INTENSE GAMMA-RAY SOURCE FOR POLARISED POSITRON BEAM GENERATION

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Abstract

In order to generate a polarised positron beam for a linear collider, an intense circularly polarised γ-ray generation is considered by passing a circularly polarised CO_2 laser beam through an optical lens series with periodic focal points, where a 5.8 GeV bunched electron beam is collided. It is shown by diffraction analysis that laser beam loss in the lens series is very small, and the beam size is reduced to 26 μm. The electron beam size is reduced to 34 μm in a superconducting solenoid with a field of 15 T. The laser power required for the γ-ray yield of 7×10^{15} γ/s for JLC is 24 kW. A single pass FEL amplification using the same electron beam at 560 MeV can produce 9.5 kW, which is not far away from the required power.

1 INTRODUCTION

A polarised positron beam for a linear collider can be generated by colliding a circularly polarised γ-rays with a metal target. Such γ-rays are generated by colliding a high energy electron beam with a circularly polarised laser beam. Recently, it was proposed to use 40 sets of 3.2 kW CO_2 lasers, the power of which are provided into 40 sets of parabolic mirrors to focus the laser beam, where a 5.8 GeV bunched electron beam is collided in series for the polarised γ-rays (Proposal I)[1].

Since a high quality optical lens is commercially available at a wavelength of 10.6 μm, we consider to use an optical lens series with periodic focal points, where the electron beam is collided for γ-rays. Each lens has a hole to pass the electron beam and the generated γ-rays. If laser beam loss is small in such a lens series, and laser and electron beam sizes are small enough, we can significantly reduce the laser power required for the γ-ray yield 7×10^{15} γ/s assumed in the above proposal. In addition, as another candidate for the CO_2 laser, a single pass FEL amplification using the same electron beam is discussed.

2 LASER BEAM OPTICS

Figure 1 shows the schematic structure of the present optical system, which is composed of 20 unit cells made of focal lenses with a cell length L_c = 210 mm, and provides periodic focal points. The electron and laser beams with 85 bunches and 104 pulses, separated each by 1.4 ns or 420 mm, are collided at the focal points. As shown in Fig.2, the initial laser beam with a Gaussian distribution with a size σ_{r00} = 2 mm, is expanded by a circular cone to a hollow beam with a hollow radius r_0 = 3 mm, and passed through the lenses. Each lens has an aperture D_a (= $2r_1$) = 30 mm, and a hole with a diameter D_h (= $2r_1$) = 6 mm to pass the electron beam and the generated γ-rays with an energy higher than 1 MeV.

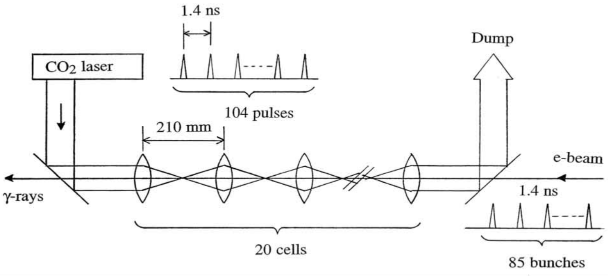

Figure 1: Schematic structure of optical lens system for Compton backscattering.

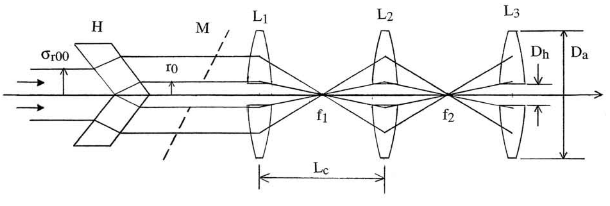

Figure 2: The initial part of the optical lens system.

In geometric optics, we expect no laser beam loss except for the lens loss due to reflection and absorption, and zero beam size at the focal points. The beam size is, however, expanded by aberrations of the lenses and also by diffraction effects. Among several kinds of aberrations, only the spherical aberration is considered here, since the focused beam size is very small. According to a numerical calculation, the aberration of a conventional lens with a focal length of 105 mm is expressed as $W(\mu m) = \xi r^4$ with $\xi = -9.06 \times 10^{-4}$ for a radius r(mm). The effects of the aberration on the laser beam profiles

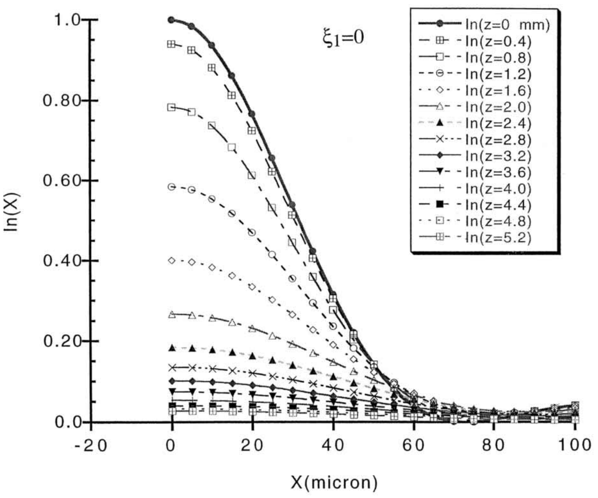

Figure 3: Normalised laser beam profiles at the first focal point in the case of no aberration.

are considerably large and accumulated algebraically, so that it is necessary to reduce the aberration significantly. The aberration can be reduced in principle to zero by modifying the spherical surface of the lenses.

By applying the Fresnel-Kirchhoff diffraction analysis, the laser beam profile is calculated numerically. Figure 3 shows the normalised profiles against the horizontal position X at the first focal point for different longitudinal position Z in the case of no aberration. The profiles are nearly Gaussian for X, and are well fitted by

$$I_n = a(Z) + b(Z) \exp[-X^2/2\sigma_r(Z)^2],$$

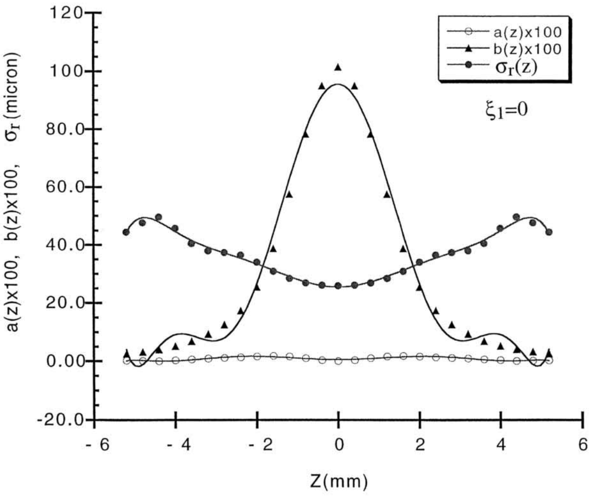

Figure 4: The parameters a(Z), b(Z) and $\sigma_r(Z)$ for the profiles at the first focal point. The solid lines are fitted with polynomials of Z up to the ninth power.

Table 1: Parameters of polarised γ-ray generation.

<table>
<tr><th></th><th>Proposal I</th><th>This work</th><th></th></tr>
<tr><td>Electron beam</td><td></td><td></td><td></td></tr>
<tr><td>Beam energy</td><td colspan="2">5.8</td><td>GeV</td></tr>
<tr><td>Normalised emittance</td><td colspan="2">10</td><td>mm mrad</td></tr>
<tr><td>Number of electrons</td><td colspan="2">10^{11}</td><td>per bunch</td></tr>
<tr><td>Number of bunches</td><td colspan="2">85</td><td>per train</td></tr>
<tr><td>Bunch length</td><td colspan="2">0.9</td><td>μm</td></tr>
<tr><td>Beam size</td><td>21</td><td>34</td><td>mm</td></tr>
<tr><td>CO$_2$ laser beam</td><td></td><td></td><td></td></tr>
<tr><td>Wavelength</td><td colspan="2">10.6</td><td>μm</td></tr>
<tr><td>Pulse length</td><td>3</td><td>3(0.9)</td><td>mm</td></tr>
<tr><td>Beam size</td><td>15.5</td><td>26</td><td>μm</td></tr>
<tr><td>Pulse energy</td><td>0.25</td><td>1.5</td><td>J</td></tr>
<tr><td>Number of pulses</td><td>85</td><td>104</td><td>per train</td></tr>
<tr><td>Laser power</td><td>3.2</td><td>24</td><td>kW</td></tr>
<tr><td>Number of lasers</td><td>40</td><td>1</td><td></td></tr>
<tr><td>Compton backscattering</td><td></td><td></td><td></td></tr>
<tr><td>Repetition frequency</td><td colspan="2">150</td><td>Hz</td></tr>
<tr><td>g-ray yield</td><td colspan="2">$7x10^{15}$</td><td>γ/s</td></tr>
<tr><td>Number of cells</td><td>40</td><td>20</td><td></td></tr>
<tr><td>Reduction factor</td><td>?</td><td>0.60(0.87)</td><td></td></tr>
</table>

The parameters a(Z), b(Z) nd $\sigma_r(Z)$ are shown in Fig.4, which are symmetric for ±Z. the beam size is minimum σ_{r0} = 26 μm at Z = 0 and gradually increases with Z. Almost the same profiles are obtained at the second focal points. The integrated intensity of the profiles is 0.99979 and 0.99351 at the first and second focal points, respectively, which suggests a weak beam loss. According to a symmetry consideration of the optical system and Fourier transformation of the profiles, however, no beam loss is expected. In the presence of aberration with the magnitude for a conventional lens given above, the profiles are nearly the same as those without aberration, but the minimum size position is shifted to Z ≈ 2.8 mm.

3 GAMMA-RAY YIELD

The electron beam size is reduced by an arrangement of quadrupole magnets in the injection beam line to a minimum size 34 μm at the entrance of a super-conducting solenoid with a field of 15 T, then the beam size is kept constant in the solenoid. Since the critical current of Nb$_3$Sn is not very high in such a high field, the solenoid needs a large amount of wire.

The lens made of ZnSe has a refraction index of 2.4028, a bulk absorption coefficient of 0.05 %/cm and a reflectivity smaller than 0.2 % by special coating. The γ-ray yield is given by

$$Y = \frac{n_e n_{s0} \eta N_b N_c f_r \sigma_T F_r}{2\pi\left(\sigma_{x0}^2 + \sigma_{r0}^2\right)}$$

where n_e(= 10^{11}e/bunch) and n_{s0} are the number of electrons and initial photons per bunch and pulse, respectively, η(= 0.97) is the average transmission factor due to the laser beam loss, N_b is the number of electron bunches, f_r(= 150 Hz) is the repetition frequency of bunch and pulse trains, σ_T is the cross section for Thomson scattering, and F_r is the reduction factor due to the increase of laser beam size along Z axis. We have F_r = 0.60 for the electron bunch length σ_z = 0.9 mm and laser pulse length σ_{sz} = 3 mm. Accordingly, we need a laser power P_L = 24 kW for the required γ-ray yield. In the presence of aberration discussed above, the reduction factor is decreased to 0.41. Meanwhile, if the laser pulse length is reduced to 0.9 mm, the required laser power is decreased to 16 kW. The parameters of the present work are summarised in Table 1 in comparison with Proposal I.

4 SINGLE PASS FEL AMPLIFICATION

As another candidate for the laser source, a single pass FEL amplification is considered using the same electron beam at an energy of 560 MeV as that for the Compton backsacttering. The electron beam size is reduced to $\sigma_{x,y}$ = 0.16 mm by a high field gradient of ± 100 T/m produced by permanent quadrupole magnets with an inner and outer radius of 20 and 77 mm, respectively. The Pierce parameter for the FEL is given by [2]

$$\rho = \left(K^2 \lambda_0^2 r_e n_0 / 16\pi\gamma^3 \right)^{1/3}$$

where K is the wiggler parameter, λ_0 is the wiggler period, r_e is the classical electron radius, n_0 is the electron density and γ is the relativistic factor of electron energy. The helical field for a circularly polarised FEL radiation is produced by a superconducting helix coil installed in the inner space of the quadrupole magnets. Using the parameters given in Table 2, we have ρ = 0.068, and expect an average power P_L = 9.5 kW, which is not far below than the required laser power.

Table 2 : Parameters of a single pass FEL amplification.

Electron beam			
Beam energy	E	560	MeV
Energy spread	σ_ε/E	1	%
Beam size	$\sigma_{x,y}$	0.15	mm
Electron density	n_0	1.5×10^{15}	e/m^3
Peak current	I_p	1.9	kA
Helical wiggler			
Period	λ_0	20	cm
Peak field	B_0	0.6	T
K-parameter	K	11.2	
Number of period	N_w	15	
Total length	L_w	300	cm
FEL			
Wavelength	λ_s	10.6	µm
Pierce parameter	ρ	0.068	
Saturation peak power	P_{sat}	72	MW
Average power	P_L	9.5	kW
Pulse energy	E_J	0.61	J
Number of pulses	N_p	104	
Repetition frequency	f_r	150	Hz

5 SUMMARY AND CONCLUSION

In the present paper, we have simply described a γ-ray generation in an optical lens series. The CO_2 laser beam is focused periodically to a size of 26 µm, and laser beam loss is very small. The required γ-ray yield is expected to be obtained by a laser power of 24 kW, which is significantly lower than the total power in Proposal I. The power is decreased to 16 kW if the laser pulse length is reduced to 0.9 mm. A single pass FEL amplification using the same electron beam at 560 MeV is expected to produce 9.5 kW, which could be another candidate for the laser source with some improvements.

REFERENCES

[1] T. Omori et.al., KEK Preprint 98-13, TMU/EXP 98-10, 1998.

[2] J. B. Murphy and C. Pellegrini, J. Opt. Soc. Am. B **2** (1985) 259.