PULSED GREEN LASER WIRE SYSTEM FOR EFFECTIVE INVERSE COMPTON SCATTERING*

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Abstract

Laser-Compton scattering has become an important technique for beam diagnostics of the latest accelerators. In order to develop technologies for low emittance beam, an Accelerator Test facility (ATF) was built at KEK. It consists of an electron linac, a damping ring in which beam emittance is reduced and an extraction line. For emittance measurement we developed a new type of beam profile monitor which works on the principle of Compton scattering between electron and laser light. In order to achieve effective collision of photon and electron, very thin size laser is required. Laser wire is one of such a technique to measure a small beam size. With green laser which is converted to second harmonics from IR pulsed laser, minimum beam waist is half of beam waist obtained using IR laser oscillator. Therefore, it is possible to obtain beam waist less than 5 μm (σ value) using green laser pulse, which is required for effective photon-electron collision. First pulsed IR seed laser is amplified with 1.5 meter long PCF based amplifier system. This high power pulsed IR laser is converted to second harmonics with a non-linear crystal. Pulsed green laser is injected inside four mirror resonator to obtain very small beam waist at IP (Interaction Point). Using a pulsed compact laser wire, we can measure 5 μm electron beam in vertical direction. From observed Compton signal profile, bunch length of electron beam is measured 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 pulsed laser wire system. We report the development of high power pulsed green generation and compact four mirror resonator parameters for effective Inverse-Compton scattering in this paper.

KEK-ATF DAMPING RING

Figure 1 shows the ATF-DR layout. The electron source is an RF gun with CsTe cathode driven by a mode-locked UV laser. The electron beam is accelerated to 1.28 GeV.

by the linear accelerator with RF cavity of 2856 MHz. After accelerated to 1.28 GeV, the electron beam is injected to the Damping Ring (DR). RF frequency of the DR is 714 MHz and the revolution frequency is 2.16 MHz.

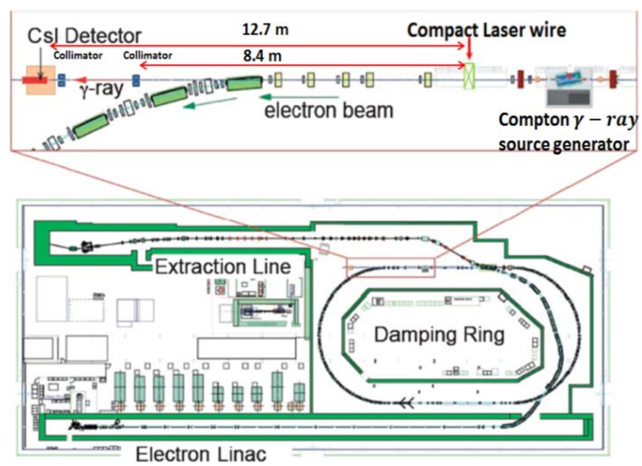

Figure 1: ATF DR layout.

COMPACT FOUR MIRROR CAVITY

The optical cavity assembly consists of four mirrors, mirror holder system and cyilindrical spacers which define length of cavity. In order to have precision control over cavity length, both plane mirror holders were 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 wavelength. Distance between concave-concave mirror is kept at 102.8 mm and distance between plane-plane mirror is kept at 103.2 mm. A complex mirror alignment scheme as shown in fig. 2 and fig. 3 is used to keep side by side distance between plane and concave mirror to 29.2 mm [1]. All mirrors are fixed with angle tilt of 8°. The cavity angle of system which indicates laser pulse crossing angle is 16°. All mirrors used in cavity design are of 1 inch diameter. The radius of curvature for two concave mirror is 101.81 mm.

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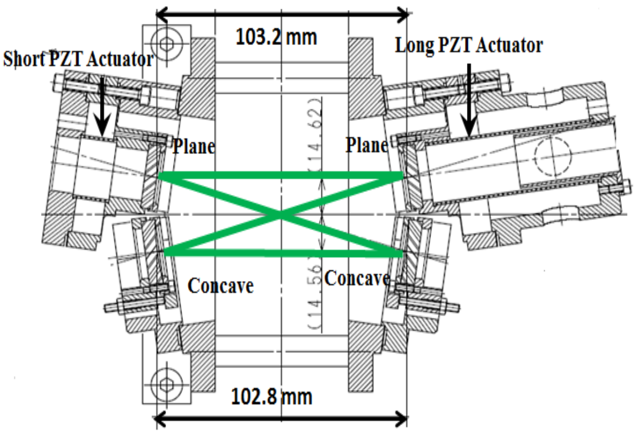

Figure 2: Cavity assemply and its mounting.

Figure 3: Four mirror cavity.

PCF BASED AMPLIFIER SYSTEM

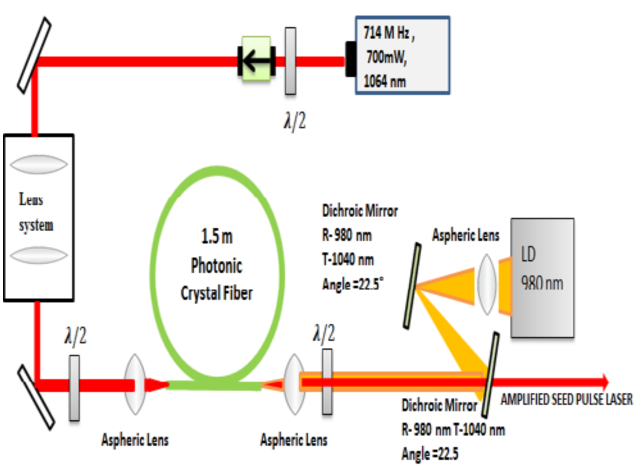

Figure 4: PCF Amplifier system setup.

For construction of system, we utilize 714 MHz mode locked laser as seed laser. The beam is focused to one end of PCF with the help of aspheric lens. At another end of PCF, pump light from laser diode is injected. Laser diode emits beam with wavelength 976 nm and has maximum power of 40 W. Special type of dichroic mirrors are used in this setup which have high reflectivity for 976 nm wavelength and high transmittance for 1064 nm beam [2]. The amplified seed laser and pump light are separated at dichroic mirror as shown in fig. 4. We used 1.5 meter long PCF for this experiment. Seed laser of 450 mW is amplified to 7 W in this setup. Thus total gain factor of 15.5 is achieved in this experiment. Figure 5 shows the amplification of seed laser with pump excitation power inside PCF.

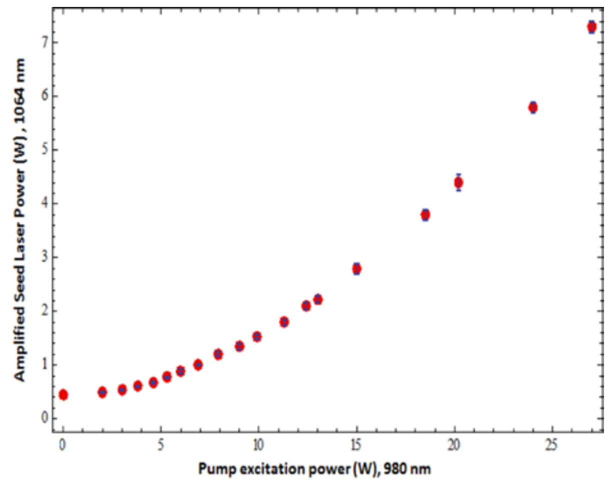

Figure 5: Amplification inside PCF.

PULSE GREEN GENERATION BY SHG

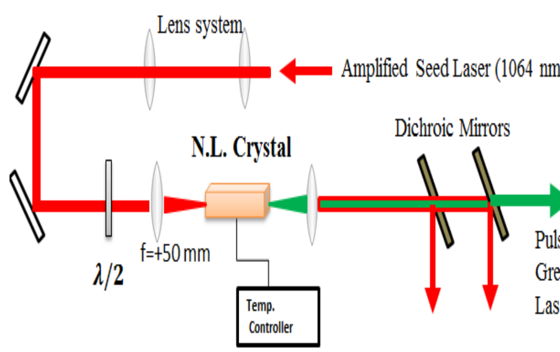

Figure 6: System setup for SHG.

High power pulsed IR laser is converted to second harmonics by 2nd order non-linear crystal. Figure 6 describes the system setup for second harmonics generation (SHG). Amplified seed laser obtained from PCF amplifier system has wavelength of 1064 nm. The first requirement for laser wire project was to obtain high power pulse green laser. Pulsed green laser was needed to achieve very small beam size and fast scanning of electron beam profile. The amplified beam from PCF pass through a half wave polarization plate to control the polarization direction required for SHG. The non-linear crystal has very small thickness so injection beam is sharply focused by using strong focusing lens. Crystal's

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temperature is set by a temperature controller which is connected with peltier device. It is very important to separate first harmonics from second harmonics of converted beam. The second harmonics generation setup is shown in fig. 6. Second harmonics generation efficiency depends on polarization control and operating temperature of crystal. 5 W of amplified seed laser is converted to 1.6 W of pulsed green laser as shown in fig. 7. Thus conversion efficiency of more than 32 % was obtained with non-linear crystal.

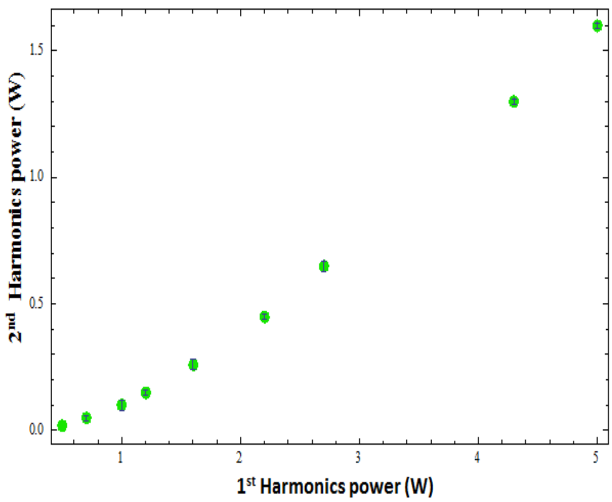

Figure 7: Second harmonics generation.

Generated pulsed green laser is input laser to compact four mirror cavity. Cavity length is scanned by piezo actuator and the resonance of optical cavity is obtained inside four mirror cavity.

POUND-DREVER-HALL FEEDBACK SCHEME

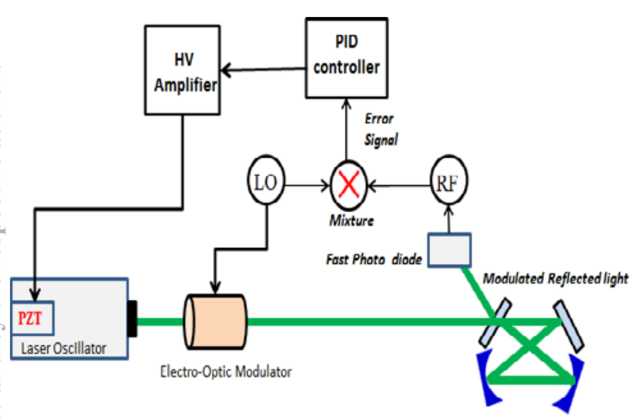

Figure 8: PDH feedback scheme.

Pound–Drever–Hall (PDH) laser frequency stabilization is a powerful technique for improving an existing laser's frequency stability [3, 46]. This arrangement is for locking a cavity to a laser. A phase modulated beam is sent to the cavity and fast photo diode detects the reflected light signal. This output after processing is applied to piezo actuator that controls the length of laser oscillator. The mixer compares the modulation signal of 15 MHz with the output of the fast photodiode, extracting the part that is at the same frequency as the modulation signal. This feedback signal is called error signal. Sending this error signal to the piezo actuator completes the feedback loop and locks the system on resonance as shown in fig. 8. Figure 9 shows error signal generated inside four mirror cavity. Error signal is given to PID controller. Proportional and integral gain of PID controller was tuned so that holding of resonance can be confirmed. PID controller output is given to Notch filter for removing electrical noise by rejecting higher bands of frequencies.

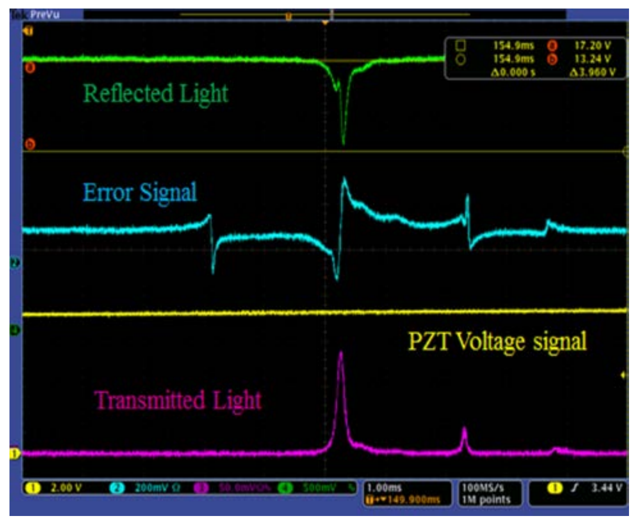

Figure 9: Error signal generation.

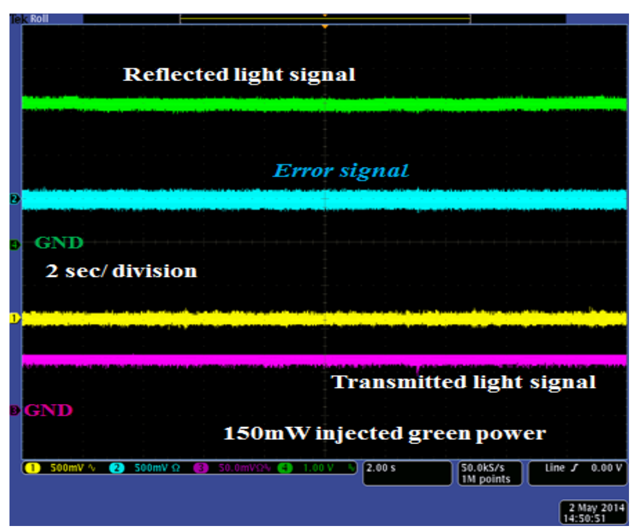

Figure 10: Holding of resonance inside four mirror cavity.

This output is amplified with high voltage amplifier and given to 714 MHz oscillator PZT. Transmitted light

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from four mirror cavity becomes stable and reflected light intensity reduces when cavity is locked. Figure 10 shows holding of resonance inside four mirror cavity with pulsed green laser. Stability of this system was confirmed for more than one hour during electron beam operation. The experiment with electron bunch is performed with 140 mW pulsed green power to the optical cavity.

The following table 1 shows measured values of four mirror optical resonator. The reflectivity of coupling plane mirror is 99.9 %, while the reflectivity of other plane mirror and two concave mirrors are 99.99%. The beam waist at IP is measured with transverse mode difference method [4]. The enhancement factor of 960 is measured at interaction point. The pulsed green power has large fluctuation at higher laser diode current. For stability of feedback, experiment with electron bunch is performed at low pulsed green power.

Table 1: Parameters of Four Mirror Optical Cavity

Parameter	**Measured Value**
Finesse	2315 ± 220
Min. beam waist (σ_s, σ_t)	$7 \pm 2\ \mu m$, $13.4 \pm 3\ \mu m$
Enhancement factor	960
Storage power	17.5 W

ELECTRON BEAM SIZE & VERTICAL EMITTANCE ANALYSIS

The PDH feedback system was turned on to detect Compton signal. The ATF clock of 357 MHz was used during this experiment. Therefore, laser frequency signal of 714 MHz is converted to 357 MHz frequency signal with frequency divider and fed to phase detector. Because of this frequency division, two peaks are observed according to two cycles of laser pulse. Figure 11 show observed counting rate in the detector while changing the relative phase between electron beam and laser pulse with laser turned on. The enhancement of the counting rate was clearly measured at a particular phase which indicated photons from laser-Compton scattering [5]. The maximum Compton signal was observed at horizontal position of -0.0350 mm and vertical position of -1.164 mm. The vertical axis of 2-D scattered plot shows deposition of energy at detector which is read by ADC in terms of counts. The counts read by ADC is converted into energy deposited in MeV at detector. The horizontal axis shows phase in radians between electron bunch and laser pulse during collision experiment. We first obtain histogram plots of all verical scan position.

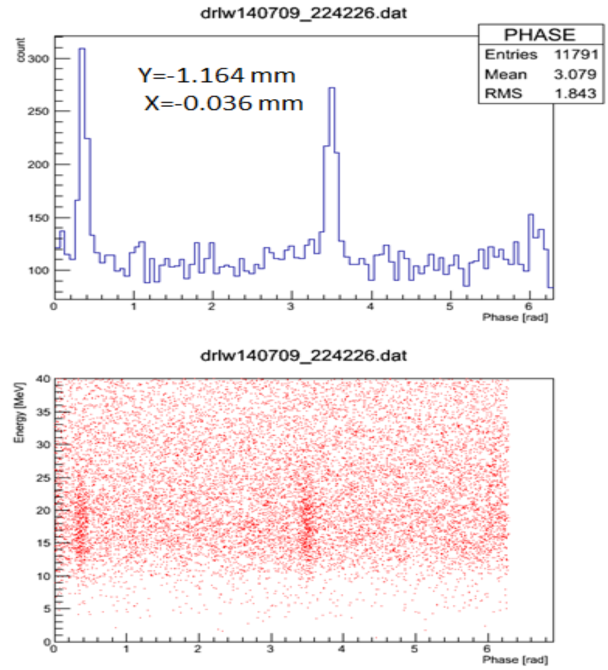

Figure 11: Compton signal observation.

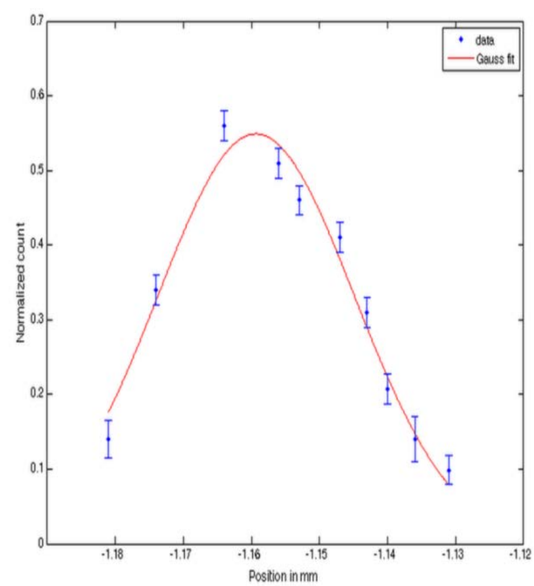

Figure 12: Normalized count with vertical scam position.

We calculate normalized count for all scan position as ratio of average peak count to average background level. The maximum S/N ratio is observed at -1.164 mm vertical scan position which is 0.56 ± 0.02. Similarly, we can calculate normalized count of other vertical scan positions with small error Figure 12 shows vertical scan result. All data of scan results are fitted to Gaussian function. The sigma value of observed Gaussian function is calculated as $14.4 \pm 1.3\ \mu m$, which is convolution of laser beam size and electron beam size. In particular, if

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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

$$\sigma_{obs}^2 = \sigma_{lw}^2 + \sigma_e^2 \qquad (1)$$

The laser wire beam waist is measured as $7\pm2\ \mu m$ using transverse mode difference method. The electron beam size can be determined as

$$\sigma_e = 12.6\pm 1.8\ \mu m.$$

We can estimate vertical emittance of beam with collected data. The beam size is basically given by equation

$$\sigma_y = \sqrt{\beta_y \epsilon_y} \qquad (2)$$

, where β_y is vertical β function at interaction point. Vertical β function at interaction point is 6.58 m. The vertical emittance value is calculated as 24.1 $\pm$6.8 pm-rad.

BUNCH LENGTH MEASUREMENT

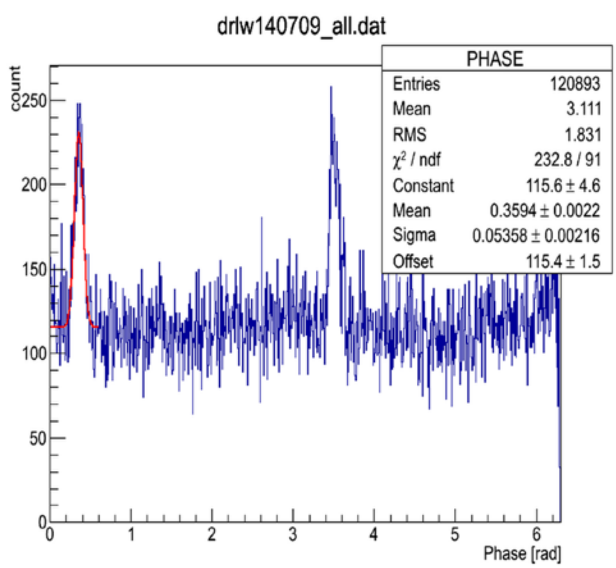

Figure 13: Gaussian fit on sum of all histogram data.

In order to measure bunch length of electron beam, we consider sum of all histogram data which are corresponding to particular vertical scan positions. The purpose is to estimate accuracy of phase measurement during our experiment. We can evaluate width of distribution for two peaks by Gaussian fitting as shown in fig. 13. We can calculate bunch length of electron beam by relative phase difference information. The laser pulse timing corresponds to mean value of the Gaussian distribution to the time of the maximum counting rate. Average value of bunch length was the convolution of the longitudinal length of the laser pulse ($\sigma = 3\ ps$) and electron bunch. Therefore, bunch length of electron beam can be calculated as

$$\sigma_z\ (ps) = \sqrt{23.5^2 - 3^2} = 23.3 \pm 0.7 \text{ ps.}$$

CONCLUSION

The longitudinal bunch length and vertical size of electron beam can be measured with relative phase difference measurement between electron bunch and laser pulse without frequency locking of laser pulse and electron RF frequency. This compact laser wire system can be used to store pulsed green power with small waist size.

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