EXCITATION OF THE GRATING BY MOVING FOCUS OF THE LASER BEAM

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Abstract

This paper considers the acceleration of charged particles, moving close to a grating surface by a laser. A laser beam, with necessary polarization, is focused on the surface of the grating into a spot size of the order of a few periods of the grating. The period of the grating is chosen equal to the wavelength of the laser light. A special device moves the laser focus along the surface of the grating, correlated with the position of the particles. In this way, the breakdown limit for the surface of the grating can be overcome due to the extremely short time of illumination of the parts of the grating. The focusing optical system, the system for sweeping the light beam, the necessary requirements for the grating and the necessary tolerances are considered. The method makes possible a gradient of 100 GeV/m with present day techniques without damage to the grating. Here is also an estimation of the luminosity for application to colliding beams.

There are proposals describing particle acceleration with a laser field, exciting a grating [1,2]. The particles are moving close to the grating surface. The laser bust of high intensity illuminates all grating, where the particles are moving. The illumination lasts for a time, which is necessary for a particle to cross the grating.

The general idea of the method proposed in this paper, is that the laser light is focused into a spot, whose size is much smaller, than the size of the grating. This focused spot is moving in longitudinal direction by a special sweeping device. So, *the focal point is following the particle* along its motion on the grating. Due to this arrangement practically all power of a laser beam is involved in a generation of accelerating fields at the position *where the particle is located.* This provides the gain in an accelerating gradient with the same power of a laser. The illumination of each part of the grating lasts an extremely short time in this method.

Fig.1 describes the idea. The light beam positions in different times are marked by figures 1, 2 and 3. The pulse of laser radiation lasts for a time t. The light sweeping device 4 is positioned on the distance R from the grating 6. Accelerated beam 5 is going close to the surface (or inside) of the grating 6 with the velocity V. The grating has the length L in the longitudinal direction (the same as an accelerated beam). The device 4 is electrically driven for sweeping in longitudinal direction. Before the accelerated beam comes to the grating, the sweeping device deflects the laser beam to the beginning of the grating 6 on the left side of Fig.1. When the beam leaves the grating, the sweeping device deflects the laser beam to the end of the grating. The angle of deflection is. The deflection lasts the time t also, this means that the angular velocity is $\Omega \cong L/(Rt)$. At the moment, when the laser beam arrives to the grating, it has an angle α with respect to the direction of the particle movement. The tangent of this angle is $tg(\alpha) \cong ct/L$, as it can be seen on Fig.1. The relation between parameters must be as following

$$\vartheta \cdot tg(\alpha) = \frac{cL}{VR},$$

where c is the velocity of light.

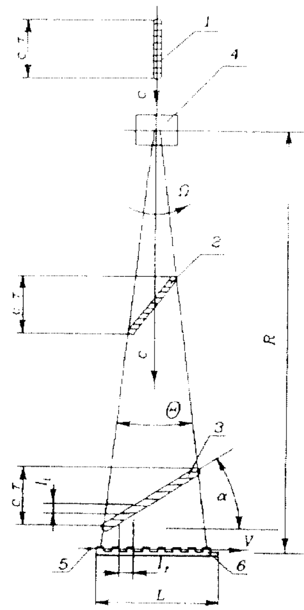

Fig.1 The principle. The comments are in the text

We can represent the field in the wave zone as integral over aperture of the sweeping device for uniform distribution the field over the aperture, $E(x,y)$=const

$$E(t) = -\frac{ik}{2\pi}\frac{exp(ikR)}{R}e^{i\omega t+\psi}\int_{-1}^{+1} e^{i(\alpha_1-\delta)\xi}d\xi$$

$$= \frac{-ik\; exp(ikR)e^{i\omega t+\psi}}{\pi \qquad R}\cdot\frac{Sin(\alpha_1-\delta)}{\alpha_1-\delta}$$

where $\chi(x,y) = \delta\cdot x$ is a phase distribution over aperture, $2x/a = \xi$, $kaSin\,\vartheta/2 = \alpha_1$, $a\times b$ is the aperture of the sweeping device, The maximum of this expression corresponds $\alpha_1 = \delta$, or $kaSin\vartheta/2 \cong ka\vartheta/2 = \delta$. In our case $\delta = \delta(t) \propto \Omega t$, it means that the maximum of the field distribution in direction to the grating also moves $\vartheta \propto \Omega t/ka$. The surface of the constant phase is defined by the relation $\omega R/c \pm \Omega t - \omega t + \psi = const.$

The longitudinal size of the laser focus on the grating in each moment of time is defined as a horizontal cross-section of the light beam, l_f on Fig. 1. A time duration of illumination in each point on the grating defined by the cross-section in direction to the sweeping center, l_t on Fig.1. These dimensions have the same order of magnitude. The duration of illumination is of the order of $\tau \cong l_t / c$. If l_t is equal to integer of the wavelength $l_t = N\lambda$, then the structure of the accelerated beam has a sequence of N bunches.

Let us consider one possible scheme which realizes the method proposed. On Fig.2 there is represented the source of coherent radiation 7, which provides a ray 8 with polarization along the direction of motion of accelerated particles. Vacuumed optical window 9 passes the laser beam into vacuumed volume 10. In this volume 10, there are mounted a long focusing lens 11 for focusing the laser beam in longitudinal direction and the sweeping device 4. For such a sweeping device a crystal KDP (KH_2PO_4)can be used (KDP is transparent for radiation with $\lambda \cong 0.2 \div 1\,\mu$m). The angle of divergence is equal to the

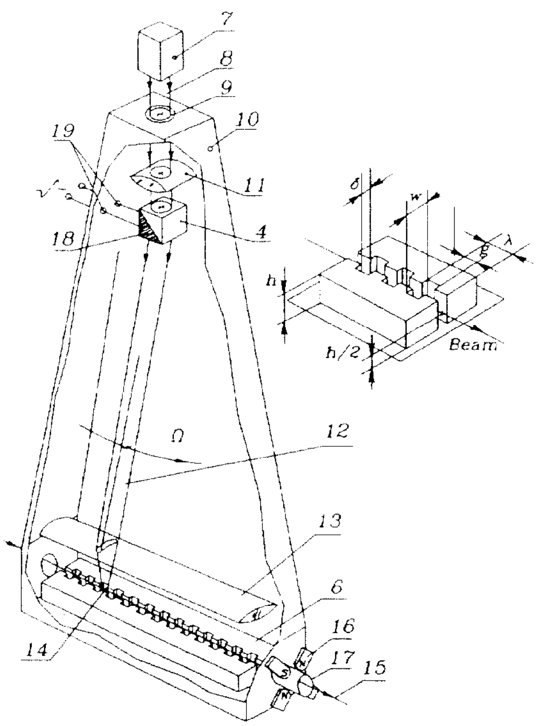

Fig.2. The Accelerating Device. The accelerating structure is represented also.

diffraction angle $\cong \lambda / a$ where a is the aperture of the sweeping device. In principle, the mechanical deflection system with piezoelectric can be used also.

After deflection the laser beam 12 goes through a cylindrical lens 13 which focuses the laser beam on the surface of the grating 6 in transverse direction into a spot size 14 of a few wavelengths. In this particular moment, the accelerated particles are placed here. The beam is moving along the trajectory 15 and is focused by quadrupole lenses 16. For serial connection of the modules the holes 17 can be used. For electrical operating by the sweeping angle, the crystal 4 has a triangle metallization 18 which is supplied by high voltage through the vacuumed connector 19. When operating voltage is applied to metallization, the effective refraction index is changed in transverse direction. This yields a deflection of the laser beam. In [3], the applied voltage about 5 kV provided the deflection angle 10^{-3}rad. The cross-section of the laser beam must be chosen with the dimensions, so that the power density is below the damage level for this crystal. Also, the sandwich type arranging can be used for obtaining the heat absorption and for more homogeneous phase distribution in the aperture of the sweeping device. The focal distance of the lens 13 is chosen small enough for obtaining small cross-sections of the laser focus on the grating and, hence, gain the electric field strength in the focal point. Each part of the lens is illuminated on short duration, so for successful focusing the material with low dispersion must be chosen. A parabolic mirror can be used instead of the lens as well. In this case the cylindrical surface is displaced along the direction of motion of the particles and the grating is placed in the focus of the parabolic mirror.

The only part of a totally generated radiation can be used as a source 7. In this case only one general source supplies few modules, and 7 can be treated as a device for splitting the light from a unique source with well known optical techniques.

The one possible candidate for the grating is the foxhole structure [4]. We will be interested in the structures having the floor from one side. The depth h of the one cell is equal to a half of the wavelength. The existence of the floor gives the basis for precise alignment of the structure. In the cell the standing wave excited which has only one variation along the y axis. This excludes the transverse kick from the wave. Considerations [4] show that with the relationship

$$1/w^2 + 1/h^2 = (2/\lambda)^2,$$

where w is the width of the cell, the phase velocity and velocity of the particles are the same for this grating. The group velocity is equal under these condition to zero, but the way of excitation of the grating allows a resonant excitation of the grating. The wavelength in the cell is about

$$\lambda_w \cong \lambda / \sqrt{1-(\lambda/2w)^2},$$

so the beam goes at the distance of about $\lambda_w / 4$ from the bottom, where the magnetic field has a minimum. The channels for the passing of the beam have a size δ which have necessary cross-sections to allow the beam passage. This channel slightly changes the resonant condition and must be taken into account in detail. The grating must be plane, but the lines of equal phase of the laser beam are placed on the lines with the same radius, calculated from the sweeping device. This yields the necessity of a phase correction. This can be made, for example, by slightly changing the thickness of the cylindrical lens 13, saving the same focusing distance. If the mirror is used, the analogous correction can be made with a parabolic profile in longitudinal direction also. This parabolic profile must have a focus in the sweeping device.

Synchronization between the particles motion and the focal spot motion must be made in such a manner that the particles do not come out of the laser spot *in average*.

Each part of the grating is illuminated by duration, which is defined by the longitudinal size l_t. For example, if we consider $l_t \cong 30\lambda$, $\lambda = 1.0\ \mu$m, then $l_t/c \cong 10^{-13}$ sec.

After the passage of one module, the particles goes to the second module and so on. The quadrupole lenses serve as a focusing element. If we consider the beam with the emittance $\varepsilon \cong 10^{-10}$ cm rad and the envelope function $\beta \cong 10$ cm, then the transverse beam size $\sigma_\perp$ will be of the order of $\sigma_\perp \cong \sqrt{\varepsilon\beta} \cong 3 \cdot 10^{-5}$ cm, or 0.3 micrometers. For the focusing system such as FODO structure, estimations with the formula for modulation of the β-function between lenses gives a modulation about 6% [5]. With such a small dimension, the aperture a of the quads can be also made small enough, providing high gradient G with small value of the pole field H, $G = H/a$. If we estimate $H \cong 1$ kGs, a = 1 mm, then G = 10 kGs/cm. From the other side, for obtain the value β [m] for the particles with momentum p [GeV/c], the gradient required is $G \cong 0.3p/\beta^2$. For the particles with p= 100 GeV/c and for β = 10 cm = 0.1 m this yields G=0.3 100/0.01 = 3kGs/cm only. The RF quadrupole focusing also may be arranged here as well [4]. This possibility is rather attractive, case strong wake field and resistive wall instability requires an adequate focusing.

If we suppose that the full energy of the laser flash is Q, a time duration is t, the number of periods is equal $n = t/T = ct/\lambda$, where $T = l/c$ is the period of radiation, then the energy stored in the field of half a period is $W \cong Q/2n$. From the other side $W \cong (1/2)\varepsilon_0 E_{max}^2 V_{eff}$, where ε_0 is the dielectric permeability of the vacuum, $V_{eff} \cong gwh \cong g\lambda^2$ is the effective volume where the energy is concentrated. From the expressions for W, one can obtain $E_m \cong \sqrt{Q/(\varepsilon_0 ct\lambda g)}$. For estimation let us take Q = 0.01 J, t= 0.1 ns, $\lambda \cong 1\mu m$, $g \cong \lambda/2 = 0.5\mu$m. This gives the field strength $E_m \cong 100$ GeV/m.

The level of damage to the grating by a laser light is strongly correlated with the duration of illumination of the grating [6]. There is no experimental data for the damage level, if illumination lasts the time $\tau \cong l_t/c \cong 10^{-13}$ sec. This time is less than the time between electron-electron collisions $\tau \approx l_{free}/v_F \cong 10^{-12}$ sec, where l_{free} is the free path length, v_F is the electron velocity at Fermi surface [7]. The time of illumination still, however longer, than the time, corresponding to the reaction of electron plasma in the metal $\tau \cong 2\pi/\omega_p = 2\pi/\sqrt{4\pi n r_0 c^2} \approx 3 \cdot 10^{-16}$ sec, where n is the density of electrons, r_0 is the classical electron radius. Some scaling with the figures [6] shows, however, the possibility for $10^8 \div 10^9$ V/cm without damage to the surface.

The energy, accepted from the field by N particles is $W_a \cong eNE_m gI(g)$ where e is the charge of a particle, $I(g)$ is a function of the order of unity - an analog of the transit time factor. The share of the energy will be

$$\eta W \cong \eta\frac{1}{2}Q\lambda/(ct) \cong eNgI(g)\sqrt{Q/(\varepsilon_0 ct\lambda g)}$$

From the last relation it follows that

$$N \cong \frac{\eta}{2eI(g)}\sqrt{\frac{\varepsilon_0\lambda^3 Q}{ctg}}.$$

With $I(g)$= 0.1, η= 0.1 (10%), this yields $N \cong 10^7$.

For estimation the luminosity for colliding beams, suppose, that it is possible to arrange the beta function value in the interaction region β^* of the order of the bunch length, i.e. $\beta^* \cong 0.5\ \mu$m. For energy $\cong$ 300 GeV it is possible to reach emittance $\cong 10^{-12}$ cm rad, this yields the transverse size $\sqrt{\varepsilon\beta^*} \cong \sqrt{5 \cdot 10^{-5} \cdot 10^{-12}} \cong 10^{-8}$cm. For a luminosity we have the formula $L = N^2 f/S$, where N is the number of colliding particles, f is the repetition rate, S is the effective cross-section of the beams in colliding region. Substitute here previous figures, we can expect $L \cong 10^{32} cm^{-2}s^{-1}$ for repetition rate f=100 Hz. Notice here that total length for acceleration up to 300 GeV can be about few meters, taking into account that a fraction of the accelerating sections is of the order 50%. The possibility of operation with high repetition rate, up to few kHz is still open. Energy losses by synchrotron radiation in the interaction point for the beam with such a small size is a subject of special consideration.

The ratio of the random component of transverse momentum per stage $\Delta p_\perp$ to the energy gained per stage $\Delta p_\parallel$ must be less if compared with angular dispersion in the beam [8]

$$\Delta p_\perp / p_\parallel \le \sqrt{\varepsilon/\beta}$$

If we substitute here $\varepsilon \cong 10^{-10}$ cm rad, $\beta \cong 10$ cm, we obtain $\Delta p_\perp / p_\parallel \cong 3 \cdot 10^{-6}$rad, i.e. the same requirement as for a linear collider, i.e. angular requirements for alignment are the same.

For such a small number of particles an appropriate method for obtaining the beam with extremely small emittance is the optical stochastic cooling method [9]. It gives emittance $\varepsilon_y \le 10^{-12}$ cm rad at 1 GeV.

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