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INFORMAL REPORT

**A PROTON LASER ACCELERATOR BY MEANS OF THE INVERSE FREE
ELECTRON LASER MECHANISM**

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A Proton Laser Accelerator by Means of the Inverse Free Electron Laser Mechanism*

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1. Introduction

The inverse free electron laser accelerator is considered to be a potential high gradient electron accelerator.^(1, 2, 3, 4, 5) In this accelerator electrons oscillating in the magnetic field of a wiggler can gain energy from a strong laser beam propagating collinearly.

The same mechanism of acceleration can work for protons and all other heavier particles. One can expect that the proton acceleration will be less effective, as it is more difficult to wiggle a heavier particle. It is indeed so, but this less efficient coupling of the proton and laser beam is partly compensated by the negligible radiative losses. These losses impose restrictions on the electron acceleration above 100 GeV.⁵

2. Equations of Motion

The equations describing the resonant acceleration of protons in a helical wiggler and circularly polarized EM plane laser wave are similar to those used for electrons,⁽¹⁻⁵⁾ except the synchrotron loss term can be neglected.

$$\frac{d\gamma_r}{dz} = A \frac{K}{\gamma} \sin \psi_r \quad (1)$$

where $\gamma = \epsilon_r / mc^2$, is the resonant energy in the rest mass units, $A = \frac{eE_L}{mc^2}$ and

E_L is the electric field strength of the laser beam.

The wiggler parameter K is

$$K = \frac{eB \Lambda}{2\pi mc^2} \quad (2)$$

where B_w is the magnetic field of the wiggler and Λ_w its period. For protons $K = 5.10^{-3} B[\text{kGs}] \Lambda_w[\text{m}]$, so it is rather difficult to build wigglers having $K \gg 1$. The acceleration phase is constant for resonant electrons. It should be chosen to provide a high acceleration gradient and stability of motion in the neighborhood of the resonant condition, $\pi/2 < \psi_r < \pi$.

The accelerator equation (1) must be supplemented by the resonant condition⁽¹⁻⁵⁾

$$2\gamma_r^2 \lambda = \Lambda_w (1 + K^2) \quad (3)$$

which relates the wavelength of the laser radiation λ with Λ_w , K and γ_r . When this condition is satisfied the phase of acceleration is constant and equal to ψ_r .

3. Accelerator Design

The resonant condition (3) can be satisfied by choosing the proper distribution of $B_w(z)$ and $\Lambda_w(z)$ along the accelerator length. Below we consider in more detail two types of accelerators: One in which the amplitude of the wiggler magnetic field is constant, $B_w = \text{const}$, while its period Λ_w is adjusted according to the growing particle energy, and the second, which has a constant value of the wiggler period, $\Lambda_w = \text{const}$, while B_w changes.

3a. Constant Field Accelerator

Using the resonant condition (3) and the definition of K , (2), the particle energy can be directly related to the value of the wiggler parameter K .

$$\gamma_r = \sqrt{\frac{\omega}{2\Omega} K(1+K^2)} \quad (4)$$

where ω is the radiation frequency and $\Omega = eB_w/mc$. Introducing this form into Eq. (1) we can establish the corresponding dependence of K along the accelerator. The equation for K is

$$\left(\frac{1}{K} + 3K\right) \frac{dK}{dz} = 4 \frac{\Omega}{\omega} A \sin \psi_r \quad (5)$$

with the solution

$$z = \frac{\omega}{4\Omega A \sin \psi_r} \left(\ln \frac{K}{K_0} + \frac{3}{2} (K^2 - K_0^2) \right) \quad (6)$$

The pair of Eqs. (4) and (6) gives a parametric dependence of the particle energy on the distance along the accelerator, $\gamma_r = \gamma_r(z)$. The initial value of the K parameter, K_0 is determined by the initial energy of injected particles.

Increasing the intensity of the laser radiation reduces proportionally the accelerator length. The acceleration gradient increases for stronger wigglers and lower frequencies of the radiation. Asymptotically, for values of $K \gg 1$, although for protons it might be difficult to fulfill this condition, we obtain

$$\gamma_r \approx \frac{16\Omega}{\omega} (A \sin \psi_r)^{3/4} z^{3/4} \quad (7)$$

Figure (1) illustrates the proton $B_w = \text{const.}$ accelerator with parameters: $\lambda = 10\mu$, $E_L = 10^{11} \text{V/m}$, $B_w = 100 \text{kGs}$ and $\psi_r = 120^\circ$. The rate of acceleration is $\approx 200 \text{ MeV/m}$, requiring an accelerator 5 km long for 1 TeV protons.

The wiggler period Λ_w must vary according to the resonant condition. In the parametric form it is given by

$$\Lambda_w = \frac{2\pi c}{\Omega} K \quad (8)$$

At the end of this accelerator, the period is of the order of several meters, and the proton oscillation amplitude in the wiggler can be large. This amplitude determines the cross-section of the radiation beam and its total power. This amplitude is³

$$a = \frac{K\Lambda_w}{2\pi\gamma} = c \sqrt{\frac{2}{\omega\Omega}} \frac{K^{3/2}}{\sqrt{1+K^2}} \quad (9)$$

and in order to reach a fraction of one centimeter.

3b. Shorter period accelerator

In the case of a shorter period accelerator we get from (3)

$$K = \sqrt{\frac{2\lambda}{\Lambda_w} \gamma_r^2 - 1} \quad (10)$$

To satisfy the resonant condition the particle energy must be $\gamma_r > \frac{\Lambda_w}{2\lambda}$.

Introducing (10) into the accelerator equation we can determine the energy dependence of protons on distance,

$$\gamma_r(z) = \left(\frac{\Lambda_w}{2\lambda}\right)^{1/2} \left\{ 1 + \left[\frac{4\lambda}{\Lambda_w} A \sin\psi_L z + \left(\frac{2\lambda}{\Lambda_w} \gamma_o^2 - 1\right)^{1/2}\right]^2 \right\}^{1/2} \quad (11)$$

For large z ,

$$\gamma_r \approx 2 \sqrt{\frac{2\lambda}{\Lambda_w}} A \sin\psi_r z \quad (12)$$

To achieve a higher rate of the acceleration the wiggler period should be shorter but then the value of the magnetic field can easily exceed technical possibilities. In the shorter period accelerator the minimal energy of injected particles can be very high. A typical dependence of the energy vs. distance in a $\Lambda_w = \text{const.}$ accelerator is shown in Fig. (2). To maintain the resonant condition the magnetic field of the wiggler must vary along the accelerator. In fact B_w is a linear function of the distance

$$B_w(z) = B_0 + \frac{8\pi\lambda}{\Lambda_w^2} E_0 \sin\psi_r z \quad (13)$$

In 1 km of $\Lambda_w = 1$ m accelerator, with the same laser beam as in previous example, the resonant magnetic field would exceed 700 kGs, i.e. this accelerator with the average acceleration gradient 600 MeV/m is beyond our technical possibilities. Technical limitations can be met with $\Lambda_w = 3$ m but then the acceleration gradient is 200 MeV/m.

4. Final Remarks

The laser acceleration of protons by means of the IFEL mechanism seems possible with an average rate of acceleration of about 200 MeV/m. That is not greater than what is obtained in synchrotron using superconducting magnets. To achieve this acceleration gradient the most powerful existing lasers would be required.

The rate of acceleration would be higher if we could use a longer wavelength radiation. For $\lambda = 1$ mm and a laser field $E_L = 10^{11}$ V/m, we could obtain 2 GeV/m. In this case however the amplitude of proton oscillations in the wiggler would be several centimeters bringing the radiation power above 10^{16} Watt.

The confinement and transport of the laser radiation could be provided by a waveguide. In an optical regime it could be a low loss waveguide described in (6). For $\lambda = 1$ mm radiation it could be a superconductive waveguide. In the last case the phase and group velocity of the EM wave is substantially different from the velocity of light c , requiring a modification of the accelerator equation (1). Because of the difference between the particle and wave velocities much longer radiation pulses would be required. This would again increase the total radiation energy required.

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Figure Captions

1. Energy versus distance in a constant field strength accelerator. $B_w = 10^5$ Gs. Laser parameters: $\lambda = 10 \mu$, $E = 10^{11}$ V/m. Resonant phase $\psi_r = 120^\circ$; Different values of K_0 correspond to different initial energy.
2. Energy versus distance in a constant period accelerator. Laser parameters and resonant phase the same as on Fig. 1.

Fig 1

Fig 2