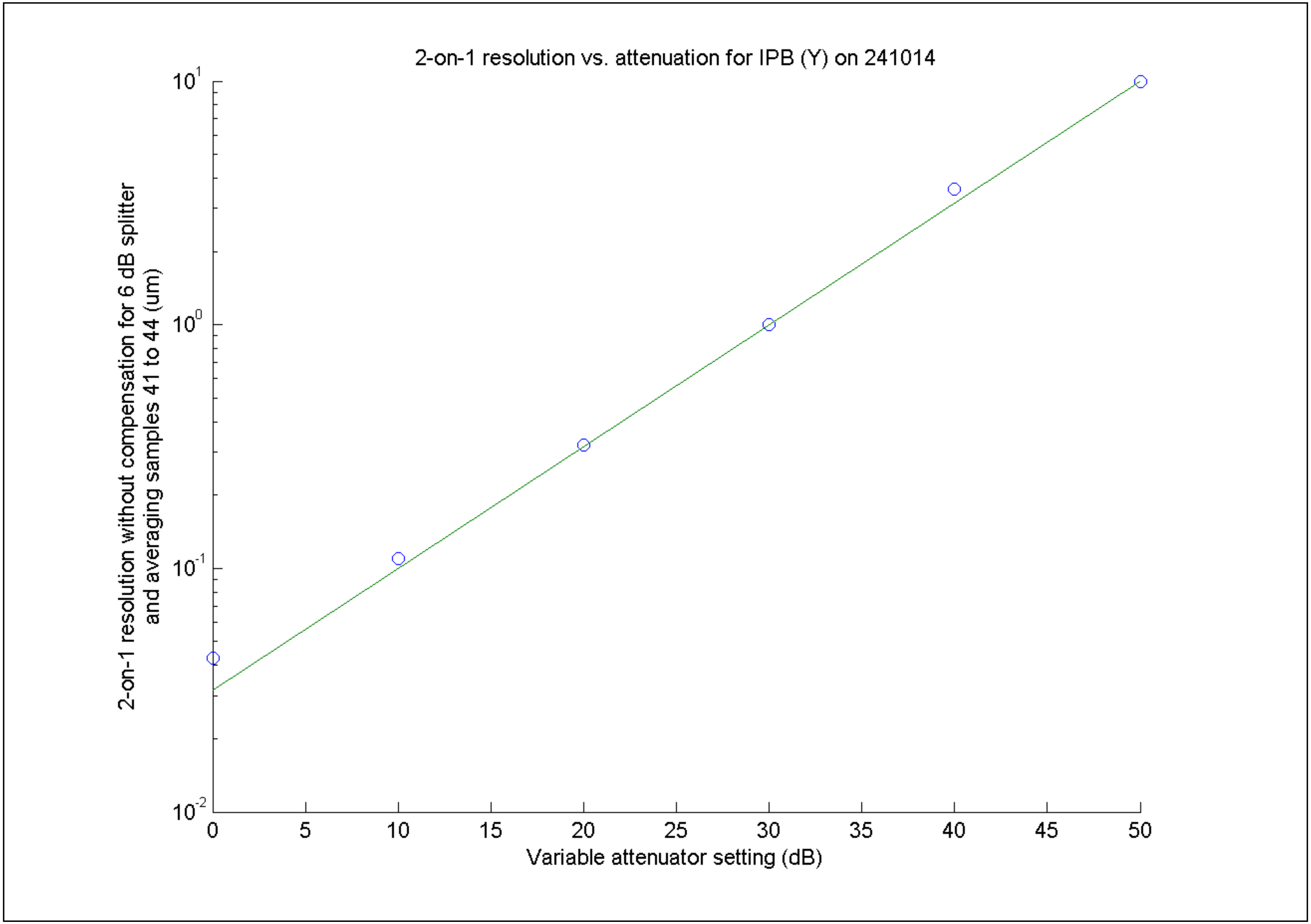
Jitter vs. charge

- Jitter measured at each charge over the same charge scan
- Calibrated at each charge, using MFB1FF for charge normalisation
- 0.047×10^{10} EXT ICT pedestal removed
- Curve shown takes $\mathrm{jitter} = 1/\mathrm{charge}$ dependence taking lowest-charge point as starting point


ICTscan2 on 311014 (averaging samples 37 to 46) using Homodyne
IPB (Y) on ADC 1-2 jitter
jitter, errorbar is error (um)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
EXT ICT (pedestal removed), errorbar is error (10^10)
24 nm

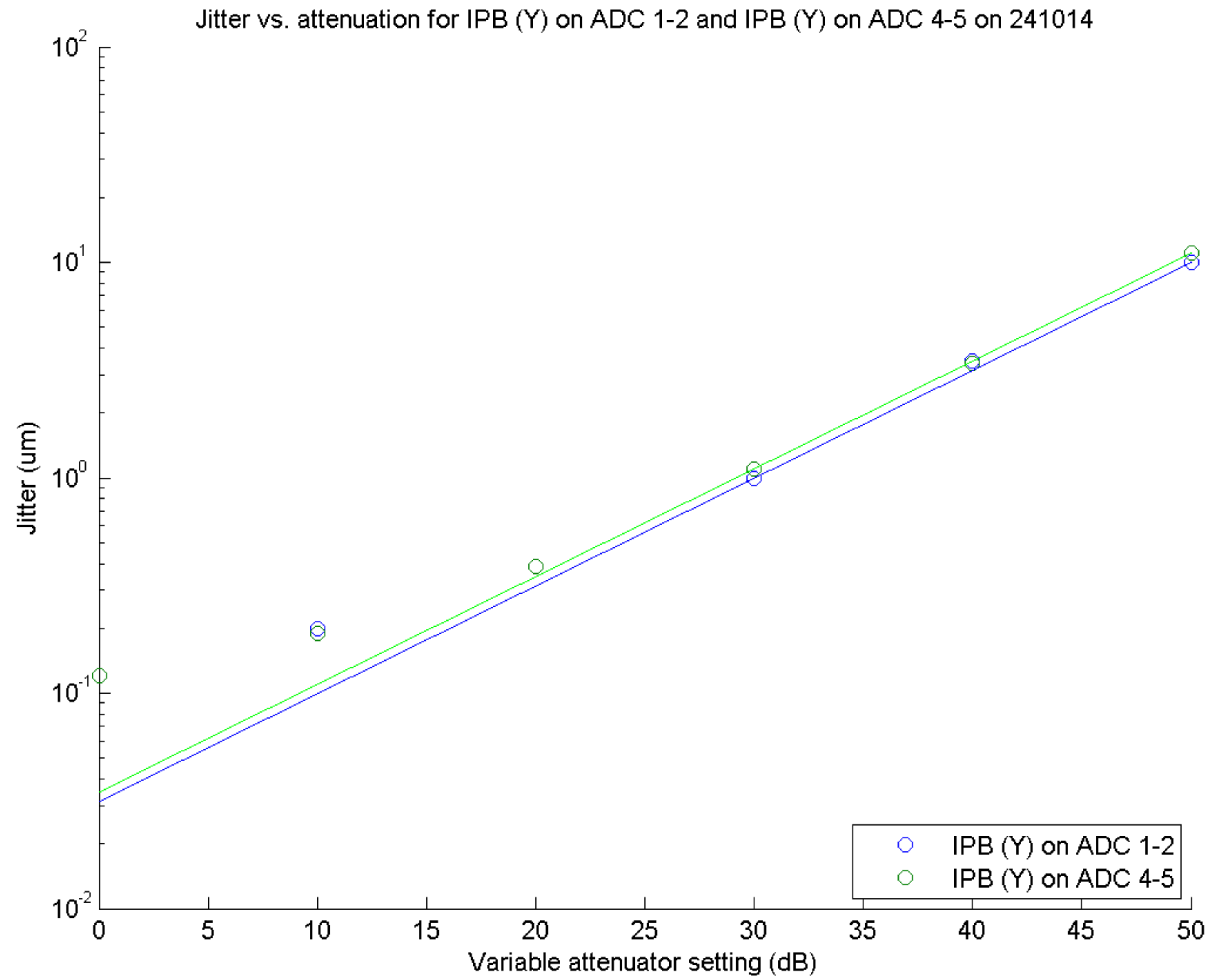
Resolution vs. attenuation

- 2-on-1 resolution vs. attenuation
- Data taken on 241014
- Operated at a charge of 0.84×10^{10}
- Calibrated at each attenuation, using reference diode for charge normalisation
- Straight line shows expected scaling with attenuation taking highest-attenuation point as starting point


2-on-1 resolution vs. attenuation for IPB (Y) on 241014
2-on-1 resolution without compensation for 6 dB splitter
and averaging samples 41 to 44 (um)
Variable attenuator setting (dB)
10^1
10^0
10^-1
10^-2
0
5
10
15
20
25
30
35
40
45
50

Jitter vs. attenuation

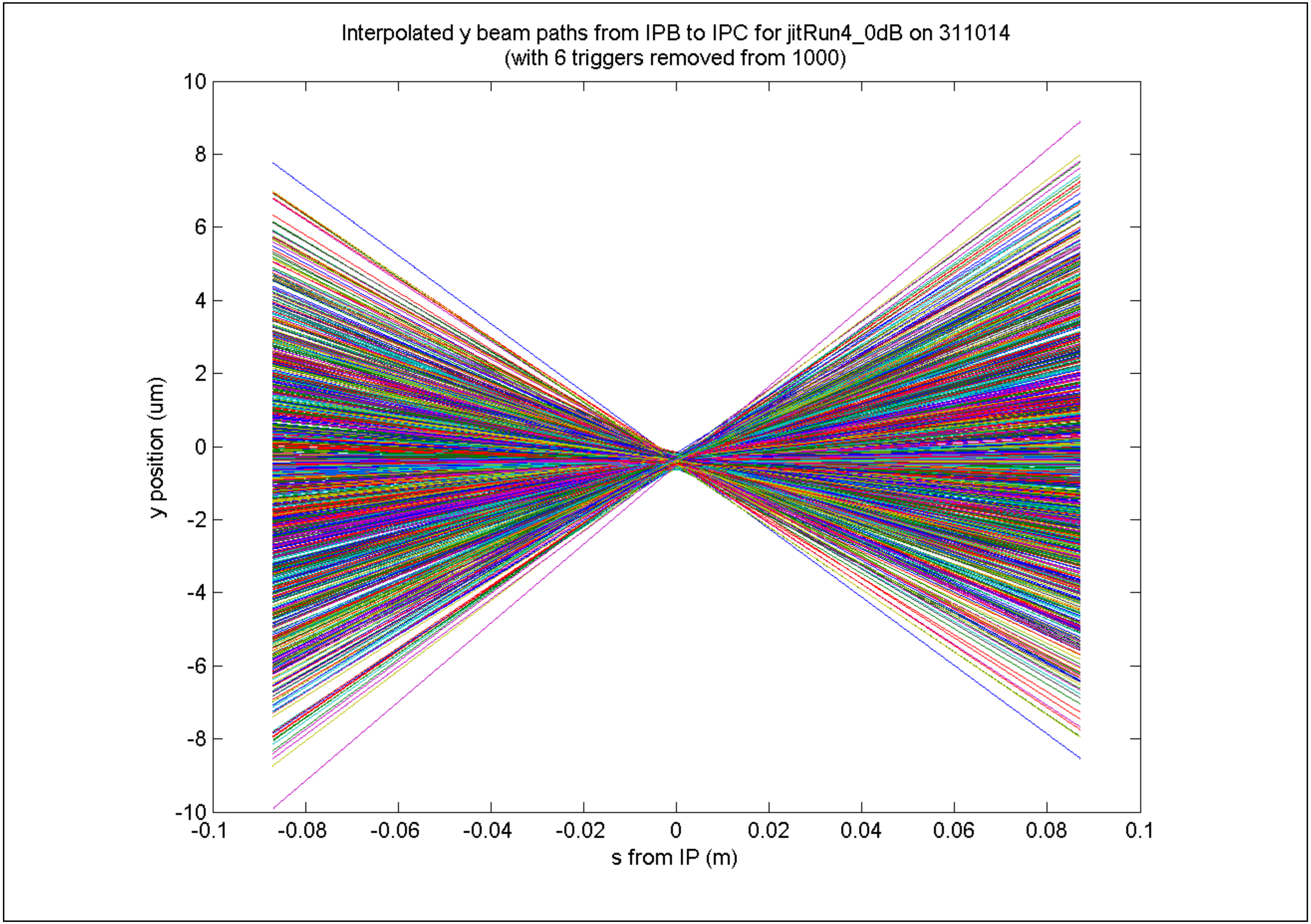
- Jitter vs. attenuation for same data set as for resolution vs. attenuation

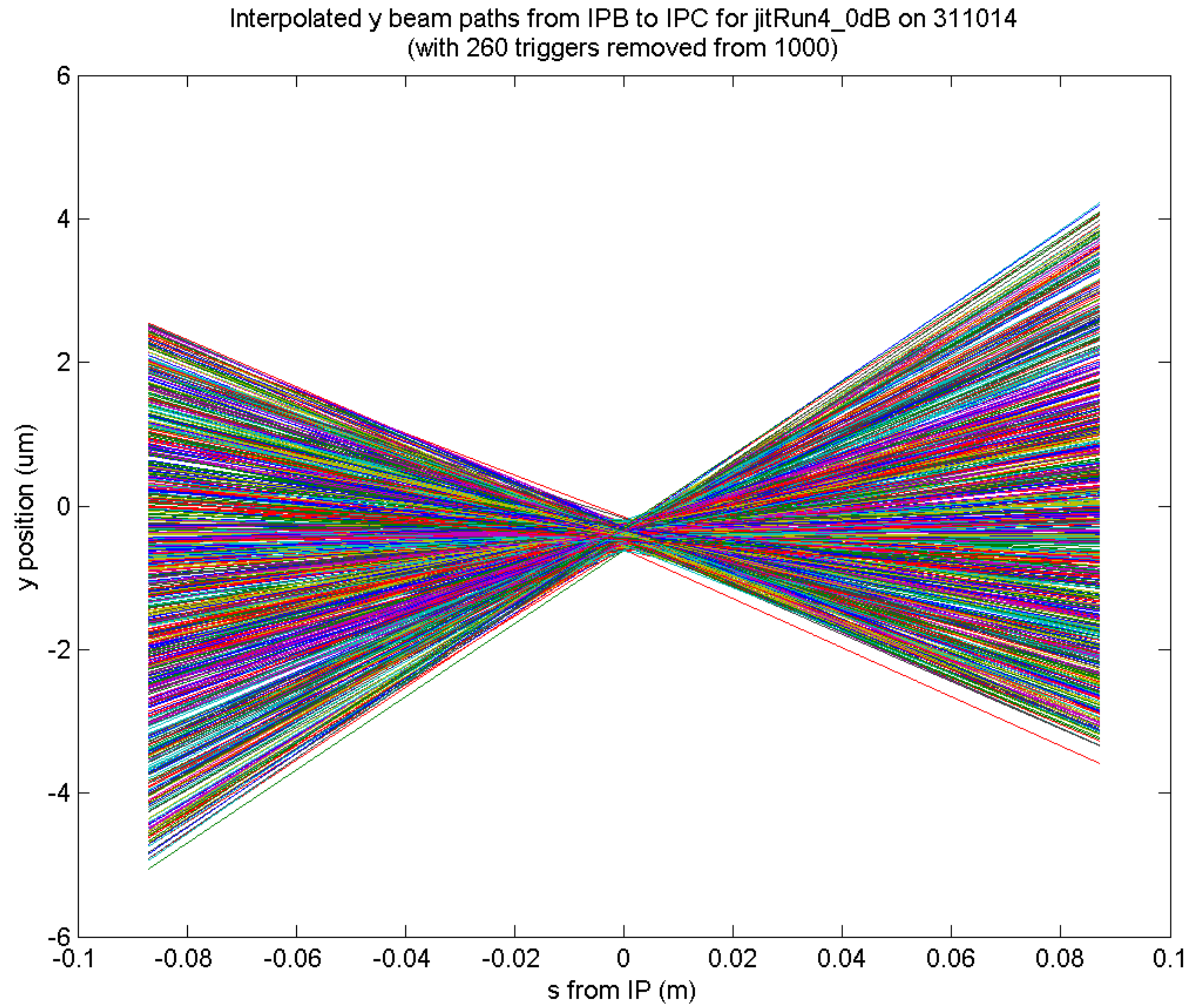


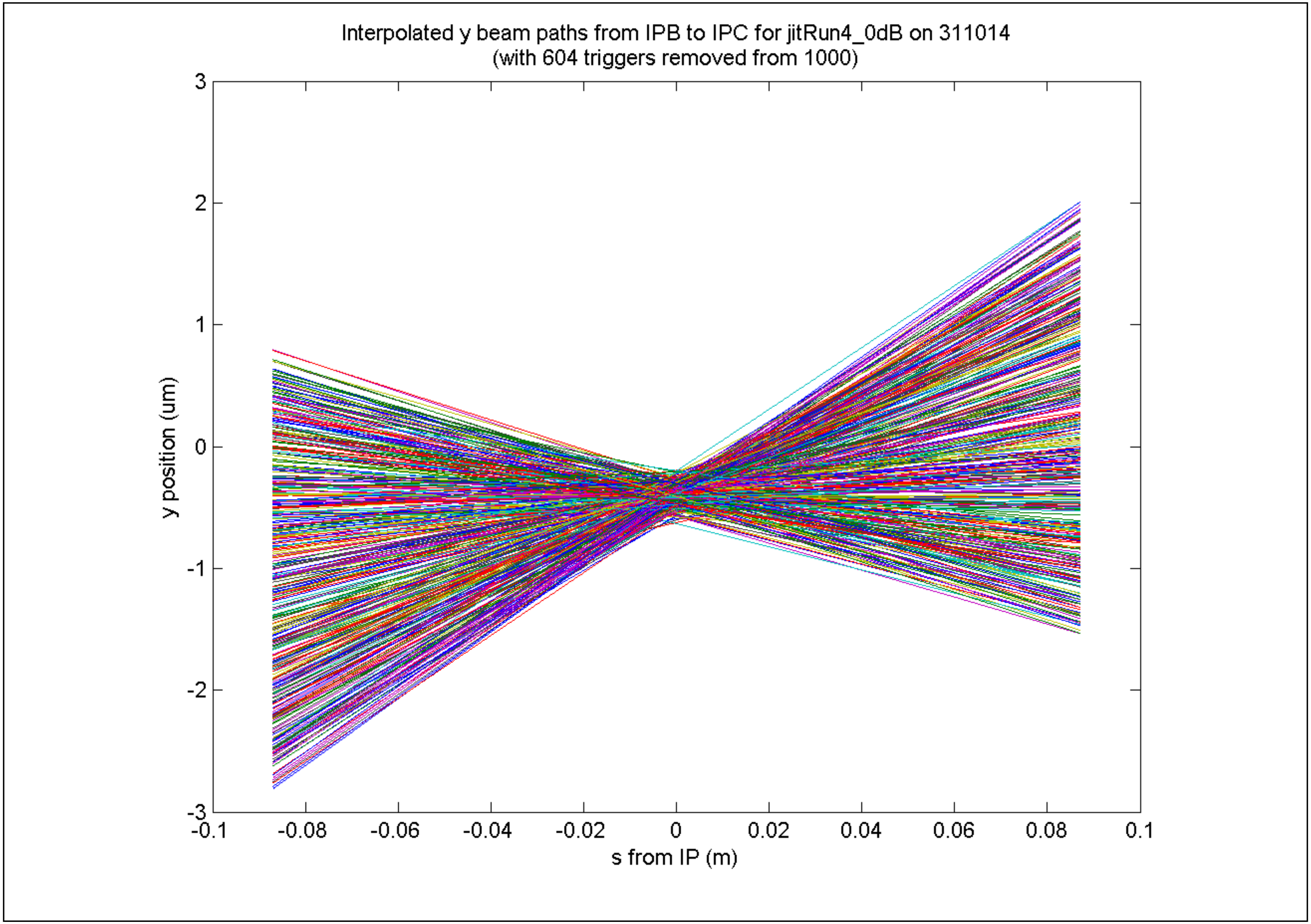
Jitter vs. attenuation for IPB (Y) on ADC 1-2 and IPB (Y) on ADC 4-5 on 241014
10^2
10^1
10^0
10^{-1}
10^{-2}
Jitter (um)
0
5
10
15
20
25
30
35
40
45
50
Variable attenuator setting (dB)
IPB (Y) on ADC 1-2
IPB (Y) on ADC 4-5

Saturation cut

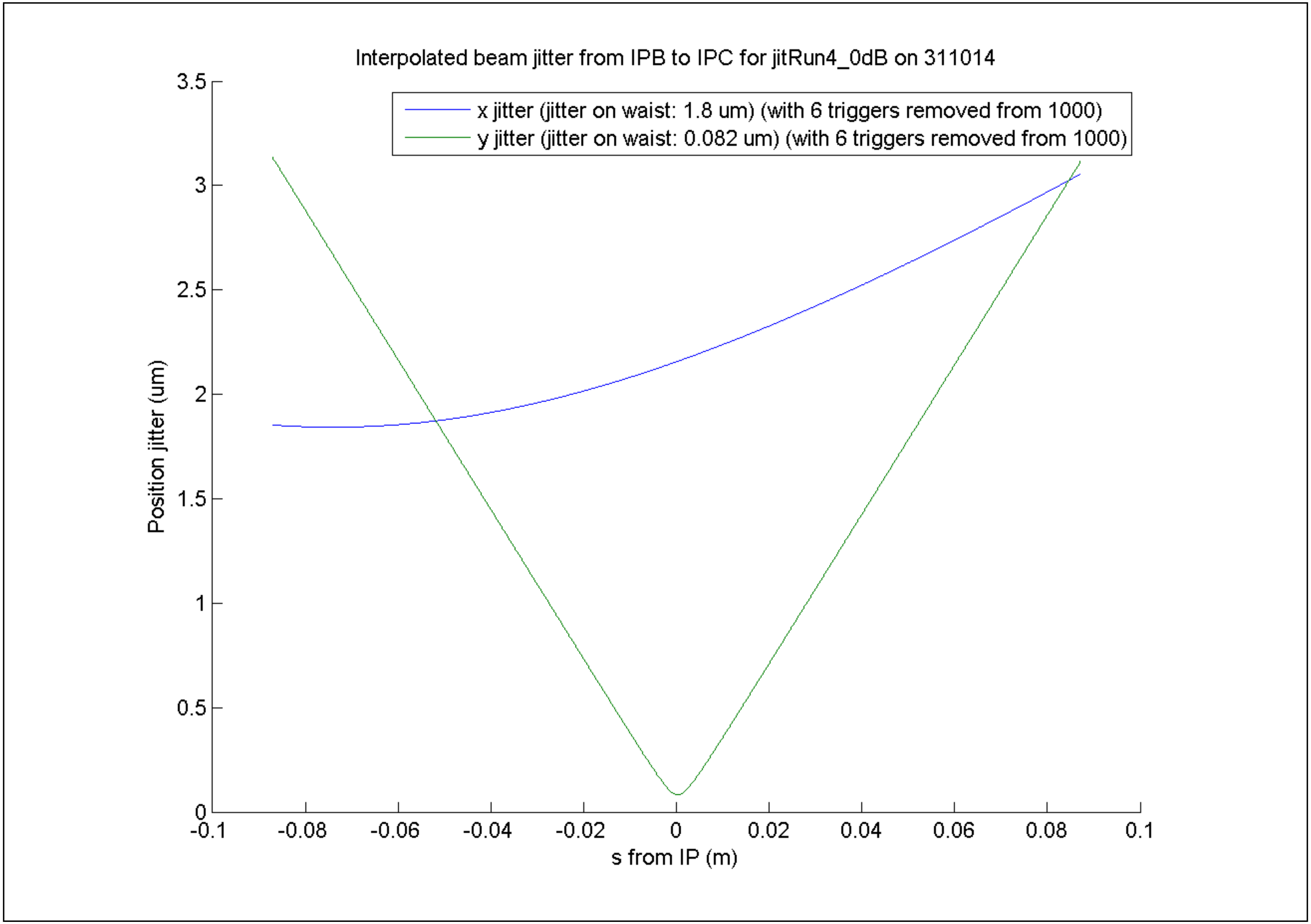
- Place cuts on $\sqrt{I^2 + Q^2}$ of:
  - 6000 ADC counts (6 triggers cut from 1000)
  - 3000 ADC counts (260 triggers cut from 1000)
  - 2500 ADC counts (604 triggers cut from 1000)
- For each:
  - Interpolate y trajectory from IPB to IPC
  - Measure interpolated jitter from IPB to IPC
- Waist at nominal IP, 0.48 x 10^{10} charge


Interpolated y beam paths from IPB to IPC for jitRun4_0dB on 311014
(with 6 triggers removed from 1000)
y position (um)
s from IP (m)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1

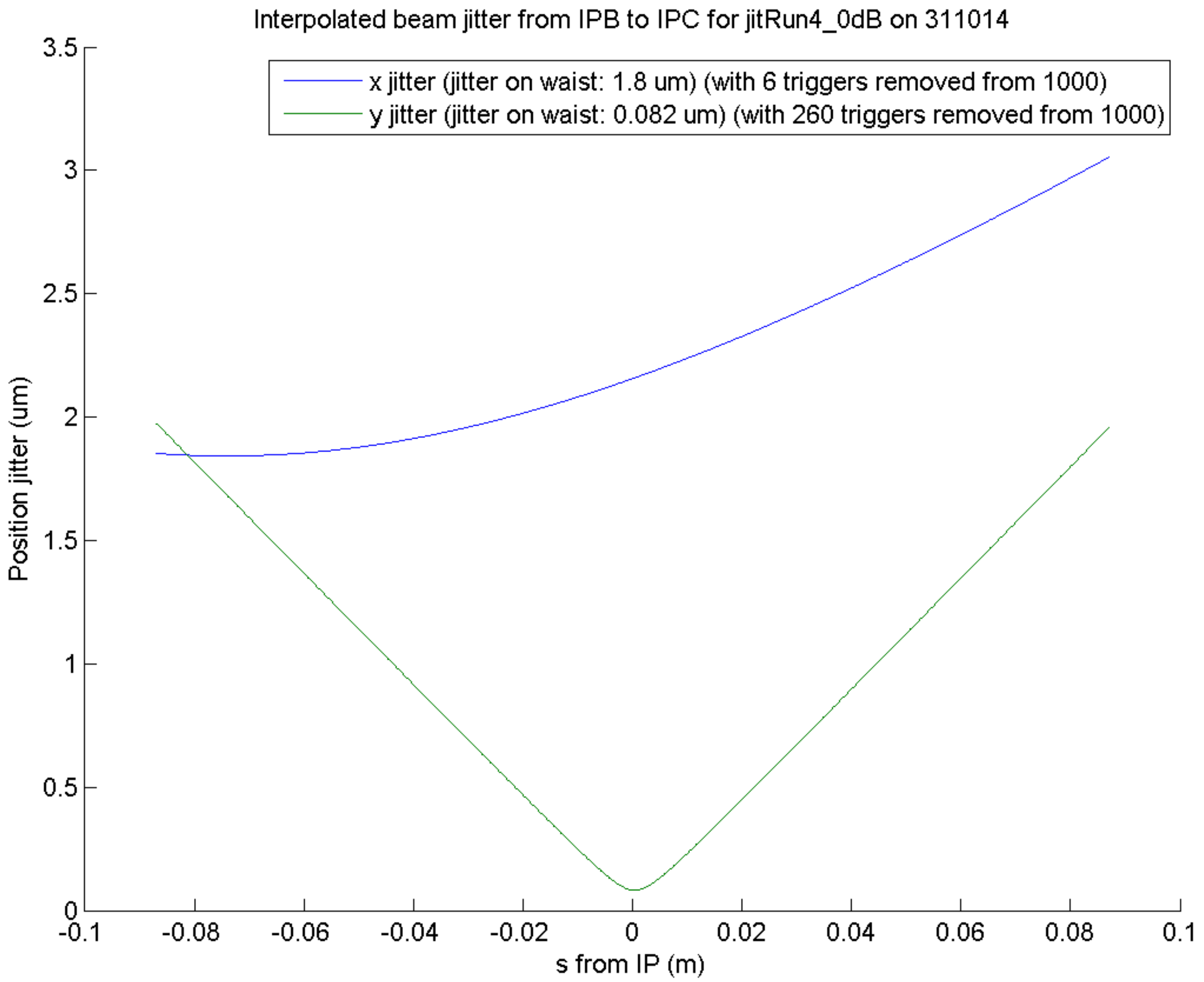

Interpolated y beam paths from IPB to IPC for jitRun4_0dB on 311014
(with 260 triggers removed from 1000)
y position (um)
s from IP (m)
6
4
2
0
-2
-4
-6
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1



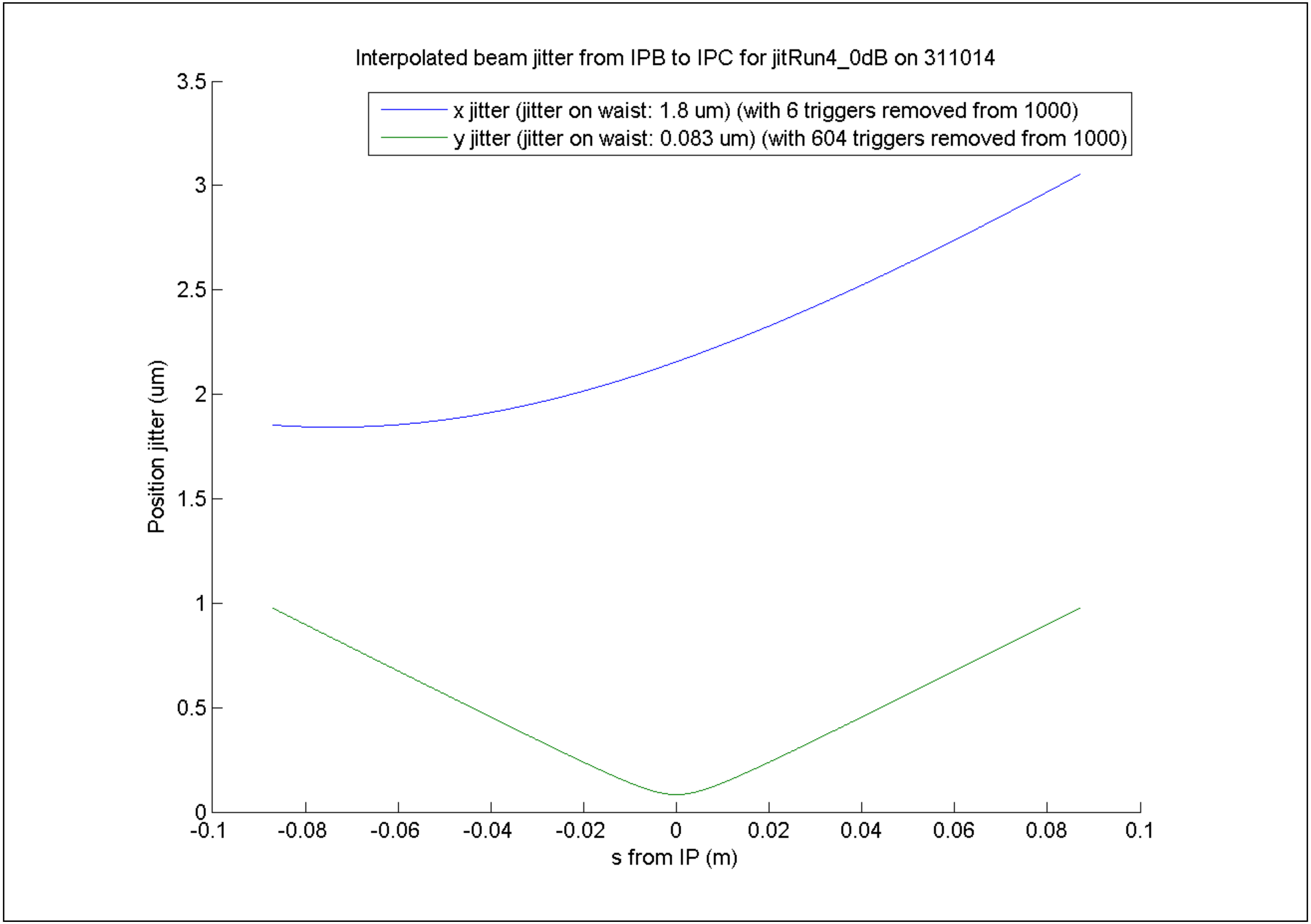
Interpolated y beam paths from IPB to IPC for jitRun4_0dB on 311014
(with 604 triggers removed from 1000)
y position (um)
s from IP (m)
3
2
1
0
-1
-2
-3
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1



Interpolated beam jitter from IPB to IPC for jitRun4_0dB on 311014
x jitter (jitter on waist: 1.8 um) (with 6 triggers removed from 1000)
y jitter (jitter on waist: 0.082 um) (with 6 triggers removed from 1000)
Position jitter (um)
s from IP (m)
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1



Interpolated beam jitter from IPB to IPC for jitRun4_0dB on 311014
x jitter (jitter on waist: 1.8 um) (with 6 triggers removed from 1000)
y jitter (jitter on waist: 0.082 um) (with 260 triggers removed from 1000)
Position jitter (um)
s from IP (m)
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1



Interpolated beam jitter from IPB to IPC for jitRun4_0dB on 311014
x jitter (jitter on waist: 1.8 um) (with 6 triggers removed from 1000)
y jitter (jitter on waist: 0.083 um) (with 604 triggers removed from 1000)
Position jitter (um)
s from IP (m)
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1

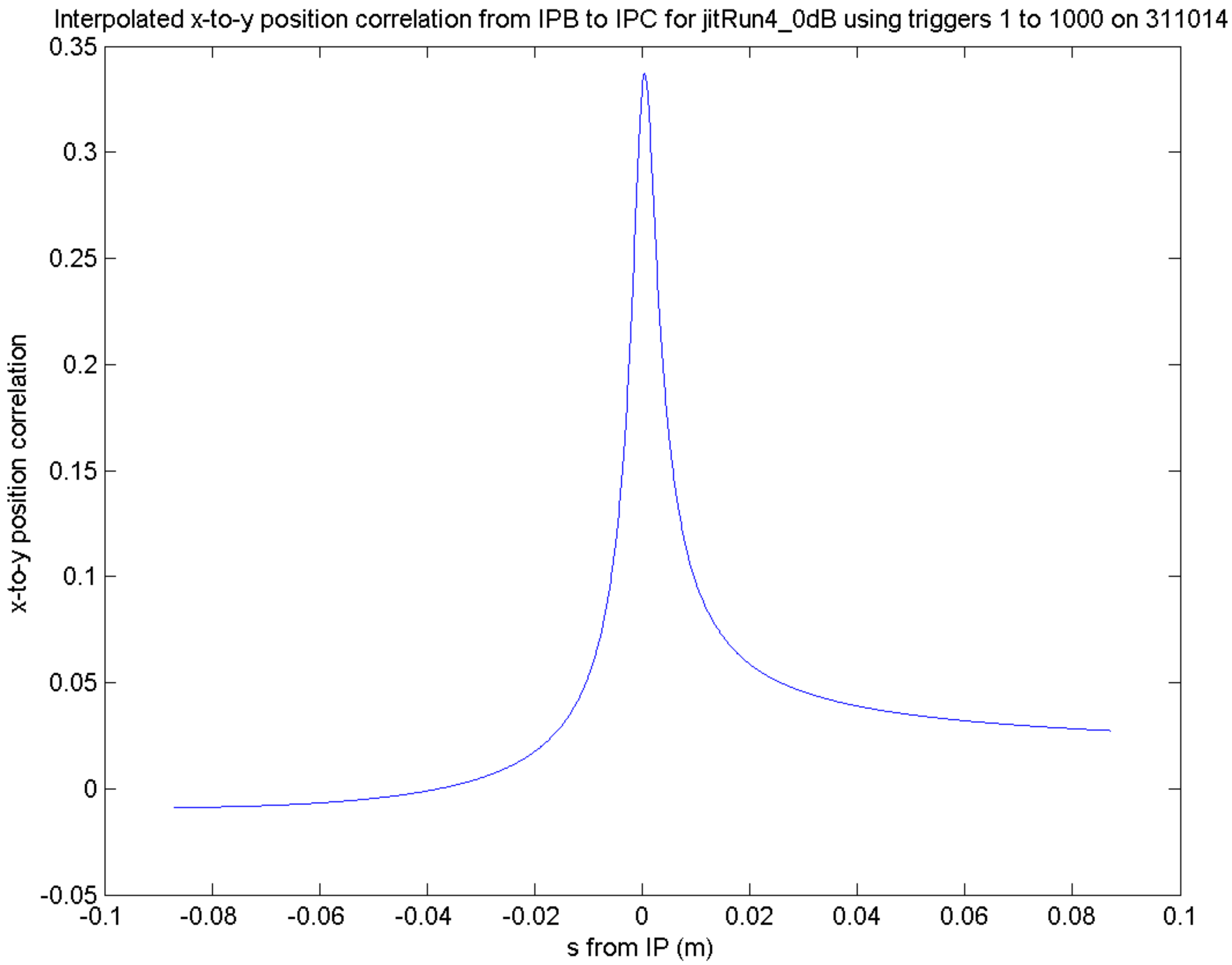
Saturation cut

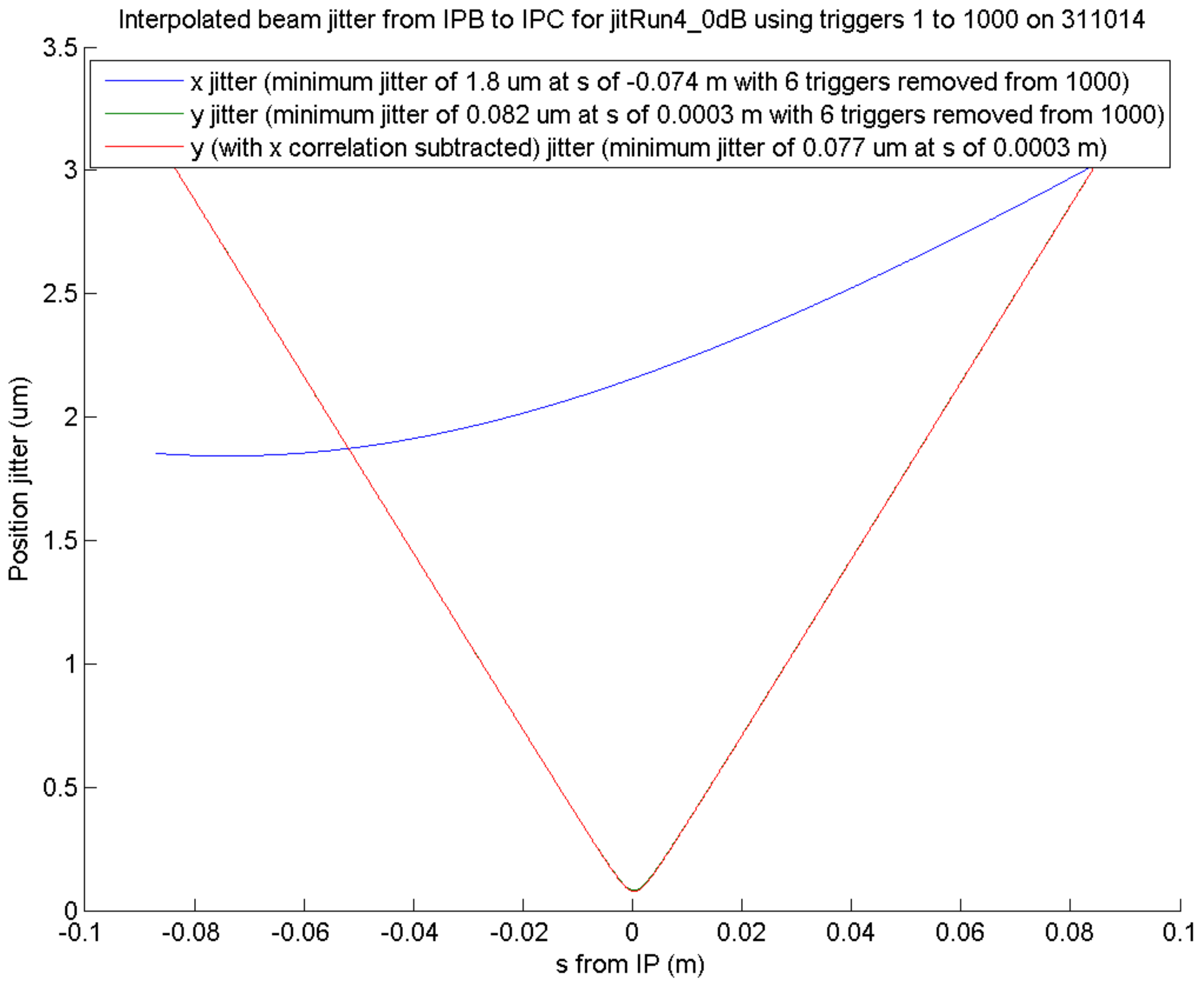
- Saturation cut leaves interpolated jitter unchanged (82 nm)
- As expected* if the BPM is not resolution limited with jitters of ~3 um at the BPMs

* Model says that there will be no y position correlation between locations on-waist and off-waist, so cutting on positions off-waist will not reduce jitter on-waist

x-to-y position correlation

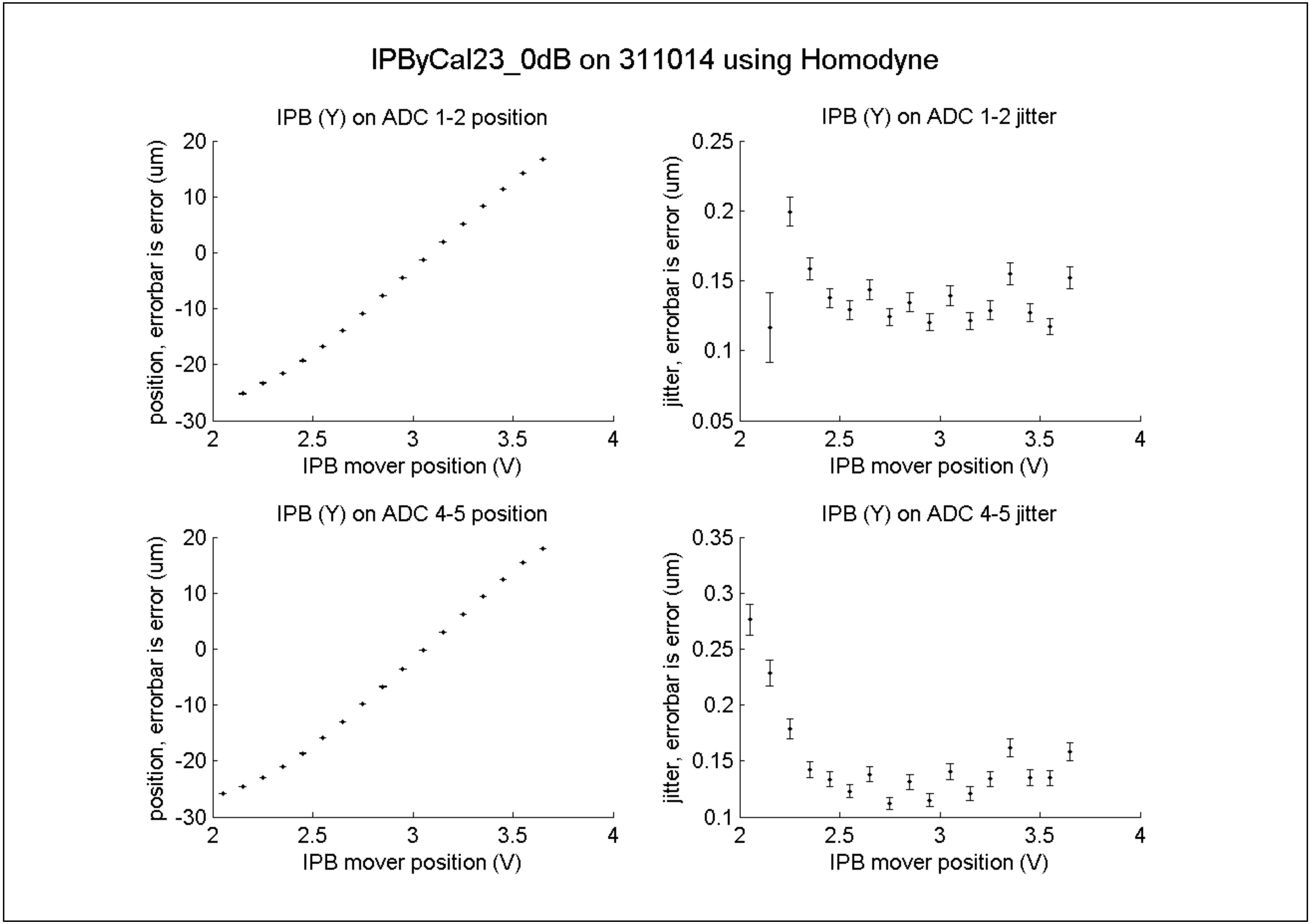
- x-to-y position correlation is:
  - < 5 % at IPB or IPC
  - < 35 % interpolated at y waist using IPB & IPC
- Removing correlation with x reduces interpolated y jitter on y waist from 82 to 77 nm


Interpolated x-to-y position correlation from IPB to IPC for jitRun4_0dB using triggers 1 to 1000 on 311014
x-to-y position correlation
s from IP (m)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1


Interpolated beam jitter from IPB to IPC for jitRun4_0dB using triggers 1 to 1000 on 311014
x jitter (minimum jitter of 1.8 um at s of -0.074 m with 6 triggers removed from 1000)
y jitter (minimum jitter of 0.082 um at s of 0.0003 m with 6 triggers removed from 1000)
y (with x correlation subtracted) jitter (minimum jitter of 0.077 um at s of 0.0003 m)
Position jitter (um)
s from IP (m)
3.5
3
2.5
2
1.5
1
0.5
0
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1

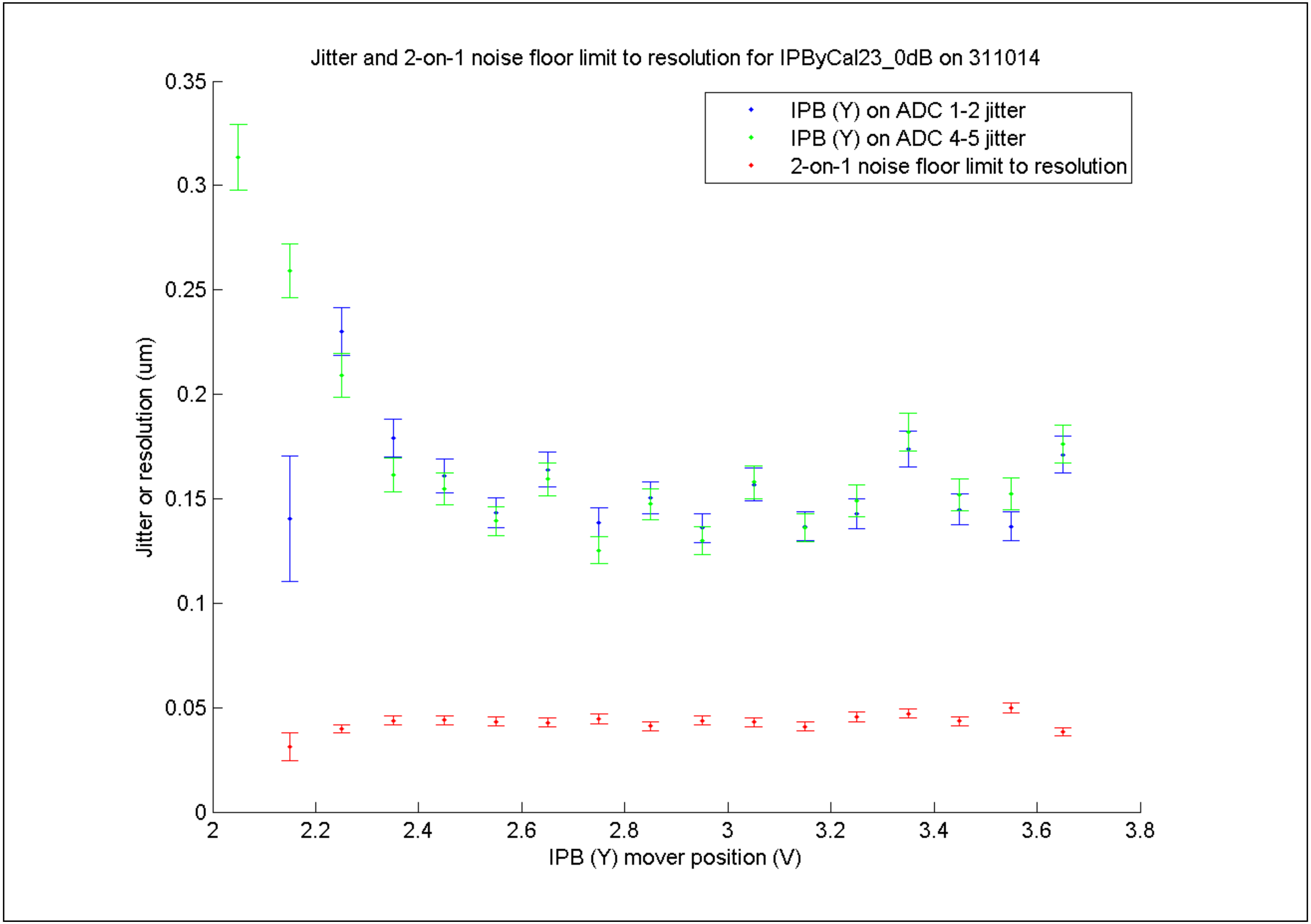
Dynamic range

- Wide mover scan of 48 um performed
- 0 dB but with 6 dB splitter (2-on-1 study)
- Data from 311014 at 0.5 x 10^{10} charge
- Constant jitter of ~120 nm measured across >30 um dynamic range suggests:
  - Wide dynamic range (cf. Honda: 5 um)
  - System is not resolution limited
- Non-linear position output at edge of scan


IPByCal23_0dB on 311014 using Homodyne
IPB (Y) on ADC 1-2 position
position, errorbar is error (um)
IPB mover position (V)
IPB (Y) on ADC 1-2 jitter
jitter, errorbar is error (um)
IPB mover position (V)
IPB (Y) on ADC 4-5 position
position, errorbar is error (um)
IPB mover position (V)
IPB (Y) on ADC 4-5 jitter
jitter, errorbar is error (um)
IPB mover position (V)

Dynamic range

- 2-on-1 noise limit to resolution calculated at each mover setting: appears constant over mover scan


Jitter and 2-on-1 noise floor limit to resolution for IPByCal23_0dB on 311014
IPB (Y) on ADC 1-2 jitter
IPB (Y) on ADC 4-5 jitter
2-on-1 noise floor limit to resolution
Jitter or resolution (um)
IPB (Y) mover position (V)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8

Jitter on waist

- jitRun16_0dB taken on 301014 after:
  - QF1FF & QD0FF current scans
  - EY, AY, Coup2 linear knobs scans
- 0.48×10^{10} charge with no splitter
- Waist at IPB
- See ‘Jitter minimisation at BPM on waist’ presentation for plots from current & linear knob scans, and jitter & correlation (with phase, charge, y’, x) vs. sample

Jitter on waist

Remove correlation with	**Jitter at IPB (Y) (nm)**	
	Single-sample	**Multi-sample**
Nothing	100	86
P2 charge	96	86
P2 phase	100	85
PIP (Y) position	100	86
IPB (X) position	100	85
All of the above	95	84

Jitter on waist

- Negligible correlation with
  - PIP (Y) position, i.e. angle in IP area
  - IPB (X) position, i.e. x, y coupling