Shintake Monitor

Nanometer Beam Size Measurement and Beam Tuning

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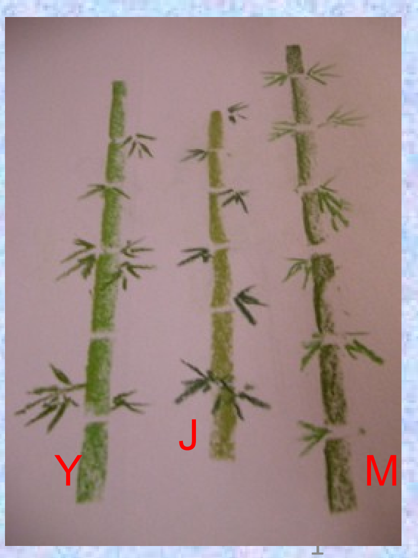


Layout

☆Role of Shintake Monitor at ATF2
☆Structure and Measurement Scheme
☆Upgrade from FFTB
☆Expected Performance
☆Procedures during Beam Tuning
☆Beam Size Measurement Errors
☆Summary

Role of Shintake Monitor

ATF: test facility for ILC@KEK

e- beam with extremely small normalized vertical emittance $\gamma\varepsilon_y$

New Extraction + Final Focus line

ATF2: Final Focus test facility

ATF2`s goals :

(1)Verify "Local Chromaticity Correction"

→ achieve 37 nm vertical beam size

(2) Stable nm beam operation

For Goal (1)…… **Shintake Beam Size Monitor (IP-BSM)**

beam size monitor at ATF2 IP using laser interference fringes as target

- Only device capable of measuring $\sigma_y < 100$ nm
- Valuable beam tuning tool

Linear Collider and Beam Sizes

linear collider → high energy without synchrotron radiation

- Clean reactions with elementary particles (e- e+)
- precise measurements of New Physics anticipated

However…. Only one chance for acceleration →**Power, luminosity challenges**

Luminosity

$$L = \frac{n_b N^2 f_{rep}}{4\pi \sigma_x \sigma_y} H_D$$

n_b: bunch number N: particles/ bunch $4\pi\sigma_x\sigma_y$: Gaussian beam intersection

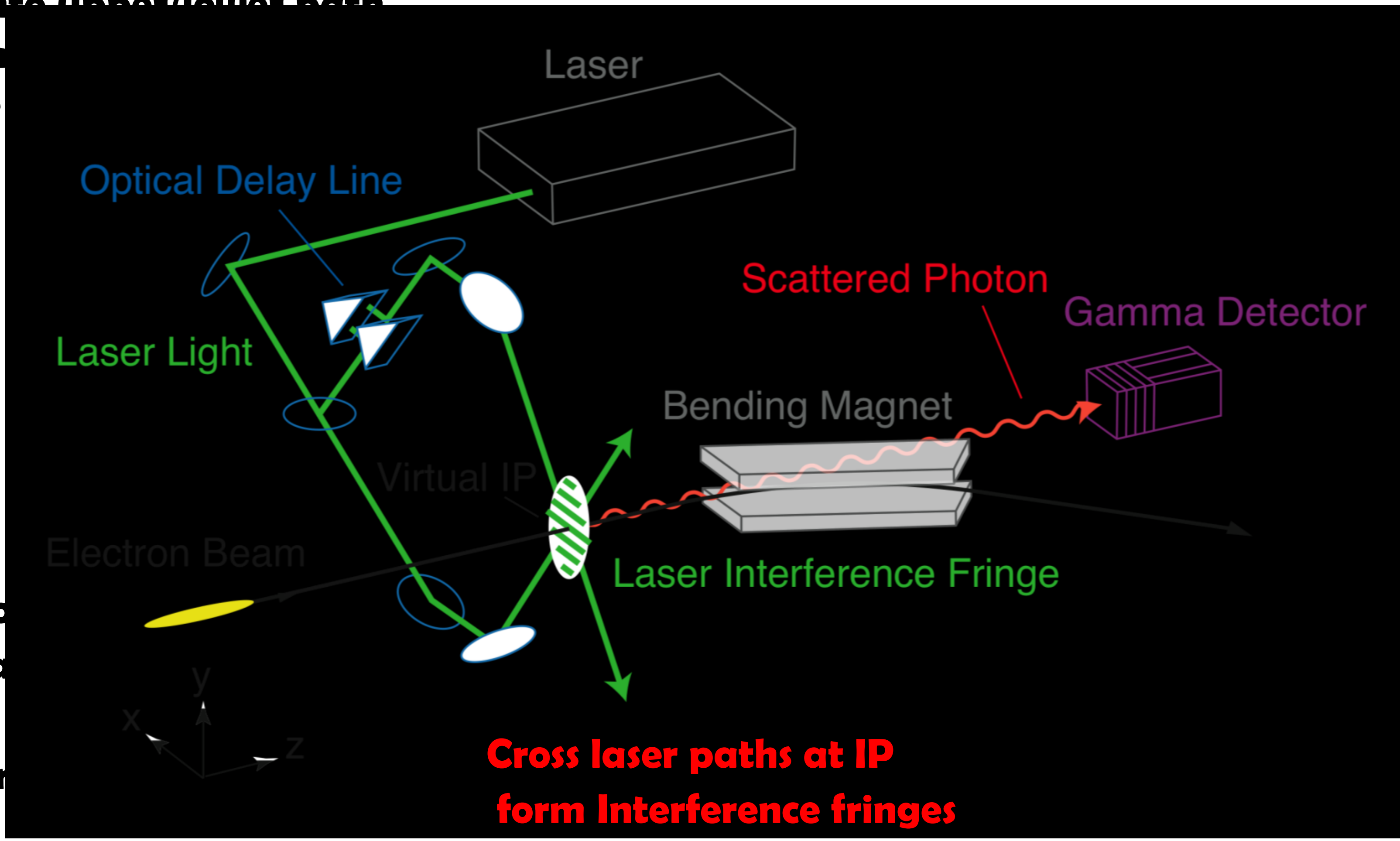
Must focusing vertical beam size at IP !!

- flat beam : $\sigma y \ll \sigma x$

Shintake Monitor aims at measuring 37 nm σ_y*
indispensible for realizing future linear colliders

Measurement Scheme

Split into upper/lower path
Optica
phase

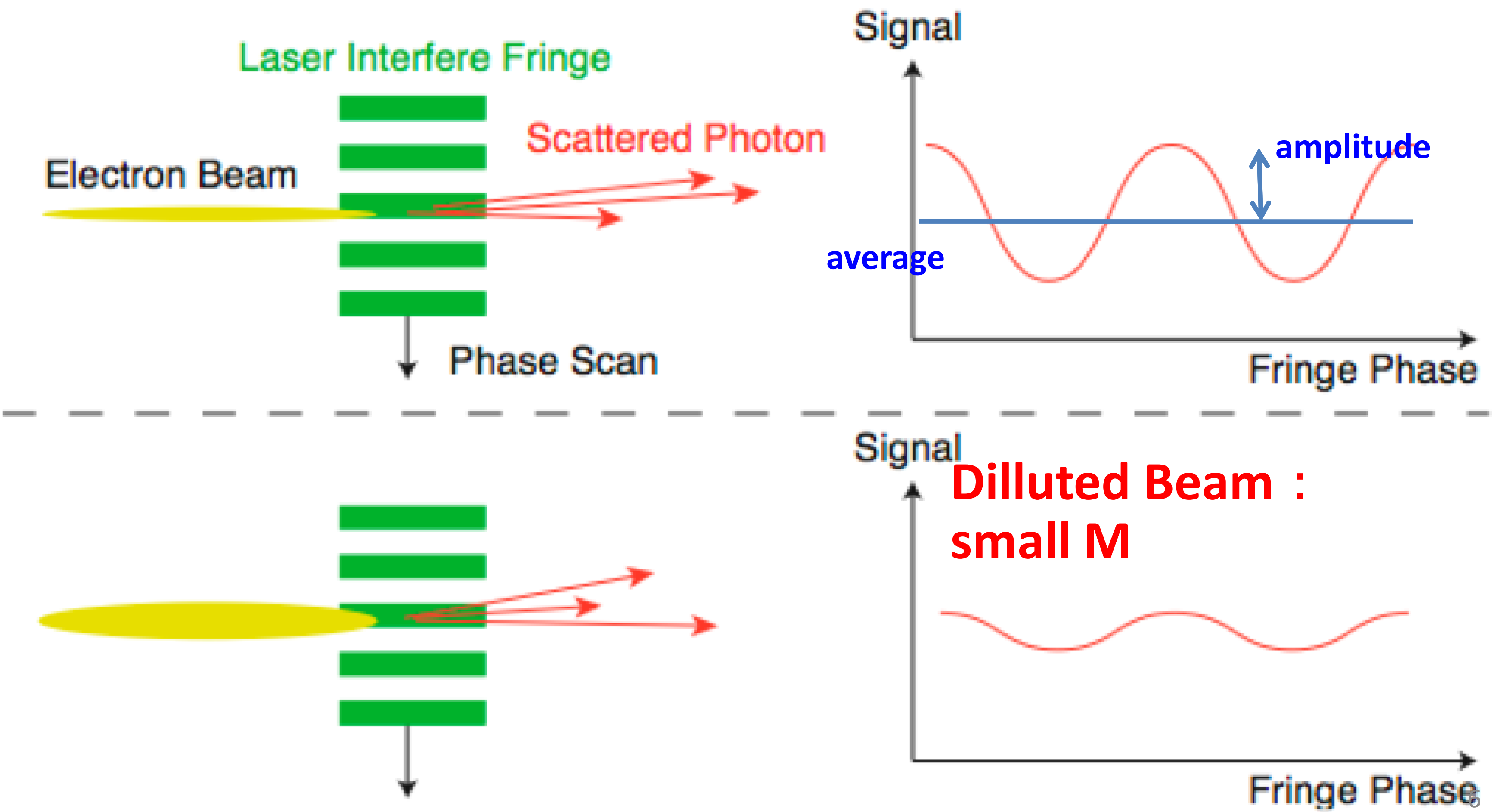


Collisio
e- bea
with
laser fr

Detector measures signal **modulation depth**

M = (amplitude) / (average)

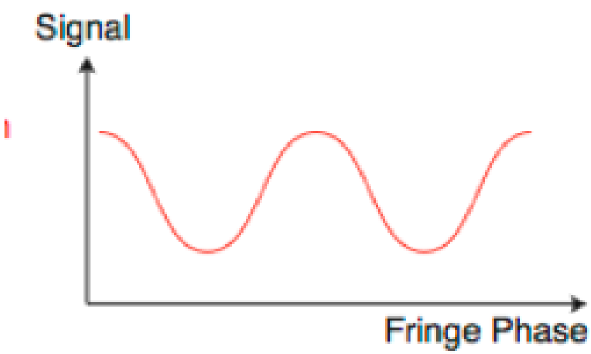
Focused Beam ： large M

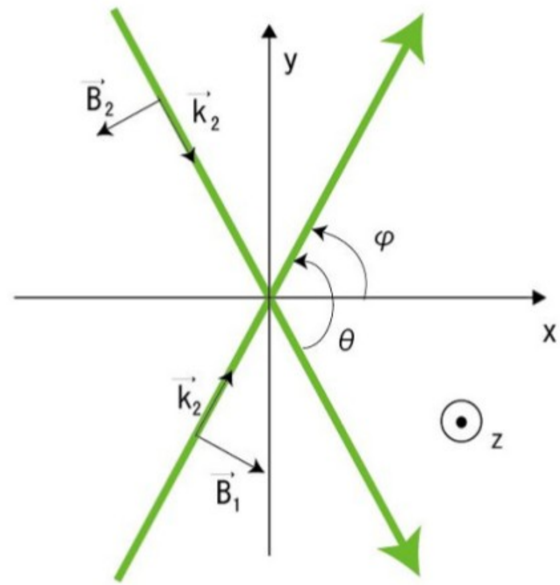


No. of signal photons : $N \propto \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(\frac{-(y-y_0)^2}{2\sigma_y^2}\right)\left(B_x^2 + B_y^2\right)dy$

Convolution of **Beam Profile** and **Fringe Intensity**

$$= \frac{N_0}{2}[1 + \cos(2k_y y_0)\cos(\theta)\exp(-2(k_y\sigma_y)^2)$$





$$M = \frac{Amplitude}{Average} = \left|\cos(\theta)\exp(-2(k_y\sigma_y)^2\right|$$

$$\Rightarrow \sigma_y = \frac{1}{k_y}\sqrt{\frac{1}{2}\ln\left(\frac{|\cos(\theta)|}{M}\right)}.$$

Beam size calculated

φ = θ/2 : half crossing angle $k_y = k\sin\varphi$

Beam Size and Modulation Depth

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

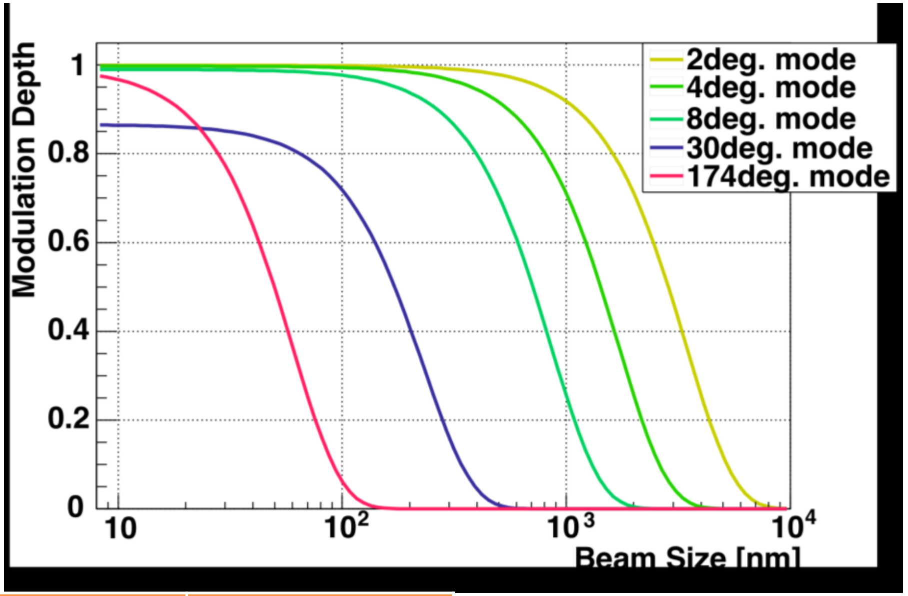
$$d = \frac{\pi}{k_y} = \frac{\lambda}{2\sin(\theta/2)} \qquad (\lambda = 532 \text{ nm for ATF2})$$

fringe pitch d

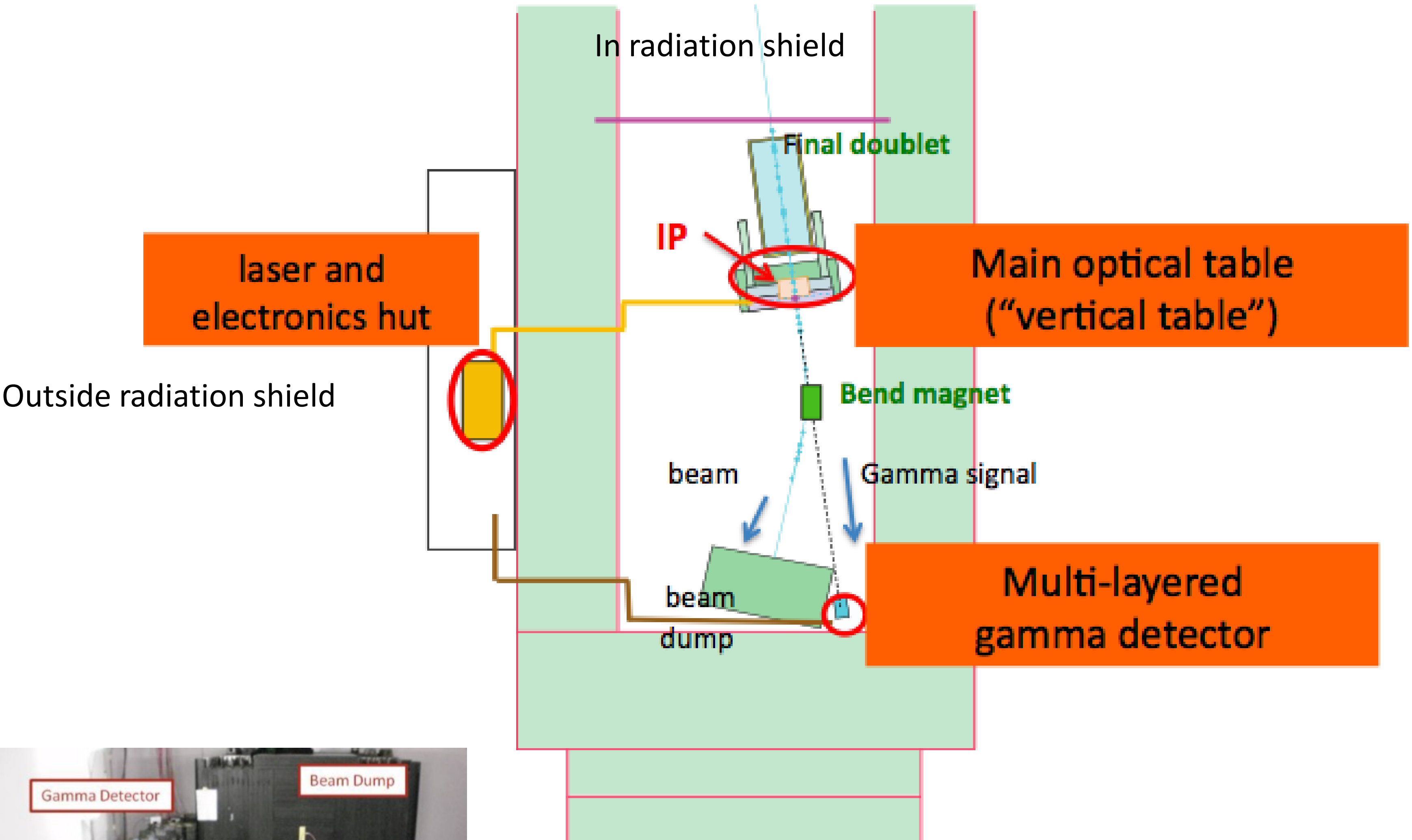
←→ θ and λ

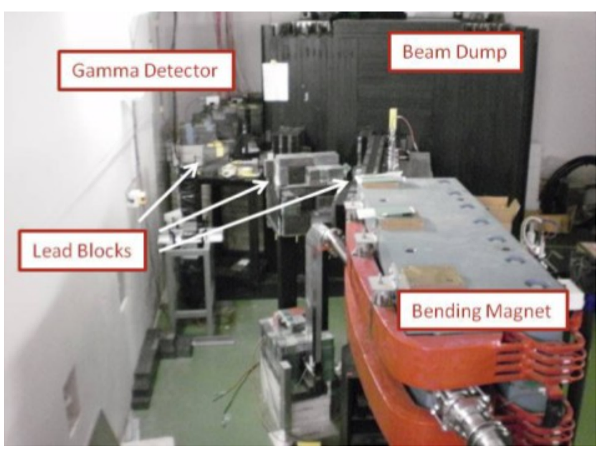
determines measurement range

σy* vs M for each mode

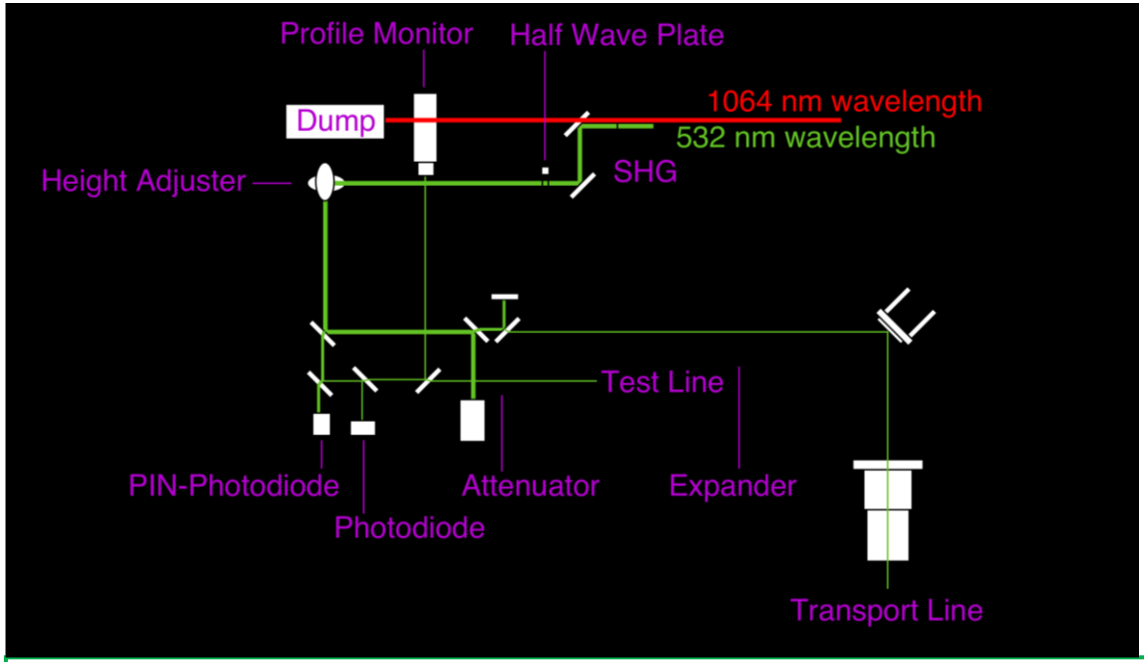


Crossing angle θ	174°	30°	8°	2°
Fringe pitch d	266 nm	1.028 µm	3.81 µm	15.2 µm
Lower limit	25 nm	100 nm	360 nm	1.4 µm
Upper limit	100 nm	360 nm	1.4 µm	6 µm


In radiation shield
Final doublet
IP
laser and electronics hut
Main optical table ("vertical table")
Outside radiation shield
Bend magnet
beam
Gamma signal
Multi-layered gamma detector
beam dump


Gamma Detector
Beam Dump
Lead Blocks
Bending Magnet

Laser Table



Nd :YAG laser

λ: 532nm (SHG)

Pulse energy: 1400mJ

Pulse width: 8ns (FWHM)

- **Laser source**
- **Prepare laser properties** for transport to IP

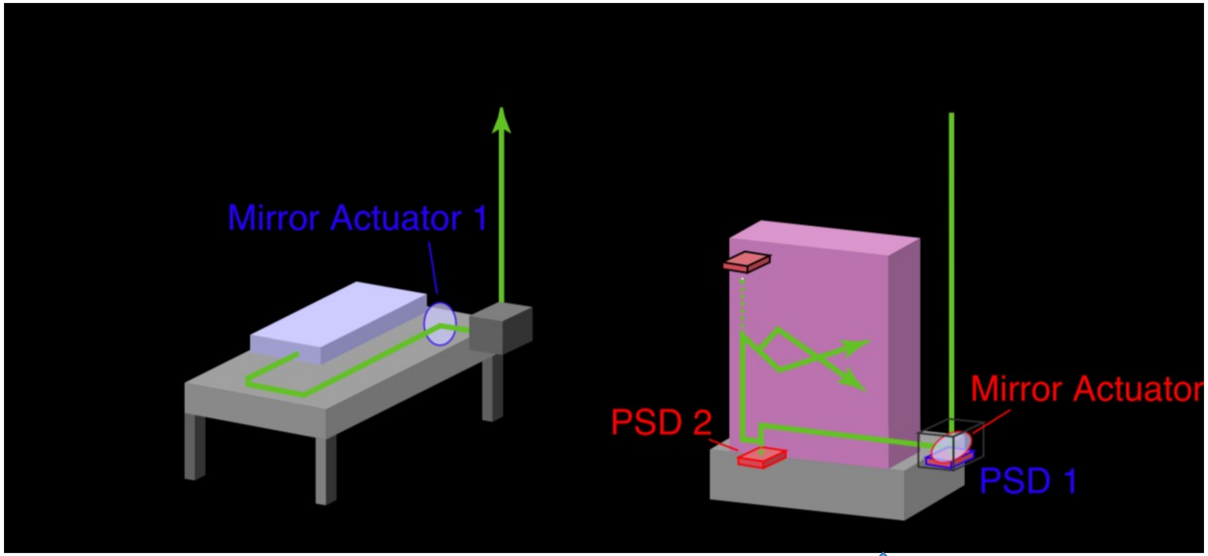
➢ profile monitor, photodiode (PD), PIN-PD, PSDs

- **Attenuator for power switching**

  low (alignment) ←→ high (inteference mode)

Laser table → vertical

20 m transport line



Vertical Table (Main Optical Table)

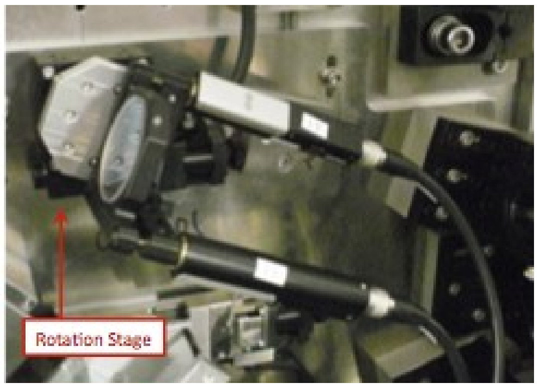
- Emerge from bottom right
- First enter reflective mirror

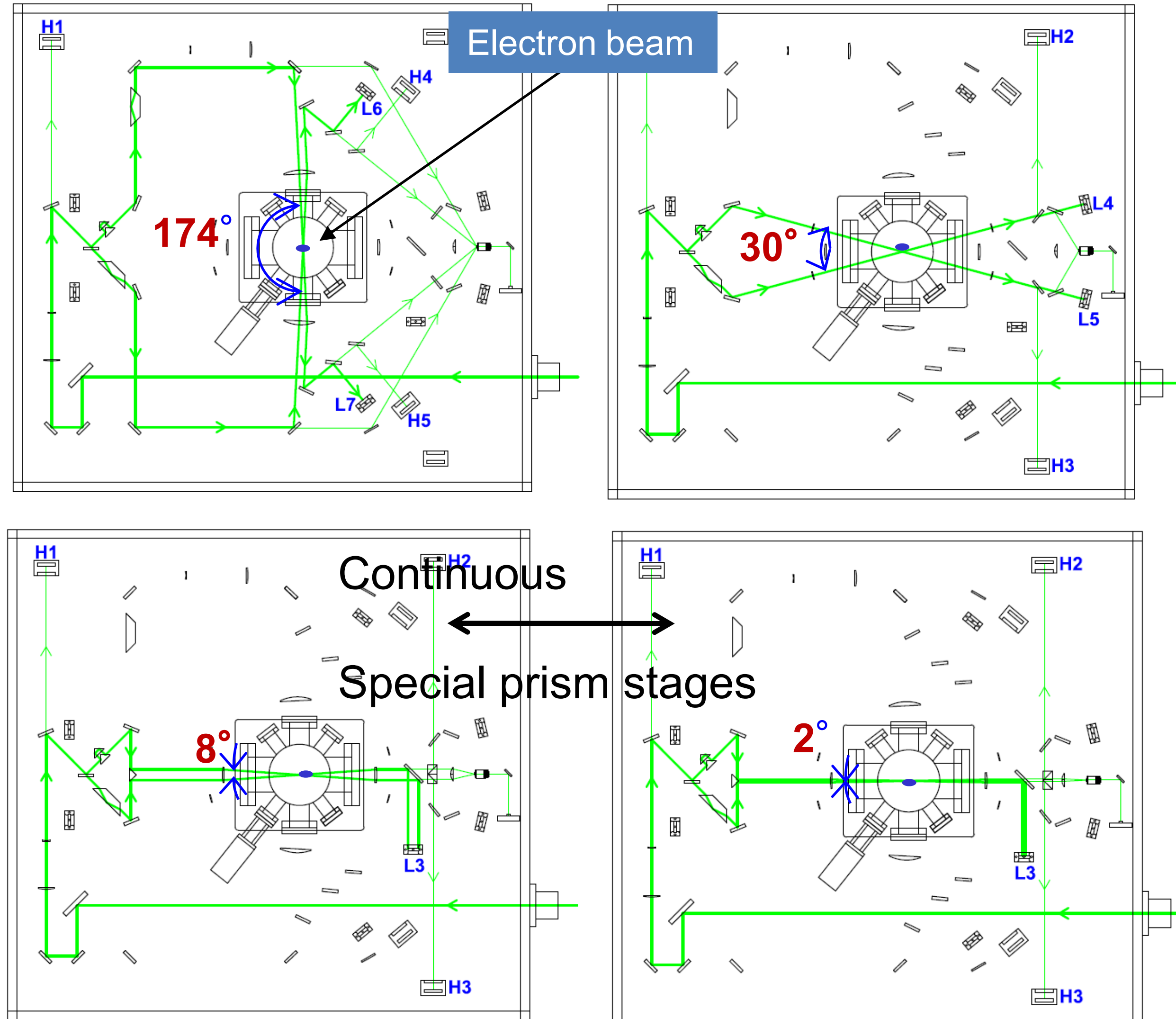
- **Reflected light split into upper/lower path**
- optical path created for each mode
  → Interference fringe

- **Transmitted light　to diagnostic section**
  PSD, photodiode (PD), PIN-PD, phase monitor

1.7 m × 1.6 m

Laser crossing angle control





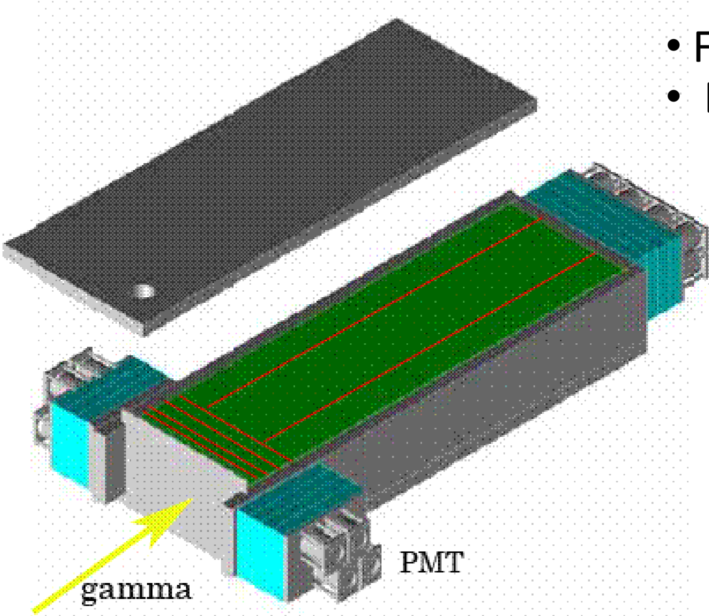
fringe pitch

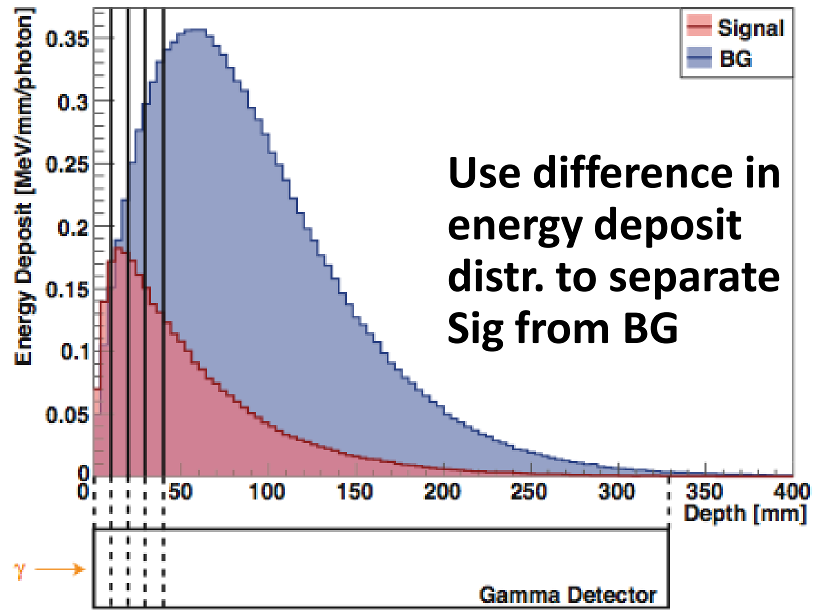
$$d = \frac{\lambda}{2\sin(\theta/2)}$$

$(\theta = \text{crossing angle})$

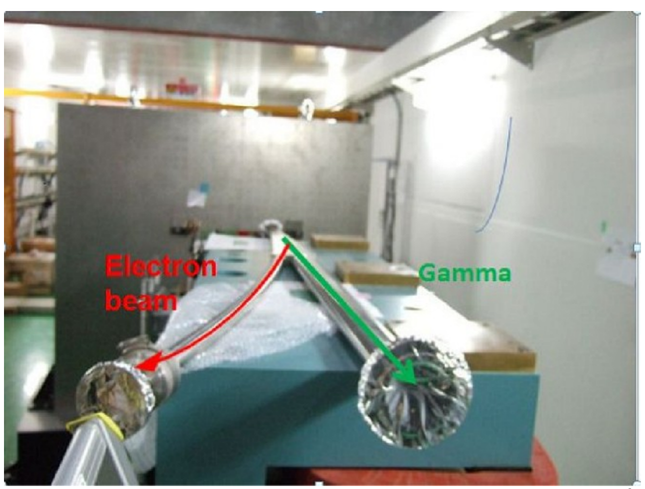
Gamma Detector

- Calorimeter-type **CsI(Tl) scintillator + PMTs**
- **Multilayer** Design
- Front 4 layers （10 mm x 4)
- Back ”bulk” (290 mm) divided into 3 horizontally





Use difference in energy deposit distr. to separate Sig from BG



BG spreads out more than Sig.

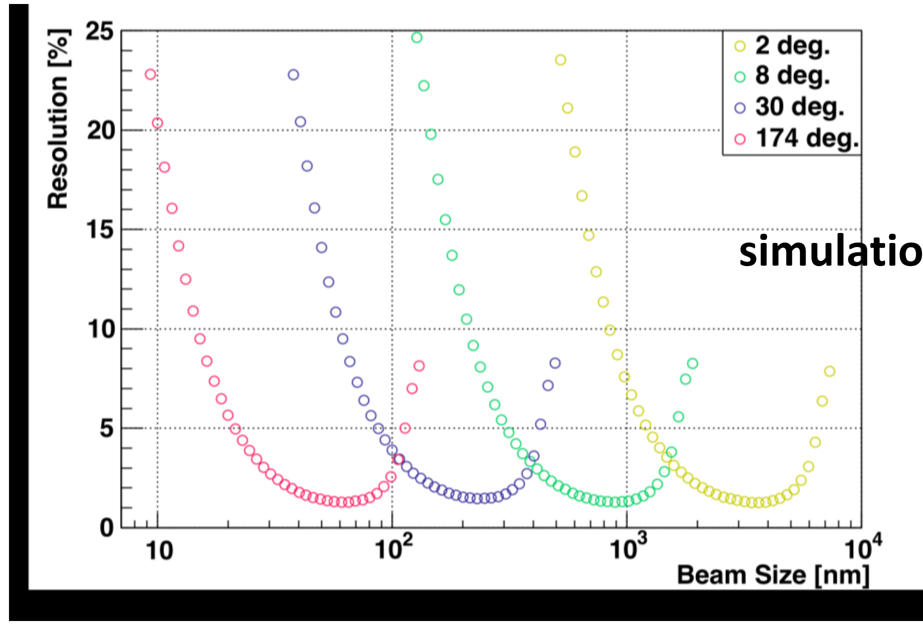
Collimators in front of detector

Expected Performance

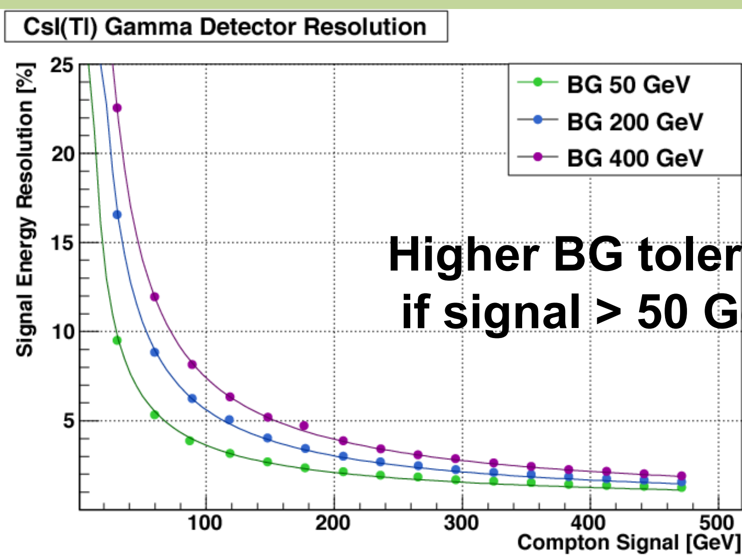
Expectation: $37 \pm 1.4\,(\text{stat})\,{}^{+0}_{-2}\,(\text{sys})$ [nm]

~ 10 % resolution for 25 nm ～6 μm

Resolution for each mode



Simulation under different BG setting



Higher BG tolerable if signal > 50 GeV

However…….

- **degraded for low S/N**
  ~ 12% in Dec, 2010
- improve by reducing BG, syst./ stat. errors

Upgrade from FFTB

ATF2 's 90 bunch measurement achieved same resolution as FFTB with 900 bunches!!

	FFTB	**ATF2**
Beam Energy	**46.6 GeV**	**1.3 GeV**
1 - photon energy	8.6 GeV	15 MeV
Detector layout	Single layer	Multi-layer
Design (σ^*x, $\boldsymbol{\sigma y^*}$)	(900 nm, **60 nm**)	(2.2 μm, **37 nm**)
Laser wavelength	**1064 nm**	**532 nm (SHG)** ***ATF2 design σy* is smaller ➔ λ is halved***
Measureable beam size range	40 – 720 nm	**25 nm – 6 μm** **+ Laser wire mode** (single pass) For σx^* (< 30 μm) ***ATF2 Shintake measures wider range of beam sizes***
Scan Method	Shifts e- beam	Scans laser fringe phase Keep beam fixed → Higher deg of freedom in beam tuning

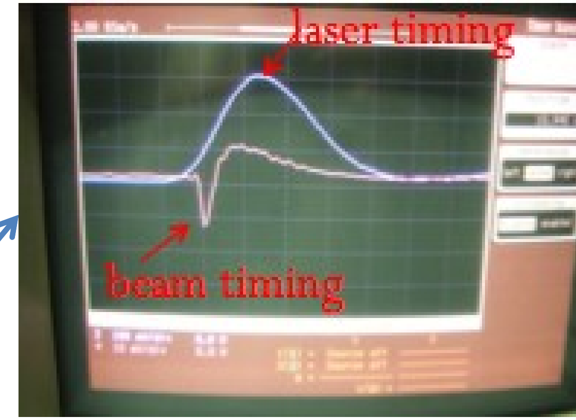
Shintake Monitor & Beam Tuning

[1] confirm σy* < 4.5 μm with wire scanner

Magnet adjustment shift beam trajectory
→ γ rays hit collimator , alter BG source / intensity
[2] **Collimator scan:** make γ ray pass 10 mmϕ center

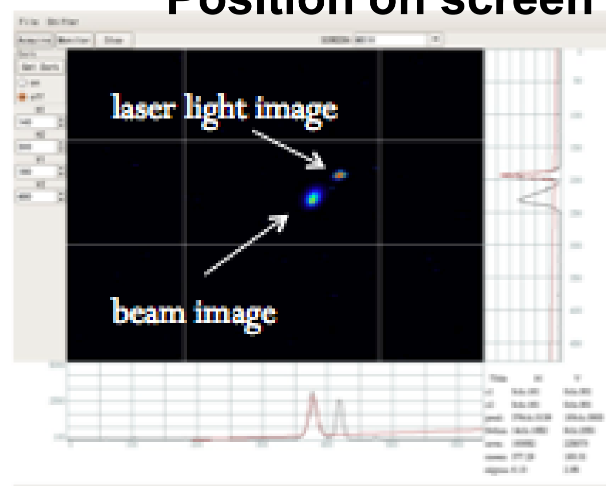
[3] **Timing Alignment :** laser vs beam (digital module TDC)

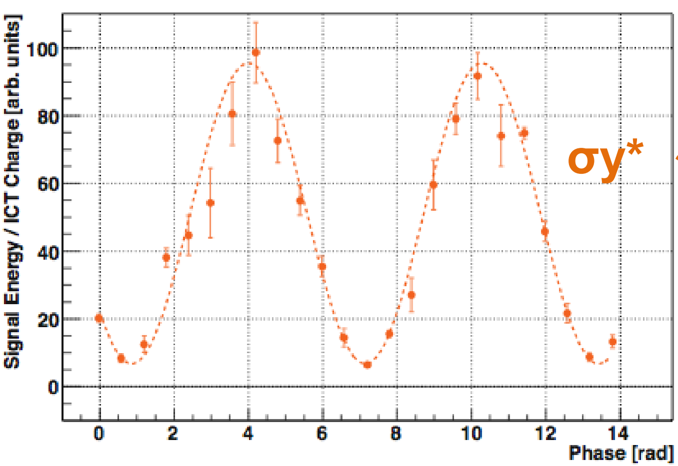
timing



[4] **Laser Position Alignment**
- **screen monitor (∼10 μm precision)**
- **transverse : laser wire scan**
- **longitudinal: z scan**

Position on screen





σy* ∼ 300 nm

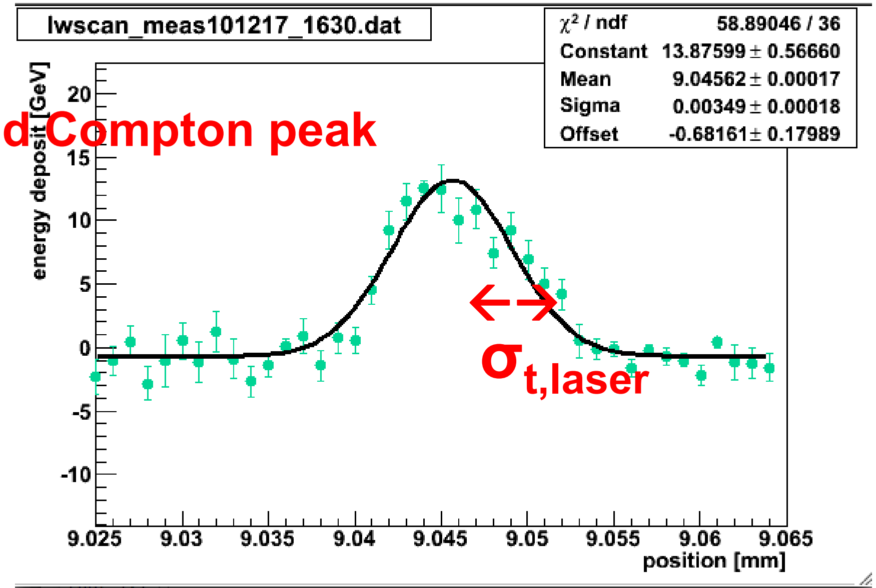
[5] Finally measure beam size by interference scan

→ feed back results to beam tuning

Transv. laser alignment laser wire scan

•Compton peak detection

•Also measures transv. laser spot size

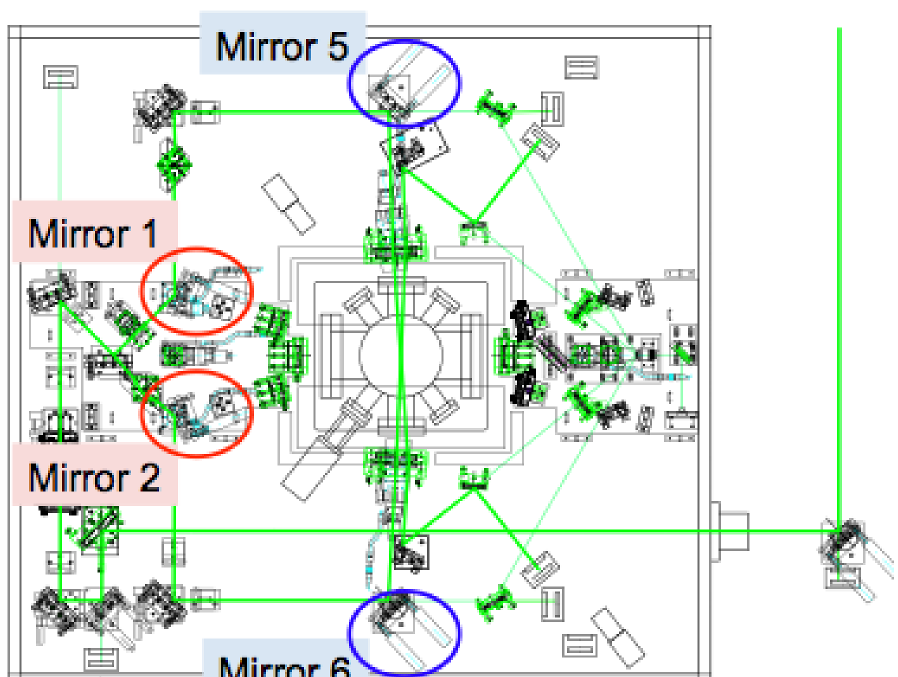


2-8, 30 deg mode

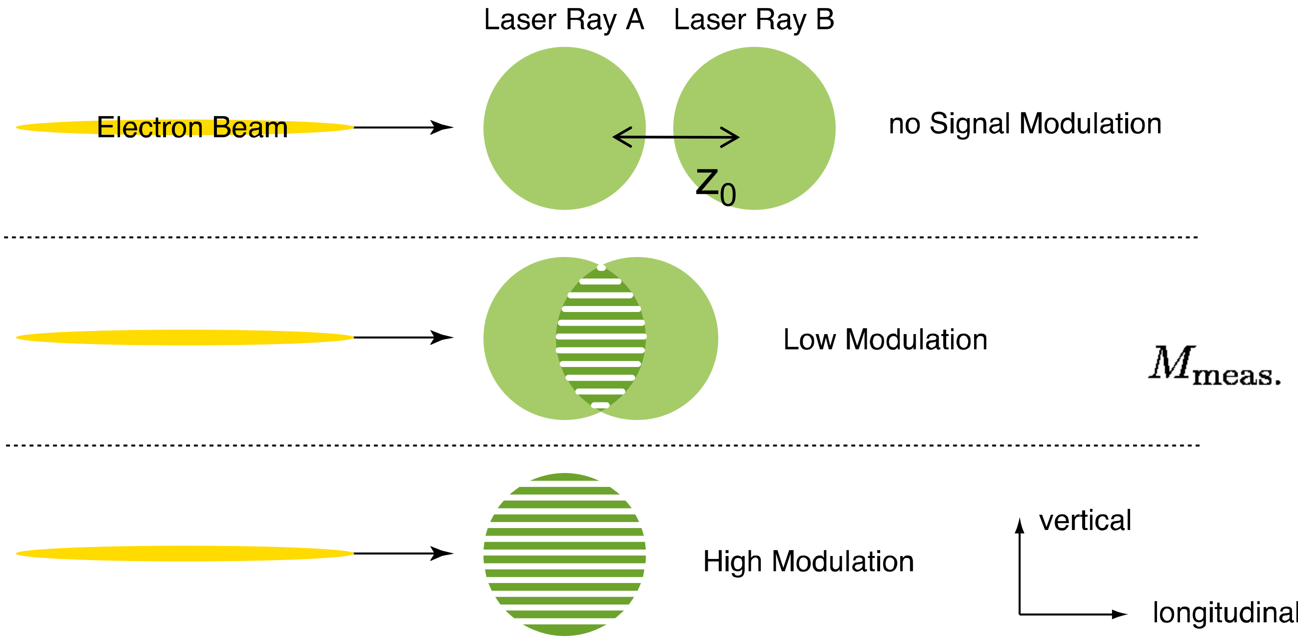
Scan with mirror 1,2

174 deg mode

scan with mirror 5, 6

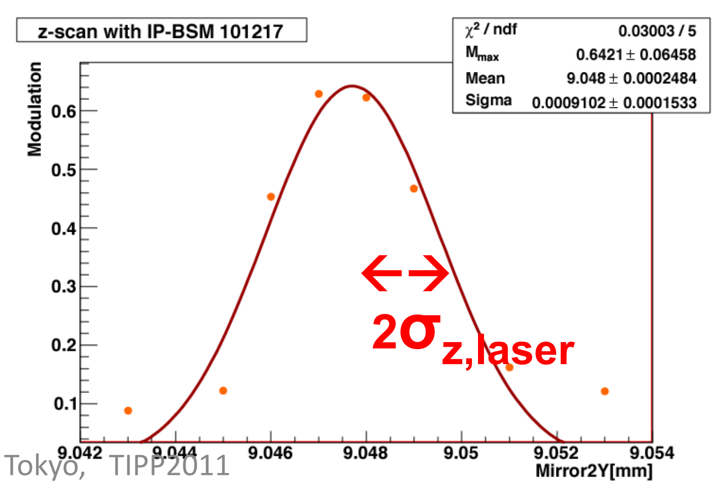


Longitudinal laser alignment : z-Scan



$$M_{\mathrm{meas.}} = \exp\left(-\frac{z_0^2}{8\sigma_{\mathrm{laser}}^2}\right) M_{\mathrm{ideal}}$$

- **find position of max M**
- ***can also get z laser spot size***



Systematic Errors

Contrast degrading bias

(*) After hardware upgrade

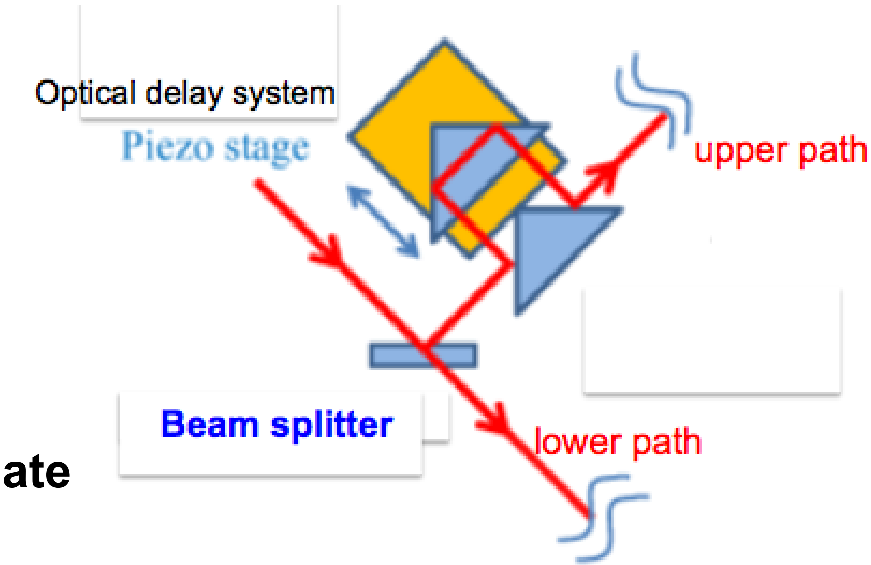
M reduction factor	**37 nm @ 174 deg**	**300 nm @6 – 8 deg**
power imbalance	99.8 ± 0.1% **(*)**	97.8 ± 1.8%
Long. alignment	> 99.1%	> 99.1%
Transv. alignment	> 99.6%	> 99.6%
Relative position jitter	> 98%	98 %
Long. Fringe tilt	99.3% - 99.6% **(*)**	> 98.2%
transv,. Fringe tilt	>99.9% **(*)**	> 99.9%
Spherical wavefronts	> 99.7% **(*)**	100%
Beam size growth	99.7%	100%
Spatial coherence	> 99.9%	> 99.9%
Total ΠC_i	**95.1% - 99.1%**	**> 91.1%**

Power Imbalance

• Beam-splitter reflects 50 % for s-polarized light.

• p-polarization existence causes
  power imbalance between
  upper and lower paths

For 37 nm after adjustment with **λ /2 wave plate**



laser path misalignment

(1) Lens focal point misalignment → **Profile (σ_{laser}) imbalance**

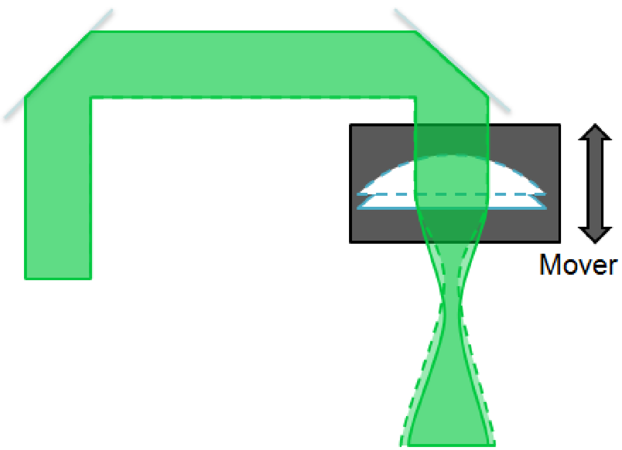
adjust lens set-up

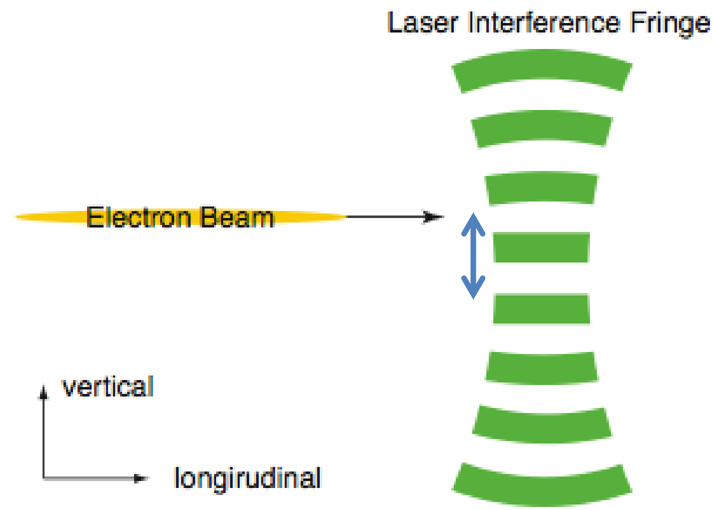
(2) Laser deviate from beam center

beam "sees" uneven fringes → **intensity imbalance**

Spherical Wavefront Effects

- offset from laser focal point
  ➔ beam “feels” distorted fringes

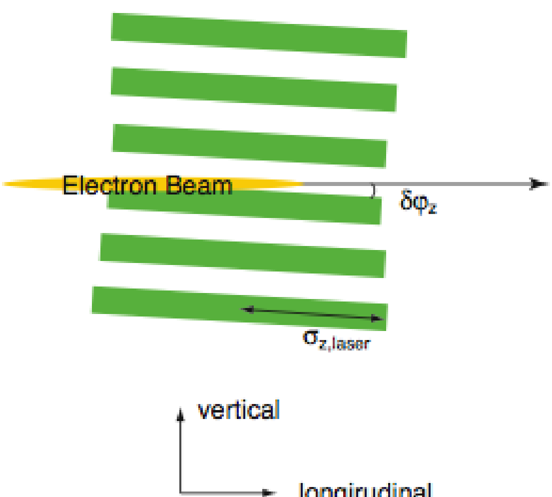




focal scan in y : Res. 0.1μm

Add mover (stroke 30 mm) to final focusing lens

Fringe Tilt



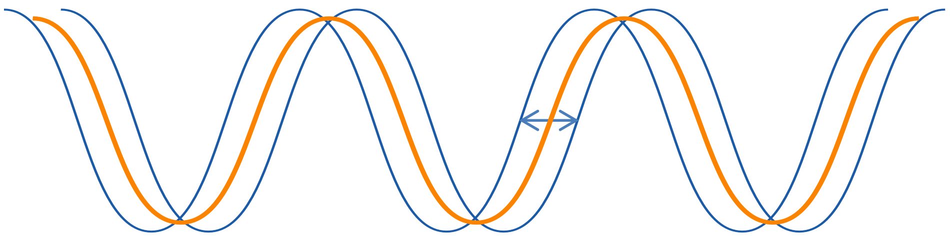
longitudinal

transverse

Tilt monitor:
PSD resolution 10 μm
→ Δφ ~0.3 mrad

Relative Position Jitter → Interference Phase Jitter

smears cosine M curve



$$C_{\text{phase}} = \exp\left(-\frac{\Delta phase^2}{2}\right)$$

Δphase < 200 mrad

- **Laser: from optical device vibrations**
- **Beam position jitter / bunch** → monitored / corrected by **IPBPMs**

statistical errors (~ 12%)

Summary on Shintake Monitor

- Measurement of nm beam size at ATF2 with laser interference fringes
- Meet expected performance for good S/N, σy* > 300 nm
- resolution depends on BG
- Beam tuning procedures
- precise laser alignment, monitoring and feedback system
- Systematic Errors
- Status and further plan coming up next

Backup

Statistical Errors

- relate to signal strength
  → error bars when fitting each signal point on M curve
- Harsher S/N + heavier effect for smaller σy

M reduction factor	Before correction	After correction
Detector resolution	99.8 ± 0.1%	
Electron current jitter	9%	2.5% (ICT)
Laser power jitter	3%	0.86 % (PD)
Relative position jitter	4%	0.5% (PSDs for laser pos.) (BPM for beam)
Relative Timing jitter	(0.7% from laser,4% from beam)	1.6%
Total	13%	10%

Detector Resolution:

- reference shower change (esp. high BG)
- Beam trajectory shifts, γ hit collimators

  → BG intensity fluctuation, alters energy spectrum
- Need to check reference shower + orbit adjustment

Laser orbit fluctuation:

- fringe phase jitter → beam feels different intensity shot–by–shot → jitters Nγ

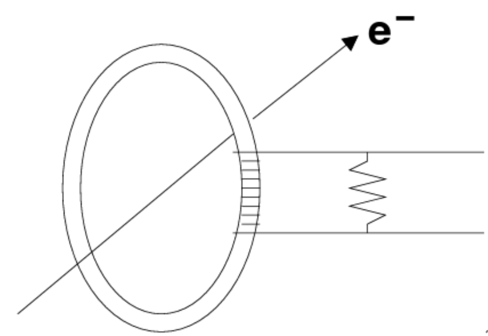
Laser timing instabilities:

- few ns error in laser - beam timing fluctuate Nγ
- **TDC** : {Laser timing: high response PIN-PDs} ←→ {beam timing :BPM }

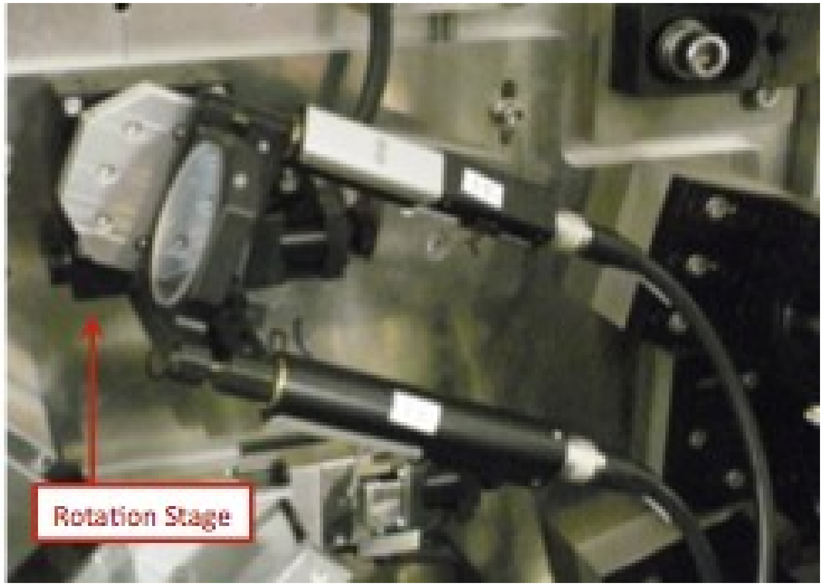
Laser power instabilities: monitored by PDs on vertical table

Current Jitter

- Nγ ∝ current (e- / bunch)
- **ICT-correction**: divide signal by current
- **ICT Monitor resolution**: 2.5 – 5% (constant)
- degraded by amplifier /HV noises, i.e. kicker magnets



Laser crossing angle control

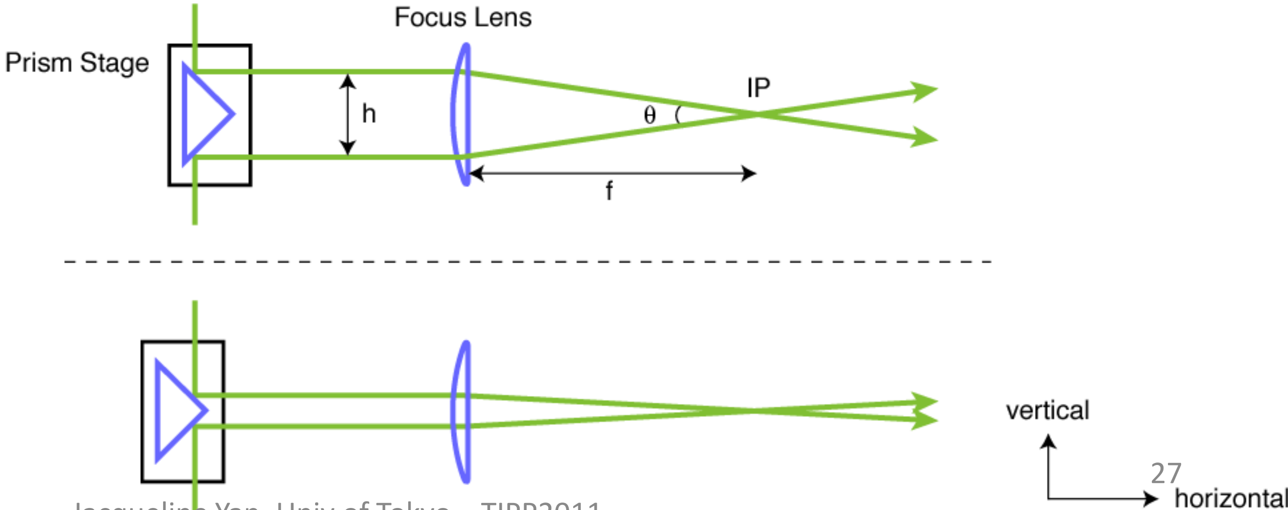


Rotating stage

Switch between
2-8, 30, 174 deg modes

Prism stage

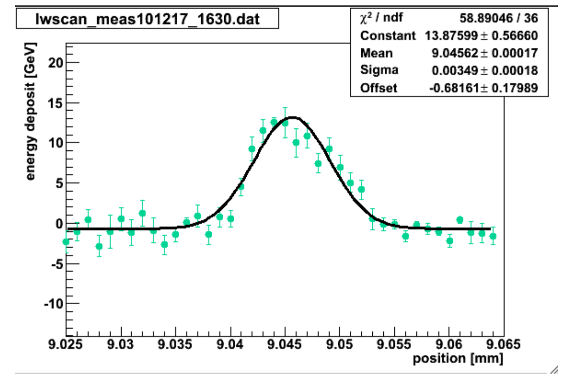
Continuous change
2 - 8 deg



laser wire scan

purpose

- Compton peak detection
- Laser path alignment
- Also measures transv laser spot size



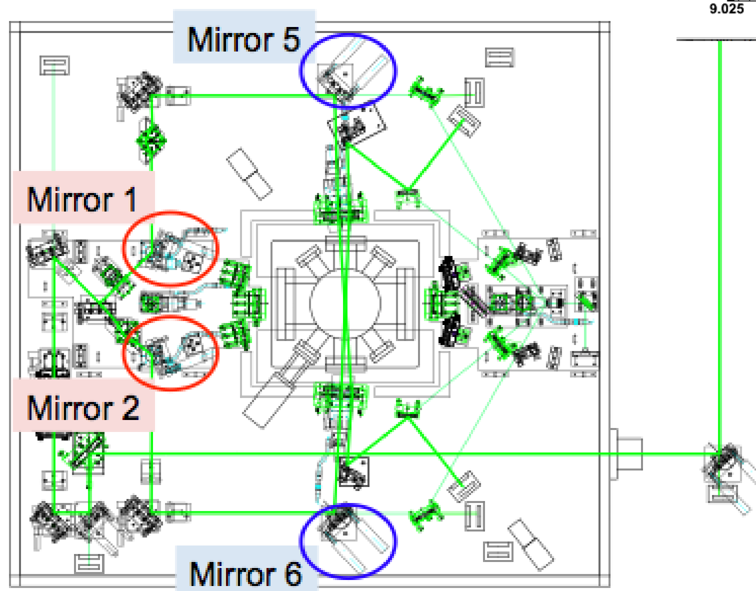
Find Compton peak

2-8, 30 deg mode

Scan with mirror 1,2

174 deg mode

scan with mirror 5, 6



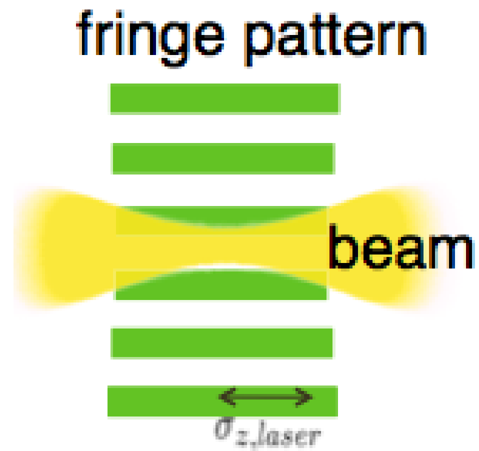
Actuator shift Δa vs. laser shift at IP Δx

$$\Delta x = C \Delta a$$

mode	C [μm/ μm]
2 - 8	8.03
30	9.64
174	6.35

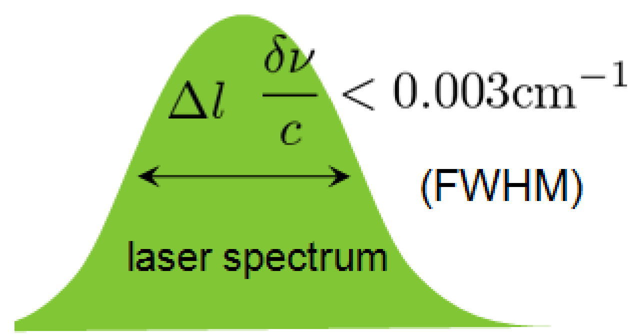
Change of beam size within fringe

- strong focusing: very small β* at IP
- **C< 0.1 %** *not serious problem*



Poor laser temporal coherence

→ difference in optical path lengths



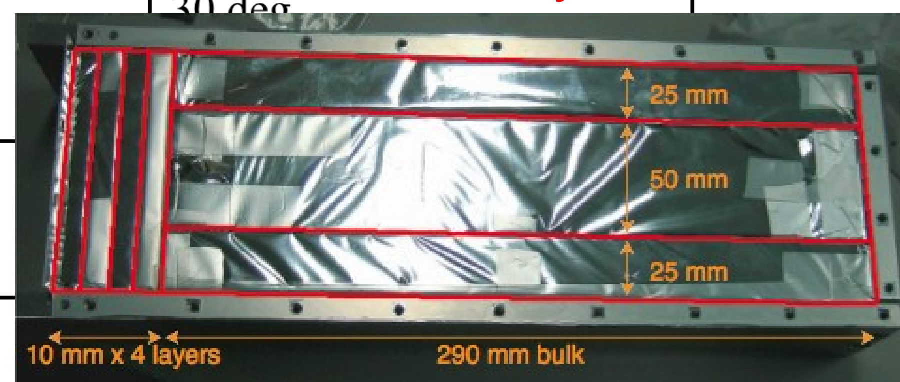
Upgrade from FFTB

*ATF2has smaller design σ_y**
→wavelegth halved (SHG)

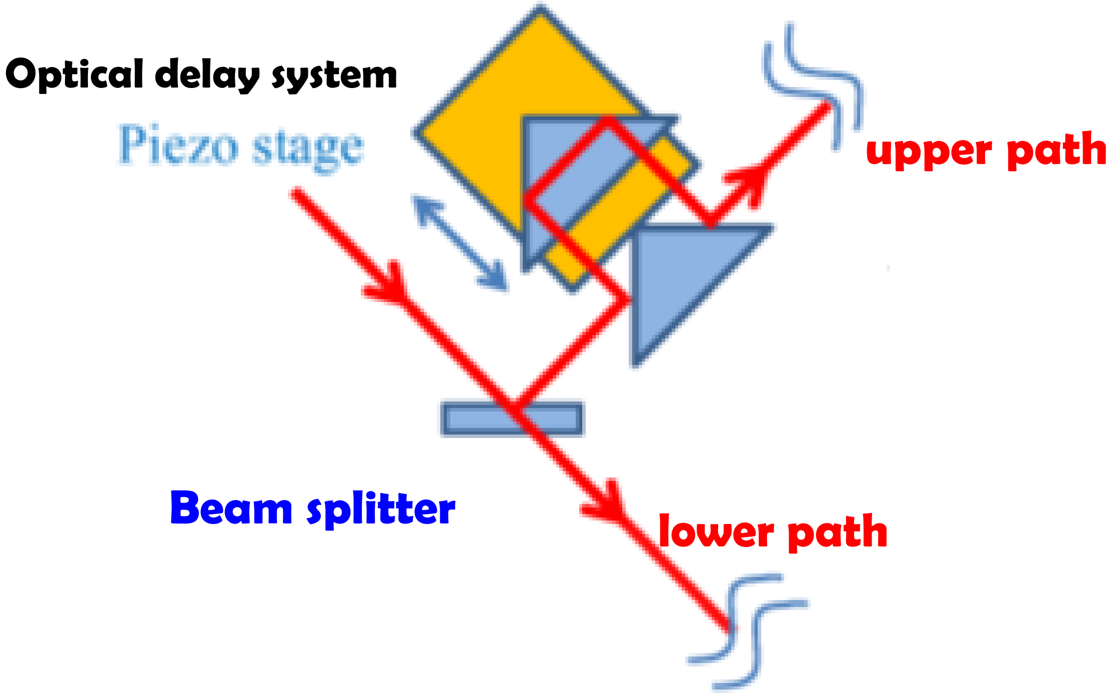
Table 2 : Electron beam and Shintake Monitor parameters: ATF2 vs FFTB.

	FFTB	ATF2
Beam energy	46.6 GeV	1.3 GeV
Repetition rate	30 Hz	1.56 Hz (3 Hz)
Electrons / bunch	1×10^{10}	0.5×10^{10}
Bunch length	3 ps	16 ps
Design beam size at IP	X : 900 nm Y: 60 nm	X: 2.8μm Y: 37 nm
Mode 1 Fringe pitch d Measurable beam sizes	174 deg 0.53μm 40 ~ 180 nm	174 deg 0.27μm 25 ~ 100 nm
Mode 2 Fringe pitch d Measurable beam sizes	30 deg 2.1μm 160 ~ 720 nm	30 deg [illegible]
Mode 3 Fringe pitch d Measurable beam sizes	6 deg (horizontal) 10.2μm 760 nm ~ 3.4μm	[illegible]
Laser wire mode (single pass)	Non	[illegible]

ATF2 Shintake measures wider range of beam sizes



New multilayer γ detector + new phase control system


Optical delay system
Piezo stage
upper path
Beam splitter
lower path