LASER RECYCLER USING AN ASYMMETRICAL CON-FOCAL CAVITY

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Abstract

Usefulness of an asymmetrical con-focal cavity as a laser recycler was examined. It was shown by calculation and experiment that a Gaussian laser beam can be recycled about thirty times at the con-focal point when the laser beam is injected in parallel with the cavity axis and it forms a waist at the plane including the con-focal point and perpendicular to the cavity axis.

INTRODUCTION

When we utilize the laser beam for charge-exchange of high energy ion beams, ion beams are often pulsed with a repetition rate of hundreds MHz. Ordinarily each ion beam pulse needs a laser pulse of significantly high pulse energy and the necessary average laser power becomes very high. Moreover, in the collision, although ion beam pulse is charge-exchanged to an intended fraction, laser pulse usually remains almost unchanged both in the pulse energy and in the spatial and temporal pulse profile. Therefore, it is desirable if laser pulses once used are repeatedly recycled at the same collision point.

ASYMMETRICAL CON-FOCAL CAVITY AS A LASER RECYCLER

Let us consider such an optical system, as is shown in Fig. 1, which consists of two concave mirrors with different radius of curvature arranged for both axes and focal points to coincide. The focal length of the mirror 1 (or 2) is $f_1 = \rho_1 /2$ (or $f_2 = \rho_2/2$). We call the con-focal point as a, the points at which laser beams pass the plane containing the con-focal point and perpendicular to the axis as c_n, and the points on the mirror 1 and 2 at which laser beams are reflected as d_n and b_n, respectively.

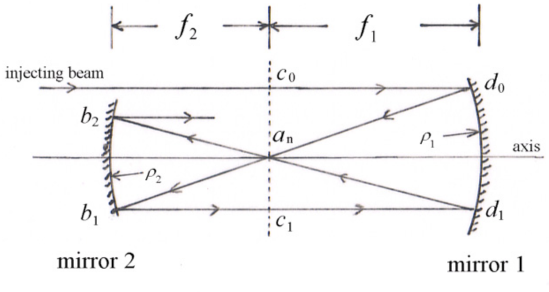

Figure 1: Asymmetrical con-focal cavity and beam path.

A laser beam is injected in parallel with the axis of the cavity from the backward and just outside of the mirror 2, passes through c_0 forming a waist, then is reflected at d_0 on the mirror 1. Since the injected beam is in parallel with the axis, the beam reflected at d_0 goes through the focal point a of the mirror 1 and comes to b_1. As is described in the next subsection, the beam at a is a waist. Since a is also the focal point of the mirror 2, the beam reflected at b_1 is in parallel with the cavity axis, passes c_1 forming a waist and goes to d_1 on the mirror 1. Then, the laser beam reflected at d_1 returns to a again forming a waist. Thus, the laser beam repeats triangular paths ; $a \rightarrow b_n \rightarrow c_n \rightarrow d_n \rightarrow a$, and comes to a as a waist every time, reducing separation of the path from the cavity axis with increase of n.

When laser beam paths are sufficiently near to the mirror axis, in the first approximation, path length of $a \rightarrow b_n \rightarrow c_n$ is equal to ρ_2 for any n, and also path length of $c_n \rightarrow d_n \rightarrow a$ equal to ρ_1. Thus, path length of $a \rightarrow b_n \rightarrow c_n \rightarrow d_n \rightarrow a$ is equal to $\rho_1 + \rho_2$ and the period of the laser beam cycle from a_n to a_{n+1} is considered to be constant. Therefore, when the injecting laser beam is pulsed with repetition period equal to the period of the laser beam cycle in the cavity, laser beam pulses comes to the focal point a simultaneously and intensity of the laser pulses will be stacked up. In the actual situation, since the beam size at a gradually increases with n, the beam intensity stacked up inside of a definite radius of the laser beam saturates to a certain value.

As is described in the reference [1], calculation based on the Gaussian beam optics suggests that a significantly high power laser beam can be stacked at the con-focal point. Similar studies [2-3] on the beam stacking in an asymmetrical con-focal cavity were performed based on the geometrical optics but experiments did not show appreciable enhancement of the stacked beam.

Evolution of the Beam Parameters

When the quality of the laser beam is enough high, the intensity distribution is considered to be Gaussian. Gaussian beam is characterized by two parameters; half of waist size (w) defined as the radius at which the beam intensity is $1/e^2$ of the peak value and Rayleigh range (z).

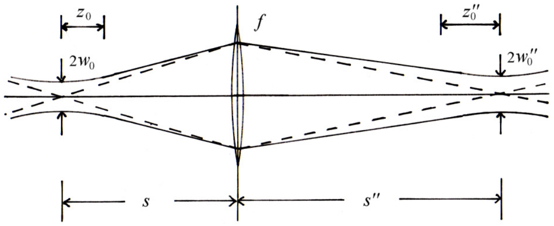

Figure 2: Gaussian beam transformation by a focal lens.

When the wavelength of the laser beam is λ, these parameters have the following relation.

$$z = \frac{\pi w^2}{\lambda}. \tag{1}$$

The Gaussian beam transformation by a focal lens is described by the following equation [4].

$$\frac{1}{s + z_0^2\big/(s-f)} + \frac{1}{s''} = \frac{1}{f}. \tag{2}$$

As is shown in Fig. 2, s (or s'') is the object (or the image) distance, f is the focal length of the lens and z_0 is the Rayleigh range. The magnification is given by the following formula.

$$m = w_0''\big/w_0 = 1\Big/\sqrt{\left[1-(s/f)\right]^2 + (z_0/f)^2} \tag{3}$$

Transformation of the Rayleigh range is given as follows,

$$z_0'' = m^2 z_0. \tag{4}$$

The injecting beam is formed to have a waist at c_0 with a half width (w_{c_0}) and a Rayleigh range (z_{c_0}) as follows,

$$w_{c_0} = \sqrt{\lambda f_1/\pi}, \tag{5}$$

and

$$z_{c_0} = f_1. \tag{6}$$

Then, half widths and Rayleigh ranges at a_n and c_n are calculated from those at c_0. Providing

$$k = \frac{f_2}{f_1}, \tag{7}$$

we have following equations for beam parameters at a_n,

$$w_{a_n} = k^{-(n-1)} w_{c_0}, \tag{8}$$

$$z_{a_n} = k^{-2(n-1)} z_{c_0}. \tag{9}$$

For those at c_n, we have

$$w_{c_n} = k^n w_{c_0}, \tag{10}$$

$$z_{c_n} = k^{2n} z_{c_0}. \tag{11}$$

Beam sizes at mirrors are also given as follows,

$$w_{b_n} = \left(k^{-(n-1)}\sqrt{1+k^{4n-2}}\right) w_{c_0}, \tag{12}$$

$$w_{d_n} = \left(k^{-n}\sqrt{1+k^{4n}}\right) w_{c_0}. \tag{13}$$

Fig. 3 shows an example of results calculated for He-Ne laser with a wavelength of 633 nm recycled in a cavity with f_1=435 mm and f_2=417 mm.

Beam Stacking

Since the laser beam is assumed to be a Gaussian beam, intensity distribution of every recycle turn is calculated from the beam size obtained in the preceding subsections. Since the laser beam half width (w) is defined as the radius at which the density becomes $1/e^2$ of the peak value, the density distribution is described as follows,

$$\rho(r) = \frac{2}{\pi w^2}\exp\left(-\frac{2r^2}{w^2}\right). \tag{14}$$

Providing ν as follows,

$$\nu = r\big/w_{c_0}, \tag{15}$$

and using the equation (8), expression for the density distribution of the beam at a recycled by n turns is given as follows,

$$\rho_n(\nu) = \left(\frac{1}{\pi w_{c_0}^2}\right)\frac{2}{k^{-2(n-1)}}\exp\left(-2\nu^2\big/k^{-2(n-1)}\right). \tag{16}$$

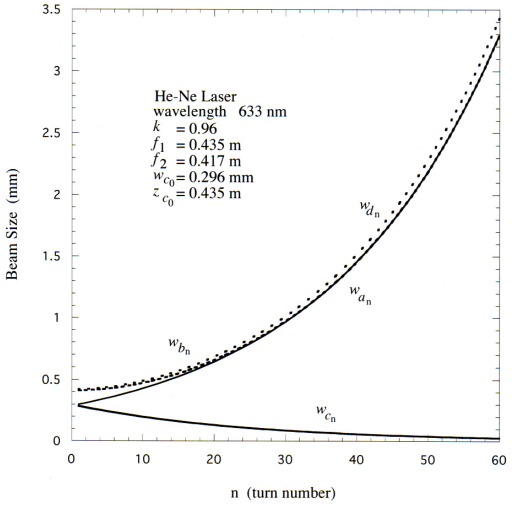

Figure 3: Evolution of the half width.

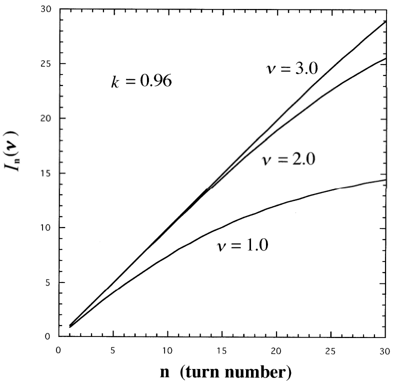

Figure 4: Evolution of the beam intensity stacked inside the beam radius of w_{c_0}, $2w_{c_0}$ and $3w_{c_0}$.

In an ideal case where the reflectance is 100 % or no beam loss accompanies with reflection, the evolution of beam density distribution stacked from the first to nth turn is obtained as $\sum_{m=1}^{n}\rho_n(\nu)$.

Finally, the stacked beam intensity is also given as

$$I_n(\nu)=\sum_{m=1}^{n} i_m(\nu), \tag{17}$$

where

$$i_n(\nu)=\int_0^r \rho_n(r)\cdot 2\pi r dr = 1-\exp\left(-2\nu^2/k^{-2(n-1)}\right) \tag{18}$$

is the beam intensity contained inside the radius r (or ν) .

Fig. 4 shows the evolution of the beam intensity stacked inside of beam radii w_{c_0} , $2w_{c_0}$ and $3w_{c_0}$. Since the beam intensity is normalized to 1 in total, the value of the ordinate means the equivalent number of the original beam. Thus, the beam intensity stacked inside of the radius $2w_{c_0}$ becomes that of 25 pulses for 30 recycle turns.

EXPERIMENT USING He-Ne LASER

In order to examine the results of the calculation in the preceding section, we observed beam stacking in a setup shown in Fig. 5, using a He-Ne laser with sufficiently high quality and a pair of mirrors with high reflectance.

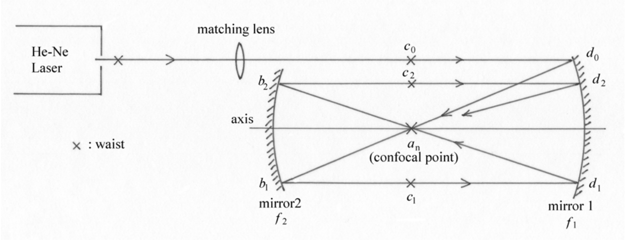

Figure 5: Experimental setup.

As the first step, in order to check if the laser is sufficiently Gaussian, the quality factor (M^2) of the He-Ne laser to be used was measured. As is shown in Fig. 6, the M^2 value is measured to be 1.04 and the beam is considered to be sufficiently Gaussian. From the data of the waist half width and the Rayleigh range obtained from Fig. 6, the position of the laser and the matching lens was defined so as to form the assumed waist at the point c_0. Then, a raw of beam spots was found on both mirrors, as is expected from the results of calculation. So, we placed a lapping foil on the plane including the con-focal point and perpendicular to the cavity axis and found such a raw of beam spots shown in Fig. 7. This figure clearly shows that the beam spots at c_n approach to a with n, and that all beams reflected by the mirror1 gather to a and are stacked up. The amount of beam paths gathering to a can be counted from the number of identified beam spots at c_n and reaches to about 30. Since beams are scattered by the lapping foil every time passing through it, the beam intensity is rapidly diminished. The halo parts seen both side of the beam spot raw are considered to be light scattered by the foil, reflected by mirrors and returned to the foil. When the foil is removed, scattering by the foil does not occur and light of these halo part will be gathered to a.

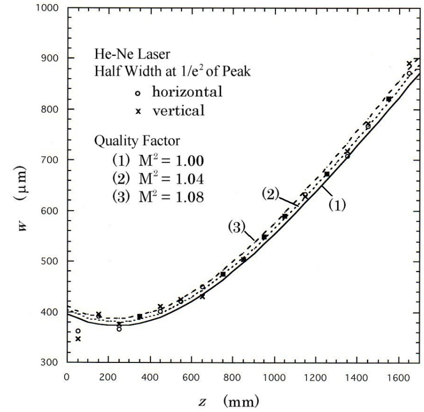

Figure 6: Propagation of the $1/e^2$ radius of the He-Ne laser to be used in the experiment.

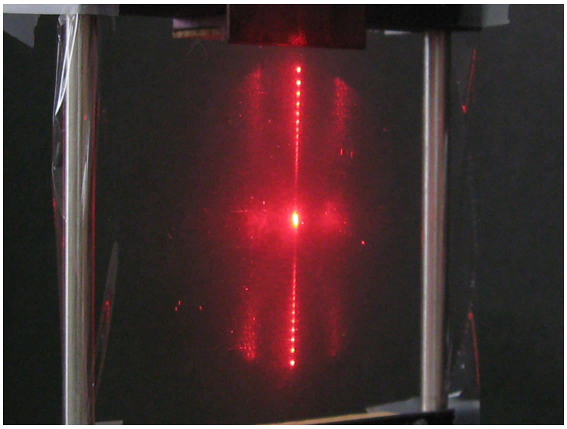

Figure 7: Raw of beam spots on the plane including the con-focal point and vertical to the cavity axis.

As the next step, quantitative measurement of the beam intensity distribution upper and lower side of the con-focal point is now being prepared in order to make clear how much turns are stacked up.

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