氏　　　　　名	RAWANKAR ARPIT
学位(専攻分野)	博士(工学)
学 位 記 番 号	総研大甲第 1710 号
学位授与の日付	平成26年9月29日
学位授与の要件	高エネルギー加速器科学研究科　加速器科学専攻 学位規則第6条第1項該当
学 位 論 文 題 目	Development on Pulsed Laser Wire for Measurement of Beam Profile
論 文 審 査 委 員	主　査　　准教授　阪井　寛志 教授　浦川　順治 教授　小川　雄二郎 准教授　照沼　信浩 助教　奥木　敏行 教授　鷲尾　方一　早稲田大学

(別紙様式 2)
(Separate Form 2)

論文内容の要旨
Summary of thesis contents

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 $\sigma_{obs}^2=\sigma_{lw}^2+\sigma_e^2$ .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 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 as λ laser wavelength, a laser oscillation cavity length of L_{laser} and optical cavity length as L_{cav}

$$L_{\text{cav}} = n\,\lambda \quad (n : \text{integer})$$
$$m\,L_{\text{cav}} = L_{\text{laser}}\ (m: \text{integer})$$

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 cylindrical 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 wavelength. Distance between concave-concave mirror is kept at 102.8±0.1 mm and distance between plane-plane mirror is kept at 103.2 ±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 proportional to wavelength 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 initial 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 (δθ) of Airy function. FSR is distance between peaks of two consecutive 0_{th} order modes. Measured Finesse with laser wire system is 2315±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 kHz/mA. Background level is measured in the range of 11±1 kHz. From observed Compton signal profile, bunch length of electron beam is calculated as 23.3±0.7 ps. Electron beam size in vertical plane is measured as 12.6±1.6 μ and vertical emittance is measured as 24.1±6.1 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.

(別紙様式 3)
(Separate Form 3)

博士論文の審査結果の要旨

Summary of the results of the doctoral thesis screening

リニアコライダーに必要なビームエミッタンスはDamping ringの放射冷却により実現され、特に垂直方向は10pm rad以下にする必要がある。そのビームエミッタンスの測定、すなわちリング内の垂直ビームサイズ直接測定のために、氏はpulseビームをレーザー共振器に共鳴し、レーザーと電子のCompton scatteringの定量的な計算を行った。その結果、測定時間として、従来では10分程度測定時間が必要なCW laser wireに比べ、数秒でのscanにて測定を可能にするlaser wire systemを本論文内にて提案した。氏の提案の特徴として、ビームサイズ(10μm)より小さなpulse beamのlaser waist size(σ value)の実現のため、Damping ringのRF周波数と同期した714MHzの周期の共鳴条件の実現は従来の2枚ミラーでは困難であること、また、5μm程度のbeam sizeを目指す設計では2枚ミラーの共振器のalignmentが厳しいことから、4枚ミラーを用いた新たなlaser wire systemを提唱し、計算上5μm程度のlaser waist sizeが生成可能であることを提唱した。これらを実現するために、氏はlaser wireの心臓部である10cm長の高反射率の４枚ミラー光共振器を一から設計し、10psのパルスレーザー(波長：1064nm)を使ったテストベンチで設計の評価を行った後に、5μm程度のlaser beam waist実現に欠かせないGreen laser(波長：532nm)にてDamping ringのRF周波数と同期した714MHzの周期でgreen pulse laser蓄積を実現した。電子ビームサイズより小さな7±1μm程度のlaser waist sizeを実現し、pulse型 laser wire systemの共振器内でレーザーwaistが設計に近いサイズを実現できること、その共振器内の増幅率1000倍程度得られていることを確認した。入射レーザーの強度の増強のため、氏は自ら1064nmのmode lockレーザーからの450mWの出力をphotonic fiberを用い、7Wまで増幅、その後、SHGによる波長変換の高効率化、特に変換結晶の温度安定化を行うことで、1.6Wの大強度green laserの安定な出力を可能とした。さらにEO変換器によるfast feedbackおよび空洞共振器のミラーをコントロールするピエゾによるslow feedbackにより、ATF damping ring北直線部内にインストールされた状態で、フィネス2000程度の４枚ミラー共振器の共鳴状態を１時間以上も安定保持しながら共振器内にpulse laser wireを実現した。博士論文の7章に、レーザーと電子の衝突実験について具体的に述べている。Lase wire system全体は1μmの精度の精密移動架台にて、laser wireを電子ビームに対してスキャンした。γ線検出器はCsI pureシンチレータ付PMTを用い、宇宙線でエネルギー校正を行った後にCompton γ線の検出を行った。データ取得の方法として、パルスレーザーでのS/N比の改善を生かすべく、ringのRF周波数に対し、レーザーの共鳴周波数の位相を360度スキャンすることで、S/N比が大きくなる測定を試みると同時にこのスキャンから新たにバンチ長の測定も行い、laser wireの新たな可能性を示した。残念ながら、強度の強いレーザーではfeedbackが安定に働かず、共振器内強度はCW換算にて17.5Wであったが、pulseレーザーの特性を生かし、S/N比0.5程度とCWに比べ、1オーダー以上の改善を見た。これにより、12.6±1.6μmのATF damping ringの垂直ビームサイズ測定を実現し、新たな４枚ミラーでのpulse laser wireによるビーム計測が今後大きく期待できることを示した。ここまでが本論文の要旨である。

論文審査では４枚ミラーの pulse laser wire system の全体について、設計方針、測定方法、評価への審査員の質問、さらに信号量の定量性に Background data を用いていることから氏の信号の評価に対する質問等を行ったが、氏は論文内容にそって、生データからの解析手順と定量的な解析結果の説明を行い、最終的に測定の妥当性を示した。以上により、研

(別紙様式 3)
(Separate Form 3)
究のまとめ方にも一定の能力を有していると判断した。本審査をもって、総合研究大学院大学の博士論文として合格と判断する。