Laser Linac Using a Lens Waveguide in Vacuum *

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Acceleration of a relativistic electron beam by the longitudinal field component of a focused laser or microwave beam is optimal when the laser beam is radially polarized. The electron energy gain between focusing optical lenses with an arbitrary optical mode cannot greatly exceed that available from a Gaussian beam of the same power. Off-axis transverse forces focus and recollimate appropriately phased off-axis electrons over the acceleration length.

Over a limited distance the longitudinal electric field associated with a laser beam of varying cross section propagating in empty space can act on co-moving relativistic electrons to produce large gains in electron energy [1, 2]. A train of lenses, perforated along their axes to accommodate the electrons, can be used to periodically refocus the laser beam and maintain the appropriate phase relationship between the electrons and the light. Such adjustment of the phase is required, since the phase velocity of a focused beam of light always exceeds c near the focal region. It turns out that the best type of laser mode for particle acceleration is a TM radially polarized field. For this mode the magnetic field is purely azimuthal, and the electric field has radial and longitudinal components. Such a mode has been realized experimentally [3–6].

When the z component of the electron angular momentum is zero, the electron trajectories are in planes of constant azimuth. Particles propagating from $z = -L$ to $z = L$ with sufficiently high energy ($\gamma^2 \gg kL/2$, where γ is the Lorentz factor and $\omega = ck$ is the laser frequency) will remain in an accelerating phase of the field over the longest distance and gain the most energy. The energy $\delta\gamma$ depends sinusoidally on the phase of the electrons with respect to the laser field, so that bunching of the electrons near the phase giving maximum $\delta\gamma$ is desirable. Such pre-bunching could be accomplished in a free-electron laser. The energy gain scales as the square root of the laser power

P, according to

$$
\begin{aligned}
mc^2\,\delta\gamma &= (8\,e^2\,P/\pi\,\varepsilon_0\,c)^{1/2}\,\eta \\
&= 31.0\ \text{MeV}\,(P/\text{TW})^{1/2}\,\eta\,,
\end{aligned} \tag{1}
$$
(abbrev. for TeraWatt)

where η is a figure of merit depending on the particular choice of the laser mode. By means of a variational calculation, one can show that η for any laser beam has an upper bound, which for large kL is

$$
\eta_{\max} = \left[\frac{1}{2}\ln kL + 0.385\right]^{1/2}. \tag{2}
$$

This is of the order of unity for reasonable injection values of γ.

A paraxial laser beam is characterized by a hierarchy of fields of different strengths. For a TM beam these are the strong transverse field $E_r \simeq cB_\phi$, the longitudinal field E_z, and the weak transverse field $E_r - cB_\phi$. Generally speaking, the longitudinal and weak transverse fields are smaller than the strong transverse field by factors of $(kZ_R)^{1/2}$ and kZ_R, where $Z_R = L$ is the Rayleigh range. The weak transverse field provides the dominant transverse force for electrons with $\gamma^2 \gg kL/2$. The TM Gaussian mode with longitudinal field E_0 at the beam focus is given by

$$
E_r \simeq cB_\phi = E_0\,\mathrm{Re}\,[e^{ikz'}\,(kr/2\,\sigma^2) \\
\cdot \exp(-kr^2/2Z_R\sigma)]\,, \tag{3}
$$

$$
E_z = E_0\,\mathrm{Re}\,\{i\,e^{ikz'}\,[\sigma^{-2} - \sigma^{-3}\,(kr^2/2Z_R)] \\
\cdot \exp(-kr^2/2Z_R\sigma)\}\,, \tag{4}
$$

$$
E_r - cB_\phi = E_0\,\mathrm{Re}\,\{-e^{ikz'}\,[\sigma^{-3}\,(r/Z_R) - \sigma^{-4}\,(kr^3/4Z_R^2)] \\
\cdot \exp(-kr^2/2Z_R\sigma)\}\,, \tag{5}
$$

where $z' = z - ct$ and $\sigma = 1 + iz/Z_R$. High-energy particles for which $-kz'$ stays near $\pi/2$ can be accel-
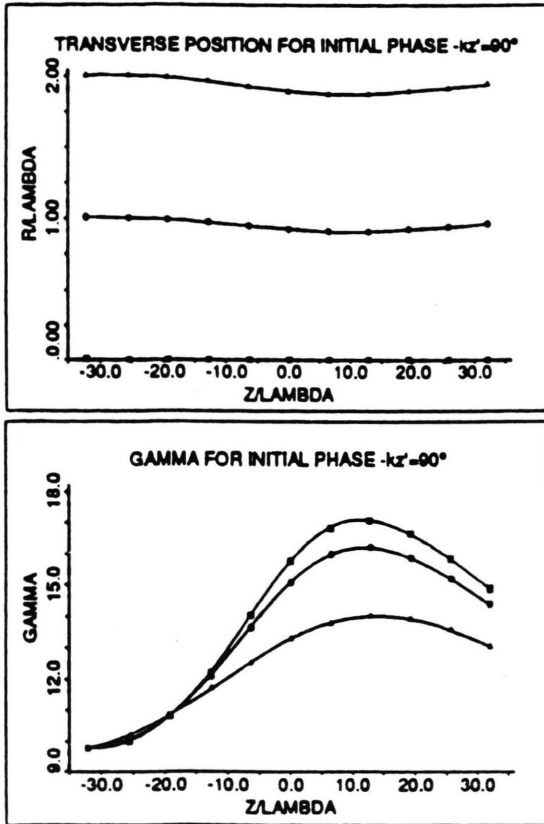

Fig. 1. Electron trajectories and energy gain in a TM Gaussian laser mode. Note the recollimation of the electron beam at the value of z where the energy gain is greatest.
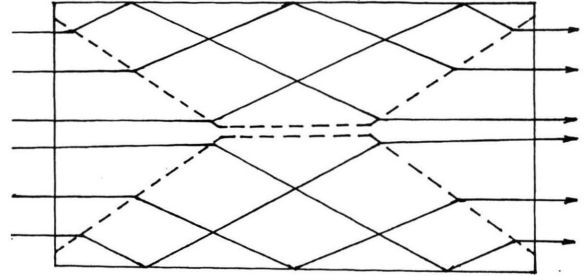

Fig. 2. "Barrel lens" favoring the TM polarization consists of a cylinder with conical holes at the ends. Light enters and leaves at the Brewster angle, and undergoes total internal reflection at the outer surface. Although not shown, the outer surface of the cylinder would actually be bowed outwards to refocus the light.

erated over the range $-Z_R < z < Z_R$, and it is easily shown that $\eta = 1$, independent of Z_R or ω. Slower particles slip to a decelerating phase faster, and so are more limited in the distance over which they can be accelerated.

Now let us consider a numerical example. The electrons are injected at $z = -Z_R$ with $-kz'$ initially equal to $\pi/2$ and zero radial momentum. We choose $P = 27.3$ GW, $Z_R/\lambda = 32$, and $mc^2 \gamma_0 = 5$ MeV. Figure 1 shows two plots showing r/λ and γ as a function of z/λ for particles with different initial values of r/λ. We see that the particle acceleration does not proceed indefinitely. At the point where the electrons reach their maximum energy, one must "do something" to refocus the optical beam and readjust its phase. We also see that the transverse forces are at first attractive, and then repulsive, so that at some point near where the electrons reach maximum energy, the electron

beam is recollimated, with a smaller radius than it had initially. In other words, the optical beam has a focusing effect on the electrons.

According to (1), the energy gain per unit length is

$$mc^2 \, \delta \gamma/(2 \, Z_R) = (2 \, e^2 \, I/\pi \, \varepsilon_0 \, c)^{1/2} \, (\eta/k \, w), \qquad (6)$$

where $w = (Z_R/k)^{1/2}$ is the laser beam radius and $I = P/w^2$ is a measure of laser intensity at the focus (twice the intensity at the lenses). From this relation we see that, for fixed I, tight focussing enhances the energy gain per length, reduces P, and should facilitate cooling of the lenses. On the other hand, the lens sizes and spacings become microscopic unless one uses long-wavelength radiation (mm waves). The emittance acceptance for the electron beam also becomes small, although the incident γ_0 can also be smaller. The above example gives energy gain on the order of 0.5 GeV/m for $\lambda = 1$ mm. The best design parameters for a laser linac have not been determined, but will be governed by such factors as lens transmission and damage, available laser sources, and manufacturing capabilities. An unconventional lens design which favors the TM polarization is shown in Figure 2. Other issues which require further study include design of the lenses, beam-loading effects and brightness limitations, FEL pre-bunching, Compton scattering producing ionizing radiation, Cerenkov radiation, slippage between electrons and short optical laser pulses, and ways to reamplify the optical beam along the linac.

Acknowledgements

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