Final Report

Magnicon Development
to Power TeV Colliders

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I. Executive Summary

This is a final report on the three-year research program entitled “Magnicon Development to Power TeV Colliders,” which was carried out in the Plasma Physics Division of the Naval Research Laboratory (NRL) under Interagency Agreement DE-AL05-91ER40638 during the period 16 May 1991 through 14 May 1994. The magnicon is an advanced microwave tube with potential application to future high gradient linear accelerators such as TeV colliders. Under this program, NRL developed magnicon theory and simulation codes, designed a complete high gain magnicon circuit at 11.4 GHz, and carried out an experimental investigation of magnicon physics in the context of a single-shot experiment using a Marx generator power supply and a plasma-induced field emission diode. Successful deflection cavity-gain experiments were carried out, and tests were begun of a complete high-gain 11.4 GHz magnicon circuit. These tests demonstrated 40 dB of gain in the 5.7 GHz deflection cavities, but discovered a high power saturation effect that appeared to be due to plasma formation in the deflection cavities. This was attributed to inadequate vacuum conditions, combined with the inability to rf condition the cavities. As a result, only low power emission was observed from the output cavity. The tests of this magnicon circuit were continued under a new Interagency Agreement DE-AIO2-94ER40861.A000, that began at the conclusion of the three-year effort outlined in this report.
II. General Introduction

The goal of this program was the development of a high power frequency-doubling magnicon amplifier at 11.4 GHz. The magnicon [1–3] is an advanced “scanning-beam” microwave amplifier tube for use in powering future high gradient linear accelerators, such as the proposed TeV linear collider known as the Next Linear Collider (NLC). The rf source for the NLC must provide a power of 500 MW to 1 GW per tube in a 200 nsec pulse at a frequency in the range of 10–20 GHz. The required power can either be generated directly in 200 nsec pulses, or generated at longer pulse lengths (e.g., 1–2 µsec) and then pulse–compressed. Because the average power required by the NLC is so large, source efficiency is a crucial consideration.

The Magnicon Mechanism

The magnicon is a “scanning beam” analog to a gyroklystron amplifier, and offers the promise of high power tubes that will operate at very high efficiency (>50%) at frequencies of 10 GHz and above. Scanning–beam devices, also called “deflection–modulated,” create phase synchronism between the transverse deflection of the beam and the phase of a rotating rf mode, so that the interaction is invariant on the rf time–scale. This phase synchronism, which occurs without requiring a separate bunching mechanism, makes possible very high efficiencies. For example, several gyrocons, which are lower frequency (typically <1 GHz) scanning beam devices, have operated at efficiencies of 80–90% [4]. However, the achievement of high efficiency by means of a scanning–beam interaction also places tight constraints on beam quality.

In order to illustrate the operating principles of the magnicon, a diagram of the NRL magnicon concept is shown in Fig. 1. A magnetized pencil beam from a 500 kV electron gun transits a drive cavity containing a rotating TM_{11} mode generated by an external rf source. The rotating magnetic fields of the TM_{11} mode convert a small fraction of the beam axial momentum into transverse momentum (Larmor motion) about the applied axial magnetic field. The beam then
enters a sequence of passive deflection cavities, also called gain cavities, where the transverse momentum creates rf fields that further deflect the beam, producing a progressively higher fraction of transverse momentum. This proceeds until the electrons exiting the final deflection cavity, also known as the penultimate cavity, have an $\alpha$≥1, where $\alpha$ is the ratio of transverse to parallel momentum. Unlike the gain cavities of the klystron, the gain cavities of the magnicon are not used to create bunching— the electron motion is synchronous with the phase of the rf fields in each of the magnicon cavities, beginning with the drive cavity.

As a result of the phase–synchronous transverse deflection of the electron beam as a whole, the beam electrons entering the output cavity execute Larmor motion whose entry point and guiding center rotate in space about the cavity axis at the drive frequency. In the output cavity, the beam transverse momentum is used to drive a cyclotron–resonant fast–wave interaction that extracts principally the transverse beam momentum. This interaction can be highly efficient, because the electrons arrive in the interaction cavity coherently gyrophased. This provides for optimum energy transfer to a mode of the output cavity that rotates synchronously with the deflection cavity modes. In a conventional gyrotron oscillator, by contrast, the electrons enter the output cavity with random gyrophase, limiting the potential efficiency, and in a gyroklystron amplifier, only partial phase bunching can be achieved. However, maintaining a tight phase bunch in the magnicon output cavity requires the use of a good quality, small radius electron beam. The cyclotron resonance extraction mechanism in the magnicon output cavity is analogous to that of a fundamental–harmonic gyrotron, although the preferred magnicon operating mode is TM rather than TE. The phase synchronism in the output cavity can take place at either the fundamental or a harmonic of the drive frequency. For an X–band magnicon, it is convenient to operate the output cavity at twice the frequency of the deflection cavities.

Comparison with Other Sources
A variety of other technologies are candidates for providing the microwave amplifier tubes for the NLC. The two strongest candidates appear to be the klystron and the gyroklystron.

A number of groups are attempting to extrapolate klystrons into X-band. As an example, the SLAC klystron, a very mature S-band technology, is being steadily extrapolated to higher power at higher frequencies. However, the extent of the extrapolation is indicated by a klystron power scaling of approximately $P \propto f^{-2}$. Thus, quadrupling the frequency while maintaining the same output power is equivalent to a 16-fold improvement in performance. This extrapolation has required a substantial improvement in beam quality, and has dictated the use of a multisection output cavity, since the fields needed to decelerate the beam in the half-wavelength gap of a single-section cavity result in rf breakdown. However, the use of multisection klystron output cavities has resulted in problems with unstable operation. In addition, klystrons are very sensitive to mismatched loads, because changes in the rf fields seen by the electrons, which are being decelerated axially, can cause electron reflection. This can result in arcing and possible damage to the tube. Compared to X-band klystrons, the magnicon fast-wave output circuit offers higher power, while providing immunity to the instabilities of multisection output cavities. Furthermore, the predominantly transverse interaction in the magnicon output cavity cannot produce electron reflection, even in the presence of large mismatches in the output waveguide. This characteristic may eliminate the requirement for high power isolators on each tube, with a large saving in cost and complexity.

The gyroklystron is a potential alternative to the klystron as an X-band amplifier tube to power the NLC. The University of Maryland has made impressive progress in their X-band gyroklystron program, over the last eight years. However, their program has been constantly challenged to suppress the myriad instabilities that can be produced by the high-$\alpha$ electron beam produced from their thermionic MIG electron gun. Our design work suggests that the magnicon should extrapolate well to X-band operation, and should have greatly improved stability (against
oscillation in spurious modes), improved phase stability, and potentially a significantly higher output efficiency than an X–band gyrokystron.

The magnicon holds out the promise of a new class of high average power, high efficiency (>50%) microwave amplifier tubes, combining high frequency (>10 GHz) and long pulse (>1 μsec) with frequency and phase stability. However, magnicon technology is significantly less mature than either the klystron or the gyrokystron. A number of critical areas must be addressed in order to demonstrate the magnicon's potential. Among the important issues are: 1) Production of a high–current electron beam with low emittance and energy spread for efficient magnicon operation, 2) Achievement of $\alpha \sim 1$ in the deflection cavities, while avoiding rf breakdown, 3) Avoidance of parasitic oscillations, and 4) Optimization of output cavity interaction to achieve $\eta \sim 50\%$. 
III. The NRL Program

The goal of the NRL program was the demonstration of high power operation of an 11.4 GHz magnicon on the NRL Long–Pulse Accelerator Facility, a single–shot Marx generator power supply using a plasma–induced field–emission diode. The approach that was taken in this program was 1) to develop an in–house magnicon theory and simulation capability at NRL, 2) to carry out preliminary gain experiments, in order to evaluate the operation of the electron beam, the microwave drive source, the diagnostics, and the deflection cavities, and finally 3) to proceed to the design and fabrication of a complete X–band magnicon amplifier experiment. An additional goal was to investigate the progress of the well–established Russian magnicon program at the Budker Institute of Nuclear Physics (INP) in Novosibirsk, and to take maximum advantage of the knowledge and expertise developed there. In this section, we recapitulate the experimental, theoretical, computational progress in the present program. We also summarize the status of the INP magnicon program as of May 1994.

NRL Gain Experiment

In parallel with the development of theory, a preliminary two–deflection–cavity gain experiment was designed, assembled, and carried out at 5.7 GHz. This experiment provided a means to acquire initial operating experience on key components of the complete magnicon amplifier experiment, while testing the linear magnicon theory that was developed (in parallel) at NRL. There were a number of important goals, including 1) development and testing of an electron beam diode, 2) testing of the rf coupling to the prototype magnicon deflection cavities, 3) installation and testing of a C–band magnetron driver, and 4) developing microwave diagnostics. In addition, the gain experiments provided a means for the early discovery and resolution of many important problems affecting the overall magnicon project.
The two-deflection-cavity gain experiment employed a field-emission diode 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. This generated a 500 keV, ~200 A, 5.5-mm-diam. solid electron beam with low initial transverse momentum. Simulation results suggested a mean initial \( \alpha \approx 0.03 \). The two cavities were of identical pillbox design, with 3.2 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. The cavities were separated by a 1-cm-diam. drift space 1.132 cm long. 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 had four coupling pins spaced at 90° intervals in one end-wall. Two adjacent “coupling” pins were “long,” for use in driving the two linear polarizations of the cavity, and the remaining two “sampling” pins were “short,” in order to measure the cavity fields without loading the cavity. The 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 of the first cavity 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. The cavities, their pickups, and all other microwave components were fully calibrated using a microwave scalar network analyzer.

The response of the first cavity, and the gain of the second cavity, as a function of the drive frequency, were measured in each circular polarization of the TM\(_{110}\) mode. For the preferred circular polarization (which co-rotates with the electron gyromotion), the linear intercavity gain was 15 dB, at a frequency shift of ~0.18% with respect to the cold-cavity frequency. These observations were in excellent agreement with theory. The experiment also showed negligible beam loading of the first cavity signal, as predicted by theory. For the opposite circular polarization, the experiment found a small (~0.06%) positive frequency shift, combined with low gain and substantial beam loading, again in good agreement with theory. The main problem
uncovered in these experiments was a tendency of the cavities to exhibit multipactor effects at higher field levels. This was attributed to inadequate vacuum conditions and surface contamination. These problems areas will be substantially improved in the final experiment by using an oil–free pumping system and baking out the cavities, while eliminating the use of rf connectors employing materials with large outgassing coefficients. The experimental work was fully documented in Ref. [7], which is included as Appendix I.

NRL Theory Development

The theory of the magnicon separates readily into two parts. The first part deals with the deflection cavities that induce transverse momentum on an initially linear electron beam, while the second part deals with the output cavity that uses the transverse momentum to generate coherent microwave radiation. The first goal was to extend the analysis of the deflection cavities published by Manheimer [3], which considered only unmagnetized cavities, to the case of magnetized TM\textsubscript{110}–mode deflection cavities required for the frequency–doubling magnicon design. In parallel with the analysis, a deflection cavity code was written to study the behavior of realistic electron beams as they transit the magnicon device. This code propagates an ensemble of electrons through a sequence of driven and passive deflection cavities, separated by drift spaces, and self–consistently solves for the rf fields and the electron trajectories. The deflection cavity code was used to study magnicon intercavity gain as a function of beam, cavity, and drift space parameters, and to follow the evolution of a “realistic” electron beam, with spreads in initial radius and transverse momentum. The analysis and simulation were completed, and documented in Ref. [5], which is included as Appendix II.

The second theory effort was to understand the magnicon TM–mode output cavity interaction. A complete theoretical analysis of this interaction was carried out, and three separate magnicon codes were written. These output cavity codes are analogous to gyrotron oscillator codes. They were used to investigate interaction efficiency as a function of the interaction
parameters (cavity length, electric field, frequency detuning, and magnetic detuning), in order to find high-efficiency regimes. The synchronism between the electron beam and the rotation of the rf mode makes possible single particle simulations of the output cavity interaction. The output cavity parameter space was investigated on a single particle basis, in order to learn the fundamental design principles for the output cavity. Next, a single-particle time-dependent code was used to investigate the accessibility of attractive final states. (The TM-mode interaction makes possible more than one steady-state solution for a given set of interaction parameters.) Finally, multiparticle steady-state codes were used to evaluate the effects of realistic spreads in position and velocity on the efficiency of these final states. We found attractive high efficiency (≥ 50%) solutions corresponding to values of beam α ≥ 1. These solutions were also constrained to keep the maximum axial electric fields well under the Kilpatrick limit. However, the solutions demonstrated sensitivity to the spreads in α, energy, and radius that may result from the diode and deflection system. This analysis and simulation is documented in Ref. [6], which is included as Appendix III.

Russian Collaboration

Contact with the Russian magnicon program at the Institute of Nuclear Physics began with an invitation to Dr. O.A. Nezhevenko, head of the program, to visit the Washington area in May 1991. Next, a two week visit was made to the INP by Dr. Steven Gold of NRL in November 1992. This visit allowed an in–depth study of the program under way at the INP, including discussions with all of the chief scientists and engineers, an examination of components of the experiment, and participation in experimental operations.

Following the INP visit, arrangements were made to bring Dr. Nezhevenko and his chief theoretical/computational physicist, Dr. V.P. Yakovlev, to the Washington area to collaborate on the NRL experiment. A two month visit took place in February–March of 1993. This visit resulted in extensive discussions with the NRL magnicon scientists, including a detailed analysis.
of magnicon physics and technology and a discussion of the lessons learned from the experimental program at the INP. It also included a joint design effort on the circuit for the NRL X-band magnicon amplifier experiment. In essence, the INP design capability, and much of the INP design experience, was transferred to NRL. In the next two sections, we summarize the INP magnicon program and present the results of the joint design effort.

The INP Magnicon Program

The major world-wide research effort on magnicons, and on the earlier scanning beam device, the gyrocon, has been carried out at the Budker Institute of Nuclear Physics in Novosibirsk. The gyrocon research program began there more than 20 years ago under G.I. Budker. The gyrocon is a low frequency, low perveance device that operates without an axial magnetic field, and must propagate the beam for long distances without significant space charge spreading occurring. The early INP gyrocons operated at frequencies below 500 MHz, but with efficiencies exceeding 80%. One of these gyrocon devices has been in continuous use at the INP for the past 15 years as an rf power supply for a linear accelerator that is the first stage of electron acceleration, and positron production, for the VEPP–4 storage ring. After a successful program of gyrocon development, the research program at the INP, now directed by Dr. Nezhevenko, developed a concept for a higher frequency scanning–beam device that was named the magnicon. The principal difference between the magnicon and the gyrocon is the introduction of an axial magnetic field, allowing for 1) the propagation of much higher currents, and 2) the use of a fast–wave output cavity that extrapolates to high powers at microwave frequencies.

The earliest proof of principal magnicon experiment was carried out at low frequency (915 MHz), resulting in a device that produced 2.6 MW at 73% efficiency using a 300 kV, 12 A electron beam. This device still included an unmagnetized drift space, but employed a fast–wave output cavity. The research was published in 1988. The INP program then shifted to the development of a high power (50 MW) tube at 7 GHz, in which the entire device is magnetized.
The INP 7 GHz frequency-doubling magnicon amplifier program has been under way for the past 5 years. The first half of that period was used to develop a very special Pierce-type electron gun, employing a very high compression ratio (~1600×) to produce a final beam current of 230A and 430 kV with a diameter of <3 mm [2,8]. In May of 1994, the INP magnicon program was hot-testing their third magnicon circuit. The first two circuits uncovered some serious difficulties with oscillations, which they hoped would be solved in the third circuit. The third circuit produced 20 MW at 25% efficiency with 47 dB gain in May 1993, and was still under test to discover the cause of an rf breakdown in its penultimate cavity that was limiting the achievable output power. [The cause was later determined to be a synchronous fourth harmonic oscillation at 14 GHz in the penultimate cavity.]

Design of the NRL X-band Magnicon Amplifier

The last phase of the three-year NRL program was the design, engineering, fabrication, testing, and operation of a complete frequency-doubling X-band magnicon amplifier. This design was carried out in collaboration with Dr. Nezhevenko and Dr. Yakovlev of the Budker Institute of Nuclear Physics during their two month visit to the Washington area in February–March of 1993. The principal goal was a magnicon circuit that is compatible with the 500 keV, 172 A, 5.5-mm-diam. beam of the NRL field-emission magnicon diode.

The Russian magnicon codes are designed to calculate the realistic rf mode structure of magnicon cavities connected by beam tunnels, to determine electron trajectories in those cavities by integrating the full Lorentz equations for the electron motion, and to find the self-consistent rf amplitude and phase in each of the cavities. The simulations propagate a finite-diameter electron beam through a sequence of 5.7 GHz deflection cavities containing synchronously rotating TM_{11} modes, followed by an 11.4 GHz output cavity employing a synchronously rotating TM_{21} mode. For the gain and penultimate cavities, iteration is used to determined the self-consistent rf amplitudes in each cavity, including the effect of a finite Q due to wall losses, and to determine the
correct rf phase. For the output cavity, an rf field amplitude is assumed, the rf phase is adjusted to optimize the efficiency, and finally the output $Q$ consistent with overall power balance calculated. The magnicon codes can also calculate a threshold for self-excitation (oscillation), that would interfere with phase-stable magnicon amplifier operation.

The final magnicon circuit parameters are shown in Table I. The circuit includes a drive cavity, two half-wavelength gain cavities, and a two-section $\pi$-mode penultimate cavity, all operating at 5.7 GHz, followed by an output cavity operating at 11.4 GHz. This configuration is shown schematically in Fig. 1. Figure 2 illustrates the “ideal” operation of the magnicon for a single, initially on-axis electron, by plotting the spatial evolution of the electron energy, pitch angle, and trajectory through the deflection cavities and the output cavity. Notice that the electron transverse momentum, plotted as the “pitch angle” or $\tan^{-1}\alpha$, progressively increases through the deflection cavities, but that most of the increase occurs in the penultimate cavity. Finally, the transverse momentum is reduced to near zero in the output cavity and at the same time the electron energy decreases by $\sim$58\%.
# Table I. Magnicon Design Parameters

| Input: | \(~1\ kW @ 5.7\ GHz\) |
| Beam: | \(500\ \text{keV, } 172\ \text{A}\) |
| Deflection cavities: | 3 half-wavelength \(\text{TM}_{110}\)-mode cavities (1 drive, 2 gain)  
\(\text{Cavity Radius}=3.2\ \text{cm}; \text{Cavity Length}=2.3\ \text{cm};\)  
\(\text{Beam Tunnel Radius}=0.5\ \text{cm}; \text{Beam Tunnel Length}=1.9\ \text{cm}\) |
| Penultimate cavity: | \(\pi\)-mode two-section \(\text{TM}_{110}\) cavity,  
\(\text{Cavity Radius}=3.2\ \text{cm}, \text{Cavity Length}=5\ \text{cm}\) |
| Output cavity: | \(\text{TM}_{210}\) mode, \(Q\sim 800\) (for 5.5-mm-diam. beam)  
\(\text{Radius}=2.15\ \text{cm}; \text{Length}=5\ \text{cm}\) |
| Maximum rf fields at walls: (Penultimate and Output Cavities) | \(~250\ \text{kV/cm}\) |
| Output: | \(f_{\text{out}} = 4f_{\text{SLAC}} = 11.4\ \text{GHz}\)  
\(P \sim 20\ \text{MW} \@ \eta \sim 24\%\) for 5.5-mm-diam. beam  
\(P \sim 50\ \text{MW} \@ \eta \sim 56\%\) for 2-mm-diam. beam  
Overall gain \(~44\sim 48\ dB\) |
Figure 3 shows the optimized simulation of the final magnicon circuit for a 5.5-mm-diam. electron beam. The interaction of a 5.5-mm-diam. beam with the cavity fields results in a large spread in the electron trajectories. A significant energy spread is first seen in the second gain cavity, but the most significant phase mixing occurs in the penultimate cavity. The nonideal effects in both of these cavities result in large part from the radial electric fields at the penultimate cavity iris and at the cavity beam tunnels. As a result of these effects, the coherence of the interaction in the output cavity is degraded, resulting in a final efficiency of only 24%. This is lower than the original target efficiency of 50%. However, the path to a higher efficiency device is straightforward, and relates directly to the use of a higher quality electron beam. This will require the use of a thermionic electron beam diode. This is discussed further in the section on a proposed thermionic magnicon experiment.

The documentation of this design was completed in Ref. [9], and has been included in this report as Appendix IV.

Status of the NRL X-band Magnicon Amplifier Experiment

The complete X-band magnicon amplifier circuit was engineered and fabricated. The circuit (shown in Fig. 4) completed the final stages of calibration and cold testing, was installed on the Long-Pulse Accelerator facility, and initial hot tests began in late December 1993. Since the single-cavity gain of the magnicon cavities is well understood, both theoretically and experimentally, the main concern in those hot tests was to demonstrate high total gain and high power operation while avoiding microwave breakdown in the magnicon cavities. Breakdown was known to be a serious potential problem, due to the limitations on the cavity vacuum and the limited surface cleaning that is feasible in a field-emission-diode experiment. (SLAC klystron cavities, by contrast, employ very high temperature bakeout, ultraclean vacuums, and rf conditioning to achieve their maximum rf fields.) In initial tests, 40 dB of gain was observed in
the deflection cavities at low drive powers. However, at higher drive powers, a saturation effect was observed, with the maximum deflection cavity powers in the range of 1–10 kW. The causes of this saturation effect were extensively investigated. It was discovered that a cavity “breakdown” process was occurring, typically initiated by the x-ray pulse from the electron beam diode. This breakdown process produces a plasma in the cavities that constitutes a nonlinear cavity load, clamping the level of rf fields in the cavity. The plasma was observed both due to its effect on the cavity loading, and directly by measuring visible light emission from within the cavities.

As a result of these observations, a study was made of methods to suppress this plasma formation, including thorough cleaning and degreasing of all surfaces, use of “mirror finish” cavities, cavity surface coatings (teflon, graphite, titanium), low temperature vacuum bakeout, rf conditioning (of the drive cavity), and lead shielding of the diode x-ray pulse. We had previously converted to an oil-free vacuum system, using cryopumps at both ends of the experiment. However, the limited vacuum conductance of the beam tunnel and the large surface area of the cavities resulted in a vacuum base pressure of ~5x10^-5 Torr in the cavities. In order to improve the vacuum, a supplementary vacuum manifold, which pumps through a pattern of holes on the sides of the cavities, was designed.

At the conclusion of the third year of the program, low power gain had been demonstrated in the deflection cavities, but gain saturation was still observed at higher drive powers. As a result, only very small output powers were produced at 11 GHz. Efforts were still in progress to improve the vacuum, to overcome the saturation effect in the deflection cavities, and to demonstrate high power operation of the output cavity.
IV. A Proposed Thermionic Magnicon Experiment

The Naval Research Laboratory has proposed to the Department of Energy the continuation of the magnicon development program for an additional three years, in order to develop a rep-rated magnicon amplifier based on a thermionic electron beam. The existing program has demonstrated computationally that an efficient magnicon requires a very high brightness electron beam, combined with a long pulse (at least 500 nsec) in order to allow for cavity fill times. There appears to be no satisfactory means to produce such a beam from a field-emission electron gun. However, the best available thermionic electron guns can produce such beams. In particular, the electron gun developed by the Budker Institute of Nuclear Physics in Novosibirsk for their 7 GHz magnicon appears to be capable of producing the required high brightness electron beam for a high efficiency 11.4 GHz magnicon device. In addition, U.S. tube companies should be able to design a comparable electron gun.

The proposed three-year follow-on program would involve the acquisition of an electron gun, the redesign of the magnicon cavities to make optimum use of the high brightness electron beam, and the engineering of a microwave circuit capable of high temperature bakeout to eliminate the multipactor and breakdown problems that were observed in the preliminary single-shot magnicon gain experiments. (The required rf fields are below those routinely achieved in SLAC klystrons.)

Design of a Thermionic Magnicon Experiment

The key to the efficient operation of a scanning beam device is the quality of the electron beam. The scanning-beam interaction mechanism results in an interaction that is invariant on an rf time scale. Thus, every temporal slice of electrons emitted from the cathode experiences identical
rf fields in the output cavity, without any requirement for beam bunching. What is critical is the extent to which every electron in that temporal slice experiences similar transverse accelerations through the magnicon deflection system, and similar decelerating fields in the output cavity. While excessive emittance or voltage ripple can have deleterious effects, the key beam quality parameter for the magnicon is the size of the electron beam.

The design of the circuit for the previous single-shot magnicon experiment is directly relevant to the proposed thermionic magnicon experiment. The operation of that circuit has been evaluated as a function of beam radius (see Appendix IV). The numerical simulation shows that the maximum size of the beam from the magnicon electron gun must satisfy the relation $r_b/\lambda < 0.04$, where $r_b$ is the beam radius and $\lambda$ is the free-space wavelength of the rf radiation, if the highest efficiencies are to be obtained. For an 11.4 GHz magnicon, this dictates the use of a maximum beam diameter of 2 mm.

The result of a simulation of the present magnicon circuit for a 2-mm-diam. beam are shown in Fig. 5. The simulation indicates that an interaction efficiency of ~56% can be attained. However, this does not appear to represent the upper limit for an X-band thermionic magnicon. Since the present circuit is optimized for the larger beam size, it is not fully optimized for the smaller beam diameter. Under the proposed program, this circuit will be redesigned to optimize performance for a 2-mm-diam. beam, with a target efficiency of at least 60%. The re-optimization of the magnicon circuit for the proposed thermionic magnicon experiment will be carried out at NRL in collaboration with INP scientists. A complete set of magnicon steady-state design codes are now operational at NRL, and an NRL-developed time-dependent magnicon code is in a preliminary testing stage. This new code supplements the Russian steady-state codes by directly determining the stability and accessibility of final states.

The small beam diameter, combined with the requirement that the beam power must be in the range of 100 to 200 MW for a 50–100 MW magnicon device, dictates a combination of high voltage (e.g. 500 kV), high current (e.g., 300 A), and high compression ratio (since the maximum
NRL design is end-coupled. End-coupling automatically preserves the quadrupole symmetry. In addition, our computational approaches are complementary, since the Russians have employed steady-state codes, while the access to modern high-performance computers has permitted NRL to develop time-dependent codes.

The NRL and INP programs have remained in excellent communication via frequent electronic mail communications. This has permitted NRL to monitor the progress of the INP program, and to learn from their progress and their problems. This continued contact has been a major advantage in speeding the progress of the NRL program.

The proposed continuation of the NRL program would permit a continuation of the collaboration with the INP magnicon program. It would include the purchase of a suitable thermionic magnicon electron gun, to use in conjunction with the circuit previously designed in collaboration with the INP, which would be reengineered for high vacuum operation. Further optimization of the circuit will be carried out using simulation codes. A continuing evaluation of the progress demonstrated, and the problems uncovered, in the INP program will help guide the path of the NRL program.
V. References


8. O.A. Nezhevenko, private communications.
VI. Figure Captions

Figure 1. Schematic design of the NRL X-band frequency-doubling magnicon amplifier

Figure 2. Simulation of the final magnicon design for a single on-axis electron, showing the spatial evolution of electron energy and velocity pitch angle, and the electron trajectory

Figure 3. Simulation of the final magnicon design for a 5.5-mm-diam. beam

Figure 4. Photograph of the magnicon cavities

Figure 5. Simulation of a magnicon using the 2-mm-diam. beam from the INP magnicon gun
Figure 1

\[ f_c \approx 2f_{\text{drive}} \]

\[ f_c \approx f_{\text{out}} = 2f_{\text{drive}} \]
Figure 3
VII. Appendices


VII. Appendices


