Development on Pulsed Laser Wire for Measurement of Beam Profile

「ビーム形状 モニター用パルスレーザーワイヤの開発」

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Abstract

Production and handling of low emittance beam is important technology for linear colliders. For the view point of high energy experiments, luminosity and energy of collider is very important. So damping ring generates low emittance beam by radiation damping process. The advent of laser based beam profile monitor has increased the scope of studying low emittance beam dynamics. An Accelerator Test Facility (ATF) was built at KEK in hope of developing techniques for the low emittance beam. It consists of an electron linac, a damping ring in which beam emittance is reduced and an extraction line. The damping ring has two arc sections and two straight sections. 4 pm –rad vertical emittance was already confirmed by CW laser wire monitor at the ATF damping ring. The main goal of ATF damping ring was production of 10 pm-rad emittance beam stably with multi-bunch beam of 210 mA. In the damping ring at ATF, vertical beam size is less than 10 μm. For emittance measurement we are developing a new type of beam profile monitor which works on the principle of Inverse Compton scattering between electron and laser light. In order to achieve effective collision of photon and electron, very thin size laser is required. By scanning the position of laser beam and counting the number of scattered photons, a projected beam profile is obtained. Such type of optical resonator system is called laser wire. Laser wire is one of such a technique to measure a small electron beam size. If we make a small waist laser beam and install it perpendicular to an electron beam, then electron interacts with the laser light and emits energetic photons in the forward direction by Inverse Compton scattering process. After the inverse-Compton scattering, all electrons are bent by magnet while emitted photons are detected by a high energy photon detector placed downstream in the forward direction. In particular, if both electron and laser beam are assumed to have Gaussian profiles with width σ_e and σ_{lw} , the observed profile is also Gaussian with width σ_{obs} expressed by

$$\sigma_{\mathrm{obs}}^2 = \sigma_{\mathrm{lw}}^2 + \sigma_{\mathrm{e}}^2 \ .$$

The purpose of this research is to develop pulsed laser wire for electron beam profile monitor with relative fast scanning at the ATF damping ring. Near 5 μm laser waist is essential to measure tiny electron beam profile precisely.

We used a four mirror Fabry-Perot optical cavity to produce laser wire. It enhances the effective laser power and improves the intensity of the signal. The geometrical properties of laser beam are

completely defined by boundary conditions formed with two concave mirrors and two plane mirrors. Pulsed repetition is same as oscillation frequency of mode locked laser. All of the frequencies in the mode locked laser can be resonant in the optical cavity when the following condition is satisfied, assuming λ as laser wavelength, a laser oscillation cavity length of L_{laser} and optical cavity length as L_{cav} .

$$L_{cav} = n\lambda \text{ (n : integer)}$$

$$mL_{cav} = L_{laser} \text{ (m: integer)}$$

The minimum beam waist is obtained in between two concave mirrors. The two concave mirrors of same curvature are used in compact resonator. Electron beam interacts with laser pulse at minimum beam waist position, which is called interaction point (IP). The optical cavity assembly consists of four mirrors, mirror holder system and cyilindrical spacers which define length of cavity. In order to have precise control over cavity length, both plane mirror holders are supported by a piezo actuator through a disk type plate spring. Hollow piezo actuators are used for laser beam to pass through them. Four mirror optical cavity is designed for 532 nm wavlength. Distance between concave-concave mirror is kept at 102.8$\pm$0.1 mm and distance between plane-plane mirror is kept at 103.2$\pm$0.1 mm. A complex mirror alignment scheme is used to keep side by side distance between plane and concave mirror to 29.2 mm. All mirrors used in cavity design are of 1 inch diameter. The radius of curvature for two concave mirror is 101.81 mm. Minimum beam size is directly praportional to wavlength of laser beam, therefore with green pulsed laser (532 nm) we can achieve half value of beam size as compare to infrared (1064nm) pulsed laser.

In our intial phase of research, we injected pulsed infrared mode locked laser with 714 MHz repetition rate to four mirror cavity. With pulsed infrared laser, achieved minimum beam size is around 12 μm. That means, with pulsed green we can obtain beam size around 6 μm in the same resonator. Important role of the cavity is to enhance the effective laser power. Laser beam from a laser oscillator is injected to the cavity through one of the plane mirrors. The laser wave inside the cavity reflects back and forth and builds up the effective power. The power enhancement realizes only when the cavity satisfies the resonance condition of a standing wave. We achieved enhancement factor of 960 inside cavity with present setup. Finesse is measured experimentally by finding the ratio of Free Spectral range (FSR) to width of resonance at half maximum ($\delta\theta$) of

Airy function. FSR is distance between peaks of two consecutive 0^{th} order modes. Measured Finesse with laser wire system is 2315$\pm$220.

Pulsed infrared laser can be converted to pulsed green laser by second harmonics generator (SHG). But non- linear crystals used for second harmonics generation has very low conversion efficiency. Therefore, we made an amplifier system for 714 MHz pulsed seed laser, before conversion to second harmonics. The seed pulse from 714 MHz mode locked laser is amplified by a main amplifier. The main amplifier is composed of an Yb doped photonic crystal fiber (PCF, core diameter: 40$\boldsymbol{\mu}$m, length:1.5 m). As PCF has a large core doped with Yb ions and a clad having periodically allocated air holes, it can significantly amplify the seed pulse without nonlinear optical effect. Amplified efficiency decreases due to the shift of the center wavelength of the laser diode (LD) output by its heating. As a result we can keep the center wavelength of the LD output at 976nm by controlling the LD temperature. At high pump power, we can achieve amplifier slope efficiency up to 40%.The 500 mW seed pulse can be amplified to more than 6W .

IR output of the amplifier is then injected into a nonlinear birefringent crystal for the second harmonics generation. The crystal is Stoichiometric $LiTaO_3$ crystal. The pulse passing through the non-linear crystal involves the fundamental (1064 nm) and the second harmonic (532 nm). We need special set of dichroic mirrors to filter infrared beam with green pulse so that only 532 nm pulse beam can pass. The scheme used for second harmonics generation is a single path system. Assuming conversion efficiency to be 20%, 1 W of second harmonics power is achieved at 5 W of IR. High LD pump power can cause PCF edge heating. Therefore for safety of PCF, we try to improve the conversion efficiency at a relatively low amplifier output.

Experiment was performed with single electron bunch inside ATF-DR and Compton signal was observed with vertical scanning of beam. The measured count rate is in the range of 6.2$\pm$1.1 kHz/mA. Background level is measured in the range of 11$\pm$1 kHz. From observed Compton signal profile, bunch length of electron beam is calculated as 23.3$\pm$0.7 ps. Electron beam size in vertical plane is measured as 12.6$\pm$1.8 μm and vertical emittance is measured as 24.1$\pm$ 6.8 pm-rad. Longitudinal bunch length and vertical beam size of electron beam was measured with laser wire system with free phase scan technique, without use of slow feedback system.

With pulsed green laser, profile of electron beam inside damping ring can be measured in vertical and longitudinal direction in very short time as compare to CW laser wire system. CW laser wire system consisted of two optical cavities (a horizontal laser wire and vertical laser wire), but present system requires only one four mirror optical cavity system for measurement of electron beam profile. Four mirror resonator has less sensitivity for misalignment comparing to two mirror cavity. Therefore overall, four mirror laser wire system is more stable and faster comparing to CW two mirror laser wire system which is previously used inside damping ring. This work is focused on design parameters of pulsed four mirror laser resonator and its application as a laser wire system. In this thesis, we describe development of this new profile monitor and measurement of electron beam profile and bunch length using free scan technique in ATF damping ring.