EVALUATION OF EXPECTED PERFORMANCE OF SHINTAKE BEAM SIZE MONITOR FOR ATF2

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Abstract

ATF2 is the final focus test facility for ILC to realize and demonstrate nanometer focusing. One of the goals of the ATF2 is a demonstration of a compact final focus system based on the local chromaticity correction. A designed beam size at the focal point is to be 37 nm in vertical. To achieve the goal, a beam size monitor capable of nanometer beam size measurement is inevitably needed. Shintake monitor satisfies the demands, and is installed at the virtual interaction point of the ATF2. Shintake monitor is a beam size monitor which uses laser interference fringe pattern to measure beam size. The beam test for the Shintake monitor was successful in measurement of signal modulation with the laser interference fringe pattern in November 2009. In April 2010, beam size of less than 1μm was achieved. We have studied the error sources, and evaluated the total error to be less than 10% for 1 minute measurement. This paper is about the evaluation of the Shintake monitor performance by analyzing beam tests data. Most systematic error sources are well understood, so that we can estimate accuracy of beam size measurement when the beam size reaches 37 nm.

BEAM TESTS

Beam tests for the Shintake monitor has performed at ATF2 virtual interaction point (IP). Figure 1 shows the Optical table of the Shintake monitor.

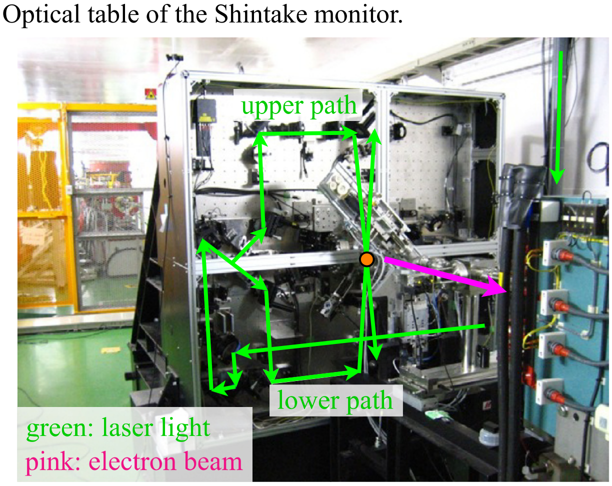

Figure 1: Optical table of the Shintake monitor

Electron beam comes from back of the optical table.

Since upper limit of beam size measurement by the Shintake monitor is about 4 μm, the beam size was to be reduced to this size to find signal modulation. In November 2009 beam size reached the measurable range and we found signal modulation.

In April 2010, the beam size of less than 1 μm was achieved. Figure 2 shows the beam size measurement when beam is 860 nm ± 40 nm (stat.) $^{+0}_{-60}$ nm (sys.). The sources of this error are discussed in the following sections.

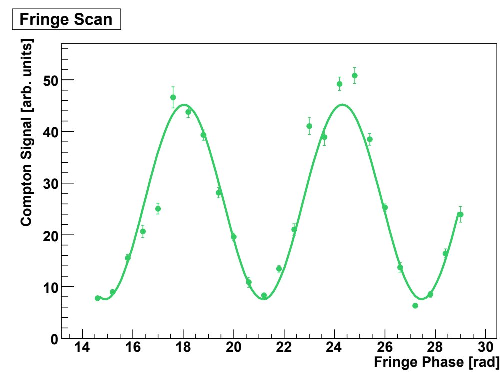

Figure 2: Beam size measurement

STATISTICAL ERROR EVALUATION FROM BEAM TESTS

Dominant sources of statistical error are:

- Resolution of the gamma detector
- Jitter of relative position between electron beam and the laser interference fringe pattern.

Resolution of Gamma Detector

Energy of the Compton signal due to the scattering of beam and laser light is significantly lower than background gamma energy. This makes the gamma detector difficult to measure signal energy. A gamma detector for the Shintake monitor is composed of multi-layer scintillators. Owing to this structure the detector acquires information on shower development. Since the Compton signal and background are different in shower development due to the energy difference, they can be separated. Using this method in the analysis, the detector can identify the signal high resolution even in severe background conditions [1]. However, resolution of gamma detector is still one of the most dominant error sources due to high energy background. In the current condition, typical S/N is about 1, and the signal resolution is about 7% per bunch. Figure 3 shows resolution of the gamma detector.

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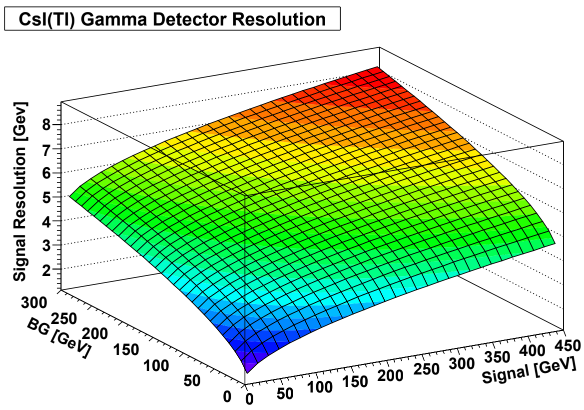

Figure 3: Simulated resolution of the gamma detector

Relative Position Jitter Between Electron Beam and Laser Interference Fringe Pattern

Since phase of the fringe pattern determines the number of scattered photons by the beam electrons, the fringe phase jitter causes signal energy jitter. Beam position jitter causes signal energy jitter in the same way. In the beam size measurement, they are evaluated as relative position jitter between the beam and the fringe pattern, and cannot be treated separately.

We evaluated the relative position jitter from beam tests. From our calculation, signal error from this effect is about 6%. More precisely, since signal amount and influence of relative position jitter is related to the interference fringe phase, signal error is also related to the phase. Figure 4 shows relation between signal error and the fringe phase.

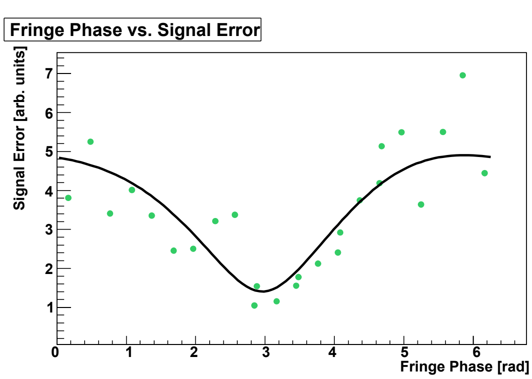

Figure 4: Relation between signal error and the fringe phase measured by beam size measurement

Black curve is fitting function expected by resolution of the gamma detector and relative position jitter influence.

SYSTEMATIC ERROR EVALUATION FROM BEAM TESTS

Several sources of systematic error reduce modulation depth. Their influence is written as

$$M_{meas.} = CM_{ideal},$$

where M_{meas} is a measured modulation depth, M_{ideal} is an ideal modulation depth and C is modulation reduction factor. The measured modulation depth is shown as the product of all modulation reduction factors and the ideal modulation depth.

Laser Polarization

In principle, laser polarization never reduces contrast of the interference fringe. However P-polarized reflectance of the laser beam splitter is not exactly 50%, because the splitter is tuned for S-polarized light. So the existence of P-polarized light causes laser power imbalance and makes the contrast small. The contrast degradation reduces signal modulation. The modulation reduction factor from polarization is written as

$$M_{meas.} = \frac{2\left(\sqrt{P_S{}^{up}P_S{}^{down}} + \sqrt{P_P{}^{up}P_P{}^{down}}\right)}{P} M_{ideal},$$

where P_S is a S-polarized laser power, P_P is a P-polarized laser power and P is the whole power of the laser. Superscripts show the light path. During the beam test in the December 2009, the modulation reduction factor was estimated to be 96.3%. After the beam test, we adjusted laser polarization with half wave plate, and now the factor is almost 100%. We calculate the modulation reduction factor from laser polarization to be less than 1%.

Laser Alignment Accuracy

If two lasers overlap only partially, the modulation becomes small [2]. The modulation reduction factor from misalignment is written as

$$M_{meas.} = \cosh^{-1}\left(-\frac{\delta t^2}{4\sigma^2_{t,laser}}\right)\exp\left(-\frac{\delta z^2}{8\sigma^2_{z,laser}}\right)M_{ideal},$$

where δt is a spatial difference between two lasers on transverse plane, δz is that in longitudinal direction, $\sigma_{t,\,laser}$ is a laser spot size in transverse direction and $\sigma_{z,laser}$ is a horizontal beam size. In beam tests, we align the laser pathway with beam position by analyzing results of the beam size measurement. We demand the alignment accuracy to have the modulation reduction factor larger than 97.5%.

Laser Temporal Coherence

If the laser temporal coherence is poor and the two laser path lengths are different, the contrast of the interference fringe is reduced, so is the signal modulation. This is because each frequency component of the laser contributes to interference in different phase under the existence of laser path length difference. The modulation reduction factor is written as

$$M_{meas.} = \exp\left(-2\pi^2\left(\frac{\delta\nu\Delta l}{c}\right)^2\right)M_{ideal},$$

where $\delta\nu/c$ is a line width of the laser and Δl is a laser path length difference. The line width of the laser which we use is less than 0.003 cm inverse. We evaluate the modulation reduction factor from laser temporal coherence to be larger than 99.7%.

Phase Jitter

Because the signal energy jitter caused by the relative position jitter between electron beam and laser interference fringe pattern is biased towards the mean value of the signal energy, the modulation depth is systematically reduced by the relative position jitter. The modulation reduction factor is written as

$$M_{meas.} = \exp\left(-\frac{\Delta phase^2}{2}\right) M_{ideal},$$

where Δphase is a phase jitter converted from a relative position jitter. The measured phase jitter from the beam tests was less than 100 mrad, and then the modulation reduction factor was calculated to be larger than 97%.

Tilt of the Fringe Pattern with Respect to the Electron Beam

When the horizontal or longitudinal axes of the interference fringe pattern are not in parallel to beam axes, measured beam size is larger than actual value. In the current beam condition, this effect is the most influential one. The measured beam size is written as

$$\sigma^2_{y,meas.} = \sigma^2_{y,ideal} + \delta\varphi^2_z \sigma^2_{z,laser},$$

where $\sigma_{y,meas.}$ is a measured beam size, $\sigma_{y,ideal}$ is an ideal beam size, $\sigma_{z,laser}$ is a laser spot size in longitudinal direction and $\delta\varphi_z$ is an angle difference between the fringe longitudinal axis and the beam direction. $\sigma_{z,laser}$ can be evaluated from beam size measurement [3]. To reduce this influence, we need to align the laser light path angles. Because the laser crossing point must not be changed by this alignment, we have to align some mirror angles delicately.

Table 1: Sources of systematic error

Source	$\Delta\sigma_y/\sigma_y$ for 1 µm (measured)	$\Delta\sigma_y/\sigma_y$ for 37 nm (expected)
Laser polarization	0.4%	0.4%
Laser alignment accuracy	< 3%	< 3%
Laser temporal coherence	< 0.4%	< 0.4%
Tilt of the laser fringe pattern	< 5%	< 2%
Phase jitter	< 3%	3%*
Laser spherical wavefront	negligible	< 2%**
Beam size growth in the fringe pattern	negligible	2%***

* Beam position monitor is needed.
** Laser focal point alignment is needed.
*** Beam optics study at upper and lower IP is needed.

TOWARDS 37 nm BEAM SIZE MEASUREMENT

We evaluated the Shintake monitor performance in the future 37 nm beam size measurement. The following sources of systematic error become significantly large and they must be considered towards the measurement.

Laser Spherical Wave Front

Gaussian beams have spherical wavefront. Wavefront curvature radius decreases with distance from focal point. Therefore if beam position is away from the laser focal point when beam pass the fringe pattern, beam senses curved fringe pattern due to the laser spherical wavefront. This effect is given by the following expression:

$$M_{meas.} = \left(1+\Delta\hat{y}^2\right)^{-\frac{1}{4}} \left(1+\Delta\hat{y}^2\left(1+z_R\frac{1+\Delta\hat{y}^2}{2k\sigma^2_x}\right)^{-2}\right)^{-\frac{1}{4}} M_{ideal},$$

where $\Delta\hat{y}$ is a distance normalized by Rayleigh length between beam and laser focal point in vertical axis and k is wave number of a laser light. To reduce this effect, we need to align laser focal point.

Beam Size Growth in the Fringe Pattern

Due to small beta function of the electron beam for the strong focusing, beam size growth within the fringe pattern is influential. The modulation reduction factor is written as

$$M_{meas.} = \left(1+4k^2_y\sigma^2_{z,laser}\frac{\varepsilon_y}{\beta^*}\right)^{-\frac{1}{2}} M_{ideal},$$

where k_y is a vertical component of wave number, ε_y is a vertical emittance and β^* is a beta function at IP. To evaluate M_{ideal}, beam optics study at upper and lower IP is needed.

Expected Performance of Shintake Monitor for 37 nm Beam Size Measurement

With estimation of all these error sources, we evaluate the Shintake monitor performance towards 37 nm beam size measurement. From our calculation, systematic error is estimated to be about 6% and statistical error would be about 10% for 37 nm beam size by 1 min. measurement.

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[3] Y. Kamiya, "Development of Shintake Beam Size Monitor for ATF2", Proceedings of the First International Particle Accelerator Conference, Kyoto, 2010.