

HIGH REPETITION RATE ENERGY MODULATOR SYSTEM UTILIZING A LASER ENHANCEMENT CAVITY *

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Abstract

In order to realize a high repetition rate seeded coherent radiation source, it is necessary to develop a seeding system which works in a continuous mode. Utilizing the longitudinal electric field in a higher transverse mode laser stored in an optical cavity, it is possible to introduce an energy modulation in an electron bunch. Through acceleration and dispersion handling, the modulation at laser wavelength can be converted into a finer density structure. It can be used as a seed of coherent radiation. We are developing a laser system to be used in the laser modulator system.

INTRODUCTION

Recent linear accelerators can realize an electron beam of high brightness and small energy spread. Based on such a high quality electron beam, SASE FEL has been realized and it has been provided as an user machine at various laboratories. At the next stage, temporal coherence and high averaged power are expected as additional characteristics to be developed. For temporal coherence, seeding scheme can be used. And for high averaged power, multiple bunch operation and/or energy recovery scheme with a superconducting cw accelerator can be used. But in order to realize the two items at the same time, a seeding system which can work at high repetition rate is necessary. Usually, seeding is done with a high peak power laser system which can work only at a low repetition rate. Here, we propose an optical cavity system which can realize a high enough electric field at ~100 MHz repetition of continuous operation. This can be used to directly modulate electron beam energy in the scale of optical wavelength. Combining the laser modulation with the bunch compression in the following stage, it can seed shorter wavelength radiation.

ACCELERATION BY AN ELECTRIC FIELD OF LASER

We would like to use an electric field of a laser for electron beam acceleration [1] [2]. Usually, it is not possible because the electric field of a plane wave is in transverse direction. Here we think a TM-wave laser beam which transfers in z -direction. The electric field is mainly in x -direction, and the magnetic field is zero in z -direction. Directly from Maxwell's equation, the following relation,

$$ikE_z = \frac{\partial E_x}{\partial x} \quad (1)$$

is obtained. Variation of transverse electric field results in a longitudinal electric field. Transferring an electron beam

along with the laser beam, the longitudinal component of the field can accelerate or decelerate the electron beam. It introduces energy modulation in the period of laser wavelength.

A higher order transverse mode, TEM₁₀-mode, is one of such a laser beam. The field profile is shown in Fig. 1. Its transverse field varies and zero-crosses at the center area of the profile. It means there is a longitudinal field at the center.

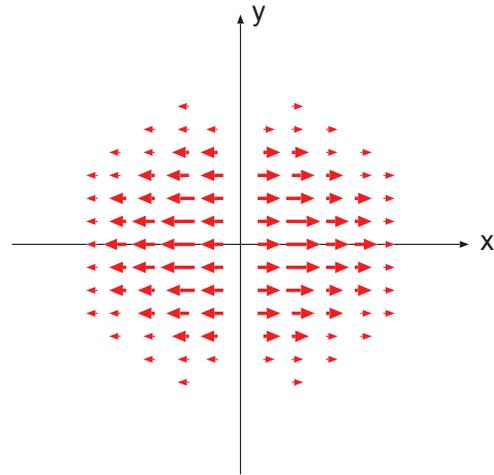


Figure 1: Profile of the higher transverse mode laser.

The x -component of the electric field can be written as,

$$E_{10}^x = A \cdot x \exp\left(-\frac{x^2}{\omega^2}\right) \exp(i(\omega t - kz + 2\phi(z))). \quad (2)$$

where $\phi(z)$ is Gouy phase, $\phi(z) = \tan^{-1}\left(\frac{z}{z_0}\right)$, z_0 is Rayleigh length ($z_0 = \frac{\pi w_0^2}{\lambda}$). Simplifying this, the transverse electric field E_x is

$$E_x = x e^{-x^2}. \quad (3)$$

And the longitudinal electric field E_z is

$$E_z = \frac{(1 - 2x^2)e^{-x^2}}{k}. \quad (4)$$

These are shown in Fig. 2.

It can be written using laser power P as,

$$E_z = \frac{1}{2z_0} \sqrt{\frac{P}{c\epsilon_0}}. \quad (5)$$

Laser beam diverges and the phase shifts in the distance of z_0 . So, the effective accelerating distance is $2z_0$. Energy gain G is then,

$$G = E_z \times 2z_0 = e \sqrt{\frac{P}{c\epsilon_0}}. \quad (6)$$

* Work supported by KAKENHI

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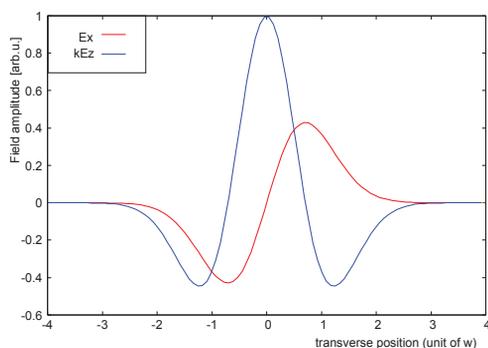


Figure 2: Transverse and Longitudinal field distribution of TEM₁₀ mode.

This does not depend on z_0 and laser spot size w_0 .

For example, at 1 MW of laser peak power, G is estimated to be 20 keV. This seems to be strong enough to introduce an energy modulation comparable with the original energy spread for 100 MeV class electron beam.

Recently, a high averaged power laser beam of 100 kW has been realized inside an optical enhancement cavity [3]. Such a development is done mainly for the photon target of laser Compton scattering sources (LCSS) [4]. Assuming a mode-locked laser pulse of ~ 10 ps duration to be stored in a ~ 100 MHz cavity at an average power of 100 kW, the peak power exceeds 10 MW. Excitation of the higher order transverse mode is also a proven technique. The finer spatial structure of the TEM₀₁ mode than that of the lowest gaussian mode has been used for measuring a small beam size of a low emittance storage ring [5].

Schematic setup of the laser modulator is shown in Fig. 3. An enhancement cavity is excited by a TEM₁₀-like beam, which is converted from a gaussian laser beam. The electron beam goes along the laser pulse inside the cavity in the same direction. It is then accelerated/decelerated by the longitudinal electric field of the laser, results in an energy modulation at the period of laser wavelength.

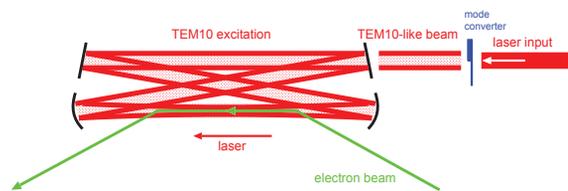


Figure 3: Schematic setup of the laser energy modulator.

REALIZATION OF A DENSITY MODULATION

A test accelerator for an energy recovery linac has been constructed and commissioned at KEK. It can be upgraded to be a 200 MeV class two-loop system in a future. Here, we assume the laser energy modulator system with the future plan. Our target is to realize ~ 30 nm scale of micro-structure

which can work as a seed of coherent radiation at an undulator.

Figure 4 shows the layout. The laser modulator cavity is installed in the inner loop. At the first turn of the inner loop, the laser field introduces an energy modulation at laser wavelength in the electron bunch. The distribution of longitudinal phase space can be controlled in the following beam line. First, at the return arc of the inner loop, by controlling the dispersion $R_{56}^{(1)}$, the phase space is stretched as shown in Fig. 5. This is for realizing density modulation after the following bunch compression. The second turn at the accelerator section is at an off-crest phase to introduce an energy chirp in the whole bunch. Then, the bunch is compressed using the dispersion at the arc of the outer loop $R_{56}^{(2)}$. By controlling the two dispersion parameters, $R_{56}^{(1)}$ and $R_{56}^{(2)}$, the imprinted energy modulation by the laser can be realized as a compressed density modulation at the final point.

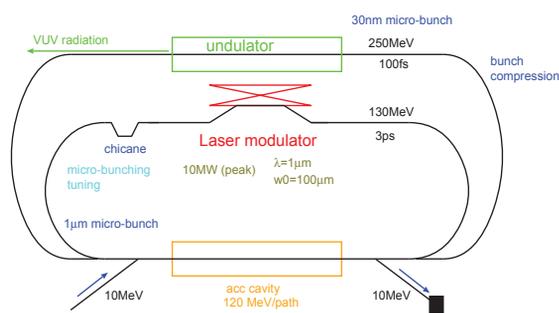


Figure 4: Layout at 2-loop ERL scheme.

Figure 5 shows an example one dimensional calculation. The laser wavelength is $1 \mu\text{m}$ and introduced energy modulation is $\Delta\gamma/\gamma = 1 \times 10^{-4}$. The accelerator RF frequency is 1.3 GHz, the energy gain is 130 MeV/path. The off-crest acceleration phase at the 2nd path is at 30 degree. It is shown that the modulated phase space distribution is stretched at first, then is recovered as a compressed density modulation. In this case, a factor 5 smaller structure than the initial laser wavelength is obtained.

Trying to have a finer structure, Fig. 6 shows the case of a factor 9 compression. Due to the non-linearity of the accelerator RF curve, it shows that a roundness remains in the final distribution, and it limits realization of a clear density modulation. One possible idea for realizing a finer structure is the EEHG scheme, which uses 2 stages of laser modulator as shown in Fig. 7. It can produce 20 nm scale structures in the bunch (Fig. 8).

DEVELOPMENT OF A LASER MODULATOR

We have been developing the laser modulator system. It stores a ~ 10 MW peak power in a ~ 100 MHz repetition enhancement cavity. We used to develop a system with a Nd based laser of 10 ps duration. Recently, we started a test with a Yb based laser of wider band width which is possible to have a shorter pulse and have an advantage to

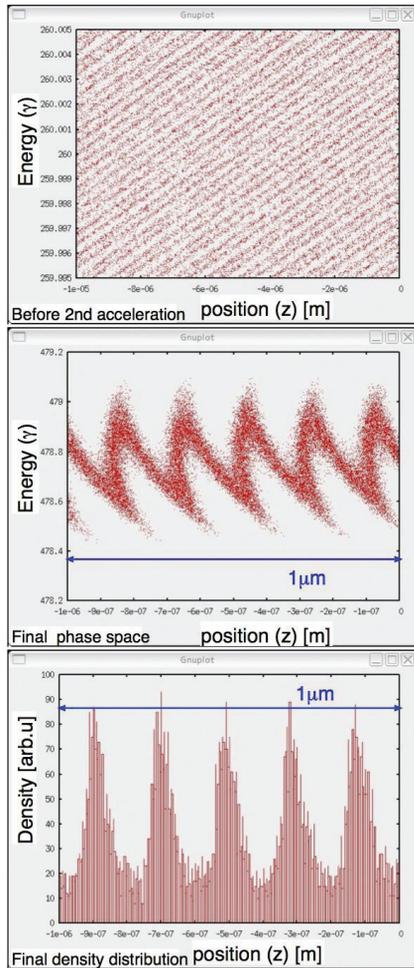


Figure 5: Longitudinal phase space (compression 1/5).

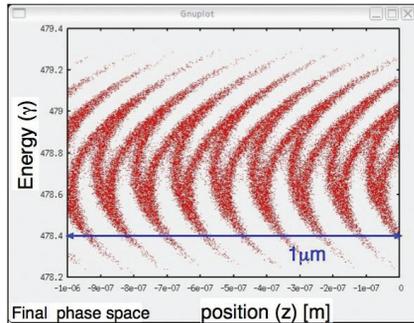


Figure 6: Longitudinal phase space (compression 1/9).

save the average power while keeping the peak power. As a first step, we made a low power test bench to test basic characteristics of the Yb based system. Figure 9 shows the Yb fiber laser oscillator used in this test. It is based on the non-linear polarization rotation mode-lock system. It also include a saturable absorption semiconductor mirror as a self-starter, and an EO modulator for fast controlling cavity resonance condition. The repetition rate is 38 MHz, and the RMS pulse duration is 120 fs.

It is known that one important problem to store a wide band laser in an enhancement cavity is carrier envelope

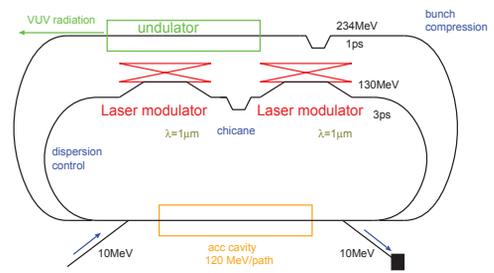


Figure 7: Layout of 2-stage system

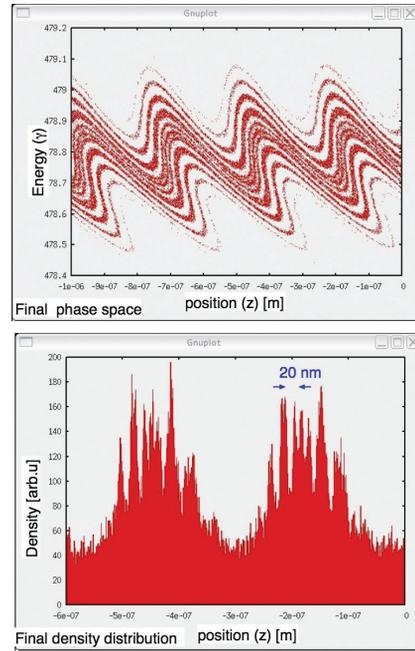


Figure 8: Longitudinal phase space of 2 stage system.

phase offset (CEO). It is the optical phase difference between pulses. When stacking many pulses in an optical cavity, they can not be stacked constructively if there is a finite CEO. It limits the enhancement gain. The effect can be seen when measuring resonance peaks of the cavity while scanning the cavity length as schematically shown in Fig. 10. In the case of zero CEO, the resonance peaks appears symmetrically

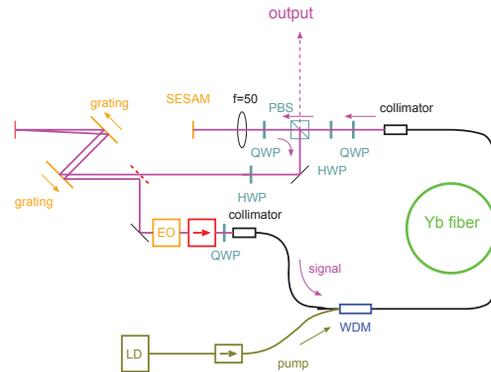


Figure 9: Schematics of the Yb fiber mode-lock oscillator.

and there is the maximum peak which can resonate in a good efficiency. But if there is a finite CEO, the structure becomes asymmetric and the efficiency drops from the ideal case. The efficiency drops considerably in the case of high enhancement gain.

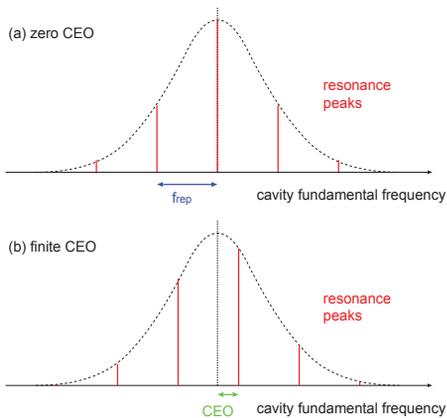


Figure 10: Effect of CEO in the structure of cavity resonances.

One way to control the CEO is to shift the laser wavelength with an Acousto-Optic modulator. The setup is shown in Fig. 11. AOM is used in a double-path layout. By controlling the driving RF frequency, it changes the laser wavelength keeping the repetition rate. It corresponds to giving an optical phase shift in the frequency domain. An experimental result with a test cavity setup of Fig. 12 is shown in Fig. 13. The Yb mode-locked laser pulse first goes through the AOM system, and then injected to the 4-mirror optical cavity of 78 MHz. The transmission signal of one of the mirrors is measured with a photo-diode while sweeping the cavity length. By adjusting the driving frequency of the AOM, the structure of resonance peaks can be controlled. This test shows that there is a simple way to control CEO when we try to use Yb based laser in a high enhancement gain cavity. Our next test item is to dynamically keep the CEO in a long period with a much higher enhancement gain.

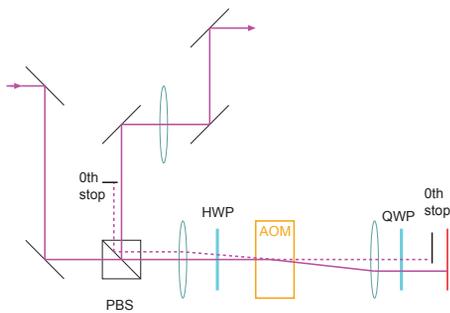


Figure 11: Setup of AOM.

SUMMARY

We propose to use a longitudinal field of a higher transverse mode laser to introduce an energy modulation for

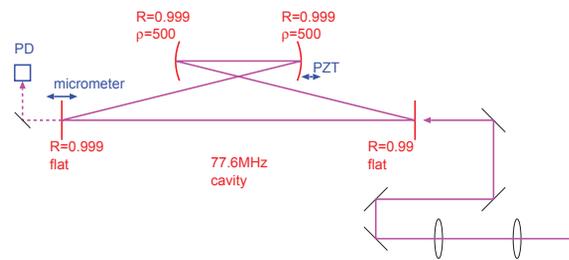


Figure 12: Setup of the enhancement cavity used in this test.

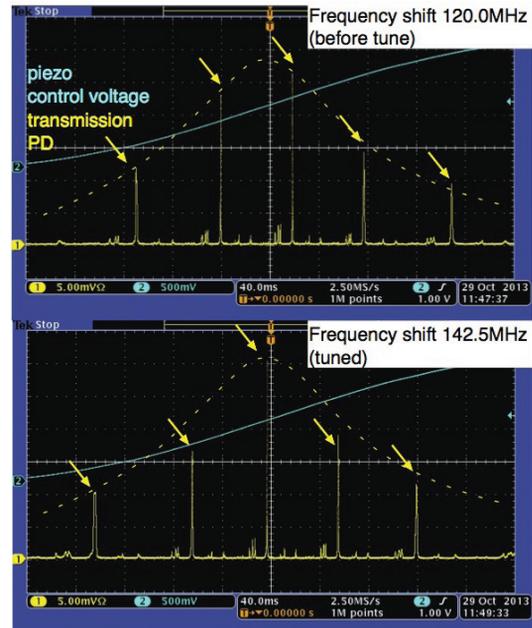


Figure 13: Experimental result of CEO control.

seeded coherent radiation. Combining with a bunch compression scheme, it can realize a finer density structure than the initial wavelength. Applying the optical cavity technique, it is possible to develop a system which works at continuous or multiple bunch operation.

We have started a basic experimental test on the laser system of the enhancement cavity.

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