

GAMMA RAY SOURCES BASED ON RESONANT BACKSCATTERING OF LASER BEAMS WITH RELATIVISTIC HEAVY ION BEAMS*

†E.G.Bessonov and *Kwang-Je Kim

†*Lebedev Phys. Inst. of the Russian Academy of Sciences, Moscow, Russia.*

**Lawrence Berkeley Laboratory, Berkeley, CA 94720 USA*

Abstract

Resonant backscattering of high-power laser beam with non-fully stripped, ultra-relativistic ion beams in storage rings is studied as a source for γ -ray beams for elementary particle physics experiments. The laser frequency is chosen to be resonant with one of the transition frequencies of the moving ions, and the bandwidth is chosen to cover the full Doppler broadening of the ions in the beam. Due to the resonance, the scattering cross section is enhanced by a large factor compared to the Thomson cross section, of the order 10^8 for some examples considered here. The performance of the LHC as a possible γ -generator or a γ - γ collider is estimated. We study the case where hydrogen-like Pb ions with 2.8 TeV per nucleon are scattered by a train of 1100 Å, 20 mJ laser pulses with the same pulse time format as the ion beam. A free electron laser can be designed satisfying the requirements. It is estimated that γ -rays of maximum quantum energy of 0.4 GeV at an average rate of $0.67 \cdot 10^{18}$ are generated in this scheme. The luminosity of the corresponding γ - γ collider will be about $0.9 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

I. INTRODUCTION

Compared to the case of Thomson scattering on free electrons, the scattering cross section of laser photons on bound electrons, when the photon energy is at resonance with one of the transition energies of non-fully stripped ions, is larger by many orders of magnitudes up to a factor $\lambda/4\pi r_e^2 \sim 10^{15}$ where λ is the laser wavelength and r_e is the classical electron radius[1-4]. Radiative cooling of ion beams has been recently proposed based on this observation [5]. With the large hadron storage rings currently being proposed or under construction, which can store high-Z ions such as Pb with an energy of several TeV per nucleon, the mechanism could also be the basis for a copious source of γ rays. As an example, we study the performance of the LHC[6] as a γ -ion or γ - γ collider when it operates as a collider for Pb ions at CM energy of 1120 TeV. The transition energy is about 60 keV, which corresponds to a laser wavelength of about 1100 Å in the laboratory frame. The laser intensity is chosen to be the saturation intensity. The Rayleigh length is chosen to be about the rms pulse length of the ion beam. It is found that several thousands γ -photons are generated per ion. With a distance about 15 cm between the ion- γ conversion point and the interaction point, which is sufficient to deflect the ion beam by two sigmas of the beam spot size, we estimate that the luminosity of

a γ - γ collider based on the resonant backscattering at the LHC will be about $0.9 \cdot 10^{33}$

II. SPONTANEOUS INCOHERENT γ -RAY SOURCES

Let a laser beam is directed against and scattered by an ion beam. Let $\hbar\omega_0$ be the transition energy *in the ion's rest frame* between two electronic states 1 and 2, and $\hbar\omega_0^L$ and $\hbar\omega_0^s$ be the corresponding energies of the incoming laser photons and the scattered photons in the laboratory frame, respectively. These quantities are related by

$$\begin{aligned}\hbar\omega_0^L &= \frac{\hbar\omega_0}{\gamma(1 - \beta \cos \psi)}, \\ \hbar\omega_0^s &= \frac{\hbar\omega_0}{\gamma(1 - \beta \cos \theta)},\end{aligned}\quad (1)$$

where $\gamma = E/Mc^2 = 1/\sqrt{1 - \beta^2}$, E is the ion energy, M its mass $\beta = v/c$, v the ion velocity, c the speed of light ψ the angle between the initial photon velocity and ion velocity, and θ the angle between final photon velocity and ion velocity. In this paper, we restrict to the case $\psi \simeq \pi$, $\beta \simeq 1$, $\gamma \gg 1$, in which case the above equations become

$$\hbar\omega_0^L \simeq \frac{\hbar\omega_0}{2\gamma}, \quad \hbar\omega_0^s \simeq \frac{2\gamma\hbar\omega_0}{1 + (\gamma\theta)^2}.\quad (2)$$

The frequency of the incoming laser photons and the scattered photons in the general case will be written as ω and ω^s respectively. Since we are considering the case near resonance in this paper, we have $\omega \simeq \omega_0^L$ and $\omega^s \simeq \omega_0^s$.

The scattering cross section of laser photons by an ion is given by[7]

$$\sigma_\omega = \frac{2\pi r_e c f \Gamma}{(\gamma\omega(1 - \beta \cos \psi) - \omega_0)^2 + \Gamma^2},\quad (3)$$

where r_e is the classical electron radius, f the oscillator strength, Γ the spontaneous linewidth given by $\Gamma = \omega_0^2 r_e c f g_1 / c g_2$, g_1 and g_2 are respectively the degeneracy factors of the state 1 (ground state) and state 2 (excited state) between which the transition occurs, and $\beta_z = \beta \cos \psi \simeq 1$.

The maximum cross-section at exact resonance $\omega = \omega_0^L$ is

$$\sigma_{max} = \frac{g_2 \lambda_0^2}{2\pi g_1},\quad (4)$$

where $\lambda_0 = 2\pi c/\omega_0$ is the resonance wavelength corresponding to ω_0 . Note that this is larger than the Thomson cross section by a factor of about $(\lambda_0/r_e)^2$, which is a very large factor.

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When the ion beam has an angular spread, $\Delta\psi$, and energy spread, $\Delta\gamma$, then, for effective interaction of all ions with the photon beam, the bandwidth $\Delta\omega$ of the incoming laser should satisfy

$$\frac{\Delta\omega}{\omega} \simeq \frac{(\Delta\psi)^2}{4} + \frac{\Delta\gamma}{\gamma}. \quad (5)$$

This follows from eq(1). The bandwidth $\Delta\omega$ given by eq(5) is usually much larger than the width of the transition frequency in the laboratory frame, i.e., $\Delta\omega \gg \Gamma/2\gamma$. Assuming for simplicity that the spectral intensity of the laser beam I_ω (power per unit area per unit frequency) is distributed uniformly in the frequency range $\Delta\omega$ so that the $I_\omega = I/\Delta\omega$, where I is the intensity (power per unit area), then the average cross-section of the photon scattering by ions is

$$\bar{\sigma} = \frac{1}{I} \int \sigma_\omega I_\omega d\omega = \pi r_e f \lambda_0 \frac{\omega}{\Delta\omega}. \quad (6)$$

The enhancement of the resonant cross section over the Thomson cross section for a broad band laser is about a factor $(\lambda_0/r_e)(\omega/\Delta\omega)$, which is smaller than that in the case of exact resonance, but is still very large. It is about 10^8 in our example later.

The number of scattered photons per ion is given by

$$\Delta n_\gamma = 2 \frac{\bar{\sigma}}{(1+D)} \left[\frac{I}{\hbar\omega} \right] \left[\frac{l_{eff}}{c} \right]. \quad (7)$$

The factor of 2 is due to the fact that relativistic particle and laser photons are making a head-on collision. The factor $(1+D)$ in the denominator is due to the saturation effect, i.e., the fact that the level populations reach an equilibrium via competition between the absorption, stimulated emission and the spontaneous emission[6]. The quantity $D = I/I_{sat}$ is the saturation parameter, $I_{sat} = (\pi c g_1 \hbar \omega_0 / \gamma^2 g_2 \lambda_0^3) (\Delta\omega/\omega)$ and l_{eff} is the effective interaction length of the laser and ion beams, which is assumed to be much longer than the spontaneous decay length $c\tau_{spont} = c\gamma/2\Gamma$ in the laboratory frame. If there are N_i number of ions in the pulse, the total number of γ -ray photons generated per ion pulse is given by $N_\gamma = \Delta n_\gamma N_i$.

Let us now consider the transition between the first excited state (principal quantum number $n = 2$) to the ground state ($n = 1$) to the ground state of a hydrogen-like ion with atomic number Z . In this case, we have $f = 0.42$, $g_1 = 1$, $g_2 = 2^2 = 4$, $\hbar\omega_0 = 3\alpha^2 m_e c^2 Z^2 / 8 \simeq 10.19 Z^2$ [eV], $\lambda_0 \simeq 1.22 \cdot 10^{-5} / Z^2$ [cm], $c\tau_{spont} \simeq 63.4\gamma / Z^4$ [cm], $I_{sat} = 21.2 (Z^8 / \gamma^2) (\Delta\omega/\omega)$ [MW/cm²], and $\Delta n_\gamma = 7.85 \cdot 10^{-3} Z^4 l_{eff} [cm] / \gamma (1+D)$.

The scattered radiation will be polarized if we will use polarized initial laser radiation. It will be possible to change the kind of polarization by changing the kind of initial polarization.

The spectral distribution of the scattered power is of the form

$$\bar{P}_\omega^s = \frac{d\bar{P}^s}{d\omega^s} = \frac{3\bar{P}^s}{\omega_{max}^s} \xi (1 - 2\xi + 2\xi^2), \quad (8)$$

where $0 \leq \xi = \omega^s / \omega_{max}^s \leq 1$, $\omega_{max}^s \simeq 2\gamma\omega_0$ is the maximum energy of the scattered photons.

III. A γ - γ and γ -ION COLLIDER BASED ON THE LHC

Consider now γ -ray generation in straight sections of high energy ion storage ring. A counter propagating laser beam is focused with a waist close to the ion beam waist. Since the the γ -ray production rate, is proportional to $D/(1+D)$, as can be seen from eq(7), the laser intensity I is optimized at $I \simeq I_{sat}$. When the ion beam emittance is, as is usually the case, much smaller than the radiation emittance, $\simeq \lambda/4\pi$, the effective interaction length l_{eff} is about twice the Rayleigh length z_R of the laser beam. For most efficient interaction, we choose z_R to be about the rms bunch length of the ion beam σ_{iz} . We also choose the length of the laser pulse to be about $2\sigma_{iz}$. Given these parameters, we obtain the peak laser power by $P_L = (z_R \lambda / 2) I$ and the laser pulse energy by $W_L \simeq (2\sigma_{iz}) P_L$.

The relevant parameters for the LHC operating as a collider for hydrogen-like Pb ions are[6]; $Z = 82$, $\gamma \simeq 3000$, $N_i = 9.4 \cdot 10^7$, bunch separation 135 ns, the rms beam transverse size $\sigma_{ix} = 1.2 \cdot 10^{-5}$ m, $\sigma_{iz} = 7.5$ cm, $\Delta\gamma/\gamma = 2 \cdot 10^{-4}$.

Following the above procedure, we find the following laser parameters: $\lambda = 1100$ Å, the pulse energy $W_L = 20$ mJ, pulse length $\simeq 500$ ps, peak power $P_L = 40$ MW, average power $\bar{P}_L = 150$ kW, and the required bandwidth $\Delta\omega/\omega \simeq 2 \cdot 10^{-4}$. A free electron laser can be designed that can meet these requirements. The only extension of the current technology would be in the mirror reflectivity at 1100 Å, but the problem could be solved by grazing incident cavity design, etc.

With these parameters, the maximum photon energy of the γ -rays is 0.4 GeV, Δn_γ is $0.9 \cdot 10^3$, and that per pulse is $0.85 \cdot 10^{11}$, and time averaged rate is $0.67 \cdot 10^{18}$ photons per second. This is indeed a very copious source of γ -rays.

A high energy ion-ion collider can therefore be converted to a γ - γ or γ -ion collider with the photon energy in the GeV range, just as a high energy electron linear collider in TeV range can be converted to a TeV γ - γ collider[8]. Assuming 1T magnetic field, a distance $b \simeq 14$ cm is required to deflect the ion beams by a distance of twice the rms spotsize. This will be the distance between the conversion point to the γ - γ interaction point. Due to the opening angle $\simeq 1/\gamma$ of the γ -rays, the cross sectional area at the interaction point is $S_\gamma \simeq \pi(b/\gamma)^2$. The luminosities $L_{\gamma\gamma}$, and $L_{\gamma i}$ of γ - γ , and γ -ion collisions are given by:

$$L_{\gamma\gamma} = \frac{N_\gamma^2 f}{S_\gamma}, \quad L_{\gamma i} = \frac{N_i N_\gamma f}{S_\gamma}, \quad (9)$$

where f is the collision frequency. For the above example, we find $L_{\gamma\gamma} \simeq 0.9 \cdot 10^{33}$ and $L_{\gamma i} \simeq 0.93 \cdot 10^{30}$.

IV. CONCLUSION

In this paper, we have studied the performance of highly relativistic ion storage rings as a γ - γ collider, when laser photons are converted into γ photons through resonant backscattering process. The perturbation on ion beam in such a process extremely gentle, and will not affect the ion beam dynamics. Nevertheless, we have seen that it gives rise to a very intense γ -ray source.

In this paper, we have only considered the example of hydrogen-like Pb ions at the LHC. Similar calculations can clearly be repeated for other ions and also for other machines

such as RHIC. Lower energy machines or lower Z ions may be interesting as high intensity x-ray generator. We will report on these calculations in a future publication.

References

- [1] K.A.Ispirian and A.T.Margarian, Phys. Lett. 44A (5) (1973), 377
- [2] N.G.Basov, A.N.Oraevsky, B.N.Chichkov, Sov. Phys. JETP, Vol.62(1), (1985), 37.
- [3] L.D.Miller, Optics communications, 30 (1979), 87.
- [4] G.C.Baldvin and N.J.DiCiacomo, IEEE Transactions on Nucl. Sci., Vol. NS-30, No 2 (1983), 891.
- [5] E.G.Bessonov, Preprint FIRAS No 6, 1994; E.G.Bessonov and Kwang-Je Kim, in preparation.
- [6] G. Brianti, Proceedings of PAC-93, pp 3917(1993).
- [7] See, for example, R.Loudon, The quantum theory of light (Clarendon Press, Oxford, 1973).
- [8] V. Telnov, Nucl. Instr. Meth., A 355, 3 (1995)