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Introduction

The Standard Model of particle physics has so far been successfully predicted and classified the discovery of all the subatomic particles, including the Higgs boson, which was discovered in 2012 [1, 2] at the Large Hadron Collider (LHC) [3]. However, despite the success of the Standard Model and the discovery of the Higgs boson, fundamental questions as the origin of the dark matter and matter-antimatter asymmetry observed in the universe remain. Moreover, a clear explanation for the origin of the Higgs mechanism, and a full confirmation of the properties of the discovered Higgs boson are not yet available. Further more precise investigations of the Higgs boson and of new physics expected beyond Standard Model requires both higher collision luminosity and energy. The LHC High Luminosity upgrade (HL-LHC) [4] is planned to increase the peak luminosity to $5 \times 10^{34} cm^{-2} s^{-1}$, however, in order to perform detailed studies of the Higgs boson with higher precision, lepton colliders such as a $e^- - e^+$ machine are essential complementary instruments.

Possible candidates for such $e^- - e^+$ machines include circular colliders, as planned in the context of the Future Circular Collider (FCC-ee) [5] at CERN and Circular Electron Positron Collider (CEPC) [6] in China, and Future Linear Colliders (FLC) as the Compact Linear Collider (CLIC) [7] at CERN and International Linear Collider (ILC) [8] under consideration in Japan. One of the limits of circular colliders is that, once the circumference is defined, the maximum achievable energy is restricted by the emission of synchrotron radiation. The advantage of linear colliders is their potential for upgrading the energy by extending the length. The ILC machine aims to achieve 200-500 GeV (extendable to 1 TeV) centre-of-mass with a luminosity of $> 0.75 \times 10^{34} cm^{-2} s^{-1}$, based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology. In order to achieve the required high luminosity, focusing of ultra-low emittance beams to nanometre level at the collision point is required.

The Accelerator Test Facility (ATF) [9] at KEK in Japan is a prototype of the damping ring built to demonstrate the small emittance beams required for the FLC. And the ATF2 [10, 11], which uses the extracted beam from ATF, is a scaled down Final Focus System (FFS) prototype of the FLC with the aim to demonstrate nanometre level focusing based on local chromaticity correction. World records of normalised vertical emittance (3×10^{-8} m in 2003) [12] and vertical beam size ($\sim$44 nm in 2014) [13] have been achieved by ATF and ATF2, respectively.

A major issue in ATF2 and all the future colliders is the control of beam halo before the interaction point (IP). Beam halo consists of tails extending far beyond the Gaussian core of the beam. These tail particles can likely be intercepted by apertures near the Final focusing quadrupole Doublet (FD). Fluxes of muons and other secondary particles which are then created, could easily exceed the tolerable levels at a detector by a few orders of magnitude [14]. Minimisation of detector background therefore needs efficient removal of the beam halo by upstream collimation. Dedicated collimation sections are planned and designed for the FLC based on the assumptions and experience from the SLAC Linear Collider (SLC) concerning the population and propagation of halo particles [15].

At ATF2, beam halo hitting on the FD and the beam pipe after the IP can generate a large amount of background through bremsstrahlung for the measurements of the nanometre beam size using the laser interferometer beam size monitor (Shintake monitor) [16]. Although a dedicated collimator system downstream of the IP is used to collimate such background photons at the entrance of the Shintake monitor, there is at present no dedicated collimator for the beam halo itself [1]. Therefore, the beam halo issue remains and may limit the use of the largest horizontal and vertical demagnification factors available in the optics. Dedicated collimators are however now being prepared within the collaboration [17]. The design of the collimators strongly relies on the transverse beam halo distribution which is currently unknown for the ATF2 beam

[1] A tapered beam pipe (TBP) has been installed at the upstream (between QD10AFF and QD10BFF) to shield background for the Shintake monitor.

line. Hence, beam halo measurements are required for the investigation of transverse beam halo distribution.

One important issue for beam halo measurements is to reach a high dynamic range. The beam halo is expected to be $\sim 10^{-3}$ of the total beam population based on experience from the SLC and past measurements. Beam core measurement are required for the proper normalization of the beam halo. Beam halo measurements using wire scanners in the old extraction line of ATF reached a dynamic range of $\sim 10^4$ [18]. Recent wire scanner measurements in the present ATF2 beam line however only achieved a dynamic range of about $\sim 10^3$ due to less favourable background conditions [19]. Single crystalline Chemical Vapor-Deposition (sCVD) diamond sensors are not only sensitive to single electron but have also been tested to have a linear response up to 10^7 electrons [20]. Two sCVD *in vacuum* Diamond Sensors (DSv) have been developed for this reason. The first DSv was installed for horizontal beam halo scanning after the interaction point (IP) of ATF2 in Nov. 2014. It aims not only to measure the beam halo distribution with large dynamic range ($> 10^6$), but also to investigate the possibility of probing the Compton recoil electrons produced in the interactions with the Shintake monitor laser beams.

Demonstrations of a beam halo monitor using polycrystalline CVD (pCVD) diamond detectors for observing electron beams directly inside the vacuum chamber was carried out at the SPring-8 Angstrom compact free-electron laser (SACLA) facility [21]. In this experiment, a pair of diamond-based detectors is mounted on the upper and lower side of the beam center to measure the beam halo on the two sides of the beam core, which passes through the gap between the two detectors without interacting with them. This detector has achived a lower detection limit of 2×10^3 electrons/pulse for single-shot measurement. Meanwhile, a linear response up to 10^7 electrons/pulse has also been demonstrated. However,"in vacuum" tests of diamond detector beyond 10^7 electrons have not yet been described in any reference.

In our experiment, we have succesfully performed a simultaneous beam core ($\sim 10^9$) and beam halo ($\sim 10^3$) measurement using a sCVD based diamond sensor [22]. It is the first time to our knowledge that a scanner based on a diamond sensor is used successfully to measure the beam core and beam halo with a dynamic range of 10^6 inside the vacuum chamber of an accelerator.

This thesis is divided into four parts:

Part I gives a general introduction on the ILC project and on the ATF/ATF2 facility. The physics motivation and the accelerator design of ILC, with emphasis on the beam halo collimation, are described in Chapter 2. The goals of ATF2 and recent status of the progress in achieving these goals are presented in Chapter 3, together with the instruments used for beam diagnostics.

Part II presents the simulations on the beam halo and Compton recoil electron studies, in Chapter 4, followed by initial beam halo measurements using wire scanners, in Chapter 5.

Part III introduces the properties of the CVD diamond sensors, in Chapter 6, followed by the design and characterisation of the DSv, in Chapter 7.

Part IV presents the beam halo measurements done using the horizontal DSv, in Chapter 8, with a discussion on the possibility of probing Compton recoil electron, in Chapter 9, and finally a summary of the results and future prospects, in Chapter 10.