Rs	=	dimensionless outer radius of inner tube, r_s/D_e	[—]
R'	=	dimensionless radial distance, $(r-r_s)/(r_o-r_s)$	[—]
r	=	radial distance	[cm]
r_o	=	inner radius of outer tube	[cm]
r_s	=	outer radius of inner tube	[cm]
T	=	dimensionless temperature, $(t-t_w)/(t_H-t_w)$	[—]
t	=	temperature	[K]
t_H	=	temperature of heating surface	[K]
t_w	=	temperature of cooling surface	[K]
$\bar{v}$	=	average velocity in z-direction	[cm/s]
Z	=	dimensionless axial distance from lower end of heater, z/D_e	[—]
z	=	axial distance from lower end of heater	[cm]
β	=	volumetric coefficient of expansion	[1/K]
λ	=	thermal conductivity of fluid	[W/cm·K]
μ	=	viscosity	[g/cm·s]
ν	=	kinematic viscosity of fluid	[cm^2/s]

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OPTIMUM IRRADIATION GEOMETRY IN CONTINUOUS LASER ISOTOPE SEPARATION

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Introduction

Recently, it was demonstrated that such isotopes as ^{2}H (deuterium),[2,5] ^{3}H (tritium)[4,6,7,11] and ^{235}U[3] could be separated by means of isotopically selective dissociation induced by infrared laser irradiation. In relation to tritium isotope separation, the authors have shown that the performance of a continuous reactor can be appropriately predicted when the intrinsic dissociation characteristics are obtained in a batch irradiation experiment.[8]

It is necessary to focus the beam when the reaction thresholds of resonant isotopic compounds are higher than the damage threshold of the window crystal installed on the reaction chamber. In this communication, the optimum geometry for focusing the laser beam is discussed for continuous laser isotope separation. Attention is paid only to the dissociation of the resonant substance (such as the tritiated compound in laser tritium isotope separation), since the selectivity is usually very high and the dissociation of the off-resonant substance (such as the protonated compound) is negligible.

1. Model Description

The schematic diagram of the focused beam irradiation geometry is shown in **Fig. 1**. The transverse fluence profile of the beam is assumed to be uniform. The pulse energy E at the focal point, laser repetition rate h, beam divergence $\Delta\theta$, and beam radius at the lens r_L are assumed to be given for a given laser. The maximum allowable fluence for the window crystal Φ_w is set somewhat lower than the damage threshold of a chosen window material (such as KCl).

In our preceding paper,[9] it was shown that the fraction of dissociated resonant compound X at the outlet of a continuous reactor was related to the volumetric flow rate Q, laser pulse repetition rate h and reaction volume V_R as

$$1-X=(1+V_R h/Q)^{-1} \tag{1}$$

To maximize Q while satisfying the specified reaction conversion (X), V_R is required to be maximized by optimizing the focal length of the lens f. V_R is related to the dissociation characteristics $q(\Phi)$ as given by

$$V_R=\int_V q\,dV \tag{2}$$

where q denotes the fractional conversion per pulse at fluence Φ. As discussed in our preceding papers,[6,8] the relation $q(\Phi)$ is described by the power law model given by

$$q=(\Phi/\Phi_c)^n \qquad \Phi<\Phi_c \tag{3-a}$$

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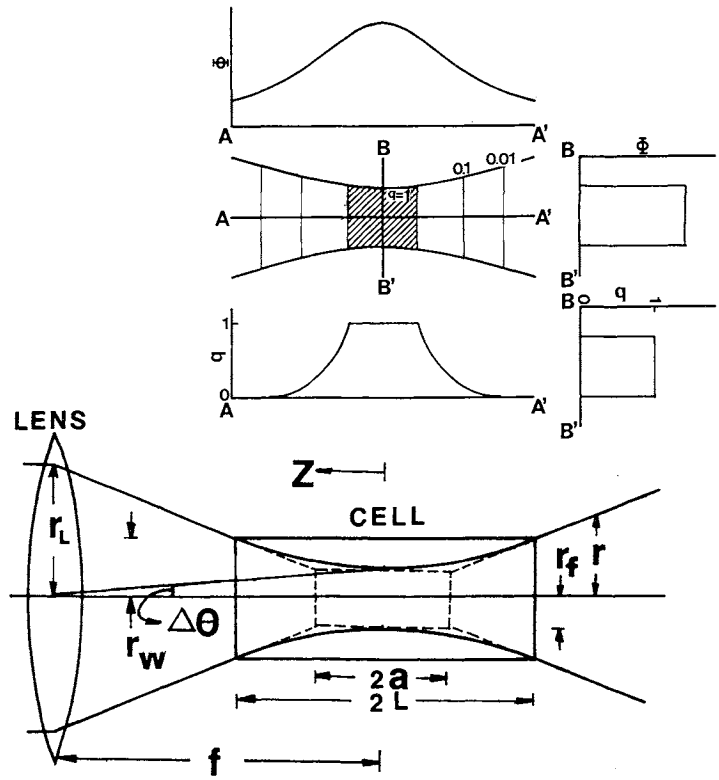

Fig. 1. Schematic diagram of axial and transverse profiles of Φ and q in focused beam geometry.

$$q=1 \qquad \Phi \geq \Phi_c \tag{3-b}$$

or with the smoothed model using a cumulative log-normal distribution (CLND) function model such as[1)]

$$q=\int_{-\infty}^{\Phi} \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(\ln \Phi-\ln \Phi_s)^2}{2\sigma^2}\right\} d\ln \Phi \tag{4}$$

It was also shown previously[9)] that the parameters in the power law model (n, Φ_c) were related to those in the smoothed model (σ, Φ_s). These dissociation parameters are assumed to be given at a given reaction condition (gas pressure, temperature and laser pulse duration).

2. Optimization

The focal fluence Φ_f is given by

$$\Phi_f=\frac{E}{\pi r_f^2}=\frac{E}{\pi(f\Delta\theta)^2} \tag{5}$$

where r_f, f and $\Delta\theta$ denote the focal radius, focal length of the lens and beam divergence, respectively. For given values of E, $\Delta\theta$ and Φ_c, Eq. (5) indicates that f is inversely proportional to the square root of the dimensionless fluence F ($=\Phi_f/\Phi_c$):

$$f \propto F^{-1/2} \tag{6}$$

Since r_f is given by $f\Delta\theta$, r_f is related to F in a manner shown as

$$r_f \propto F^{-1/2} \tag{7}$$

The beam envelope is given by

$$r^2=r_f^2(1+Z^2/a^2) \tag{8}$$

where Z and a are the axial distance from the focal point and the Rayleigh range, respectively. Since f (which is equal to Z at $r=r_L$) is much larger than a in the focused-beam geometry, the following approximation holds:

$$\frac{r_L}{f} \cong \frac{r_w}{L} \cong \frac{r_f}{a} \tag{9}$$

In terms of F for given r_L, a is given by

$$a \cong f r_f/r_L \propto F^{-1} \tag{10}$$

From Eqs. (7) and (10), the focal volume V_f ($\equiv 2\pi r_f^2 a$) is dependent on F in a manner given by

$$V_f \propto F^{-2} \tag{11}$$

The relation between the dimensionless reaction volume Y ($=V_R/V_f$) and the dimensionless fluence F was reported elsewhere (Eqs. (6) to (9) in reference 8), when the power law model (Eqs. (3-a) and (3-b)) was used to describe the dissociation characteristics (q as a function of Φ). The maximization of V_R is discussed using this relation: Y is proportional to F^n when F is less than unity and proportional to $F^{3/2}$ when F is sufficiently larger than unity.

Consequently, V_R ($=YV_f$) is dependent on F as

$$V_R \propto F^n F^{-2}=F^{n-2} \qquad \text{for} \quad F<1 \tag{12}$$

$$V_R \propto F^{3/2} F^{-2} = F^{-1/2} \qquad \text{for} \quad F \gg 1 \qquad (13)$$

Since the value n is usually larger than 2.5, there is a value of F that gives maximum V_R. For convenience in comparison, V_R is normalized with V_{R1} (the V_R value at $F=1$) and plotted against F for $n=2.5$, 5.5 and 8.5 in **Fig. 2** (solid lines).

When the dissociation characteristics are described using the CLND model, on the other hand, the dependence of Y on F, $Y(F)$, is obtained merely in a numerical way. Therefore, the dependence of V_R^* (reaction volume based on Eq. (4)) upon F was obtained numerically using the relation

$$V_R^* \propto Y(F) \cdot F^{-2} \qquad (14)$$

as shown with broken lines in Fig. 2.

Let F_{opt} denote the value of F to yield maximum V_R. F_{opt} is found typically between $F=1$ and $F=2$, and it tends to increase with increasing n for both models (Eqs. (3) and (4)). The smoothed model (Eq. (4)) is found to give slightly higher value of F_{opt} for a given value of n. Once the optimum F is known, the focal length of the lens f is determined as

$$f = \{E/(\pi F_{\text{opt}} \Phi_c \Delta\theta^2)\}^{1/2} .$$

In conclusion, a method has been shown to determine the optimum way of focusing the laser beam using Fig. 1 for a given value of n in continuous laser isotope separation.

Nomenclature

a	=	Rayleigh range	[cm]
E	=	pulse energy	[J]
F	=	Φ/Φ_c = dimensionless fluence	[J/cm^2]
f	=	focal length of lens	[cm]
h	=	pulse repetition rate	[s^{-1}]
L	=	cell half-length	[cm]
n	=	parameter in Eq. (3-a)	[—]
Q	=	volumetric flow rate	[cm^3/s]
q	=	fractional conversion per pulse	[—]
r	=	beam radius	[cm]
r_f	=	focal radius	[cm]
r_L	=	beam radius at lens	[cm]
r_w	=	beam radius at cell window	[cm]
t	=	number of pulses	[—]
V_f	=	$2\pi r_f^2 a$ = focal volume	[cm^3]
V_R	=	reaction volume based on Eqs. (3-a) and (3-b)	[cm^3]
V_R^*	=	reaction volume based on Eq. (4)	[cm^3]
X	=	reaction conversion	[—]

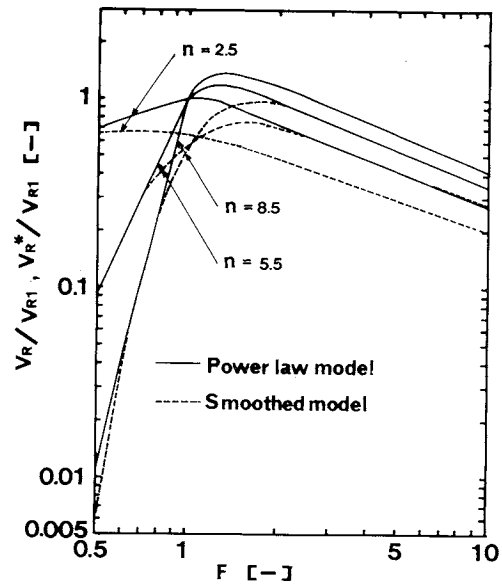

Fig. 2. Dimensionless reaction volumes V_R/V_{R1} and V_R^*/V_{R1} as a function of dimensionless fluence F.

Y	=	dimensionless reaction volume	[—]
$\Delta\theta$	=	beam divergence	[—]
Φ	=	fluence	[J/cm^2]
Φ_c	=	critical fluence	[J/cm^2]
Φ_f	=	focal fluence	[J/cm^2]
Φ_s	=	saturation fluence in smoothed model	[J/cm^2]
σ	=	parameter in Eq. (4)	[—]

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