Test Results from the LLNL 250 GHz CARM Experiment*

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Abstract

We have completed the initial phase of a 250 GHz CARM experiment, driven by the 2 MeV, 1 kA, 30 ns induction linac at the LLNL ARC facility. A non-Brillouin, solid, electron beam is generated from a flux-threaded, thermionic cathode. As the beam traverses a 10 kG plateau produced by a superconducting magnet, ten percent of the beam energy is converted into rotational energy in a bifilar helix wiggler that produces a spiraling, 50 G, transverse magnetic field. The beam is then compressed to a 5 mm diameter as it drifts into a 30 kG plateau. For the present experiment, the CARM interaction region consisted of a single Bragg section resonator, followed by a smooth-bore amplifier section. Using high-pass filters, we have observed broadband output signals estimated to be at the several megawatt level in the range 140 to over 230 GHz. This is consistent with operation as a superradiant amplifier. Simultaneously, we also observed K_a band power levels near 3 MW.

I. INTRODUCTION

The LLNL CARM project has been aimed at developing a high-power source for current drive and disruption control in Alcator-C, an ongoing tokamak experiment, and it is this potential application that dictated the choice of frequency. High-power radar applications also are of interest, although these would generally be at lower frequencies. As high-power drive sources are difficult to find at 250 GHz, the experiment was configured as a self-contained oscillator/amplifier combination. The experiment was fielded at the ARC induction linac facility at LLNL,[1] using a superconducting magnet that was provided by UCLA.

II. APPARATUS

The overall CARM experimental configuration is shown in Fig. 1. A 1.1 kA, 1.2 MeV electron beam is generated from a hot cathode, Pierce gun injector, and is accelerated further through 10 induction cells to a final beam energy near 2 MeV. Beam transport at a nominal, 1-2 cm diameter is achieved through a series of solenoids generating some 500 G on axis. Magnetic flux through the cathode is controlled by a bucking coil. At the 2 MeV level, the beam is focussed into a 12-mm-diam pipe immersed in a 10 kG, axial guide field provided by the superconducting magnet, where a 30-50 G transverse field generated by a bifilar wiggler converts some of the axial into transverse momentum. After leaving the wiggler, the electrons undergo further momentum conversion as the beam drifts into the 25-30 kG, high-field plateau where the RF interaction takes place inside a 7-mm-diam pipe. The RF circuit here consists of a single, 18-cm-long Bragg section followed by a 20 cm long, smooth-walled amplifier section, all positioned inside the 40 cm long, high-field plateau. The Bragg section supports a standing wave, and thus can act as a self-contained cavity oscillator. For a nominal Q = 5000, the calculated start-oscillation threshold is 200 A. Calculated cavity fill times are in the 20-30 ns range. The entire RF section is contained inside an aluminum strongback that functions as the vacuum envelope. The configuration shown in Fig. 1 has a pair of Bragg sections bracketing a smooth-walled resonator section; this arrangement was tried initially but was damaged due to beam strike and overheating. Table I summarizes the experimental parameters for the single-Bragg configuration.

The diffraction tank is designed as a calibrated, high-power attenuator. The microwave beam is dissipated in the Eccosorb AN-72 absorptive lining. For the initial experiment, the tank was calibrated only for the TE_{11} mode at 250 GHz (on-axis port positioned at the downstream flange) and 25-40 GHz (waveguide stub located off axis). An auxiliary, uncalibrated, broadband port is attached directly to the beamdump; a small, immersible turning mirror is used to deflect energy from the narrow, 250 GHz beam into this diagnostic. The measured attenuation was 31.5 dB for the calibrated, 250 GHz channel, and 32-38 dB for K_a band. Losses in the overmoded waveguide runs leading from the diffraction tank to the detectors in the control room were calibrated separately. Further details concerning the diffraction tank are contained in a companion paper.[2]

III. RESULTS

The experiment consisted of optimizing the electron beam transmission through the accelerator, wiggler, and RF circuit section, and then maximizing the output power by adjusting the cathode flux, the wiggler current, and the axial field in the high-field region. The electron beam current was monitored at the injector, at the entrance to the wiggler, and at the entrance to the beam dump. Typically, we were able to transmit 700 A out of a total 1100 A emitted from the injector, through the 7-mm-diam RF section.

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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Microwave power was measured in the control room, using separate detectors for the 250 GHz and the K_a band channels, respectively, with signals carried from the diffraction tank through two separate waveguide runs. The 25-mm-diam aperture placed in front of the receiving horn discriminated against modes with nulls on boresight, i.e., modes other than $TE_{1,n}$. Waveguide sections were used as high-pass filters to bound the signal frequency. During initial runs, we also carried out more precise frequency measurements, using a heterodyne system.

Typically, we observed simultaneous signals near beam pipe cutoff (K_a band), consistent with gyrotron-type operation, and above 140 GHz, over a large range of axial B field and alpha. The broadband, high-frequency signals were consistent with operation as a superradiant CARM amplifier excited by noise. Heterodyning with a subharmonic mixer and a 60-90 GHz, tunable source (BWO) serving as the local oscillator, and using a 173 GHz high-pass filter, we detected high-frequency signals over the full local-oscillator range, suggesting frequency components as high as 270 GHz, although aliasing with a 180 GHz maximum frequency could not be ruled out. For the high-frequency signal, we estimated a peak power of 53 MW, using a Hughes 47328H-3111 diode detector with a calibrated sensitivity valid for 250 GHz. Because of the rapid falloff of detector sensitivity with frequency, however, and assuming the actual signal frequency to be significantly below 250 GHz, this power estimate may be optimistic by an order of magnitude. The power level at K_a band was estimated at 3.5 MW, using a detector calibration valid for 26 GHz. The pulse width in the 250 GHz channel typically had a spiky appearance, although intermittently we also saw pulsewidths of 5-10 ns. The pulsewidth at K_a band generally corresponded to the beam pulsewidth, about 30 ns.

In a subsequent run, having damaged the heterodyne system earlier, we only used high-pass filtering corresponding to cutoff frequencies of 140, 173, and 230 GHz. Sweeping through the magnetic field range 25-55 kG, and velocity ratio $0.2 < \text{alpha} < 0.4$, we observed the strongest signals above 230 GHz with field values near 29 kG. Unlike the lower frequency signals, we were unable to see the 230 GHz filtered signal through the on-axis probe on the diffraction tank. In order to observe these signals, we had to connect the 250 GHz channel to the uncalibrated, broadband port at the side of the beam dump, with the small turning mirror inserted. The relative signal strengths through the different filters, all going into an identical detector, are shown in Fig. 2. The 230 GHz filtered signal amplitude was within an order of magnitude of the lower frequency amplitudes, and hence should have been equally detectable with the on-axis probe.We believe this signal may have had a null on boresight. With the magnetic field at 29 kG but reducing the wiggler field to achieve alpha ~ 0.15, we intermittently observed 60-80 mV amplitudes on the 230 GHz filtered signal. This is an order of magnitude stronger than the other observed signals, and it may indicate excitation of a Bragg section resonance, though not necessarily the TE_{11} mode.

IV. Conclusion

In initial beam runs on a 250 GHz CARM experiment in an oscillator-amplifier configuration, we have observed upshifted signals over a wide frequency range, from 140 to over 230 GHz. We conservatively estimate the power levels to be on the order of several megawatts. Simultaneously we have measured 3.5 MW peak power at K_a band frequencies, corresponding to conventional gyrotron operation. Most of the observed high-frequency signals are consistent with operation as a superradiant amplifier starting from noise. Anomalously strong signals observed intermittently, indicate possible excitation of the single Bragg section resonator.

V. References

[1] M. Caplan, B. Kulke, D. G. Bubp, D. McDermott, and N. C. Luhmann, Jr., "A 250 GHz CARM Oscillator Experiment Driven by an Induction Linac," 12th Int. Free Electron Laser Conf., Paris, France, Sept. 17-21, 1990.

[2] B. Kulke, M. Caplan, and R. Stever, "250 GHz Cold Tests for the LLNL CARM Experiment," this Proceedings.

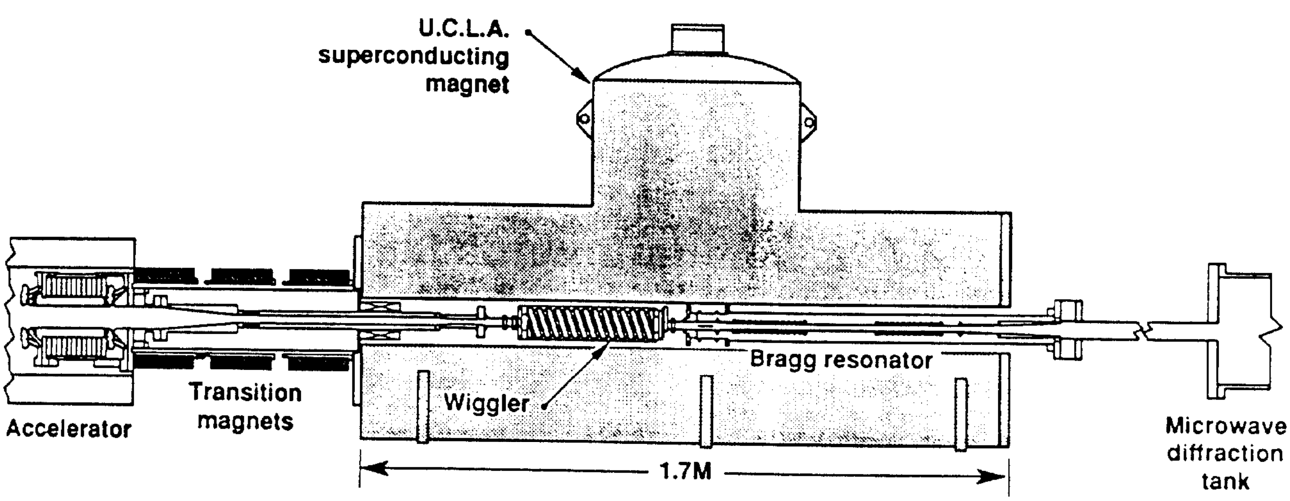

Fig. 1. CARM experimental configuration. In this experiment, only a single Bragg section was used.

Table 1. CARM Experimental Parameters

Electron beam:	
Energy	1.7 - 1.9 MeV
Current	500-600 A
Diameter in RF section (est.)	5 mm
Pulse width in RF section	30 ns
Repetition rate	1 Hz
Wiggler:	
Configuration	bifilar helix, six periods
Pitch/diameter	5.28 cm/5.2 cm
Drive	15 V, 8 A, watercooled
Transverse field on axis	50 G
Axial field in wiggler region	10 kG
RF oscillator section:	
Mode	TE_{11}
Op. frequency/cutoff frequency	250 GHz/25 GHz
Phase velocity/c	1.005
Bragg section length/diameter	18 cm/7 mm
No. of sinusoidal corrugations	300
Corrugation amplitude	45 μm
Theoretical Q	5000
Theoretical alpha (velocity ratio)	0.3
B field on axis	25-30 kG
RF amplifier section:	
Smooth-pipe length/diameter	20 cm/7 mm
B field on axis	25-30 kG

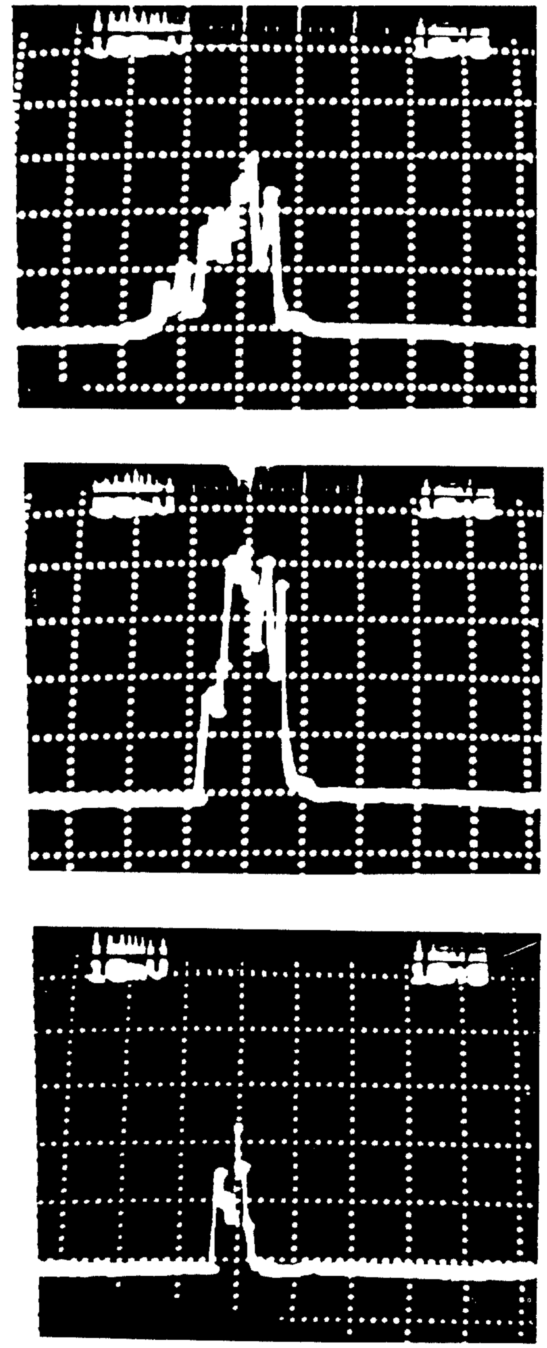

Fig. 2. Signal traces detected at broadband port, using different waveguide highpass filters, and a Hughes 47328H-3111 detector. Time scale is 10 ns/div throughout.

- Top trace, 140 GHz cutoff filter, 100 mV/div.
- Center trace, 173 GHz cutoff filter, 50 mV/div.
- Bottom trace, 230 GHz cutoff filter, 10 mV/div.