2008 ILC School Lecture 09

Beam Instrumentation

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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

Contents

Session 1

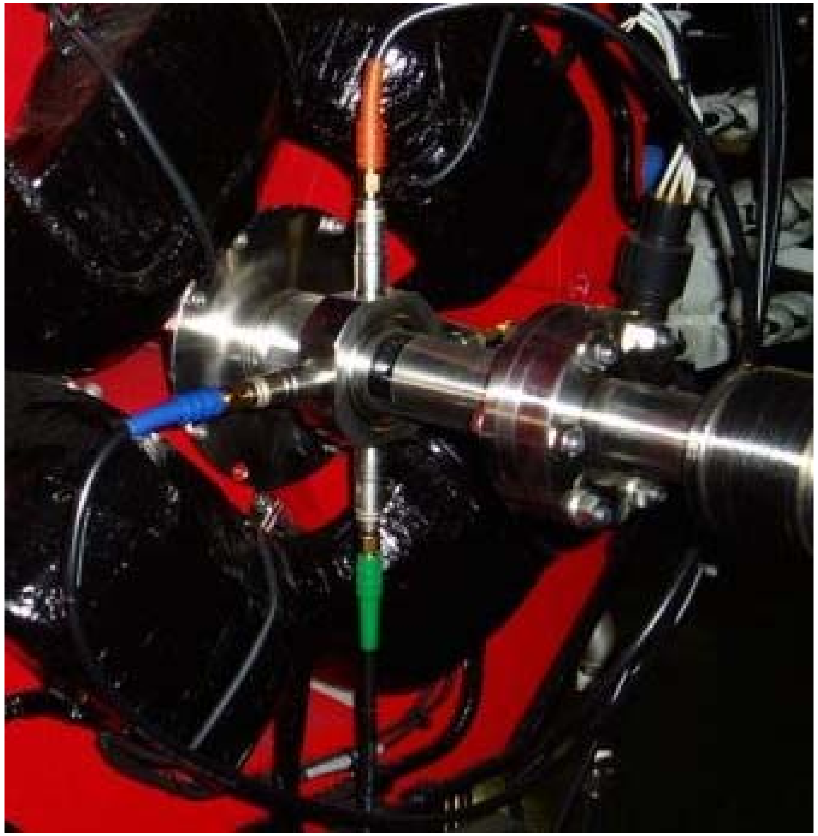
Beam Position Monitors

1-1. Stripline Beam Position Monitor

1-2. Button type Beam Position Monitor

1-3. Cavity Beam Position Monitor

1-1. Stripline Beam Position Monitor



Picture of the stripline BPM in ATF .

Stripline BPM

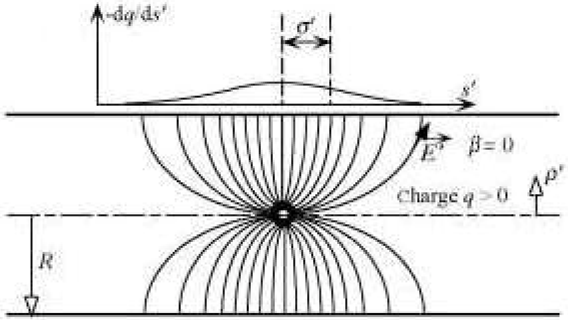
Beam position monitor with wall current.

What is the wall current ??

Wall Current

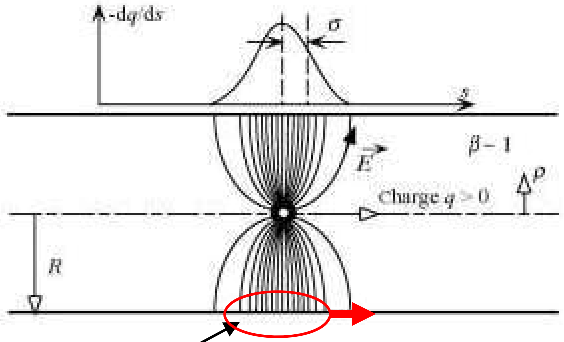
Field Distribution in the Beam Pipe

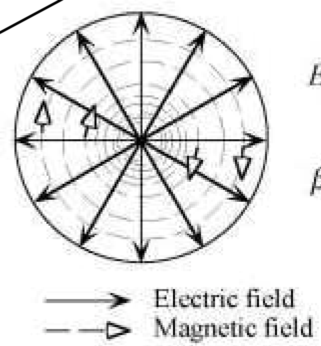
Field Distribution for Point Charge
(Electron Rest Frame)



finite electric field,
no magnetic field

Charge moves along the pipe.





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

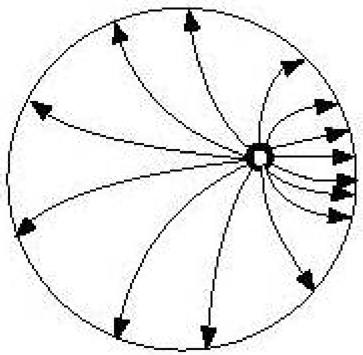
$$\beta \equiv \frac{v}{c},\ \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

"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

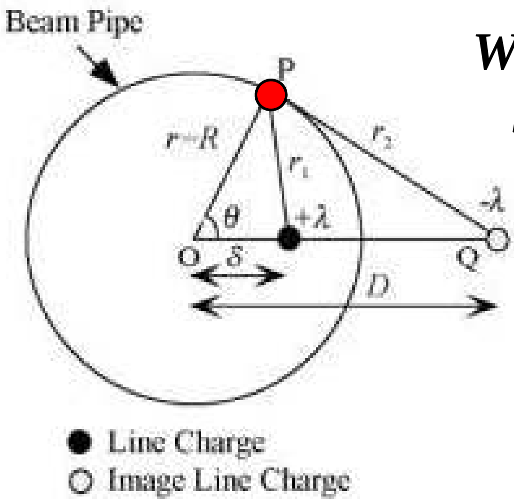


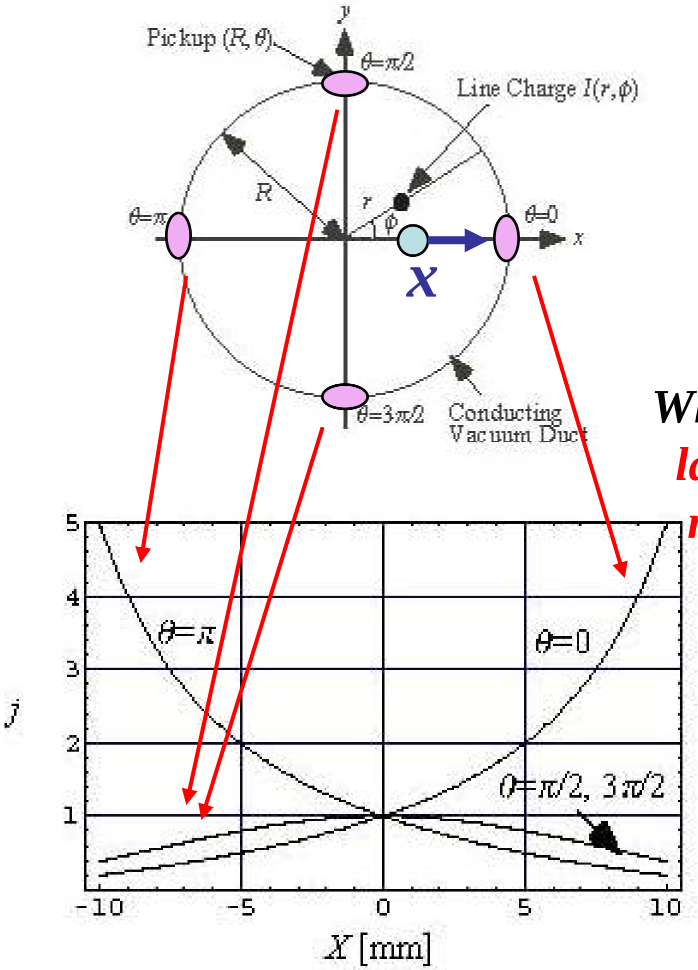
Image Charge

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

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

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

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

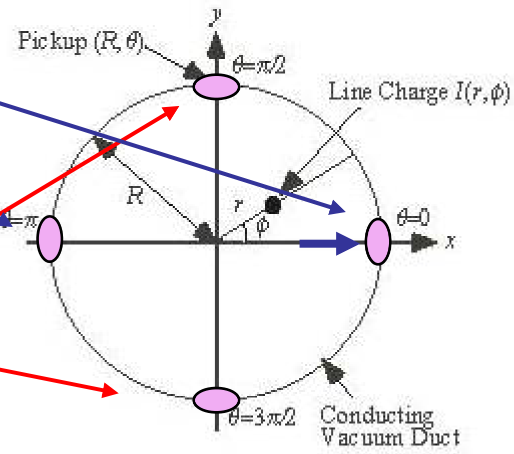
r << R

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

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

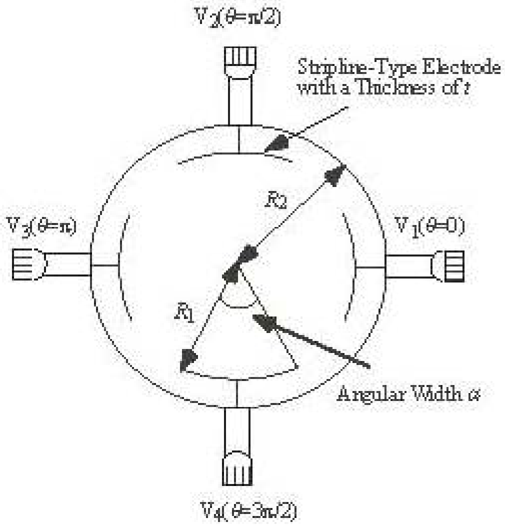
$$\left(\frac{\Delta}{\Sigma}\right)_x=\frac{j_1(r,\phi,R,\theta_1)-j_3(r,\phi,R,\theta_3)}{j_1(r,\phi,R,\theta_1)+j_3(r,\phi,R,\theta_3)}=\frac{r\cos\phi}{R/2}=\frac{x}{R/2}$$

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



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

Position Sensitive Factor
for the Electrode with Finite Opening Angle



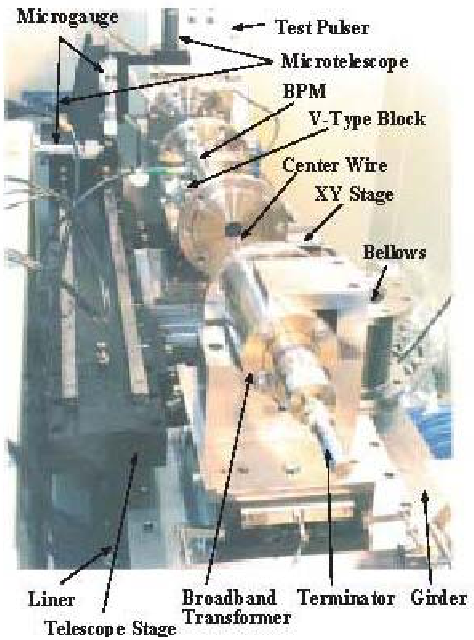
Angle width of the electrode is α.

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

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

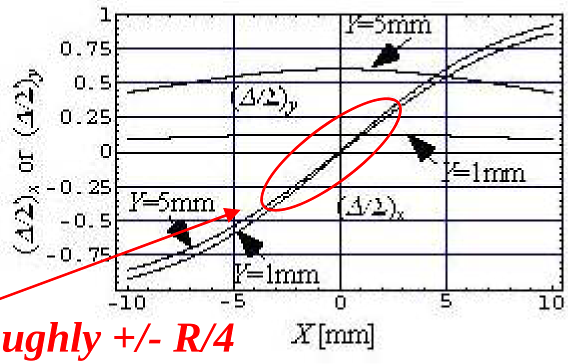
$$S_\delta = \frac{R}{2}\frac{\alpha}{\sin\alpha}$$ ***Position Sensitive Factor***

Mapping of the Stripline Signal

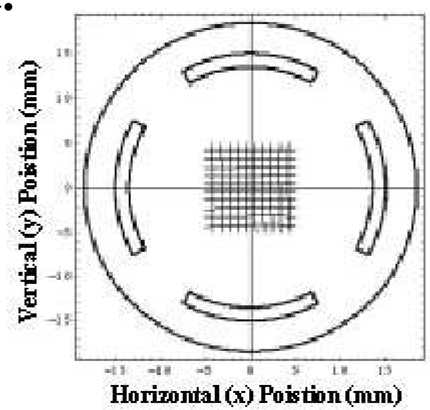


The nonlinear effect is calibrated offline analysis.

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

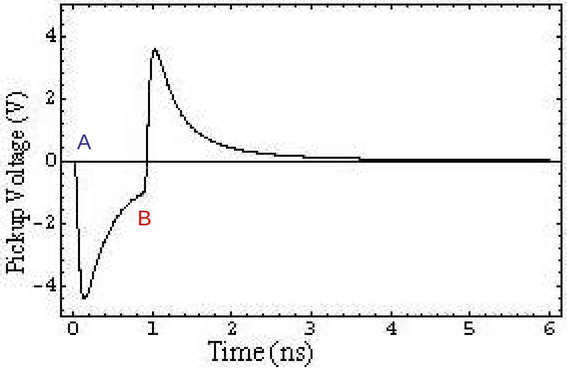


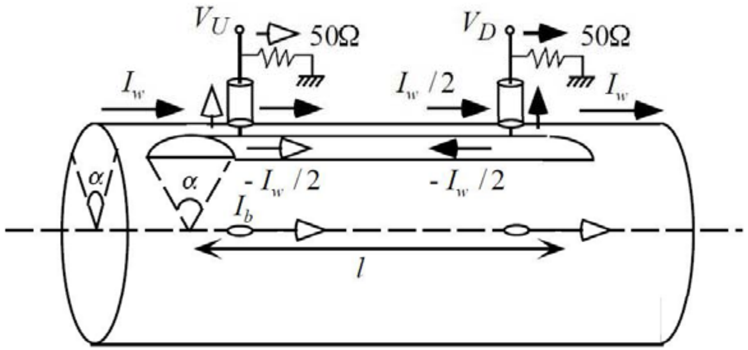
Linear region is roughly +/- R/4



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

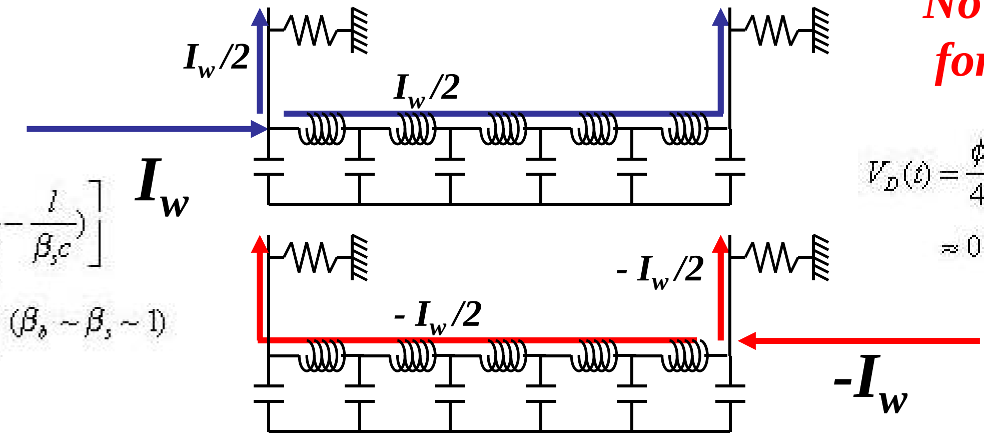




$$\frac{1}{2}I_w = \frac{1}{2}\left(\frac{\alpha}{2\pi}\right)$$

No signal output for downstream pickup

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



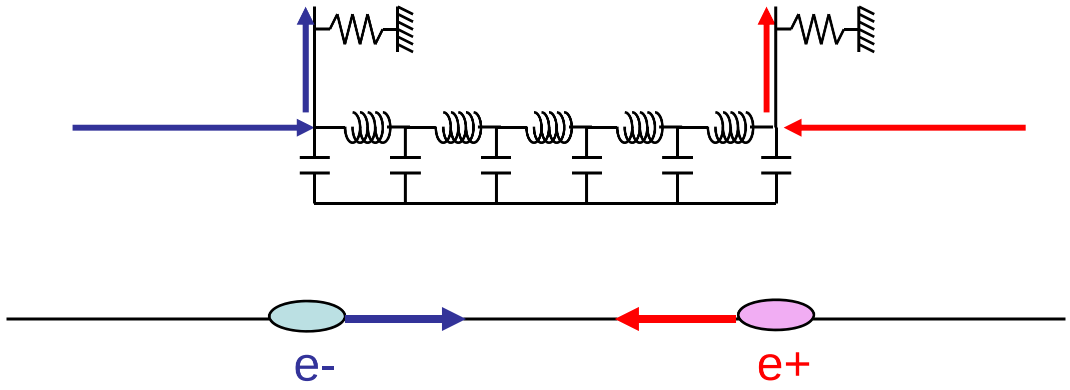
$$V_D(t) = \frac{\phi Z}{4\pi}\left[I_b\left(t - \frac{l}{\beta_s c}\right) - I_b\left(t - \frac{l}{\beta_b c}\right)\right]$$
$$\approx 0 \ (\beta_b \sim \beta_s \sim 1)$$

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

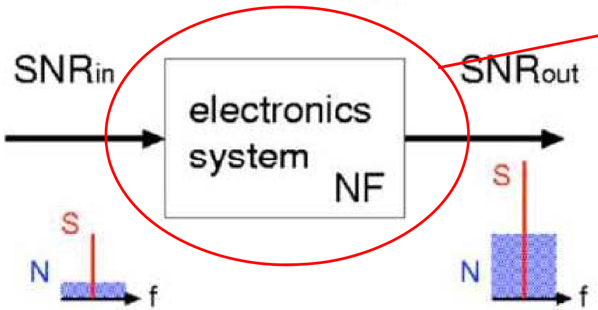
$\delta x = 1.3\ \mu m$ ***This is the theoretical limit .***

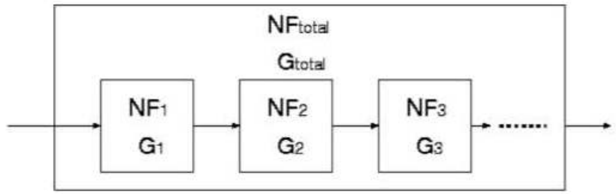
Readout of the Stripline BPM

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

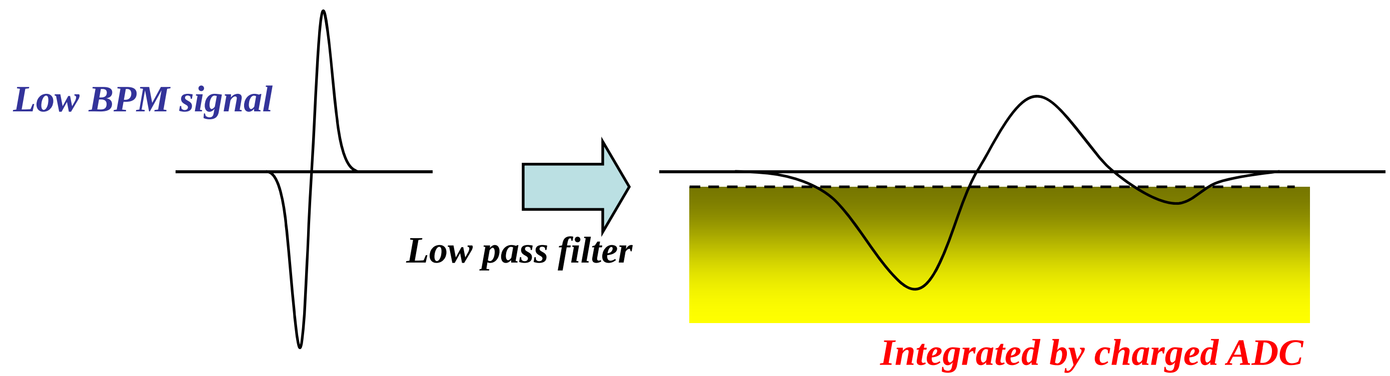
Introduction of the ATF readout electronics

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.

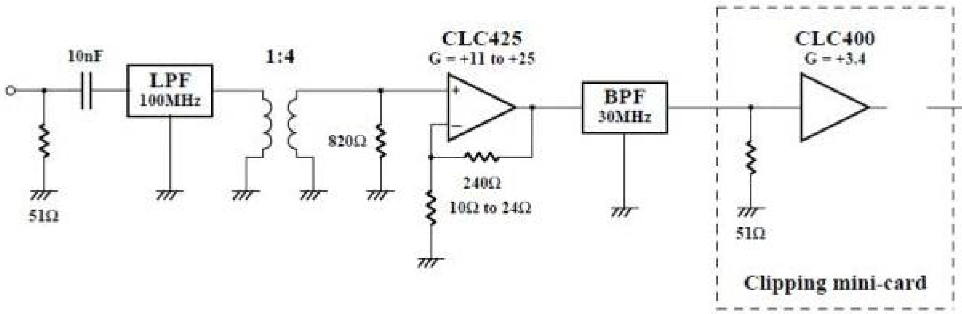
- we can measure the beam position at the first turn of injection, the first turn information is very helpful for the injection tuning.

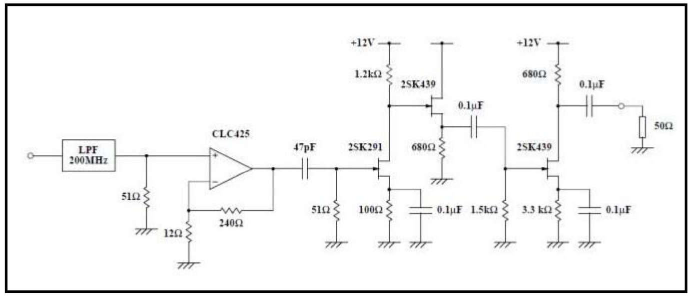
ATF readout electronics is using diode clipping circuit .



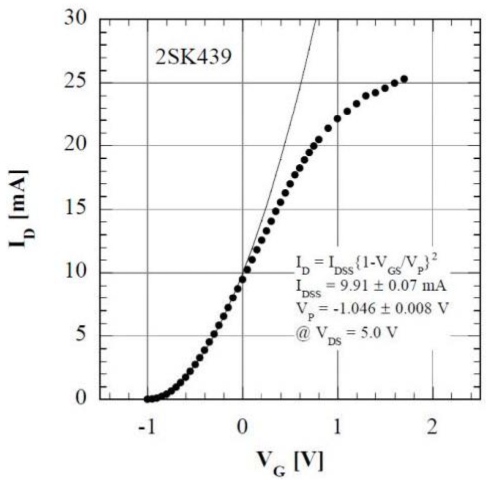
Readout of the Stripline BPM

Performance of the ATF readout electronics



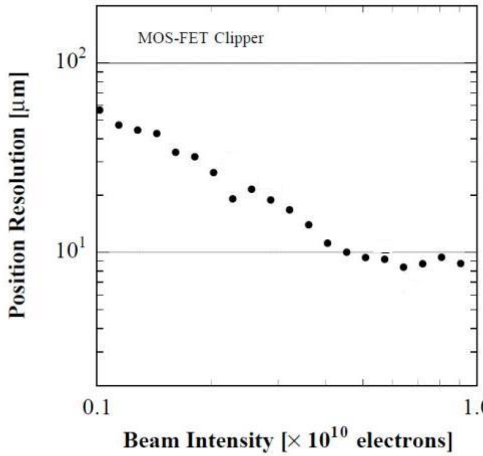


Signal Response of the circuit



This nonlinear effect is calibrated and corrected .

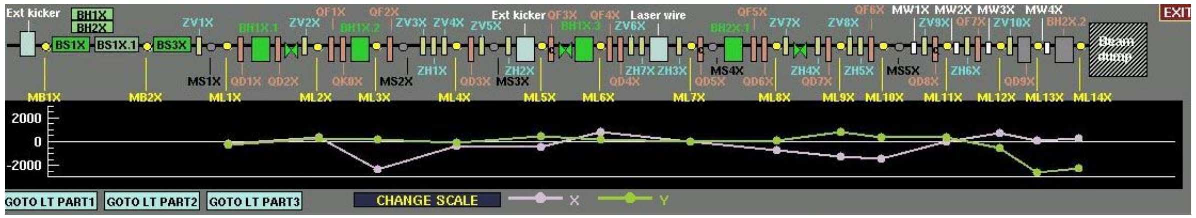
Position Resolution



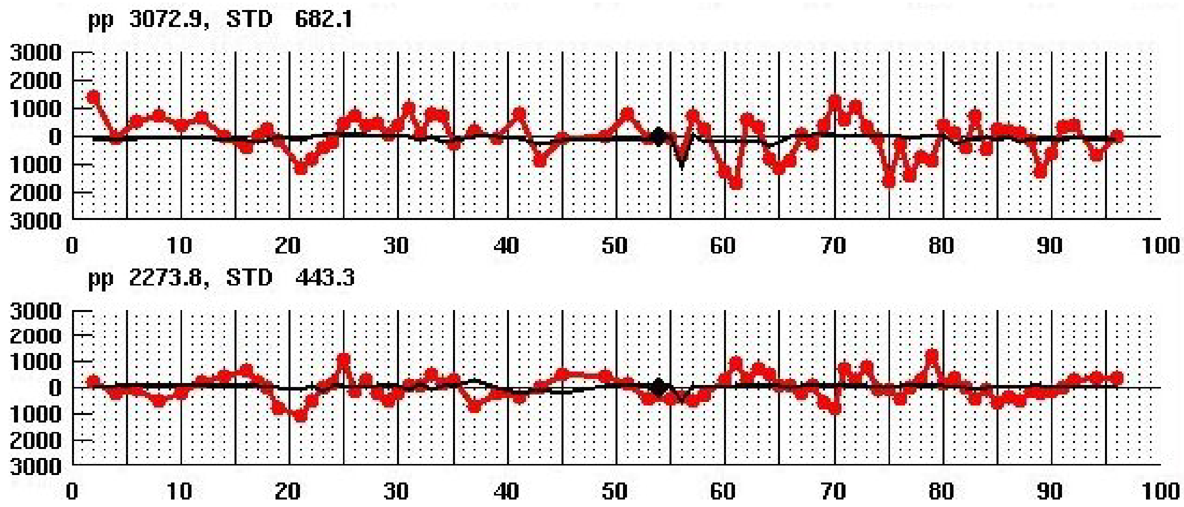
The position resolutio is around 10 μm at 1e10 beam intensity.

Beam orbit measurement in ATF with Stripline BPM

Beam orbit measurement in ATF extraction line.

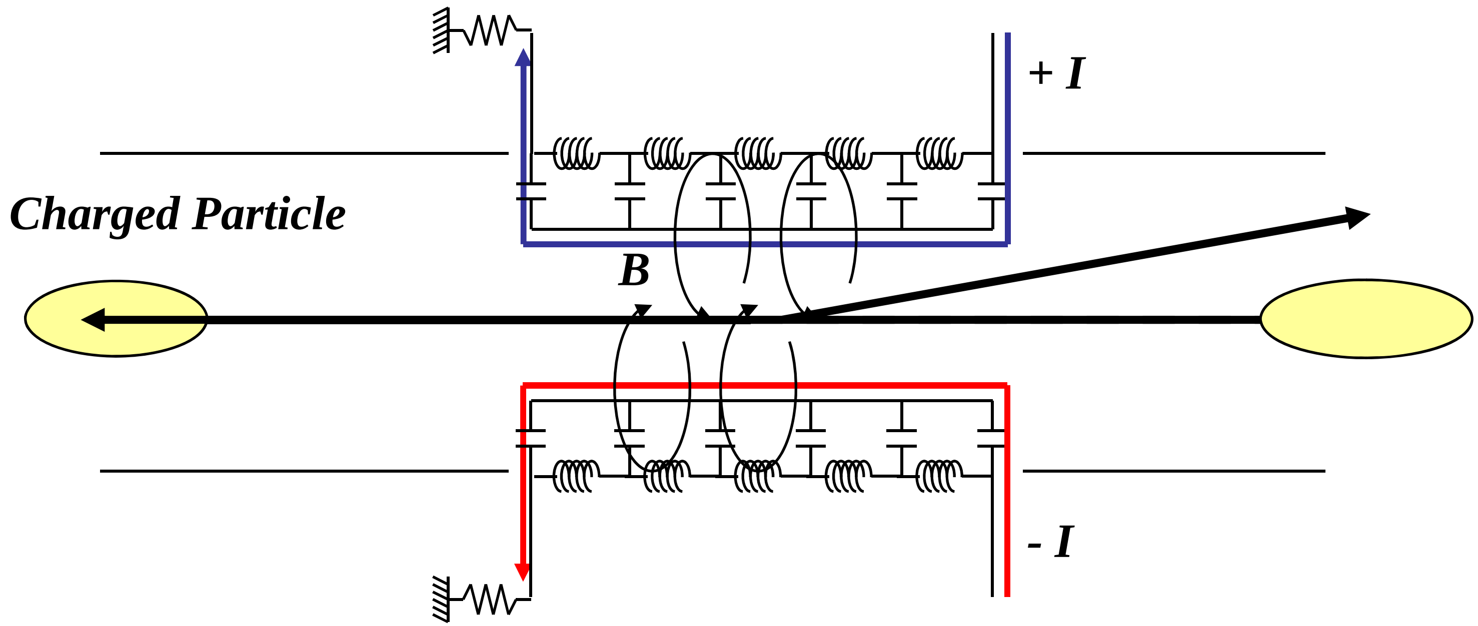


Beam orbit measurement in ATF damping ring.
the ATF damping ring has 96 BPMs.



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 !

Summary 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 ; 1μm
for the transport line ; 10μm

-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 the storage ring and the beam transport line

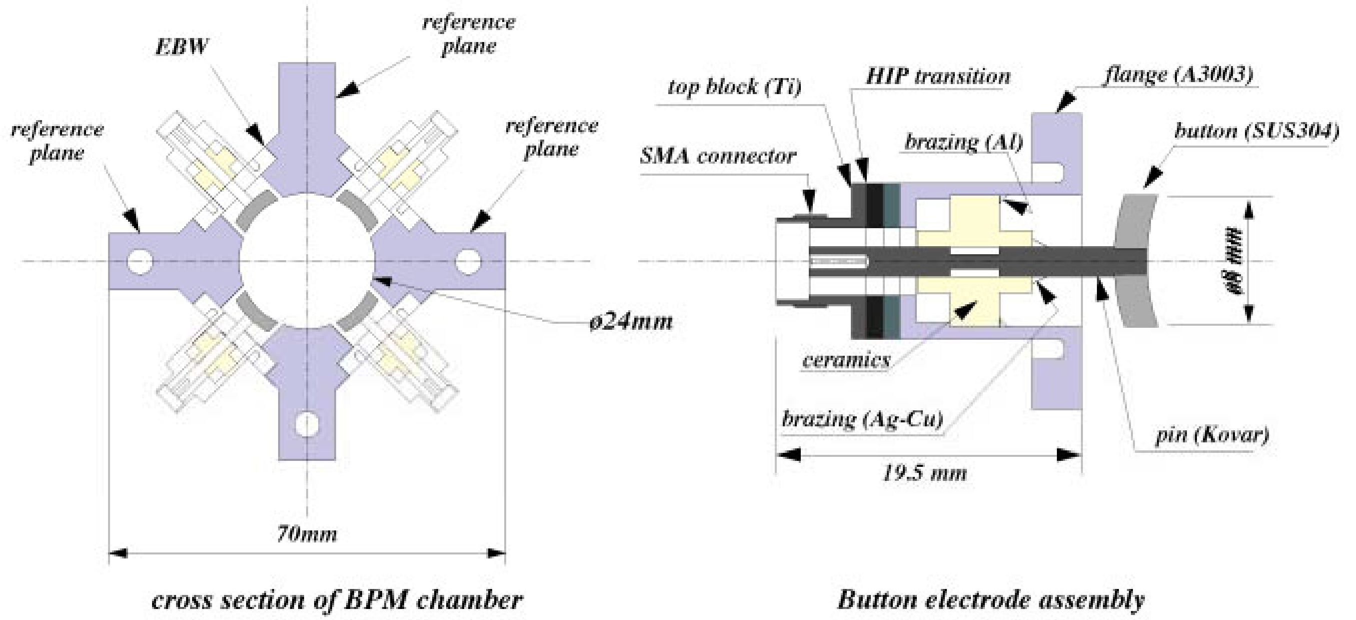
- Application to ILC

- can use for the injector BPM
- difficult to use in the transport line after RTML for their poor resolution
- difficult to use in damping ring for their large impedance

Button type BPM

Pickup voltage is determined by the capacitance of the electrode.

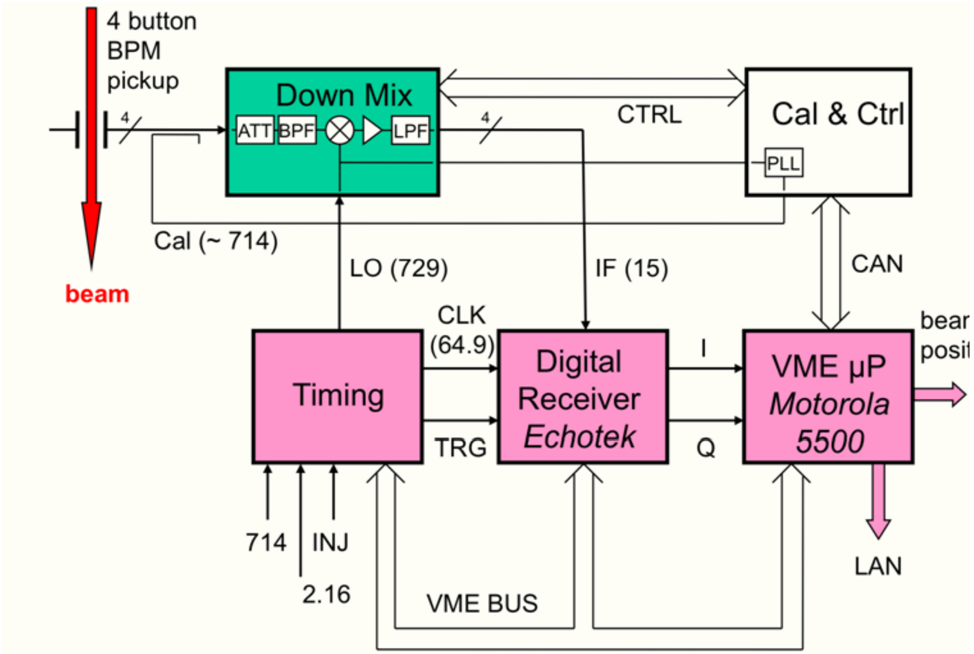
$$V = q/C$$

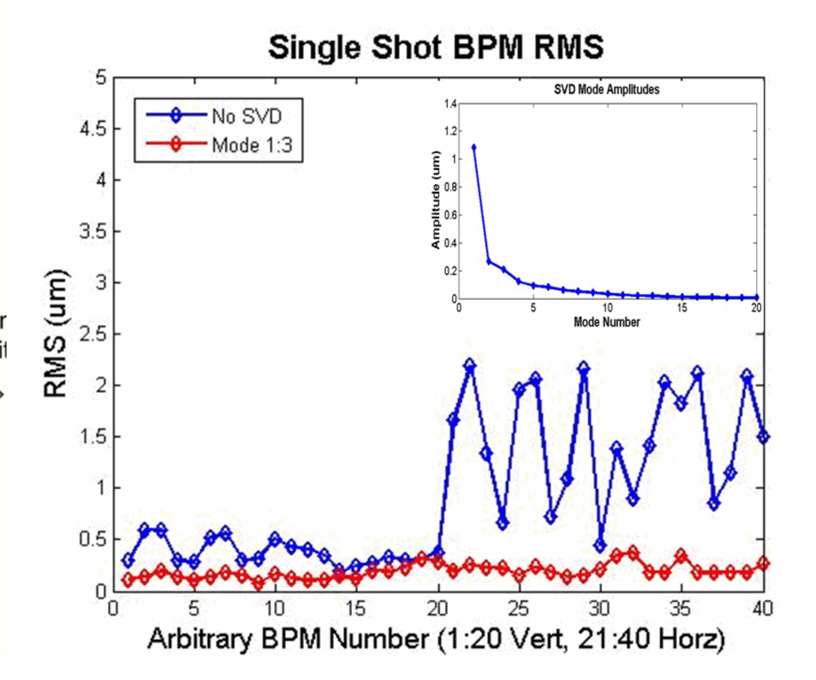


By making the electrode with small impedance, we can use the BPM in the damping ring.

But, the pickup voltage is small for their small impedance,
and the resolution is limited by the impedance

Readout electronics of BPM in the storage ring





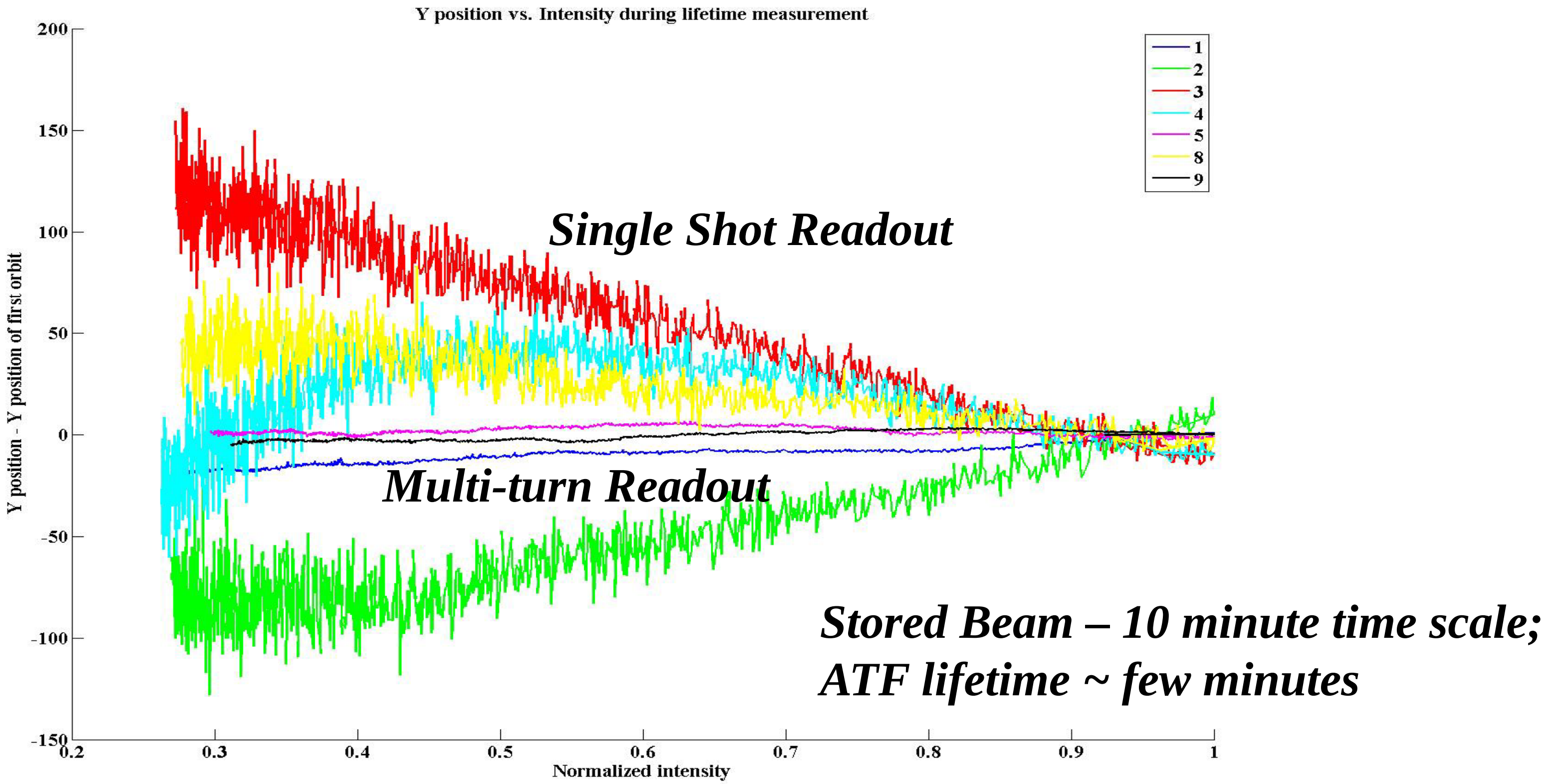
***By accumulated ti the many turn of position data* (around 500,000),**

***we can measure the beam position with the resolution of 800 nm in the storage ring*.**

Furthermore, by removing modes with horizontal and vertical correlation,

***we can measure the beam position with the resolution of 200 nm in the storage ring*.**

Beam Position Readout vs. Beam Intensity



Single shot readout is useful for the injection tuning, but small accuracy.

We can read the beam position with small intensity dependence with multi-turn readout, the accurate and the high resolution readout is useful for the fine ring tuning.

Summary of Button type Beam Position Monitor

-Dynamic range;

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

-Resolution ;

- depends on the readout electronics

for the single shot measurement ; 20μm

for the multi-turn measurement ; 800nm online, 200nm offline

-Accuracy and Offset ;

- good for the multi-turn measurement

- no good for the single shot measurement.

-Nondestructive Monitor with Small Impedance

- both for the storage ring and the beam transport line

- Application to ILC

- can use for the injector BPM (Stripline BPM can get higher resolution)

- can use in damping ring

- difficult to use in the transport line after RTML for their poor resolution

1-3. Cavity Beam Position Monitor

Concept of Cavity BPM

Stripline and Button type 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

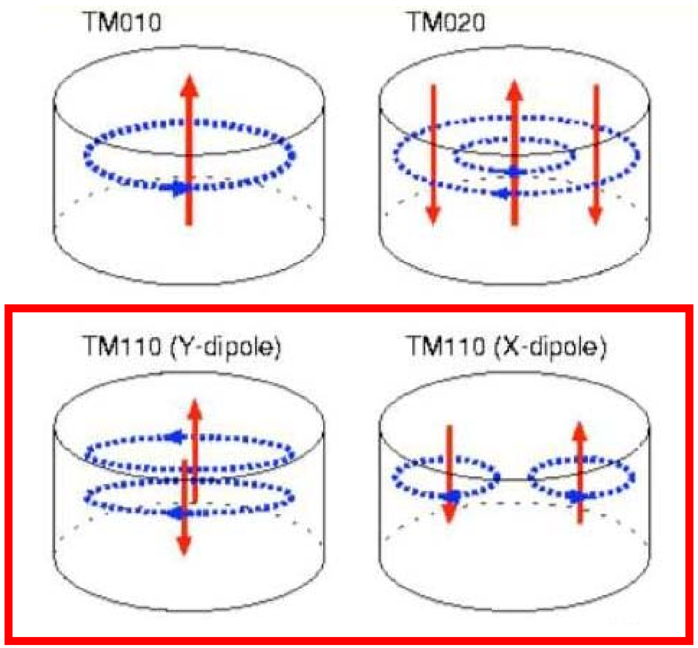
$$x = S_b \frac{V_1 - V_3}{V_1 + V_3} \qquad S_b = \frac{R}{2} \frac{\alpha}{\sin\alpha}$$

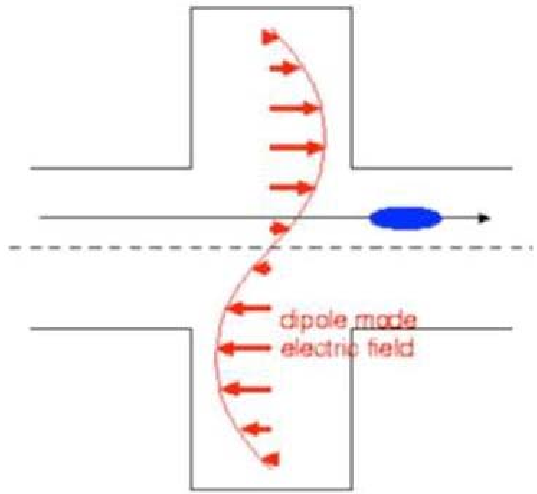
Cavity BPM

- 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

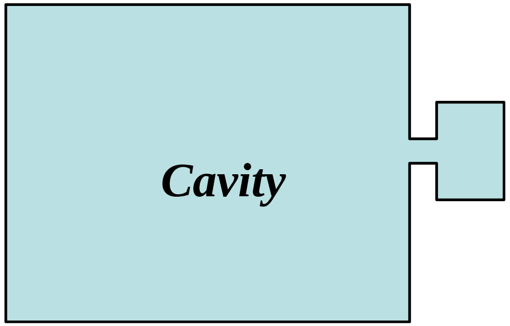
Q value (Loaded Q) ; The decay rate of the stored energy

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

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 $U = \frac{V_{exc}^2}{\omega(R/Q)} = \frac{\omega}{4}(R/Q)q^2$

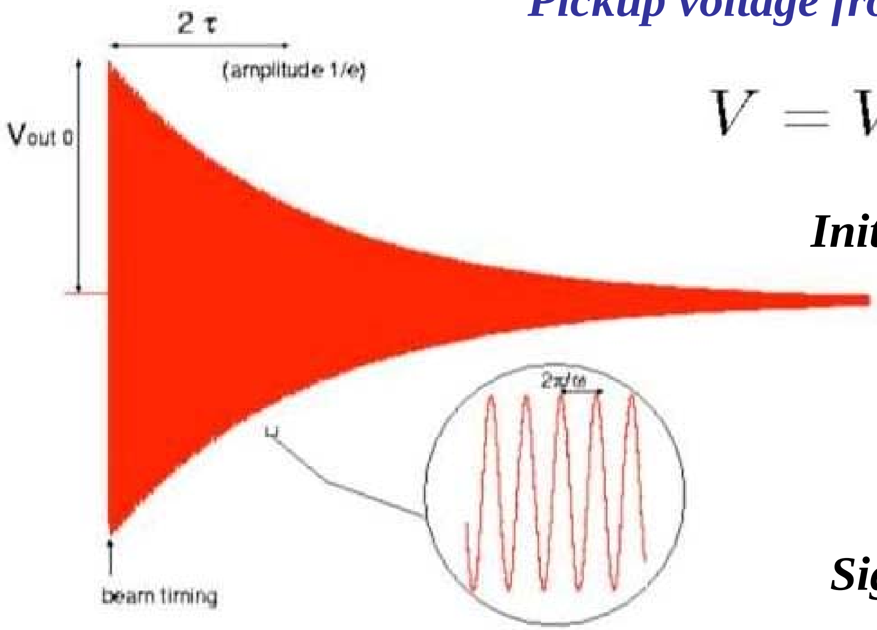
The pickup voltage also is expressed with R/Q .

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

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

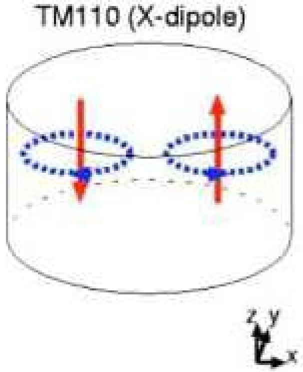
Defined by R/Q, Q_{ext} and q

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

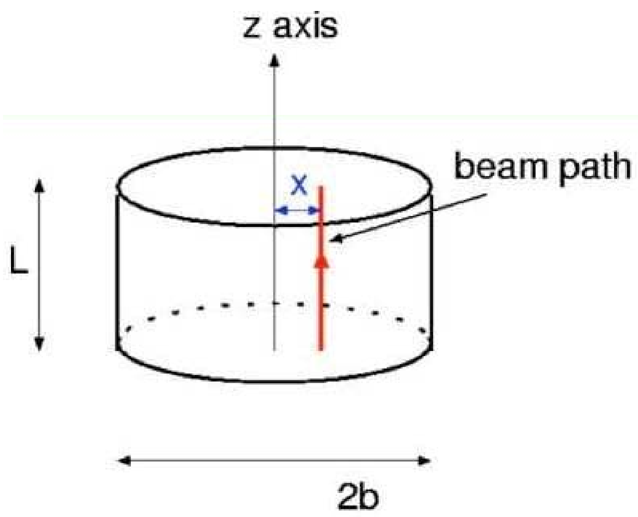


Electric Field of the dipole mode is

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

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

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 ;

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

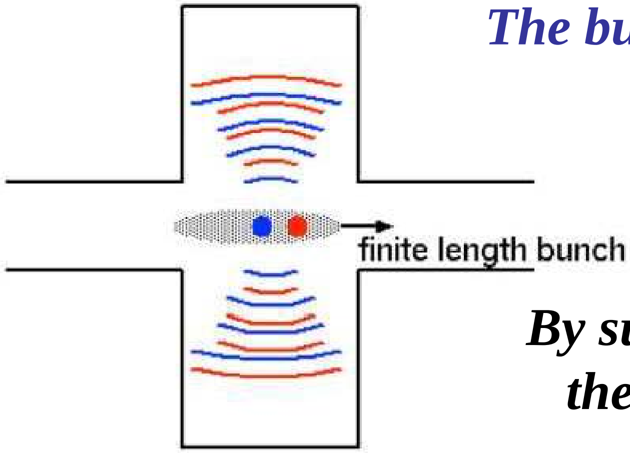
$$R/Q = 50.5 \times (\frac{\omega}{c})^3 L T^2 x^2$$

The pickup voltage is proportional to the position offset .

We can measure the beam position from the pickup voltage .

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

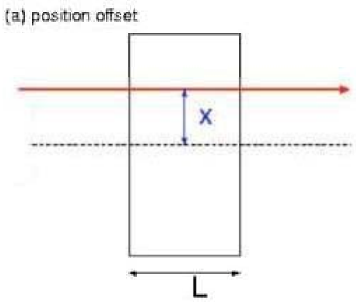
$$V_{total\ exc} = V_0 \int_{-\infty}^{\infty} \rho \cos\left(\frac{\omega z}{c}\right) = V_0 \exp\left(-\frac{\omega^2 \sigma_z^2}{2c^2}\right)$$

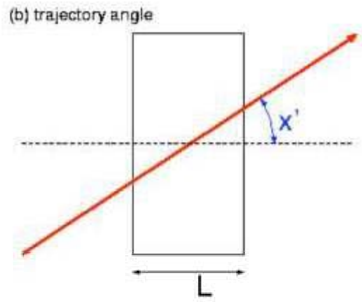
The excitation voltage is weaker by suppressing each other for $\sigma_z << c/\omega$.

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

Feature of the Pickup Signal

Effect of the beam angle

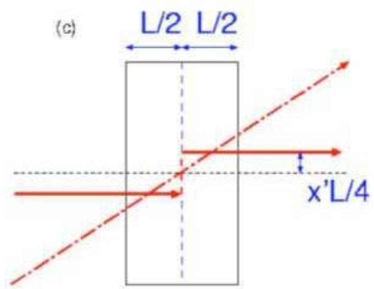




$$\text{position signal} = Ax\sqrt{L}\,\underline{\sin(\omega t)}$$

$$\begin{aligned}\text{angle signal} &= Ax'\frac{L}{4}\sqrt{\frac{L}{2}}\sin(\omega(t+L/4c)) \\ &\quad -Ax'\frac{L}{4}\sqrt{\frac{L}{2}}\sin(\omega(t-L/4c)) \\ &= Ax'\frac{L}{2}\sqrt{\frac{L}{2}}\sin\left(\frac{\omega L}{4c}\right)\underline{\cos(\omega t)}\end{aligned}$$

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



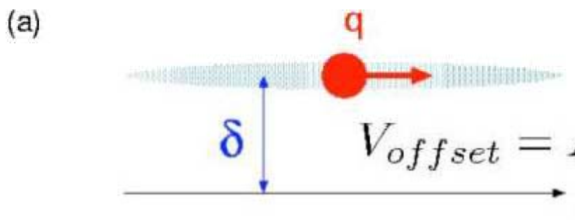
Angle sensitivity is proportional to L^2 .

Small L is better.

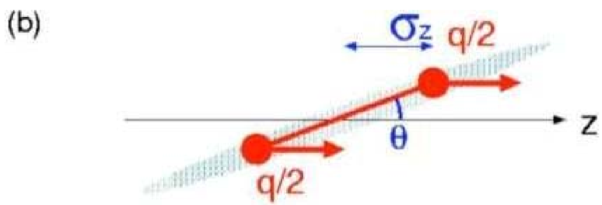
$$\frac{\text{angle signal}}{\text{position signal}} = \frac{L}{2\sqrt{2}}\sin\left(\frac{\omega L}{4c}\right)\frac{x'}{x} \sim \frac{\omega L^2}{8\sqrt{2}c}\frac{x'}{x}$$

Feature of the Pickup Signal

Effect of the bunch tilt



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



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

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

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

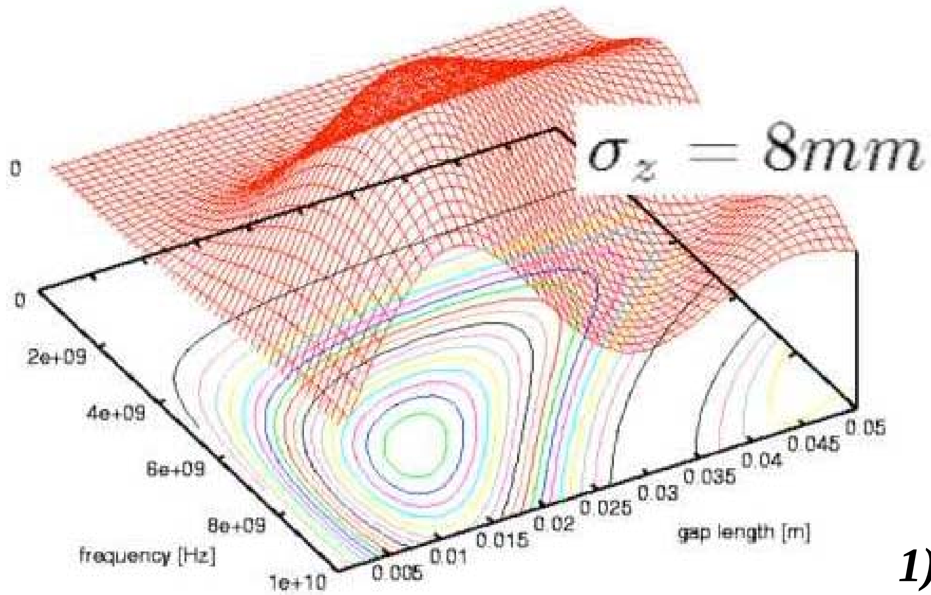
Phase of angle signal is shifted by 90degrees from that of bunch tilt.

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

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.

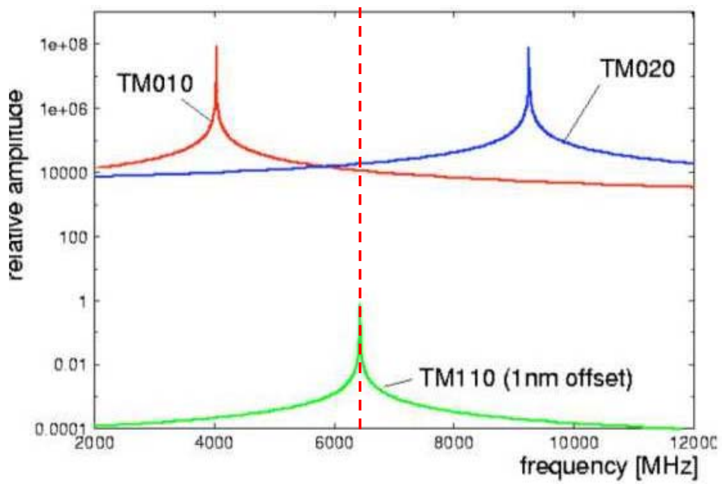
3) Cavity is as small as possible
to reduce the effect of the beam angle.

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



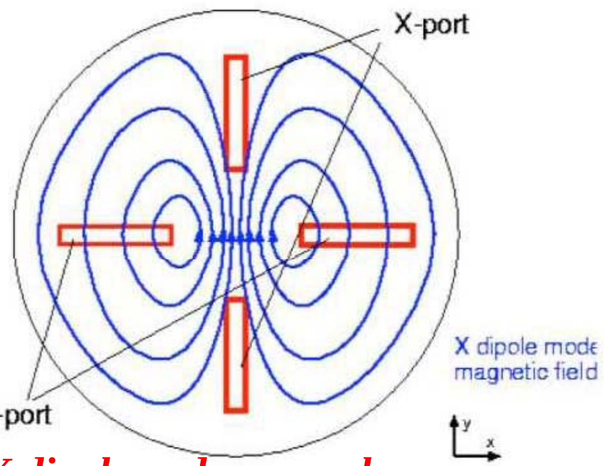
Since the amplitude of monopole mode is huge to the dipole mode, the tail is affect to the dipole mode signal.

-Bandpah filetr

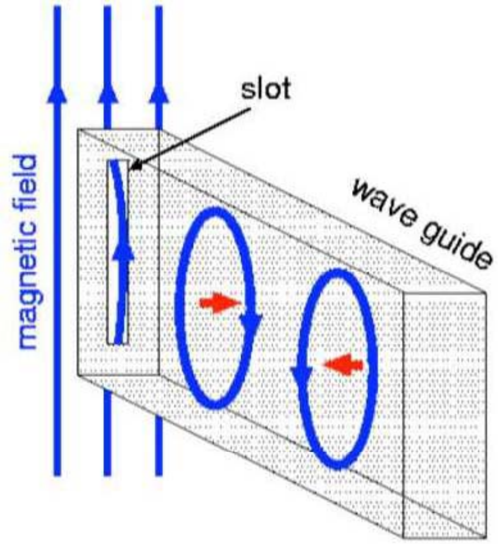
-Mode selectable coupler

Dipole Mode Selectable Coupler 1

No couple to Y dipole and monopole

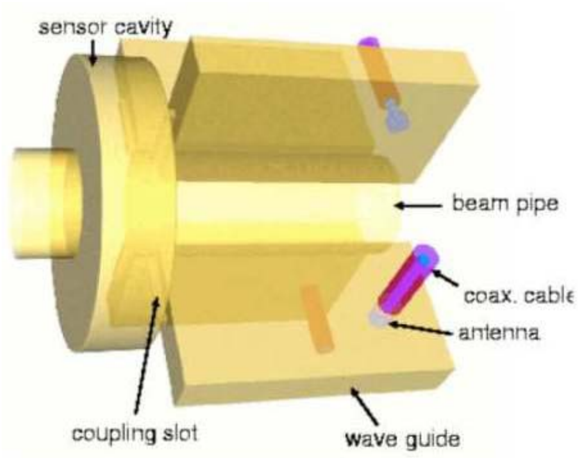


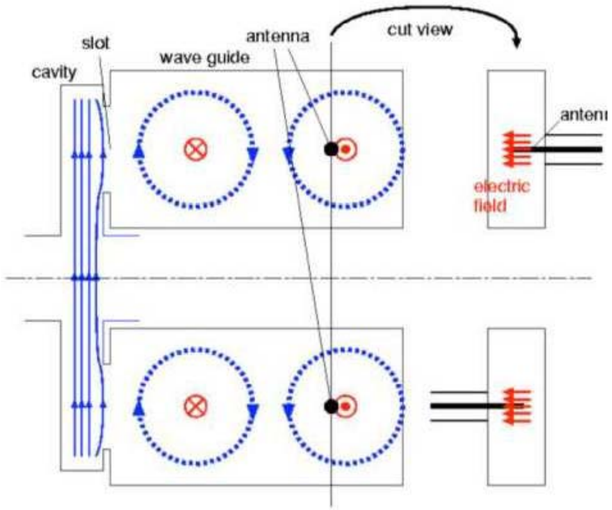
No couple to X dipole and monopole



Magnetic coupling with slot shape hole

Dipole Mode Selectable Coupler 2

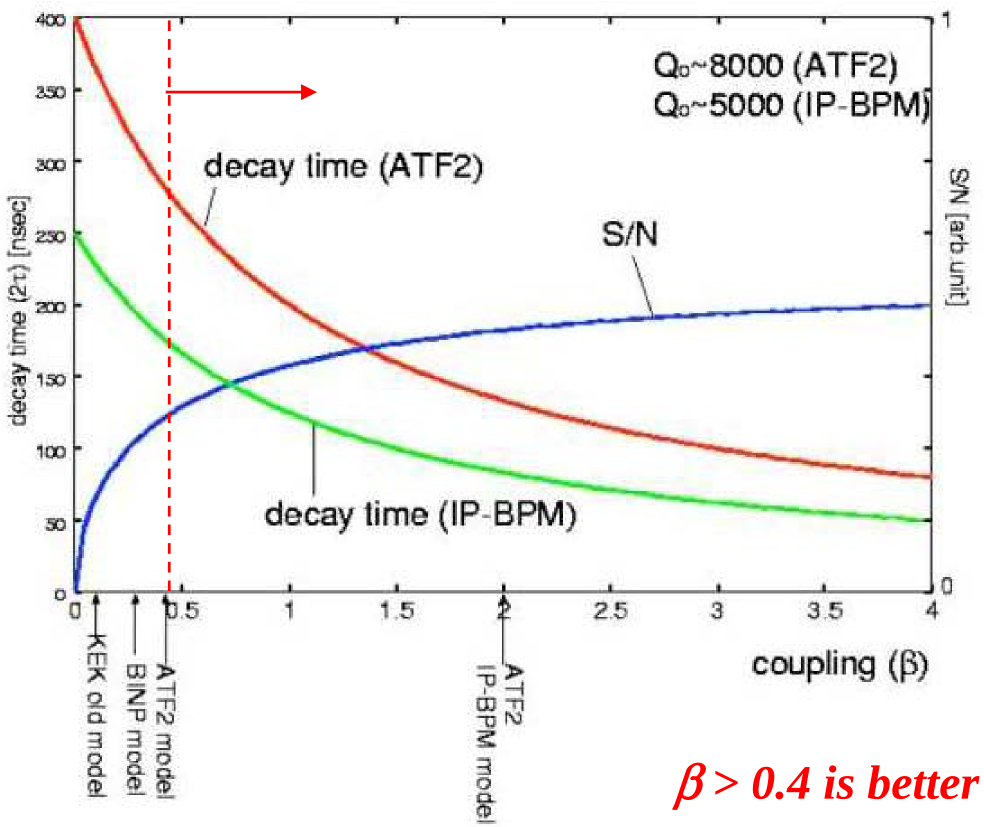




In order to be mode cleaning,
the coaxial cable is connected after the wave guide.

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

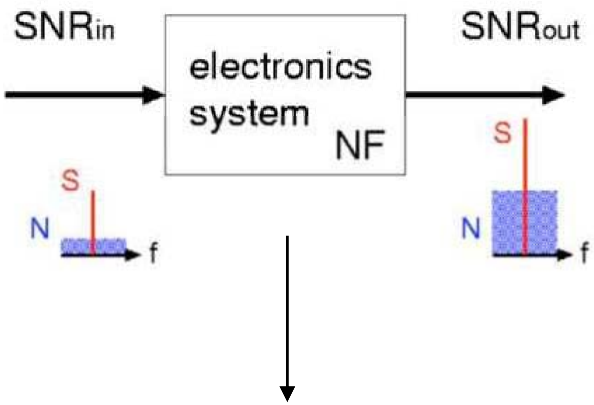
$$p_{TN} \approx kTf_{BW}$$

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

For the bandwidth of 3MHz

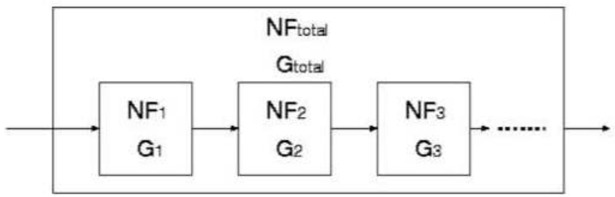
$$p_{TN}[dBm] = -174 + 10\log f_{BW} = -109\text{dBm}$$

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



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 .

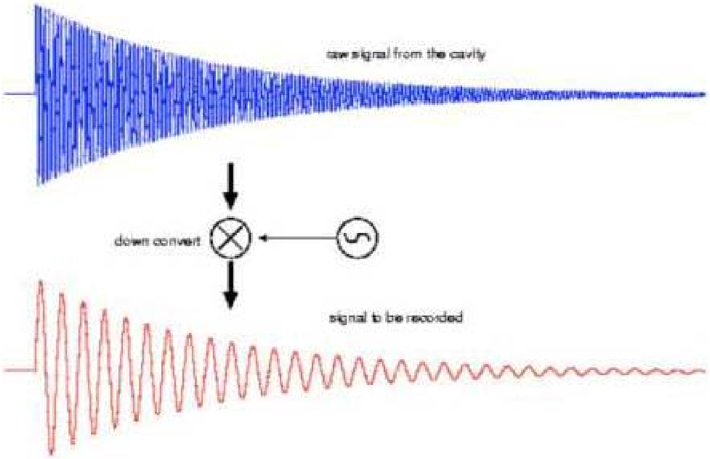


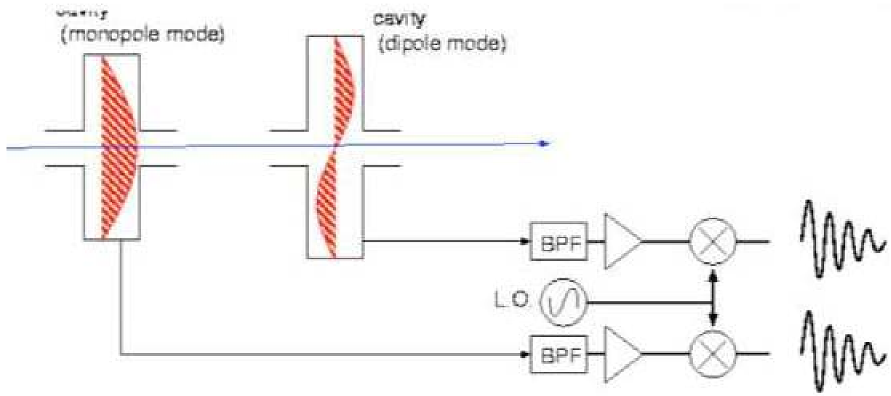
$$NF_{total} = \underline{\underline{NF_1}} + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots$$

The first amp is the main noise source

Readout Electronics of Cavity BPM

Frequency Conversion





Frequency is converted to useful frequency for the readout

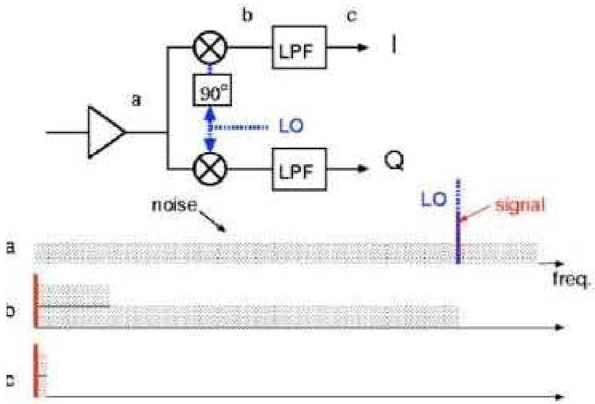
$$A\sin(\omega_1 t + \underline{\underline{\phi_1}}) \times B\sin(\omega_2 t + \phi_2) = \frac{AB}{2}[\cos((\omega_1 - \omega_2)t + (\underline{\underline{\phi_1}} - \phi_2)) - \cos((\omega_1 + \omega_2)t + (\phi_1 + \phi_2))]$$

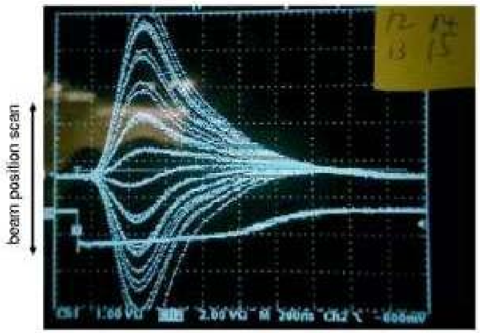
Converted signal keeps the phase information of the initial RF.

Readout Electronics of Cavity BPM

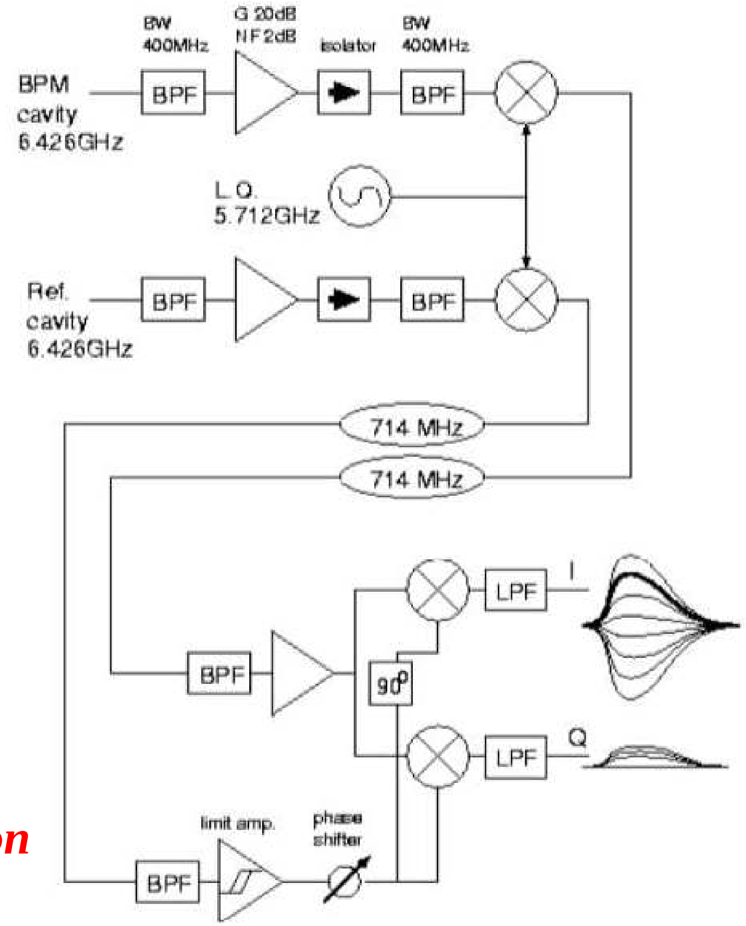
Homodyne Method

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



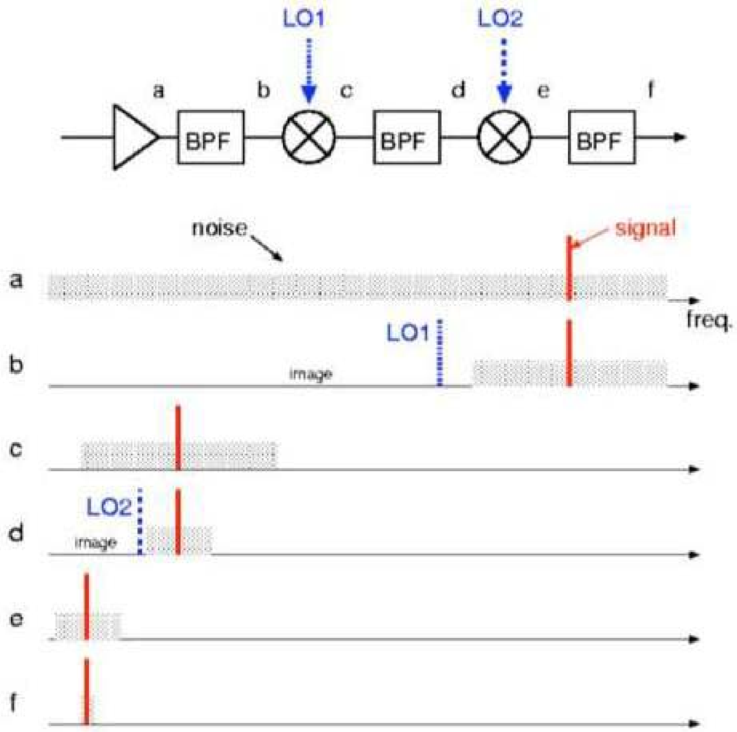


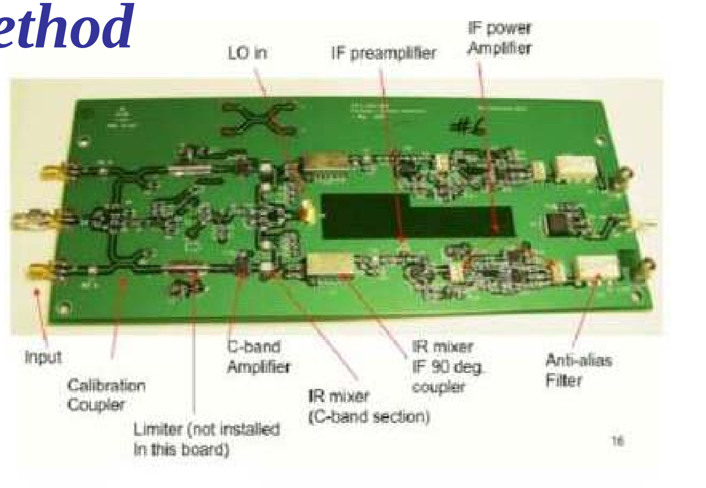
Position information
is converted to
the amplitude information

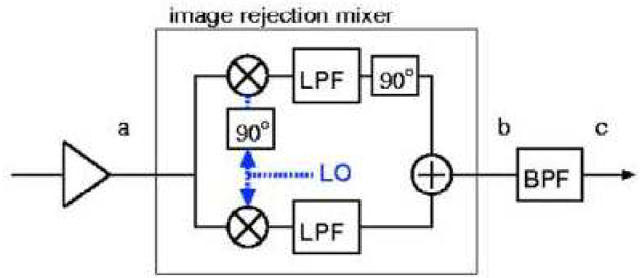


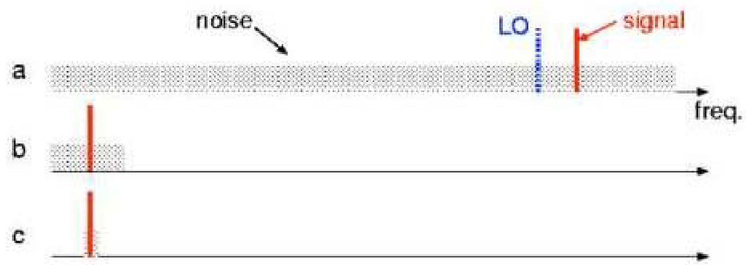
Readout Electronics of Cavity BPM

Heterodyne Method





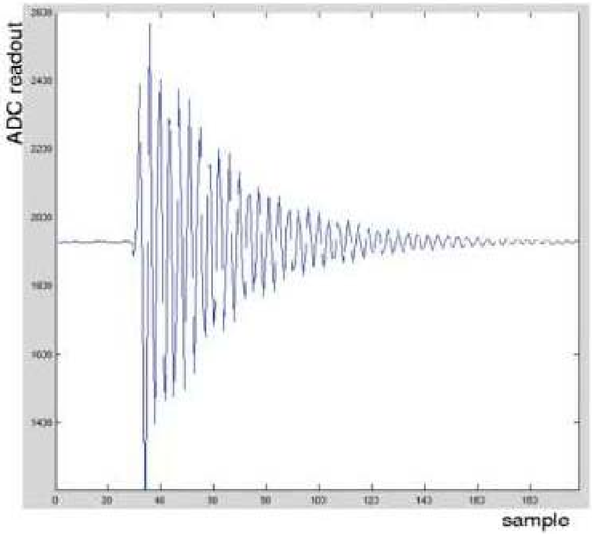




-Frequency is converted to lower frequency .
-Converted signal has
phase and amplitude information.

Readout Electronics of Cavity BPM

Heterodyne Method (continued)



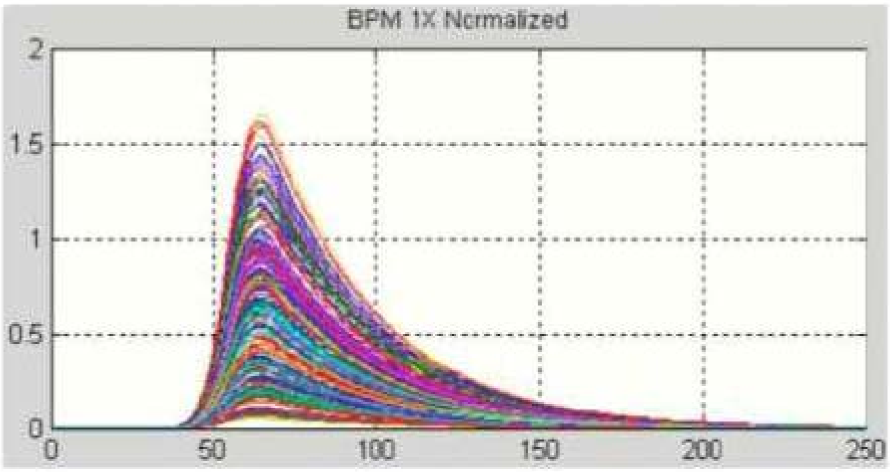
Down converted signal is fitted by readout software.

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

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

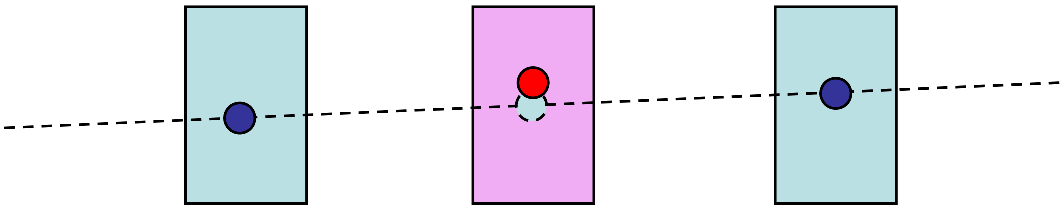
$$Q_Y = \frac{A_Y}{A_{Ref}}\cos(\phi_Y - \phi_{Ref})$$

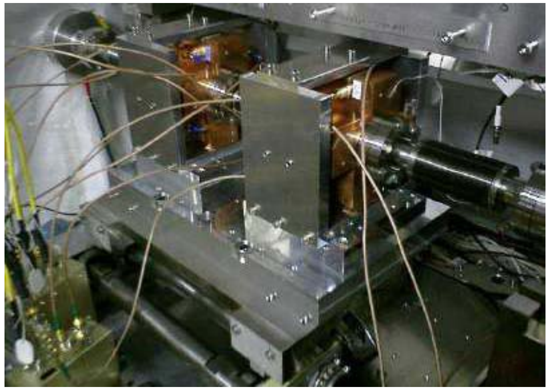
Position information is converted to the amplitude information by the readout software.



Resolution Measurement

Position resolution measurement is done with 3 BPMs





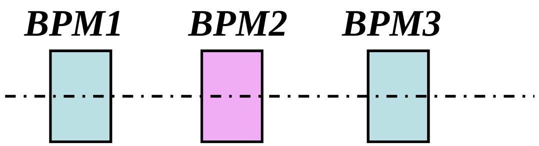
The position resolution is evaluated by comparing
the masured BPM position
and the evaluated position from another 2 BPM position .

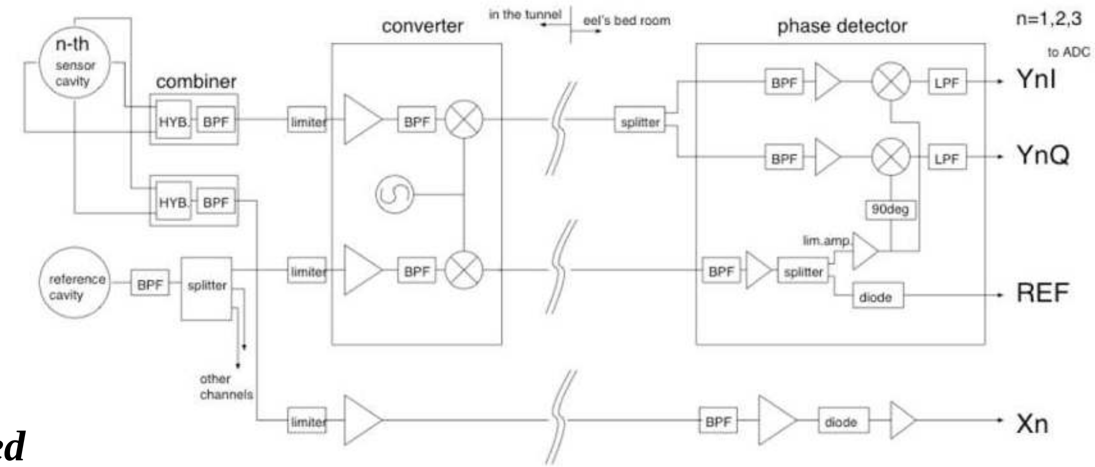
$$X2(X1,X3) = \frac{X1+X3}{2}$$

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

Achieved Resolution in ATF

Readout electronics is Homodyne type electronics.





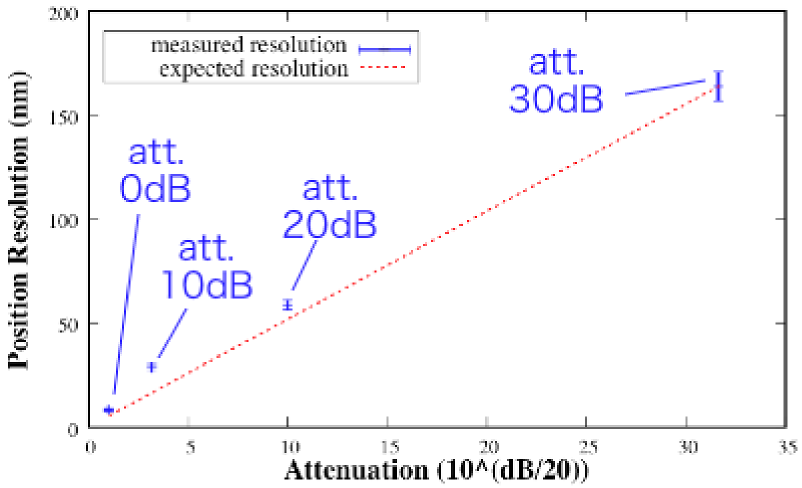
The position resolution is evaluated by comparing the Y2 signal and the Y2 value evaluated from BPM1 and BPM2 information.

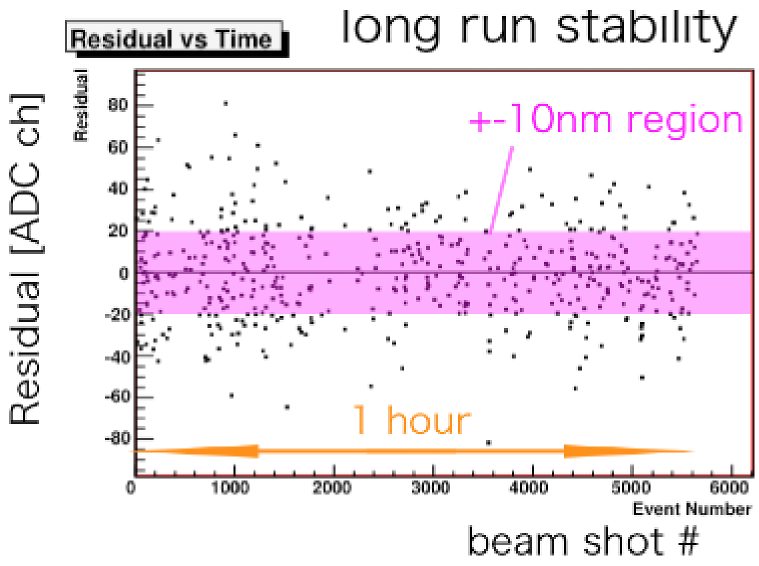
$$
\begin{aligned}
Y2I \;=\; & a_0 + a_{Y1I} \times Y1I + a_{Y3I} \times Y3I + a_{REF} \times REF \\
& + a_{X1} \times X1 + a_{X3} \times X3 + a_{Y1Q} \times Y1Q + a_{Y3Q} \times Y3Q \\
& + a_{Y1I^2} \times Y1I^2 + a_{Y3I^2} \times Y3I^2
\end{aligned}
$$

Δ = Y2I – Y2I (Y1I,Y1Q,X1,Y3I,Y3Q,X3)

Achieved Resolution in ATF

Continued …





The ***8.72 +-0.28(stat) +-0.35(sys) nm*** ***resolution is achieved in ATF .***

@0.7x10^10 e/bunch, dynamic range: 5 micron.

electronics noise limit:

5nm@0.7x10^10 e/bunch

unknown noise: 7 nm (vibration measured by laser interferometer: 4nm)

ILC Main Linac BPM

Requirements:

- High resolution (< 1μm for single pass).
- Big beam-pipe aperture (78mm diameter).
- HPR washable and cleanness required.
- Need to withstand wide thermal excursion without vacuum leak.
- Bunch-to-bunch signal acquisition required (low Q_L).
- No interference with acc. cavity HOM (1.6-1.9GHz and > 2.3GHz).

Candidate of the ILC Main Linac BPM

Design selection:

Cavity BPM with 4 slots coupled.

→ high resolution, good fiducialization, withstand to thermal excursion.

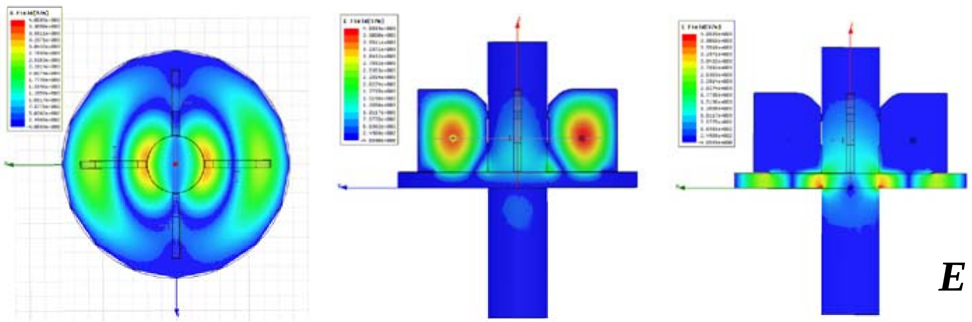
Use 2nd higher mode

→ match to big beam pipe, easy to get low Q_L.

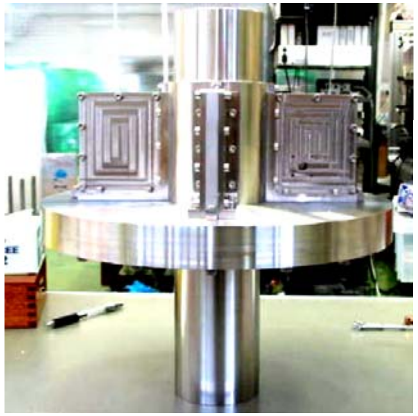
4 slots open to beam pipe

→HPR washable.

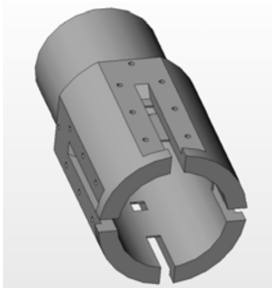
Calculation by HFSS

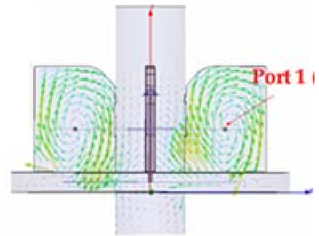


E field



Used mode	*TM120*
Resonance freq.	*2.04GHz*
Loaded Q	*260*
Bandwidth	*8MHz*





H field

Summary of Cavity BPM

- Dynamic range
  - We can adjust the dynamic range by putting the attenuator at the front of readout electronics (1mm - 100μm for ATF2).

-Resolution
  - Determined by the thermal noise .
  - 8.7nm was achieved in ATF.

-Accuracy;
  - We need online calibration for position sensitive factor .
  - Time response is defined by cavity Q value .

- Nondestructive Monitor with Large Impedance
  - only for the beam transport line

- Application to ILC
  - can use in the transport line after RTML for their poor resolution, including main linac
  - difficult to use in damping ring

Session 2

Beam Current Monitors

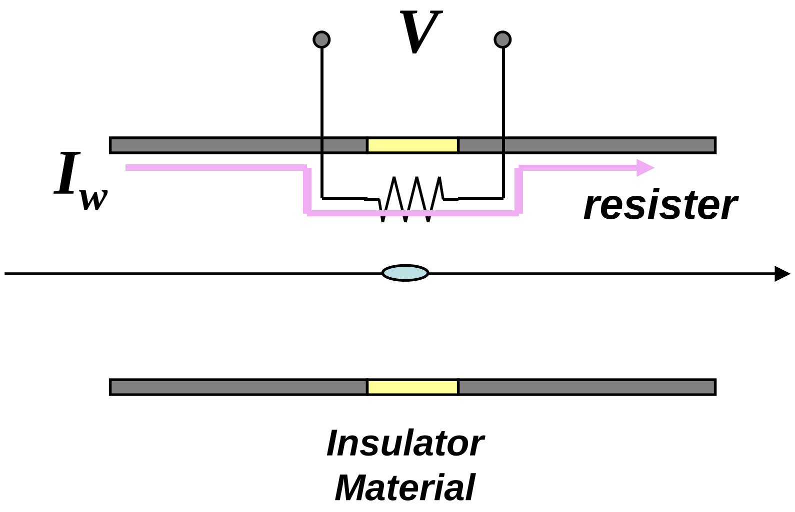
2-1. Wall Current Monitor

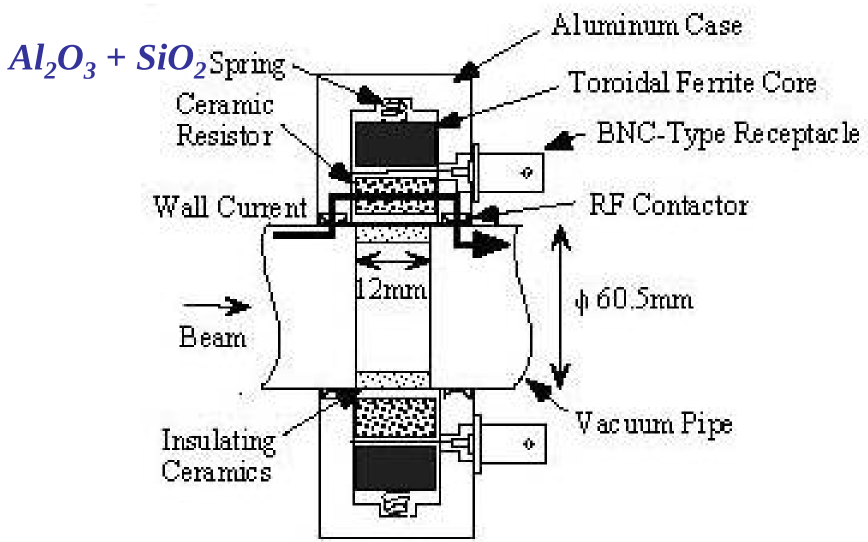
2-2. Integrated Current Transformer (ICT)

2-1. Wall Current Monitor

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

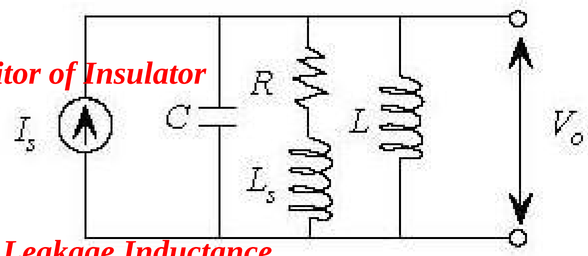
Mechanism of the Beam Current Measurement with Wall Current





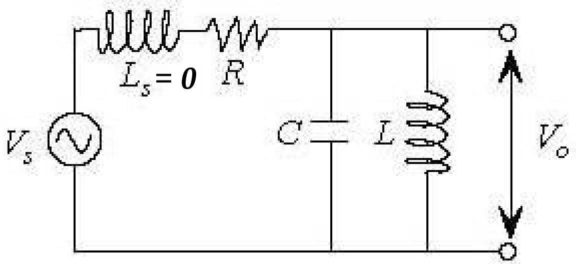
Equivalent Circuit of WCM

Equivalent Circuit of WCM



For the first step, the leakage inductance is 0.

Equivalent Circuit as Voltage Source



frequency domain

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

time domain (defined by Laplace Transform)

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

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

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

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) $k > 1$

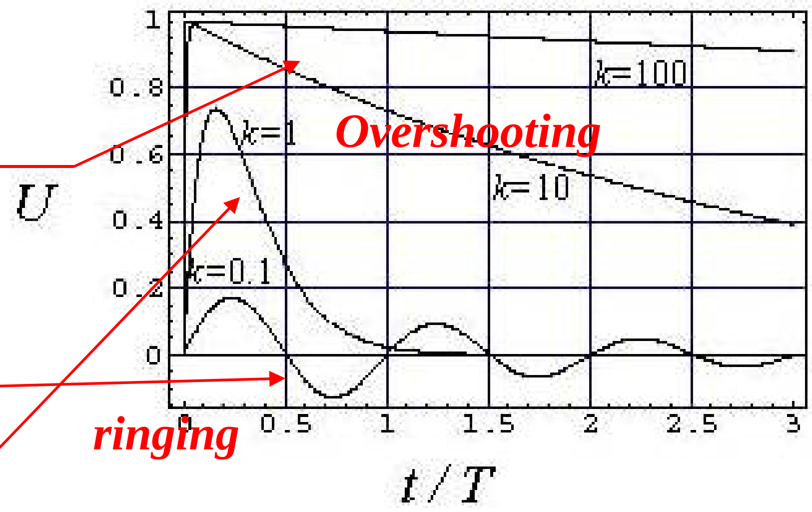
$$U(t) = \frac{k}{\sqrt{k^2-1}} e^{-\frac{2\pi k t}{T}} \left[e^{\frac{2\pi t\sqrt{k^2-1}}{T}} - e^{-\frac{2\pi t\sqrt{k^2-1}}{T}} \right]$$

(2) $k < 1$

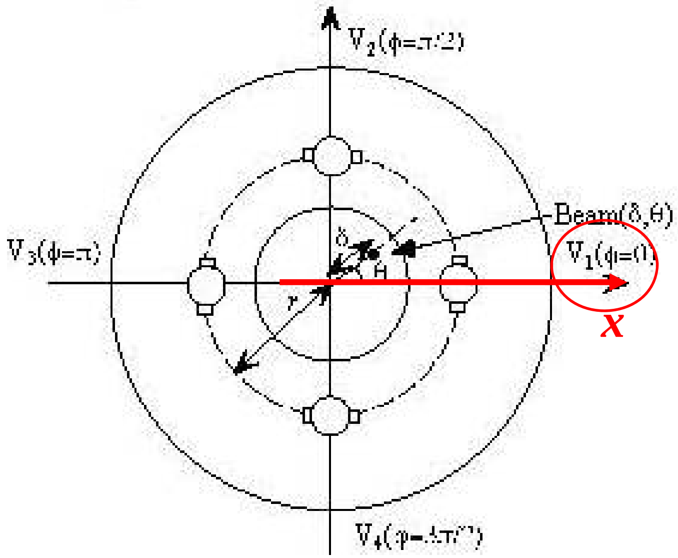
$$U(t) = \frac{2k}{\sqrt{1-k^2}} e^{-\frac{2\pi k t}{T}} \sin\left(\frac{2\pi\sqrt{1-k^2}}{T}\right)$$

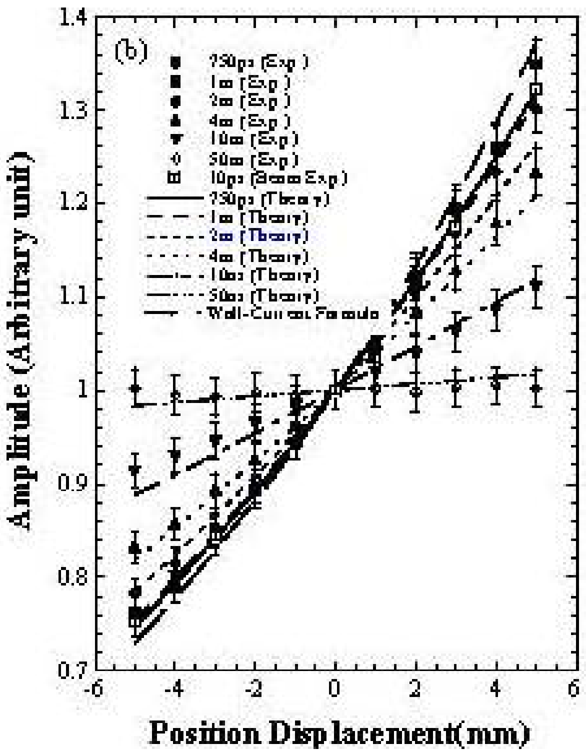
(3) $k = 1$

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



Position Dependence of Pickup Signal





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

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

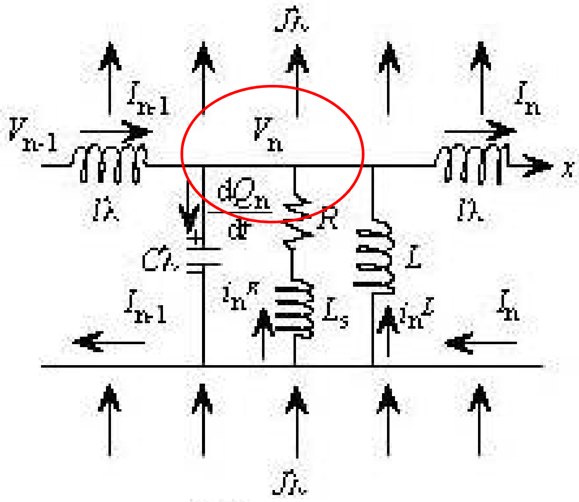
$${\omega_0}^2 = \left(\omega^2 C + \frac{j\omega\exp(-j\alpha)}{\sqrt{R^2+\omega^2 {L_s}^2}} + \frac{1}{L}\right) l$$

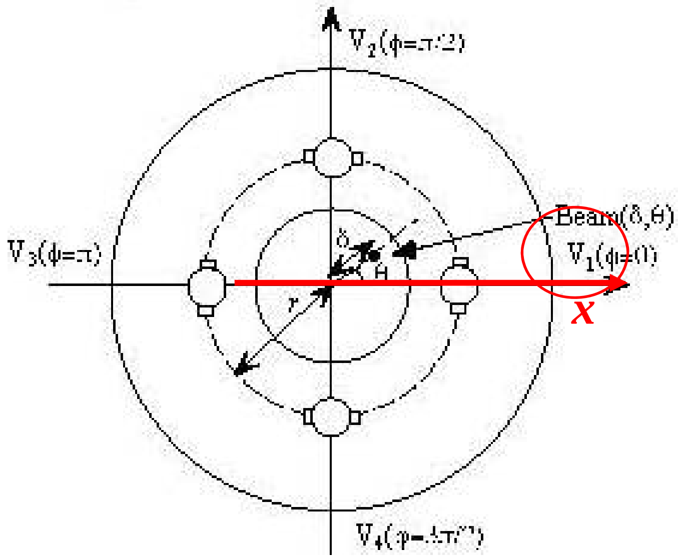
For the high frequency, the output signal has the large position dependence.

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

Signal Pickup of Wall Current Monitor

Equivalent circult with several pickups.





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

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

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

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

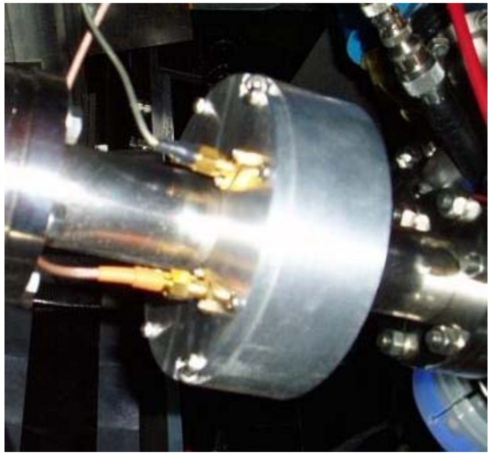
$$Q_n = C\lambda V_n$$

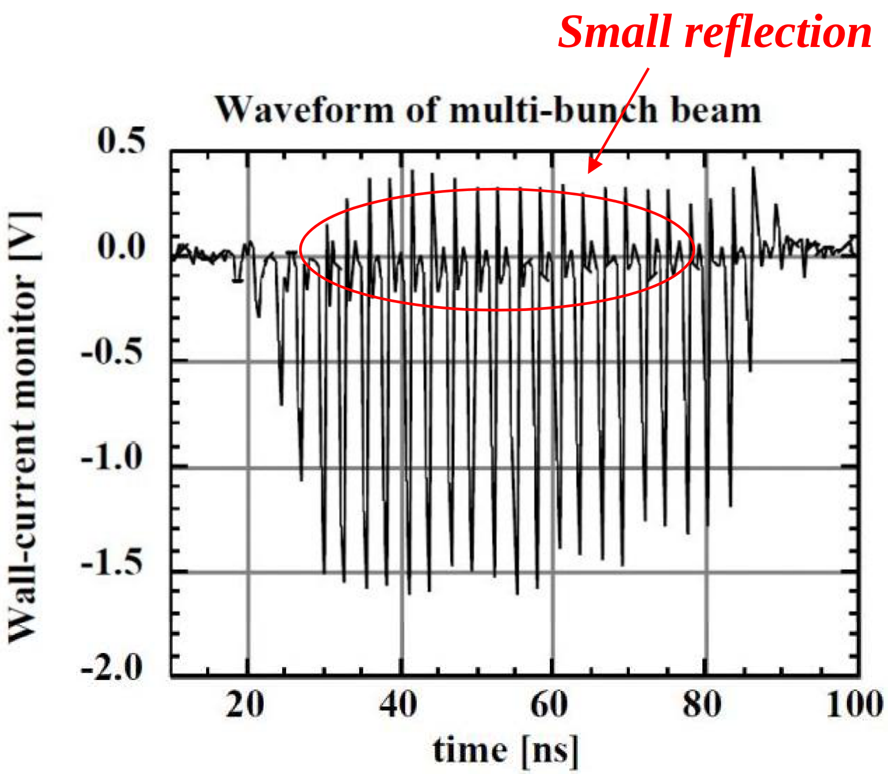
$$\frac{1}{l}\frac{d^2V(x)}{dx^2} + \left[\omega^2 C + \frac{j\omega\exp(-j\alpha)}{\sqrt{R^2+\omega^2 L_s^2}} + \frac{1}{L}\right] V(x) = j\omega J(x)$$

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

Response of Pickup Signal

WCM in ATF





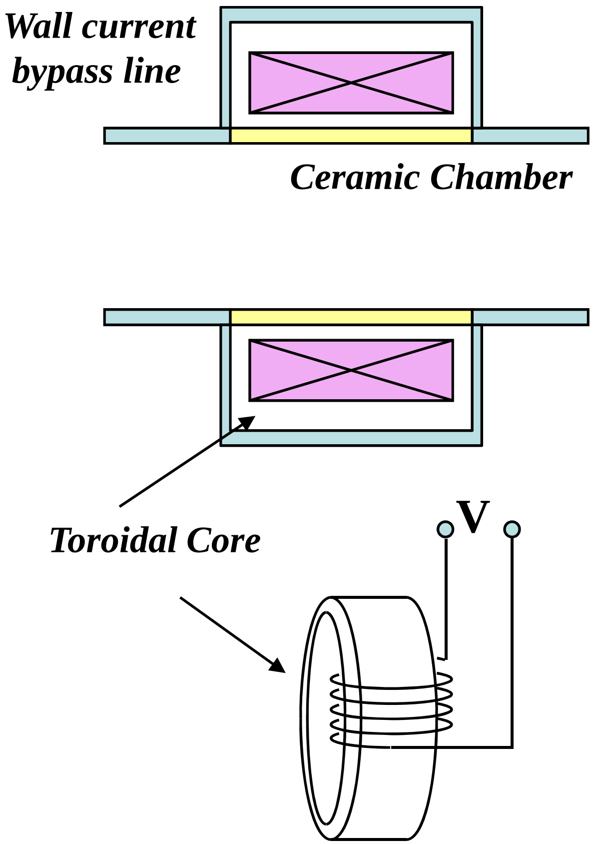
Beam current for 2.8ns bunch separation was measured .
However, it is difficult to measure the absolute bunch charge .

Summary of Wall Current Monitor

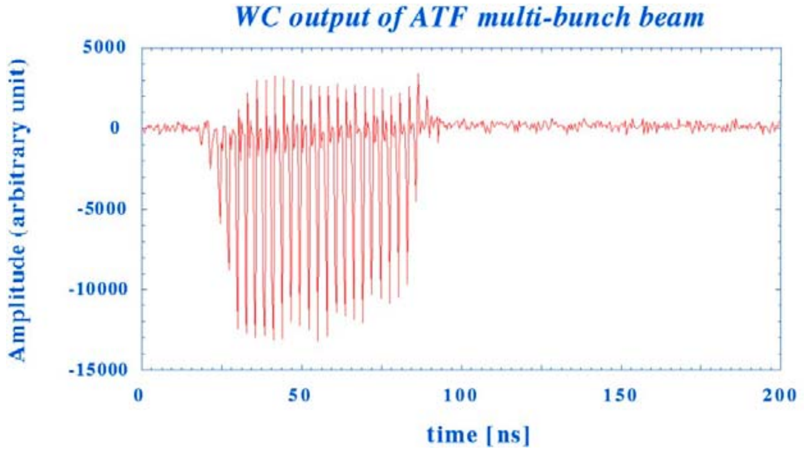
- ***Resolution ;***
  - ***The time resolution is defined by the readout frequency.***
- ***Accuracy and Offset ;***
  - ***Strongly depends on the external noise .***
  - ***For the high frequency, large position dependence exists .***
  - ***with thermal drift***
- ***Nondestructive Monitor***
  - ***both for beam transport line and storage ring***
- ***Application to ILC***
  - ***can use both in the transport line and damping ring for the bunch to bunch distribution measurement .***

2-2. Integrating Current Transformer

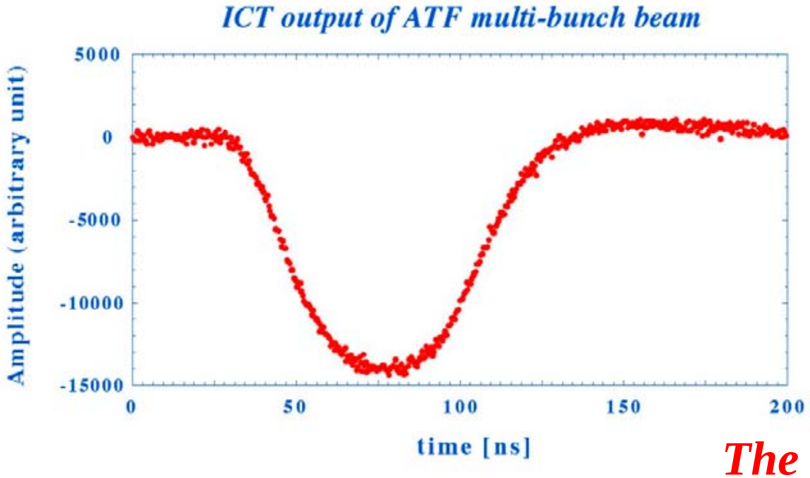
The Integrating Current Transformer (ICT) is a capacitively shorted transformer and a fast readout transformer in a common magnetic circuit designed to measure the charge in a very short pulse with high accuracy.



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*
- *Application to ILC*
  - *can use as the bunch to bunch distribution measurement after damping ring*
  - *can use as the beam current monitor for all of the ILC*

Session 3

Beam Profile, Beam Size Monitors

3-1. Fluorescent Screen Beam Profile Monitor

3-2. Optical Transition Radiation Monitor

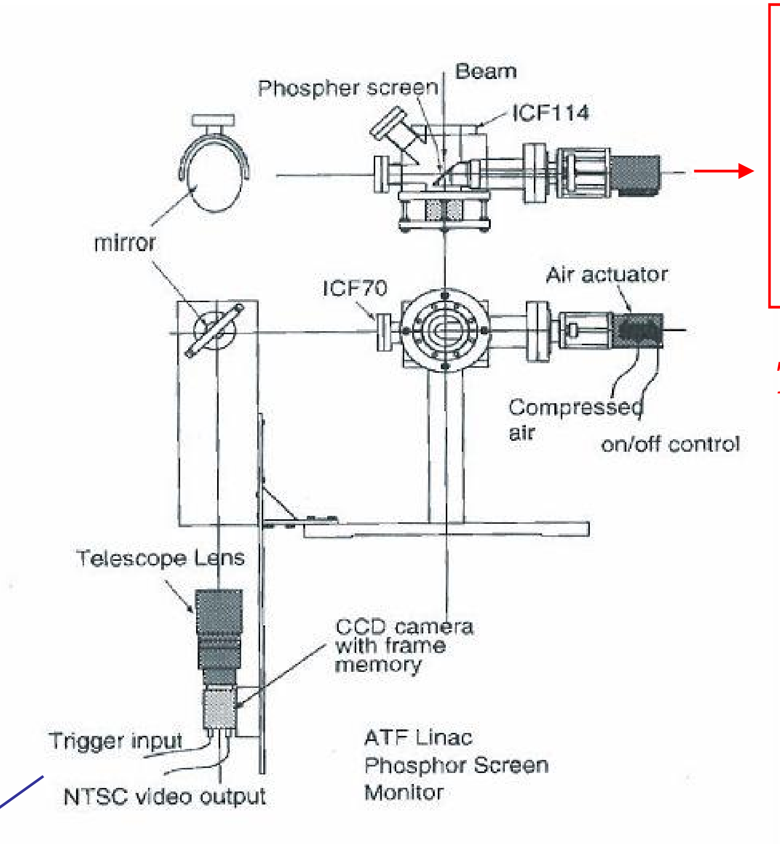
3-3. Wire Scanner Beam Profile Monitor

3-4. Laser Wire Scanner

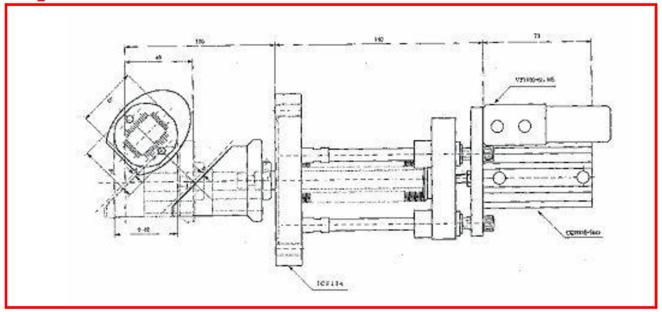
3-5. Synchrotron Radiation Monitor

3-6. X-ray Synchrotron Radiation Monitor

3-1. Fluorescent Screen Beam Profile Monitor



fluorescent screen



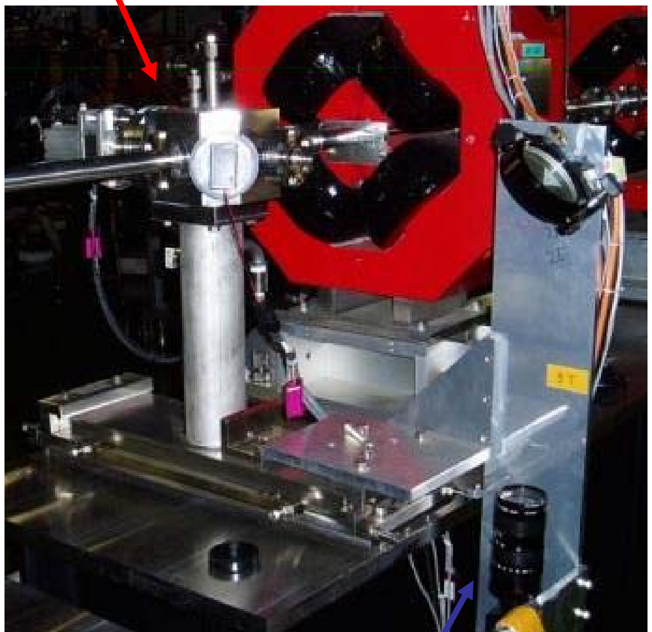
The alumina fluorescent screen is inserted to beam line at the profile measurement.

Gated CCD Camera

The gate timing of CCD camera is synchronized to the beam timing.

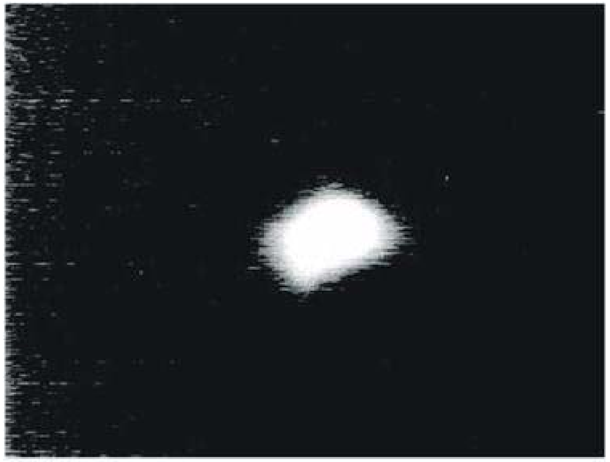
Picture of Screen Monitor in ATF

Vacuum chamber
with fluorescent screen



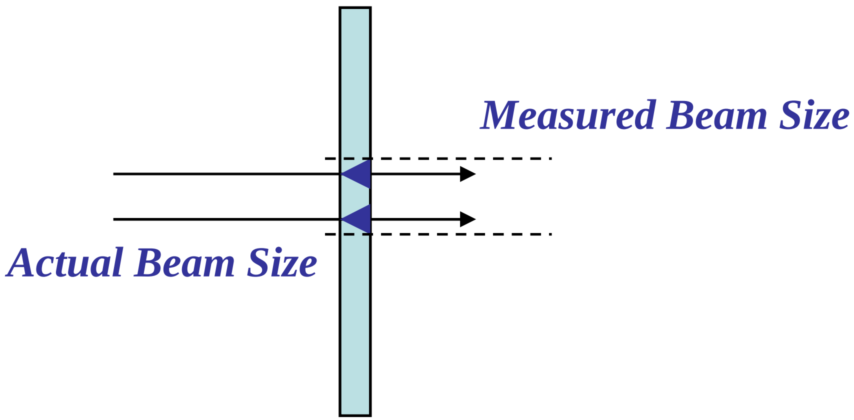
Gated CCD Camera
with Telescope

Measured Beam Profile



Measurable Limit of Fluorescent Screen Monitor

Measured beam size is larger than the actual beam size by the thermal diffusion of the screen material.



Since the amount of the thermal diffusion is comparable to the screen thickness, The measured beam size is limited by the screen thickness (~100μm).

Summary of Fluorescent Screen Monitor

-Dynamic range;

- around 10mm (defined by the screen size and range of CCD)

Resolution ;

- >> 100μm (defined by the screen thickness and the pixel size of CCD)

Offset ;

- around 1mm (defined by the initial setting errors)

Stability and Accuracy;

- Single shot ; very stable.

-Destructive

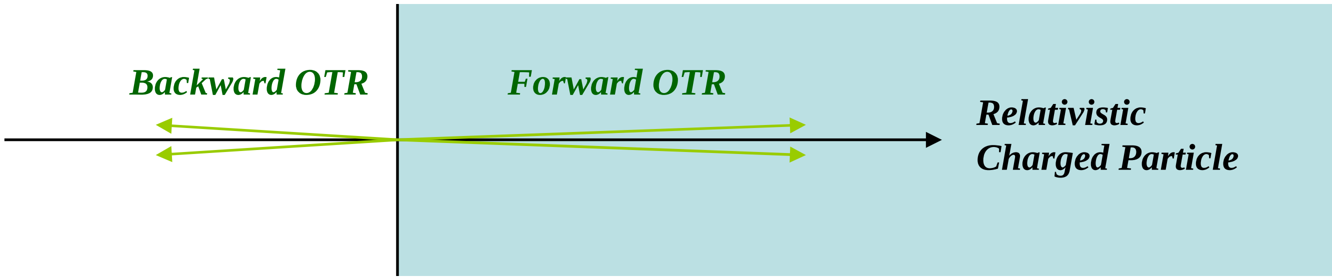
- Only for the beam transport line .

- Application to ILC

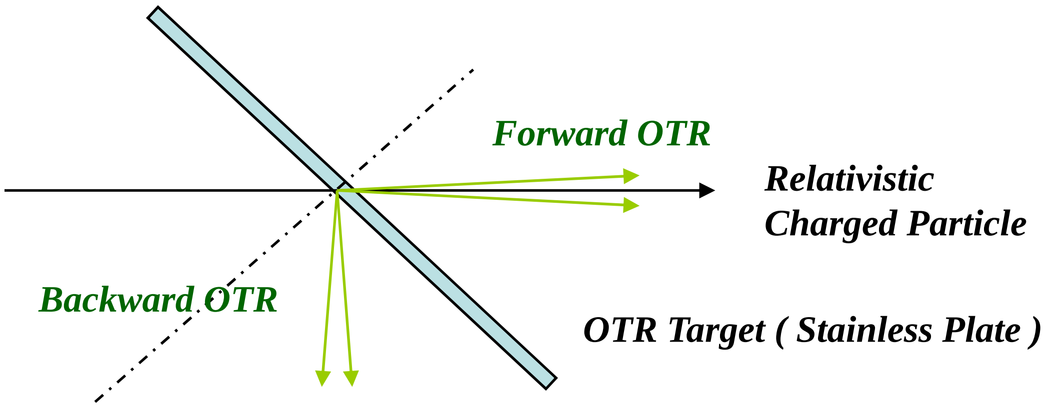
- can use for the beam commissioning, especially for the injector

3-2. Optical Transition Radiation Monitor

Optical transition radiation is produced by relativistic charged particles when they cross the interface of two materials of different dielectric constants.



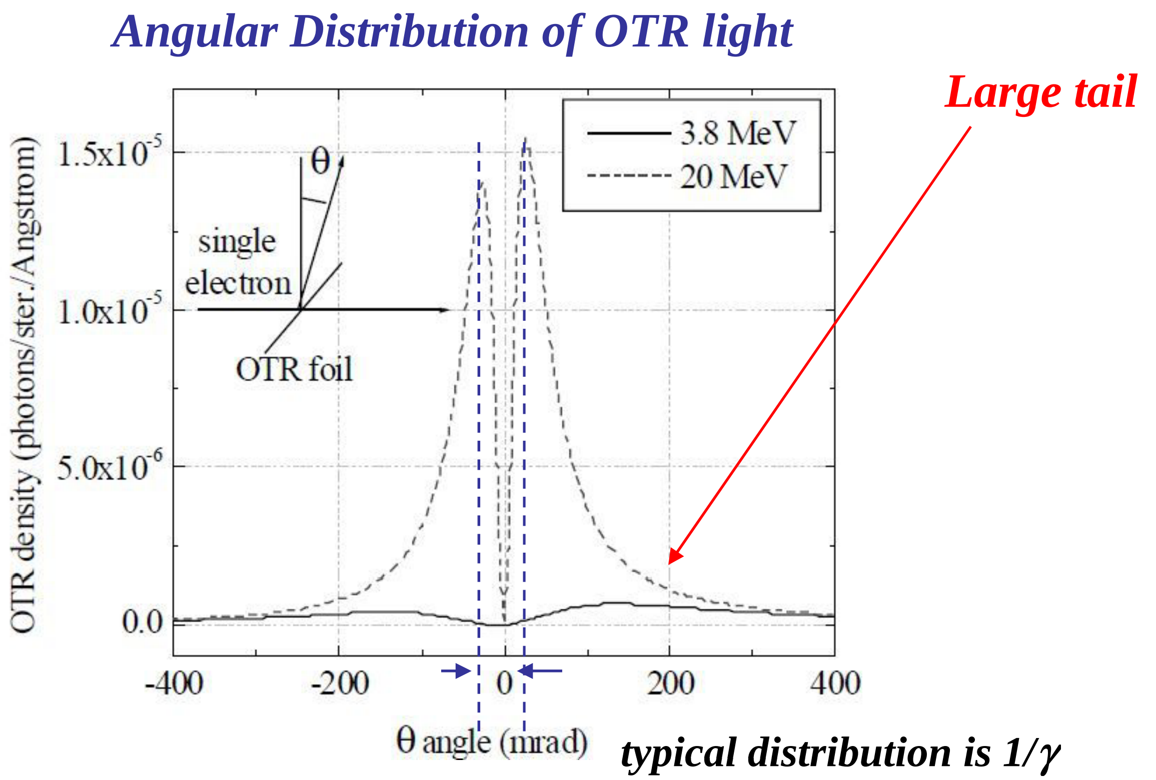
OTR target for using beam instrumentation



This light is used for the beam measurement.

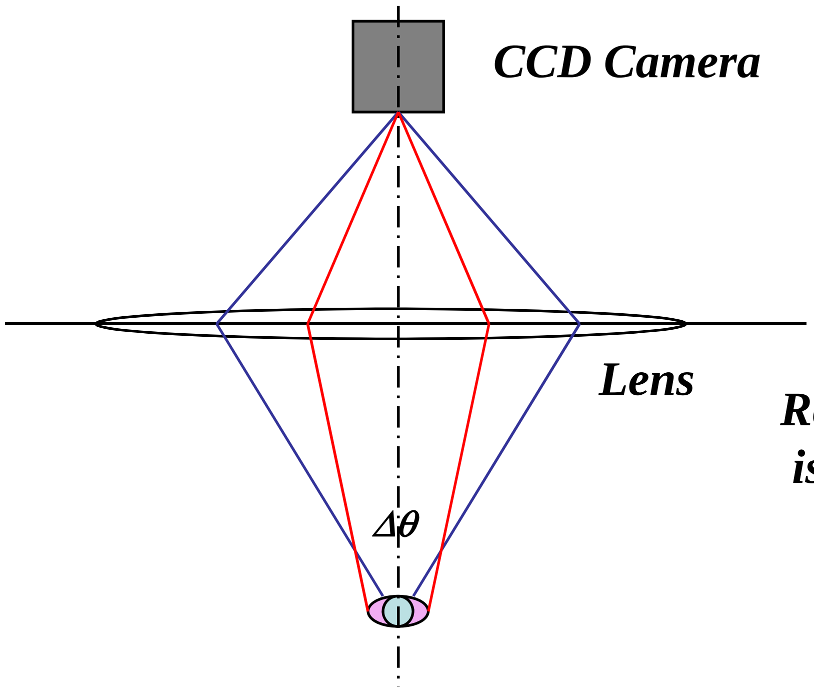
The radiation is emitted just the surface of the material and no diffusion !

Angular Distribution of the OTR Light



By correcting** the large angular light **with large aperture lens,
we can measure the** small beam size **with OTR.

Measurable Limit of OTR Beam Profile Monitor

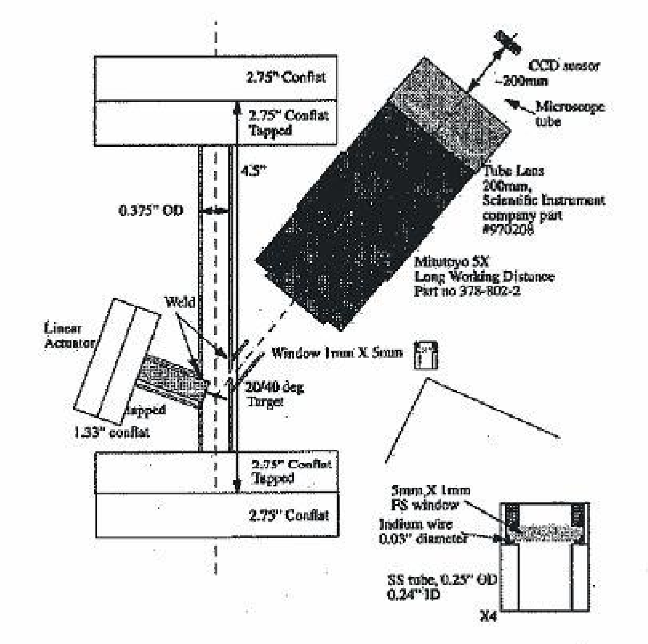


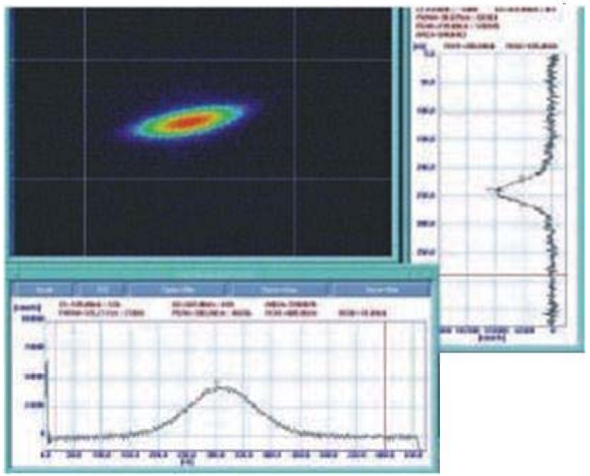
Resolution of the beam size measurement is limited by the diffraction limit .

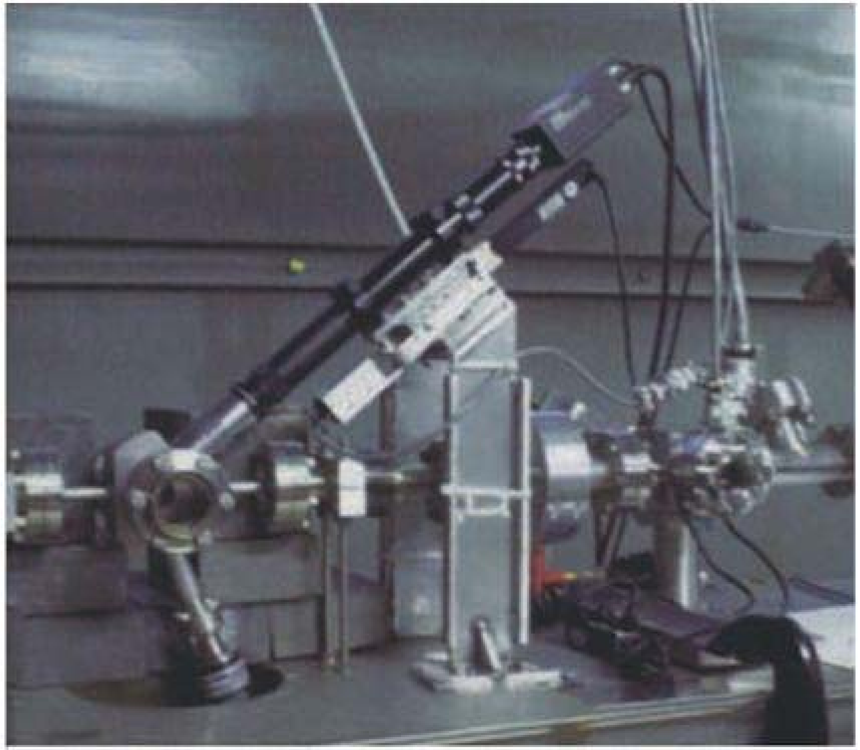
$$\Delta x > \lambda/4\pi\Delta\theta$$

The large aperture lens makes the measurement of the small beam size.

Example of the Wide Aperture Lens System in ATF



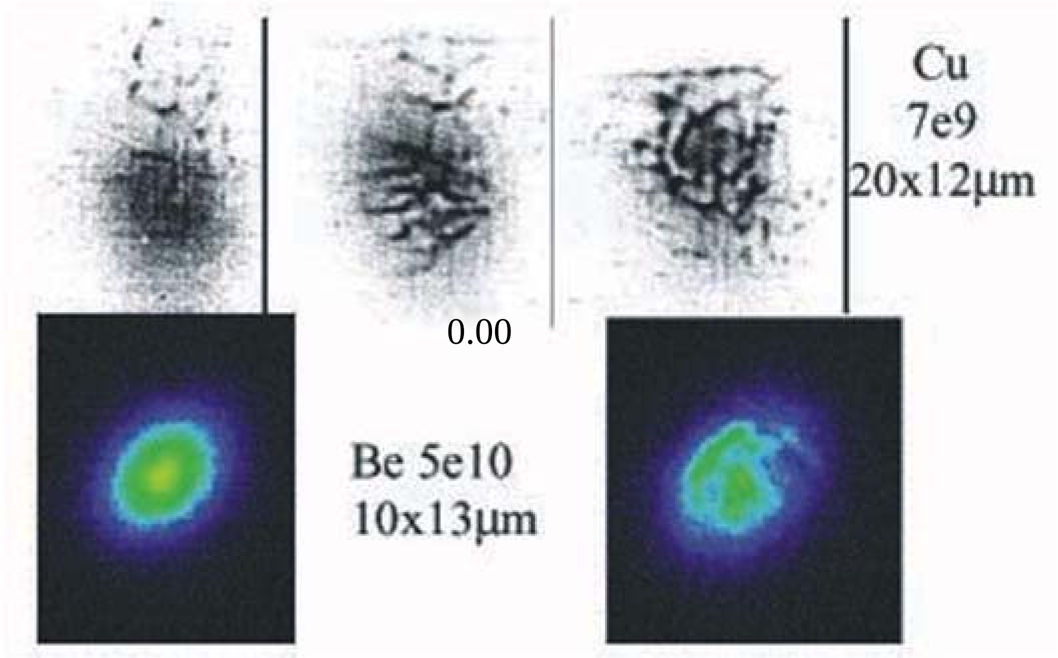




Minimum measured beam size is 10 μm by the OTR monitor

Damage of the OTR Target

The problem is the damage of the OTR target



The OTR target should be selected to the small damage target .

Summary of OTR Beam Profile Monitor

-Dynamic range;

0.1mm - 1mm

(defined by the magnification of the telescope of CCD camera)

-Resolution ;

10μm beam size was measured in ATF.

-Offset ;

around 1mm (defined by the initial setting errors)

-Accuracy;

- Calibration of the magnification ratio of the telescope.
- Aberration of the lens system
- Imperfection of the focal length adjustment

-Destructive

Only for the beam transport line .

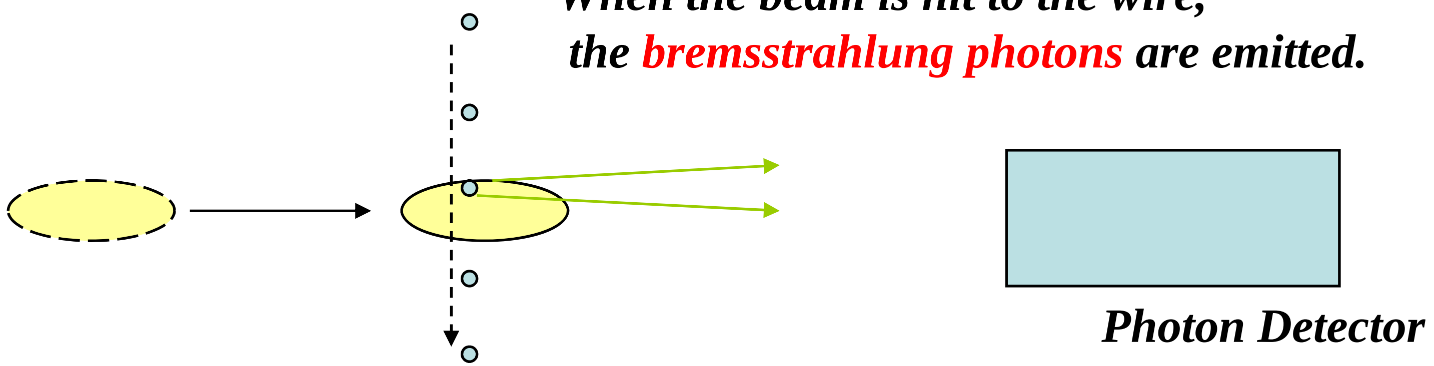
- Application to ILC

-difficult to use,

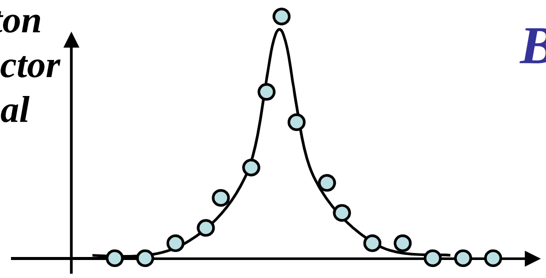
but have possibility to the small beam size measurement for commissioning

3-3. Wire Scanner Beam Profile Monitor

When the beam is hit to the wire,
the bremsstrahlung photons are emitted.

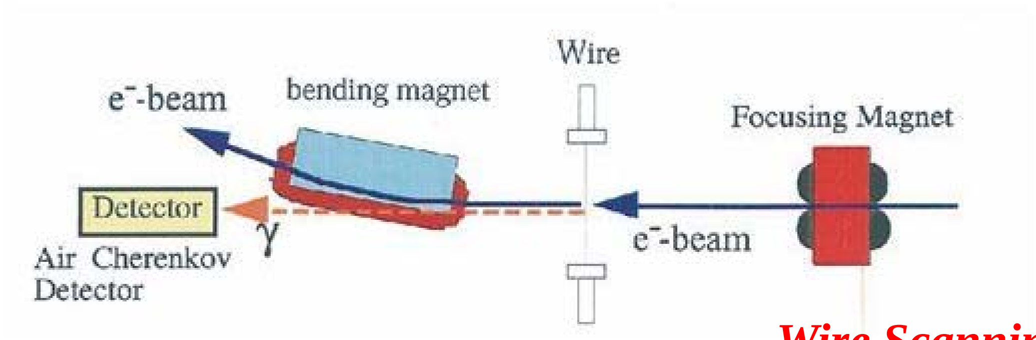


Wire position is moved by the mover stage.



By taking the detector signal dependence of the mover position, beam profile was measured.

Wire Scanner in ATF

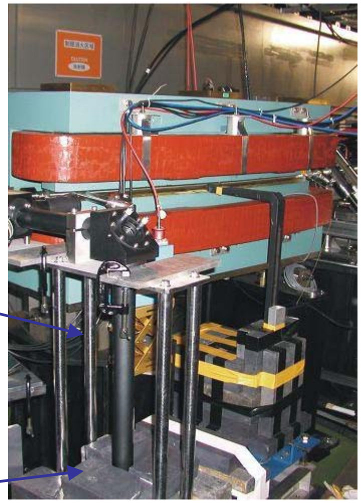


Wire Scanning System

Cherenkov light
is generated.

Light Guide

PMT



Gamma-ray detector

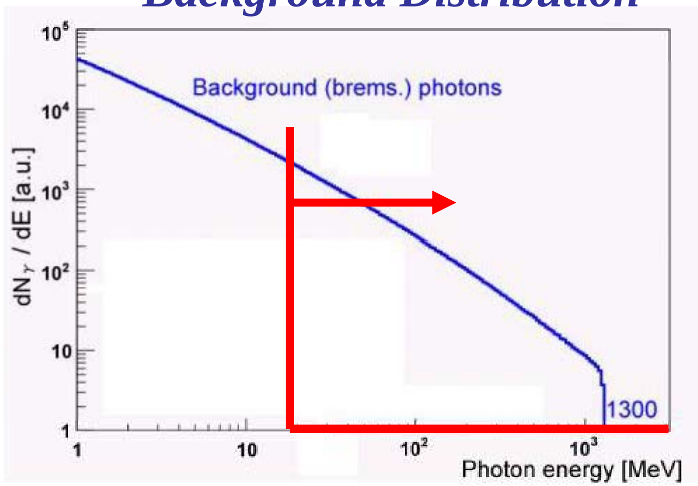
Mover Stage

Vacuum Chamber
Wire mount is in the Chamber

Air Cherenkov Detector was used for the Gamma Detector

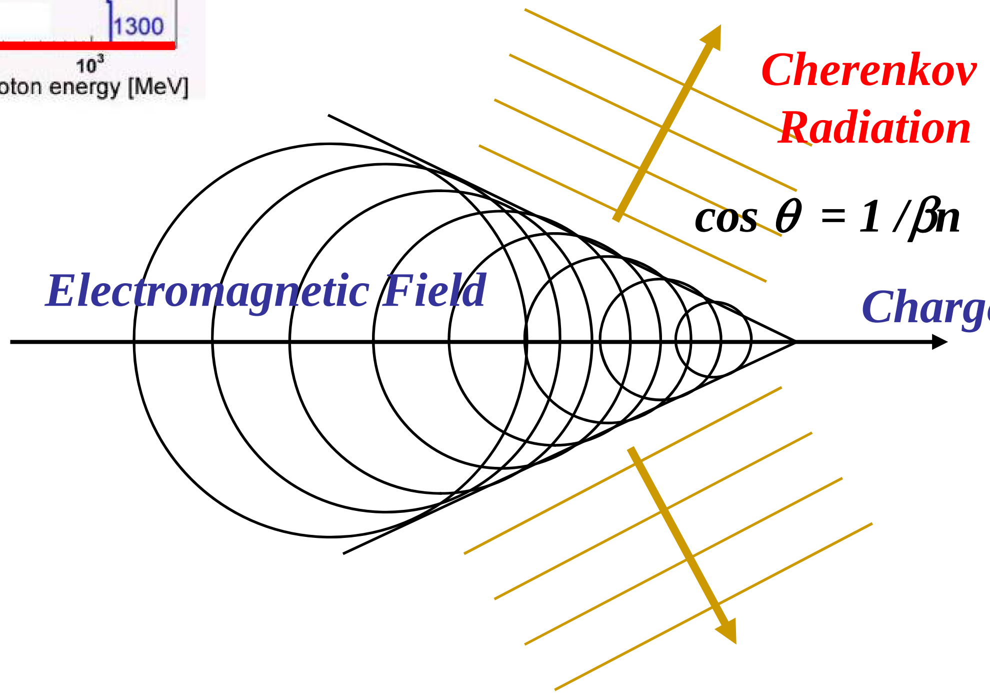
Air Cherenkov Detector

Background Distribution



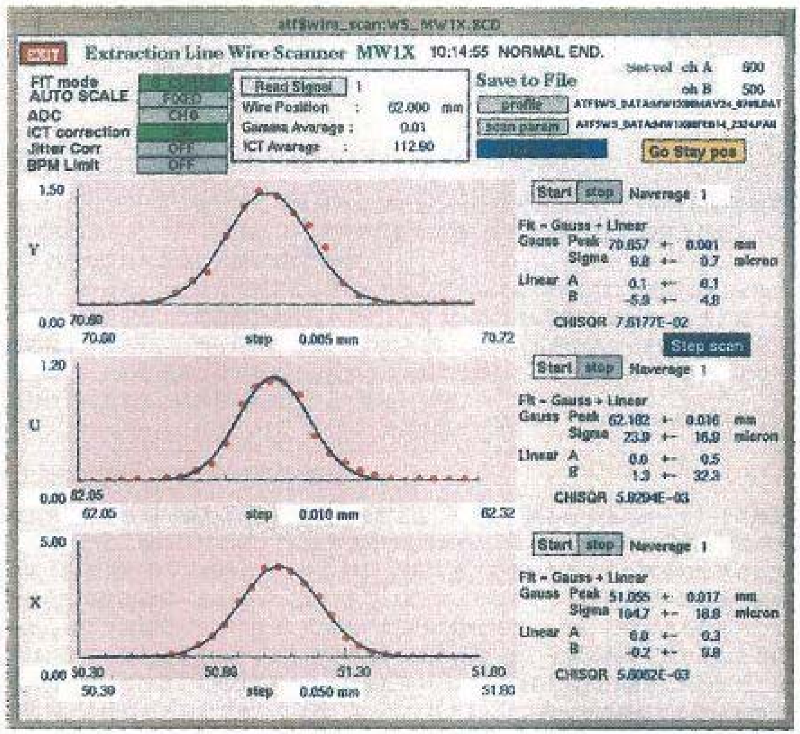
Cherenkov Radiation
is emitted when β > 1/n.

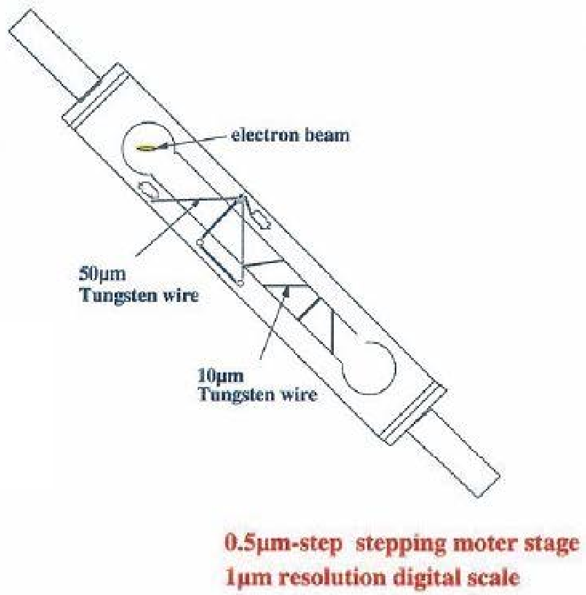
For the air, n=1.0003 ,
the threshold is E > 21 MeV.



Measured Profile by Wire Scanner

Wires are mounted to horizontal and vertical direction and tiled wires for measuring the beam coupling.

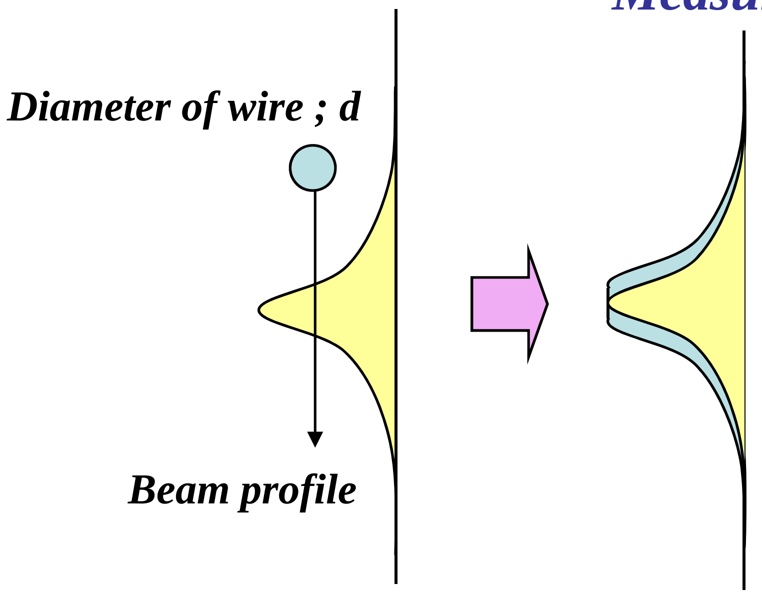




We can measure the horizontal and vertical beam size and their coupling with single stage.

Limit of the Measured Beam Size

Measured Profile by Wire Scannner



The measured beam size by wire scanners are expressed as the second order moment of the convoluted shape of the gaussian function to the round shape.

$$\sigma = \sqrt{\sigma_0^2 + (d/4)^2}$$

The limit of the measurable beam size is d/4 .

In the ATF, since 10µm wire was used for the beam size measurement, the limit of the beam size measurement is 2.5µm .

Summary of Wire Scanner Beam Profile Monitor

-Dynamic range;

- For large profile, PMT HV gain is increased .
(1mm for ATF)

-Resolution ;

d/4 is the mechanical limit of the measurement .
(2.5μm for ATF)

-Accuracy;

Since wire scanner is multi-path measurement,
the beam fluctuation affect to the beam size measurement.

-Partly destructive Monitor

- Since the beam loss is 0.01% order,
we can use the beam with the beam size measurement.
- But, only for the beam transport line .

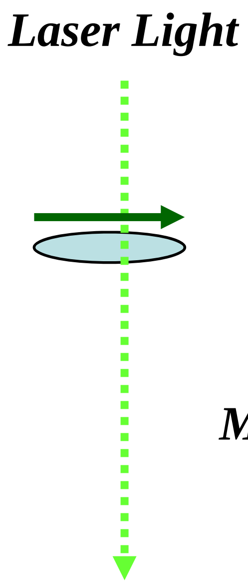
- Application to ILC

- can use for the injector

3-4. Laser Wire Scanner

Laser Compton Scattering

When electron beam collide to laser light,
the gamma ray is generated by Compton scattering



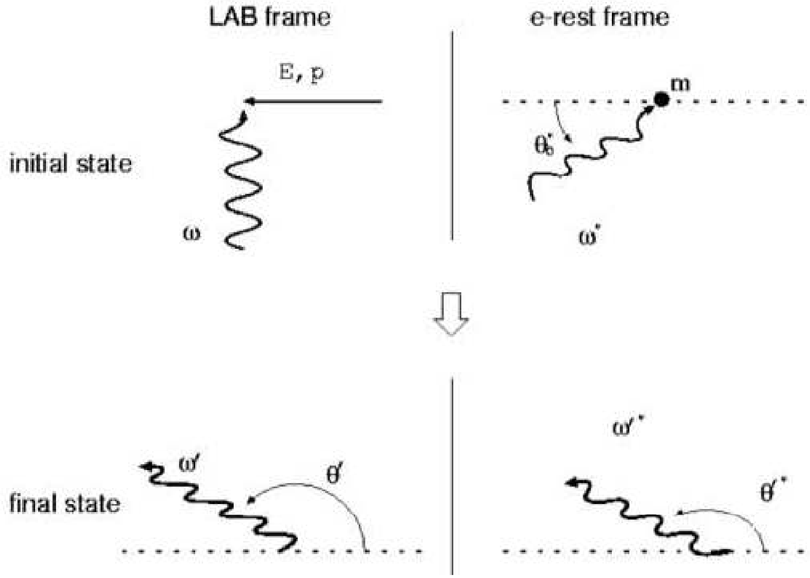
Mechanism of the Compton scattering
is defined by Klein-Nishina Formula.

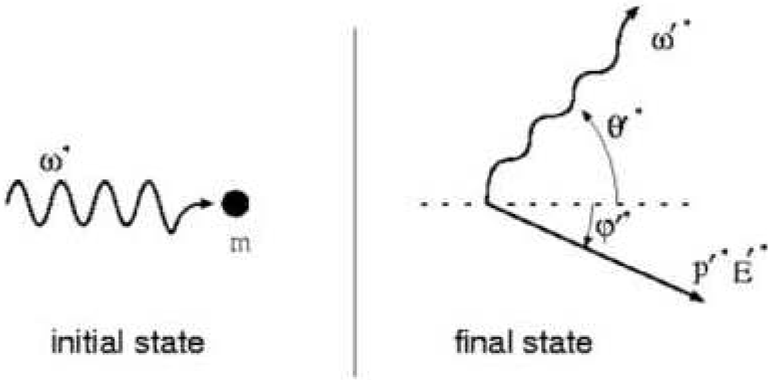
Klein-Nishina Formula

Compton scattering is described by the elastic scattering of electron and photon in electron rest frame.

$$\omega = h\nu = \frac{hc}{\lambda}$$

$$\omega'_{max} = \frac{\gamma\omega}{\gamma - \sqrt{\gamma^2 - 1}}$$



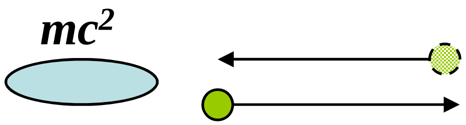


Differential Cross Section of Compton Scattering

$$\frac{d\sigma}{d\Omega^*} = \frac{r_0^2}{2}\left(\frac{\omega'^*}{\omega^*}\right)^2\left[\frac{\omega^*}{\omega'^*} + \frac{\omega'^*}{\omega^*} - 1 + \cos^2\theta'^*\right]$$

Energy Shift for High Energy Electron Collision

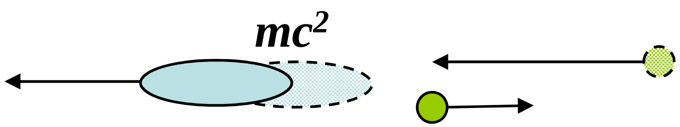
For collision with low energy electron beam



$\gamma\omega/2$ =2.9keV for ATF for 532nm

Photon energy in electron rest frame is quite smaller than electron mass.
Electron do not move after scattering.

For collision with high energy electron beam

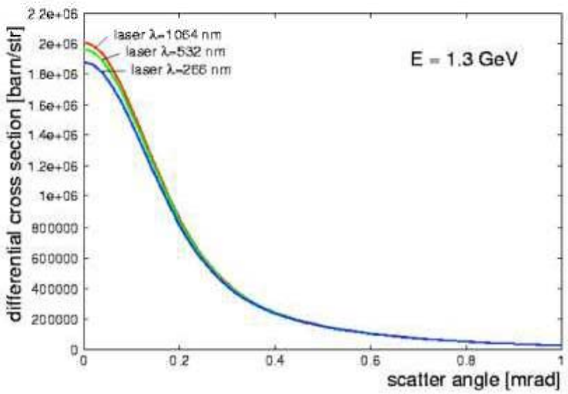


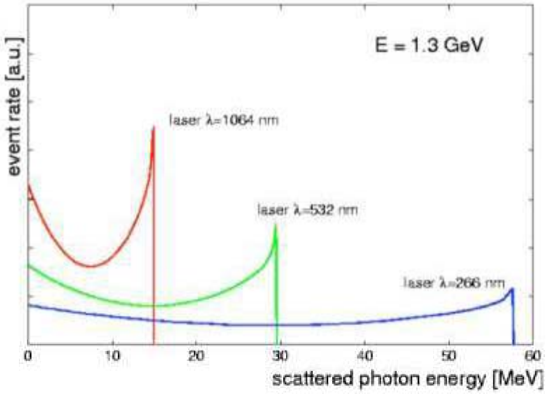
$\gamma\omega/2$= 0.55MeV for 532nm

Photon energy in electron rest frame is comparable to electron mass.
Electron move after scattering.
Then the scattered photon energy is shifted to be low.

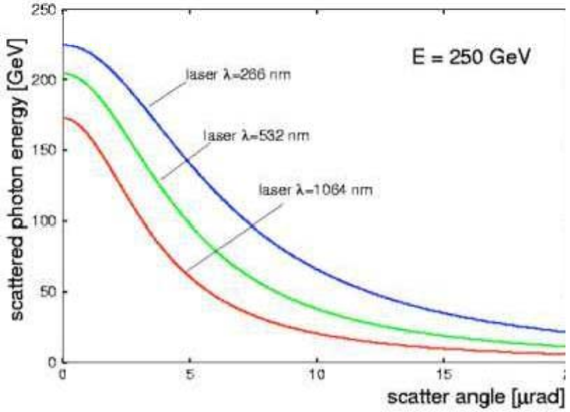
Differential Cross Section of Compton Scattering

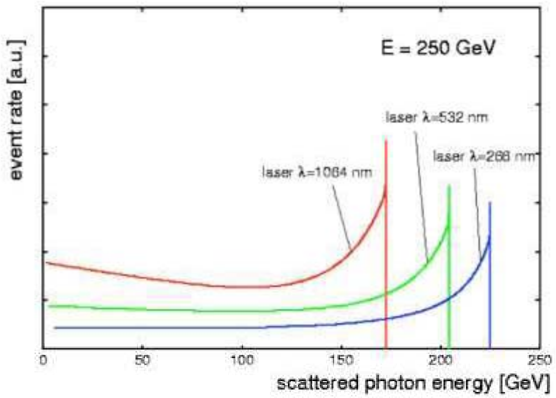
For ATF beam





For ILCBDS

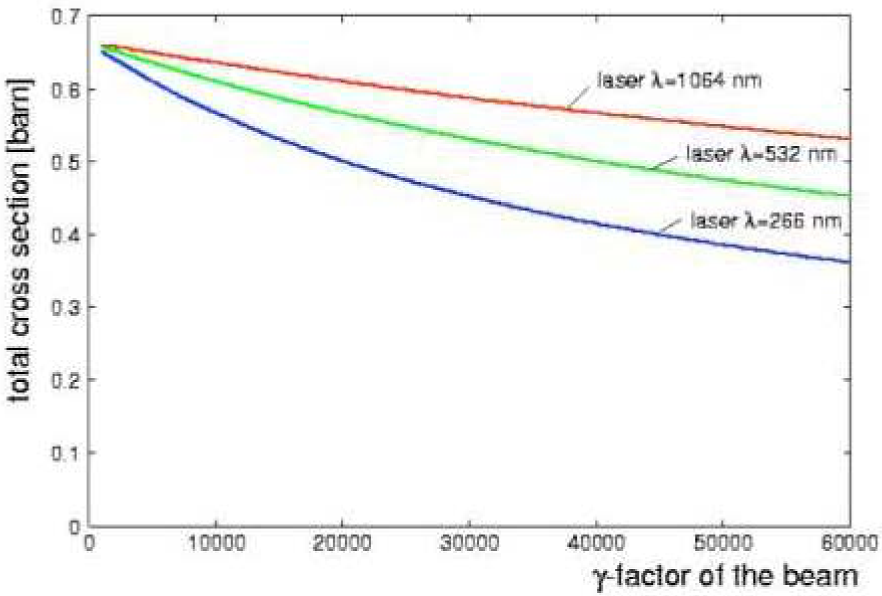




Scattering angle is ultra forward direction.
Photon energy is shifted for high energy beam.

Total Cross Section of Compton Scattering

The total cross secion depends on the energy of electron beam.
But, the dependence is small .



$$\frac{dY}{dt} = \sigma \mathcal{L}$$

$$\mathcal{L} = \frac{\lambda}{hc^2} \frac{PN_b}{\sqrt{2\pi}\sqrt{\sigma_e^2 + \sigma_{laser}^2}}$$

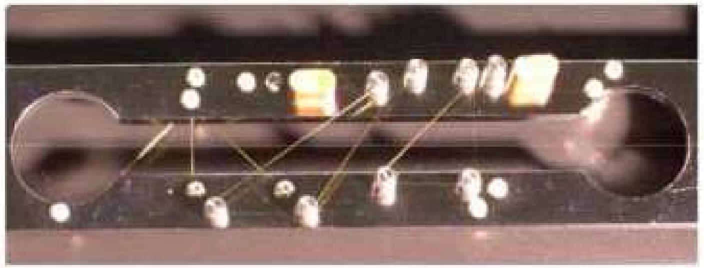
Rough estimation of the signal

When we have 1000 photons per a collision for 10μm beam,
the requirement of the peak laser power is 10MW.

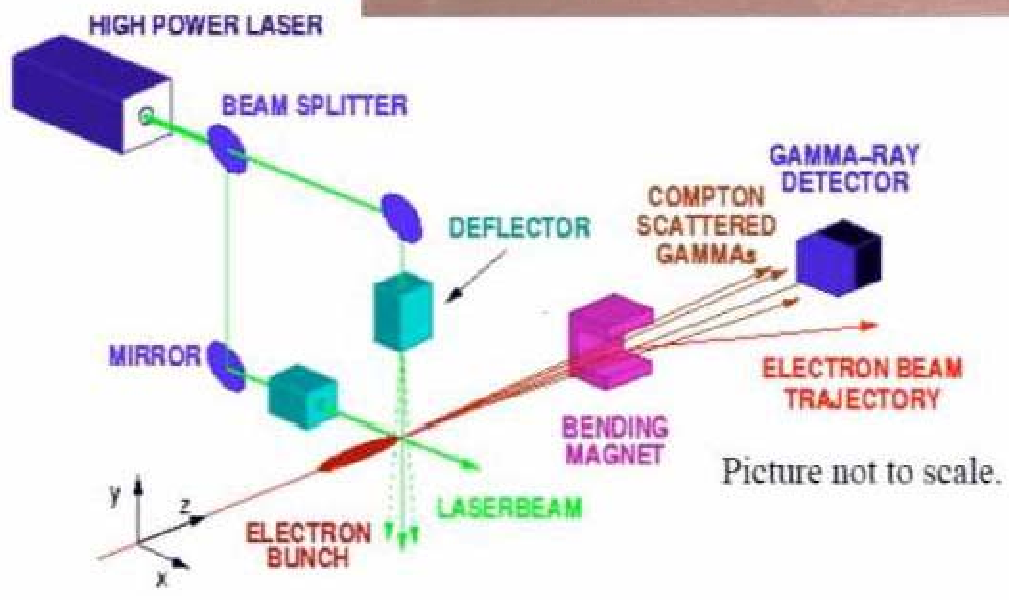
Pulsed Laser Wire Scanner

Concept of Pulsed Laser Wire

When we measure the small beam size or high intensity beam, material wire was cut by thermal stress !

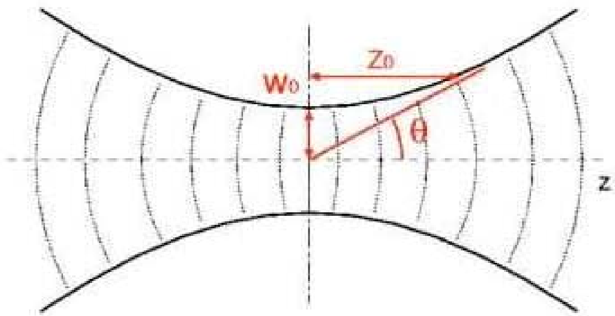


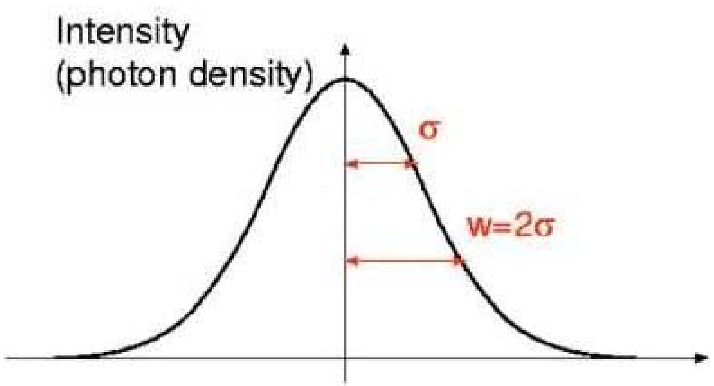
Not destroyed wire ;
Small diameter wire ;
Laser Wire



Gaussian Beam

Laser beam is ideally Gaussian beam





$$E(t,x,y,z) \equiv \psi(x,y,z)\exp(i\omega t - ikz)$$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} - 2ik\frac{\partial}{\partial z}\right)\psi(x,y,z) = 0$$

$$\begin{aligned} E_{mn}(t,x,y,z) &= \\ A\frac{w_0}{w(z)}\exp\left(-\frac{x^2+y^2}{w^2(z)}\right) & H_m\left(\frac{\sqrt{2}x}{w_0}\right) H_n\left(\frac{\sqrt{2}y}{w_0}\right) \\ \times\exp\left(-ik\cdot\frac{x^2+y^2}{2R(z)}\right) & \exp\left(i\Phi(z)\right) \times \exp(i\omega t - ikz) \end{aligned}$$

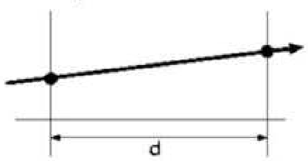
$$\begin{aligned} w(z) &= w_0\sqrt{1+\left(\frac{z}{z_0}\right)^2}, \\ R(z) &= z\left\{1+\left(\frac{z_0}{z}\right)^2\right\}, \\ \Phi(z) &= (m+n+1)\arctan\left(\frac{z}{z_0}\right), \\ z_0 &= \frac{\pi w_0^2}{\lambda}, \end{aligned}$$

In generally, laser light is TM$_{00}$ mode

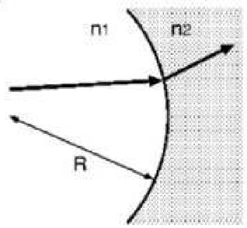
Lens Design for Injection System

Transportation of Light

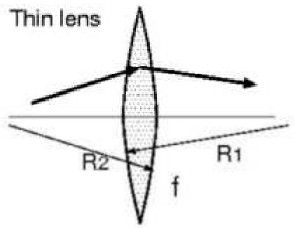
***In order to make a small laser wire,
the injection lens system is very important .***



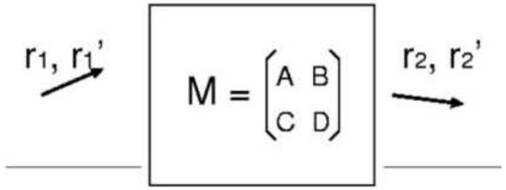
$$\begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$$



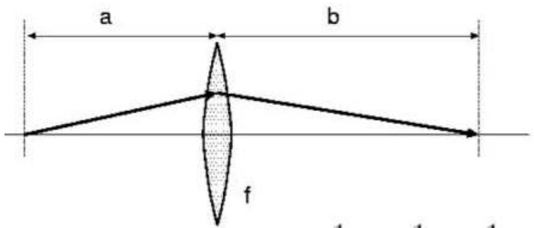
$$\begin{pmatrix} 1 & 0 \\ \frac{n_2-n_1}{n_2 R} & \frac{n_1}{n_2} \end{pmatrix}$$



$$\begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$



$$\begin{pmatrix} r_2 \\ r_2' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_1 \\ r_1' \end{pmatrix}$$



$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

Linear transportation of laser system is defined by Transfer Matrix

Spherical Aberration

The difference from linear system with the spherical lens

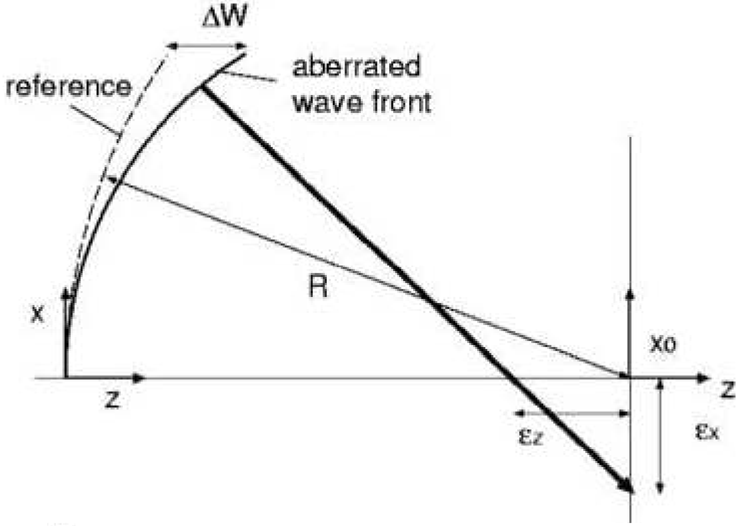
The focal point is different by injection position

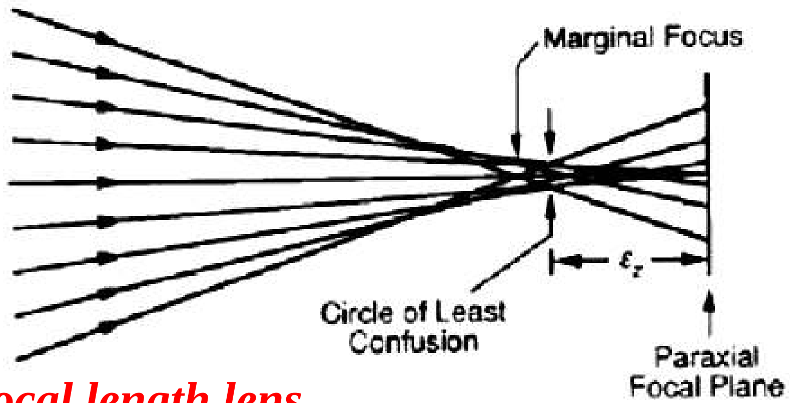
The larger aberration for larger offset

The amount of the beam emittance is evaluated by

$$\varepsilon_x = -R\frac{\partial \Delta W(x,y)}{\partial x} \qquad \varepsilon_z = -\frac{R^2}{x}\frac{\partial \Delta W(x,y)}{\partial x}$$

$$\varepsilon_x = -4RW_{040}\rho^3 \qquad \varepsilon_x \propto R\Phi^3\rho^3 \approx \frac{\rho^3}{f^2}$$

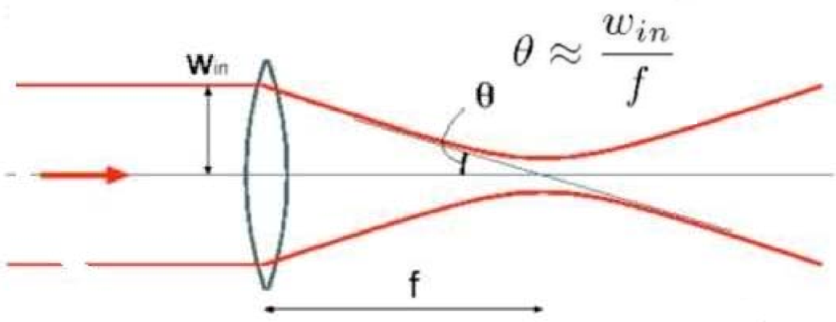




Spherical aberration is large for small focal length lens .

Design Concept of the Focus Lens

$$F\# = \frac{f}{D}$$



Beam size is defined by

- diffraction limit

$$w_{diff} = \underline{M}^2 \frac{\lambda}{\pi\theta} = M^2 \frac{\lambda}{\pi} F\#$$

Performance of Laser *Smaller F# is better*

- spherical aberration

$$w_{sph} = \frac{kD^3}{2f^2} = \frac{kD}{2F\#^2}$$

For the single lens,
small F# makes spherical aberration large.

If we design the lens without spherical aberration by F#,
the measured beam size is expressed by

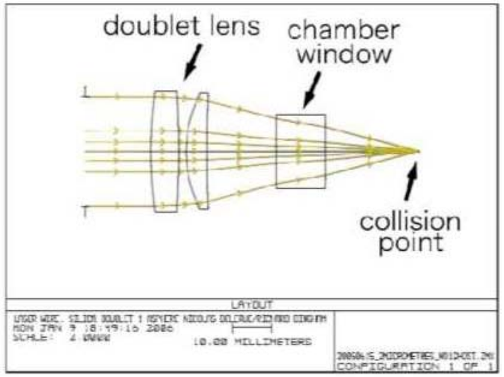
$$w_0 = \sqrt{w_{diff}^2 + (2\sigma_{RMS})^2}$$

Lens Design for ATF2 Laser Wire Scanner

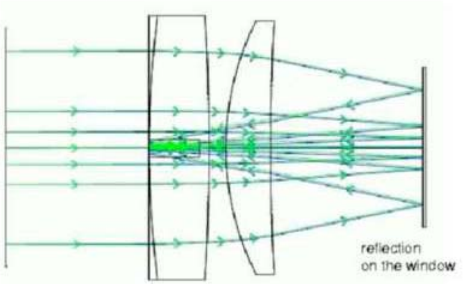
F#=2 Lens

Lens without spherical aberration by F#=2

Design by simulation code (ZEMAX)



Design to be close to the focal point



Take care of the lens and window damage from reflection light.

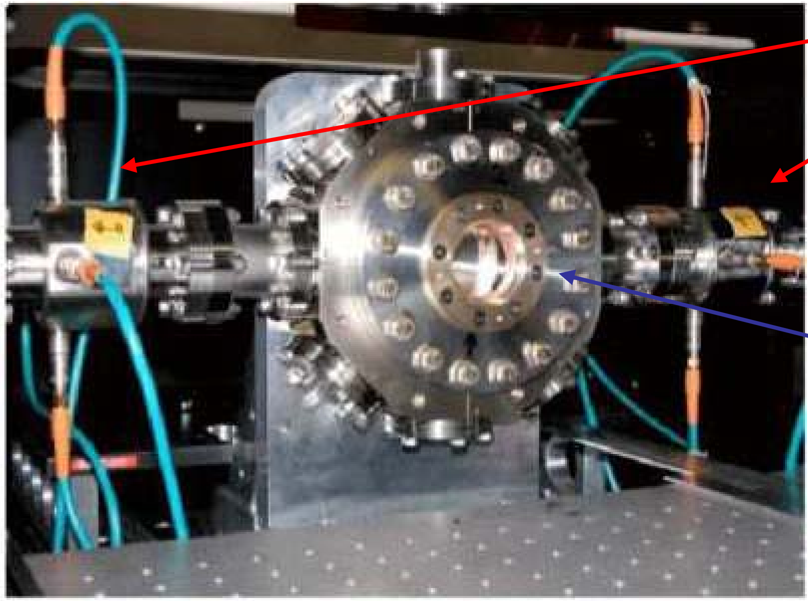
Beam Experiment in ATF Beamline

At transport line

For the preliminary test,
laser wire system was installed in ATF extraction line with F#=10 lens.

Laser wire chamber in ATF extraction line

Injection lens system
is in the box.



Stripline BPM

Laser extraction port

Laser position is changed by the mirror in the injection system.

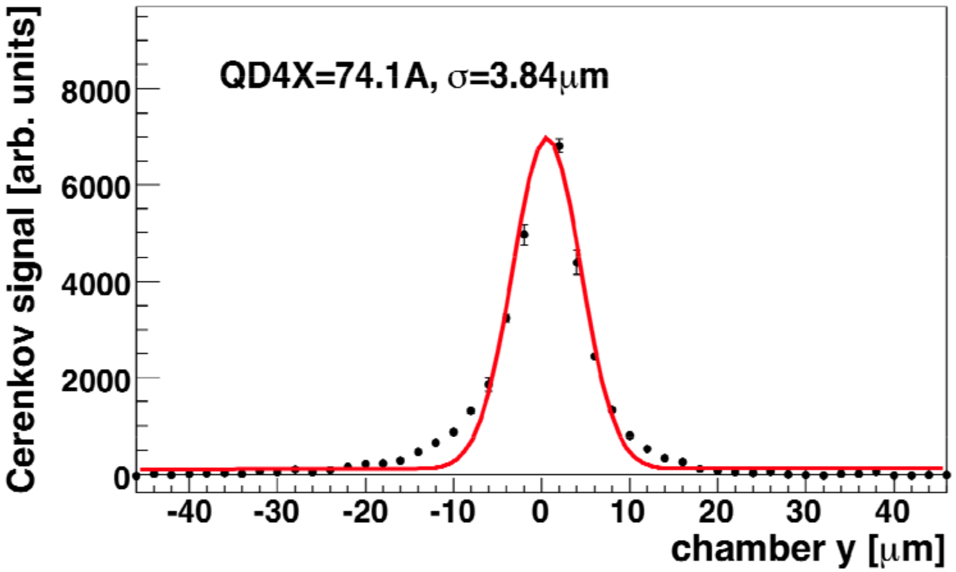
Preliminary Results of Laser Wire in ATF

Collision with micron order beam (2μm).

Training of the collision timing adjustment

Test of photon detector (silica aerogel Cherenkov)

Index 1.017, Threshold 2.8MeV



3.84μm beam size was achieved.
(ILC requirement is 1μm.)

Summary of Pulsed Laser Wire Scanner

- Dynamic range;

- defined by signal to noise ratio (100μm for ATF2)

- Resolution ;

- determined by the laser waist (1μm for ILC requirement)

- Accuracy;

-laser waist and waist position should be stabilized

the laser improvement , focus lens development

- affect to the beam jitter

- Partly destructive

- We can use in both storage ring and transport line.

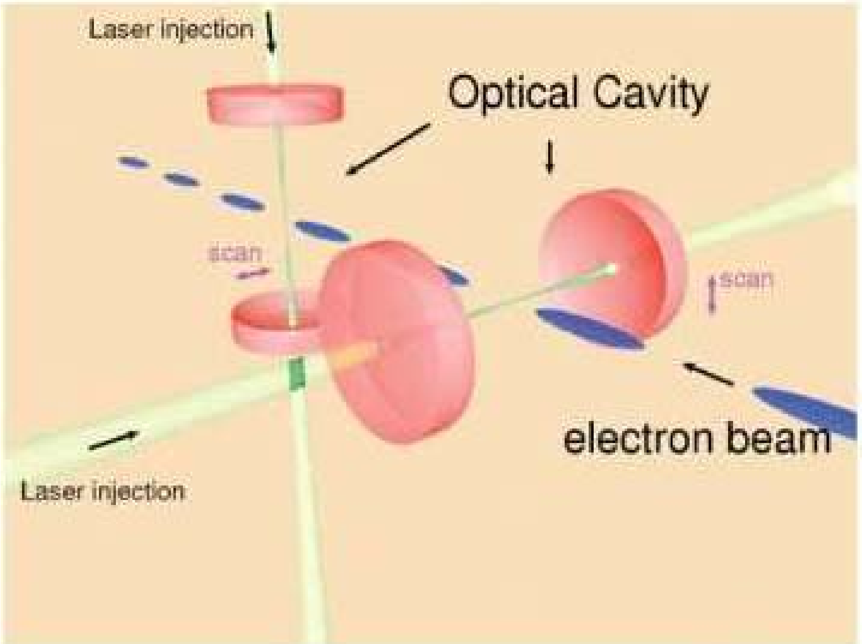
- Application to ILC

- major candidate in the main linac

Cavity based Laser Wire Scanner

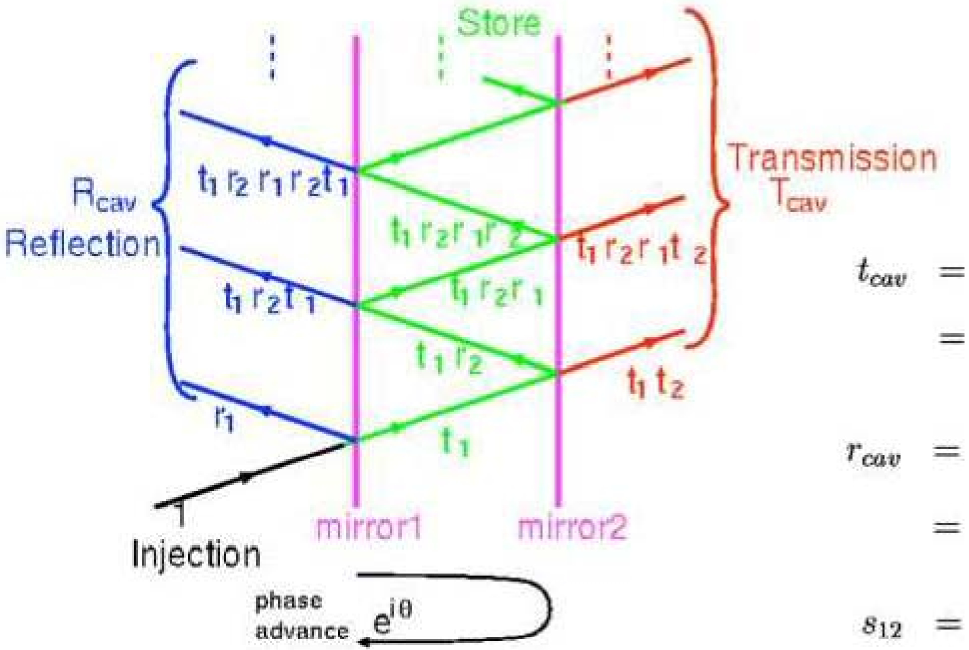
Concept of Cavity based Laser Wire

The peak power of CW laser is small,
but we can use the CW laser by amplification in optical cavity.



The advantage of the cavity based laser wire is laser wire stability (position and waist) by well stability of CW laser and mode cleaning effect in the optical cavity .

Laser Cavity Resonator



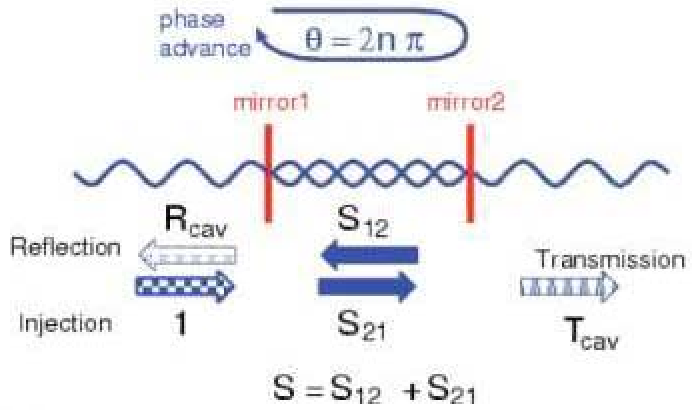
$$
\begin{aligned}
t_{cav} &= t_1 t_2[1 + r_1 r_2 e^{i\theta} + (r_1 r_2 e^{i\theta})^2 + \cdots] \\
&= \frac{t_1 t_2}{1 - r_1 r_2 e^{i\theta}}
\end{aligned}
$$

$$
\begin{aligned}
r_{cav} &= r_1 - t_1 r_2 t_1 e^{i\theta}[1 + r_1 r_2 e^{i\theta} + (r_1 r_2 e^{i\theta})^2 + \cdots] \\
&= r_1 - \frac{t_1 r_2 t_1 e^{i\theta}}{1 - r_1 r_2 e^{i\theta}} \quad ,
\end{aligned}
$$

$$
\begin{aligned}
s_{12} &= t_1[1 + r_1 r_2 e^{i\theta} + (r_1 r_2 e^{i\theta})^2 + \cdots] \\
&= \frac{t_1}{1 - r_1 r_2 e^{i\theta}} \\
s_{21} &= t_1 r_2[1 + r_1 r_2 e^{i\theta} + (r_1 r_2 e^{i\theta})^2 + \cdots] \\
&= \frac{t_1 r_2}{1 - r_1 r_2 e^{i\theta}} \quad .
\end{aligned}
$$

Laser Resonance in Optical Cavity

When cavity length is $m\lambda/2$*,*
the laser power is expressed by



Transmittance

$$T_{cav} = |t_{cav}|^2 = \frac{T_1 T_2}{(1-\sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2}\sin^2\frac{\theta}{2}}$$

Reflectivity

$$R_{cav} = |r_{cav}|^2 = (R_1 + T_1) - \frac{T_1(1 - R_1 R_2 - T_1 R_2)}{(1-\sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2}\sin^2\frac{\theta}{2}}$$

Stored Power

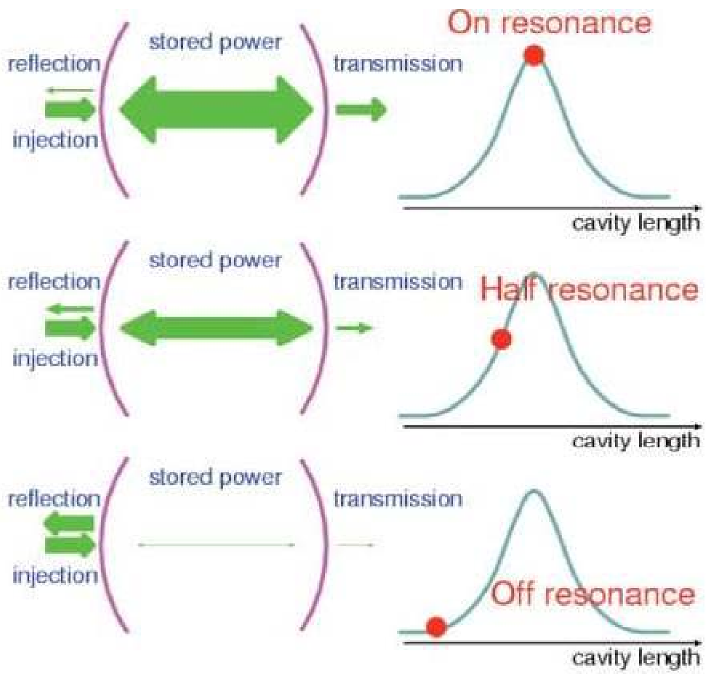
$$S_{cav} = |s_{12}|^2 + |s_{21}|^2 = \frac{T_1(1+R_2)}{(1-\sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2}\sin^2\frac{\theta}{2}}$$

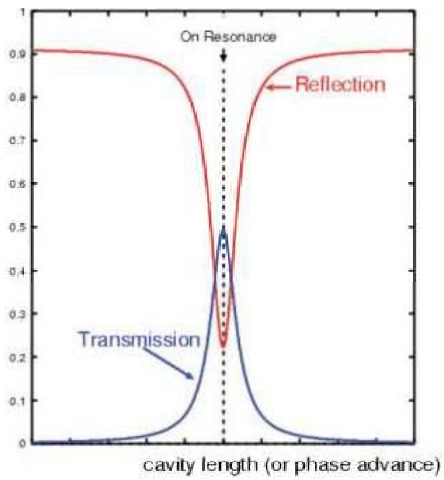
$$= \frac{1+R_2}{T_2} T_{cav} \sim \frac{2}{T_2} T_{cav} \quad (\text{if } R_2 \sim 1) \quad .$$

$T_2 = 1 - R_2$

Injected laser light is enhanced
by optical cavity with high reflection mirror

Finess of the Optical Cavity





$$\mathcal{F} \equiv \frac{\mathrm{FSR}}{\mathrm{fwhm}} = \frac{\pi\sqrt{R_M}}{1 - R_M}$$

Finess is the power enhancement factor in the opticsl cavity .

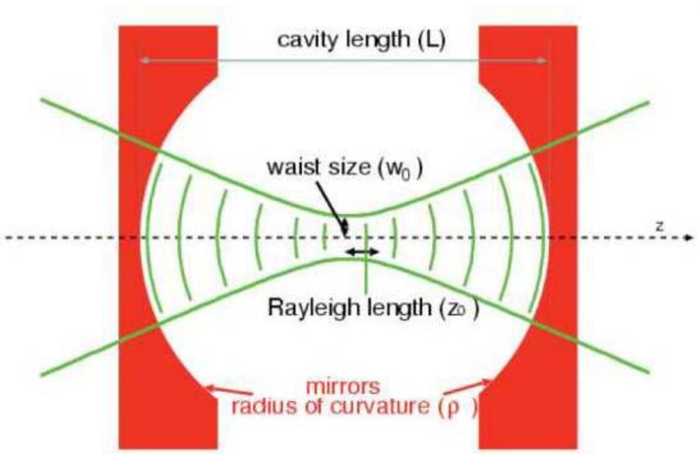
- defined by the reflectivity of the optical cavity .

- corresponds to the resonance width .

because for the high refrectivity mirror ,

the requirement of the laser phase shift is tight .

Beam Waist and Optical Matching



Condition of injection matching

$$R(-L/2) = -\rho \text{ and } R(L/2) = \rho$$

Wavefront is same to mirror surface.

Mode cleaning effect

Beam waist is defined by

$$w_0^2 = \frac{\lambda}{\pi}\frac{\sqrt{L(2\rho - L)}}{2}$$

2ρ – L is very important number to defined the beam size.

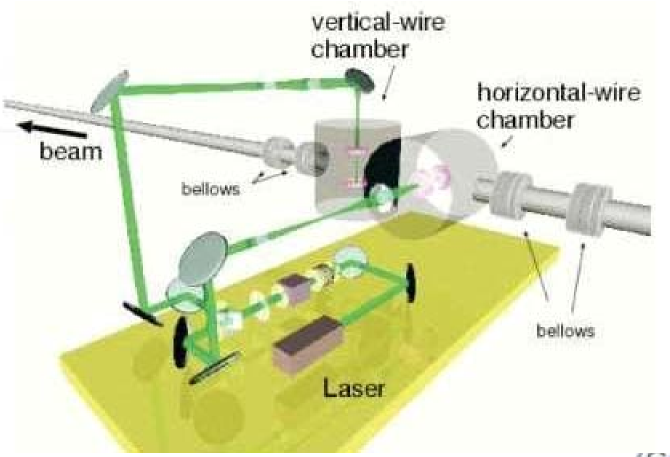
For small beam waist,

***- The divergence is large to affect the** spherical aberration of lens in injection system.*
Therefore, the injection efficincy is not good .

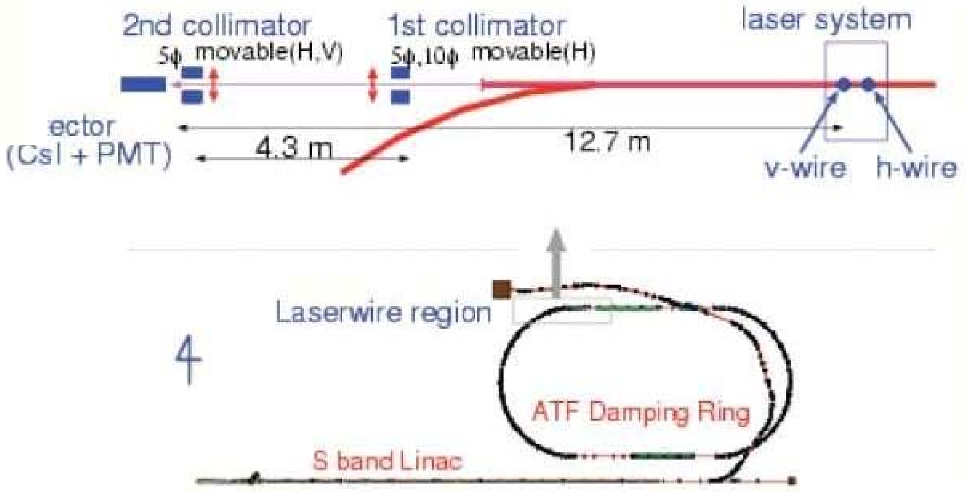
- The Rayleigh length is short.

Beam waist is limited around 10μm

Experimental Setup of the Cavity based Laser Wire in ATF



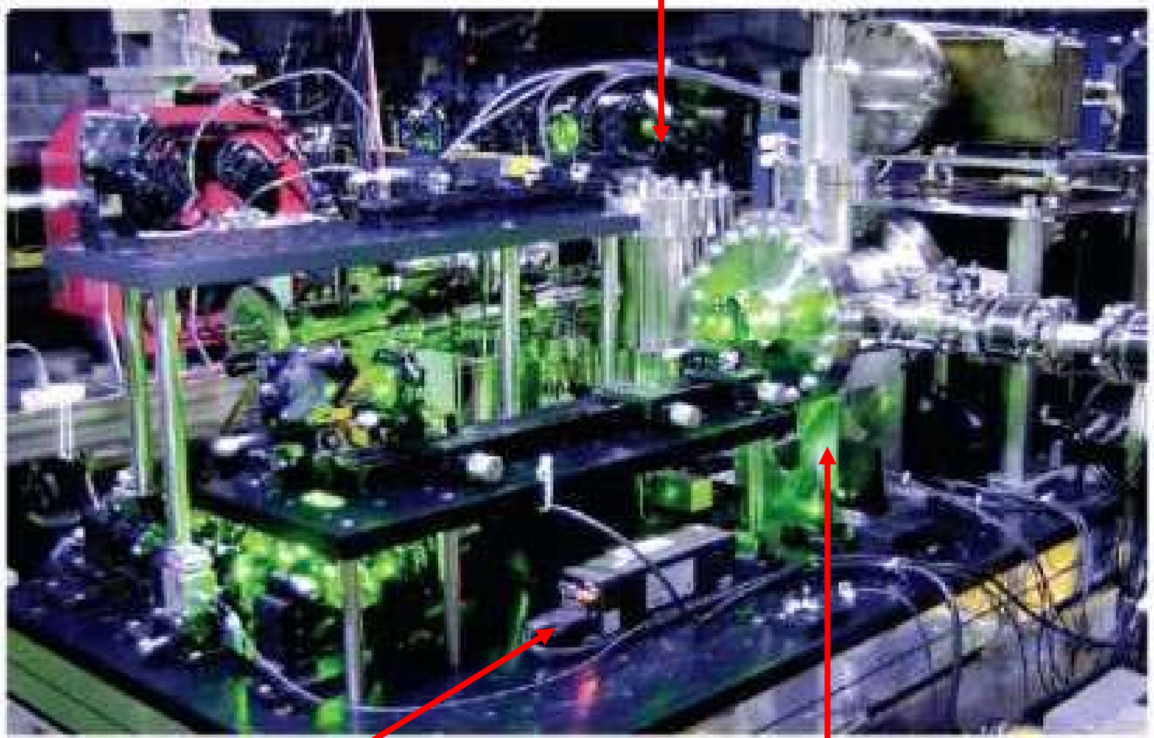
Laser wire system is located at the straight line of ATF damping ring



We have two laser path to make the horizontal and vertical laser wire.

Optical Table of ATF Laser Wire Scanners

Vacuum chamber for horizontal measurement

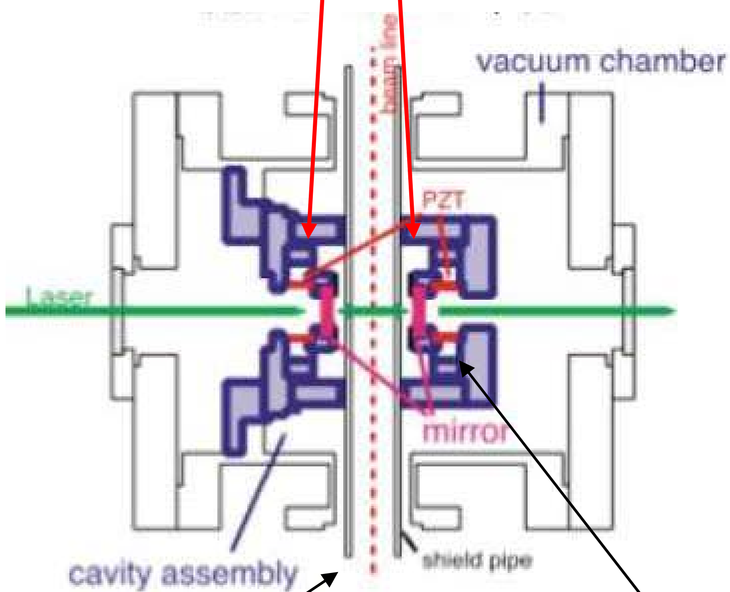


50mW Nd:YAG CW laser *Vacuum chamber for vertical measurement*

All of the apparatus on the table is moved by stepping moter.

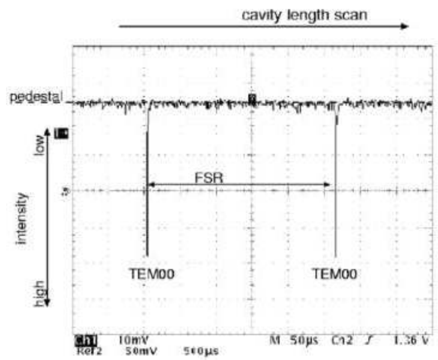
Optical Resonance Cavity for ATF Laser Wire

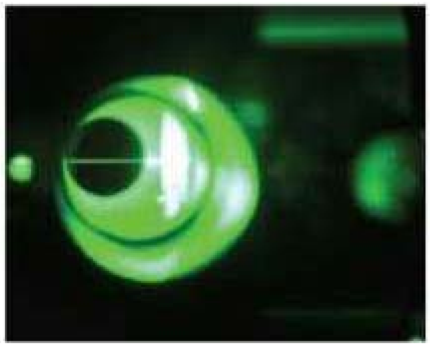
Optical cavity with 2 mirrors



Smooth pipe to reduce impedance

Cavity Length is controlled by piezo actuator

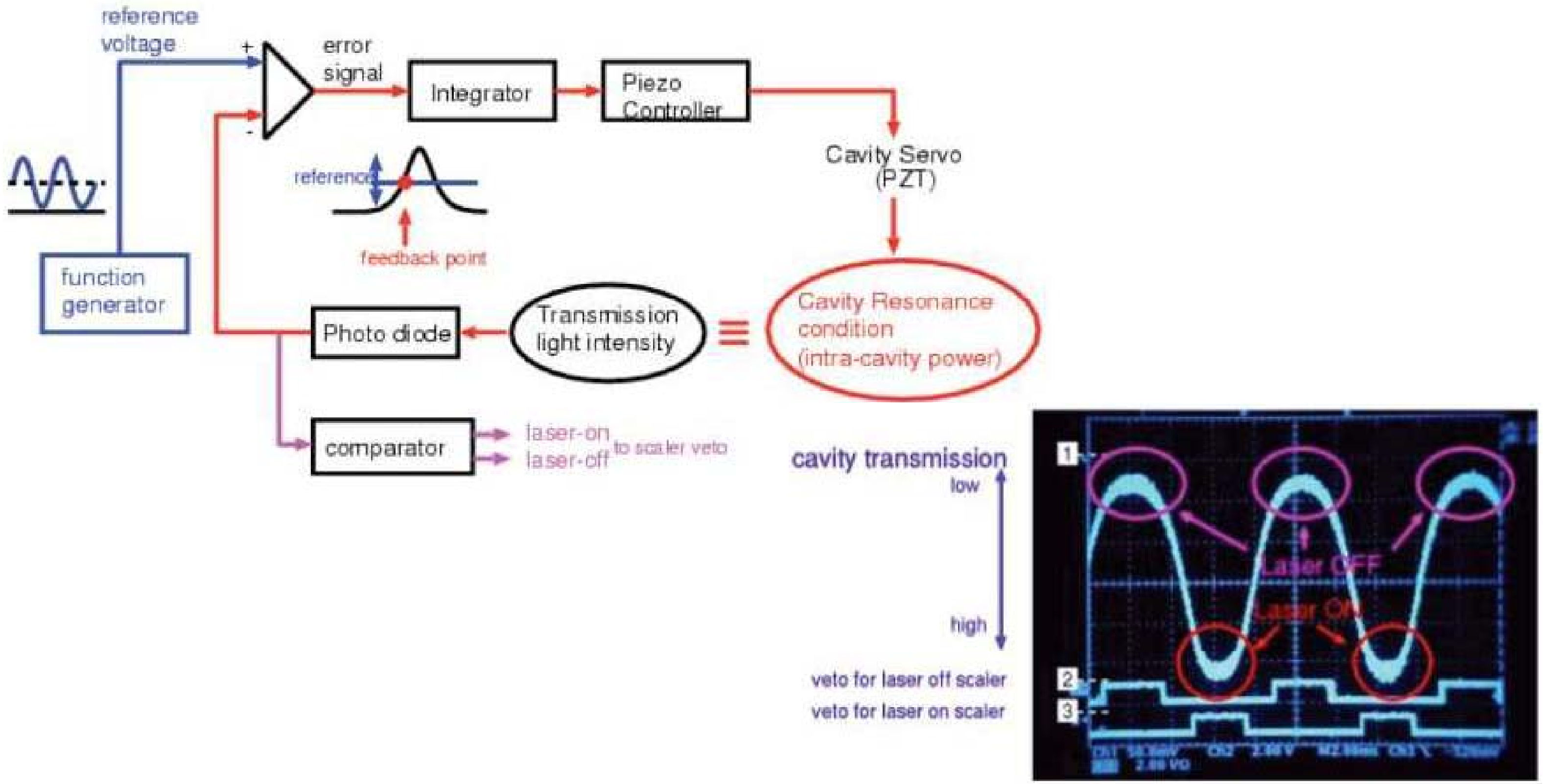




We use 0.997% mirror, F = 1000

Laser Control at Beam Size Measurement

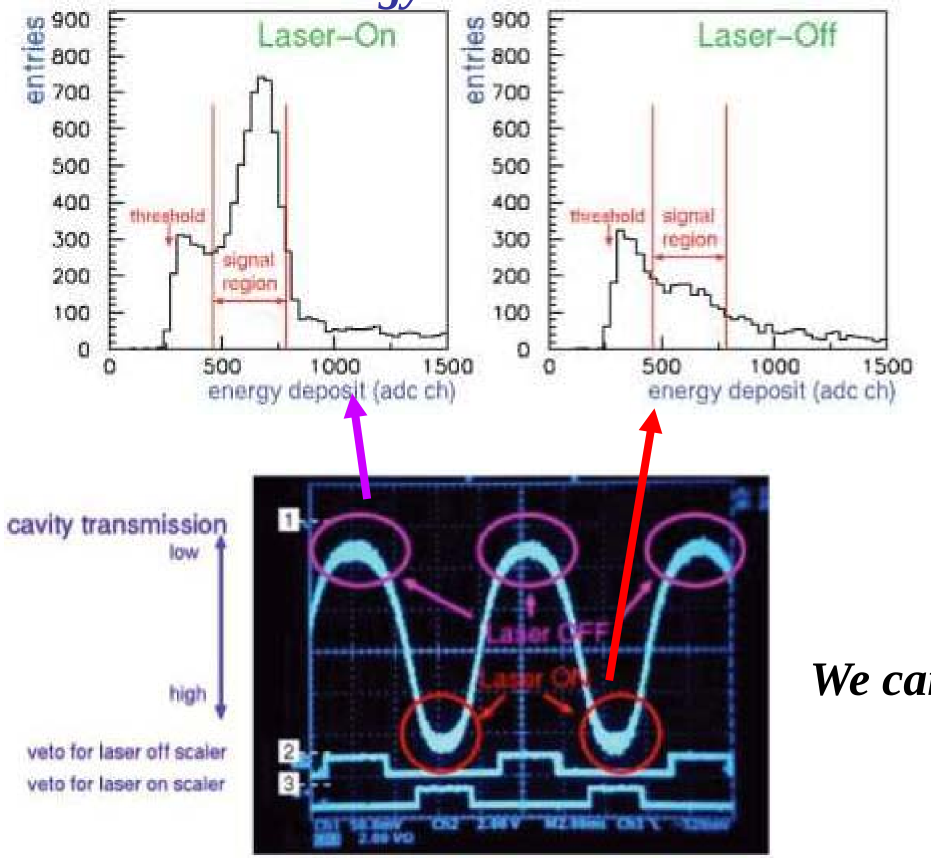
Cavity length is modulated with piezo actuator
to make laser on and off signal continuously .



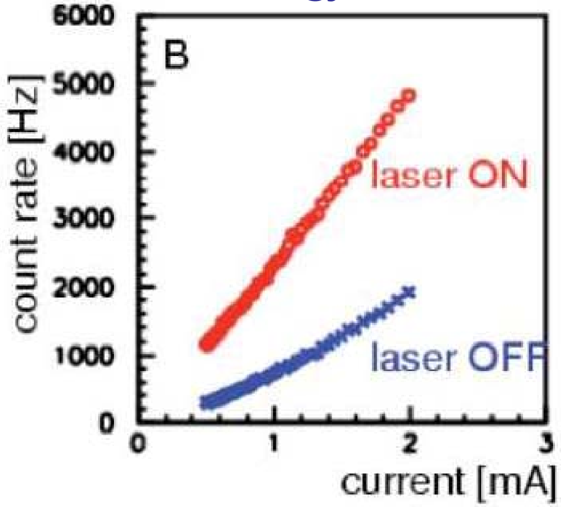
Measured Signal with CsI Scintillator

Since laser beam collision is occurred by 1 collision per 1000turn,
we can measure the each photon energy .

Energy distribution



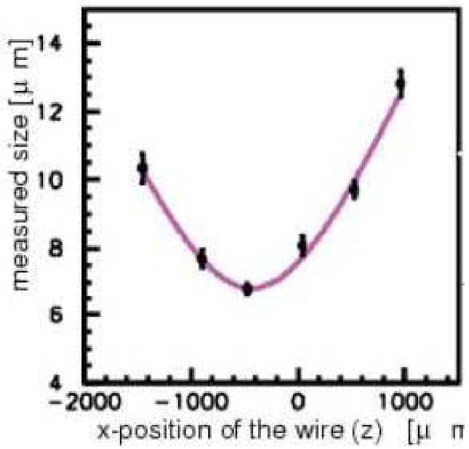
Collision rate
in energy window

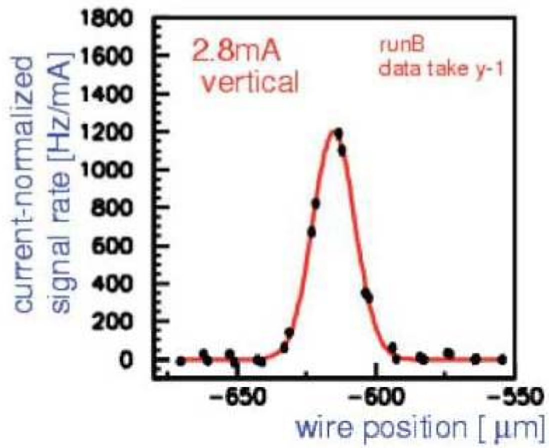


We can measure the on/off signal dependence

Beam Size Measurement

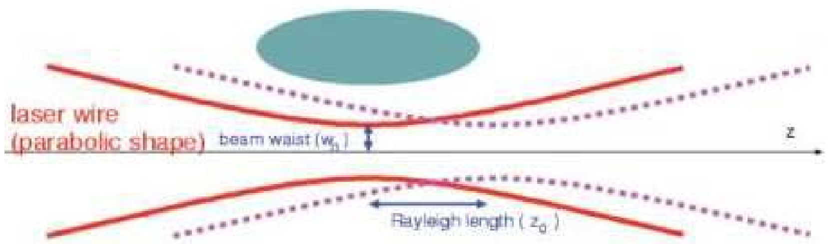
Since Rayleigh length is short (0.59mm for 5μm waist), we must adjust the beam center to the laser waist center.





Measured profile should subtract the effect of the laser wire waist.

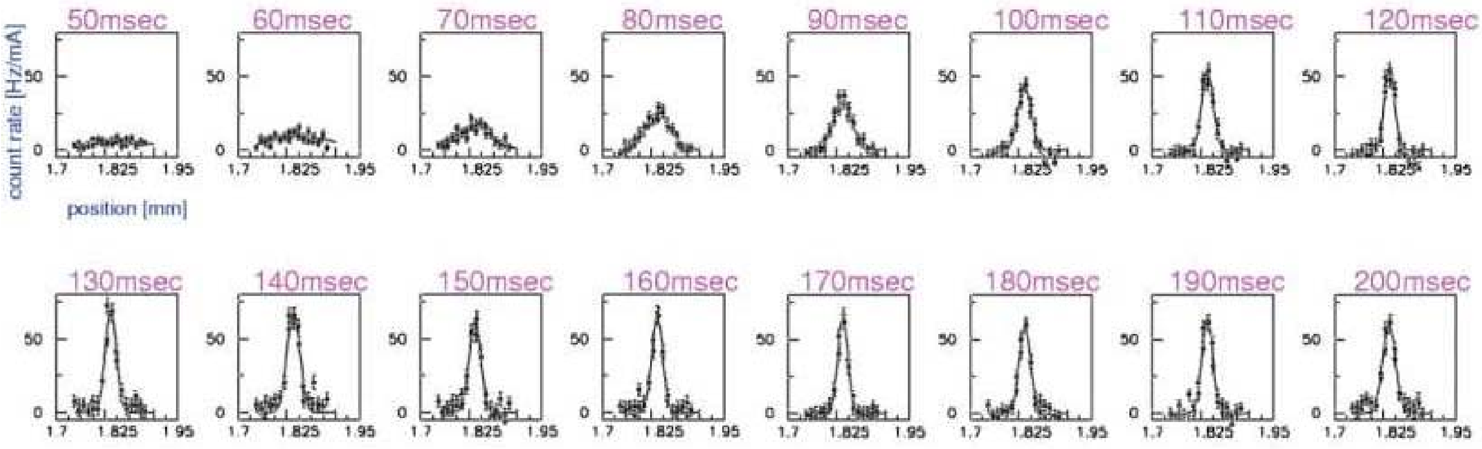
$$\sigma_e = \sqrt{\sigma_{meas}^2 - \sigma_{lw}^2}$$



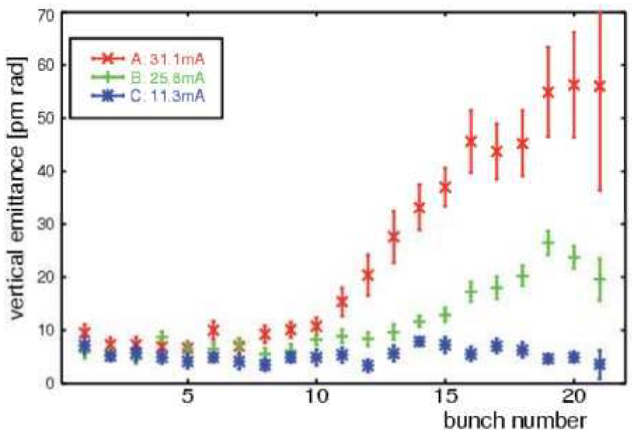
Measured minimum beam size is 5μm with 5μm rms. laser wire.

Further Application

***Beam damping measurement** with time gate*



***Multibanch beam measurement** with arrival time difference to the detector.*



We observed beam size enhancement by fast ion effect.

Comment

We believe this is not beam size enhancement, but the dipole oscillation .

Summary of Cavity based Laser Wire Scanner

-Dynamic range;

- defined by signal to noise ratio (100μm in ATF)

-Resolution ;

- determined by the laser waist (5μm in ATF)

-Accuracy;

-laser waist and waist position is stable by mode cleaning effect in optical cavity.

- affect to the beam jitter, and not to separate the beam jitter and beam size growth.

-Partly destructive

- used in storage ring, because of the small collision rate.

- Application to ILC

- can use in the damping ring

3-5. Synchrotron Radiation Monitor

Beam profile (beam size) measurement in the storage ring

- Cannot use the material target for the large beam loss

- Utilizing the special feature of storage ring – synchrotron radiation

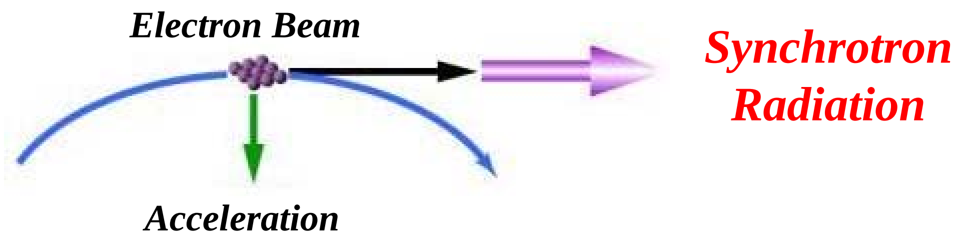
The synchrotron radiation monitor is useful for the beam instrumentation in the storage ring.

Synchrotron Radiation Monitor is used for

-Beam profile, beam size monitor
-Bunch length monitor

Synchrotron Radiation

Synchrotron radiation is emitted to the beam direction, when the beam has the bending filed.



Distribution of the radiation

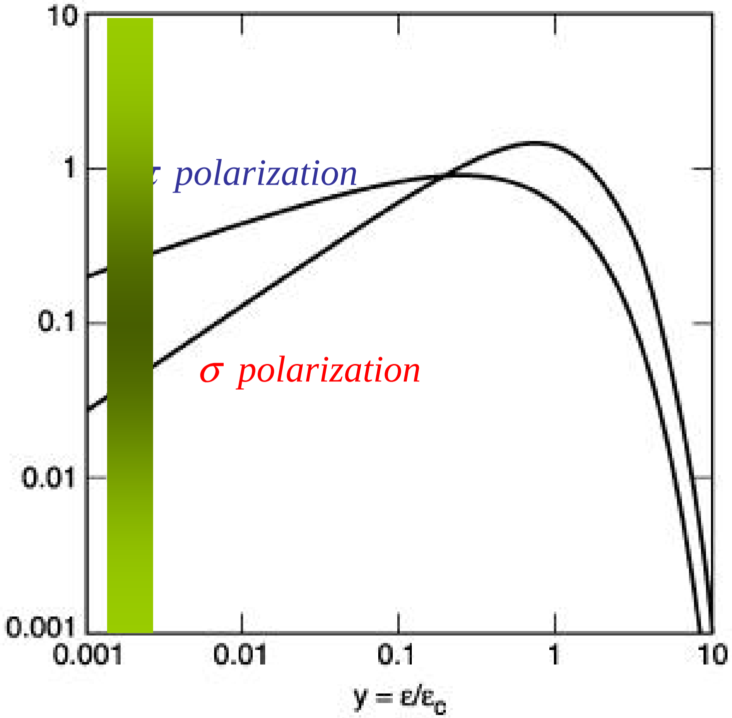
$$P(\lambda,\gamma,\psi_0,\rho,\Delta\lambda,I_B,\Delta\psi,\Delta\theta)=\int_{-\psi_0+\Delta\psi}^{+\psi_0+\Delta\psi}\frac{2}{3}\frac{e_0\Delta\lambda\Delta\theta\,I_B\,\rho^2}{\varepsilon_0\beta\lambda^4\gamma^4}\left[1+(\gamma\psi)^2\right]^2\left[\underbrace{K_{2/3}\left[\xi(\lambda,\psi)\right]^2}_{\sigma\ \text{polarization}}+\underbrace{\frac{(\gamma\psi)^2}{1+(\gamma\psi)^2}K_{1/3}\left[\xi(\lambda,\psi)\right]^2}_{\pi\ \text{polarization}}\right]$$

Energy Distribution of Synchrotron Radiation

Critical Energy of the Synchrotron Radiation

ε_c [keV] = 0.665 E^2 [GeV] B[T])

Visible Light



Example of the ATF beam

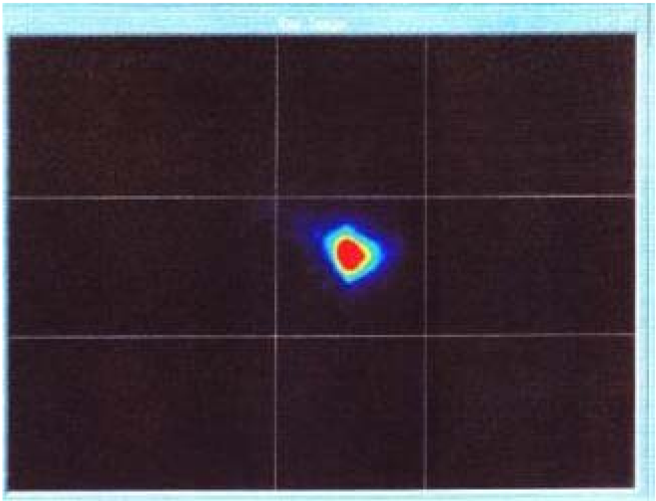
-1.3 GeV of the electron beam
-0.9 T of the bending field

$\boldsymbol{\varepsilon_c}$ **= 1 keV**

We can use the visible light,
since the energy distribution is wideband.

Measured Result of the Beam Profile

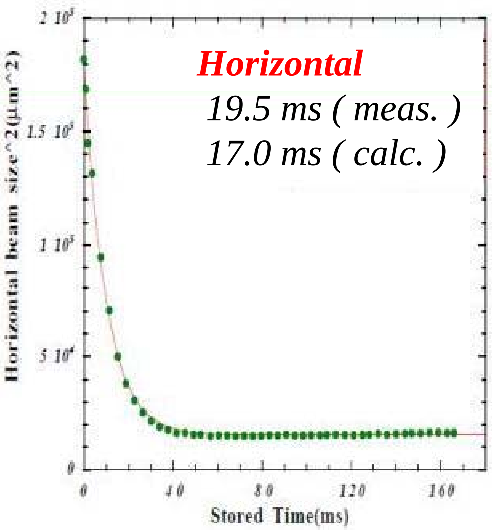
Measured Beam Image

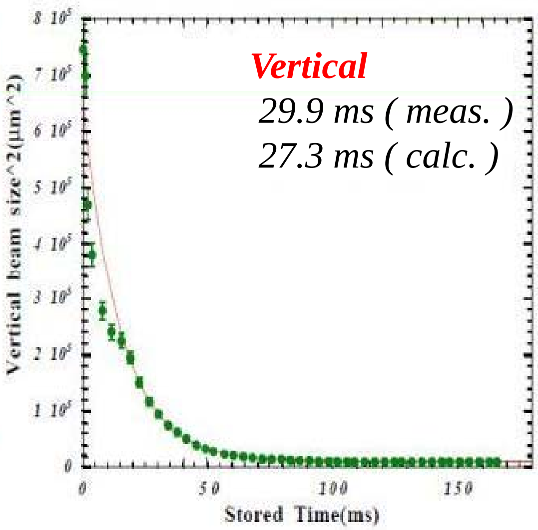


Gate interval ; 1ms

Time dependence of the beam size .

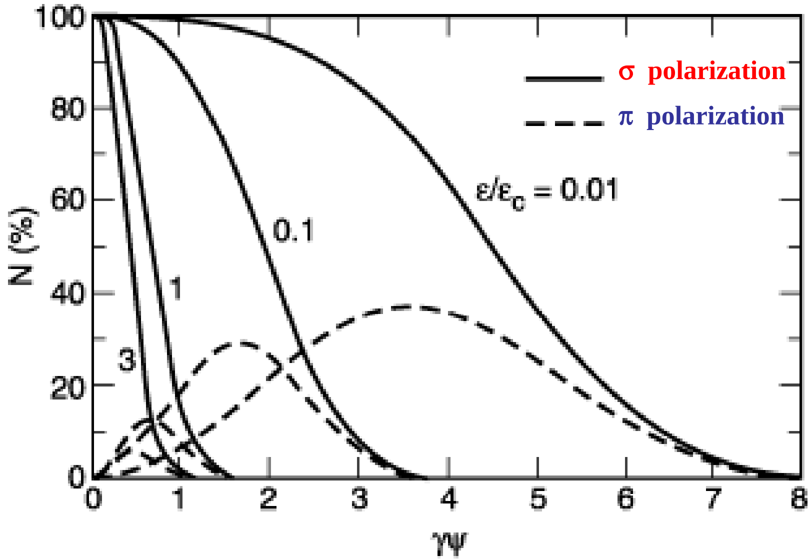
The beam size damping is measured by the SR monitor .





Measurable Limit for SR Beam Profile Monitor

Angular Distribution of the Synchrotron Radiation



$$\sigma_y > \frac{\lambda}{4\pi\sigma_\psi} = \frac{\gamma\lambda}{4\sqrt{2\pi}}\frac{1}{C(y)}$$

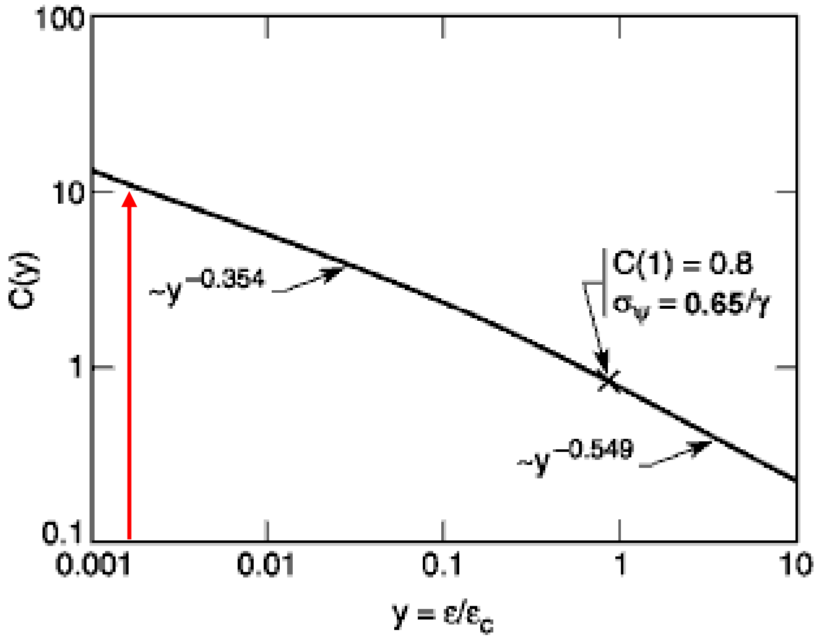
-1.3 GeV of electron beam
-0.9T of bending field
-500nm of the wave length

$\sigma_y > 12\mu m$

Beam Divergence of the Synchrotron Radiation

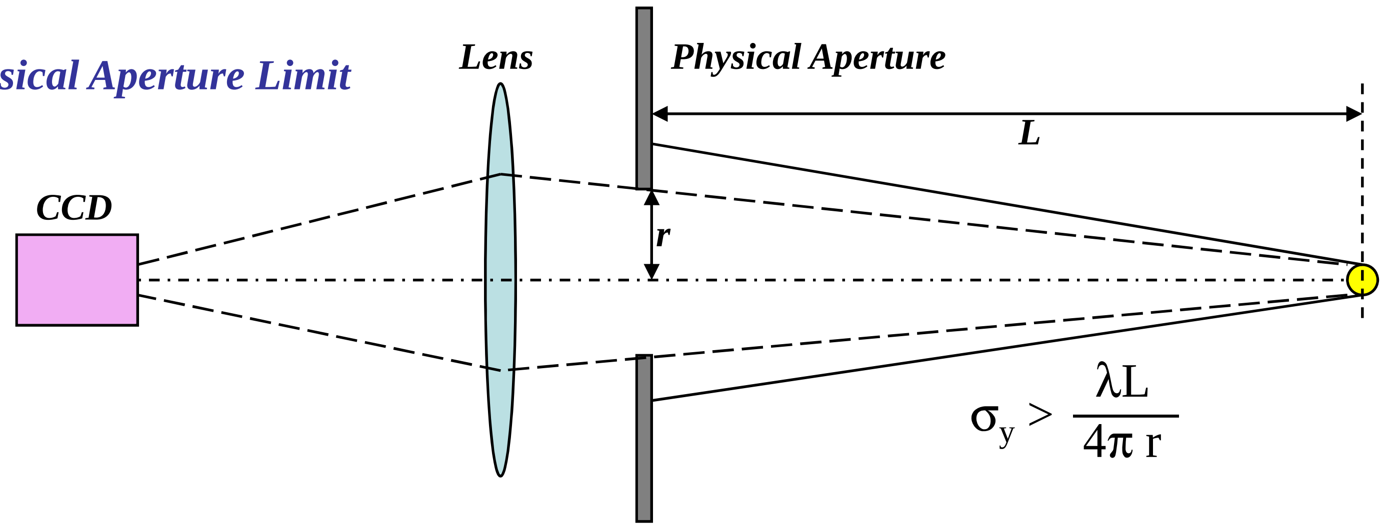
Synchrotron radiation occurs in a narrow cone of nominal angular width ~1/γ.

$$\sigma_\psi = \frac{1}{\gamma}\sqrt{\frac{2}{\pi}}\,C(y)$$

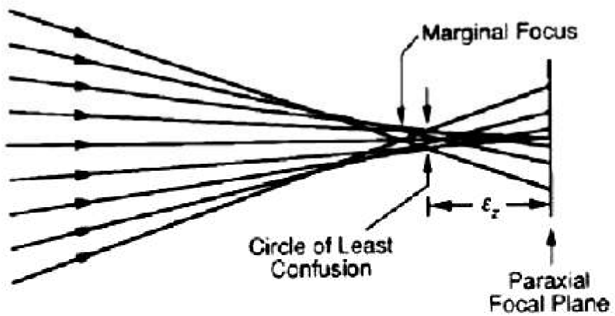


Other Limits to the Beam Profile Measurement

Physical Aperture Limit



Spherical Aberration of Lens



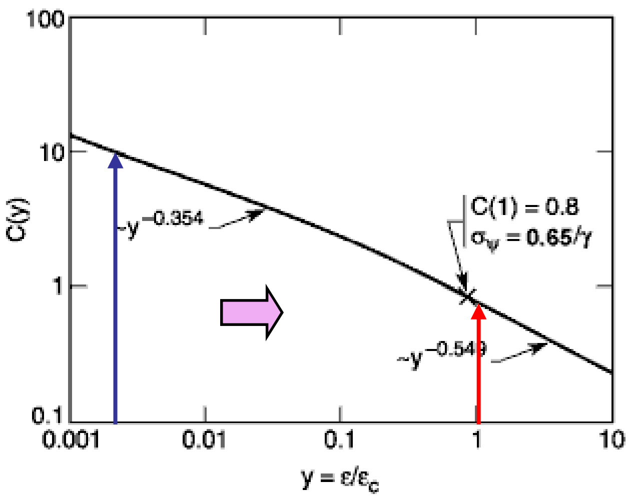
Summary of SR Beam Profile Monitor

- Dynamic range;
  - Depends on the magnification of the telescope (1mm for ATF setting)
- Resolution ;
  - Defined by the diffraction limit and others (30-50μm for ATF)
- Accuracy;
  - Since we accumulate the signal of more than 1ms interval, beam fluctuation affect to the measurement
- No destructive monitor
  - Possoble to use in the storage ring
  - Cannot use in the transport line for their small signal
- Application to ILC
  - can use in damping ring at large beam size.

3-6. X-ray Synchrotron Radiation Monitor

The monitor to measure the small beam size with SR light in the storage ring.

500nm → ***1nm***



Diffraction Limit

x 0.002

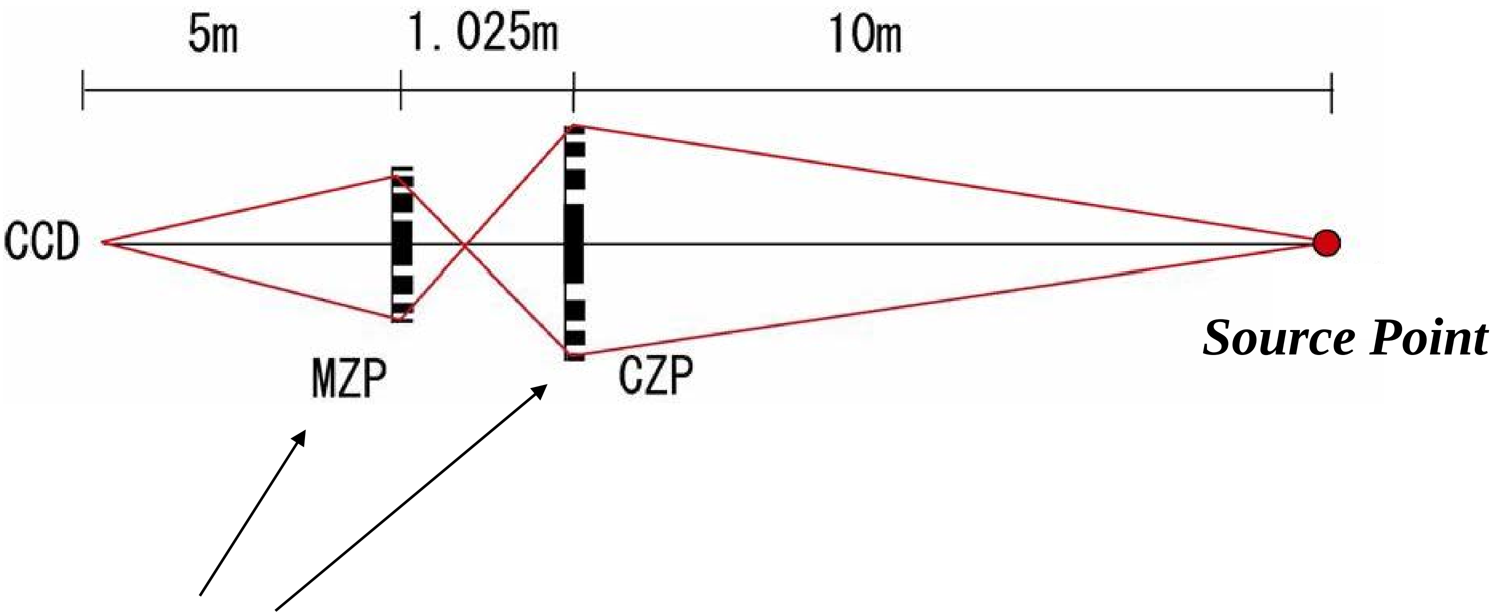
$$\sigma_y > \frac{\lambda}{4\pi\sigma_\psi} = \frac{\gamma\lambda}{4\sqrt{2\pi}}\frac{1}{C(y)}$$

x 0.1

When we used the 1nm X-ray for the beam size measurement, the diffraction limit is improved by factor 50 .

Physical aperture limit and the spherical aberration of lens also improved by the small divergence angle of X-ray .

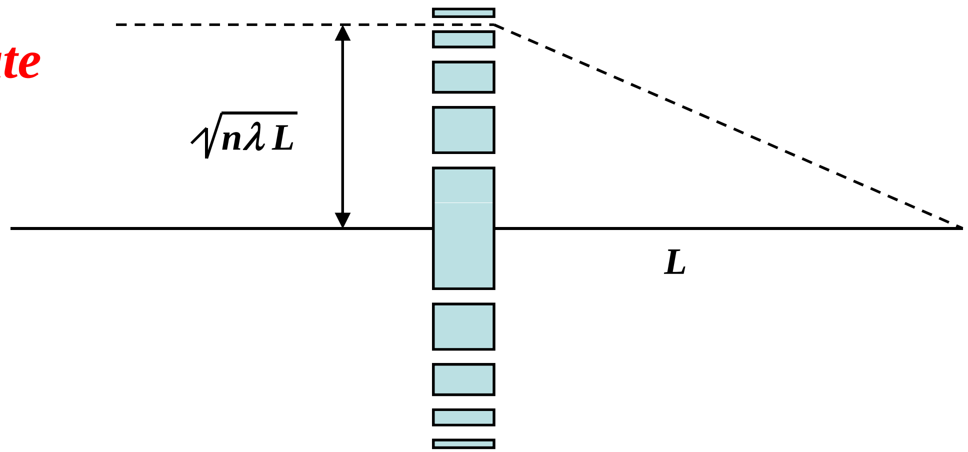
Principle of the X-ray SR Monitor



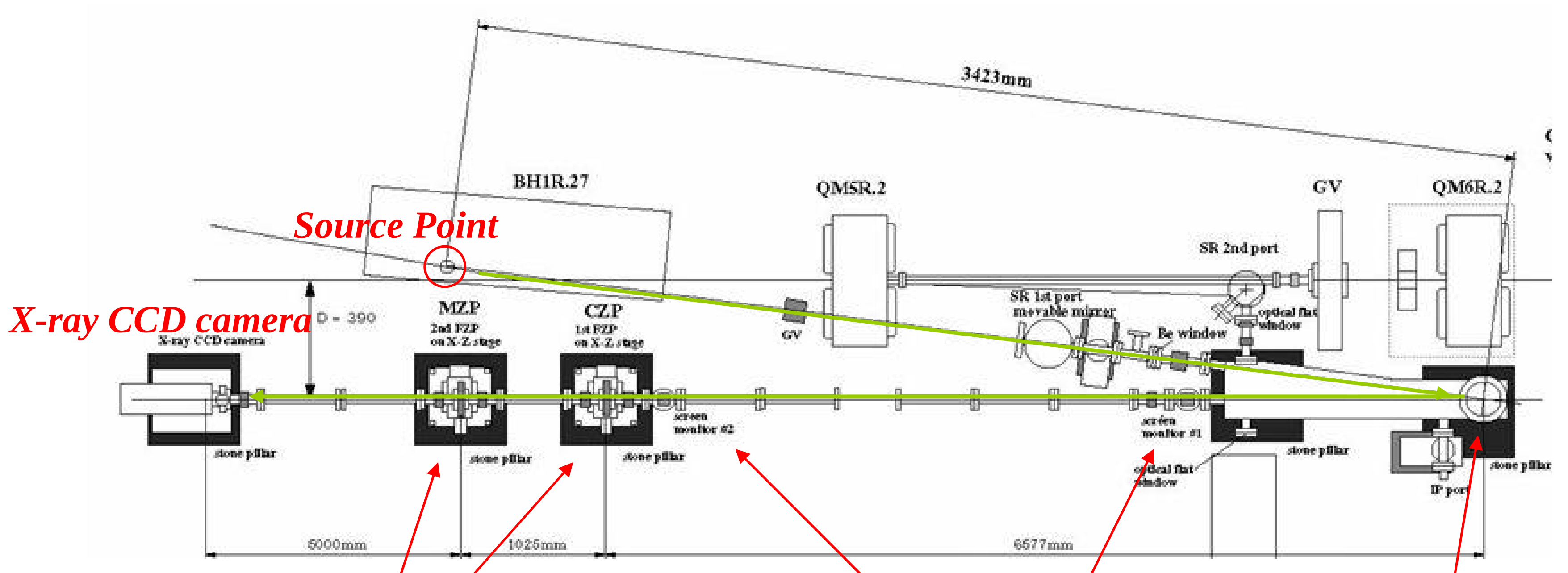
Fresnel Zone Plate

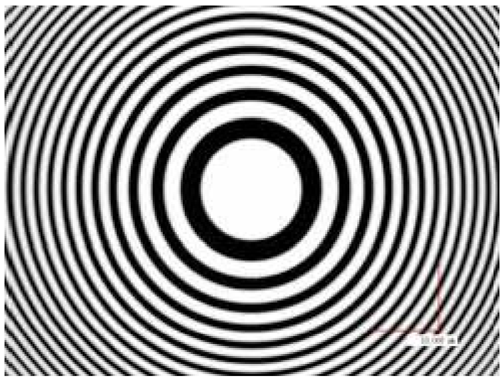
Lens for X-ray

$f = r_1^2/\lambda$

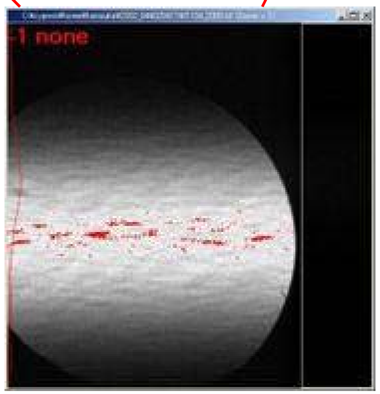


Experimental Setup





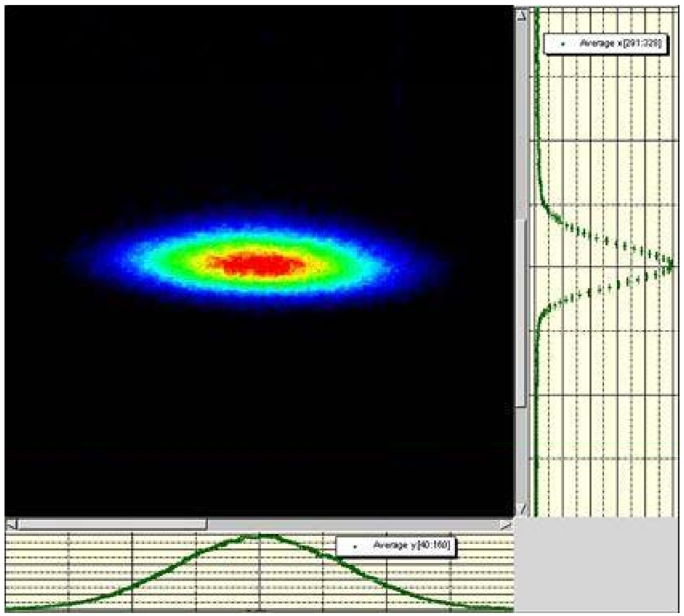
Fresnel Zone Plate



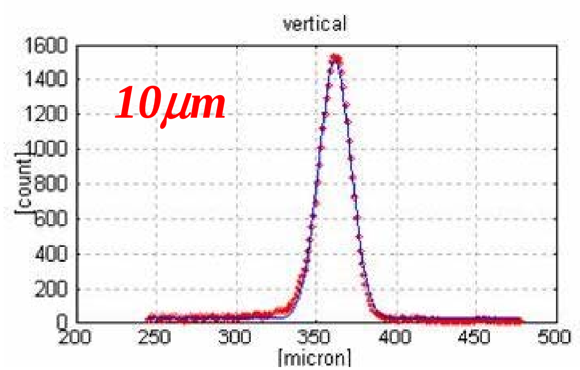
X-ray Screen

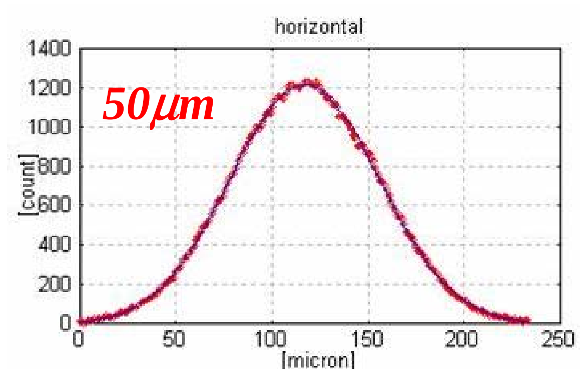
Measured Profile at ATF

Measured Profile at ATF damping ring



Shutter Interval ; 1ms





Summary of XSR Beam Profile Monitor

- *Dynamic range;*
  - *Depends on the magnification of the telescope (500mm for ATF setting)*
- *Resolution ;*
  - *Defined by the diffraction limit and others (1mm for ATF)*
- *Accuracy;*
  - *Since we accumulate the signal of more than 1ms interval, beam fluctuation affect to the measurement*
- *No destructive monitor*
  - *Possoble to use in the storage ring*
  - *Cannot use in the transport line for their small signal*
- *Application to ILC*
  - *can use in damping ring at small beam size.*

Session 4

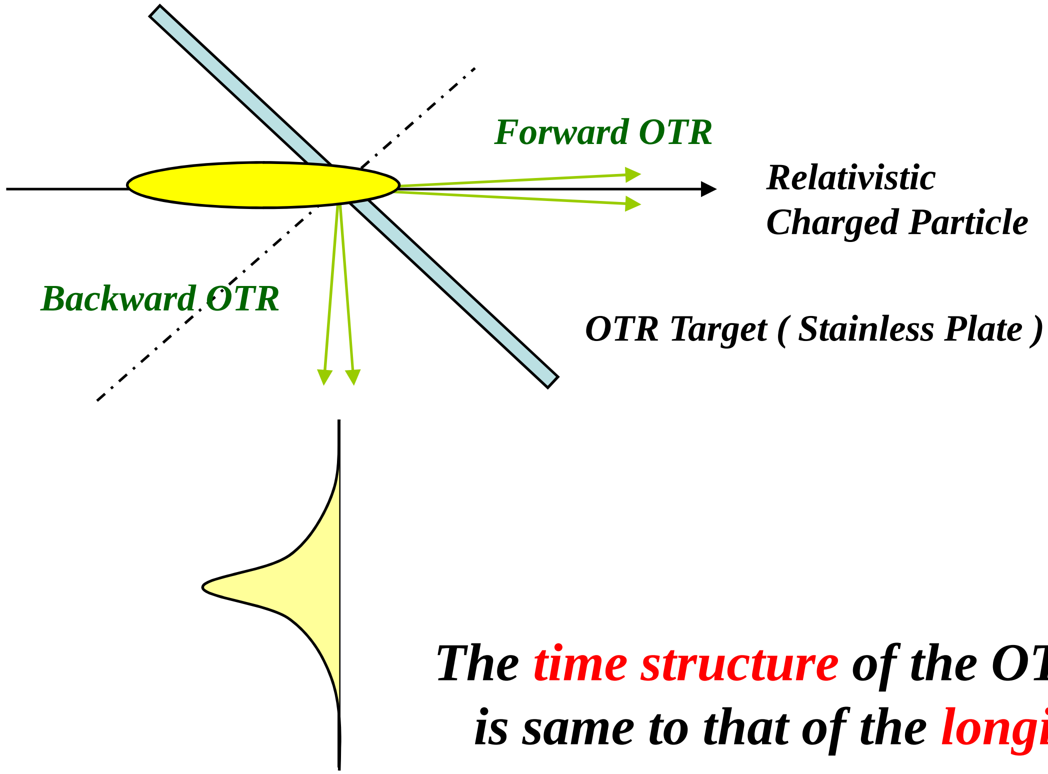
Bunch Length Monitors

4-1. OTR, ODR monitors

4-2. Synchrotron Radiation Monitor

4-1. OTR, ODR monitors

OTR is also used for the bunch length measurement

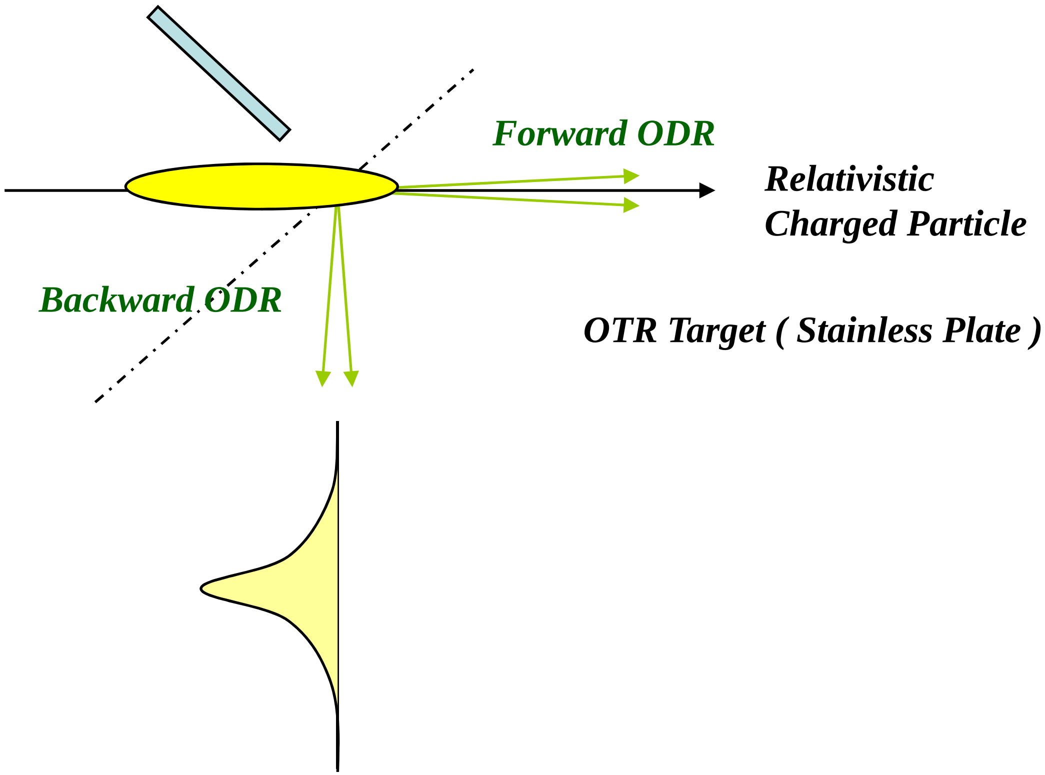


The time structure of the OTR light is same to that of the longitudinal profile of the beam.

Optical Diffraction Radiation (ODR)

- *When the beam pass through near by the conductive target, optical diffraction radiation (ODR) is emitted.*

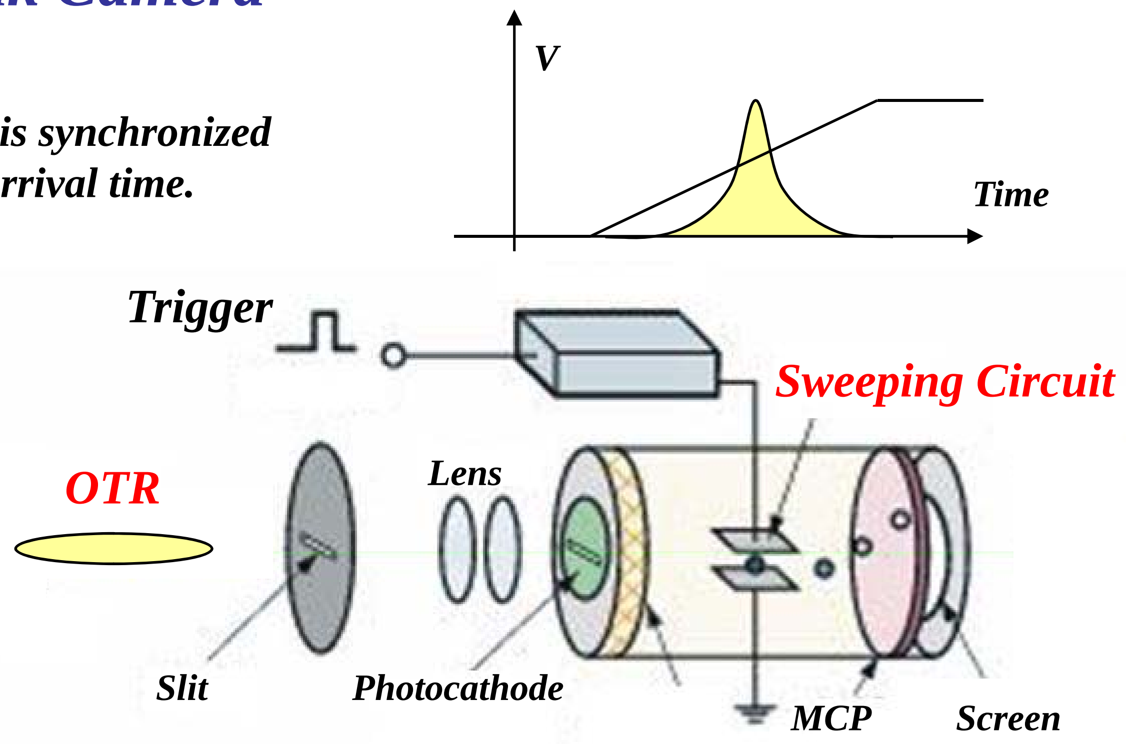
- *The time structure of the ODR light also has same time structure of the beam.*

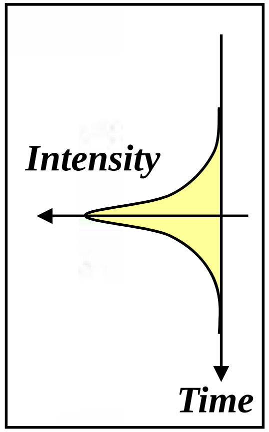


Apparatus of the Bunch Length Measurement

Streak Camera

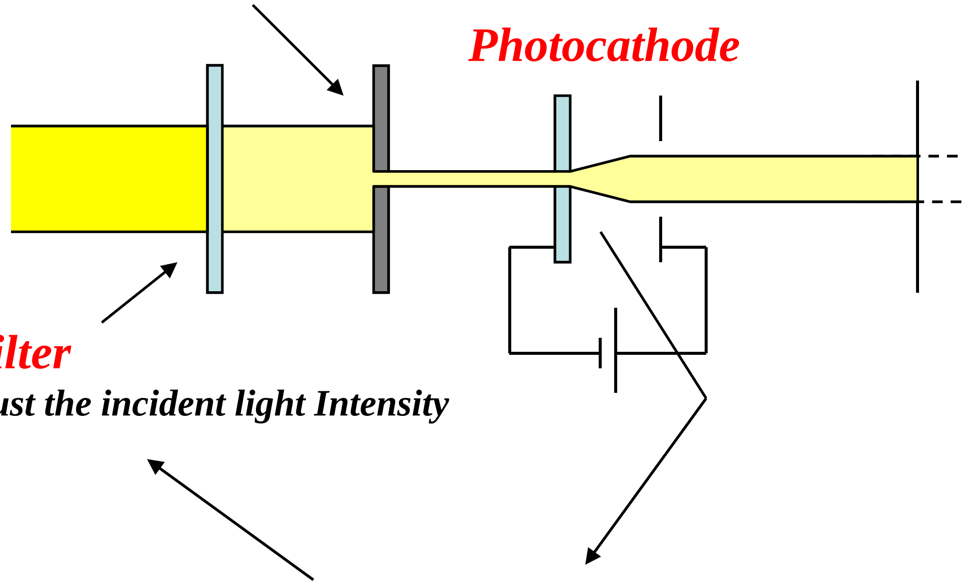
Trigger timing is synchronized to the beam arrival time.





The time information is converted to the space information on the screen

To make accurate measurement

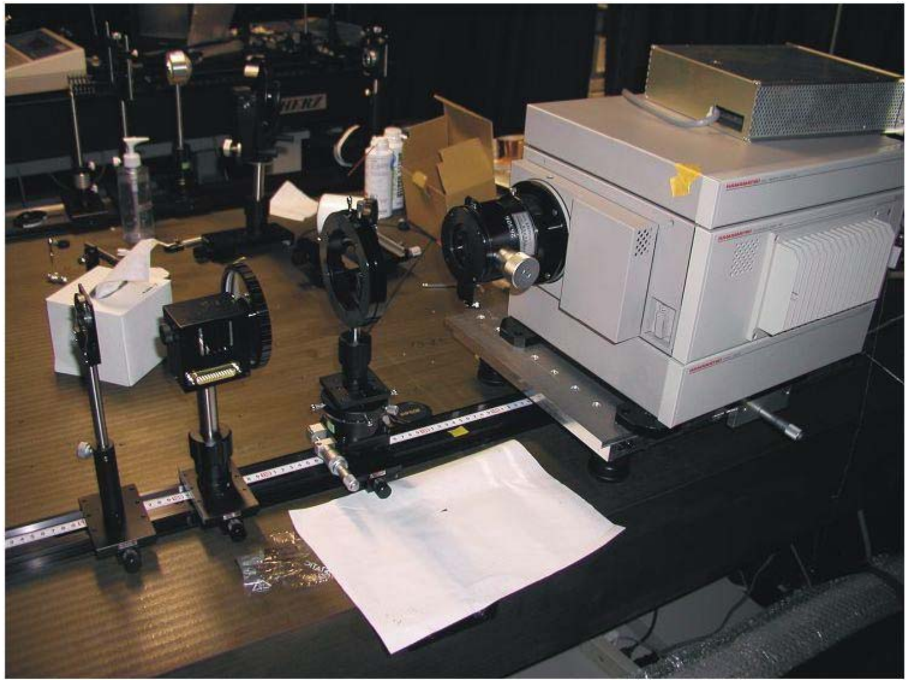


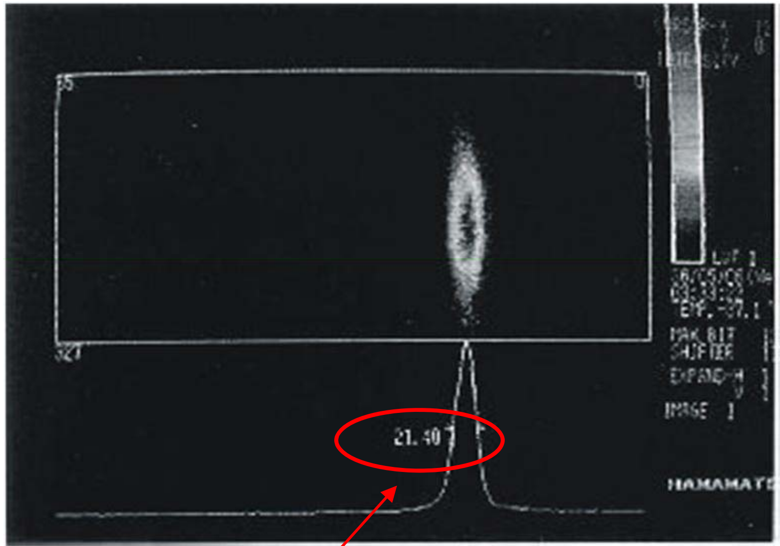
This size is affect to the bunch length measurement.

At the exit of the photocathode,
the electron energy is small to affect the electron spot size.
The amount of space charge effect is depends on the intensity.

Bunch Length Measurement in ATF Linac

Apparatus of the Stream Camera





Bunch Length measured by streak camera

Summary of OTR, ODR Bunch Length Monitor

-Dynamic range;

10ps – 10μs (depends on the performance of the streak camera)

- defined by the rise time of the sweeping circuit of the streak camera.

-Resolution ;

100fs – 100ps (depends on the performance of the streak camera)

- defined by the voltage of the sweeping circuit of the streak camera

-Accuracy;

- depends on the voltage of the photocathode of the streak camera

and beam size and intensity of the OTR, ODR light on the streak camera

-Destructive

- OTR is destructive, but ODR is not destructive

-Application to ILC

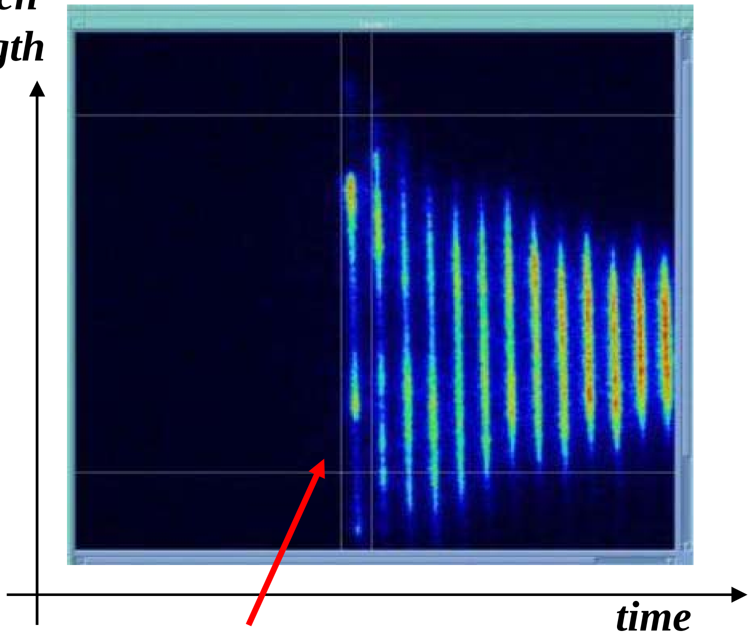
- OTR monitor can use as the bunch length monitor at injector

- ODR monitor can use as the bunch length monitor after RTML

4-2. Synchrotron Radiation Monitor

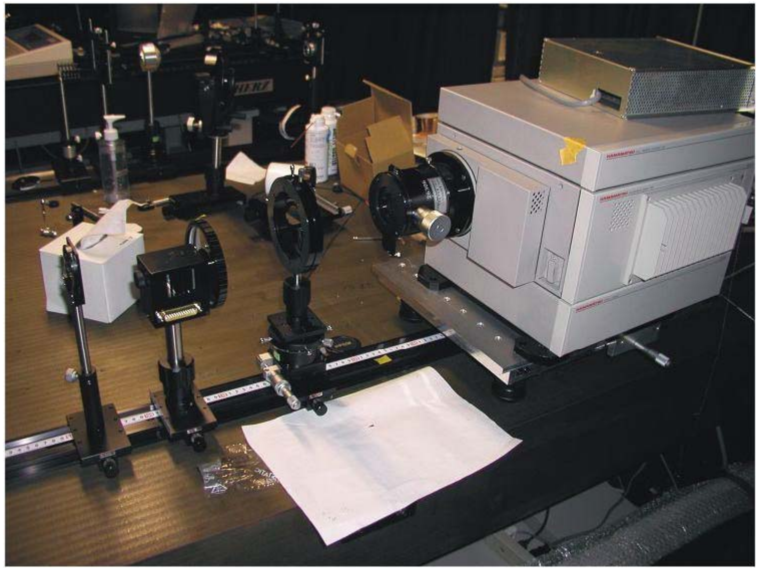
Measured bunch Length with Streak Camera

Bunch Length



time

Injection timing

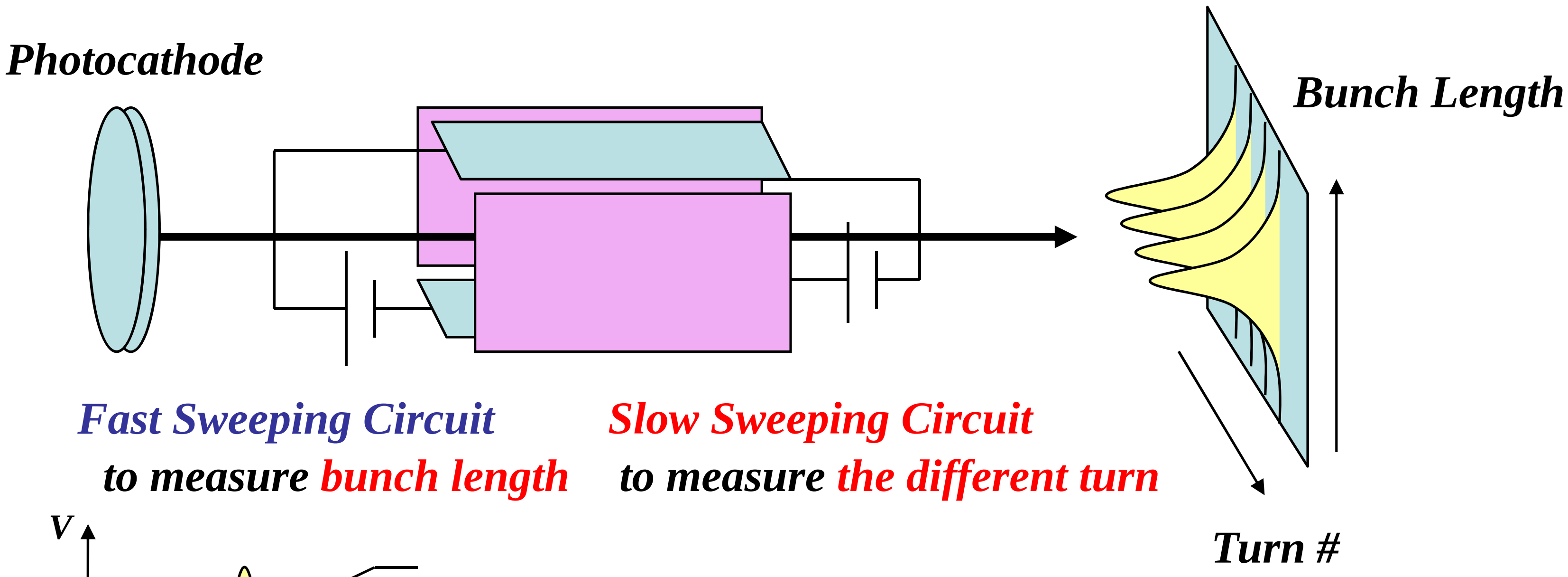


Bunch length shorten in time.

Since the bunch length can be measured at the single shot, the variation of the bunch length and the longitudinal oscillation can be observed with the streak camera.

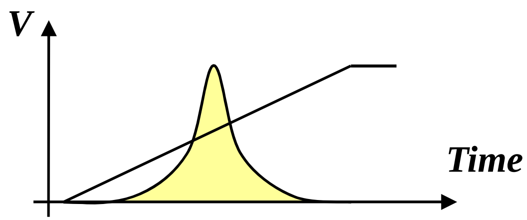
Streak Camera for Storage Ring

For the bunch length measurement in storage ring, we can measure the bunch length of several turn with slow sweeping circuit.



Fast Sweeping Circuit
to measure bunch length

Slow Sweeping Circuit
to measure the different turn



Summary of SR Bunch Length Monitor

-Dynamic range;

- Depends on the sweeping circuit of the streak camera.
(1ns for ATF)

-Resolution ;

- Defined by the HV of the photocathode and light intensity
(10ps for ATF)

-Accuracy;

- Good for the single shot measurement.
- Need to take care of the incident light intensity to the streak camera

-No destructive monitor

- Can use in the storage ring

- Application to ILC

- can use as the bunch length monitor in damping ring

Summary Table of the Beam Instrumentations

	Injector	Damping Ring	Main Linac
Beam Position	Stripline BPM	Button BPM	Cavity BPM
Beam Current	Wall Current ICT	Wall Current ICT DCCT	Wall Current ICT
Beam Size	Screen, OTR Wire Scanner	SR, XSR Cavity Laser Wire	Pulse Laser Wire
Bunch Length	OTR	SR	ODR

Session 5

Beam Emittance Measurement

5-1. Emittance Measurement at Beam Transport Line

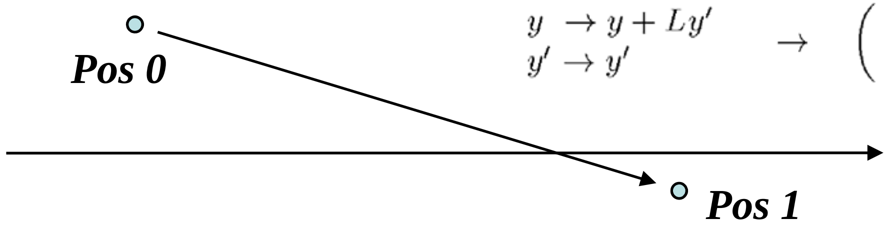
5-2. Emittance Measurement in Storage Ring

Single Particle Dynamics

1) Free Space

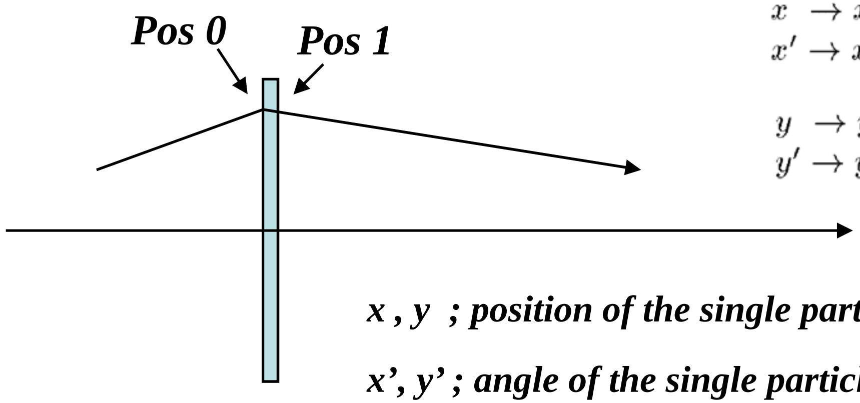
$$\begin{array}{l} x \to x + Lx' \\ x' \to x' \end{array} \quad \to \quad \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix} = \begin{pmatrix} 1 & \mathrm{L} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}$$

$$\begin{array}{l} y \to y + Ly' \\ y' \to y' \end{array} \quad \to \quad \begin{pmatrix} y_1 \\ y'_1 \end{pmatrix} = \begin{pmatrix} 1 & \mathrm{L} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$



Transfer Matrix

2) Quadrupole Magnet (Thin-lenz Approximation)



$$\begin{array}{l} x \to x \\ x' \to x' - Kx \end{array} \quad \to \quad \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -K & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}$$

$$\begin{array}{l} y \to y \\ y' \to y' + Ky \end{array} \quad \to \quad \begin{pmatrix} y_1 \\ y'_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ +K & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$

$$K \cong \frac{0.3L[\mathrm{m}]}{E[\mathrm{GeV}]} \frac{\partial B_y}{\partial x}$$

x , y ; position of the single particle

x', y' ; angle of the single particle

Transfer Matrix

In general, the transfer matrix between 2 position is expressed as

$$\boldsymbol{M} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\psi + \alpha_1 \sin\Delta\psi) & \sqrt{\beta_1\beta_2}\sin\Delta\psi \\ \frac{\alpha_1 - \alpha_2}{\sqrt{\beta_1\beta_2}}\cos\Delta\psi - \frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\Delta\psi & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\Delta\psi - \alpha_2\sin\Delta\psi) \end{pmatrix}$$

$$= \begin{pmatrix} \sqrt{\beta_2} & 0 \\ -\alpha_2/\sqrt{\beta_2} & 1/\sqrt{\beta_2} \end{pmatrix} \begin{pmatrix} \cos\Delta\psi & \sin\Delta\psi \\ -\sin\Delta\psi & \cos\Delta\psi \end{pmatrix} \begin{pmatrix} 1/\sqrt{\beta_1} & 0 \\ \alpha_1/\sqrt{\beta_1} & \sqrt{\beta_1} \end{pmatrix}$$

$$= T^{-1}(s_2) \begin{pmatrix} \cos\Delta\psi & \sin\Delta\psi \\ -\sin\Delta\psi & \cos\Delta\psi \end{pmatrix} T(s_1)$$

$$T(s) \equiv \begin{pmatrix} 1/\sqrt{\beta_z(s)} & 0 \\ \alpha_z(s)/\sqrt{\beta_z(s)} & \sqrt{\beta_z(s)} \end{pmatrix}$$

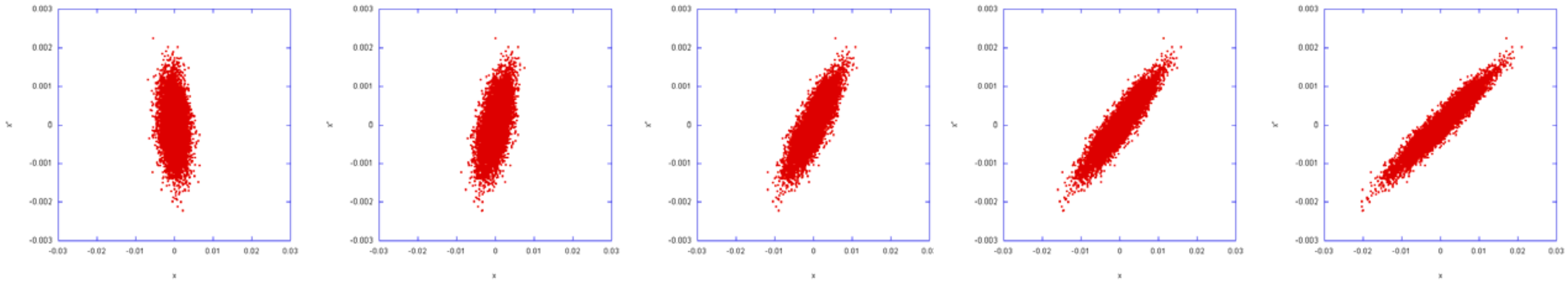
When we define to $V = \begin{pmatrix} u \\ v \end{pmatrix} \equiv T \begin{pmatrix} z \\ z' \end{pmatrix}$***, V moves circular motion as***

$$V_1 = \begin{pmatrix} \cos\Delta\psi & \sin\Delta\psi \\ -\sin\Delta\psi & \cos\Delta\psi \end{pmatrix} V_0$$

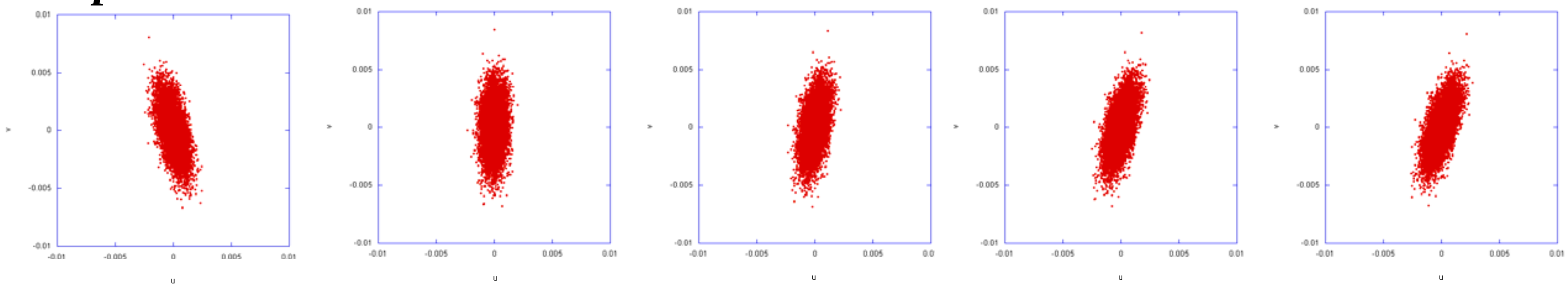
Behavior as a Beam

We can select any set of (α,β), mathematically.

x-x' space



u-v space

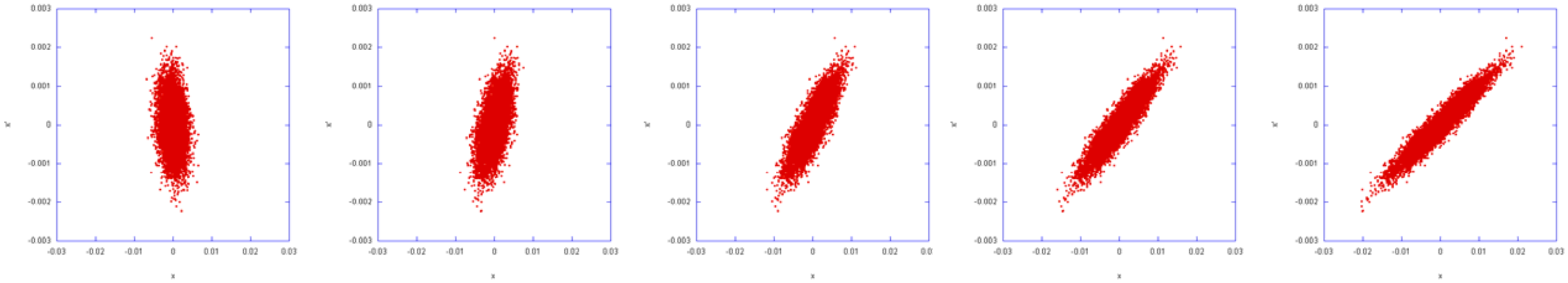


For any set of the (α,β),
all of the linear transformation in (x,x') plane
is expressed as the rotation in (u,v) plane.

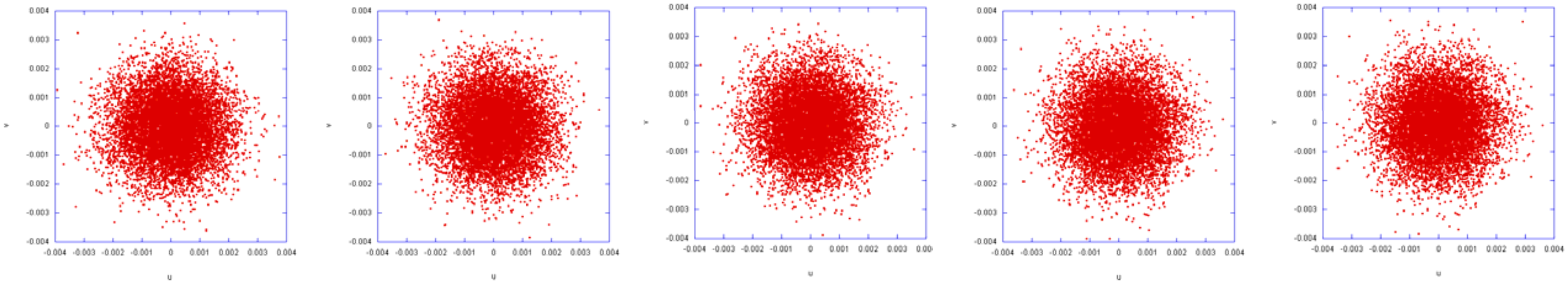
Twiss Parameters

However, when we select the special set of (α,β) , the beam distribution in u-v space is round shape .

x-x' space



u-v space



By selecting the Twiss parameters α, β

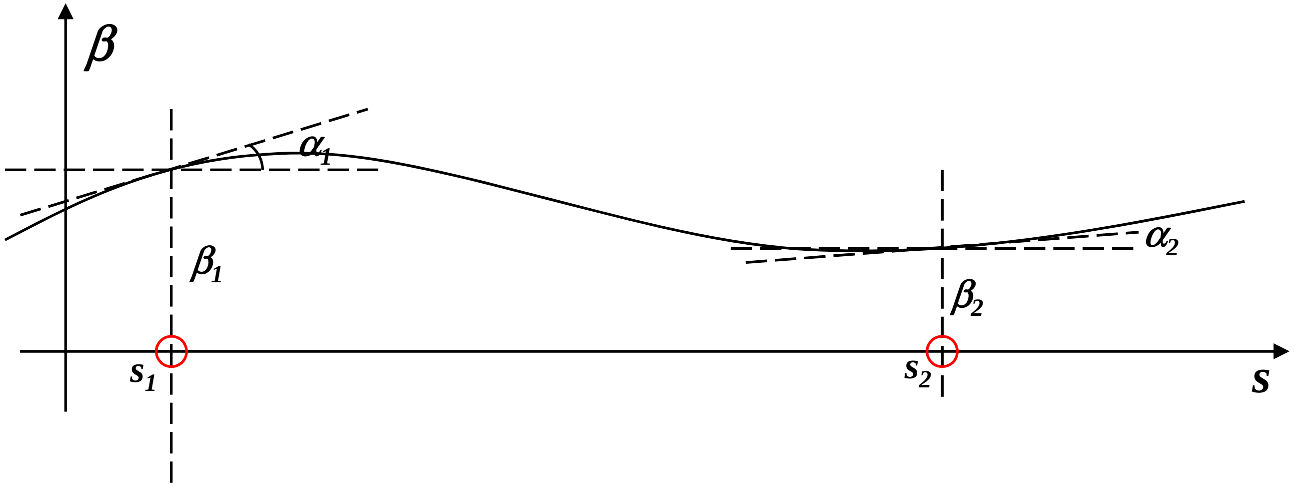
$$< u^2 >=< v^2 >= \varepsilon$$

Emittance

$$< uv >= 0$$

$$\begin{aligned}
< x^2 > &= \beta < u^2 >= \beta\varepsilon \\
< xx' > &= < uv > -\alpha < u^2 >= -\alpha\varepsilon \\
< x'^2 > &= \frac{< v^2 > -2\alpha < uv > +\alpha^2 < u^2 >}{\beta} = \frac{1+\alpha^2}{\beta}\varepsilon = \gamma\varepsilon
\end{aligned}$$

Transfer of the Twiss Parameters

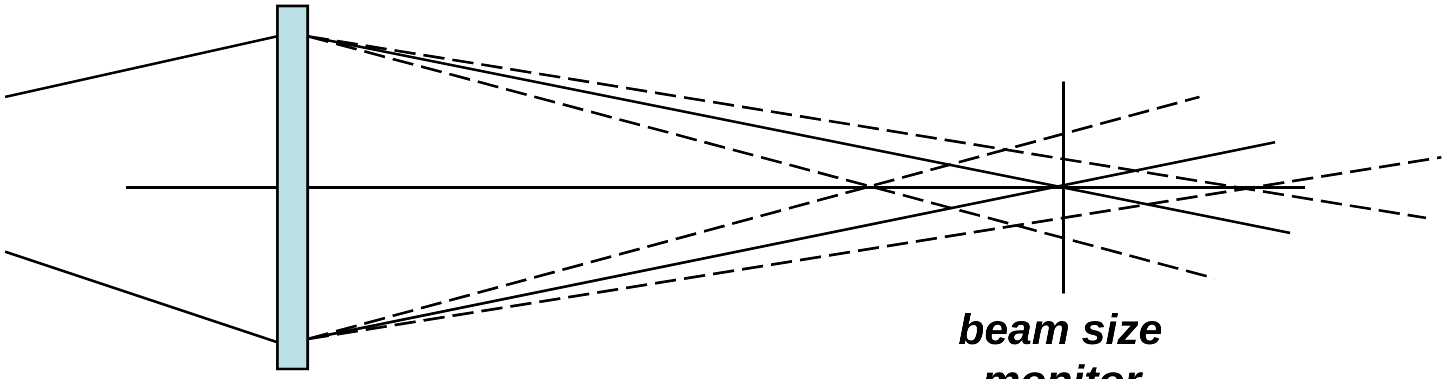


Once Twiss parameters are defined,
the transportation of the Twiss parameters along the beam line
are calculated by the following formula with "transfer matrix" .

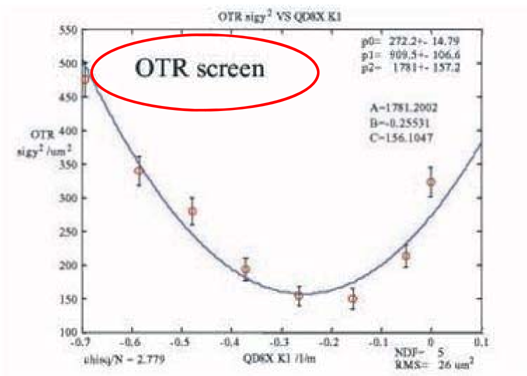
$$\begin{pmatrix} \beta_2 \\ \alpha_2 \\ \gamma_2 \end{pmatrix} = \begin{pmatrix} M_{11}^2 & -2M_{11}M_{12} & M_{12}^2 \\ -M_{21}M_{11} & 1+2M_{12}M_{21} & -M_{12}M_{22} \\ M_{21}^2 & -2M_{22}M_{21} & M_{22}^2 \end{pmatrix} \begin{pmatrix} \beta_1 \\ \alpha_1 \\ \gamma_1 \end{pmatrix}$$

Emittance Measurement by Waist Scan

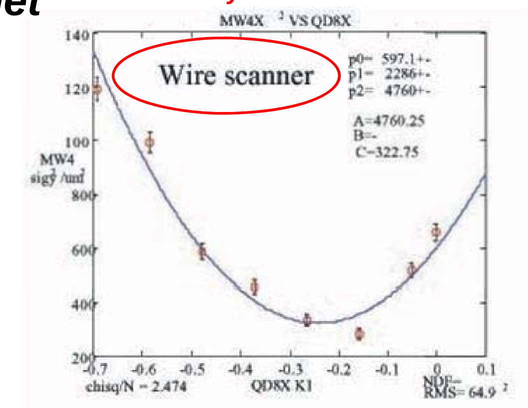
Beam Emittance can be measured
by measuring the beam size for various magnet setting.



ε_y = 41pm



ε_y = 38pm



$$\sigma_x^2 = B_x (K - A_x)^2 + C_x$$

$$\varepsilon_x = \frac{\sqrt{B_x C_x}}{m_{12}^2}$$

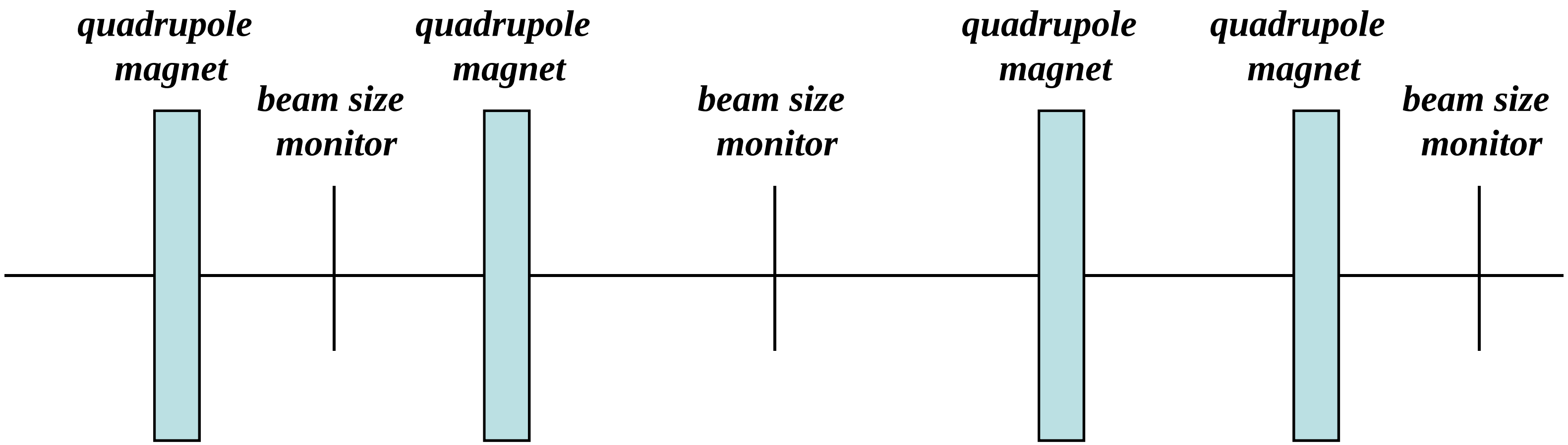
$$\beta_{x,0} = \sqrt{\frac{B_x}{C_x}}$$

$$\alpha_{x,0} = \frac{m_{11} - m_{12} A_x}{m_{12}} \beta_0$$

We can measure the emittance with one beam size monitor and we don't need the special emittance measurement section .

But, we must change the optics in the emittance measurement.

Emittance Measurement with several Beam Size Monitors



Free parameters are $\alpha, \beta, \varepsilon$.

We need at least 3 beam size monitors to measure the emittance.

We can measure the emittance without optics modifications.

But, we must make a long emittance measurement section in the beamline.

How to put the Beam Size Monitor for the Emittance Measurement

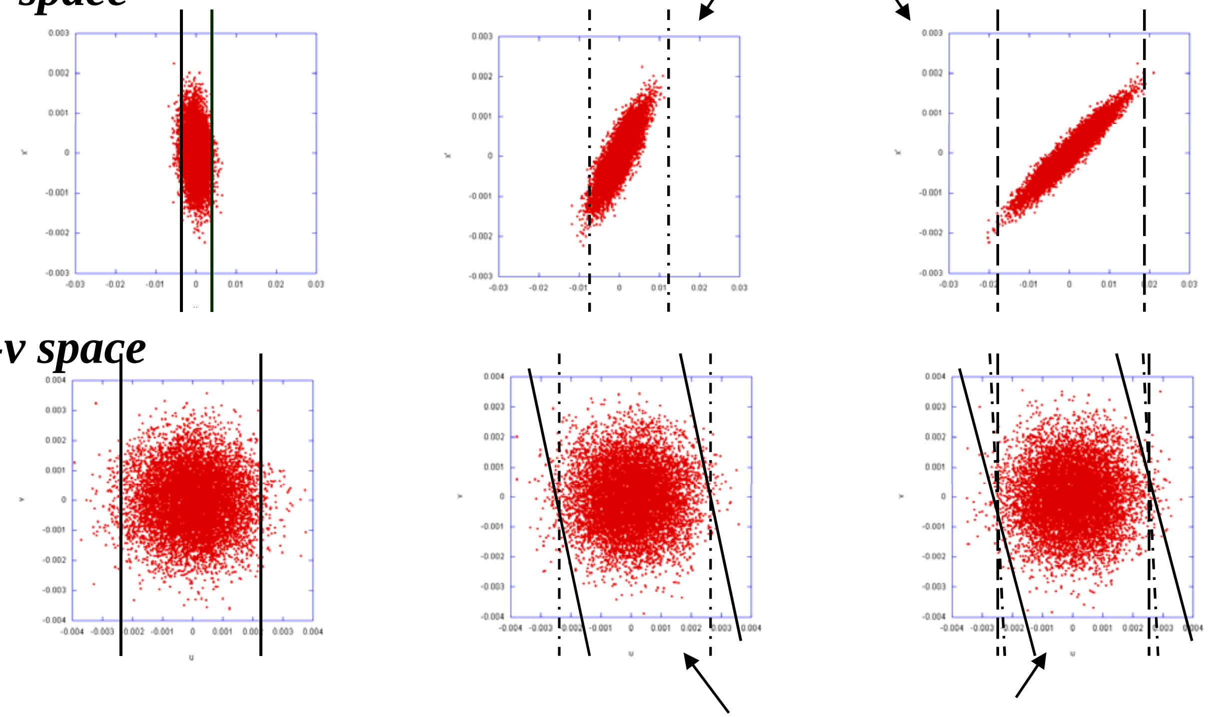
Example ;

Phase Space change along the beam line for the drift space beam travel.

Beam size difference is large !

x-x' space

u-v space



Phase advance is small !

These 2 measurement is not independent .

In order to make the measurements independent, we must put the beam size monitors to be appropriate phase advances.

How to put the Beam Size Monitor for the Emittance Measurement

3 Beam Profile Monitor ;

60 degrees of phase advances in between monitors are better setting.

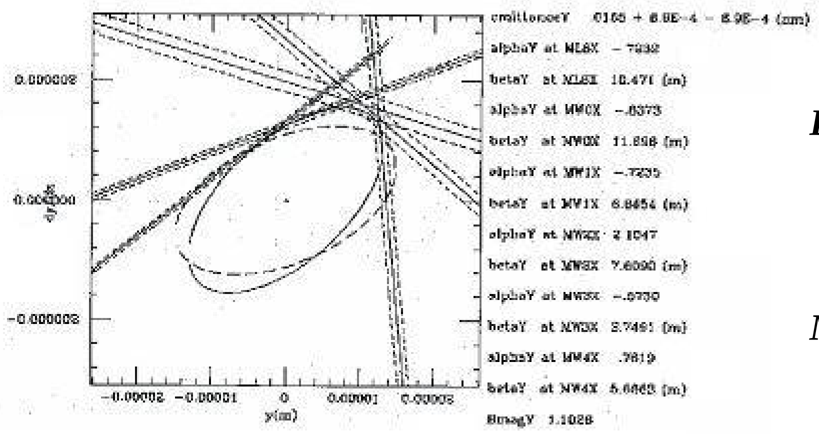
4 Beam Profile Monitor ;

40-50 degrees of phase advances are better setting.
We can evaluate the error of the emittance measurement system.

5 beam Profile Monitor ;

30-50 degrees of phase advance are better setting.
We can make a cross check of each measurement .

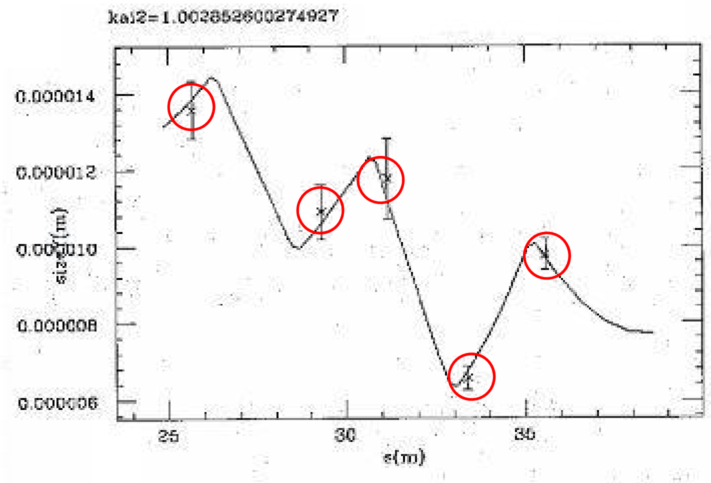
Emittance Measurement at ATF



Beam size are measured with 5 wire scanners .

- The measurement required at least 3 beam size monitor.
- The others are for the consistency check.

Measured vertical emittance is 16.5 pm.



Beam Size along the beam line

- ***Cross is the measurement.***
- ***Solid line is expected beam size along the beam line.***

Summary of Emittance Measurement at Beam Transport Line

Emittance Measurement by Waist Scan

- ***We can measure the emittance with one beam size monitor and we don't need the special emittance measurement section .***
- ***We must change the optics in the emittance measurement.***

Emittance Measurement with several Beam Size Monitors

- ***We need at least 3 beam size monitors to measure the emittance.***
- ***We can measure the emittance without optics modifications. We can use the beam at the downstream beam apparatus.***
- ***We must make a long emittance measurement section in the beamline.***

5-2. Beam Emittance in Storage Ring

In the storage ring ,

- beta function change ; all of the ring parameters also change

- put the several monitor ; difficult to make the space

We cannot use the emittance measurement by same method of transport line .

In general, the beam size is expressed as

$$\sigma = \sqrt{\beta \varepsilon + \left(\eta \frac{\Delta p}{p} \right)^2}$$

We need the information of beta function and dispersion function to measure the beam emittance by single monitor.

Energy Shift in Storage Ring

The circumference of the storage ring is defined by the RF frequency of the ring.

$$C = \frac{cN}{f} \qquad N\text{ ; harmonic number of the ring}$$

The circumference and momentum correspond by the definition of momentum compaction factor

$$\frac{\Delta C}{C} = \alpha \frac{\Delta p}{p}$$

Thereby,

$$\frac{\Delta p}{p} = -\frac{1}{\alpha}\frac{\Delta f}{f}$$

Energy in the storage ring can be changed by RF frequency shift .

$$\Delta x = \eta \frac{\Delta p}{p} = -\frac{\eta}{\alpha}\frac{\Delta f}{f}$$

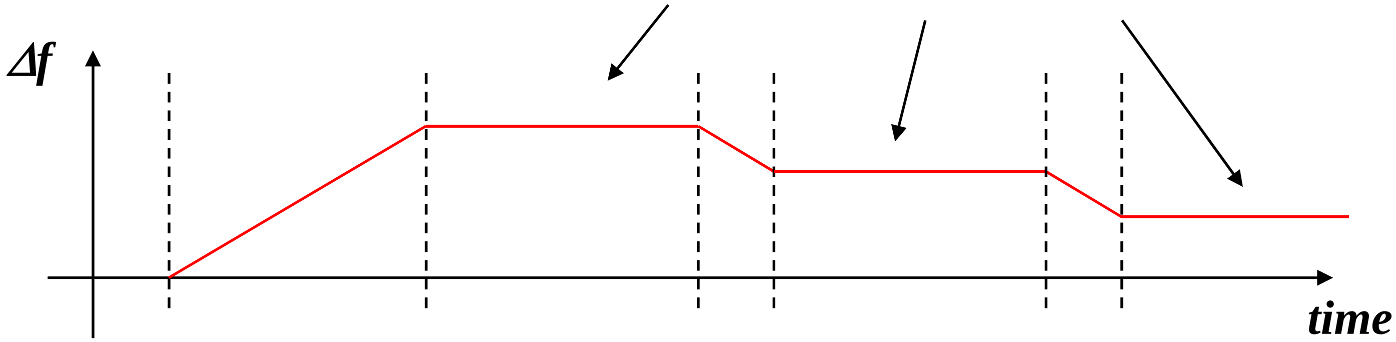
$$\boxed{\eta = -\alpha f \frac{dx}{df}}$$

Dispersion Measurement in Storage Ring

The dispersion is evaluated by measuring the frequency dependence of position .

$$\eta = -\alpha f \frac{dx}{df}$$

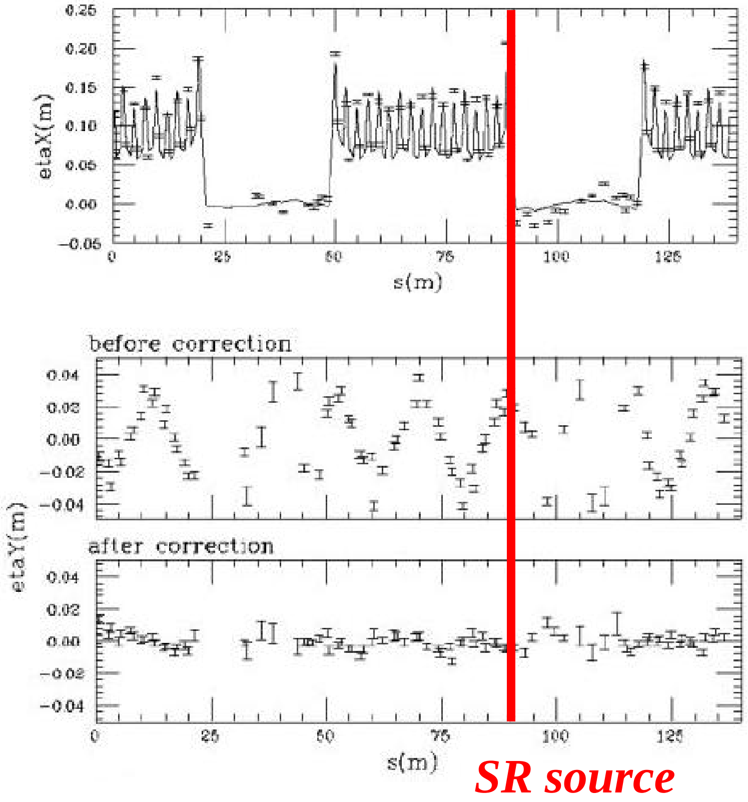
Beam position should be measured for the several frequency (beam energy)



The ramping time should be slower than the synchrotron frequency.

If ramping time is faster than synchrotron frequency, the longitudinal beam oscillation is generated .

Measurement of the Dispersion Function at ATF



Normally, we change the RF frequency by 10kHz .
  - momentum compaction is 2e-3
  - RF frequency is 714MHz

The energy can changed by 0.7%.

Since the dispersion is measured at BPM ,
the dispersion at SR source is evaluated by fitting .

Vertical residual dispersion is one of the main vertical emittance source.

Dispersion measurement is not only used for the emittance evaluation,
but also for the vertical emittance tuning.

Measurement of the Beta Function in Storage Ring

When the strength error is generated at the quadrupole $\begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix}$

The transfer matrix of the storage ring is expressed by

$$\begin{aligned}\bar{M} &= \begin{pmatrix} 1 & 0 \\ -k & 1 \end{pmatrix}\begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu & \cos\mu - \alpha\sin\mu \end{pmatrix} \\ &= \begin{pmatrix} \cos\mu + \alpha\sin\mu & \beta\sin\mu \\ -\gamma\sin\mu - k(\cos\mu + \alpha\sin\mu) & \cos\mu - \alpha\sin\mu - k\beta\sin\mu \end{pmatrix} \\ &= \begin{pmatrix} \cos\bar{\mu} + \bar{\alpha}\sin\bar{\mu} & \bar{\beta}\sin\bar{\mu} \\ -\bar{\gamma}\sin\bar{\mu} & \cos\bar{\mu} - \bar{\alpha}\sin\bar{\mu} \end{pmatrix}\end{aligned}$$

, where the tune will be changed to

$$\cos\bar{\mu} = \cos\mu - \frac{1}{2}k\beta\sin\mu$$

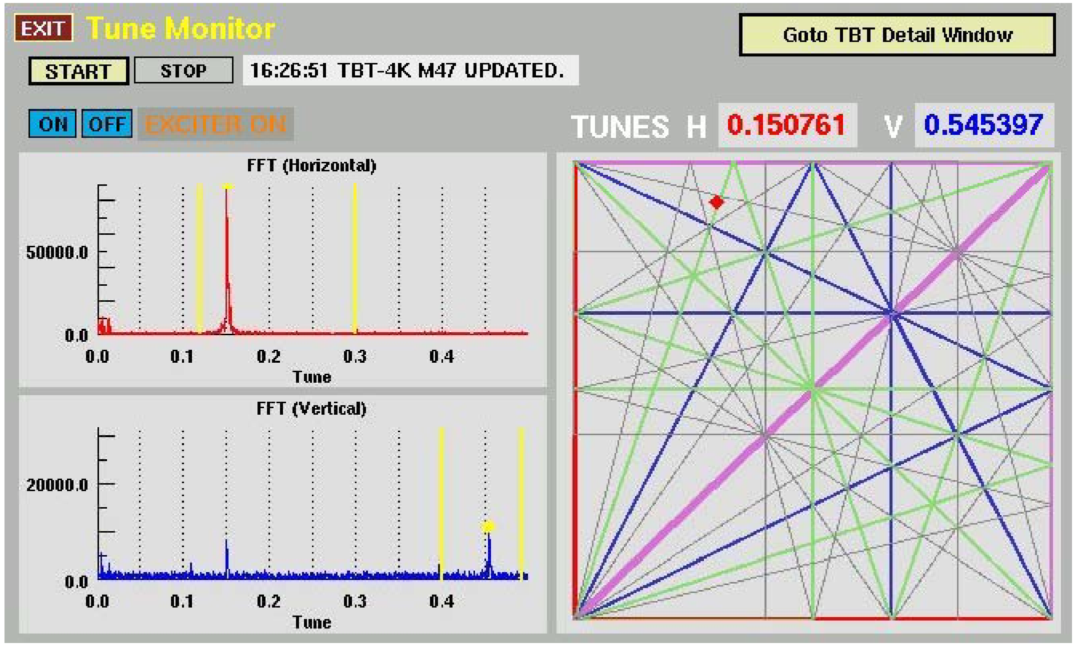
$$\Delta\mu = -\frac{\Delta\cos\mu}{\sin\mu} = \frac{1}{2}k\beta$$

$$\Delta\nu = \frac{1}{4\pi}k\beta$$

Beta function at the quadrupole can be measured by changing the quadrupole strength .

Tune Measurement at the ATF

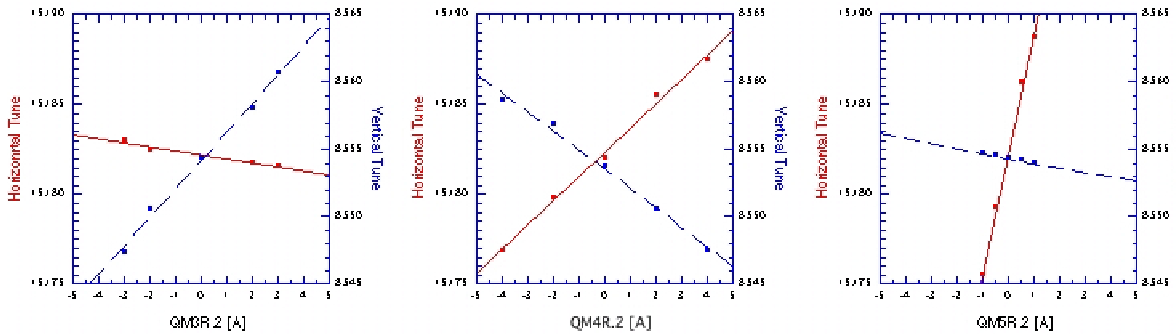
-Beam is oscillated by stripline kicker .
-The turn by turn beam position is measured by BPM .
-The beam position data is converted to the frequency domain by FFT .

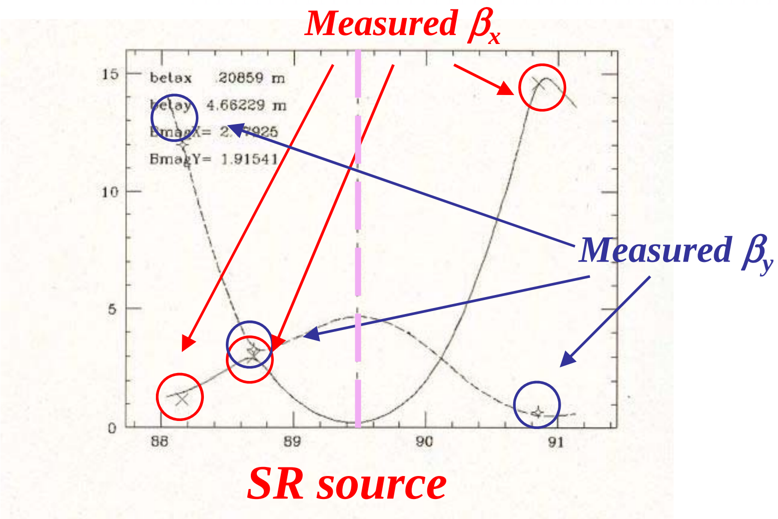


The result of tune measurement .

The beta function measurement at SR source point

The beta function is evaluated at the Quadrupole Magnet near by the SR source.
In order to evaluate the Twiss parameters α and β,
we must measure the beta function at least 2 quadrupoles .





Beta function at SR source is evaluated by the fitting .

The fitting is including the optics information .

Summary of Emittance Measurement in Storage Ring

In order to evaluate the beam emittance, we must measure the beta function and dispersion function

$$\sigma = \sqrt{\beta\varepsilon + \left(\eta\frac{\Delta p}{p}\right)^2}$$

Beta function measurement ;
by changing the strength of quadrupole magnets around the source point

Dispersion Measurement ;
by changing the RF frequency of the storage ring

Thank you for your attention !