Cyclotron Autoresonance Maser (CARM) Amplifiers for RF Accelerator Drivers

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Abstract

Cyclotron autoresonance maser (CARM) amplifiers are under investigation as a possible source of high-power (>100 MW), high-frequency (>10 GHz) microwaves for powering the next generation of linear colliders. A design for a high-power, short pulse, 17.136 GHz CARM amplifier, utilizing a 500 kV linear induction accelerator, is presented.

I. INTRODUCTION

A. Next Generation Collider Requirements

The next generation of TeV e^+e^- linear colliders of reasonable length and cost will require [1,2,3] at least an order-of-magnitude increase in the accelerating gradient above the ~ 10-20 MeV/m that is presently achieved using conventional S-band klystron drivers. In order to obtain these accelerating gradients, the RF peak power and frequency must be increased substantially. The RF peak power breakdown limit is increased by increasing the frequency and decreasing the RF pulse length.

At present, designs for the next generation collider have settled on 17.136 GHz as a reasonable choice for the operating frequency [4,5,6]. The typical peak power that will be required per source is in the 500 MW to 1 GW range, with rf pulse lengths in the neighborhood of 25–50 ns [4,5]. For such a design, accelerating gradients may be on the order of 200 MeV/m.

RF sources capable of fulfilling all of the requirements of these accelerators do not yet exist. Stanford's two mile linear accelerator, SLAC, is powered by S-band klystrons; however, SLAC operates at 2.86 GHz. Because klystrons are very difficult to operate above ~10 GHz, alternative high power RF sources need to be investigated.

B. Promising Sources

Promising sources that may replace the klystron for driving the next generation linear collider are gyroklystrons, free electron lasers (FELs), and Cyclotron Autoresonance Maser (CARM) amplifiers [7,6]. These masers have the potential to operate as high-gain, high-efficiency, high-power amplifiers in the frequency regime applicable to this next generation of colliders.

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C. Description of a CARM

The CARM is similar to a gyrotron, except that the electromagnetic wave propagates with a phase velocity close to the speed of light. The CARM typically employs relativistic electron beams with pitch angles ($\alpha = v_\perp/v_z$) smaller than that of the gyrotron. However, unlike gyrotrons and free-electron lasers, there are few experimental demonstrations of the CARM [8,9,10].

In design of a high-peak power CARM amplifier, the electron beam energies which result in the most attractive operation are typically in the 0.5 – 2 MeV range. Consequently, beam generation for a high-power CARM amplifier is well suited to two accelerator technologies. Both high-voltage (500 kV – 1 MV) SLAC-type pulse modulators and linear induction accelerators can be used for e-beam generation. For CARM designs based on induction accelerators, the peak beam powers and beam pulse durations result in the generation of rf pulses which are already well suited to the requirements of future colliders. In addition, a unique feature of CARM amplifiers that use a bifilar helical wiggler to spin-up the electron beam is that the wiggler can be designed so that the phase stability of the CARM is substantially enhanced.

We have completed the design study of an induction accelerator driven CARM amplifier with a 500 kV electron beam, and we are currently assembling such a CARM amplifier. This design is attractive for a proof-of-principle CARM amplifier experiment. Results of the design study, as well as final design parameters, are presented in this paper.

II. THEORY

The CARM interaction occurs when electrons undergoing cyclotron motion in an axial magnetic field ($\mathbf{B} = B\hat{\mathbf{z}}$) interact with an electromagnetic wave ($\omega, \mathbf{k}$) with wavevector nearly parallel to the axial field $\mathbf{B}$. The resonance condition is then $\omega - k_z v_z = s\Omega_c$, where s is the harmonic number and Ω_c is the relativistic cyclotron frequency defined by $\Omega_c \equiv \Omega_{c0}/\gamma \equiv q_e B/\gamma m_0 c$. The well-known resonance condition for the CARM is thus $\omega = s\Omega_{c0}/\gamma(1 - \beta_z/\beta_{ph})$ where γ and β_z are the electron energy and velocity in the $\hat{\mathbf{z}}$ direction. The wave phase velocity is given by $\beta_{ph} \equiv v_{ph}/c = \omega/ck_z$. As is apparent from the resonance condition, the CARM is capable of operation at a large Doppler upshift from the cyclotron frequency (in contrast to the gyrotron). For $\gamma_0{}^2 \gg 1, \beta_{\perp 0} \approx 1/\gamma_0$, and $\beta_{ph} \approx 1$, there is a $\gamma_0{}^2$ frequency upshift from the relativistic cyclotron frequency Ω_c (or a γ_0 upshift from the nonrelativistic cyclotron frequency, Ω_{c0}). For the numerical results given here, we consider only CARM operation at the fundamental of the cyclotron frequency ($s = 1$).

III. Design

A. Introduction

We have completed the design of a CARM amplifier utilizing a 500 kV linear induction accelerator (LIA) [11]. The CARM amplifier has been designed to run in the TE_{11} mode at 17.136 GHz. A three period bifilar helical wiggler with a wiggle wavelength of 9.21 cm and a field of up to 50 G will be used to spin-up the electron beam. Other parameters from the experiment are listed in Table 1.

Parameter	Design Value
Beam Energy	500 keV
Beam Current, I_b	500 A
Pulse Length	30 ns
Beam Pitch, $\alpha_0 \equiv \beta_{\perp 0}/\beta_{z0}$	0.4
Frequency, $\omega/2\pi$	17.136 GHz
Mode	TE_{11}
Waveguide Radius, r_w	1.3 cm
Phase Velocity, β_{ph}	1.088
Guide Field, B_0	3.06 kG
Detuning, Δ	0.4
Input Power, P_{in}	800 W
Est. Velocity Spread, σ_{p_z}/p_z	$< 1.6\%$
Energy Spread, σ_γ/γ	$< 1.6\%$
Efficiency, η, untapered	13.5% ($\sigma_{p_z} = 0$)
	9.3% ($\sigma_{p_z} = 0.02$)
Output Power, P_{sat}	33.6 MW ($\sigma_{p_z} = 0$)
	23.3 MW ($\sigma_{p_z} = 0.02$)
Saturation Length, z_{sat}	0.93 m ($\sigma_{p_z} = 0$)
	1.01 m ($\sigma_{p_z} = 0.02$)
Gain	46.2 dB ($\sigma_{p_z} = 0$)
	44.6 dB ($\sigma_{p_z} = 0.02$)

Table 1: CARM amplifier design parameters.

B. Efficiency Optimization

Figs. 1, 2, and 3 show how the efficiency, the beam pitch, and the saturation length of the CARM amplifier vary with detuning. Different curves in the figures represent different values of coupling and of waveguide radius. The value of $\varepsilon/\varepsilon_c$ indicates how close the interaction is to the theoretical threshold for excitation of an absolute instability, with $\varepsilon/\varepsilon_c = 1$ corresponding to this threshold. For $\varepsilon/\varepsilon_c > 1$, the interaction is further prone to excite an absolute instability. Because of the short pulse length of the induction linac, it is unclear how much of a problem absolute instabilities will pose. The convective instability may still be able to dominate the absolute instability for values of $\varepsilon/\varepsilon_c > 1$. However, the CARM amplifier design is based on operation for values of $\varepsilon/\varepsilon_c$ just below 1. With such a coupling value, it is clear from Fig. 1 that higher detunings yield higher efficiencies, however Fig. 1 does not plot efficiencies for $\Delta > 0.4$ because the efficiency falls off rapidly.

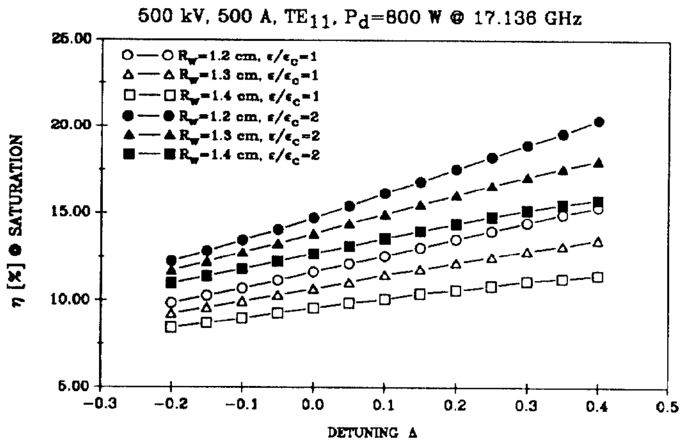

Figure 1: CARM amplifier efficiency.

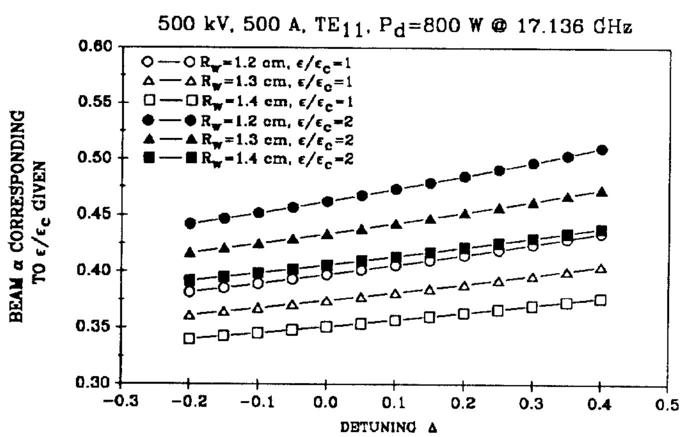

Figure 2: CARM amplifier beam pitch.

C. Phase Stability

We have demonstrated through simulations that a CARM amplifier that utilizes a bifilar helical wiggler to increase the pitch of the electron beam can be optimized to have excellent phase stability. By setting the wiggler guide field and wiggle field to the right values, the correlation between γ_0 and $\beta_{\perp 0}$ runs exactly tangent to the zero phase shift curve for the CARM interaction, as shown in Fig. 4. This dramatically enhances the phase stability of the CARM amplifier. Fig. 5 shows the optimal phase stability results. For the design parameters of Table 1, a phase stability of $\pm 0.8°$ is predicted over a voltage variation of $\pm 1\%$.

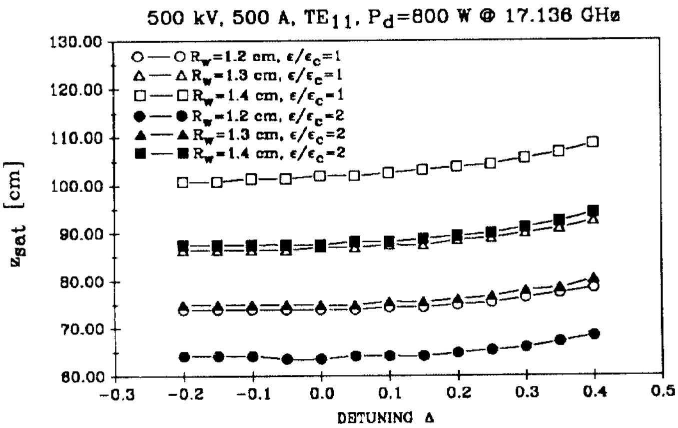

Figure 3: CARM amplifier saturation length.

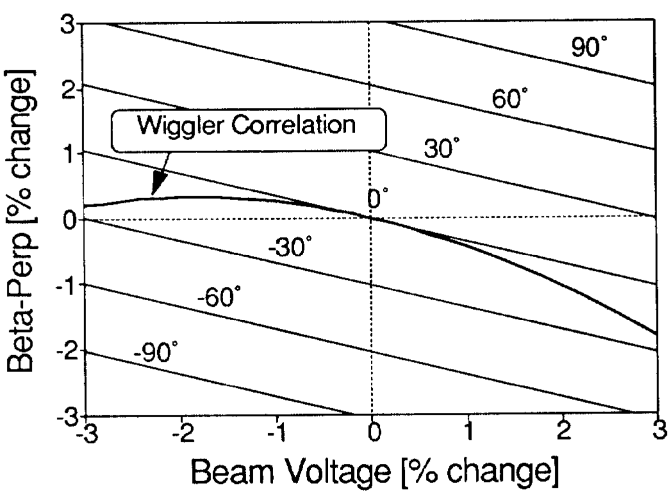

Figure 4: CARM amplifier constant phase curves over beam pitch and beam voltage. The optimal wiggler correlation is superimposed.

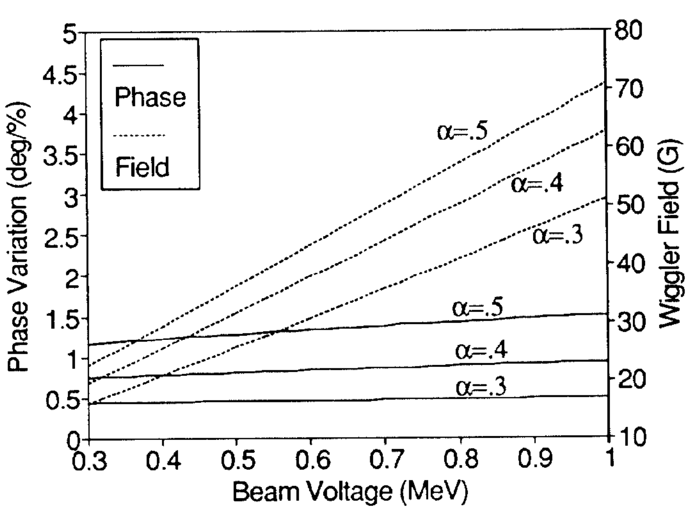

Figure 5: CARM amplifier phase stability over beam voltage for three different values of beam pitch, with wiggler design optimized to maximize phase stability.

IV. CONCLUSIONS

The CARM amplifier is a promising source of high frequency radiation for future linear colliders. Interaction efficiencies are predicted to be in the 10-40% range, with higher efficiencies attainable by magnetic field tapering.

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