20th ATF2 Project Meeting

March 22, 2018

IPBPM resolution

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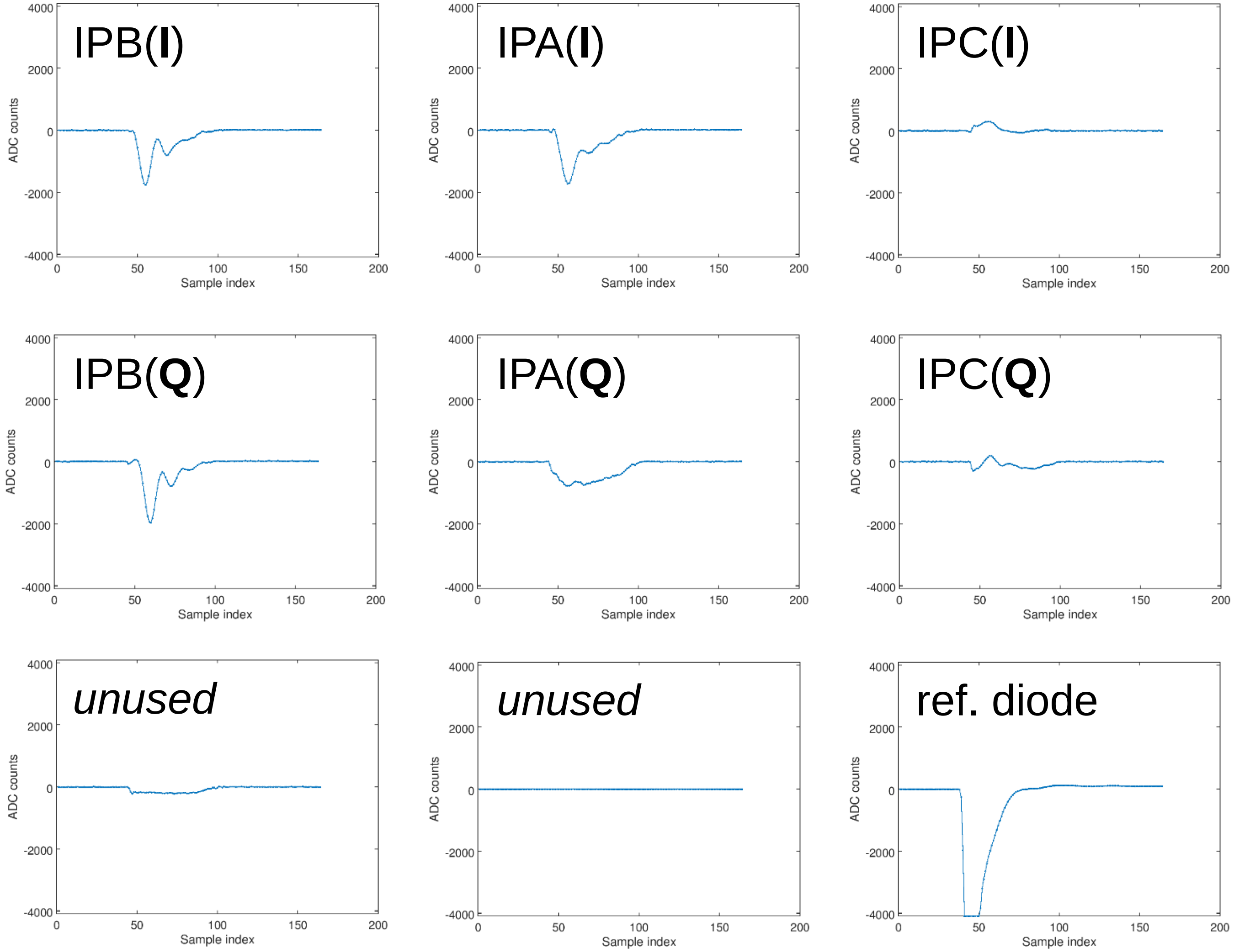
Contents

- Position analysis and calibration methods
- Resolution analysis and methods
- Latest results

FONT waveforms



Calculating position

For a cavity BPM, the charge-normalized position-dependent I' is:

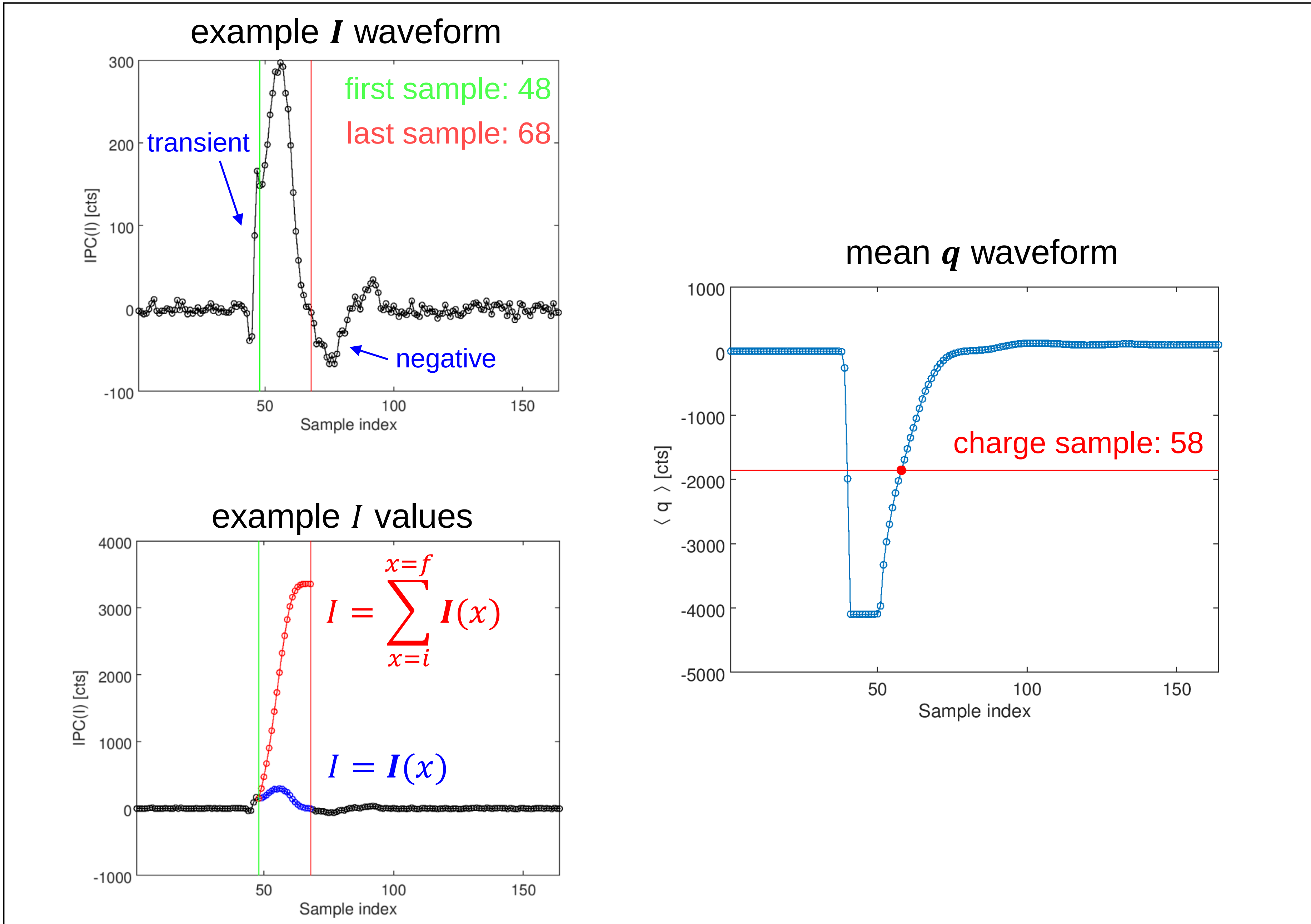
$$I' = \cos\theta \frac{I}{q} + \sin\theta \frac{Q}{q}$$

where q represents bunch charge and I and Q are scalar representations of the $\boldsymbol{I}$ and $\boldsymbol{Q}$ waveform vectors. Two options:

Single-sample	$I = \boldsymbol{I}(x)$	use sample x
Multi-sample	$I = \sum_{x=i}^{x=f} \boldsymbol{I}(x)$	integrate from sample i to sample f

Note that single-sample mode is always used for q as studies suggest integrating the charge waveform has little effect, whereas averaging $\boldsymbol{I}$ and $\boldsymbol{Q}$ typically does improve resolution. By convention the sample to use for the charge is the one that ensures $\langle|q|\rangle \sim 2000$ ADC counts.

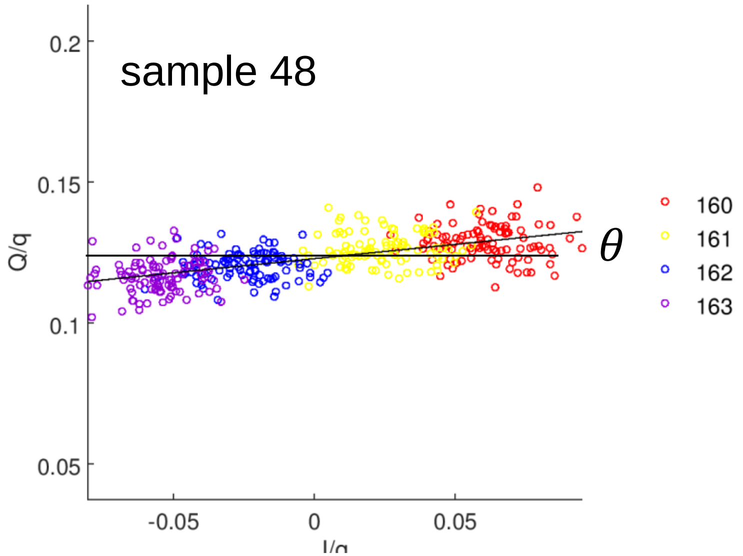
In either case, the single-sample x or the first and last samples of the integration range i and f are parameters to be optimized.

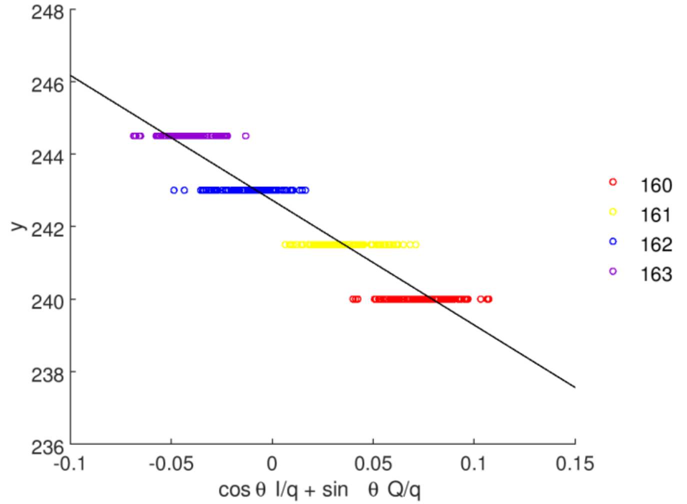

example I waveform
first sample: 48
last sample: 68
transient
negative
IPC(I) [cts]
Sample index
example I values
$I = \sum_{x=i}^{x=f} \boldsymbol{I}(x)$
$I = \boldsymbol{I}(x)$
IPC(I) [cts]
Sample index
mean q waveform
charge sample: 58
⟨ q ⟩ [cts]
Sample index

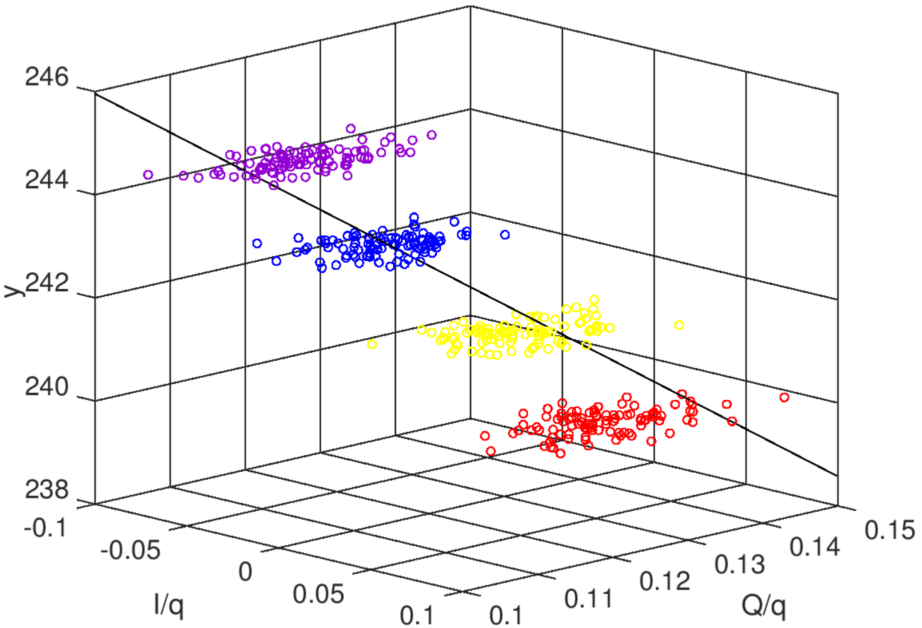
Calibration

- The relationship between actual beam position y and I' must be determined by changing effective beam position by known amount
- Ideally would use IPBPM movers but recent calibrations performed by displacing beam itself using QD0FF vertical mover
- Calibration involves determining two parameters: k and θ
- Traditionally a two-stage calibration is performed:
  - First perform a least-squares fit of Q as a function of I
    Let $Q = mI + c$, then $\theta = \tan^{-1}(m)$
  - Then fit calibration constant k from plot of I' vs. y
    Let $\mathrm{y} = mI' + d$, then $k = 1/m$
- Alternatively the calibration could be done in a single stage:
  - Fit $y = a_I I + a_Q Q + c$
  - Then $\theta = \tan^{-1}\left(\frac{a_Q}{a_I}\right)$ and $k = \frac{1}{\sqrt{a_I^2 + a_Q^2}}$

Calibration example



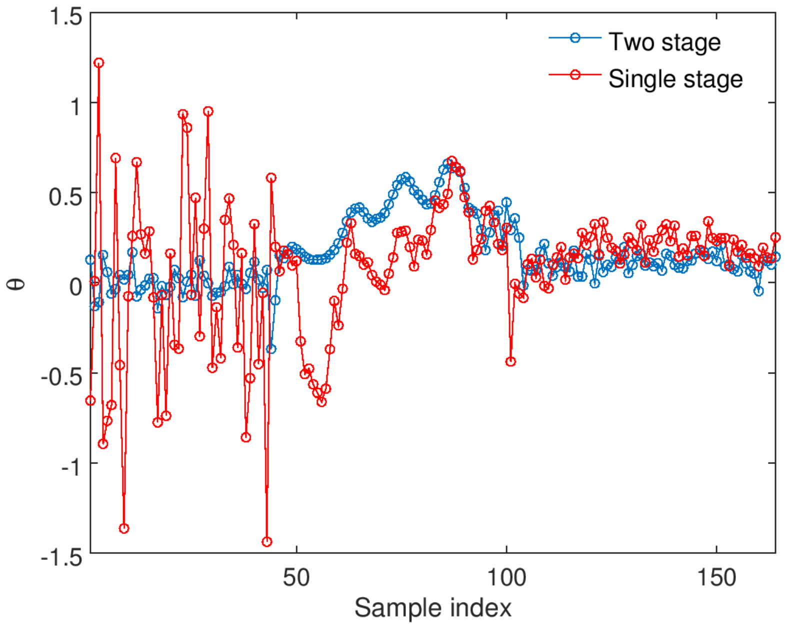




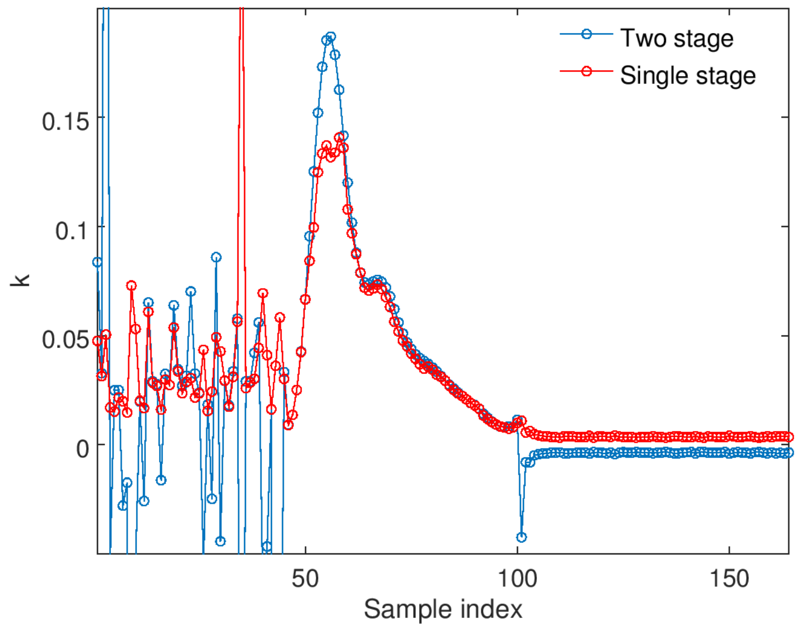
Calibration parameters

Scan the sample index over the entire waveform to see how θ, k evolve.

θ



k



Resolution

- Denote measured vectors of BPM positions y_i, y_j and y_k where $y_i = \gamma_i + \epsilon_i$ i.e. measured position is sum of true beam position vector γ_i and random error vector ϵ_i
- Predict position at one BPM as a function of positions at other two:

$$Y_i = C_{ij} y_j + C_{ik} y_k$$

prediction coefficients

- Calculate residual (difference between measurement and fit):

$$R_i = y_i - Y_i = y_i - (C_{ij} y_j + C_{ik} y_k)$$

- Standard deviation of residual vector is related to those of error vectors as follows:

$$\sigma_{R_i}^2 = \sigma_{\epsilon_i}^2 + C_{ij}^2 \sigma_{\epsilon_j}^2 + C_{ik}^2 \sigma_{\epsilon_k}^2$$

- Assuming $\sigma_{\epsilon_i} = \sigma_{\epsilon_j} = \sigma_{\epsilon_k} = \sigma$, the resolution is thus given by:

Question: How are prediction coefficients determined?

$$\sigma = \sqrt{\frac{\sigma_{R_i}}{1 + C_{ij}^2 + C_{ik}^2}}$$

Answer: Using three different methods.

1. “Geometric” method

Use the linear transfer matrices to express the position at the selected BPM as a function of the positions at the other two:

$$y_C = \left(M_{AC}^{11} - \frac{M_{AB}^{11} M_{AC}^{12}}{M_{AB}^{12}} \right) y_A + \left(\frac{M_{AC}^{12}}{M_{AB}^{12}} \right) y_B$$

In the case of the IP each transfer matrix corresponds to a drift:

$$M = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

So the prediction coefficients have very simple forms

$$C_{CA} = 1 - \frac{L_{AC}}{L_{AB}} = -2.156, \qquad C_{CB} = \frac{L_{AC}}{L_{AB}} = 3.156$$

2. “Fitting” method

The prediction coefficients are given by:

$$\begin{pmatrix} C_{ij} \\ C_{ik} \end{pmatrix} = [y_j \quad y_k]^{-1} \cdot y_i$$

i.e. the results from least-squares minimization of the residual vectors R_i

3. “Minimum resolution” method

The prediction coefficients are determined by explicitly minimizing the resolution itself:

$$\sigma = \sqrt{\frac{\sigma_{R_i}}{1 + C_{ij}^2 + C_{ik}^2}}$$

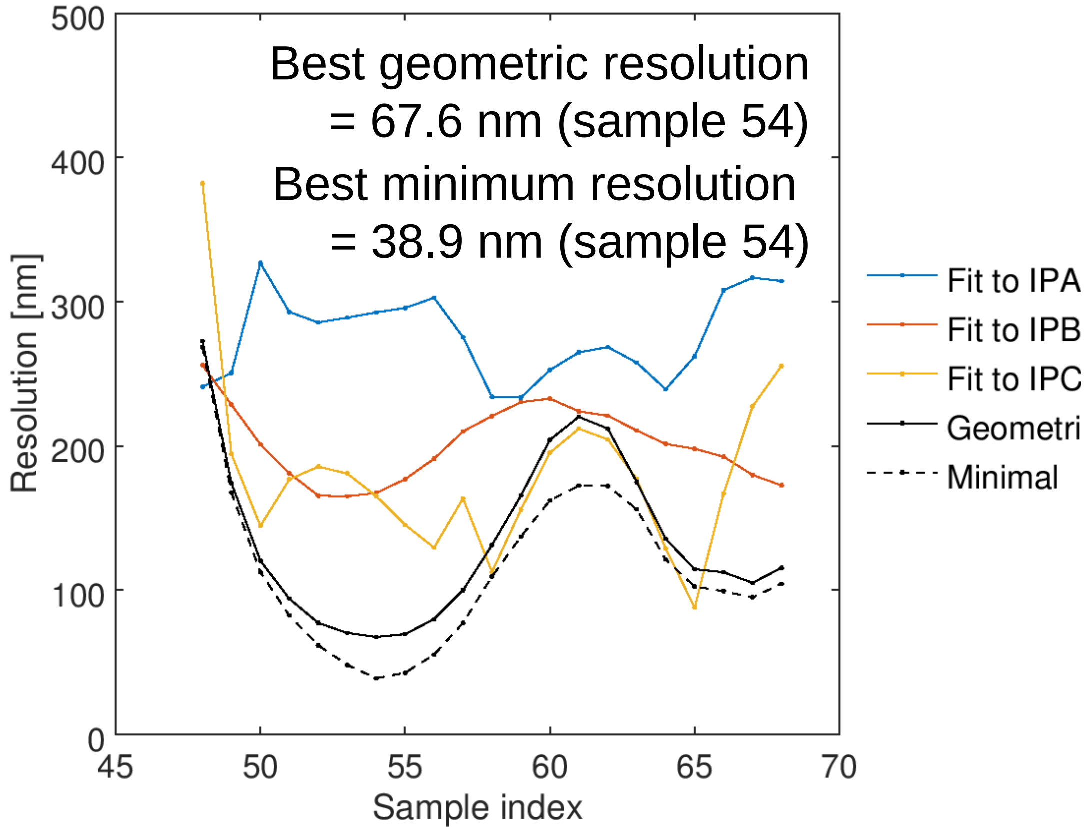
Comparison of methods

- **Geometric method** preferred. System fully constrained so that whichever BPM is used for prediction, a single result is obtained which is very easy to interpret.
- **Minimal resolution method** gives the minimum resolution consistent across the three BPMs for a given data set. This result is guaranteed to be an improvement on the result from the geometric method.
- **Fitting method** only one of the three to give different results depending on which BPM is used for prediction. The method does give information about the relative performance of the BPMs but the interpretation is not straightforward. If the results from the fitting method are drastically different to the value from the geometric method, it indicates a problem with the position measurement.
- **Multi-parameter method** involves using parameters other than the positions at the other BPMs (e.g. charge, Q') to predict the position at the BPM of interest. Can be insightful.

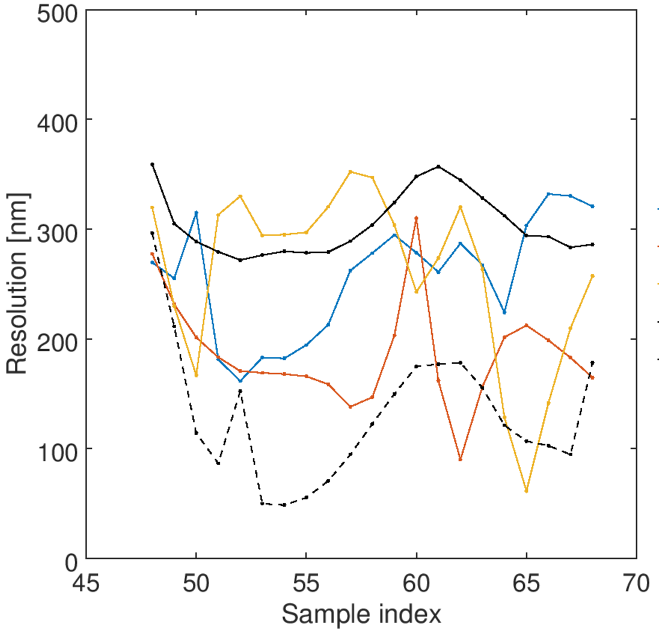
Single-sample resolution

jitRun2 (090218)

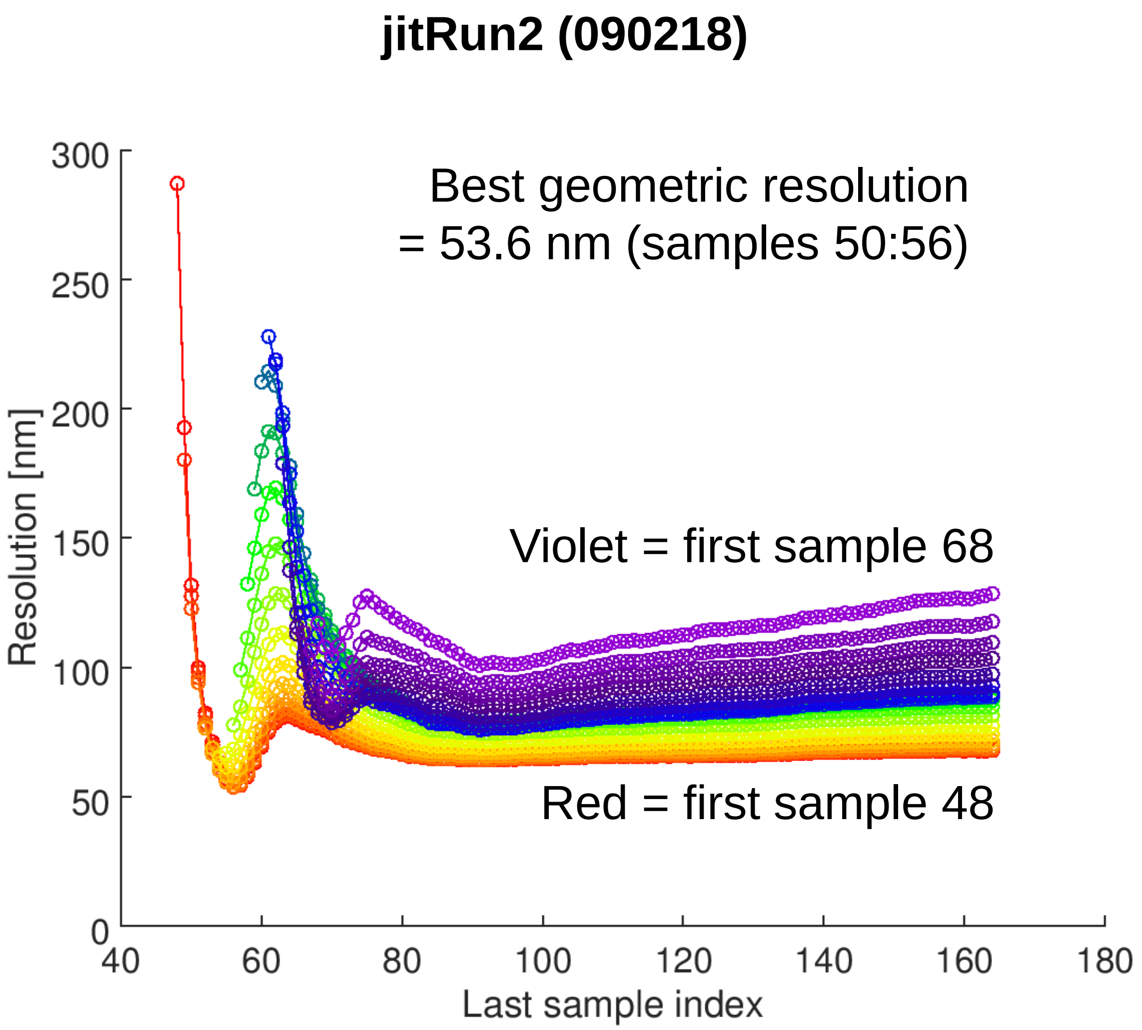
two stage calibration



single stage calibration

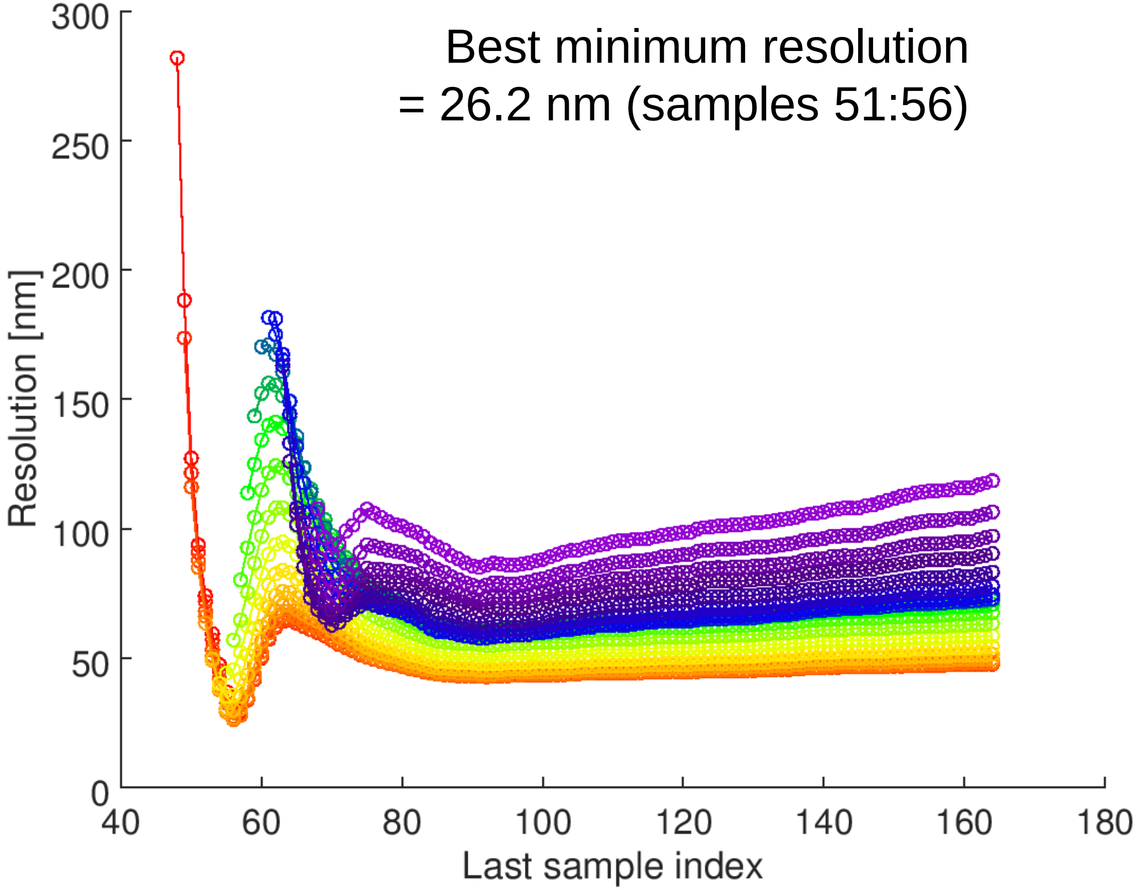


Multi-sample resolution (geo)



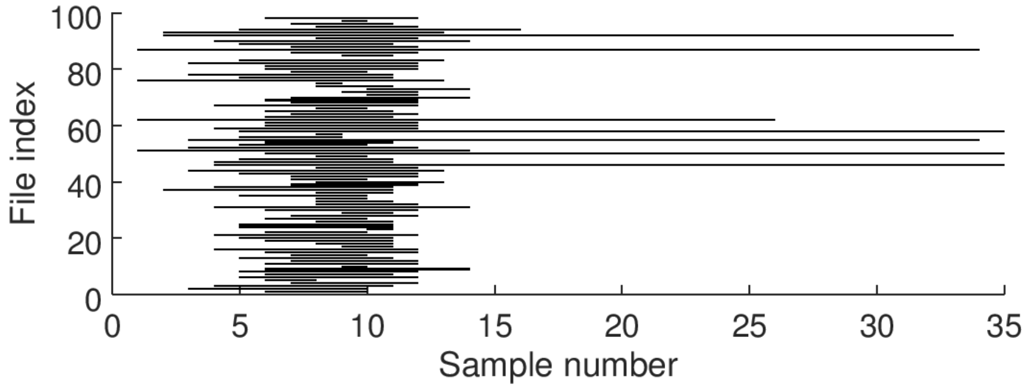
Multi-sample resolution (min)

jitRun2 (090218)

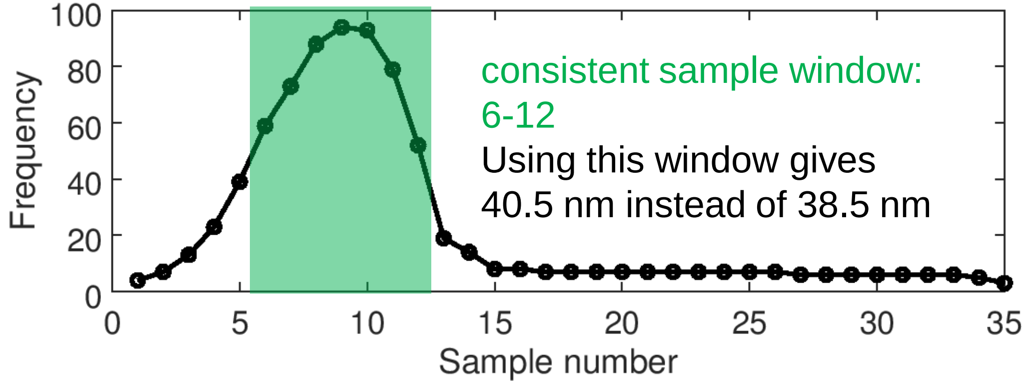


Sample window optimization

- Try every possible option for the integration window to see which consistently delivers best results.
- Performance metric: minimal jitter of corrected beam (i.e. bunch 2, feedback on).

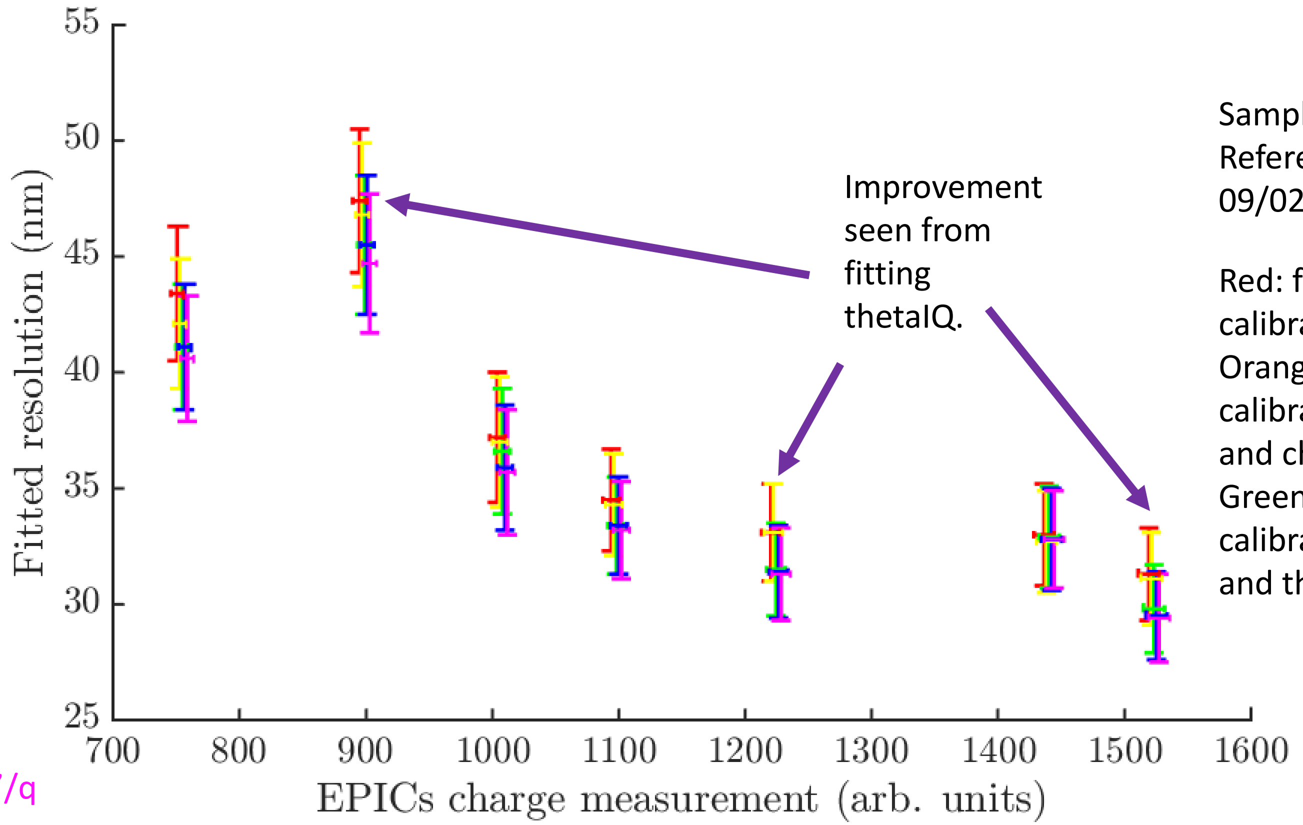


Each horizontal line represents optimized sample window for a given file.
e.g. best result was for file **gainRun4_10dB_0.9_repeat**.
Minimum jitter found was **38.5 nm** using samples 3-13 (where sample 1 denotes bunch arrival).



Histogram showing which samples most frequently appear in optimized sample window e.g. out of 98 files analysed, optimized sample window included sample 9 for all but 4 files.

Charge Scan Resolution IPA



Improvement seen from fitting thetaIQ.

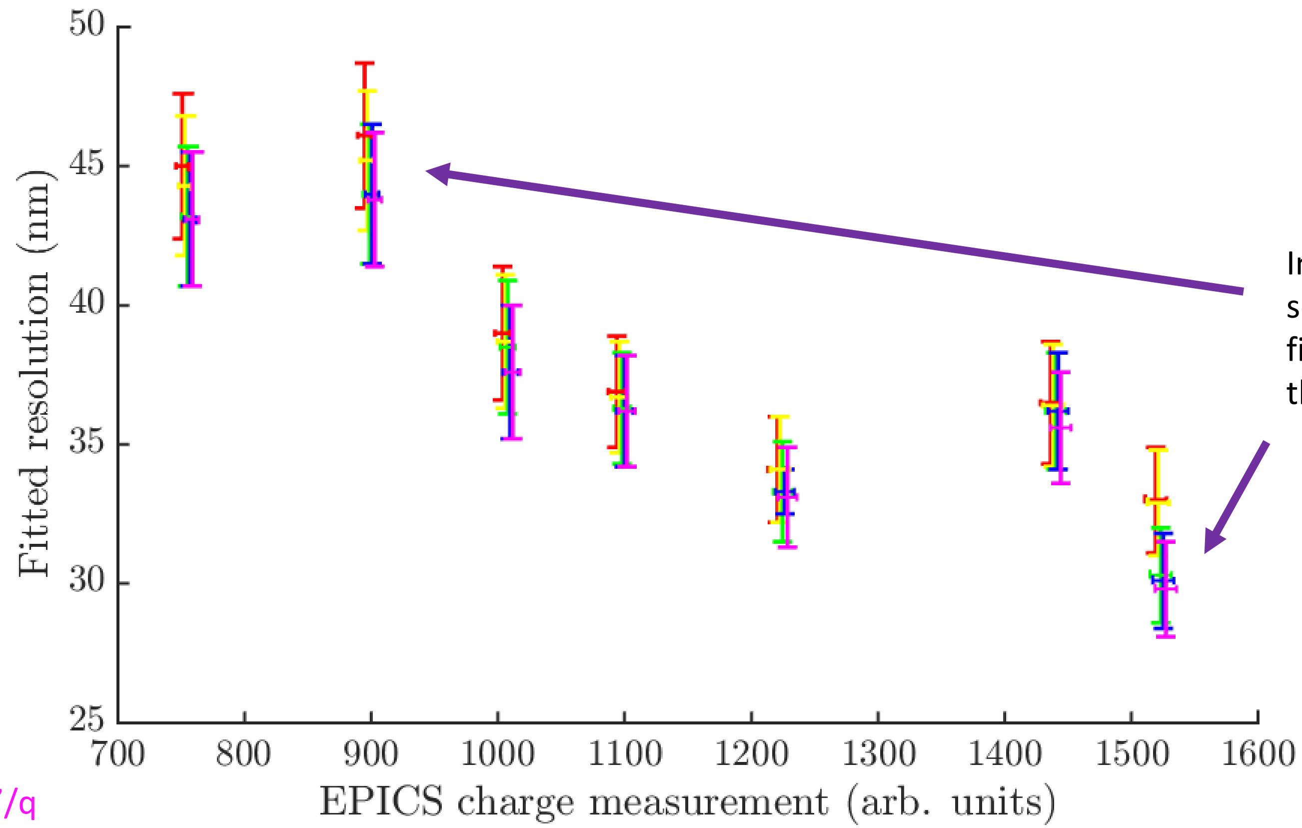
Samples: 50:57
Reference 57
09/02/2018

Red: fitting out calibration constant.
Orange: fitting out calibration constant and charge.
Green: fitting out calibration constant and theta.

Fit to:
Position,
Position and 1/q
I/q and Q/q
I'/q, Q'/q, 1/q
I'/q, Q'/q, 1/q, self Q'/q

Charge Scan Resolution IPB

Red: fitting out calibration constant.
Orange: fitting out calibration constant and charge.
Green: fitting out calibration constant and theta.



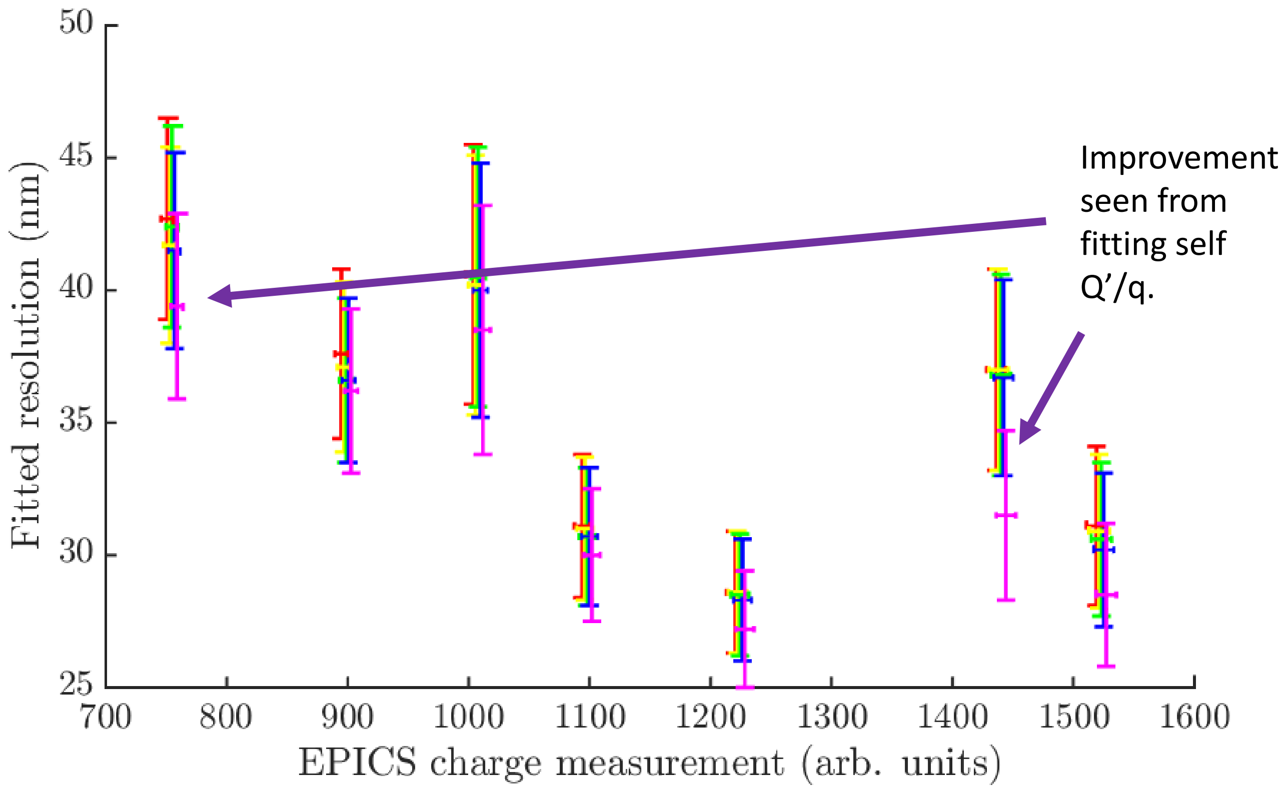
Improvement seen from fitting thetaIQ.

Fit to:
Position,
Position and 1/q
I/q and Q/q
I'/q, Q'/q, 1/q
I'/q, Q'/q, 1/q, self Q'/q

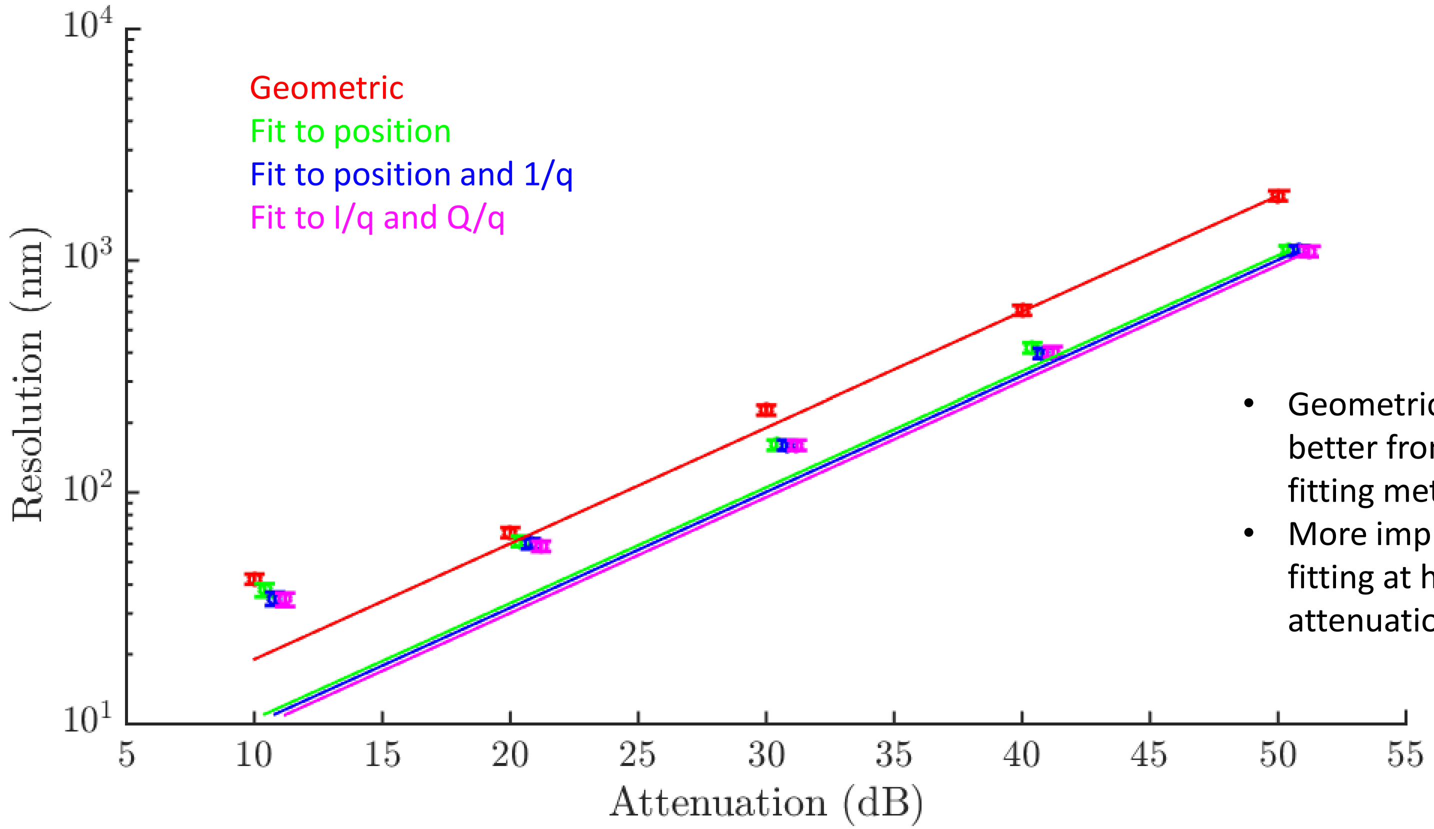
Charge Scan Resolution IPC

Red: fitting out calibration constant.
Orange: fitting out calibration constant and charge.
Green: fitting out calibration constant and theta.

Fit to:
Position,
Position and 1/q
I/q and Q/q
I'/q, Q'/q, 1/q
I'/q, Q'/q, 1/q, self Q'/q

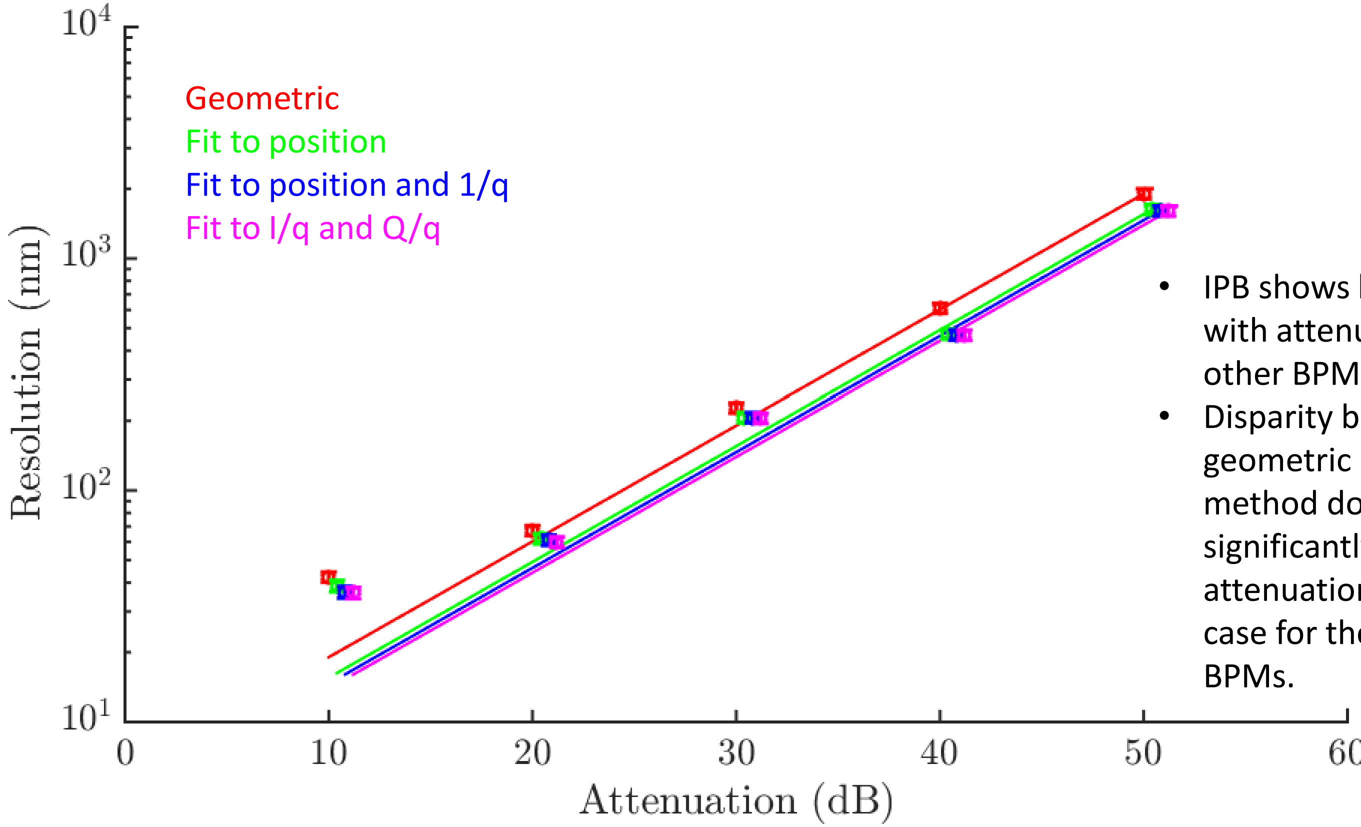


IPA Attenuation Scan



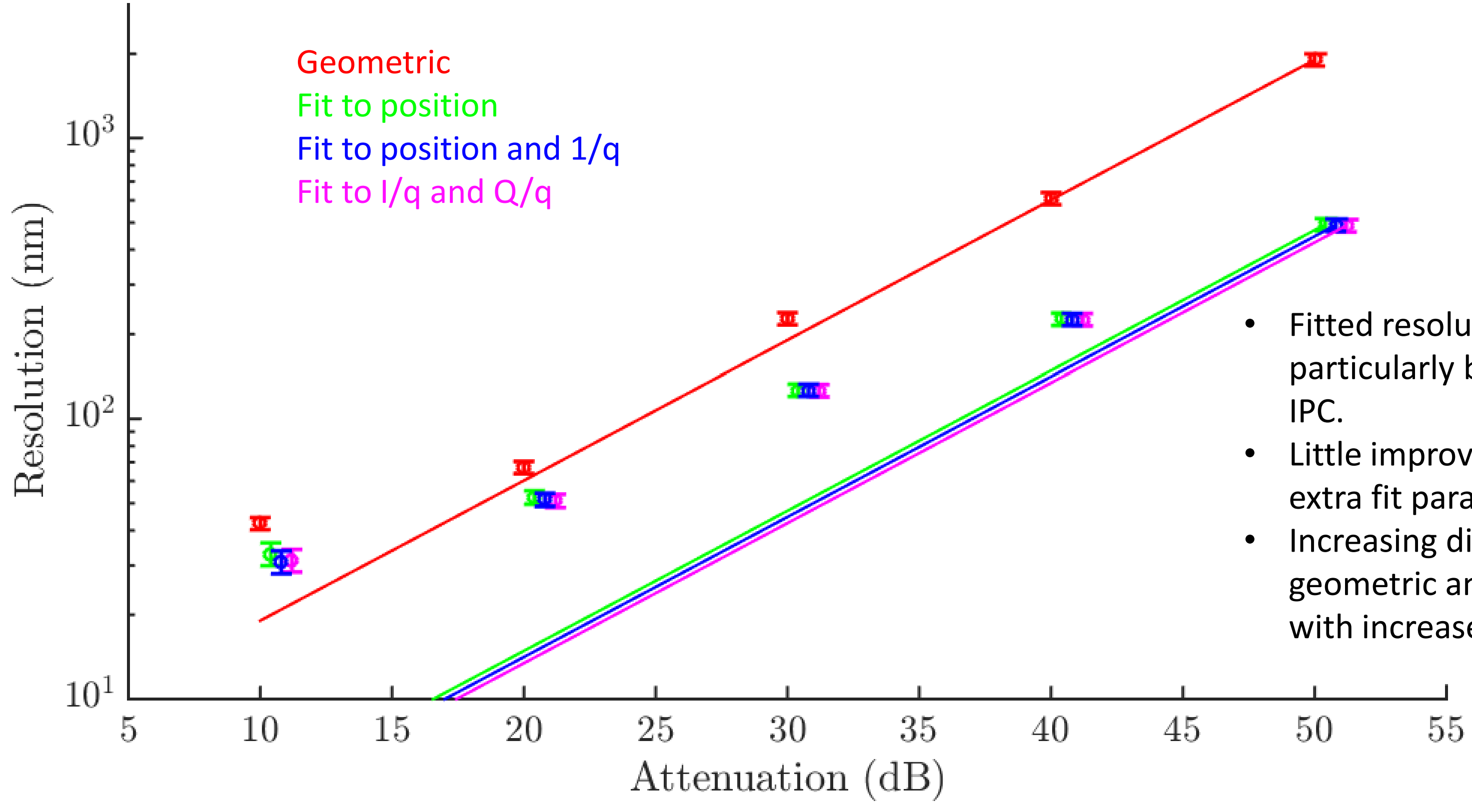
- Geometric method scaled better from 50 dB than fitting method.
- More improvement from fitting at higher attenuations.

IPB Attenuation Scan



- IPB shows better scaling with attenuation than the other BPMs.
- Disparity between geometric and fitting method does not increase significantly at higher attenuations, as was the case for the other two BPMs.

IPC Attenuation Scan



- Fitted resolutions scale particularly badly from 50 dB for IPC.
- Little improvement from adding extra fit parameters.
- Increasing disparity between geometric and fitted resolutions with increased attenuation.

New best resolution result

- This study was performed at a charge ~0.5 x 10^{10}. Dipole **10 dB attenuation.**

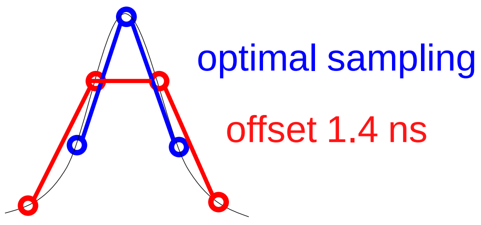
Single sample
Integrating 10 samples

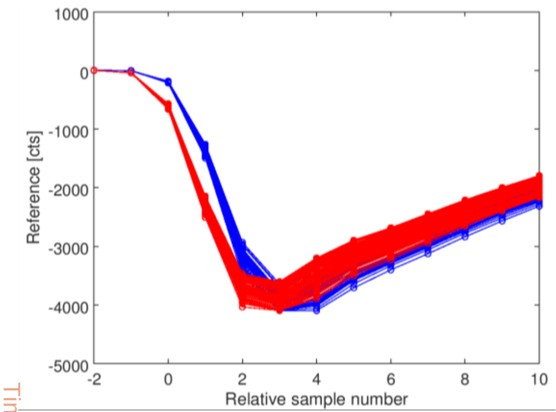
Parameter	Geometric	Fitting	Multi-parameter fits	
No. param	2	3	6	11
Parameters used to predict vertical position at 3rd BPM.	Y1 Y2	Y1 Y2 + const.	Y1I' Y2I' Y1Q' Y2Q' + Y Ref charge + const.	Y1I' Y2I' Y1Q' Y2Q' + Y Ref charge X1I' X2I' X1Q' X2Q' + X Ref charge + const
IPA Res (nm)	47	47	42	40
IPB Res (nm)		47	37	36
IPC Res (nm)		62	32	32
IPA Res (nm)	20	20	19	19
IPB Res (nm)		20	19	19
IPC Res (nm)		21	17	17

- Unfortunately this result proved difficult to replicate in June, due to operational issues at higher charges from unwanted parasitic signals.

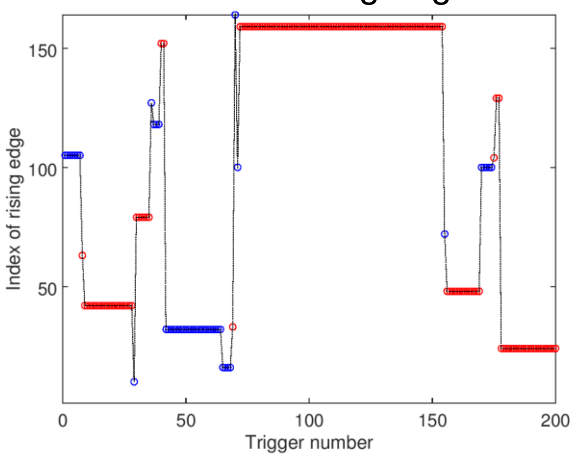
Sample jumps: jump3

- Fortunately plenty of jumping during the Friday day shift – took data (downstream board only) as soon as it happened, but noted that the upstream board was affected too
- Sample window can jump by a non-integer number of fast clock cycles
  - Particularly obvious upstream: as the scan delays are typically used to shift the ADC clocks in order to catch the peaks of the Σ signals, a 1.4 ns shift completely changes the shape of the sampled signal
  - Also visible in the shape of the reference diode
    - For each trigger, locate the rising edge of the reference signal
    - By superimposing the rising edges, it is immediately evident that there are two distinct populations
    - The red lines correspond to a sample clock lagging by 1.4 ns relative to the blue lines

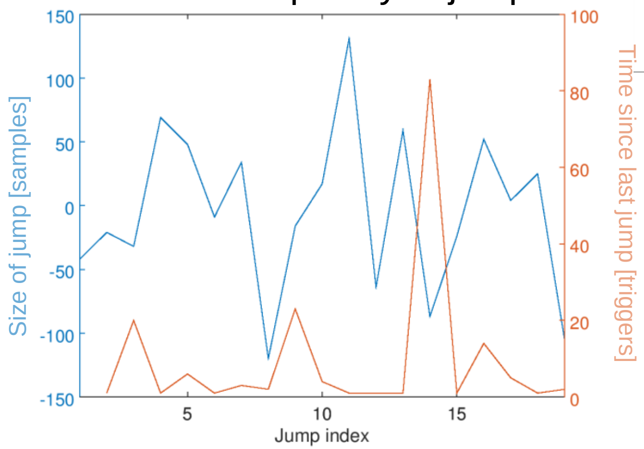




Index of rising edge



Size and frequency of jumps



Too small a data set to make any definitive conclusions about the size and frequency of sample jumps

Conclusion

- Best resolution achieved to date: 20 nm
- New calibration procedure does not perform very well – can it be refined?
- No easy solution for the sample jumping