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The development of C-Band Cavity Beam Position Monitor with a position resolution of nano-meter

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ATF

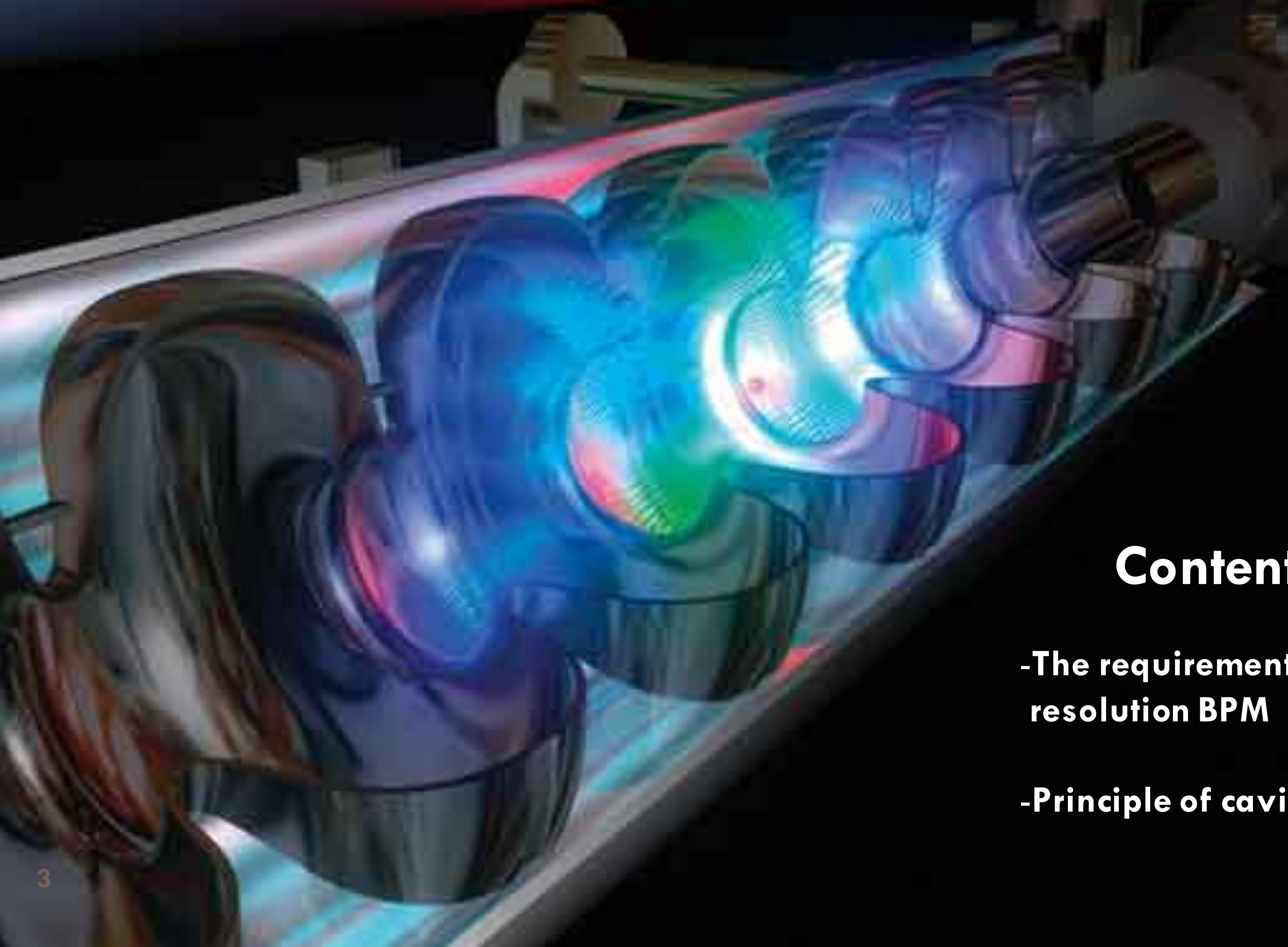
IPAC16

Contents

- **Introduction of cavity type beam position monitor**
  - **The requirement for high resolution BPM**
  - **Principle of cavity BPM**

- **The development of Low-Q IP-BPM**
  - **The design of Low-Q IP-BPM**
  - **The characteristics of Low-Q IP-BPM**
  - **The electronics system of Low-Q IP-BPM**
  - **The beam test results of Low-Q IP-BPM**
  - **The beam feedback test by using Low-Q IPBPM**

INTRODUCTION



Contents

-The requirement for high resolution BPM

-Principle of cavity BPM

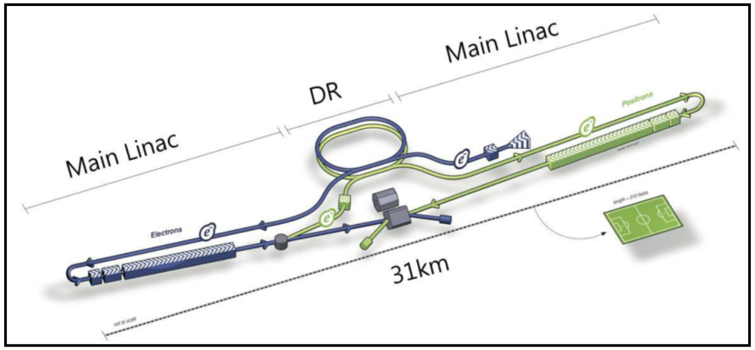
Introduction
- The requirement for low-Q IPBPM

- 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.

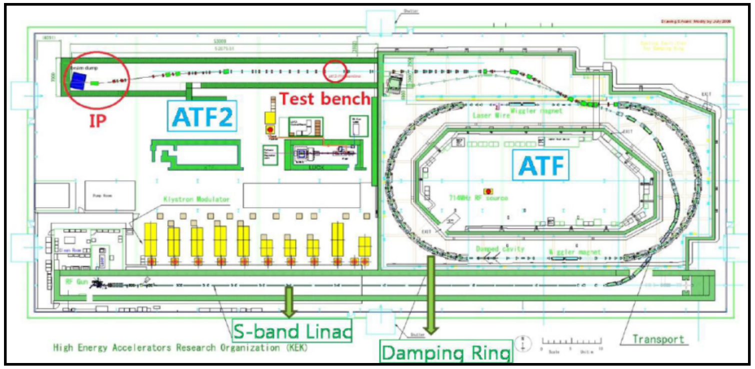
High luminosity ⇨ Small beam size (~ nm level) ⇨ Precise orbit control (~nm resolution)

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 !



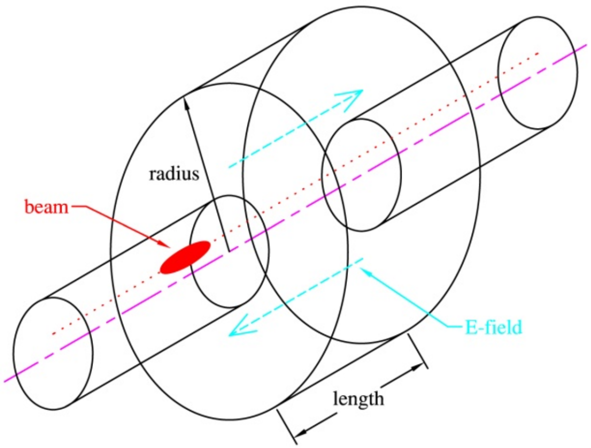
ILC scheme

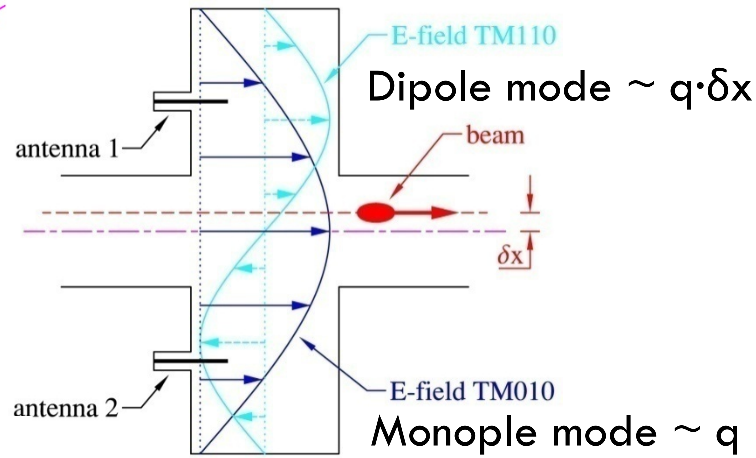


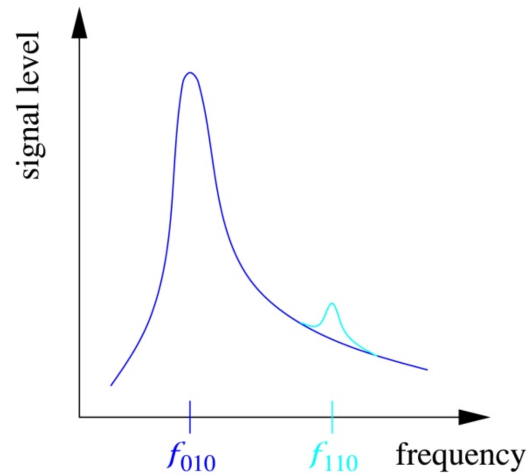
ATF layout

Introduction / Cavity BPM

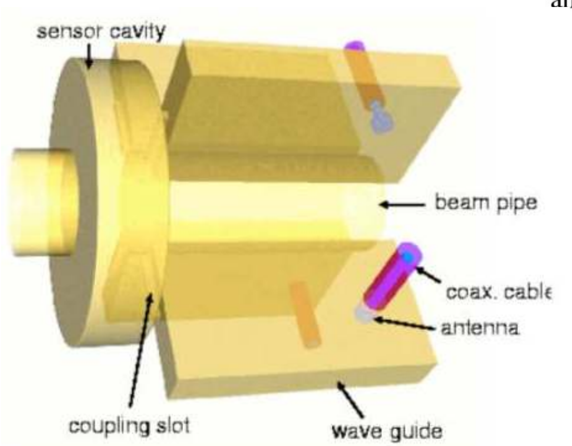
- **Principle** **Generates dipole (TM110) and monopole (TM010) modes**







Needs monopole mode(TM110) suppression!

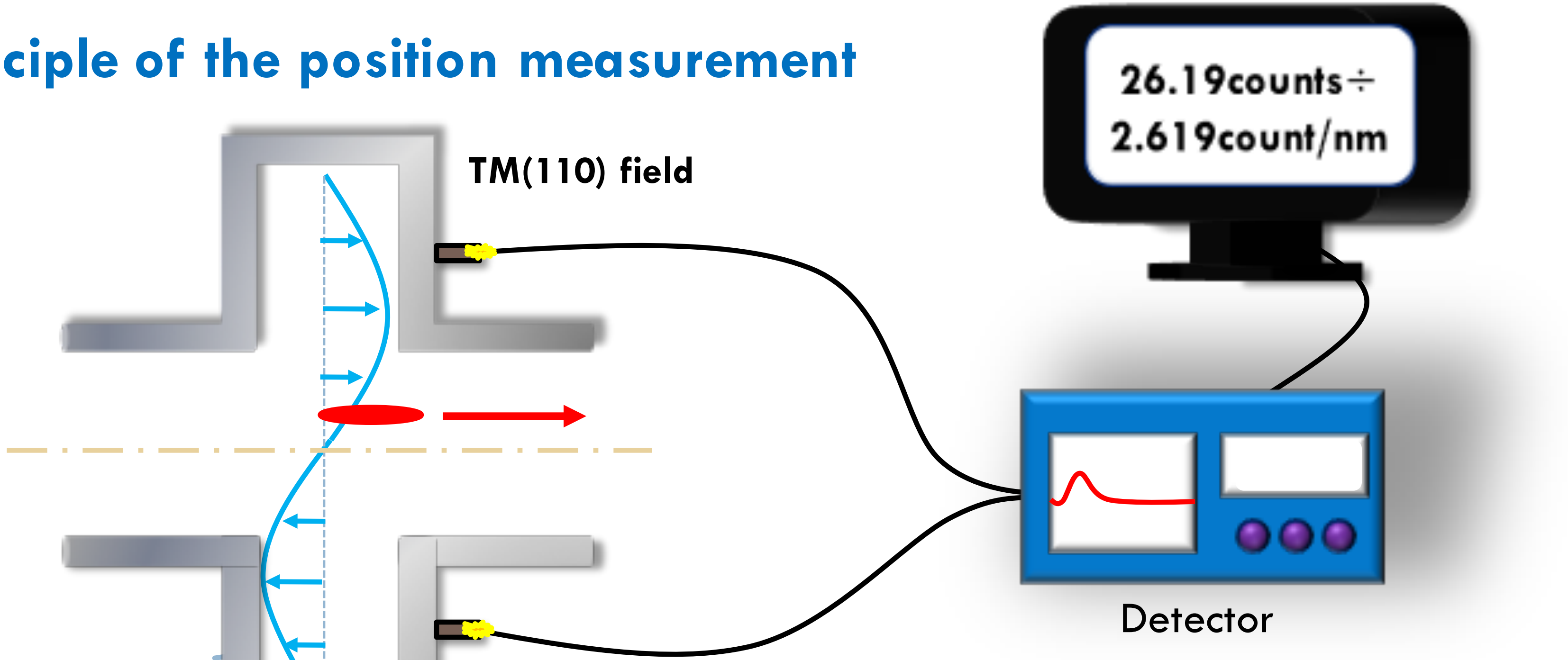


Dipole mode selectable coupler

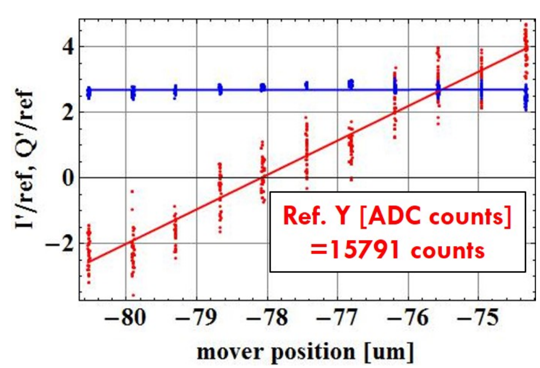
1. **Small thermal noise due to narrow band width (~ MHz).**
2. **No signal at zero position.**
3. **Position is calculated with the dipole mode of cavity pickup**
4. **Normalization from different signal (monopole mode).**

Introduction / Cavity BPM

- Principle of the position measurement



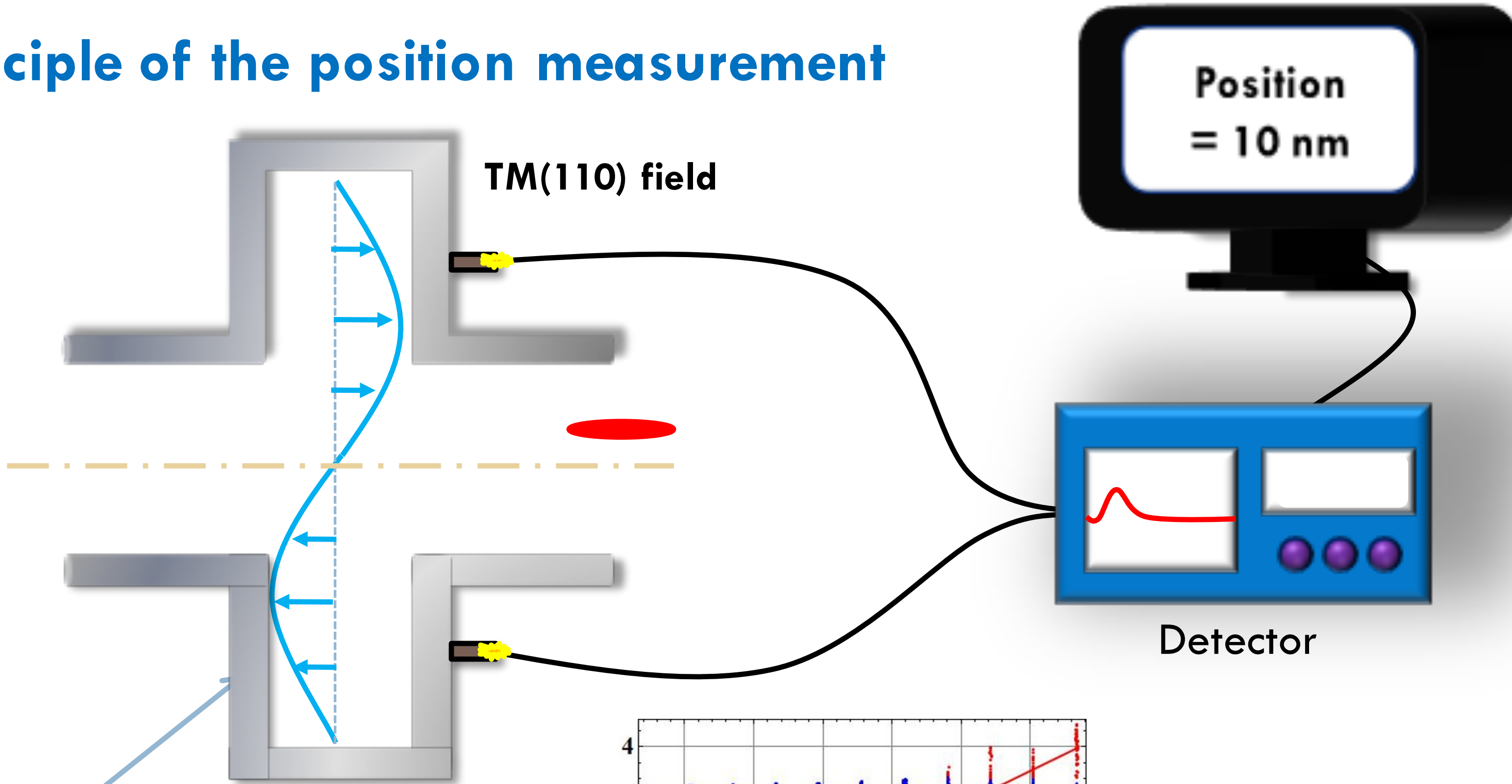
Cavity type
Beam position resolution



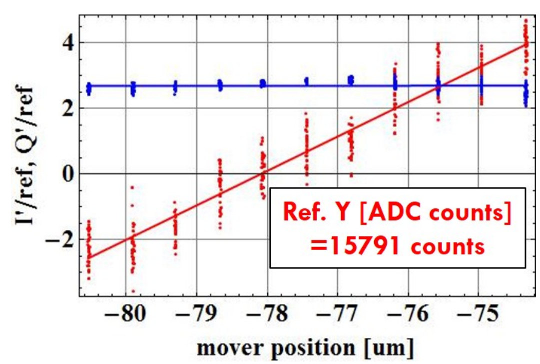
The calibration
Factor of BPM
= 2.619 counts/nm

Introduction / Cavity BPM

- Principle of the position measurement

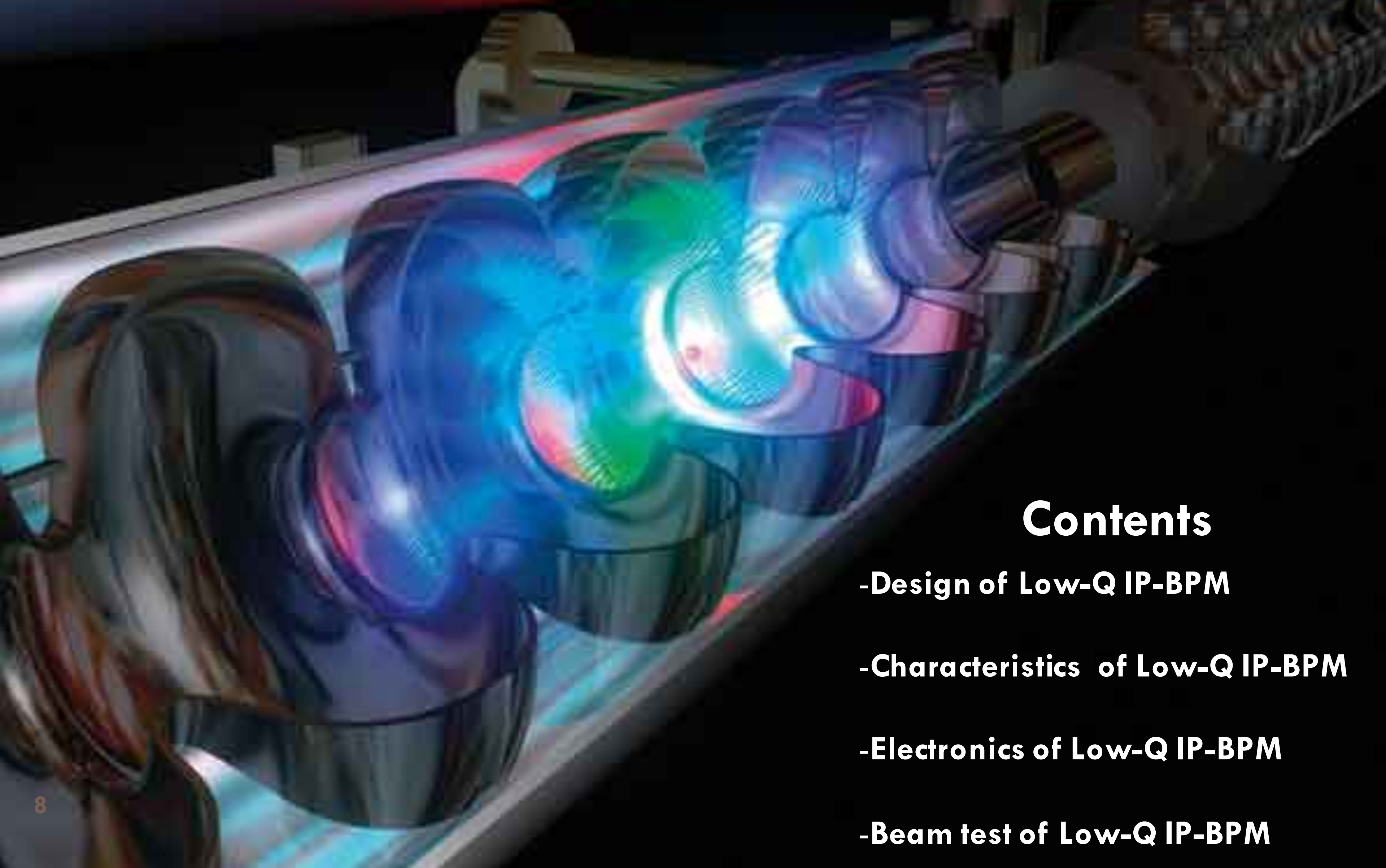


Cavity type
Beam position resolution



The calibration
Factor of BPM
= 2.619 counts/nm

Low-Q IP-BPM



Contents

- -Design of Low-Q IP-BPM
- -Characteristics of Low-Q IP-BPM
- -Electronics of Low-Q IP-BPM
- -Beam test of Low-Q IP-BPM

Design of Cavity BPM

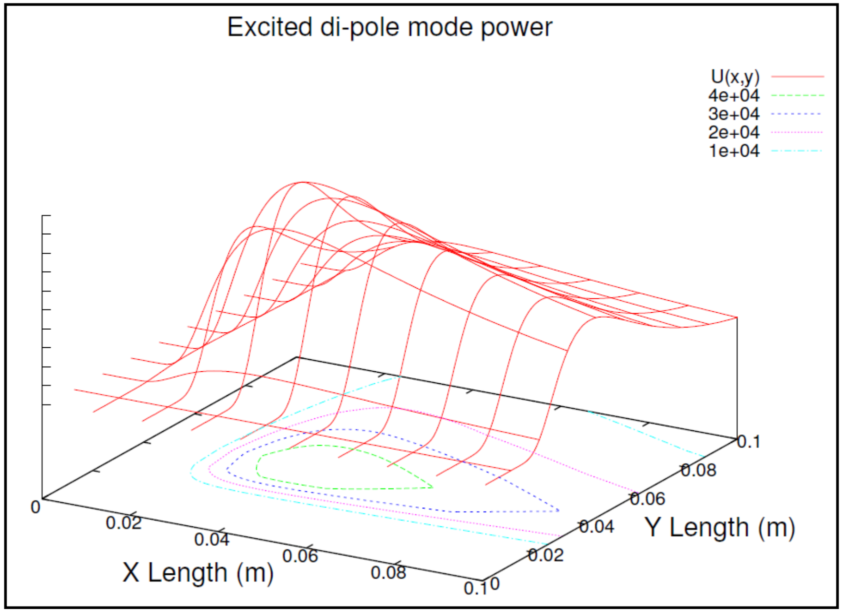
- **Usual cavity BPM was designed to cylindrical shape, but our low-Q IP-BPM was designed to rectangular shape to get the more higher beam position resolution.**

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

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 electron beam is synchronized to the accelerating frequency of the ATF DR, *714* MHz, it is convenient to design *f0 to be integral multiplication of 714 MHz. Therefore, f0 is designed to be 5.712 GHz (= 714 MHz X* 8) and 6.426 GHz (= *714* MHz *X 9) for X and Y respectively.*

Design of Low-Q IP-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

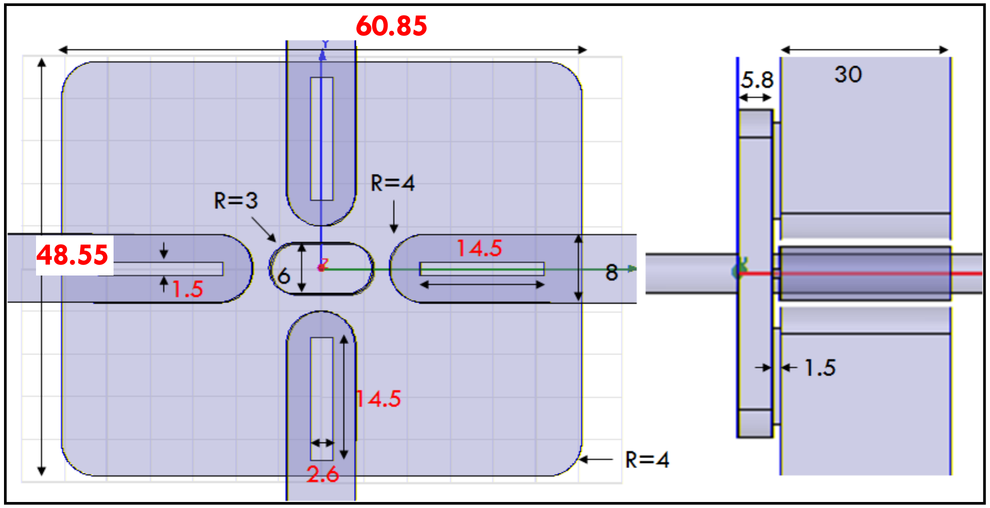
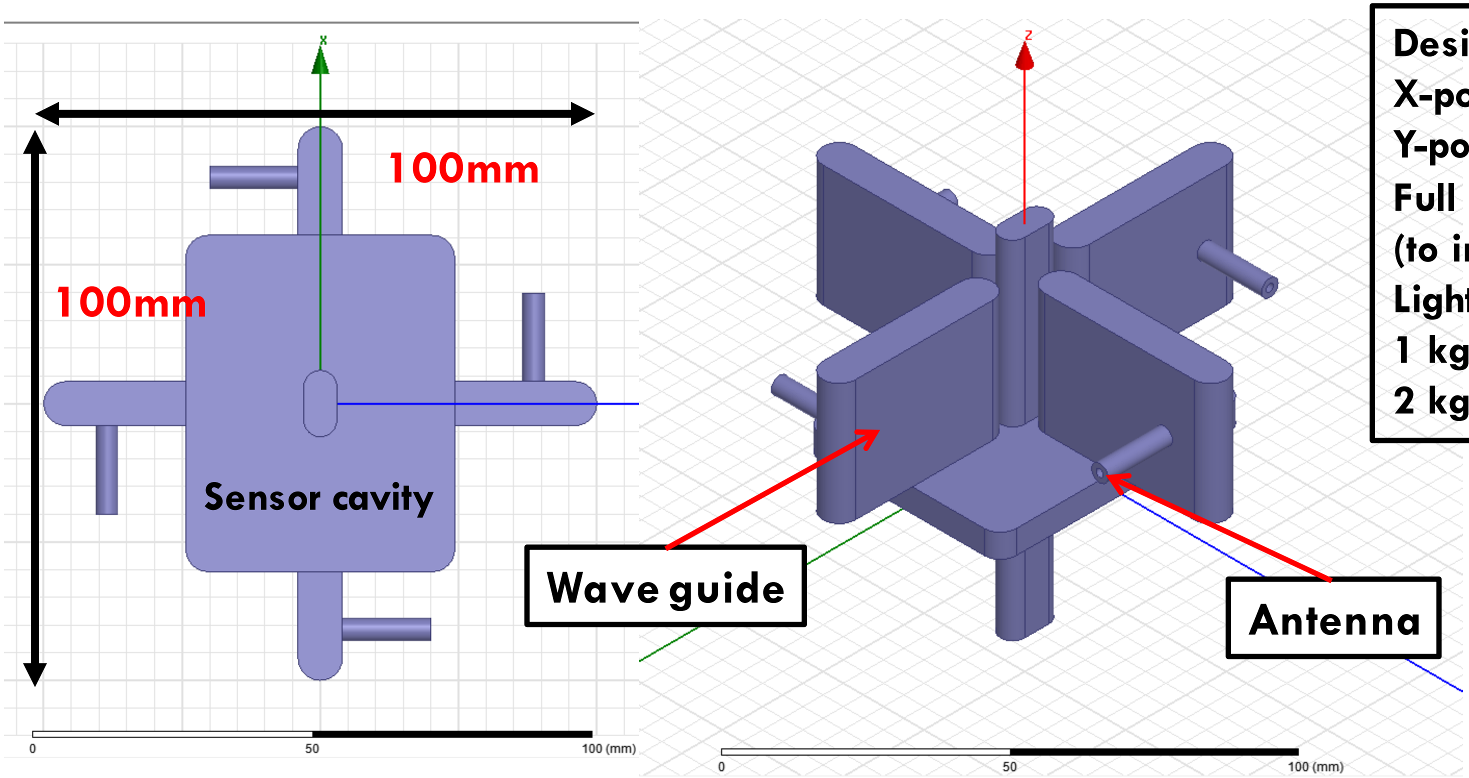


Figure 1: Dimension of cavity

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.

11cm Low-Q IP-BPM design

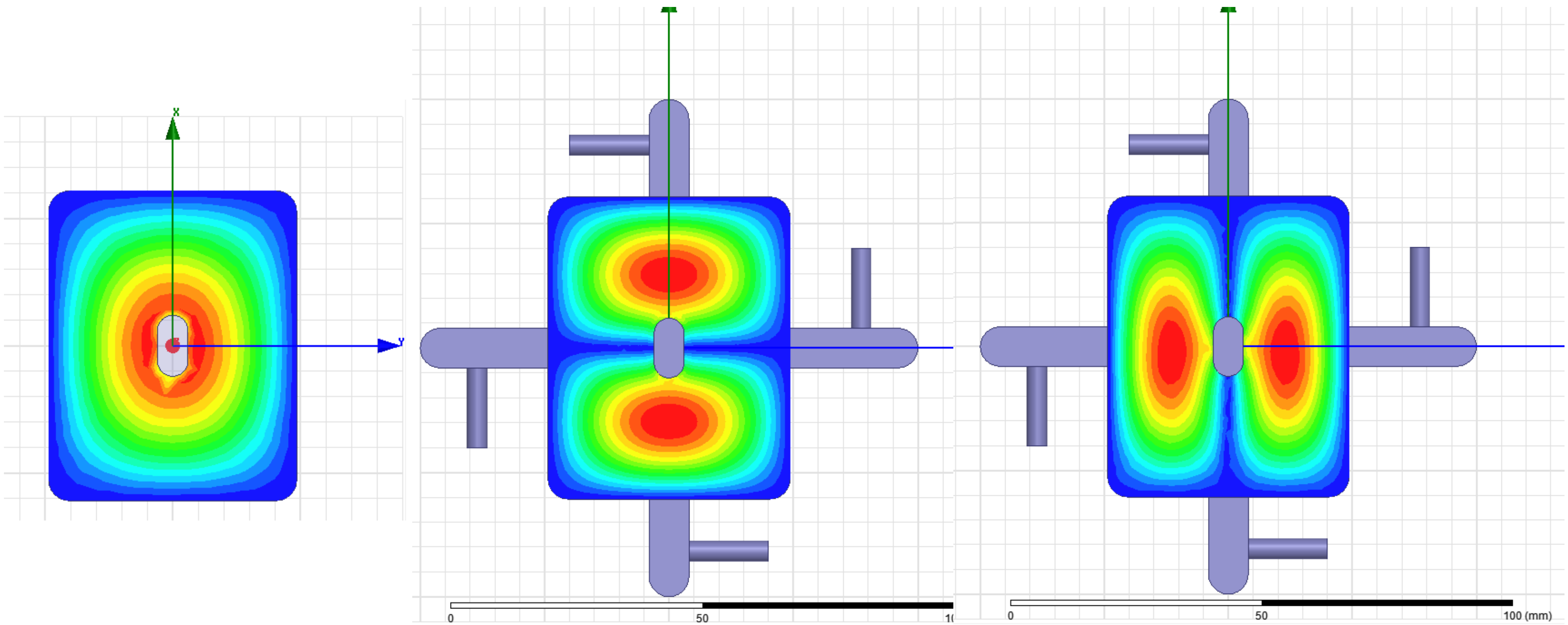
- 11cm Low-Q IP-BPM drawings of HFSS



Designed frequency
X-port: 5.712 GHz
Y-port: 6.426 GHz
Full size : 11cmx11cm
(to install IP-Chamber)
Light weight:
1 kg (Single)
2 kg (Double)

11cm Low-Q IP-BPM sensor cavity design

- Electric field mapping of HFSS simulation



Mono-pole mode :3.9808 GHz

X-dipole mode :5.7148 GHz

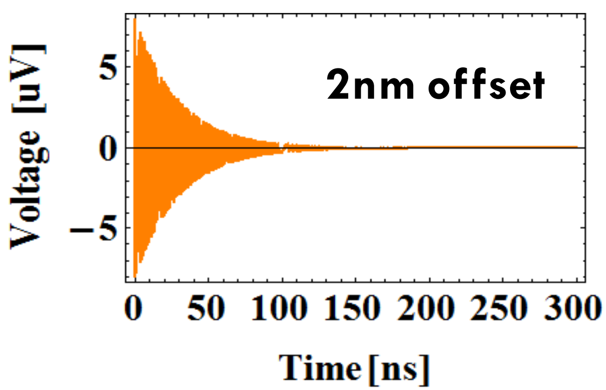
Y-dipole mode : 6.4270 GHz

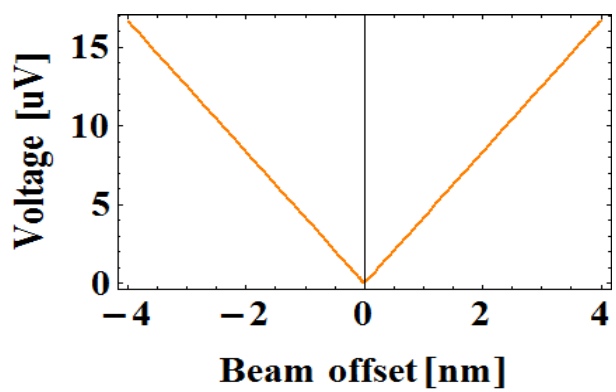
Results of HFSS simulation

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.)

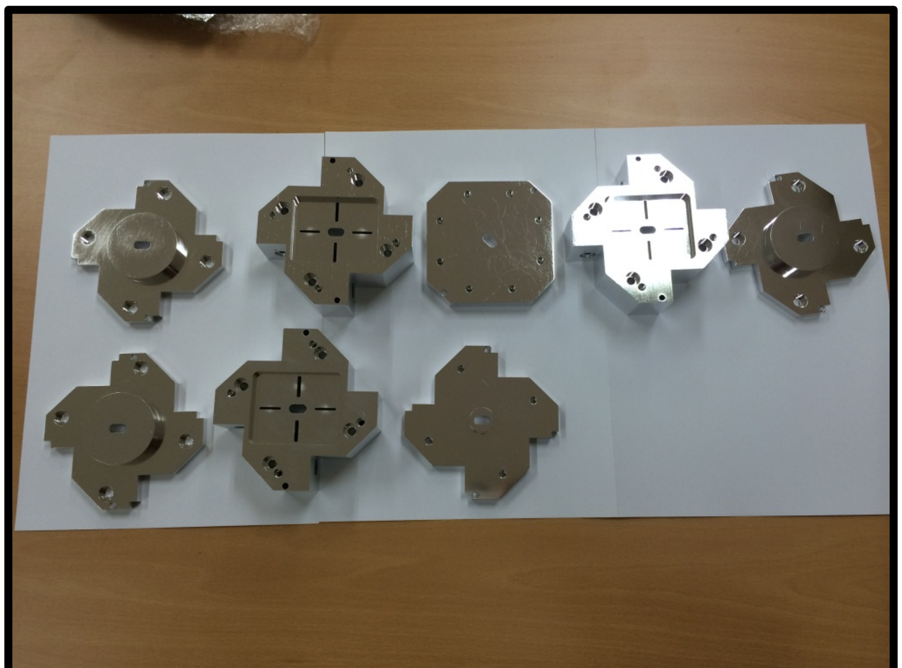


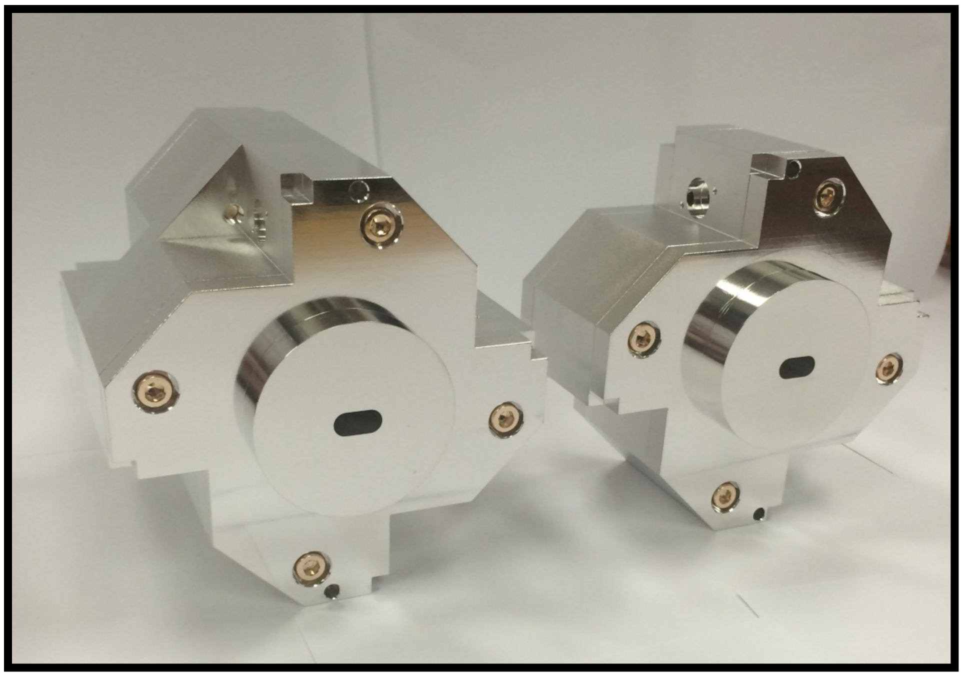


Parameter	Value	Unit
q (charge)	~ 1.6	nC
Beam energy	1.3	GeV
Bunch length	8	mm

The fabrication of Low-Q IP-BPM

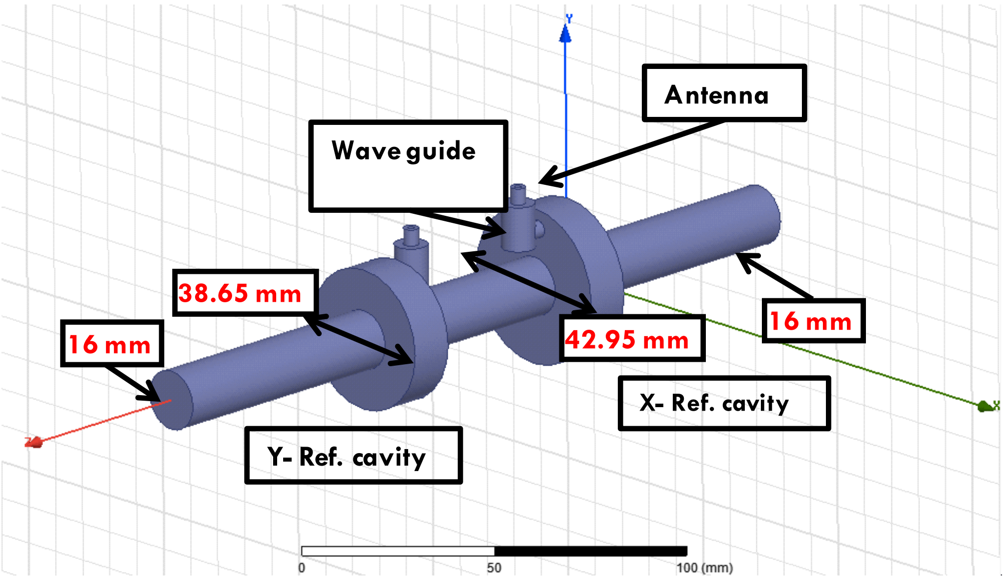
- **Made by Aluminum** (2kg for double block)
  - Precise surface machining within 4um.
  - IPBPM A & B are fabricated together in same block.
  - IPBPM C was fabricated to single block.





Reference cavity BPM design

- Cavity shape for HFSS simulation



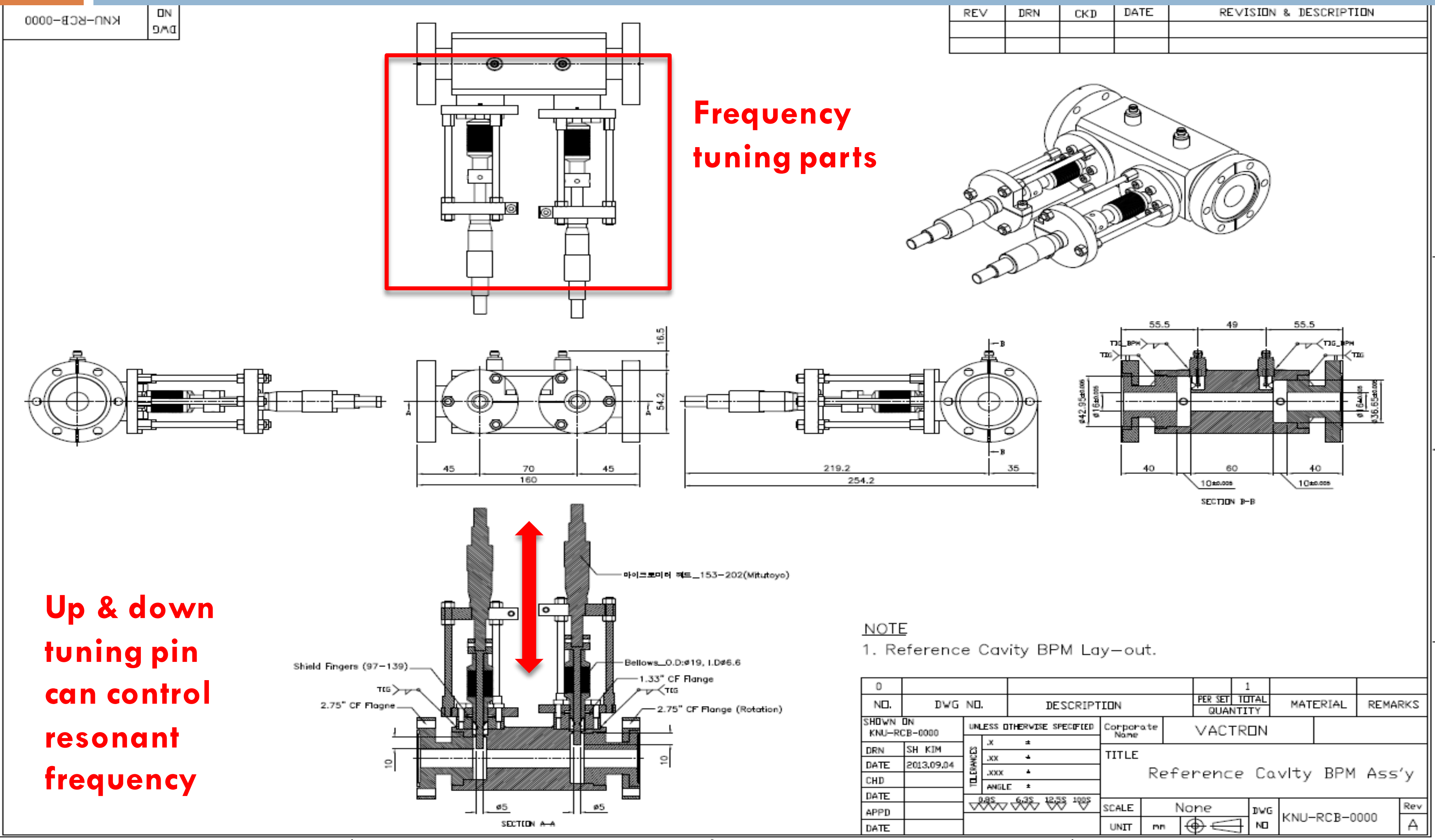
- For the charge normalization
- Only depends on beam charge

- Material of BPM:
Stainless steel (SUS304)

Output signal strength
= 22 ~ 5dB (1.6nC ~ 0.32nC)
This output strength too strong to connect LO input. So, we added additional attenuator.

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

Reference cavity BPM design



Frequency tuning parts

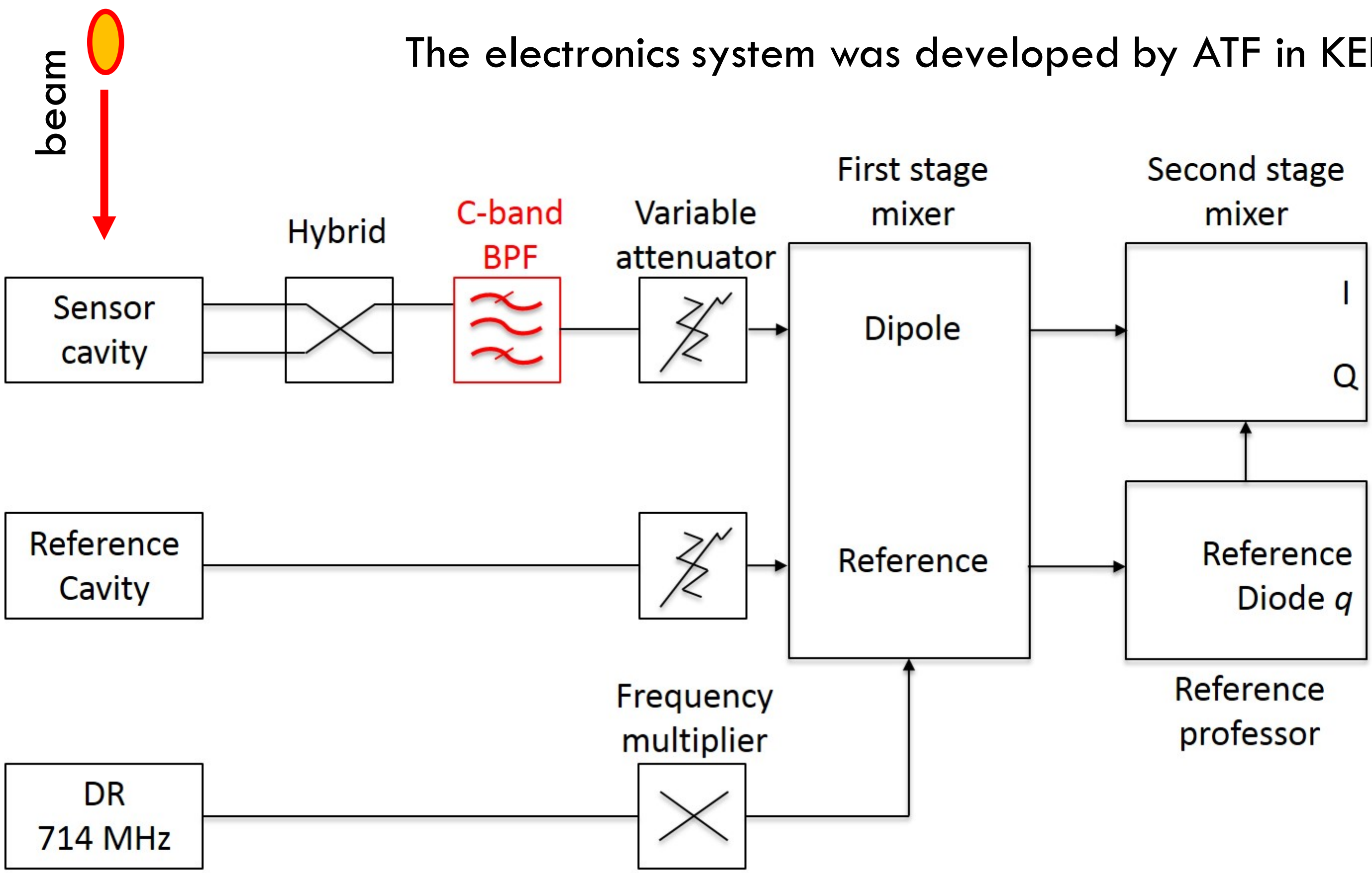
Up & down tuning pin can control resonant frequency

Electronics for Low-Q IPBPM

The electronics system was developed by ATF in KEK.

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

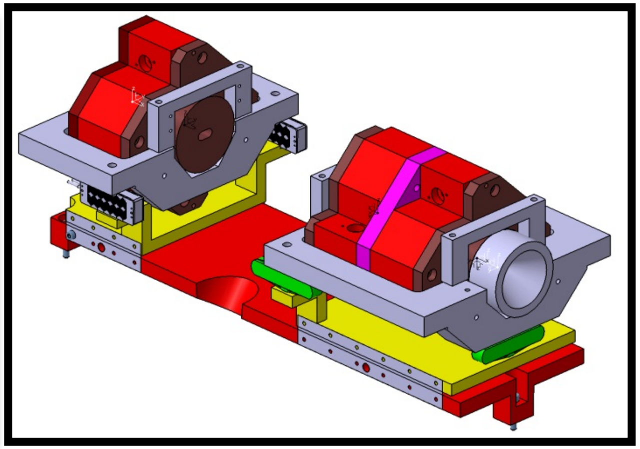
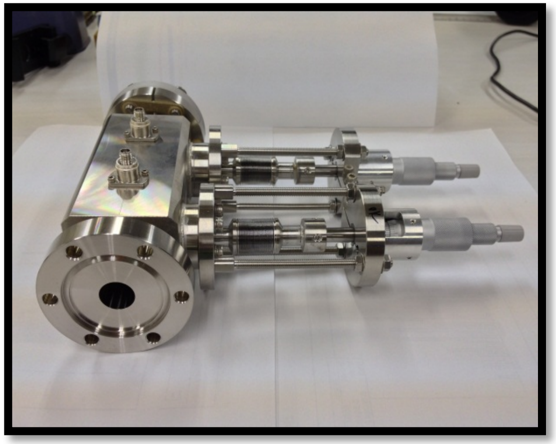
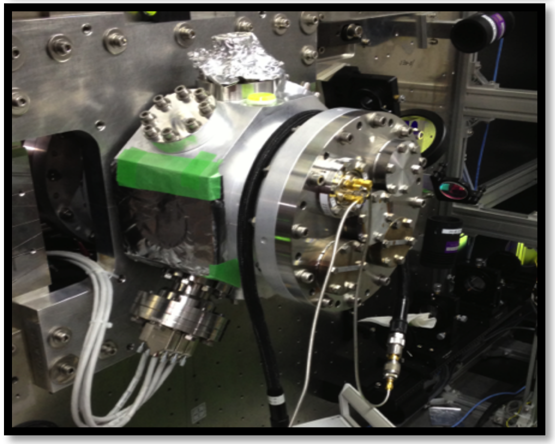
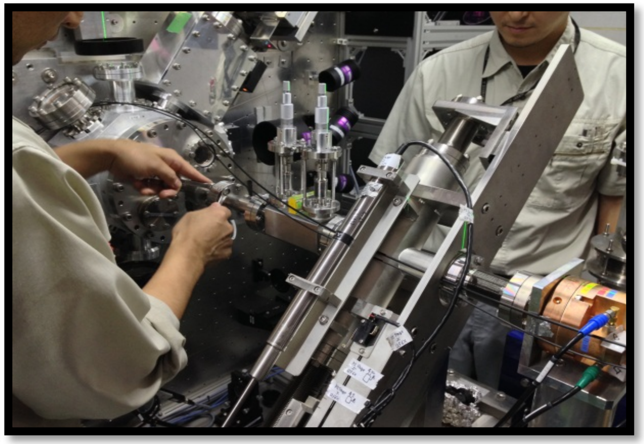
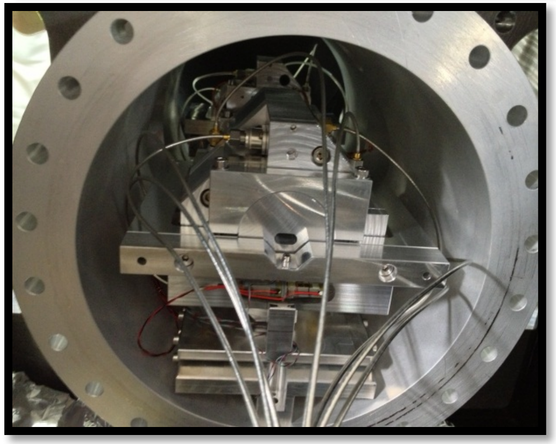
The output signals are amplified to measure by using ADC.



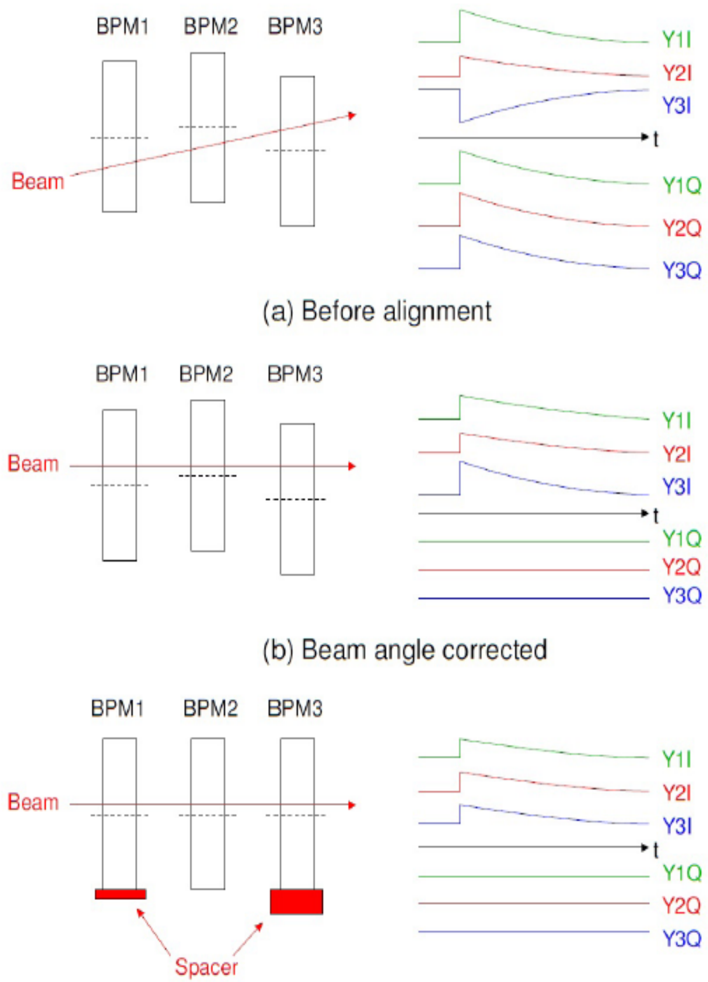
Total Gain from combiner to Detector : 40 + var.att + DC-amp

Installation of IP-BPM system with alignment check

- The IP-BPM system installation

Beam position resolution measurements



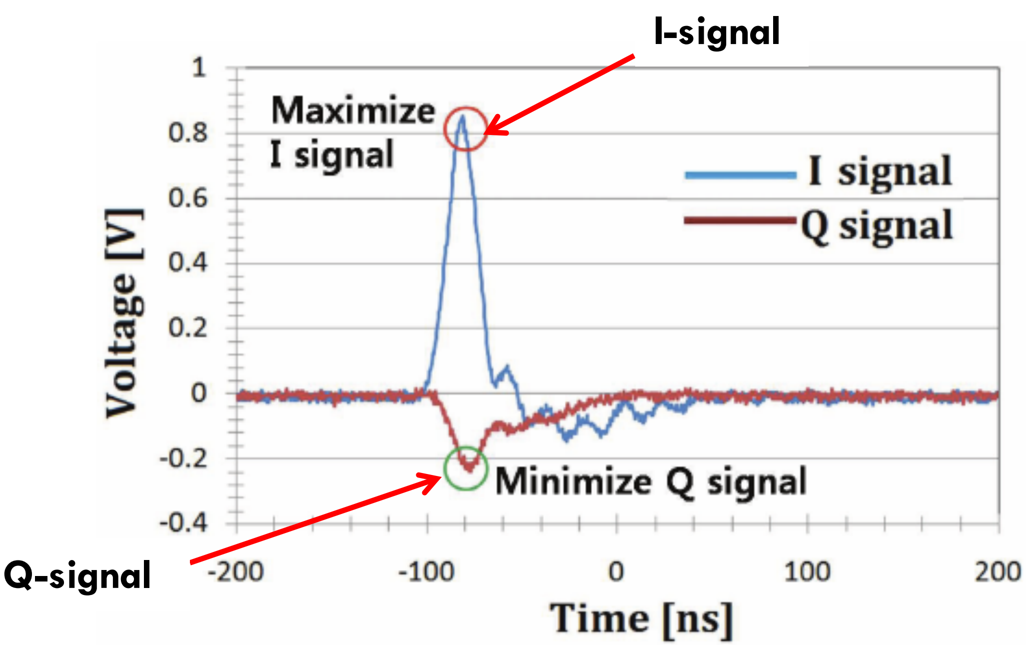
(a) Before alignment

(b) Beam angle corrected

(c) Cavity height aligned

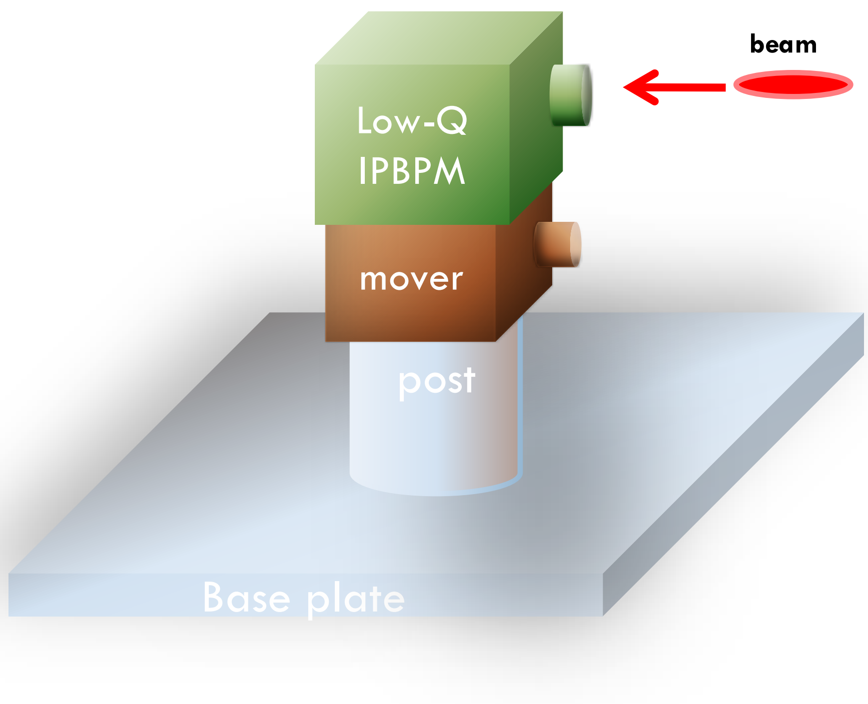
I-Q tuning

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.

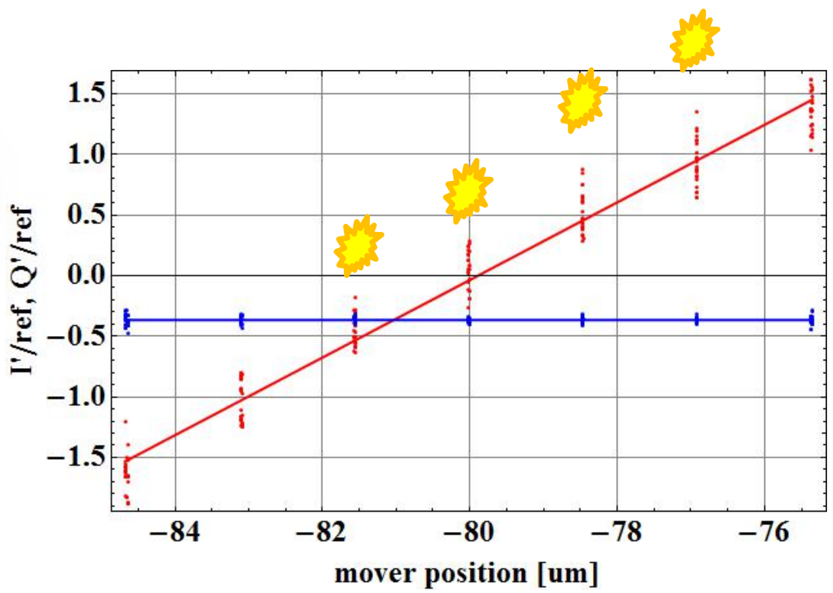


Beam position resolution measurements

IP-BPM calibration beam test

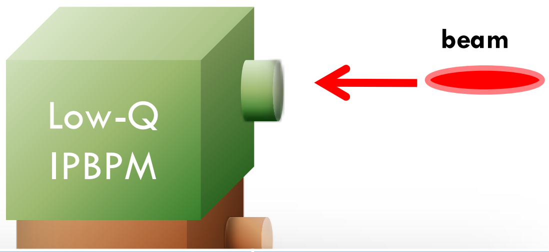


The calibration run measure the voltage variation due to different mover position by using piezo mover then we can calculate The Calibration factor of IPBPM.



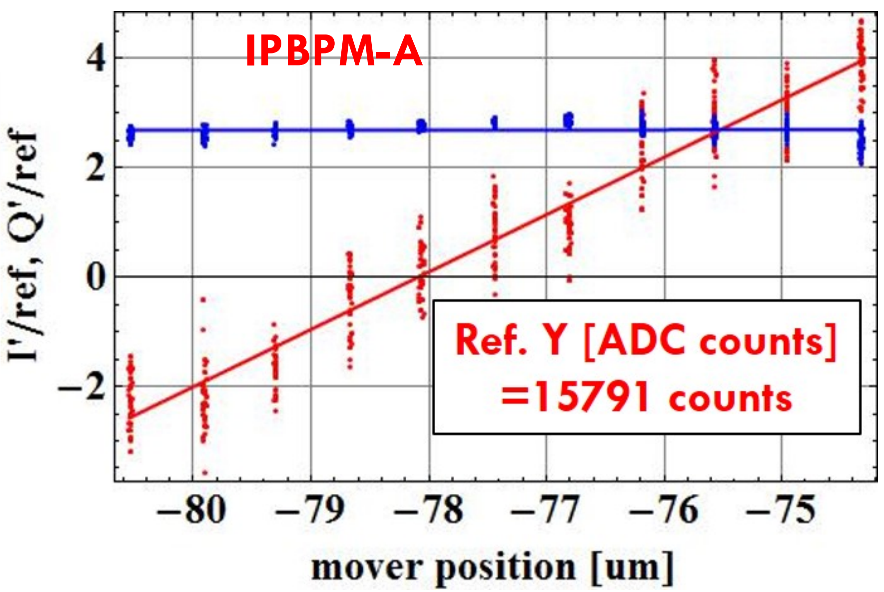
Beam position resolution measurements

IP-BPM calibration beam test



Channel of BPM	Calibration factor [ADC counts/um]	Norm. Calibration factor [/um]
IPA-YIQ	2618.96	0.3198
IPB-YIQ	2489.56	0.3040
IPC-YIQ	1040.60	0.1271

The calibration run measure the voltage variation due to different mover position by using piezo mover then we can calculate The Calibration factor of IPBPM.



Beam position resolution measurements

We take an extrapolating method by using geometrical relation between three IP-BPMs.

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, $\sigma_1 = \sigma_2 = \sigma_3 \equiv \sigma$

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

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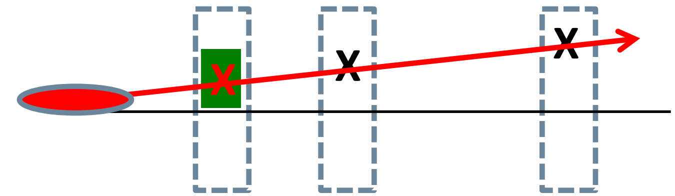
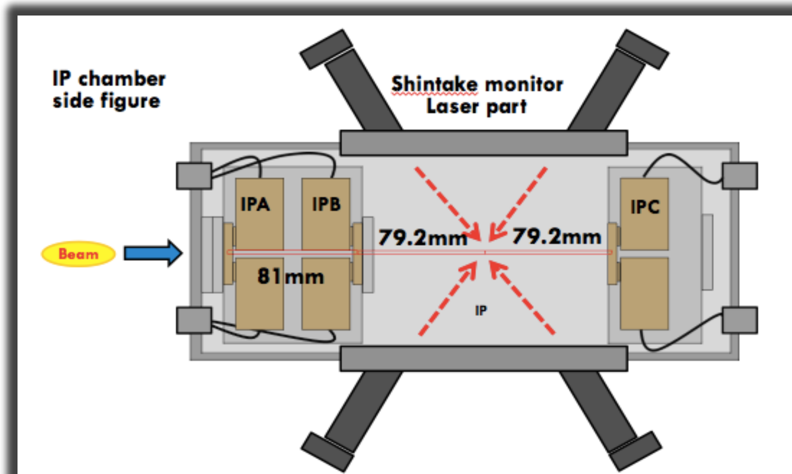
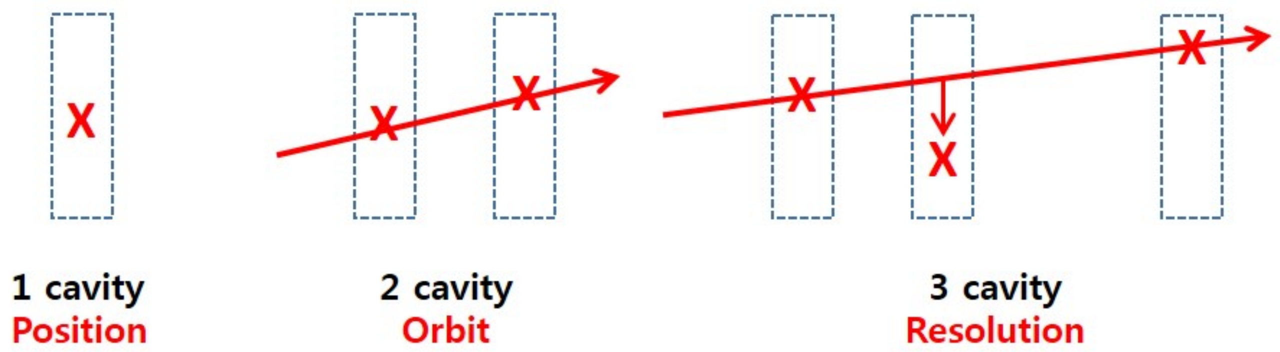


Beam position measurement and prediction

	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



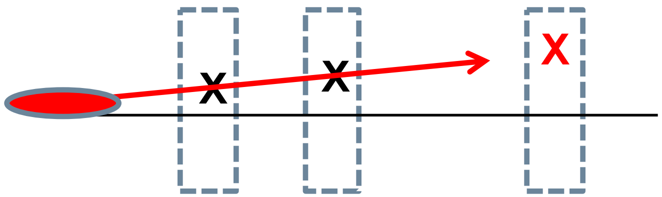
Beam position resolution measurements



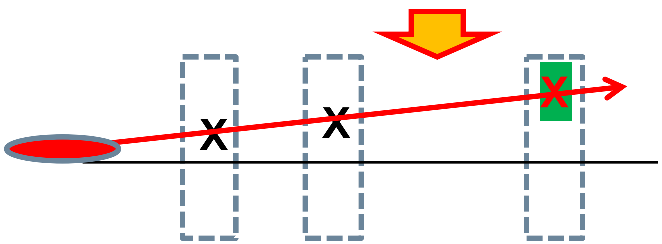
- Predicted position(ADC counts) for IPA was calculated as follow equation,
  - Predicted position of IPA-YI' = a1*IPB-YI'+ a2*IPB-YQ'+a3*IPC-YI'+ a4*IPC-YQ'+ a5*Ref-Y +a6*IPB-XI'+ a7*IPB-XQ'+a8*IPC-XI'+ a9*IPC-XQ'+ a10*Ref-X+a11
  - Residual of IPC-YI' = Measured IPC-YI' – Predicted IPC-YI'
  - The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

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

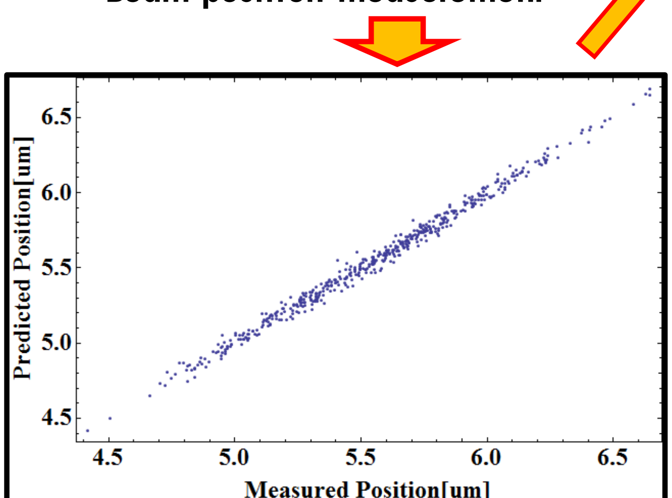
The results of IPBPM resolution test at June 2015 in ATF2 (30% beam charge)



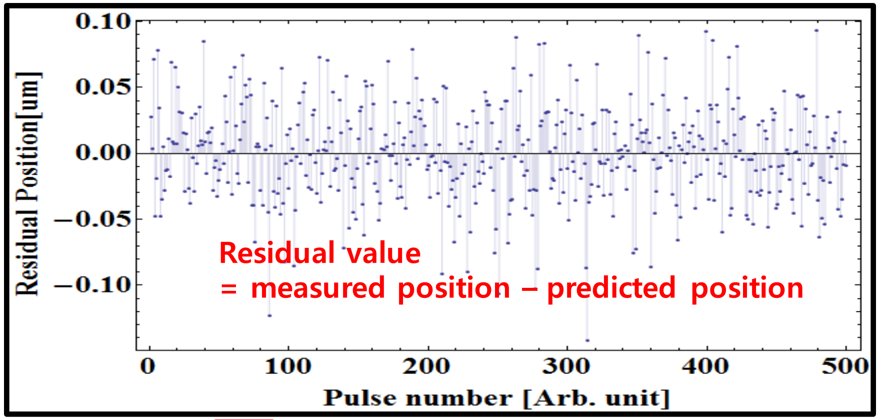
Beam position prediction

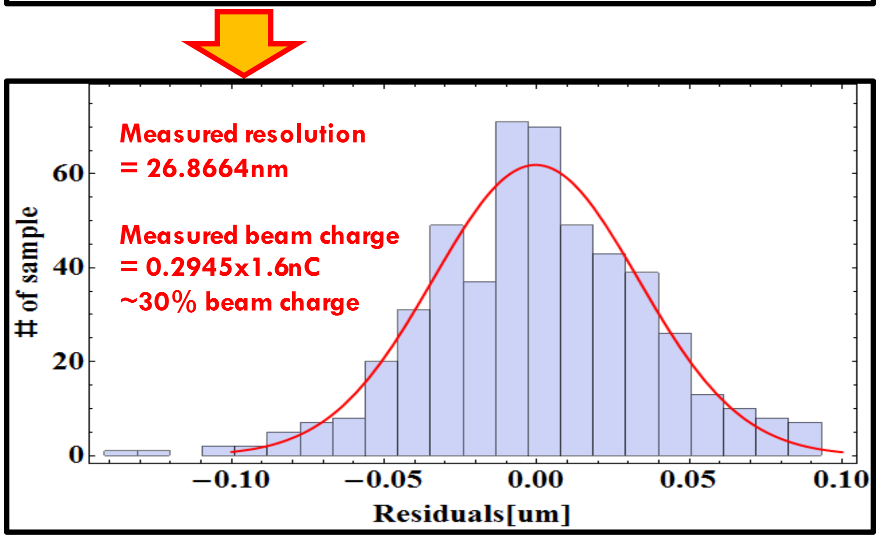


Beam position measurement



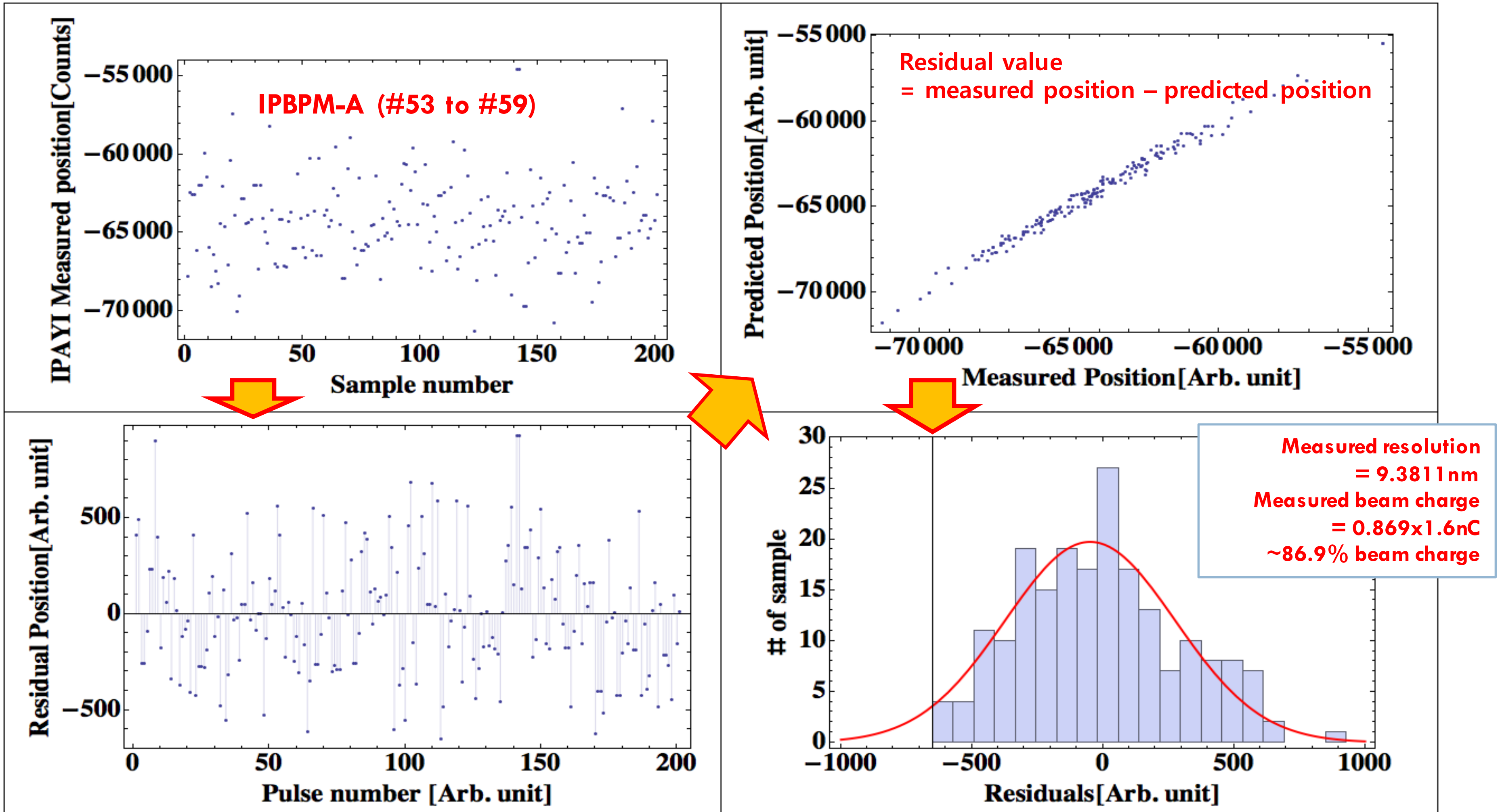
Convert to residual





$$\text{Norm. Resolution} = \text{Geo. factor} \times \frac{\text{RMS of residual}}{\text{Calibration factor}} \times \frac{\text{Measured charge}}{\text{Nominal charge}} = \mathbf{7.9nm}$$

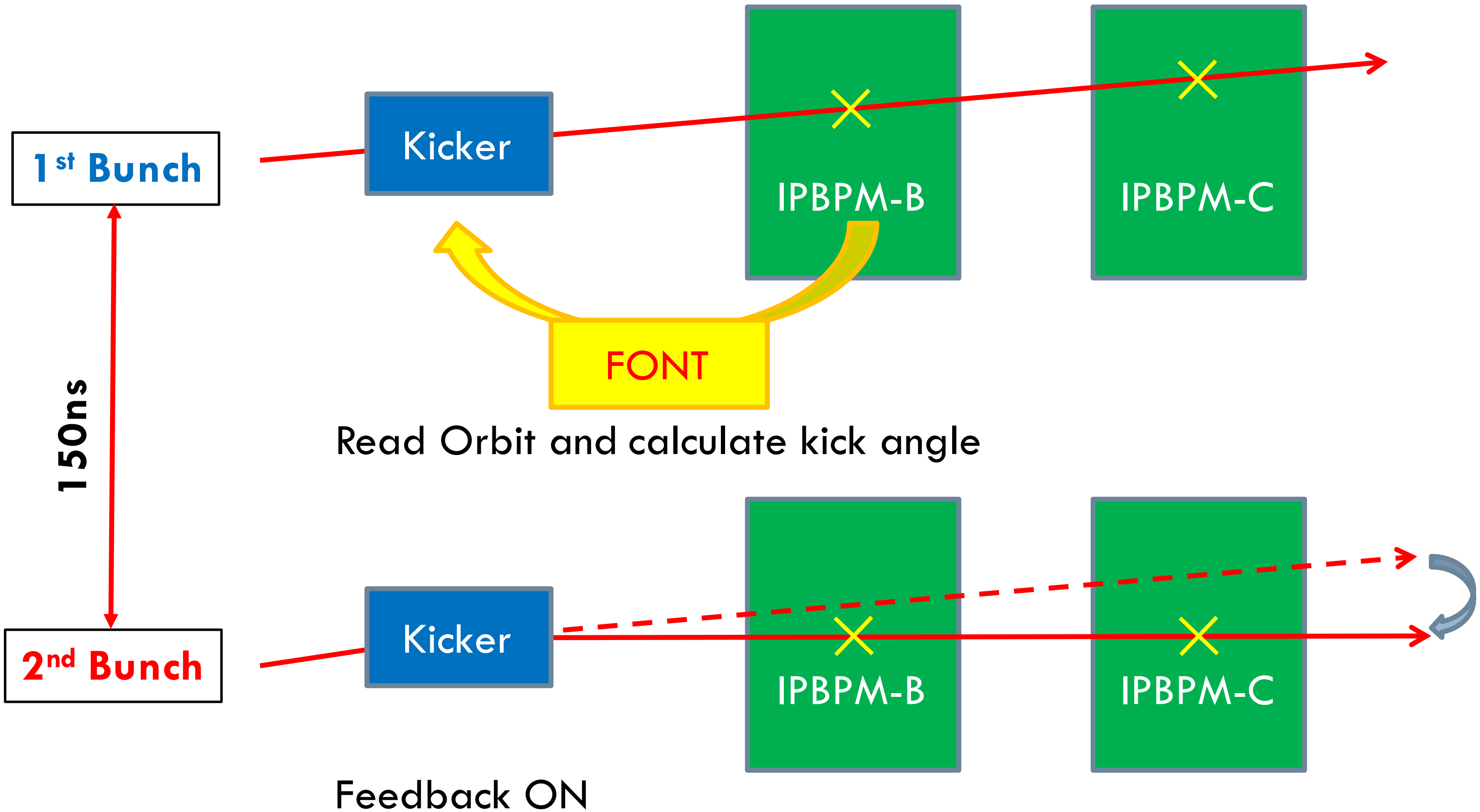
The results of IPBPM resolution test at March 2016 in ATF2 (87% beam charge)



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

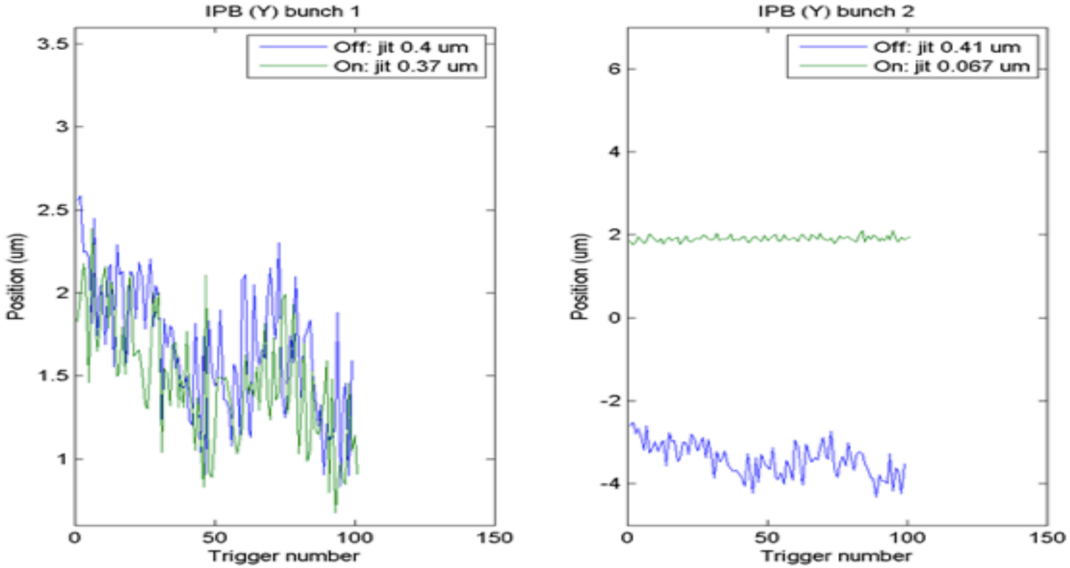
IPBPM beam orbit feedback study

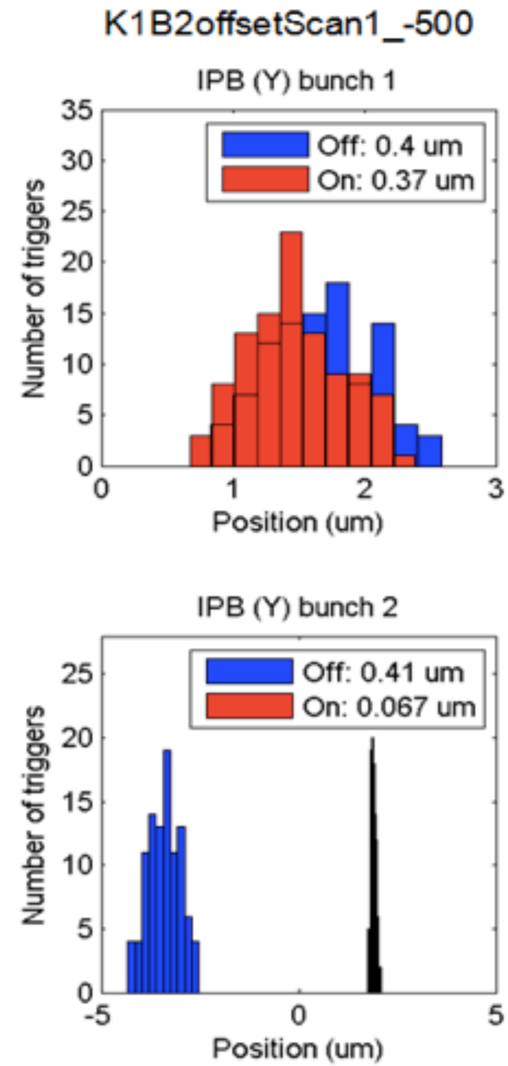
- The fast beam orbit feedback study was performed by using FONT system.
- The test was performed under two bunch operation mode with 150ns bunch spacing.



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

IPBPM beam orbit feedback study





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 IP-BPM 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%.

Thank you for your attention !