Described is a focusing system for charged particles in a laser driven linac, with an accelerating structure that is open on one side. The structure is illuminated from the open side by a focused laser spot, which is traveling along the structure in correlation with the position of the particles. This method allows for the reduction of the power required for generation of the necessary accelerating gradient, and reduction of the time of illumination of each point in the structure. This makes a laser driven linac a realistic system. The focusing system is a combination of FODO structure arranged with quadrupole lenses of appropriate dimensions and RF focusing. The Final Focusing system is arranged with the help of a bifrequency RF focusing system supplied by laser radiation of fundamental and doubled frequency.

Introduction

The method proposed is described in [1]. The basis is that the focused laser spot is moved in the longitudinal direction by a special sweeping device, so that the focal point follows the particle in its motion along the accelerating structure.

Because the sweep of the laser focus is limited to a distance of about 2-3 cm, the accelerating device looks like a sequence of 2 cm long accelerating structures with the focusing elements between them. For an appropriate accelerating structure, the pass holes have a dimensions that is a fraction of a wavelength of the laser radiation.

In this report the focusing required to keep the beam inside the transverse dimensions like a fraction of a micrometer is explored. This is connected with the smallest emittance available.

For realization of high luminosity the envelope function in the interaction region must be of the order of the bunch length, which is about $0.1-1\lambda$, where $\lambda$ is the wavelength of the laser radiation. This requires the final focusing lenses have extremely short focal lengths and placed close to the interaction region.

The method

The scheme that realizes the method proposed is represented on Fig. 1. Here the source of coherent radiation 1, provides a ray 2 with necessary direction of polarization. A half wavelength plates are used for preparing it. Further there is installed an electro-optical crystal 3 with triangle metallization 4, what makes the deflecting prism [2] (a sweeping device). Focusing lens 5, serve for focusing the laser beam in longitudinal direction. Further, the laser beam 6 goes through a cylindrical lens 7 which focuses the laser beam on the surface of the structure 8 in transverse direction into a spot 9 with a transverse size of a few wavelengths of the laser light. In this particular moment, the accelerated particles are placed here. The beam is moving along the trajectory 10 and is focusing by quadrupole lenses 11, 12.

After the passage of one module, the particle goes to the second module and so on.

Fig.1. The Accelerating Device. The accelerating structure is represented also.

The typical power required to supply one structure of 2 cm long is $\approx 10^{4}$ milliJoules in this method. For radiation with $\lambda \equiv 1 \mu m$ this provides $\geq 30$ GeV/m.

After the passage of one module, the particle goes to the second module and so on.

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1 Present Address: Cornell University, Newman LNS, Ithaca, NY, 14850. e-mail: mikhail@lns62.cornell.edu
The size of the laser focus in the region of the second short focusing cylindrical lens 7 defined by the diffraction angle \( \theta \equiv \lambda / \alpha \) where \( \alpha \) is the aperture of the sweeping device. So it has the order \( l_s = \lambda \cdot R / a \), where \( R \) is the distance between the sweeping device (lens 5 on Fig. 1) and the lens 7.

Utilization the shot focusing cylindrical length reduces the transverse size of the spot to the few wavelengths due to that circumstance that it is installed close to the accelerating structure and the ratio \( r / a = 1 \), where \( r \) is the distance between the second lens 7 and the structure 8.

The maximal aperture of the deflecting system in longitudinal direction, can be made equal to the sum of the accelerating structure and focusing elements' lengths. If we accept for the practical reason this figure as \( A = 3 \, \text{cm} \), \( R = 3 \, \text{m} \), then ratio \( R / a = 100 \). So the diffraction length of the spot in longitudinal direction can be of the order \( l_s \equiv 100 \lambda \). This value gives the maximal possible value for \( Q \) --factor of one cell of accelerating structure.

The deflection angle may be increased by the optical elements, but the number of resolved spots \( M \) is invariant. \( M \equiv \Delta n \cdot (L / \lambda) \), where \( \Delta n = \Delta n(V) \) is a change of refraction index by the voltage \( V \), applied to metallization, \( L \) is the length of deflecting device along the light direction. In KDP (potassium dihydrogen phosphate) crystal \( \Delta n \equiv 10^{-4} \), in KTN (potassium tantalate niobat) crystal \( \Delta n \equiv 7 \cdot 10^{-3} \) is possible [2,3]. Basically, \( M \) value gives the number for the lowering the laser power and also, the number for reducing the duty of the structure heating. For segmented crystal with \( L \equiv 30 \, \text{cm} \), one can expect \( M \equiv 30 \div 700 \).

Each part of the grating structure is illuminated by duration, which is defined by the longitudinal size \( l_s \). For example, if we consider \( l_s \equiv 100 \lambda \), \( \lambda = 1 \, \mu \text{m} \), then \( l_s / c \equiv 3 \cdot 10^{-12} \, \text{sec} \). For \( \lambda = 10 \, \mu \text{m} \) this value is ten times more.

### The dimensions

The number of the particles required for the method [1] is four orders of magnitude lower, than for the linear collider projects with the same level of luminosity.

A lot of damping rings were considered for linear collider schemes. The typical emittances referred to 3 GeV are \( \varepsilon_z = 5 \cdot 10^{-8} \, \text{cm} \cdot \text{rad} \) - radial and \( \varepsilon_y = 5 \cdot 10^{-10} \, \text{cm} \cdot \text{rad} \) - vertical. The energy spread about \( \sigma_k = 10^{-3} \) and the bunch length \( \sigma_t = 5 \, \mu \text{m} \). The length of the beam after one stage compression is of the order 500 \( \mu \text{m} \) and the number of the particles is about \( N = 10^{15} \). The second stage compresses the beam typically to \( 100 \, \mu \text{m} \) at 10 GeV. So if we need only \( N = 10^9 \), we can loose four orders of magnitude in intensity by scrapping the extra particles ejected from appropriate damping figures, thereby coming to the necessary figures in the emittance \( 10^{-10} \, \text{cm} \cdot \text{rad} \) at 3 GeV. For pre-bunching the FEL mechanism can be used here.

There are proposals for an accelerating structure what could be scaled to the wavelength, corresponding to laser radiation [4,5,6]. We will consider the requirements for the structure described in [5] (See Fig.1). The channels for the passing of the beam have a size \( \delta \leq 0.2 \lambda \).

#### Transverse electron focusing

The beam size must be keep small enough to pass trough the channels. A short wavelength of betatron oscillations helps against the resistive wall instability [7] and wakefield influence reduce. The longitudinal and transverse wakes normalized for one cell are \( W_x = -7 \, \text{KV} / \text{pC} \) and \( W_y = 2.2 \cdot 10^{-5} \, \text{KV} / \text{pC} / \mu \text{m} \), correspondly for the accelerating structure with \( \lambda \equiv 10 \mu \text{m} \), \( \delta = 2 \mu \text{m} \), \( w = 7 \mu \text{m} \) it Fig.1 and the bunch with the longitudinal length \( \sigma_l \equiv 1 \, \mu \text{m} \) [8].

The focusing system includes the quadrupole lenses of appropriate dimensions and a RF focusing of different nature. The lenses are displayed at the distance, which defined by the emittance of the accelerating beam between the grating and by technical reasons. In case of the traveling laser focus supply, this is the maximal possible sweeping distance for the unit. If we consider the focusing system such as FODO structure, with the lenses having the length \( 2l \) with the distance between them \( L \), the period of FODO structure will be equal to \( 2(L+l) \).

For the betatron tune shift we have an expression

\[
\cos \mu \equiv 1 - (L + 2l)^2 / 2l^2,
\]

where \( F \) is the lens focal distance. So \( F \equiv (L + 2l) / \sqrt{(1 - \cos \mu)} = (H_p) / (2G) \), where \( G \) is the lens gradient, \( (H_p) \) is the magnet rigidity of the particle. From the last expression it yields

\[
G / H_p = k = \sqrt{(1 - \cos \mu)} / (2l(l + 2l)),
\]

where \( k \) is the focusing parameter of the lens, \( k [1 / l^2] = 3 \cdot G[kG / \text{cm}] / l [\text{GeV} / \text{c}] \). The modulation \( M \) of the \( \beta \) - function between the lenses looks like [9]

\[
M^2 = \frac{\beta_{\max}}{\beta_{\min}} = \frac{1 + \tanh \left( \frac{\tan \phi + \frac{L}{l}}{ \frac{1}{\beta_{\max}} - \frac{1}{\beta_{\min}} \phi} \right)}{1 - \tanh \left( \frac{\tan \phi + \frac{L}{l}}{ \frac{1}{\beta_{\max}} - \frac{1}{\beta_{\min}} \phi} \right)}
\]

\( \phi = l / \sqrt{k} \) -is the phase shift in the half of the lens. If we estimate \( L = 2 \, \text{cm} \), \( l = 0.2 \, \text{cm} \), \( \mu = \pi / 6 \), then \( k = 0.5 / (2l(L + 2l)) = 0.5 \cdot 10^5 / (2 \cdot 2 \cdot 2.4) \approx 5 \cdot 10^{-1} \, l^2 \), \( \phi^2 = F \cdot k = 2 \cdot 10^{-2} \), and \( M^2 \equiv 1.5 \). For maximal value of the envelope function we have [9]

\[
\beta_{\max} = \frac{1}{k} \cdot \left( \frac{2l^3}{\sqrt{2l^3 + Ll}} \right) = \frac{2M \cdot (L + 2l)}{\sqrt{2l^3 + Ll}} \cdot \frac{2l^3}{\sqrt{2l^3 + Ll}}
\]

which for previous values of \( L \) and \( l \) gives \( \beta_{\max} \equiv 15 \text{cm} \) and \( \beta_{\max} \equiv 10 \text{cm} \). If the beam has the emittance \( \varepsilon \equiv 10^{-10} \, \text{cm} \cdot \text{rad} \), then the transverse beam size \( \sigma_{\text{trans}} \) will be of the order \( \sigma_{\text{trans}} \equiv \sqrt{\beta_{\max}} \equiv 3.9 \cdot 10^{-5} \, \text{cm} \), or \( 0.4 \, \mu \text{m} \).

Thus, the focusing with the quadrupole lenses at initial stage of acceleration is acceptable only for the wavelength of the laser light about 10 \( \mu \text{m} \), what defines the transverse dimensions of the structure.
With such dimensions, the radius of aperture $b$ of the quads can be also made small enough, providing high gradient $G$ with small value of the pole field $H$, $G = H / b$. If we estimate $H \approx 15 \text{ kGs}$, $b = 0.01 \text{ mm}$ (20 $\mu$m in dia of aperture), then $G = 15 \cdot 10^5 \text{ kGs/cm}$. From the other side, for obtaining the value $k [1/\text{m}^2]$ for the particles with momentum $p$ [GeV/c], the gradient required is $G \approx 0.3pk$.

For the particles with $p = 10 \text{ GeV/c}$, this yields for $k = 5 \cdot 10^3 \cdot 1/\text{m}^2$, $G = 1.5 \cdot 10^5 \text{ kGs/cm}$. At higher energy the actual emittance becomes adiabatically lower and the envelope function value can be increased.

Let us estimate the RF focusing [10,11] what occurs if the particle is going out of the RF crest in a phase $\varphi$. If $x, y = 0$ (the transverse coordinates, calculated from the beam axes) the effective factors of the lens can be evaluated as

$$k_x = - \frac{1}{pc} \frac{\partial F}{\partial x} \approx \frac{e \lambda E_m}{2mc^2 \nu^2} \sin \varphi,$$

$$k_y = - \frac{1}{pc} \frac{\partial F}{\partial y} \approx \frac{e \lambda E_m}{2mc^2 \nu h} \sin \varphi.$$

Substitute here $\lambda = 10 \mu$m, $\gamma = 2 \cdot 10^4 (10 \text{ GeV})$, $w = 5 \mu$m, $E_m = 10^4 \text{ V/m}$, we obtain $k_x = 2 \cdot 10^3 \sin \varphi [\text{m}^{-2}]$. There is a proposal to use this force for alternating phase focusing (APF), when the phase of the beam with respect to the RF crest is periodically changed, $\varphi = \pm \varphi_0$ [11]. In our case this can be made by arranging periodical delay of the accelerating light arriving to the grating, for example, by modulation of the thickness of the lens 7.

The possible scheme also is that the RF focusing by the first harmonic grove and, after doubling, the second harmonic radiation from the general source can be used both for driving the first harmonic groove and, after doubling, the second groove. For arranging a doublet of the focusing lenses, one can use the phase shift between the RF crest and the beam $\varphi = \pi / 2$. Such a tiny lens, not sensitive for the magnetic field can be easily installed inside the detector.

**Conclusion**

Due to the emittance available, the first stage of the laser driven linac at the energy about $10 \text{ GeV}$ will require a $10 \mu$m wavelength if the only FODO structure with the quadrupole lenses is used.

The necessity to obtain the beta function in the interaction region of the order of $1 \mu$m requires very strong focusing lenses. The RF focusing system looks attractive for this purpose.

The general conclusion is that the necessary focusing can be arranged for the system described.

**References**


