The NRL X-Band Magnicon Amplifier Experiment*

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Abstract

We present a progress report on a program to develop a high-power X-band magnicon amplifier for linear accelerator applications. The goal of the program is to generate 50 MW at 11.4 GHz, using a 200 A, 500 keV electron beam produced by a cold-cathode diode on the NRL Long-Pulse Accelerator Facility. The initial experiment, designed to study the gain from the first (driven) deflection cavity to a second (passive) deflection cavity, has been completed. A gain of ~15 dB has been observed in the preferred circular polarization, at a frequency shift of approximately –0.18%, in good agreement with theory and simulation. In addition, a design study for a complete magnicon circuit is under way.

I. INTRODUCTION

The magnicon,[1–3] a "scanning beam" microwave amplifier tube related to the gyrocon,[4] is a potential replacement for the klystron for powering future high-gradient linear accelerators. Scanning beam devices modulate the insertion point of the electron beam into the output cavity in synchronism with the phase of a rotating rf wave. This synchronism creates the potential for an extremely efficient interaction in the output cavity, since every electron will in principle experience identical decelerating rf fields. In the magnicon, the output interaction is gyrotron-like, and requires a beam with substantial transverse momentum about the applied axial magnetic field. The transverse momentum is produced by spinning up the electron beam in a sequence of TM_{110} deflection cavities, the first of them driven by an external rf source. The output cavity employs an rf mode that rotates at the same frequency as the deflection cavity mode. As a result, the beam entering the output cavity is fully phase modulated with respect to the output cavity mode. The optimum magnetic field in the deflection cavities is approximately twice the cyclotron resonant value at the drive frequency. On the other hand, the output cavity operates as a first harmonic cyclotron device. These two constraints lead naturally to the design of a second-harmonic amplifier, in which the output cavity operates at twice the frequency of the deflection cavities and employs a TM_{210} mode. The overall design concept is shown in Fig. 1. This circuit will include a drive cavity, two simple half-wavelength deflection cavities, a two-section penultimate cavity, and an output cavity.

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In this paper, we discuss a preliminary experiment, employing only two 5.7 GHz deflection cavities, the first driven by an external source. We have performed parametric studies of the gain between these two cavities, preparatory to the design of a complete deflection system that will spin up an electron beam to high α for injection into an 11.4 GHz output cavity. Here, α is the ratio of perpendicular to parallel velocity.

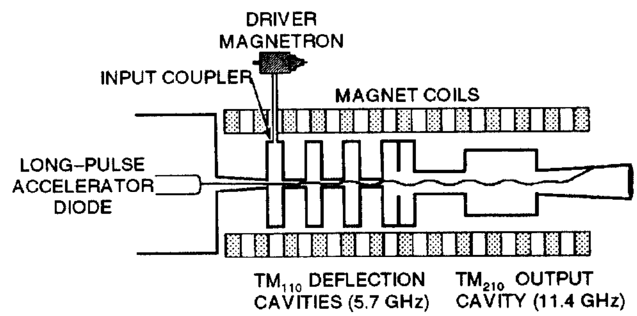

Figure 1. NRL magnicon design concept.

II. APPARATUS

This experiment was carried out on the NRL Long-Pulse Accelerator Facility.[5] It employed a field-emission diode [see Fig. 2], designed with a flat magnetic field of 1.7 kG in the anode-cathode gap, followed by adiabatic compression to a final magnetic field of 8.1 kG, to generate a 500 keV, ~200 A, 5.5 mm diam solid electron beam with low initial transverse momentum. Simulation results using a version of the Stanford Electron Optics Code[6] suggest a mean α~0.03. This beam was used to power a two-cavity amplifier experiment. The two cavities are of identical pillbox design, with 3.20 cm radius and 2.265 cm length. The length was chosen so that the transit time of a 500 keV electron equals half of an rf period. They are separated by a 1-cm-diam drift space 1.132 cm long. This length is approximately half of an electron gyroperiod. The cavities were fabricated from stainless steel, to permit the penetration of pulsed magnetic fields, with a copper coating on the interior surfaces to decrease the ohmic losses. Each has four coupling pins spaced at 90° intervals in one end-wall. Two adjacent "coupling" pins are "long," for use in driving the two linear polarizations of the cavity, and the remaining two "sampling" pins are "short," in order to measure the cavity fields without significantly loading the cavity. The

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first cavity was driven in a circularly-polarized TM_{110} mode by a C-band magnetron at ~5.7 GHz. Circular polarization was generated by driving the two coupling pins with a $\pi/2$ phase difference using a 3 dB hybrid coupler. In the second (gain) cavity, the two sampling pins led to matched loads, while the two coupling pins were connected through coaxial attenuators to crystal detectors.

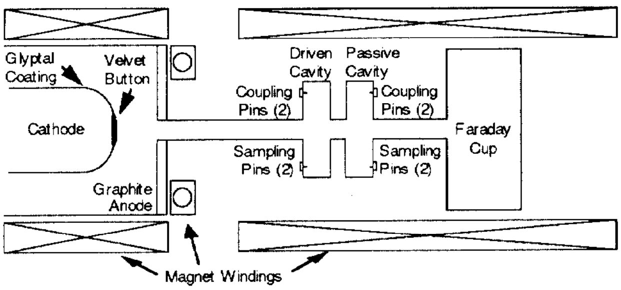

Figure 2. Schematic of the two-cavity experiment.

The cavities, their pickups, and all other microwave components were fully calibrated using a microwave scalar network analyzer. Five microwave signals were monitored on each experimental discharge, including the magnetron signal, signals from each linearly polarized sampling pin of the first cavity, and signals from each coupling pin of the second cavity. In addition, a balanced mixer was used to combine the first cavity signal with the signal from a separate local oscillator tuned as closely as possible to the operating frequency of the magnetron. This "mixed" signal was used to set the exact magnetron frequency (using a mechanical tuner), to adjust the magnetron voltage to avoid excessive frequency chirp, and to guard against frequency drift. In addition, phase or frequency shifts due to the effects of the beam on the drive cavity could be observed.

III. MAGNICON THEORY AND SIMULATION

The linear theory of the magnetized deflection cavities was first presented by Karliner, *et al.*,[1] and is developed in detail by Hafizi, *et al.*[7] The linear theory has been evaluated for a single on-axis electron, with no initial transverse momentum, and without finite beam radius and finite velocity spreads. Furthermore, it assumes that the electron energy is not changed by transit through the deflection cavities. In order to consider the use of more realistic beam parameters, a numerical simulation code for the deflection cavities was developed.[7] It is a self-consistent steady-state code that propagates particles through the TM_{110} fields of the first (driven) deflection cavity, through a drift space, and then through successive deflection cavities and drift spaces. The rf field amplitudes are made (by iteration) self-consistent with the finite value of cavity Q and with the energy lost by the electron beam in transit through each cavity. The rf phase in each of the passive cavities is assumed to be the optimum phase to extract electron beam energy from an initially on-axis electron, since this should be a good approximation to the phase that is driven by a finite electron beam.

IV. EXPERIMENTAL RESULTS

The response of the first cavity, and the gain of the second cavity were measured as a function of frequency in each circular polarization of the TM_{110} mode. The measurements were carried out at 500 keV, with a beam current of ~170 A, and a magnetic field of 8.1 kG. This magnetic field corresponds to the theoretical value at which, for the preferred circular polarization (which corresponds to electron gyromotion in the same sense as the rotation of the mode), the beam does not load the cavity Q.

The predicted and measured response of the first cavity as a function of frequency in the preferred circular polarization are shown in Fig. 3. Simultaneous measurements are made at the cavity sampling pins in each linear polarization of the cavity. The data are normalized to the calculated signal level from the cavity at constant magnetron drive power at the center of the cold cavity resonance in the absence of the electron beam. This normalization is based on cold tests of all components of the system. Theory predicts that the center of the resonance will be shifted by –0.18%, and that the beam loading should be very close to zero. This is indicated by a curve whose height is normalized to one, and whose width is consistent with Q ~1100, the value measured in the absence of the beam. The experimental center frequency and resonance width are in good agreement with theory. In addition, while the experimental data for the two linear polarizations consistently differ by ~3 dB, perhaps due to cumulative calibration errors, the two data sets bracket the theoretical curve.

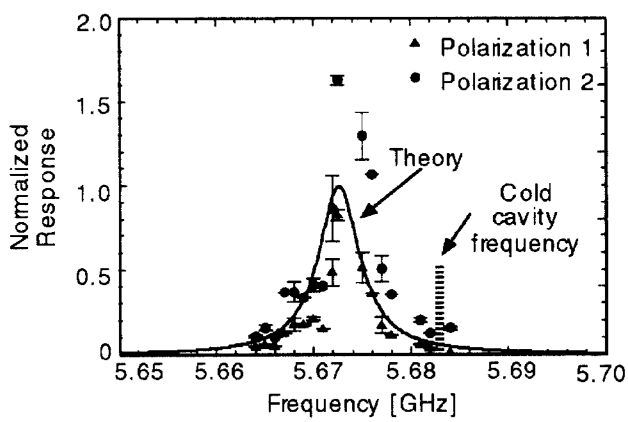

Figure 3. Response of the drive cavity in the preferred circular polarization—theory and experiment.

The predicted and measured gain of the second cavity in the preferred circular polarization are shown in Fig. 4. Theory predicts a gain of ~15 dB, with the resonance shifted by –0.18% from the cold frequency of the second cavity. The experimental gain measurements are in good agreement with the theoretical curve in amplitude, center frequency, and bandwidth. However, there is a persistent imbalance in the two linear polarizations, which may be in part calibration error, but also may reflect a true asymmetry in the cavity excitation (elliptical polarization), perhaps due to a small misalignment of the electron beam, or some asymmetry in the mode of the drive cavity.

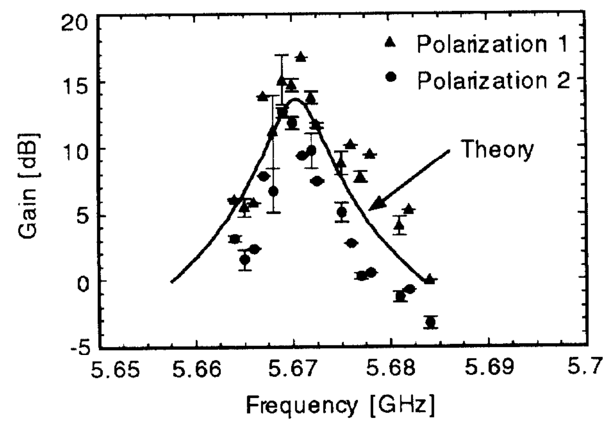

Figure 4. Two-cavity gain in the preferred circular polarization—theory and experiment.

V. DISCUSSION

The overall purpose of a complete set of magnicon deflection cavities is to coherently spin up an electron beam to high α for injection into an output cavity. With this goal in mind, the present experiment was designed to measure the gain between a driven and a passive deflection cavity, which could constitute the first section of a complete deflection system. In this two-cavity experiment, high gain (~15 dB) was observed in the preferred circular polarization, in good agreement with the predictions of theory.[8] However, one should note that the present experiment was carried out at very low signal levels, in order to eliminate the possibility of multipactor or breakdown phenomena interfering with the basic gain measurement. Under these conditions, the resulting coherent beam α should be quite small ($\lesssim$0.01). This is less than the initial random α produced by the diode.

In future experiments, higher drive powers and additional deflection cavities will be employed, in order to achieve a final $\alpha \gtrsim 1$. An important requirement in those experiments will be the suppression of multipactor and breakdown effects through a combination of improved cavity design and improved vacuum techniques. The effect of initial electron radial and velocity spreads on the gain measured in the present experiment is predicted to be quite small. Nevertheless, such spreads may have a large effect on the quality of the final high α electron beam generated by a full sequence of deflection cavities, resulting in a lowering of the efficiency of the output cavity interaction.[9] In this regard, the real test of the final multicavity deflection system will be to produce a high α electron beam, while minimizing the spread in energy, α , and gyrophase. A design study for a complete magnicon circuit is under way.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

[1] M. M. Karliner, *et al.*, "The Magnicon—An advanced version of the gyrocon," *Nucl. Instrum. Methods Phys. Res.* **A269**, 459 (1988).

[2] O. A. Nezhevenko, "The Magnicon: A New RF Power Source for Accelerators," *Conf. Record—1991 IEEE Particle Accelerator Conf.*, (IEEE, New York, 1991), pp. 2933-2942.

[3] W. M. Manheimer, "Conceptual design of a high power, highly efficient magnicon at 10 and 20 GHz," *IEEE Trans. Plasma Sci.* **18**, 632 (1990).

[4] G. I. Budker, *et al.*, "The Gyrocon—An efficient relativistic high-power vhf generator," *Part. Accel.* **10**, 41 (1979).

[5] N. C. Jaitly, *et al.*, "1 MV Long Pulse Generator with Low Ripple and Low Droop," in *Digest of Technical Papers—Eighth IEEE Int. Pulsed Power Conf.* (IEEE, New York, 1991), pp. 161-165.

[6] W. B. Herrmannsfeldt, "Electron Trajectory Program," SLAC Report No. 226, 1979 (unpublished).

[7] B. Hafizi, *et al.* "Analysis of the Deflection System for a Magnetic-Field-Immersed Magnicon Amplifier," *IEEE Trans. Plasma Sci.* **20**, 232 (1992).

[8] S.H. Gold, *et al.*, "Study of Gain in C-Band Deflection Cavities for a Frequency-Doubling Magnicon Amplifier," *IEEE Trans. Plasma Sci.*, to be published [August, 1993].

[9] B. Hafizi, *et al.*, "Nonlinear Analysis of a Magnicon Output Cavity," *Phys. Fluids*, to be published [1993].