論文の内容の要旨

Precise Measurement of Nanometer Scale Electron Beam Sizes Using Laser Interference by Shintake Monitor

(レーザー干渉型新竹モニターによる

ナノメートル電子ビームサイズの精密測定)

ジャクリン　ヤン

The International Linear Collider (ILC) is essential for the precise measurement of the properties of Higgs boson and new physics. The Higgs boson, responsible for elementary particle masses, was discovered at the Large Hadron Collider (LHC) in 2012, thereby completing the particle spectrum of the Standard Model. There is compelling motivation for new physics beyond the Standard Model e.g. SUSY, the lightest of which is a dark matter candidate. In contrast to proton collisions at the LHC, the ILC collides electrons and positrons, which are point-like particles whose colliding energies are controllable. This realizes clean interactions with less background, enabling better knowledge of the initial states and particle mass resolution. Also, because the ILC is a linear collider, higher collision energies can be achieved without being limited by the synchrotron radiation loss problematic at circular electron-positron colliders. The current ILC design and physics program require a high luminosity of about 2×10^{34} $cm^{-2}s^{-1}$ while minimizing power consumption. This calls for the focusing of its electron and positron beams to nanometer sizes at the interaction point (IP).

The Accelerator Test Facility 2 (ATF2) was constructed at KEK as a realistic scaled down test prototype of the final focus system (FFS) of the ILC. The Goal 1 of ATF2 is to focus the vertical beam size (σ_y) to 37 nm, scaled by energy from the ILC design σ_y of 5.9 nm, and by doing so, demonstrate a FFS design for the ILC featuring a novel beam focusing method called the Local Chromaticity Correction scheme. The merits of this

FFS design are a shorter FFS beam line and less beam halo compared to preceding designs.

The subject of this thesis, the Shintake Monitor, is a beam size monitor installed at the virtual IP of ATF2 for the purpose of measuring its O(10) nm σ_y. Featuring a technique of using laser interference fringes as a probe to scan the electron beam, the Shintake Monitor is the only existing device that has demonstrated measurement of σ_y below 100 nm. In 1992, it achieved measurement of $\sigma_y \sim 70$ nm at the FFTB experiment at SLAC, where an older FFS design was used. In the years that followed, various upgrades were made to the Shintake Monitor to adapt it for measuring the smaller σ_y under the ATF2 environment.

The measurement scheme of the Shintake Monitor (see Fig. 1) is as follows: a pulsed laser beam is split into upper and lower paths, which cross at the IP to form laser interference fringes. The collision of the electron beam against the fringes ejects photons by inverse Compton scattering. A modulation pattern is produced in the photon energy by scanning the fringe phase with respect to the electron beam using a piezo-electric stage. The σ_y is calculated from this modulation measured by a downstream gamma-ray detector. The laser optics are designed to accommodate a wide range of σ_y from about 25 nm to a few μm with better than 10% accuracy.

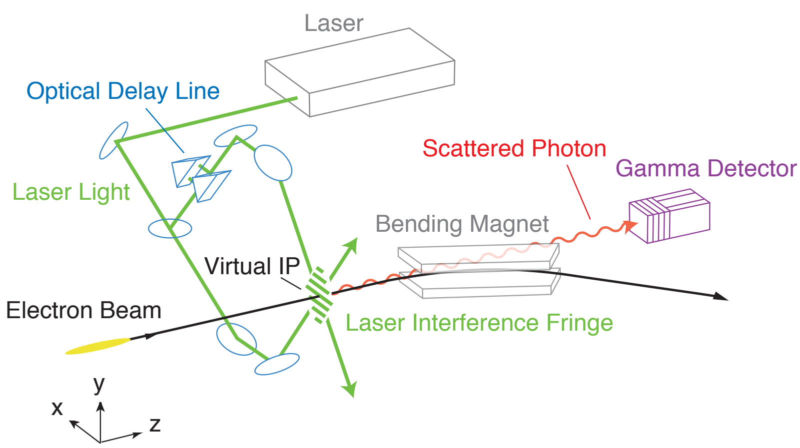

Figure 1: Measurement scheme of the Shintake Monitor

This thesis describes the design concepts and performance of the Shintake Monitor, focusing the most important personal contribution of the author, which is an extensive study of systematic errors which enabled the precise extraction of σ_y from the measured signal modulation. These systematic errors are called “modulation reduction factors” because they cause under-evaluation of modulation i.e. over-evaluation of σ_y. In particular, an original method was developed for extracting the dominant M reduction factor, the fluctuation of the relative phase between the laser and the electron beam, by fitting fringe scan data. The reliability of the method was demonstrated using simulation assuming realistic ATF2 conditions. Some examples are shown in Fig. 2; the left plot shows that phase jitter with a wider range of amplitudes can be extracted with precision better than a few % with respect to the input phase jitter; the right plot shows that using the extracted phase jitter values, the reduction in the modulation due to phase jitter can be corrected.

Other modulation reduction factors besides phase fluctuation are related to laser properties e.g. polarization, profile, power, and the position alignment precision with respect to the electron beam at the IP. Based on various measurements conducted of these laser properties and the gamma-ray detector response, systematic errors were evaluated for beam time data collected in 2014 spring.

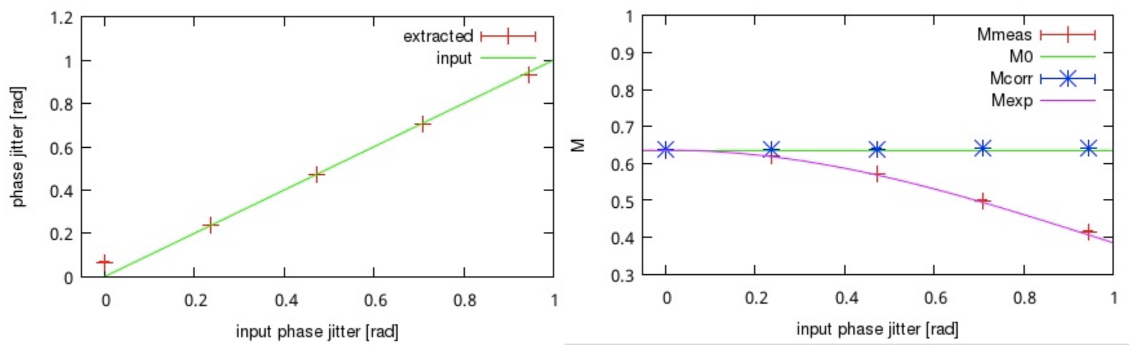

Figure 2: The reliability of the original phase jitter extraction method is demonstrated using simulation assuming realistic experiment conditions. Shown here are the results of 1000 pseudo experiments. [left] The horizontal and vertical axes are the input and extracted values of phase jitter, respectively. [right] While the “measured modulation” (red points) is reduced by phase jitter, the corrected modulation (blue points) based on the extracted phase jitter values is consistent with the nominal modulation (green line) with a precision of better than a few %.

The effective beam tuning using the Shintake Monitor contributed essentially to the ATF2 beam focusing progress; by June 2014, the focusing of σ_y to below 45 nm has been demonstrated on repeated occasions with a measurement stability of about 5%. Some examples are shown in Fig. 3. After the evaluation of systematic errors, the full beam size evaluation for a set of world record continuous σ_y measurements is

$$\sigma_y = 39.7 \pm 0.6(stat.)^{+2.6}_{-4.0}(syst.) \text{ nm}$$

The corresponding measurement resolution is about 10%. The results of the systematic error studies indicate that the ATF2 Goal 1 has been achieved within error ranges.

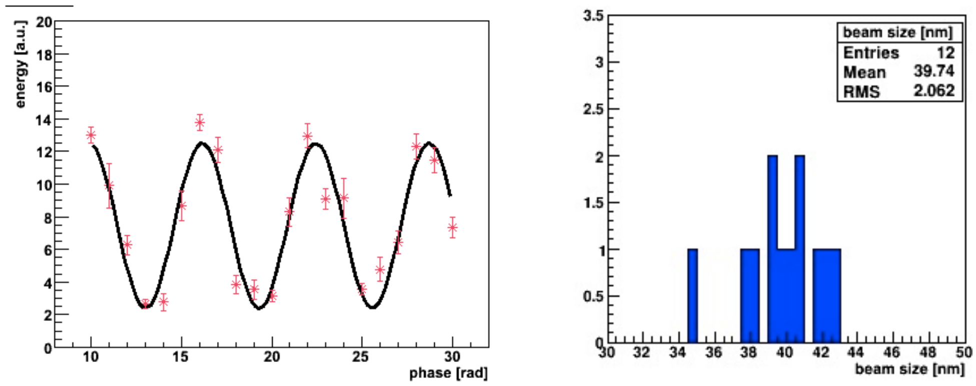

Figure 3 Examples of small σ_y measurements in June 2014: [left] Measurement of modulation corresponding to ATF2 Goal 1 beam size σ_y = 37.1±1.5 nm. This is the upper bound before correction of systematic effects. [right] 12 continuous σ_y measurements during about 50 min; the result after systematic error analysis is $\sigma_y = 39.7 \pm 0.6(stat.)^{+2.6}_{-4.0}(syst.)$

Because the ATF2 is a scaled prototype of the ILC FFS with similar difficulties in beam tuning, various technologies verified at ATF2 are applicable to the ILC. Therefore, the precise evaluation of O(10) nm σ_y measured by the Shintake Monitor was a large step towards demonstrating the feasibility of realizing the ILC. By resolving several issues in performance and design, the Shintake Monitor is also a promising candidate for the O (nm) resolution beam size monitor necessary for the beam line commissioning at the actual ILC.