Beam Quality in a Cyclotron Autoresonance Accelerator[1]

B. Hafizi†, P. Sprangle‡ and J. L. Hirshfield§
†Icarus Research, 7113 Exfair Road, Bethesda, MD 20814
‡Beam Physics Branch, Plasma Physics Division
Naval Research Laboratory, Washington, DC 20375
§Omega-P, Inc., 2008 Yale Station, New Haven, CT 06520
and Yale University, PO Box 6666, New Haven, CT 06511

Abstract – The axial velocity spread for a gyrating electron beam produced by cyclotron autoresonant acceleration is determined. The parameter range chosen for analysis is that of interest in harmonic generation of cm-wavelength radiation to drive a next-generation electron-positron collider.

I. Introduction

The cyclotron autoresonant accelerator (CARA) may have application as a compact, low-energy injector for a high-gradient accelerator or for use in a source of radiation that requires low-energy electrons. Recent calculations of the efficiency for production of rf power at a harmonic of the rotation frequency for an electron beam prepared using a CARA show that good beam quality is important for achieving high efficiency.[1] For example, when a nonlinear (resonant) taper in magnetic field is employed in the harmonic convertor, 5-th harmonic conversion efficiency at 14.25 GHz was predicted to fall from 70% to 30% when the axial velocity spread was increased from zero to 2% in a 7 A, 150 kV electron beam. It is thus crucial to understand the origins of finite velocity spread during cyclotron autoresonant acceleration, in order to design accelerators capable of producing beams with spreads below 1%. This paper presents preliminary results of a numerical study of the evolution of axial velocity spread during acceleration by a CARA operating in the TE_{11} mode at S-band.

Prior theoretical studies of the acceleration process[2] have shown that rapid trapping of particles occurs at the resonant phase[3], that substantial energy gain can be obtained[4], but that a practical upper limit to beam energy will exist when a fast wave rf accelerating field is employed[5]. If an accelerating field with a phase velocity equal exactly to the light velocity is employed then–in principle–unlimited acceleration can occur. Means for arranging this in practice include the use of dielectrically-lined waveguides or coaxial waveguides operating in the TEM mode. For the former, acceleration gradients determined in our analysis to date have been smaller than those for fast wave unlined waveguides. For the latter, elementary considerations show that axicentric orbits experience acceleration to an energy no greater than the potential drop between the inner and outer conductors. For properly phased electrons with fixed, small off-axis displacement of guiding centers, the energy increases with time like $t^{2/5}$ in the asymptotic limit. This is to be compared with the $t^{2/3}$ scaling for the conventional autoresonance acceleration. As a result, consideration here will be limited to fast-wave accelerators for producing 20-100 MW beams in the energy range up to 1 MeV for use in the harmonic generation of cm-wavelength radiation to drive a next-generation electron-positron collider. In this paper we present results from time-dependent simulation of the CARA to illustrate the quality of the electron beam generated, as measured by the axial velocity spread.

II. Numerical Results

The simulation results presented here are obtained by following the motion of a group of 100 electrons in the field of a TE_{11} mode in a circular waveguide which is immersed in a guide magnetic field. The amplitude of the rf field is assumed to vary slowly due to beam loading of the circuit. The guide field is tapered along the z axis in order to maintain resonance, i.e., $\Omega_0/\gamma = \omega(1 - n\beta_z)$, where $\Omega_0 = |e|B_0/mc$ is the gyrofrequency in the axial component of the guide field $B_0(z)$, e is the charge and m is the mass of an electron, c is the vacuum speed of light, γ is the relativistic mass factor, $\beta_z = v_z/c$ is the ratio of the axial velocity to c, ω is the rf frequency and $n = c/(\omega/k_z)$ is the refractive index for the waveguide mode with axial wavenumber k_z. Tapering of the axial component

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of the guide field implies the presence of transverse components since the magnetic field is solenoidal and approximately irrotational. The Lorentz equations of motion for the electrons are simplified by retaining only the resonant terms and integrated by a 4-th order Runge-Kutta method, using 10^4 mesh points. The slow-scale spatial variation of the rf is expressed as $\exp\{i\int_0^z dz'[\Delta k(z') + i\Gamma(z')]\}$, where $\Delta k(z)$ is the wavenumber shift and $\Gamma(z)$ is the damping rate. The slow-scale Maxwell equations then lead to explicit expressions for $\Delta k(z)$ and $\Gamma(z)$. The electrons enter the waveguide as a pencil beam consisting of axicentric orbits, but with finite emittance. The parameters for the simulation results presented here are shown in Table 1. The initial emittance value of 14.14 mm-mrad is twice the ideal emittance for a 50 A beam drawn from a 5 cm^2 thermionic cathode at a temperature of 0.16 eV.

Table 1

Frequency $\omega/2\pi$	2.85	GHz
Input Power	50	MW
Waveguide Radius	8.824	cm
Refractive Index	0.937	
Waveguide Length	168	cm
Initial Energy	100	keV
Final Energy	1	MeV
Current	50	A
Initial Normalized Emittance	14.14	mm-mrad
Initial Beam Radius	0.638	mm
Final Beam Radius	2.7	cm
Initial Axial Velocity Spread	0.015	%
Final Axial Velocity Spread	0.11	%
Initial Magnetic Field	0.592	kG
Final Magnetic Field	1.45	kG

Table 1: Parameters for simulation of CARA at S-band.

The waveguide radius is chosen to be large enough so that the refractive index is close to unity and, therefore, the interaction is close to autoresonance. As a consequence the waveguide is somewhat overmoded and supports all TE and TM modes through TM_{21}. However, other simulations show that CARA operation below cutoff for the TM_{11} mode is also possible.

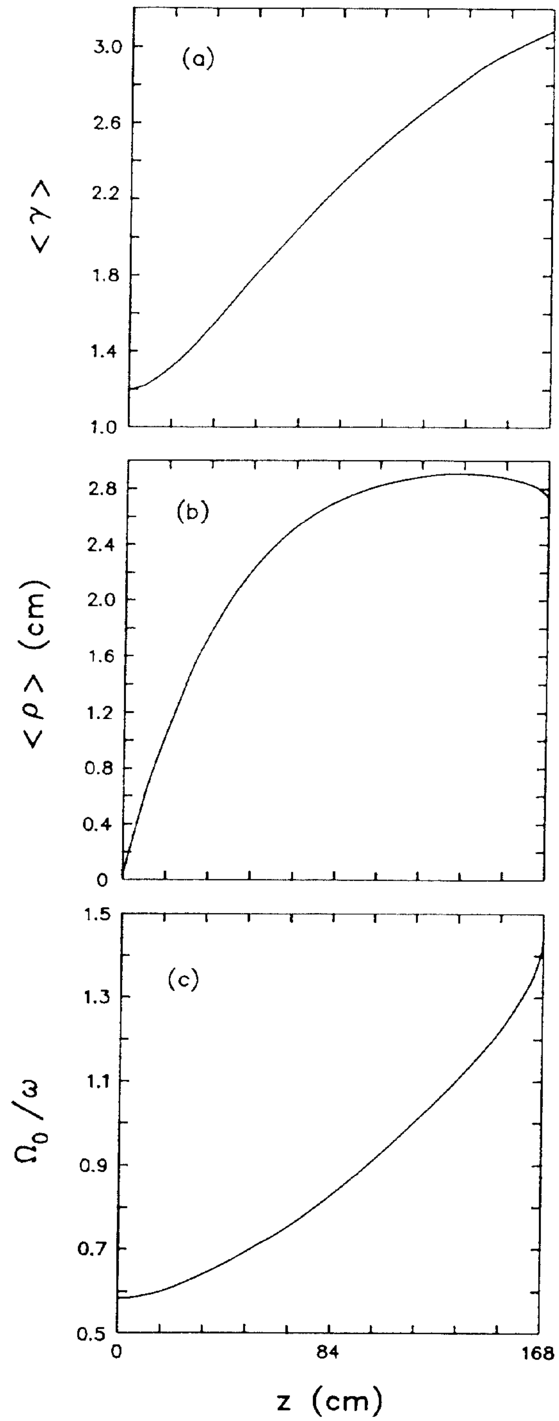

Fig. 1: Results from numerical simulation of CARA operating at S-band with 100 keV initial electron energy. (a) Mean beam relativistic factor; <> indicates an average over the electron distribution. (b) Mean beam gyroradius. (c) Ratio of gyrofrequency to rf frequency.

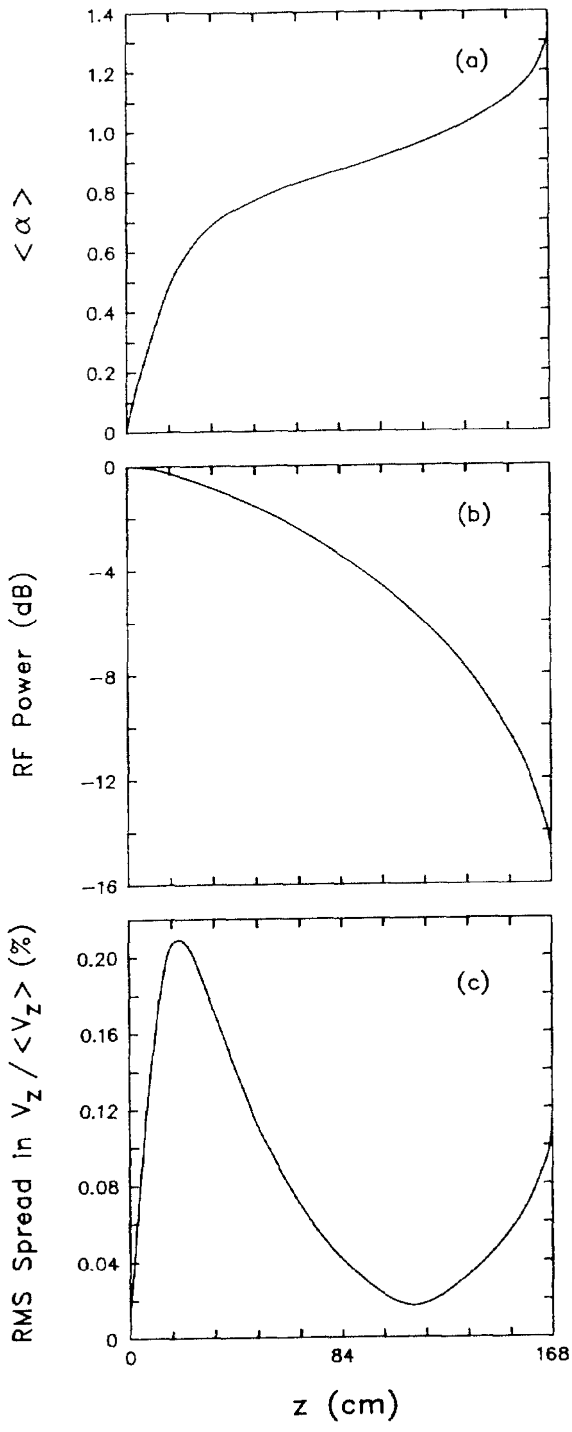

Fig. 2: Results from numerical simulation of CARA operating at S-band with 100 keV initial electron energy. (a) Mean beam α. (b) Depletion of rf power. (c) Ratio of root-mean-square spread in axial velocity to mean axial velocity.

Figures 1(a), (b) and (c) show the mean γ (averaged over the ensemble of electrons), the mean gyroradius, $\rho = \gamma v_\perp/\Omega_0$ where $v_\perp$ is the transverse component of the electron velocity, and the ratio of the gyrofrequency to the rf frequency, Ω_0/ω, all as functions of axial distance z. (In the figures, $<>$ indicates the average over the electron distribution.) Figure 1(a) shows that the beam energy increases to about 1 MeV in a distance of 168 cm. Beyond $\sim$ 100 cm, the rise in energy is principally directed into the transverse component of the electron velocity. To maintain resonance this is accompanied by a rise in the magnetic field which tends to reduce the axial electron velocity due to the transverse components of the magnetic field. This, in turn, leads to a further rise in the field to preserve the resonance. The net effect is the rapid rise observed in Fig. 1 (c) and is responsible for restraining the beam radius from approaching the waveguide radius, as indicated in Fig. 1(b).

Figure 2(a) shows the increase in the mean beam $\alpha \equiv v_\perp/v_z$ as the electrons are accelerated. The acceleration process, of course, leads to depletion of the rf power down the waveguide, as shown in Fig. 2(c). Finally, the root-mean-square (rms) spread in the axial velocity of the electrons, normalized to the mean axial velocity, is shown in Fig. 2(c). It is observed that the spread in the axial velocity, which is the key figure-of-merit in evaluating the quality of the beam for radiation generation purposes, is much smaller than 1%.

III. Conclusion

We have presented some preliminary numerical results for a > 95% efficient CARA operating at S-band. In particular, we have shown that the quality of the electron beam generated by this accelerator, as measured by the axial velocity spread on the beam, is consistent with the requirement for efficient generation of cm-wavelength radiation in a 5-th harmonic converter.

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