IPBPM results
&
Principal Component Analysis

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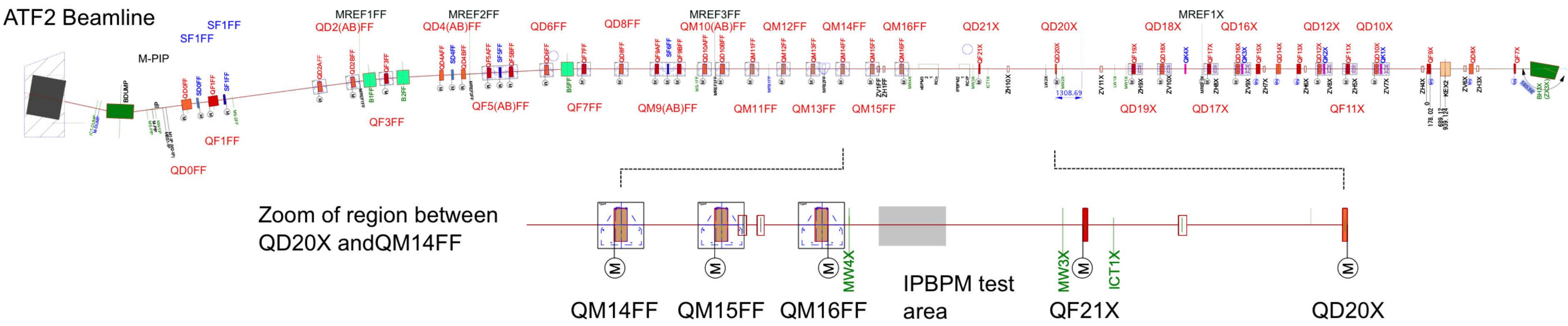
Contents

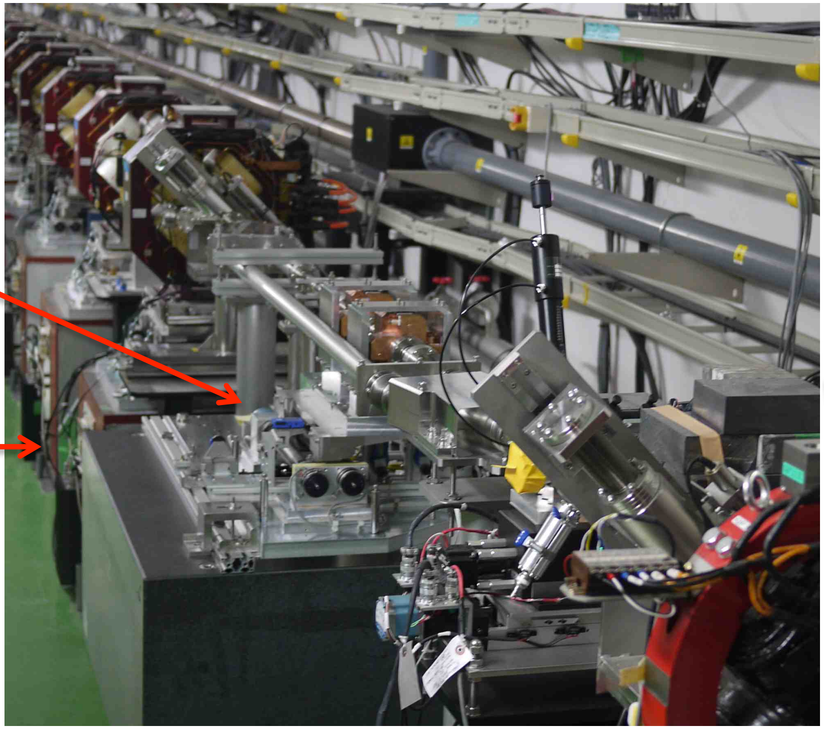
IPBPM test system location



2011 Nov. ~ Dec.

Cam mover system

Granite table

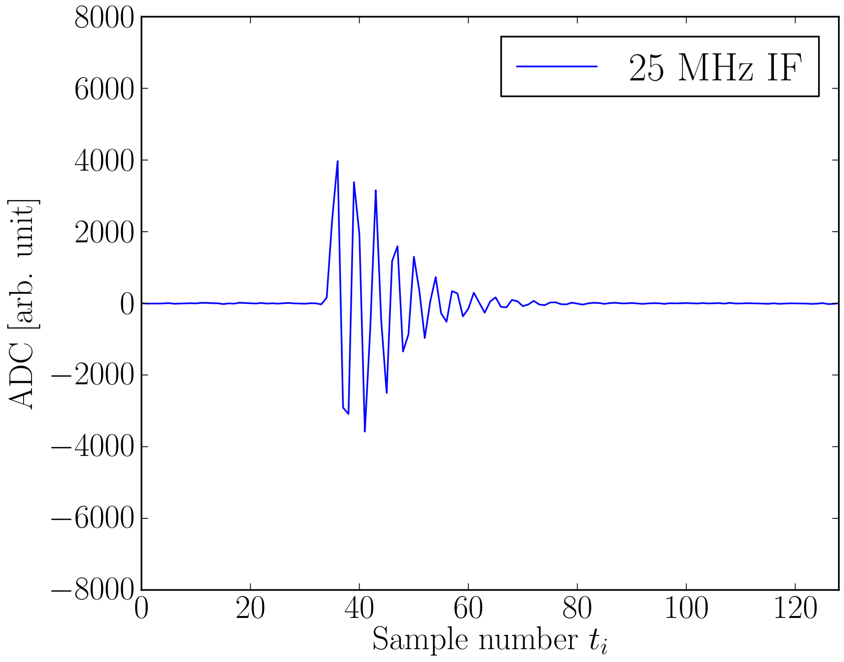


Electronics hidden near floor

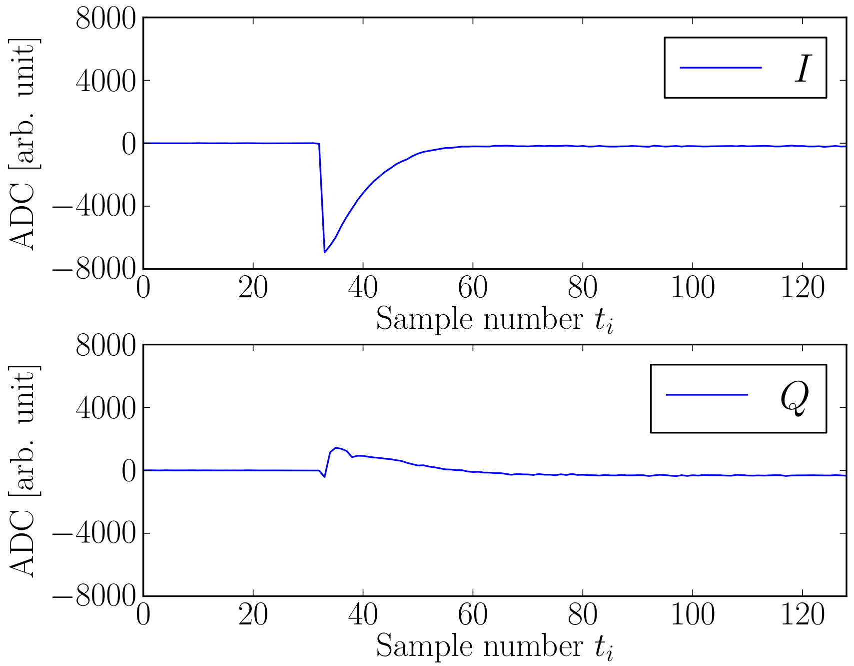
Electron beam direction

Heterodyne/Homodyne signal

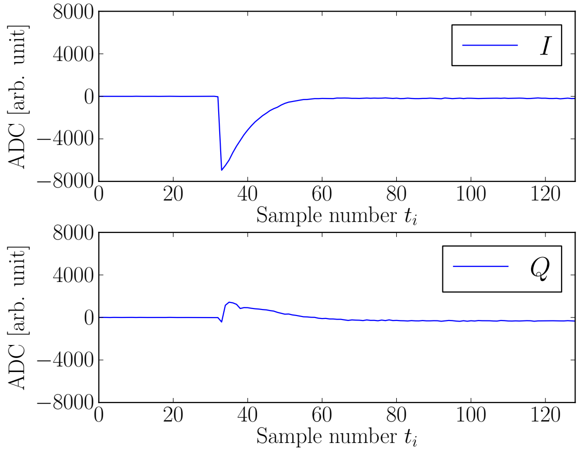
Heterodyne processing digitized signal (Non-zero IF signal)

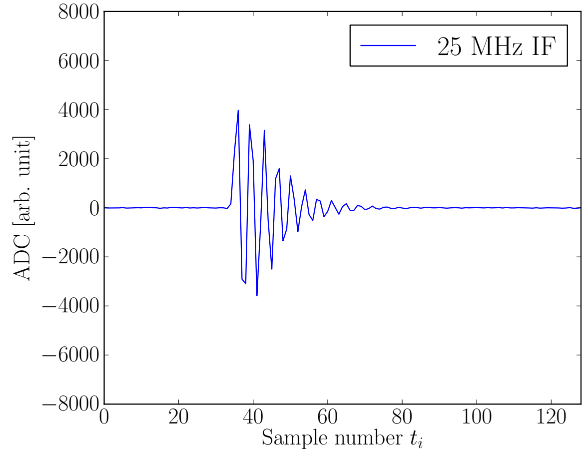


Homodyne processing digitized signal (Zero IF signal)



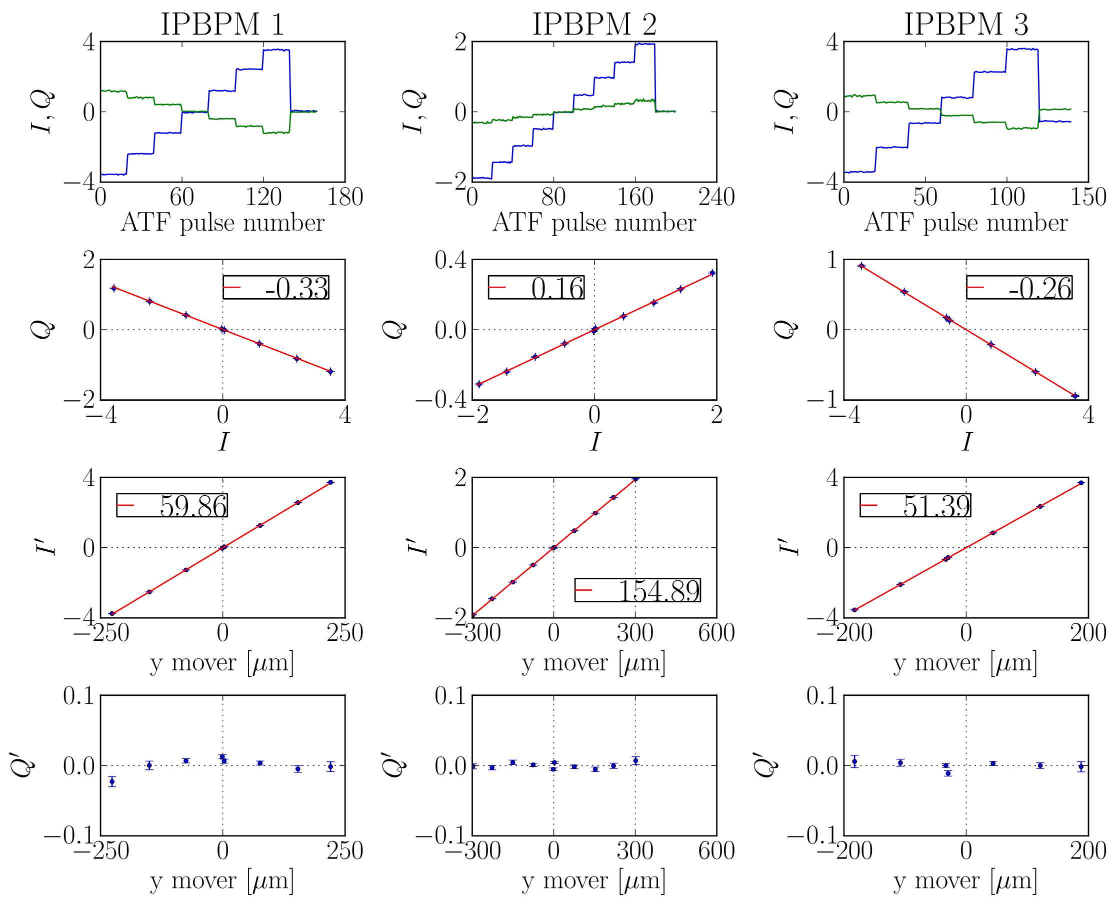
Digital signal processing





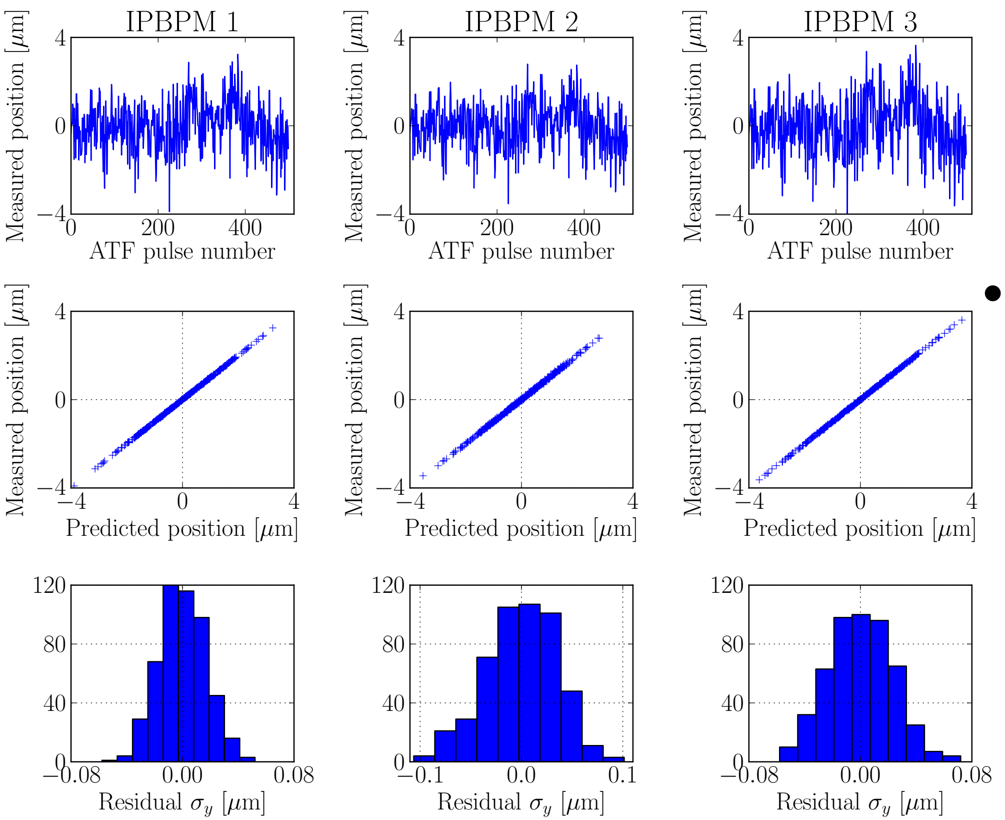
Technique		# of parameters	Parameters
Single point	To sample at single point	1	t_{samp}
Filter	Digitally filtering the *I/Q* waveform before sampling	2	$\Delta f_{\mathrm{homo}}, t_{\mathrm{samp}}$
Integration	Integrating	2	$t_{\mathrm{int},0}, t_{\mathrm{int},1}$
DDC	Digital down-conversion (Digital mixer, Digital LO, digital filter)	3	$\omega_{\mathrm{DDC}}, \Delta f_{\mathrm{DDC}}, t_{\mathrm{DDC}}$

Calibration



- Homodyne with 30 dB attenuation
- Each digital signal processing techniques show similar performance
- Heterodyne shows similar performance

IPBPM triplet resolution



- 3.6 nm position resolution with 0.788 x 10^{10} electron/pulse and 29.55 ps bunch length

Principal Component Analysis

- To transform the raw data (either homodyne or heterodyne signals) into a basis which explains the variation in the data
- The data is a vector d with dimension N so the transformation to the new coordinates is

$$\mathrm{y} = \mathrm{W}^{\mathrm{T}}\mathrm{d}$$

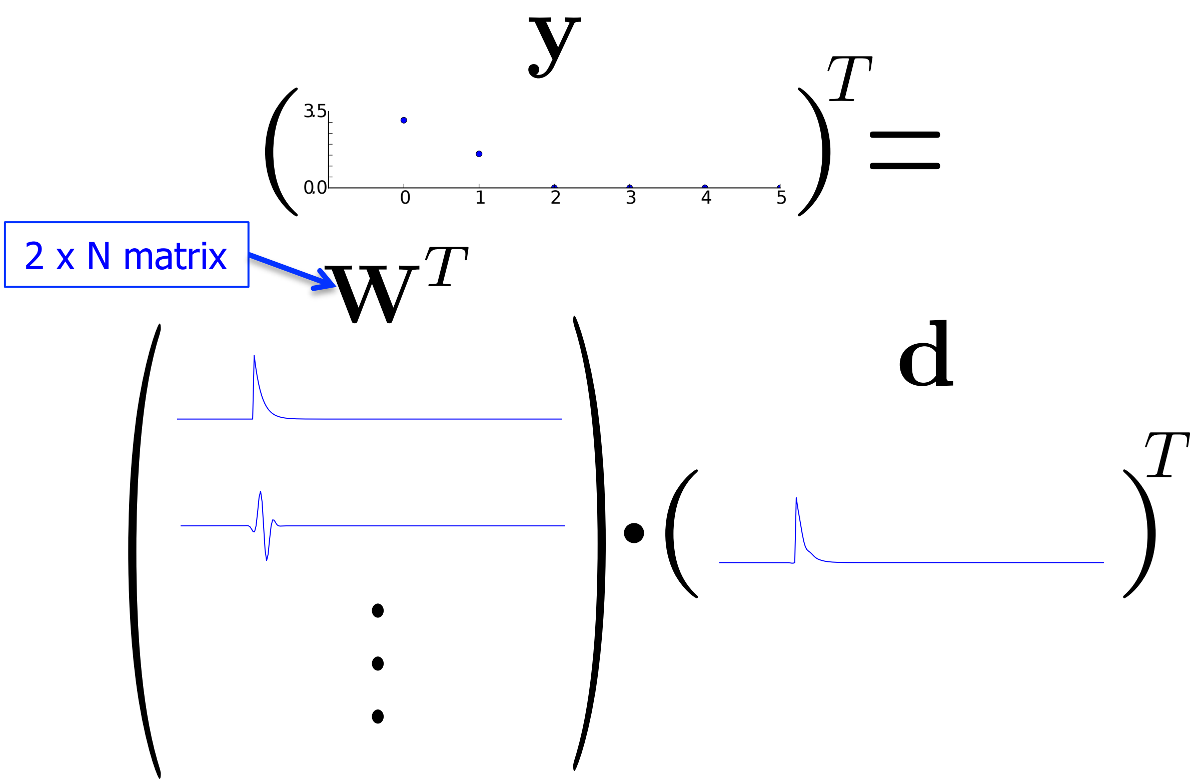
  - W^T : can be considered a rotation matrix that transforms the data into another linear vector space
- The PCA is a method of determining the transformation matrix W, but keeping the variability of the original data
- W is simply determined by taking singular value decomposition of a data matrix of all the calibration waveforms

PCA example (cont.)

$$\mathrm{d} = \mathrm{d}_{\mathrm{dipole}} + \mathrm{d}_{\mathrm{unwanted}}$$

d_dipole : Vary depending on the position of the beam and charge

d_unwanted : Some variability but independent of the signal of interest



PCA determine the basis (cont.)

- Making a transformation W^T which makes the covariance of y a diagonal matrix
- The covariance of the transformed data y can be calculated by

$$\begin{aligned}
\mathrm{cov}(\mathbf{y}) &= \mathrm{cov}\left[\mathbf{W}^T\mathbf{d}\right] \\
&= \mathrm{E}\left[(\mathbf{W}^T\mathbf{d})(\mathbf{W}\mathbf{d}^T)\right] \\
&= E\left[\mathbf{W}^T\mathbf{d}\mathbf{d}^T\mathbf{W}\right] \\
&= \mathbf{W}^T E\left[\mathbf{d}\mathbf{d}^T\right]\mathbf{W} \\
&= \mathbf{W}^T \mathrm{cov}\left[\mathbf{d}\right]\mathbf{W}.
\end{aligned}$$

Rearranging

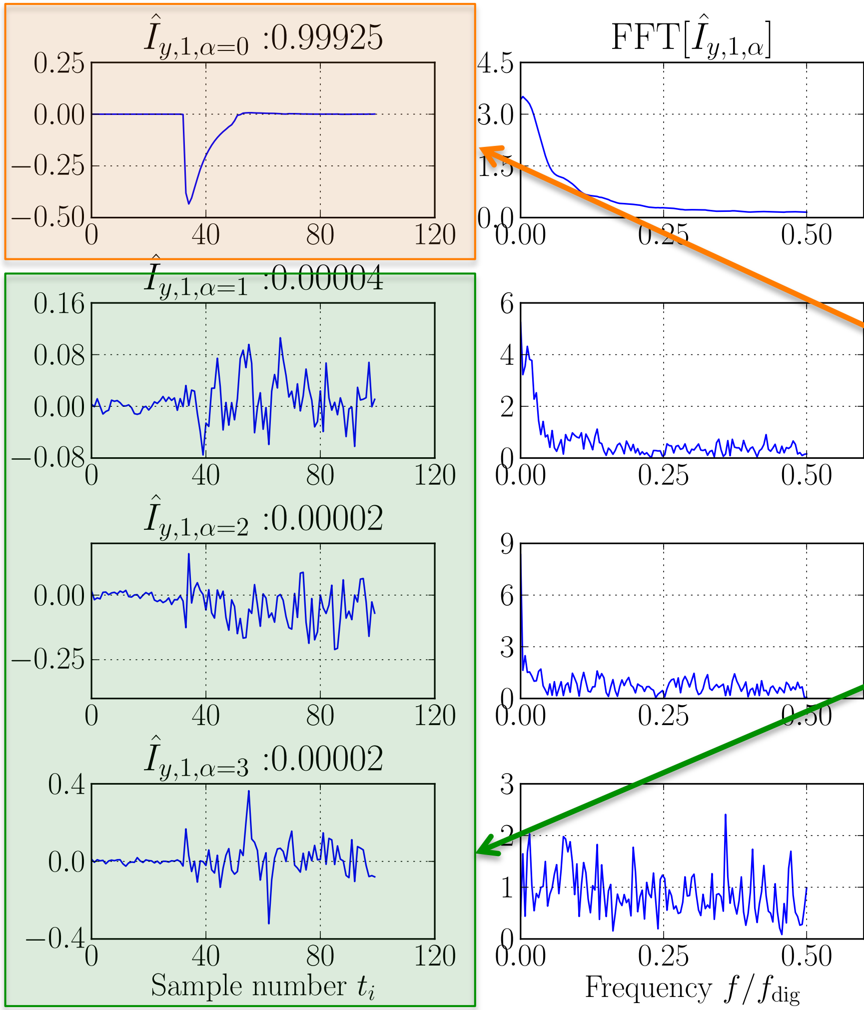
For the covariance matrix of d

$$\begin{aligned}
\mathrm{cov}\left[\mathbf{d}\right] &= \mathbf{W}\mathrm{cov}\left[\mathbf{y}\right]\mathbf{W}^T \\
&= \mathbf{U}\mathbf{S}\mathbf{V}^T.
\end{aligned}$$

- The transformation matrix W^T can be identified with V^T and the diagonal covariance matrix with S
- To calculate the PCA of a give set of data is to basically calculate the covariance of the signal data d then to take the SVD of this covariance matrix

PCA (cont.)

Homodyne signal



Basis vectors

$$I(t_i) = \sum_j \alpha_j \hat{I}_j(t_i)$$

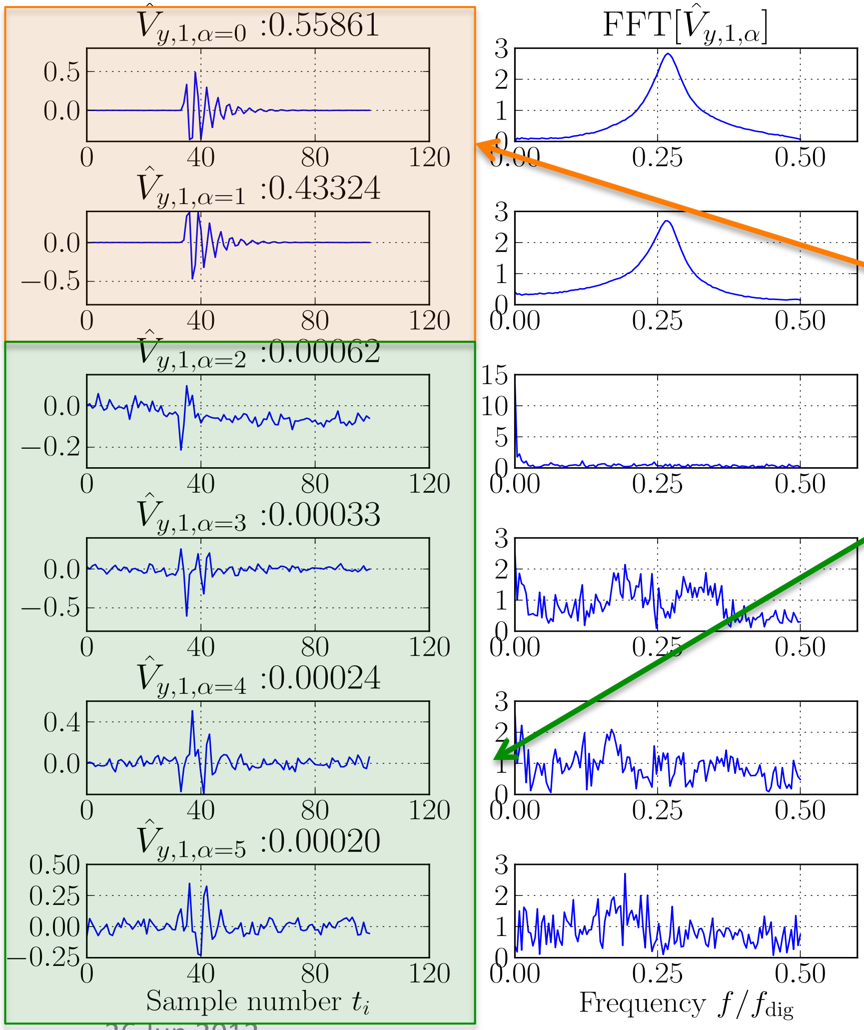
$$Q(t_i) = \sum_j \beta_j \hat{Q}_j(t_i)$$

Coefficients, relative contribution of the basis vectors

- The principal component of the signal accounts for 99 % of the waveform variance
- Second and following components for almost none of the variation in the I signal

PCA (cont.)

Heterodyne signal



Basis vectors

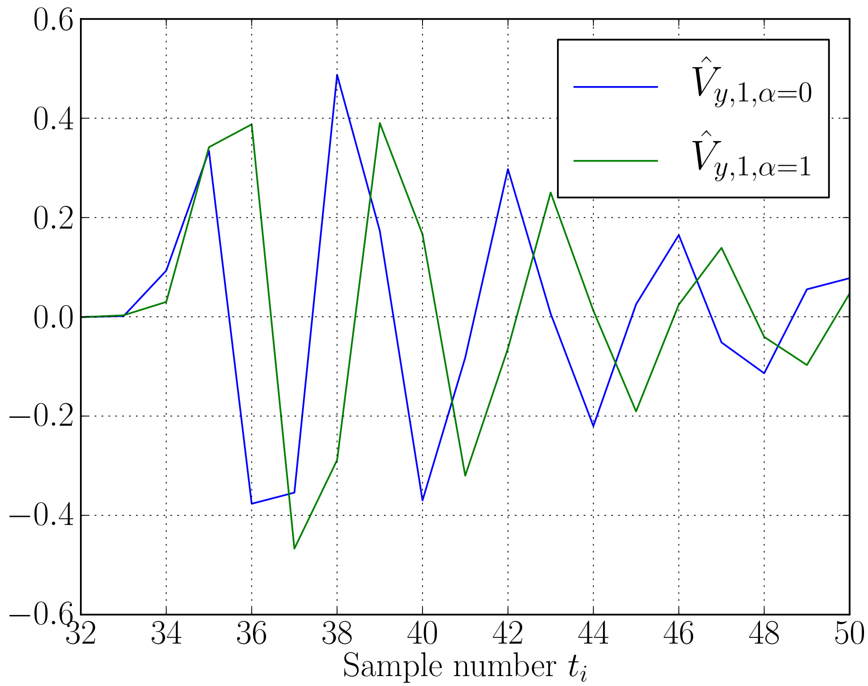
$$V(t_i) = \sum_j \alpha_j \hat{V}_j(t_i)$$

Coefficients, relative contribution of the basis vectors

- First and second modes are clearly dipole like
- Below these are other contaminating modes at the few percent level

PCA (cont.)

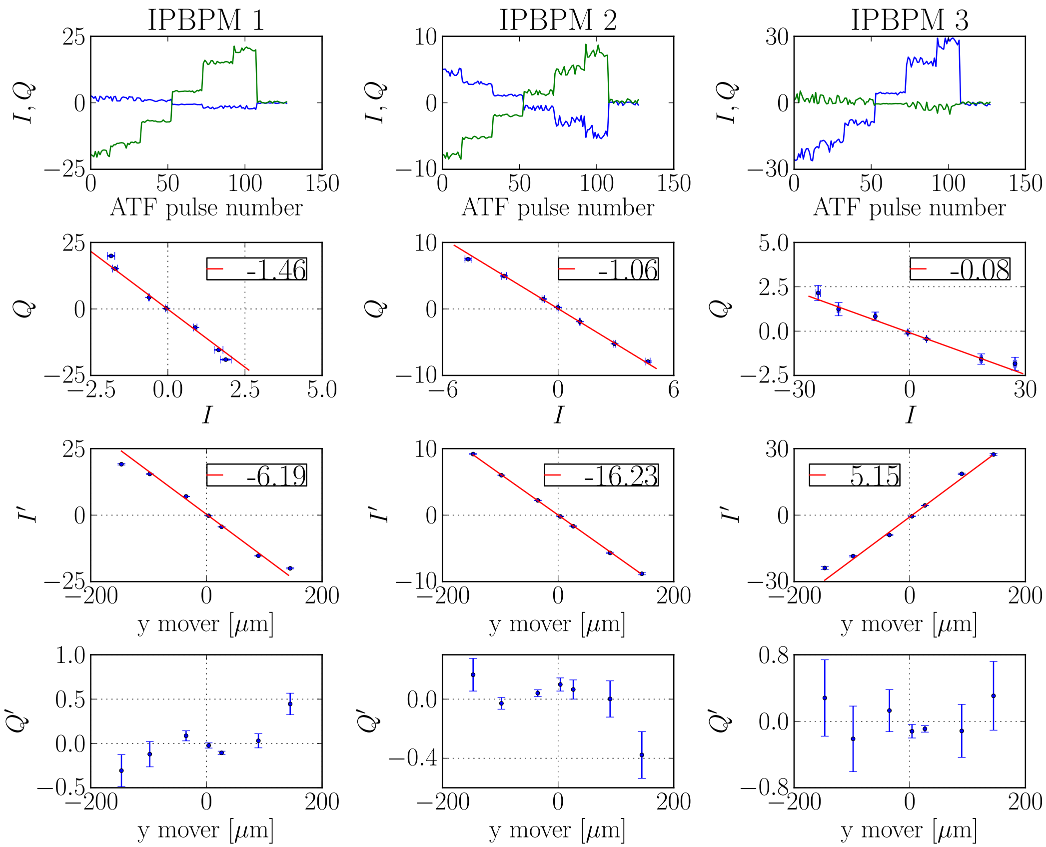
Heterodyne signal



To understand the physical interpretation of the two highest variance modes, plotted together

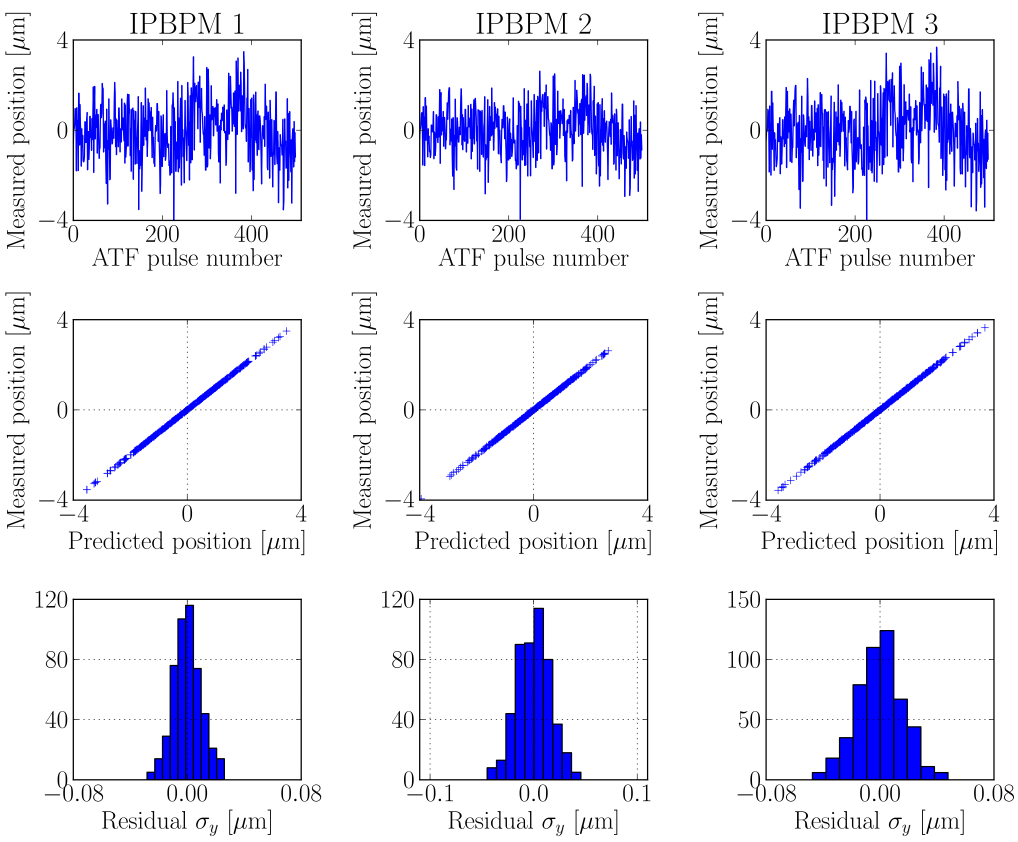
Clearly the principal and secondary components are orthogonal so much the same as I and Q like signals

PCA calibration (cont.)



- Application of the calibration is just the dot product of the basis vector with a pulse of recorded data
- The value of this dot product can be used for I or Q analysis
- The calibration plot looks very similar to the traditional signal processing as shown before

PCA triplet resolution (cont.)



- Gives similar results compare to other digital signal processing methods with the parameter optimization
- The position resolution for the PCA method is better than single point sampling, similar to the filter and integration methods
- 4.3 nm position resolution with 0.788 x 10^{10} electron/ pulse and 29.55 ps bunch length

Summary

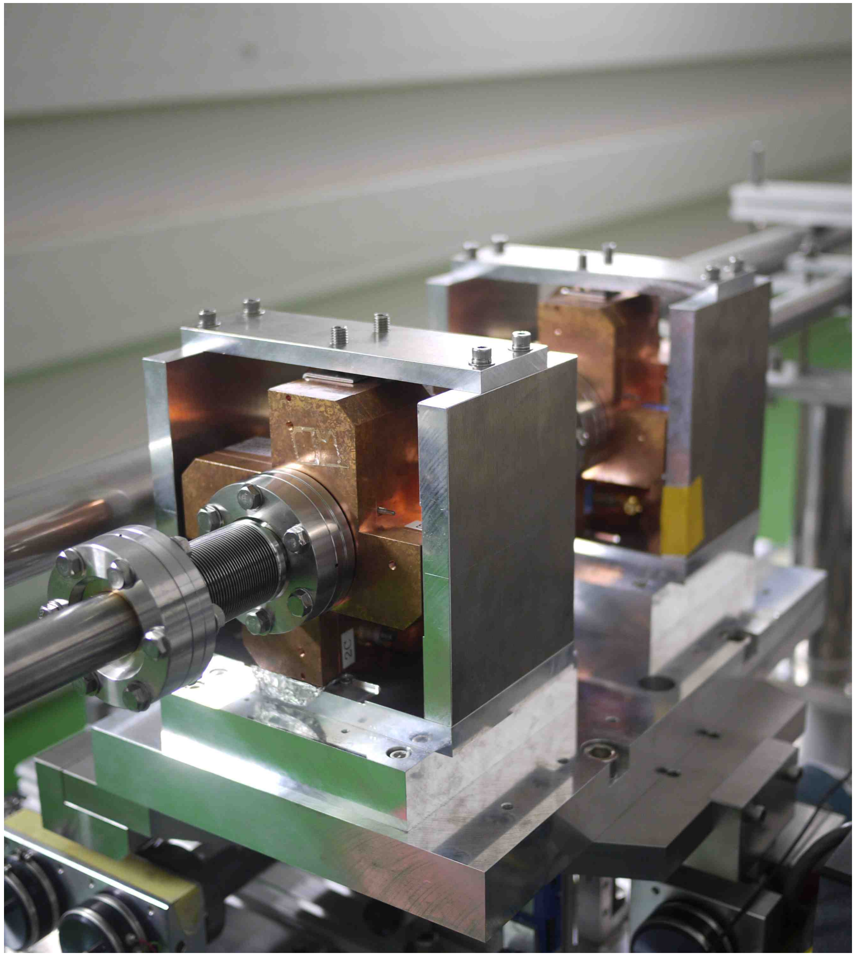
- The IPBPMs system were tested in an upstream location of the ATF2 extraction beam line to achieve good resolution
- Two radio frequency down-conversion methods,
  - homodyne and heterodyne signal processing
- Different digital processing methods
  - Single sample point, filter, integration for homodyne signals
  - DDC for heterodyne signals
- The RMS vertical position residual : 3.6 nm
  - the homodyne signals processing, the integration of the digital processing method
  - The beam intensity : 0.788×10^{10} electron/pulse
  - The bunch length : 29.55 ps

Summary

- A Principal Component Analysis (PCA) is a promising idea to determine the beam position in a model independent way
- The method clearly determines the principal component which is easily interpreted in a physical sense
- The IPBPM data are used to test this new technique, which give similar results which the RMS vertical position residual is 4.3 nm compared to more standard processing methods with parameter optimization
- Very simple to apply to the cavity BPM data when the digital signal processing method is not clearly identified
- Could be very useful in the early stages of BPM commissioning when the optimal parameters are poorly known
- Will be published soon

Back up

Interaction point BPM (IPBPM)



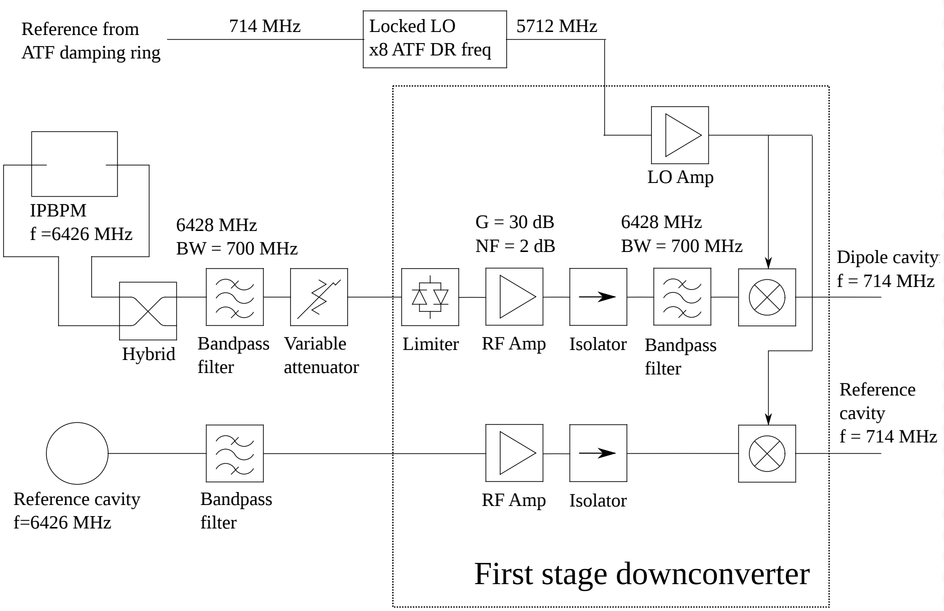
- Rectangular cavity shape
  - To measure beam position in X direction and Y direction, independently with single cavity
- Short cavity length in the z direction
  - Low angle sensitivity
  - Since large angle jitter due to the strong focus at IP
- Ultra high position sensitivity
  - In order to measure nanometer beam offset

Electronics

First stage

C –band -> 714 MHz

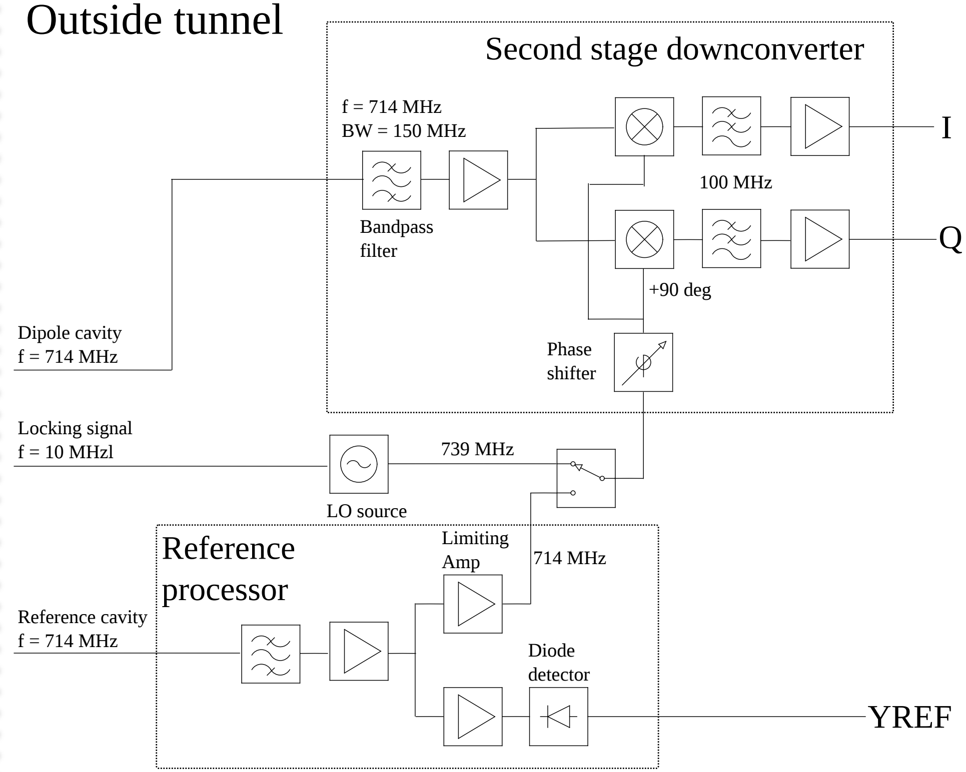
ATF2 tunnel system



Second stage

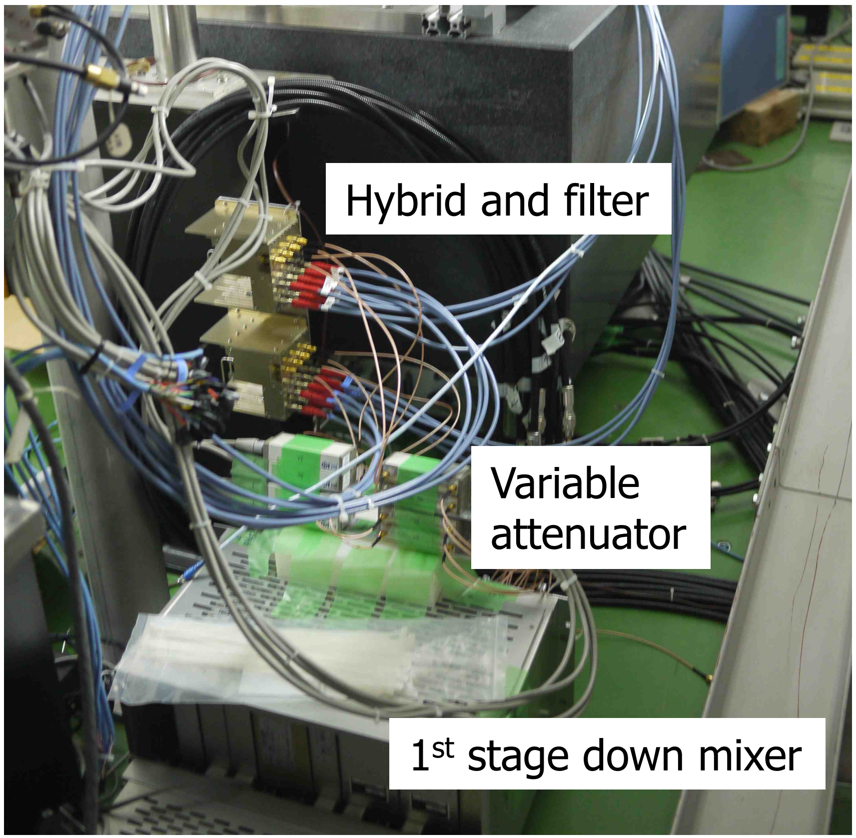
714 MHz -> baseband or 25 MHz

Outside tunnel

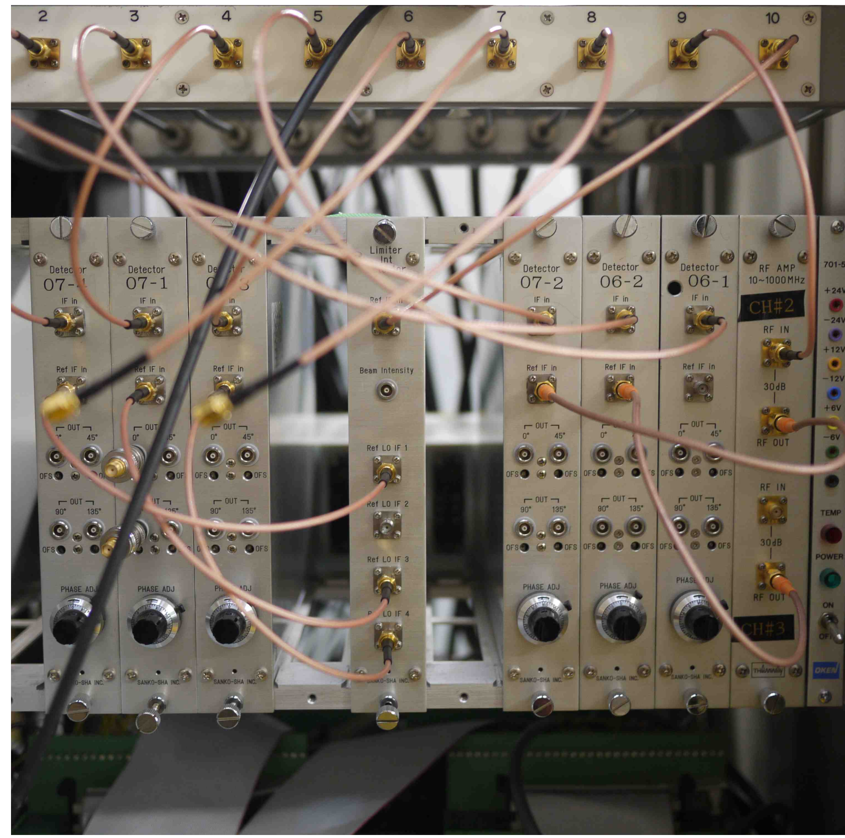


Hardware installation

First stage of down mixer (C-band - > 714 MHz)
@ in the tunnel



Second stage of down mixer (714 MHz -> I, Q)
@ the outside of the tunnel



Data taking

Three, 8 hour ATF2 shift per week over three weeks (2011. Nov. ~ Dec.)

Label		
W1-HO-CA-RA	Homodyne	
W1-HO-CA-RA-C	Homodyne	Varied bunch charge
W1-HO-CA-RA-B	Homodyne	Varied bunch length
W2-HO-CA-RA	Homodyne	
W3-HE-CA-RA	Heterodyne	
W3-HE-CA-RA-C	Heterodyne	Varied bunch charge

WN : N is Week number
HO/HE : Homodyne/Heterodyne
CA : Calibration attenuation value in dB
RA : Resolution attenuation value in dB
C/B : Charge scan, Bunch length scan

40, 30, 20 dB attenuator for calibration
40, 30, 20, 0 dB attenuator for resolution