

# ACCELERATION RATE IN THE NONCOLLINEAR SCHEME OF LASER PARTICLE ACCELERATION

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## Abstract

The acceleration rate up to 1 GeV/m for a pure laser driven acceleration scheme [1,2] is demonstrated. It is shown that under certain conditions the phase slippage between laser field and the charged particles could be less than  $\pi/2$  providing efficient coupling. The comparison with the optical scheme used in [3,4] is carried out which revealed the advantage of our configuration for high energy particles acceleration.

## INTRODUCTION.

In recent years with the increased power of available lasers the interest to pure laser driven vacuum particle accelerator substantially increased. In our previous papers [1,2] we have suggested a new particle acceleration method where the particle beam crosses the radiation cavity at an angle to its axis through the holes located on the edge of the first Frenel zone. This configuration provides necessary component of the electric field along the direction of particles motion and synchronism between particles and the radiation field. It was also demonstrated numerically that radiation field structure (TEM<sub>00</sub> mode) is not violated by placing holes in the cavity on the edge of the first Frenel zone.

A similar idea of particle acceleration was presented in [3,4]. Both cases have common features: first - the termination of the interaction between particle and radiation beam by means of mirrors with holes is used, second - the full interaction length in the section is defined by coherent length where the phase slippage between particle and the wave is less than  $\pi/2$ . The main difference between the schemes is due to the fact that the configuration [1] provides radiation focusing while VLA scheme [3] exploited parallel (up to the diffraction divergence of the radiation) beam. It would be demonstrated below that this difference turned out to be significant for the efficient coupling of the accelerated high energy particles and the radiation.

For easier comparison of the above scheme the parameters given in [3] where used to calculate actual acceleration rate values.

## PHASE CONDITIONS

The scheme of laser driven accelerator cell first proposed in [1] is schematically shown on Fig. 1

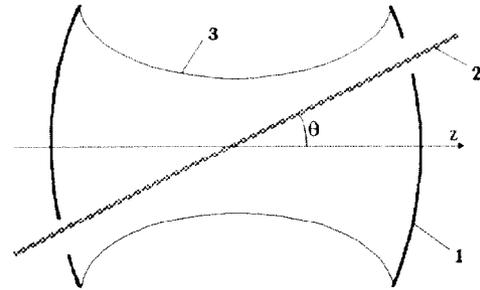


Figure 1. Laser driven accelerator cell scheme.  
1- cavity mirror, 2 - charged particle beam, 3 - radiation field TEM<sub>00</sub> mode

It is usually considered that phase slippage make laser field inadequate for particle acceleration. The main problem is averaging of the acceleration effect due to periodical structure of the radiation field. What makes our scheme different is termination of interaction between particle and field at the mirror surface. Actually by placing the holes at the edge of the first Frenel zone we use only one radiation length i.e. on the way through the cavity the charged particle experience only accelerating field without any deceleration regions. On the contrary VLA scheme is based on many radiation lengths cell with interchanging relative phase sign in it.

Here we evaluate the phase conditions for charged particle crossing the confocal cavity at an angle  $\theta$ .

For the TEM<sub>00</sub> Gaussian mode the local phase of the radiation can be presented as:

$$\varphi = kz + \frac{kr^2}{2\left(z + \frac{L}{2z}\right)} - \arctg(2z/L) - \omega t, \quad (1)$$

where  $k$  is a wave number,  $z$  is longitudinal coordinate with origin in the center of the resonator,  $L$  is the length of the resonator,  $r$  is the transverse coordinate. To define the phase slippage between the relativistic electron crossing the resonator at an angle  $\theta$  and the radiation we express  $t$  in (1) as a function of electron position.

$$t = \frac{z}{c\beta_z}, \quad (2)$$

where  $c\beta_z$  is the longitudinal velocity of the electron. Thus we get

$$\varphi = kz \left(1 - \frac{1}{\beta_z}\right) + \frac{kr^2}{2\left(z + \frac{L}{2z}\right)} - \text{arctg}(2z/L). \quad (3)$$

The relative phase change on the whole way across the resonator can be expressed as  $\Delta\varphi = \varphi(z = L/2) - \varphi(z = -L/2)$ . Substituting it to (3) and taking into account that  $r(z = \pm L/2) = \theta L/2$  (for  $\theta \ll 1$ ) we obtain

$$\Delta\varphi = -\frac{\pi L \left(1 + \frac{9}{8} \gamma^2 \theta^2\right)}{\lambda \gamma^2} + \frac{\pi}{2} \quad (4)$$

where  $\gamma$  is the relativistic factor of the charged particle. As it is evident from (4) the phase slippage is defined mainly by the relation between  $L$ ,  $\theta$  and  $\lambda$ . In our case  $\Delta\varphi$  is limited and small enough to provide phase slippage less than  $\pi$ .

#### ACCELERATION RATE.

For the simplicity we assume that the particle energy  $\gamma$  can be considered constant. That is particularly valid if we limit ourselves to the case of high initial energy and short interaction length what actually correspond to our case. The laser field resembles Gaussian beam with  $TEM_{00}$  mode with  $w_0$  - beam waist radius;  $L = 2L_R$  - resonator length;  $\lambda$  - radiation wavelength. Several common definitions are presented below which will be used in our evaluation.

$$L_R = \frac{\pi w_0^2}{\lambda} \quad \text{- Rayleigh length,} \quad (5)$$

$$\text{tg}\theta \leq \frac{w_0 \sqrt{2}}{L_R} \quad \text{- angle of noncollinearity.} \quad (6)$$

For the adopted approximations the acceleration rate for the charged particle with energy  $\gamma$  crossing the cavity at angle  $\theta$  can be expressed as follows.

$$T = \frac{eE_0\theta}{L} \int_0^L \cos\left(\frac{\pi(1+\gamma^2\theta^2)}{\lambda\gamma^2} z\right) * F\left(\frac{z-L_R}{L_R}\right) dz \quad (7)$$

where

$$F(x) = \cos\left(\frac{2\pi x}{1+1/x^2} - \text{arctg}(x)\right) * \frac{(1+x^2)^{3/2}}{\exp\left(\frac{2\pi x^2}{1+x^2}\right)} \quad (8)$$

represents the shape of the Gaussian beam field amplitude on the axis of the particle beam and describes the influence of the  $TEM_{00}$  mode field constant phase surface

curvature on the value of the electric field vector projection to the particle motion axis.

The accelerating electric radiation field  $E(s)$  excluding fast oscillating term along the axis of the particle beam in the cavity is presented on Fig.2 which reflects the geometry of the configuration. One can see that  $E(s)$  is positive on the whole way. This reflects one of the main differences between our and VLA scheme - our configuration exploits efficiently the whole length of the acceleration structure without phase sign changing. At the same time it impose rather strong limitations on the geometrical proportions of the configuration.

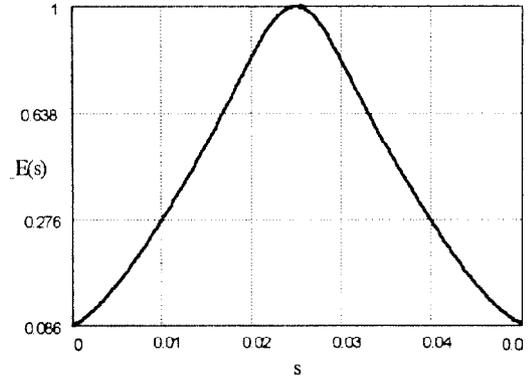


Figure 2. Acceleration field  $E(s)$ .  $s$  - is the distance along the axis of particle motion in the cavity.

We can rewrite the expression (7) introducing new universal variable.

$$T(l) = eE_0\theta G(l), \quad (9)$$

$$\text{where } l = \frac{\pi L(1+\gamma^2\theta^2)}{2\lambda\gamma^2} \quad (10)$$

is the phase parameter describing the acceleration condition. The numerically calculated function is given by the Fig.3.

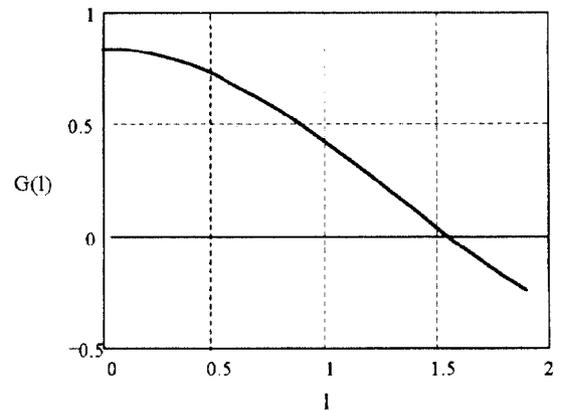


Figure 3.  $G(l)$  function.

The acceleration is possible only when the parameters  $L$ ,  $\lambda$ ,  $\gamma$ ,  $\theta$  satisfy the condition  $0 < l < \pi/2$ . This impose some limitations on the possibilities of the suggested scheme in particular initial  $\gamma$  should be high enough to ensure reasonable parameters of the cavity. Universal variable  $l$  is actually Frenel number of the particle beam position on the cavity surface.

In what follows we evaluate the actual value of the rate for the given parameters:  $P=10^{13}$  W,  $\lambda = 10 \mu\text{m}$ ,  $L = 5$  cm. The radiation beam radius  $w_0 = 2.8 \cdot 10^{-4}$  m according to (5), Angle  $\theta = 10^{-2}$ , field amplitude for the defined radiation beam waist  $E_0 = 1.6 \cdot 10^{11}$  V/m,  $\gamma = 1000$ .

For certainty we have taken the energy of particles being accelerated high enough to make our assumption that  $\gamma = \text{const}$  valid. So we can use the formulae  $T = eE_0\theta G(0.785)$ .

Substituting all the parameters we get:  $T = 940$  MeV/m. This is the mean acceleration rate of our scheme.

#### DISCUSSION AND CONCLUSION.

The key point of our scheme that it provide phase slip  $< \pi/2$  condition with the hole mirror resonator if the position of this hole is not out of the first Frenel zone. On the other hand we had shown that if the hole is on the border of the first Frenel zone the Gaussian mode is conserving and the angle between particle beam and mode axis is large enough to provide strong enough coupling between optical and particle beams respectively.

From the above results one can see that the configuration [1] is more efficient, namely with the given parameters the gain is 6 times higher. Some additional gain up to tens of percent can be obtained using shorter section as it is evident from the Fig.3.

From our point of view another very important distinction is that with scheme [1] the inter-cavity radiation is used while scheme [3] is based on the single pass radiation beam. For high Q value of the laser resonator it can give up to two orders gain additionally.

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