

ENHANCEMENT OF LASER POWER FROM A MODE LOCK LASER WITH AN OPTICAL CAVITY

M. Nomura[#], K. Hirano, M. Takano, NIRS, Chiba, Japan
 S. Araki, Y. Higashi, T. Taniguchi, J. Urakawa, Y. Yamazaki, KEK, Tukuba, Japan
 Y. Honda, N. Sasao, K. Takezawa, Kyoto University, Kyoto, Japan
 H. Sakai, University of Tokyo, Chiba, Japan

Abstract

We have a plan to produce a high-flux x-ray via the Compton scattering of an electron beam with a high intensity pulsed laser beam which is realized in a Fabry-Perot optical cavity externally excited by a pulsed laser. Dispersive phase shift may be a serious issue for stacking laser pulses in a high finesse optical cavity. The optical cavity was formed by a couple of concave mirrors with 99.9% reflectivity. We measured the power reflection from an optical cavity as a function of the cavity length. The experimental result shows a small asymmetry in the structure of longitudinal mode excitation suggesting the dispersion effect.

INTRODUCTION

We plan to produce a high flux x-ray for medical uses [1]. Fig. 1 shows the conceptual design of the x-ray source. The x-ray is produced from the inverse Compton scattering of electrons in a storage ring with the laser pulse in an optical cavity. Laser pulses from a mode-locked laser are coherently stacked inside of the cavity, realizes a high intensity photon target. We have been developing the high finesse optical cavity to be used in this project.

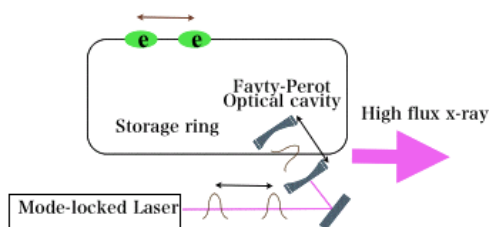


Figure 1: Conceptual design of the high flux x-ray source.

The technique to store a laser light from a CW laser in an optical cavity has been utilized in the field of particle accelerators [2]. Replacing the CW laser with a mode-locked pulse laser, the laser power can be concentrated within a short period equivalent to the electron bunch length. If the repetition period of the laser pulse coincides with the bunch spacing of the electron beam, the interaction efficiency of the laser and the electron can be maximized. This scheme enables an improvement of two orders of magnitude in the x-ray flux with respect to the case of a CW laser of same power.

At the first stage of the development, we have done a test experiment of stacking laser pulses from the mode-

locked laser in a Fabry-Perot optical cavity formed by mirrors with 99.7% reflectivity. We have succeeded in achieving an enhancement factor of 230 times and the stored power of 690 W [3].

At the next stage, we upgraded the reflectance of the cavity mirrors to 99.9%. The power reflection from the optical cavity was measured as a function of the cavity length (ΔL : the difference of cavity lengths between the one in the laser oscillator and the external cavity).

First, we describe the principle of storage of laser pulses from a mode-locked laser and then explain the setup of the experiment. Discussion about the experimental results is given at the last section.

PRINCIPLE OF STACKING LASER PULSES FROM A PULSED LASER

Coherent storage of a laser light in an external optical cavity has been commonly used with a CW laser beam. In the CW laser case, the relationship between the length of the external cavity (L_{cav}) and the laser wave length λ which depends on the cavity length of the laser oscillator (L_{laser}) must satisfy eq. (1) to make the external cavity be resonating.

$$L_{cav} = n \cdot \frac{\lambda}{2}, \quad n: \text{interger.} \quad (1)$$

We call this relation as resonance condition (or call the cavity as being on resonance).

In the case of a pulsed laser, Fig. 2 schematically explains the optical paths in which the injected laser pulses experience. From the coherent superposition of these optical paths and integrations along Z axis, the reflected, transmitted and stored laser power on resonance can be calculated.

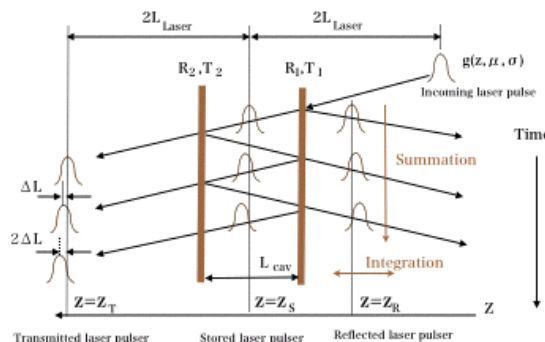


Figure 2: Schematic diagram of laser pulses injected into an optical cavity.

The reflectivity R_{cav} , transmissivity T_{cav} and enhancement factor S_{cav} of the optical cavity on the

[#]manomura@popsvr.tokai.jaeri.go.jp

resonance condition can be expressed as eq. (2) ~ (4), respectively.

$$R_{cav} = \int \left[\sqrt{R_1} \sqrt{g(z, z_R, \sigma)} - T_1 \sqrt{R_2} \sum_{n=1}^{\infty} \left(\sqrt{R_1 R_2} \right)^{n-1} \sqrt{g(z, z_R + (2 \cdot \Delta l + 2 \cdot \delta_{cav} + \delta_{laser}) \cdot n, \sigma)} \right]^2 dz / P_0, \quad (2)$$

$$T_{cav} = T_1 T_2 \int \left[\sum_{n=0}^{\infty} \left(\sqrt{R_1 R_2} \right)^n \sqrt{g(z, z_T + (2 \cdot \Delta l + 2 \cdot \delta_{cav} + \delta_{laser}) \cdot n, \sigma)} \right]^2 dz / P_0, \quad (3)$$

$$S_{cav} = \frac{T_1(1+R_2)}{2} \int \left[\sum_{n=0}^{\infty} \left(\sqrt{R_1 R_2} \right)^n \sqrt{g(z, z_S + (2 \cdot \Delta l + 2 \cdot \delta_{cav} + \delta_{laser}) \cdot n, \sigma)} \right]^2 dz / P_0, \quad (4)$$

$$P_0 = \int g(z, \mu, \sigma) dz, \quad (5)$$

where Z_R , Z_T and Z_S are shown in Fig. 2 and δ_{cav} and δ_{laser} are the position shifts caused by the dispersive phase shift of the optical cavity and the laser cavity, respectively. R_i and T_i denote the mirror's reflectivity and transmissivity, the suffix i indicates the entrance ($i=1$) and exit ($i=2$) mirrors. P_0 is the power of the incoming laser pulse. We approximate the laser pulse envelope by a Gaussian shape $g(z, \mu, \sigma)$. μ is the position of the bunch centre on Z axis and σ is the laser pulse width.

It is clear from eq. (2) ~ (4) that R_{cav} , T_{cav} and S_{cav} depend on Δl , δ_{cav} and δ_{laser} . These terms dilute the overlap of the laser pulse envelopes at the every round-trip and make the R_{cav} be increased and the T_{cav} and S_{cav} be decreased. In order to store the laser pulses efficiently, these terms must be reduced as small as possible. The $\Delta l = 0$ means that the optical cavity round-trip time matches with the laser pulse repetition period.

In frequency domain picture, the pulse from a mode-locked laser can be expressed as a summation of many CW laser lights which differ from each other by $c/(2L_{laser})$ in frequency, where c is the speed of light. In order to store the laser pulses efficiently, the resonance conditions for those all CW laser lights have to be satisfied. This means all laser frequency modes must coincide with the longitudinal modes of the external cavity (See Fig. 3.). If some of the modes do not match completely, for example due to the dispersion, the laser pulse in the optical cavity can be broadened and the efficiency of the storage becomes worse.

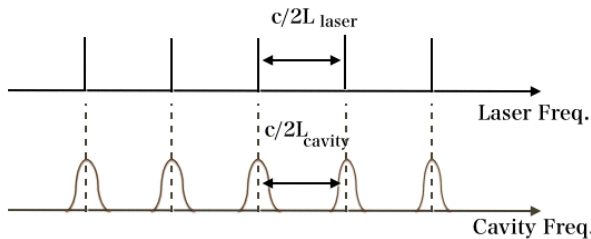


Figure 3: Frequency domain picture.

EXPERIMENT SETUP

In this section, we describe a laser system, a Fabry-Perot optical cavity and a total optical system. The laser is a passively mode-locked laser using a semiconductor saturable absorber mirror (SESAM). The specifications of the laser are listed in Table 1. The mode-locked laser has a piezoelectric transducer (PZT) to finely control its pulse repetition rate. We scanned this PZT to observe the longitudinal mode excitation of the external cavity.

Table 1: Laser specifications

Mode Lock:	Passive type (SESAM)
Repetition R:	357MHz
Pulse width :	7.3psec (FWHM)
Wave Length :	1064 nm
Power P:	~ 6W

A 42cm long Fabry-Perot optical cavity supported by a cylindrical block of super-invar is designed for this experiment. The picture of the optical cavity and its specifications are shown in Fig. 4 and Table 2, respectively. The cavity length is designed to make the free spectral range (FSR) be coincided with the repetition rate of the mode-locked laser (357-MHz). The beam waist calculated from the cavity length and the mirror curvature is 180 μm and the beam diameter on the mirrors is 440 μm . Two multi-layer dielectric mirrors with a reflectivity of 99.9% for 1064 nm wavelength were coated at the same time to have same optical properties.

Table 2: Optical cavity specifications

Cavity	Super Invar
Cavity Length	0.42 m
Mirror Reflectivity	99.9%
Mirror curvature radius	250 mm



Figure 4: Picture of the optical cavity.

The optical layout is depicted in Fig. 5. The laser output of the mode-locked laser is transported using four mirrors and fed into the Fabry-Perot optical cavity through a set of concave and convex lens. The laser power was adjusted with half wave plate and polarized beam splitter 1 (PBS1). During this experiment, the laser output power was reduced down to $\sim 25\text{mW}$ for safety. The set of concave and convex lens matches the laser beam to the fundamental transverse mode of the optical cavity.

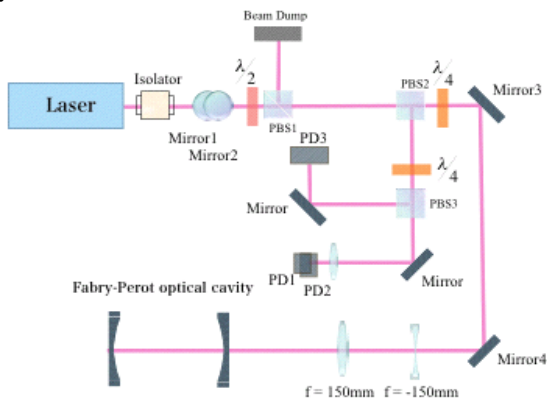


Figure 5: Optical layout.

EXPERIMENTAL RESULT

To observe the structure of the longitudinal mode excitation, we measured the reflected power from the optical cavity while scanning the PZT controlling the cavity length of the laser oscillator. Fig. 6 shows the result. There are sharp spikes in the reflected power, which represent the resonance of the external cavity. The distance between spikes corresponds to the FSR of the cavity. From eq. (2), it is easy to be understood that Δl is minimized at the peak of the largest spike. The peak-height distribution of the five spikes seen in Fig.6 has a small asymmetry around the central peak. We have not observed this kind of asymmetry with the use of mirrors with reflectivity of less than 99.7%. It seems that high reflectance mirrors increased the number of summation of laser pulses in Fig. 2 so that the δ_{cav} and δ_{laser} becomes affecting the superposition of the pulses. Usually, the dispersion effect of the passive optical cavity is almost

negligible for pico-second pulses ([4]), so that the asymmetry seems to be originated mainly from δ_{laser} .

The minimum R_{cav} in Fig. 6 was still smaller than 10%, 90% of the injected power could be stored in the cavity. Therefore, the dispersion effect doesn't affect the stored power strongly in this measurement. But when we use mirrors with reflectivity of higher than 99.9% aiming to increase the stored power, the stored power might be restricted by this effect. Stabilization of the carrier and the repetition frequency of the mode-locked laser, which was studied in [5], might be needed in the future.

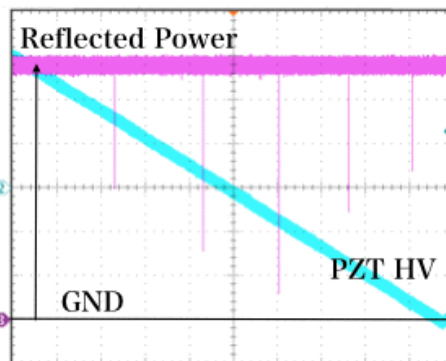


Figure 6: The reflected power from the optical cavity while sweeping the PZT in the laser oscillator.

SUMMARY

We measured the reflected power from the optical cavity formed by mirrors with 99.9% reflectivity as a function of Δl . We observed a small asymmetry in the amount of longitudinal mode excitation. It might be caused by the dispersive phase shift of the laser pulses. The effect on the efficiency of the power storage was still not so strong for the optical cavity used in this experiment. But aiming to develop an optical cavity of higher enhancement factor, it can be a serious issue in the future.

ACKNOWLEDGEMENTS

We would like to express our gratitude to all members of KEK-ATF group for their helpful support. This research was supported by the budget for Advanced Compact Accelerator Project of National Institute of Radiological Sciences and Grant-in-Aid Scientific Research (1344078) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

REFERENCES

- [1] J.Urakawa et al. proceedings Cool03.
- [2] H.Sakai et al. J. J. Appl. Phys 41 (2002) 6398.
- [3] In preparation.
- [4] R. J. Jones and Jun Ye, Opt. Lett. 27, 1848 (2002)
- [5] R.J.Jones et al. Phys. Rev. Lett. 86,3288(2001)