CARM and Harmonic Gyro-Amplifier Experiments at 17 GHz*

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Abstract

Cyclotron resonance maser amplifiers are possible sources for applications such as electron cyclotron resonance heating of fusion plasmas and driving high-gradient rf linear accelerators. For accelerator drivers, amplifiers or phase locked-oscillators are required. A 17 GHz cyclotron autoresonance maser (CARM) amplifier experiment and a 17 GHz third harmonic gyro-amplifier experiment are presently underway at the MIT Plasma Fusion Center. Using the SRL/MIT SNOMAD II induction accelerator to provide a 380 kV, 180 A, 30 ns flat-top electron beam, the gyro-amplifier experiment has produced 5 MW of rf power with over 50 dB of gain at 17 GHz. The gyro-amplifier operates in the TE_{31} mode using a third harmonic interaction. Because of its high power output, the gyro-amplifier will be used as the rf source for a photocathode rf electron gun experiment also taking place at MIT. Preliminary gyro-amplifier results are presented, including measurement of rf power, gain versus interaction length, and the far-field pattern. A CARM experiment designed to operate in the TE_{11} mode is also discussed.

I. INTRODUCTION

A. Next Generation Collider Requirements

At present, designs for the next generation colliders have settled on 11-30 GHz as a range of reasonable operating frequencies. Some parameterizations put the optimum operating frequency at 17 GHz[1,2]. 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[1]. For such a design, accelerating gradients may be on the order of 200 MV/m.

Sources capable of fulfilling the requirements of these accelerators are under development. Promising sources are gyroklystrons[3], free electron lasers[2], CARMs, relativistic klystrons, and gyro-TWT amplifiers.

B. CRM theory

In cyclotron resonance masers, electrons undergoing cyclotron motion in an axial magnetic field couple to a fast electromagnetic wave. The CRM resonance condition is $\omega - k_z v_z = s\Omega_c$, where ω is the rf wave frequency, k_z is the parallel wave number, v_z is the axial electron velocity, s is the harmonic number, and $\Omega_c \equiv q_e B/\gamma m_0 c$ is the relativistic cyclotron frequency. For the gyro-amplifier, the $k_z v_z$ term in the resonance condition is small, but the CARM makes use of this term to operate at a significantly upshifted frequency with phase velocity close to unity. This operating regime has the unique feature that the electrons maintain resonance with the rf wave even as they lose energy, hence the term, "autoresonance." This autoresonance combined with the upshifted frequency make the CARM an appealing rf source.

A gyro-amplifier using harmonic interactions obtains the same advantage as the CARM–lower magnetic field for a given operating frequency–with the added advantages of being less sensitive to beam quality. For both the CARM and the gyro-amplifier, tapering the magnetic guide field offers the added benefit that the electrons can be kept in resonance as they lose energy, thereby enhancing the efficiency of the amplifier.

II. DESIGN

Initially, we designed a 17 GHz CARM amplifier utilizing a 500 kV, 500 A, 30 ns flat-top beam pulse generated by the SRL/MIT SNOMAD-II linear induction accelerator[4]. A diagram of the experiment is shown in Fig. 1. A three period bifilar helical wiggler with a wiggler period of 9.21 cm and a field of up to 60 G is used to add pitch to the beam, which is injected by a thermionic Pierce-type gun. The design pitch for the CARM is $\alpha = 0.4$. The beam then travels through a region of adiabatic compression where the magnetic field increases to 4 kG for extracting energy via the upshifted CRM resonance. A 17 GHz input signal is injected into the interaction region using a 45° wire-mesh coupler. This signal copropagates with the beam in 1.27 cm radius waveguide, where the signal is resonantly amplified.

Using the experimental setup for the CARM amplifier, we observed a TE_{31} gyro-amplifier mode at third harmonic. The beam settings for operation in this mode are 380 kV, $\alpha = 1.0$, and a 2.7 kG guide field.

Cold-beam studies predict efficiencies of ~20% for the CARM amplifier [4] in the absense of magnetic field tapering, and ~15% for the third harmonic gyro-amplifier, for this unoptimized design, given our beam parameters. These efficiencies can be improved by magnetic field tapering. Optimized relativistic harmonic gyro-amplifier designs can be expected to yield up to > 40% efficiency at the second harmonic [5]. The gyro-amplifier efficiency drops off much more slowly than that of the CARM as beam quality deteriorates, however. At 10%-15% axial velocity spread, for example, CARM operation is

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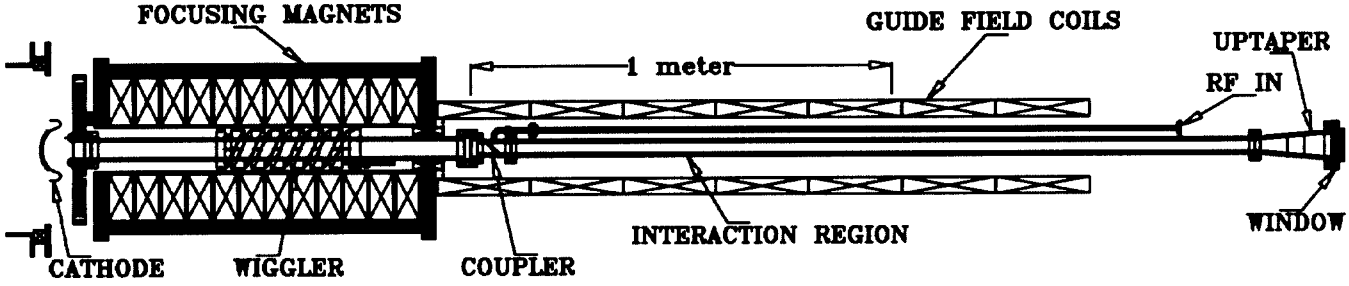

Figure 1: Experimental diagram (to scale).

infeasible, while the gyro-amplifier efficiency still can be as high as 10%.

III. EXPERIMENTAL RESULTS

A. CARM Amplifier

To date, CARM amplifier operation has not been observed. Our beam transport must be improved in order to achieve beam qualities necessary for CARM operation.

B. Gyro-amplifier

Operation of the third harmonic gyro-amplifier at high power has been observed, and unprecedented results have been obtained. We measured 5 MW of power in the TE_{31} mode for a beam voltage of 380 kV and a beam current of 180 A, giving an efficiency of 7%. The current, depending on whether we run the cathode temperature limited or space-charge limited, can be from 150-300 A. Interestingly, increasing the current does not greatly increase the rf power, possibly indicating that at higher current, the space-charge limited electron beam has significantly poorer beam quality than a temperature limited beam. A typical voltage trace and rf pulse for the gyro-amplifier is shown in Fig. 2. Experimental evidence suggests that the rf pulse is narrower than the voltage pulse due to the onset of absolute instability. We observe that as we increase the pitch in the beam, absolute instability occurs at earlier time and has an increasingly detremental effect on the amplified rf power.

Our output power for the gyro-amplifier was calculated by measuring a 1-D far-field pattern from the output rf window with a calibrated detection horn, attenuator, and diode. We then use the pattern to obtain relative power in the various TE modes. Normally this cannot be uniquely determined from a 1-D pattern, but by ignoring TM modes and the TE_{01} mode since they have very little coupling to the CRM resonance for an axis encircling beam, we can obtain a unique distribution of power. By integrating the measured pattern, we then obtain absolute power in each of the TE modes. A typical far-field pattern and subsequent TE mode content and power calculation is shown in Fig. 3. We estimate the error in this power measurement to be ±2 dB. Plans to measure the power using a calibrated directional coupler are in progress.

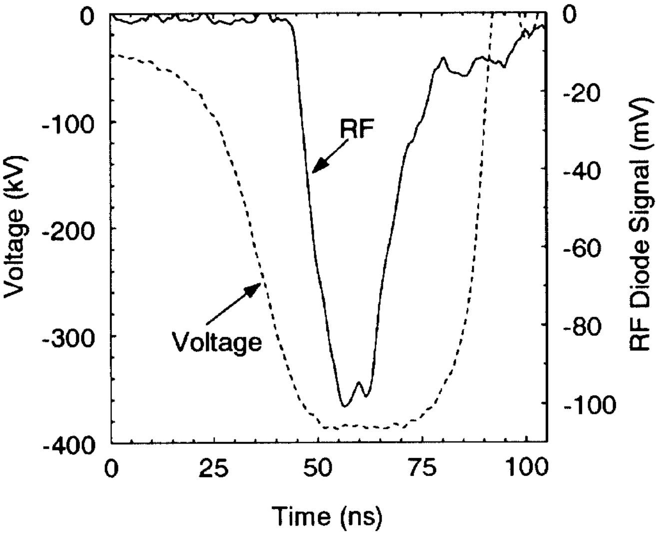

Figure 2: Voltage and rf pulses.

The injected rf drive power was also measured using a far-field pattern measurement; however, the uncertainty in the measurement is larger since we cannot rule out TM modes from the distribution. The input pattern clearly contains a wide mix of modes, with power in the synchronous TE_{31} mode estimated at not more than 50 W minimum in order to obtain rf amplification, for a total of over 50 dB of rf gain.

We measured the rf power gain versus interaction distance by sliding a strong "kicker" magnet down our interaction tube to eject the beam at various distances along the interaction. The results of this measurement are shown in Fig. 4. The optimum magnetic field profile is also shown in the figure, verifying that a taper in the field allows increased rf power. The gain history measurement was made by putting the detec-

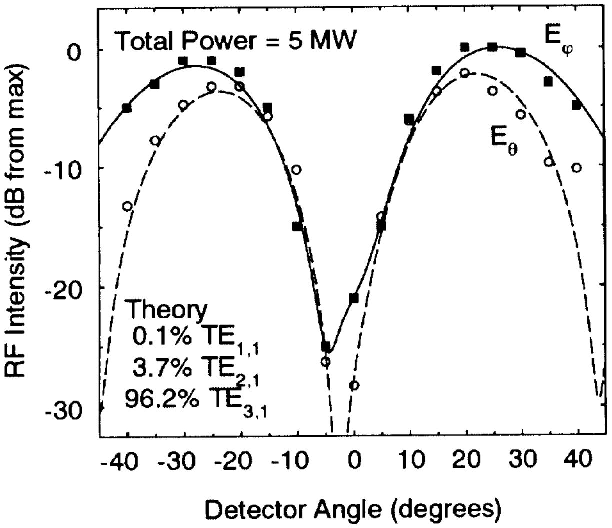

Figure 3: Far-field scan of the amplified rf.

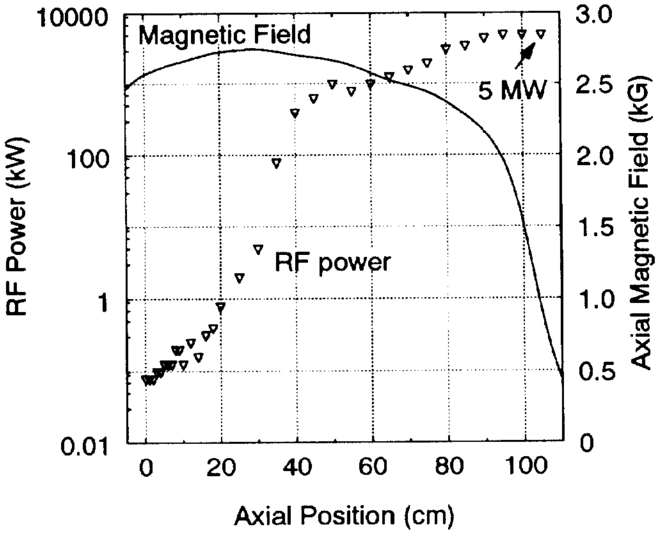

Figure 4: Gain history and magnetic field profile.

tion diode at the peak angle for TE_{31} output. Note that at small interaction distances, the signal from the magnetron masks the TE_{31} signal because the magnetron injects only a fraction of TE_{31} power. Also, due to limitations in positioning the kicker magnet, the rf drive power is injected into the interaction region 15 cm before the point marked as 0 cm in Fig. 4. Thus the total gain of the system is over 50 dB even though the figure only shows an increase of 48 dB from start to finish.

The theoretical output power of the gyro-amplifier depends strongly on beam pitch. This is a difficult quantity to measure. Simulations predict that our pitch is $\alpha = 0.75 - 1.0$. For our beam parameters of 380 kV and 180 A, with α in this range, predicted output power for a non-tapered magnetic field and a cold beam is 8-12 MW. As we increase our pitch, absolute instabilities occur. For a guide field of 2.7 kG, absolute instability is predicted to occur at $\alpha \geq 1.1$, consistent with experimental observation.

IV. CONCLUSIONS

Third harmonic gyro-amplifier operation has been observed to produce 5 MW of 17 GHz TE_{31} rf power at 7% efficiency with a tapered magnetic field. The gyro-amplifier shows a single pass gain of over 50 dB, which allows it to operate with very low power drive sources. This third harmonic gyro-amplifier is presently the planned source for the 17 GHz rf gun experiment at MIT. A second harmonic gyro-amplifier experiment has also been designed and will be tested shortly.

The output power and efficiency of the gyro-amplifier are still much lower than theory predicts, even for very poor quality ($\sim$15% axial velocity spread) electron beams. Plans for improvement of our beam transport include shortening our bifilar helical wiggler, shortening of the entire system by redesigning the magnetic transport, and minor modifications to the electron gun geometry. Design of a sever to damp absolute instabilities is also in progress.

Output power of 5 MW at 17 GHz with gain of over 50 dB from a gyro-amplifier operating at third harmonic is unprecedented. Nevertheless, substantial improvement of the operation is expected with optimization of the amplifier for operation on this mode. This power level, combined with the low operating voltage and field, makes the harmonic gyro-amplifier a promising source of rf power.

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