A BEAM FOCUSING SYSTEM FOR A LINAC DRIVEN BY A TRAVELING LASER FOCUS

A.A. MIKHAILICHENKO, BudkerINP, 630090, Novosibirsk, Russia[1]

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 is 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 λ 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.

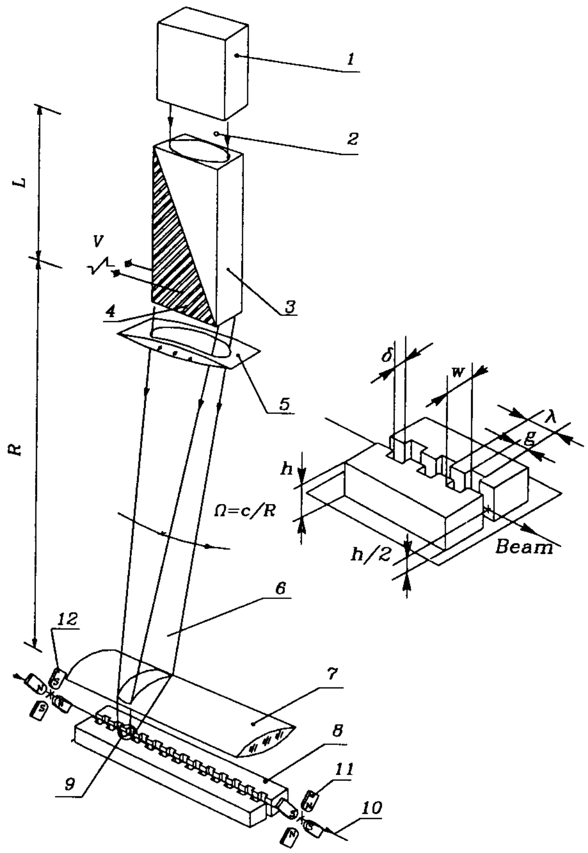

Fig.1. The Accelerating Device. The accelerating structure is represented also.

The operating voltage initially deflects the laser beam to the beginning of the accelerating module (left side on Fig.1). Starting of this moment of time and synchronized with the motion of the particles accelerated, the sweeping device 3 is supplied by the changing voltage on the metallization 4. This voltage changes the direction of the laser beam 6, so that the focal point 9 is follows the beam.

The device 1 can be treated as a device for splitting the light from a unique source with optical techniques. This yields a simple way for the *phase* synchronization for few modules. Synchronization between the particle's motion and the focal spot motion must be made in such a manner that the particles does not *on average*, come out of the laser spot. The typical power required to supply one structure of 2 cm long is ≤ 10 *milliJoules* in this method. For radiation with $\lambda \cong 1\,\mu m$ this provides ≥ 30 *GeV/m*.

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

[1] Present Address: Cornrell 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 $\cong \lambda / a$ where *a* is the aperture of the sweeping device. So it has the order $l_t \approx \lambda \cdot R / a$, where R is the distance between the sweeping device (lens 5 on Fig. 1) and the lens 7.

Utilization the shot focusing cylindrical length 7 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 $r / a \approx 1$, 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 $a \cong 3\,cm$, $R \approx 3m$, then ratio $R / a \approx 100$. So the diffraction length of the spot in longitudinal direction can be of the order $l_f \cong 100\lambda$. 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. $M \cong \Delta n \cdot (L / \lambda)$, where $\Delta n = \Delta n(V)$ is a change of refraction index by the voltage *V*(*t*), applied to metallization, *L* is the length of deflecting device along the light direction. In KDP (potassium dihydrogen phosphate) crystal $\Delta n \cong 10^{-4}$, in KTN (potassium tantalate niobat) crystal $\Delta n \cong 7 \cdot 10^{-3}$ 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 $L \cong 30\,cm$, one can expect $M \cong 30 \div 700$.

Each part of the grating structure is illuminated by duration, which is defined by the longitudinal size l_t. For example, if we consider $l_t \cong 100\lambda$, $\lambda = 1\,\mu m$, then $l_t / c \cong 3 \cdot 10^{-13} sec$. For $\lambda = 10\,\mu m$ 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 $\varepsilon_x \approx 5 \cdot 10^{-8} cm \cdot rad$ - radial and $\varepsilon_y \approx 5 \cdot 10^{-10} cm \cdot rad$ - vertical. The energy spread about $\sigma_\varepsilon \cong 10^{-3}$ and the bunch length $\sigma_z \cong 5\,mm$. The length of the beam after one stage compression is of the order 500 μm and the number of the particles is about $N \approx 10^{10}$. The second stage compresses the beam typically to $100\,\mu m$ at 10 *GeV*. So if we need only $N \approx 10^6$ we can loose four orders of magnitude in intensity by *scrapping* the extra particles ejected from appropriate damping ring, thereby coming to the necessary figures in the emittance $10^{-10} cm \cdot rad$ 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 $\delta \le 0.2\lambda$.

Transverse electron focusing

The beam size must be keepd 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 $W_\parallel \cong -7kV/pC$ and $W_\perp \cong 2.2 \cdot 10^2\, V/pC/\mu m$ correspondly for the accelerating structure with $\lambda \cong 10\,\mu m$, $\delta = 2\mu\, m$, $w = 7\mu\, m$(see Fig.1) and the bunch with the longitudinal length $\sigma_l \cong 1\,\mu m$ [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 2*l* 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 $Cos\mu \cong 1 - (L + 2l)^2 / 2F^2$, where F is the lens focal distance. So $F \cong (L + 2l) / \sqrt{2(1 - Cos\mu)} = (H\rho)/(2Gl)$, where *G* is the lens gradient, *(Hρ)* is the magnet rigidity of the particle. From the last expression it yields

$$G/(H\rho) = k = \sqrt{2(1 - Cos\mu)} / (2l(L + 2l)),$$

where *k* is the focusing parameter of the lens, $k\,[1/m^2] = 3 \cdot G\,[kGs/cm]/p[GeV/c]$. The modulation M of the β– function between the lenses looks like [9]

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

$\phi = l\sqrt{k}$ -is the phase shift in the half of the lens. If we estimate L = 2 cm, l = 0.2 cm, $\mu = \pi/6$, then $k = 0.5/(2l(L + 2l)) = 0.5 \cdot 10^5 / (2 \cdot 2 \cdot 2.4) \cong 5 \cdot 10^3\ 1/m^2$, $\phi^2 = l^2 \cdot k = 2 \cdot 10^{-2}$, and $M^2 \cong 1.5$. For maximal value of the envelope function we have [9]

$$\beta_{max} \cong M \frac{1}{|k| \cdot l} \sqrt{\frac{2 + L/l}{2/3 + L/l}} = \frac{2M \cdot (L + 2l)}{\sqrt{2(1 - Cos\mu)}} \sqrt{\frac{2 + L/l}{2/3 + L/l}}$$

which for previous values of L and l gives $\beta_{max} \cong 15cm$ and $\beta_{min} \cong 10cm$. If the beam has the emittance $\varepsilon \cong 10^{-10}\, cm \cdot rad$, then the transverse beam size $\sigma_{\perp max}$ will be of the order $\sigma_{\perp max} \cong \sqrt{\varepsilon \beta_{max}} \cong 3.9 \cdot 10^{-5}$cm, or 0.4 μm.

Thus, the focusing with the quadrupole lenses at initial stage of acceleration is acceptable *only* for the wavelength of the laser light about 10 μm, 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 $H \cong 15$ *kGs*, b = 0.01 *mm* (20 μm in dia of aperture), then G = $1.5 \cdot 10^4$kGs/cm. From the other side, for obtaining the value $k\,[1/m^2]$ for the particles with momentum p [*GeV/c*], the gradient required is $G \cong 0.3pk$. For the particles with p = 10 *GeV/c*, this yields for $k \approx 5 \cdot 10^3 \cdot 1/m^2$, $G = 1.5 \cdot 10^4$ *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 φ. If *x, y* ≈ 0 (the transverse coordinates, calculated from the beam axes) the effective factors of the lens can be evaluated as

$$k_x = -\frac{1}{pc}\frac{\partial \langle F_x \rangle}{\partial x} \cong \frac{e\lambda E_m}{2mc^2 \gamma w^2} Sin\varphi,$$

$$k_y = -\frac{1}{pc}\frac{\partial \langle F_y \rangle}{\partial y} \cong -\frac{e\lambda E_m}{2mc^2 \gamma wh} Sin\varphi .$$

Substitute here $\lambda = 10\,\mu m$, $\gamma = 2 \cdot 10^4 (10\ GeV)$, $w \approx 5\mu m$, $E_m \approx 10^{11} V/m$, we obtain $k_x \approx 2 \cdot 10^5 Sin\varphi\,[m^{-2}]$. 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 slots of the structure is going in horizontal direction and vertical focusing made by quadrupoles. This can reduce the betatron wavelength, in principle, two times.

The final focus

If we suppose, that the beta function value in the interaction region β^* is of the order of the bunch length σ_l, i.e. $\sigma_l \approx \beta^* \cong 0.5$ μm, then the variation of the envelope function from the interaction point at the distance s= 1 *cm* will be $\beta = \beta^* + s^2/\beta^* \approx 1/0.5 \cdot 10^{-4} \cong 2 \cdot 10^4 cm$. With such an envelope function $\sigma_{\perp max}$ will be of the order $\sigma_{\perp max} \cong \sqrt{\varepsilon\beta} \cong 1.4 \cdot 10^{-4}$ *cm*, or 1.5 micrometers for the transverse emittance value $\varepsilon \cong 10^{-12}$*cm rad*.

The mostly natural way to arrange the final focus lens is the RF focusing, discussed above. A laser radiation of general and multiple frequency can be used here.

The laser radiation, phased with the main driving one can excite the single groove directly from the side. The quadrupole parameter for the particle what is going out of the RF crest is described above. Substitute here $\lambda = 10\,\mu m$, $\gamma = 2 \cdot 10^6$ (pc =1*TeV*), $w \approx 5\mu m$, $E_m \approx 10^{11} V/m$, we obtain $k_x \approx 4 \cdot 10^4 \cdot Sin\varphi\,[m^{-2}]$. For $\varphi = \pi/2$ this expression has a maximum and variation of the focusing strength has a quadratic dependence with the deviation ψ from the angle $\varphi = \pi/2$, $k_x \approx Cos\psi$. For the longitudinal length of the grove about $g \cong 5\mu m$, the focal distance will be

$$F \cong 1/kg \cong 1/4 \cdot 10^4 5 \cdot 10^{-6} = 5 \text{ [Meters/cell]}.$$

Equivalent gradient of the quadrupole lens is $G \cong 0.3pk \cong 1.2 \cdot 10^7 kGs/cm$. Of cause there is no possibility to arrange a magnetic quadrupole with such a gradient. So the lens with ≈ 500 cells will have the focal length $F \approx$ 1 *cm*. So, this multicell lens will have the total length of 0.5 *cm*.

For flattering the longitudinal dependence of the gradient (elimination the quadratic term in $k_x \approx Cos\,\psi$ as a function of ψ), one can use the *second and higher harmonics* of the laser radiation, excited an additional groove, placed on the beam trajectory close to the first groove. For phasing, the highest harmonics can be generated by the multiplying the frequency in nonlinear crystal. As initial, the splitted radiation from the general source can be used both for driving the first harmonic grove 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 emittances available, the first stage of the laser driven linac at the energy about 10 *GeV* will require a 10 μm 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.

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