Energy Gain, Stability, and Bunching in Gas-Loaded Hermite-Gaussian Laser Linac *

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Gas-loaded Hermite-Gaussian laser linacs yield greater gain and interaction lengths then vacuum linacs, however, optical beam and drift tube damage are not adequately alleviated in uniformly loaded devices. These problems can be resolved if the loading is graded so as to accommodate the phase velocity variation of the laser beam.

1. Introduction

Lasers with peak power capacities in excess of 1 TW are available today, which makes them potentially useful as the driving mechanism for particle accelerators. In particular, a vacuum linac based on the longitudinal field of a Hermite-Gaussian beam is feasible [1]. Such an accelerator would possess modest gain per focal passage (GFP) and require a 5–10 MeV minimum injection energy for electrons which are accelerated over a distance of two Rayleigh lengths. Lower injection energy is attainable with greater field strength, implying higher laser power or sharper focus. The main obstacle is that electrons must be removed from interaction with the beam at the limits of the acceleration range, where the field strength is high. Thus drift tubes or confocal lens arrangements in vacuum wave guides may be damaged by the strong optical field and would also damage the optical beam. We investigate here the use of a uniform dispersive gas of refractive index n ($n - 1 \approx 10^{-5}$) and a graded density gas, described by $n(z)$, as a means of obtaining phase-matching. The grading might be realized by flow through a conducting pipe, heated at its ends, or by such means as optical saturation.

2. Energy Gain in the Gas-Loaded Hermite-Gaussian Beam Mode

The on-axis GFP of relativistic particle accelerated by the field of a Hermite-Gaussian beam mode is given by $W = f(n) W_0$, where $W_0 = 2e(P_L/\pi \varepsilon_0 c)^{1/2}$ is the GFP of the plane polarized (1, 0) mode, in terms of the laser power P_L, and $f(n)$ is a performance factor that depends only on the index n of the medium:

$$f(n) = \int_{-\psi_i}^{\psi_i} \cos(\delta \tan\psi - 2\psi)\, d\psi\,, \tag{1}$$

neglecting collisions. The integration limits satisfy $\delta \tan\psi_i - 2\psi_i = \pm(\pi/2)$, where $\delta = (n-1) k z_q$, n is the refractive index, and $k = 2\pi/\lambda$. This determines the injection coordinate $z_i = x(n) z_q$. Four values of δ are of particular interest: (a) $\delta = 0$, the vacuum, for which $f = x = 1$, (b) $\delta = 0.33$, yielding maximum interaction length, for which $f = 1.5$, $x = 14$, (c) $\delta = 1$, yielding maximum energy gain, for which $f = 2.4$, $x = 4.25$, and (d) $\delta = 2$, for which the phase velocity equals c at beam focus, yielding $f = 1.9$ and $x = 1.86$. In Fig. 1 are shown computer solutions for the gain as function of injection energy. The dependence of the injection energy and the gain on δ is understood by noting that the injection energy is minimized by matching phase and particle velocities at or near the injection point, while the maximum gain is obtained by matching at a Rayleigh length from focus.

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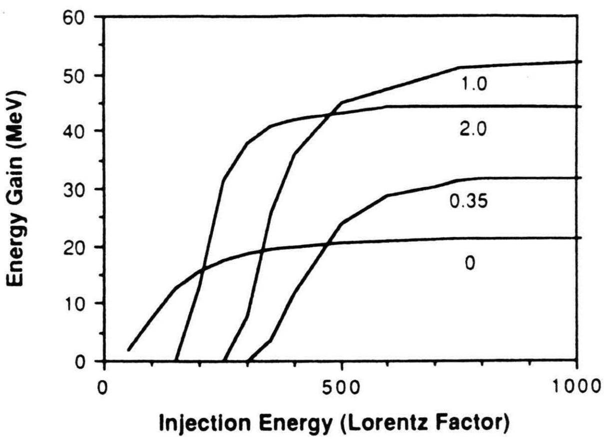

Fig. 1. The energy gain of electrons moving along the beam axis as a function of the injection energy for various values of δ.

3. Stability of the Particle Beam in the Uniformly-Loaded H-G Beam

For relativistic motion near the z-axis, the force equation in the x, y directions, to first-order in x and y, is found to be of the form of a damped oscillator:

$$\frac{d^2 \xi}{dZ^2} + \Gamma(Z) \frac{d\xi}{dZ} + K_{x,y}(Z)\,\xi = 0\,, \tag{2}$$

where $\xi = x/z$ or y/z, $Z = z/z_q$, $\Gamma(Z)$ is a damping constant

$$\Gamma(Z) = \kappa(Z) \frac{1 - Z^2}{(1 + Z^2)^2}\,, \tag{3}$$

and $K_{x,y}(Z)$ are spring constants in the uncoupled x, y directions:

$$K_x(Z) = -\kappa(Z)\left\{\left[\delta + \frac{1}{1+Z^2}\right]\left[\frac{2\cos\delta Z - \sin\delta(1-Z^2)}{(1+Z^2)^2}\right. + Z\frac{\cos\delta(1-Z^2) + 2\sin\delta Z}{(1+Z^2)^3}\right\}. \tag{4}$$

$K_y(Z) = K_x(Z)$, evaluated at $n = 1$. The function $\kappa(Z) = W_0/\gamma(Z)\, m_0 c^2$ varies slowly. The damping constant is always positive in the acceleration regime, being proportional to E_z. The spring constants are positive (negative) before (after) the focus. Transverse stability of the particle beam is thus restricted to half the beam length. The spring constants K_x and K_y are plotted in Fig. 2 for two values of δ. K/E tends to zero as Z^{-2}. This indicates that addition of nonlinear terms to (2) should be desirable when $|Z| \gg 1$.

4. Energy Gain in Graded-Load Linacs

The index n may in principle be graded such that particles of given injection characteristics are captured and accelerated indefinitely. This may be attempted to offset various effects simultaneously, as (a) phase slippage, (b) group velocity walkoff, and (c) effects due to saturation. We consider (a) for c.w. laser beams, yielding $n(z) = v_0(z)/c$ in relativistic limit, where $v_0(z)$ is the on-axis vacuum phase velocity. The gain, in the same limit, is then

$$W = \pi \sin\phi\, W_0\,. \tag{5}$$

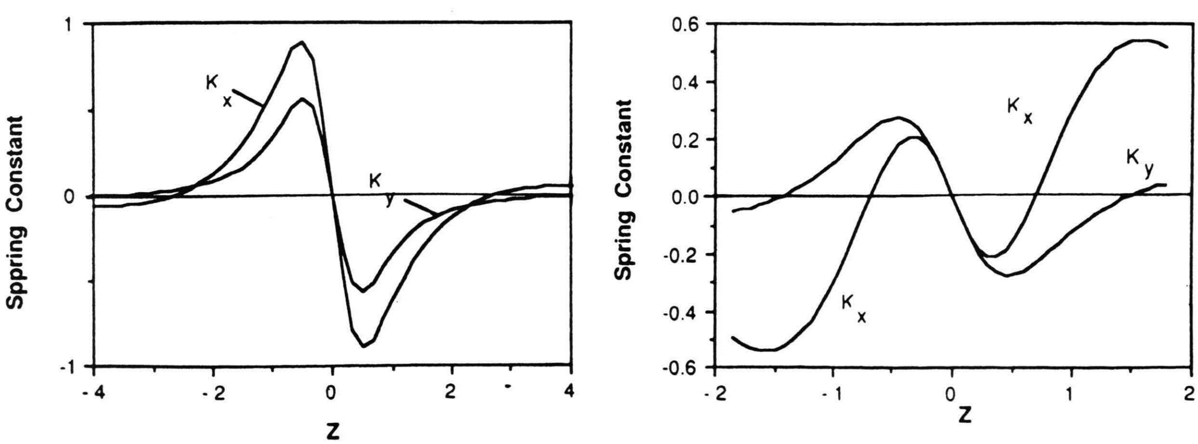

Fig. 2. The normalized spring constants $K_x(Z)/\kappa(Z)$ and $K_y(Z)/\kappa(Z)$ in the transverse directions $\parallel$ and $\perp$ to the direction of laser polarization. (a) $\delta = 1$, (b) $\delta = 2$.

The gain increase of the graded linac is thus at most a factor of π. On the other hand, the principal advantage of the grading is that the limits of the vacuum and uniform-load linacs of the interaction length and injection energy are removed. In addition, the grading produces more favorable stability properties.

5. Stability of Particle Beam in Graded Linac

Beam stability depends on the value of the phase ϕ. The results show that in the range $0° < \phi < 90°$ the particle trajectory relative to that of a point moving with the phase velocity of the field is unstable in the z-direction, causing debunching of the particles. For $90° < \phi < 180°$, stability exists in three dimensions along the entire beam length. At a small cost, as the phase must be somewhat above the value of maximum acceleration (90°), it is thus possible to obtain simultaneous focusing and bunching of the electron beam.

6. Conclusion

GFP values for Gaussian beams are typically an order of magnitude or two below those of more efficient beam geometries [2]. However, a lens wave guide linac with little optical beam deterioration should be possible, provided the beam propagates through a dispersive medium that is graded in the axial direction. The possibility of constructing such a device depends mainly on the degree to which a medium meeting the above requirements can be assembled.

Acknowledgement

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