Experimental Demonstration of High Efficiency Electron Cyclotron Autoresonance Acceleration

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First experimental results are reported on the operation of a multimegawatt 2.856 GHz cyclotron autoresonance accelerator (CARA). A 90–100 kV, 2–3 MW linear electron beam has had up to 6.6 MW added to it in CARA, with an rf-to-beam power efficiency of up to 96%. This efficiency level is larger than that reported for any fast-wave interaction between radiation and electrons, and also larger than that in normal conducting rf linear accelerators. The results obtained are in good agreement with theoretical predictions.

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In a cyclotron autoresonance accelerator (CARA), an injected linear electron beam is energized using rf fields of a guided fast wave whose group velocity is greater than the axial velocity of the beam [1]. Continuous gyroresonant acceleration can be maintained in CARA by spatial tapering of the strength of an axial magnetic field and/or of the waveguide wall radius, so as to satisfy continuously the Doppler-shifted cyclotron resonance condition

$$\omega(1 - n\beta_z) = \Omega/\gamma\,. \tag{1}$$

Here ω is the radian frequency of the wave, n is the wave group velocity and β_z is the axial electron velocity (both normalized to the velocity of light), $\Omega = eB/m$ is the rest electron gyrofrequency in a static magnetic field B, and γ is the relativistic energy factor. For a plane wave in vacuum with $n = 1$, it has been shown [2,3] from the relativistic equations of motion that Eq. (1) can be satisfied with B a constant, so that resonance is automatically maintained as $\gamma \to \infty$ and $\beta_z \to 1$. In view of the practical simplification afforded by constructing a CARA using smooth-wall unloaded waveguide for which $n < 1$, the concept of autoresonance has been generalized to include spatially tapered group velocity $n = n(z)$ and magnetic field $\Omega = \Omega(z)$. To achieve high efficiency in the transfer of rf power to electron beam power, the actual taper profiles required must take into account rf power depletion along the acceleration path, a condition that is not explicit in Eq. (1). Also not evident in Eq. (1) is an upper energy limit in CARA, set either by depletion of the available rf power or by stalling that occurs when β_z decreases to zero as Ω increases; this upper energy limit is discussed below.

This Letter presents experimental evidence from the initial operation of a CARA, where ~25 A beams were accelerated to over 360 kV with rf-to-beam power transfer efficiencies that exceeded 90%. These observations are significant for demonstrating a novel means for generation of multimegawatt gyrating electron beams, and for showing—as prior analysis predicts [1,3,4]—that conditions exist where an rf accelerator can operate with efficiency values that exceed values found heretofore in other fast-wave interactions between radiation and electrons [5], and that compare favorably with efficiency values for high group velocity industrial rf linear accelerators [6].

Requirements for high power gyrating beams exist in radiation sources such as gyroharmonic converters [7], gyrotron cavity oscillators [8], and gyroklystrons [9]. In these devices, low spreads in beam energy and pitch angle are required. Analysis has shown that CARA can provide suitable multimegawatt beams with good beam quality for these applications, provided the injected linear beam has low axial velocity spread [1,4]. Typically, the energy acquired by a beam in CARA resides in transverse motion; the axial velocity is only weakly affected. Other applications of high-power gyrating beams may exist in radiation processing applications, such as electron beam dry scrubbing of flue gases and sterilization of medical supplies and food. For these applications there may be only a mild requirement for beam quality. But for most applications, the efficiency of the accelerator should be as high as possible to minimize wall-plug power demands.

Prior experiments on gyroresonant acceleration employed TE_{111} mode cavities, as initiated by Jory and Trivelpiece [10] based on the analysis of Roberts and Buchsbaum [2]. Thus McDermott, Furuno, and Luhmann [11] showed that ~450 kV could be added to a 25 mA, 2 kV beam with an efficiency of about 8.3%. Kou *et al.* [12] demonstrated that 210 kV could be added to a 400 mA beam at 9.23 GHz with an efficiency of 42%. Balkcum *et al.* [13] published a design for a 17.4 GHz, 150 kW sixth-harmonic gyroamplifier with a predicted acceleration efficiency of 39%. However, with the short interaction length of a cavity (typically less than one free-space wavelength), provision of a magnetic field profile that affords local gyroresonance along the interaction path is nearly impossible; in consequence, a constant field was employed in the above-cited works whose value was chosen to maximize the beam's energy gain. Simulations carried out based on an exact theory [14] for TE_{111} mode cavity acceleration in a uniform magnetic field showed that under practical conditions efficiency values can be expected not to exceed about 40%, with lower values as the beam's energy gain increases.

In the approach taken in CARA experiments described here, a cylindrical waveguide driven in a rotating TE_{11} mode is used to accelerate the beam, as in prior low-power experiments by Shpitalnik [15]. With a resulting interaction length of five or more free-space wavelengths, the theoretically dictated magnetic field tapers can be reasonably approximated with individually powered external coils. Moreover, simulation studies have shown that small detunings of the field can be used to minimize beam parameter spreads and to maximize efficiency. Furthermore, a waveguide CARA is intrinsically capable of multimegawatt operation since use of a smooth-wall low-loss traveling wave structure ensures that power dissipated in ohmic wall losses is distributed and is small compared to beam power, and that high fields that can lead to multipactor discharges are avoidable; these features may not be shared by a cavity or low group velocity traveling-wave structure. In addition, high efficiency and good beam quality can be achieved without microbunches over the full temporal length of a multimicrosecond rf power pulse in a waveguide CARA as a result of operation with high group velocity, since rf energy can be replenished from the source as rapidly as it is taken up by the beam. This is in contrast to conventional rf linear accelerators (designed for high energy gain) which operate at small group velocity, and where efficiency is limited to typically a few percent [16] to avoid undue energy spread between successive beam microbunches. Low energy industrial linear accelerators with high group velocity can operate with efficiencies up to about 85% [6].

A schematic drawing of the apparatus used in the experiments reported here is shown in Fig. 1. The gun is a 100 kV convergent flow diode with a nominal perveance of $1 \times 10^{-6}\,\mathrm{A\,V^{-3/2}}$. A three-axis trim coil system surrounds the gun to permit adjustment of the magnetic field in the convergence region. A pencil beam with a 95% radius of 4 mm exits an iron pole piece following

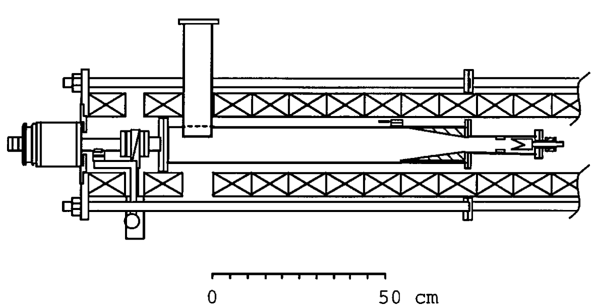

FIG. 1. Schematic of CARA used in experiments reported in this Letter. Shown (from left) are the electron gun, pumping port, gate valve, waveguide input (one of two), CARA waveguide (internal tapers not shown), rf sample point, conical absorber, beam collector, individually powered field coils, and flux bars.

the anode into a $\sim$800 G axial guide field. An all-metal gate valve between the gun and CARA allows system bakeout and rf processing without deleterious exposure of the cathode. Base pressure in the system reached 2×10^{-9} Torr following bakeout and rf processing. A 10-cm long cutoff beam tunnel is tapered from radius 1.25 up to 3.81 cm at the entrance to the CARA TE_{11} mode waveguide. Microwave power at 2.856 GHz from an XK-5 former SLAC klystron is fed radially into CARA through two WR-284 rectangular waveguides that are positioned 90° from one another around the cylindrical waveguide. The klystron output is split using a 3-db sidewall coupler that introduces 90° phase shift into one arm so that, with identical length waveguide feeds to CARA, a rotating TE_{11} mode is launched. Higher modes are cut off at 2.856 GHz in the 3.81 cm radius pipe. Matching stubs in the waveguide feeds ensure a return loss of less than -22 db. The CARA waveguide is tapered from 3.81 to 5.08 cm radius over a 20.3 cm length, and the overall CARA length is 50.9 cm. The taper in CARA waveguide radius corresponds to a variation in normalized group velocity n from 0.590 to 0.796. A 20.3 cm conical rf absorber made from Cerralloy 60:40 BeO:SiC, with a central hole tapering in radius down to 2.32 cm, serves as an rf termination for CARA, but allows the accelerated beam to pass through to the beam collector. The absorber is coated with electrodag to allow drainage of stray charge. Four weakly coupled rf pickoff probes are disposed along CARA to allow monitoring of rf absorption by the beam. Twelve 16 cm inside diameter guide field coils, each 10.8 cm in length, surround CARA. The currents in the coils are set by computer to produce axial field profiles that nearly duplicate theoretically dictated profiles. After passage through the conical absorber, the beam is collected by a thermally and electrically insulated Faraday cup, cooled by metered passage of water. Thermistors measure the temperature rise of the water to allow heat generated by absorption of the beam to be inferred; typical average beam powers (for 1 pps operation) are 2–10 W. This simple means of measuring beam power is accurate to within $\pm 5\%$, as confirmed against known beam power levels when CARA is not energized.

Results of a typical run are shown in Fig. 2. For this example, a 25 A, 95 kV beam is injected and 5.2 MW of rf power at 2.856 GHz is introduced into CARA. The magnetic field profile is adjusted according to theory for these parameters, and then fine-tuned to maximize absorption. In Fig. 2(a) the rf power pulse as sampled at the end of CARA is displayed both with and without the injected beam. The beam pulse width is purposely set to be about 1 μsec less than the rf pulse width, so that the beam interacts with the rf fields only during the flat-top portion of the rf power pulse. The magnitude of power diminution is measured using a calibrated attenuator that allows resetting of the detector signal without the beam present to the same level as observed with the beam. For the example shown, the measured diminution is 12 db, corresponding to transmission of 6.3% of the rf power. Simultaneous measurement of power reflection during the beam pulse showed reflection typically to increase by about 3% of the incident power level. Skin effect wall losses in the CARA waveguide amounted to about 0.02%. These data indicate that the beam had taken up 90.7% of the incident power, and 93.7% of the power that was actually propagating into CARA, corresponding to the addition of 4.7 to the 2.4 MW injected beam for a total beam power of 7.1 MW. The calorimetric measurement of power flow into the beam collector confirmed this measurement to within $\pm 5\%$, after correction for a small scrape-off loss of transmitted current at the conical absorber. The simulations for this case predict a final beam energy of 298 kV, as compared with the measured value of 284 kV. The predicted mean velocity ratio α is 0.87, and the predicted axial velocity and energy spreads are 0.15% and 1.0%. Simulations have also shown that detrapping and reduced efficiency in CARA result if the beam quality is poor. Figure 2(b) shows the experimental magnetic field profile (solid curve) used to achieve these results, together with the exact resonant profile dictated by theory for these parameters (dashed curve). Also shown are rf power flow predictions for both magnetic field profiles; in either case the calculated rf power remaining at $z = 55$ cm is 5.8% of that incident, as compared with the measured value of 6.3% at $z = 51$ cm. The rf power flow curves in Fig. 2(b) for the exact resonant profile and for the experimental profile are nearly identical. This fact together with the observed high-power flow value into the beam are evidence for strong trapping of accelerated particles in the effective potential well formed by the beating of the Doppler-shifted rf wave and the wavelike gyromotions. Evidently, the trapping remains strong so long as the actual profile does not deviate too far away from the resonant profile, a point predicted in the prior analysis [1]. When the direction of the axial guide magnetic field was reversed, negligible rf power was taken up by the beam, since the sense of rf field rotation was opposite to the sense of particle rotation. This observation showed that the level of counterrotating TE_{11} mode excited by the two-port waveguide feed was negligible. Figure 3 shows beam power and efficiency values measured over a range of parameters for injected beams and rf power levels, using the techniques described above. Of course, different magnetic field profiles were used for each set of experimental parameters. As seen, beam powers up to 9.6 MW have been produced with efficiency values up to 96%. Progression to higher powers was not undertaken due to pressure rise in the system above 1×10^{-7} Torr that arose due to outgassing.

These measurements indicate that cyclotron autoresonance acceleration can be a nearly ideal power transfer process, as predicted in prior theoretical studies [1,3,4]. This occurs because all the injected beam particles are rapidly captured into the relative phase that maximizes the rate of energy absorption from the rf traveling wave, and because the group velocity and magnetic field tapers synchronize the particle's gyration phase with the Doppler-shifted phase of the guided wave. The degree of perfection that can be maintained in this synchronism diminishes as the axial velocity spread of the injected beam increases; for

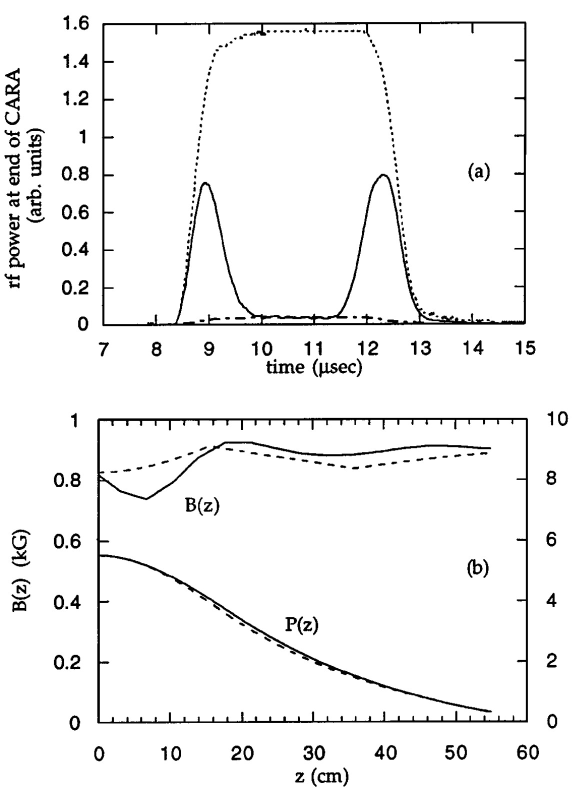

FIG. 2. (a) Pulse shape of rf power at the end of CARA with (solid line) and without (dashed line) the injected beam. The lower dashed trace is the same as the upper, but attenuated by 12 db. (b) Idealized (dashed line) and actual (solid line) profiles of magnetic field $B(z)$ along CARA, and rf power profiles $P(z)$ calculated for each.

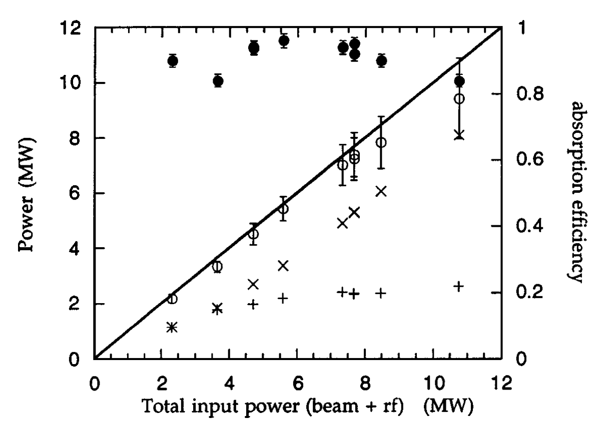

FIG. 3. Total beam power (○), efficiency (●), CARA injected beam power (+), and initial rf power (×) plotted *versus* total input power. The solid line corresponds to 100% efficiency.

the gun used in the experiments reported here the rms axial velocity spread was computed to be less than 0.1% [17] at the entrance to CARA. Only a small spread in beam energy in CARA is predicted because all particles experience nearly the same accelerating fields; leading particles cannot significantly diminish the field acting upon trailing particles since the incoming rf energy from the source replenishes spent energy as fast as it is taken up by the beam.

These observations are not meant to imply that it is practical to build a high energy electron accelerator based on CARA principles. For particles that remain in resonance it has been shown [1] that the maximum energy $\gamma_{\max}$ that can be achieved in CARA prior to stalling (i.e., $\beta_z \to 0$) is given by

$$\gamma_{\max} = \gamma_0 + \left(\frac{\gamma_0^2 - 1}{1 - n_f^2} \right)^{1/2}, \tag{2}$$

where γ_0 is the injection energy and n_f is the normalized group velocity at the end of CARA. For example, with $n_f = 0.95$ and injection energies of 100, 200, 300, or 400 keV, one finds from Eq. (2) that maximum beam energies would be 1.17, 1.78, 2.32, or 2.82 MeV. Equation (2) applies provided the rf power level exceeds $(mc^2/e)I(\gamma_{\max} - \gamma_0)$, where I is the beam current; otherwise, a lower limit sets in due to rf power depletion. It was shown that $\gamma_{\max}$ is independent of the actual profiles of either the magnetic field or group velocity tapers required [1]. Equation (2) implies that an arbitrarily high energy can be reached if one allows n_f to approach unity. However, for a wave guided by an empty pipe, this requires an ever-increasing waveguide radius and a corresponding ever-decreasing acceleration gradient. The accelerator length required to reach $\gamma_{\max}$ would become impractically large. But notwithstanding these considerations, for applications requiring beams with energies up to a few MeV such as those listed in the third paragraph of this Letter, CARA may well prove to be a suitable beam source. The results shown here provide experimental confirmation of the prediction that a fast-wave gyroresonant interaction can transfer nearly all the rf power of a guided wave onto an electron beam.

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