Low-Q cavity BPM with an ultra-high position resolution

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PAL

Contents

Introduction

Introduction

A requirement of High resolution cavity BPM for future collider

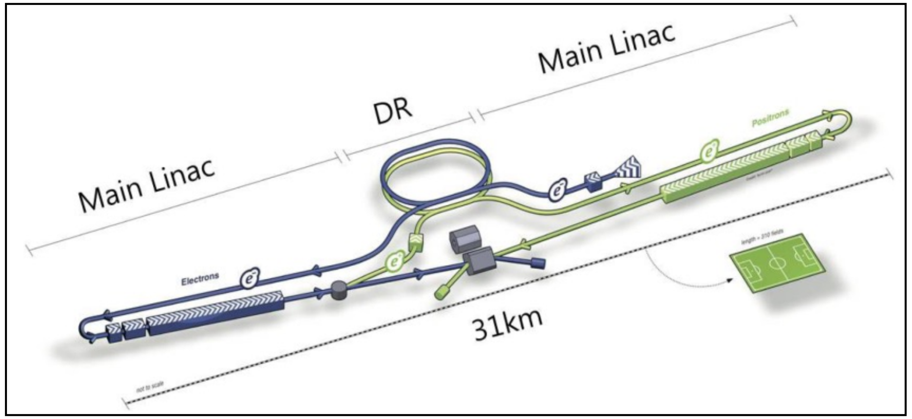
- **Realization of a precise beam handling is strongly required in future accelerators such as linear colliders (LC) and X-ray free electron lasers (XFEL). It goes without saying that a high resolution beam position measurement is the key.**

High luminosity ⇨ Small beam size (~ nm level) ⇨ Precise orbit control (~nm resolution)

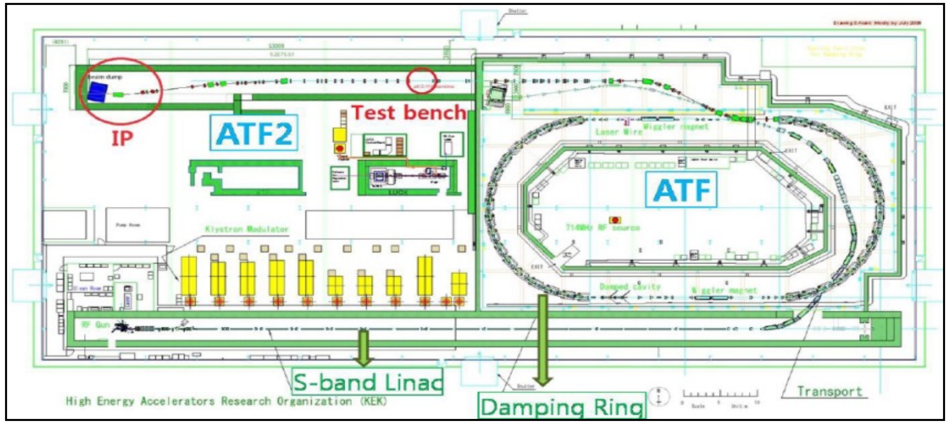
Multi bunch operation with 150ns Bunch spacing ⇨ Requirement of the fast beam feedback system ⇨ Short decay time of BPM below 50ns

∴ Low-Q cavity type BPM !

ILC scheme

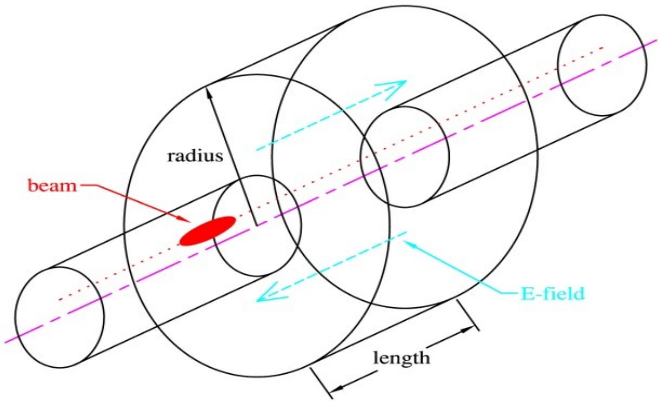


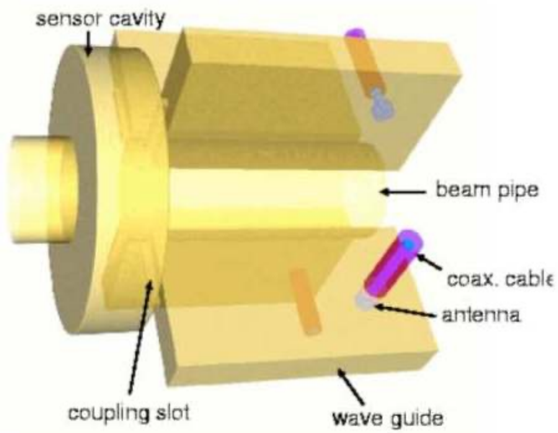
ATF layout



Introduction / Cavity BPM

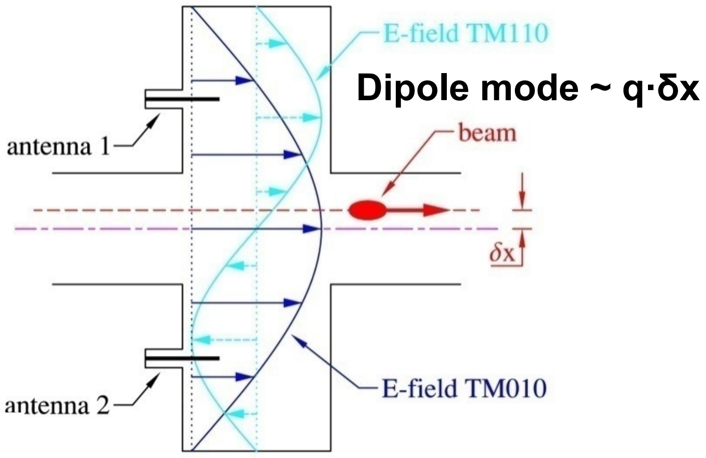
Principle of cavity BPM



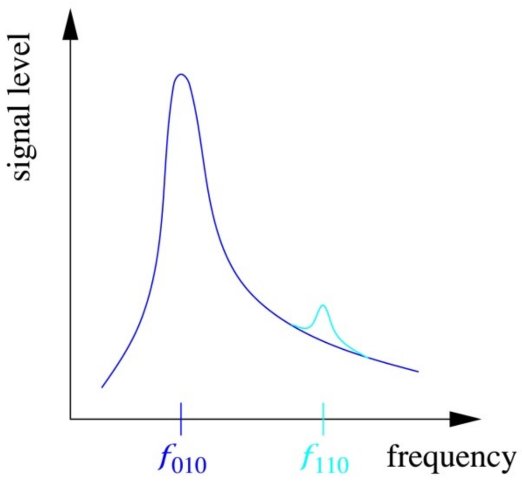


Dipole mode selectable coupler

Generates dipole (TM110) and monopole (TM010) modes



Monopole mode ~ q



Needs monopole mode suppression!

1. Small thermal noise due to narrow band width (~ MHz).
2. No signal at zero position.
3. Position is calculated with the dipole mode of cavity pickup
4. Normalization from different signal (monopole mode).

Design of Low-Q cavity IPBPM

Design of Low-Q Cavity IPBPM

Key point of cavity BPM design for high beam position resolution

- Usual cavity BPM was designed to cylindrical shape, but our low-Q IPBPM was designed to rectangular shape to get the more higher beam position resolution in vertical plane.

$$U = \frac{V_{totalexc}^2}{\omega(R/Q)} = \frac{\omega}{4}(R/Q)q^2\exp\left(-\frac{\omega^2\sigma_z^2}{c^2}\right).$$

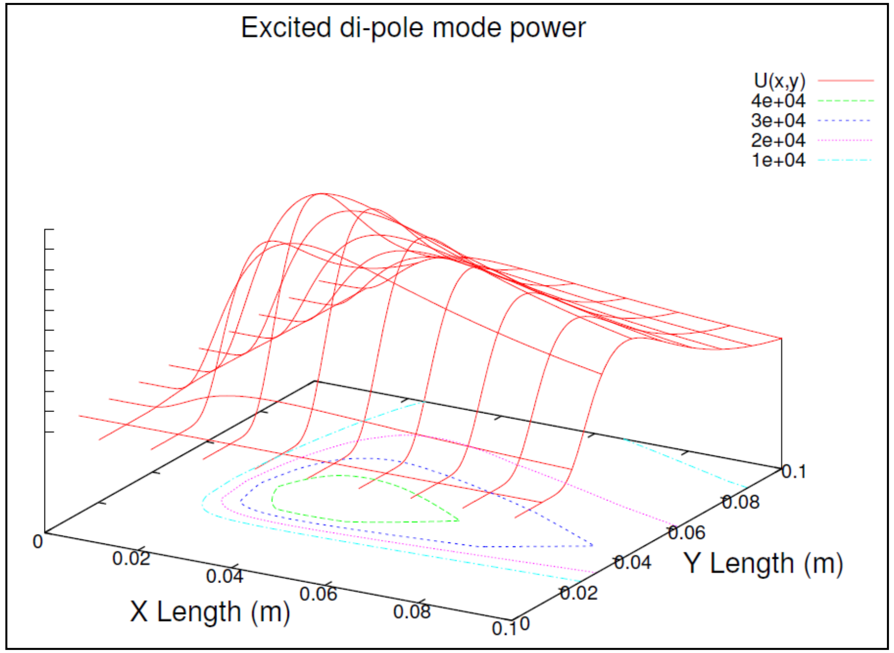
m,n,l = mode number
a,b,L = x,y,z, length

$$\frac{R}{Q}(y) = \frac{8LT^2}{\omega\epsilon_0 ab}\left(\frac{2\pi}{b}\right)^2 y^2 \Rightarrow V_{out0} \propto \sqrt{R/Q}$$

Bunch length *σz = 8 mm, typical value for ATF beam,* is *assumed. Also, cavity length in Z direction L* is fixed. The output power would be maximum at C-Band region, approximately 5 ~ *7 GHz.*

$\omega = 2\pi f = ck$, resonant frequency is represented as

$$f = \frac{1}{2\pi}c\sqrt{k_x^2 + k_y^2 + k_z^2} = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{L}\right)^2}.$$



Since the electron beam is synchronized with the ATF DR's accelerating frequency of 714 MHz, it is practical to design f_0 as an integer multiple of 714 MHz. Therefore, f_0 is set to 5.712 GHz (714 MHz × 8) for the X direction and 6.426 GHz (714 MHz × 9) for the Y direction.

Design of Low-Q Cavity IPBPM

Determine of resonant frequency of Low-Q cavity BPM

- **The rectangular design is determined since f0 for TM210 or TM120, which is mainly determined by cavity size in X and Y direction, a and b. From simulation and measurements of test cavities, a = 60.85 mm and b = 48.55 mm were determined.**

Parameters	Length[mm]
X direction (= a)	60.85
Y direction (= b)	48.55
Z direction (= L)	5.8
X-beam pipe	12
Y-beam pipe	6

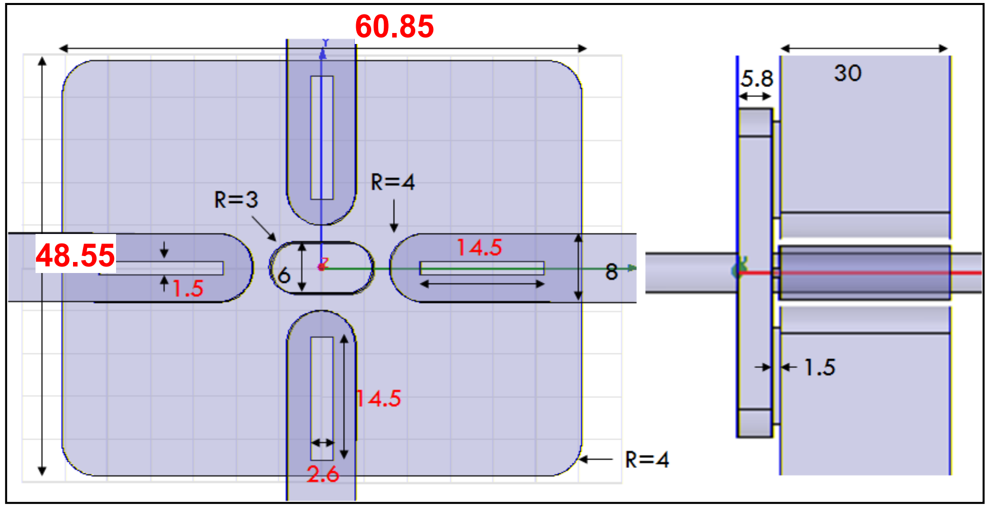


Figure 1: Dimension of cavity

The cavity length L has to be shortened in order to reduce angle sensitivity. However, shorter L decreases R/Q, which reduces position sensitivity also. To recover position sensitivity, Rp is required to be small, in order to prevent leakage of the field from the cavity.

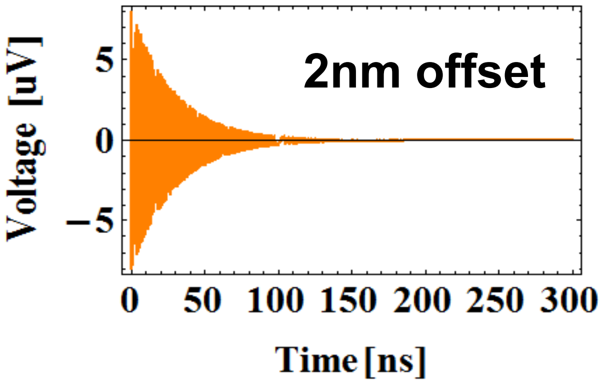
Design of Low-Q Cavity IPBPM

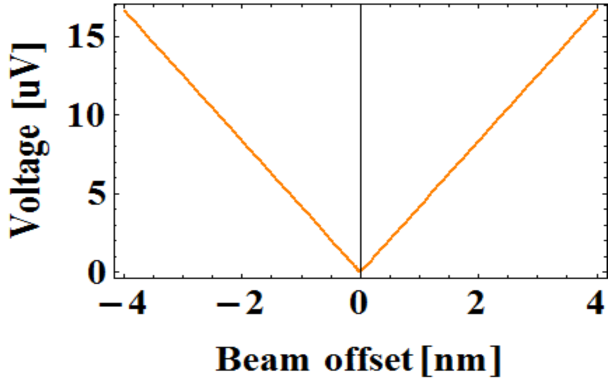
Results of 3D physics simulation

11cm AL ver.

f_0 (GHz)	Δf (MHz)	Q_L	Decay time(ns)	S21(dB)	S21	β	Q_0	Qext
6.4270	11.10	579	14.34	-1.36	0.855	5.9	3996	677
5.7148	7.4	772	21.51	-1.85	0.808	4.2	4021	956

Output signal for Y-port (11cm AL ver.)



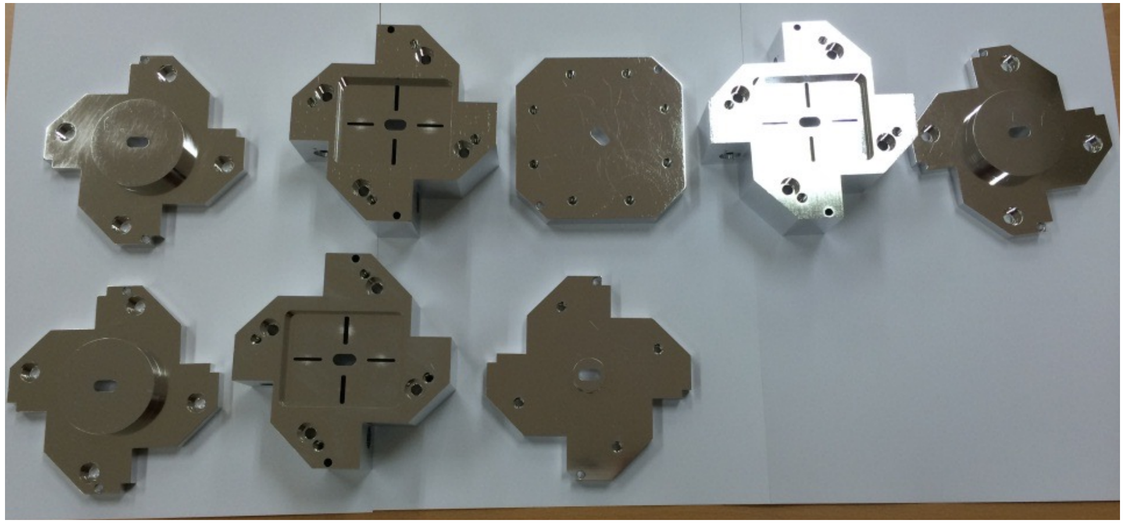


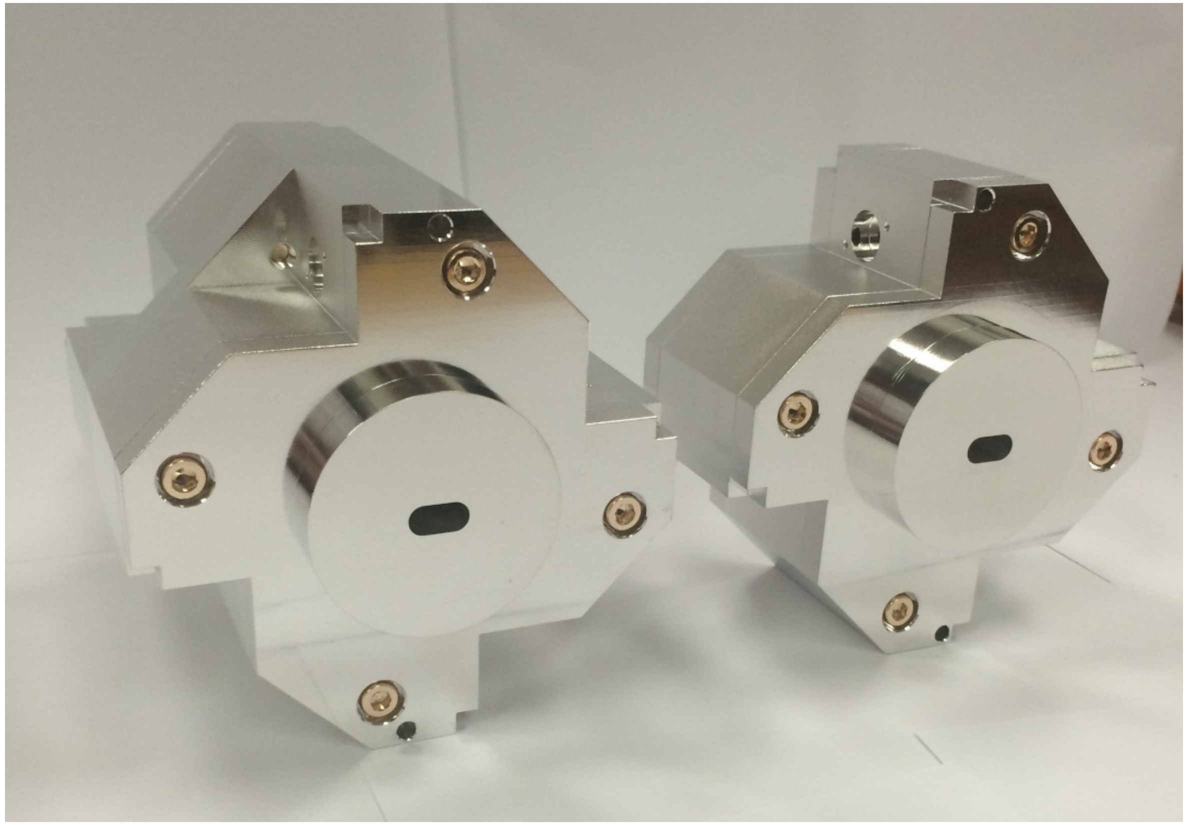
Parameter	Value	Unit
q (charge)	~ 1.6	nC
Beam energy	1.3	GeV
Bunch length	8	mm

The Fabrication of Low-Q IPBPM

Fabricated Low-Q cavity BPM

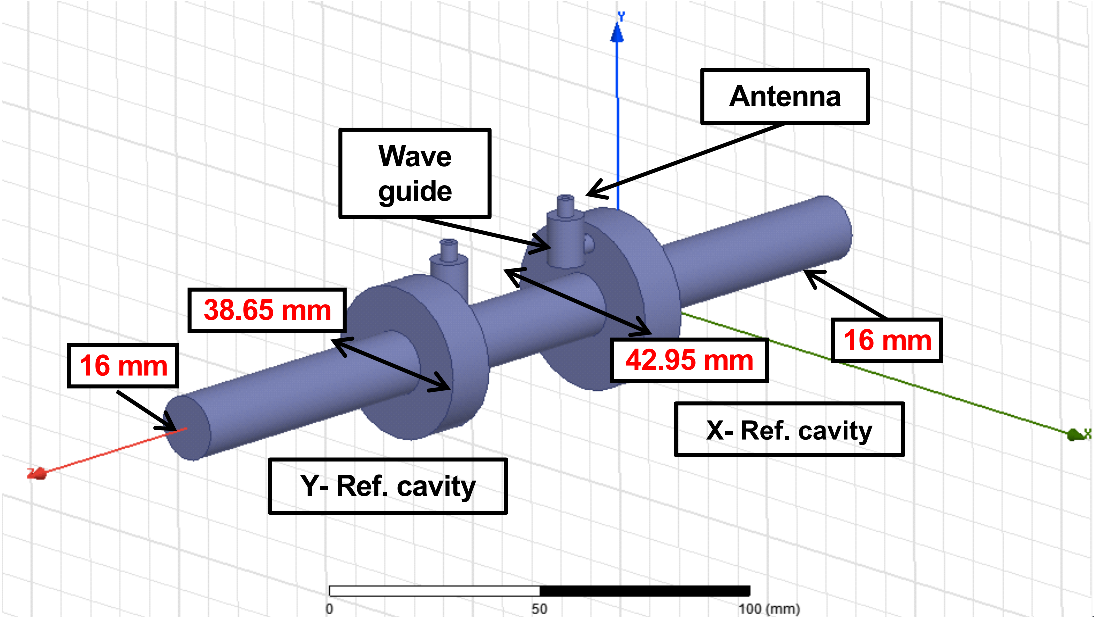
- **BPM body: Aluminum (2kg for double block)**
  - **Precise surface machining within 4um.**
  - **IPBPM A & B are fabricated together in same block.**
  - **IPBPM C was fabricated to single block.**
  - **These BPM are installed inside vertical vacuum chamber**





Reference Cavity BPM Design

Reference cavity BPM for Low-Q cavity BPM



- For the charge normalization

- Ref. signal strength only depends on beam charge
- Phase of Low-Q cavity BPM are locked by beam

- Material of BPM:
 Stainless steel (SUS304)

Output signal strength
= 22 ~ 5dB (1.6nC ~ 0.32nC)

Port	f_0 (GHz)	β	Q_0	Q_{ext}	Q_L	τ (ns)
X-port	5.712	0.00964	1201.20	124578	1189.73	33.157
Y-port	6.426	0.01528	1228.83	80421.2	1210.34	30.029

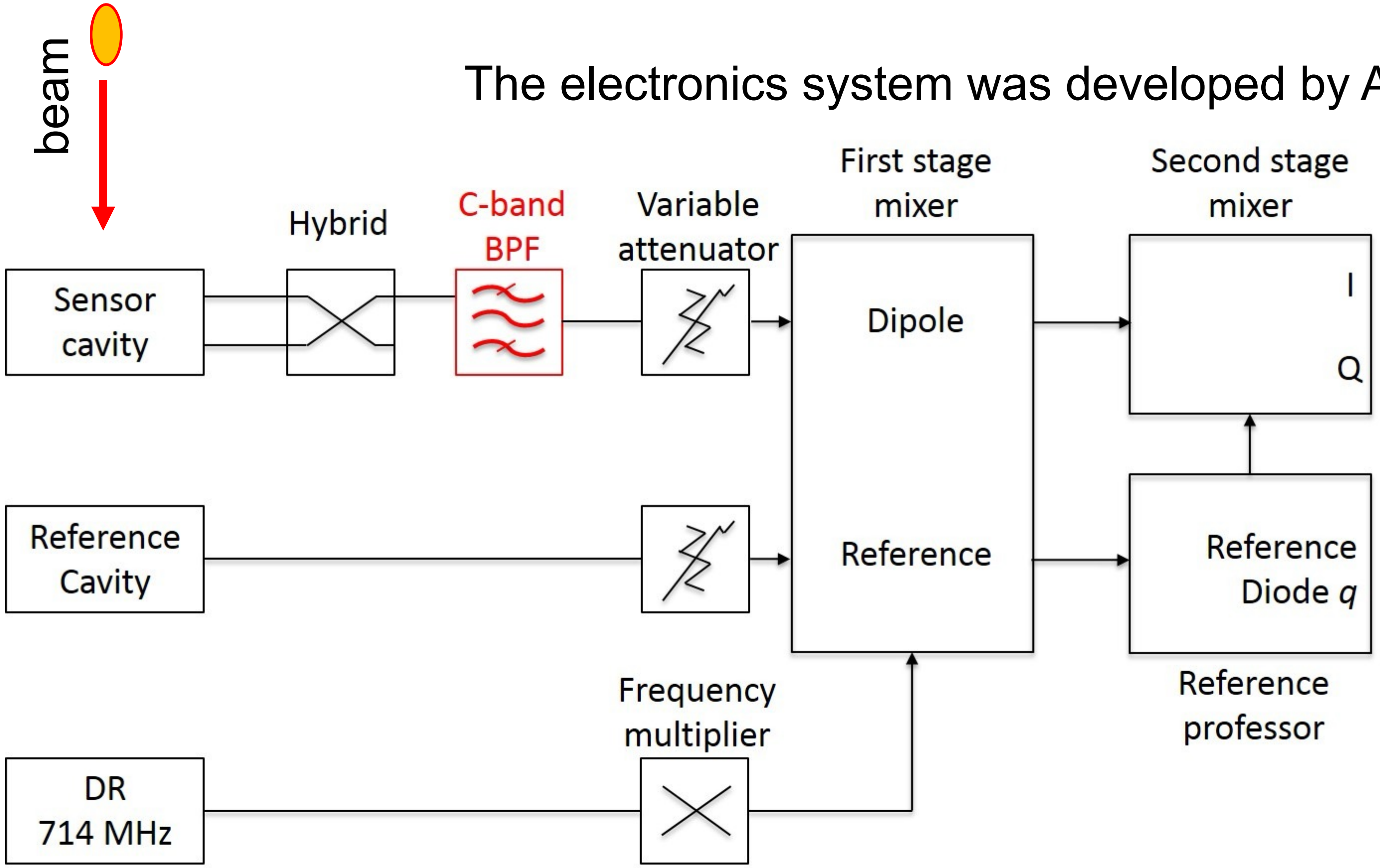
Electronics for Low-Q Cavity IPBPM

Heterodyne electronics for Low-Q cavity IPBPM

The electronics system was developed by ATF in KEK.

Sensitivities at 1x10^{10}e/bunch
4.7uV/nm in X
3.1uV/nm in Y ,

The output signals are amplified to measure by using ADC.

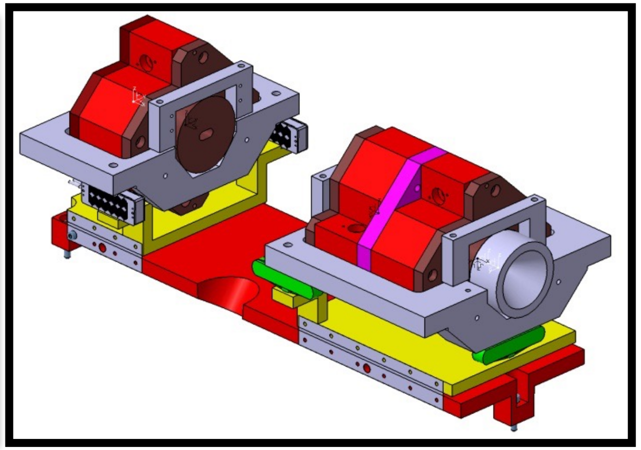


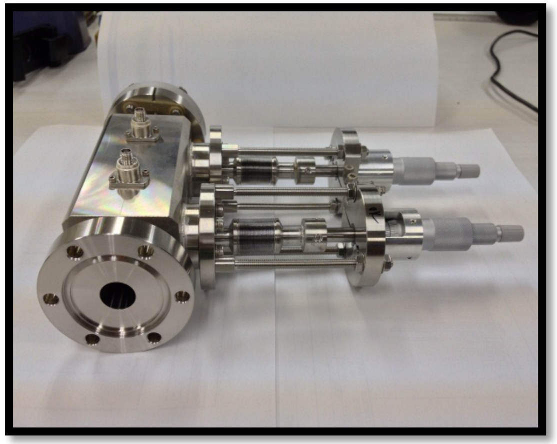
Total Gain from combiner to Detector : 40 + var.att + DC-amp

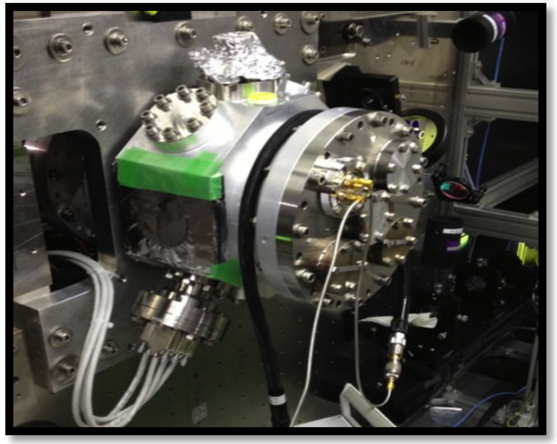
Beam test results of Low-Q cavity IPBPM

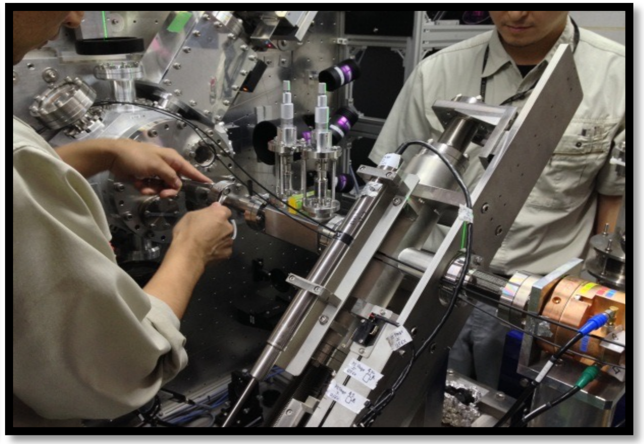
Low-Q Cavity IPBPM System Installation

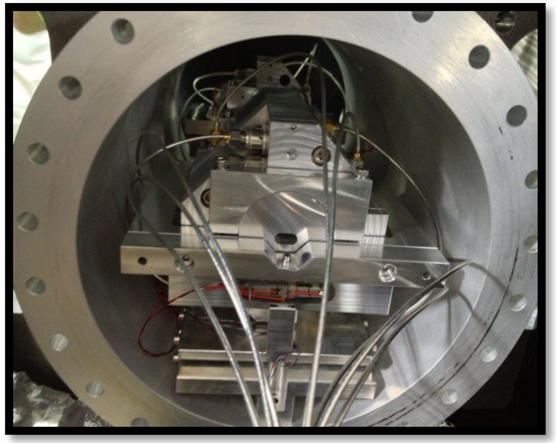
Installation of Low-Q cavity BPM inside vertical vacuum chamber





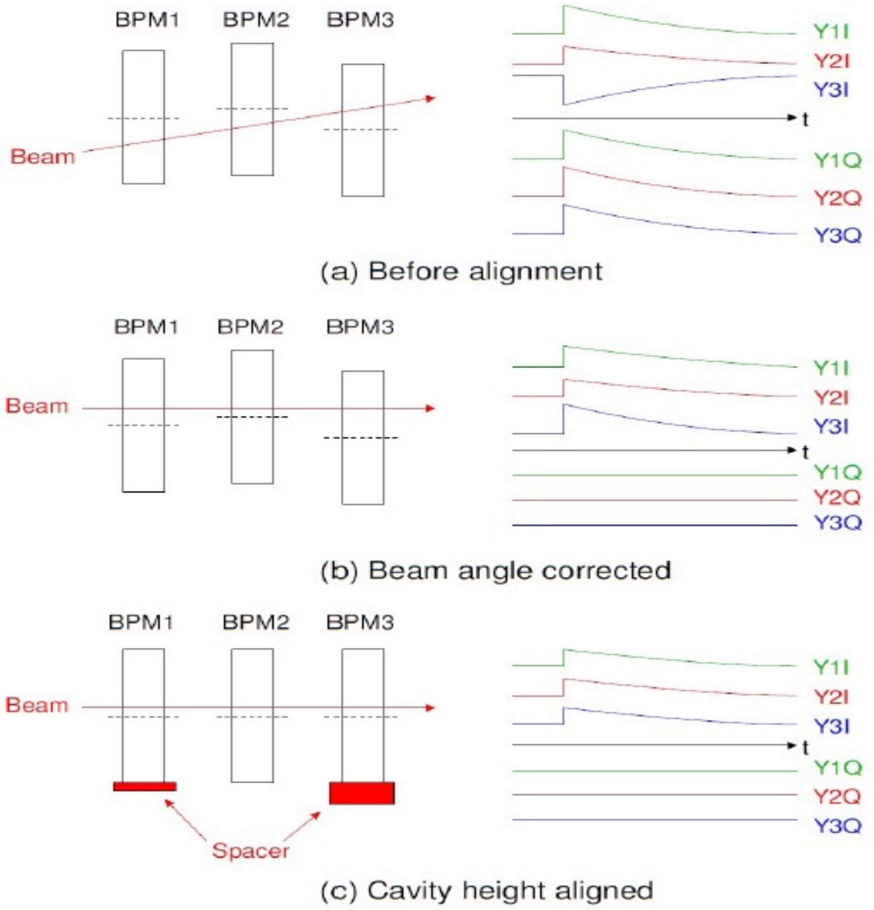




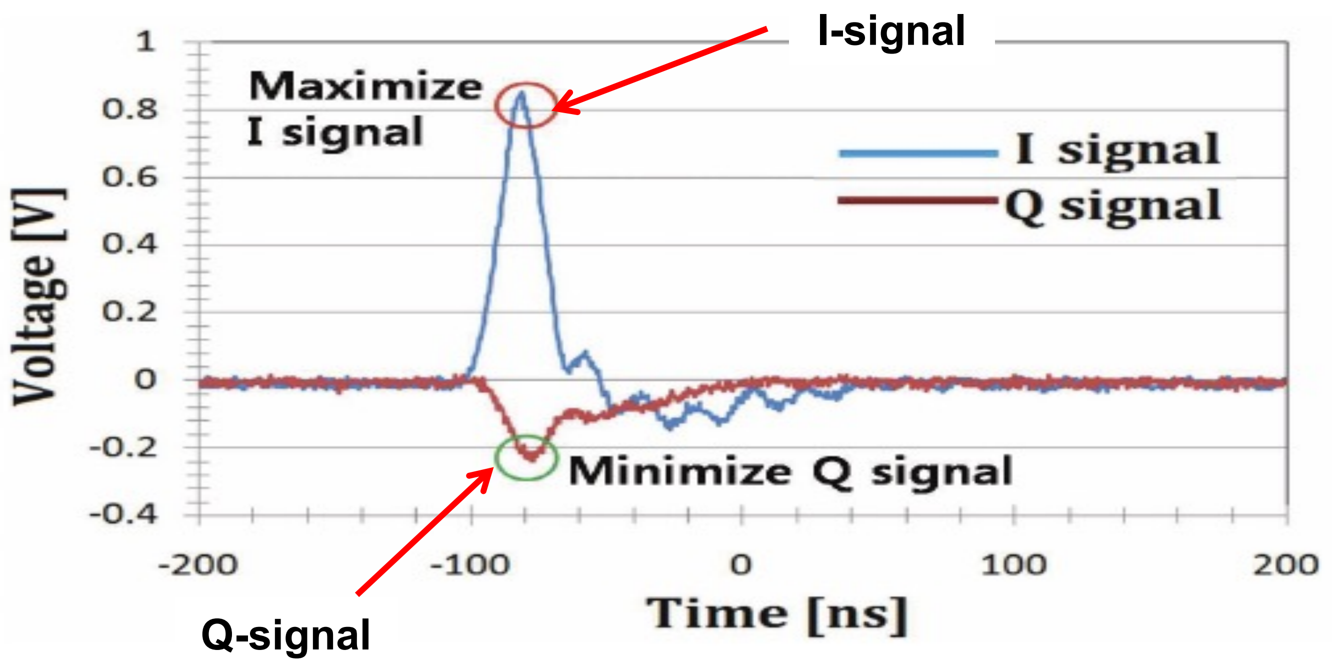


Beam Position Resolution Measurements

I-Q tuning of cavity BPM



I-Q tuning was performed by using oscilloscope. When I signal shows the maximum position, Q signal was set to minimum position by using phase shifter.



Beam Position Resolution Measurements

Geometrical factor between three Low-Q cavity IPBPMs.

Differences are expressed by ;

$$f_1 = I_1 - \frac{I_2 Z_{13} - I_3 Z_{12}}{Z_{23}} = \frac{I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}}{Z_{23}}$$

$$f_2 = I_2 - \frac{I_3 Z_{12} + I_1 Z_{23}}{Z_{13}} = \frac{-I_1 Z_{23} + I_2 Z_{13} - I_3 Z_{12}}{Z_{13}}$$

$$f_3 = I_3 - \frac{I_2 Z_{13} - I_1 Z_{23}}{Z_{12}} = \frac{I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}}{Z_{12}}$$

$$f_0 \equiv I_1 Z_{23} - I_2 Z_{13} + I_3 Z_{12}$$

$$f_1 = \frac{f_0}{Z_{23}}, \quad f_2 = \frac{f_0}{Z_{13}}, \quad f_3 = \frac{f_0}{Z_{12}}$$

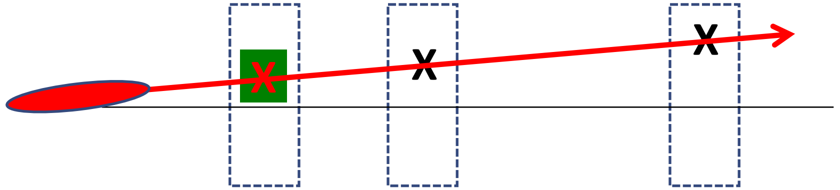
$$\frac{\partial f_0}{\partial I_1} = Z_{23}, \quad \frac{\partial f_0}{\partial I_2} = -Z_{13}, \quad \frac{\partial f_0}{\partial I_3} = Z_{12}$$

Residuals are expressed by ;

$$\begin{pmatrix} \Delta f_1^2 \\ \Delta f_2^2 \\ \Delta f_3^2 \end{pmatrix} = \begin{pmatrix} 1 & (\frac{Z_{13}}{Z_{23}})^2 & (\frac{Z_{12}}{Z_{23}})^2 \\ (\frac{Z_{23}}{Z_{13}})^2 & 1 & (\frac{Z_{12}}{Z_{13}})^2 \\ (\frac{Z_{23}}{Z_{12}})^2 & (\frac{Z_{13}}{Z_{12}})^2 & 1 \end{pmatrix} \begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \end{pmatrix} = A \begin{pmatrix} \sigma_1^2 \\ \sigma_2^2 \\ \sigma_3^2 \end{pmatrix}$$

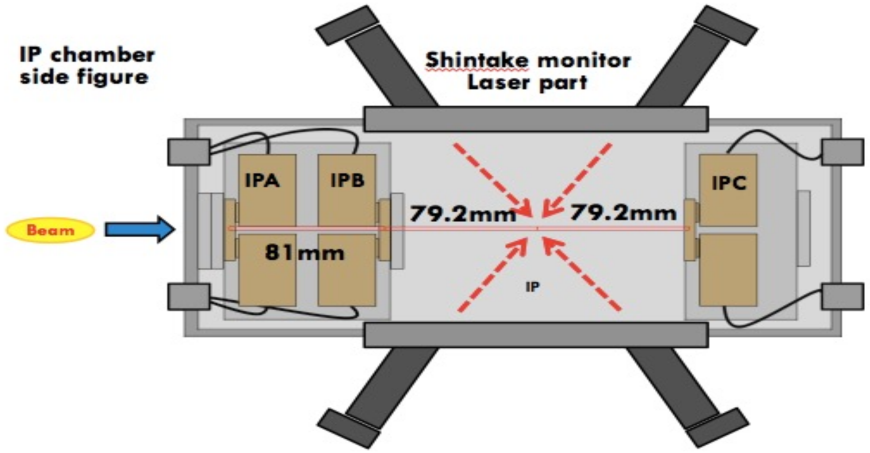
Since det A is zero, $\sigma_1 = \sigma_2 = \sigma_3 \equiv \sigma$

$$\sigma = \Delta f_1 / \sqrt{1 + (\frac{Z_{13}}{Z_{23}})^2 + (\frac{Z_{12}}{Z_{23}})^2} = \Delta f_2 / \sqrt{(\frac{Z_{23}}{Z_{13}})^2 + 1 + (\frac{Z_{12}}{Z_{13}})^2} = \Delta f_3 / \sqrt{(\frac{Z_{23}}{Z_{12}})^2 + (\frac{Z_{13}}{Z_{12}})^2 + 1}$$



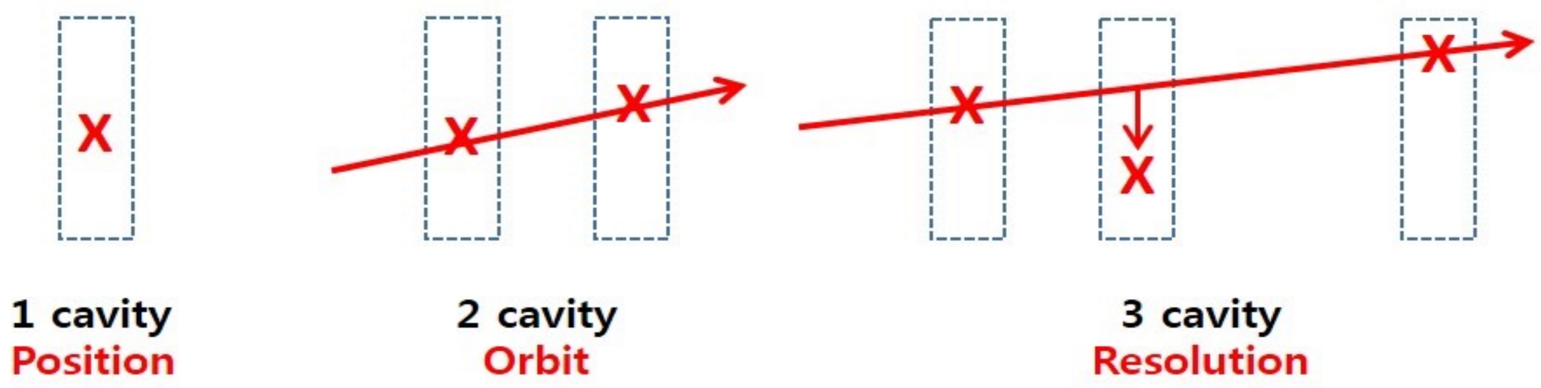
Beam position measurement and prediction

	IPBPM-A (Interpolated by IPBPM-B and C)	IPBPM-B (Interpolated by IPBPM-A and C)	IPBPM-C (Interpolated by IPBPM-A and B)
Geometrical factor	0.531065	0.802629	0.271567



Beam Position Resolution Measurements

Position residual calculation by using three Low-Q cavity IPBPM

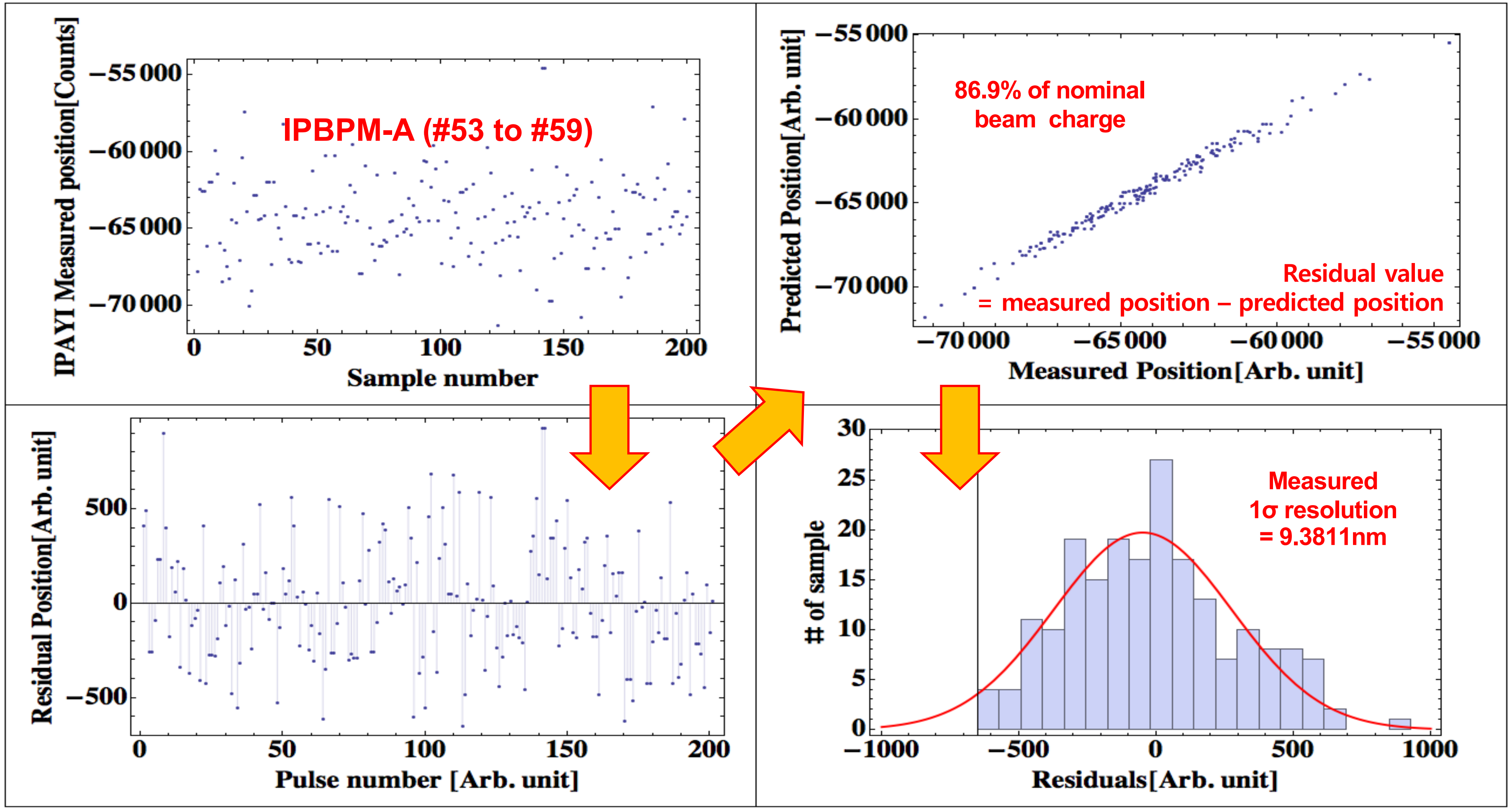


Predicted position(ADC counts) for IPA was calculated as follow equation,

- **Predicted position of IPA-YI' = a1*IPB-YI'+ a2*IPB-YQ'+a3*IPC-YI'+ a4*IPC-YQ'+ a5*Ref-Y+a6*IPB-XI'+ a7*IPB-XQ'+a8*IPC-XI'+ a9*IPC-XQ'+ a10*Ref-X+a11**
- **Residual of IPC-YI' = Measured IPCx-YI' – Predicted IPC-YI'**
- **The beam position resolution proportional to 1/(beam charge).**

$$\text{Norm. Resolution} = \text{Geometrical factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured beam charge}}{\text{Nominal beam charge}}$$

Beam Position Resolution of Low-Q IPBPM



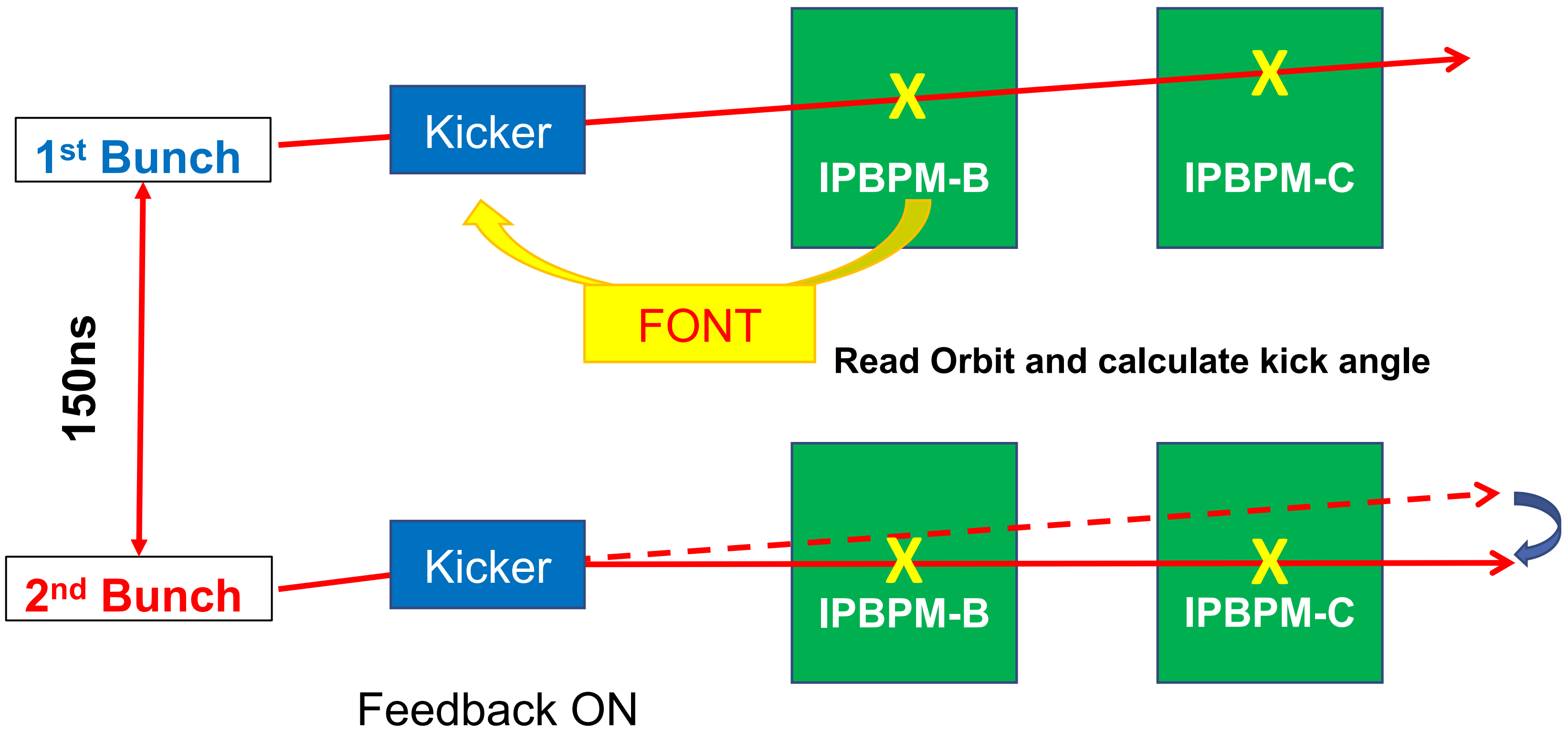
$$\text{Norm. Resolution} = \text{Geo. factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured charge}}{\text{Nominal charge}} = 9.3811\text{nm}*0.869\% = \mathbf{8.1586nm}$$

Feedback system with Low-Q cavity IPBPM

Low-Q IPBPM Beam Orbit Feedback Study

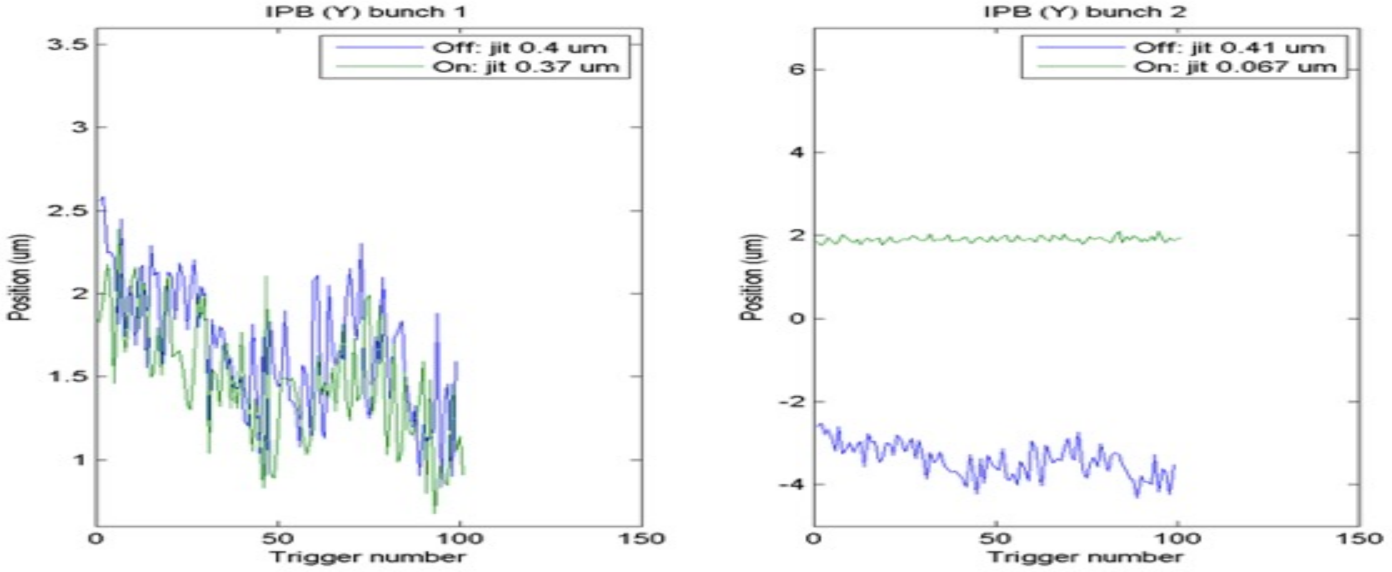
Feedback On Nanosecond Timescales(FONT) system developed by Oxford.

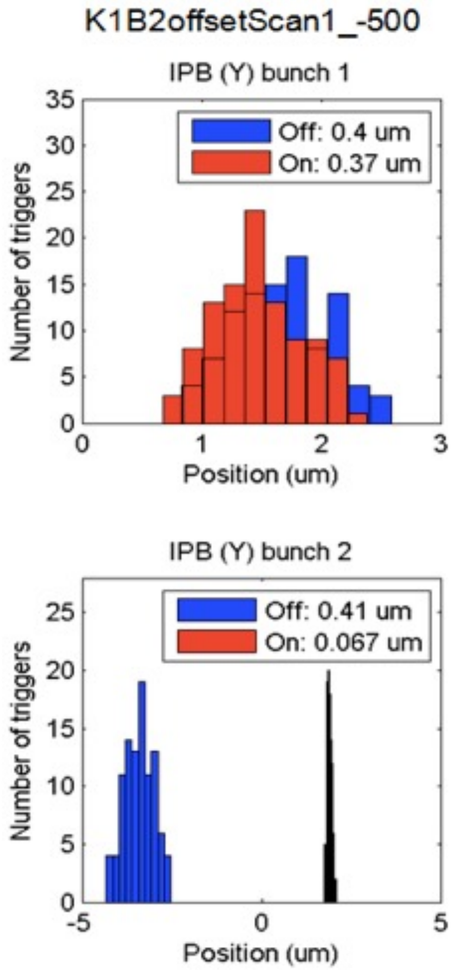
- The fast beam orbit feedback study was performed by using FONT system.
- The test was performed under two bunch operation mode with 150ns bunch spacing.



Low-Q IPBPM Beam Orbit Feedback Study

Feedback study results with FONT & Low-Q IPBPM system





Beam jitter w/o feedback: 370nm.
Beam jitter with feedback: 67nm
~82% beam jitter was reduced
and well focused orbit feedback.

Summary

- 11cm AL. Low-Q cavity IPBPM was developed and fabricated to achieve 2nm beam position resolution with wide dynamic range. The beam test was performed at the Interaction point of ATF2.

- Beam position resolution measurements of low-Q IP-BPMs was performed. The measured beam position resolution was 10nm with 87% beam charge, which resolution corresponds to 8nm of normalized beam position resolution.

- The feedback study by using IP-BPM was also performed and we reduced beam jitter ~82%.

- The use of such high-resolution beam position monitors and feedback systems is expected to greatly benefit the CEPC (Circular Electron Positron Collider) as well.

Thank you !