Beam Instrumentation

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Beam Instrumentation
Lecture 2

Beam Instrumentation Devices
for Beam Profile, Bunch Length Measurement (Transport Line)

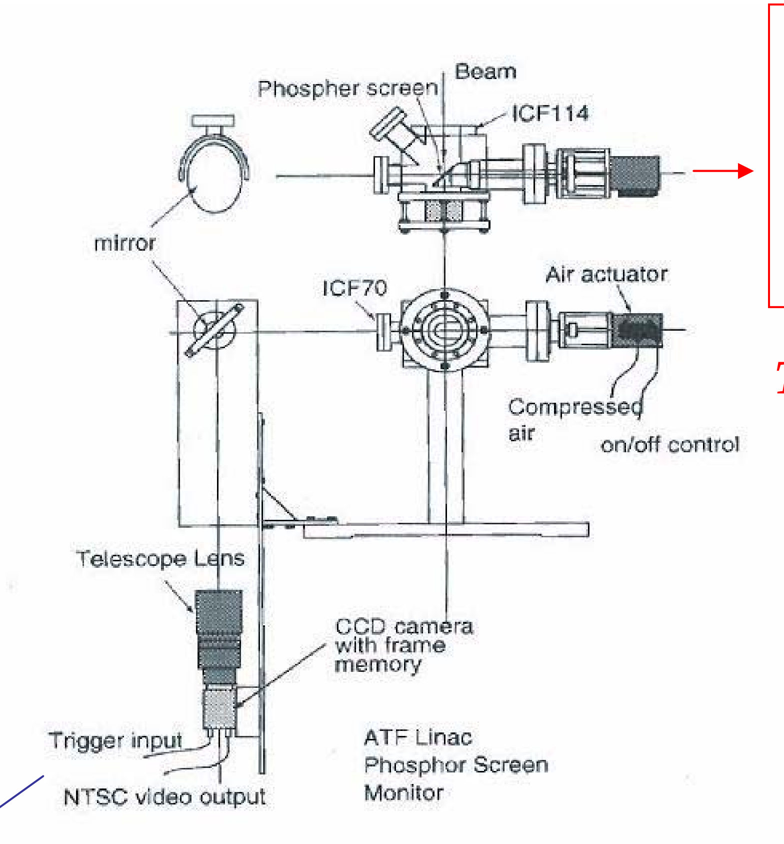
- ***Fluorescent Screen Beam Profile Monitor***
- ***Optical Transition Radiation Monitor (OTR monitor)***
- ***Wire Scanner***

(utilizing the collision with the Material Target)

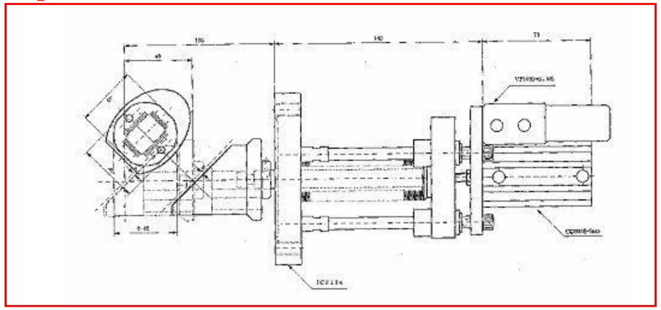
Beam Instrumentation Technology
to measure the Beam Emittance (Transport Line)

Fluorescent Screen Beam Profile Monitor

Fluorescent Screen Beam Profile Monitor



fluorescent screen



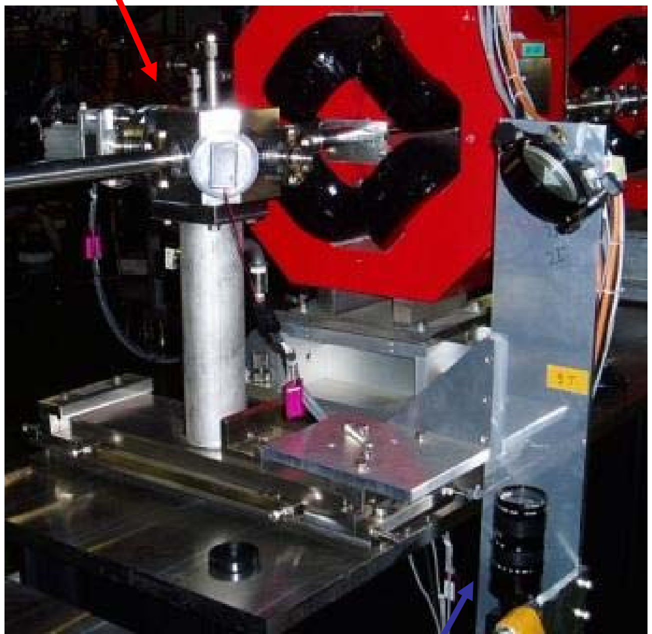
The alumina fluorescent screen is inserted to beam line at the profile measurement.

Gated CCD Camera

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

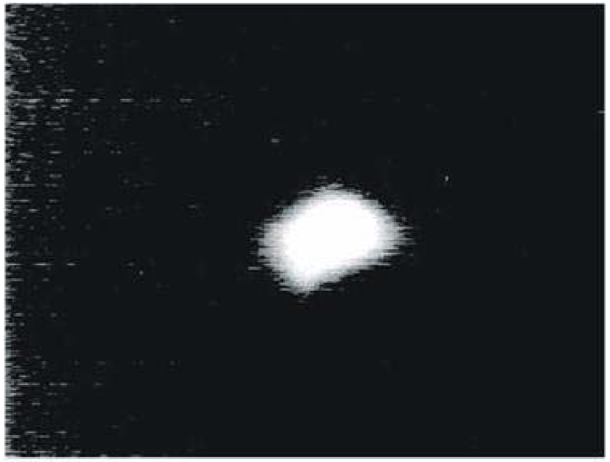
Picture of Screen Monitor in ATF

Vacuum chamber
with fluorescent screen



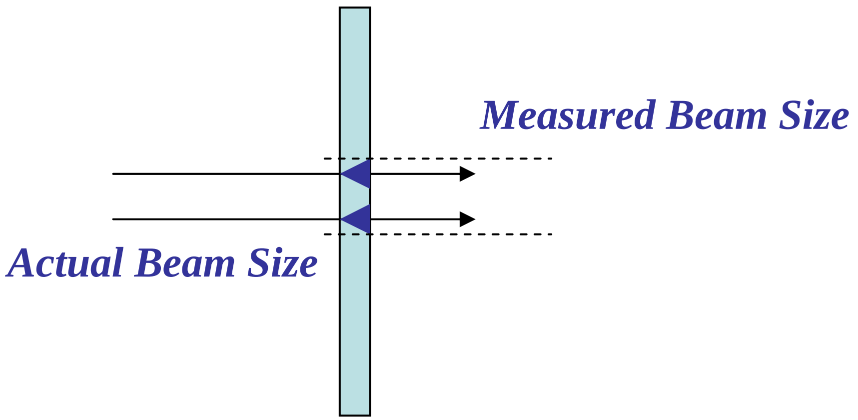
Gated CCD Camera
with Telescope

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).

Critical Performance Characteristics 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.

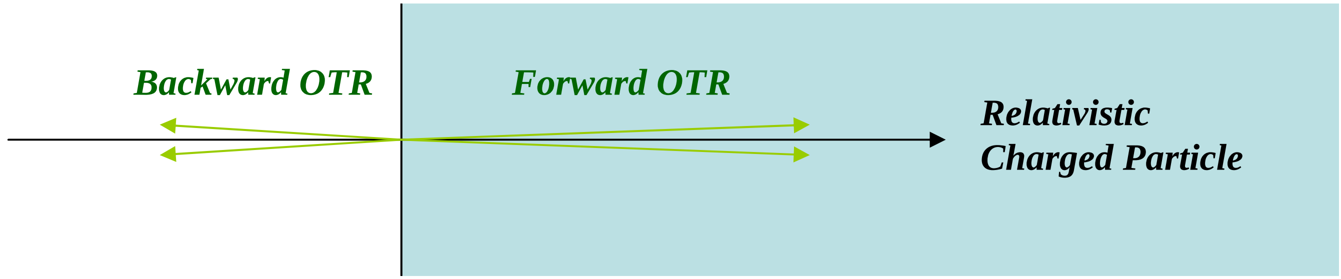
-Destructive

Only for the beam transport line .

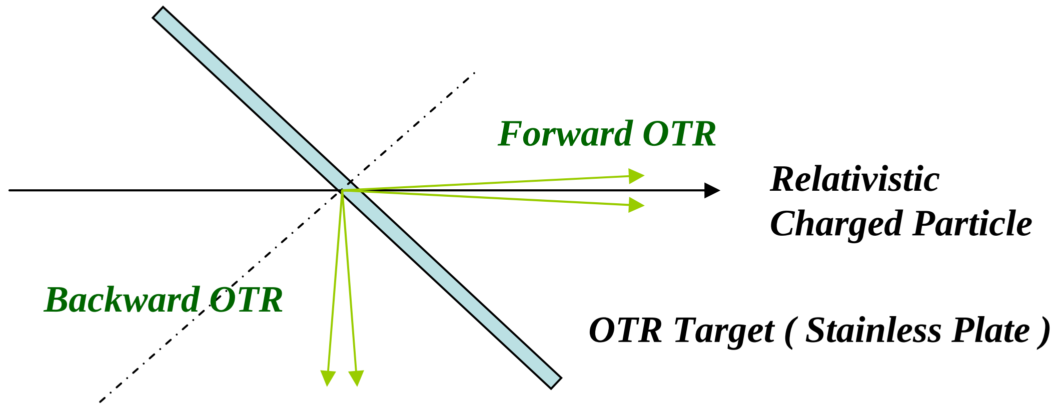
Optical Transition Radiation Monitor

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.



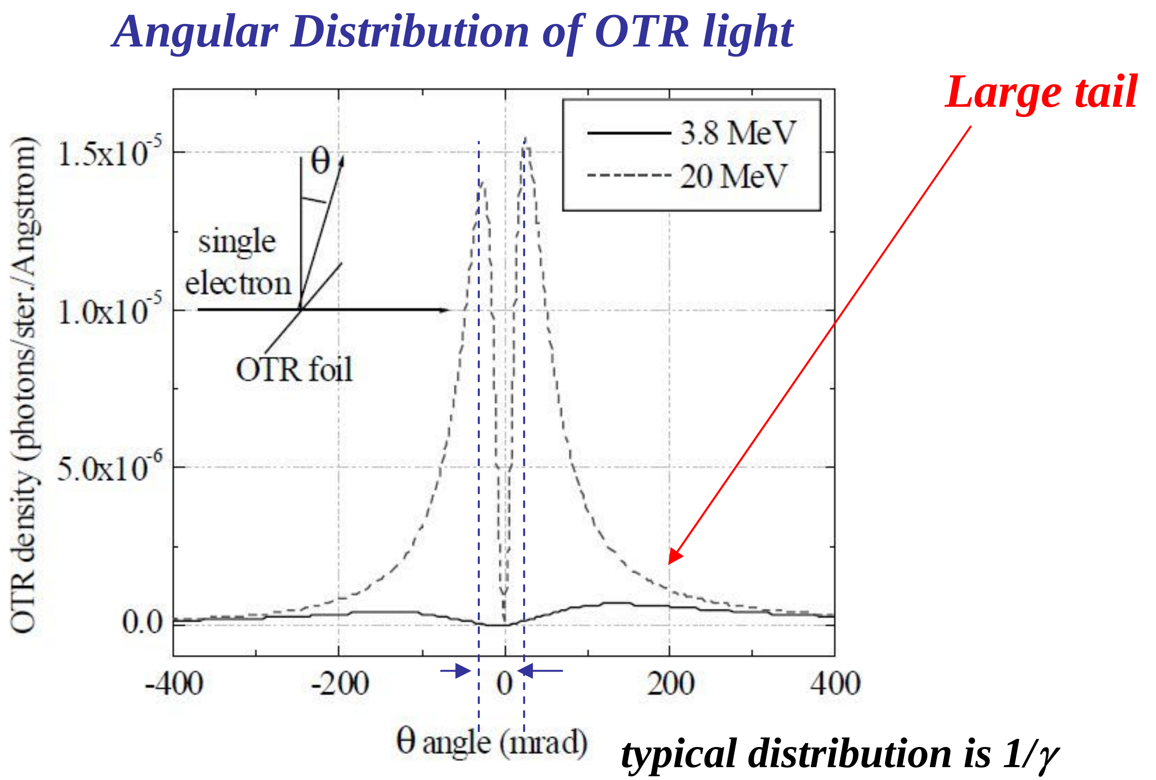
OTR target for using beam instrumentation



This light is used for the beam measurement.

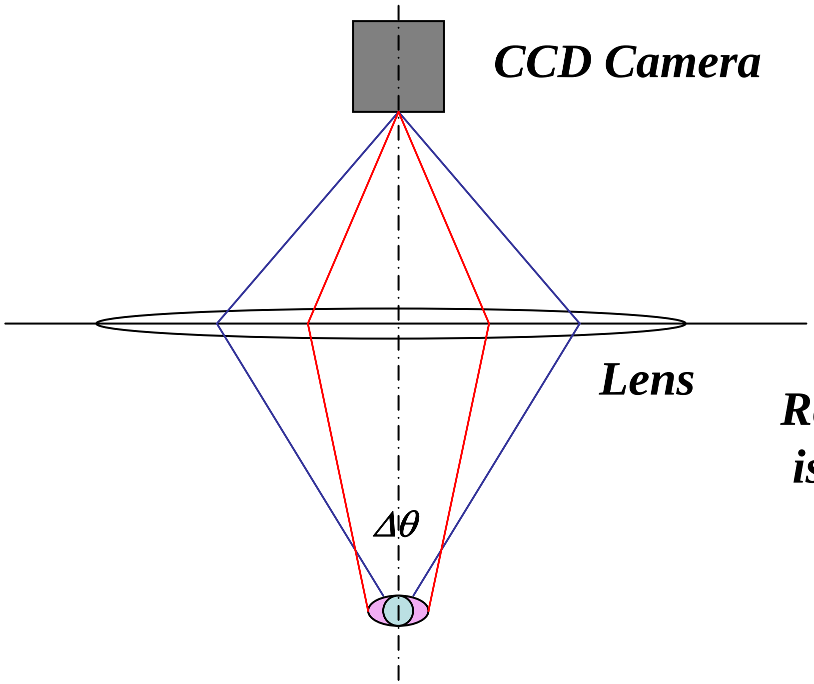
The radiation is emitted just the surface of the material and no diffusion !

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

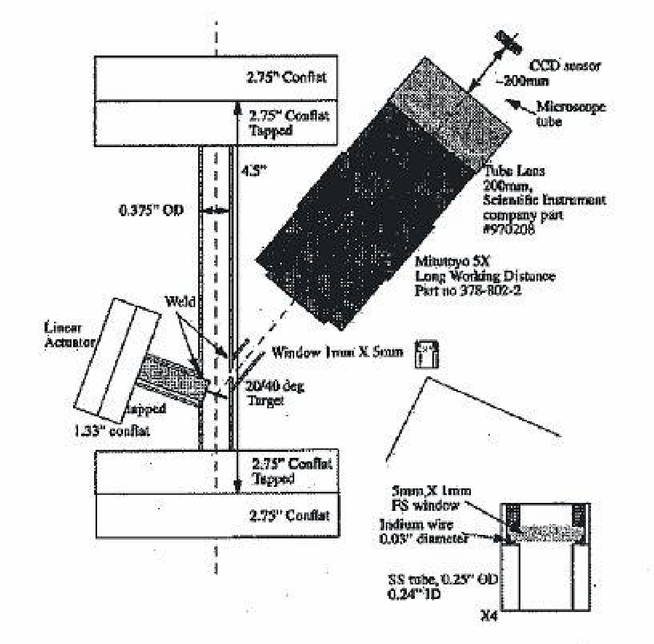


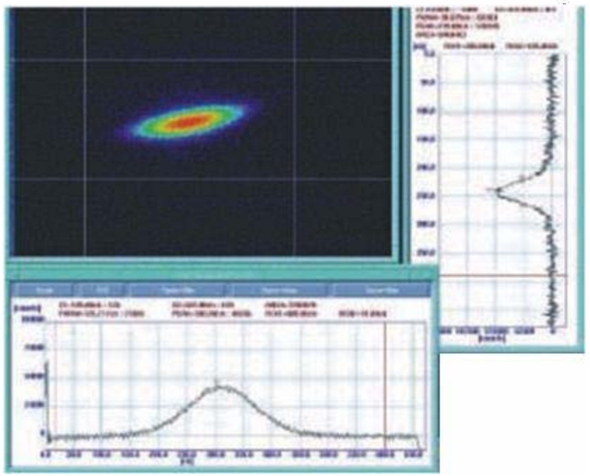
Resolution of the beam size measurement is limited by the diffraction limit .

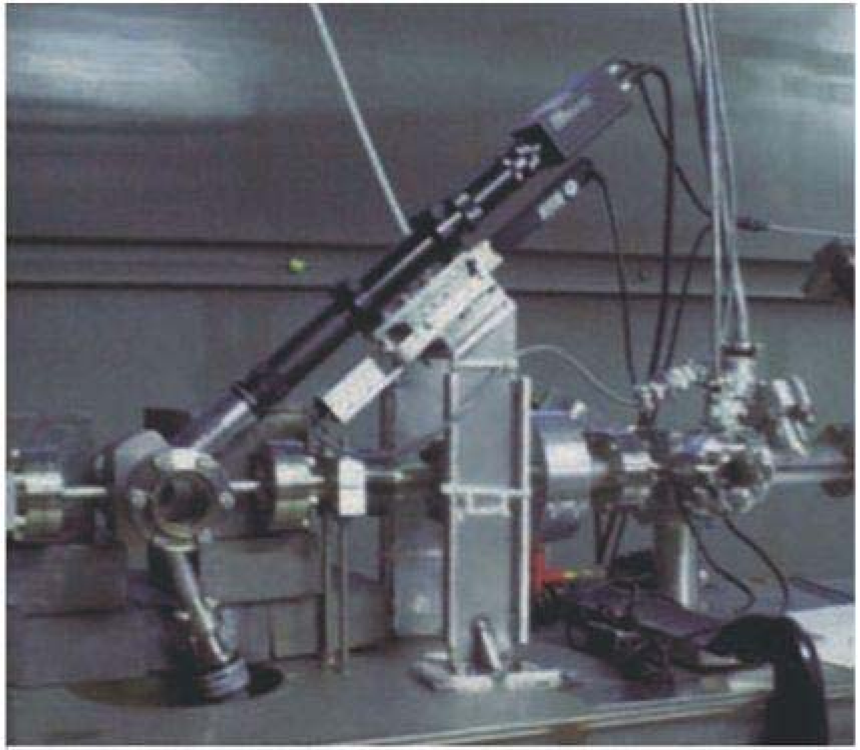
$$\Delta x > \lambda / 4\pi \Delta\theta$$

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

Example of the Wide Aperture Lens System in ATF



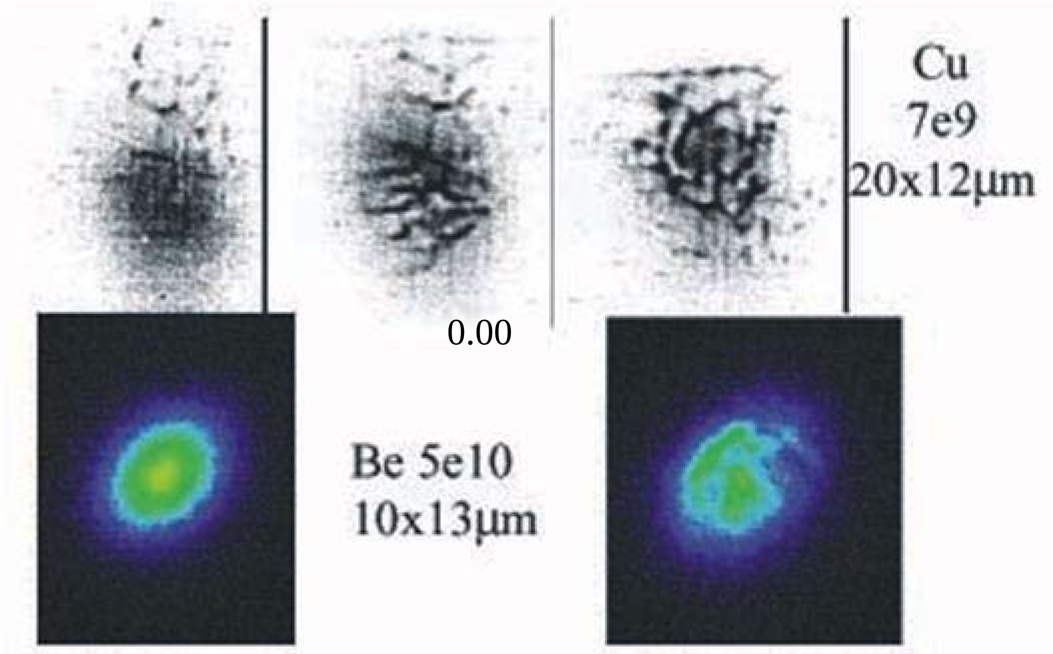




Minimum measured beam size is 10 μm by the OTR monitor

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 .

Critical Performance Characteristics 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;

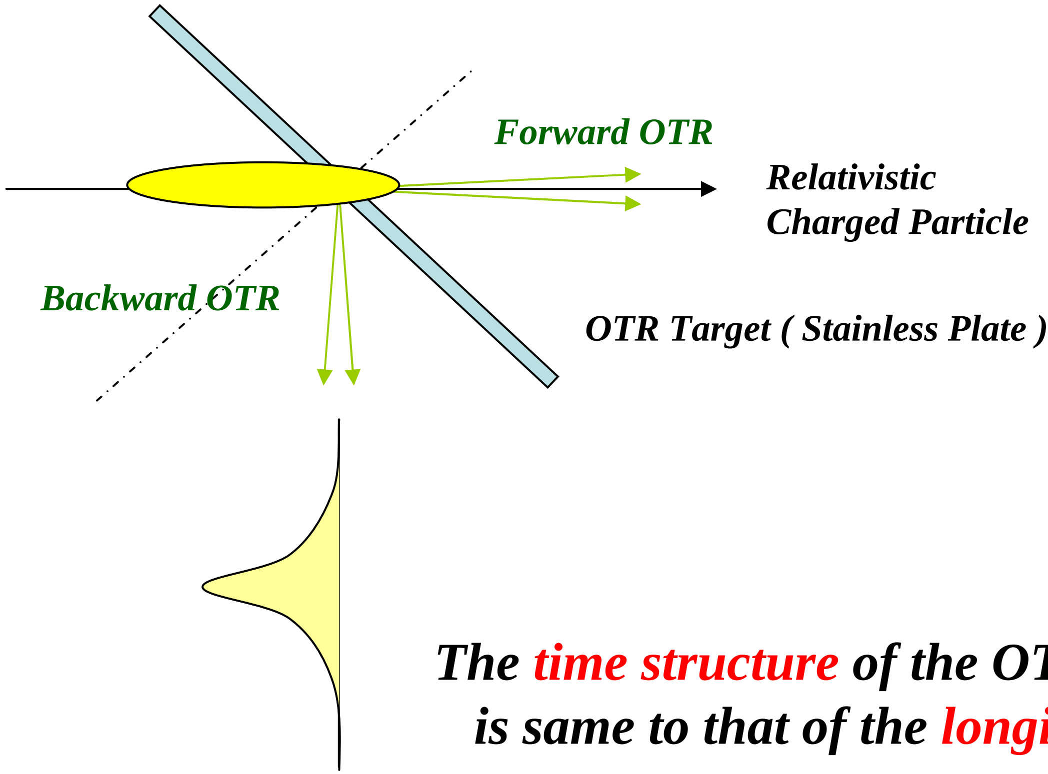
- ***Calibration of the magnification ratio of the telescope.***
- ***Aberration of the lens system***
- ***Imperfection of the focal length adjustment***

-Destructive

Only for the beam transport line .

Bunch Length Measurement with OTR light

OTR is also used for the bunch length measurement

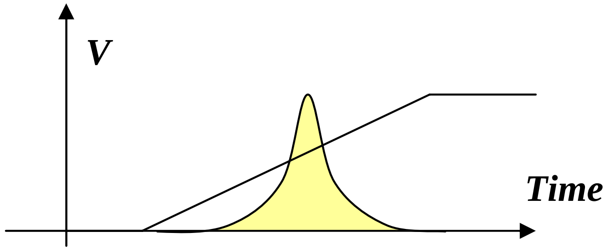


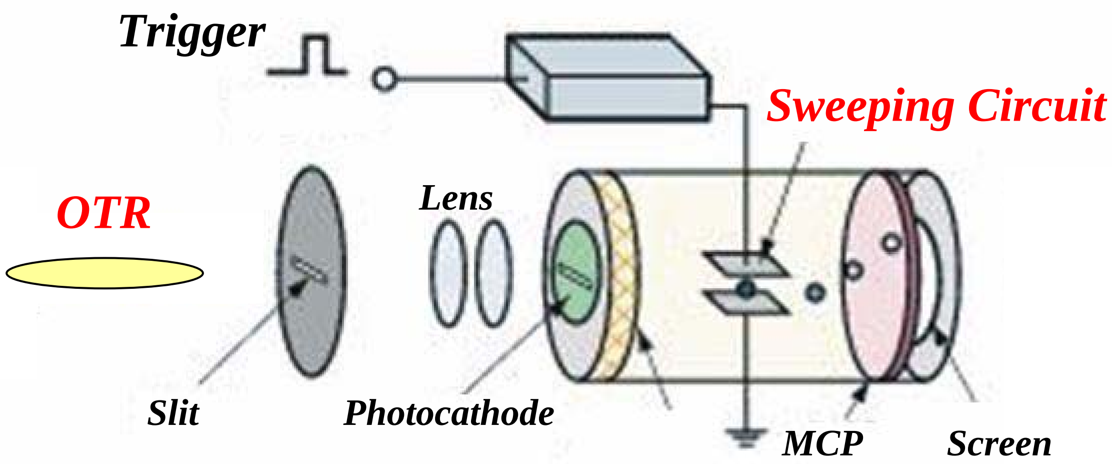
The time structure of the OTR light is same to that of the longitudinal profile of the beam.

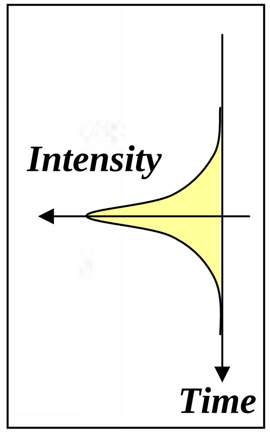
Apparatus of the Bunch Length Measurement

Streak Camera

Trigger timing is synchronized to the beam arrival time.







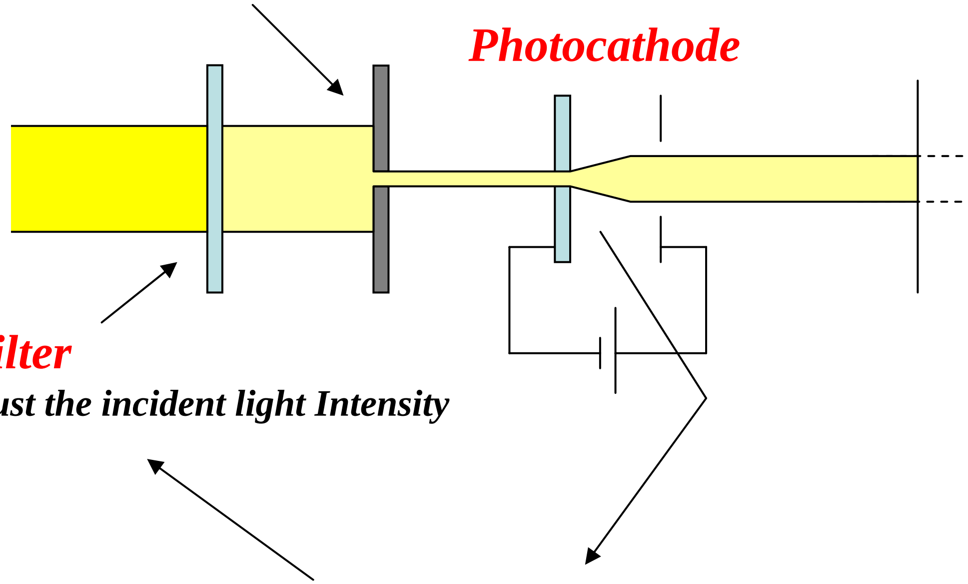
The time information is converted to the space information on the screen

To make accurate measurement

Slit

to make small light size

Photocathode



ND filter

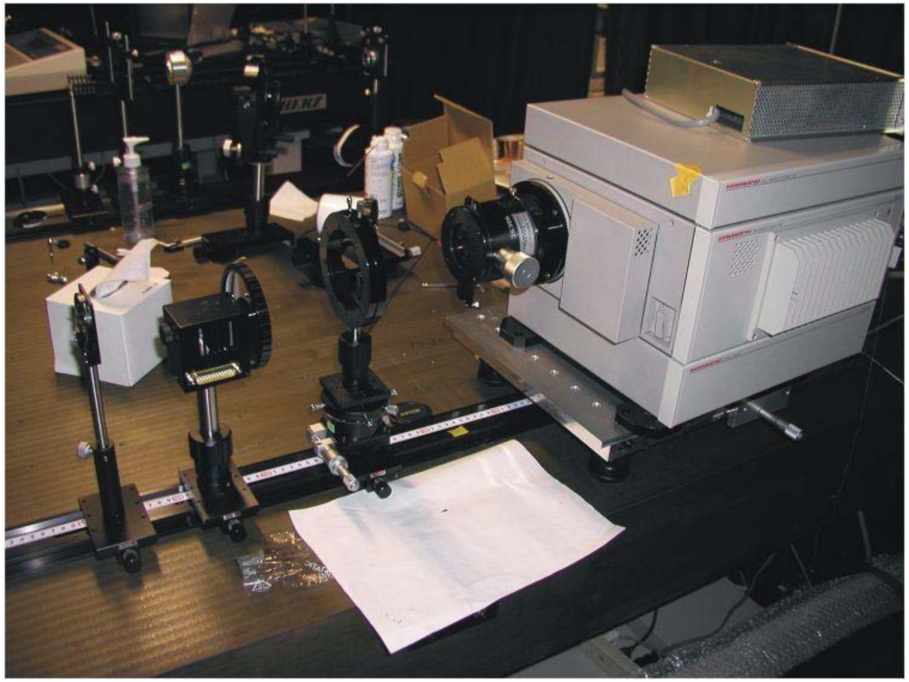
to adjust the incident light Intensity

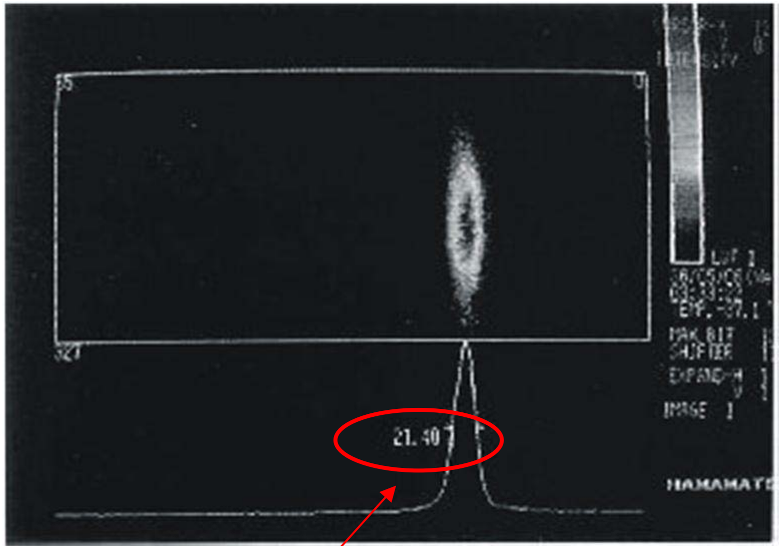
This size is affect to the bunch length measurement.

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





time

Bunch Length measured by streak camera

Critical Performance Characteristics of OTR 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 light on the streak camera

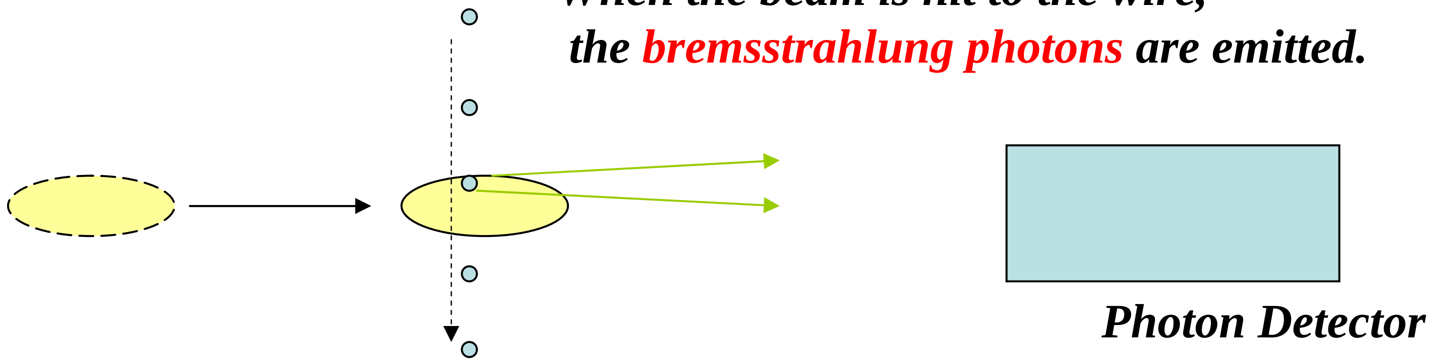
-Destructive

Only for the beam transport line .

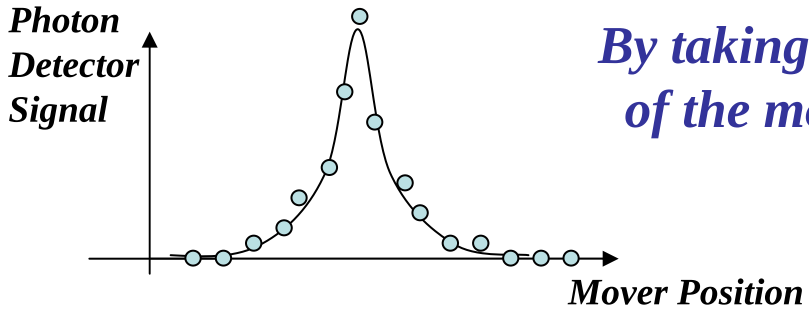
Wire Scanner Beam Profile Monitor

Wire Scanner Beam Profile Monitor

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

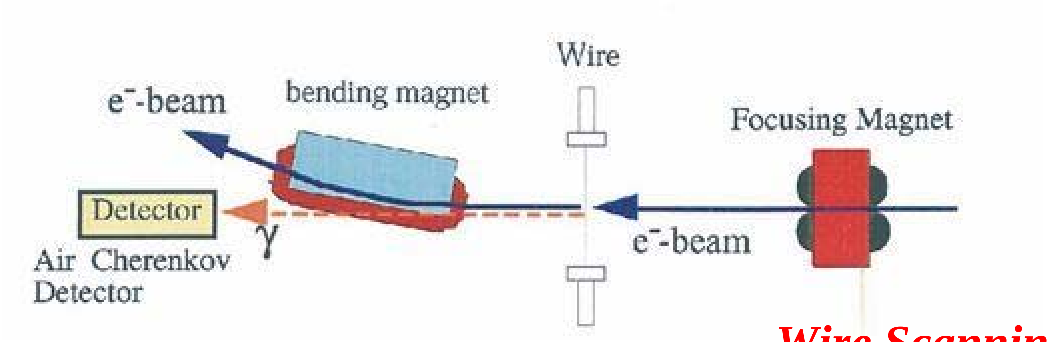


Wire position is moved by the mover stage.



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

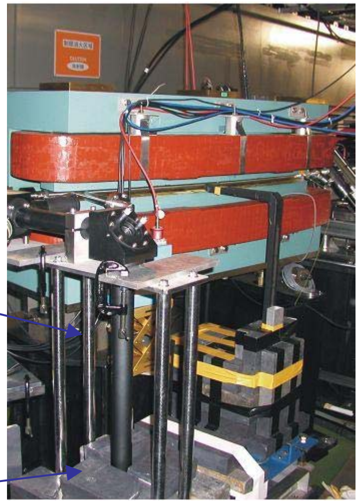
Wire Scanner in ATF



Cherenkov light
is generated.

Light Guide

PMT



Gamma-ray detector

Wire Scanning System

Mover Stage

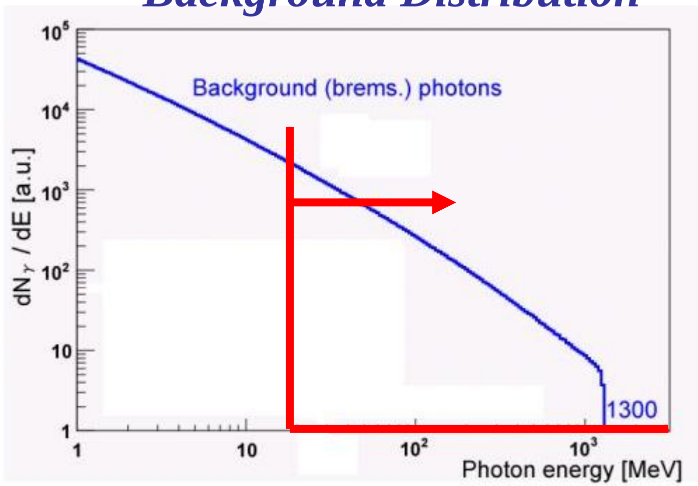
Vacuum Chamber

Wire mount is in the Chamber

Air Cherenkov Detector was used for the Gamma Detector

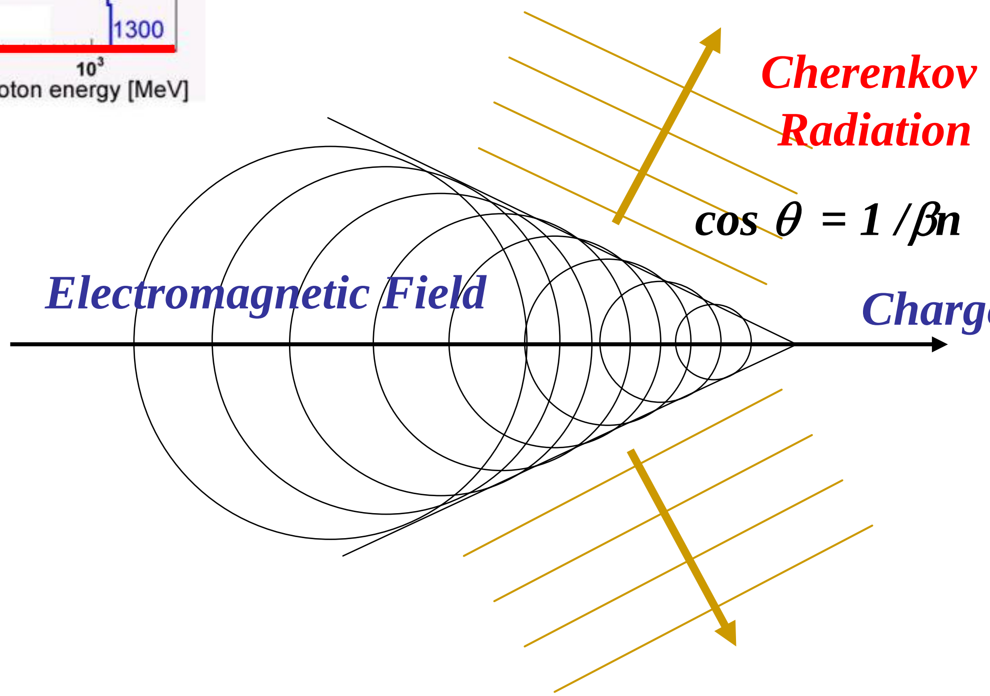
Air Cherenkov Detector

Background Distribution



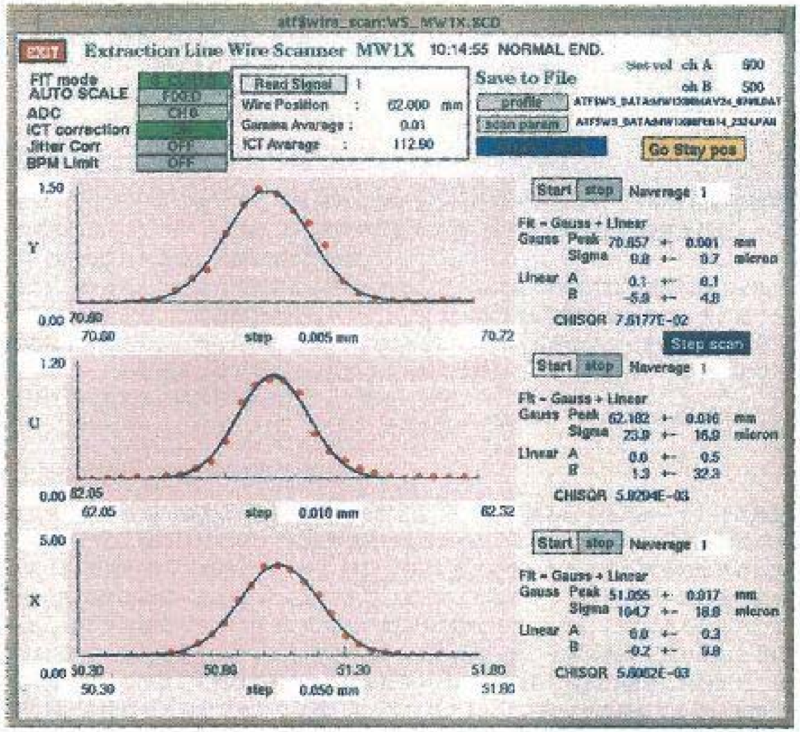
Cherenkov Radiation
is emitted when $\beta > 1/n$.

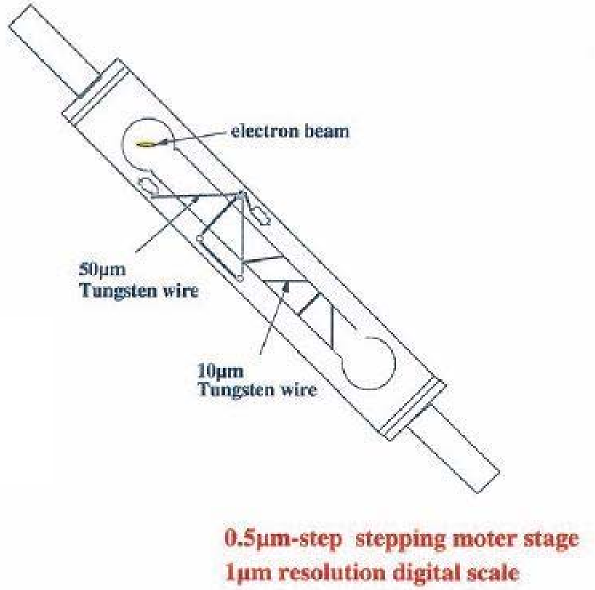
For the air, n=1.0003 ,
the threshold is E > 21 MeV.



Measured Profile by Wire Scanner

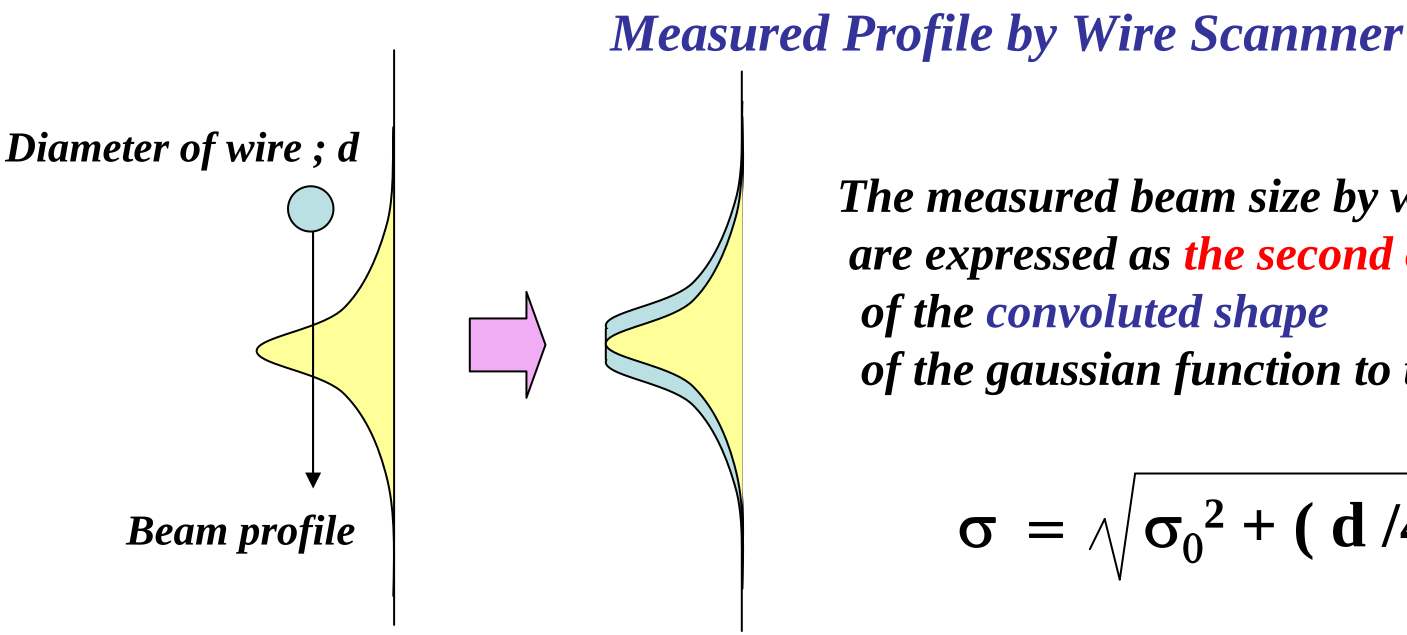
Wires are mounted to horizontal and vertical direction and tiled wires for measuring the beam coupling.





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

Limit of the Measured Beam Size



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 .

Critical Performance Characteristics 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.

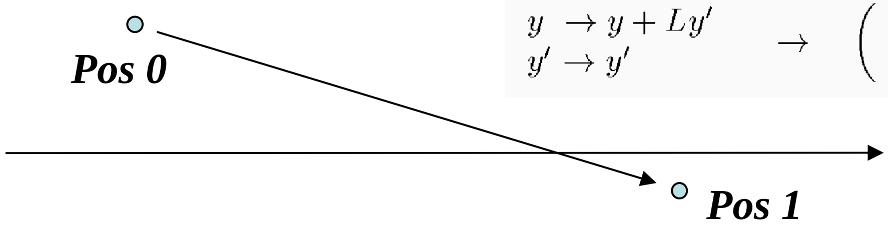
-Partly destructive Monitor

- 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 .

Emittance Measurement in Beam Transport Line

Single Particle Dynamics

1) Free Space

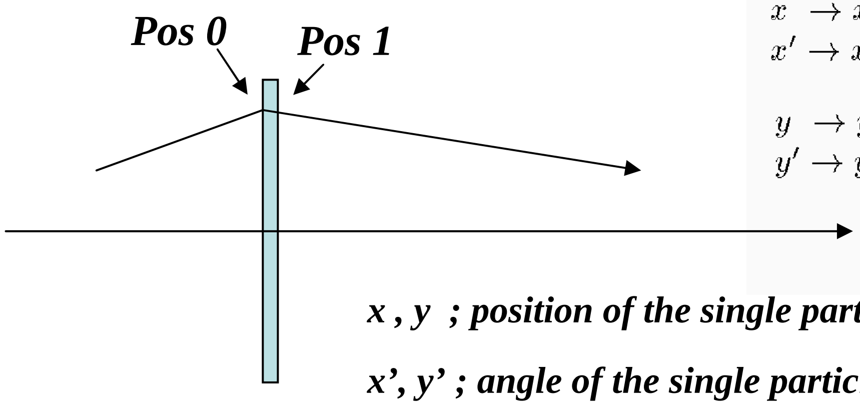


$$x \rightarrow x + Lx', \quad x' \rightarrow x' \quad \rightarrow \quad \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix} = \begin{pmatrix} 1 & \mathrm{L} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}$$

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

Transfer Matrix

2) Quadrupole Magnet (Thin-lenz Approximation)



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

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

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

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

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

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

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

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

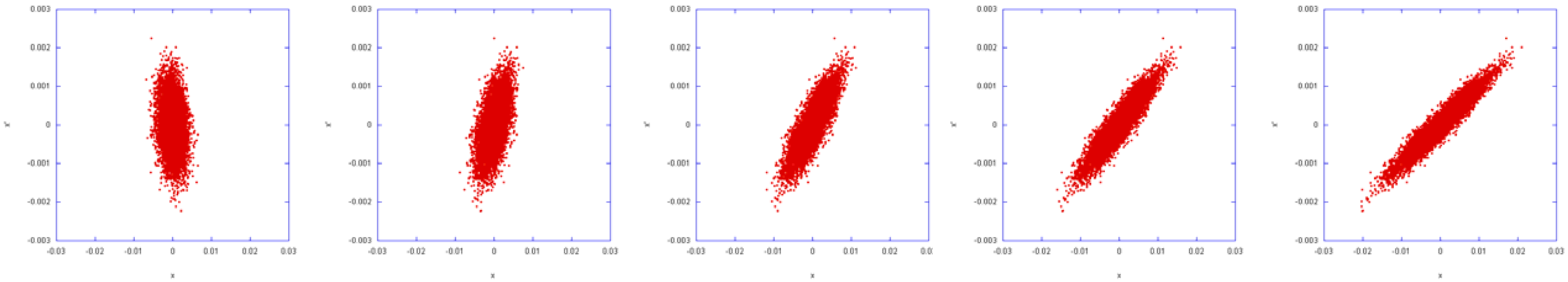
When we define to $V = \begin{pmatrix} u \\ v \end{pmatrix} \equiv T \begin{pmatrix} z \\ z' \end{pmatrix}$***, V moves circular motion as***

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

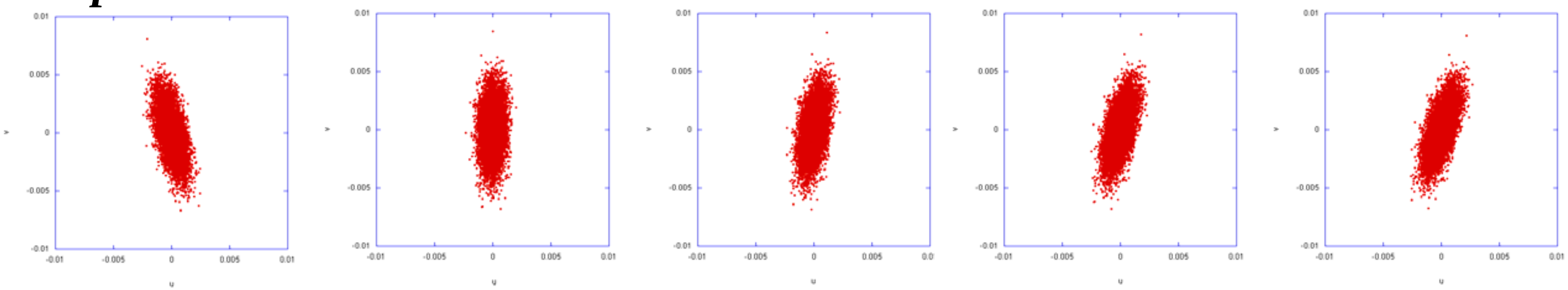
Behavior as a Beam

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

x-x' space



u-v space

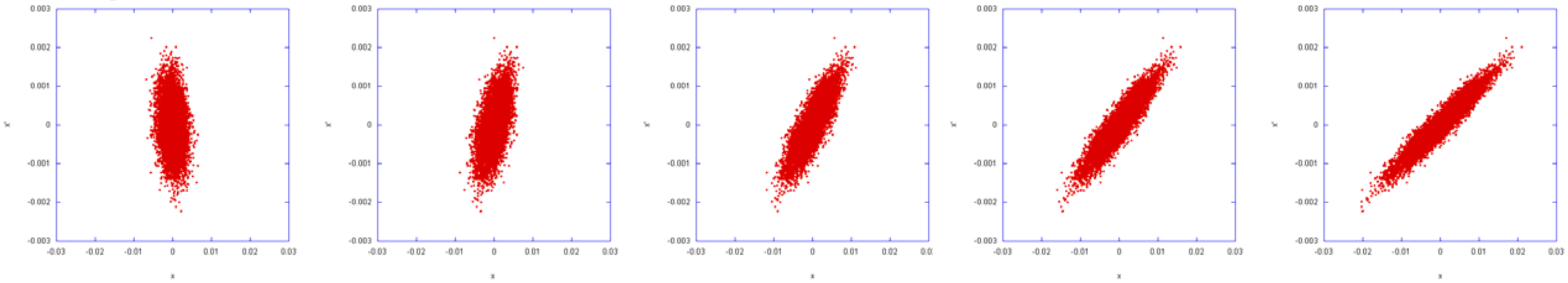


For any set of the (α,β),
all of the linear transformation in (x,x') plane
is expressed as the rotation in (u,v) plane.

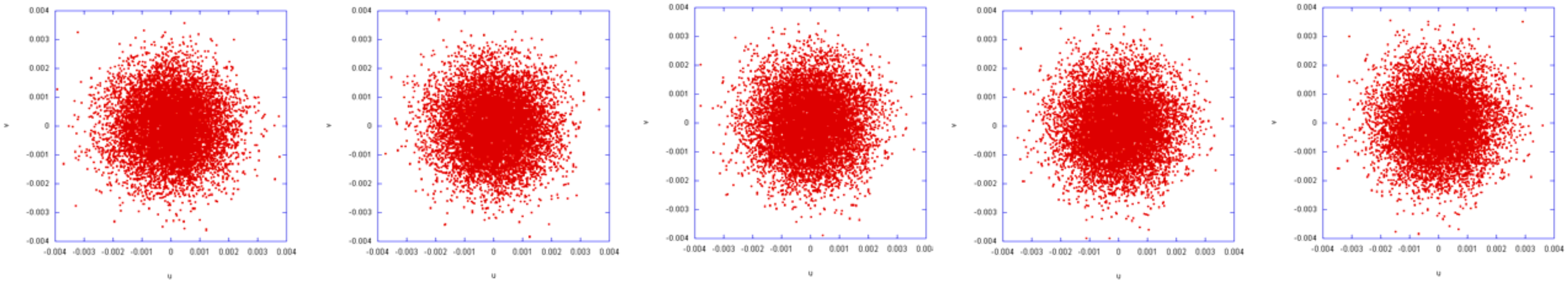
Twiss Parameters

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

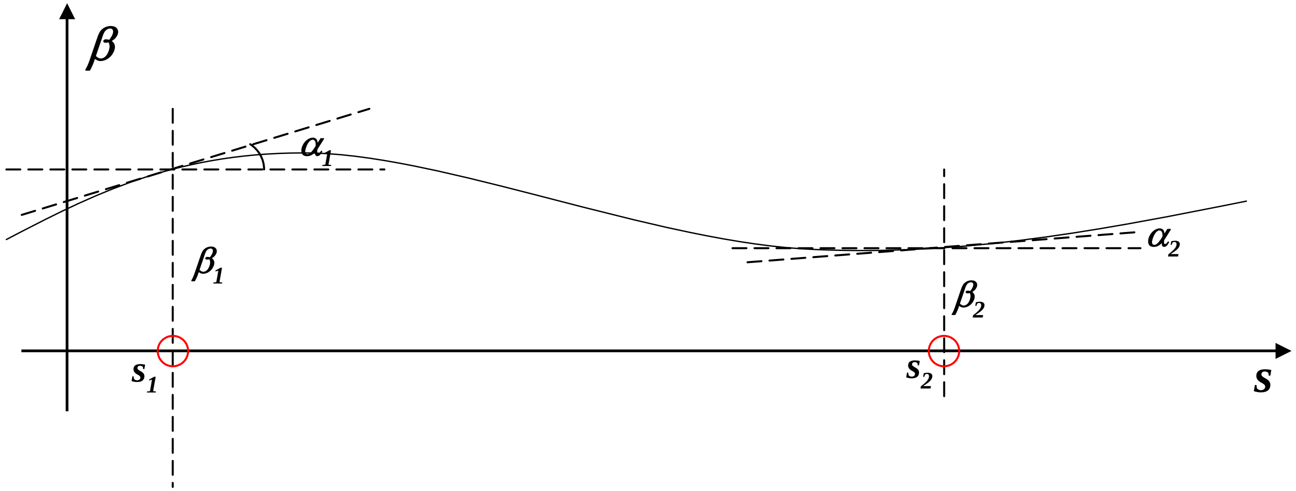
$$< u^2 >=< v^2 >= \varepsilon$$

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

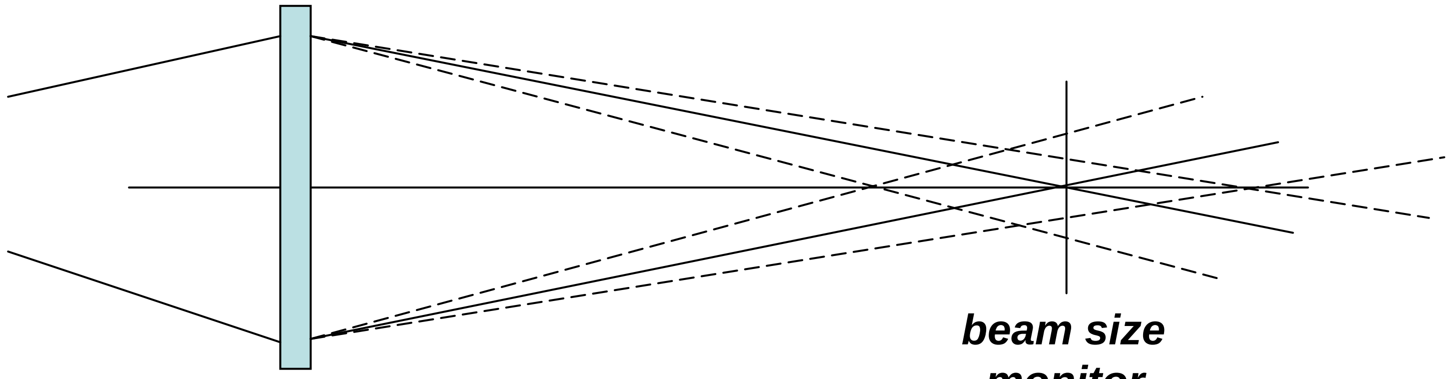


Once Twiss parameters are defined,
the transportation of the Twiss parameters along the beam line
are calculated by the following formula with "transfer matrix" .

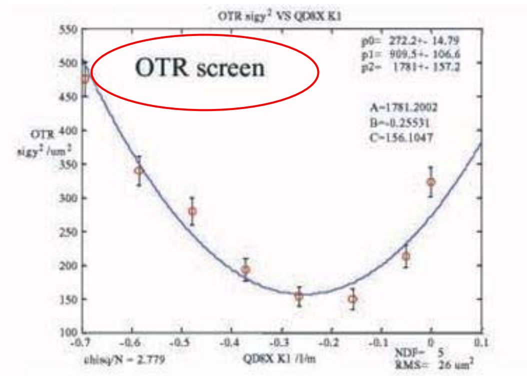
$$\begin{pmatrix}\beta_2\\ \alpha_2\\ \gamma_2\end{pmatrix}=\begin{pmatrix}M_{11}^2 & -2M_{11}M_{12} & M_{12}^2\\ -M_{21}M_{11} & 1+2M_{12}M_{21} & -M_{12}M_{22}\\ M_{21}^2 & -2M_{22}M_{21} & M_{22}^2\end{pmatrix}\begin{pmatrix}\beta_1\\ \alpha_1\\ \gamma_1\end{pmatrix}$$

Emittance Measurement by Waist Scan

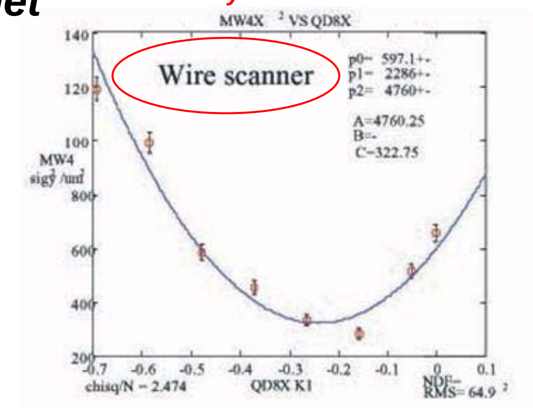
Beam Emittance can be measured by measuring the beam size for various magnet setting.



ε_y = 41pm



ε_y = 38pm



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

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

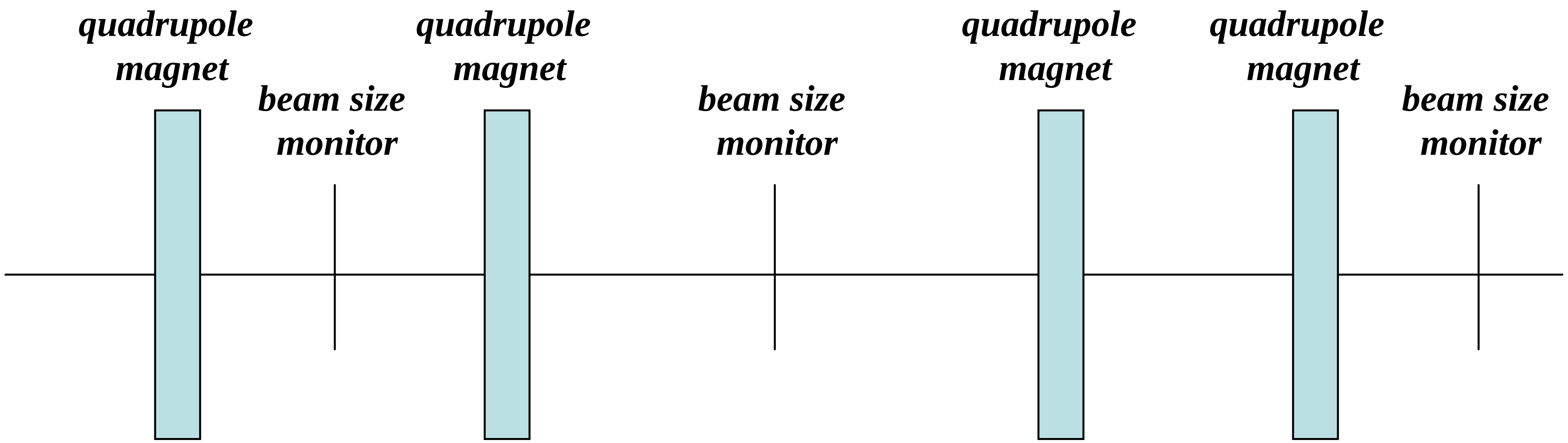
$$\beta_{x,0} = \sqrt{\frac{B_x}{C_x}}$$

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

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 α, β, ε.
We need at least 3 beam size monitors to measure the emittance.

We can measure the emittance without optics modifications.

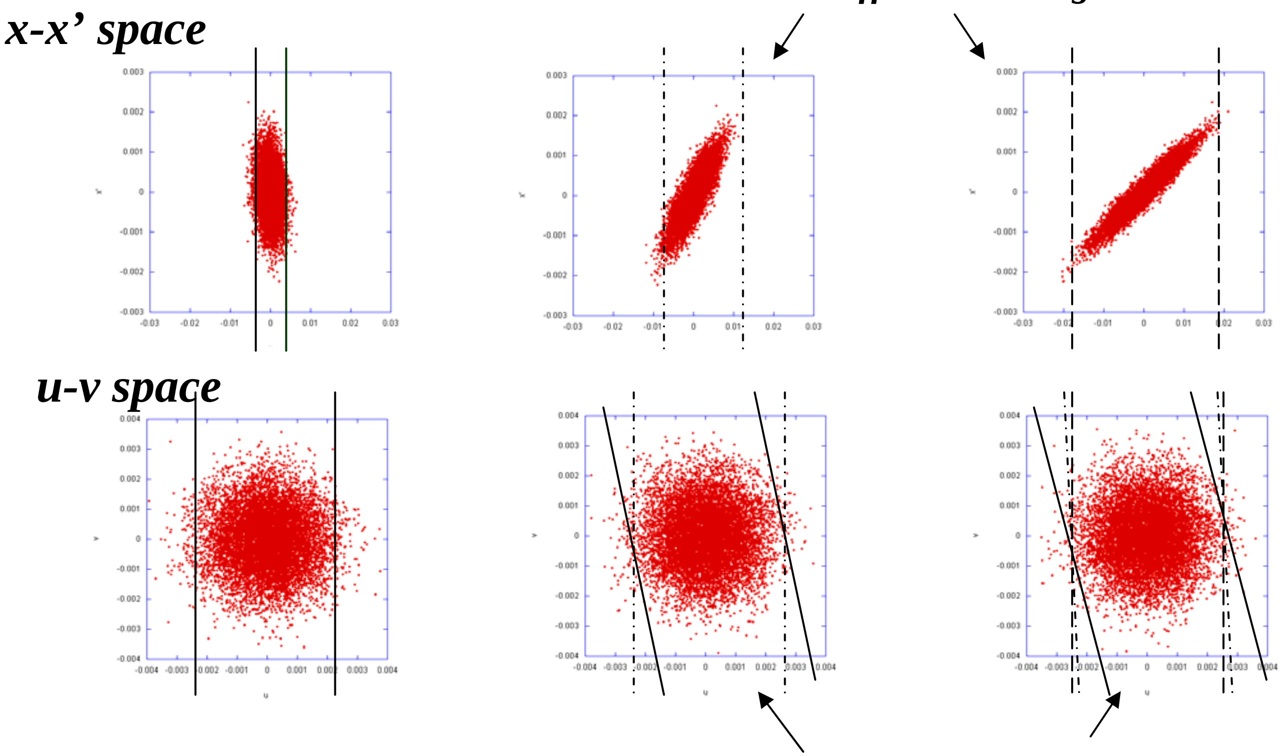
But, we must make a long emittance measurement section in the beamline.

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 !



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.

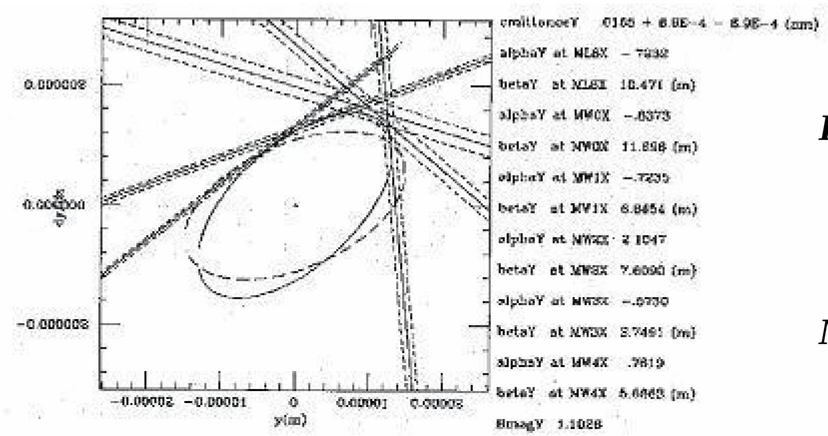
4 Beam Profile Monitor ;

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 .

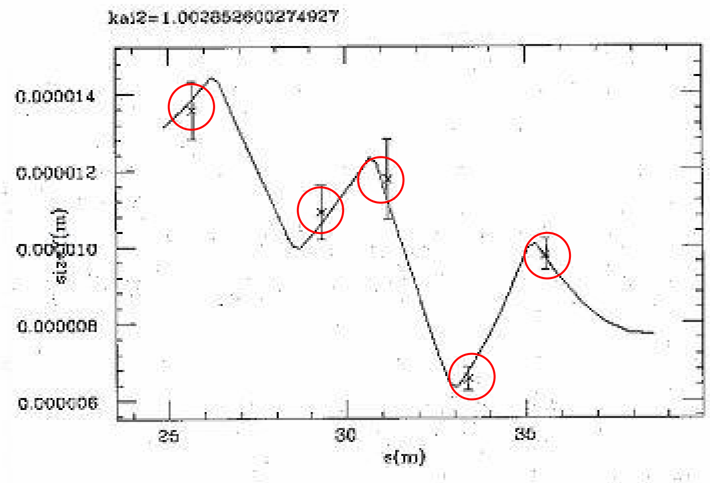
Emittance Measurement at ATF



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

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.