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Coherent Radiation from Electron beams in Plasma Ion Channels

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Abstract

Relativistic electrons undergoing betatron motions inside plasma ion channel can produce synchrotron radiations ,and form bunches under the ponderomotive force produced by the electromagnetic radiation in resonance with the elctrons.The mechanism of the bunching and radiation process are presented in this paper.The difficulties of achieving a SASE ICL(Self Amplified Spontaneous Emission Ion Channel Laser)through coherent radiation process in ion channel are discussed and highlighted,with possible approaches to tackle with such difficulties offered.

Introduction

The significant progress in Free Electron Laser technology in recent years,especially in VUV and X-ray region, has enabled a number of potential applications in fields ranging from biological science to high-energy physics.Meanwhile,the limitations exhibited by traditional wigglers in X-Ray region,for which no effecitve reflective optical component exists,have also spurred interest in search for alternatives.Due to the strong electrostatic field produced by laser-plasma interactions,the utilization of plasma ion channel as a medium for either incherent and coherent radiation by electrons have attracted increasing interest. compared to static magnetic wigglers,the plasma wigglers have a number of potential advantages:the effective wiggler strength is much greaterïijŇthe betatron motion period and the wiggler strength are tunable through laser intensity,and the relative compactness of the whole device.In this article,we will focus mainly on the mechanism of the coherent radiation of the electrons,and the unique characteristics it presents ,which makes its SASE process worth further investigation.

The principles of ion channel laser

A beam of relativistic electrons injected into fully ionized plasma will undergo betatron oscillation uner the influence of the strong electrostatic field produced by the ions.Driven by a EM wave in resonance with the electrons,the electrons are going to form bunches under the ponderomotive force and produce synchrotron radiation at frequencies of $\omega_n = 2\gamma_{z0}^2 n\omega_\beta/(1+a_\beta/2)^{\frac{1}{2}}$,where $\omega_\beta$is the betatron frequency,which equals to $\omega_p/(2\gamma_{z0})^{\frac{1}{2}}$,where $\omega_p$is the plasma frequency ,and $\gamma_{z0}$is the initial electron kinetic energy,$a_\beta = \gamma_{z0} k_\beta r_\beta$is the betatron strength parameter which is analogous to the wiggler parameter of FEL,and $r_\beta$is the betatron amplitude which is different from electron to electron,and smaller than the beam radius r_b,which is in turn assumed to be smaller than the ion channel radius r_a.

The steady state regime

We start from the 1D motion equation of the electron motion inside the ion channel,if we consider the radial velocity of the electrons to be too small to affectγ,the motion of a electron is simply given by:

$$r = \rho_r sin(\theta_r), \tag{1}$$

$$p_r = \rho_r \theta_r^{'} cos(\theta_r), \tag{2}$$

$$p_z = \rho_z. \tag{3}$$

Now we introduce a perturbation by an electromagnetic wave with a vector potential of $-ia_r e^{i(kz-\omega t)}$and linearly polarized in the half angle between x and y axis for convenience,the electron equations of motion can be written down:

$$\begin{aligned} \frac{d\theta}{dz} &\simeq k(1-\frac{1}{\overline{\overline{\beta_{\|}}}}) + \frac{k_\beta}{\overline{\overline{\beta_{\|}}}} \\ &\simeq k_\beta (1-\frac{\gamma_r^2}{\gamma^2}) \qquad (4) \\ &\simeq 2k_\beta \eta_j \qquad (5) \end{aligned}$$

$$\begin{aligned} \frac{d\gamma}{dz} &= \frac{1}{\gamma} \frac{\partial (a_\beta e^{i\theta} - ia_r e^{i(kz-\omega t)})}{\partial t} (a_\beta e^{i\theta} - ia_r e^{-i(kz-\omega t)}) \\ &= -\frac{1}{\sqrt{2}\gamma} k a_\beta a_r e^{i\theta} \end{aligned} \tag{6}$$

and the field equation:

$$\begin{aligned} (\frac{\partial}{\partial z} + \frac{1}{c}\frac{1-\overline{\beta_{\|}}}{\overline{\beta_{\|}}}\frac{\partial}{\partial t}) a_r &= \frac{1}{2k}\frac{4\pi e^2}{mc^2}\frac{n_\perp}{l_{\|}} (\gamma_0 \omega_\beta \langle \frac{r_\beta e^{-i\theta}}{\gamma} \rangle - ia_r \langle \frac{1}{\gamma} \rangle) \\ &= \frac{k}{2} (\frac{\omega_e}{\omega})^2 (\gamma_0 \omega_\beta \langle \frac{r_\beta e^{-i\theta}}{\gamma} \rangle - ia_r \langle \frac{1}{\gamma} \rangle) \end{aligned} \tag{7}$$

The $\overline{\beta_{\|}}$is the average longitudinal velocity in terms of the speed of the light,which is approximately equal to 1 in the fast-wave limit.In the SASE regime however,the slippage due to the velocity difference is non-negligible.

The SASE regime

In order for SASE to occur,however,a number of requirements need to be met.To amplify the radiation,the gain must be larger than 1.Nevertheless,Since thepierce parameter of ion channel $\rho = \frac{1}{\gamma_r}(\frac{a_\beta}{4}\frac{\omega_e}{ck_\beta})^{2/3}$ is a function of the betatron amplitude rather than a constant , the average gain of the whole electron bunch $\overline{G}$should determine whether the total power of the radiation is amplified or not:

$$\overline{G} = 4\sqrt{3}\pi\langle\rho\rangle N_\beta \tag{8}$$

We assume the initial radial distribution of the electrons to be uniform,the averaged gain is thus:$\overline{G} = 2\sqrt{6}\pi\rho_b N_\beta$,where $\rho_b$is the pierce parameter for electron with betatron amplitude of the beam radius. We go on to define the gain length $l_g$and the cooperation lengthl_c:

$$l_g = \frac{\lambda_\beta}{2\sqrt{2}\pi\rho_b}$$
$$l_c = \frac{\lambda}{2\sqrt{2}\pi\rho_b} \tag{9}$$

It's also required,for SASE to occur,that the axial energy spread be much smaller than the average pierce parameter:$\frac{\Delta\gamma}{\gamma} < \rho$,weassume the initial kinetic energy of the electrons to be the same and apply the condition $\frac{d(\gamma-\Phi)}{dt} = 0$,it's not diffiuclt to find out$\frac{\Delta\gamma}{\gamma} \simeq a_\beta^2/4$in the small signal approximation,thus,for a matched beam with a beam radius of $r_{bm} = (\varepsilon_n/\gamma k_\beta)^{1/2}$,this implies the condition:

$$\lambda > \frac{\pi\varepsilon_n}{4\sqrt{2}\gamma\rho_b} \tag{10}$$

$$\tag{11}$$

where$\varepsilon_n$is the beam emittance,since $\rho$is usually much smaller than 1,this condition is much more stringent than the SASE FEL condition $\lambda > \frac{4\pi\varepsilon_n}{\gamma}$ In addition ,it's desirable that the radiation emitted have a narrow spectrum $\frac{\Delta\omega}{\omega} \ll 1$,which can only occur under the condition $a_\beta^2 \ll 1$.

Conclusion

The production of coherent narrow-band self-amplified radiation by the ion channel is significantly impeded by the radial position spread of the electrons,which prompts us the shortcomings of the one dimensional model, which do not take into account the coupling of the betaron motion and the transversal lorentz force as a bunching mechanism.It's possible that under the influence of the transversal ponderomotive force,the spread of the radial position of the electrons could become uch smaller,which leads to a smaller axial enrgy spread,the wakefield electron accelerator also provide novel electron source which could potentially offer electron beams with both narrow energy spread and position spread to utilize the potential of the ion channel light source.

References

[1] D.H.Whittum et al.Phys.Rev.Lett.**64**,2511(1990)

[2] E.Esarey et al.Phys.Rev.E.**65**,056505(2002)

[3] R.Bonifacio et al.Phys.Rev.A.**44**,R3441(1991)