Beam Instrumentation

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JAS-2008, RRCAT

2008 / 1/7 – 1/11

Beam Instrumentation
Lecture 4

High Resolution Beam Position Monitor

Cavity Beam Position Monitor (Cavity BPM)

- ***RF cavity based technology***
- ***with nanometer resolution***

Introduction

Basic Idea of Beam Measurement

Fundamental Relation of RF cavity

Concept of Cavity BPM

Stripline BPM

- the position sensitive factor was defined by mechanical geometry
- zero position also produce the large signal for each electrode.
- large thermal noise for wide bandwidth (a few 100MHz)

Difficult to get high resoultion

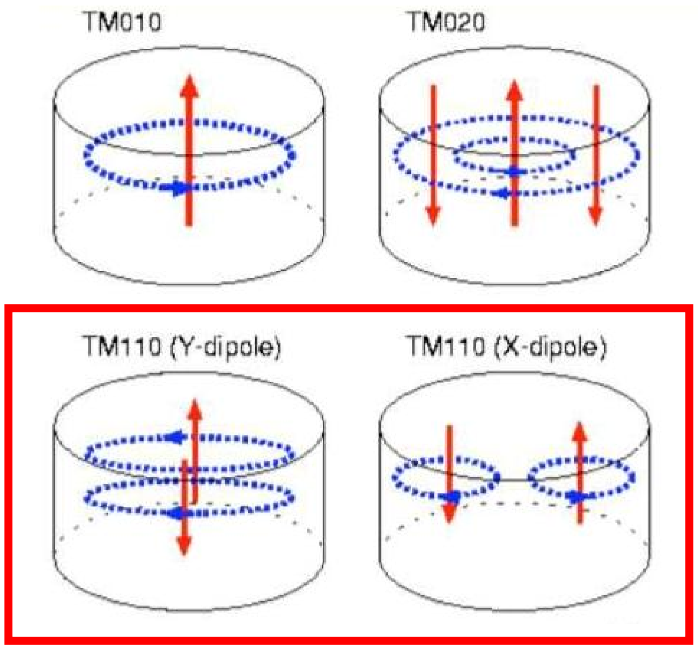
$$x = S_\phi \frac{V_1 - V_3}{V_1 + V_3} \qquad S_\phi = \frac{R}{2}\frac{\alpha}{\sin\alpha}$$

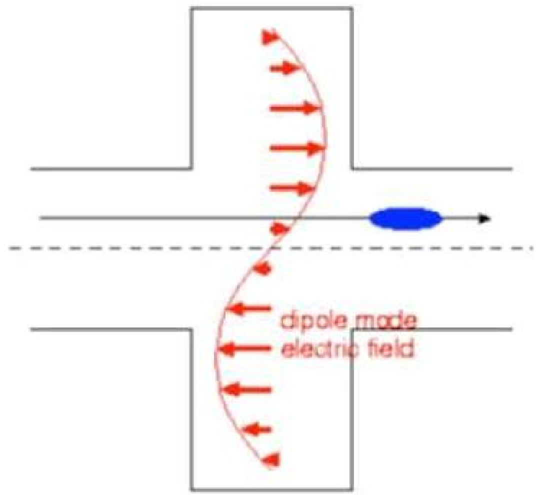
Cavity BPM

- position is calculated with the dipole mode of cavity pickup
- no signal at zero position
- samll thermal noise for narrow bandwidth (a few MHz)

Possible to get high resolution

TM110 mode for position measurement





Monopole Mode ; Uniform to the transverse direction

Dipole Mode ; No field at Center, 2 modes exists

We will use these modes for position measurement

Q value of RF Cavity

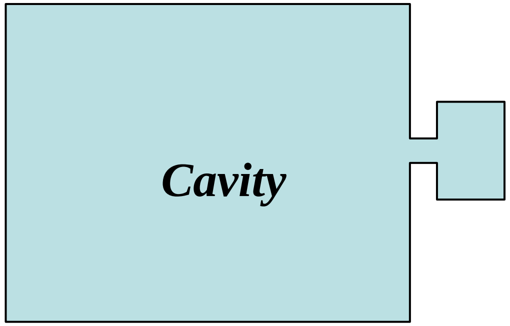
Q value (Loaded Q) ; The decay rate of the stored energy

$$Q_L \equiv \frac{\omega U}{P}$$

Q_0 ; energy loss by the thermal loss

- defined by the cavity material and the surface condition

$$Q_0 \equiv \frac{\omega U}{P_{wall}}$$



Q_{ext} ; energy loss from signal pickup

- defined by the pickup port design

$$Q_{ext} \equiv \frac{\omega U}{P_{out}}$$

Q value consists of two component Q_0 and Q_{ext} .

Coupling Constant (β) ;

$$\beta \equiv \frac{P_{out}}{P_{wall}} = \frac{Q_0}{Q_{ext}}$$

The ratio of Q_0 and Q_{ext}

R/Q of RF Cavity

R/Q ; ***Relationship between the stored energy and electrical field***

$$R/Q = \frac{|\int \overrightarrow{E} d\overrightarrow{s}|^2}{\omega U}$$

The interaction between beam and cavity is expressed with R/Q .

The excitation voltage by the beam is $V_{exc} = \frac{\omega}{2}(R/Q)q$

Thereby, the beam induced energy is $U = \frac{V_{exc}^2}{\omega(R/Q)} = \frac{\omega}{4}(R/Q)q^2$

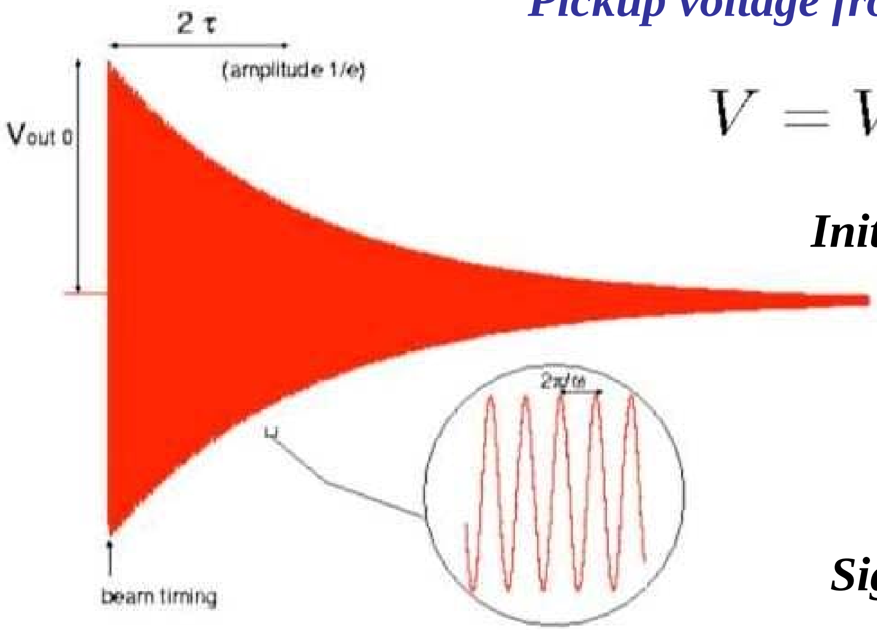
The pickup voltage also is expressed with R/Q .

The output power from the port is $P_{out} = \frac{\omega U}{Q_{ext}} = \frac{\omega^2 q^2}{4Q_{ext}}(R/Q)$

Thereby, the output voltage is $V_{out\,0} = \sqrt{ZP} = \frac{\omega q}{2}\sqrt{\frac{Z}{Q_{ext}}(R/Q)}$

The external Q is Qext, the impedance is Z for the port .

Signal from the RF Cavity



Pickup voltage fron the RF cavity

$$V = V_{out\,0} e^{-\frac{t}{2\tau}} \sin(\omega t + \phi)$$

Initial voltage from the pickup port

$$V_{out\,0} = \frac{\omega q}{2} \sqrt{\frac{Z}{Q_{ext}} (R/Q)}$$

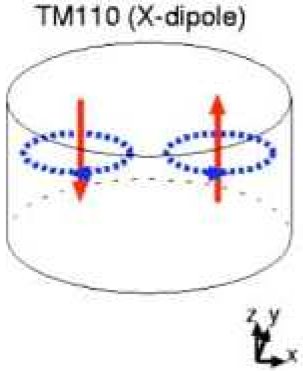
Defined by R/Q, Q_{ext} and q

Signal decay time

$$\tau = \frac{Q_L}{\omega} = \frac{Q_L}{2\pi f}$$

Determined by the Q_L

R/Q of the dipole mode of Pillbox Cavity

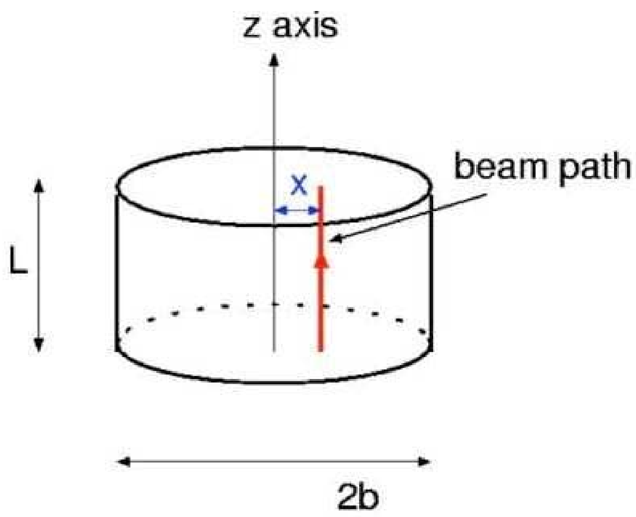


Electric Field of the dipole mode is

$$E_z = E_0 \cos\phi J_1(rk)e^{i\omega t}$$

$$k_{110} = \omega_{110}/c = \frac{3.83}{b}$$

R/Q is calculated with its definition



$$R/Q(x) = \frac{|V|^2}{\omega U}$$

$$V(x) = \int_0^L E_z dz$$

$$U = \frac{1}{2}\int \epsilon_0 |E_z|^2 dV$$

$$R/Q = 50.5 \times (\frac{\omega}{c})^3 LT^2 \underline{\underline{x^2}}$$

$$T = \frac{\sin\frac{\omega L}{2c}}{\frac{\omega L}{2c}}$$

R/Q of dipole mode is proportional to x^2 .

Beam Position Measurement by measuring the dipole mode

Back to the relation of the pickup voltage ;

$$V_{out\,0} = \sqrt{ZP} = \frac{\omega q}{2}\sqrt{\frac{Z}{Q_{ext}}(R/Q)}$$

$$R/Q = 50.5 \times (\frac{\omega}{c})^3 L T^2 x^2$$

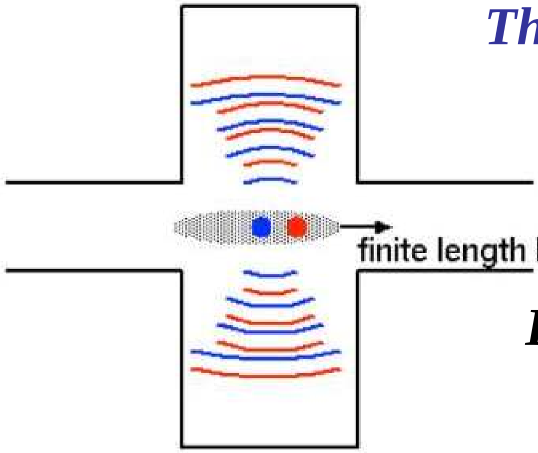
The pickup voltage is proportional to the position offset .

We can measure the beam position from the pickup voltage .

Cavity Design

Feature of the Pickup Signal

Effect of the finite bunch length



The bunch length distribution

$$\rho = \frac{1}{\sqrt{2\pi}\sigma_z} \exp\left(-\frac{z^2}{2\sigma_z^2}\right)$$

By superposition of the longitudinal distribution, the total excitation voltage is expressed as

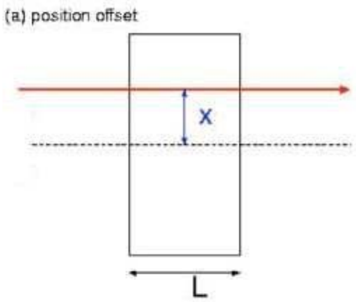
$$V_{total\ exc} = V_0 \int_{-\infty}^{\infty} \rho \cos\left(\frac{\omega z}{c}\right) = V_0 \exp\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right)$$

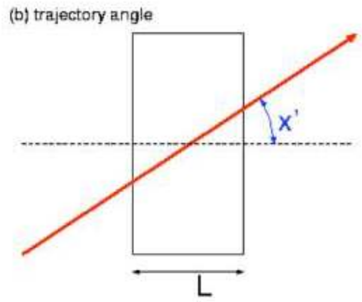
The excitation voltage is weaker by suppressing each other for $\sigma_z << c/\omega$.

We shuold better to select lower RF frequency than bunch length.

Feature of the Pickup Signal

Effect of the beam angle



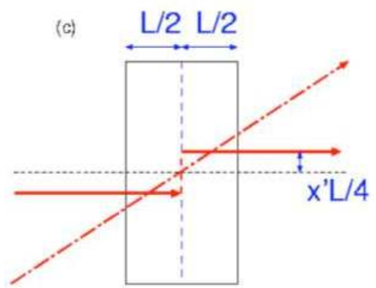


$$\text{position signal} = Ax\sqrt{L}\sin(\omega t)$$

$$\text{angle signal} = Ax'\frac{L}{4}\sqrt{\frac{L}{2}}\sin(\omega(t+L/4c)) - Ax'\frac{L}{4}\sqrt{\frac{L}{2}}\sin(\omega(t-L/4c))$$

$$= Ax'\frac{L}{2}\sqrt{\frac{L}{2}}\sin\left(\frac{\omega L}{4c}\right)\cos(\omega t)$$

Phase of angle signal is shifted by 90degrees from position signal



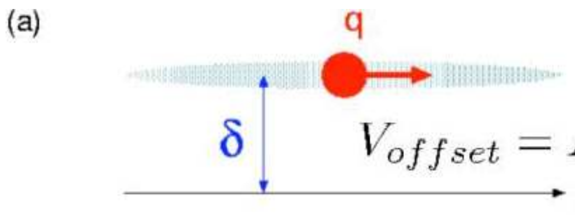
Angle sensitivity is proportional to L^2 .

Small L is better.

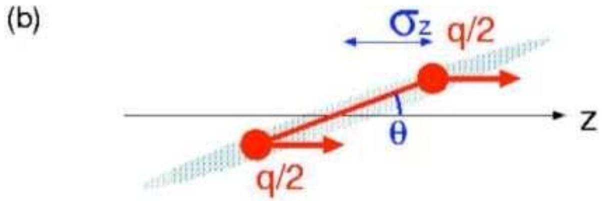
$$\frac{\text{angle signal}}{\text{position signal}} = \frac{L}{2\sqrt{2}}\sin\left(\frac{\omega L}{4c}\right)\frac{x'}{x} \sim \frac{\omega L^2}{8\sqrt{2}c}\frac{x'}{x}$$

Feature of the Pickup Signal

Effect of the bunch tilt



$$V_{offset} = Aq\delta \sin(\omega t)$$



$$V_{+} = A\frac{q}{2}\frac{\theta\sigma_z}{2}\sin(\omega(t + \sigma_z/c))$$

$$V_{-} = -A\frac{q}{2}\frac{\theta\sigma_z}{2}\sin(\omega(t - \sigma_z/c))$$

Phase of angle signal is shifted by 90degrees from that of bunch tilt.

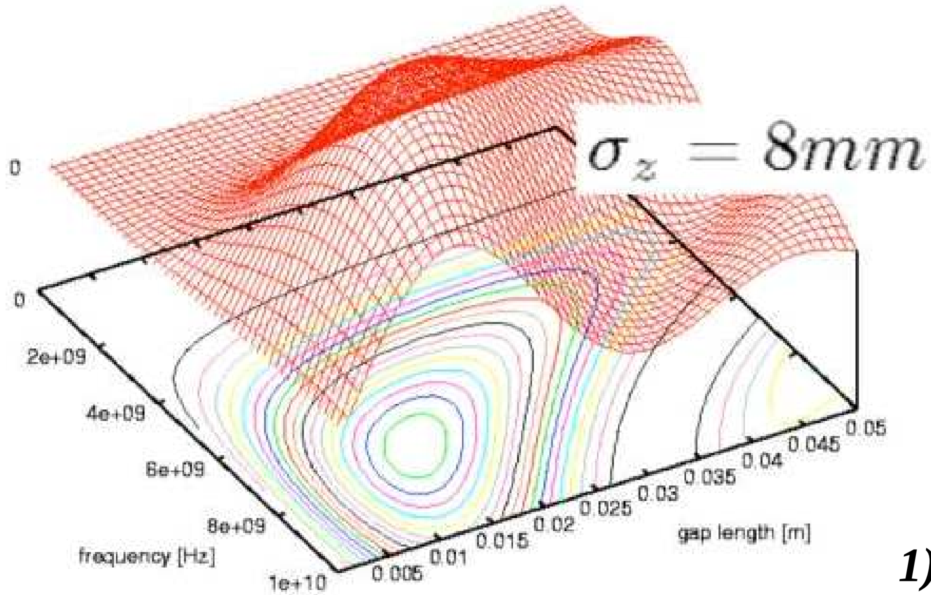
The sensitivity of the bunch tilt is proportional to σ_z^2 .

$$\begin{aligned} V_{tilt} &= V_{+} + V_{-} \\ &= \frac{Aq\theta\sigma_z}{2}\sin\left(\frac{\omega\sigma_z}{c}\right)\cos\omega t \\ &\approx \frac{Aq\theta\omega\sigma_z^2}{2c}\cos\omega t \end{aligned}$$

Small σ_z is better.

Not only the amplitude, but also the phase detection is important to the measurement .

Selection of the RF frequency and Cavity Length



Beam induced voltage of dipole mode is a function of

- ***bunch length***
- ***frequency of dipole mode***
- ***cavity gap***

1) Cavity voltage is set to be 8 mm .
(parameter of the accelerator)

2) Frequency is set to around 6GHz.

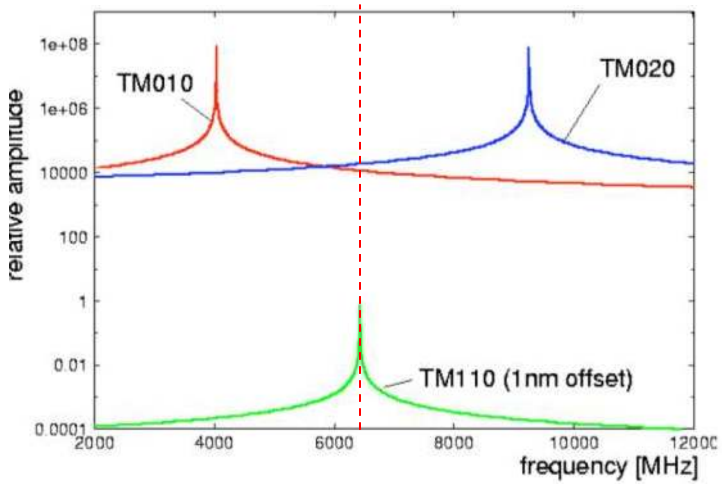
3) Cavity is as small as possible to reduce the effect of the beam angle.

Feature of the Pickup Signal

Effect of the tail of monopole mode

We must select the dipole frequency to separate the monopole mode.

Mode	f_0	R/Q [Ω]	Q_L
010	4.03 GHz	14300	8000
020	9.25 GHz	9880	8000
110	6.43 GHz	1.17×10^{-12} (1nm)	6000



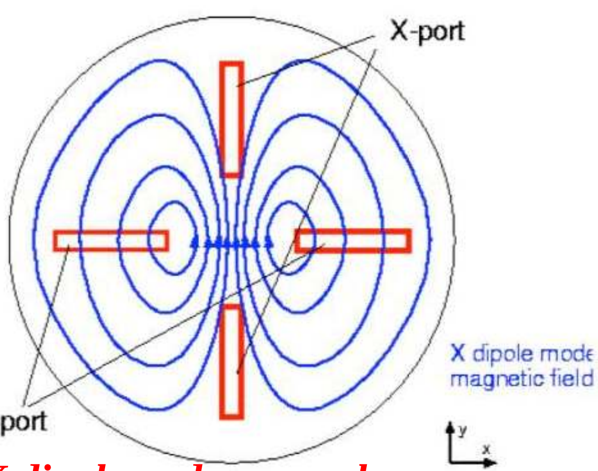
Since the amplitude of monopole mode is huge to the dipole mode, the tail is affect to the dipole mode signal.

-Bandpah filetr

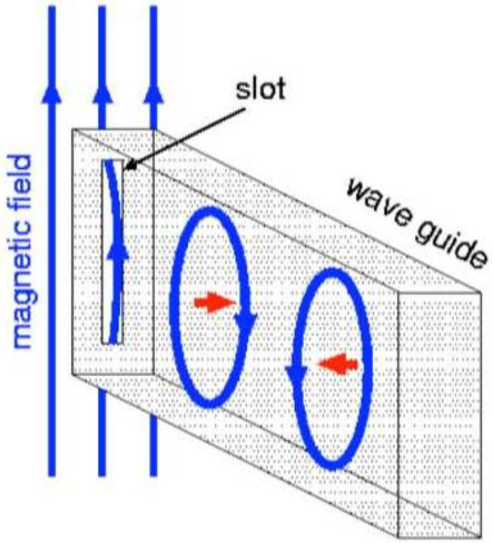
-Mode selectable coupler

Dipole Mode Selectable Coupler 1

No couple to Y dipole and monopole

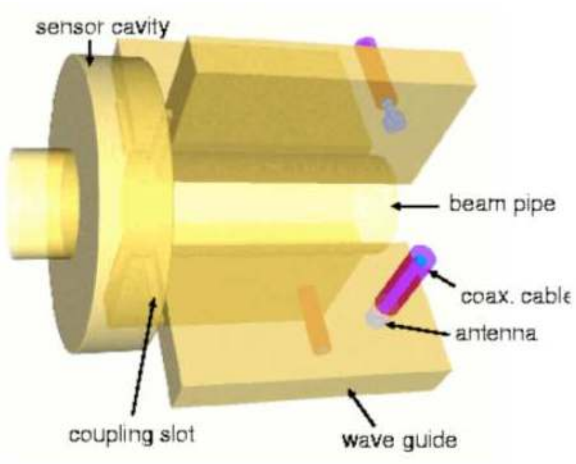


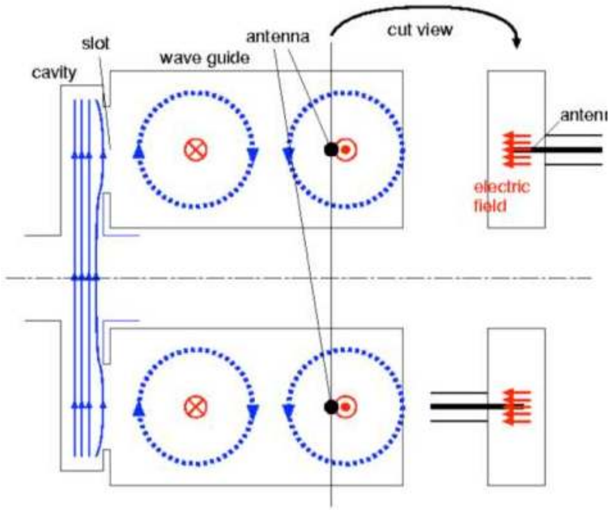
No couple to X dipole and monopole



Magnetic coupling with slot shape hole

Dipole Mode Selectable Coupler 2

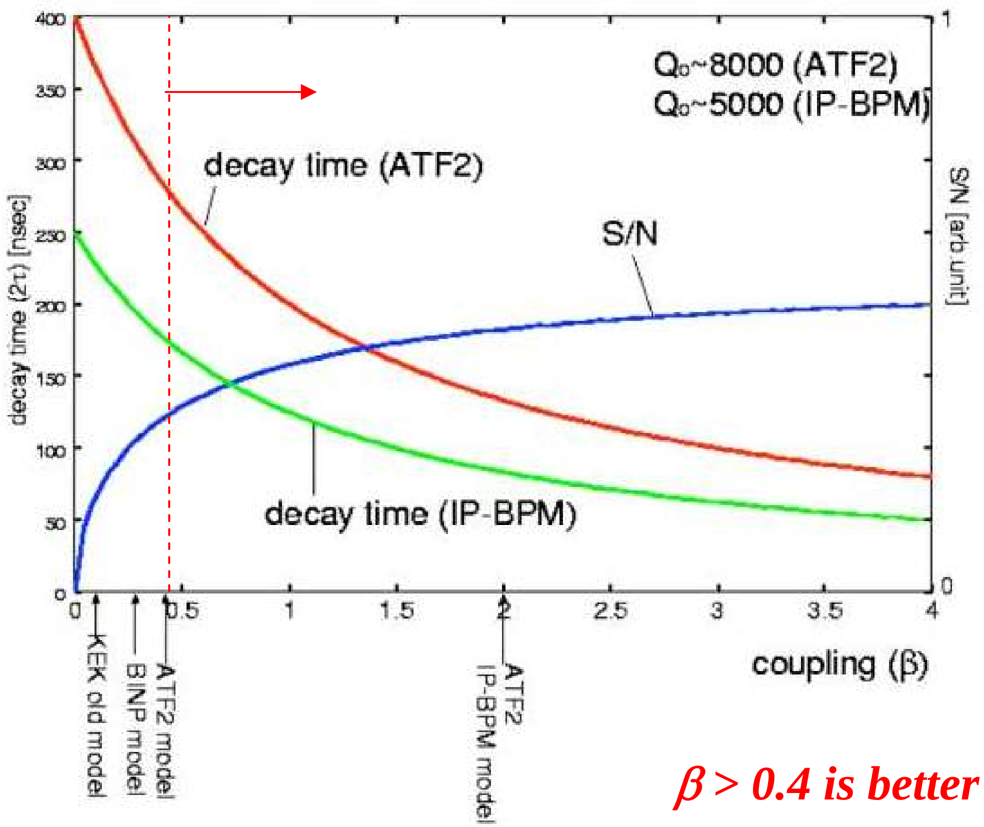




In order to be mode cleaning,
the coaxial cable is connected after the wave guide.

In order to minimize the electrical offset of the cavity,
the diagonal 4 output ports are put to the cavity.

Design of the Coupling of the Pickup Port



***S* ; proportional to the signal sensitivity of RF cavity**

***N* ; Thermal Noise**

$$p_{TN} \approx kTf_{BW}$$

$$V_{TN} \approx \sqrt{4kTZf_{BW}}$$

Bandwidth is proportional to 1/τ.

β > 0.4 is better for the good S/N ratio.

Resolution Limit of the Cavity BPM

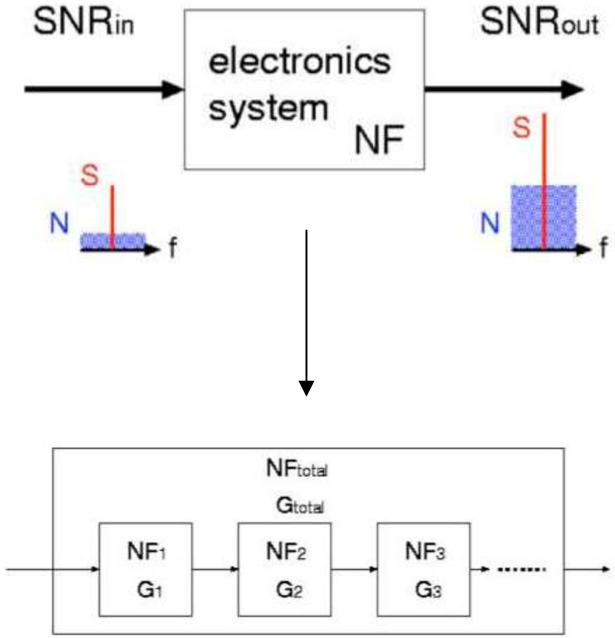
Thermal Noise

$$p_{TN} \approx kTf_{BW}$$
$$V_{TN} \approx \sqrt{4kTZf_{BW}}$$

For the bandwidth of 3MHz

$$p_{TN}[dBm] = -174 + 10\log f_{BW} = -109\text{dBm}$$

$$NF = \frac{SNR_{in}}{SNR_{out}}$$



This value corresponds to 4nm resolution for the ATF beam condition.

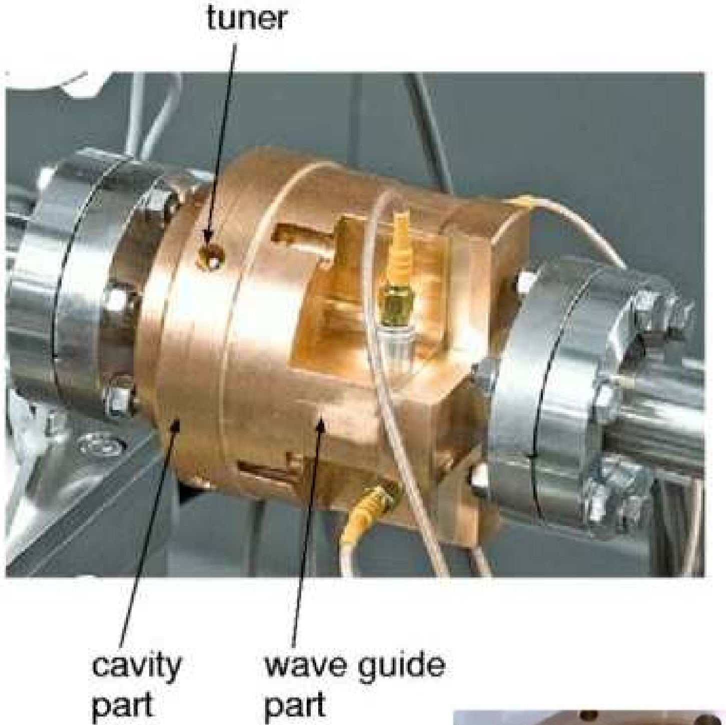
But, the noise is amplified by the amplifier in the readout circuit to 12nm resolution .

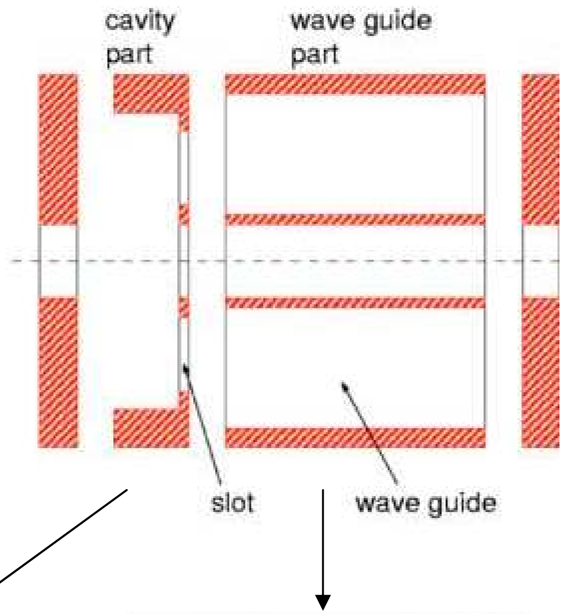
$$NF_{total} = \underline{\underline{NF_1}} + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots$$

The first amp is the main noise source

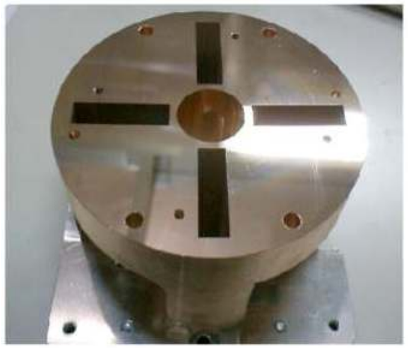
Cavity Assemble

RF Cavity Beam Position Monitor for ATF2





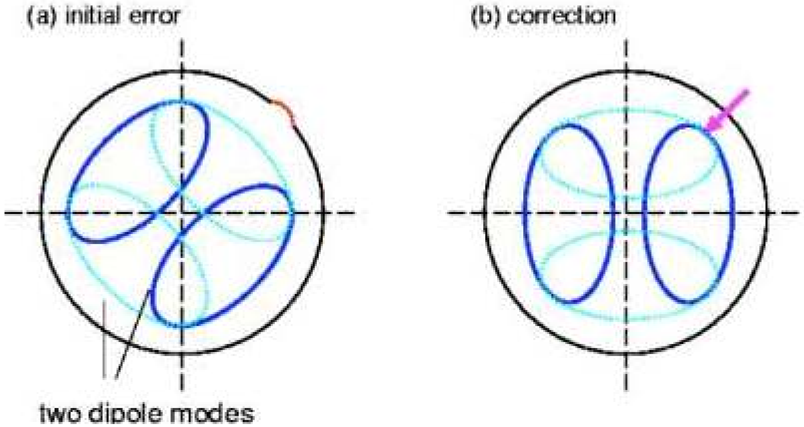
RF cavity with slot



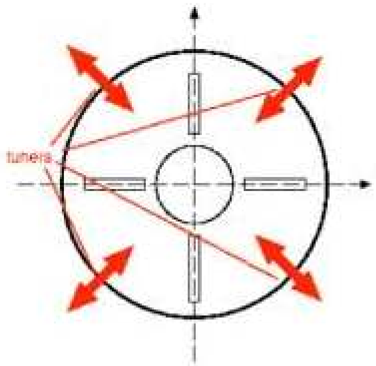
Wave guide

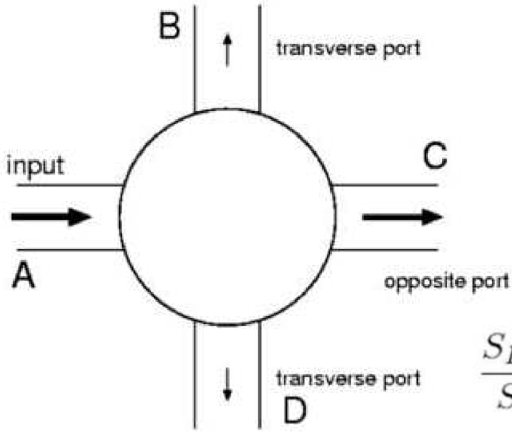
Cavity Assemble

XY Isolation of the Dipole Mode Signal



XY isolation is tune
with the push-pull tuner
by keeping the dipole frequency.





$$\frac{S_{BA}(\text{transverse})}{S_{CA}(\text{opposite})}$$

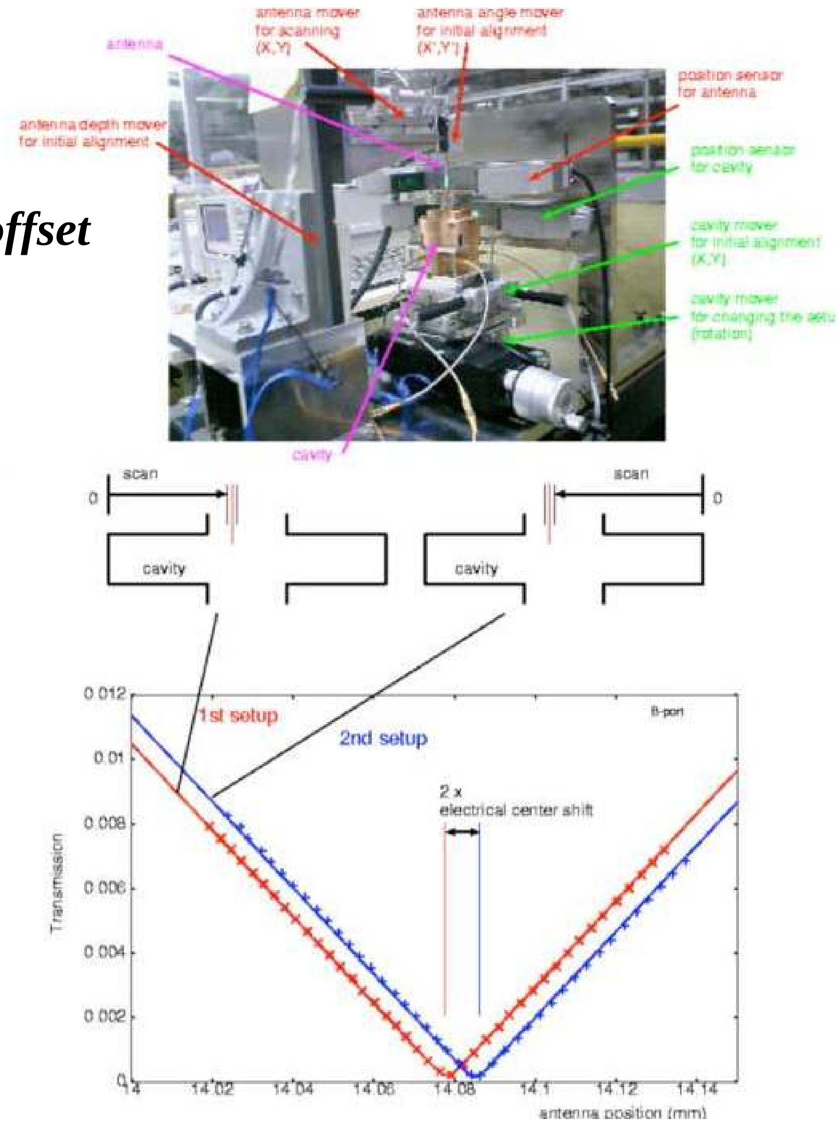
Measurement is done
with network analyzer of S_{12} methode

Offest Measuremnt

Electrical offset with respect to mechanical offset is measured offline analysis .

***Electrical offset is evaluated by measuring the offset** from both side of mechanical reference .*

The mechanical offset (including machining error) was less than 10μm .



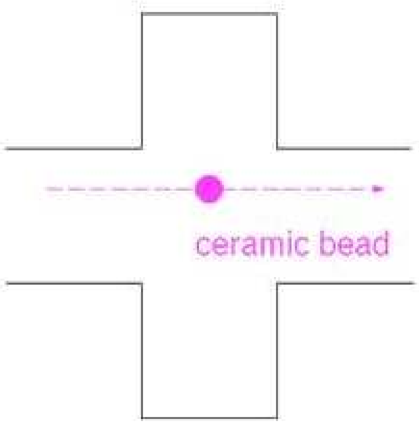
Measurement of the R/Q for the RF Cavity

Bead perturbation method for R/Q measurement

$$\frac{\Delta f}{f_0} = \frac{-\int_{\Delta V} \epsilon \mid \mathbf{E} \mid^2 \mathrm{dV}}{4W} = -\frac{\epsilon \mid \mathbf{E} \mid^2 \Delta V}{4W}$$

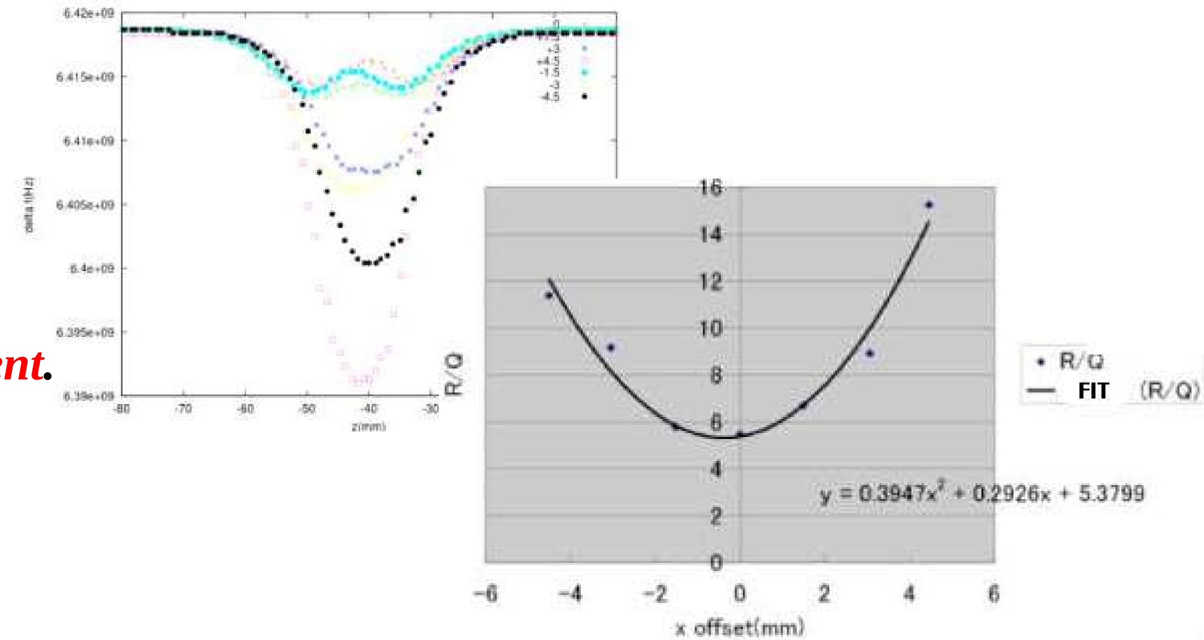
$$\mid \mathbf{E} \mid = 2\sqrt{-\frac{W}{\epsilon \Delta V}\frac{\Delta f}{f_0}}$$

$$\frac{R}{Q} = \frac{\mid \int \mathbf{E} d\mathbf{s} \mid^2}{2\omega_0 W} = \frac{\mid \int \sqrt{\mid \Delta f \mid} \mathrm{ds} \mid^2}{\pi f_0^2 \epsilon \Delta V}$$



Ceramic bead is used for the off-center field measurement.

- ***no magnetic coupling***
- ***with electric coupling***



Readout Electronics

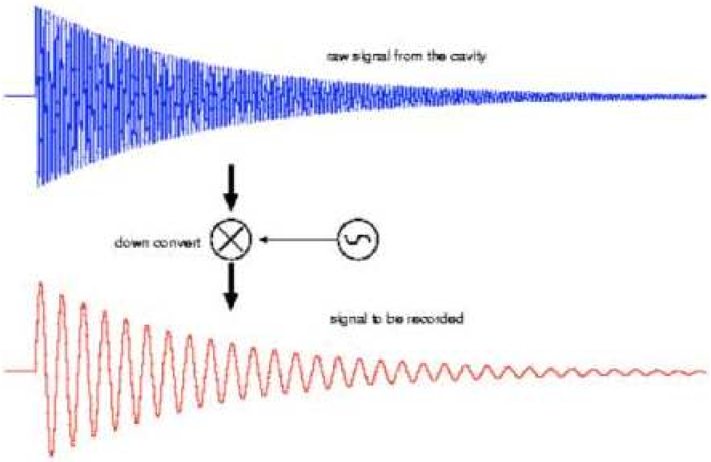
Introduction of two method

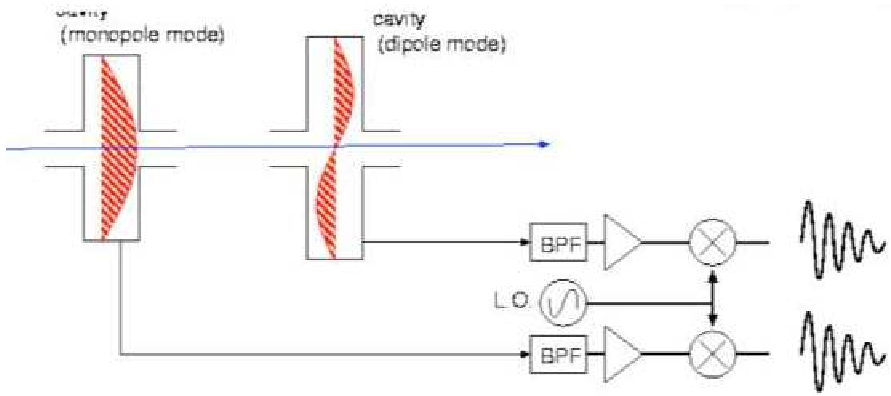
1) Homodyne Method (developing by KEK)

2) Heterodyne Method (developing by SLAC)

Readout Electronics of Cavity BPM

Frequency Conversion





Frequency is converted to useful frequency for the readout

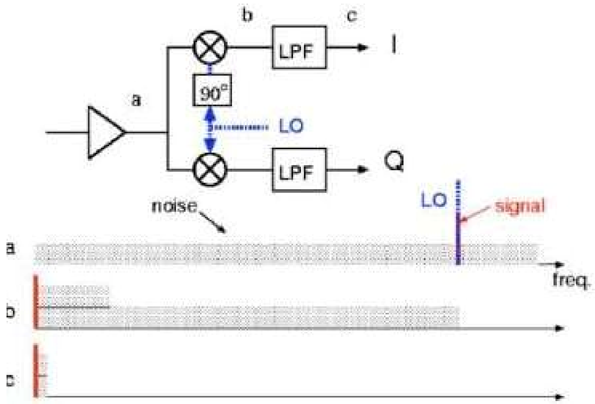
$$A\sin(\omega_1 t + \underline{\underline{\phi_1}}) \times B\sin(\omega_2 t + \phi_2) = \frac{AB}{2}[\cos((\omega_1 - \omega_2)t + (\underline{\underline{\phi_1}} - \phi_2)) - \cos((\omega_1 + \omega_2)t + (\phi_1 + \phi_2))]$$

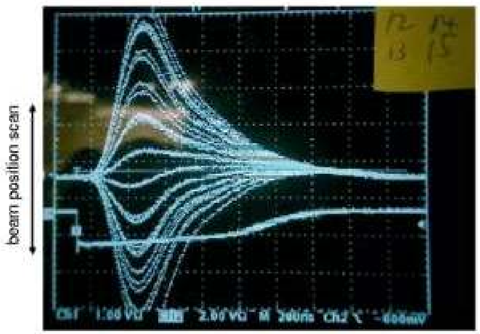
Converted signal keeps the phase information of the initial RF.

Readout Electronics of Cavity BPM

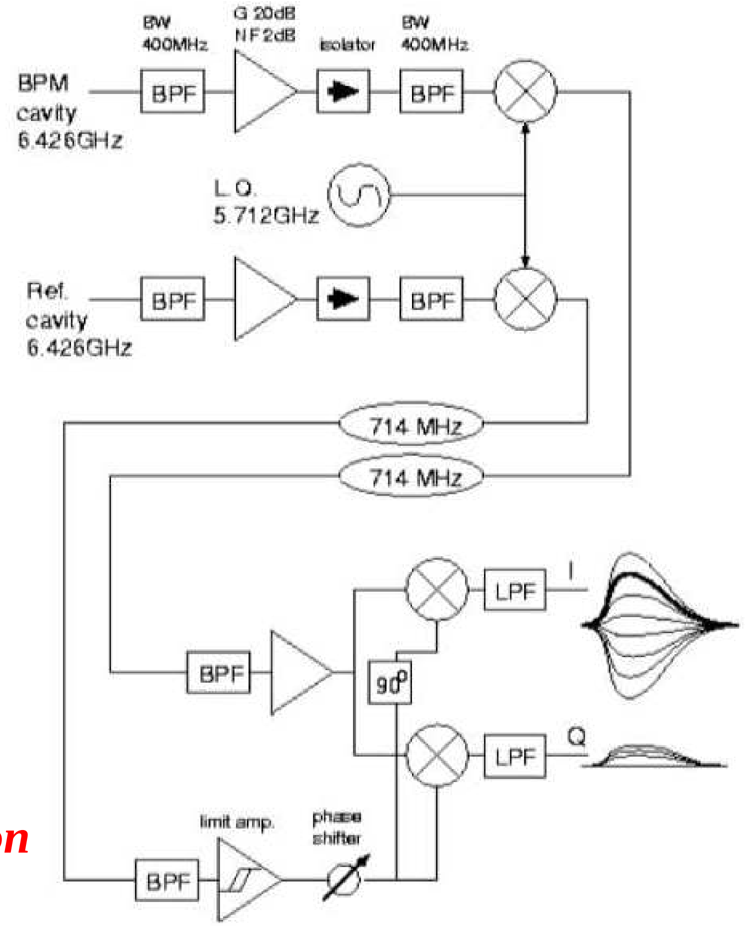
Homodyne Method

-Frequency is directly converted to be 0 .
-Converted signal has amplitude information only.



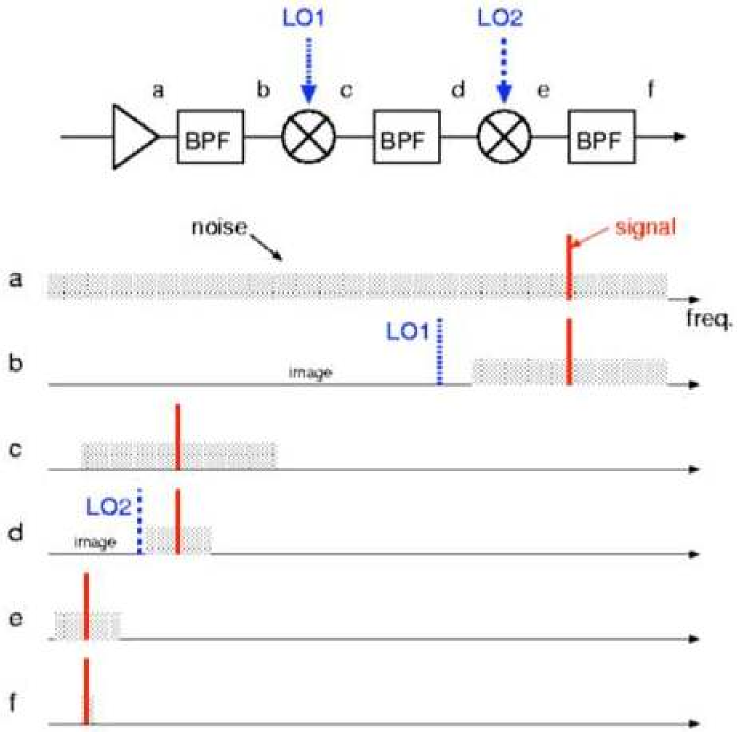


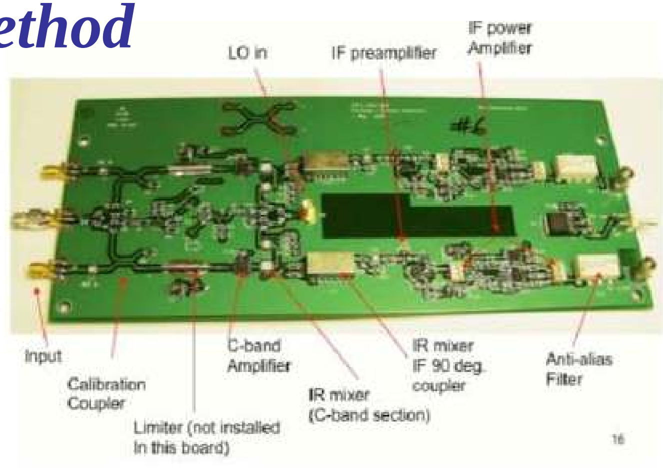
Position information is converted to the amplitude information

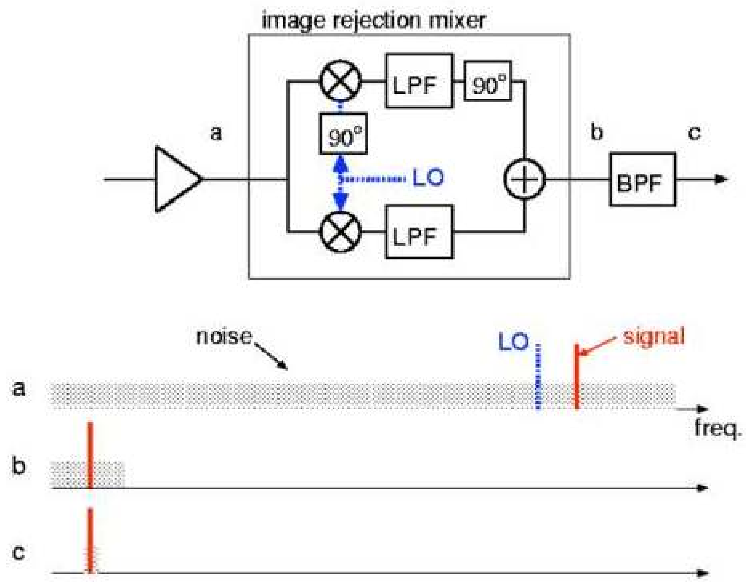


Readout Electronics of Cavity BPM

Heterodyne Method





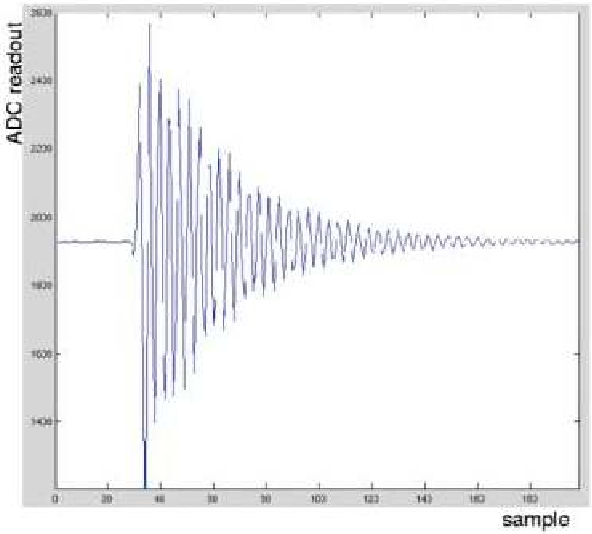


-Frequency is converted to** lower frequency **.

-Converted signal has
phase and amplitude information.

Readout Electronics of Cavity BPM

Heterodyne Method (continued)



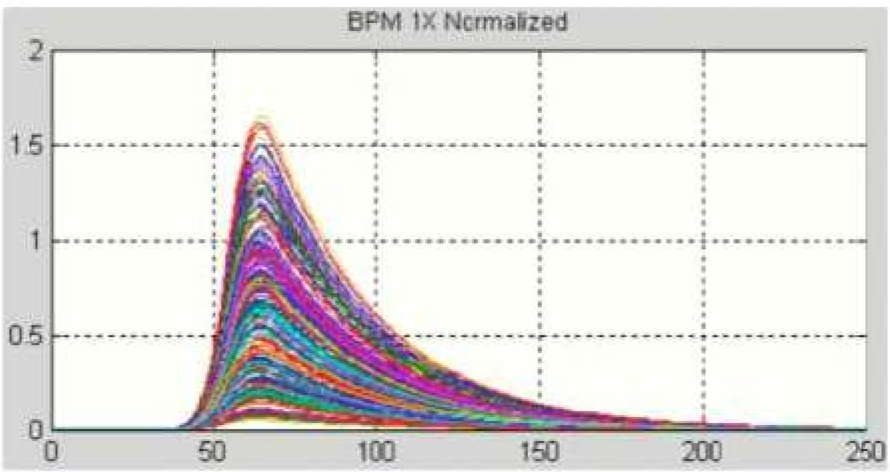
$$V = V_0 + Ae^{-\Gamma(t-t_0)}\sin(\omega(t-t_0)+\phi)$$

$$I_Y = \frac{A_Y}{A_{Ref}}\sin(\phi_Y - \phi_{Ref})$$

$$Q_Y = \frac{A_Y}{A_{Ref}}\cos(\phi_Y - \phi_{Ref})$$

Position information is converted to the amplitude information by the readout software.

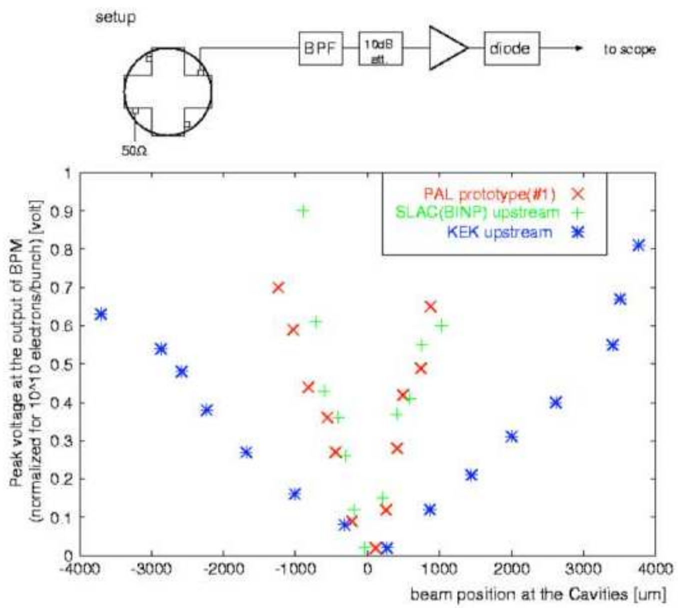
Down converted signal is fitted by readout software.



Beam Test in ATF

Characteristic Measurement with Beam

Position Sensitivity Measurement



-Amplitude measurement with diode

-Position was changed by beam steer

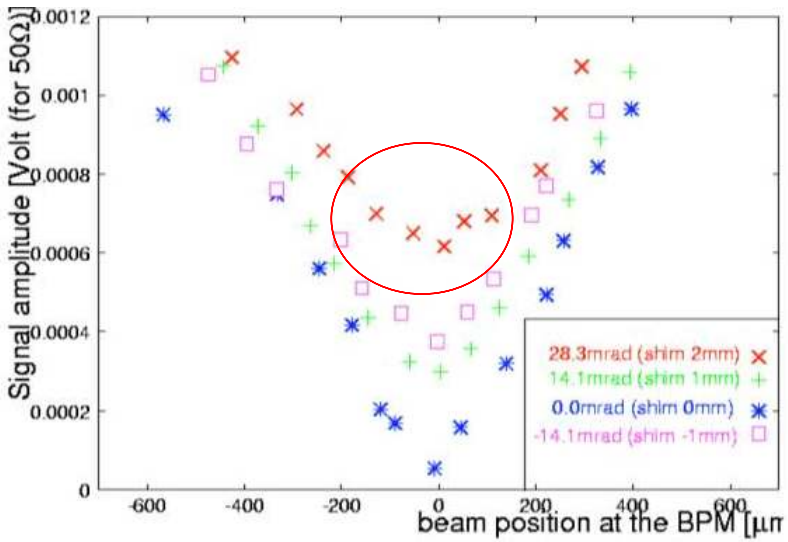
-Calibrated with stripline BPM

The position sensitivity is consistent with the design value.

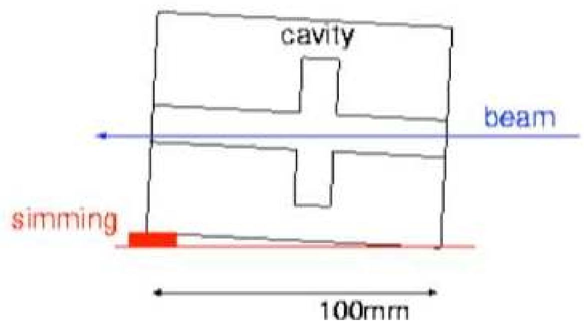
The position sensitivity should be evaluated by comparing other BPM signal, because the signal include the attenuation of the cable loss and so on .

Characteristic Measurement with Beam

Angle Sensitivity Measurement



The beam angle is generated with shim .



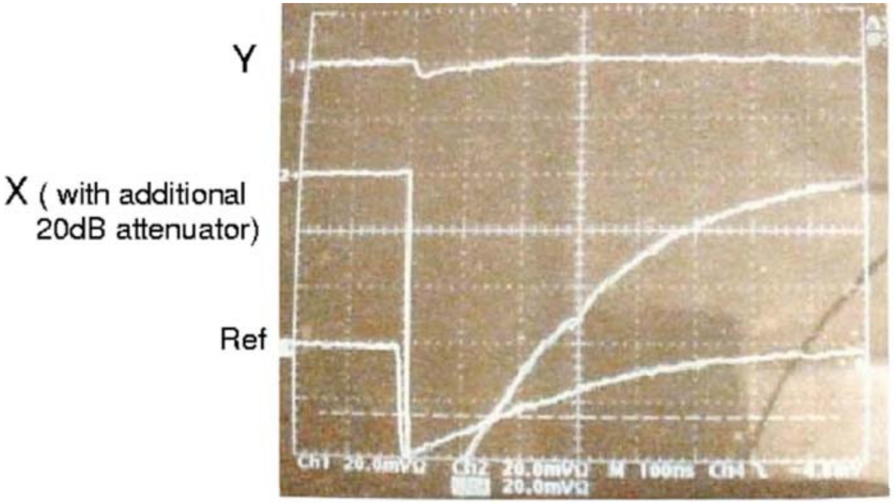
Measured angle sensitivity

10nm / nrad

Consistent with design

We can cancelled by using phase information.

Confirmation of XY Isolation



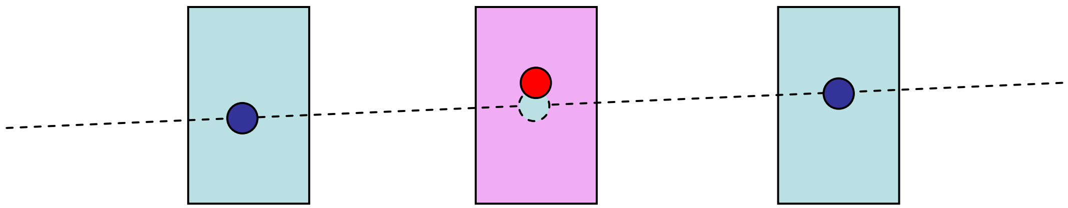
offset in x 5mm, signal in Y-port < 50 µm
< -40dB x-y isolation

XY isolation was confirmed by measuring Y signal, when beam has X offset .

Measure XY coupling was almost 40dB, consistent with the design .

Resolution Measurement

Position resolution measurement is done with 3 BPMs



The position resolution is evaluated by comparing
the masured BPM position
and the evaluated position from another 2 BPM position .

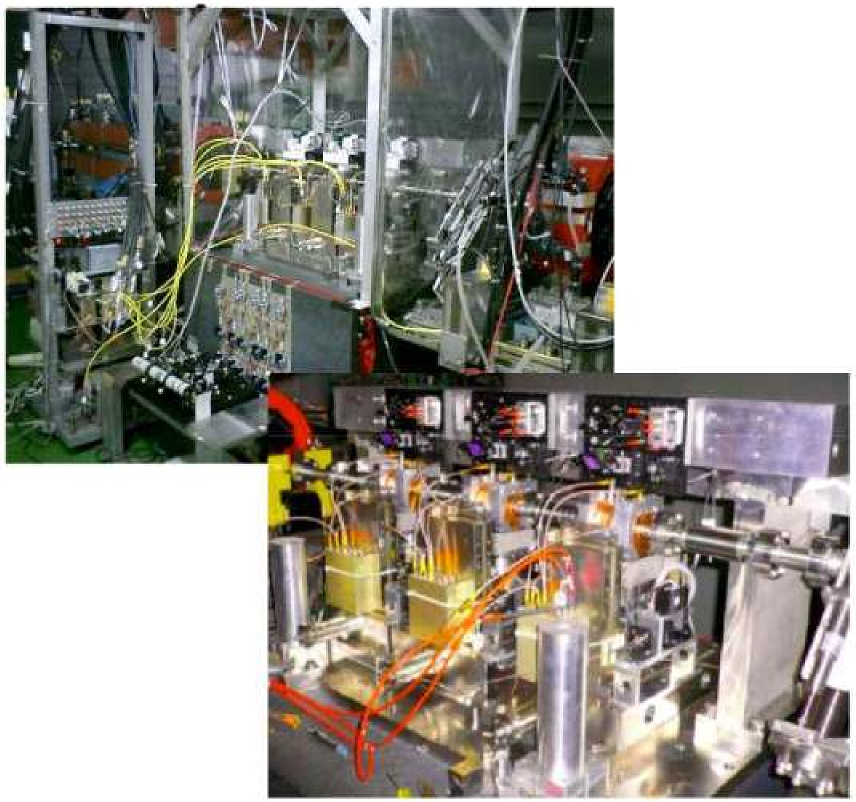
$$X2(X1,X3) = \frac{X1+X3}{2}$$

$$\sigma\,(X2-X2(X1,X3)) = \sqrt{\sigma_{X2}^{2} + \frac{\sigma_{X1}^{2} + \sigma_{X3}^{2}}{4}} = \sqrt{\frac{3}{2}}\,\sigma_X$$

Resolution Measurement

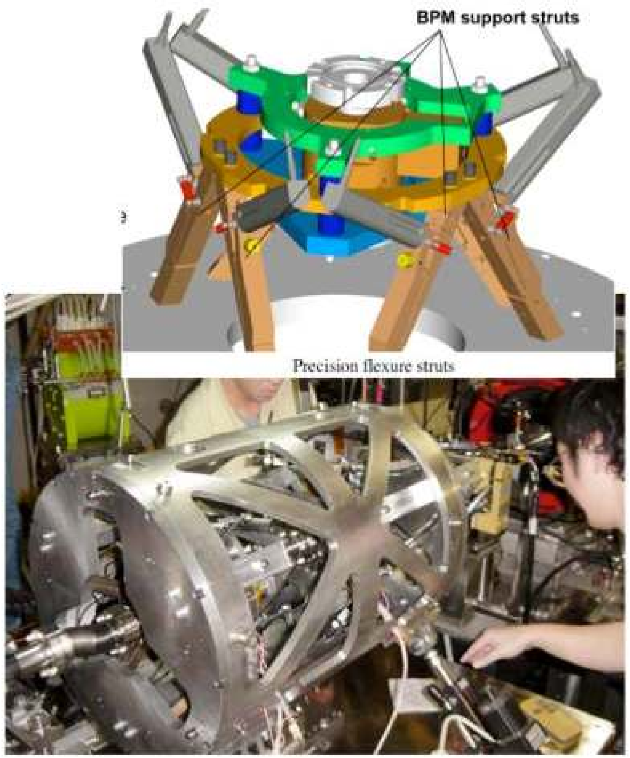
We must stabilized the relative position of BPMs within nm level .

Setup of KEK cavity BPM



BPM position is stable by position feedback.

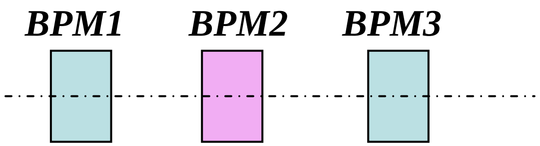
Setup of SLAC cavity BPM

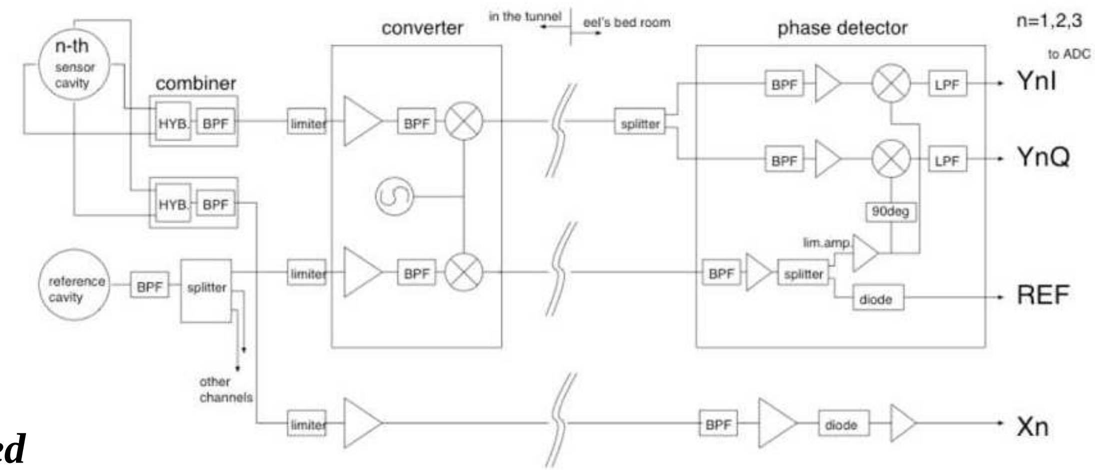


BPM position is stable by using mechanical stable stage.

Achieved Resolution in ATF

Readout electronics is Homodyne type electronics.





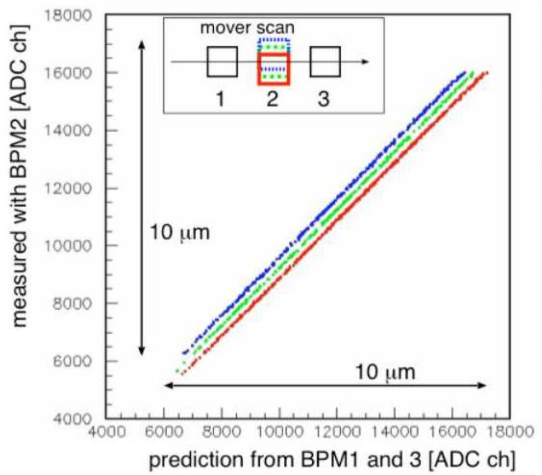
The position resolution is evaluated by comparing the Y2 signal and the Y2 value evaluated from BPM1 and BPM2 information.

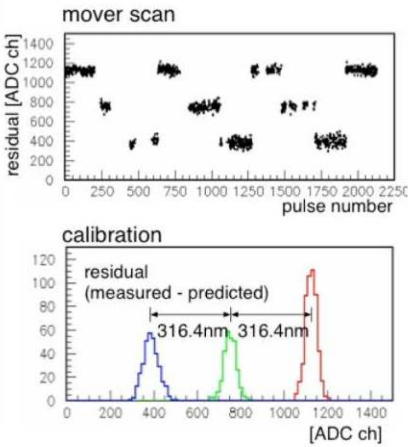
$$
\begin{aligned}
Y2I \quad = \quad & a_0 + a_{Y1I} \times Y1I + a_{Y3I} \times Y3I + a_{REF} \times REF \\
& + a_{X1} \times X1 + a_{X3} \times X3 + a_{Y1Q} \times Y1Q + a_{Y3Q} \times Y3Q \\
& + a_{Y1I^2} \times Y1I^2 + a_{Y3I^2} \times Y3I^2
\end{aligned}
$$

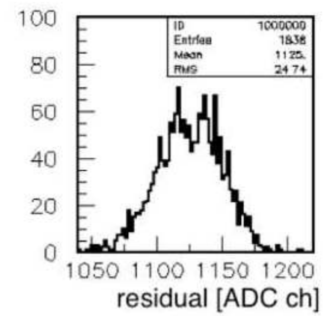
Δ = Y2I – Y2I (Y1I,Y1Q,X1,Y3I,Y3Q,X3)

Achieved Resolution in ATF

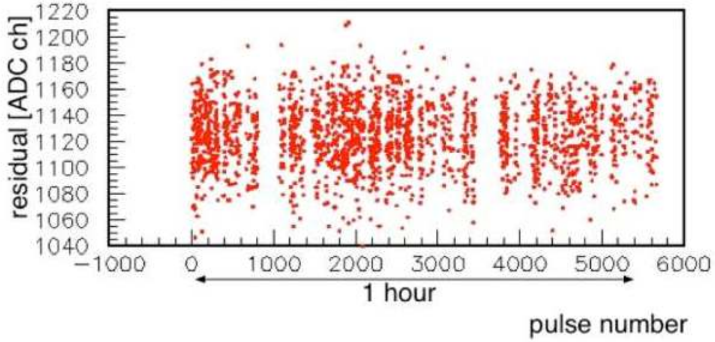
Continued …







RMS of the residual
= 21.2 nm
resolution of the BPM
$=\sqrt{2/3}$ x RMS
= 17.3 nm



Calibration was done
by changing the BPM2 position.

The 17.3nm resolution is achieved in ATF .

Some Comment of Cavity BPMs

The SLAC team achieved comparable resolution of the KEK team with Heterodyne method .

In present, by using high gain, small aperture type BPM, 5nm resolution is achieved with Homodyne method .

Critical Performance Characteristics of Cavity BPM

-Dynamic range;

- We can select the dynamic range by putting the attenuator at the front of readout electronics.

(1mm - 100μm for ATF2)

-Resolution ;

- Determined by the thermal noise .

(10nm for ATF2)

-Accuracy;

- We need online calibration for position sensitive factor .

- Electrical center is defined within 10μm to mechanical center.

- Time response is defined by cavity Q value .

-Large Impedance

- Used for transport line

- Possoble to use in the storage ring, but large impedance source .