Beam Instrumentation

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Beam Instrumentation
Lecture 3

Beam Instrumentation Devices
for Beam Profile, Bunch Length Measurement (Storage Ring)

- ***Synchrotron Radiation Monitor (SR monitor)***
- ***X-ray Synchrotron Radiation Monitor (XSR monitor)***
- ***Synchrotron Radiation Interferometer***

(utilizing the Synchrotron Radiation)

Beam Instrumentation Technology
to measure the Beam Emittance (Storage Ring)

Synchrotron Radiation Monitor

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

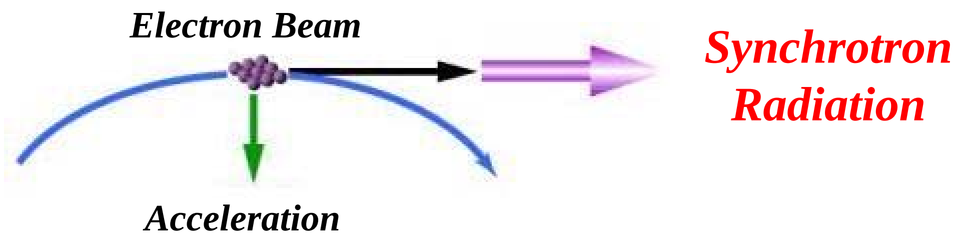
The synchrotron radiation monitor is useful for the beam instrumentation in the storage ring.

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

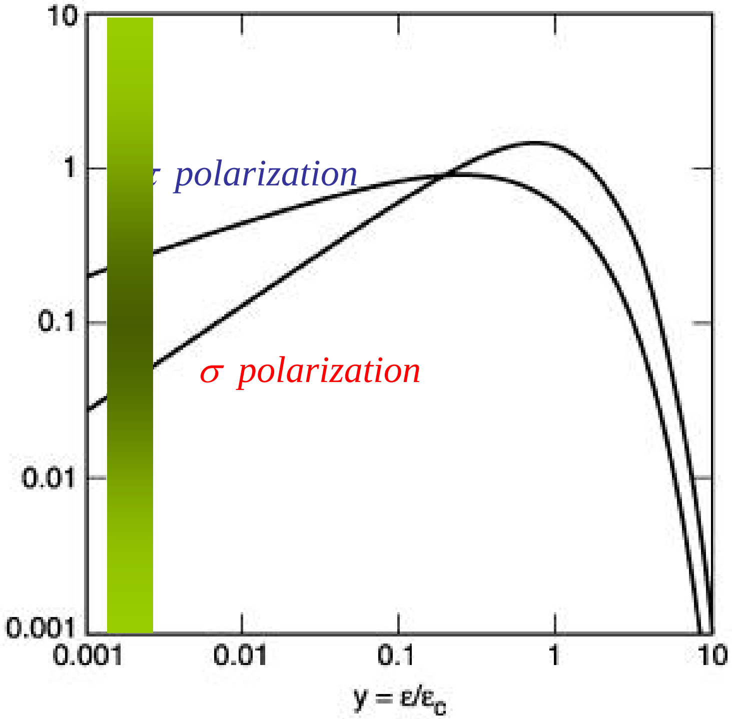
$$P\left(\lambda,\gamma,\psi_0,\rho,\Delta\lambda,I_{\mathrm{B}},\Delta\psi,\Delta\theta\right)=\int_{-\psi_0+\Delta\psi}^{+\psi_0+\Delta\psi}\frac{2}{3}\frac{e_0\Delta\lambda\Delta\theta\, I_{\mathrm{B}}\rho^2}{\varepsilon_0\beta\lambda^4\gamma^4}\left[1+(\gamma\psi)^2\right]^2\left[\underbrace{K_{2/3}\left[\xi\left(\lambda,\psi\right)\right]^2}_{\sigma\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

Energy Distribution of Synchrotron Radiation

Critical Energy of the Synchrotron Radiation

$$\varepsilon_c \text{ [keV]} = 0.665\ E^2 \text{ [GeV] B[T])}$$

Visible Light



Example of the ATF beam

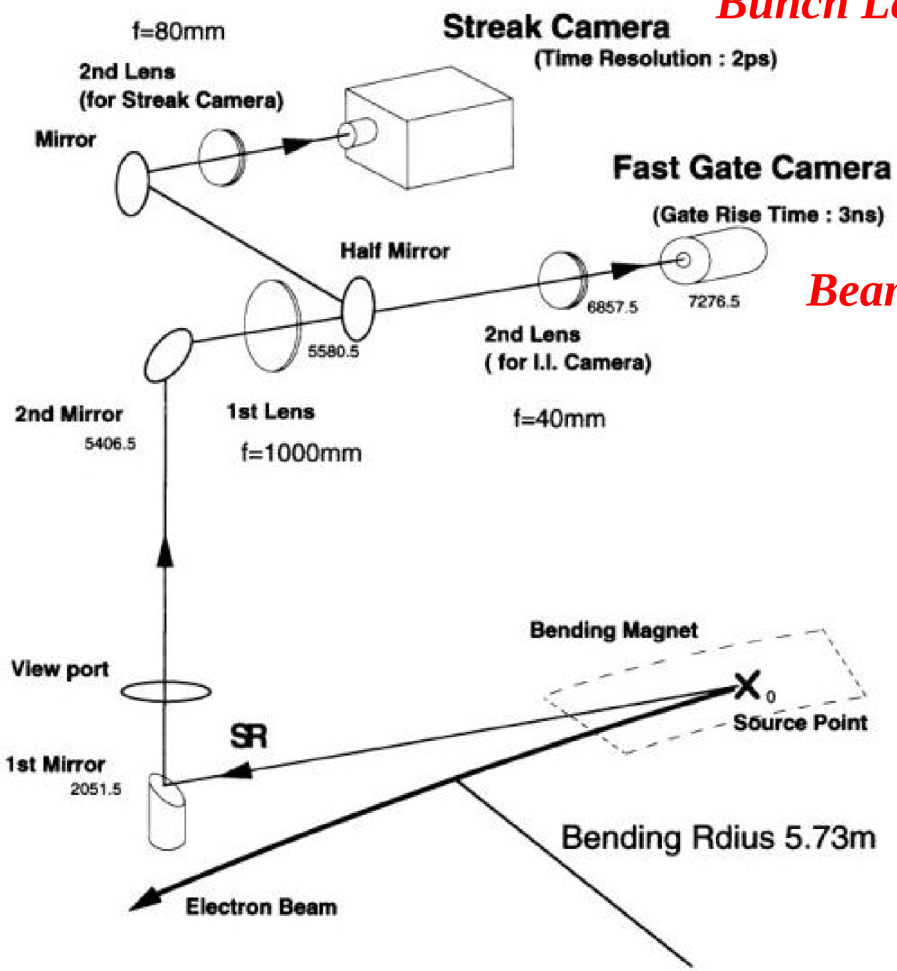
-1.3 GeV of the electron beam
-0.9 T of the bending field

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

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

Experimental Setup at ATF

Bunch Length Measurement



Beam Profile Measurement

Calibration of the Magnification Factor

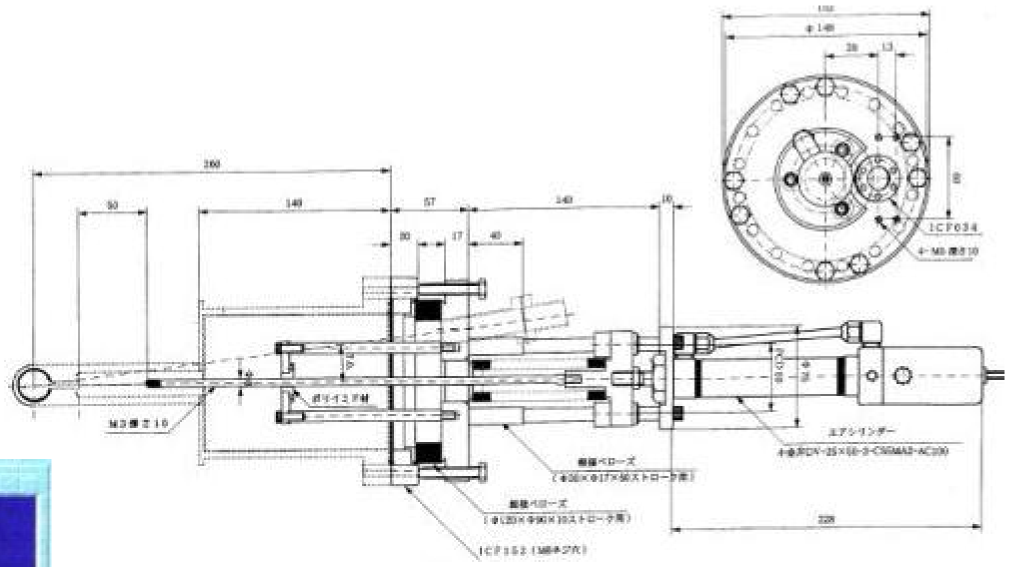
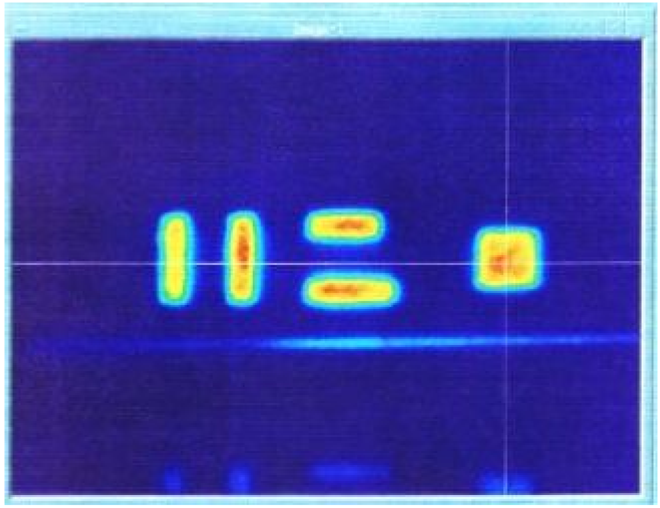


Image of the reference target

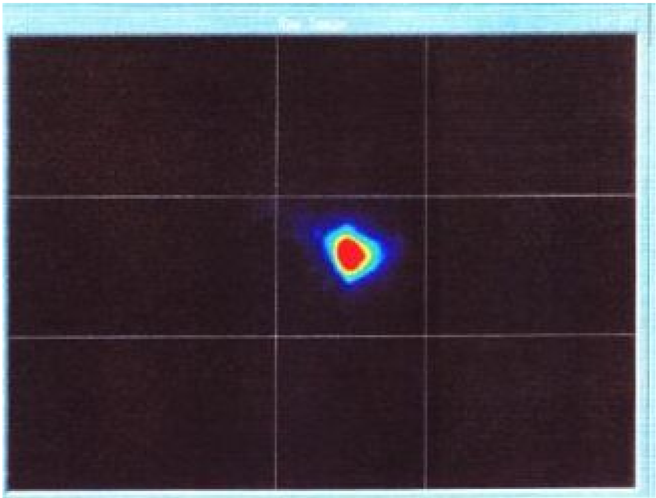


Some target patterns are printed at the reference target.

The reference target is inserted to the beam line for the calibration of the magnification factor of the telescope.

Measured Result of the Beam Profile

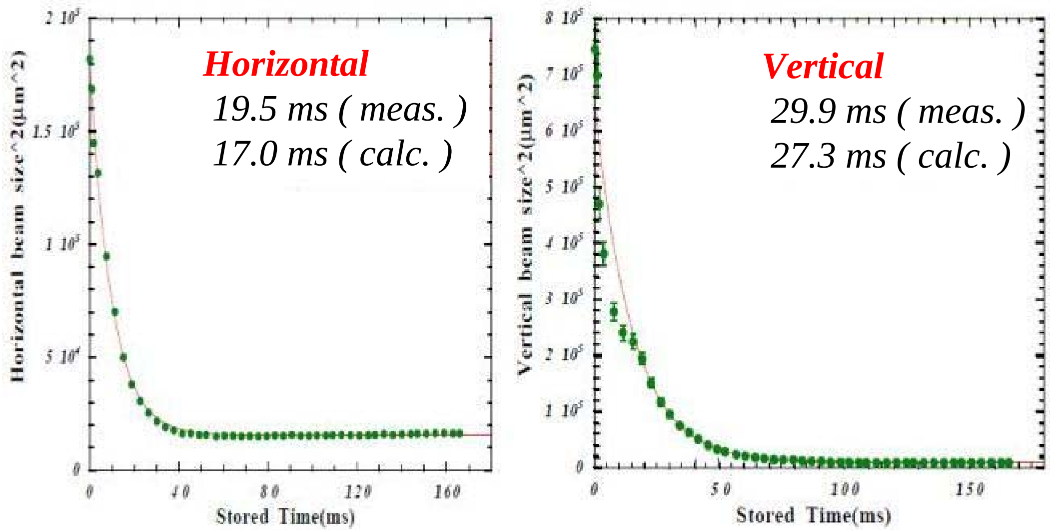
Measured Beam Image



Gate interval ; 1ms

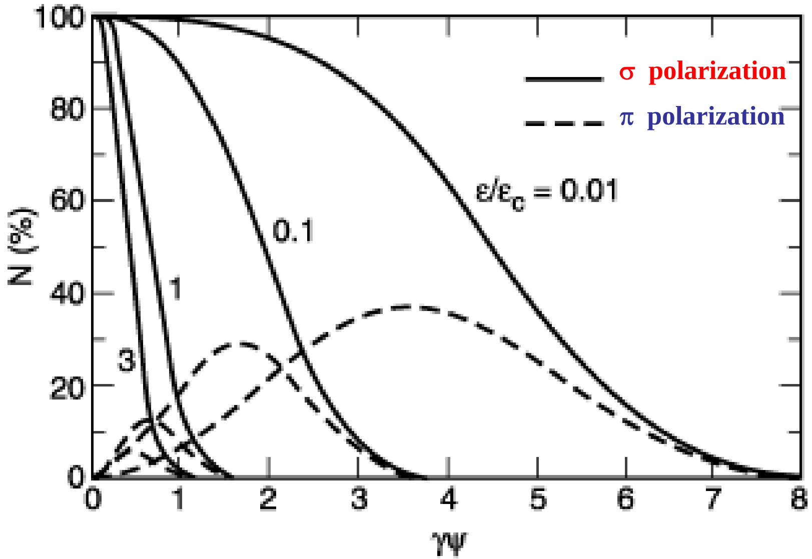
Time dependence of the beam size .

The beam size damping is measured by the SR monitor .



Measurable Limit for SR Beam Profile Monitor

Angular Distribution of the Synchrotron Radiation



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

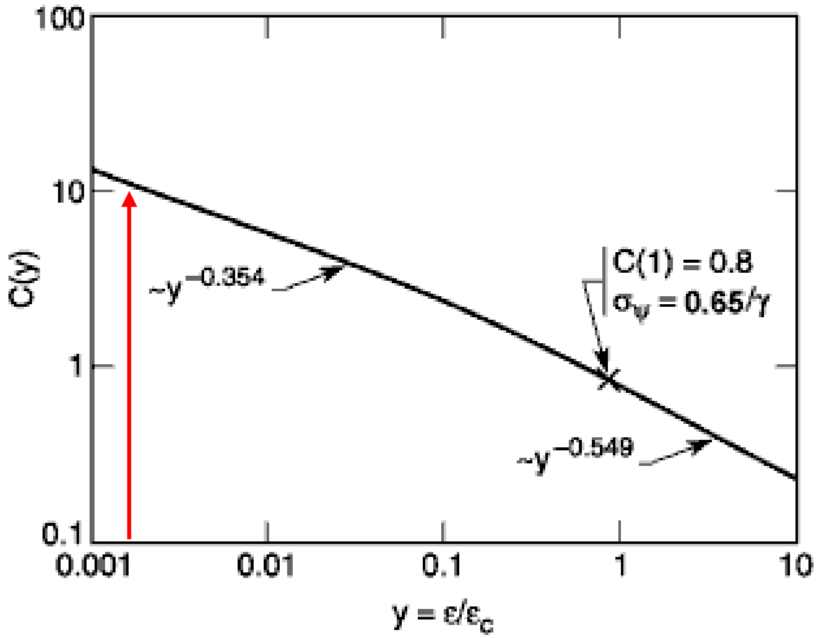
-1.3 GeV of electron beam
-0.9T of bending field
-500nm of the wave length

$\boxed{\sigma_y > 12\mu m}$

Beam Divergence of the Synchrotron Radiation

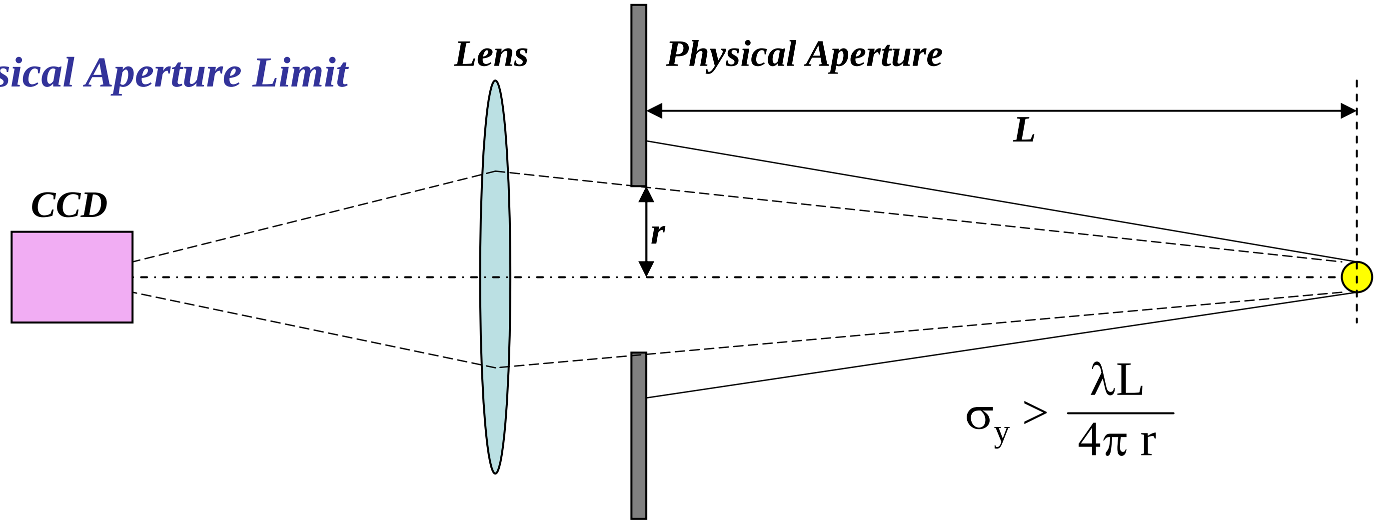
Synchrotron radiation occurs in a narrow cone of nominal angular width ~1/γ.

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



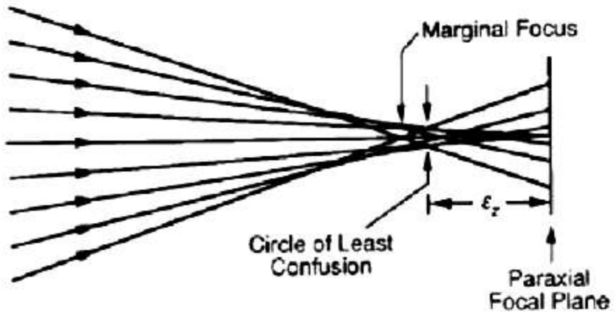
Other Limits to the Beam Profile Measurement

Physical Aperture Limit



$$\sigma_y > \frac{\lambda L}{4\pi r}$$

Spherical Aberration of Lens



Critical Performance Characteristics 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

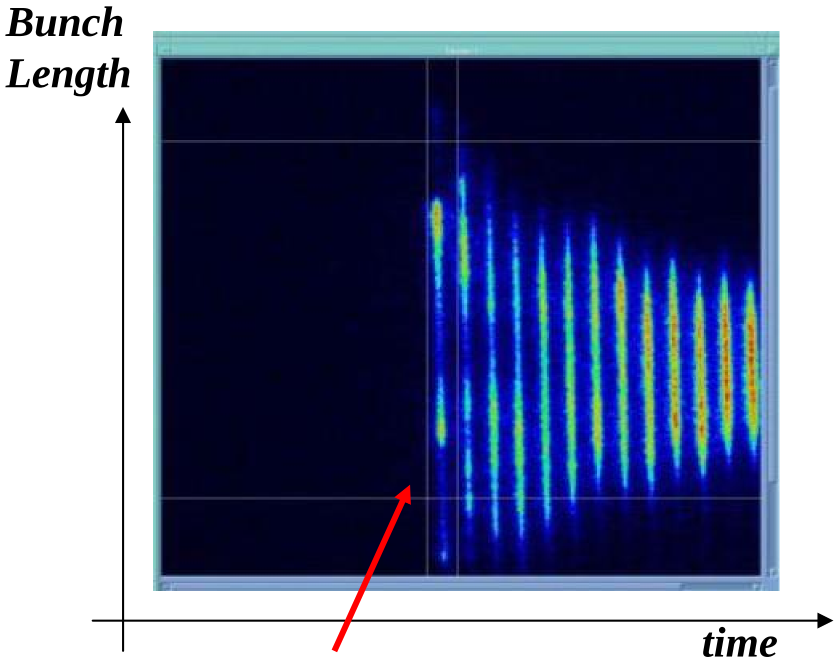
-No destructive monitor

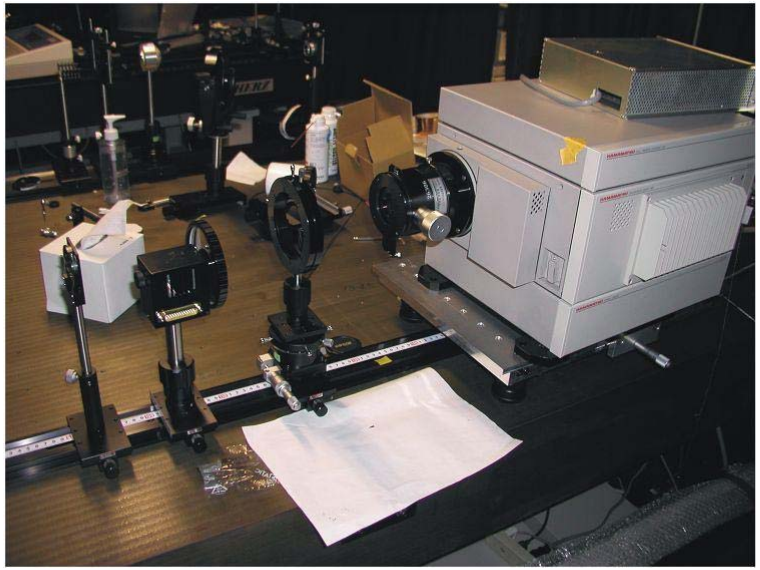
- Possoble to use in the storage ring

- Cannot use in the transport line for their small signal

Measured Result of the Bunch Length

Measured bunch Length
with Streak Camera





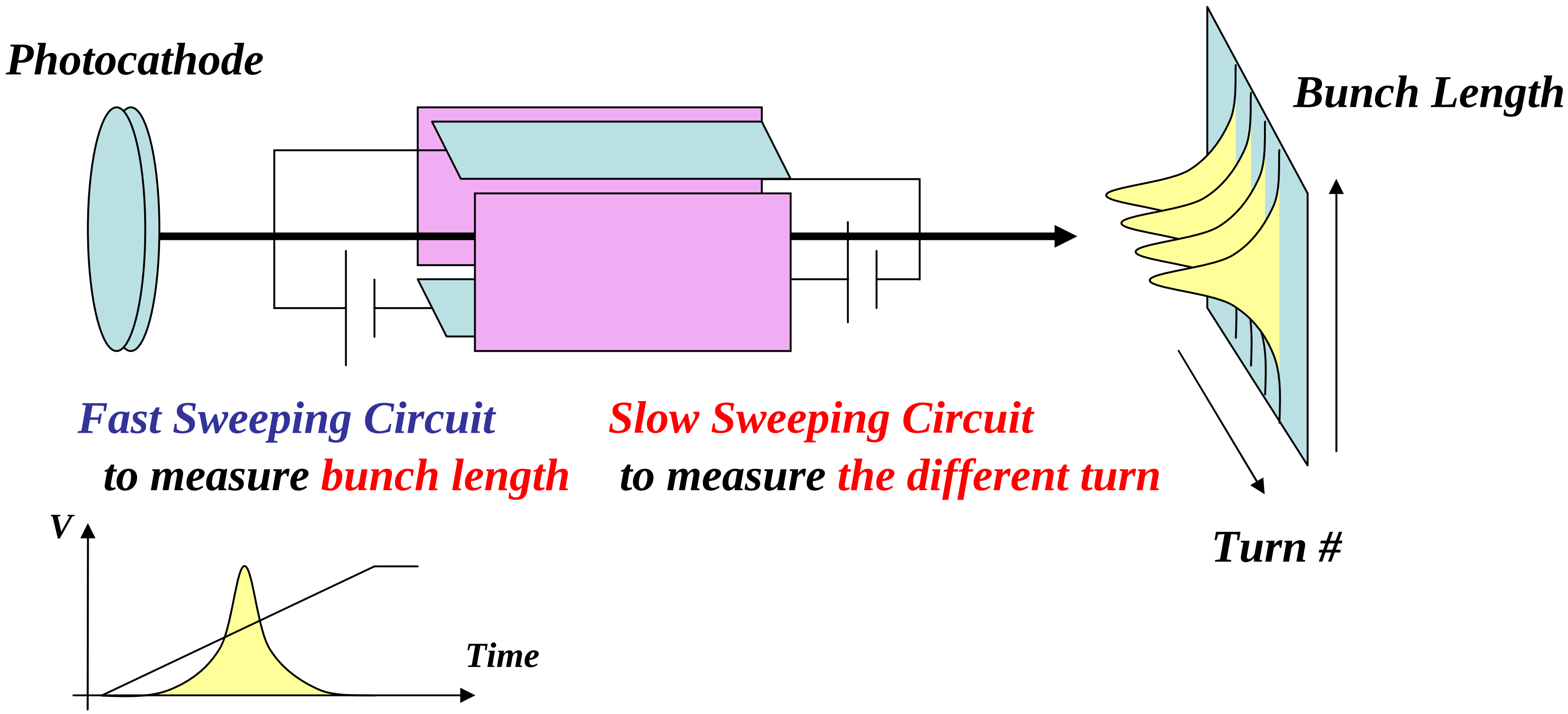
Injection timing

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.



Critical Performance Characteristics 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

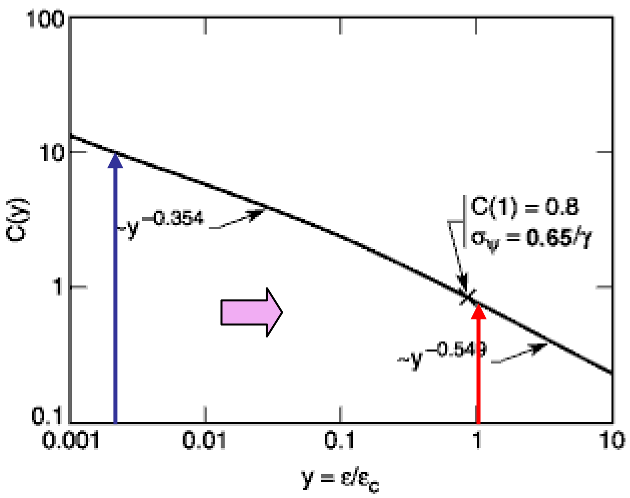
- Can use in the storage ring

X-ray Synchrotron Radiation Monitor

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

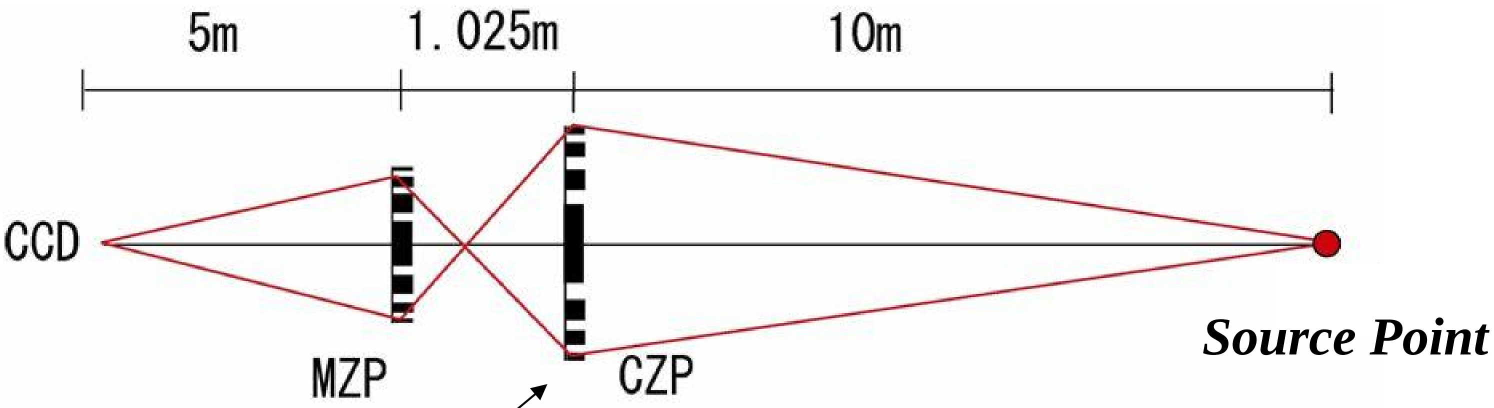
$$\sigma_y > \frac{\lambda}{4\pi\sigma_\psi} = \frac{\gamma\lambda}{4\sqrt{2\pi}} \frac{1}{C(y)}$$

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 .

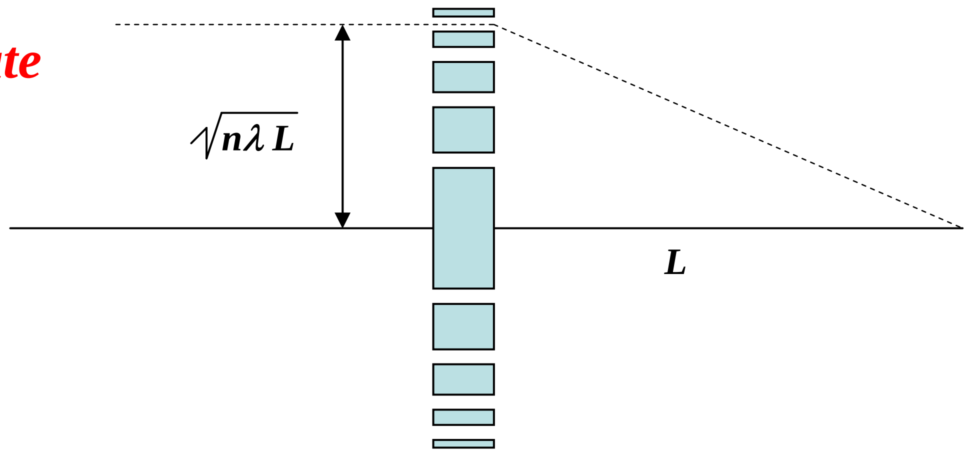
Principle of the X-ray SR Monitor



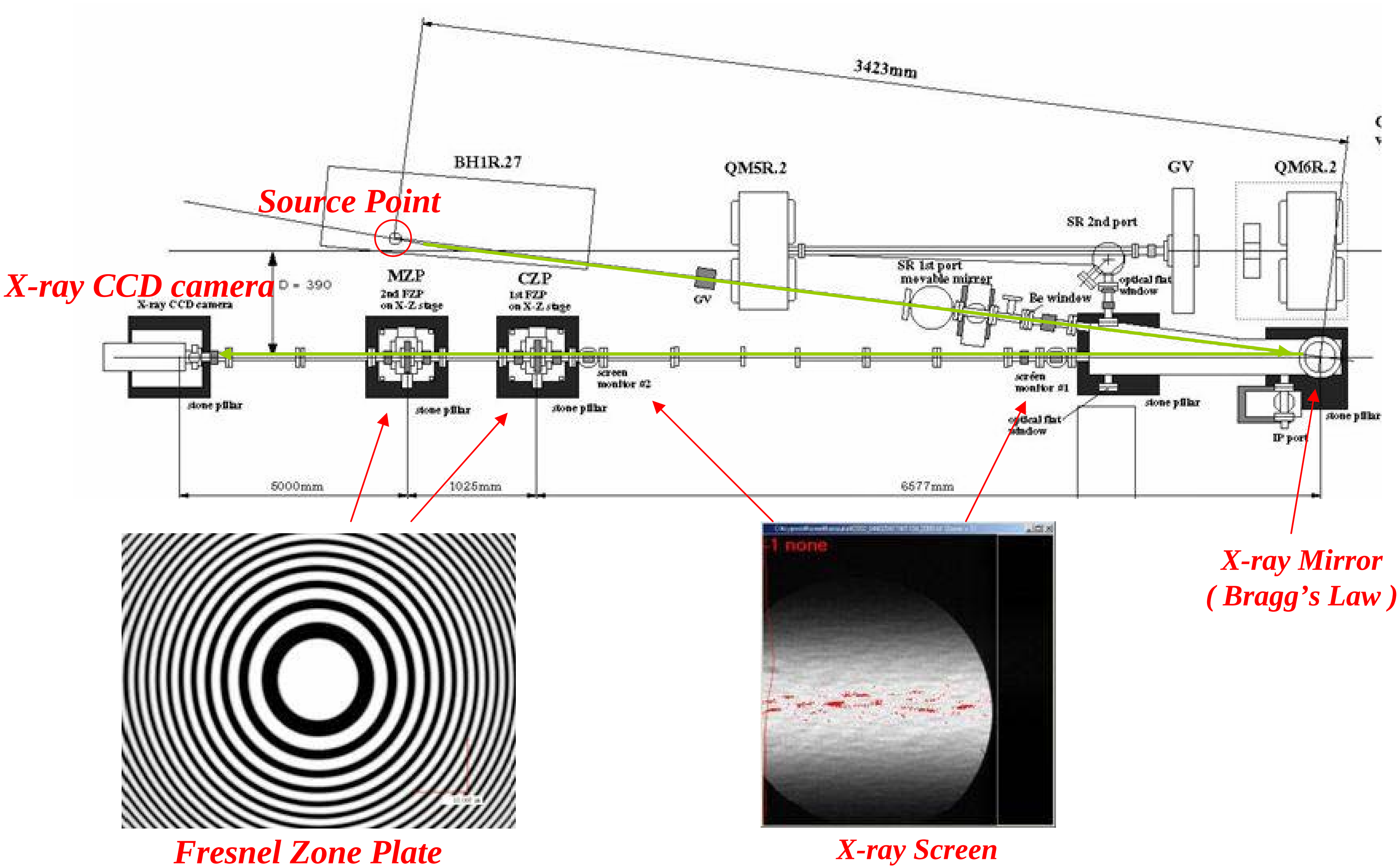
Fresnel Zone Plate

Lens for X-ray

$f = r_1^2/\lambda$

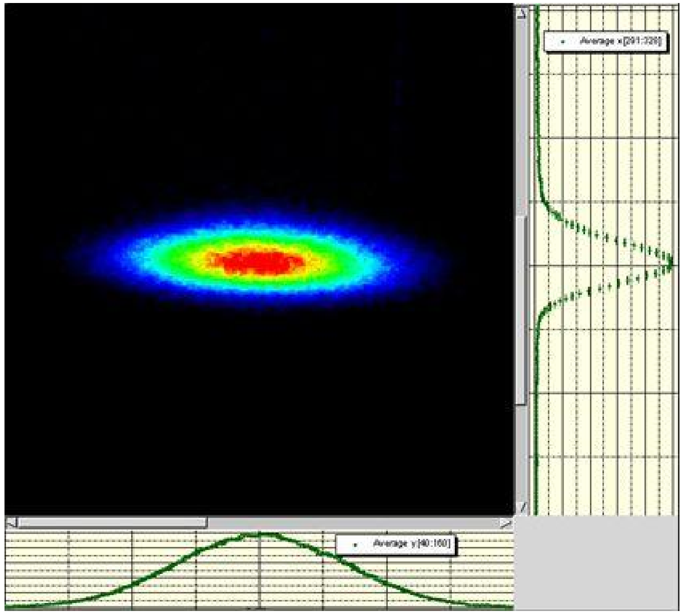


Experimental Setup

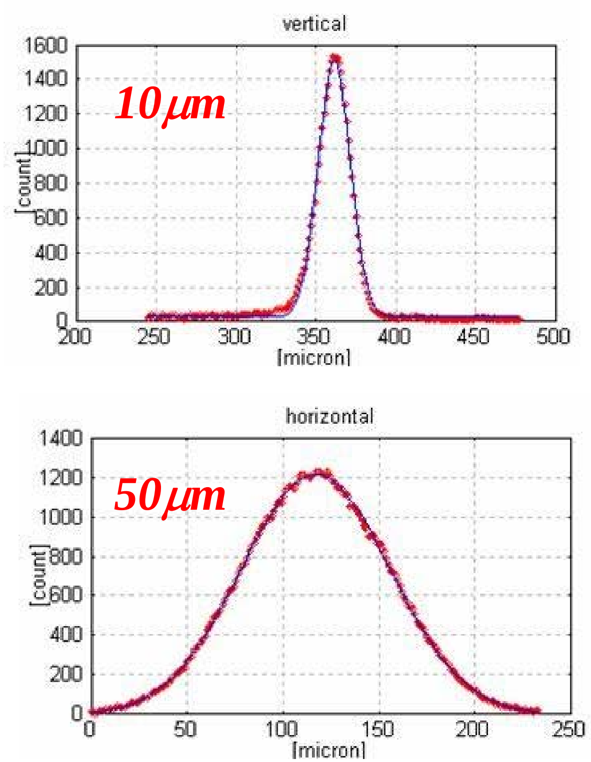


Measured Profile at ATF

Measured Profile at ATF damping ring



Shutter Interval ; 1ms



Critical Performance Characteristics of XSR Beam Profile Monitor

-Dynamic range;

- Depends on the magnification of the telescope
(500μm for ATF setting)

-Resolution ;

- Defined by the diffraction limit and others
(1μm 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

SR Interferometer

SR Interferometer

SR beam profile monitor

- Small beam size can not be measured.

X-ray SR beam profile monitor

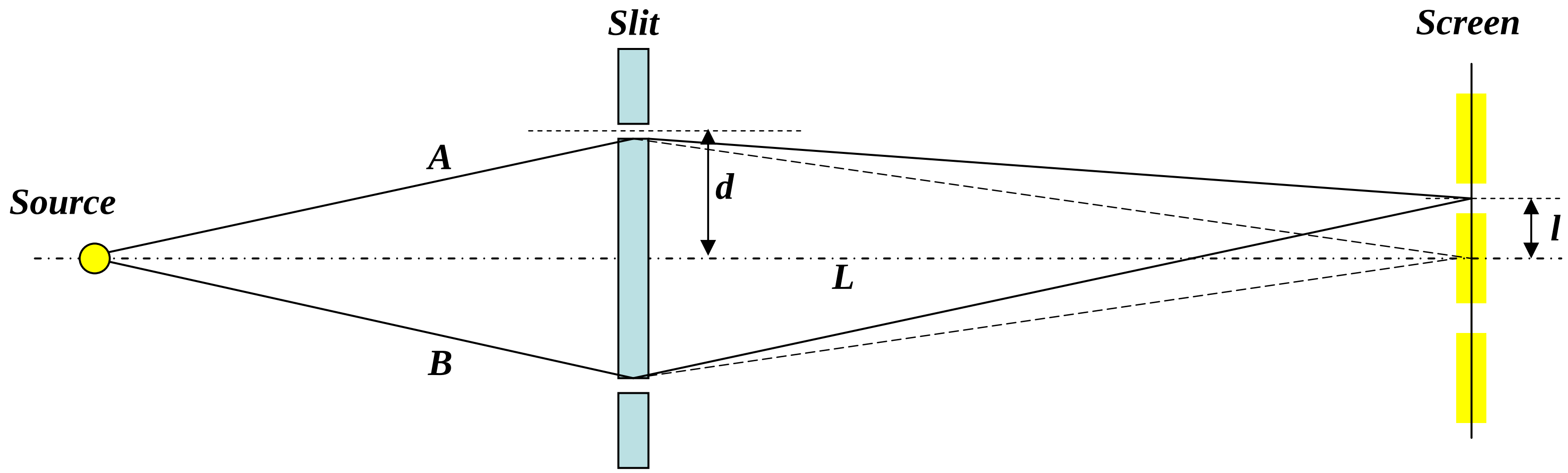
- Small beam size can be measured.
- Most of the X-ray devices are expensive .
  (i.e. one fresnel zone plate is roughly a few 10k$.)

SR interferometer

- Beam size monitor (not beam profile monitor) for small beam size
- Use for the visible light of synchrotron radiation

SR interferometer is used of the path length of the visible light (interference pattern).

Interference Pattern



Path length difference on screen,

$$A = \sqrt{L^2 + (d - l)^2} = L + l\,(l - d) / L$$

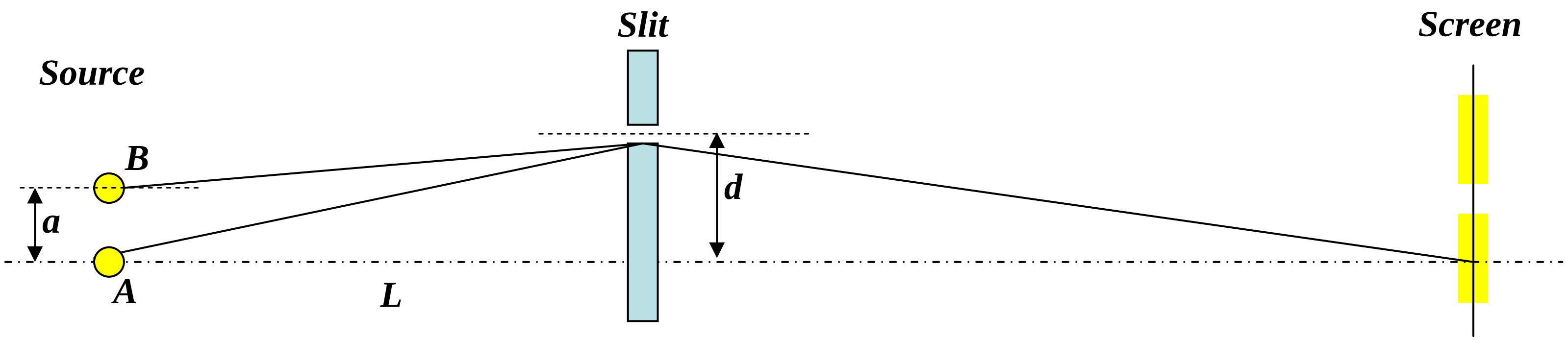
$$B = \sqrt{L^2 + (d + l)^2} = L + l\,(l + d) / L$$

$$A - B = -2\,dl / L$$

Interference pattern is on

$$A - B = -2\,dl / L = n\lambda$$

Principle of the Interferometer



Path length difference to slit

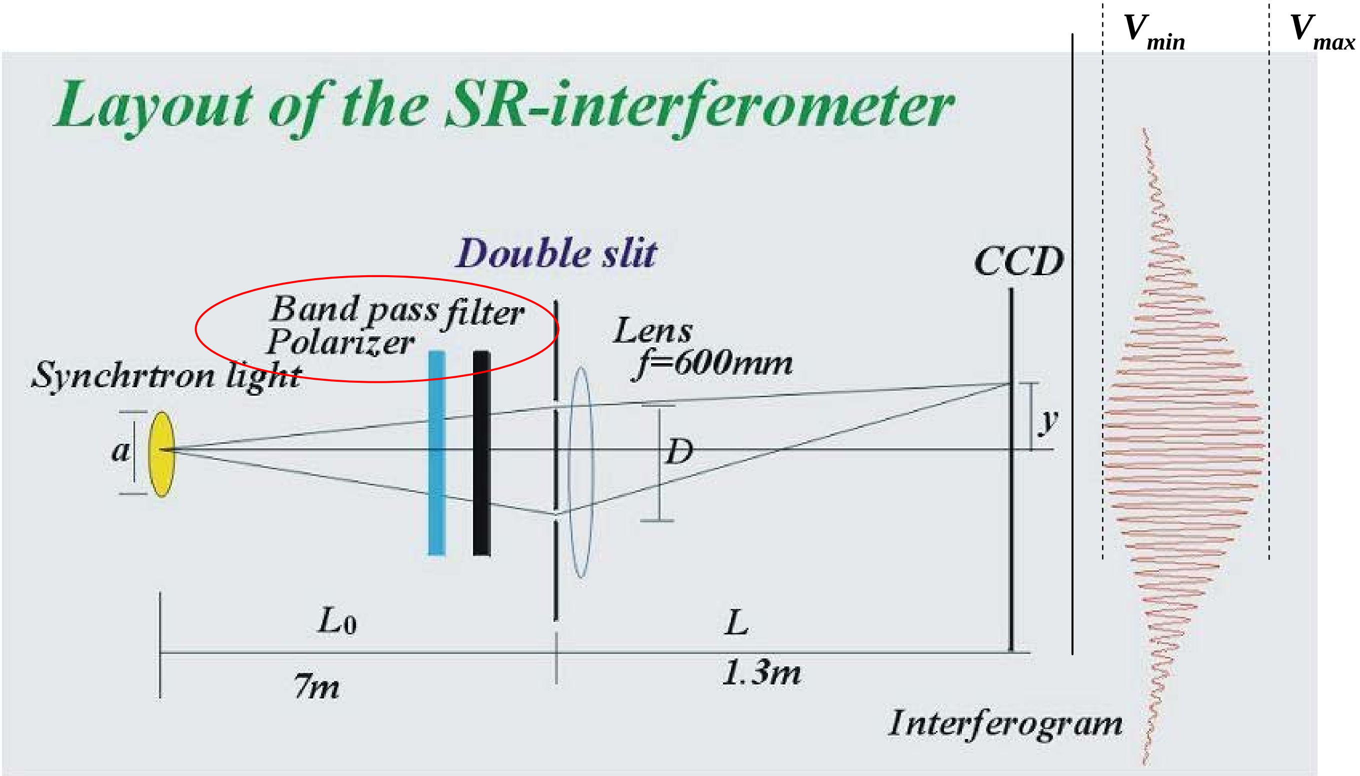
$$A = \sqrt{L^2 + d^2} = L + d^2 /L$$

$$B = \sqrt{L^2 + (d - a)^2} = L + d(d - a)/L$$

$$A - B = -2da/L$$

When (A-B) is comparable to the wave length λ ,
the interference pattern is not perfect .

Interference Pattern of SR Interferometer



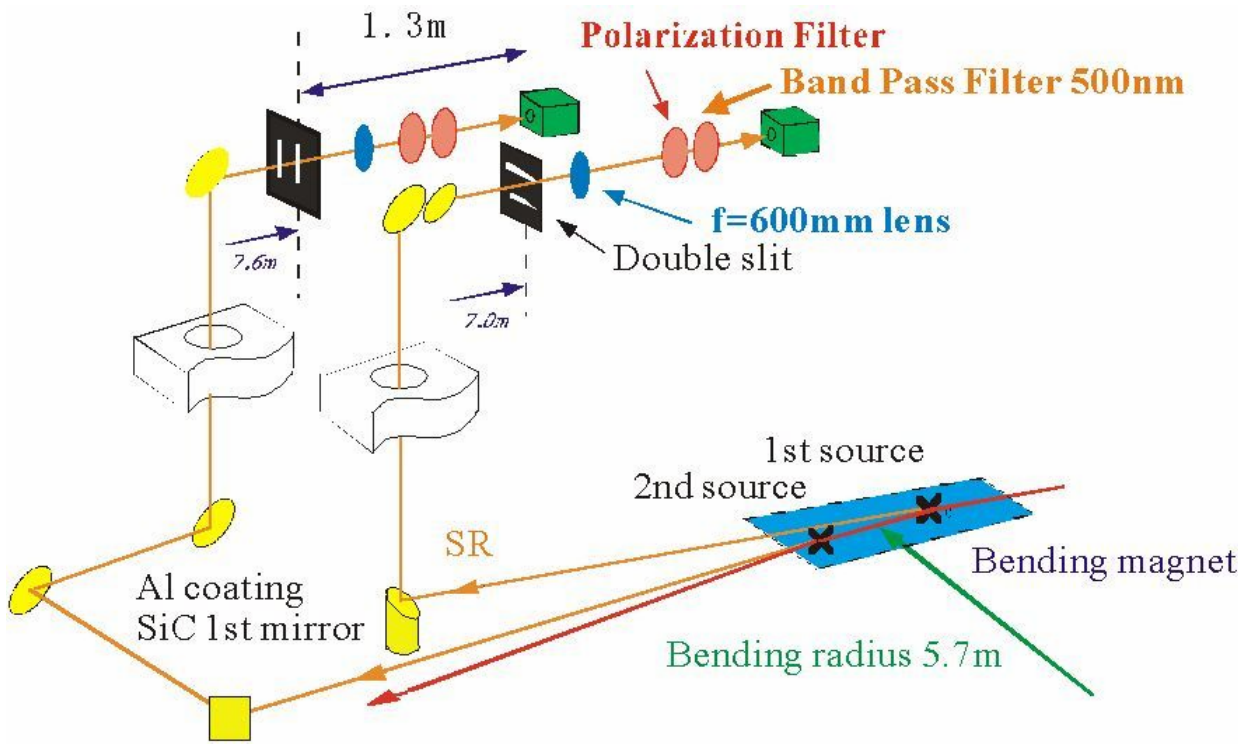
Amount of the interference

$$\gamma = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$

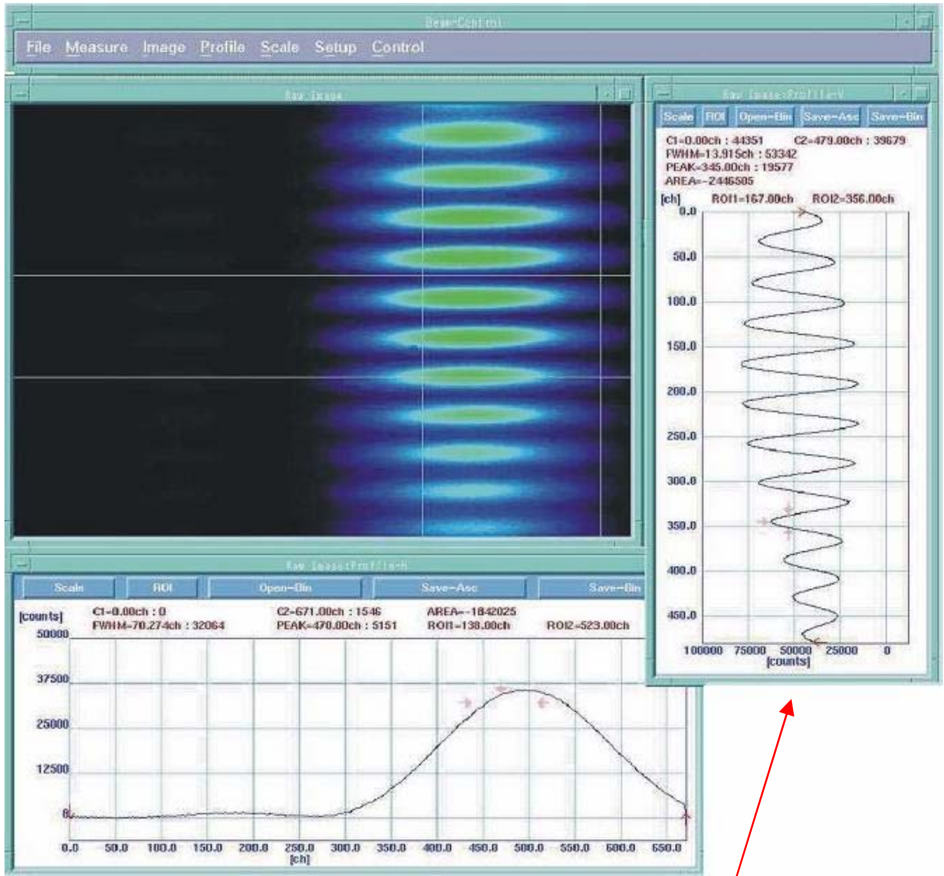
Beam size is evaluated as

$$\sigma_{beam} = \frac{\lambda L_0}{\sqrt{2}\pi D}\sqrt{\ln\left(\frac{1}{\gamma}\right)}$$

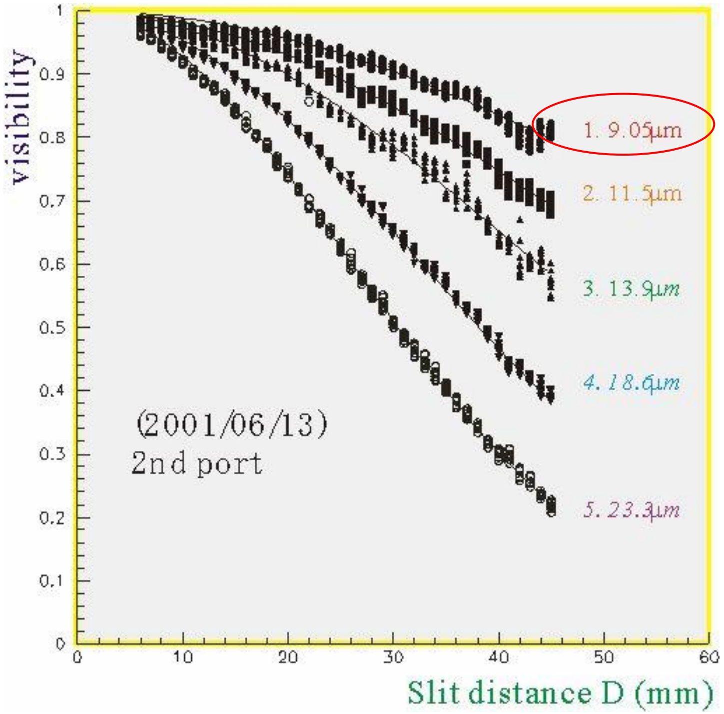
Experimental Setup of the Interferometer



Experimental Result in ATF



Projection of the interference pattern.

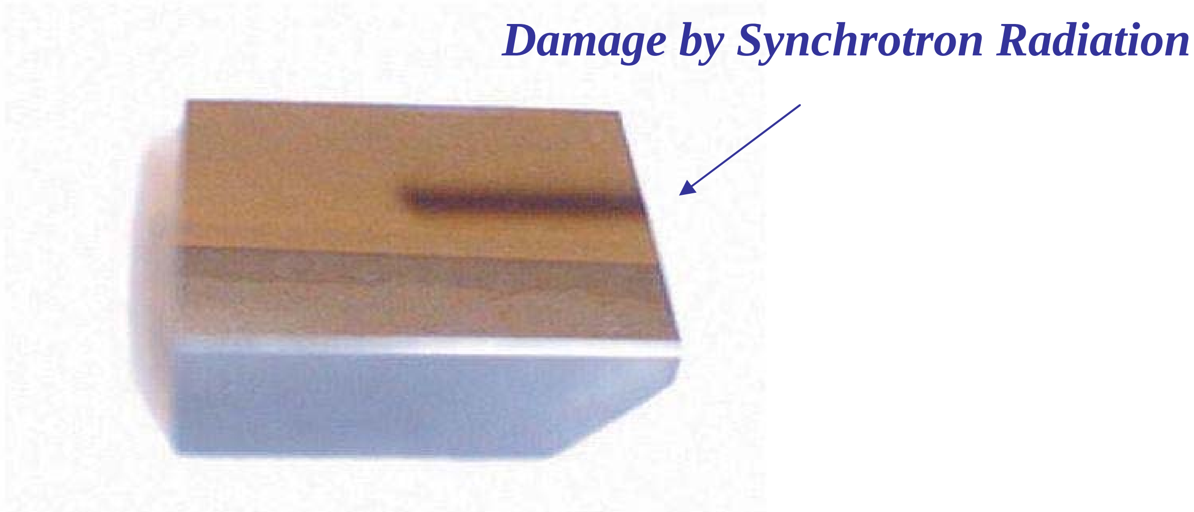


Beam size was evaluated by the slit scan mrthod.

$$\gamma = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$

$$= \exp\left(- \frac{2\pi^2 D^2 \sigma_{beam}^2}{\lambda^2 L_0^2} \right)$$

1st Mirror Damage of the Synchrotron Radiation



This damage makes the light intensity deference for each slit .
For off center beam to the damage, it makes visibility worse .

- strongly affect to the SR interferometer measurement

We can focus the light out of the damage.
For the SR monitor, it makes light intensity small .

- small effect for the beam size measurement of SR monitor

Critical Performance Characteristics of SR Interferometer

-Dynamic range;

- Difficult to measure the large beam size, because the visibility of beam core is too good .
(100μm for ATF)

-Resolution ;

- Defined by the intencity for large slit setting .
(10μm for ATF)

-Accuracy;

- Since we accumulate the signal of more than 1ms interval, beam fluctuation affect to the measurement
- The measurement is just beam size measurement .

-No destructive monitor

- Possoble to use in the storage ring
- Cannot use in the transport line for their small signal

Emittance Measurement in Storage Ring

Evaluation of the 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.

$$C = \frac{cN}{f}$$ *N ; 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 .

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

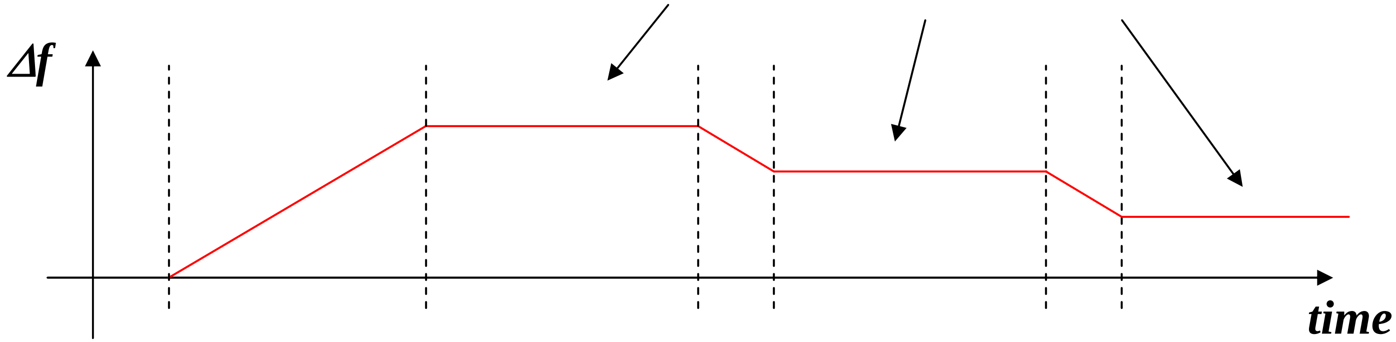
$$\boxed{\eta = -\alpha f \frac{dx}{df}}$$

Dispersion Measurement in Storage Ring

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

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

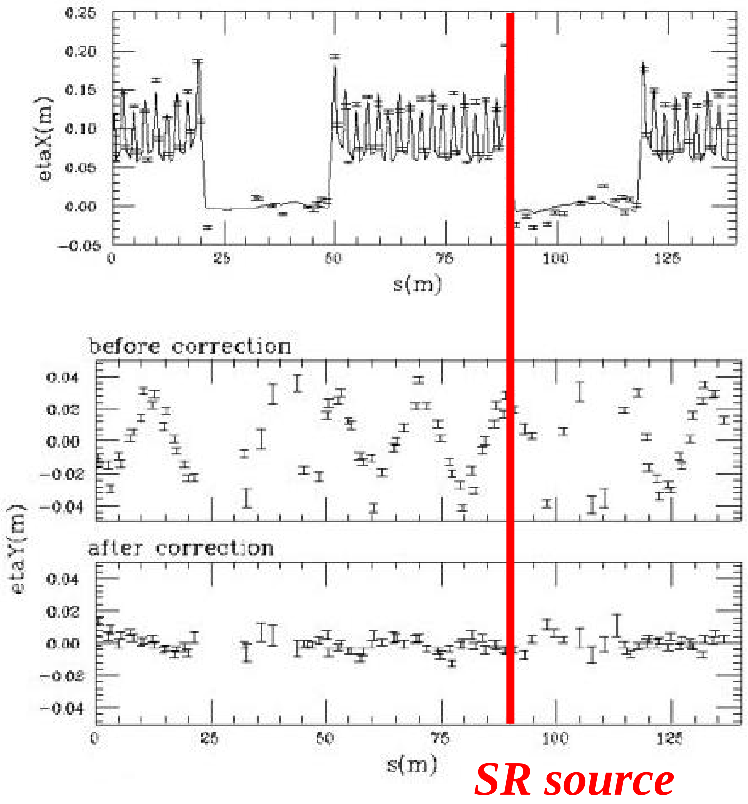
Beam position should be measured for the several frequency (beam energy)



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

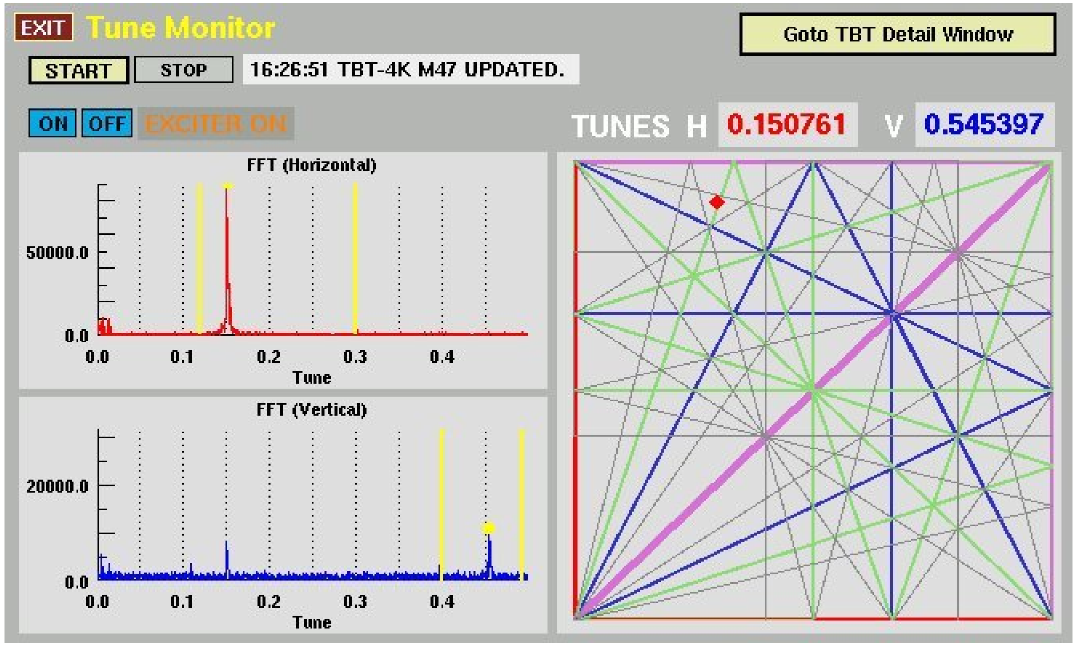
$$\cos\bar{\mu} = \cos\mu - \frac{1}{2}k\beta\sin\mu$$

$$
\begin{aligned}
\Delta\mu &= -\frac{\Delta\cos\mu}{\sin\mu} = \frac{1}{2}k\beta \\
\Delta\nu &= \frac{1}{4\pi}k\beta
\end{aligned}
$$

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

Tune Measurement at the ATF

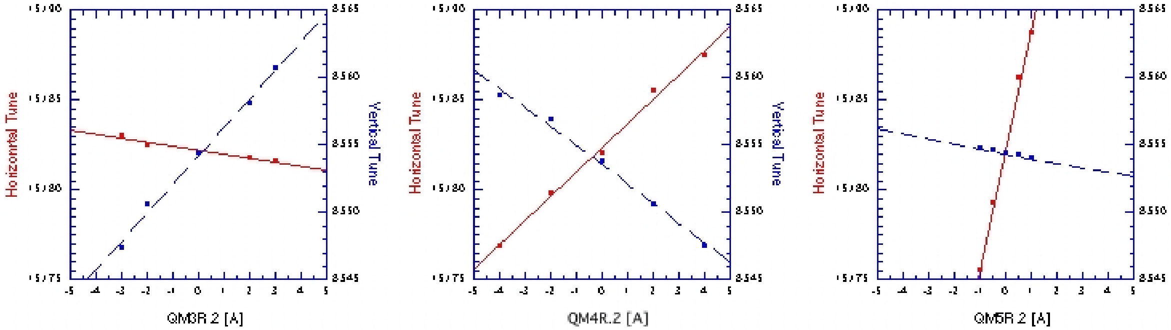
-Beam is oscillated by stripline kicker .
-The turn by turn beam position is measured by BPM .
-The beam position data is converted to the frequency domain by FFT .

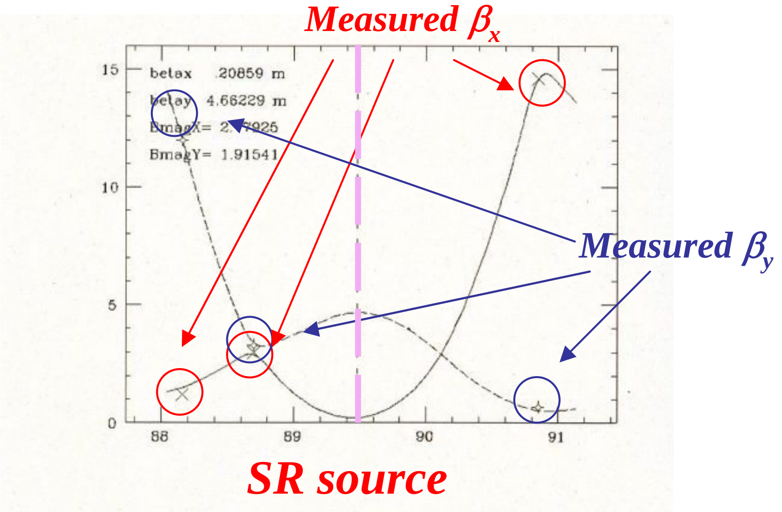


The result of tune measurement .

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