Calibration and performance of RF (cavity) BPMs
2nd PACMAN Workshop (Debrecen)

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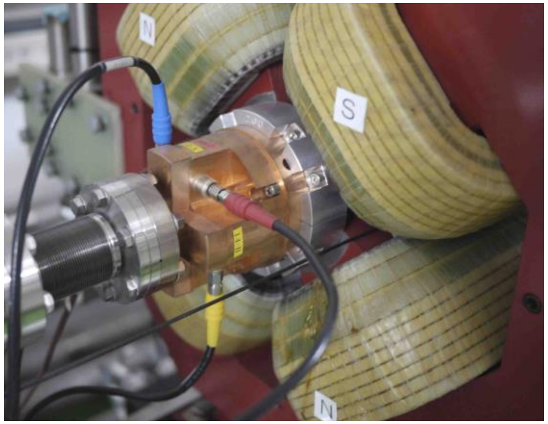

Background/introduction

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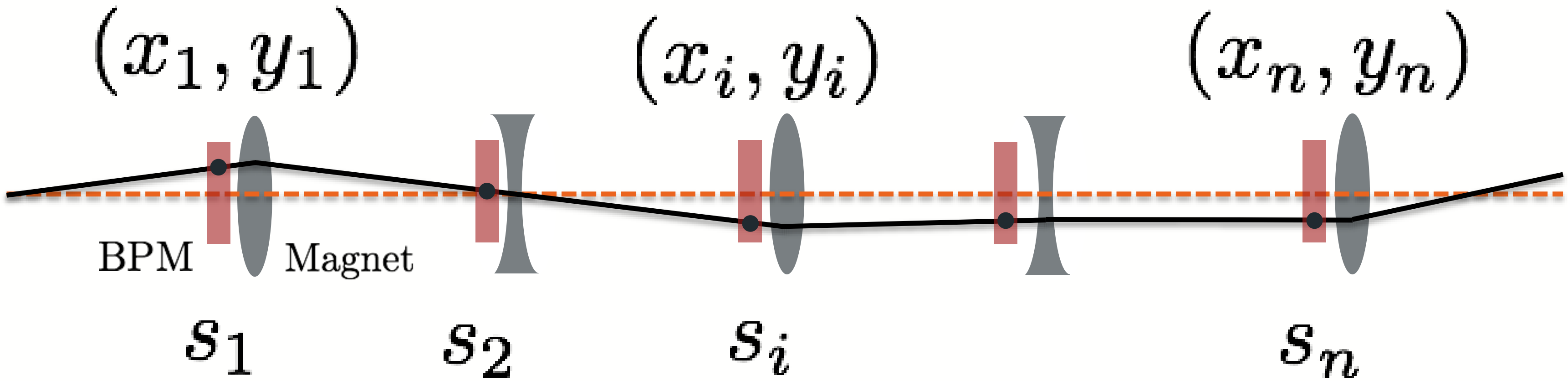
Beam position monitoring (BPM)



- Large number of magnetic (electrostatic) elements in periodic lattice
- Particle beam position needs to be monitored for
- Typically instrument quadrupoles with BPMs
- Required for large number of alignment and optimisation measurements (dispersion measurement, orbit feedback, beam based alignment, wakefield etc)

Introduction

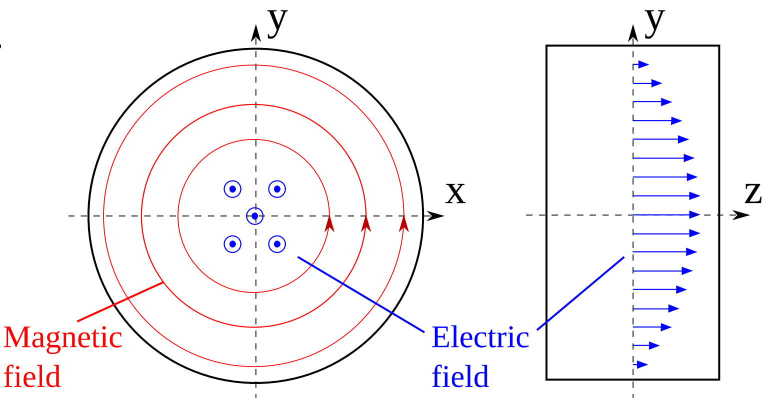
- Cavity beam position monitors
- Replacing existing button and strip-lines in more challenging environments
- Growth in
- Free electron lasers
- Linear Colliders (ILC, CLIC etc)
- Test facilities
- Resolution, stability and low charge operation (USP)
- 10 nm resolution achievable
- Stable
- Issues : Ab-initio calibration and alignment

- Existing systems
- LCLS(2)
- SACLA
- European-XFEL
- Swiss-FEL
- Linear Colliders (CLIC Test Facility 3 CALIFES, ILC Accelerator Test Facility 2)
- ELI-NP (Extreme Light Infrastructure Nuclear Physics)

Cavity BPM principle of operation

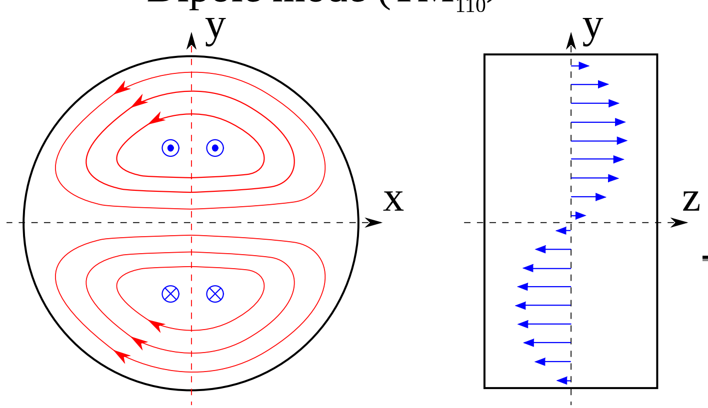
- Form resonant cavity around beam line
- Excite Transverse Magnetic (TM) modes (TM_{010} and TM_{110})
- Signal depends on
  - Beam position
  - Beam angle
  - Bunch tilt
- Angular signals are 90 degrees out phase compared with position

Monopole mode (TM_{010})



$$V \propto q$$

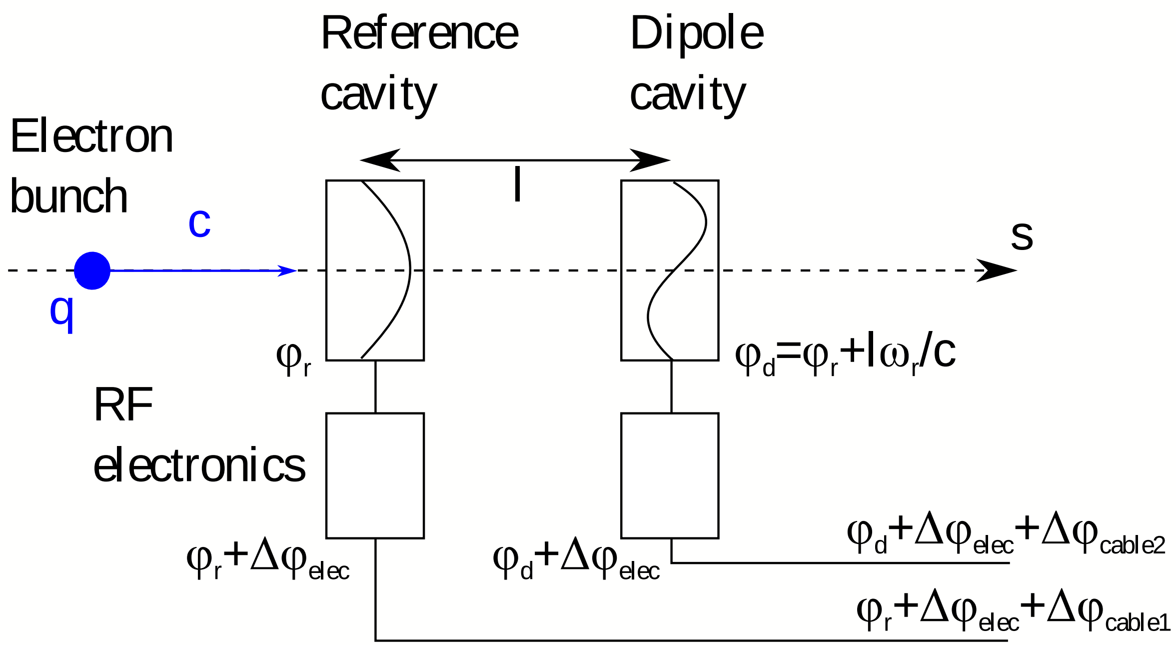
Dipole mode (TM_{110})



$$V \propto qd$$

$$V(t) = q\, e^{-t/\tau - i\omega t}(S_d d + S_{d'} d' e^{\pi i/2} + S_\theta \theta e^{-\pi i/2})$$

Cavity BPM principle of operation



- Require a “reference” monopole cavity
- Reference cavity monitors beam arrival phase and charge
- Compare dipole cavity signal magnitude and phase to reference

Anatomy of CBPM system

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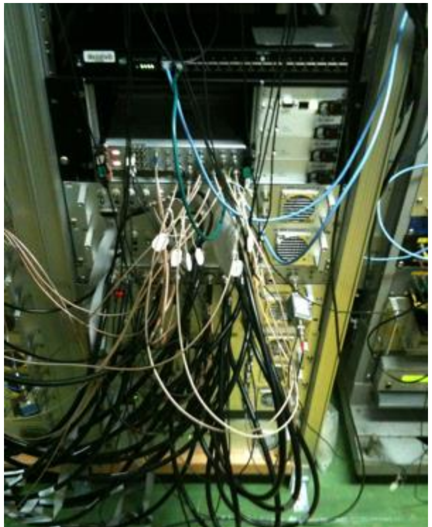
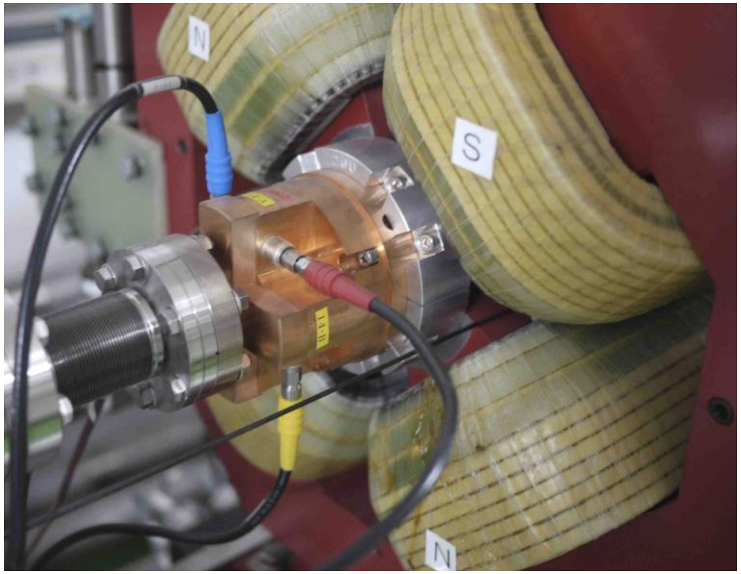
- Cavity BPM system typically consist of
- Pick up
  - Cylindrical most common (L, S, C, X band examples)
  - Common mode rejection via slot waveguides
- Down conversion electronics
  - Hetrodyne or homodyne
- Digitizer
  - 100s MHz, 14-bit
- Software (online) analysis
  - Singular value decomposition

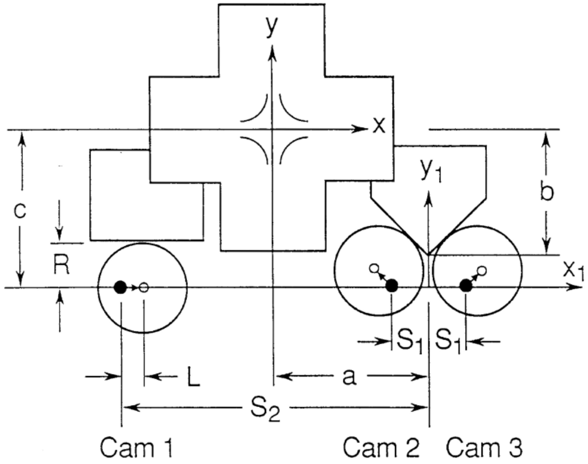




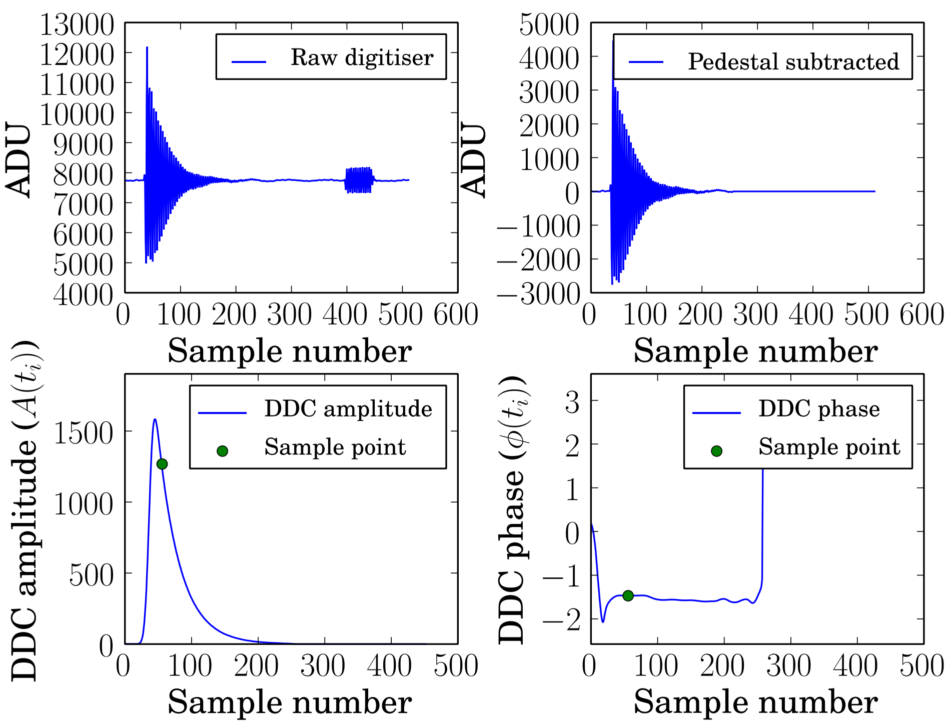

BPM mounting and mover system



Cam base
magnet mover



Signal processing



1. Pedestal subtract
2. Mix with complex digital oscillator and filter

$$y_{\mathrm{DDC}} = \mathrm{Filt}\left[V_{\mathrm{cavity}} \times V_{\mathrm{LO}}\right]$$

3. Calculate amplitude and phase

$$A(t_i) = \sqrt{y_{\mathrm{DDC}}(t_i) \cdot y^*_{\mathrm{DDC}}(t_i)}$$

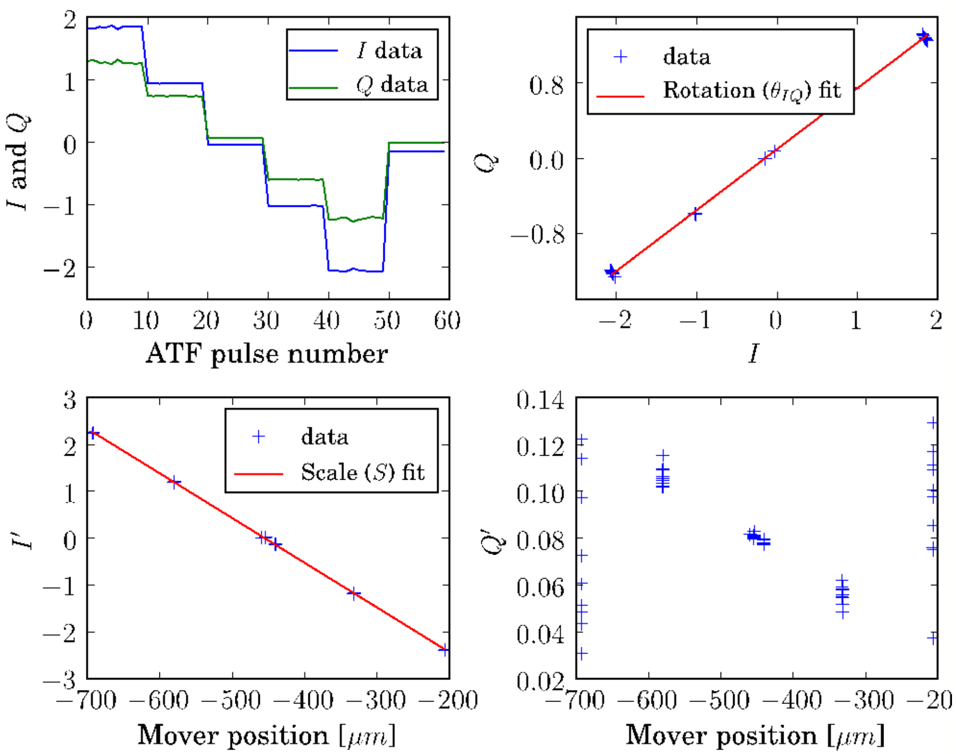
$$\phi(t_i) = \arctan\left[\frac{\mathrm{Im}[y_{\mathrm{DDC}}(t_i)]}{\mathrm{Re}[y_{\mathrm{DDC}}(t_i)]}\right]$$

4. Calculate In and Quadrature phase signals

$$I = \frac{A_d}{A_r}\cos(\phi_d - \phi_r)$$

$$Q = \frac{A_d}{A_r}\sin(\phi_d - \phi_r)$$

Calibration



1. Move BPM and calculate/record I and Q
2. Magnitude of signal proportional to position displacement, phase of displacement signal

$$\theta_{IQ} = \tan^{-1}\left(\frac{dQ}{dI}\right)$$

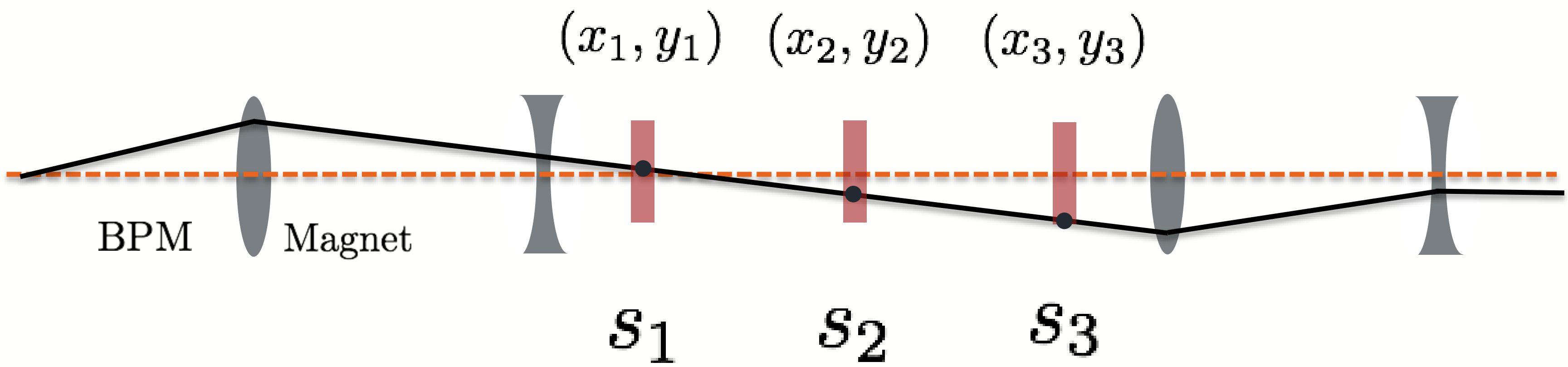
3. Rotate I and Q such that I′ is position dep

$$I' = I\cos(\theta_{IQ}) + Q\sin(\theta_{IQ})$$

4. Gradient between I′ and position is calibration constant

$$\frac{1}{S_y} = \frac{dI'}{dY_{\text{pred}}}$$

Measuring resolution (test system)



- Typically in test systems form triplet of BPMs (no intervening elements)
- Sufficient to predict coordinates in 1 BPM from other 2 BPMs

$$p_{x,3} = \frac{s_3 - s_1}{s_2 - s1}(x_2 - x_1)$$

Resolution measurement (operating system)

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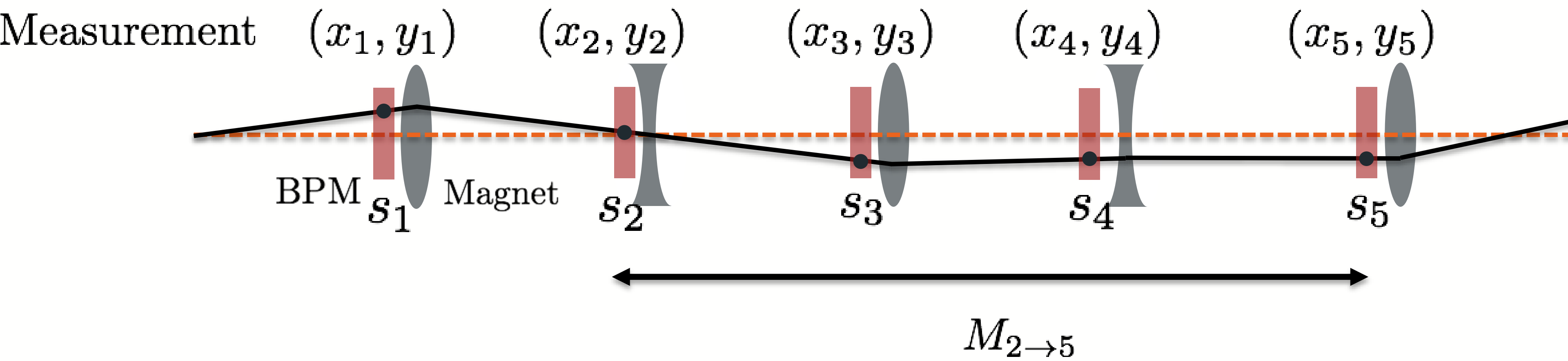
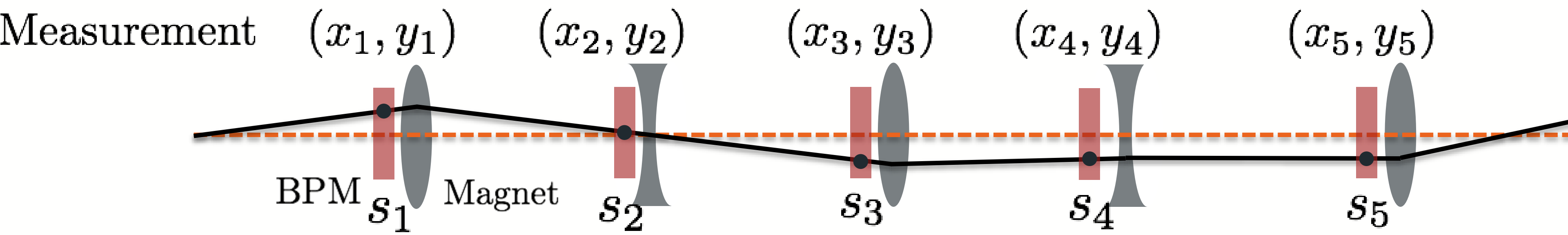


- Need to predict position in BPM 5 given positions (measurements) in BPMs 1,2,3 & 4
- Can connect each BPM{1,2,3,4} to BPM5 with a matrix
- E.g BPM2 to BPM5

$$\mathbf{p}_5 = M_{2\to5}\mathbf{v}_2$$

- What is the transfer matrices are poorly- or unknown?

Resolution measurement (operating system)



- Need to predict position in BPM 5 given positions (measurements) in BPMs 1,2,3 & 4
- Can connect each BPM{1,2,3,4} to BPM5 with a matrix
- How to determine using data only? $p = \mathbf{d}_j \mathbf{v}_j$

$$\begin{pmatrix} d_{1k} \\ d_{2k} \\ d_{3k} \\ \vdots \\ d_{Mk} \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & \cdots & d_{1,i\neq k} & \cdots & d_{1N} \\ d_{21} & d_{22} & d_{23} & \cdots & d_{2,i\neq k} & \cdots & d_{2N} \\ d_{31} & d_{32} & d_{33} & \cdots & d_{3,i\neq k} & \cdots & d_{3N} \\ \vdots & \vdots & \vdots & & \vdots & & \vdots \\ d_{M1} & d_{M2} & d_{M3} & \cdots & d_{M,i\neq k} & \cdots & d_{MN} \end{pmatrix} \cdot \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ \vdots \\ v_N \end{pmatrix}$$

$$d_i = \mathbf{D}_{ij}\mathbf{v}_j = \mathbf{d} = \mathbf{D}\mathbf{v} = \mathbf{U}\mathbf{S}\mathbf{V}^{-1}\mathbf{v}$$

Invert D using Singular Value Decomposition (SVD)

ATF2 performance example

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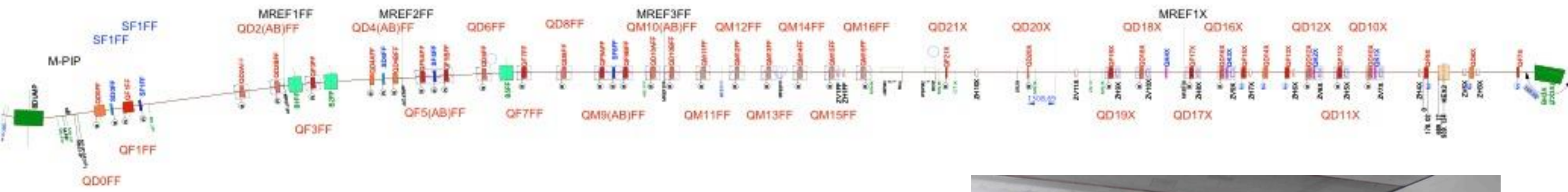
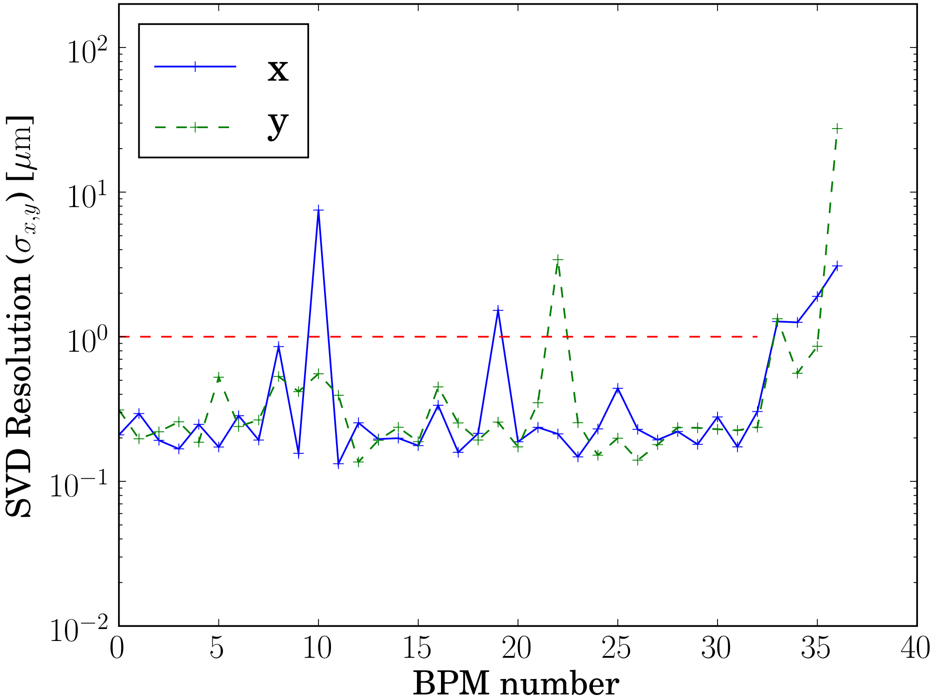
ATF2 (KEK, Japan)



- ILC/CLIC final focus test accelerator
- Aim to produce scaled ILC focus size
- System resolution calculated using SVD
- ~40 cavity beam position monitors, located in each quadrupole and sextupole
- C- and S- Band BPMs
- Most have 20 dB of attenuators

ATF2 system resolution example



- Prediction position from all other BPMs (vertical and horizontal)

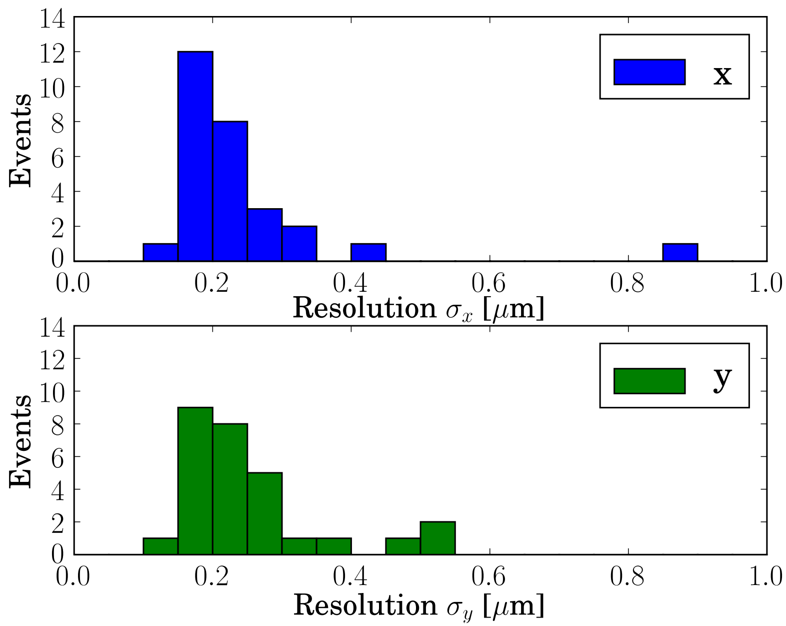
$$p = \mathbf{d}_j \mathbf{v}_j$$

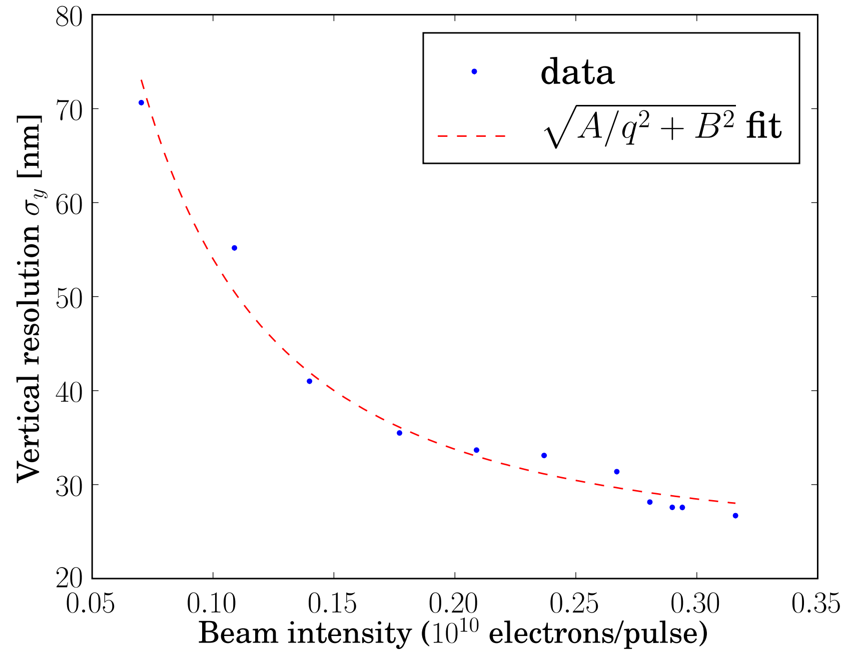
- Compare predicted displacement with measurement (residuals)

$$\delta d = d_i - p_i$$

- RMS/Sigma of these residuals defined as resolution
- Expect vertical and horizontal resolution to be the same
- Beam orbit can also change measured resolution

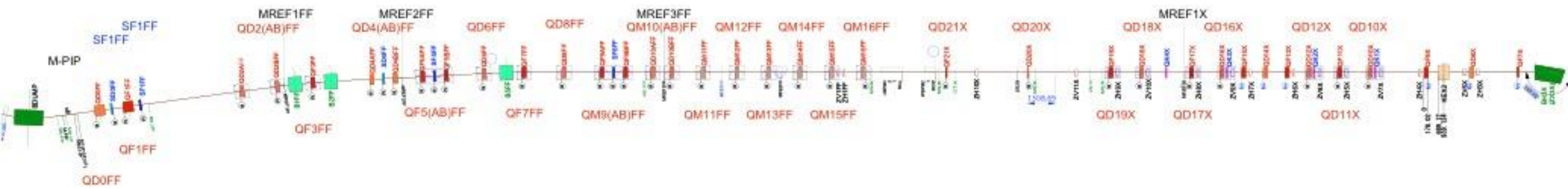
System resolution

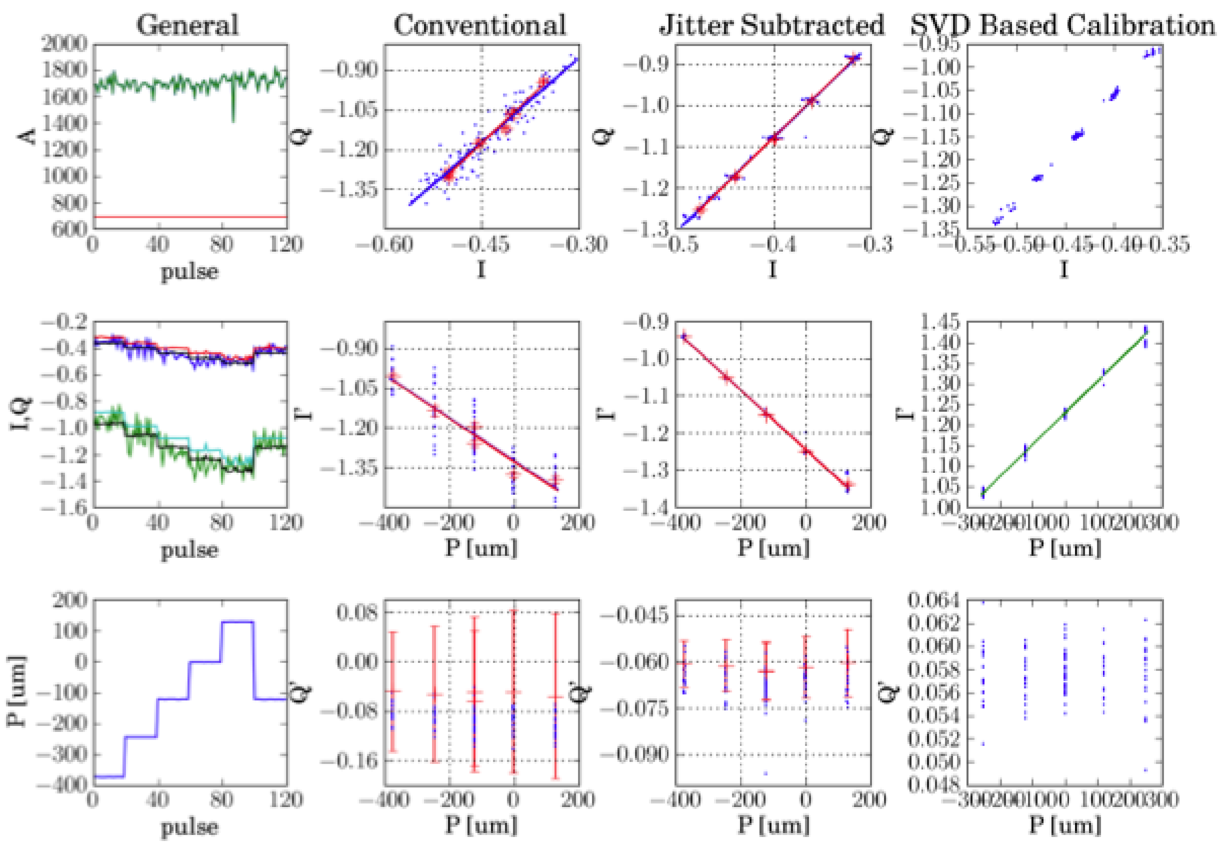




- System resolution calculated using SVD
- Resolution on average ~200 nm with 20 dB of attenuation
- Without attentuation ~27 nm

Calibration stability





Calibration stability

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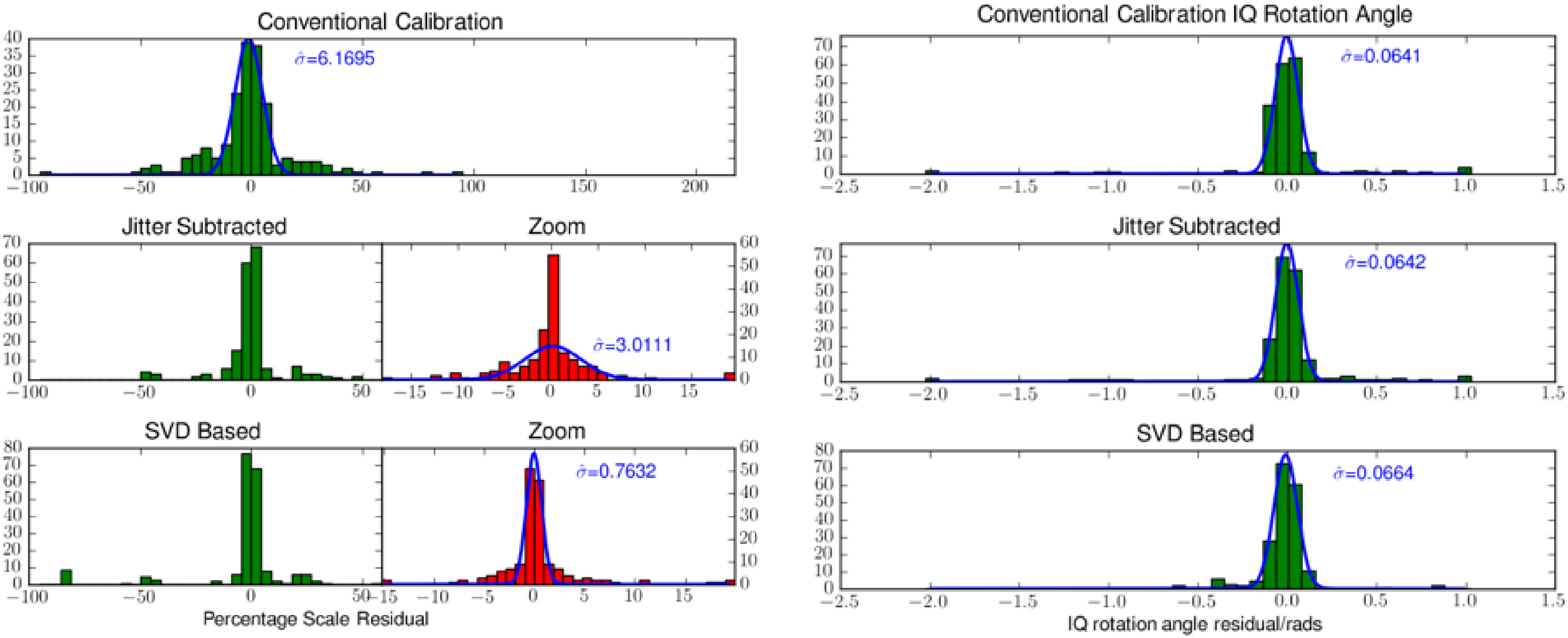
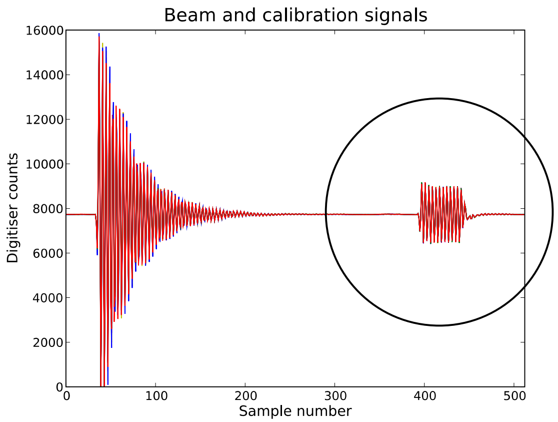
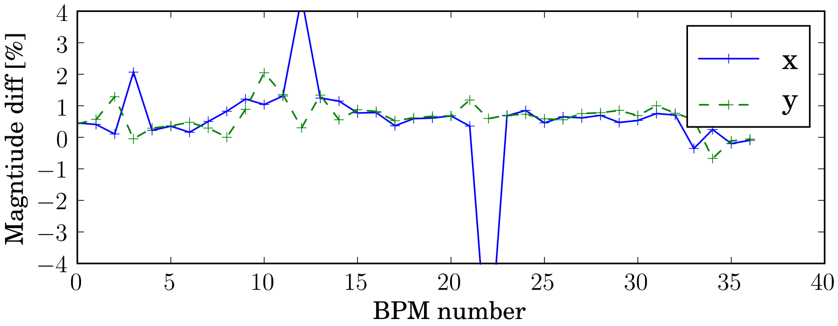
- 3 week period, measure calibration constants (scale and IQ-rotation) each week
- Compare to first week
- Compute correlation matrices before and during calibration

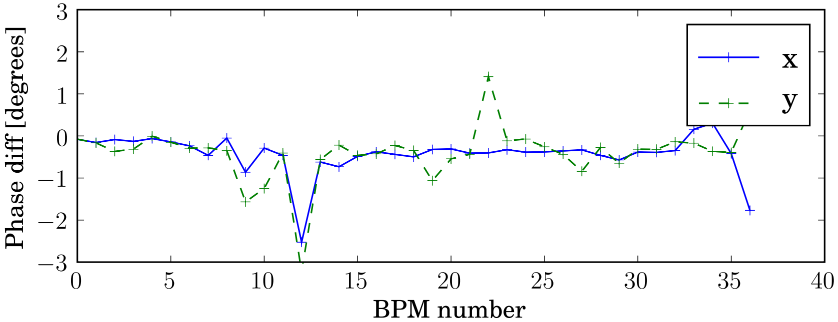


Monitoring calibration

- Inject stable RF signal at cavity frequency to all channels
- Measured at start and end of a 5 day operation period (Monday – Friday)
- **Perform exactly same RF analysis as for BPM signal**
- Compare over time
- Difference in scale ~1%
- Difference in RF phase 0.1 degree @ C-band

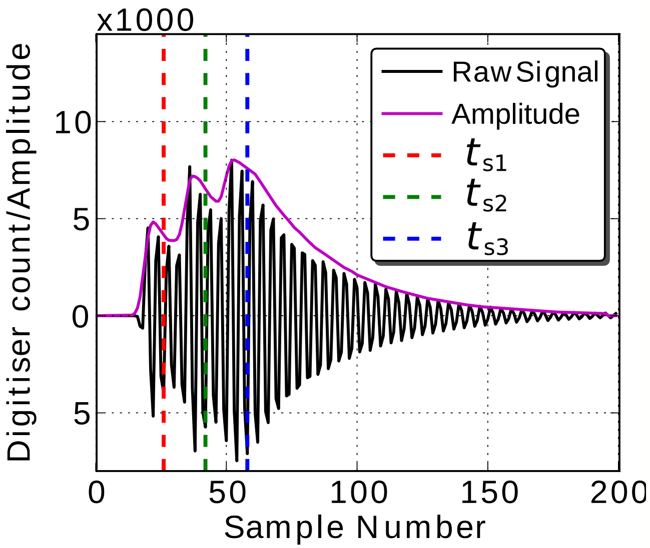






Problems with cavities

- Ab-initio alignment a problem -> excellent PACMAN exists
- **Ab-initio calibration also a problem**
- RF phase (cable lengths, phase-locking)
- Scale variations (temperature gain drifts)
- **Short bunch separation (CLIC)**
- Overlapping signals in BPMs
- Extraction of position signal along CLIC train



First measurements from PACMAN BPM

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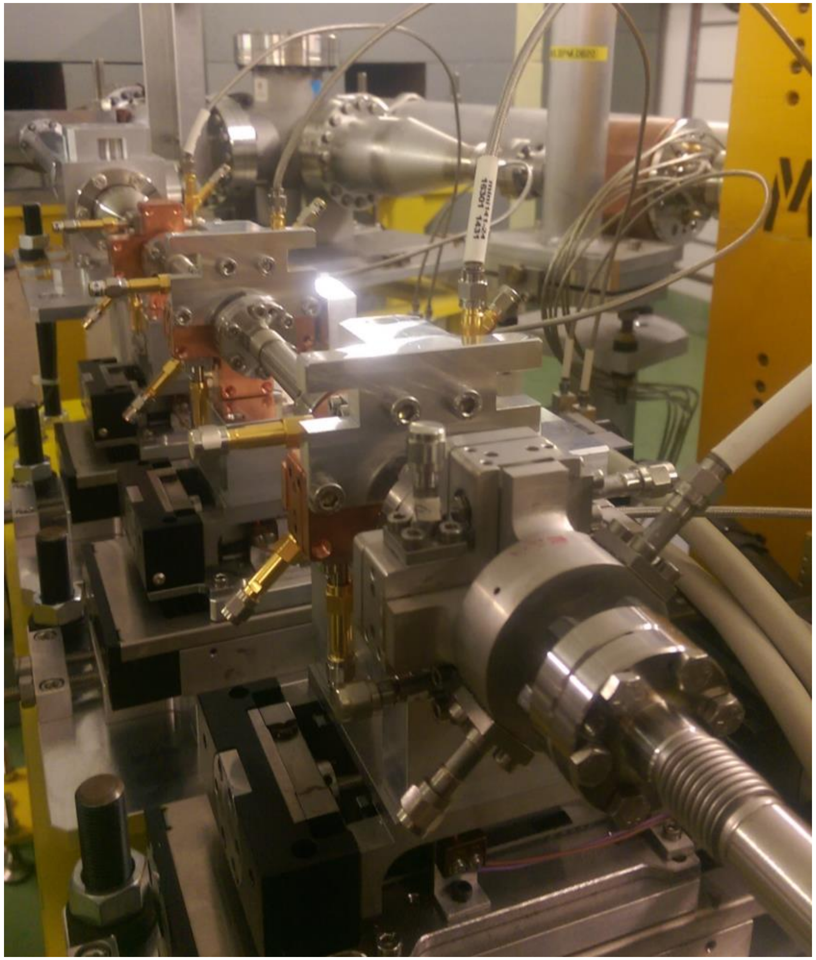
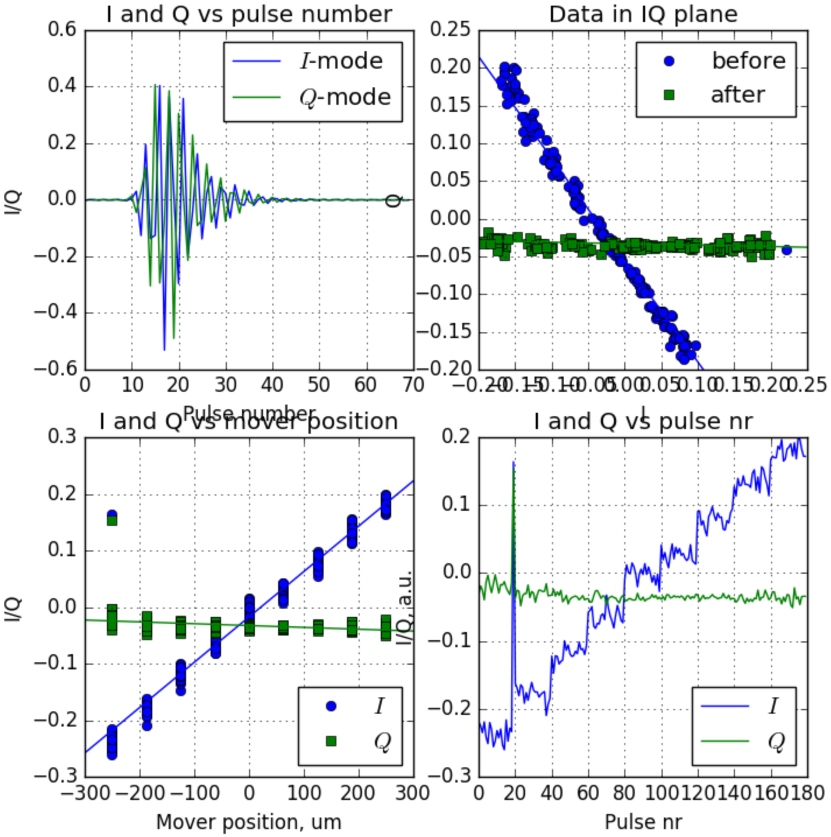
Data taken in last few months



Triplet of 15 GHz, Copper resonant cavities



Conclusions

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- Cavity beam position monitors are routinely used for ILC test facilities
- Resolution and stability for ILC achievable(d)
- Resolutions of 10s nm routinely possible
- Stable over weeks of operation
- Ab-initio alignment and calibration always a problem

- CLIC BPMs are significantly more challenging (not really discussed in this talk)
- CLIC bunch train is a serious complication
- Resolution performance is also difficult to meet (<50 nm)

Backup slides and applications

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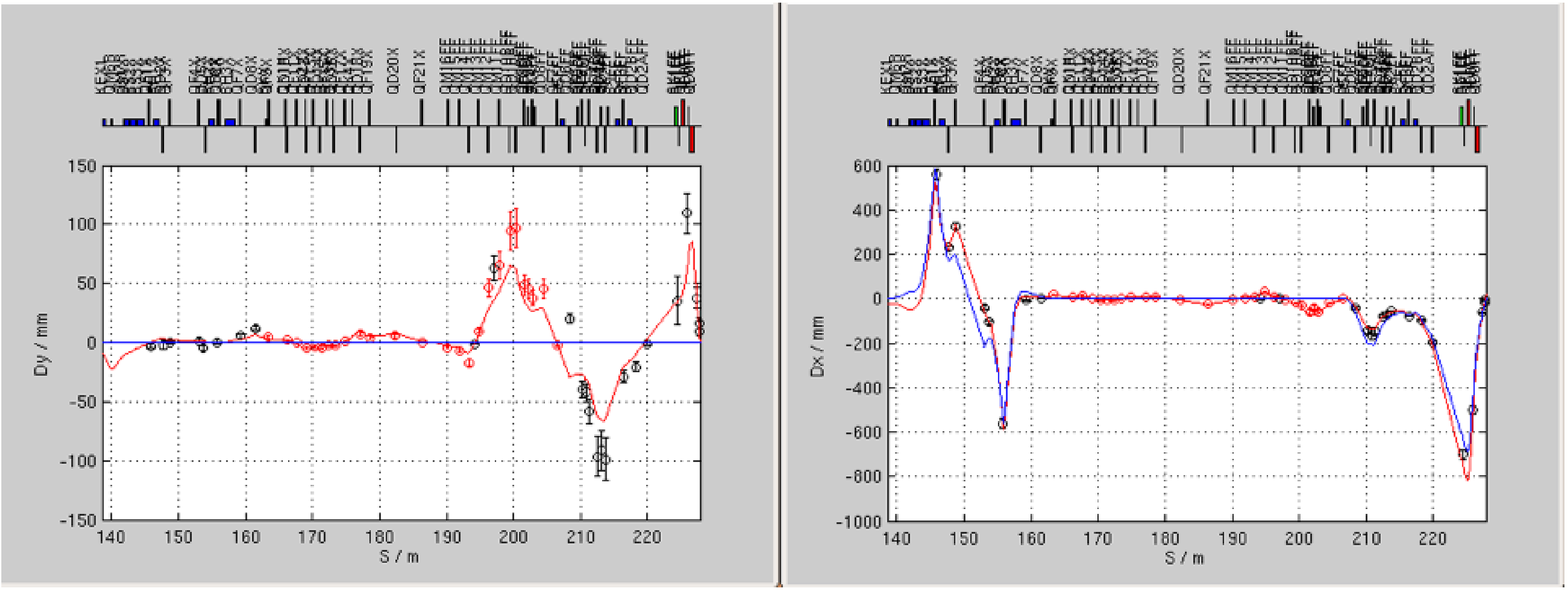
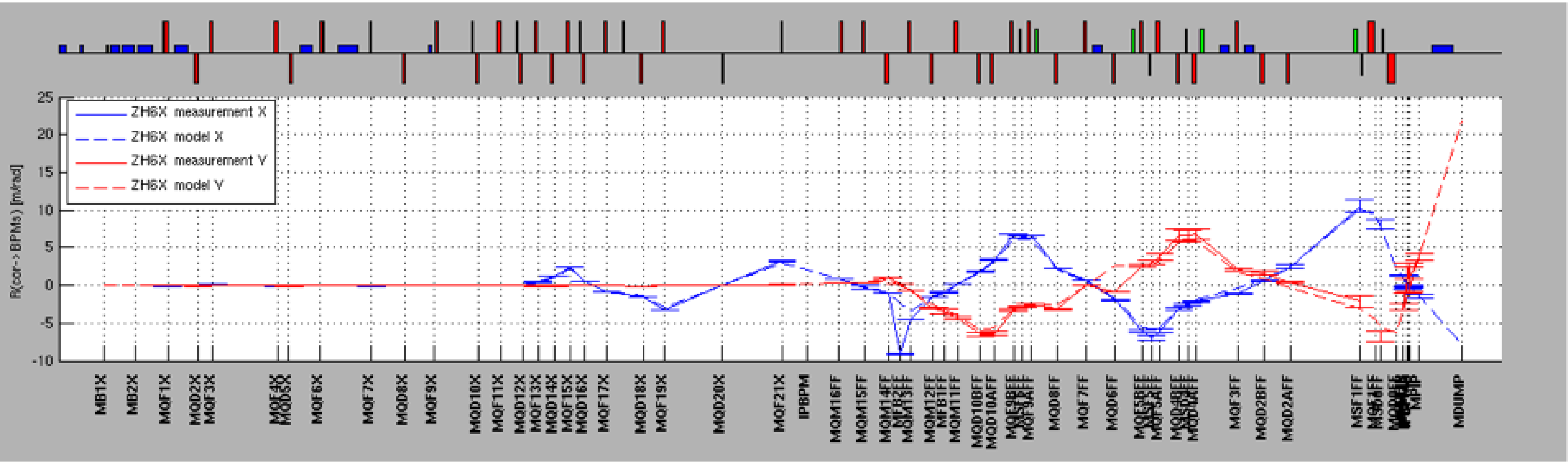
Dispersion measurement

- Dispersion measurement
- Adjust energy of bunch using damping ring RF
- Measure position in ATF2



Dispersion measurement

- Kick beam using dipole magnet
- Use BPM system to monitor response
- Compare with model of accelerator



Wakefield kick measurements

- Move a wake-field source upstream
- Measure orbit distortion downstream