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Intensifying gamma-rays by inverse Compton scattering with an optical resonator

Y.Yamazaki* and H.Takahashi**

Abstract

Presently, the Power Reactor and Nuclear Fuel Development Corporation(PNC) is investigating the best way to treat high-level radioactive nuclear wastes from reactors. As part of their basic research on the transmutation of fission products, PNC developed a high-power CW electron linac for various applications, in particular for studying the use of strong γ-rays for transmuting the medium-lived fission products (MLFP) of Sr-90 and Cs-137. As the results of studies of transmutation by photoreaction have shown, high-flux and high-energy γ-rays (~ 15MeV) are needed. However, to make an approach feasible it is very important to generate the γ-rays at a reasonable cost. To increase the intensity of the γ-rays, a high-current electron beam and a high-power laser are needed. This paper reports our findings which show that to generate γ-rays by inverse Compton scattering effectively, the photons accumulated in a optical resonator must intensify the monochromatic γ-ray flux by the collisions of inverse Compton scattering with electrons. The method we discuss employs inverse Compton scattering with an optical resonator composed of very high-reflectance, low-absorptance mirrors. With advances in technology, the flux of γ-rays that can be attained is of the order of 10^18, and its efficiency is 0.9% using this method. If future technological progress results in a mirror with a reflectance of 8N and absorptance of 0.001ppm, then it might be possible to achieve a flux of the order of 10^20, and an efficiency of more than 30%. In the case of a concentric resonator, the density of the photon's beam at the interaction point can be higher than that in a confocal type, so that a γ-ray flux of the same order as the 8N case may be achieved.

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光共振器を用いた逆コンプトン散乱による γ線の増倍方法の検討

山崎良雄*、高橋博**

要旨

現在、動燃事業団では原子炉から生ずる高レベル核廃棄物の最適な処理策を研究中である。その中で核変換の基礎研究のため、特にSr-90、Cs-137のFP核種の変換のための大強度のγ線発生の研究などの、さまざまな応用を含んだ大電力電子線形加速器の開発を行っている。光核反応による核変換の研究の結果として、大強度高エネルギー（約15MeV）のγ線が必要である。しかし、エネルギーコストを考慮にいれたγ線発生を検討することが、核変換の実現性を考えるうえで重要である。γ線の強度を増強させるためには、大電流の電子ビームと大強度のレーザーが必要である。この報告書では、γ線を効率的に発生させるために、光共振器に光子を蓄積し、そこでの電子ビームとの逆コンプトン散乱により、単色γ線を増強させることを検討する。この方法では、高反射率、低損失の鏡からなる光共振器を用いる必要がある。現在の技術水準から考えると、この方法で、10の18乗程度のγ線発生が見込め、エネルギー効率は0.9%であった。仮に、反射率８Ｎ、損失0.001ppmの鏡の製作が可能となれば、10の20乗のγ線発生が可能で、エネルギー効率は30%以上に達する。また、従来の共焦点型の共振器よりも電子との相互作用点に光子の密度を集中できる共振器を用いれば、現在の技術水準の鏡を用いても10の18乗程度のγ線発生が可能であることが判明した。

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1. Introduction

Presently, the Power Reactor and Nuclear Fuel Development Corporation(PNC) is investigating the best way to treat of high-level radioactive nuclear wastes from reactors as a link in the chain of Japanese government's policy; "OMEGA Project"[1]. For basic research into the transmutation of fission products, PNC developed a high-power CW electron linac for various applications[2][3], especially for using strong γ-rays for transmuting the medium-lived fission products (MLFP) of Sr-90 and Cs-137. The bremstralung γ-rays produced by relativistic high-energy electrons can transmute these fission products within a short time because of their high intensity. However, the efficiency of producing the high-energy γ-rays by bremstralung is not high enough for transmuting MLFP. Another way that has been suggested is to use the electron accelerator for transmuting FP using the (n,γ) reaction after making neutrons. This suggestion arose because of the well-established electron accelerator technology for the 100 MeV energy range, but its efficiency is not high. To produce the high-intensity high-energy γ-rays needed, the annihilation reaction of positrons with electrons was studied, but this requires cooling of the beam to enhance of the annihilation process[4]. A further way to produce the high-energy γ-rays is by inverse Compton scattering of a laser by relativistic electrons, as is practiced in physics experiments[5]. Nomura, Takahashi and his colleagues[6] also explored the possibility of creating γ-rays efficiently by using a storage ring and regaining the energy loss due to scattered electrons by capturing them with a RF bucket and accelerating them to recirculation.

As the results of studies of transmutation by photoreactions have shown, high-flux and high-energy γ-rays (~ 15MeV) are needed. However, for the approach to be feasible it is very important to generate the γ-rays at a reasonable cost. To produce monochromatic, high-flux γ-rays, several studies of inverse Compton scattering were proposed in recent years. Inverse Compton scattering is one good method of producing high-energy γ-rays, but the total cross-section between the electron and the photon is small, so that the energy needed for transmutation cannot be reduced. To increase the intensity of the γ-rays, a high-current electron beam and a high-power laser are needed. This paper reports that to generate γ-ray by inverse compton scattering effectively, the photons accumulated in a optical resonator should intensify the monochromatic γ-ray flux by the collisions of inverse Compton scattering with electrons[7][8][9].

2. Status of high-intensity monochromatic γ-ray sources

Since the prediction of Milburn[10], and Arutyunian and Tumanian[11] that high-energy quasi-monochromatic photon beams could be produced by inverse Compton scattering between a laser photon and high-energy electron beam, several laboratories have studied and detected experimentally this process for physics research. Table.1 summarizes the main successes of laser-backscatter γ-rays[12]. The first experiment to actually use laser-backscattered photons as a beam in a physics experiment was conducted at SLAC in 1969, but the γ-ray flux was not very high. For nuclear physics research, the first real γ-ray beam was developed at the ADONE storage ring of Frascati National Laboratories; The flux was 5*10^4 [s^-1] γ-rays in energies up to 80MeV[13][14]. BNL has produced up to the order of 10^7 [s^-1] γ-rays, of energies up to 700MeV in the LEGS project[12]. Recently, a group at Duke University investigated γ-ray production in a storage-ring free-electron laser, aiming to obtain 10^9-10^11 [s^-1] γ-rays with energy of 2-55MeV[15]. In Japan, the Electro-Technical Laboratory(ETL) in Tsukuba launched into a study of generating γ-rays in a storage ring[16]. Furthermore, γ-rays were successfully obtained from the interaction between a storage-ring FEL photon and a high-energy electron beam in a storage ring[17]. In addition, projects for γ-γ colliders in future linear colliders demand high-energy and high-flux γ-rays. As a method to get such γ-rays, laser backscattering is the most hopeful[18].

Laboratory	SLAC	Frascati	BNL	Duke	ETL
Electron[GeV]	20	1.5	3.0	1.1	0.5
Photon [eV]	1.78	2.41	6.2	12	1.2
γ-ray [MeV]	5000	80	700	150	23
γ-ray flux [1/s]	500	10^5	2*10^7	2*10^11	2*10^7

Table.1 Main successes of laser-backscatter γ-rays.

3. Inverse Compton scattering

The process of inverse Compton scattering to produce monochromatic γ-rays in laboratory frame work is shown schematically in Fig.1.

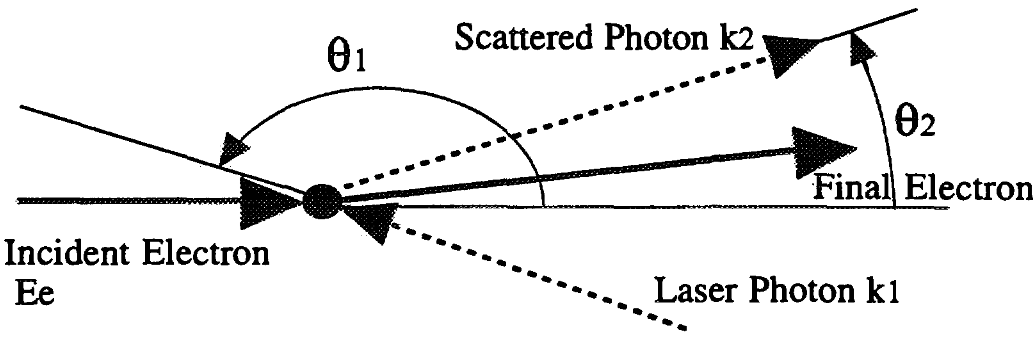


Fig.1 Schematic of the photon-electron scattering process in a laboratory frame work.

The Energy of a γ-ray generated by inverse Compton scattering is given by:

$$k_2 = \frac{k_1(1-\beta\cos\theta_1)}{1-\beta\cos\theta_2 + k_1/E_e\{1-\cos(\theta_2-\theta_1)\}} : \qquad (1)$$

$$E_e = \gamma\mu \ , \ \mu = mc^2, \ \gamma = 1/(1-\beta^2)^{1/2} : \qquad (2)$$

where θ_1 and θ_2 is the angle between a vector of an initial electron and an initial photon momentum, and between an initial electron and a scattered γ-ray, respectively. E_e,k_1,k_2 are the energy of the initial electron, the initial photon, the scattered γ-ray. The differential cross-section for unpolarized electrons and photons is known as the Klein-Nishina formula in the rest system of the incident electron:

$$\frac{d\sigma}{d\Omega} = 2\left[\frac{r_0 k_2}{x_1\mu}\right]^2 \left[4\left(\frac{1}{x_1}+\frac{1}{x_2}\right)^2 - 4\left(\frac{1}{x_1}+\frac{1}{x_2}\right) - \left(\frac{x_1}{x_2}+\frac{x_2}{x_1}\right)\right] : \quad (3)$$

$$x_1 = -\frac{2\gamma k_1}{\mu}(1-\beta\cos\theta_1) \ , \quad x_2 = -\frac{2\gamma k_2}{\mu}(1-\beta\cos\theta_2) : \quad (4)$$

where $d\sigma/d\Omega$ is the differential cross-section, and r_0 is the classical radius of the electron, 2.82*10^-15 m.

We can calculate the maximum γ-ray energy generated from eq.(1) (2). In the case of $\theta_1=\pi$ and $\theta_2=0$, the energy of scattered photons reaches the maximum. For example, if a photon source in laser backscattering is chosen as some typical conventional laser with high-average power, the maximum energy of scattered γ-rays can be estimated from incident electron energy, as shown Fig.2.

To get 15MeV γ-rays, an incident electron energy about 1GeV is needed at least, using a Nd:YAG laser. In the case of KrF, electron energy of 500MeV is enough, but in the case of the CO_2 laser, more than 2.5GeV energy must be available. In future, free electron lasers(FEL) may be more useful as laser photon sources; with them, we will have more high-powered and shorter-wavelength lasers than the present ones. Therefore, if the incident electron energy is lower than about 500MeV, it is essential that a short-wavelength laser, enough to generate 15MeV γ-rays, is acquired. To aim to produce 15MeV γ-rays with high efficiency and low cost, it is very important to select how much incident electron energy and laser photon energy are needed. However, up to now in our discussions, considerations about this point have not been deep. It is assumed in the following discussion that the laser photon wavelength selected is 1μm, because this wavelength is in the infrared region which is comparatively easy to obtain by FEL. The incident electron energy chosen is about 1GeV.

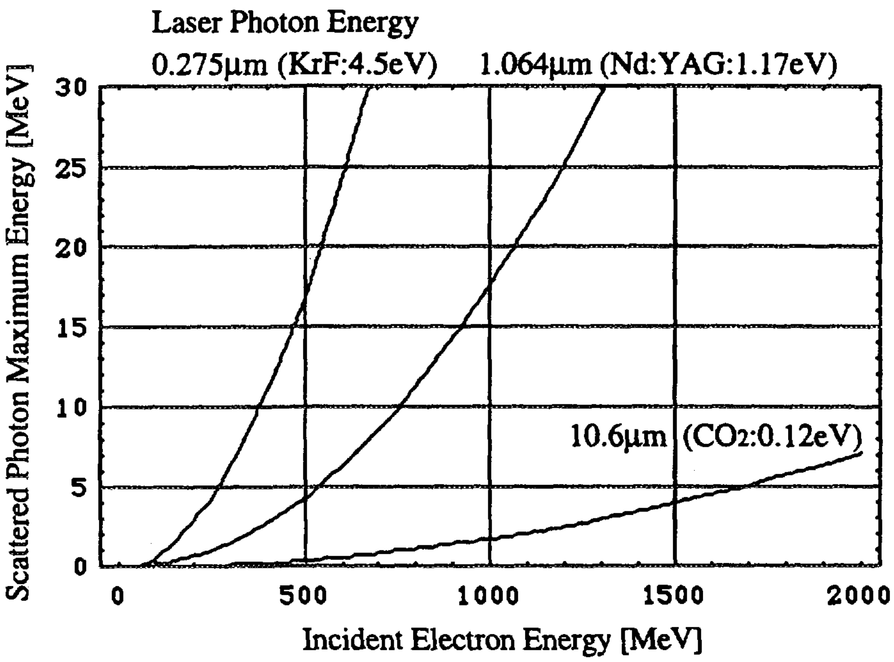


Fig.2 Scattered photon maximum energy in using typical conventional lasers.

The energy of scattered γ-rays, known from Eq (1),(2), depends on the angle θ_1 of collision between the laser photon and the electron. Fig.3 shows the energy of scattered photon for typical collision angles, assuming that the incident electron energy is 1GeV, and laser photon wavelength is 1μm. The energy of the scattered γ-rays is maximum at θ_2=0, and at the angle bigger than 0.002 rad, it is less than about 1MeV. When the collision angle θ_1 is equal to 180 degrees, i.e., a head-to-head collision, maximum γ-ray energy is obtained. The γ-ray maximum energy in the case of 90 degrees is about half that obtained in the head-to-head case.

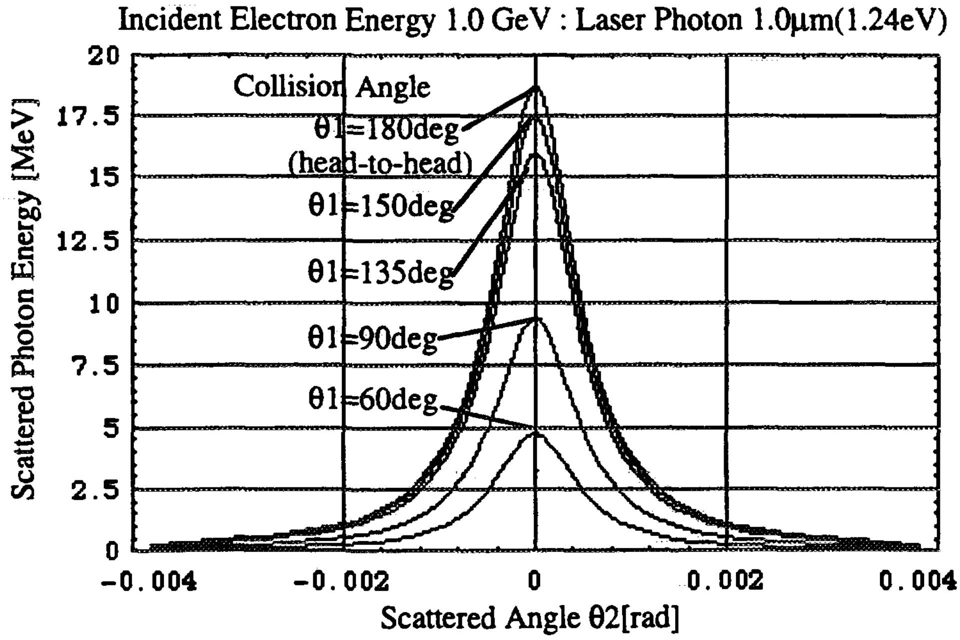


Fig.3 Dependence of γ-ray energy on scattered angle for each angle of collision.

The angular distributions of the differential cross-sections for typical collision angles are shown in Figures.4 and 5. Compton backscattering radiation is concentrated in a small cone within $\theta_2 \leq 1/\gamma$ (γ=1956.95). As Eqs (3) and (4) show, the differential cross-section of laser backscattering also depends on the collision angle between the electron and photon. But its differences are not large and so can be neglected. However, attention should be paid to increasing the cross-section value as the collision angle decreases.

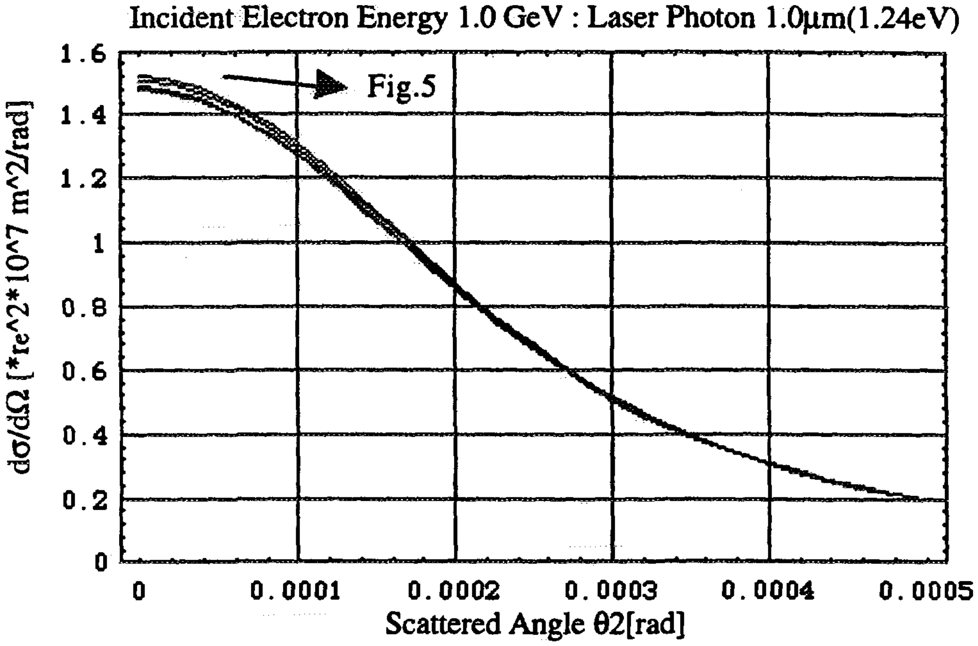


Fig.4 Dependence of the differencial cross section on the scattered angle for each typical collision angle.

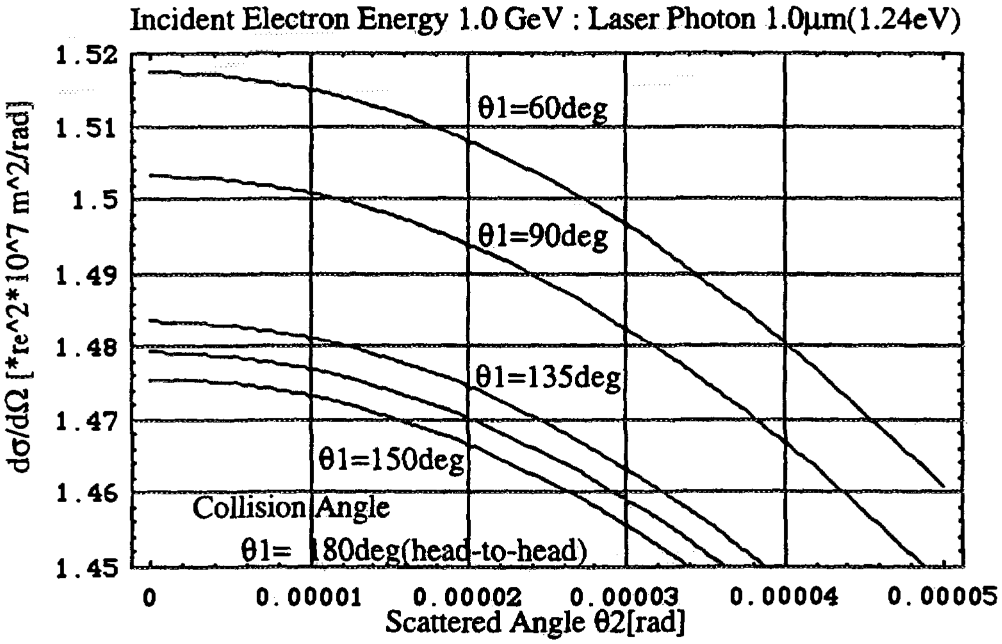


Fig.5 Enlargement of part of Fig.4.

4. Optical resonator

In general, an optical resonator consists of two mirrors in the shape of plane or concave. Fig.6 shows some commonly used examples of mirror configurations for stable cavities. For our purpose, it is necessary to have a stable low-loss resonator to store as many high-density photons as possible. The conditions to satisfy this demand are set out in the following formula[19].

$$0 \leq \left(1-\frac{L}{R_1}\right)\left(1-\frac{L}{R_2}\right) \leq 1 \qquad (5)$$

where L is the spacing between the two mirrors, and R_1, and R_2 are the curvatures of the mirrors. Fig.7 illustrates the parameters to satisfy Eq (5). This diagram, known as a Boyd-Kogelnik plot, is very convenient for finding whether a resonator is stable or unstable[20][21][22]. It is very important to align the configuration of the two mirrors. Considering the difficulty involved in the alignment, and the necessity for precision in mode volume and photon beam's size, the best type of the resonator must be selected.

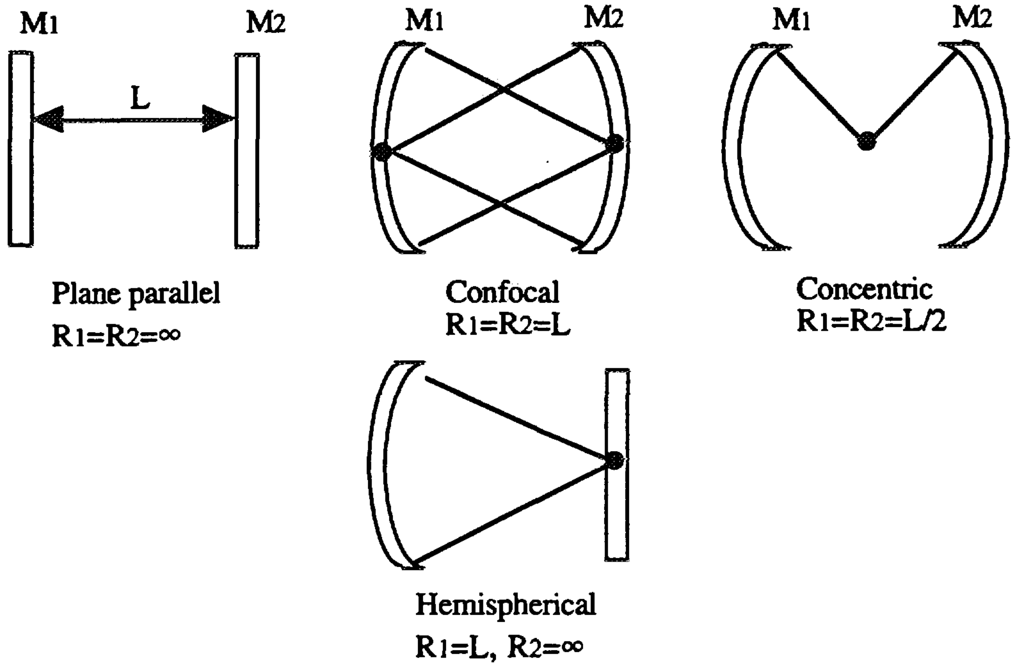


Fig.6 Examples of mirror configurations for optical resonators with low-loss.

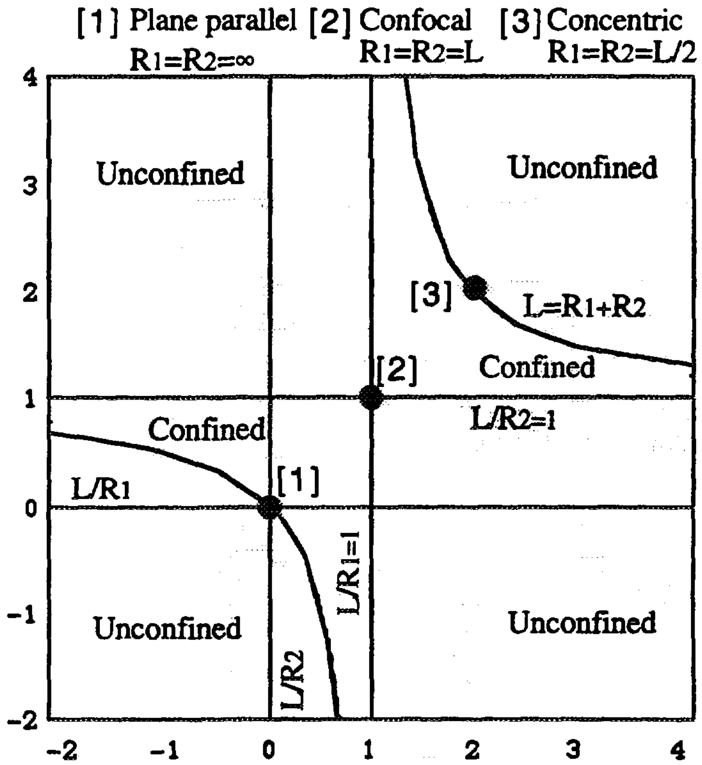


Fig.7 Confinement diagram for optical resonators.

Recently, there has been much progress in the production of high reflectivity and very low-loss mirrors, so it is possible to get an optical resonator with high photon storage capacity. In general, the performance of an optical resonator is determined by the characteristics of the mirrors and their geometry. An enhancement ratio Ir of photon flux using the optical resonator is given by:

$$A+R+T=1 : \tag{6}$$

$$I_r=\left(1-\frac{A}{1-R}\right)^2\frac{\mathcal{A}}{T} : \tag{7}$$

$$\mathcal{A}=\frac{1}{1+F\sin^2(\omega L/c)}\ ,\quad F=\left(\frac{2R}{1-R^2}\right)^2 : \tag{8}$$

where A, R, T are the absorptance, the reflectance, the transmittance of the mirror, respectively. $\mathcal{A}$ is the Airy function, F is the coefficient of finesse, and ω is the angular frequency of the photon. Fig.8 demonstrated the dependence of the enhancement ratio in the resonator on the phase difference of the mirrors' performance. A rise in the mirrors' performance, which means a higher reflectance and lower absorptance, increases the peak of the enhancement ratio. On other hand, as the resonance width of the cavity becomes narrower, a higher stability of the pumping laser and high accuracy of th mirrors' alignment are demanded to satisfy the condition of the resonance.

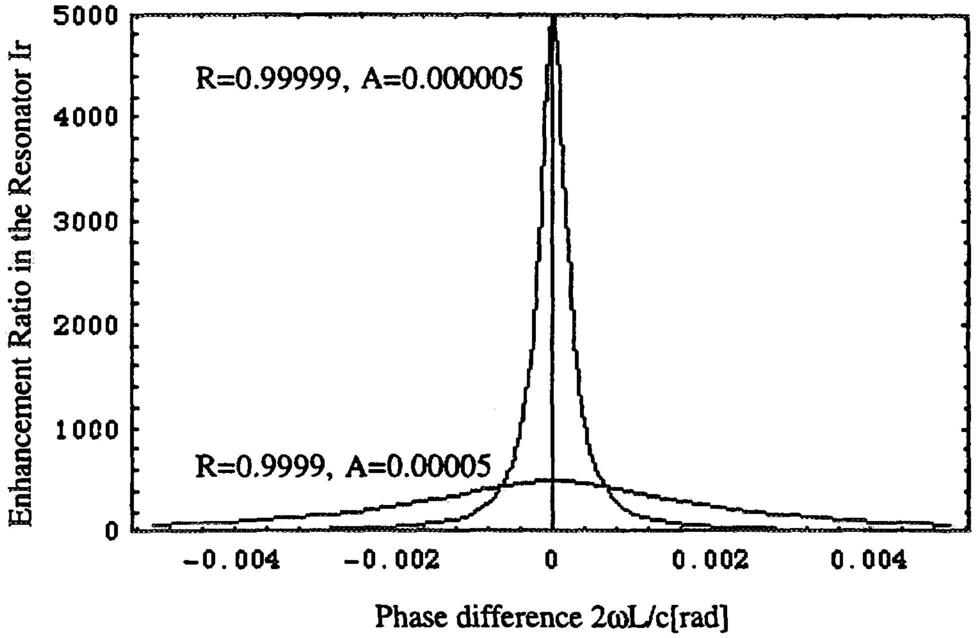


Fig.8 Enhancement ratio in the resonator for each refrectance of mirror

In the resonator and vacuum condition, the spatial distribution of the electric field for a Gaussian light beam, including higher-order modes, is known to be a function of the Hermite polynomial[19]:

$$E_{l,m}(x,y,z) = E_0 \frac{w_0}{w(z)} H_l\left[\sqrt{2}\frac{x}{w(z)}\right] H_m\left[\sqrt{2}\frac{y}{w(z)}\right]$$

$$\times \exp\left[-\frac{x^2+y^2}{w^2(z)} - \frac{ik(x^2+y^2)}{2R(z)} - ikz + i(l+m+1)\eta\right] : (9)$$

$$w(z) = w_0\sqrt{1+(z/z_0)^2}, \qquad z_0 = \pi w_0^2/\lambda : \qquad (10)$$

$$R(z) = (z^2+z_0^2)/z, \qquad \eta = \tan^{-1}(z/z_0) : \qquad (11)$$

where *Hl,m* is the Hermite polynomial of order *l,m,* R(z) is the radius of curvature of the wavefronts, w, w_0 is the beam spot size, the minimum, and η is the phase factor. λ is the wave length of light. Fig.9 illustrates a beam shape in the resonator given by Eq (9),(10),(11). We can form an optical resonator merely by inserting at points z_1 and z_2 two mirrors with radii of curvature R_1 and R_2, and so obtain the sizes of beams at any z point.

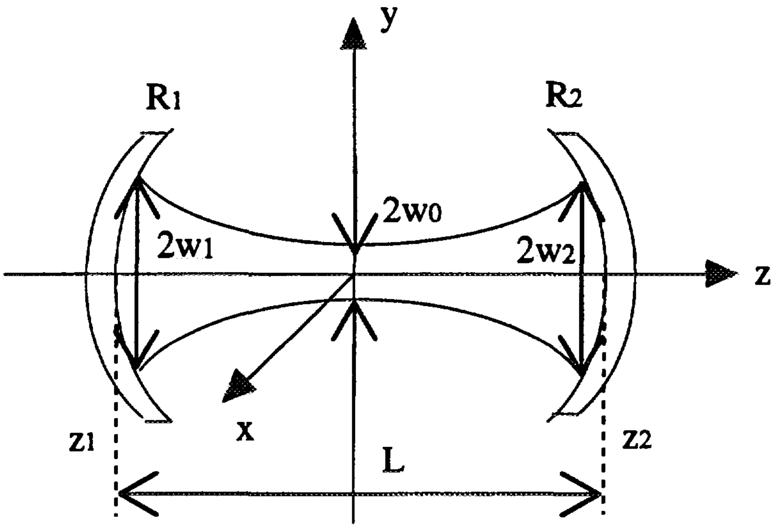


Fig.9 Diagram of a beam shape in the resonator.

For example, assuming the parameters of the optical resonator; L=2m, $R_1=R_2=2m$, and $\lambda=1\mu m$. we can calculate the beam size at any z point and the spatial distribution of the electric fields of light in the resonator from Eq (9),(10),(11).

Fig.10 shows the dependence of the beam spot size on the z axis. The distributions of electric fields of light at the minimum spot size (z=0) and mirrors in the case of the TEM00 mode are illustrated in Fig.11. Fig.12 represents the distribution of x versus z at y=0 also for the TEM00 mode. We find that the light wavelength is exactly 1μm through z axis. Fig.13 shows the distributions of electric fields of some low-order optical beam modes in the resonators at z=0, where the beam spot size is minimum.

If the resonator has a finite Fresnel number($N=a^2/L\lambda$; a is the mirror radius.), a power loss because of a diffraction loss is unavoidable. The diffraction loss increases with the decrease of the Fresnel number of the resonator. If a big enough Fresnel number is selected(N>>1), the diffraction loss is negligible. This loss also is greater the higher the transverse mode indices, meaning that to store the fundamental mode TEM00 in the optical resonator without power loss is the easiest of all resonant modes[20].

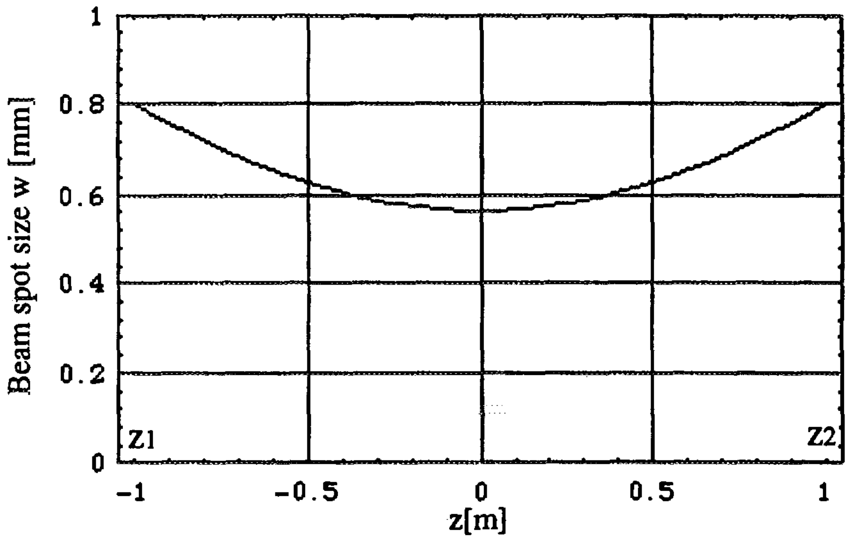
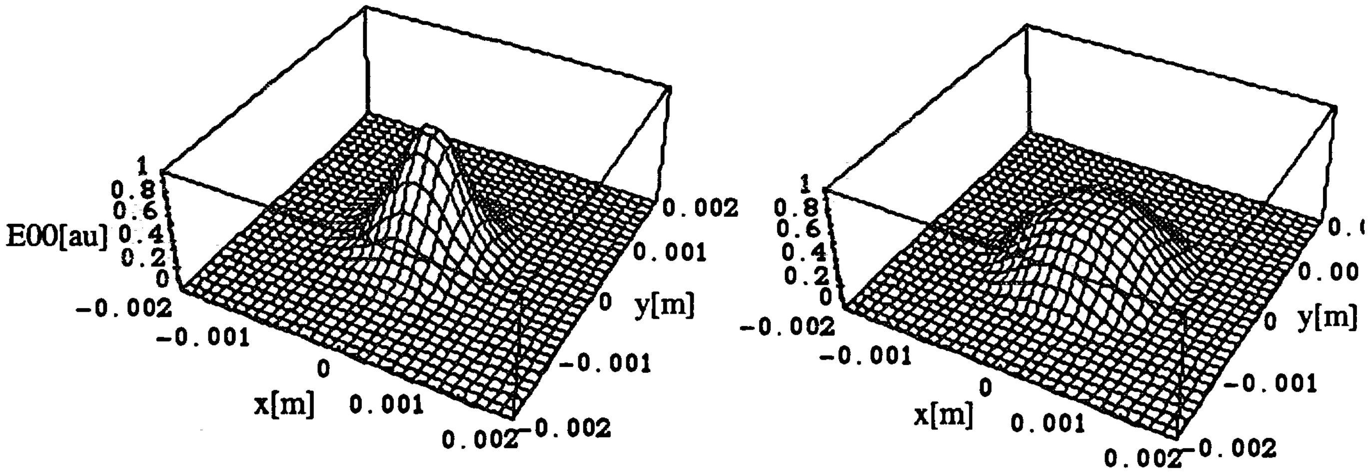
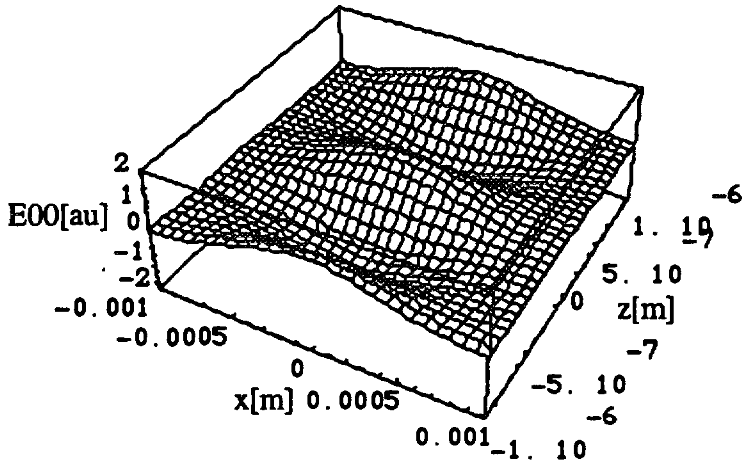


Fig.10 The beam spot size in the resonator.



z=0 (Minimum spot size) **z=z1, z=z2 (At the mirror)**

Fig.11 Electric fields of TEM00 mode at z=0 and mirrors.



Distribution for x vs. z (y=0)

Fig.12 Electric fields of TEM00 mode for x vs.z (y=0).

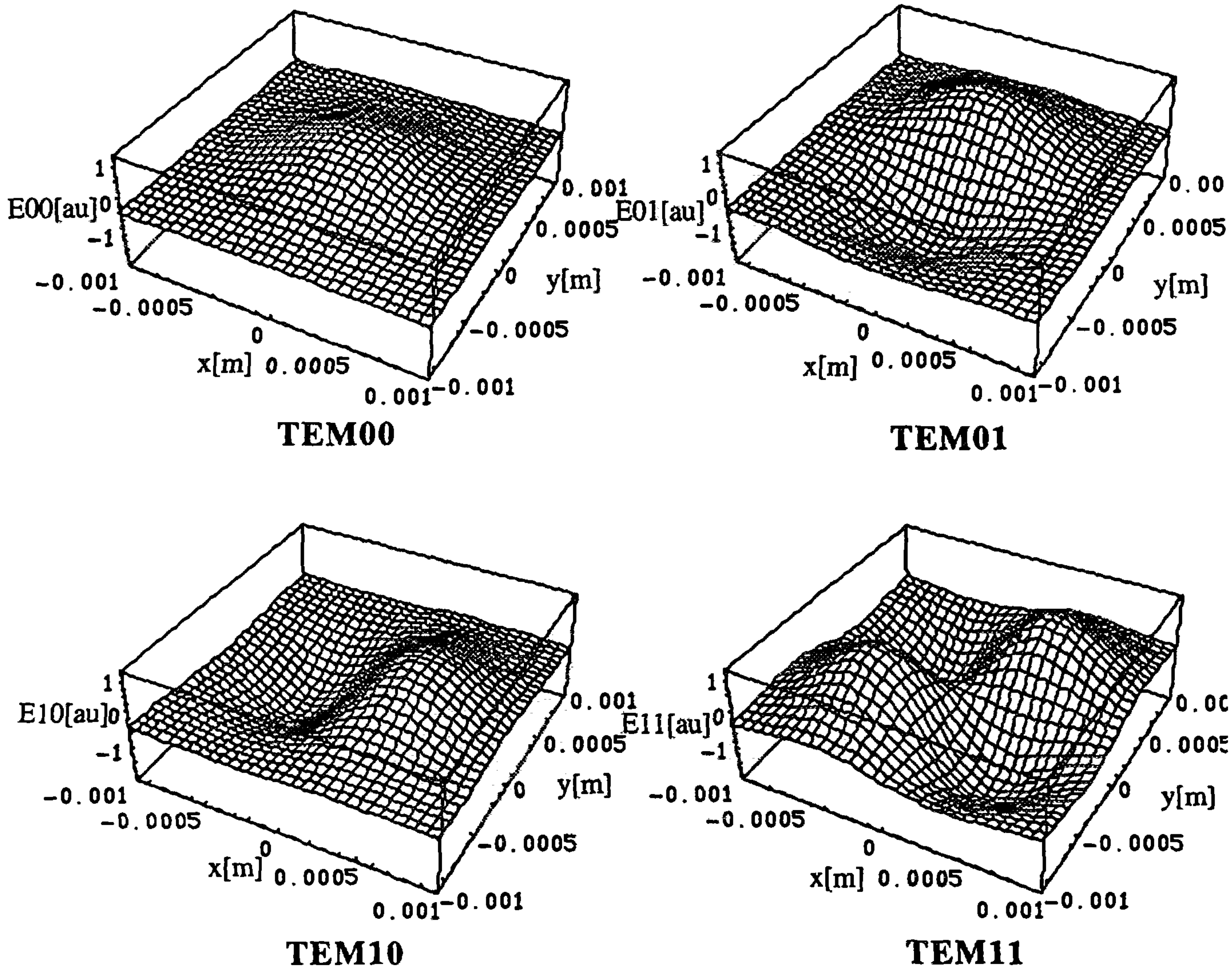


Fig.13 Electric fields of some low-order optical beam modes.

5. Results

As discussed, to produce very high intensity monochromatic γ-rays it is important to selected mirrors with a good performance, and make a high Fresnal number resonator. In actuality, we must also consider reducing the radiation damage to the mirrors. To attain do this, the angle between the beam's axis and the resonator's axis and the spacing between mirrors must be chosen so it is large enough to avoid radiation from the interaction point. Large-radius mirrors could make a resonator with a large Fresnel number; we assume in the following discussions that such mirrors will be manufactured in the near future. The model parameters of the resonator are shown in Table.2.

Resonator (Confocal type)	
Mirror	
radius	0.1m
spacing	2.0m
curvature	2.0m
Fresnel number	5000
Pumping laser (CW laser)	
wave length	1.0μm
laser power	100W
Setting Angle	45°
Electron beam	
Average current	1A
Energy	1GeV
Beam size	1mmϕ
Electron flux:Fe	6.25*10^18(e-/s)

Table.2 Initial parameters used to calculate the production of γ-rays using an optical resonator.

To roughly estimate the production of γ-rays, the following formulae were used:

$$N_p = \left(I_r \times W_{laser} \times \frac{L}{c} \right) / J_{laser} \tag{12}$$

$$F_\gamma = F_e \times \frac{N_p}{V} \times I_{int} \times \frac{d\sigma}{d\Omega} \times \Delta\Omega : \tag{13}$$

$$Eff = \frac{\Sigma P_\gamma}{\Sigma P_e + \Sigma P_{ph}} : \tag{14}$$

where N_p is the quantity of photons in the resonator, W is the power of the incidental laser in unit of Watts, and J is the energy of laser photon in unit of Joules. V is the volume of photon beam, F_γ, F_e is the flux of γ-rays and electrons, I_{int} is the effective interaction length, and $d\sigma/d\Omega$ is the differential cross-section obtained by the Klein-Nishina formula. The efficiency of generation of γ-rays is defined by the ratio γ-rays' power vs. electron and initial photon power. If $\Delta\Omega$ is chosen $1/\gamma$, and I_{int} is equal to the beam size(~1mm), we obtain some interesting values. Thus, the photon beam's minimum spot size in the resonator is 1.13mmϕ, and its size on the mirror is 1.60mmϕ. Table.3 shows the results of the calculations.The γ-ray flux generated depends greatly on the reflectance, absorptance, and the transmittance of the mirrors used in the resonator. If the reflectance of the mirrors comes up to 6N, the flux of γ-rays attained is of the order of 10^18, and its possible efficiency is 0.6%. This case is readily achievable using recent technologies. However, considering the cost of producing the γ-rays, these values are not high enough to apply to the transmutation plan. To recover the energy for the accelerator and the laser is needed. If future technologies can make a mirror of 8N, so that the γ-rays flux obtained is of the order of 10^20, and its efficiency is more than 30%, then the method would be applicable. As another way to generate intense γ-rays, a concentric resonator whose spacing between mirrors is double that of the confocal cases has been proposed. In this case, the size of the beam's minimum spot is smaller than that of the confocal type, and the density of photon's beam in the interaction point is also higher, so that a γ-ray flux of the same order as of the 8N mirror can be achieved.

γ-ray Emax:15MeV	R=4N A=20ppm	6N 0.5ppm	8N 0.001ppm	Concentric 6N, 0.5ppm
Photon power[GW]	1.3*10^-3	0.2	11	0.2
Photon quantity:Np	4.2*10^16	6.7*10^18	3.7*10^20	1.3*10^19
γ-ray flux:Fγ [1/s]	1.6*10^16	2.5*10^18	1.4*10^20	1.6*10^20
Efficiency:Eff	0.0038%	0.6%	33.7%	38.4%

Table.3 Estimations of γ-rays flux and efficiency for each type of optical resonator.

6. Summary

One of the proposed sources of γ-rays to apply to the transmutation of nuclear wastes has been considered. This method used inverse Compton scattering with an optical resonator composed of very high reflectance and low absorptance mirrors. Assuming the use of recent advances in technologies, the flux of γ-rays that can be attained is of the order of 10^18, and its efficiency is 0.9% using this method. If future progress allows us to make a mirror with a reflectance of 8N and an absorptance of 0.001ppm, it is possible that a flux could be generated in the order of 10^20, with an efficiency of more than 30%. In the case of a concentric resonator, the density of photon's beam in the interaction point can be higher than it is in a confocal type, so that a γ-ray flux of the same order as that of the 8N mirror is achieved.

7. Acknowledgements

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