Beam Instrumentation

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Beam Instrumentation
Lecture 5

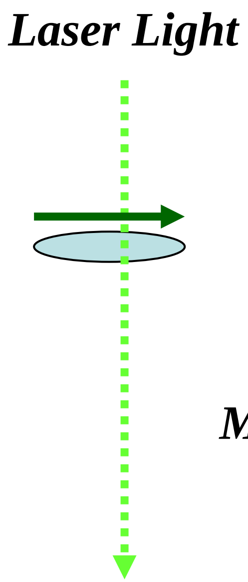
Beam Profile Monitor besed on Laser Compton Scattering

- ***Pulsed Laser Wire Scanner***
- ***Cavity based Laser Wire Scanner***
- ***Laser Interferometer (Shintake Monitor)***

Laser Compton Scattering

Laser Compton Scattering

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



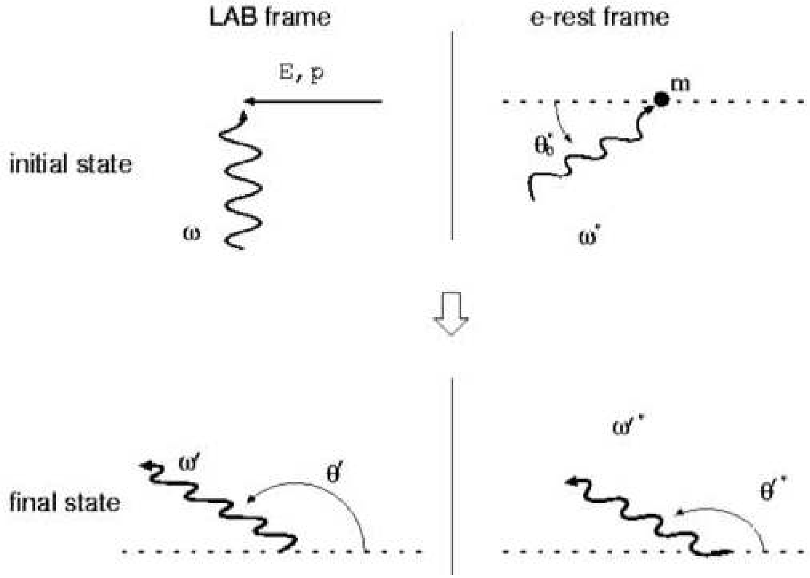
Mechanism of the Compton scattering
is defined by Klein-Nishina Formula.

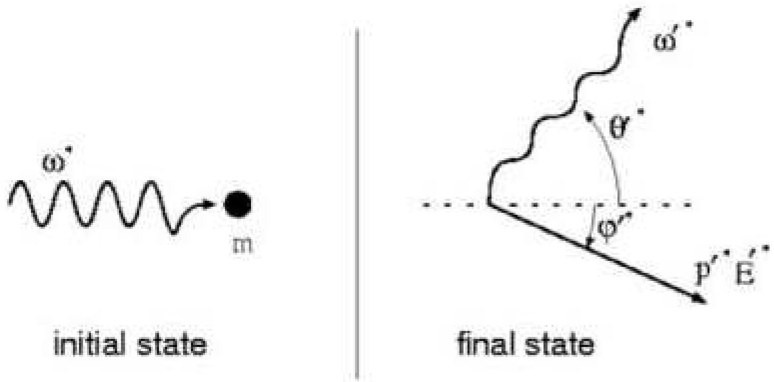
Klein-Nishina Formula

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

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

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



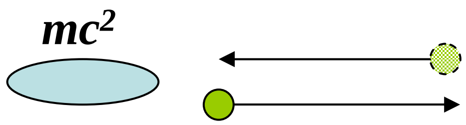


Differential Cross Section of Compton Scattering

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

Energy Shift for High Energy Electron Collision

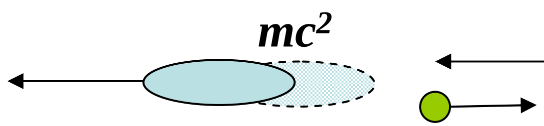
For collision with low energy electron beam



$\gamma\,\omega/2 = 2.9$*keV 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

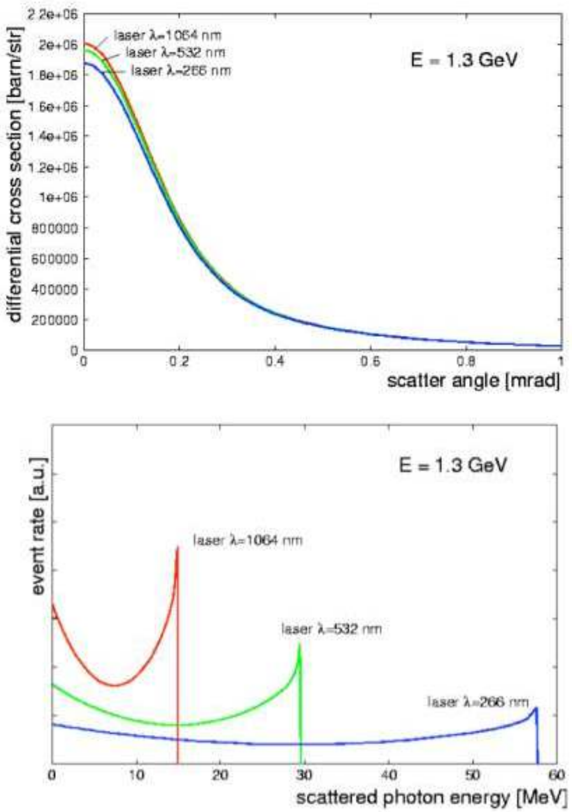


$\gamma\,\omega/2 = 0.55$*MeV for 532nm*

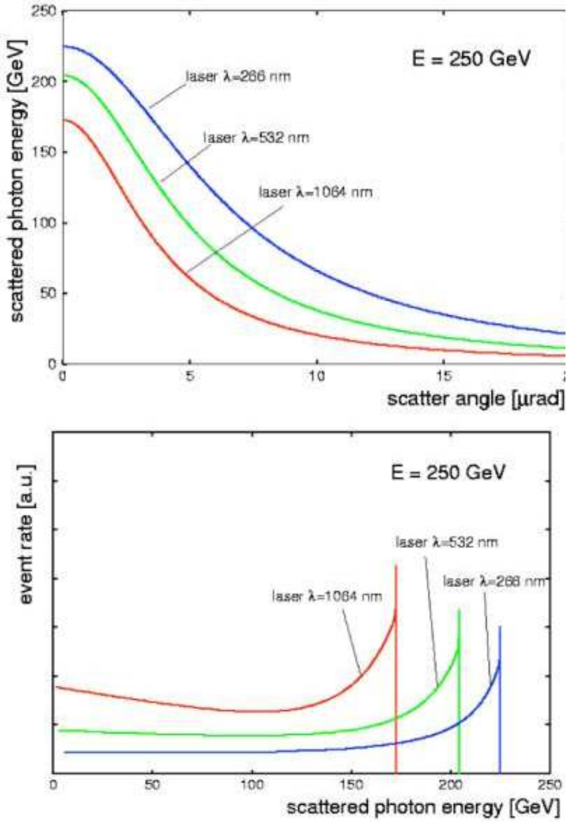
Photon energy in electron rest frame is comparable to electron mass.
Electron move after scattering.
Then the scattered photon energy is shifted to be low.

Differential Cross Section of Compton Scattering

For ATF beam



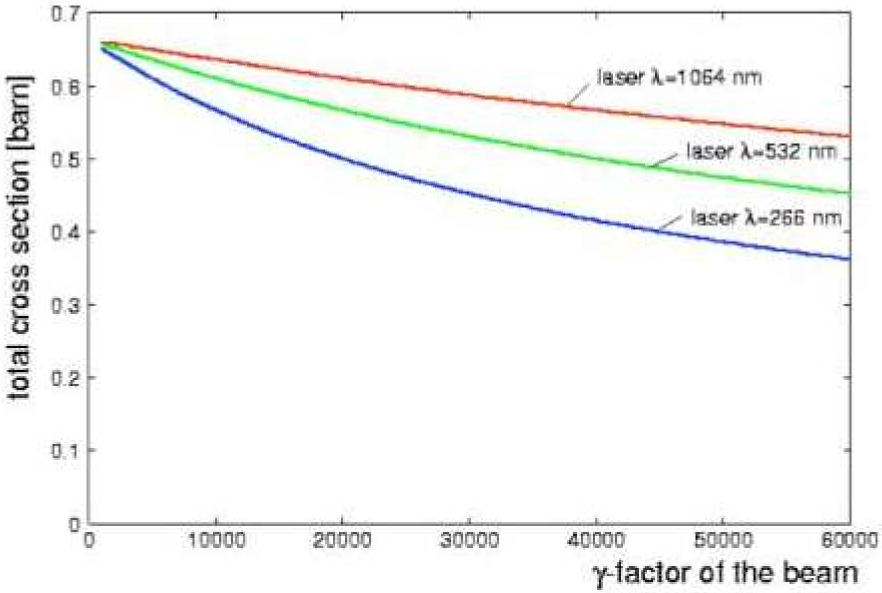
For ILCBDS



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 .



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

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

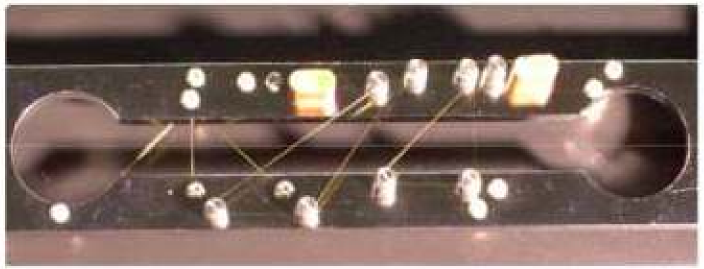
Rough estimation of the signal

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

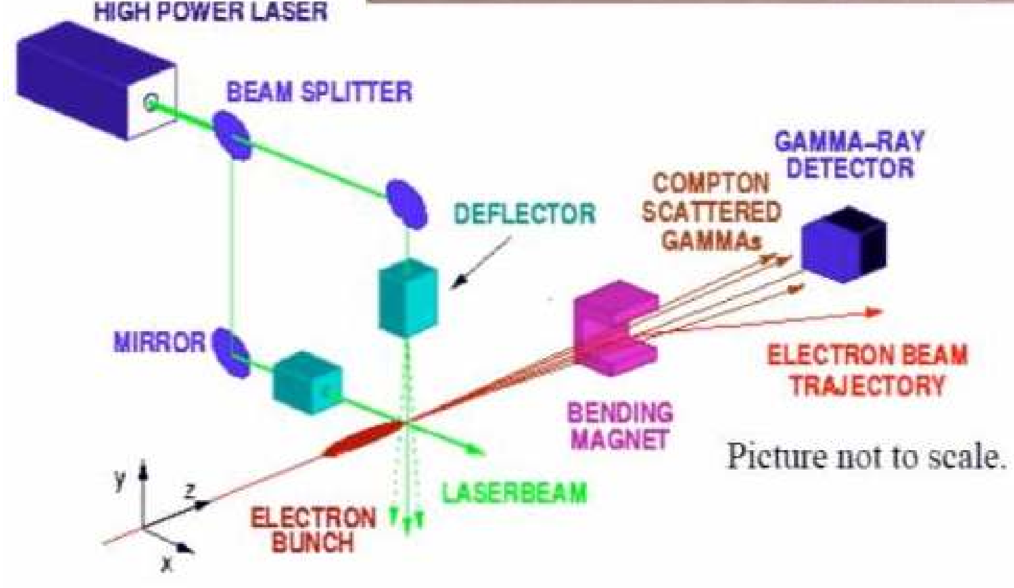
Pulsed Laser Wire Scanner

Concept of Pulsed Laser Wire

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

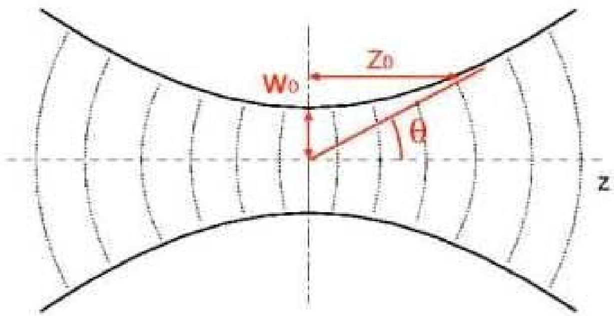


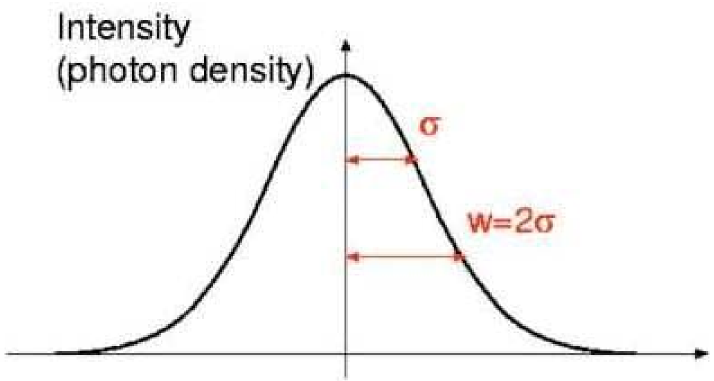
Not destroyed wire ;
Small diameter wire ;
Laser Wire



Gaussian Beam

Laser beam is ideally Gaussian beam





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

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

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

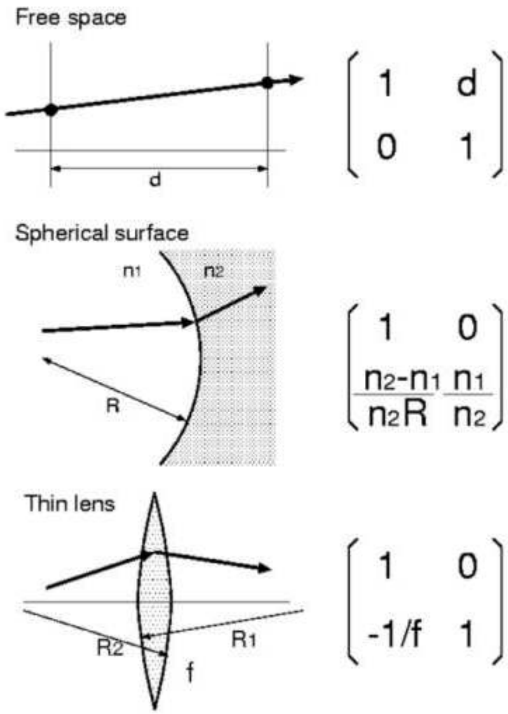
$$\begin{aligned} w(z) &= w_0\sqrt{1+\left(\frac{z}{z_0}\right)^2}, \\ R(z) &= z\left\{1+\left(\frac{z_0}{z}\right)^2\right\}, \\ \Phi(z) &= (m+n+1)\arctan\left(\frac{z}{z_0}\right), \\ z_0 &= \frac{\pi w_0^2}{\lambda}, \end{aligned}$$

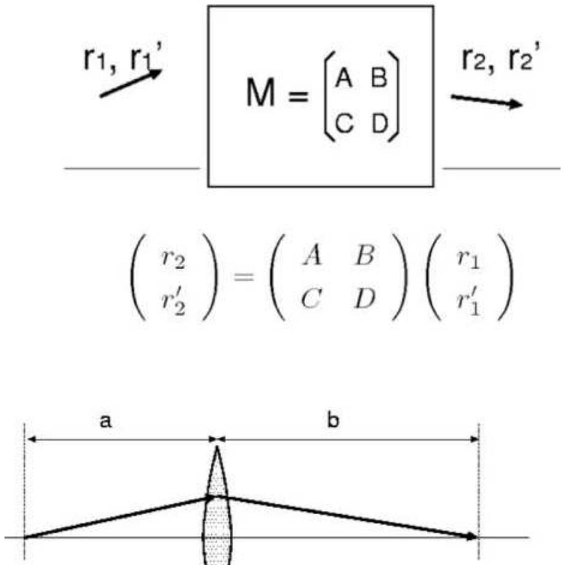
In generally, laser light is TM_{00} mode

Lens Design for Injection System

Transportation of Light

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





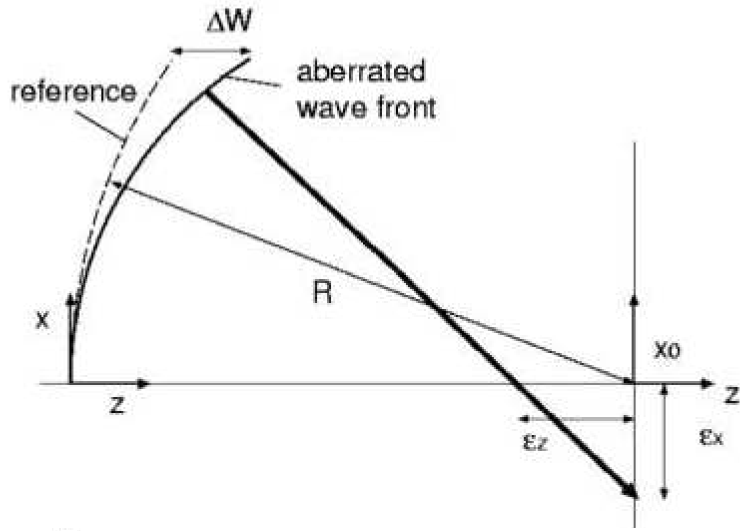
$$\begin{pmatrix} r_2 \\ r_2' \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} r_1 \\ r_1' \end{pmatrix}$$

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

Linear transportation of laser system is defined by Transfer Matrix

Spherical Aberration

The difference from linear system with the spherical lens



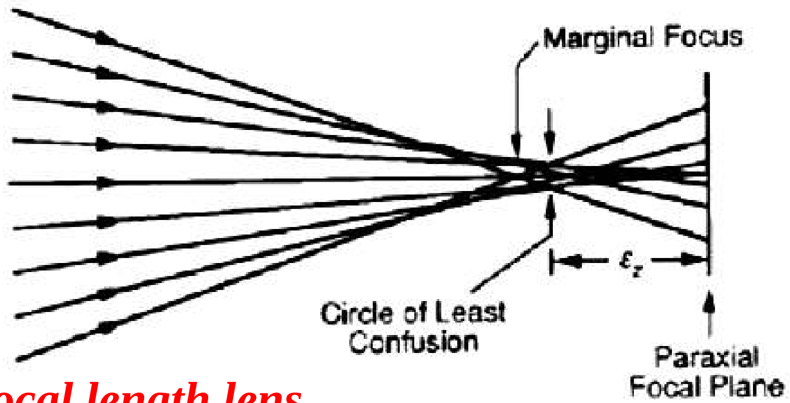
The focal point is different by injection position

The larger aberration for larger offset

The amount of the beam emittance is evaluated by

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

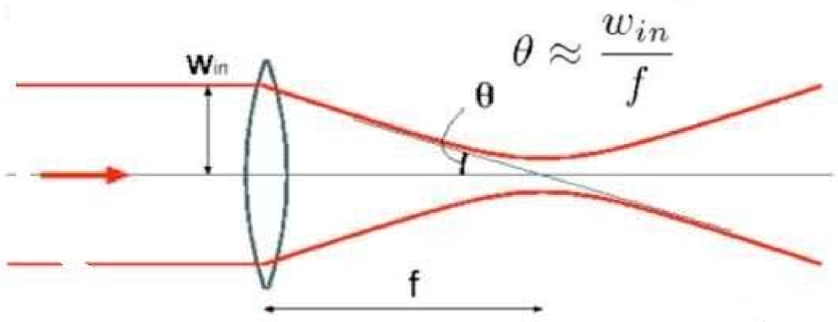
$$\varepsilon_x = -4RW_{040}\rho^3 \qquad \varepsilon_x \propto \underline{R\Phi^3\rho^3 \approx \frac{\rho^3}{f^2}}$$



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.

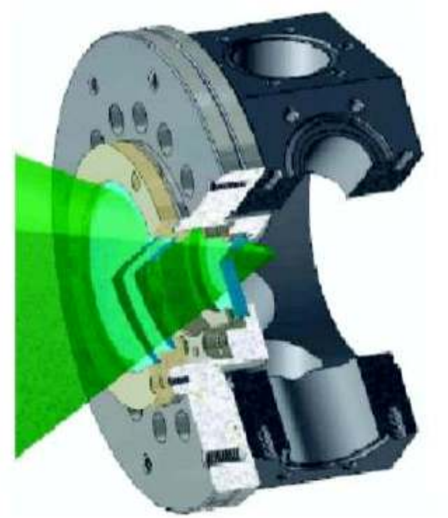
If we design the lens without spherical aberration by F#,
the measured beam size is expressed by

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

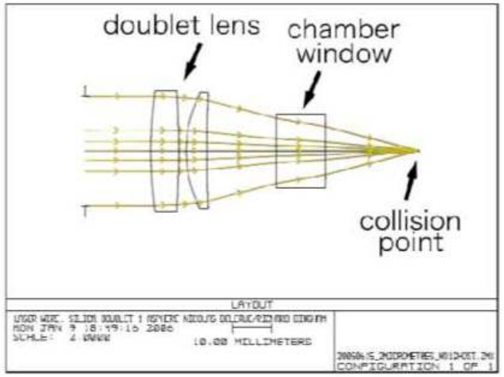
Lens Design for ATF2 Laser Wire Scanner

F#=2 Lens

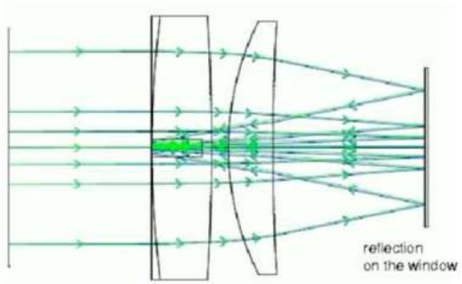
Lens without spherical aberration by F#=2



Design by simulation code (ZEMAX)



Design to be close to the focal point



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

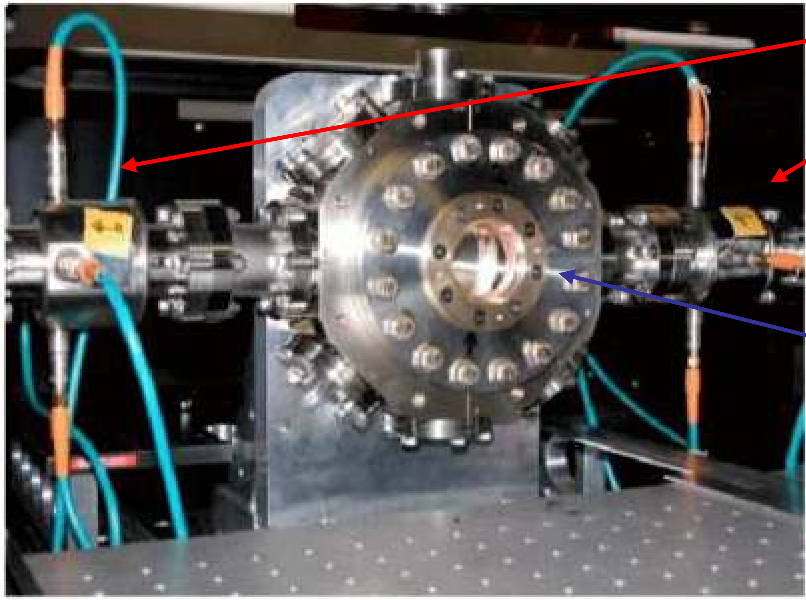
This lens was just installed at the end of 2007 for the preliminary test for ATF2, the collision experiment will be started from Jan. 2008.

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



Stripline BPM

Injection lens system is in the box.

Laser extraction port

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

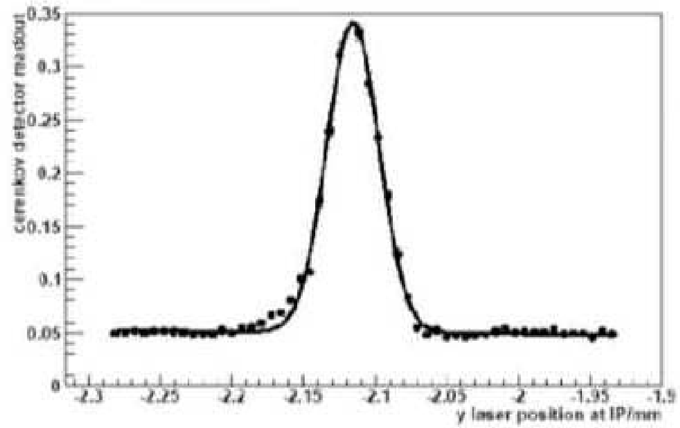
Preliminary Results of Laser Wire in ATF

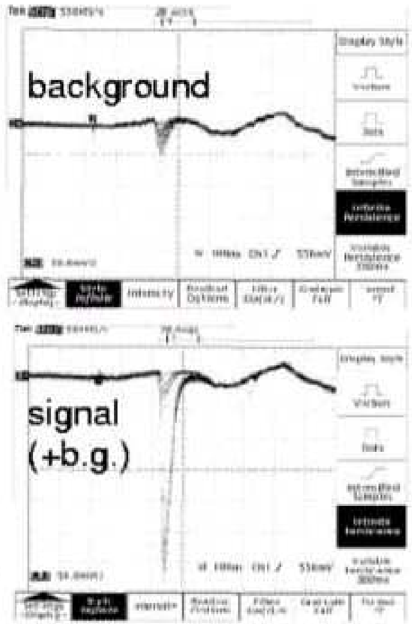
Collision with micron order beam (2μm).

Training of the collision timing adjustment

Test of photon detector (silica aerogel Cherenkov)

Index 1.017, Threshold 2.8MeV





measured profile is 6.8μm

include the laser wire size, laser jitter, beam jitter

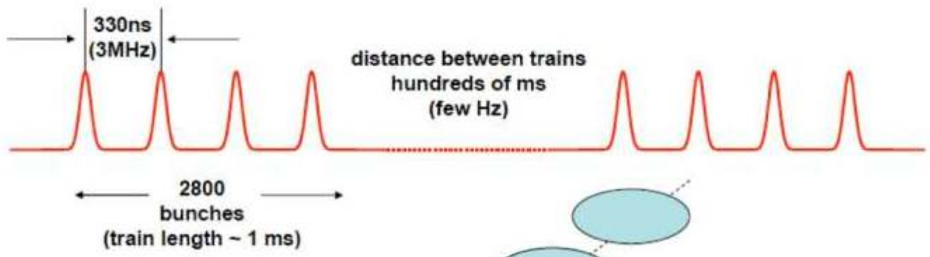
Further Application

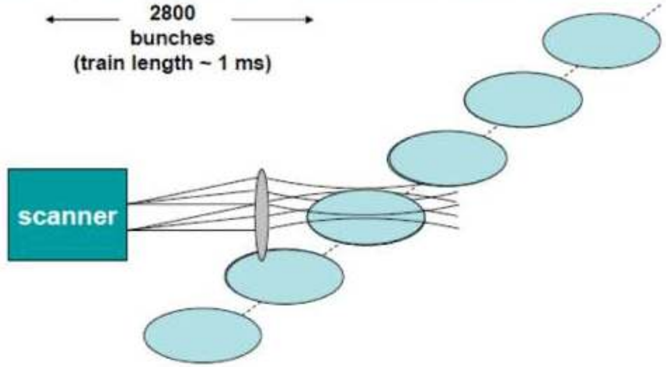
Fast Scan with EO Device

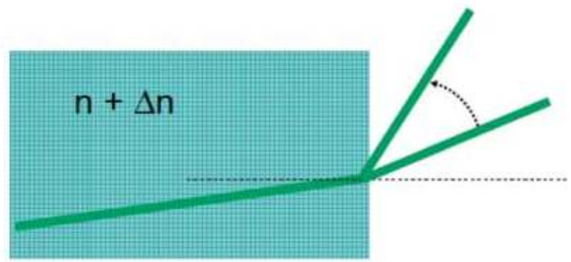
Test of beam size measurement within the bunch train

In order measure the beam size of each pulse of ILC beam, we must measure the beam size within 1ms.

ILC bunch structure







Fast scan is applied with by changing the refractive index of EO device.

Critical Performance Characteristics of Pulsed Laser Wire Scanner

-Dynamic range;

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

-Resolution ;

- determined by the laser waist (1μm for ATF2)

-Accuracy;

-laser waist and waist position should be stabilized

laser improvement , focus lens development

- affect to the beam jitter

-Partly destructive

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

-Further development

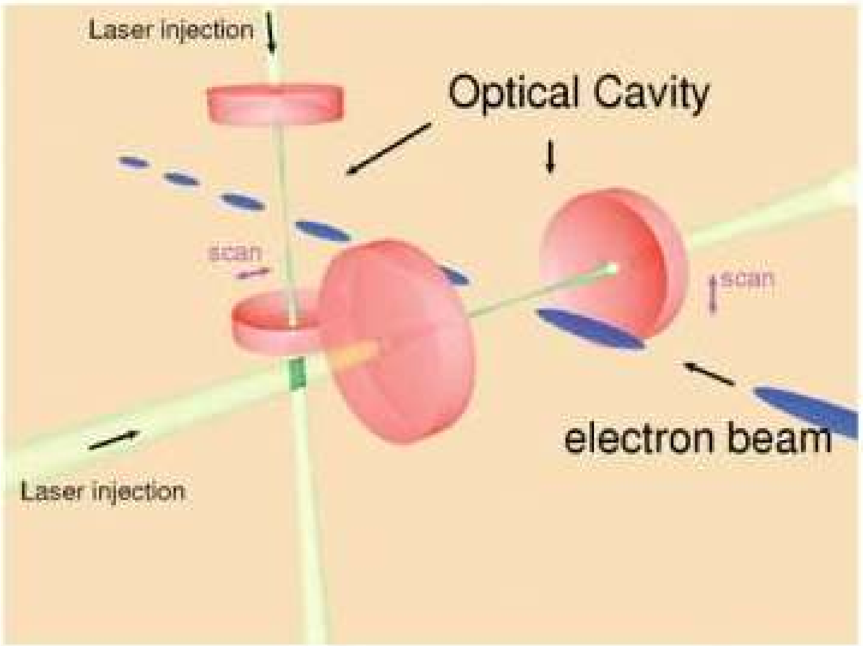
- Make a small and stable laser wire and collide to beam.

- Establish of the fast scan with EO device.

Cavity based Laser Wire Scanner

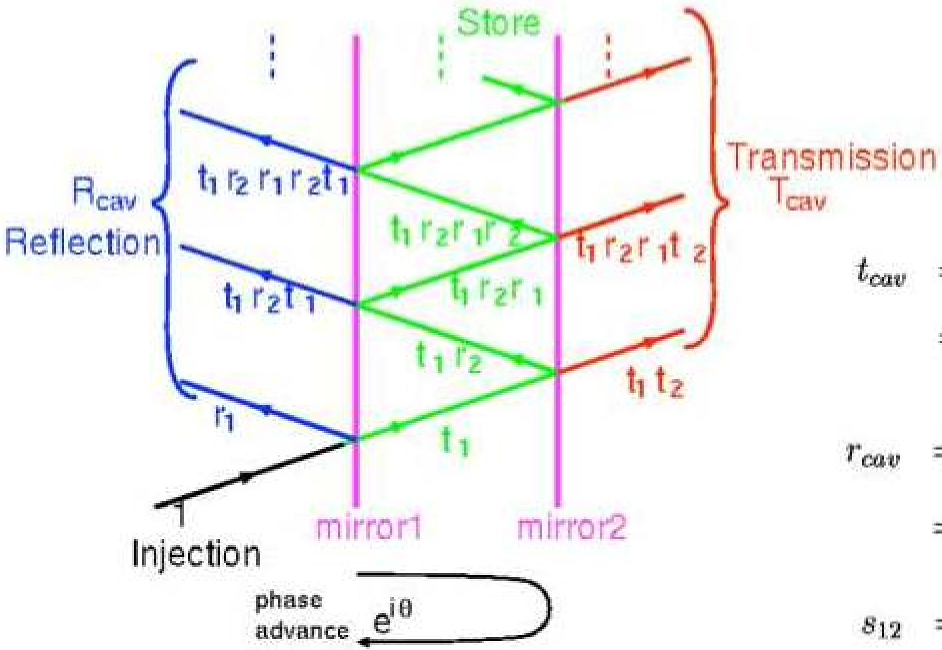
Concept of Cavity based Laser Wire

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



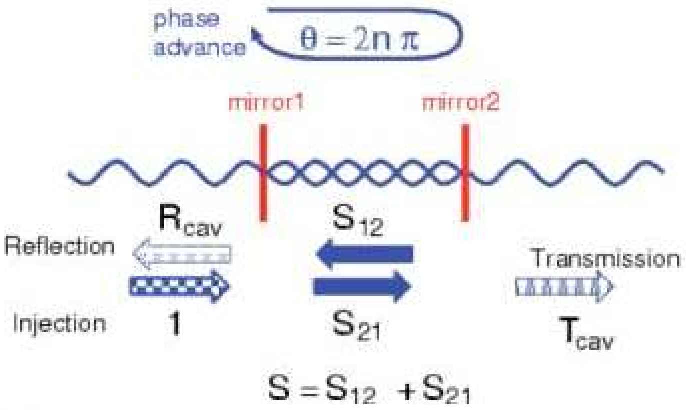
$$
\begin{aligned}
t_{cav} &= t_1 t_2 [1 + r_1 r_2 e^{i\theta} + (r_1 r_2 e^{i\theta})^2 + \cdots] \\
&= \frac{t_1 t_2}{1 - r_1 r_2 e^{i\theta}}
\end{aligned}
$$

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

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

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

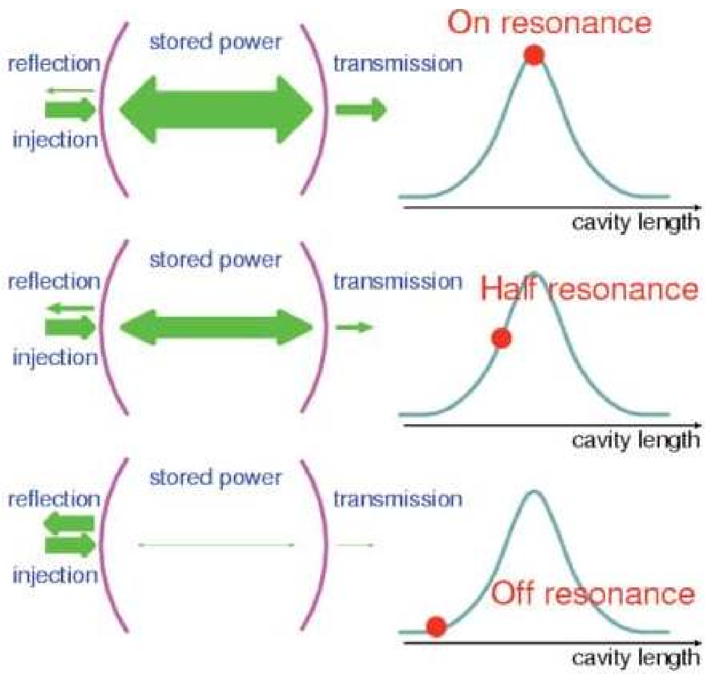
$$S_{cav} = |s_{12}|^2 + |s_{21}|^2 = \frac{T_1(1+R_2)}{(1-\sqrt{R_1 R_2})^2 + 4\sqrt{R_1 R_2}\sin^2\frac{\theta}{2}}$$

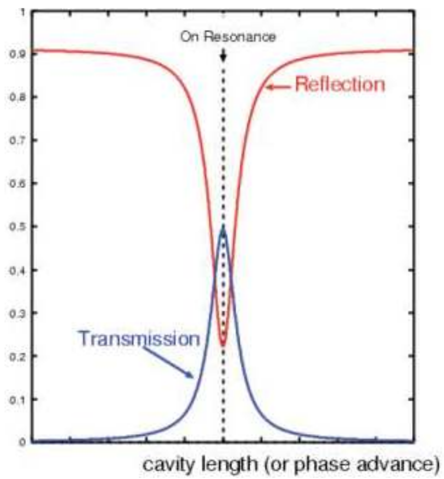
$$= \frac{1+R_2}{T_2} T_{cav} \sim \frac{2}{T_2} T_{cav} \quad (\text{if } R_2 \sim 1) \quad .$$

$T_2 = 1 - R_2$

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

Finess of the Optical Cavity





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

Finess is the power enhancement factor in the opticsl cavity .

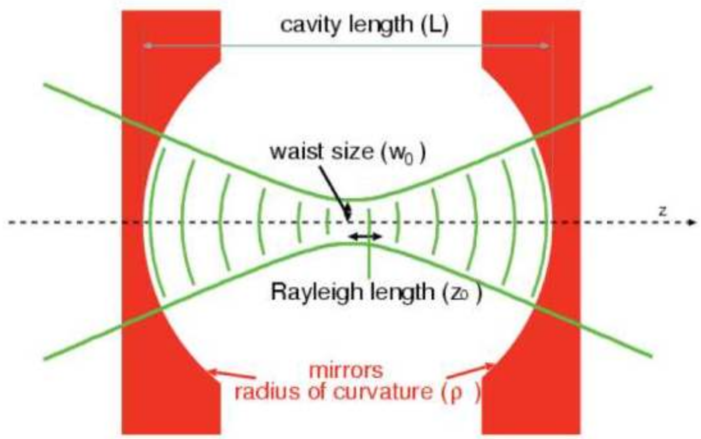
- defined by the reflectivity of the optical cavity .

- 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

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

$2\rho - L$ is very important number to defined the beam size.

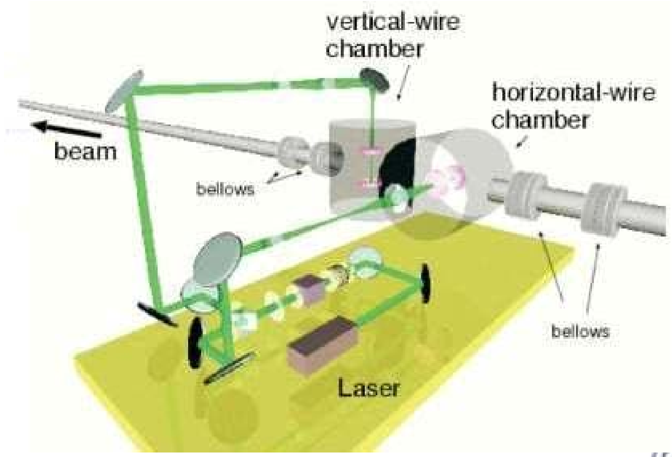
For small beam waist,

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

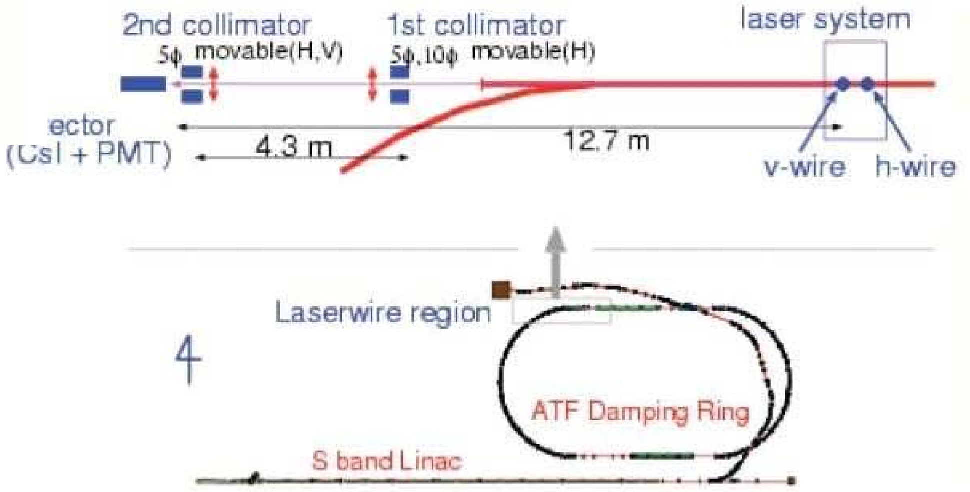
- *The Rayleigh length is short.*

Beam waist is limited around 10μm

Experimental Setup of the Cavity based Laser Wire in ATF



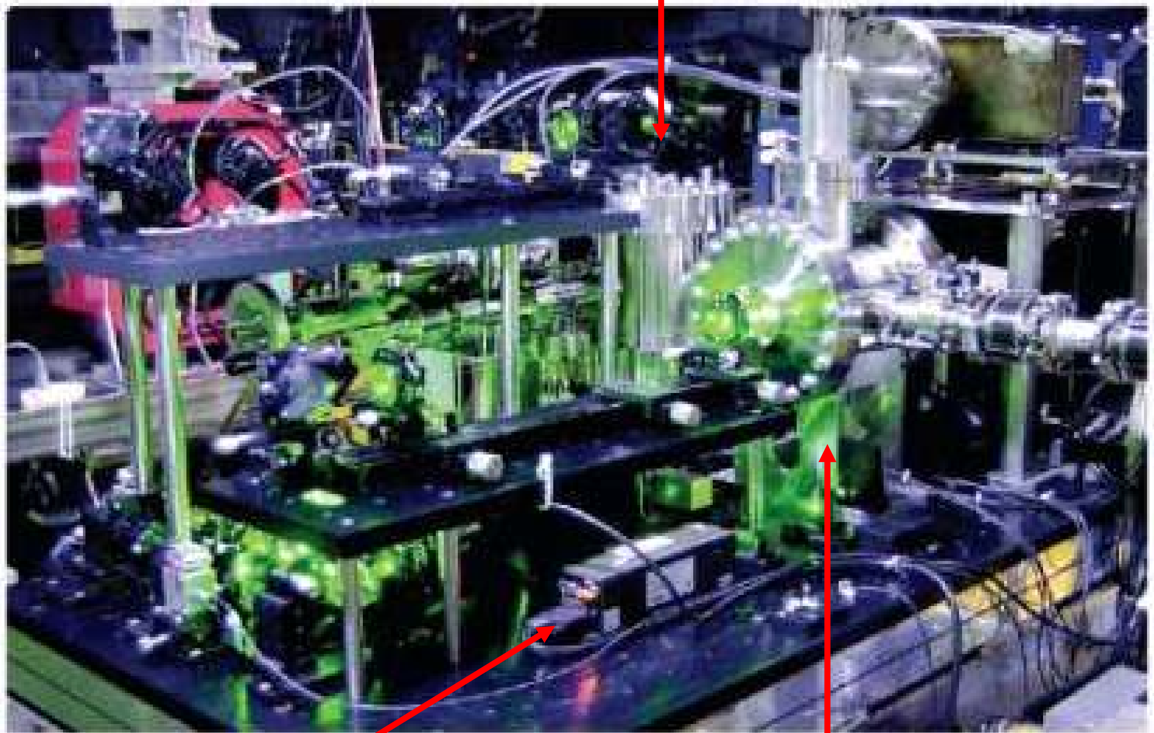
Laser wire system is located at the straight line of ATF damping ring



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

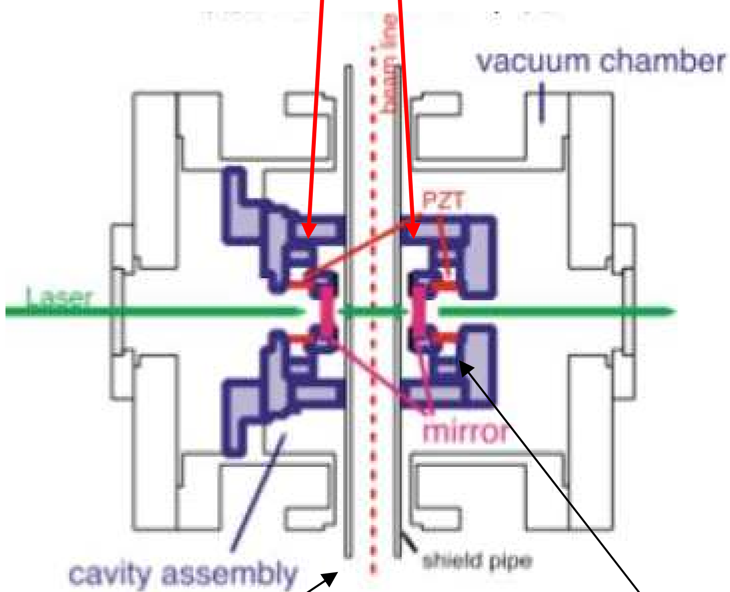


50mW Nd:YAG CW laser　　***Vacuum chamber for vertical measurement***

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

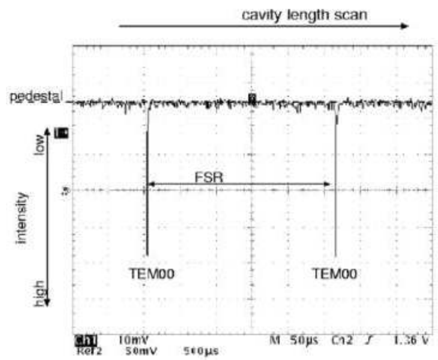
Optical Resonance Cavity for ATF Laser Wire

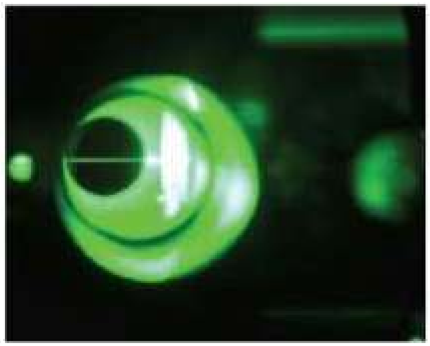
Optical cavity with 2 mirrors



Smooth pipe to reduce impedance

Cavity Length is controlled by piezo actuator

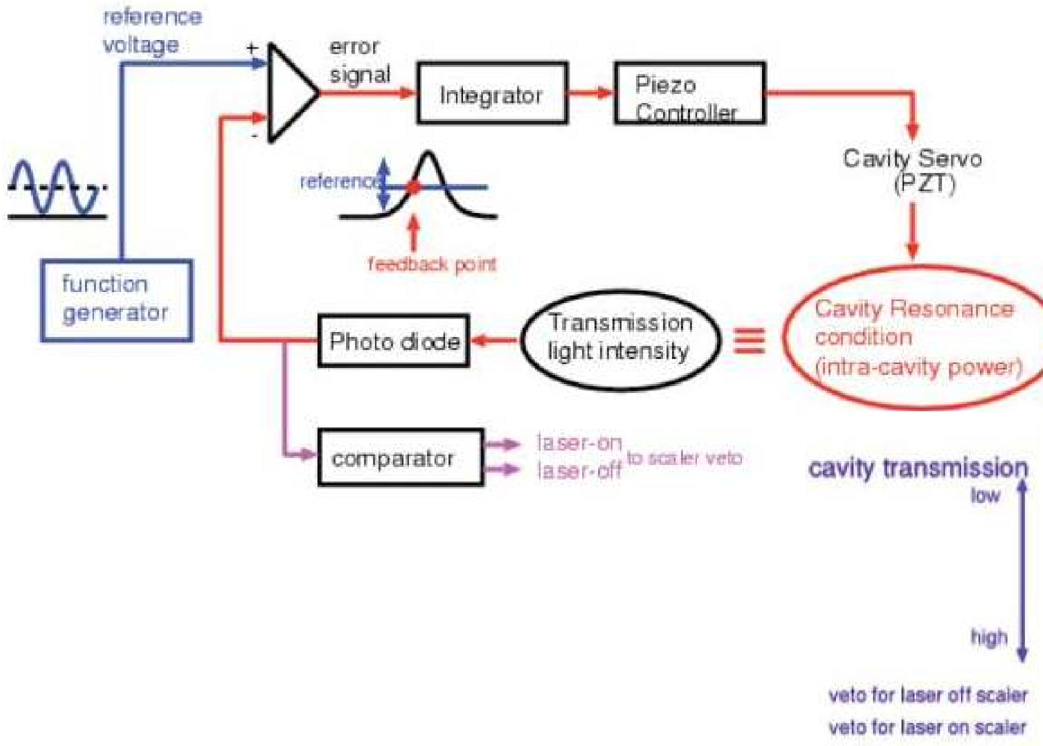


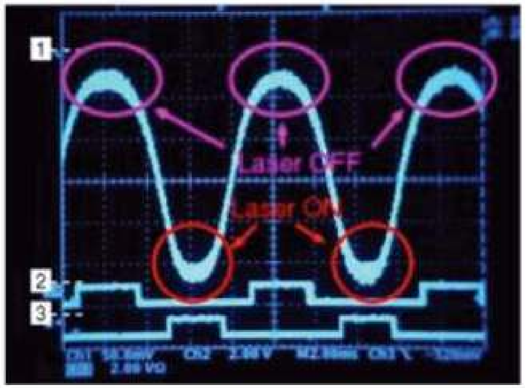


We use 0.997% mirror,
F = 1000

Laser Control at Beam Size Measurement

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

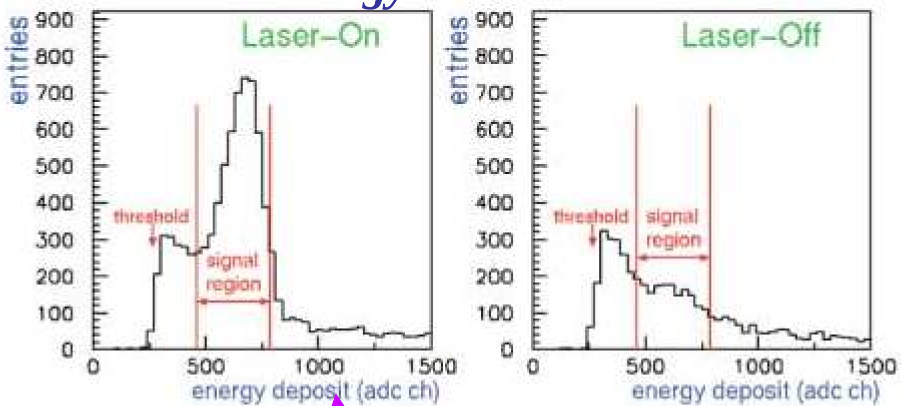


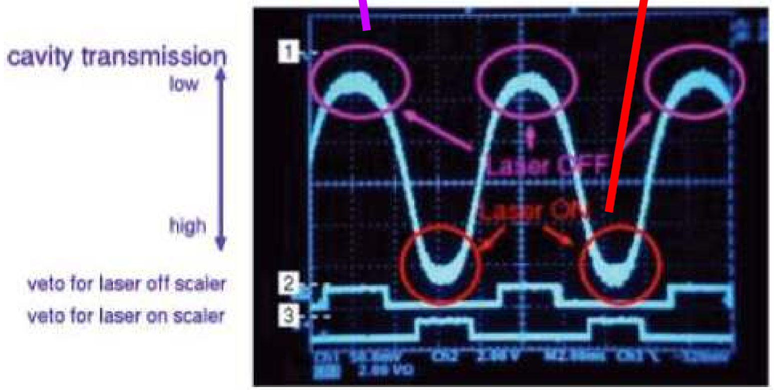


Measured Signal with CsI Scintillator

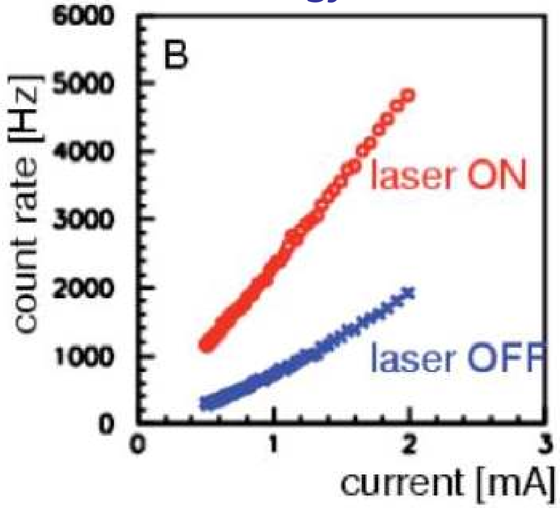
Since laser beam collision is occurred by 1 collision per 1000turn, we can measure the each photon energy .

Energy distribution





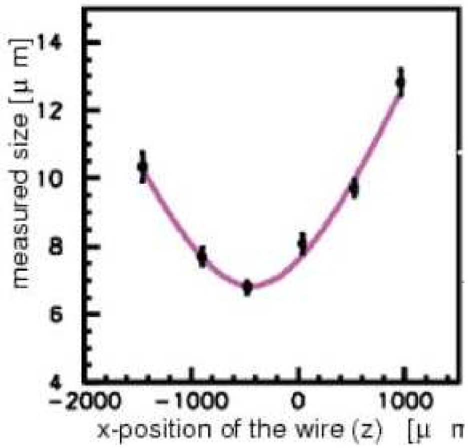
Collision rate in energy window

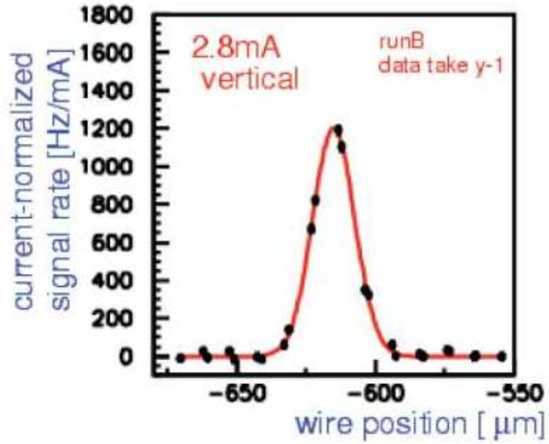


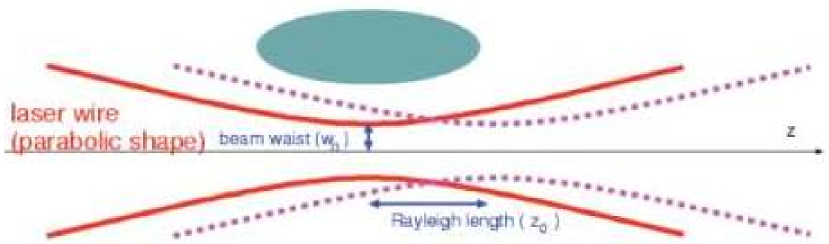
We can measure the on/off signal dependence

Beam Size Measurement

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







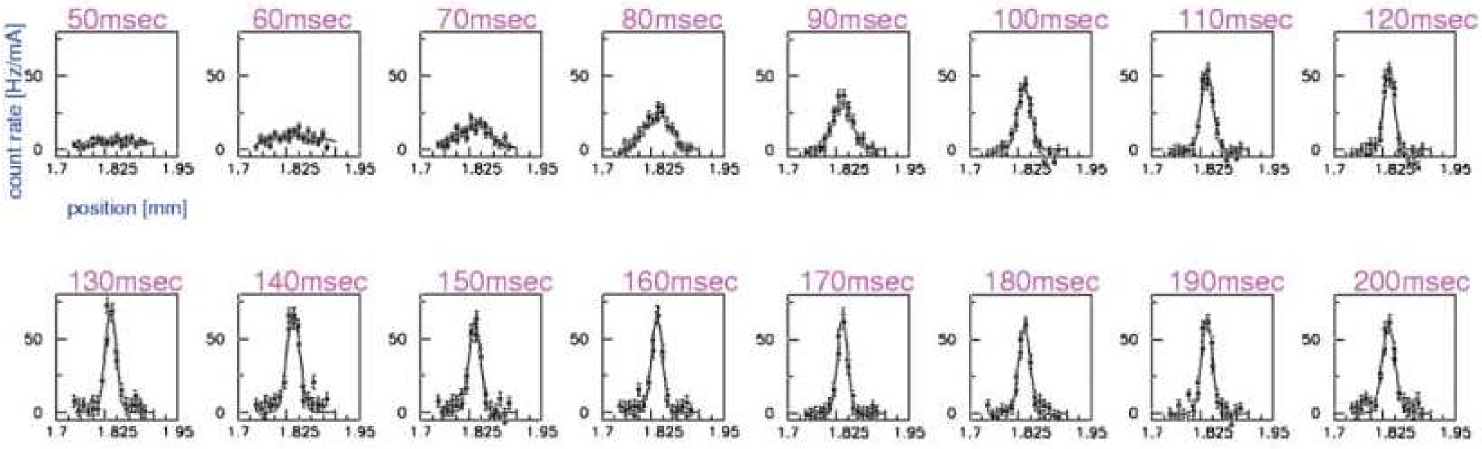
Measured profile should subtract the effect of the laser wire waist.

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

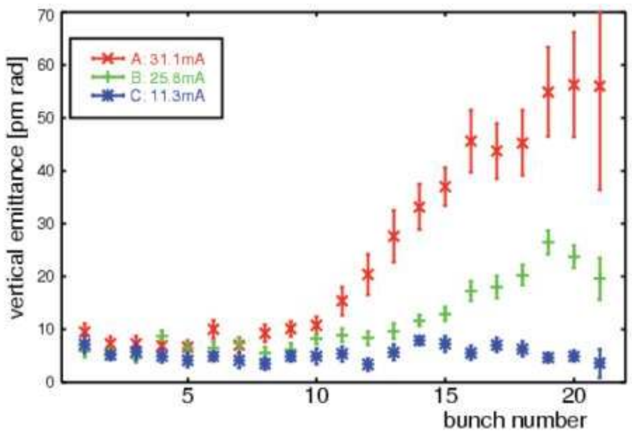
Measured minimum beam size is 5μm with 5μm rms. laser wire.

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 .

Critical Performance Characteristics 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.

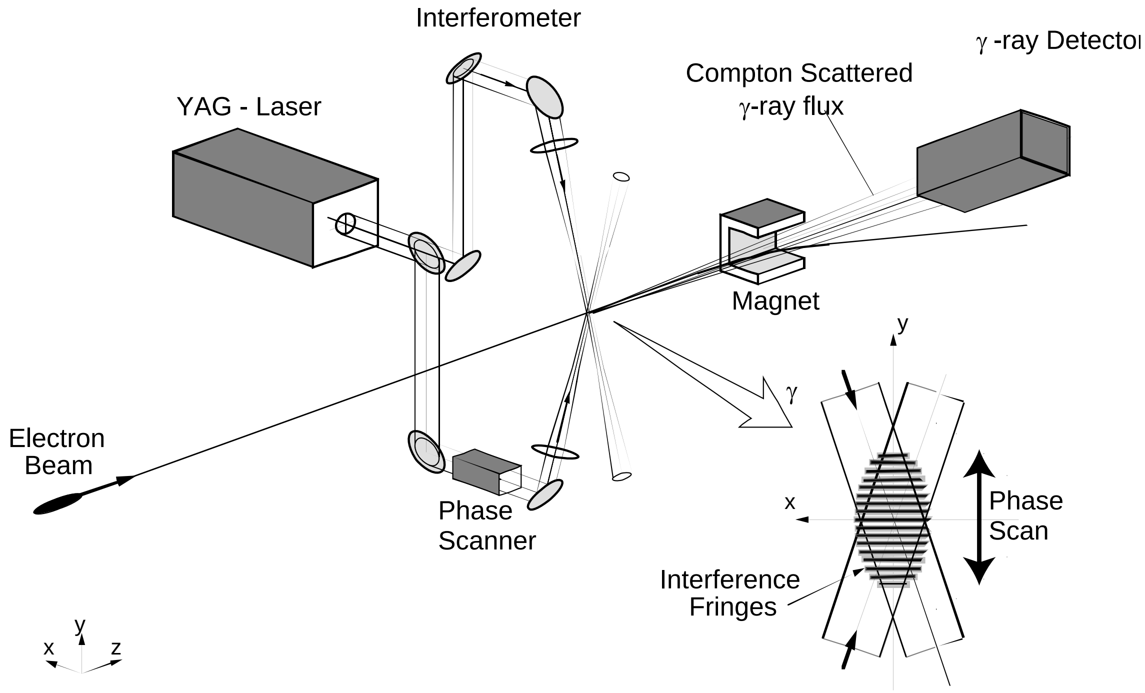
- affect to the beam jitter, and not to separate the beam jitter and beam size growth.

-Partly destructive

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

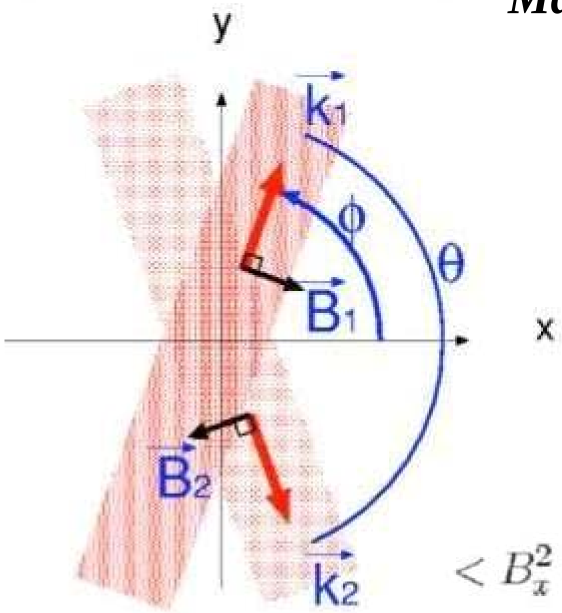
Laser Interferometer
(Shintake Monitor)

Concept of Beam Size Measurement with Laser Interferometer



Laser light is divided to laser path and collide at beamline to make a interference pattern .

Interference Pattern



Magnetic field of laser light

$$\overrightarrow{B_1} = B\cos(\omega t - \overrightarrow{k_1}\cdot\overrightarrow{r})\hat{B}_1$$

$$\overrightarrow{B_2} = B\cos(\omega t - \overrightarrow{k_2}\cdot\overrightarrow{r})\hat{B}_2$$

$$\overrightarrow{B_1} + \overrightarrow{B_2} = \begin{pmatrix} 2B\sin\phi\sin(k_y y)\sin(\omega t - k_x x) \\ 2B\cos\phi\cos(k_y y)\cos(\omega t - k_x x) \end{pmatrix}$$

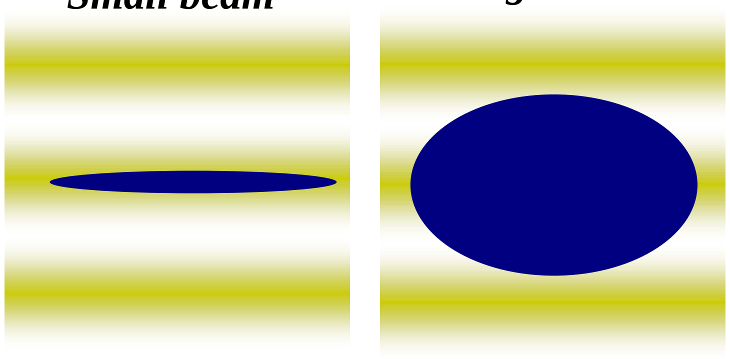
$k_x \equiv k\cos\phi$、$k_y \equiv k\sin\phi$

$$\begin{aligned} < B_x^2 + B_y^2 > &= 2B^2[\sin^2\phi\sin^2(k_y y) + \cos^2\phi\cos^2(k_y y)] \\ &= B^2[1 + \cos\theta\,\underline{\cos(2k_y y)}] \end{aligned}$$

$$\boxed{d = \frac{\pi}{k_y} = \frac{\lambda}{2\sin(\theta/2)}}$$

The distance of the interference pattern is defined by laser collision angle .

Beam Size Evaluation with Laser Interferometer



Emitted Photon is evaluated by the convolution of beam distribution.

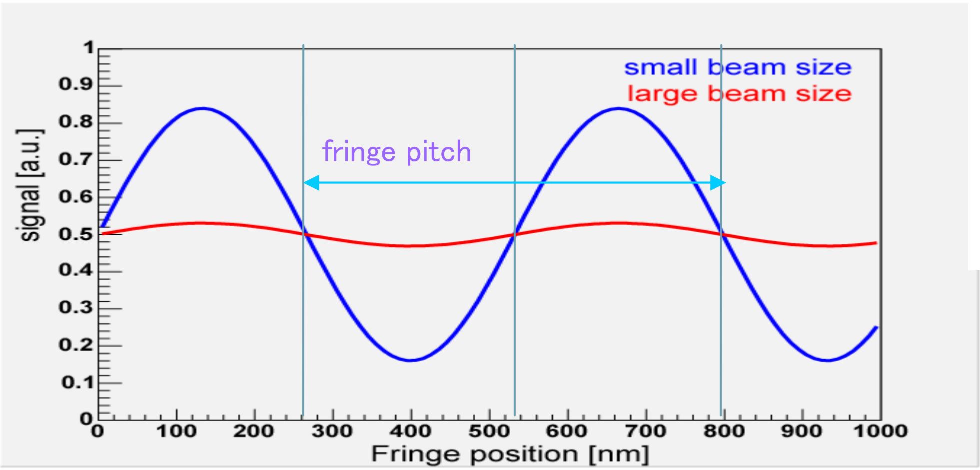
$$N_\gamma \propto \int_{-\infty}^{\infty} \exp[-\frac{(y-y_0)^2}{2\sigma_y^2}](1+\cos\theta\cos 2k_y y)dy$$
$$= N_0[1+\cos(2k_y y_0)\cos\theta]\exp[-2(k_y\sigma_y)^2]$$

$$N_\pm = N_0[1\pm\cos\theta\exp[-2(k_y\sigma_y)^2]]$$

Amount of interference

$$M \equiv \frac{N_+ - N_-}{N_+ + N_-}$$
$$= |\cos\theta|\exp[-2(k_y\sigma_y)^2]$$
$$= |\cos\theta|\exp[-2(\frac{\pi\sigma_y}{d})^2]$$

$$\sigma_y = \frac{d}{2\pi}\sqrt{2\ln\left(\frac{|\cos\theta|}{M}\right)}$$



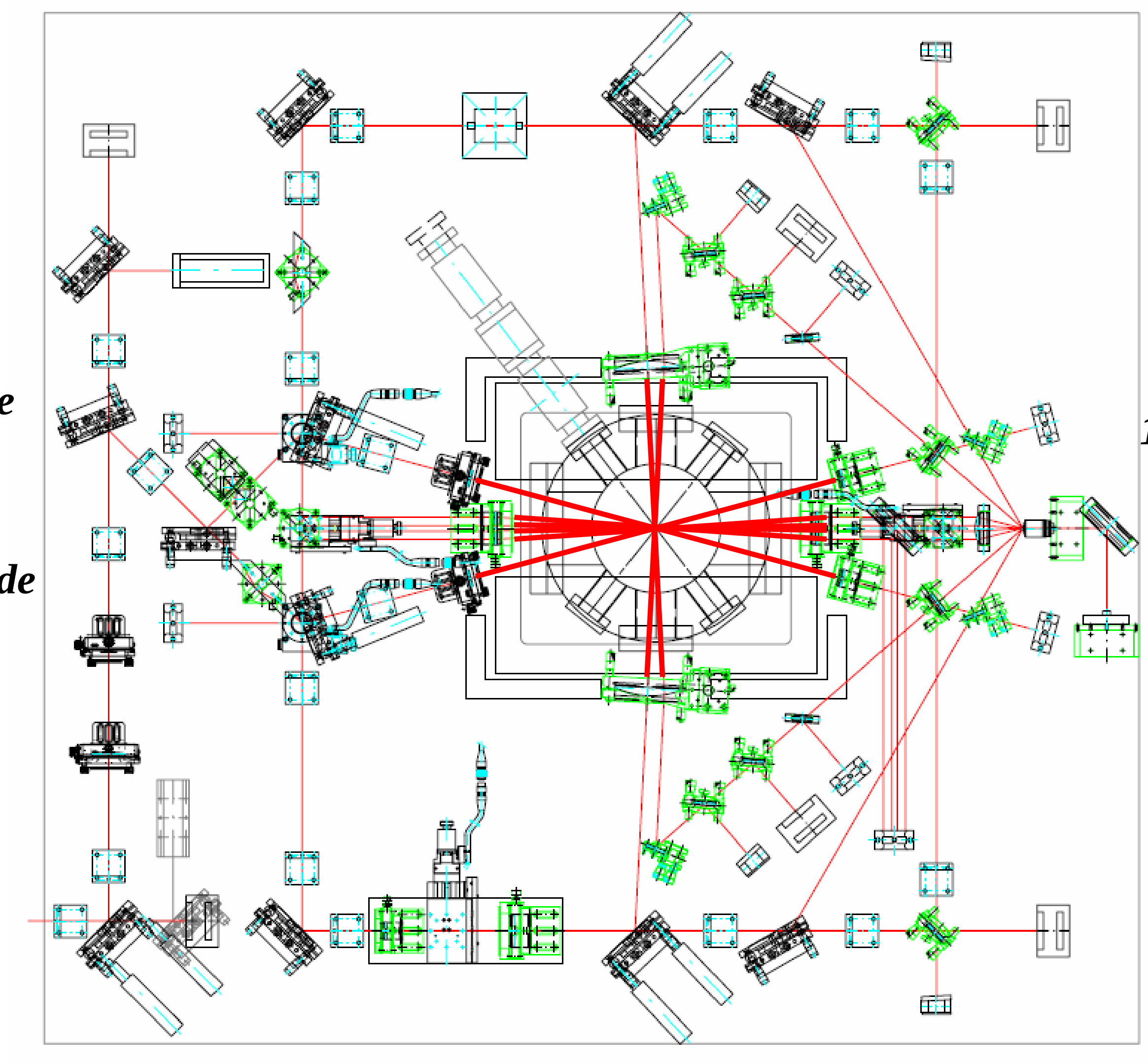
Layout of the Laser Table

2 degree mode

8 degree mode

30 degree mode

174 degree mode



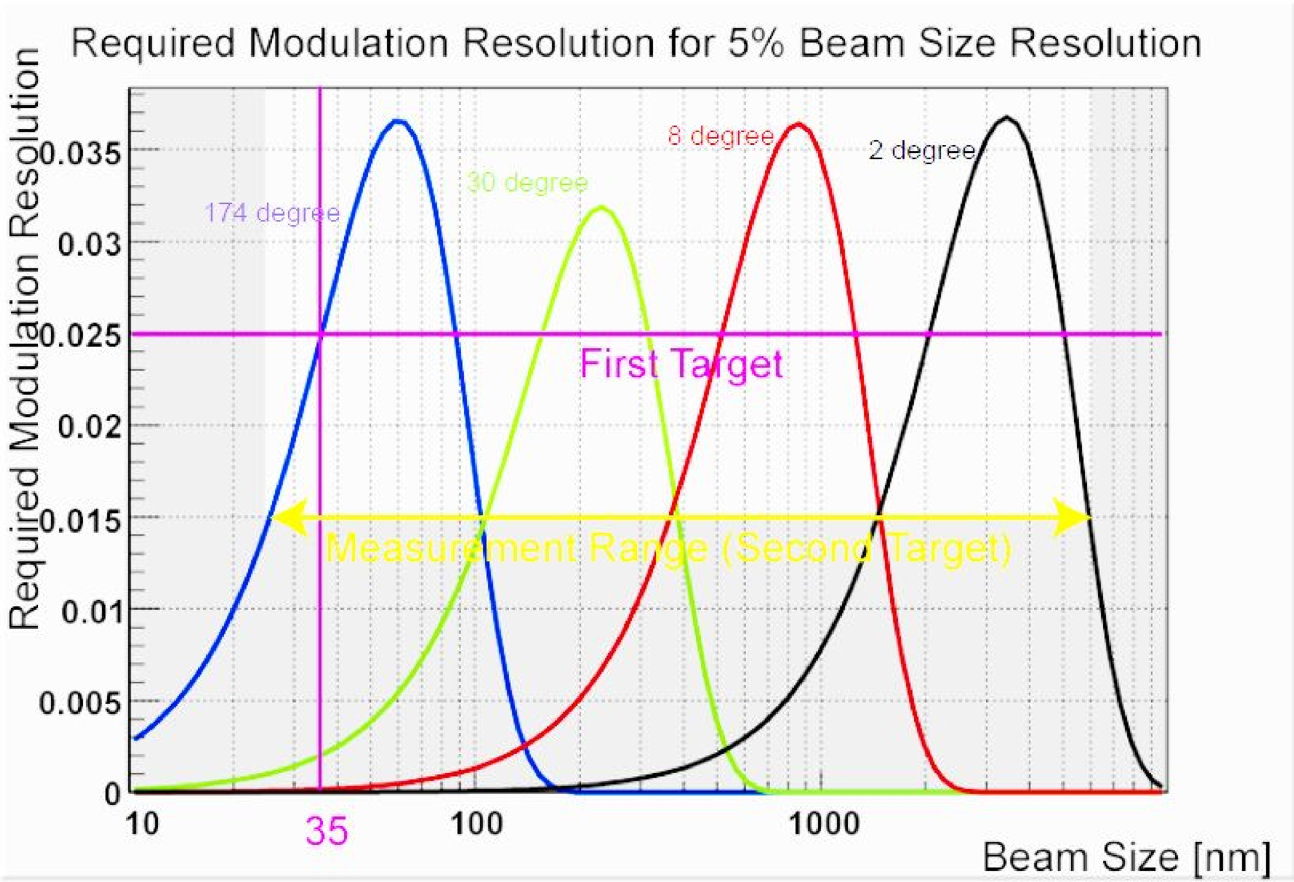
15mm pitch

3.8mm pitch

1.03mm pitch

266nm pitch

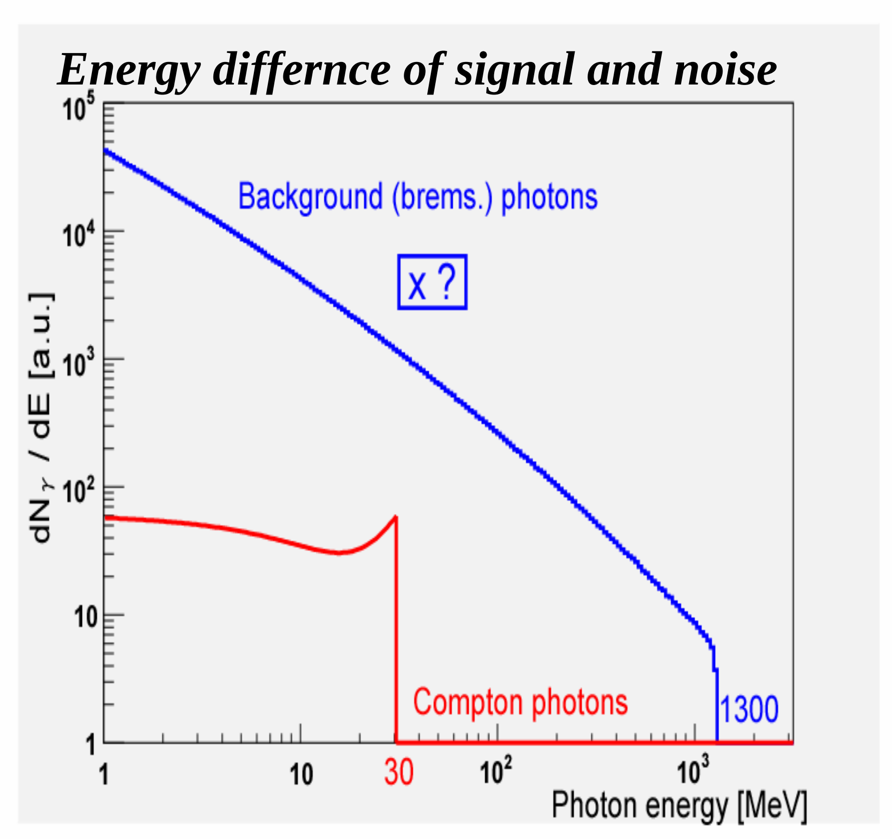
Measurable Range of Laser Interferometer

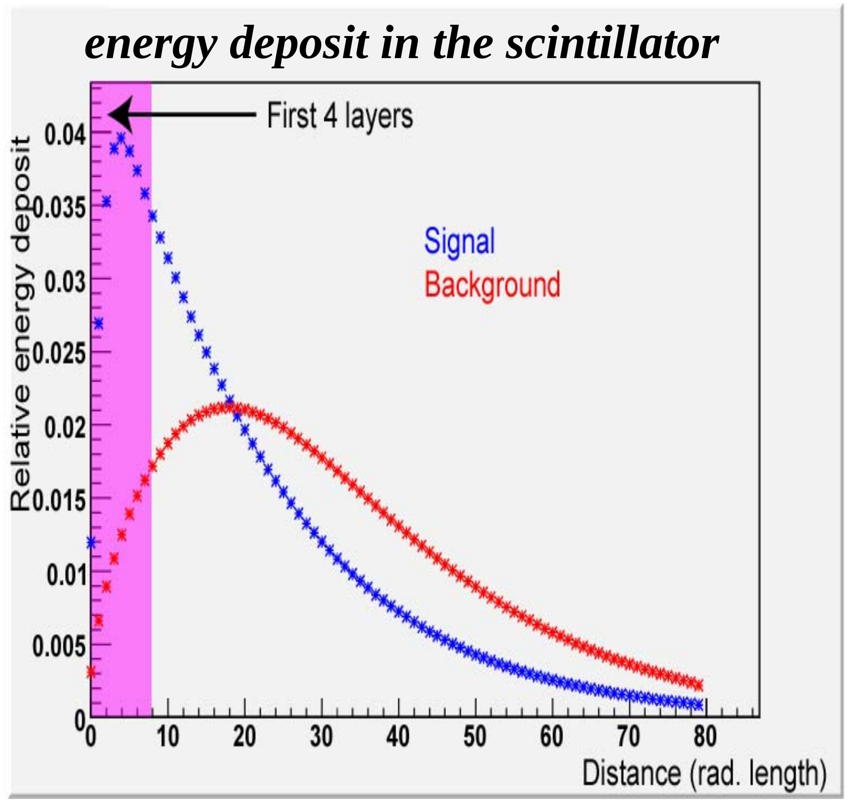


By changing 4 laser collision angle,
we can measure 25 – 6000 nm of beam size.

Photon Signal Detection for Laser Interferometer

Since S/N is very tight for the Laser Interferometer,
we must prepare the appropriate photon detector .

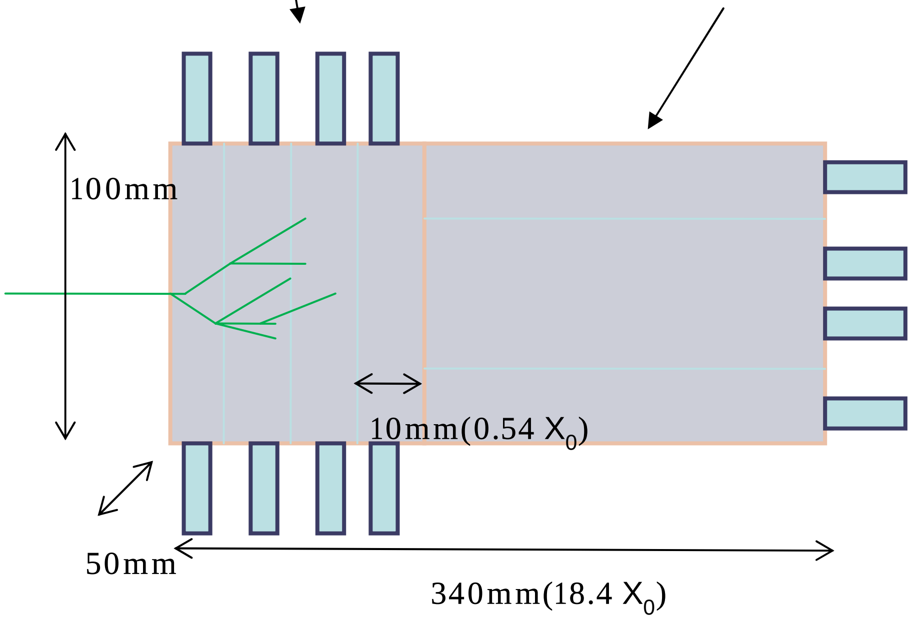


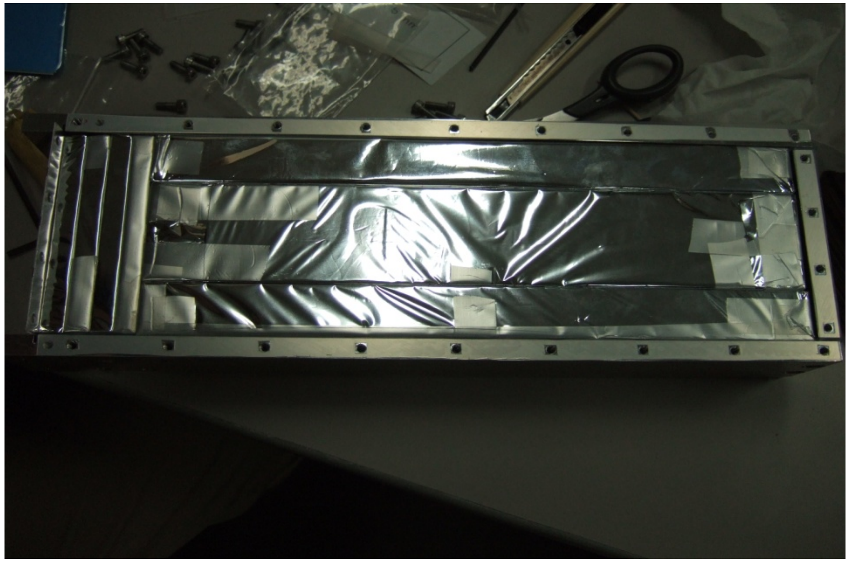


Photon Detector for Laser Interferometer

Most of signal is deposited in first 4 layers .

Most of noise is deposited in last large layers .

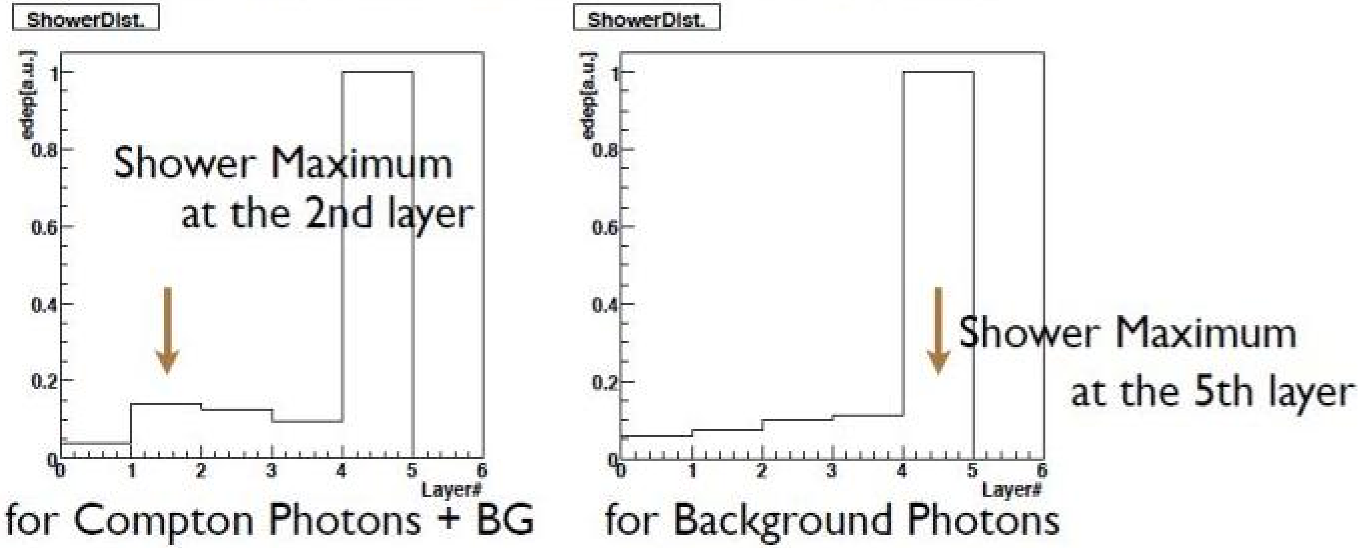




We can separate the signal and noise by using the difference of energy deposit.

Test of Photon Detector Performance

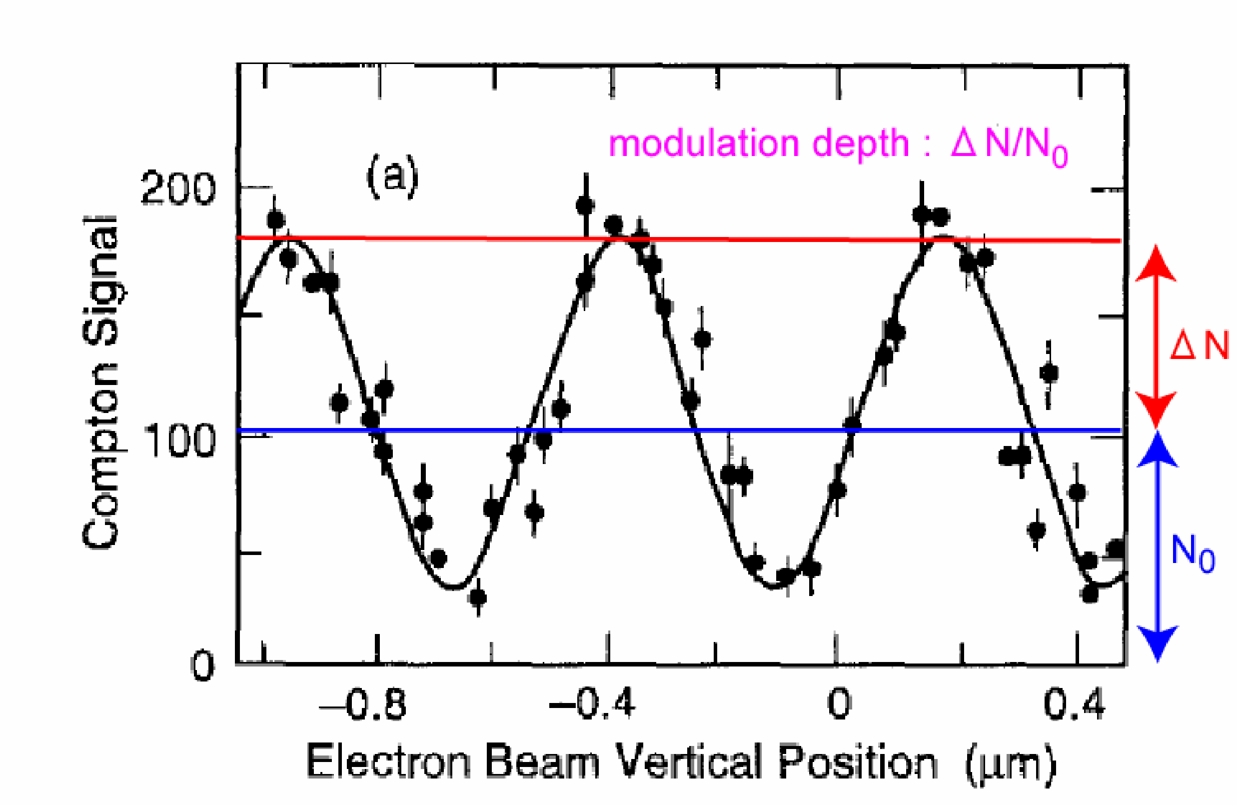
Preliminary Results of the shower distribution measurement



Performance of photon detector is tested in ATF beamline with pulsed laser wire scanner signal (same photon distribution) .

We found the signal and noise can be separated .

The beam size measurement at FFTB in SLAC



The 70nm beam size was measured in SLAC by laser interferometer.

Laser wavelength ; 1064nm

Beam energy ; 45GeV

Critical Performance Characteristics of Laser Interferometer

-Dynamic range;

- Determined by the laser wavelength and collision angle.
(25 – 6000 nm for ATF2 design)

-Resolution ;

- Determined by the laser wavelength and collision angle and laser phase stability (ATF2 target is 10% of the beam size).

-Accuracy;

- depends on the beam stability
- depends on laser stability
- depends on geometrical vibration

Summary of 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

What is the required performance ?

- ***Dynamic range ?***
- ***Resolution ?***
- ***Offset ?***
- ***Stability and Accuracy ?***

Thank you for your attention !