DEVELOPMENT OF CW LASER WIRE IN STORAGE RING AND PULSED LASER WIRE

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Abstract

Future accelerators require a high resolution beam profile monitor that can measure the beam non-destructively and works at high beam intensity. Laser based beam monitors can be the solution. Accelerator Test Facility at KEK has been developing various types of Laser Wire monitors. CW Laser Wire with a build-up optical cavity has been used to measure the small emittance beam at the damping ring. Pulsed Laser Wire has been developed to measure a small focused beam at the extraction line. This paper introduces these systems.

INTRODUCTION

Laser-Compton scattering has become an important technique for beam diagnostics of the latest accelerators. Laser wire is one of such a technique to measure a small beam size. When a laser beam is injected transversely across the electron beam, some of the photons in the laser beam interact with the electron beam via the Compton scattering. It produces high energy gamma rays in the forward direction of the electron beam. Since the flux of the Compton scattering signal is proportional to the convolution of the electron beam and the laser beam, transverse profile of the electron beam can be measured by scanning the laser position while measuring the Compton signal.

One of the advantages of laser based methods is that it never be damaged by a high intensity beam. This feature enables the laser wire to be used in the situation of high crossing rate in storage rings or high density multi-bunch beam of linear colliders. At the same time, due to the small cross section of Compton scattering, the measurement can be done without disturbing the beam. Since it is possible to measure the beam at the equilibrium condition of a storage ring in a direct way, the measurement can be a powerful tool for knowing the condition of the ring [1].

On the other hand, high laser power is required to obtain enough amount of signal. Realization of the high power laser beam is one of the keys in the development. The spatial resolution is determined from the transverse size of the laser beam. Realization of small waist size is another important point.

Accelerator Test Facility (ATF) in KEK is an unique test accelerator that can produce a low emittance beam required in the future linear colliders. To experimentally prove the realization of the ultra-low vertical emittance beam in the damping ring, we have developed our first laser wire monitor of cw build-up cavity type in the ring. During the R&D work of the system, we have demonstrated various variation of the monitor, namely, multi-bunch measurement, higher-order mode upgrade, and pulsed laser application. Later, development of another scheme of laser wire that uses high power pulse laser has started at the extraction line of ATF.

BUILD-UP CAVITY LASER WIRE

Principle of Build-up Cavity

Build-up cavity is an established technique to realize a high power laser field with a well defined spatial structure. The simplest example of a build-up cavity is the Fabry-Perot type shown in Figure 1. Boundary condition introduced by two spherical mirrors facing each other defines the spatial structure of the laser field allowed inside the cavity. Distance between the mirrors and curvature of the mirrors are the parameters to design the waist size (w_0) of the laser.

$$w_0^2 = \frac{\lambda}{\pi}\frac{\sqrt{L(2\rho - L)}}{2} \tag{1}$$

In order to realize the small waist size, the cavity has to be designed close to the unstable configuration ($2\rho \sim L$). Note that the rms size (σ) of the photon distribution is related to the w_0 as, $2\sigma = w_0$.

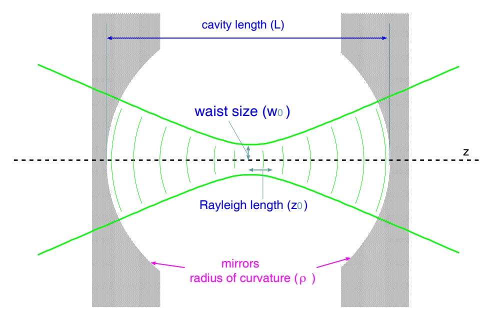

Figure 1: Fabry-Perot cavity and its eigen mode.

Another 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 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. Sharpness of the resonance width is represented by the cavity finesse (F), it is defined from the reflectance of the cavity mirrors as, $\frac{\pi}{1-R}$. Power enhancement factor is given as $\frac{2F}{\pi}$. High reflectance mirror can realize a high enhancement factor, though it results in a narrow resonance width and difficult to control.

In our system, wavelength of the laser is 532 nm, rms size of the laser wire is $\sim 6\ \mu$m and the enhancement factor is $\sim$ 1000.

CW Laser Wire System

Setup of the cw laser wire system at ATF damping ring is depicted in Figure 2. Thanks to the power enhancement of the cavity, it is a compact system with a relatively small laser source. The whole setup is on a mover table to scan in the beam measurement.

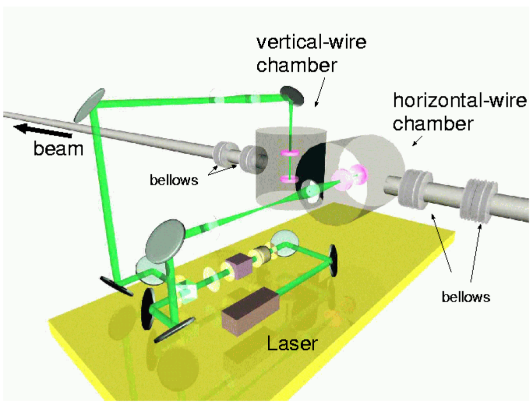

Figure 2: Setup of the laser system.

The cavity is placed inside the vacuum chamber as shown in Figure 3. The cavity mirrors are placed on a piezo actuator to actively control the cavity length. The relative position of the mirrors is rigidly fixed once the cavity structure is assembled, except only a few μm change of the piezo to keep the resonance. It enables to realize a stable small laser waist size.

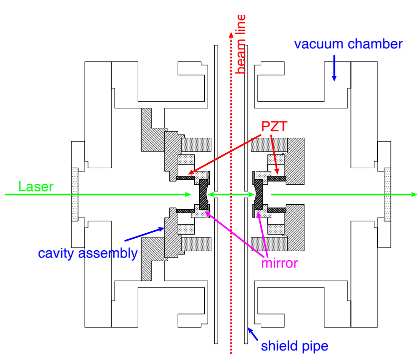

Figure 3: Vacuum chamber and the structure of the cavity assembly.

A CsI detector of 70 × 70 × 300 mm^3 is located 13 m downstream of the collision point. A 5 mm diameter collimator is located in front of the detector to reduce beam background. Since the signal rate is $\sim$kHz whereas the beam crossing rate is 2 MHz, each detected signal can be considered as a single photon. The detector system simply counts up the gamma ray whose energy is consistent with the Compton scattered photon. To precisely subtract the contribution of beam background, laser on/off status is quickly switched during the measurement. It is realized by shaking the cavity mirror to vary the resonance condition. Monitoring the laser output from the cavity, status of the laser power is judged and it controls the count up electronics. Example of the laser power modulation during the beam measurement is shown in Figure 4.

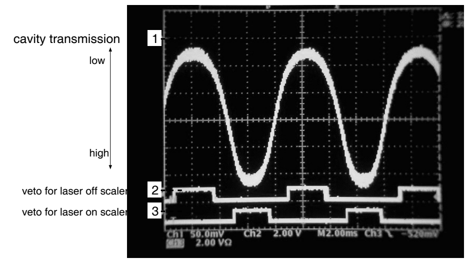

Figure 4: Laser modulation.

Beam Measurement

After current and time normalization of the count rate and subtracting the background rate, signal rate can be calculated for each step of the scan. Changing the laser wire position by mover table, beam profile data as shown in Figure 5 can be obtained in 10 minute. Since the measured peak width includes the contribution of laser width, the intrinsic size of the electron beam is calculated after subtracting its contribution by $\sqrt{\sigma_{meas}^2 - \sigma_{laser}^2}$.

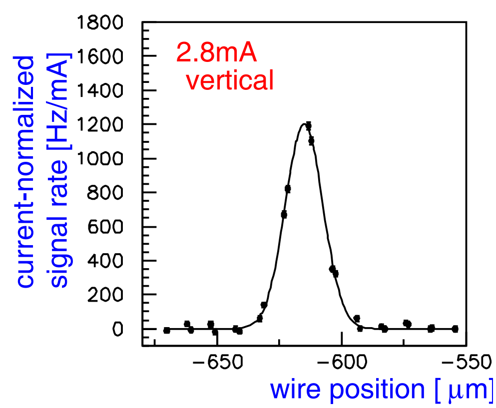

Figure 5: Example of the measurement.

There are several methods to estimate σ_{laser}. One special and quick way is from the measurement of the optical phase shift experienced near the waist (Guoy phase). Detail description of the method can be found elsewhere [2]. Here, we describe a direct way to scan the laser waist by the electron beam. Repeating the profile measurement while changing longitudinal position of the laser system, variation of the measured peak width can be obtained as shown in Figure 6. By fitting the data with both laser and electron sizes left as free parameters, σ_{laser} can be obtained. This method has been used to confirm the laser size during beam measurements.

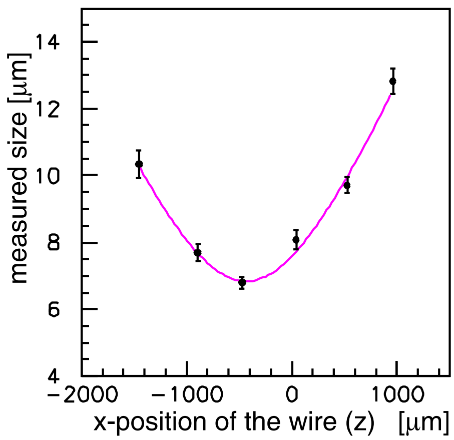

Figure 6: Example of laser waist scan.

Multi-bunch Beam Measurement

By identifying the detection timing of each Compton signal with respect to the reference clock of ring revolution, it is possible to separately measure profile of each bunch in a multi-bunch beam train [3]. It allows us to study intra-train beam instabilities. Figure 7 is an example of multi-bunch measurement. It shows that beam size increases along bunch number. Since this monitor measures projected size of beam profile in many turns of revolution, it can not tell whether the reason of the growth is bunch oscillation or actual beam size increase.

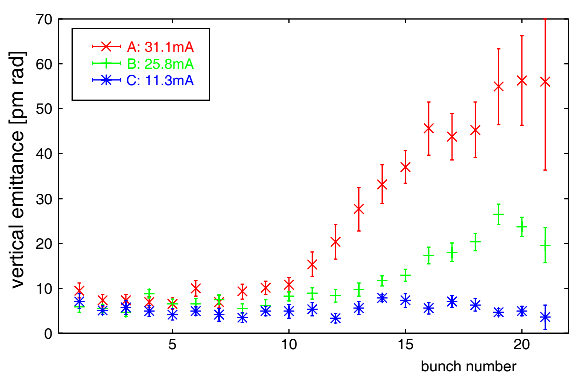

Figure 7: Example of multi-bunch measurement.

Higher-mode Laser Wire

Further reduction of the waist size to improve the spatial resolution is not straight forward because of the diffraction limit. Rayleigh range, the longitudinal length of the waist, becomes short and the horizontal beam size affects the vertical size measurement. There also are practical difficulties in using shorter wavelength laser and its high reflectivity mirror.

There has been an idea to push the resolution by only a simple modification of the build-up cavity [4]. It utilizes a higher-order transverse mode (TEM_{01}) of the cavity which has finer structure in the cross section profile as shown in Figure 8. Utilizing TEM_{01} mode as a laser wire, it has a sensitivity to smaller electron beam size than the rms size of the laser.

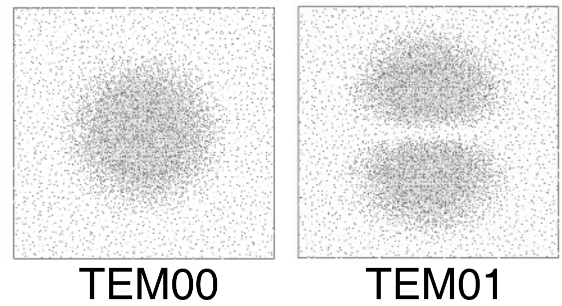

Figure 8: Cross section profile of the lowest mode TEM_{00} and the higher-order mode TEM_{01}.

An example of beam measurement is shown in Figure 9. The depth of the central dip sensitively responses the beam size of 0.2 $\sim$ 1 σ_{laser}. Assuming the profile of the beam to be Gaussian, the measured data is fitted leaving both the laser and the electron beam size as free parameters.

There are several technical points to realize TEM_{01} mode in the build-up cavity. Since an additional phase factor which depends on the order of transverse mode shifts the resonance condition of TEM_{01} from that of TEM_{00}, separate excitation from TEM_{00} has no problem. But, TEM_{10} mode, which is same as TEM_{01} but 90 degree rotated one, can contaminate to the TEM_{01} mode and results in tilt of the profile. In order to solve this problem, we artificially split the resonance condition of the two modes by slightly bending the cavity mirror.

Pulsed Cavity

By replacing the cw laser source with a mode-locked pulse laser, more efficient laser-beam collision can be realized (Figure 10) [5]. Build-up cavity works with mode-locked pulse laser as well, but an additional condition of pulse repetition has to be satisfied. The round-trip time of the cavity has to match with the pulse repetition of the laser source. Hence, precise control of the absolute cavity length is important. In this case, the curvature of the cavity mirrors is the only parameter to control waist size. In order to realize a small spot size, mirrors of specially designed curvature are needed. Timing synchronization with the accelerator beam has to be taken care of in the case of pulsed laser. Since build-up cavity is quite sensitive to the laser's frequency stability, vibration of the mirrors in the laser source due to the phase lock loop servo can disturb the build-up cavity's resonance.

If the laser pulse duration is shorter than the electron bunch, the bunch length can be measured by scanning the relative timing of laser and beam. Figure 11 is an example of such a scan of 28.6 psec beam with 3 psec laser pulse.

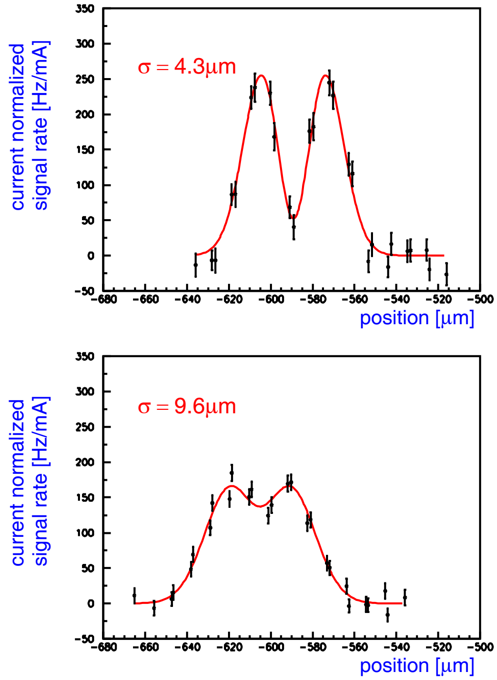

Figure 9: Beam measurement of higher-order mode laser wire. Example of two data for a different size of beam. In this measurement, σ_{laser} was 10.5 μm.

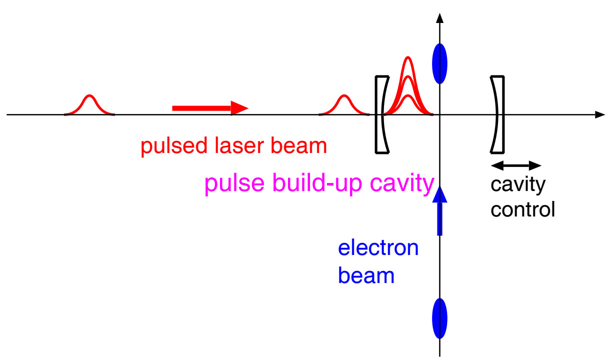

Figure 10: Pulsed build-up cavity scheme.

Since this technique can produce high intensity Compton signal with a multi-bunch beam, application for a laser-Compton based compact X-ray source [6] and polarized gamma-ray source [7] has been studied and demonstrated .

Self-start Recirculation Cavity

In order to realize a high enhancement factor, the build-up cavity scheme requires fine control of cavity length in sub-nm precision. The technical limit of high finesse cavity for stable operation in the environment of the machine tunnel was around F$\sim$3000 in our experience with the mechanical feedback system.

To realize stable cavity excitation even with a much higher finesse cavity, a new scheme has been proposed. Figure 12 shows the schematic layout. The build-up cavity is included in the optical loop of a ring laser oscillator. The

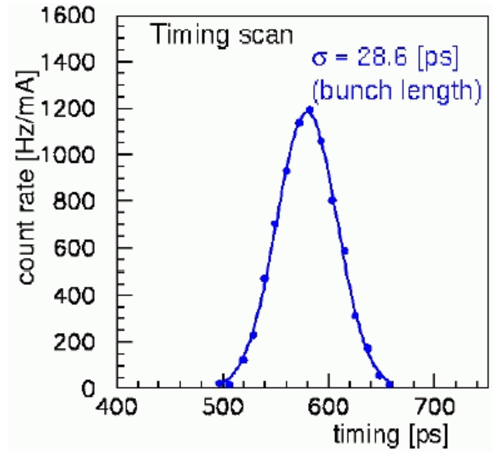

Figure 11: Timing scan data of laser pulse and electron bunch. Bunch length of the electron beam can be measured.

cavity works as a narrow band-path filter to choose the longitudinal modes of the laser oscillation. The laser waves in the cavity's frequency band recirculate the amplifier, and spontaneous oscillation starts if the loop gain exceeds the overall loss. Figure 13 is the result of a test experiment to prove the principle of this scheme. Recirculating power of the optical loop was measured while changing the pump power of laser amplifier. It was confirmed that automatic excitation started above the threshold LD current of 350 mA. This test experiment has done with the build-up cavity of finesse 30000, and no active control was needed to keep the build-up power. This scheme enables us to design much compact laser wire system in turn-key operation.

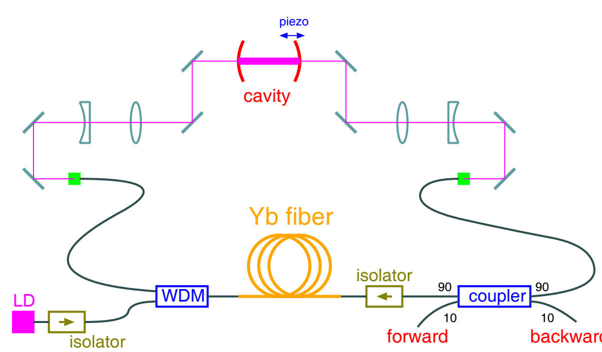

Figure 12: Schematic of the self-start recirculation system.

PULSED LASER WIRE SYSTEM FOR SINGLE PATH BEAM LINE

Another type of laser wire monitor has been developed at the extraction line of ATF. It is a brute force system with a high power pulsed laser of 300 MW peak power and 300 psec pulse duration. So, it does not need a build-up cavity to have enough signal. The schematic layout of the system is shown in Figure 14. The laser beam produced at the laser hatch located outside of the beam tunnel is transferred

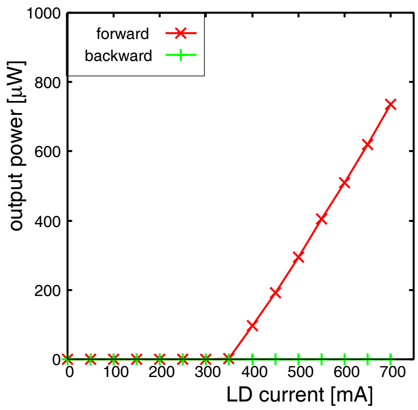

Figure 13: Result of the test experiment. Automatic oscillation starts above LD current 350 mA.

and injected into the beam with 90 degree collision angle. Focusing the laser into a very small spot size of $\sim \mu$m requires a special lens system as shown in Figure 15. It is attached to the vacuum chamber to place it as close as possible to the interaction point. The achievable smallest spot size is determined not only by the diffraction limit but also the aberrations of the optics. Careful designing of the input beam diameter is necessary. An example of the smallest beam profile measured with this system is shown in Figure 16. It demonstrated that the resolution of the monitor is better than 2.9 μm, and stable collision of 300 psec laser and 30 psec beam. For further improvement of spot size, mode quality of the initial laser beam has to be improved.

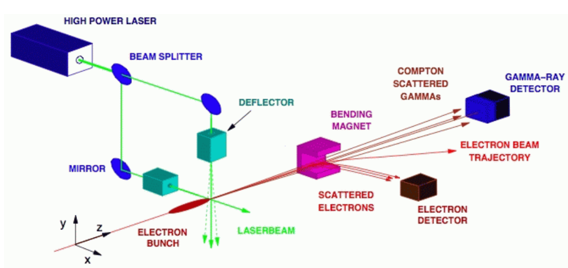

Figure 14: Layout of the pulse laser wire.

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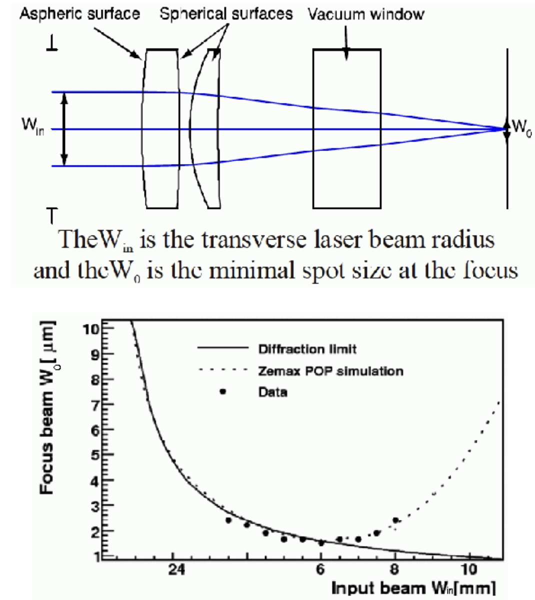

Figure 15: Design and performance of the lens system.

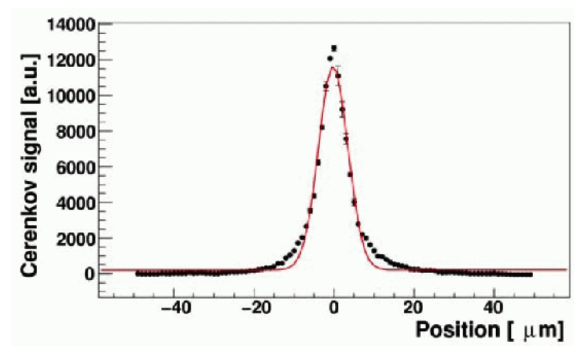

Figure 16: Example of the smallest measured beam profile.

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