ON THE PULSAR SECONDARY ELECTRON-POSITRON PLASMA PRODUCTION IN LOW-ENERGY REGION

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An analytical description of low-energy falling-off of the secondary electron and positron distribution functions is proposed with the account of the effect of the inverse Compton scattering (ICS) on particle acceleration and plasma production. The resulting particle distribution with the described low-energy falling-off may lead to the instability in magnetosphere plasma.

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1. INTRODUCTION

It is known that a pulsar activity is related to ultrarelativistic electron-positron plasma which is produced near neutron star polar cap (PC) and moves along open magnetic force lines [1,2]. The plasma production is determinated by the neutron star rotation in super-strong magnetic field (about 10^{12} G). It results from the particle acceleration in a vacuum gap above the polar cap which is a part of open force line region where a longitudinal (along the magnetic field) electric field exists. The plasma production process undergoes in several steps [2,3].

Electrons being torn from the pulsar surface are accelerated in the longitudinal field of the gap up to gamma-factors $\Gamma_{pr} = \varepsilon_{pr} / mc^2 \geq 10^7$. There are two mechanisms of energy losses for such electrons – a curvature radiation (CR) and an inverse Compton scattering (ICS). CR arises due to motion of fast electron along curved magnetic force line; the energy maximum of CR belongs to frequencies $\sim 0.3\omega_{cr}, \omega_{cr} = 3c\Gamma_{pr}^3 / 2R_c$, with R_c being a curvature radius of magnetic force line. ICS of primary electrons may take place by photons of thermal emission of hot polar cap (with temperature about 10^5 K [4,5]), by the pulsar low-frequency emission near light cylinder [2] and by low-energy photons of eigenmodes of the gap [6]. In this work we are to consider the last factor influence.

CR and ICS photons propagating in the pulsar curved magnetic field create 1-st generation electron-positron pairs. The electrons and positrons of 1-st generation are born at high Landau levels going down to the normal state they emit synchrophotons which also are capable to produce pairs (of 2-nd generation).

In previous paper [7] we obtained the low-energy asymptotic of distribution function $f(\Gamma)$ with falling-off without influence of ICS. We showed that it was determinated by exponential factor $\exp\left(-\Gamma_0^2 / \Gamma^{-2}\right)$, where Γ_0 is the maximum position of the function $f(\Gamma)$. Here we consider the ICS acting on primary particle acceleration and pair production in low-energy region.

2. THE ICS ACTING ON THE PRIMARY ELECTRON ACCELERATION

The primary particle equation of motion in vacuum gap is [3]

$$c\frac{d\Gamma_{pr}}{dz} = \frac{e}{mc}E_{\|}(z) - \dot{\Gamma}_{pr}^{CR} - \dot{\Gamma}_{pr}^{ICS}, \tag{2.1}$$

where $E_{\|}(z)$ is the longitudinal electric field in the gap, $\dot{\Gamma}_{pr}^{CR}, \dot{\Gamma}_{pr}^{ICS}$ are the energy losses due to CR and ICS. They are given by

$$\dot{\Gamma}_{pr}^{CR} = \frac{2e^2\Gamma_{pr}^4}{3mc^2R_c^2}, \quad \dot{\Gamma}_{pr}^{ICS} = \frac{4\sigma_T u}{3mc}\Gamma_{pr}^2, \tag{2.2}$$

with $\sigma_T = (8\pi/3)(e^2/mc^2)^2$ being the Thomson cross-section and u being the energy density of low-energy radiation required for ICS.

The energy density u is a parameter characterizing the ICS acting on entire considered process. For the thermal emission of the pulsar polar cap one has $u \leq 10^6\,\text{erg/cm}^3$. For the low-energy radiation in the pulsar gap according to radio observation data we have $10^8\,\text{erg/cm}^3 \leq u \leq 10^{10}\,\text{erg/cm}^3$.

The detailed description of the primary electron acceleration process using the equation (2.1) has not been possible yet because there is not the exact solving of the problem about the determination of the longitudinal field with taking into account its screening by produced plasma. To obtain simple approximate solution and analytical estimations let us use the equation for the longitudinal field in framework of Arons' model [1]:

$$E_{\|}(z) \approx \frac{3\Omega B_s}{cR_{H3}} z(z_c - z)(1-\xi^2)\Theta(z_c - z), \tag{2.3}$$

where $\xi = \vartheta/\vartheta_{PC}$, $0 \leq \xi \leq 1$, ϑ is an angle between the magnetic axes and a line undergoing from the center of the star to the exit point of the given force line from polar cap. $\vartheta_{PC} \approx \sqrt{\Omega R_{H3}/c}$ is an angle radius of the polar cap and a value z_c is the gap height depending on ξ.

According to the procedure from [7], let us estimate characteristic length at which the energy losses due to

ICS become dominant and corresponding primary electron gamma-factor. If CR dominates then the estimation of the height z_{CR} at which the energy losses due to CR almost compensate acceleration process, is given by [7]

$$z_{CR} \approx \left(\frac{3R_c^2}{2r_e}\right)^{1/7} \left(\frac{R_{H3}c^2}{3\omega_H \Omega z_c}\right)^{3/7},$$

where $r_e = e^2/mc^2, \omega_H = eB_s/mc$. For pulsar parameters $P = 0.1$ s, $B_s = 1.3 \cdot 10^{12}$ G, $z_c \approx 2 \cdot 10^4$ cm we have $z_{CR} \approx 1.2 \cdot 10^4$ cm, the numerical solving of the equation (2.1) gives the dependence $\Gamma_{pr} = \Gamma_{pr}(z)$, shown in Fig. 1 (curve 1). The estimation of the maximum gamma-factor of primary electron is

$$\Gamma_{pr}^{\max} \approx \left(3R_c^2/(2r_e z_{CR})\right)^{1/3} \sim 10^7 .$$

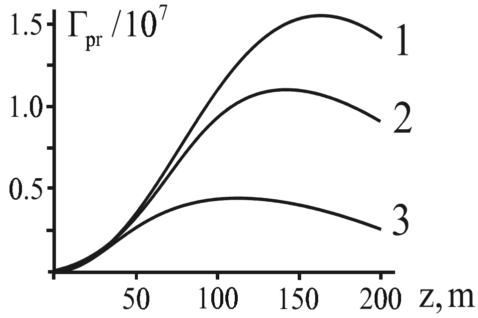

Fig. 1. *The dependence of primary particle gamma-factor on height z for various mechanisms of losses: 1–without ICS [7]; 2–with ICS ($u = 10^7$ erg/cm^3); 3–with ICS ($u = 10^9$ erg/cm^3)*

Let us consider the ICS acting on primary particle acceleration with various values of u. From (2.2) we obtain the value of gamma-factor $\Gamma_{pr}^{(eq)}$ at which the energy losses due to CR and ICS become comparable

$$\Gamma_{pr}^{(eq)} = R_c\sqrt{2\sigma_T u}/e . \tag{2.4}$$

If $\Gamma_{pr} >> \Gamma_{pr}^{(eq)}$ then the CR energy losses dominate, in opposite case ICS losses are significant and for the last case we have from (2.1): $eE_{\|}(z) \approx \sigma_T u \Gamma_{pr}^2(z)$ then the gamma-factor of primary particle is given by

$$\Gamma_{pr}(z) \approx mc^2/(\sigma_T u z), \quad z \sim z_{ICS}, \tag{2.5}$$

where z_{ICS} is a height at which the particle almost compensated by ICS. For z_{ICS} we obtain an equation

$$eE_{\|}(z_{ICS}) z_{ICS}^2 \approx (mc^2)^2/(\sigma_T u). \tag{2.6}$$

For the Arons' field (2.3) in case of $z_{ICS} << z_c$ we obtain the estimation for z_{ICS}

$$z_{ICS} \approx \left(\frac{(mc^2)^2 cR_{H3}}{e\Omega B_s z_c \sigma_T u}\right)^{1/3}, \tag{2.7}$$

The maximum value of gamma-factor is then

$$\Gamma_{pr}^{\max} \approx mc^2/(\sigma_T u z_{ICS}) \propto u^{-2/3}, \tag{2.8}$$

the estimations yield in this case $z_{ICS} \sim 10^4 ... 1.5 \cdot 10^4$ cm, and $\Gamma_{pr}^{\max} \sim 3 \cdot 10^6 ... 1.5 \cdot 10^7$ with low-energy radiation density 10^{10} erg/cm$^3 > u > 10^8$ erg/cm^3. The numerical integration of (2.1) with various values of u gives the dependences $\Gamma_{pr} = \Gamma_{pr}(z)$, shown in Fig. 1 (curves 2 ,3).

3. PAIR PRODUCTION BY CURVATURE RADIATION AND ICS PHOTONS

Let us consider the process of the electron-positron plasma production in the region above the pulsar vacuum gap. Distribution functions of photons N and produced particles f satisfy the kinetic equations (KE)

$$c\frac{\partial N}{\partial z} + \frac{3kcB'}{4R_c}\frac{\partial N}{\partial \varepsilon} = -w_\gamma(\varepsilon,k)N + q_{CR} + q_{ICS}, \tag{3.1}$$

$$c\frac{\partial f}{\partial z} = Q_{ICS}(\Gamma,z) + Q_{CR}(\Gamma,z), \tag{3.2}$$

where $k = \hbar\omega/mc^2$, β is an angle between the photon momentum and the magnetic field strength, $\varepsilon = 3kB'\sin\beta/4$ is a dimensionless photon energy, $B' = B/B_{cr}$, $B_{cr} = m^2c^3/(e\hbar)$, and $w_\gamma(\varepsilon,k)$ is a probability of pair production by a photon [8]. Functions q_{CR}, q_{ICS}, Q_{CR}, Q_{ICS} are sources for the photons and secondary plasma particles:

$$q_{CR} = \int F_{pr}(\Gamma_{pr}) P_{CR}(\Gamma_{pr},k) d\Gamma_{pr}, \tag{3.3}$$

$$q_{ICS} = \int F_{pr}(\Gamma_{pr}) N_{soft}(\vec{k}_1) w_{ICS} d\Gamma_{pr} d^3k_1, \tag{3.4}$$

$$Q_{CR} = \int w_\gamma N_{CR} \delta(\Gamma - 1/\sin\beta) d^3k, \tag{3.5}$$

$$Q_{ICS} = \int w_\gamma N_{ICS} \delta(\Gamma - 1/\sin\beta) d^3k, \tag{3.6}$$

$$w_\gamma = \frac{3^{1/2}\alpha_f c}{2^{5/2}\lambda\!\!\!^{-} k}\varepsilon e^{-2/\varepsilon}, \varepsilon \geq 3B'/2, \tag{3.7}$$

($\lambda\!\!\!^{-} = \hbar/mc$). The condition in (3.7) corresponds to the pair production threshold $k\sin\beta \geq 2$. N_{soft} is the distribution functions of photons of low-energy radiation in the gap, $F_{pr}(\Gamma_{pr}) = n_e\delta(\Gamma_{pr} - \Gamma_{pr}(z))$ is the distribution function of the primary electrons with the concentration n_e. The values P_{CR} и w_{ICS} are probabilities of the curvature radiation and ICS as functions of the energy of final photon [3, 9]

$$P_{CR}(\Gamma_{pr},k) = \frac{\sqrt{3}\alpha_f c}{2\pi R_c}\frac{\Gamma_{pr}}{k}\Phi\left(\frac{k}{k_c}\right), k_c = \frac{3\lambda\!\!\!^{-}}{2R_c}\Gamma_{pr}^3$$

$$w_{ICS} = \frac{5r_e^2}{2V\Gamma_{pr}^2(mc^2)^2}\frac{\delta\left(k - k_1\dfrac{1 - v_{pr}\cos\alpha}{1 - v_{pr}\cos\zeta}\right)}{k_1 k(1 - v_{pr}\cos\zeta)}, \tag{3.8}$$

with $\Phi(x) = x\int_x^\infty K_{5/3}(y)dy$, $v_{pr} = \sqrt{\Gamma_{pr}^2 - 1}/\Gamma$, and α is an angle between primary electron and initial soft photon momenta, ζ is an angle between primary electron and final photon momenta, V is a volume of region in which ICS is considered. Taking into account (3.8) one can rewrite (3.4) in a form

$$q_{ICS} = \frac{5\pi r_e^2 n_e}{V k \Gamma_{pr}^2(z)} \int dk_1 N_{soft}(k_1) \propto \frac{1}{k}. \quad (3.9)$$

In equations (3.5) and (3.6) $\delta-$ functions mean that a gamma-factor of secondary particle after synchrotron radiation is determinated only by the angle β of photon which produces the particle. Indeed, let γ be the electron (positron) gamma-factor before synchrotron emission. In pulsar magnetic field the relation [10] $\gamma = k/2$ takes place; let us calculate the particle gamma-factor after synchrotron emission. May the pair components are produced at Landau levels n_- and n_+ with angles θ_- and θ_+ to the magnetic field direction. As it is shown in [10], the pair production probability has a maximum under $\theta_- = \theta_+ = \theta$ and $n_- = n_+ = n >> 1$. Then from conservation of the momentum projection to the field direction

$$p_- \cos\theta_- + p_+ \cos\theta_+ = \hbar \frac{\omega}{c} \cos\beta$$

the relation between angles θ and β arises

$$2p\cos\theta = \hbar\omega\cos\beta / c, \; p = \sqrt{(\hbar\omega/2c)^2 - m_e^2 c^2},$$

or in an equivalent form

$$\sin^2\theta = (k^2 \sin^2\beta - 4)/(k^2 - 4). \quad (3.10)$$

Let us come to the frame K', where the particle motion along magnetic field is absent, the velocity of this frame is $v_{\|} = \cos\theta\sqrt{1-1/\gamma^2}$. After synchrotron emission the particle gamma-factor in this frame is to be $\Gamma' = 1$, returning to the initial frame we have

$$\Gamma = \Gamma' / \sqrt{1 - v_{\|}^2} = 1/\sqrt{\sin^2\theta + \cos^2\theta/\gamma^2},$$

then, using (3.10), we obtain $\Gamma = 1/\sin\beta$.

We find the solution of KEs (3.1) and (3.2) in a form

$$N = N_{CR} + N_{ICS}, \; f = f_{CR} + f_{ICS}, \quad (3.11)$$

and distributions $N_{CR}, N_{ICS}, f_{CR}, f_{ICS}$ satisfy equations

$$c\frac{\partial N_{CR}}{\partial z} + \frac{3ckB'}{4R_c}\frac{\partial N_{CR}}{\partial \varepsilon} = -w_\gamma(\varepsilon,k)N_{CR} + q_{CR},$$

$$c\frac{\partial f_{CR}}{\partial z} = Q_{CR}(\Gamma, z), \quad (3.12)$$

$$c\frac{\partial N_{ICS}}{\partial z} + \frac{3ckB'}{4R_c}\frac{\partial N_{ICS}}{\partial \varepsilon} = -w_\gamma(\varepsilon,k)N_{ICS} + q_{ICS},$$

$$c\frac{\partial f_{ICS}}{\partial z} = Q_{ICS}(\Gamma, z). \quad (3.13)$$

The solutions for N_{CR}, f_{CR} were obtained before [3] with the low-energy asymptotics [7]

$$N_{CR} = \frac{const}{k^2}\Phi\left(\frac{k}{k_c}\right)\phi(\varepsilon,k), \; z \geq \frac{4R_c\varepsilon}{3kB'},$$

$$\phi(\varepsilon,k) = \begin{cases} 1, & \varepsilon < 3B'/2 \\ \exp\left(-\dfrac{k_*^2}{k^2}\varphi(\varepsilon)\right), & \varepsilon \geq 3B'/2 \end{cases}, \quad (3.14)$$

$$k_*^2 = \frac{\alpha_f R_c}{2\sqrt{6}\lambda\!\!\!^{-} B'}, \quad \varphi(\varepsilon) = \int_{3B'/2}^{\varepsilon} x\, e^{-2/x}\, dx,$$

$$f_{CR}(\Gamma) = \frac{n_{CR}}{\eta_{CR}}\Gamma^{-2/3} e^{-\left(\frac{\Gamma_0}{\Gamma}\right)^2} \Theta\left(\Gamma - \frac{R_c}{z}\right), \quad (3.15)$$

$$\Gamma_0 \approx 0.4 B'\Lambda(k_m)\sqrt{\frac{\alpha R_c}{\lambda\!\!\!^{-}} e^{-\frac{4}{3B'}}}, \quad (3.16)$$

where n_{CR} is the concentration of the particles being produced by CR-photons and

$$\eta_{CR} = \int_{\Gamma_{min}}^{\Gamma_{max}} e^{-(\Gamma_0/\Gamma)^2}\Gamma^{-2/3} d\Gamma \quad (3.17)$$

is normalizing factor.

From (3.14) we see that under $k < k_c$ the CR-photon spectrum is a power-law: $N_{CR}(k) \sim 1/k^{5/3}$. The exponential decreasing of the photon distribution (3.14) in case of $k\sin\beta > 2$ ($\varepsilon \geq 3B'/2$) is explained by the resulting photon deficit due to intensive pair production. According to [3], the pair production process becomes the most effective when

$$k\sin\beta \approx \frac{4}{3B'\Lambda(k)}, \; \Lambda(k) = \ln\left(\frac{k_*}{k}\right). \quad (3.18)$$

In similar way we obtain the solutions for the distributions N_{ICS}, f_{ICS}, (ICS contribution). From (3.13) we have for the ICS-photon distribution

$$N_{ICS} = \text{const} \cdot \phi(\varepsilon,k)/k^2. \quad (3.19)$$

Substituting the formulae (3.6), (3.19) to the equation for f_{ICS} and integrating, we obtain for the secondary plasma distribution

$$\frac{\partial f_{ICS}}{\partial z} = \frac{4\Gamma}{R_c\Lambda^2} N_{ICS}\left(k = \frac{4\Gamma}{3B'\Lambda}, z; z_0\right). \quad (3.20)$$

Here $z_0 = z - s_\gamma$ is a height of photon emission point and s_γ is a photon path length. If $\beta << 1$ we have simple relation $s_\gamma \approx R_c\beta$. It can be obtained by writing the length of the interval between photon emission and pair production points and using the magnetic force line equation [2]: $s_\gamma^2 = (\vec{r} - \vec{r}_0)^2 \approx (\Delta r)^2$, $r = A\sin^2\vartheta$, where the parameter of the magnetic force line is introduced $A = R_L/\xi^2, R_L = c/\Omega$. For the photon emission point we have $r_0 = A_0 \sin^2\vartheta_0$. In case of $\vartheta, \vartheta_0 << 1$ and tiny changing of ξ (when one has $A \approx A_0$) we have $\Delta r = 2A\vartheta\Delta\vartheta$, the angle difference $\Delta\vartheta$ is related to β. Actually, having written the equations of tangent (using coordinates $z = r\cos\vartheta$, $y = r\sin\vartheta$) in the emission and the absorption points in a form $z = P_0 y + \text{const}$, and $z = Py + \text{const}$, with $P_0 = 2/3\vartheta_0$, $P = 2/3\vartheta$, we obtain $tg\beta \approx \beta = (P_0 - P)/(1 + P_0 P)$. From here we have a relation $\beta = 3\Delta\vartheta/2$. Thus we obtain

$$s_\gamma \approx \Delta r = 2r\Delta\vartheta/\vartheta = 4r\beta/(3\vartheta) = R_c\beta,$$

$R_c = 4r/(3\vartheta)$ being a curvature radius of the dipolar field force line.

Equations (3.18) and (3.20) lead to the following relation between Λ and Γ

$$3\Lambda\sqrt{\alpha_f R_c B'} = \Gamma e^{\Lambda}\sqrt{32\sqrt{6}\lambda}, \quad (3.21)$$

hence the factor Λ weakly (logarithmically) depends on Γ. It can be seen from (3.14) and (3.16) that the low-energy behavior of the produced particle distributions is determinated by an exponential factor

$$\exp\left(-\frac{\Gamma_0^2}{\Gamma^2}\right),\ \Gamma_0 \approx 0.4B'\Lambda(k_m)\sqrt{\frac{\alpha R_c}{\lambda}e^{-\frac{4}{3B'}}}. \quad (3.22)$$

From (3.20) we obtain

$$f_{ICS}(\Gamma) = \frac{n_{ICS}}{\eta_{ICS}\Gamma}e^{-\left(\frac{\Gamma_0}{\Gamma}\right)^2}\Theta\left(\Gamma - \frac{R_c}{z}\right)\Theta(\Gamma_{ICS} - \Gamma), \quad (3.23)$$

with n_{ICS} being the concentration (in a point with coordinate z) of the particles produced by ICS photons,

$$\eta_{ICS} = \int_{\Gamma_{\min}}^{\Gamma_{ICS}} e^{-(\Gamma_0/\Gamma)^2}\Gamma^{-1}d\Gamma \quad (3.24)$$

is a normalizing factor and Γ_{ICS} is a high-energy end of the spectrum, for which one can write

$$\Gamma_{ICS} = \frac{3}{4}B'k_{ICS}\Lambda(k_{ICS}),\ k_{ICS} \sim k_{soft}^{\max}\Gamma_{pr}^2(z), \quad (3.25)$$

where $k_{soft}^{\max}$ is a maximum value of k in the spectrum of low-energy initial photons.

4. THE RESULT DISCUSSION

We have shown that taking into account pair production by ICS photons leads to the appearance of the additional part in the spectrum of the secondary plasma particles of 1-st generation (3.23). According to (3.19) ICS-photons have a power-law spectrum $N_{ICS}(k) \propto k^{-2}$, that is why the power-law asymptotic of the distribution function of particles produced by ICS photons is given by $f_{ICS}(\Gamma) \propto \Gamma^{-1}$. The fast falling-off of the distribution function N_{ICS} with decreasing k (but still $k\sin\beta \geq 2$) is described by the same absorption coefficient $\phi(\varepsilon,k)$ (3.14), that in case of curvature radiation. There is an exponential factor $\exp\left(-\Gamma_0^2/\Gamma^2\right)$ which results from coefficient $\phi(\varepsilon,k)$ in the spectrum (3.23), describing the decreasing of the distribution function $f_{ICS}(\Gamma)$ in the low-energy region. The function (3.23) is a distribution function in a point z (point O in Fig. 2) and it is determined by all ICS-photons arriving to this point with various angles β (from different magnetic force lines).

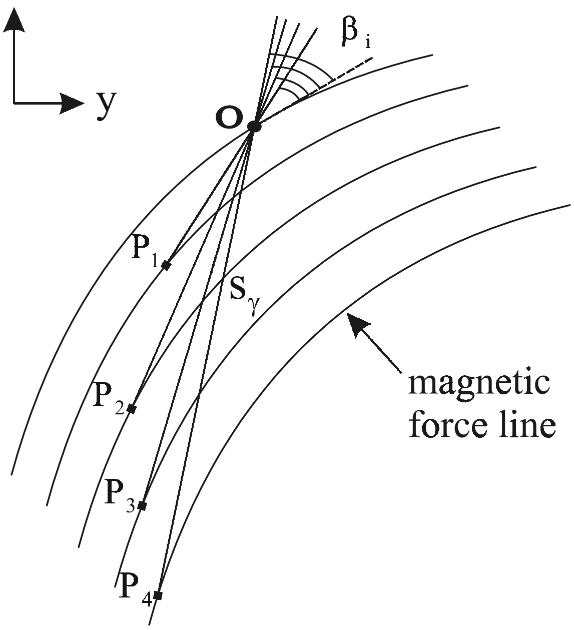

Fig. 2. A scheme demonstrating the secondary particle distribution in the point O, $P_1 ... P_4$ are photon emission points

In case of high values of energy density of low-energy radiation (which enters our model as a parameter) the particle production by ICS-photons may predominate over the pair production by CR-photons. In this case a transition when $\Gamma = \Gamma_{ICS}$ between ICS- and CR-part of the secondary particle spectrum is expected and after it remains only the part related to the curvature radiation. The distribution function of secondary plasma particle (with low-energy, ICS- and CR-asymptotics) normalized by the concentration is shown in Fig. 3.

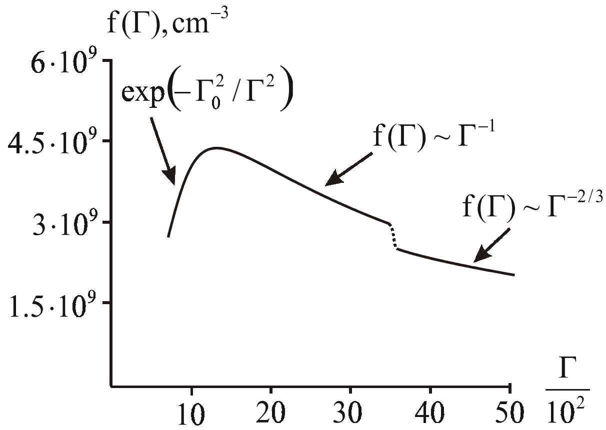

Fig. 3. The distribution function of the 1-st generation particles (in a point with $z = 2000$ m). The low-energy falling-off, CR- and ICS-asymptotics are shown

5. CONCLUSIONS

We have considered the ICS acting on the primary particle acceleration in the pulsar vacuum gap and the pair production by ICS-photons. It has been shown that in case of high values of the energy density of the soft radiation in the gap ICS energy losses may predominate over CR-losses and determinate the maximum value of primary particle gamma-factor.

The low-energy behavior of the distribution functions of the 1-st generation particles produced by curvature radiation and ICS photons has been considered in this work. It has been shown that the distributions contain exponential factor $\exp\left(-\Gamma_0^2/\Gamma^2\right)$, describing the fast distribution decreasing in the region of small gamma-factors. The expression for the distribution function maximum position has been obtained. We have obtained the ICS-photon distribution function and the distribution of the particle produced by ICS-photons.

It is important to note that the distribution functions of secondary plasma obtained in the work with low-energy falling-off may lead to arising of the flux instability and the wave generation that may be important for the pulsar radio emission theory.

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О ГЕНЕРАЦИИ ВТОРИЧНОЙ ЭЛЕКТРОННО-ПОЗИТРОННОЙ ПЛАЗМЫ В МАГНИТОСФЕРЕ ПУЛЬСАРА В ОБЛАСТИ МАЛЫХ ЭНЕРГИЙ

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Предложено аналитическое описание низкоэнергетического завала функций распределения электронов и позитронов, порождаемых в магнитосфере пульсара, с учетом влияния обратного комптоновского рассеяния на ускорение частиц и рождение пар комптоновскими фотонами. Возникающее распределение частиц вторичной плазмы с завалом в области малых энергий может приводить к развитию неустойчивости.

ПРО ГЕНЕРАЦІЮ ВТОРИННОЇ ЕЛЕКТРОННО-ПОЗІТРОННОЇ ПЛАЗМИ У МАГНІТОСФЕРІ ПУЛЬСАРУ В ОБЛАСТІ МАЛИХ ЕНЕРГІЙ

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Пропонується аналітичний опис низькоенергетичного завалу функцій розподілу електронів та позитронів, які породжуються у магнітосфері пульсару. Враховується вплив зворотного комптонівського розсіювання на прискорення часток та народження пар комптонівськими фотонами. Виникаючий розподіл часток вторинної плазми с завалом в області малих енергій може приводити до розвитку нестійкості.