Beam Instrumentation

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Introduction

Beam Instrumentation Devices

What do you want to measure ?

- Beam Position
- Beam Current
- Beam Profile, Beam Size, Beam Emittance
- Bunch Length

Where to put the instrumentation devices ?

- In storage ring
  nondestructive, low impedance
- At beam transport line
  single path or accumulated the signal with short gated

Critical Performance Characteristics for Beam Instrumentation Devices

-Dynamic range;
better to be wide

-Resolution ;
better to be small

-Offset ;
better to be small

-Stability and Accuracy;
better to be stable and accurate

-Destructive
destructive monitor is used only for the transport line.

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First 3 days ; introduction of basic beam instrumentation devices and beam instrumentation technology

Lecture 1 ; (storage ring and beam transport)

Beam Position Measurement

Beam current Measurement

Lecture 2 ; (beam transport line)

Beam Profile (Beam Size) Measurement
Bunch Length Measurement
Emittance Measurement

Lecture 3 ; (storage ring)

Beam Profile (Beam Size) Measurement
Bunch Length Measurement
Emittance Measurement

Table of Contents in this Lecture
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Last 2 days ; introduction of advanced beam instrumentation devices
(developed in ATF and developing for ATF2)

Lecture 4 ;

Beam Position Monitor

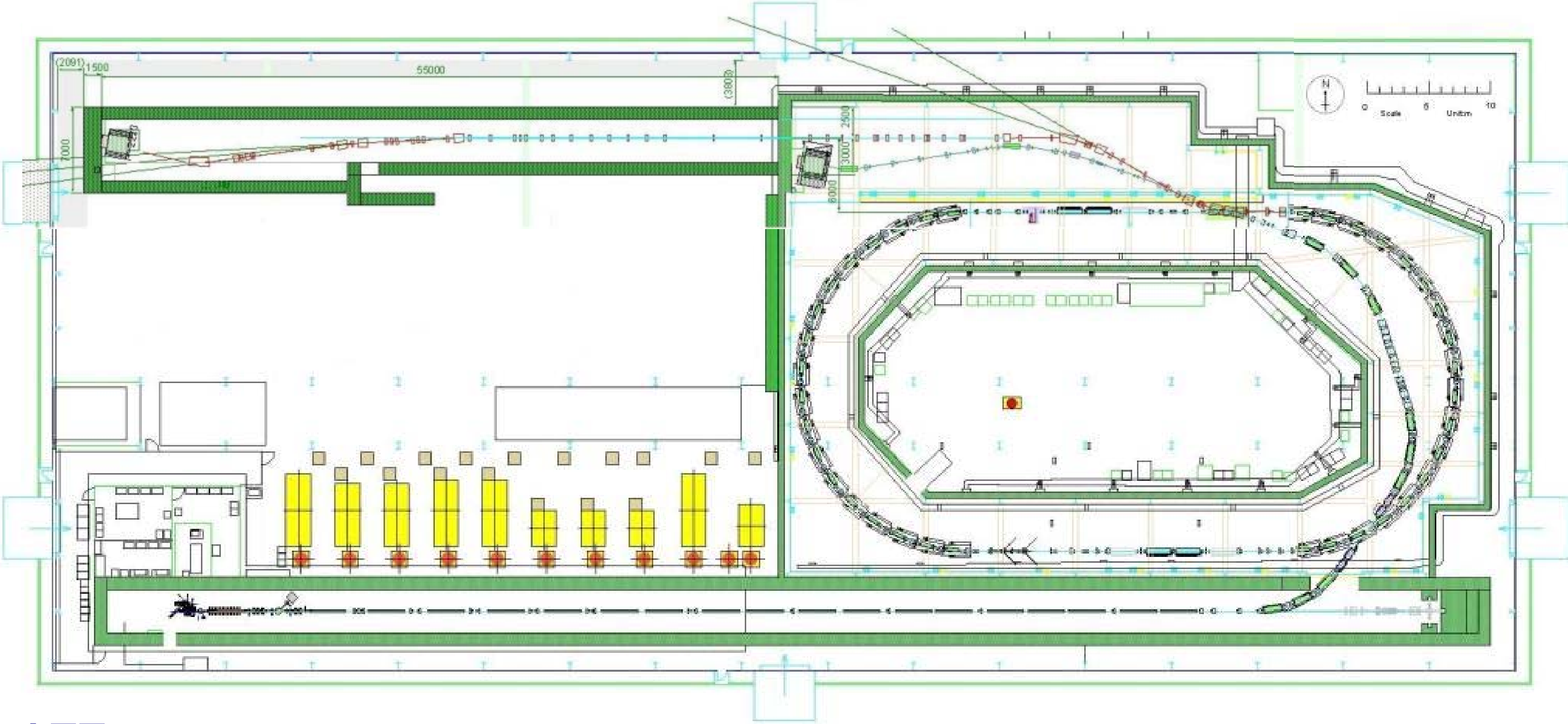
- with nanometer resolution
- cavity based technology

Lecture 5 ;

Beam Profile Monitor

- utilizing the laser Compton scattering
- laser wire scanner
- laser interference monitor (Shinatake Monitor)

Accelerator Test Facility (ATF) in KEK



ATF

***Accelerator** only for the accelerator technology development*

Consist of the linac, transport line, storage ring …

Low emittance (small beam size) after damping ring

ATF2

Development the final focus test beamline and the beam instrumentation devices

Beam Instrumentation
Lecture 1

Beam Instrumentation Devices
for Beam Position Measurement (Ring, Transport Line)

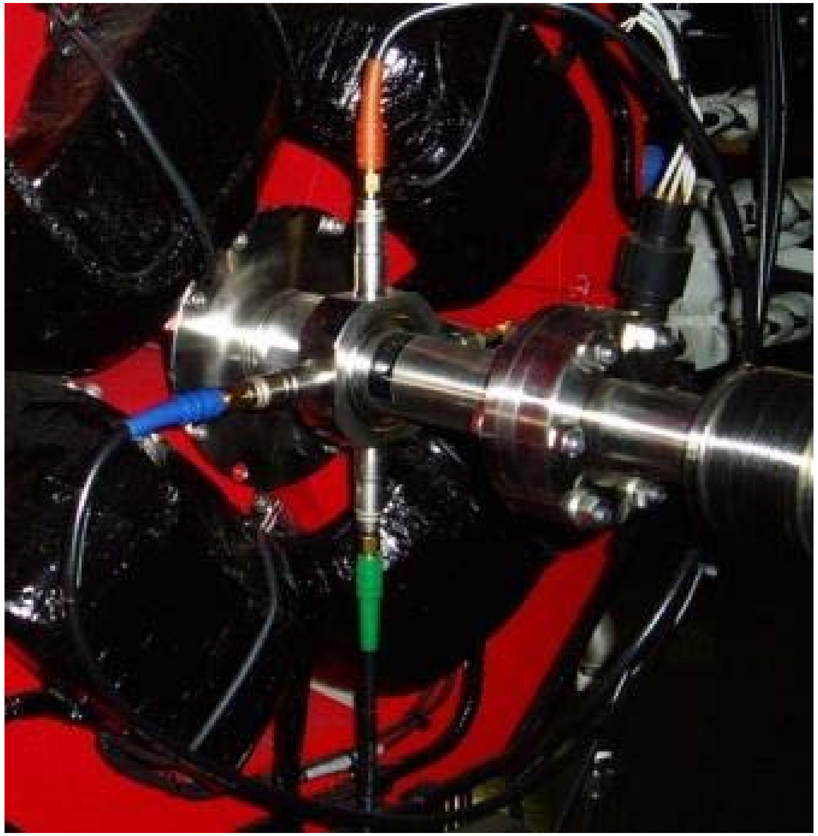
- ***Stripline Beam Position Monitor (Stripline BPM)***

Beam Instrumentation Devices
for Beam Current Measurement (Ring, Transport Line)

- ***Wall Current Monitor (WCM)***
- ***Integrating Current Transformer (ICT)***

Stripline Beam Position Monitor

Stripline Beam Position Monitor



Picture of the stripline BPM in ATF .

Stripline BPM

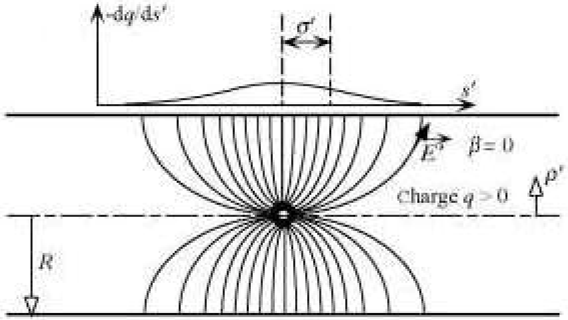
Beam position monitor with wall current.

What is the wall current ??

Wall Current

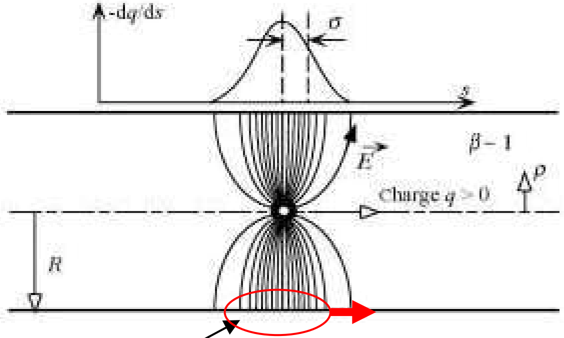
Field Distribution in the Beam Pipe

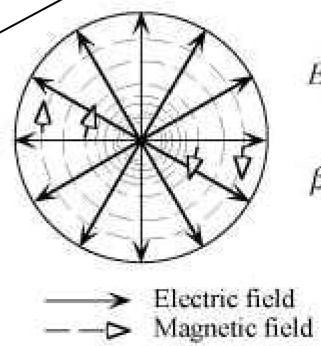
Field Distribution for Point Charge (Electron Rest Frame)



finite electric field,
no magnetic field

Charge moves along the pipe.





$$E_\rho = \gamma E'_\rho,\ B_\phi = \frac{\beta\gamma E'_\rho}{c},\ s = \frac{s'}{\gamma},\ \rho = \rho'$$

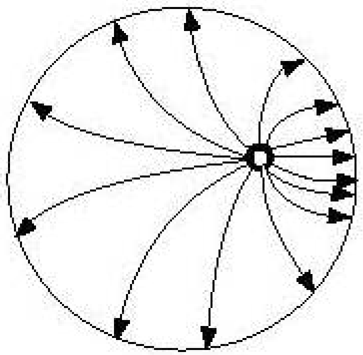
$$\beta \equiv \frac{v}{c},\ \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

"Wall Current"

The Distribution of the electric filed is roughly

$$\sigma'_w = \frac{R}{\sqrt{2}},\ \sigma_w = \frac{R}{\sqrt{2}\gamma}$$

Wall current of the off-center line charge



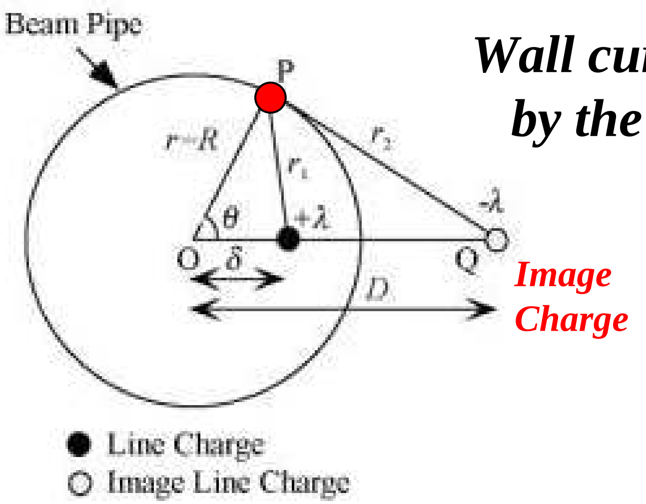
Electrical potential on the pipe is the sum of the line charge and image charge.

$$V_p = -\int_{r_0}^{r_1} E_r^{(+\lambda)} dr - \int_{r_0}^{r_2} E_r^{(-\lambda)} dr = -\frac{\lambda}{2\pi\varepsilon_0}\left[\ln r_1 - \ln r_2\right]$$

$$r_1^2 = (r\cos\theta - \delta)^2 + (r\sin\theta)^2$$

$$r_2^2 = (r\sin\theta)^2 + (D - r\cos\theta)^2$$

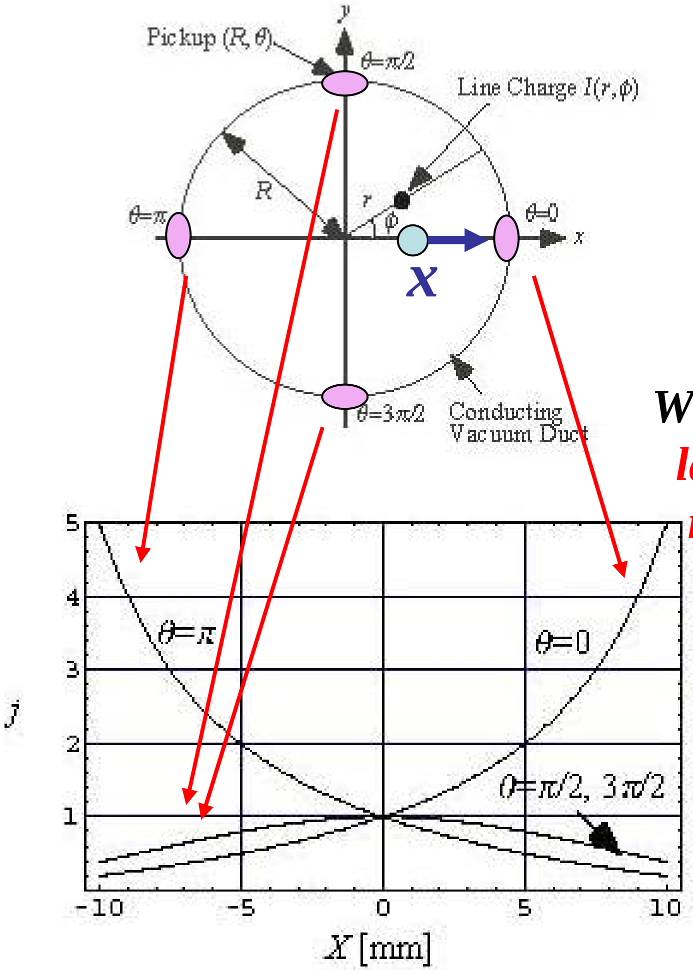
Expressed with image charge



Wall current distribution of the line charge can be driven by the derivative of the electrical potential

$$\sigma = -\varepsilon_0 \left(\frac{\partial V_p}{\partial r}\right)_{r=R} = \frac{-\lambda}{2\pi R} \frac{R^2 - \delta^2}{R^2 + \delta^2 - 2\delta R\cos\theta}$$

Wall current of the off-center line charge 2



Wall current induced each electrode.

The wall current can be driven by

$$j(r,\phi,R,\theta)=\frac{I(r,\phi)}{2\pi R}\frac{R^4-r^4}{R^2+r^2-2rR\cos(\theta-\phi)}$$

When the line charge has horizontal offset,
large difference between horizontal off-diagonal signal,
no difference between vertical off-diagonal signal .

↓

We can use the wall current as the position monitor.

The basic Idea of beam position measurement with wall current

$$j(r,\phi,R,\theta)=\frac{I(r,\phi)}{2\pi R}\frac{R^2-r^2}{R^2+r^2-2rR\cos(\theta-\phi)}$$

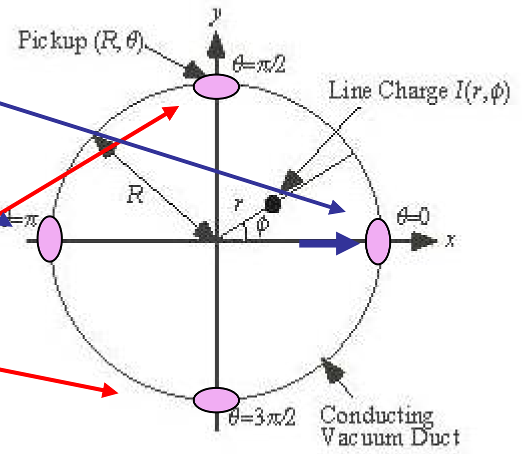
r << R

$$j_i(r,\phi,R,\theta_i)=\frac{I(r,\phi)}{2\pi R}\left[1+\left(\frac{2r\cos(\theta_i-\phi)}{R}\right)\right]$$

The differences of the off diagonal position (Δ / Σ) are

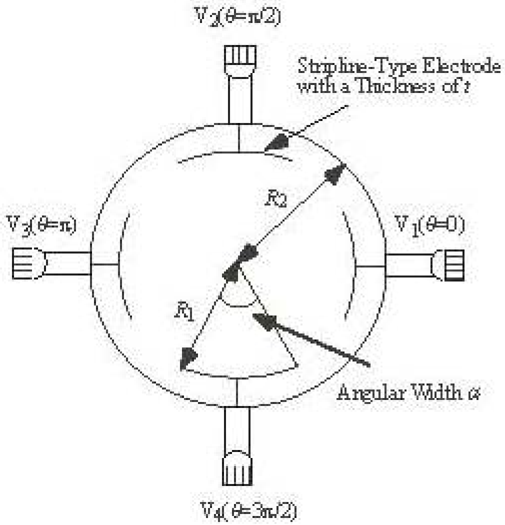
$$\left(\frac{\Delta}{\Sigma}\right)_x=\frac{j_1(r,\phi,R,\theta_1)-j_3(r,\phi,R,\theta_3)}{j_1(r,\phi,R,\theta_1)+j_3(r,\phi,R,\theta_3)}=\frac{r\cos\phi}{R/2}=\frac{x}{R/2}$$

$$\left(\frac{\Delta}{\Sigma}\right)_y=\frac{j_2(r,\phi,R,\theta_2)-j_4(r,\phi,R,\theta_4)}{j_2(r,\phi,R,\theta_2)+j_4(r,\phi,R,\theta_4)}=\frac{r\sin\phi}{R/2}=\frac{y}{R/2}$$



The (Δ / Σ) are proportional to the line charge position.

Position Sensitive Factor for the Electrode with Finite Opening Angle



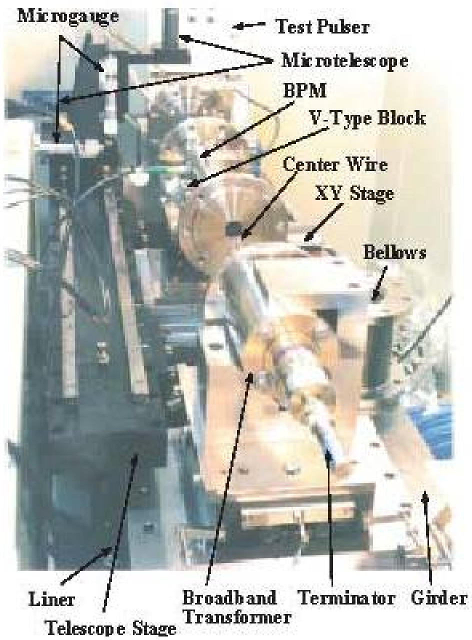
Angle width of the electrode is α.

$$x = \delta\cos\phi = S_\phi \frac{V_1 - V_3}{V_1 + V_3}$$

$$= S_\phi \frac{\int_{-\alpha/2}^{\alpha/2} \sigma(\delta,\phi,R,\theta_1)d\theta - \int_{\pi-\alpha/2}^{\pi+\alpha/2} \sigma(\delta,\phi,R,\theta_3)d\theta}{\int_{-\alpha/2}^{\alpha/2} \sigma(\delta,\phi,R,\theta_1)d\theta + \int_{\pi-\alpha/2}^{\pi+\alpha/2} \sigma(\delta,\phi,R,\theta_3)d\theta} \approx S_\phi \delta\cos\phi \frac{2}{R}\frac{\sin\alpha}{\alpha}$$

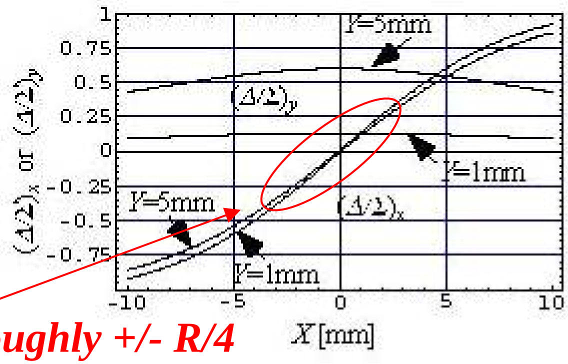
$$S_\phi = \frac{R}{2}\frac{\alpha}{\sin\alpha}$$ **Position Sensitive Factor**

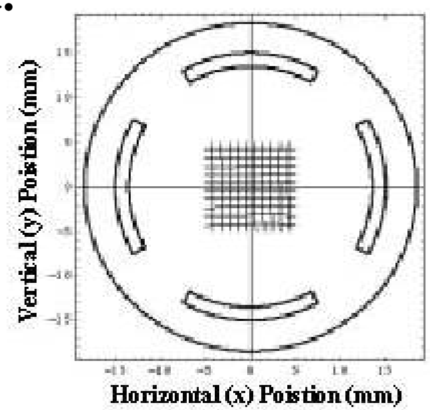
Mapping of the Stripline Signal



The nonlinear effect is calibrated offline analysis.

-BPM is moved by mover.
-Induced voltage is measured for each electrode.
-The nonlinear calibration factor is measured by the mapping procedure.

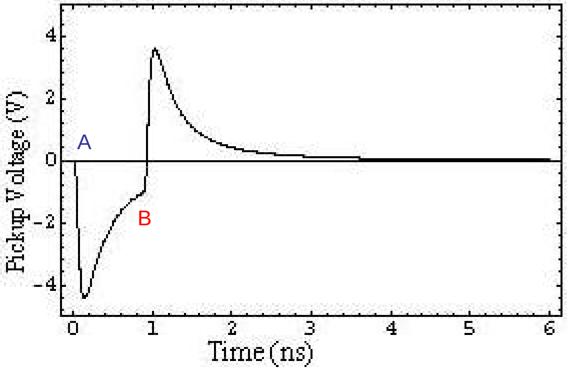


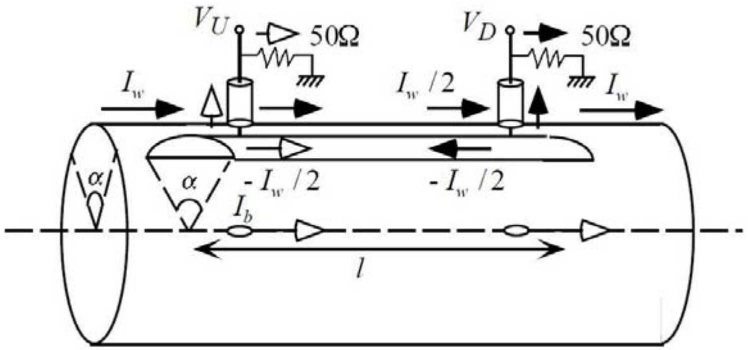


Linear region is roughly +/- R/4

Even though we can use the nonlinear region for the beam position with calibration curve, since signal induced one electrode is too small to make the accurate measurement, we define the dynamic range of stripline BPM as around +/-R/4.

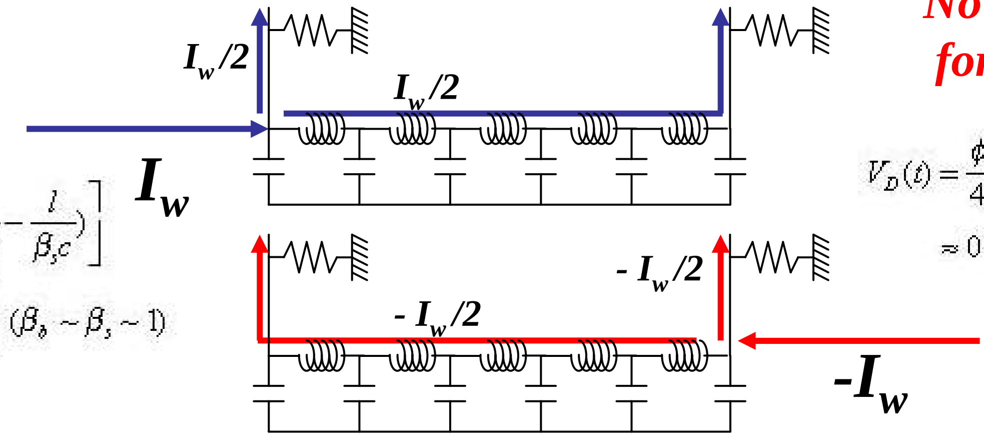
The readout of the stripline BPM





$$\frac{1}{2}I_w = \frac{1}{2}\left(\frac{\alpha}{2\pi}\right)$$

No signal output for downstream pickup

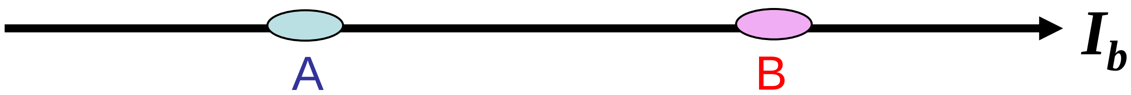


$$V_U(t) = \frac{\phi Z}{4\pi}\left[I_b(t) - I_b(t - \frac{l}{\beta_b c} - \frac{l}{\beta_s c})\right]$$

$$\approx \frac{\phi Z}{4\pi}\left[I_b(t) - I_b(t - \frac{2l}{c})\right] (\beta_b \sim \beta_s \sim 1)$$

$$V_D(t) = \frac{\phi Z}{4\pi}\left[I_b(t - \frac{l}{\beta_s c}) - I_b(t - \frac{l}{\beta_b c})\right]$$

$$\approx 0 \ (\beta_b \sim \beta_s \sim 1)$$

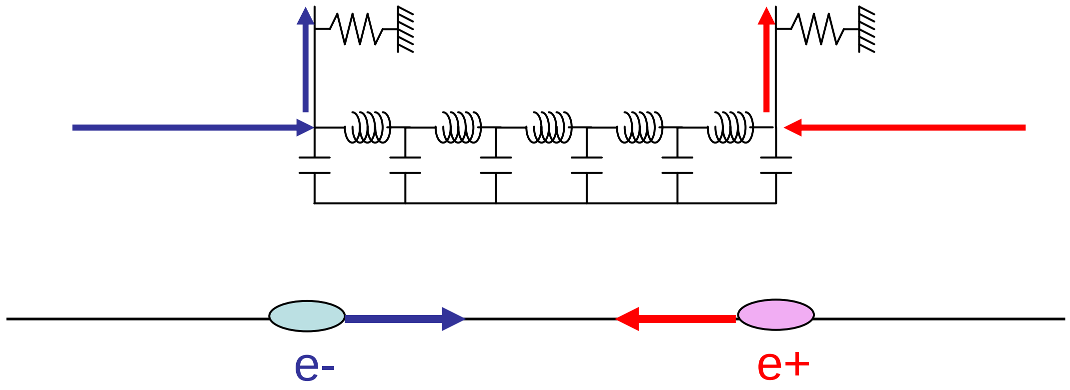


Application to e+ e- Ring

In the e+ e- ring,
the both electron and positron beams are stored in the same ring.

Since the beam directions are opposite direction,
we can measured the beam position for electron and positron beams.

pick up only the electron information *pick up only the positron information*



Resolution Limit of the Stripline BPM

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

$$\delta x = \sqrt{\left(\frac{\partial x}{\partial V_1}\right)^2 \delta V_1^2 + \left(\frac{\partial x}{\partial V_3}\right)^2 \delta V_3^2}$$

$V_1 \sim V_3 = V$ ***(around the center)***

$$\delta x = \frac{\sqrt{2}S_b}{2}\frac{\delta V}{V}$$

The signal is propotional to the current

$$V = \frac{\Delta\phi\, Z\, I_b}{4\pi}$$

The noise is defined by thermal noise

$$\delta V = \sqrt{4kT\,(BW)\,Z}$$

(BW) ; bandwidth defined by the electorode
for 10cm stripline,

Rough Estimation of the Position Resolution

For the storage ring, the signal is propotional to the beam current

$$V = \frac{\Delta\phi \, Z \, I_b}{4\pi}$$

i.e.) $R = 15mm$, $\Delta\phi = 30$ *degrees,*
$I_b = 50mA$ *(for sampling frequency of readout)*

$V = 104mV$

The noise is defined by thermal noise

$$\delta V = \sqrt{4kT\,(BW)\,Z}$$

i.e.) for 10cm stripline,

$$(BW) = \frac{c}{4L} = 750MHz$$

$\delta V = 0.025mV$

Therefore, the resolution limit is roughly

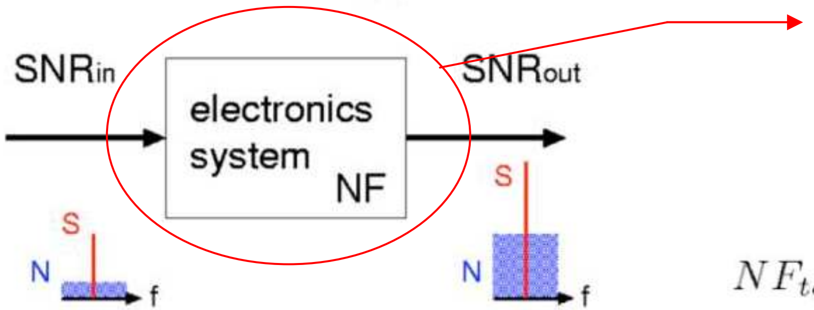
$\delta x = 1.3\ \mu m$ ***This is the theoretical limit .***

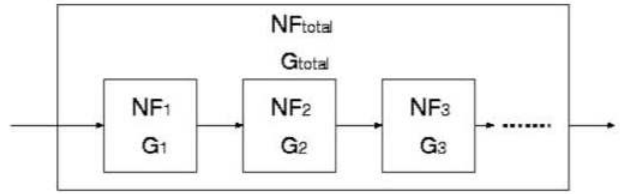
Readout of the Stripline BPM

Noise Amplification in Readout Electronics

The noise is also amplified in the amplifier of readout electronics.

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





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

The first amplifier is dominant noise source .

Comments for the beam transport line

Since the beam position signal is single path, the signal must be gated.

In generally, the resolution in transport line is not good to that in storage ring for its large amplification factor of the electronics.

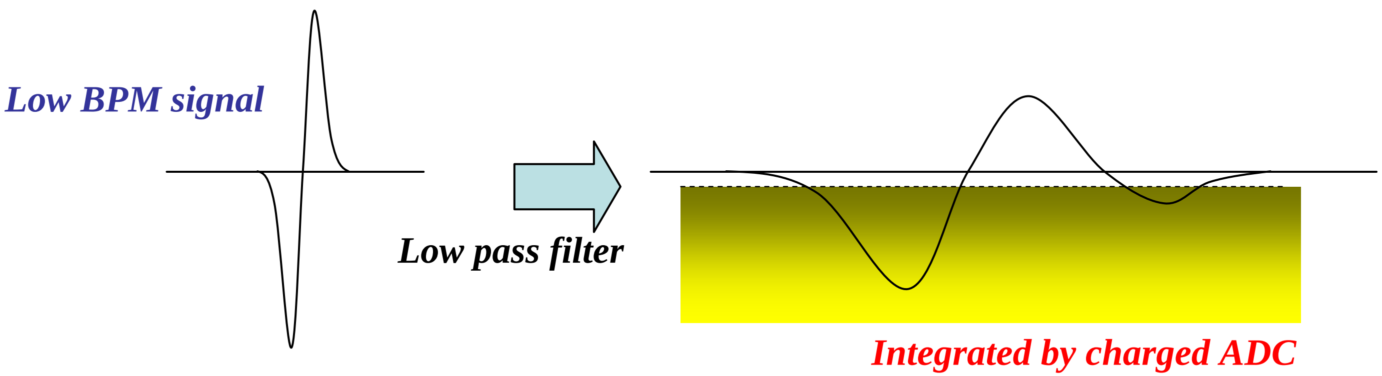
Readout of the Stripline BPM

Introduction of the ATF readout electronics

ATF readout electronics is the single path readout.

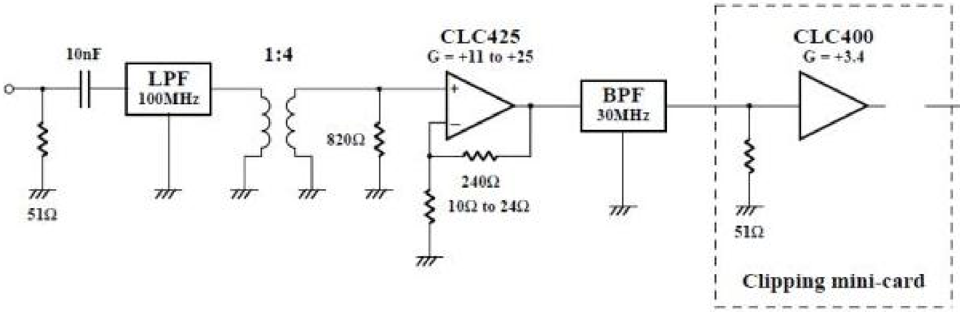
- we can measure the beam position with this electronics not only for the storage ring, but also for the beam transport line.
- we can measure the beam position at the first turn of injection, the first turn information is very helpful for the injection tuning.

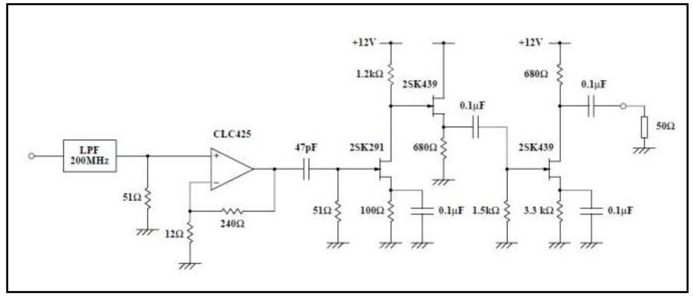
ATF readout electronics is using diode clipping circuit .



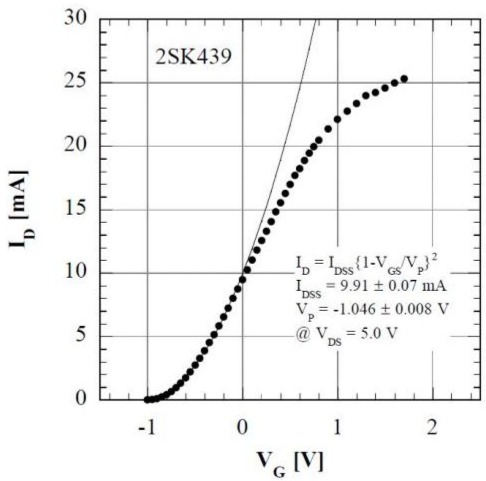
Readout of the Stripline BPM

Performance of the ATF readout electronics



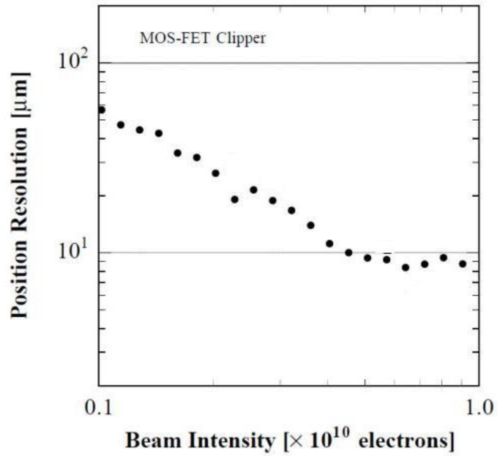


Signal Response of the circuit



This nonlinear effect is calibrated and corrected .

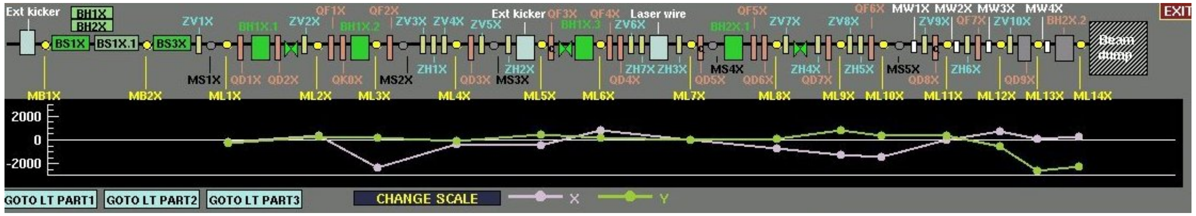
Position Resolution



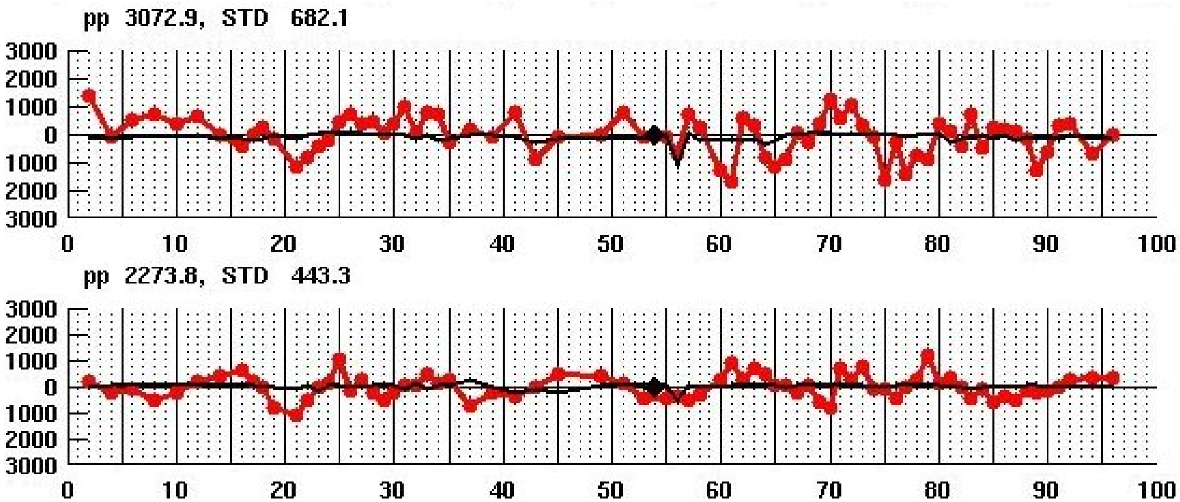
The position resolutio is around 10 μm at 1e10 beam intensity.

Beam orbit measurement in ATF with Stripline BPM

Beam orbit measurement in ATF extraction line.

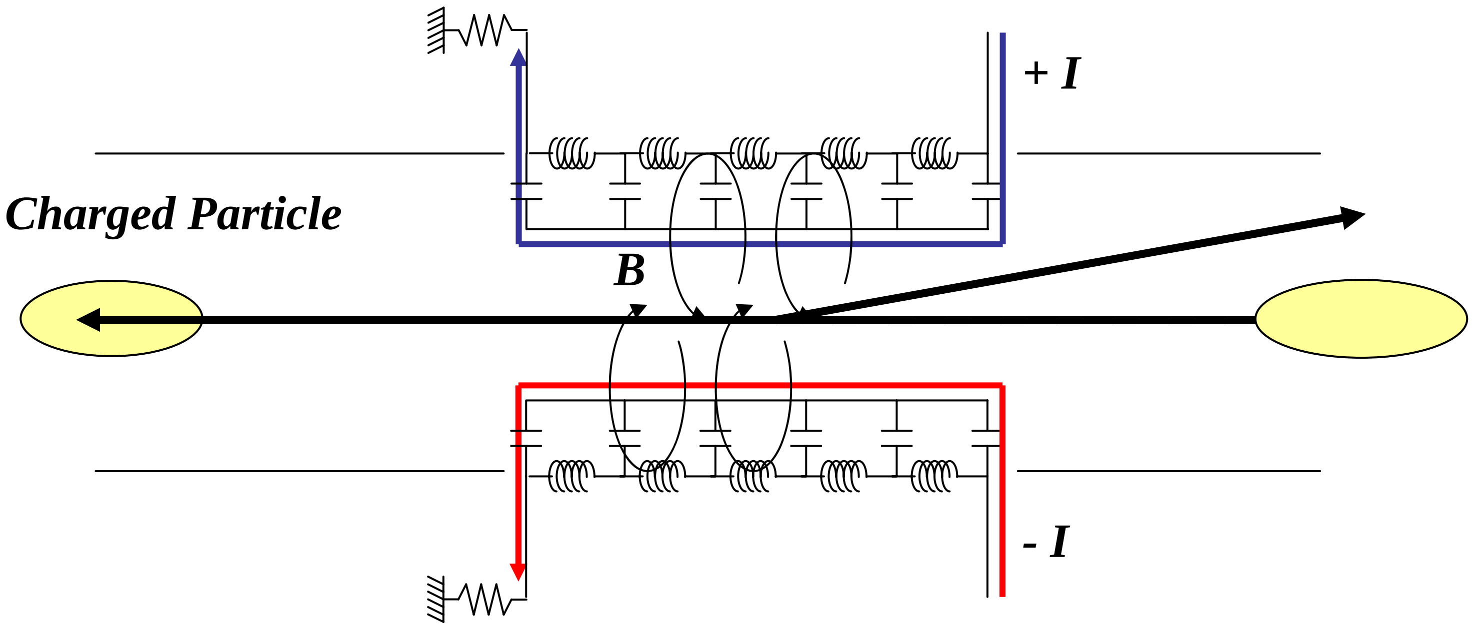


Beam orbit measurement in ATF damping ring.
the ATF damping ring has 96 BPMs.



Application of the Stripline Beam Position Monitor

Beam Kicker



The electrode of the stripline kicker is used for the beam kicker .
- Possible to very fast response kick !

The current should be opposite direction to the beam .
- In e+e- ring, only one beam can be kicked !

Critical Performance Characteristics of Stripline Beam Position Monitor

-Dynamic range;

- limited by the vacuum chamber diameter (+/- r / 4)

-Resolution ;

- defined by the thermal noise and the first amplifier of readout electronics

for the storage ring ; 1 μm

for the transport line ; 10 μm

-Accuracy and Offset ;

- with thermal drift (around micron level)

- necessary for the offset calibration.

- necessary of the calibration of the characteristics of readout electronics

-Nondestructive Monitor

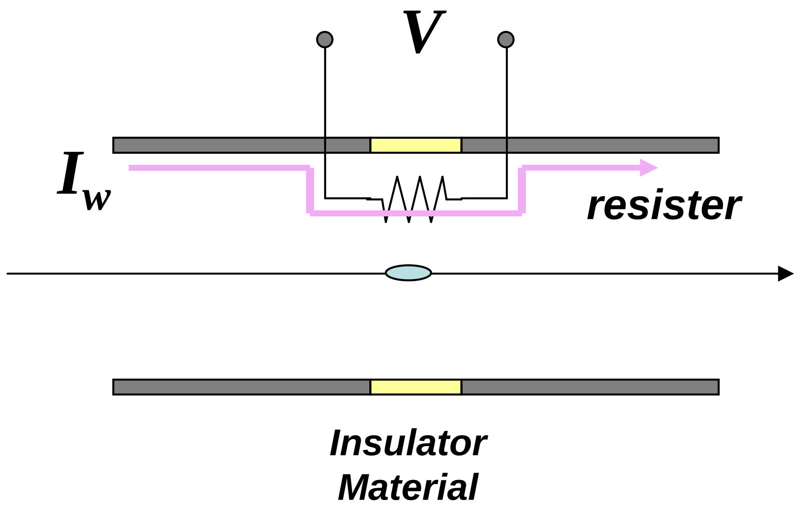
- both for beam transport line and storage ring

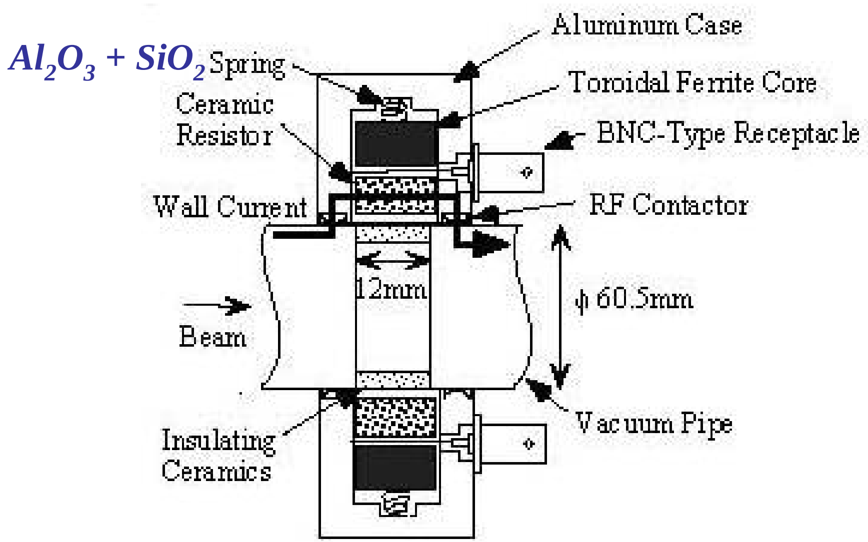
Wall Current Monitor

Wall Current Monitor

Wall current is used not only the position measurement,
but also beam current measurement.

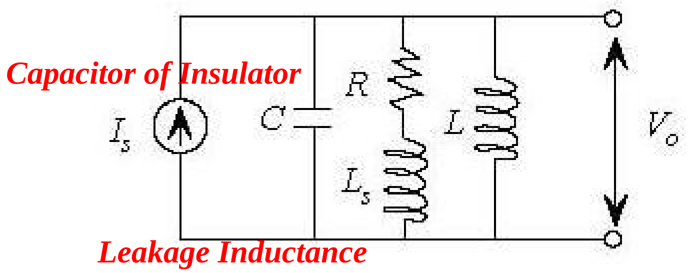
Mechanism of the Beam Current Measurement with Wall Current





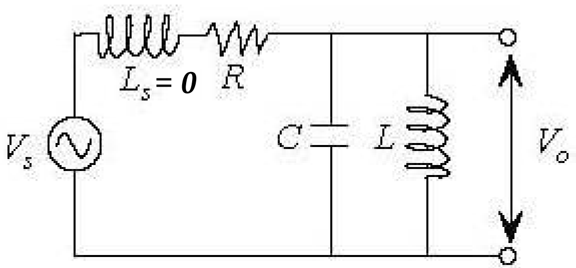
Equivalent Circuit of WCM

Equivalent Circuit of WCM



For the first step,
the leakage inductance is 0.

Equivalent Circuit as Voltage Source



***time domain** (defined by Laplace Transform)*

$$V_0(t) = \mathcal{L}^{-1}[I(s)V_s(s)]$$

$$V_0(s) = I(s)V_s(s)$$

$$I(s) = \frac{s/RC}{s^2 + (1/RC)s + (1/LC)}$$

frequency domain

$$V_0 = \frac{j\omega L}{R - j\omega L - \omega^2 LCR} V_s$$

Response Function of the Equivalent Circuit

Response Function for Step Pulse

$$V_0(t) = \mathcal{L}^{-1}[I(s)V_s(s)] \longrightarrow U(t) = \mathcal{L}^{-1}[I(s)/s]$$

$$I(s) = \frac{s/RC}{s^2 + (1/RC)s + (1/LC)}$$

When we defined by $k = \frac{1}{2R}\sqrt{\frac{L}{C}},\ T = 2\pi\sqrt{LC}$

(1) $k > 1$

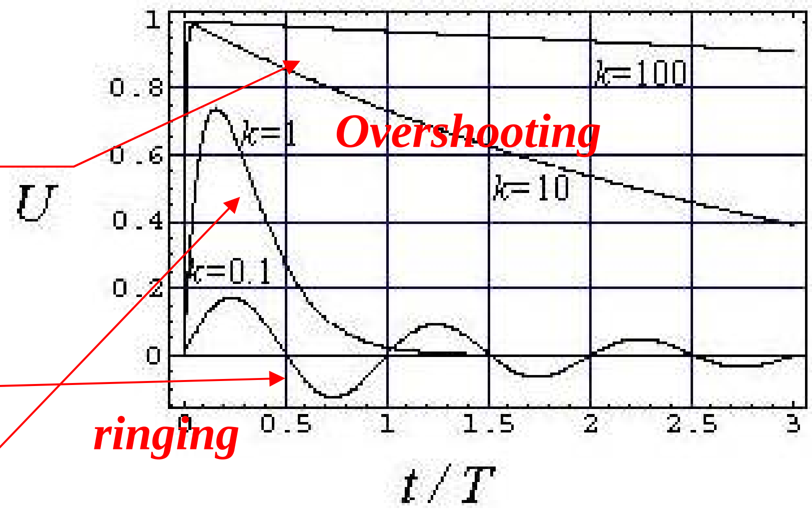
$$U(t) = \frac{k}{\sqrt{k^2-1}} e^{-\frac{2\pi k t}{T}} \left[e^{\frac{2\pi t\sqrt{k^2-1}}{T}} - e^{-\frac{2\pi t\sqrt{k^2-1}}{T}} \right]$$

(2) $k < 1$

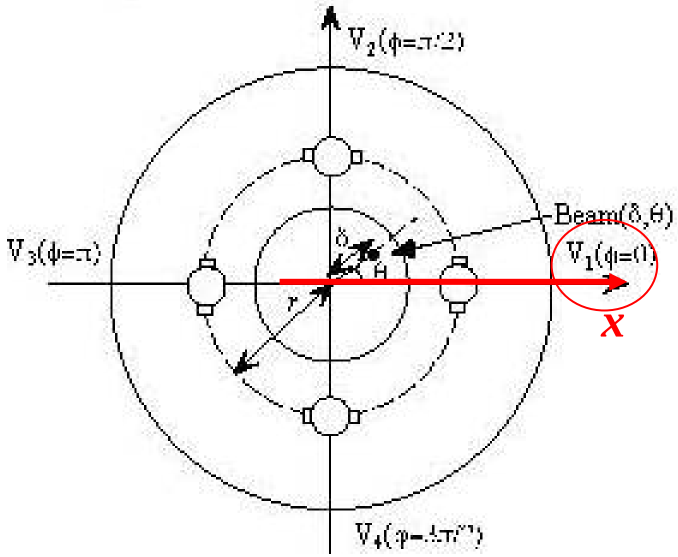
$$U(t) = \frac{2k}{\sqrt{1-k^2}} e^{-\frac{2\pi k t}{T}} \sin\left(\frac{2\pi\sqrt{1-k^2}}{T}\right)$$

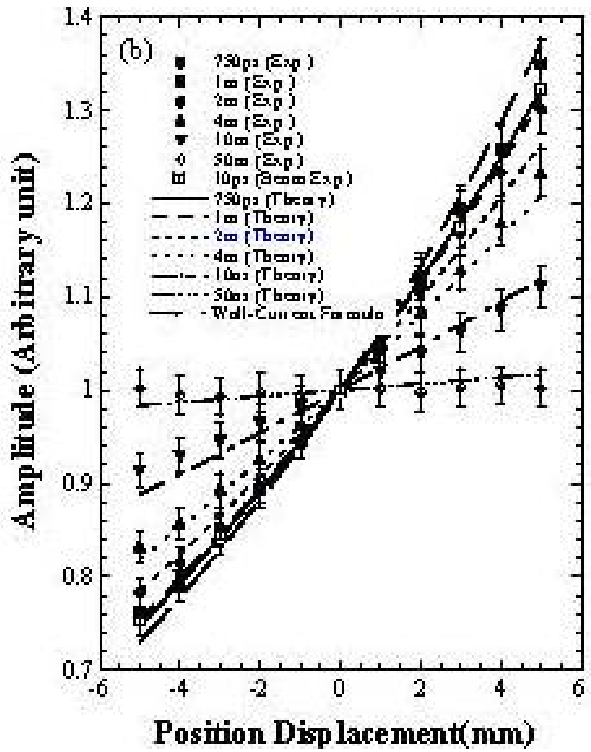
(3) $k = 1$

$$U(t) = \frac{4\pi k}{T} t e^{-\frac{2\pi k t}{T}}$$



Position Dependence of Pickup Signal





By integration, with V(0)=0, V'(0)=0

$$V(x) = \frac{I}{2\pi r\sqrt{\omega_0^{\,2}}}\frac{j\omega l(r^2-\delta^2)}{r^2+\delta^2-2r\delta\cos(\phi-\theta)}\sin\left[\sqrt{\omega_0^{\,2}}(\phi-\theta)\right]$$

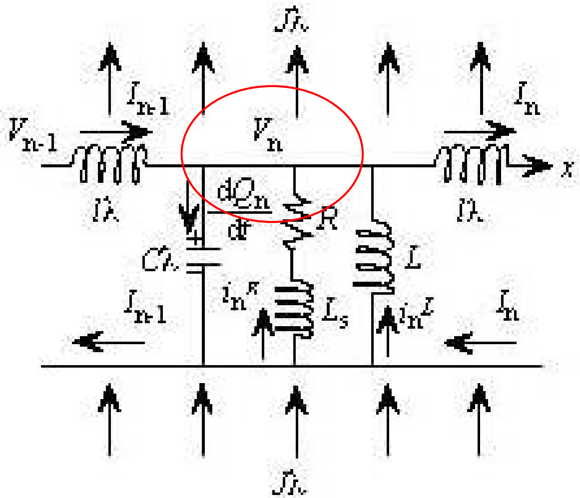
$$\omega_0^{\,2} = \left(\omega^2 C + \frac{j\omega\exp(-j\alpha)}{\sqrt{R^2+\omega^2 L_s^{\,2}}} + \frac{1}{L}\right) l$$

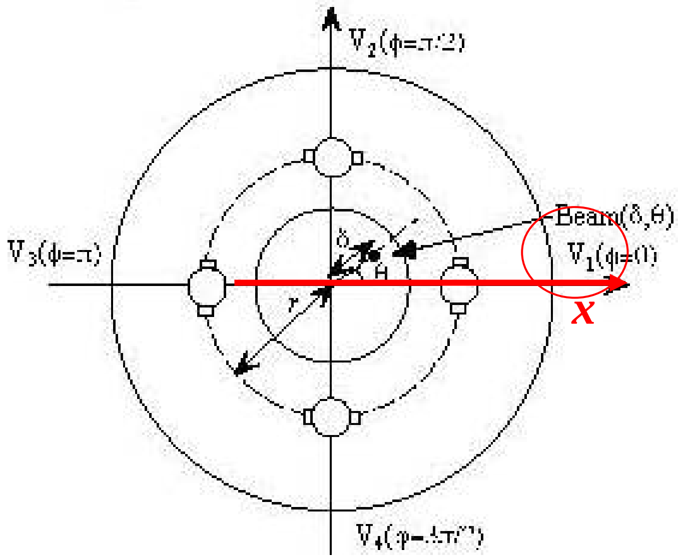
For the high frequency, the output signal has the large position dependence.

In order to use WCM as the current monitor, outputs of 4 connectors must be superposed .

Signal Pickup of Wall Current Monitor

Equivalent circuit with several pickups.





$$I_{n\text{-}1} - I_n - \frac{dQ_n}{dt} + i_n{}^R + i_n{}^L - J\lambda = 0$$

$$\frac{R}{\lambda} i_n{}^R + \frac{L_s}{\lambda}\frac{\partial i_n{}^R}{\partial t} = -V_n$$

$$\frac{L}{\lambda}\frac{\partial i_n{}^L}{\partial t} = -V_n$$

$$V_{n-1} = l\lambda \frac{\partial I_{n\text{-}1}}{\partial t} + V_n$$

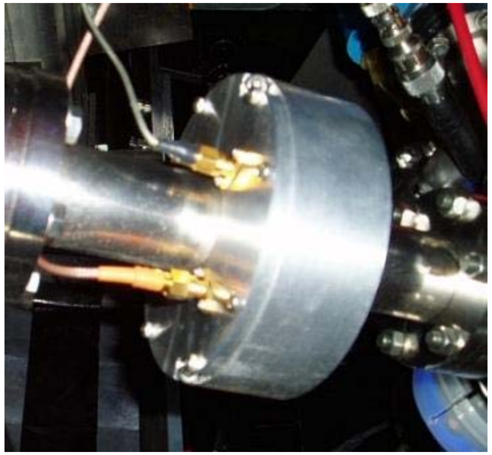
$$Q_n = C\lambda V_n$$

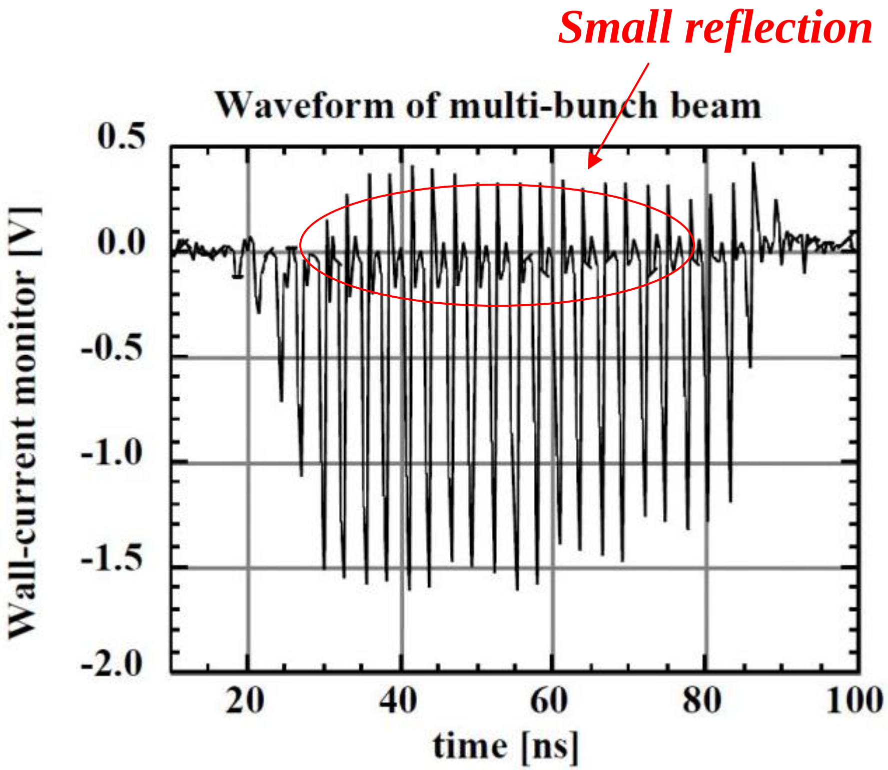
$$\frac{1}{l}\frac{d^2V(x)}{dx^2} + \left[\omega^2 C + \frac{j\omega \exp(-j\alpha)}{\sqrt{R^2 + \omega^2 L_s{}^2}} + \frac{1}{L}\right] V(x) = j\omega J(x)$$

$$\alpha = \tan^{-1}(L_s\omega / R)$$

Response of Pickup Signal

WCM in ATF





Beam current for 2.8ns bunch separation was measured .
However, it is difficult to measure the absolute bunch charge .

Critical Performance Characteristics of Wall Current Monitor

-Resolution ;

- The time resolution is defined by the readout frequency.

-Accuracy and Offset ;

- Strongly depends on the external noise .
- For the high frequency, large position dependence exists .
- with thermal drift

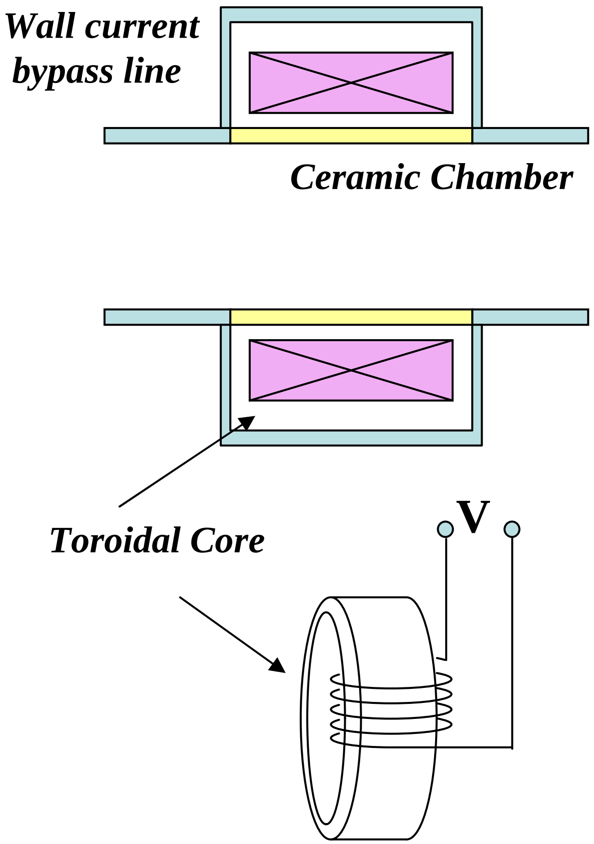
-Nondestructive Monitor

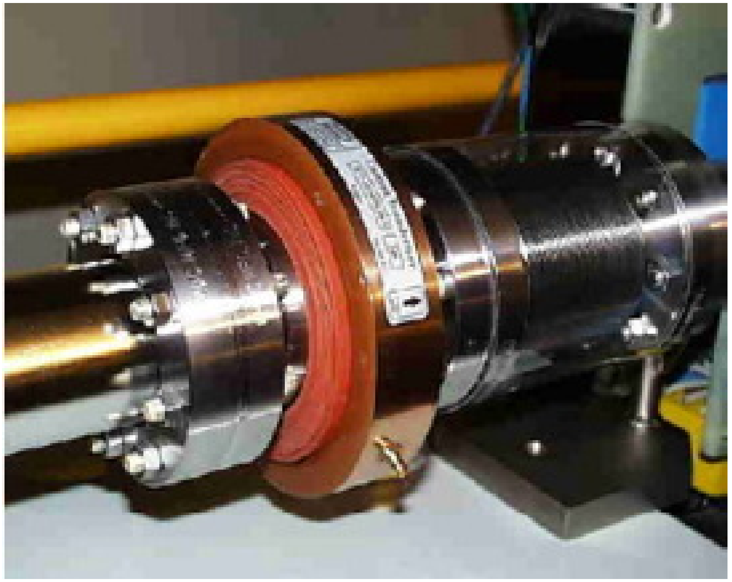
- both for beam transport line and storage ring

Integrating Current Transformer

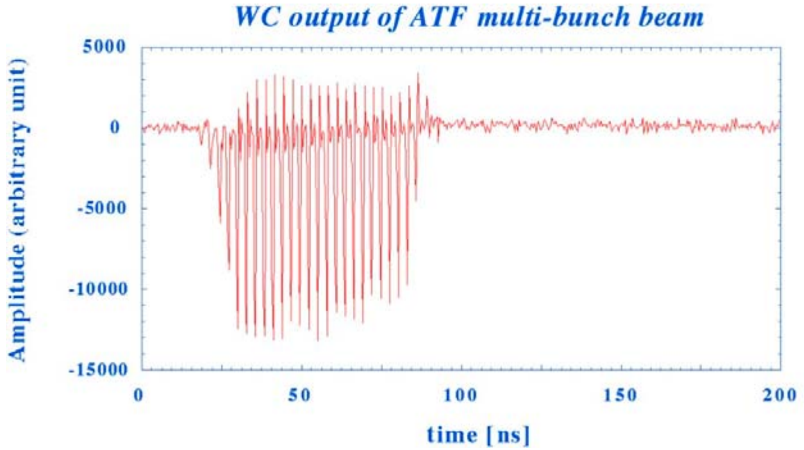
Integrating Current Transformer

The Integrating Current Transformer (ICT) is a capacitively shorted transformer and a fast readout transformer in a common magnetic circuit designed to measure the charge in a very short pulse with high accuracy.

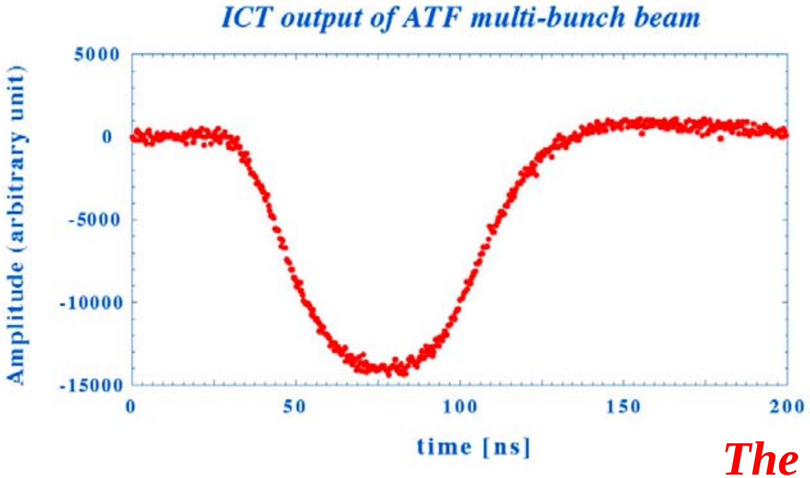




Measured Waveform of ICT



Bunch Structure measured by WCM



Bunch Current measured by ICT

The total bunch charge can be measured.

Critical Performance Characteristics of Integrating Current Transformer

-Resolution ;

- The time resolution is defined by the time constant of toroidal core.

-Accuracy and Offset ;

- Linearity error is less than 0.1% .

- Off-center position sensitivity is small (0.01%/mm)

- Small effect of the external noise .

-Nondestructive Monitor

- both for beam transport line and storage ring