INITIAL OPERATION OF AN X–BAND MAGNICON AMPLIFIER EXPERIMENT

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We present a progress report on a program to develop a high–power second harmonic magnicon amplifier at 11.4 GHz for linear accelerator applications. The experiments are being carried out on the NRL Long–Pulse Accelerator Facility using a plasma cathode to create the electron beam. Typical beam parameters are 500–700 kV, 170–250 A, 5.5 mm diameter, with a ~300 nsec voltage flattop. The accelerator operates single pulse with a $\sim 10^{-2}$ Hz repetition rate. A complete five cavity magnicon circuit was designed via computer simulation, fabricated, and cold tested. In early tests, a low power saturation effect was observed in the deflection cavities, apparently due to plasma formation caused by the diode x–ray flux and by inadequate vacuum conditions. Following a major effort to improve the vacuum and surface conditions, recent experiments have shown that it is possible to "burn through" this low power saturation effect, and achieve high fields in the 5.56 GHz penultimate cavity when the drive cavity is excited by a 10 kW input signal. Synchronous with the penultimate cavity signal, a 100–200 nsec multi-MW frequency–doubled output pulse is observed at 11.12 GHz.

I. INTRODUCTION

The magnicon [1,2] is a scanning–beam microwave amplifier that is under consideration as an alternative to klystrons in powering future high–gradient linear electron accelerators. Scanning–beam amplifiers 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. The transverse momentum is produced by spinning up the electron beam in a sequence of TM_{110} deflection cavities, the first driven by an external rf source. The output cavity employs an rf mode that rotates in synchronism with the deflection cavity modes. 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, while 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 (see Fig. 1). This is the configuration that is under investigation at NRL, as well as at the Budker Institute of Nuclear Physics (INP).

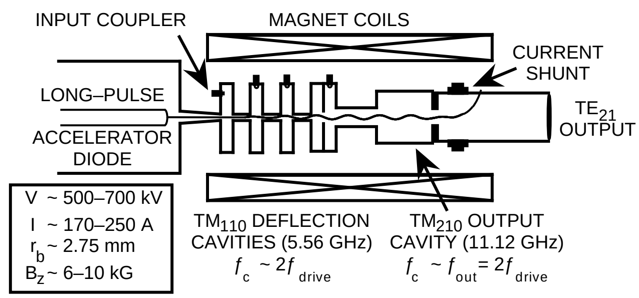

Fig. 1. NRL X–band magnicon schematic.

II. MAGNICON DESIGN

Following a two–deflection cavity gain experiment that demonstrated ~15 dB of gain and good agreement with theoretical predictions [3], a complete 11.4 GHz frequency–doubling magnicon amplifier circuit as illustrated in Fig. 1 was designed via computer simulation [4]. These simulations were designed to produce a pitch angle of ~45° at the end of the penultimate cavity, i.e., $\alpha = v_\perp / v_{||} \sim 1$, where $v_\perp$ and $v_{||}$ are the electron velocity components perpendicular and parallel to the applied magnetic field. Both single particle and 2–mm–diam. simulations achieved efficiencies of ~56%. (The 2–mm beam corresponds to the predicted performance of the INP thermionic magnicon electron gun for a 6.5 kG magnetic field.) However, the 5.5–mm–diam. simulation, corresponding to the present diameter of the NRL beam, achieved an efficiency of only ~23% due to the substantial energy spread and phase–mixing of the beam entering the output cavity.

III. EXPERIMENTAL RESULTS

The complete five–cavity circuit, including a drive cavity, two gain cavities, and a two–section π–mode penultimate cavity, all operating at 5.56 GHz in the TM_{110} mode, followed by an 11.12 GHz TM_{210}–mode output cavity, was fabricated, cold tested, calibrated, and placed under

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vacuum on the NRL Long–Pulse Accelerator (LPA) Facility. Each of the cavities has a calibrated rf pickup, and the output from the last cavity can also be monitored at the end of the experiment using microwave pickups. The power is coupled out of the output cavity through an iris, and simultaneously converted to the TE_{21} mode which is then radiated through a 3.5–cm lucite window. The various rf signals are measured using calibrated attenuators and crystal detectors. The first cavity is driven by rf from a tunable C–band magnetron.

Initial tests were carried out at the design voltage and current (500 kV, ~170 A), and at magnetic fields ranging from 6.5–10 kG. The beam is produced from a velvet cathode by plasma–induced field emission. The voltage pulse consists of a 100 nsec risetime, a ~300 nsec flattop, and a 500 nsec falltime. During the voltage falltime, the diode impedance collapses, often resulting in substantially larger currents than during the voltage flattop. In addition, the deflection cavity gain increases at lower voltage. As a result, oscillation often occurs during the trailing voltage pulse. However, the signal at the voltage flattop seems to correspond to stable amplification. The initial tests of the complete magnicon circuit demonstrated high gain (~40 dB) in the deflection cavities at low values of the drive signal, but showed a nonlinear saturation effect in the deflection cavities at higher drive signals. As the drive power was increased, the signals in each of the deflection cavities appeared to saturate at ~1–10 kW. This saturation effect appears to be due to plasma formation in the cavities, initiated by the diode x–ray pulse, generated due to inadequate vacuum and surface conditions, and sustained by the microwaves. This plasma constitutes a nonlinear load on the cavities, clamping the microwave signal without completely shorting out the cavities. As a result, only small signals (<100 kW) were seen from the output cavity.

A major effort was made to improve the vacuum, including a redesigned vacuum manifold that improved the pumping of the deflection cavities by an order of magnitude. In addition, the cavities were disassembled, thoroughly cleaned with detergents and solvents, reassembled, and put through a low–temperature (~120° C) bakeout. Following this, a new set of measurements were begun. The low power saturation effect was still seen. However, at higher currents, voltages, and magnetic fields (e.g., 650 kV, 300 A, 11 kG), a new regime of behavior was observed in the deflection cavities. Greatly increased signal levels were seen in the second and third deflection cavities (with a nominal 1 kW signal in the first cavity), with the third cavity signal rising rapidly (~30 nsec) to approximately 1 MW, before suffering an rf breakdown. The penultimate cavity also reached high power (~100 kW) in a short pulse, before breaking down.

The next step was to assemble a heterodyne frequency diagnostic to measure the spectrum of the output radiation. This diagnostic combined the output signal with a local oscillator in a double-balanced mixer, and then acquired the difference signal using a Tektronix DSA602 digital oscilloscope with an analog bandwidth of ~1 GHz, a 2 GS/s digitizing rate, and an FFT (fast fourier transform) capability. By varying the local oscillator frequency, spectral components can be determined to a precision of a few MHz.

Using this diagnostic, a search was made for the predicted magnicon output frequency of 11.12 GHz. At the higher magnetic fields (~11 kG) that maximized the deflection cavity gain, only low frequency signals (<9.5 GHz) were observed. However, as the magnetic field was reduced, the predicted magnicon line appeared in the emission spectrum. Under a variety of conditions, the only spectral peak at frequencies greater than 9.5 GHz was a strong feature at 11.12 GHz. In order to assure that only this frequency component would be measured, K_u-band waveguide–to–coax adapters, with a 9.5 GHz cutoff frequency, were used as microwave pickups. Two pickups, one stationary, and one that swept on an 81–cm–radius arc about the output window, were used to measure the radiation antenna pattern. An anechoic enclosure was built around the pickups and the output window. The results for the E_θ scan are shown in Fig. 2. Each point is the average of three experimental shots, and the value from each shot is normalized by the power at the stationary pickup. A similar pattern was measured in E_r. Fig. 2 is in good agreement with the calculated far–field pattern of the TE_{21} mode. Using this data, one can relate the power received by a K_u–band pickup at the angular peak of the pattern to the total power radiated into 2π. The total power received by the pickup is calculated from the signals received by calibrated crystal detectors by determining (in a one–step transmission measurement) the total attenuation due to coaxial cable loss and fixed and variable attenuators.

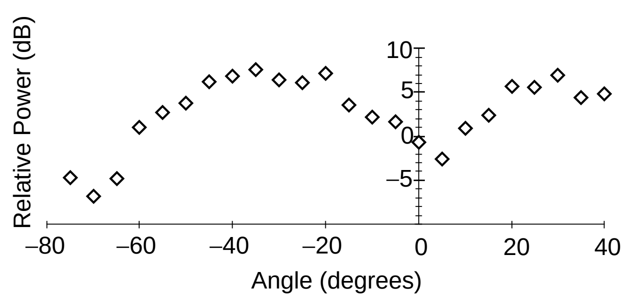

Fig. 2. Angular scan of E_θ component of antenna pattern.

Next, a scan of output power versus magnetic field was made with one pickup at the angular maximum of the antenna pattern. The results are shown in Fig. 3. The power is seen to peak in the vicinity of 7.3 kG. Using the procedure outlined above, the largest signals correspond to a total radiated power of 99 dBm, or 8 MW. The overall uncertainty in this number is still under investigation, but is estimated as ±3 dB. At 7.3 kG, the typical beam current is 225 A at 650 kV. Accordingly, the best estimate of the magnicon efficiency is 5.5%. Figure 3 also shows the results from time dependent simulations of the output cavity, assuming α=0.3 [5]. This α was chosen to yield approximately the same peak power as the experimental value. It is noteworthy that the simulations predict high power output over a much broader range of magnetic fields (P>2 MW for 6.5<B<11 kG) than is observed in the experiment.

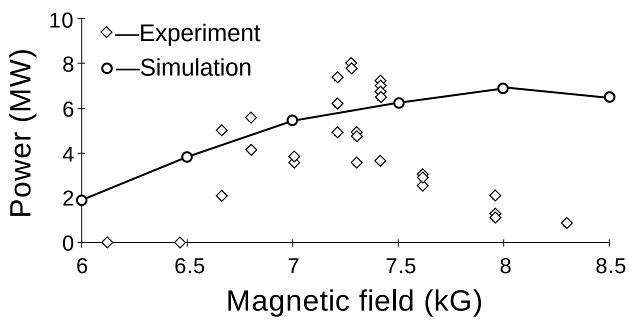

Fig. 3. Output power vs magnetic field.

The microwave measurements are still in progress. At this point, it is known that the signal in the output cavity is precisely 2× the frequency of the penultimate cavity signal. Also, at 7.5 kG, the shot-to-shot variation in the timing of the penultimate cavity signal is tracked by the timing of the output cavity signal. Furthermore, the penultimate cavity signal is only present (during the voltage maximum) if the 5.56 GHz drive signal is present in the first deflection cavity. However, we have not yet determined the gain in each of the cavities, the bandwidth of the interaction, or the degree to which the output signal is frequency or phase locked to the drive signal. We have also not determined the reason for the rapid decrease in output power as the magnetic field is increased (far more rapid than predicted by simulations) or the significance of the low frequency signals observed at higher magnetic fields.

IV. CONCLUSIONS

The NRL magnicon experiment previously demonstrated the basic magnicon gain mechanism in two–deflection–cavity experiments. However, those experiments were forced to operate at very modest power levels to avoid an unanticipated gain saturation effect, that occurred as intracavity powers approached the kilowatt level. In the test of the full five–cavity magnicon circuit, the same gain saturation effects were observed despite substantial improvements in the overall vacuum system. Experimental tests demonstrated that the saturation was due to plasma formation, caused by inadequate vacuum and surface conditions, and initiated by the large x–ray flux from the accelerator diode region. A program of progressively improving the vacuum conditions, while at the same time pushing the envelope of magnicon parameters by operating at higher current, voltage, and magnetic field, has demonstrated that this low power saturation effect can be "burned through" in short (~50–200 nsec) high power pulses in the deflection cavities, generally followed by rapid rf breakdown. Under the right combination of experimental parameters (650 kV, 225 A, 7.3 kG magnetic field), a large amplified signal is observed in the penultimate cavity at 5.56 GHz, and synchronous with it, a ~100 nsec FWHM frequency–doubled output pulse at 11.12 GHz. Based on a scan of the far–field antenna pattern and absolute calibration of the detected microwave signals, the best shots correspond to 8 MW ± 3 dB at an efficiency of ~5%.

Work is in progress to further characterize and optimize the operation of the present magnicon experiment. However, it is evident that the NRL program must transition to a thermionic diode, a cw magnet, and a rep–rated modulator in order to demonstrate the feasibility of efficient, long–pulse, high–duty–factor magnicon amplifiers at 11.4 GHz for linear accelerator applications.

V. ACKNOWLEDGMENTS

The authors are grateful for many useful discussions with W. M. Manheimer, A. Fisher, and R. Fischer, for the expert technical assistance of C. A. Sullivan in earlier phases of this program, and for the design collaboration with O. A. Nezhevenko and V. P. Yakovlev of the INP. This work was supported by the U.S. Department of Energy under Interagency Agreement DE–AI02–94ER40861.A000, and by the Office of Naval Research.

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