High Power, High Frequency Lasertron RF Sources J. Norem, E. Chojnacki, and R. Konecny

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Introduction

High power rf sources have historically been limited to frequencies at which intense electron beams could be efficiently modulated. We have been exploring the power, frequency and efficiency limitations associated with the use of lasertrons[1] for generating modulated beams and using these beams as high power microwave sources. This effort is an extension of wake field accelerator development, and will proceed as part of the Argonne Wakefield Accelerator construction and use.[2]

In the lasertron the electron beam is produced from the photoelectric effect at the photocathode, thus the electron pulse closely resembles the laser pulse in density and spatial extent. One configuration for this device is shown in Fig. 1 where a dielectric Čerenkov coupler is used to transfer power from the electron beam to the rf field.



Figure 1: The Cerenkov Lasertron.

Operation at high power and high frequencies, (~GW, \gtrsim THz) seems possible using laser optics to compensate electron aberrations due to geometrical optics and space charge. In this paper we show results of simulations that indicate electron pulse lengths of the order of 0.25 ps can be produced if other aberrations are controlled, describe an optical system to compensate aberrations and generate pulse trains from a short pulse laser, discuss design constraints and limitations of rf couplers, and describe constraints on the system as a whole.

Electron Optics

The maximum frequency at which an electron beam can be modulated is determined by the minimum pulse length associated with aberrations in electron optics. The primary distortions that increase axial bunch length are path length differences caused by transverse effects near



Figure 2: Laser optics compensate transverse effects.

the photocathode due to space charge or external fields. We assume that these effects can be compensated with shaped laser pulses as shown in Fig. 2 using a technique described below. Longitudinal space charge fields also directly widen the bunches, however, and this mechanism determines a minimum pulse length which is a function of the bunch and cavity parameters.

In order to study the effects of space charge and laser properties on the minimum bunch length, the initial stages of the acceleration process were numerically simulated using a one dimensional model. The evolution of the bunch is followed assuming a Lorentz force balance dp/dt = eEfor each electron. The electric field can be expressed in the form

$$E_z(z,t) = E_0 \sin(2\pi f t + \phi) \exp(-z^2/2l_z^2) - E_{sc}, \quad (1)$$

where E_0 is the maximum rf electric field, l_z is the characteristic length of the cavity, and f = 1.3 GHz is the resonant frequency of the photocathode cavity. The fields due to space charge are evaluated using retarded potentials of the beam and its image, $E_{sc} \sim 0.36$ MV/m/nC for a laser spot radius $r_l = 1$ cm.

A large contribution to the bunch width is due to the nonrelativistic part of the acceleration process. At low energies, trailing electrons see a reduced accelerating field due to space charge, $E_{\bullet} \sim E_0/2$, and accelerate more slowly, lengthening the distance from the front of the bunch. At relativistic energies all electrons are moving at nearly c so the spatial distribution is fairly well maintained. If transverse effects can be corrected, electron bunch lengths, τ_e , can approach the pulse length of the laser even for high currents, as shown in Fig. 3. For the reasons given previously, the widths of high charge pulses show a strong dependence on the accelerating field at the photocathode and less sensitivity to the length of the cavity, roughly $\tau_e \sim E_0^{3/2} l_z^{0.15}$. Thus effects such as dark current, surface breakdown, and power limitations provide the ultimate limits on bunch length.





Figure 3: Pulse length vs charge per bunch for a 0.2 ps laser pulse in the absence of aberrations.



Laser Optics

The optical system must create a pulse train and shape individual pulses in addition to stabilizing the intensity and position of the laser beam. A system which can produce the required laser pulses is shown in Fig. 4. The pulse train is created by dividing the initial pulse and separately delaying the parts. Then a scatterer is used as part of the focusing system to realign the parts on axis. This can be done iteratively to produce p^n pulses, where p is the number of pulses into which a single bunch is divided and n is the number of times the process is repeated. To be efficient, the scatterer must scatter by small angles[3] and the wave front shaping, which selectively delays parts of the beam to form the required cup shaped geometry, can be done at an intermediate focus upstream of the photocathode.

Intensity stabilization can be accomplished by means of a Pockels cell/polarizer system operated by sampling a small fraction of the laser beam and laser centroid stabilization follows from the action of the scattering surfaces.

RF Couplers

There are a number of options for rf couplers: slowwave, planar slab/grating (orotrons), fields, plasmas, each of which can be coherent or incoherent. In all coupler



Figure 5: Resonant frequency for cylindrical dielectric liners with $\epsilon = 3$. f_1 is exact solution for first radial mode, f_2 is second radial mode, and Geom is from approximate expression given in the text.

considerations the output power will scale with energy and current of the driving beam pulses, which will be of large diameter compared to the radiation wavelength. Thus, to accommodate the drive beam and high peak powers, gross coupler dimensions will also have to be large compared to radiation wavelengths. On the other hand, relativistic contraction effects require that the transverse dimensions of the coupler, D, must satisfy $D < \gamma \sigma_z$, where γ and σ_z are the relativistic factor and bunch length, otherwise the fields would lose the modulation of the beam.

The electromagnetic radiation extracted from the prebunched electron beam can be at the fundamental frequency of the bunch separation. The nominal frequencies considered here are 30 GHz, 500 GHz, and 1 THz. The lower frequency at high power is of interest to the accelerator community and the higher frequencies at moderate to high power is of interest to the novel rf source community in general. Of the several types of couplers considered, the simplest are slow-wave structures suitable to the frequency range of interest, requiring no external rf input. At 30 GHz dielectric-lined or iris-loaded waveguide will be adequate. At 500 GHz and 1 THz dielectric-lined waveguide operating at a second or third radial mode may still be appropriate, but a planar dielectric slab or diffraction grating would also work well, be easier to fabricate, and scale to even higher frequencies. The thickness of the dielectric lining in the slow-wave structure or the dielectric slab in a planar coupler is approximately given by the geometrical relation for Čerenkov reflections in a slab, $\lambda = 4d\sqrt{\epsilon} - 1$, where λ , d, and ϵ , refer to the wavelength, thickness and dielectric constant. For thin coatings at the fundamental this relation breaks down and more precise expressions[4] have to be used as illustrated in Fig. 5.

A wiggler has been considered as an output coupler in conjunction with an input signal to trap the electron bunch at the top of a ponderomotive bucket and allow the bunch to execute a half bounce. At high frequencies (500 GHz) the electron bunch lengths considered here tend to be broader than the ponderomotive separatrix, indicating that the pre-bunched nature of the beam can not be utilized. At low frequencies (30 GHz) the resonant wiggler wavelength tends to be prohibitively large, > 0.5 m. Thus, FEL-type rf extraction will be given no further consideration here.

The output power from a slow-wave coupler will build up step-wise as each bunch passes through and leaves a fraction of its energy in a wake field moving with the group velocity and frequency of a chosen mode. Steady state will be achieved when the first "slug of rf" exits the coupler and is subsequently replaced by the wake of another electron bunch as shown Fig. 6. If the first electron bunch exits the coupler at time t = 0, steady-state power will be achieved at time

$$t_s = \frac{L(1-\beta_g)}{\beta_g c}, \qquad (2)$$

where L is the length of the coupler, β_g is the normalized forward group velocity of the particular mode, and c is the velocity of light. This time, of course, must be short compared to the period of the photocathode cavity. The number of bunches superimposing their wake energy at steady state is the integer round-down of $n = t_s f$, where f is the frequency of the electron bunch spacing. Neglecting finite bunch length effects, resistive losses, and smoothing effects from external waveguide plumbing, the output power at any time can then be determined from n and the wake potential gradient of a single bunch, given by

$$E_w = \frac{q\,\omega\,r}{2\,Q\,(1-\beta_g)}\,,\tag{3}$$

where q is the charge per bunch, ω is the angular frequency of the mode, r is the shunt impedance, and Q is the cavity quality factor. The steady-state power is then

$$P_0 = \frac{(n E_w)^2 \beta_g c Q}{r \omega} = \frac{r \omega \beta_g c n^2 q^2}{4 Q (1 - \beta_g)^2} \cdot \qquad (4)$$

As an example, listed in Table I are parameters of several dielectric-lined waveguide couplers designed for 30 GHz, 500 GHz and 1 THz at beam energies that will be available from the Argonne Wakefield Accelerator linac. The power ratings in Table I take into account a finite bunch length. Plumbing of rf from the coupler section can be accomplished by radiating out the end or from the side in a variety of geometries.

Table I. Parameters of several dielectric Čerenkov couplers for a 1 nC/pulse beam, inner radius of the dielectric liners 0.5 cm, d is the thickness if the liner, $\epsilon = 2.55$, and σ is the temporal width of the bunch.

η	P_0	σ	n	d	L	f	U
%	MW	ps		mm	m	GHz	MeV
45	27	1	13	1.34	0.19	30	2
49	178	1	30	1.28	0.49	30	12
7	424	0.25	251	0.25	1.0	500	12
0.08	9.3	0.25	450	0.12	1.0	1000	12



Figure 6: Power exiting lasertron slow-wave rf coupler.

Performanace Limitations

By way of summary, the following items will all play a role in the limits of lasertron performance. The frequency of the photocathode cavity which determines the temporal time duration of the electron bunch train. Maximum low frequency if power into the photocathode cavity and linac, as well as physical dimensions, which determines allowable beam loading, or charge per pulse. Available pulse length and power from the laser. Success of laser optics to compensate pulse broadening due to electron optics. Dimensions of the rf coupler which will determine maximum output power in regard to breakdown and charging of any dielectrics. Efficiency of the rf coupler which is constrained at high frequencies by resistive losses and length of the coupler. The length of the coupler is in turn limited by the first item above, temporal duration of the bunch train. These issues are receiving experimental and theoretical effort as part of the Argonne Wakefield Accelerator program.

This work supported in part by the U. S. Department of Energy Division of High Energy Physics, Contract No W-31-109-ENG-38.

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